

THE MINERAL FACIES OF ROCKS

BY

PENTTI ESKOLA

Preface.

The present paper is preliminary in a double sense of the word. In the first place, it is a preliminary report of an investigation on the Norwegian Eclogites, which will be treated in detail in another publication. But at the same time it is a report of the present state of a series of investigations carried on since 1914 with the aim of clearing up the relations between the chemical and mineralogical composition in different kinds of rocks.

The rocks are here dealt with in groups, called Mineral Facies. It follows from the nature of this paper that the various groups will be treated in a rather different manner. The groups called the Hornfels, the Sanidinite and the Amphibolite facies will be here treated shortly, as it is possible to refer to earlier more detailed investigations. In the case of a number of other facies brevity is imperative, because they are still too little studied from the present view-point. In my study of the eclogites I was led to some conclusions that seem to be new and deserving of general interest. It was thought advisable on this occasion to give a summary of these results, without entering into details. The chapters dealing with the eclogite facies are therefore somewhat longer than the other.

This paper is a part of the results of my work done during a visit to Christiania in 1919-1920. My cordial thanks are due to Norwegian geologists who all showed me the kindest helpfulness. In this connection I wish especially to name

Professor Dr. V. M. GOLDSCHMIDT, Director of the Mineralogical Institute of the University of Christiania, Professor J. SHELIG, Director of the Mineralogical and Geological Museum of the University of Christiania, Professor Dr. W. C. BRØGGER, Dr. H. H. REUSCH, Director of the Geological Survey of Norway, and Professor Dr. C. F. KOLDERUP, Director of Bergens Museum.

Professor GOLDSCHMIDT has had a very effective share in my work. During frequent colloquies with him most of the problems here treated were discussed, and many of the ideas developed have grown from his suggestions. For all his kindness I wish to express to him my most sincere thanks.

To Mr. OLAF ANDERSEN of the Geological Survey of Norway I am very obliged for much valuable help and especially for his kindness in making grammatical corrections in my manuscript.

These studies have been carried out with assistance from two funds for the advancement of scientific research in my native country, Finland, namely, ALFRED KORDELIN'S General Trust for the Advancement of Progress and Knowledge, and HERMAN ROSENBERG'S Travelling Bursaries Trust of the University of Helsingfors.

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Introduction.

F. BECKE, U. GRUBENMANN and C. R. VAN HISE have based the study of metamorphism on the physico-chemical principle of re-adjustment of systems in correspondence with changes in the attendant physical conditions. V. M. GOLDSCHMIDT first proved that metamorphic rocks, by re-crystallization, may have arrived at a very perfect state of chemical equilibrium. This conclusion was the result of a study of the contact metamorphic hornfelses of the Christiania region in Norway.¹ The present writer found, in the rocks of an Archaean metamorphic area in Southwestern Finland,² a similar perfect state of equilibrium, though with other minerals as stable phases. The writer proposed to use the term metamorphic facies to designate a group of rocks characterized by a definite set of minerals which, under the conditions obtaining during their formation, were at perfect equilibrium with each other. The quantitative and qualitative mineral composition in the rocks of a given facies varies gradually in correspondence with variations in the chemical bulk composition of the rocks.

A tendency towards a state of equilibrium is, of course, a general feature in all kinds of crystallization, and in fact igneous rocks also may have reached it. Thus we may speak

¹ V. M. GOLDSCHMIDT, Die Kontaktmetamorphose im Kristianiagebiete. Vid.-Selsk. Skrifter. I. Math.-Naturv. Klasse, 1911. No. 1. This monograph will in the following be shortly called „Kontaktmetamorphose“.

² P. ESKOLA, Om sambandet mellan kemisk och mineralogisk sammanställning hos Orijärvitraktens metamorfa bergarter (with an English Summary: On the Relations between the Chemical and Mineralogical Composition in the Metamorphic Rocks of the Orijärvi Region). Bull. Comm. géol. Finl. n:o 44, 1915. In the following called shortly „Sambandet“.

of igneous facies, parallel to the metamorphic. Both these conceptions may properly be headed under a more general term, the mineral facies.

A mineral facies comprises all the rocks that have originated under temperature and pressure conditions so similar that a definite chemical composition has resulted in the same set of minerals, quite regardless of their mode of crystallization, whether from magma or aqueous solution or gas, and whether by direct crystallization from solution (primary crystallization) or by gradual change of earlier minerals (metamorphic recrystallization).

By defining for each crystalline rock its place amongst the mineral facies we arrive at a mineralogic-chemical classification, the divisions of which, the largest as well as the smallest, up to the very finest variations, are given by nature itself.

On the first line we have the two parallel branches: that of the igneous and that of the metamorphic rocks. In each of them we have as many facies as there are different sets of minerals in any series of chemically similar rocks. The number of the facies thus being *a priori* undefined, the system will be so comprehensive and elastic as to be adaptable to every degree of progress and refinement of the science. The definite associations of minerals which appear in each facies in a quantitative correspondence with the variation in the chemical composition represent the smaller divisions of the facies system. An example of this kind of classification was afforded by GOLDSCHMIDT in the case of the hornfels rocks, and the divisions corresponding to definite associations were called classes.

Detailed investigation shows that the mineral associations of various rocks very often represent equilibrium in such a state of perfection that the characteristics of the ideal equilibria may be deduced from them. It is therefore possible to use these associations as a basis of classification. In cases of rocks that do not follow the rules of mineral association in any facies we may at least find, by comparative study, the facies which they have tended to approach during the chief phase of their mineral development.

Certain difficulties arise from the specific kind of action of unequal pressure or stress (cf. Sambandet p. 18 and 116). During stress action no true equilibria are possible. However, the ideal equilibria may even here be used as norms of the classification, as pointed out by J. JOHNSTON and P. NIGGLI.¹

We must also be aware of the complication that arises from the fact that pressure influences the origin of minerals in two different manners: (I) by moving the equilibria towards the associations and modifications which have the smallest volume and (II) by preventing volatile components from escaping, whereby the formation of hydrated minerals is favoured and the temperature of crystallization is depressed. The importance of this latter kind of action has been much emphasized by N. L. BOWEN in his masterly treatise on the development of the igneous rocks.² This fact does not, however, lessen the validity of the facies principle, as this only takes into account the actual mineral development with all components present.

We have before us the task of investigating all varieties of rocks in order to clear up the correlation between their chemical and mineralogical composition. This programme was for the first time expressed by V. M. GOLDSCHMIDT in 1914,³ when he had already begun to explore the Scandinavian Mountain Region with the explicit purpose of determining, by means of the mineral parageneses, the zones of the mountain chain in which conditions of different temperature and pressure had prevailed during the metamorphism. Shortly after I proposed the conception of metamorphic facies and the classification based upon it, without knowing of GOLDSCHMIDT's paper. In his first publication on the regional-metamorphic rocks in the Caledo-

¹ J. JOHNSTON and P. NIGGLI, The General Principles Underlying Metamorphic Processes. *Journal of Geology* 21, 1913, p. 612.

² N. L. BOWEN, The Later Stages of the Evolution of the Igneous Rocks. *Jour. Geol.* XXIII, 1915, Suppl.

³ V. M. GOLDSCHMIDT, Om mineralogiens opgaver. (Tiltrædelsesforelæsnings holdt den 28. september 1914). „Naturen“, novbr. 1914.

nian Chain¹ the latter already used the facies conception proposed by me as a basis of division.

H. VÄYRYNEN recently studied a series of igneous rocks in Southern Österbotten in Finland² and dealt with them from view-point of the facies principle. He arrived hereby at many interesting suggestions concerning the mineral development at magmatic crystallization.

Earlier the mineral associations had been subjected to a special study by P. NIGGLI with regard to the chloritoid-schists in the Gotthard region,³ this paper thus having a direct bearing on the facies-petrology.

A large amount of work, still unpublished, has been done by Professor GOLDSCHMIDT on the rocks of the Scandinavian mountains. I have myself undertaken an investigation of that facies to which the eclogites belong, and a summary of this study will already be given in this paper. Furthermore I am at present working with a series of metamorphic rocks from Eastern Fennoscandia.

From what has been said it will appear that the quantity of work done with the special aim of clearing up the facies relations of rocks is not quite inconsiderable. Much more, however, remains to be done.

Petrographical descriptions in the literature may of course also be utilized to deduce rules of mineral association; in the following will be given a summary of such a literature research on Archaean metamorphic rocks in Finland and Sweden.

¹ V. M. GOLDSCHMIDT, Die Kalksilikatgneise und Kalksilikatglimmerschiefer des Trondhjem gebietes. Vid.-Selsk. Skrifter. I. Mat. Naturv. Klasse. 1915. N:o 10.

² HEIKKI VÄYRYNEN, Etelä Pohjanmaan graniitti-dioriittisten vuorilajien petrologiaa. Helsinki 1920. (Dissertation. Will be published in German language in Bull. Comm. géol. Finl.).

³ P. NIGGLI, Die Chloritoidschiefer und sedimentäre Zone am Nordrande des Gotthardmassivs. Beitr. zur geol. Karte der Schweiz, 36, 1912.

Stable and Unstable Relics.

Here it would seem useful to repeat some general statements concerning the relict phenomena in crystalline rocks (Sambandet p. 24 and 118).

Relics may appear whenever a rock has been successively subjected to various physical conditions, each set of which tend to produce a definite facies. If a mineral, stable in the earlier facies, is also stable in the later facies, it will, unless stress action sets in, be preserved in its original form and present a stable relict. This is a very common case, e. g. feldspar in amphibolites etc., quartz in very many various rocks. But when a mineral, or a definite association of minerals, becomes unstable, it may yet escape alteration and appear as an unstable relict.

The discrimination between the stable and unstable relics, so far as I know, never made clear before, throws light on many common and important petrographical phenomena. We may here mention only uralitization, as an example. It has been tacitly assumed that the pyroxenes by metamorphism most likely would be converted into amphiboles. From the view of the facies-conception this statement must be much restricted, and we may say, that uralitization takes place when pyroxene-bearing rocks are brought under the conditions of the amphibolite-facies (which is the name proposed later for a certain facies). But even in the rocks of amphibolite facies the diopside may be a stable constituent, viz. in those rocks in which femic lime is present in excess over the hornblende ratio (in the simplest case $\text{CaO} : (\text{Mg}, \text{Fe})\text{O} = 1 : 3$). We may, in such a rock, find diopside seemingly in process of alteration into hornblende, and yet the diopside is not an unstable mineral. It is only unstable in the presence of excess of magnesia, and in the case supposed the alteration had gone so far as possible at the composition given, and the rock had arrived at an equilibrium.

We may now suppose a gabbro brought under the conditions of the amphibolite facies. Then two cases are possible:

Either the gabbro has a composition at which the diopside is stable in the amphibolite facies (a rather rare instance), or there are, in the rock, ferrous oxide and magnesia in excess of the ratio named above. In the former case the original diopside of the gabbro will preserve itself as a stable relic, in the latter case it will be uralitized. If, nevertheless, we find diopside in such a rock, then it is an unstable relic. Such gabbroid rocks are not rare e. g. in the Fennoscandian Arhaean, where the largest part of gabbros have been completely uralitized or had crystallized already primarily in the same facies.

A common phenomenon, fairly well illustrative of the tendency towards equilibria, is the formation of armours around such minerals which have become unstable in their association, but have not been brought beyond their fields of existence in general (the armoured relics).¹ Thereby the associations of minerals in actual contact with one another become really stable. If, however, the constituent minerals of a rock containing armoured relics are named without noting this phenomenon, it may be taken as an unstable association.

Many phenomena at the contacts of two minerals, such as so-called coronas, reaction rims etc., by J. J. SEDERHOLM classified under the collective term synantetic minerals,² are such armours.

¹ When H. BACKLUND (Geol. Fören. i Stockholm Förh. XXXX, 1918, p. 257) called my definition of armoured relics a „helfhypothesis“, this proves only that he had failed to understand the phenomenon. There is nothing of a hypothesis in the conception of armoured relics, but a statement of the simple fact that minerals occurring in an association against the phase-rule are commonly isolated from the other minerals by the armour which is formed by the reaction product of the non-congressible minerals. And the occurrence of such phenomena does by no means need any helping hypothesis, as it is itself one of the fairest proofs of the equilibrium theory, the armour-mineral being stable with the associations on both sides and isolating the non congressible neighbours from each other.

² J. J. SEDERHOLM, On Synantetic Minerals. Bull. Comm. géol. Finl. n:o 48, 1916.

Metamorphic Facies.

So far as metamorphic rocks are concerned, the main lines of the facies-classification will be conformable to BECKE'S and GRUBENMANN'S and VAN HISE'S well-known divisions in depth-zones. Thus the facies principle, so far from bringing any revolution in the science, may directly continue upon the work founded by those classicists in the metamorphic petrology, with the aim of ascertaining with ever greater exactitude the temperature and pressure conditions under which rocks have originated.

We may actually start from GRUBENMANN'S three depth-zones of crystalline schists, and will find the most typical rocks of each zone to compose a facies in the sense defined. These three facies, however, are not identical with the depth-zone groups (GRUBENMANN'S orders), these latter being more comprehensive and less sharply defined. In each depth-zone we shall find more than one facies.

Even the difference just pointed out would defend the proposition of a new nomenclature for the facies system, in spite of the actual agreement with the depth-zone system. But there is still another reason. The prefixes kata, meso and epi refer to a supposed origin at a certain depth, corresponding to temperatures and pressures within definite limits. The facies-principle, on the other hand, is based directly upon the mineral associations and is thought to serve as a means of clearing up these limits. Therefore it must not be forged into a finished scheme.

The most natural nomenclature in the facies system would, I think, be one where every rock-name would be composed of two parts, the former expressing the typical mineral constituents and the latter the facies. GOLDSCHMIDT already practiced this method in the systematics of the hornfels, using hornfels as a facies-name, though it is not quite correctly a facies name in our sense, as each facies should comprise all possible chemical variations, while e. g. a limestone is not called a horn-

fels. Terms immediately adaptable to the facies systematics do not exist, they must be fixed by arbitrary definitions.

A mineralogical nomenclature has also already been in use in salt-petrography, a branch of science on the firmest physico-chemical basis.

The facies-classification being still very little elaborated it seems premature to propose any detailed nomenclature. In the following will be given at first a short synopsis of five central metamorphic facies, corresponding to the most essential portions of kata, meso and epi rocks respectively, the contact metamorphic rocks of the Christiania type and the so-called pyrometamorphic rocks. In the present paper I will quite provisionally call the three first-named facies by the names of the rocks having a gabbroid bulk composition, in which the mineral composition is most sensitively variable. Thus we have the greenschist facies, amphibolite facies and eclogite facies. The contact metamorphic facies named will simply be called the hornfels facies, and for the pyrometamorphic rocks we use the name sanidinite facies after their best known representative.

We shall at first see which mineral associations are characteristic for these five facies in rocks with a gabbroid bulk composition. I have, in the following table, selected analyses for which the corresponding mineral composition, or the mode, is known, and have considered the exact agreement of the analyses of less importance, as presently no one denies that representatives of all these rocks may be quite identical in composition, disregarding the percentages of water.

As pyrometamorphic rocks (of the sanidinite facies) having a gabbroid bulk composition do not seem to have been analyzed, I have instead of such a rock put an analysis of a hypersthene-augite bearing diabase, belonging to the igneous parallel facies which will be termed the diabase facies.

	Diabase facies: Diabase. Shtsheliki, Olonez, Carelia. W. WAHL, Fennia 24, 3, 1908, p. 20.	Hornfels facies: Essexite-hornfels. Aarvold, Christiania. V. M. GOLDSCHMIDT Die Kristallinen Schiefer, 1910, p. 176.	Greenschist facies: Epidote-chlorite-schist. Val de Bagne, Wallis. U. GRUBENMANN, Die Kristallinen Schiefer, 1910, p. 211.	Amphibolite facies: Amphibolite. Kisko, Finland. P. ESKOLA, Bull. Comm. géol. Finl. 44, 1915, p. 51.	Eclogite facies: Eclogite. Burgstein, Tirol. L. HEZNER, T. M. P. M. 22, p. 466.
SiO ₂	49.15	49.19	44.82	49.73	46.26
Al ₂ O ₃	11.48	14.32	20.18	16.05	14.45
Fe ₂ O ₃	3.97	6.00	3.47	2.44	4.41
FeO	13.22 NiO 0.07	8.28	4.04	7.96	5.82
MnO	0.44	0.09	n. d.	0.20	n. d.
MgO	5.39	5.70	7.84	7.84	11.99
CaO	8.63 BaO 0.04	8.55	10.82	10.22	11.66
Na ₂ O	2.64	3.48	2.03	2.99	2.45
K ₂ O	1.36	0.79	1.30	0.61	1.51
TiO ₂	2.41	2.98	2.38	0.56	0.28
P ₂ O ₅	0.32	n. d.	n. d.	0.12	n. d.
H ₂ O	0.57 FeS ₂ 0.22	0.51	3.61	1.03	1.10
Sum	99.91	99.71	100.49	99.75	99.93
Sp. G.	3.090	3.021	3.05	2.99	3.45
Mode	Plagioclase 48.4 Hypersthene-augite 37.4 Hornblende, mica, iron ore etc. 14.2	Plagioclase . 48 0/0 Hypersthene 17 " Diopside . . 18 " Biotite, iron ore etc. . . 17 "	Epidote 43 0/0 ² Chlorite 24 " Albite 18 " Mica, iron ore etc. 15 "	Plagioclase . . 26.5 0/0 Hornblende . . 71.5 " Quartz 20 " Iron ore and rutile 1.0 "	Omphacite 48.5 0/0 Garnet . . . 50.5 " Iron ore and rutile 1.0 "

¹ Determined by the writer ² Calculated by the writer.

In the description of the different facies it seems useful to make a distinction between critical and typical constituent minerals and associations. Critical constituents or associations are such whose occurrence is already a criterion of the rocks belonging to a certain facies, i. e. minerals or associations only stable under those definite conditions of that facies. As typical, on the other hand, we designate generally all the minerals stable in a facies, they may either have originated at the crystallization of that facies, in which case we call them congeneric, or they may be stable relics.

Besides the typical minerals rocks may contain minerals not stable in their association. They are either unstable relics or posterior products.¹

Although the names of the facies here used are provisional they must still be used in a strictly defined sense. With the sanidinite facies we thus class all the pyrometamorphic rocks containing, when silicate-rocks, regular associations of some of the following silicatic type minerals:

Sanidine (homogeneous potash soda feldspars), plagioclase, sillimanite, cordierite, clinoenstatite-diopside (homogeneous mixtures of clinoenstatite, clinohypersthene and diopside), wollastonite, olivine. The sanidine and the clinoenstatite-diopside are critical.

With the hornfels facies we understand the groups of contact-metamorphic rocks which show the same mineral facies as the contact-metamorphic rocks of the inner contact-zones in the Christiania region, regardless of their composition or structure or premetamorphic development, and excluding such so-called hornfelses which show some other mineral development. Type minerals are orthoclase, plagioclase, andalusite, cordierite, biotite, hypersthene-enstatite (orthopyroxene), diopside, wollastonite, grossularite-andradite, olivine. The association of hypersthene and diopside is critical.

¹ The term secondary products, frequently used to designate the things here called the posterior products, seems to me less adequate, as the rocks, after their main mineral formation, have often passed through several stages of posterior changes, that might then be spoken of as secondary, tertiary, quaternary etc.

The amphibolite facies is that metamorphic facies the rocks of which follow those rules of mineral association which I found in the metamorphic rocks in the Orijärvi region. They always, when their composition allows it, contain some mineral of the amphibole group. Type minerals are microcline, plagioclase, muscovite, andalusite, cordierite, almandite, anthophyllite and cummingtonite, diopside, wollastonite, grossularite-andradite, olivine.

The greenschist facies includes metamorphic rocks containing some of the following minerals:

Albite, sericite, chlorite, talc, serpentine, epidote, calcite, dolomite. The associations of potash mica with chlorite and of epidote with albite are especially characteristic.

The definition of the eclogite facies can hardly be put in a few words. The typical silicate minerals are garnets (pyrope-almandite-grossularite), monoclinic pyroxenes (clinopyroxenes) being isomorphic mixtures of some of the silicates diopside, jadeite, pseudojadeite ($(Ca, Mg, Fe) Al_2 Si_4 O_{12}$) and a few others in small amounts, hypersthene-enstatite (orthopyroxene), olivine, disthene. The garnets with more than 30 mol. % pyrope and the jadeite and jadeite-bearing pyroxenes are critical of this facies. Rutile is a characteristic minor constituent. Many eclogites contain biotite, but in other cases no potash-mineral seems to have been stable.

Certain minerals are common to several facies. Thus quartz and calcite are stable under widely various conditions. A limestone may show the same mineral (calcite) in all the facies. Diopside exists in all but the greenschist facies.

There are, of course, gradual transitions between the facies; the transition points between definite minerals or associations are different, and combination of temperatures and pressures may have different effect upon the changes.

In rocks belonging to a definite facies, the relations between their chemical and mineralogical composition may be expressed graphically, so that the mineral associations appear directly from the diagrams based on the chemical analyses. Such a graphical solution is practicable, if the number of the components controlling the mineral composition can be reduced

to an extent allowing of a diagrammatic expression. The principle of the Osann triangle has proven most useful, but it allows only three components to be represented simultaneously, while the rocks have a much larger number. By rational choice and restriction I have, however, succeeded in finding a method of expression useful for the majority of rocks of more common composition, and having excessive silica, so that always the compounds highest in silica can be formed. In one corner of the triangle is located the alumina not combined with potash or soda, in another the lime and in the third one magnesia with ferrous iron. The minor constituents are, after subtracting the amounts of $(Al, Fe)_2O_3$, CaO and $(Mg, Fe)O$ combined in them, left out of consideration.

By this method all the common silicate minerals excepting those containing soda or potash can be expressed, and some salient features of the mineral paragenesis in the five facies of rocks appear clearly, most of the characteristic and variable minerals being compounds of ferro-magnesia, lime or alumina. In all the rocks of the hornfels, the greenschist and the amphibolite facies, with the exception of the alkaline series (in which $(K_2O + Na_2O) > Al_2O_3$), soda is only present in the form of albite.¹ But in the eclogite facies soda in all kinds of rocks enters into the jadeite exclusively. Potash, in the non-alkaline rocks, may enter into the potash feldspar or into the micas. In the last-named mineral the proportions of alumina in excess of the ratio $K_2O : Al_2O_3 = 1 : 1$ will be expressed in the triangle projection under consideration, and only the potash feldspar compound is entirely lacking.

I shall quote from my previous paper (Sambandet p. 129) the rules of calculation of the A, CF values which are used in the following diagrams for non-alkaline rocks with excessive silica.

¹ Concerning the presence of some soda in common amphiboles and micas and pyroxenes cf. „Sambandet“ p. 36 and 124. -- The soda amphibole, glaucophane, and paragonite, the soda mica, occur in non-alkaline rocks belonging to some little known facies probably related to the eclogite facies (cf. p. 176).

„Previous to calculating the values intended for use in plotting the triangle projections, it is appropriate to make the correction for the ilmenite, magnetite and titanite already in the percentages of weight. The amount of ilmenite is estimated by the geometrical method, and the amount of FeO, which, with sufficient accuracy, may be taken for 50 0/0 of the ilmenite, is subtracted from the total FeO. In the same way the Fe₂O₃ (70 0/0) and the FeO (30 0/0) in the magnetite are subtracted from the total percentages of Fe₂O₃ and FeO respectively. An analogical method is applied to the titanite whose CaO-content (30 0/0) is subtracted from the total CaO.“

„Thereupon the molecular proportions are calculated from the percentages, and may be used without recalculation into mol.-0/0. SiO₂ and H₂O are left out of consideration. The further treatment is as follows: Fe₂O₃ is added to Al₂O₃. FeO, MgO and MnO are added together. The value of CO₂ is subtracted from that of CaO to eliminate the calcite present. The mol. value of P₂O₅, multiplied by 3.33, is subtracted from CaO to eliminate the apatite.“

Furthermore Na₂O and K₂O are subtracted from Al₂O₃, the former being thereupon left out of consideration. The remaining molecular numbers of Al₂O₃ -- (K₂O -- Na₂O) -- A, CaO -- C and MgO -- MnO -- FeO -- F are re-calculated to 100 0/0.

The Hornfels Facies.

Fig. 1 represents the hornfels facies. The Roman figures designate the location of the ten hornfels classes. The Arabic figures are the points of the analyses of the hornfelses of classes 1 - 7 taken from GOLDSCHMIDT'S „Kontaktmetamorphose“.

1. Andalusite-cordierite-hornfels (p. 148). A, = 69; C = O; F = 31. (A, = 68; C = O; F = 32).
2. Plagioclase-andalusite-cordierite hornfels (p. 154). A, = 48; C = 28; F = 24 (mode not known).
3. Plagioclase-cordierite-hornfels (p. 156). A, = 32; C = 11; F = 57. (A, = 51; C = 19; F = 30).
4. Plagioclase-hypersthene-cordierite hornfels (p. 162). A, = 27; C = 11; F = 62. (A, = 48; C = 26; F = 26).
5. Plagioclase-hypersthene-hornfels (p. 169). A, = 28; C = 21; F = 51. (A, = 37; C = 31; F = 32).
6. Plagioclase-diopside-hypersthene-hornfels (p. 176). A, = 22; C = 34; F = 44. (A, = 24; C = 40; F = 36).
7. Plagioclase-diopside-hornfels (p. 188). A, = 6; C = 47; F = 47. (A, = 5; C = 50; F = 45).

If only the typical minerals were present, the points representing the analyses would be located within those fields or at those lines, whose corner points correspond to the composition of the constituent minerals. The hornfelses, however, also contain biotite, a mineral present in most the hornfelses of classes 1-7. The quantity of ferrous oxide and magnesia

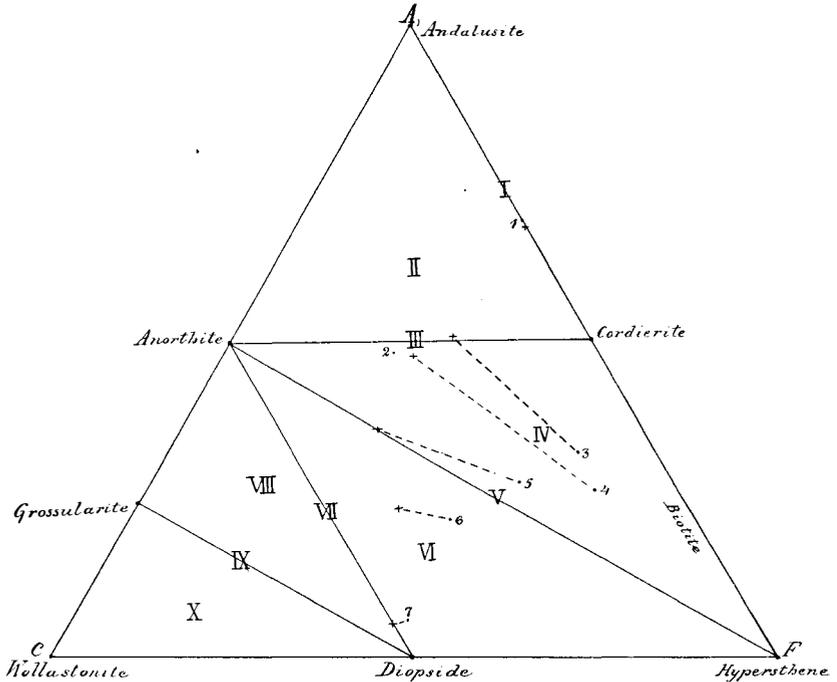


Fig. 1. The A,CF-projection of the hornfels facies.

in this mineral influences the location of the plotting points, but its existence depends upon the presence of water which does not appear in the triangle. All the points deviate from their proper positions in a direction towards the biotite field.

I have therefore also calculated the A,CF-values after having subtracted the oxides entering into the biotite, whose percentages were taken from the modes given by Goldschmidt. The values thus corrected have been quoted above within parentheses and plotted on the triangle (fig. 1) with crosses

united to the respective points by dotted lines. It may be seen that the new values, from which the biotite has been eliminated, show perfect agreement with the theory.

The A,CF-triangle gives an instructive synopsis of the associations possible and actually existing in the rocks of the hornfels facies. The whole field has been divided into five smaller triangles. A point plotted from a rock analysis is located within that triangle the corners of which correspond to the composition of their minerals, and no other minerals represented in the figure are possible in that association. Thus we have a graphical illustration of the application of phase-rule, that three minerals at most may occur together as rock-making constituents in a three-component system.

The hornfels facies seems to be restricted to the inner parts of the contact-metamorphic aureoles around laccolitic igneous bodies. Towards the outer contact zones this facies gradually passes into another metamorphic facies which so far is little known but seems to be related to the amphibolite facies. The latter is represented in the contact products of most batholithic masses, and transitional forms between the hornfels and the amphibolite type occur frequently (e. g. the Eker gneiss in Harz).¹ In the contact products of hypabyssal bodies and volcanic products types transitional to the sanidinite facies may be expected.

Rocks of very various composition and premetamorphic development, metamorphosed in the hornfels facies, have been described. In the Christiania region there occur sedimentogeneous hornfelses of argillaceous and sandy materials, and contact-marbles, and besides many kinds of eruptivogeneous hornfelses.

The Sanidinite Facies.

Rocks and mineral associations of the kind that I here call the sanidinite facies have been very much studied in long times. Such petrographical standard works as A. LACROIX'

¹ V. H. ERDMANNSDÖRFFER, Der Ekergneiss im Harz. Jahrb. d. preuss. geol. Landesanstalt, 1909, XXX.

treatise on inclusions in the volcanic rocks¹ and R. BRAUNS' work on the sanidinites of the Laach Lake district² deal with this facies. BRAUNS was the first to define the characters of the pyrometamorphism and its relations to the other kinds of mineral genesis.

There seems to exist no analyses of pyrometamorphic rocks, owing to their manner of occurrence as non-homogeneous small inclusions. Thanks to experimental investigations in the laboratory, the stability relations are, however, better known than in any other facies.³

Fig. 2 shows quite schematically the rules of paragenesis for rocks with an excess of silica.

Aluminium silicate in pyrometamorphic rocks is always sillimanite, and experimental work has proved that this is the only stable form at all temperatures⁴ below the melting point. (Whether the andalusite in the hornfels facies is truly stable or presents a false equilibrium (cf. Sambandet p. 141) has not yet been ascertained.)

Very remarkable is the difference in the pyroxene. While, in the hornfelses, the magnesium silicate forms a distinct phase, the orthopyroxene, it crystallizes here in solid solution with the diopside in all proportions. This has been shown experimentally by N. L. BOWEN.⁵

In pyrometamorphic rocks evidence is lacking, probably because no pyroxenes from rocks with adequate bulk composition have been studied.⁶ In the corresponding igneous facies

¹ A. LACROIX, *Les Enclaves des Roches Volcaniques*. Macon 1893.

² R. BRAUNS, *Die Kristallinen Schiefer des Laacherseegebietes*. Bonn 1912.

³ Summaries are given by: H. E. BOEKE, *Grundlagen der physikalisch-chemischen Petrographie*. Berlin 1915. — PAUL NIGGLI, *Neuere Mineralsynthesen I*, *Fortschritte der Min., Kristallogr. und Petrogr.* Band 3, 1915. *Id.*, *ibid.* II, Band 6, 1919.

⁴ G. A. RANKIN and F. E. WRIGHT, *The Ternary system CaO—Al₂O₃—SiO₂*. *Am. Journ. Sc.*, XXXIX, 1915, p. 1.

⁵ N. L. BOWEN, *The Ternary system Diopside Forsterite-Silica*. *Am. Journ. Sc.* XXXVIII, 1914, p. 239.

⁶ I have examined all the analyses of pyroxenes published in HINTZE'S (II, p. 1104—1113) and DOELTER'S (II, 1, p. 507—566) hand-books. . . In picrites, basalts, andesites and diabases, the magnesium diopsides

the entstatite-augites were described in a well-known paper by W. WAHL.¹ They are very common in meteorites which are, even in other respects, very typical representatives of the same facies.

Synthetic wollastonite is able to take up a maximum of 17 per cent of diopside.² Analyses of natural wollastonite often

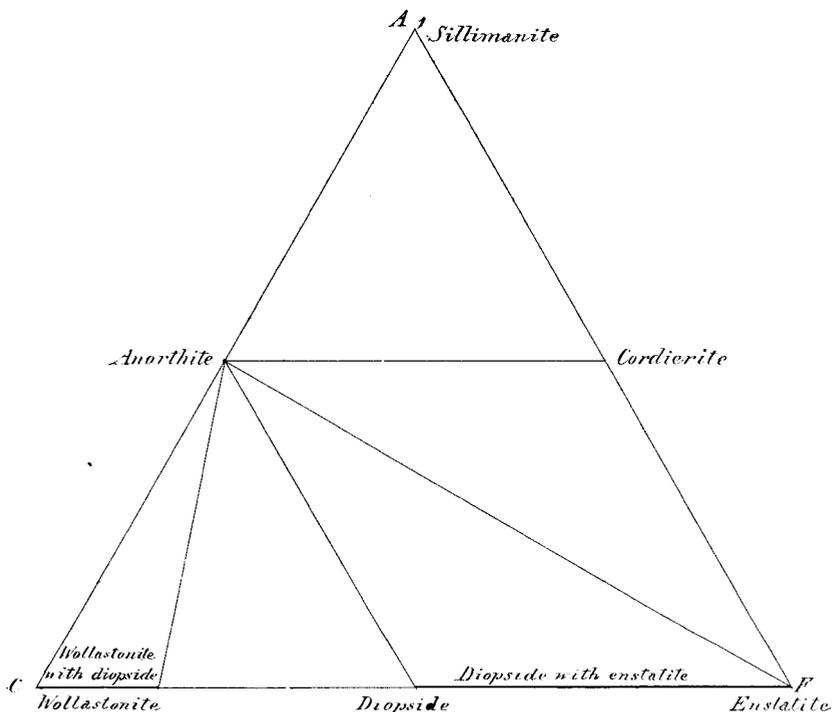


Fig. 2. The A,CF-projection of the sanidinite facies. The thick lines designate solid solutions.

show some magnesia,³ but no general difference between those from volcanic products and deep-seated rocks can be inferred.

(enstatite-augites) are fairly frequent, but no reliable analysis of such minerals from any metamorphic rock was found, excepting the highly aluminous fassaite.

¹ W. WAHL, Die Enstatitaugite. T. M. P. M. 26, 1907.

² J. B. FERGUSON and H. E. MERWIN, Wollastonite and related Solid Solutions in the Ternary System Lime Magnesia—Silica. Am. Journ. Sc. XLVIII, 1919, p. 165.

³ C. HINTZE, Mineralogie II, p. 1015.

The solid solutions may, therefore, exist in other facies, too. No garnets are stable in the sanidinite facies. The wollastonite may therefore occur in association with anorthite, against the rules of the hornfels facies. An example of this association was recently described by H. A. BROUWER from ejected volcanic blocks from Java.¹

The character of the alkali feldspar is also a very distinctive feature of the two facies compared. In the hornfels orthoclase and albite occur, in the sanidinites both these compounds form solid solutions. The stability-relations of the alkali feldspars, with special regard to their geological mode of origin, have been critically studied by E. MÄKINEN.²

Still a radical difference exists in the modifications of silica. Its stable forms in the sanidinite facies are tridymite and cristobalite.³ In the hornfels facies only quartz has been met with.

In the natural occurrences the sanidinite-rocks show poor approximation to true equilibria. Relics from various other facies are almost invariably present.

As appears from the previous outline, the divergencies between the two facies are great. They apparently are not so much due to a difference in the pressure than in the temperature, this having been considerably depressed, in the hornfels facies, by the pressure which has prevented the volatile components from escaping.

The Greenschist Facies.

The rocks of the greenschist facies belong to the uppermost zone of the lithosphere and chiefly originate under considerable stress. It is mainly owing to the last-named circumstance, that in them may be noted more variability in the

¹ H. A. BROUWER, Studien über Kontaktmetamorphose in Niederl. Ost. indien. Centralbl. f. Min. etc. 1920, 37.

² EERO MÄKINEN, Über die Alkalifeldspäte, Geol. För. i Stockh. Förh., 39, 1917, p. 121—184.

³ CLARENCE N. FENNER, The Stability Relations of the Silica minerals. Am. Journ. Sc. XXXVI, 1913, p. 331—384. — See also N. L. BOWEN, *ibid.* XXXVIII, 1914, p. 218, and J. B. FERGUSON and H. E. MERWIN, *ibid.* XLV, 1918, p. 417—426.

mineralogical characters than in any other rocks, and instead of one facies there will probably be necessary to separate several.¹ Chloritoid, paragonite, disthene, staurolite, garnets, glaucophane and certain fibroid amphiboles are all regarded as typomorphic of the epi-rocks, but probably no one of them belongs to the greenschist facies.

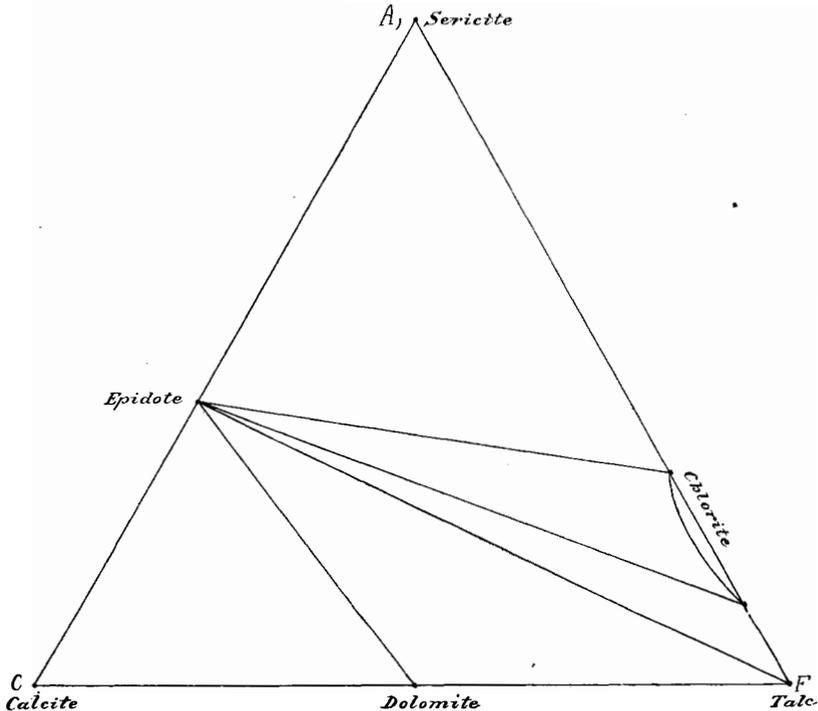


Fig. 3. The A,CF-projection of the greenschist facies.

Greenschist-rocks are fairly common, especially in the Alpine mountain-zones. They have been studied in a large number of localities which we do not need to enumerate here.

Of the typical minerals of this facies named above all but the albite are represented in fig. 3.

I am at present studying rocks of the greenschist facies from eastern parts of Fennoscandia, where they occur in manyfold

¹ Cf. NIGGLI, op. cit.

development, but I do not yet possess analyses of them. The greater part of the rocks of the crystalline schists of third order in GRUBENMANN'S classification conform to this facies, and a large number of analyses are given in his text-book, but unfortunately the mineral composition of the rocks analyzed has not been given. Therefore no analyses have been plotted on this triangle.

The paragenetic relations are here different from those in all the other facies because of the appearance of carbonates. Now, the calcite and dolomite are apparently stable in all the different facies, in contact with any of the silicates or quartz. In metamorphosed limestones there occur very many minerals, the calcite apparently playing the rôle of an indifferent medium. Likewise the carbonates, in the rocks of the greenschist facies, are quite regularly found in association with sericite and chlorites; the boundary lines of the association fields do not seem to signify the notice "no admission for outsiders" that they do in the other facies-triangles.

This seeming controversy has a very natural explanation: In all the other facies and in the greenschist facies in the rocks the projection points of which lie within the field sericite-epidote-talc, the carbonates are indifferent only so far as the carbon dioxide cannot escape. As soon as this is possible, the carbonates will interact with the silicates and the free silica under formation of lime or ferro-magnesia silicates.

But in all the rocks of the greenschist facies containing more lime than necessary to form epidote with the alumina available, the carbonates are stable in the presence of free silica, under all circumstances. If, on the other hand, lime silicates are brought under the conditions of the greenschist facies in the presence of carbon dioxide, they will transform themselves into carbonates and epidote.

Petrographical experience shows, moreover, that there exists a range of physical conditions, were the epidote and its relatives (zoisite etc.) do not originate from carbonate-bearing sediments, and the only silicates in such rocks are fine scaly micaceous minerals. This is a further facies to which probably belong many of the lime-phyllites and certainly a large part of

the products of the atmospheric weathering. We may name it the lime-phyllite facies.

V. M. GOLDSCHMIDT¹ has by means of NERNST's theoreme calculated the equilibrium curve $\text{CaCO}_3 + \text{SiO}_2 = \text{CaSiO}_3 + \text{CO}_2$, and pointed out that the curves for the equilibria of the formation of aluminous and ferromagnesian lime silicates run at lower temperatures than the calcite-wollastonite curve.

In Eastern Fennoscandia I have had good opportunities of studying the different stages of combination of lime and silica². Starting from the eastern boundary of the pre-Cambrian area one finds at first limestones and marles of the lime-phyllite and the greenschist facies and then going towards the west, meets with tremolite-limestone, and further the diopside and wollastonite set in representing a crystallization under successively higher temperatures. All the three last-named minerals in the limestone and lime-silicate-rocks belong to the amphibolite facies. The reactions between the lime-magnesia carbonates and the silica are in fact the most sensitive indicators of variations in the pressure and temperature in the rocks that we know.

The Amphibolite Facies.

In my previous paper (Sambandet) I dealt with this facies in the rocks of the Orijärvi region in south-western Finland. In fig. 4 all the rock-analyses there published have been plotted on the A,CF-triangle and, moreover, analyses of Archaean metamorphic rocks in Finland and Sweden from the following publications:

- P. J. HOLMQUIST, The Archaean Geology of the coast-regions of Stockholm. G. F. F. 32, 1910.
 H. E. JOHANSSON, Die eisenerzführende Formation in der Gegend von Grängesberg. G. F. F. 32, 1910.

¹ V. M. GOLDSCHMIDT, Die Gesetze der Gesteinsmetamorphose. Vid.-Selsk. Skr., Mat.-Naturv. Kl. 1912, N:o 22. p. 12.

² PENTTI ESKOLA, VICTOR HACKMAN, AARNE LAITAKARI ja W. W. WILKMAN, Suomen kalkkikivi. With an English summary by P. E.: Limestones in Finland. With 75 figures and a map. Suomen Geologinen Toimisto, Geoteknisiä Tiedonantoja N:o 21, 1919.

- H. E. JOHANSSON, The Flogberget Iron Mines. G. F. F. 32, 1910.
- EERO MÄKINEN, Ytterligare om kontakten vid Naarjärvi i Lavia. G. F. F. 36, 1914.
- Hj. SJÖGREN, H. E. JOHANSSON and NAIMA SAHLBOHM, Chemical and Petrographical Studies on the Ore-bearing Rocks of Central Sweden G. F. F. 36, 1914.
- EERO MÄKINEN, Ein archaisches Konglomeratvorkommen bei Lavia in Finnland. G. F. F. 37, 1915. Über Uralitporphyrit aus Pellinge in Finnland. G. F. F. 37, 1915.
- PER GEIJER, Falutraktens berggrund och malmfyndigheter. Sveriges G. U., ser. C, N:o 275, 1917.

I studied, moreover, the available Swedish and Finnish petrographical literature, in order to find out to what degree the rules of association would have general application to the Archaean of Fennoscandia. Many valuable statements were found in the writings of the authors named above and still in some papers by A. E. TÖRNEBOHM, H. BÄCKSTRÖM and A. GAVELIN. In general, notes on paragenetic relations are rare in the literature.

In the amphibolite facies, in its typical development, the correspondence between the chemical and mineralogical composition is exceedingly regular, so that the mineralogical composition can be calculated from the chemical analysis with great exactness. An especial simplification of the relations is due to the fact that water always seems to have been present in quantities sufficient to allow of the formation of the hydrated minerals of this facies. Thus e. g. the quantity of the mica is controled only by the proportions of potash and ferro-magnesia and alumina. In those rocks in which the quantity of potash is sufficient to form mica with all the $(Mg,Fe)O$ and Al_2O_3 available, the amount of micas is controled exclusively by the proportions of the latter oxides. The excessive potash then goes to form potash feldspar. In these rocks our A,CF triangle expresses quantitatively the proportions of the chief mineral constituents except potash and soda feldspar and quartz.

In fig. 4 the different mineral associations have been marked with different signs, so that the reader may convince himself

that the points of the analyses really lie within those fields at whose corner points their constituent minerals are located.¹

In rocks containing insufficient amounts of K₂O to form micas there appear some of the following minerals: Andalusite, cordierite, anthophyllite. The amounts of these in proportion to the micas are controlled by the amount of potash and do not

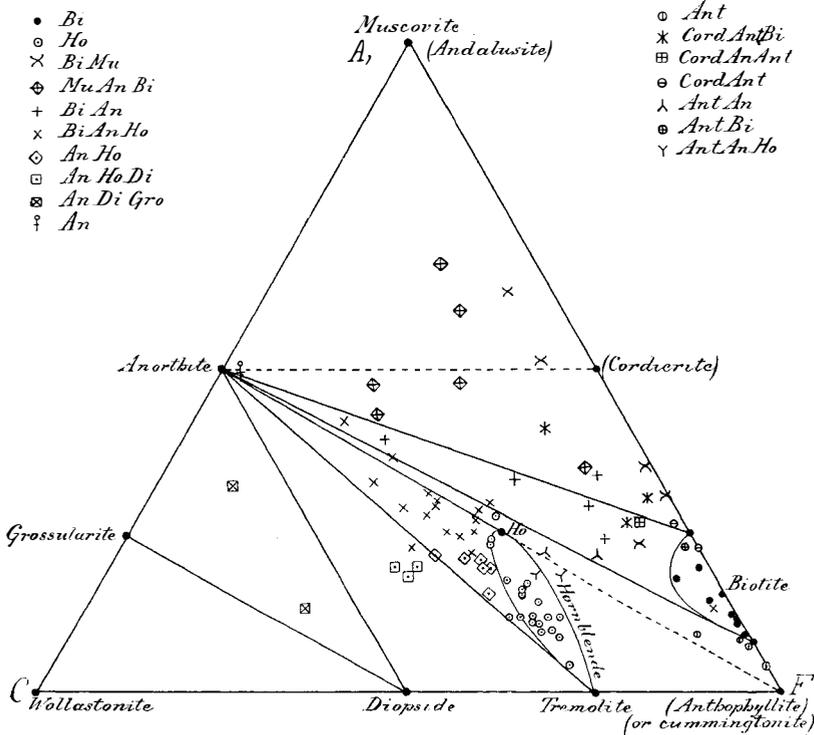


Fig. 4. The A,CF-projection of the amphibolite facies. All the associations whose designations are explained in the upper left hand side are such having excessive potash, but no excess of alumina. The location of the plotting-points, for these rocks, is an exact measure of the mineralogical composition. Those associations whose designations are explained on the upper right hand side are such having a deficiency in potash. For these the location of plotting-points is no perfect indication of the mineralogical composition.

¹ There are a few exceptions, e. g.: a biotite hornblende-plagioclase-rock is located within the an-di ho-field, and a biotite-feldspar-rock within the bi-mu-an-field. All such cases may probably be ascribed to analytical errors, the rocks being leptites, very poor in compounds under consideration, and the errors appearing magnified. Misleading results

therefore appear quantitatively in the A,CF-triangle. But I have found another triangle projection („Sambandet“ 43 and 128), by which they may be expressed in a quantitative manner, and in those also the theory has proved wholly conformable to the facts.

It appears from what has been said above, that the potash feldspars should not occur in association with andalusite, cordierite or anthophyllite. In the Orijärvi region it was found that in fact they do not, and this fact had struck me long time before the above theories were built up. The same relation has been noted by P. GEIJER¹ from the Falun region and several other sulphide-ore fields in Central Sweden. In other districts in Finland and Sweden, however, microcline appears to be stable with cordierite or andalusite (or sillimanite which in such cases often takes the place of andalusite, a fact of much significance). This must be explained so that we have in such cases to do with another though closely related facies, in which the micas did not originate when the relations of the bases would have allowed it. This subdivision is especially common in the corresponding igneous facies (cordierite-granite etc.).

The Eclogite Facies.

Doubtless members of the eclogite facies are only the olivine- and enstatite-rocks, olivine-pyropes, eclogites, chloromelanites and jadeitites.

The eclogite facies comprises but a part of the rocks which U. GRURENMANN has classed under the kata-rocks, or the rocks of the deepest zone. Neither soda-lime nor potash feldspars have been observed in congenetic association with the critical minerals of this facies, viz. eclogite-garnet and monoclinic pyroxenes of the diopside-jadeite series. Thus all kinds of gneiss

could, of course, also follow, if rock minerals with variable composition (hornblende, biotite etc.) would happen to have an extraordinary composition, outside of their fields plotted on the triangles on basis of existing analyses.

¹ Op. cit. (Sveriges G. U., ser. C., n:o 275, 1917).

must be excluded. In the same way no wollastonite seems to exist here.

The eclogitic micaschists (micaschisti eclogitici) of FRANCHI¹ are certainly very closely related to the eclogite facies. Their constituents are soda pyroxene, garnet, mica (near sericite) and quartz, besides amphibole and feldspar as posterior products. Colourless mica, as well as biotite, generally occur in all kinds of eclogite, but it is difficult to say, if it is strictly congenetic.

The question, whether the quartz is typical in the eclogite facies, must also be left open.

Calcite almost certainly may occur in the eclogite facies.

In the most cases where eclogites occur, it seems that their facies is restricted to comprise only variations between definite limits of the rock composition, a feature only observed in this facies, and ascribable, as will be discussed somewhat more closely in the chapter dealing with the igneous eclogites, to the fact that most eclogites have originated at temperatures above the melting temperatures of many other rocks. Such high temperatures, however, are probably not a material condition for the formation of the eclogite rocks, while these rocks certainly cannot originate except under very high pressures, and therefore it is well-nigh possible that quartz may belong to the lower temperature portion of the eclogite facies, whilst in the higher temperature portions, solid silica could not exist.

Despite the existence of only two chief phases, garnet and pyroxene, in the eclogite rocks (to which, however, often is added disthene), their composition shows comparatively wide variation owing to solid solutions.

The A,CF triangle is not well adapted to express the rules of association in this facies, as soda and an equivalent amount of alumina, omitted in this triangle, enter here into the pyroxene to form solid solutions with lime- and ferro-magnesia compounds. For the sake of comparison with the other facies I have, how-

¹ S. FRANCHI, Über Feldspaturalitisierung der Natron-Thonerde-Pyroxene aus den eklogitischen Glimmerschiefern der Gebirge von Biella (Graische Alpen). N. J. Min. etc. 1902, II, p. 112—126. Idem, Giacimenti alpini ed apenninici de rocce giadeitiche. Atti del congresso intern. di scienze storiche. Roma 1904.

ever, constructed this triangle here also (fig. 5), and most available analyses of eclogites and their minerals, including those of Norwegian examples (eclogites 18—23) made for my investigation, have been plotted on it.

The portions of the triangle which correspond to compositions actually occurring in the eclogite facies comprise but two

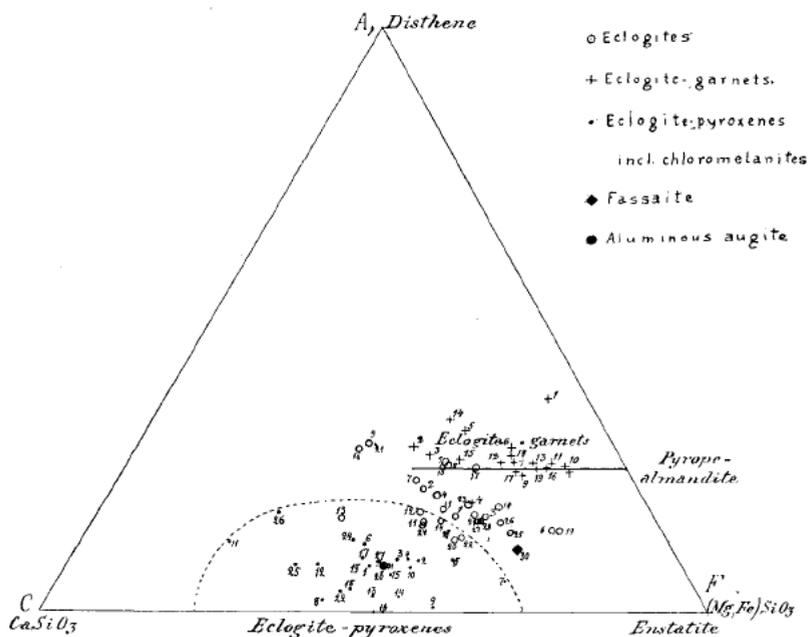


Fig. 5. The A,CF-projection of the eclogite facies.¹

fields: garnet-clinopyroxene-disthene and garnet-orthopyroxene-clinopyroxene. It is peculiar of this facies that monomineralic rocks occur frequently, as e. g. the olivine-rock, enstatite-rock, garnet-rock, chloromelanitite, jadeitite. The metasilicate, enstatite, plays a much less important rôle than the orthosilicate, olivine. Most of the combinations possible have been observed, but the olivine alone and the combination garnet-clinopyroxene are most common.

¹ Figures 5, 6 and 7 have been lent from my treatise on eclogites under preparation, and fuller explanation of the figures will be given there.

On the A,CF-projection (fig. 5) I have plotted no other rock-analyses than such of eclogites. As appears from their location between the garnet and the pyroxene fields, they mostly consist almost exclusively of garnet and clinopyroxene. Some of them, however, contain appreciable amounts of disthene, as eclogites 9 and 16. Others, as 19, a Norwegian eclogite, are olivine-bearing. The olivine-rocks and enstatite-rocks, if plotted on this triangle, would be located almost exactly on the F-point. For the jadeitites, mostly consisting of very pure jadeite only, this graphical method is not at all adaptable.

The close relation between eclogites and chloromelanites and jadeitites, and gradual transition between them, was pointed out by DAMOUR¹ and L. S. PENFIELD² and especially by LAURA HEZNER³. In the Norwegian eclogites, as I have found, the pyroxene varies between almost pure diopside and a chloromelanite containing 8 pct. Na₂O. Pyroxenitic portions of such eclogites are true chloromelanites.

Whilst the enstatite, olivine and disthene in the eclogite rocks are the same as in the other facies where they occur, the garnets and clinopyroxenes in the eclogite rocks exhibit quite peculiar characters in their ability of forming solid solutions or isomorphous mixtures. These relations may be made clear here.

The eclogite-garnets present an isomorphous series of almandite and pyrope in all proportions up to 75 mol. % pyrope, and with small amounts of grossularite. As seen in fig. 6 in which all the available analyses of almandites, pyropes and grossularites have been plotted on a triangle, the garnets in granites, gneisses and mica-schists, cordierite-rocks, gabbros and amphibolites show a limited ability of taking up pyrope in solid solution, the maximum amount being 33 mol. % Mg₃Al₂Si₃O₁₂.⁴

¹ DAMOUR, quot. in Groths Zeitschr. Kryst. 6, p. 291.

² L. S. PENFIELD, Am. J. Sc. 46, 1893.

³ LAURA HEZNER, N. J. B.-B. XX, 1914.

⁴ There are two exceptions: the garnet from amphibolite, n:o 4 („hornblende-gneiss“ from Namaputra, Zs. Kr. 36, 421) and that from granite n:o 8 („Lithoklasen einer grossen Pegmatitmasse“ from Ruwenzori, Zs. Kr. 50, 512). The only descriptions of the occurrences accessible to me, viz. those in the summaries of Zs. Kr., are not sufficiently detailed to

Here the garnets from Norwegian labradorite-rocks have been regarded as eclogite-garnets, this being justifiable because they are closely related to the eclogites and, by clustering together with pyroxenes etc., show transitions into true eclogite in the Bergen and Sogn areas in Norway.

Pyropes only exist in rocks belonging to the eclogite facies. As long ago shown by C. DOELTER¹ and

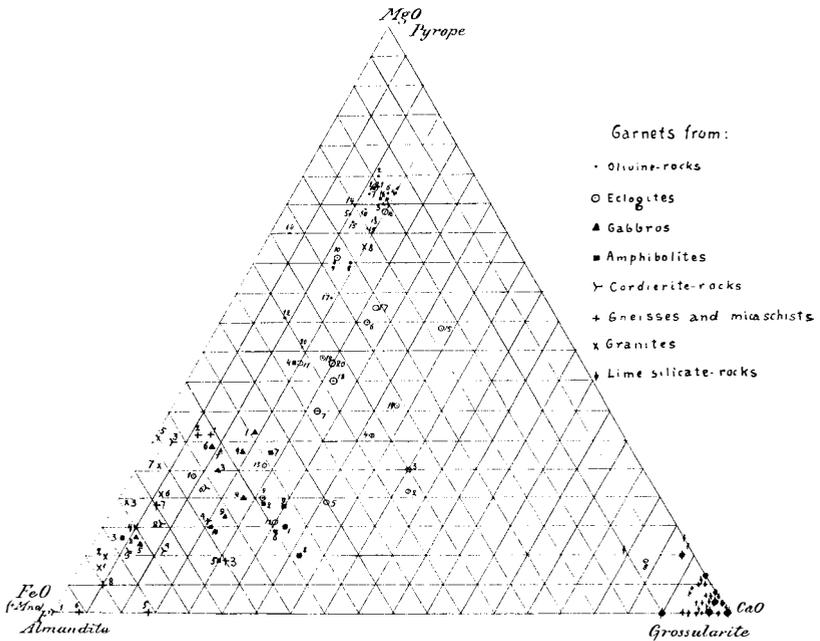


Fig. 6. The proportions of FeO, MgO and CaO in rock-forming garnets.

later verified by many others, the pyrope in serpentinized olivine-rocks is a primary magmatic mineral. Garnets rich in pyrope has also been met with in many eclogites regarded as metamorphic. Other modes of occurrence are not known. The garnets occurring in cordierite- or anthophyllite-bearing rocks or in amphibolites, rich in magnesia as these rocks may be, nevertheless are always almandites.

be of any real value in the present discussion. The hornblende-gneiss from Namaputra, whose garnet is a precious variety, would seem to be a changed eclogite.

¹ C. DOELTER, T. M. M. 1873.

The eclogite-garnet may as well be almandite (as the eclogite-garnet n:o 12, from Vanelvsdalen, Söndmöre, Norway) as pyrope (n:o 10 from Almklovdalen, Norway, n:o 16 from Jagersfontain, South-Africa, and n:o 21 from Böhrigen, Saxony), or also grossularite (as n:o 8, from Frankenthal, Silesia).¹ Most eclogite-garnets are mixtures of all the three compounds in proportions not met with in the garnets from any other rocks.

The ability of taking up grossularite in solid solution seems, however, to be limited in the eclogite-garnets (see fig. 6).

All the eclogite-garnets are low in titanium, a very remarkable feature.

Garnets containing more than 75 mol. % of pyrope are not known. Whether purer pyropes are unstable even in the eclogite facies or the material has never been sufficiently poor in iron, is still uncertain.

The eclogite-pyroxenes exhibit no less discrepancy as compared with the pyroxenes of the other facies, than the garnets.

Fig. 5 shows the ratios of ferro-magnesia, lime and the amount of alumina not combined with soda in the jadeite molecules. As appears, most eclogite-pyroxenes contain such an excess of alumina. They also show great variation in their CaO: (Mg, Fe)O ratio and still in the amount of silica. In all the cases, however, their composition may be expressed in terms of the silicates proposed by TSCHERMAK,² to which the pseudo-jadeite, $R''R'''(SiO_3)_4$, of CLARKE³ must be added. In all, there are then the following silicates: $Ca(Mg, Fe)Si_2O_6$, $CaSiO_3$, $(Mg, Fe)SiO_3$, $(Mg, Fe)(Al, Fe)_2SiO_6$, $Ca(Al, Fe)_2SiO_6$, $NaAlSi_2O_6$, $NaFeSi_2O_6$ (in small amounts), $(Ca, Mg, Fe)(Al, Fe)_2(SiO_3)_4$.

Fig. 7 represents the same pyroxenes as fig. 5, but here also the total alumina, inclusive that combined with soda in jadeite, has been shown, and the two points representing one and the same analysis have been united by a line. The great

¹ H. TRAUBE, N. J. 1889, I, 197. Though chemically identical with a grossularite-diopside-hornfels the rock would seem from description to be genetically a true eclogite, embedded in serpentine.

² G. TSCHERMAK, T. M. P. M. 32, 1914.

³ F. W. CLARKE in R. HEBER BISHOP, Investigations and Studies in Jade, p. 133 New York 1906.

variation in the amount of jadeite appears clearly. As an example, a jadeite (no: 28) has also been plotted; its ACF-point is located nearly at the corner A.

All the other silicates except diopside and jadeite occur in rather small amounts only. There are, however, some analyses which point to a considerable admixture of the pseudojadeite. Such are e. g. analyses of jadeitic stone implements n:os 21¹ and 26², both from the Alps. I have also found such a highly aluminous pyroxene in a fine-grained eclogite from Saltkjael in Selje, Norway (point 29).

It seems that earlier investigators have not been aware of the bearing which the existence of such remarkable pyroxenes, high in lime and alumina, has on the problem here dealt with. These pyroxenes characterize the eclogite facies and have the same relation to the anorthite as the jadeite has to albite.

Besides in the eclogite rocks aluminous pyroxenes occur in volcanic rocks (near the sanidinite facies). These differ from the eclogite-pyroxenes in being low in jadeite; their aluminous compound may be mostly computed as $MgAl_2SiO_6$. Fe_2O_3 is high, and Na_2O , when present, enters into the aegirite. They are often rich in TiO_2 , while the eclogite-pyroxenes are low, like all the silicate minerals in the eclogites.

In fig. 5 and 7 has been plotted, for the sake of comparison, a pyroxene from a leucite-tephrite containing 9.04 % Al_2O_3 , (point 31), taken at random from table XII in „Quantitative Classification“.

Point 30 represents a fassaite from the Fassa Valley, the only example of aluminous pyroxene (10.10 % Al_2O_3) known in contact-metamorphic formations. It is an enstatite-augite, containing more MgO than any eclogite-pyroxene analyzed.

As a summary it may be stated that the pyroxene compounds are greatly miscible in the volcanic rocks, much less miscible in the rocks of the hornfels and the amphibolite facies. but in the eclogite rocks their ability to form solid solutions reaches its maximum, though the diopside and enstatite are not miscible in all proportions here.

¹ LAURA HEZNER, N. J. Min. etc. B.-B. XX, p. 141.

² S. FRANCHI, Boll. R. Comitato geol. d'Italia, 1900, n:o 2.

U. GRUBENMANN remarks¹ that the presence of disthene in the eclogites does not mean any excess of alumina in the rock. This is true, if the feldspar ratio, $(K_2, Na_2, Ca)O : Al_2O_3 = 1$, is regarded as a standard. Such a view, however, has no meaning, as feldspars do not exist here. We may well say that the appearance of disthene may be attributed to an amount of

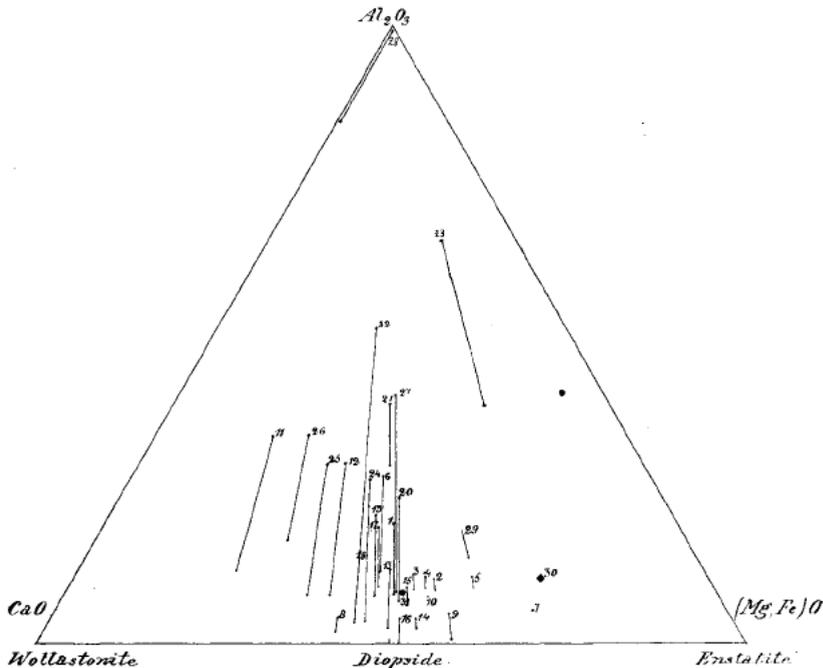


Fig. 7. The A,CF-projection of the eclogite-pyroxenes, incl. chloromelanites and jadeite (n:o 28). For each pyroxene is plotted also the ACF-projection, showing the proportion of the total Al_2O_3 . — The corresponding values are combined by lines. The designations are the same as in fig. 5.

alumina excessive of that which may possibly enter into the combination of garnet and pyroxene present.

Rutile is the titanium mineral of the eclogite facies besides ilmenite, the garnets and pyroxenes being generally almost devoid of titanium. In other facies (greenschist, amphibolite, hornfels) the rutile occurs only when the concentration

¹ Die Kristallinen Schiefer, 1910, p. 196.

of TiO_2 in proportion to FeO and CaO is very high. In rocks of eclogitic composition the occurrence of rutile is altogether critical and its alteration into titanite or ilmenite, when an eclogite is amphibolitized, is a striking phenomenon in many eclogites from Norwegian occurrences.

Another facies closely related to that of eclogite is one characterized by eclogite-garnet, glaucophane, lawsonite and paragonite (?). It might be designed as the hydrated eclogite facies and probably belongs to a region of somewhat lower temperature. These remarkable rocks are associated with eclogites and jadeitites on the island Syra, in the Alps and in California.

In the Norwegian eclogites no glaucophane-bearing varieties are known, but primary hornblende of the common kind and green colour is fairly frequent. Still more often a similar hornblende occurs as a posterior product. This happens when the eclogite has been brought under the conditions of the amphibolite facies, and comprises the processes well-known under the terms kelyphitization (SCHRAUF) and feldspathuralitization (FRANCHI).¹ In both these the alteration begins in the pyroxenes and also makes a more rapid progress in these minerals than in the garnets. Very often we find eclogites in which all the pyroxene has been altered into hornblende in myrmekite-like intergrowth with plagioclase. In the igneous Norwegian eclogites the development often has been the following: When the crystallization of the garnet was completed and liquid magma was still present, the conditions of the amphibolite facies set in, and now hornblende and plagioclase crystallized directly from the magma around the garnet. The latter may thus be an unstable relic, if its field of stability does not continue into lower temperatures than that of the pyroxene.

¹ S. FRANCHI, loc. cit. N. J. 1902, II.

Igneous Facies.

F. BECKE has in many publications laid stress on the intimate connection between the igneous and the metamorphic development of eruptivogeneous metamorphic rocks. Recently, in a lecture on different types of the metamorphism, given in April 1920 in Stockholm and Christiania,¹ he traced the development of a cooling rock-mass, showing that there is gradual transition between the processes taking place before and those taking place after the complete consolidation of the magma. Thus the sharp distinction between the igneous and metamorphic phenomena is more theoretical than practical.

We call such rocks metamorphic which have originated by gradual replacement of the constituents of earlier rocks, with or without changes in the bulk composition. To the metamorphic rocks we oppose the primary rocks, i. e. all those that have crystallized at once from a large mass of solution, either aqueous or what is generally called magma, giving rise to the igneous rocks.

In accordance with the general law controlling chemical systems under given temperature and pressure, it follows that the mineralogical composition of an igneous rock will be the same as that of a metamorphic rock, provided that both have obtained their actual set of minerals under the same conditions.

At the first glance it will seem that this theoretical postulate has no application in practice. Equilibrium cannot be arrived at unless the minerals already crystallized out are in continuous interaction with the rest magma and with each other and, above all, the crystallization may proceed at a constant temperature. Now, E. BAUR² has set forth a hypothesis according to which the crystallization of the igneous rocks should have proceeded isothermically, the consolidation having been due to a gradual

¹ Will be published in this journal.

² E. BAUR, *Chemische Kosmographie*, München 1903, and *Zeitschr. für phys. Chem.*, 42, p. 567.

removal of the mineralizers. Acceptable as this hypothesis may be in certain cases, the cooling cannot be denied as a fact, and many features in the igneous rocks tell us that they have passed the fields of more than one chemical equilibrium. I believe indeed that petrographical evidence in this direction has not yet been sufficiently estimated. I shall name a drastic example from my own experience.¹

A coarsely crystalline granodiorite, or quartz-monzonite, in Namama region in Transbaikal contains, in a eugranitic mass, crystals of hornblende in the ideal form, being the combination of (110), (001) and (101). This mineral is the most idiomorphic of the main constituents and must be regarded as the first one to crystallize out from the magma. Thereafter follow, in the series of idiomorphism, the plagioclase, the orthoclase and last the quartz, in part in graphic intergrowth with the orthoclase. The order of idiomorphism is remarkably distinct and the whole structure tells of a quiet crystallization in an unagitated magma basin. No later metamorphic influence can be traced. Yet the hornblende was not the first mineral to separate, but was formed at the expense of other, still earlier minerals. In the crystals of hornblende one finds corroded remnants of diopside, and all around them are numerous grains of iron ore, titanite and epidote, all these having apparently been formed as by-products at the formation of the hornblende. This mineral is consequently, on the one hand, a uralite and, on the other hand, an apparent primary magmatic mineral. At the earlier stages of the crystallization here existed diopside and perhaps also olivine, for in some dark nodules in this rock one finds hornblende in granular aggregates that from their form seem to be pseudomorphs after olivine.

This is a single case, but I believe the conclusion may be generalized widely: It must be a common rule that, at the consolidation of magmas, minerals are formed and again resorbed,

¹ P. ESKOLA, *Igneous Rocks of Sviatoy Noss in Transbaikal*. Öfvers. Finska Vet. Soc. Förhandl. (In print).

Very instructive examples, with theoretical explanations of the mineral development during the last magmatic stages, are given by VÄYRYNEN (op. cit.).

and in most cases we see no trace of them any more. The phenomena similar to that just named, are of common occurrence, but as they are more often met with in rocks that show traces of stress influence they have, often erroneously, been regarded as metamorphic.

Experimental work has in later times thrown much light on the mineral development in igneous rocks.¹ N. L. BOWEN has, from these results combined with a rich geological experience, constructed a general view of the magmatic development.² In the process of differentiation the residual magma, from which minerals crystallizing at high temperatures are at first separated out, becomes successively enriched with substances lowering the crystallization temperature. A definite magma thus passes through all these stages which are, in some way, analogous to our facies.

Thus we often find, in igneous rocks, minerals belonging to different facies, the earlier of them having escaped resorption only in consequence of a rapid cooling.

On the other hand, we always see in the igneous rocks a tendency towards certain equilibria, apparently corresponding to the conditions during the last stage of consolidation. And when we know what mineral associations belong to the perfect equilibrium in each facies, we are able without any difficulty to state the facies under the conditions of which the rock has performed its crystallization. This is still further facilitated by the fact that perfect equilibria are not by any means rare in the igneous rocks.

We know of igneous rocks belonging to each of the five mineral facies outlined above.

¹ Among those works at the Geophysical Laboratory of the Carnegie-Institution having special bearing on the formation and resorption of minerals during the process of consolidation may be named:

N. L. BOWEN, *The System Diopside-Forsterite-Silica*. Am. Journ. Sc. XXXVIII, 1914, p. 207, and

OLAF ANDERSEN, *The System Anorthite-Forsterite-Silica*, *ibid.* XXXIX, 1915, p. 407.

² *Op. cit.* (Journal of Geology 1915, suppl.).

The Hornblende-Gabbro Facies.

Very commonly igneous rocks have arrived at equilibria in the amphibolite facies. A gabbroid magma there gives rise to a hornblende-gabbro. These rocks usually occur in the form of large batholiths which have intruded in the earth's crust in connection with orogenic movements and now fill up anticlines of raised up formations. They are especially common in the large pre-Cambrian areas in many lands.¹ The crystallization in such "central" batholiths, in most cases, took place during the upward movement of the rock-masses. It seems uncertain, whether the crystallization, as BAUR assumes, was due to a slow removal of the volatile compounds or to a slow cooling. The mechanical agitation caused by the movements during the crystallization no doubt also favoured the arrangement to the stable state. The fact is, in any case, that these rocks actually show mineral associations conforming to the rules of the amphibolite facies. In the Fennoscandian Archaean known to me granites, granodiorites, hornblende-gabbros and hornblende-peridotites in such batholiths are, as to their mineral composition, nearly identical with those chemically identical metamorphic rocks between whose strata the batholiths have intruded.

The Gabbro Facies.

Quite an analogous parallellism as between amphibolites and hornblende-gabbros will be found prevailing between the hornfelses and those igneous rocks which have caused their contact-metamorphism. The eruptive masses here in consideration are, in most cases, laccolitic bodies and have intruded up to the higher levels of the earth's crust where the temperature was lower. Cooling may therefore have played the main rôle during the crystallization; we must expect traces from various conditions preserved, and in fact we find frequent deviation

¹ Cf. FRANK D. ADAMS, The Origin of the deep seated Metamorphism of the pre Cambrian Crystalline Schists, *Compt. rend. XI Congres géol. internat.* Stockholm 1910, p. 563.

from the stable state. Aluminous pyroxenes may have been preserved as unstable relics instead of the stable diopside¹ and, in consequence of imperfect resorption, often due to armouring, olivine may occur in rocks with excessive silica. Many other examples could be named. Nevertheless, there are numbers of examples of such igneous rocks mineralogically almost identical with the corresponding hornfelses. Thus a normal norite, composed of plagioclase, diopsidic pyroxene and hypersthene, may be mineralogically identical with a plagioclase-hypersthene-diopside-hornfels of class VI.

The Helsinkite Facies.

Primary igneous rocks having the mineral characters of the greenschist facies exist in the form of albite-epidote-rocks, the so-called helsinkites, of southern Finland, as described by A. LAITAKARI.² The helsinkites are medium-grained or coarse-grained rocks occurring in the Archaean in close connection with and showing gradual transition into the common pegmatitic and aplitic granites. They apparently represent phases of rock in which large quantities of water under high pressure have caused an extraordinarily large depression of the crystallization temperature. Other primary igneous albite-epidote-rocks, named epidote-syenites, have been described by E. MÄKINEN from Österbotten in Finland,³ and by myself from Sviatoy Noss in Transbaikal.⁴

The Diabase Facies.

Volcanic rocks show a mineral development similar with that of the pyrometamorphic rocks, or the sanidinite facies.

¹ The same deviations may, of course, also be found in metamorphic rocks. Note the fassaite, an aluminous pyroxene, at contacts of limestone!

² A. LAITAKARI, Einige Albitepidotgesteine von Südfinnland. Bull. Comm. géol. Finl. n:o 51, 1918.

³ E. MÄKINEN, Öfversikt av de prekambriskas bildningarna i mellersta Österbotten. Bull. Comm. géol. Finl. n:o 47, 1916.

⁴ P. ESKOLA, op. cit.

The same development may also be met with in such hypabyssal dike- and sill-rocks as many diabases.¹ The latter in fact may show the most perfect state of equilibrium in this facies; therefore I here call it provisionally the diabase facies.

Generally the volcanic rocks exhibit a very imperfect state of equilibrium. Some of their minerals have been formed at the intratelluric period under the conditions of the gabbro or hornblende-gabbro facies. They appear as phenocrysts in the lavas. Therefore e. g. the enstatite and augite commonly have crystallized as separate phases and do not form solid solutions, or enstatite-augite, which is the stable product formed by crystallization from melts under atmospheric pressure.

On the other hand, the natural quenching, which the lavas are subjected to, often causes the appearance of volcanic glass, a kind of unstable products only met with in the sanidinite and the diabase facies.

The Igneous Eclogite Facies.

All the Norwegian eclogites studied by me are of igneous origin. Concerning the eclogites in the Bergen region which occur in close connection with the labradorite-rock, this conclusion was at first drawn by Th. HIORTDAHL and M. IRGENS.² Later C. F. KOLDERUP, by detailed geologic and petrographic investigation³ brought full evidence that the eclogites are a differentiated variety derived from the same magma as the labradorite-rocks. The latter belong to the series called the Bergen-Jotun-group of Caledonian eruptives by V. M. GOLDSCHMIDT.⁴

¹ In Sweden and Finland many rocks have been called diabases that have a mineral development typical of the gabbro facies.

² TH. HIORTDAHL og M. IRGENS, Geologiske Undersøgelser i Bergens Omegn. Universitets-program for andet halvaar 1862.

³ CARL FRED. KOLDERUP, Die Labradorfelse des westlichen Norwegens II. Die Labradorfelse und die mit denselben verwandten Gesteine in dem Bergengebiete. Bergens Museums Aarbog 1903, N:o 12.

⁴ V. M. GOLDSCHMIDT, Übersicht der Eruptivgesteine im Kaledonischen Gebirge zwischen Stavanger und Trondhjem. Videnskapsselsk. Skr. I. Mat. naturv. Kl. 1916. No. 2

Another eclogite-bearing area which has provided material for my studies is that in the districts of Nordfjord, Søndmøre and Nordmøre in the western coast-region of Norway.¹ The main part of the rock crust here is gneiss that has been regarded as pre-Cambrian. In it are embedded elongated masses of olivine-rock, many of them accompanied by eclogite schliers or bed-formed masses. Other lenticular, rounded or irregular masses of eclogite are embedded immediately in gneiss. Labradorite-rocks occur at many places in evident connection with the olivine-rocks and eclogites.

A common evidence of the igneous origin of the Norwegian eclogites is their structure. The garnet is always free from inclusions, whereas the metamorphic garnet is usually filled up with quartz-grains. Mostly the garnet, having crystallized first, appears as rounded grains enclosed in the pyroxenes, but at several localities on Holsenö in the Bergen region a hypersthene-eclogite contains xenomorphic garnet filling the interstices between the pyroxenes.

When enclosed in labradorite-rocks or in gneiss the eclogites have consolidated earlier than their country-rock,² and the same also is true of eclogites connected with olivine-rocks.

Frequently the crystallization has begun in the eclogite facies, garnet and pyroxene having separated out, but has continued in the hornblende-gabbro facies, as already pointed out. The hornblende and feldspar then fill up the interstices between the anterior generation of minerals.

¹ H. H. REUSCH, Grundfjeldet i søndre Søndmør og en del af Nordfjord. Forh. i Videnskabs-Selsk. i Christiania 1877.

W. C. BRØGGER, Ueber Olivinfels von Søndmøre. N. J. f. Min. etc. 1880, II.

J. H. L. VOGT, Olivinstenen i indre og søndre Søndmøre. Nyt Mag. for Naturvidensk. 1883.

H. H. REUSCH, Nye Oplysninger om Olivinstenen i Almeklovdalen og Sundalen paa Søndmøre. Forh. i Videnskabs-Selsk. i Chr.ania 1883.

² GOLDSCHMIDT (Op. cit. p. 54 and 129) states that also the gabbros of the Bergen-Jotun group are older than the labradorite-rocks and remarks that this fact, being in disharmony with Bowen's theory of the magmatic development of rocks, cannot yet be explained in any way.

At the boundaries the eclogites enclosed in gneiss have a zone altered into amphibolite. The opposite alteration, from gabbro into eclogite which should have taken place if the current theory of the metamorphic genesis of the eclogite were true, has never been observed.

From other countries the literature contains descriptions of eclogites with truly crystalloblastic structure. There are eclogites in such series of crystalline schists which have been interpreted as sedimentogeneous, and e. g. the eclogitic mica-schists seem to be sedimentogeneous themselves. From our experience in the other facies it would only seem probable that there should exist sedimentogeneous as well as eruptivogeneous eclogites. We must, however, bear in mind that foliation or even an evidence of re-crystallization in an eclogite is not a proof that the rock has formerly been a gabbro. The eclogite minerals may very well have re-crystallized in the same form.

Many occurrences regarded as metamorphic certainly need revision in this respect. This seems especially to be the case with those enclosed in eruptive gneisses. An earlier opinion, still current in the eighties of the last century, regarded the eclogites as igneous rocks, but when the theory of metamorphism was applied on the massifs of foliated "central gneiss", the eclogites enclosed in them must follow. Later they were regarded as very typical metamorphic rocks, and when the opinion turned to interpret the gneiss as igneous, now the eclogites did not follow. The students of eclogites in the subsequent period therefore had much trouble in finding out complicated explanations of the kind of metamorphism in the eclogites.

At any rate, we have, in the Norwegian eclogites, examples of primary crystallizations. There is another interesting mode of occurrence of igneous eclogite in the diamond-bearing kimberlites in South Africa and Australia. Besides diamonds and other minerals the blue ground and yellow ground contain fragments of rocks among which such of eclogite are most frequent.

There has been a considerable difference of opinion concerning the origin of the eclogite nodules.¹ Some investigators

¹ See PERCY A. WAGNER, *Die diamantführenden Gesteine Südafrikas*. Berlin 1909.

have interpreted them as fragments of an eclogite formation in a great depth, brought up by the explosion-like eruptions of the kimberlite, while others have seen in them segregations from the kimberlite magma. As the chief argument in favour of the former opinion the fact has repeatedly been set forth that these nodules, in their mineral composition, are perfectly similar to true eclogites, and especially that they contain disthene, a mineral formerly only known from crystalline schists. It is psychologically interesting that this argument, which only owes its existence to a conservative tendency of the minds, by some geologists has been thought more weighty than the following facts favouring the segregation theory: The extensive distribution and persistent characters of the nodules in the kimberlite pipes in South Africa and N. S. Wales, the non-occurrence of usual eclogite in the same regions¹ and, above all, the occurrence of diamond in the nodules, even enclosed in the garnet. When the last-named fact forced R. BECK to accept the segregation theory², he did not use the name eclogite but proposed a new term, griquaite, to designate these igneous aggregates.

Having found a perfect parallism between the igneous and metamorphic rocks in all the other facies we have no difficulties in assuming an igneous eclogite and may regard the segregation theory as definitely proven.

In this paper I have not used the term griquaite for the igneous eclogites, though many reasons would make it desirable to have different designations for both kinds of rock. The term eclogite, however, has old traditions as a name of an igneous rock, and it may happen that a greater part of the eclogites will be once more regarded as igneous rocks. Provisionally I have used the old name commonly for all the eclogites.

¹ F. P. MENNELL (The Geological Structure of Southern Rhodesia. Quart. J. Geol. Soc. 66. 1910, p. 353) mentions that eclogite should occur in pre Cambrian schists around granite massifs in Rhodesia. Unfortunately no characteristics of the rock have been given, and thus it does not seem granted that here is an eclogite and not e. g. a garnet-amphibolite or diopside-grossularite-skarn.

² R. BECK, Untersuchungen über einige südafrikanische Diamantlagerstätten. Zeitschr. deutsch. geol. Ges. LIX, 1907, 275.

A few words may be said in this connection about the jadeitites and chloromelanitites. L. PIRSSON¹ explains these rocks as metamorphosed phonolites. It is true that certain analyses show some resemblance to phonolite, the jadeite being able to take some potash in solid solution, but the largest part of the analyses of jadeitite show a close approximation to the jadeite formula and are free from potash. Therefore it would seem most natural to assume that the jadeitite has originated by monomineralic crystallization differentiation under a high pressure where the mineral jadeite was stable with its melt.²

The crystallization temperatures of the eclogite rocks will be raised with the pressure. Eclogites occupy a volume about 15 pct. smaller than that of corresponding gabbros, and the magma probably has a still larger volume. The volume of jadeitite (0,300, sp. g. = 3,33) is as much as 22 pct. smaller than that of the corresponding molecular mixture of albite and nephelite (sp. vol. = 0,383, sp. g. = 2,61). When it has formerly been generally assumed, in physico-chemical petrology, that pressure has little influence on transformation points, this was only because such large changes in volume were not considered.

The critical minerals of the eclogite facies cannot be obtained from melts under atmospheric pressure, but the facts now set forth concerning the genesis of the eclogite would seem to evidence that they are stable in contact with magmas under very high pressures.

When brought upwards nearer the earth's surface, the eclogite-minerals become unstable. We actually find traces of alteration, either in the hornfels, the amphibolite or in the greenschist facies. Considering the slow rate of gradual denudation by which deep-seated rocks generally have been brought up to the earth's surface, it would seem wonderful that such unstable things at all have surpassed the depth-zone of the amphibolite, so dangerous for their existence, as there the

¹ L. PIRSSON in HEBER BISHOP, *Investigations and Studies in Jade*. 1906. I, p. 161.

² K. A. KTENAS (T. M. P. M. 26, 1907) arrived at the same conclusion concerning the jadeitites in the Kyklades, the Greek Archipelago.

temperature was still high enough to make the velocity of transformations considerable. This wondering leads us to a very interesting statement.

Unstable things are made lasting by means of quenching. Now we shall find that nature, wherever eclogites occur, has practiced a kind of quenching. The most effective method was that in the case of the diamond-bearing pipes, where the eclogite nodules were thrown up to the earth's surface by violent explosions.

Other eclogites occur in Norway, Scotland, Erzgebirge, Fichtelgebirge and certain other districts in the Hercynian zone, in the Alps, Apennines, in Greece and in West-American Cordillera (California). Jadeitites are known from Burmah, Tibet(?), Turkistan, Mexiko(?) and the Alps. All the localities are in post-Cambrian folding-zones where deep-seated portions of the earth's crust have been brought up to high levels by orogenic and isostatic movements and thereby been exposed to a quick denudation. This can be called a geological quenching.

Eclogites are not known from the Archaean areas of Finland, Sweden or Northern America or other similar extensive old resistant shields. This is surprising, as it is just here that we have the deepest portions of the earth's crust laid bare. The relations will, however, be easily understood when we realize that here extensive continental areas have been elevated and subjected to denudation during enormous periods of time. Eclogites, if they ever existed there, could be converted into amphibolites. The garnet-amphibolites might be relict eclogites, but as they invariably bear almanditic garnet, it seems that more magnesian garnets are not likely to be preserved as relics, and we have no traces left of them.

From what was said above concerning the raise of the melting temperature of eclogites under pressure it would seem likely that there exists a zone in the deepest parts of the earth's crust where gabbroid material exists stable in the form of eclogite, at temperatures under which a gabbro would melt if the pressure would be reduced.

This conclusion has formerly been drawn by L. L. FERMOR¹ who states that eclogite must be the high pressure form of gabbro and adds further on (p. 44): „We must, therefore, assume that in the infraplutonic zone the basic rocks are present as eclogites and the more acid rocks as garnetiferous granites²

My conception of an infra-plutonic zone extends HARKER'S view of scattered magma-reservoirs, with walls, the nature of which is not considered, to a continuous shell round the earth, the whole of which shell is a potential magma. This shell, being composed of rocks of the consistency of a plastic solid, may afford a cushion upon which the isostatic operations of the earth, believed in by some geologists, have their foundation. Any portion of this shell may become a reservoir on reduction of the superincumbent pressure.“

The melting point of a solid is raised by increasing pressure in direct proportion to the absolute temperature and the diminuation of the volume in melting, and in opposite proportion to the heat of fusion. If the melting points and the latent heats of the eclogite minerals were known, it would be possible with some approximation to calculate the pressures corresponding with various temperatures, under which the eclogite will just be retained in a solid form. It would be desirable, and perhaps it would not be impossible, to solve this problem experimentally. Perhaps the pure jadeite, having such a great change of volume by melting, could be most conveniently investigated.

So far the theory of the eclogite-zone is merely a plan of future investigation. But it is very suggestive of further conclu-

¹ L. L. FERMOR, Garnet as a Geological Barometer. Rec. Geol. Surv. of India, Vol. XLIII.

² To this assumption of Fermor we must remark that, as we have seen, the almanditic garnets occurring in acid rocks have a much wider field of stability than the more pyropic garnets found in the eclogites. While the latter only occur in the eclogite facies, the almandites extend over the whole of the eclogite and amphibolite and part of the hornfels facies; they do not, therefore, indicate such high pressures as the eclogite minerals proper. The manganese garnets, present in many of the Indian rocks dealt with by Fermor, have a still wider field of existence and in fact may originate even under atmospheric pressure.

sions: If the critical minerals of the eclogite facies are such which only arrive at the earth's surface under especially favourable conditions without being changed, there might very likely exist other high pressure forms of material that never have been exposed, because being too quickly changeable when the pressure is reduced.

There are certain facts pointing towards such a hypothesis that such minerals may exist. We have the isomorphic series of the jadeite minerals in which the pseudojadeite plays an important rôle. This is a silicate high in lime and alumina.¹ Perhaps silicates still richer in lime, and perhaps even a pure soda-lime-pyroxene, having the same metal ratio as the labradorite feldspar, may exist as solids in great depths. If such a silicate could be spoken of as really existing, the problem of the labradorite-rocks would be much simplified.

The hypothesis under consideration is rich in suggestions concerning the state of the zones beneath the earth's crust. But it is better to wait till experimental research has thrown more light on these problems.

On the Norm, the Quantitative Classification and the Facies Classification.

The calculated standard mineral composition or the norm of the igneous rocks² has become the most valuable aid in studying and comparing rock analyses, even for those petrologists who are not advocates of the quantitative classification. It will therefore be useful to discuss the norms in relation to the facies principle.

For the authors of the quantitative classification two different points of view were imperative in the choice of the standard

¹ The jadeitite from Schaffis, Biel Lake, Switzerland, (LAURA HEZNER, N. J. B.-B. XX p. 141) contained 10.86 % CaO, 4.67 % Na₂O and 6.33 % MgO besides 25.29 % Al₂O₃.

² WH. CROSS, J. P. IDDIGS, L. V. PIRSSON and H. S. WASHINGTON, Quantitative Classification of Igneous Rocks. Chicago 1903.

minerals: (1) The calculation of the norm should be made as simple as possible and (2) the standard minerals should be such as actually exist, so that the normative mineral composition would at least be possible. For the sake of simplicity the standard minerals were divided into the salic and femic groups and the alferic minerals were excluded. After the exclusion of the latter many of which are common rock making minerals it was no longer possible to form the norm merely of important actual rock-minerals, and even such not at all existing in rocks, like åkermanite, as well as mere chemical abstractions, such as the sodium metasilicate, were accepted as normative minerals.

But in proceeding to calculate the norm, the authors made all efforts not to violate the rules of mineral association in natural rocks. We read (op. cit. p. 186): „The method of calculation adopted is based upon a number of commonly observed chemico-mineralogical relations that obtain in the rock-making minerals,

“ In the statements that follow reference is repeatedly made to the „degree of affinity“ controlling the combination of elements in minerals.

It is clear, from the stand-point of the chemical statics, that such terms as „chemico-mineralogical relations in the rock-making minerals“ and „degree of affinity“ have no sense unless in reference to a definite chemical equilibrium. This also appears from the fact that the rules of calculation of norms tend to comply with the requirements of the phase-rule in that modification later proposed by V. M. GOLDSCHMIDT, applied to the mineral associations in the rocks.¹

Thus the authors of the quantitative classification, with the minerals left after rejecting many, unconsciously aimed at reconstructing a definite mineral facies, viz. the hornfels or the gabbro facies. This facies was accepted, in preference to e. g. the hornblende-gabbro facies, because it includes a greater number of non-alferic minerals than any other. If the authors had clearly realized the fact that it was the system of minerals in a definite chemical equilibrium that they wanted, the rules of the norm calculation would probably have been somewhat diffe-

¹ „Kontaktmetamorphose“ p. 123.

rent. But even as it is, the norm system must be regarded as exceedingly successful.

Let us now see, whether we could make the norms better, our aim being to calculate, from a rock analysis, so far as possible the corresponding mineralogical composition in the gabbro facies.

In this facies there occur biotite, but its presence and quantity are controlled by the presence of water and perhaps still other circumstances which we do not yet understand (cf. Sambandet, p. 82 and 139). We are wholly unable, in this facies, to calculate the biotite, and must simplify our norm to comprise only water-free minerals.

Instead of biotite we then get the cordierite which really occurs, either besides or without biotite, in rocks of this facies when they have excessive alumina, which, on the whole, is a rare phenomenon in igneous rocks.¹ The calculation of the amount of this mineral does not involve any difficulty or complexity, and its inclusion in the norm would be a stage towards better agreement with the actual conditions. But we may remember that excessive alumina is, in igneous rocks, so to speak a pathological character, and it is a very welcome feature of the norm, that we there, in the percentage of normative corundum, have a direct measure of this abnormality.

The leucite probably does not belong to the gabbro facies, but to the sanidinite or diabase facies mentioned above. I cannot, however, propose anything better instead of it. Its substitute in the deep-seated rocks is commonly biotite the amount of which we cannot calculate (cf. above).

Anorthite and wollastonite in association also belong to the sanidinite facies, the association being stable only at very low pressures. In the gabbro facies they would combine to form grossularite. This, like a few other remarks of a similar character, has little practical importance because of the rare issue of such a composition in the igneous rocks (kedabekite).

¹ Cf. A. OSANN, *Petrochemische Untersuchungen I.* Ab. Heidelberger Ak. Wiss. Mat.-naturw. Kl. 2. 1913, p. 29.

A somewhat more weighty objection against the norm follows from the following consideration: In the gabbro and the amphibolite facies, in rocks with excessive silica and with excessive lime, i. e. having normative diopside, titanium dioxide, in the stable association, enters into the titanite and not in the ilmenite. It would be an improvement, if the norms were calculated in accordance with this fact.

Still it might be remarked that FeO and MgO are not distributed proportionally in the femic minerals, as calculated in the norm, and the norms would be more correct, if the distribution of the bases would be based upon ratios calculated from actual analyses of minerals separated from the same rock.

On the whole, the norm system cannot be materially better than it is, if practical utility is kept in view. It is, moreover, very fortunate that most of the objections for inconsistency with the actual equilibrium refer to cases outside the range of variation in normal igneous-rock series. In the most common and widely distributed rocks the norms show a good approximation to the corresponding associations in the gabbro facies.

Therefore I think the norms will enjoy lasting use in the far future, regardless of the quantitative classification. We may pay some attention to the latter also from the point of view of the facies-principle.

If the norm was a successful characteristic of potential mineralogical features in the rocks, it is then the more regrettable that the authors of the quantitative classification soon departed from the chemico-mineralogical line in some degree it was still followed in the division of classes and orders and went on to develop a merely arithmetical system. Yet those boundary-lines in the gradual variation of the chemical rock composition, where new minerals appear, are in every facies, and thus also in that schematized gabbro facies represented in the norm system, such natural boundaries that they should have been accepted with thankfulness, as a basis of detailed grouping. Within such boundaries quantitative proportions could have been used.

These natural lines are evident to such a degree that petrographers accustomed to use the norm have unconsciously began

to class rocks after them, as appears from terms such as „rocks with normative corundum“, „or with normative olivine“, or „nephelite“, or „aegirite“, etc., and they well know that in such terms are expressed some very essential characters of the rocks, also appearing in the actual mineral composition.

The various series of modal development, i. e. what I have called the facies, would then present themselves as the first divisions. This would be a quantitative chemico-mineralogical classification.

Another classification, still more devoid of that schematic regularity characteristic of the „Quantitative System,“ but having the advantage of always following the natural lines and being capable of unlimited development, would be that entirely based on the facies-principle, where each facies is successively divided according to its own rules of mineral association. This is the facies-classification proposed in the present paper.

It may be objected that the facies classification will also be unnatural or, at least, one-sided, as it does not take into account the genetic relations of rocks. This I fully admit, but I agree with the authors of the quantitative classification when they say that there is needed a classification based „only on facts or relations determinable in the rock itself“,¹ and also that discussions of genetical relationships are „essential to the complete understanding and description of rocks, but are not applicable to the construction of a petrographic system“. ² Here I would merely remark, that the petrologists cannot, in the future any more than in the past, be detained from expressing such relations in systems and giving names to the rocks to signify their comagmatic relations. And such names will probably continue to be those in common use, while the facies classification may perhaps be used much in the same way as the American system is actually used nowadays: we complete the characteristic of a rock by calculating its „subrang“. The corresponding operation in the facies system is only so much simpler, as we

¹ Op. cit. p. 108.

² Op. cit. p. 110.

here have but to name the characteristic stable minerals of a rock, whereby its place in the system is given.

Yet I believe the facies classification will prove the most adequate system possible in discussing magmatic differentiation and congenetic relations of rocks. For the modern development of physico-chemical petrology has now fully justified BRØGGER's conclusion almost 30 years ago, that the sequence of differentiation is parallel to the sequence of separation of the mineral constituents.
