Some mineralogical transformations in crystalline schists.

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THE twofold division of metamorphic rock-series into (*a*) Isophysical rock-series and (*b*) Isochemical rock-series, as proposed by P. Niggli[1] in his paper, 'Die Gesteinsassoziationen und ihre Entstehung', introduces into metamorphic petrology two very useful terms, which will be of service in the metamorphic researches that await the attention of the petrologist.

Among such investigated rock-series one may call to mind the studies on the chloritoid-schists of the St. Gotthard massif,[2] the glaucophane-schist suite of the Bagne valley (Wallis),[3] the calc-silicate series of the Trondhjem region,[4] the contact rocks of the Kristiania[5] and Comrie[6] areas. Of these the last are particularly illustrative of an isophysical rock-series, wherein a chemically wide group of assemblages conforming to the composition of shale-limestone sediments is represented in the free-silica and quartzless hornfelses. The crystalline schists of the Ordovician volcanic horizons of the Trondhjem region, studied by Carstens,[7] exemplify another isophysical series in dynamic metamorphism.

Among isochemical rock-series we turn to the pelitic crystalline

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[1] P. Niggli, Verhandl. Schweiz. Naturf. Gesell., 1921, 101 Jahresvers. for 1920 in Neuenburg, part 2, pp. 123–147. [Min. Abstr., vol. 2, p. 315.] These terms are further defined and described in U. Grubenmann and P. Niggli, 'Die Gesteinsmetamorphose,' 1924, part I, pp. 481-484. Isophysical is synonymous with isograde or isofaciel used in conjunction with isograd, in treating metamorphism from the standpoint of the facies classification (Geol. Mag., 1924, vol. 61, p. 167).

[2] P. Niggli, Beitr. geol. Karte der Schweiz, 1912, N. Folge, Lief. 36, p. 1.

[3] T. J. Woyno, Neues Jahrb. Min., 1911, Beilage-Band 33, p. 136.

[4] V. M. Goldschmidt, Vid. Selsk. Skrifter, Kristiania, 1915, no. 10.

[5] Ibid., 1911, no. 1.

[6] C. E. Tilley, Quart. Journ. Geol. Soc. London, 1924, vol. 80, p. 22.

[7] C. W. Carstens, Norsk Geol. Tidsskr., 1922, vol. 7, p. 186.

schists of the Stavanger area[1] as the most thoroughly investigated, where detailed study by V. M. Goldschmidt reveals the chemical identity of varying mineral assemblages zonally arranged around Caledonian eruptives. Identical mineral assemblages were long ago recognized by G. Barrow[2] in his work on the crystalline schists of the south-east Highlands, but little detailed chemical work had been carried out.

The study of progressive metamorphism, whether it be concerned with the regional metamorphism of large mountain tracts or with the local metamorphism of small areolas surrounding intrusive rocks, brings constantly before the student two prime problems of determining,

(*a*) The genetic relations of the mineral assemblages of an isochemical rock-series,

(*b*) The varied mineral assemblages constituting particular isophysical rock-series.

Viewed from the standpoint of the facies classification these two problems resolve themselves into a study of the genesis of the critical index-minerals of the facies in an isochemical rock-series, and the broader problem of determining the mineral groupings of any one facies throughout the wide range of chemical composition revealed in rock masses. As I have expressed it elsewhere,[3] the elucidation of equivalent grades of metamorphism in a series of mixed sediments (or igneous rocks)—in a word, the determination of *isograde assemblages*.

It is hardly necessary to add that study along these lines is yet in its infancy. We are, so to speak, only at the threshold of an unexplored region, nevertheless the fruitful results already acquired in the pioneer studies of regional tracts, as the Scottish Highlands and the Scandinavian mountain area, lead one to hope that from such model metamorphic regions the solution to these problems will eventually be wrested.

In the realm of thermal metamorphism our knowledge is less scanty than in the case of regional metamorphism. This of course is due to two factors: firstly, more detailed investigations of thermal aureoles, and secondly, the data acquired in the laboratory investigation of silicate melts, have thrown a flood of light on the mineral relations obtaining in the inner zones of thermal aureoles. Much work yet remains to be done with the outer zones. Study here is intimately bound up with a determination of the constitution of very fine-grained sediments such as muds and shales. In the near future the application of X-ray studies to such

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[1] V. M. Goldschmidt, Vid. Selsk. Skrifter, Kristiania, 1920, no. 10.

[2] G. Barrow, Quart. Journ. Geol. Soc. London, 1893, vol. 49, p. 330.

[3] C. E. Tilley, Geol. Mag., 1924, vol. 61, p. 167.

fine-grained material may lead to important results, and throw light on this vexed problem.

When the dynamically metamorphosed rocks come to be considered, we enter a region as yet unexplored by experimental research, a state of affairs brought painfully to our notice by the large number of unsynthesized minerals characteristic of crystalline schists. Progress has therefore been much slower in this branch of metamorphism; meanwhile an intensive field and laboratory study of crystalline schists in the light of physico-chemical data already accumulated should mark a great forward step. Those large mountain tracts particularly in which detailed mapping has revealed a great unbroken sequence of rocks in graded stages of metamorphism offer a wide and fruitful field for the metamorphic petrologist who may begin anew a quantitative study of the mineral assemblages and their spatial distribution. The first obvious line of attack is the elucidation of the varied mineral groupings in distinct isochemical rock-series that the particular metamorphic province has developed. This, indeed, was the method initiated by Barrow in his pioneer work of 1893, studies made more comprehensive by extended research resulting in the publication of the metamorphic map of the south-east Highlands in 1912.[1]

The pelite isochemical rock-series.—The dominant sediment type of such metamorphic provinces is the normal pelite, and it is therefore natural that our knowledge of the mineral assemblages of this chemical type is less incomplete than with other rock-series. Illustrative of such an isochemical series, it will serve to compare analyses of several mineral assemblages of the series, and these are quoted from the text-books in the accompanying table.

	I.	II.	III.	IV.	V.	VI.
SiO_2 ..	60·24	58·32	57·29	60.62	58·59	63·41
Al_2O_3 ...	18·46	20·00	20.60	18.50	19·48	19·22
Fe_2O_3 ...	2·56	2·01	2·40	1.32	1·07	2·74
FeO ...	5·18	4·98	5·48	5·65	5·31	4·00
MgO ...	2·33	1·85	1·76	2·42	3·31	2·84
CaO ...	0.33	0·66	0.37	1·66	1·72	0.65
Na_2O ...	1·57	1·26	1·40	1·81	1·65	1·21
K_2O ...	4·09	4·49	4·30	4·02	4·59	4·36
$H_2O \pm$ ...	3·99	4·10	4·05	3·09	3·24	0·60
TiO_2 ...	0.92	0·98	0·97	0·80	0.92	0.65
P_2O_5 ...	0·11	0·15	0·14	0·08	0.15	—
MnO ...	0.07	0·22	0·41	0·07	0.13	0·05
CO_2 ...	0·08	0·43	0·05	—	—	—
Accessories ...	0·22	0·57	1·02	0·05	—	—
	100·15	100·02	100·24	100·09	100·16	99·73

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[1] G. Barrow, Proc. Geol. Assoc. London, 1912, vol. 23, p. 268.

I. Slate: Vermont, U.S.A.
II. Chlorite-muscovite-phyllite: Stavanger, Norway.
III. Spessartine-almandine-chlorite-mica-schist: Stavanger, Norway.
IV. Almandine-biotite-mica-schist: Stavanger, Norway.
V. Kyanite-staurolite-almandine-mica-schist: Ta-ku Shan, Liautang, China.
VI. Sillimanite-almandine-orthoclase-cordierite-gneiss: Södermanland, Sweden.

Despite the knowledge so far obtained of the various facies in this pelitic rock-series, little study has been made of the genetic relations obtaining among the constituent facies. Each mineral grouping has been studied rather as a complete assemblage, but a closer acquaintance with the mineralogical transformations that result in the passage from a lower to a higher assemblage is highly desirable. Here it is that the fuller recognition of the element of progression in metamorphism brings us into closer contact with the genetic aspect of the subject. To illustrate the point at issue, little is known concerning the nature of the mineralogical reactions which culminate in the production of the critical index-minerals of the zones of the rock-series now under discussion; for example, the genesis of (*a*) biotite, (*b*) almandine or spessartine, (*c*) staurolite or kyanite, (*d*) sillimanite.

Analyses of metamorphic rocks.—As representing originally mechanical mixtures of the detritus of pre-existing rocks and their degradation products, metamorphosed sediments constitute accidental assemblages, whose chemistry, obeying no simple law of distribution, is widely variable from point to point through any rock unit. From the nature of the case it follows that chemical analyses of sediments and their metamorphic derivative have not the significance of igneous rock analyses, which in themselves in large measure portray the stage of descent of the magmatic melt of which they are the record. Sediment analyses simply record the bulk composition of discontinuously varying mineral aggregates. Much care is necessary in the selection of such material for analysis, and it is not improbable that the wide disagreement sometimes observed between a rock analysis and the published petrographical description of the analysed rock is to be traced to an inhomogeneity of the selected material.

One further point deserves comment. The great majority of the minerals characteristic of crystalline schists are generated independent of the silica content of the rock over wide limits. As striking examples we need only mention the silica-poor, alumina-rich minerals of the chloritoid-ottrelite group, and also staurolite. Schists with chloritoid as a prominent constituent show silica percentages ranging in the wide interval between 30 and 80. The passive role of silica must therefore be considered when analyses of sedimentary rocks are compared, and for the case of the pelitic isochemical rock-series the relations of a series of rock analyses are best discovered by a graphical plot of the oxide groups alumina, alkali oxides, and combined magnesia and ferrous oxide (all iron as FeO).

Analyses of metamorphic minerals.—When we turn to the available record of metamorphic minerals, we find a great gap in our knowledge of the composition of those minerals which are found widely distributed in the mass of crystalline schists. I refer now not to such minerals as cordierite or the scapolites, or stress minerals entirely confined to metamorphic rocks, but to those minerals common to both igneous rocks and metamorphosed sediments, particularly to the common micas, muscovite and biotite, pyroxenes and amphiboles, chlorites, and serpentines. Inspection of suites of analyses of the micas and the chlorites shows that the material chosen has come almost exclusively from igneous rocks, vein material, or well-crystallized material in druses and vughs. Analyses of these minerals extracted directly from the groundmass of slates, contact rocks, or crystalline schists are few indeed.

In the present unsatisfactory state of the knowledge of the constitution of these minerals it is obviously of great importance that such analyses should be carried out. Much attention has been devoted of late to the solution of the muscovite-biotite problem, and various complicated hypothetical formulae have been devised to explain the constitution of these micas, but it is clearly unprofitable for the metamorphic petrologist to substitute hypotheses for facts. The wide range of composition revealed in rock-making micas makes it imperative that analyses of the material in the setting of the crystalline schists should be available in order to understand the genetic problems connected with their metamorphism.

Graphical representation of analyses.—In order to visualize the analyses of mineral assemblages in the pelite isochemical rock-series, a triangular plot with alkalis, $FeO+MgO$, and Al_2O_3 as the three variables may be used with advantage. In order to utilize a greater area of the triangle, the three variables are taken as $K_2Al_2O_4$, $MgO+FeO$, and Al_2O_3; all Fe_2O_3 being converted to and treated as FeO.

Compositions of the muscovite-chlorite system.—In the accompanying diagram (fig. 1) the field *KMS* represents the composition field of mixtures of kaolin (or other hydrated aluminium silicate), muscovite ($H_2KAl_3Si_3O_{12}$), and the chlorites with iron-ores. This indeed should be the field of normal pelitic sediment as represented by shales and slates.

It is easy to test this by plotting in the recast analyses of slates. For this purpose thirty-two first-class analyses of slates have been taken free or almost free from CaO. The concentration field of these is also shown in fig. 1. It is seen that only half the field is enclosed within the area *KMS*. The extension of the field below *MS* is indicative either of a considerable percentage of orthoclase or albite in the slates, or the composition of the muscovites of slates does not correspond to the usual formula given by Tschermak. Most of the slates have been petrographically described, and the published descriptions do not allude to the frequency of felspar, such as is demanded by the plot, and although fine-grained albite is likely to be mistaken for quartz, it may be doubted whether the assumed presence of felspar is the chief contributory cause of the discrepancy. These doubts are further strengthened when the few actual reliable analyses[1] of rock-making muscovites of slates and

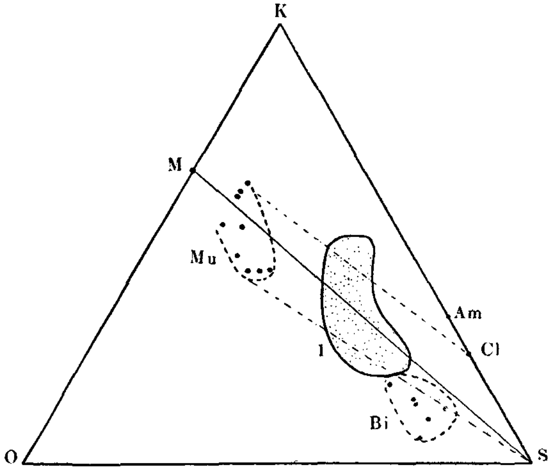

FIG. 1. Concentration field of slates (area 1).

[K = kaolin, O = orthoclase and albite, S = serpentine and iron-ores, Am = amesite, M = theoretical muscovite, Mu = field of muscovite from slates and mica-schists, *Bi* = *field of biotite* from mica-schists, Cl = limit of field of rock-making chlorites in sediments.]

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[1] Quart. Journ. Geol. Soc. London, 1893, vol. 49, p. 355; Bull. U.S. Geol. Survey, 1910, no. 419, p. 286; Neues Jahrb. Min., 1912, vol. 1, p. 399; H. Rosenbusch, 'Elemente der Gesteinslehre,' 4th edit. by A. Osann, 1922–1923, p. 587; C. Doelter, 'Handbuch der Mineralchemie,' 1915, vol. 2, part 2, p. 422.

mica-schists are plotted in the diagram. These are plotted in the figure, and it is seen that the majority of them fall below the line *MS*.

In the case of chlorite, the scarcity of analyses of material present in the groundmass of slates or phyllites is even more apparent; but for our immediate purpose this desideratum is not so pressing, as the combination of chlorite with the accessory iron-ores is represented in the plot over a sufficiently wide range to cover great variation in the composition of the rock-making chlorites. The point *Cl* represents, in fact, the limit reached towards amesite in the available analyses of rock-making chlorites of pelites. The extended field revealed by the plotted positions of the muscovite analyses is now seen to cover a large part of the slate concentration field. The extension of the latter towards alumina indicates the presence of kaolin or related minerals, and doubtless the presence of detrital albite throws the field in the direction of *O*, but the few analyses represented in this part of the field do not give decisive evidence on this point by the relative potash-soda ratios.

Genesis of biotite.—As is well known, one of the first stages in the conversion of slates and phyllites into crystalline schists or into hornfelses on approaching igneous contacts is the production of biotite amidst the chlorite-sericite groundmass. We know, too, solely from optical determinations, that the composition of the biotite changes as metamorphism advances. Examination of any thermal aureole reveals that the little flakes of biotite as the igneous contact is approached gradually develop a deeper red tint, indicative, no doubt, of continuous enrichment in ferrous oxide. Similarly, in the case of the crystalline schists the earliest formed biotites are often green to brown-green in colour, eventually developing the common red-brown tint as the grade of metamorphism advances.[1] What other changes go hand in hand with this increase in FeO (if such it be) are quite uncertain. There does not appear to be recorded more than one analysis of biotite from pelitic hornfelses, that carried out by Jannasch in 1886. Better testimony of the limited knowledge of this aspect of the subject could scarcely be imagined.[2]

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[1] C. E. Tilley, Quart. Journ. Geol. Soc. London, 1925, vol. 81, p. 103.

[2] A. F. Hallimond (Min. Mag., 1924, vol. 20, p. 193) and F. F. Grout and G. A. Thiel (Amer. Min., 1924, vol. 9, p. 228) have pointed out the possible importance of stilpnomelane as a constituent of metamorphosed sediments, especially in relation to its optical similarity to biotite. Lack of knowledge of the constitution of groundmass 'chlorites' and 'biotites' prevents as yet any estimate of the rôle accorded to stilpnomelane in metamorphosed sediments.

generated, as analyses of the rocks of the phyllites of the Ardennes[1] first revealed. Here, indeed, the garnet arises at an earlier stage than the development of brown biotite. The presence of lime also probably favours early generation of garnet, and the grossular molecule is frequently not unimportant in analyses of almandines from pelitic rocks. The early generation of garnet in the Loch Lomond area, among the albite-schists, probably finds its explanation in the presence of lime as calcite in the pelitic sediment. The essential garnet molecule, however,

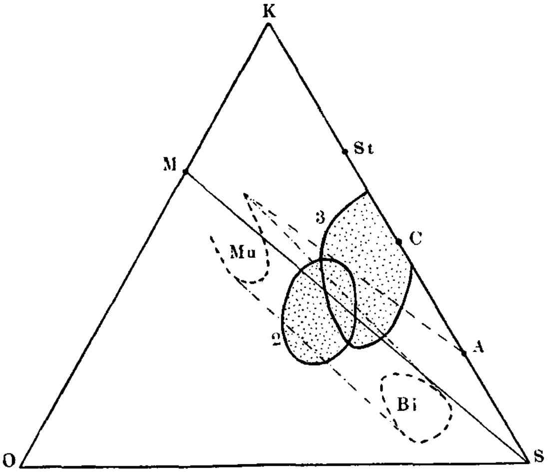

FIG. 2. Concentration field of mica- and garnet-mica-schists (2), and of chloritoid-schists (3).
[C = chloritoid, A = almandine, K = kyanite, St = staurolite.]

in metamorphosed normal pelitic sediment is almandine. Its genesis in the garnet zones of metamorphic provinces is still obscurely known. Two obvious sources suggest themselves, (*a*) chlorite, (*b*) biotite, to which may be added as contributor iron-ores.

The fact that it is possible to draw garnet isograds in regions of progressive metamorphism, points clearly to the conclusion that one dominant reaction is involved in the first production of almandine. Examination of those rocks situate at the first points of entry of garnet in pelitic sediments in the southern Highlands, frequently reveals the garnets in skeleton form, growing at the expense of the surrounding

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[1] A. Renard, Bull. Mus Roy. Hist. Nat. Belg., 1882, vol. 1, p. 10.

Boeke[1] in a noteworthy contribution to the muscovite-biotite problem has already clearly shown that Tschermak's conception of the constitution of the micas cannot be maintained, and this fact is clearly demonstrated in the plot of analyses[2] of rock-making biotites in pelitic rocks shown in fig. 1. After allowing for the inclusion of Fe_2O_3 as FeO, in the diagram, the analyses fall too far below the line *MS*.

The difficulty now arises that the composition field of biotite is not enclosed within the muscovite-chlorite field. That part of the slate belt below the line *MS* is, however, comprised within the muscovite-biotite field. Either the limited number of analyses of muscovite do not show the variation limit of rock-making muscovites, i.e. varieties still richer in potash exist, or else, as the fields muscovite-chlorite and muscovite-biotite have a common field, biotite is a product of a reaction between potash-rich muscovite and chlorite, with the accompanying formation of a muscovite less rich in potash. More analyses of the muscovites of slates and schists will be necessary before a solution of this problem is reached.

Muscovite-biotite-schists and almandine-biotite-schists.—In fig. 2 the concentration field of biotite- and biotite-garnet-schists, free from potash-felspar and aluminium silicates, in fact the rocks typical of the biotite and almandine zones, is plotted, based on twelve analyses. A large number of analyses of rocks of this type is not available. The field of these rocks is almost completely enclosed in the fields of muscovite-biotite-almandine (*Mu-Bi-A*). The field is much more restricted than in the case of slates. The reason for this is obvious. The metamorphic line of descent of slates is varied, some as will be shown later belong to the same isochemical series as the typical chloritoid- and staurolite-schists. As in the case of the slate field, there is an extension of this field below the lower limit of *Mu-Bi*, to be ascribed to the presence of albite.

Genesis of almandine.—The march of metamorphism of regional type in pelitic sediments leads on from muscovite-biotite-schists to garnet-bearing schists. The common garnet of the garnet zone is essentially an almandine usually with very low percentages of magnesia and ferric oxide. In manganese provinces, spessartine-almandine is readily

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[1] H. E. Boeke, Neues Jahrb. Min., 1916, vol. 1, p. 83.

[2] Quart. Journ. Geol. Soc. London, 1893, vol. 49, p. 355; Nyt Mag. Naturv. 1886, vol. 30, p. 818; Mitt. Thurg. Naturf. Gesell., 1888, vol. 8, p. 13; H. Rosenbusch, 'Elemente der Gesteinslehre,' 4th edit. by A. Osann, 1922–1923, p. 655; Zeits. Krist., 1923, vol. 57, p. 416; C. Doelter, 'Handbuch der Mineralchemie,' 1916, vol. 2, part 2, p. 695.

minerals. In thin slices the development of such skeleton and amoeboid almandines from laths and scales of chlorite, interspersed among quartz grains, is shown by mica-schists occurring along the garnet isograd. The relations there seen make it quite clear that garnet is arising from chlorite. The reverse process of chlorite arising on the ruins of garnet, is common enough in petrographical observation, but the direct development of garnet from chlorite is much less familiar. To understand the mechanism of this production analyses of rock-forming chlorites and almandines in pelites must be reviewed.

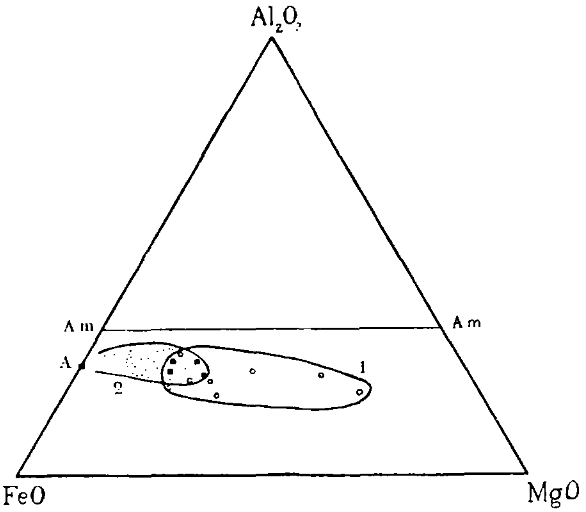

FIG. 3. Concentration fields of chlorite (1) and almandine (2) in pelites. [A = almandine, Am = amesite end-members.]

As in the case of muscovite and biotite, there are few available analyses of rock-making chlorites in pelites. These [1] are plotted in fig. 3 (field 1), FeO being separated from MgO. The field of almandines of pelites is also indicated (field 2). Considering the ratio RO/Al_2O_3 it is seen that there is correspondence in the two minerals; were that the only consideration, the formation of garnet from chlorite would only

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[1] C. Hintze, 'Handbuch der Mineralogie,' 1897, vol. 2, p. 728; M. F. Heddle, 'Mineralogy of Scotland,' 1901, vol. 2, p. 125; H. Rosenbusch, 'Elemente der Gesteinslehre,' 4th edit. by A. Osann, 1922–1923, p. 587; Neues Jahrb. Min., 1897, vol. 2, pp. 156, 215; Amer. Journ. Sci., 1886, ser. 3, vol. 32, p. 307.

require addition of silica. But it is in the ratio FeO/MgO that rock-making chlorites and almandines reveal discrepancies. The two fields overlap, this overlap being based on four analyses[1] of garnets (Fort Wrangel, Wittichen, Dachsbusch, Laacher See).

Almandines preponderate in the left-hand part of the field, not overlapped by the chlorite field. Whilst then some chlorites have the appropriate FeO/MgO ratio of that of actual almandines, many almandines cannot be thus satisfied. Nor can they be satisfied if it be assumed that iron-ores take part in the reaction, as will be seen from the diagram.

As specific examples of this non-agreement we may note the careful analyses of Penfield on the composition of almandine and the chlorite resulting from its degradation, for the case of the Lake Superior and Salida almandines, and further the compositions of the garnets and chlorites of the schists of the Stavanger region. In these cases the chlorites are all much richer in magnesia than the garnets. Actual exchange of magnesia for ferrous oxide, alumina being unchanged, is suggested. The position is still further complicated by the fact that almandines frequently contain appreciable percentages of the grossular and spessartine molecules, which cannot be accounted for in chlorite analyses.

One of the standard equations for the production of garnet from biotite is given in the reaction, biotite + quartz = almandine + orthoclase. There is a considerable body of evidence in support of such a development in high-grade pelites, but I believe this reaction is not typical of the almandine zone proper. In the garnet zone of the southern Highlands, orthoclase is a rare mineral, and where present can generally be assigned to its original presence as a detrital mineral (as in arkoses, cf. the Moine gneisses). It is, of course, to be understood that these remarks apply specifically to pelitic sediments. In the metamorphosed calcareous sediments of the almandine zone, potash-felspar may be abundantly generated, as the calc-silicate rocks of the Highlands testify. If garnet arises from biotite in the almandine zone, such a reaction finds no place, and a biotite derivation at this early stage has, I believe, yet to be demonstrated.

Chloritoid-rocks.—The concentration field of the chloritoid-schists, based on thirty analyses, is shown in fig. 2 (field 3). It is seen that chloritoid-schists cannot be strictly considered in the same isochemical series as the pelitic mica-schists, though the two fields overlap. The

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[1] Dana, 'System of Mineralogy,' 1892, p. 442; C. Doelter, 'Handbuch der Mineralchemie,' 1921, vol. 2, part 3, pp. 365, 368.

principal distictions are lower alkalis, and in part higher alumina and iron oxides. The most complete treatment of the chloritoid-schists is that given by Niggli in the paper already quoted. Chloritoid begins already to form in the chlorite zone, at the expense of kaolin or sericite in the presence of iron oxides, and persists into higher zones.

Staurolite-rocks.—The concentration field of the staurolite-rocks is practically coincident with that of the chloritoid field of fig. 2, and these rocks are to be considered in one and the same isochemical series. Van Hise[1] has stated that 'staurolite rocks usually contain orthoclase or at least some potash felspar'. This statement I believe not to represent the facts. In the typical staurolite-rocks of the Highlands and the St. Gotthard region, potash-felspar is absent, nor is there evidence of its former presence, and it is to be doubted whether potash-felspar is generated in pelites in regional metamorphism below the metamorphic grade of the sillimanite zone. The generation of staurolite from chloritoid, of which evidence is provided in the staurolite-rocks of the Piz Scopi and other areas, is doubtless one of the principal reactions by which this mineral is developed in the crystalline schists. The evidence for this transformation I have already summarized in a previous paper.[2]

Index-minerals of pelites and the depth zones.—The index-minerals, biotite, almandine, staurolite, kyanite, in their pelitic assemblages are lumped together in the meso-zone of Grubenmann's classification of the crystalline schists. Chlorite is relegated to the epi-zone, and sillimanite allotted to the kata-zone. It is such examples as these that demonstrate the inadequacy of the depth zone hypothesis to express the diversity of mineral assemblage in an isochemical rock-series. It is to the credit of the facies classification that the finer expression of this mineral diversity is adequately provided for. The recognition of metamorphic zones, mapped with precision in regional tracts of crystalline schists, is clearly in harmony with the scheme of the facies classification, which, based on physical and chemical principles, yet freed from any concept of depth or *a priori* pigeon-holing, can grow in strength and completeness with the onward march of petrological research.

Conclusion.—If the foregoing remarks have settled little, they at least have demonstrated some of the desiderata to be acquired before any adequate conception is obtained of the chemical reactions taking place in what is probably the most intensively investigated of the isochemical rock-series. In view of the wide range of composition of the constituent

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[1] C. R. Van Hise, Monograph U.S. Geol. Survey, 1904, no. 47, p. 328.

[2] C. E. Tilley, Geol. Mag., 1925, vol. 62, p. 318.

minerals, elaborate calculations of their composition, starting from the bulk analysis of the metamorphic rock, are to be looked upon with grave suspicion. The mechanism of the mineralogical transformations in crystalline schists is something much more complex than is explained away by the customary simple equations. The most pressing need is a closer chemical investigation of the common minerals occurring in the groundmass of metamorphic rocks.