THE GRAPHICAL ANALYSIS OF MINERAL ASSEMBLAGES IN PELITIC SCHISTS*

JAMES B. THOMPSON, JR., *Harvard University, Cambridge, Massachusetts.*

ABSTRACT

The principal minerals used as metamorphic indicators in pelitic schists are, to a first approximation, phases in the system: SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O. At a given pressure, temperature and humidity (activity of H_2O), quartz-bearing assemblages in this system are dependent on the relative amounts of Al_2O_3, MgO, FeO, and K_2O. These assemblages may be shown three-dimensionally in the tetrahedron: Al_2O_3-MgO-FeO-K_2O. Assemblages which include muscovite as well as quartz may be represented successfully in two dimensions by projecting the compositions of minerals onto some suitable plane with the composition KAl_3O_5 as point of projection. This projection is applicable to rocks over a wide range in bulk composition and through wide range of metamorphic conditions. It also provides a unique characterization of the mineral facies observed in pelitic schists. The principal variation in composition of most of the minerals involved is given by the ratio $MgO/MgO+FeO$. This ratio may commonly be determined with sufficient accuracy by simple measurements of optical or other physical properties.

INTRODUCTION

In the classic work of Barrow (1893, 1912) in the Scottish Highlands, and in numerous field and petrographic studies since that time, regional metamorphic zoning has been described and mapped in terms of the successive appearance of certain minerals or mineral assemblages in aluminous schists. Such schists are generally formed by the metamorphism of pelitic sediments. The principal indicator minerals in the order of their appearance in the area studied by Barrow, are: chlorite, biotite, almandite, staurolite, kyanite and sillimanite. Other minerals of pelitic schists have been used as indicators by various authors. A chloritoid isograd has been drawn in the Taconic area by Balk (1953; see also Tilley, 1925). Heald (1950) has drawn an isograd on the first appearance of the pair: orthoclase+sillimanite.

A pelitic schist is not a simple chemical system and the mineralogic variations that have been observed do not lend themselves readily to graphical analysis. Certain components such as ZrO_2, CO_2, S or P_2O_5 are not present in the above mentioned "indicators" in measurable amounts and may be dismissed if we simply omit from consideration those phases in which such components appear in measurable amounts—regarding these latter phases, in effect, as the crucible in which the others react. Even with eliminations of this sort, however, we are still faced with a polyphase, multicomponent system and rather arbitrary simplifi-

---

* Contribution from the Department of Mineralogy and Petrography, Harvard University No. 382.

cation is necessary. Possible consequences of this simplification will be discussed at the end of this paper.

The Choice of Components

To a first approximation the indicator minerals listed above may be regarded as phases in the six-component system: SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O, a system which also includes minerals such as muscovite, quartz, andalusite, cordierite and others commonly associated with the above indicators. It is apparent that this is but an approximation when we consider the known content of Fe_2O_3 or TiO_2 in a typical biotite, CaO or MnO in garnet, or Na_2O in muscovite or potassic feldspar, even though in many instances it is possible to give the compositions of these minerals in terms of the six components listed above and leave very little of their substance unaccounted for. The success of such an approximation may be measured by its applicability which will be discussed more fully below. However, it must be remembered that in any specific natural occurrence an apparently anomalous mineral association may be related to an unusual abundance, in one or more of the minerals, of some neglected component.

It may seem of little value that the system is now narrowed down to six components, since even at a specified temperature and pressure a three-dimensional model is needed to represent completely the phase assemblages in a system of as few as four components. Though this is true enough, we can profit from the fact that we are not interested in *all possible* assemblages in the system, but in only those that occur in rocks under present consideration. Specifically, the schists and gneisses in which mineral zones have been mapped almost invariably contain quartz, and we are not seriously restricting our field of observation if we omit from the present discussion all assemblages where quartz is not present. Now, since quartz is virtually pure SiO_2, it is clear that an increase or decrease in the amount of SiO_2 in a quartzose rock will be reflected simply in an increase or decrease of quartz, other things being equal, and that the minerals present other than quartz are dependent on the relative amounts of components other than SiO_2.

The Graphical Status of H_2O

The restriction that quartz be present thus has the effect of reducing the compositional variables by one so that we are left, for graphical purposes, with a five-component system: Al_2O_3-FeO-MgO-K_2O-H_2O. Were a phase corresponding to any of these other components commonly present we could eliminate it as we did SiO_2, but this does not appear to be the case. It is possible that a fluid phase made of nearly pure H_2O was

present in such rocks at one time or another, but it is not a phase that we observe in typical thin sections of a schist or gneiss, nor are there "holes" where such a phase might have been. There is to be sure, even in a schist or gneiss, evidence of H_2O in excess of that combined in the crystalline phases, and evidence that this extra H_2O is concentrated along the grain boundaries, but it would be unwarranted to assume from this that such an intergranular film may be regarded, even approximately, as either pure H_2O chemically or like a bulk aqueous fluid in its physical properties. We shall, however, eliminate H_2O from our graphical analysis, but for rather different reasons.

It is apparent, from comparison of chemical analyses of pelitic sediments (Clarke, 1924, pp. 516–518 and p. 552) with those of typical schists and gneisses derived therefrom (Clarke, p. 553 and pp. 625–626) that such rocks lose H_2O when metamorphosed, and, from consideration of the minerals involved, that the higher the grade of the metamorphism, the greater the loss.

Whether a rock will tend to gain or lose H_2O at a given pressure and temperature is dependent on the activity, a_{H_2O}, or chemical potential, μ_{H_2O}, of H_2O in the rock (or its intergranular film) relative to its immediate surroundings.

If a_{H_2O} or μ_{H_2O}, or the humidity η,[1] in the rock is higher than in its surroundings, the rocks will tend to lose H_2O, and vice versa. In an open system of this sort the stable phase-assemblage will be dependent on the

---

[1] $a_{H_2O} = e^{\dfrac{\mu_{H_2O} - \mu_{H_2O}{}^*}{RT}}$ where $\mu_{H_2O}{}^*$ is the chemical potential of H_2O in some standard

or reference state. The *relative humidity of* meteorologists may be regarded as an activity of H_2O expressed in per cent (rather than on a fractional basis as is usual in chemical literature) and where the standard state is water-saturated air (or distilled water) at the P and T in question. A more useful standard state, for geologic purposes, would be the stable form of pure H_2O at the P and T in question. This would be virtually identical with the meteorological standard state at low pressures and temperatures and have the advantage of being independent of other components present at high temperatures and pressures. The activity of H_2O with standard state so defined will be referred to henceforth as simply the "humidity." More formally:

$$\eta \equiv e^{\dfrac{\mu_{H_2O} - \mu_{H_2O}{}^0}{RT}}$$

where $\mu_{H_2O}{}^0$ is μ_{H_2O} for the stable form of pure H_2O at P, T. There are no other "humidities" in standard geological parlance with which it may be confused, and it is virtually identical with the meteorological relative humidity in a surface or near-surface environment. Furthermore, the intuitive connotations commonly associated with the word "humidity" are qualitatively correct with respect to η but not with respect to μ_{H_2O}. Specifically: a rise in temperature at constant P and η will, in general, tend to dehydrate the system and a rise in temperature at constant P and μ_{H_2O} will tend to hydrate the system.

temperature and pressure, the *activities* or *chemical potentials* of those components to which the system is open, and upon the *relative amounts* of those components to which the system is closed, or, in our specific case, on P, T, η, and the relative amounts of Al_2O_3, MgO, FeO and K_2O. This includes as a limiting case, the possible occurrence of pure H_2O as a separate phase. Such an occurrence would correspond to unit (or 100 per cent) humidity at any given pressure and temperature. This would be the practical maximum value for the humidity at the given pressure and temperature owing to the choice of the stable form of the pure substance (at P, T) as standard state. A humidity less than unity (or 100 per cent) might be visualized, graphically, as the situation which would prevail if a hypothetical form of H_2O, more stable than the actual stable one at the P and T in question, were present in the system. In general the graphical analysis of mineral assemblages neglecting the amount of H_2O relative to other components seems to work. This is consistent either with the presence of pure H_2O as a phase at the time the assemblage formed, or with the assemblage having reached its final state in accord with some externally controlled humidity.

THE TETRAHEDRON: Al_2O_3-MgO-FeO-K_2O

Compositions with respect to the remaining four components, Al_2O_3, MgO, FeO, and K_2O, may be plotted in the tetrahedron of Fig. 1. The portion Al_2O_3-$KAlO_2$-FeO-MgO or "A-K-F-M" has been employed by Barth (1936, also Osberg, 1952) for the illustration of mineral assem-
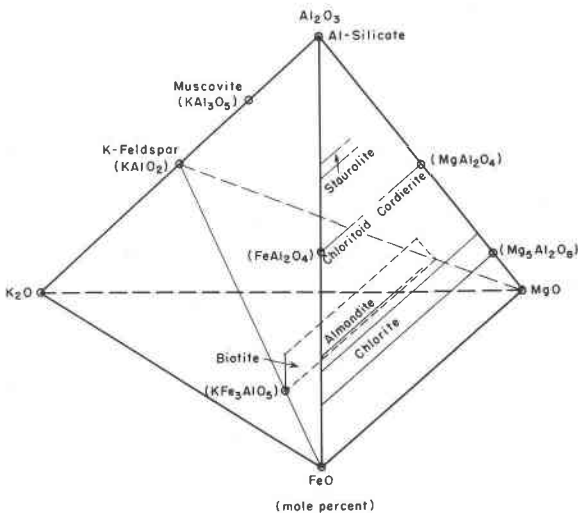

FIG. 1. The system SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O showing phases stable with quartz at P, T, η, as plotted in tetrahedron Al_2O_3-MgO-FeO-K_2O.

blages in schists. The "A-K-F" diagram of Eskola (1915) is similar but treats ($MgO+FeO$) as one component. Barth (p. 819) gives practical convenience as the reason for disregarding H_2O, but not without misgivings (p. 822). Eskola and Osberg assume H_2O to have been in excess. We have justified its elimination on a different basis which includes the latter as a limiting case.

A tetrahedral diagram is cumbersome for written presentation. Barth employed a perspective view developed by H. von Philipsborn (1928), and Osberg showed the Al_2O_3-FeO-MgO face with biotite projected onto the line FeO-MgO, the point of projection apparently being indefinitely removed from FeO-MgO in the plane $KAlO_2$-FeO-MgO. Barth's diagram is difficult to visualize particularly if several assemblages are to be shown, and Osberg's diagram, which resembles one that we shall describe below, does not clarify the relationships of potash feldspar when it appears in association with aluminous minerals such as almandite or cordierite.

The usefulness of the "A-K-F" diagram of Eskola, as extensively employed by Turner (1948) and other authors, is impaired by the lumping of MgO and FeO as one component. Though Fe^{++} and Mg substitute for each other readily (and perhaps nearly ideally) in solid solutions, they definitely do not behave as one component. Eskola (1915, p. 123) was, to some extent, aware of this, and the point has been clarified and emphasized by Bowen (1925). The ratios $MgO/(MgO+FeO)$, in pairs of coexisting mineral phases typically differ by easily measurable amounts. Furthermore the nature of any system of the type: X-MgO, at any given P and T is commonly quite different from the analogous system: X-FeO. One may, for example, compare the systems: SiO_2-MgO (Bowen and Andersen, 1914) and SiO_2-FeO (Bowen and Schairer, 1932) at any P and T where both are not entirely liquid.

The approach outlined below will make use of the fact that muscovite, like quartz, is nearly ubiquitous in metamorphosed pelites and rocks of comparable composition. The principal exceptions occur in the inner parts of certain contact aureoles and in the highest grades of regional metamorphism. Consequently we have relatively little interest in assemblages which do not include muscovite. Muscovite, however, is unlike quartz in that its composition is not that of a simple limiting component such as SiO_2. The solution of the problem is thus more complicated and may be regarded, graphically, as a projection onto some appropriate surface of the compositions of phases in equilibrium with muscovite.

THE REPRESENTATION OF PHASES OCCURRING WITH MUSCOVITE

The compositions of most natural muscovites, with respect to the components considered, lie at or very near the point labeled "KAl_3O_5"

in Fig. 1. At any given P, T and η the range of composition of muscovite will thus be a small volume at and near "KAl_3O_5," the surface of which will be terminus to all tie lines, compatibility triangles and compatibility tetrahedra for those assemblages in this system which include muscovite in addition to quartz. The surface of the volume for muscovite compositions should resemble, in general features, that of a wind-faceted pebble, and be characterized by smooth surfaces (termini of tie lines), edges (termini of triangles) and corners (termini of tetrahedra). The opposite ends of the tie lines, opposite edges of the triangles, and opposite faces of the tetrahedra will also constitute a surface giving the compositions of phases compatible with muscovite. The latter surface, consisting of three-phase triangles (three phases, that is, in addition to quartz and muscovite), bundles of two-phase tie lines, and one-phase areas, will be topologically like an ordinary three-component compatibility diagram except that points upon it will not, as a rule, be co-planar. We may, however, construct a map of such a surface by some suitable projection of it. An important consideration in so doing is to avoid, as far as possible, points of projection that would lead to overlapping of different portions of the projected surface. Thus in a simplified, two-dimensional analogue (Fig. 2), F would be a suitable point of projection for phases in equilibrium with phase α, but Q would not. In some instances it may not be possible to avoid overlap in projection. As shown in Fig. 2 this is most likely where the ubiquitous phase has a wide range of compositional variability. Fortunately, muscovite, in terms of the components considered shows but minor variation in composition from $KAl_3Si_3O_{10}(OH)_2$, or "KAl_3O_5" in the tetrahedron of Fig. 1. This means that tie lines from other phases to muscovite will be very nearly radial to "KAl_3O_5," and that the choice of this as point of projection will make any overlap highly unlikely.

A convenient surface to receive the projection is the plane: Al_2O_3-MgO-FeO. Many of the indicator minerals have compositions already lying in or very near it. The essential features of the projection are shown in Fig. 3. Compositions in the sub-tetrahedron A-P-F-M will project onto the area A-F-M, those in the volume N-O-P-F-M onto the extension of the plane A-F-M beyond the line F-M, and those in the sub-tetrahedron B-N-O-P onto the extension of the plane AFM beyond A. Compositions in the plane N-O-P will project to points indefinitely removed from A. We might, for convenience, define compositions in the volume A-F-M-N-O-P as projecting in the *positive* sense onto A-F-M and those in the volume B-N-O-P as projecting in the *negative* sense onto A-F-M. Though Fig. 3 aids in visualization the actual operation is more readily accomplished by formula as indicated in Fig. 4. Mineral assemblages

typical of the lower sillimanite zone in west-central New Hampshire are shown in Fig. 5. Nearby rocks in the kyanite zone have similar assemblages with kyanite taking the place of sillimanite. The "negative" part of the projection has been shown in Fig. 5, but is trivial, for many purposes, since each possible assemblage is represented in the positive part even though all bulk compositions are not.

Another convenient plane upon which to project is the plane that includes the edge MgO-FeO and is parallel to the edge Al_2O_3-K_2O (Fig. 6).
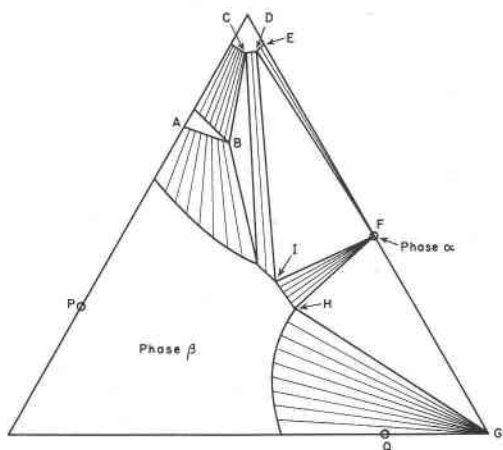
FIG. 2. The phases in equilibrium with phase α, a fixed compound, are shown by the line running G-H-I-D-E. If the compositions of these phases are projected through point F into some straight line, no portions of G-H-I-D-E will be superimposed in the projection. Phases in equilibrium with β, a solution, are given by the line running A-B-C-D-F-G. Projection through a point such as P would result in the portions A-B and B-C being partly superimposed. If a phase has an extreme range of solution it may not be possible in some instances to choose a point such that there will be no overlap. If the phase is a fixed compound, lying on the periphery of the triangle (or surface of the tetrahedron as in the example in the text), then no difficulty can arise if the point of projection be chosen as the composition of the compound, as all tie lines must then be radial to that point.

In this case all compositions in the tetrahedron project in the positive sense, but the lack of resemblance to a standard triangular diagram is perhaps confusing. The method of plotting is shown in Fig. 7 with the projected fields of several minerals indicated, as in Fig. 4. In Fig. 8 the sets of assemblages shown in Fig. 5 are plotted again in the alternative projection. The two projections are entirely equivalent, the first more easily adapted to triangular coordinates and the second to orthogonal coordinates. The first provides relatively more "working room" in the
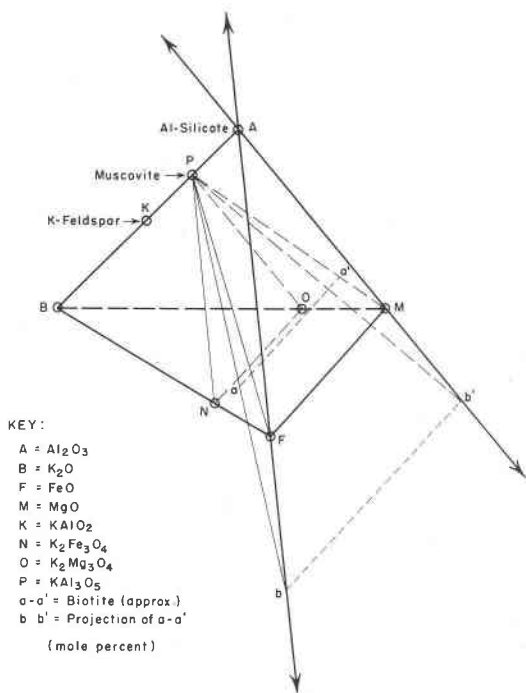
FIG. 3. The tetrahedron Al_2O_3-K_2O-FeO-MgO showing projection through idealized muscovite composition onto plane determined by Al_2O_3, FeO and MgO.

less aluminous range of composition, and the second does the same for the more aluminous range of composition.[1]

Although our concern has been mainly with plotting the compositions of coexistent minerals, a rock composition may also be plotted provided the content of all mineral phases not appearing in the projection has first been subtracted from the total bulk composition. This may be

[1] In a way the above procedures are analogous to the conventional method of presenting high-temperature experimental data in a system such as "FeO"-SiO_2 (Bowen and Schairer, 1932). Actually, as the authors emphasize, this study was of ternary equilibria in the system Fe-Si-O, and the "binary" diagram represents phases in equilibrium with an iron crucible. Both wustite and liquid, in this system, contain more oxygen than in a purely ferrous system, and their compositions are projected, by calculation, onto the line FeO-SiO_2. The calculation of Bowen and Schairer is equivalent to projection along lines parallel to the edge Si-O. Allen and Snow (1955), use a different calculation in their work in the system Ca-Fe-Si-O, and their "ternary" diagram is a projection, through oxygen, onto the plane CaO-FeO-SiO_2, of phases in equilibrium with iron. The relative amount of "Fe_2O_3" in the phases in the above systems is commonly small, hence the method of projection makes little practical difference. A closer analogy to our procedure would be to project through Fe as that is the composition of the ubiquitous phase.
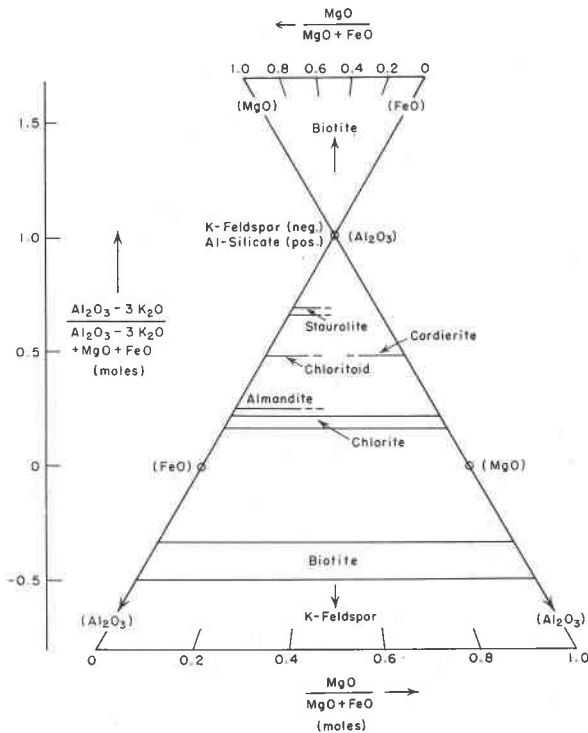
Fig. 4. System SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O showing possible phases in equilibrium with quartz and muscovite at P, T, η. Projection is through point KAl_3O_5 of Fig. 1 onto plane Al_2O_3-MgO-FeO.

accomplished by direct calculation from the mode, or by making a norm-like calculation based on an assumed distribution of the pertinent components. Though previous authors have emphasized calculations of this sort, the value of making them is doubtful except perhaps for purposes of "predicting" the mineral composition of a rock under metamorphic conditions other than those observed. We can see, in thin section, what phases and assemblages are actually present and, if necessary, can calculate the bulk composition from the mode. For purposes of finding out about the physical environment during metamorphism, however, the important consideration is with regard to the relative compositions of coexisting phases, not their relative amounts. The bulk composition of a given assemblage or the relative modal abundance of the phases, may thus, for present purposes at least, be regarded as simply a pre-metamorphic accident (except with regard to H_2O), though admittedly of prime importance in determining the pre-metamorphic nature of the rock.—A plea might also be inserted at this point for the reporting, in petrographic
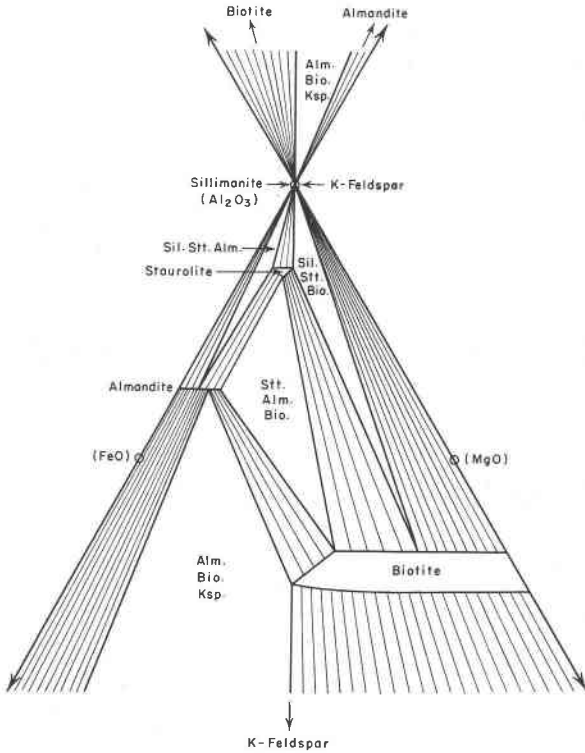
Fig. 5. Phases with muscovite and quartz in the system SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O as observed (schematically) in the lower sillimanite zone of west-central New Hampshire. Projection as in Figure 4.

descriptions of metamorphic rocks, of specific assemblages rather than just averaged modes. Slides from several specimens may contain mutually incompatible assemblages and much information of physico-chemical value may be lost in the averaging.

THE EFFECTS OF OTHER COMPONENTS

There are two possibilities with regard to a component not considered in the above analysis. One possibility is that the extra component is not present in measurable proportions in any of the phases with which we have been concerned. In this case the mutual equilibrium among these phases is not affected by the presence of the extra component. This component must then be present in some other phase or phases than those appearing in our projection. The total number of coexisting phases containing SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O and any one other component is limited by the phase rule. Hence, if more than one of these phases con-

tains the extra component, the possible number of phases pertinent to our projection must be correspondingly limited. As long as any of the phases in the projection remain, however, their mutual equilibria are independent of the presence of the extra component and the phases that contain it.
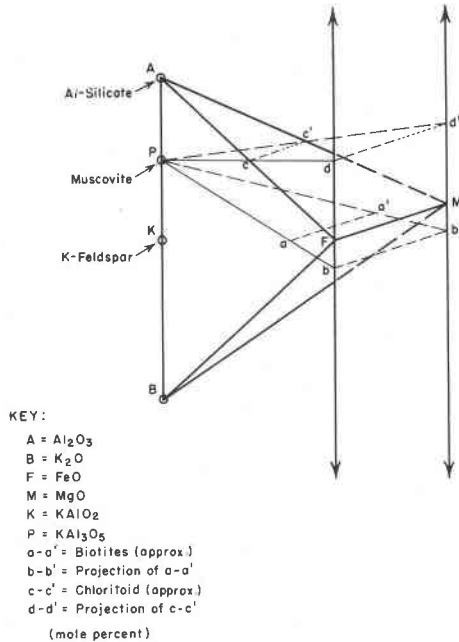

KEY:

A = Al_2O_3
B = K_2O
F = FeO
M = MgO
K = $KAlO_2$
P = KAl_3O_5
a–a' = Biotites (approx.)
b–b' = Projection of a–a'
c–c' = Chloritoid (approx.)
d–d' = Projection of c–c'

(mole percent)

FIG. 6. The tetrahedron Al_2O_3-K_2O-FeO-MgO showing projection through idealized muscovite composition onto plane passing through FeO and MgO and parallel to the line Al_2O_3-K_2O.

The other possibility is that the neglected component *does* enter one of the phases of concern. In this case the mutual equilibria of these phases are affected, and those phases that incorporate the extra component may be stabilized so as to appear in assemblages where they would not otherwise be present. The most likely offenders will be discussed individually.

Na_2O may occur in significant proportions in either potassic feldspar or muscovite and to a lesser and perhaps negligible extent in biotite. The point at which the feldspar would project would not, however, be altered by this substitution, and the other projected phases contain little or no Na_2O. The problem of anomalous stabilization of muscovite or potassic feldspar is also cancelled by the fact that Na_2O is commonly sufficiently abundant that a fundamentally sodic phase is present. This

is typically albite in high-grade assemblages or low-grade assemblages poor in alumina, and typically paragonite in the more highly aluminous low-grade assemblages. Where the albite or paragonite contains no extraneous component other than soda the variance of the assemblage is the same as it would be if no soda were present. Quantitatively, however, equilibria involving muscovite or potassic feldspar would be somewhat displaced relative to the corresponding equilibria in a soda-free system.
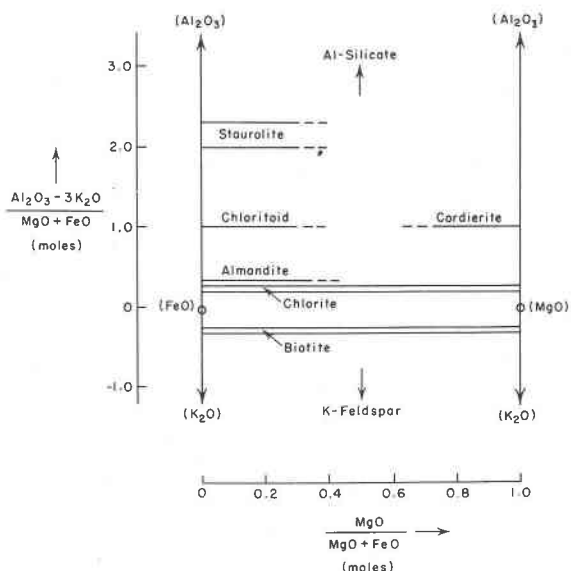

Fig. 7. System SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O showing possible phases in equilibrium with quartz and muscovite at P, T, η. Projection is through point KAl_3O_5 of Fig. 1 onto plane parallel to edges Al_2O_3-K_2O and MgO-FeO.

The principal difficulty arises with the occurrence of a calcic plagioclase rather than albite.

CaO is also troublesome through the occurrence of a grossularite component in the garnet, and MnO may be significant in either garnet or chloritoid. Occurrences of four of the projected phases in one assemblage are known, though not common, and several examples are known to the writer. In some of these the garnets have been shown to have a significant content of CaO, or MnO, or both. It is probably best, for purposes of the projections discussed herein, to either disregard, or at least treat with caution, any garnet in which the sum of components other than pyrope and almandite is more than a few per cent.

In plotting compositions of minerals containing extraneous components the writer does not simply subtract the CaO or MnO, but also Al_2O_3, K_2O, etc. such that the material subtracted represents an inde-
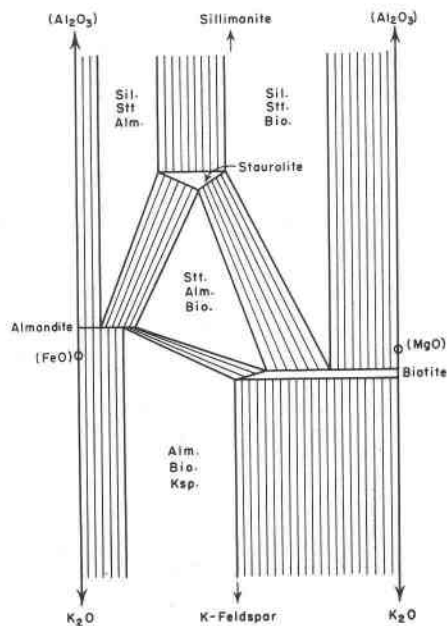
Fig. 8. Phases with muscovite and quartz in the system SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O as observed (schematically) in the lower sillimanite zone of west-central New Hampshire. Projection as in Fig. 7 and equivalent to Fig. 5.

pendently variable component of the mineral itself. Thus in a garnet analysis[1] yielding:

(a)	$Ca_3Fe_2^{+++}(SiO_4)_3$	2.4	mole per cent
(b)	$Ca_3Al_2(SiO_4)_3$	5.5	mole per cent
(c)	$Mn_3Al_2(SiO_4)_3$	2.1	mole per cent
(d)	$Fe_3^{++}Al_2(SiO_4)_3$	71.7	mole per cent
(e)	$Mg_3Al_2(SiO_4)_3$	18.3	mole per cent

the plotted composition would be on the basis of (d) and (e) recalculated to 100 per cent.

It might be pointed out that if the systems were closed to H_2O and that component not present in excess, then coexistence of four of the projected phases should be much more common than it is. As a rule it is not possible to vary the H_2O-content of most mineral assemblages without the appearance of a new phase. This is not consistent with an inherited bulk-content of H_2O, but is consistent with an externally controlled humidity.

[1] The garnet from the Gassetts schist, Chester, Vermont.

Iron Oxides

Fe_2O_3, as a component, has been omitted from consideration though typically present in small amounts in most ferromagnesian minerals. Ferric or partly ferric phases such as magnetite, hematite, or stilpnomelane are also fairly common in metamorphosed pelites.

The writer has considered the possibility that the activity of oxygen might, like the humidity, be externally controlled. In such a case Fe_2O_3 would behave graphically like FeO, and both magnetite and hematite could be treated as phases in the projection, plotting at the point marked "FeO" in either Fig. 4 or Fig. 7. Stilpnomelane would then project somewhere between the line "FeO-MgO" and the range of chlorite. In general, however, the analysis of pelitic assemblages has been more successful when the system has been treated as closed to oxygen, and Fe_2O_3 kept as a separate component graphically. This is emphatically the case in the common occurrence reported by James and Howland (1955) of *both* magnetite and hematite in metamorphosed iron formation. In any occurrence of this sort the activity of oxygen at any given pressure and temperature is fixed internally, not externally, owing to the presence of two phases in the two-component system Fe-O.

Mineral Facies in Pelitic Schists

In order to construct a complete projection for the indicator minerals at any locality it is necessary that the rocks at that locality show enough variation in bulk composition that all three-phase assemblages are represented (five-phase assemblages counting quartz and muscovite). Owing to the normal variation, from bed to bed, in many clastic sediments, it is quite commonly possible to construct a major portion of such a projection on the basis of one outcrop or group of adjacent outcrops, and it is indeed wise in attempting to do so to find an area where rocks of considerable heterogeneity are intimately interstratified. Where a complete or nearly complete construction can be made it can be said to characterize the *mineral facies* for the pelitic schists at that locality. It is thus not any one assemblage but the set or "ensemble" of assemblages that defines the facies. Only then can we specify that any two rocks of identical composition (except for H_2O) from separated isofacial localities, will have the same mineral composition as required by the definition of Eskola (1915, p. 114). Clearly, many assemblages may occur in more than one facies, and one assemblage is in general insufficient to determine the facies other than within gross limits.

The compositions at the corners of the three-phase fields will, in general, show *continuous variation* from place to place in response to variation in P, T and η at the time of formation of the rocks. In addition
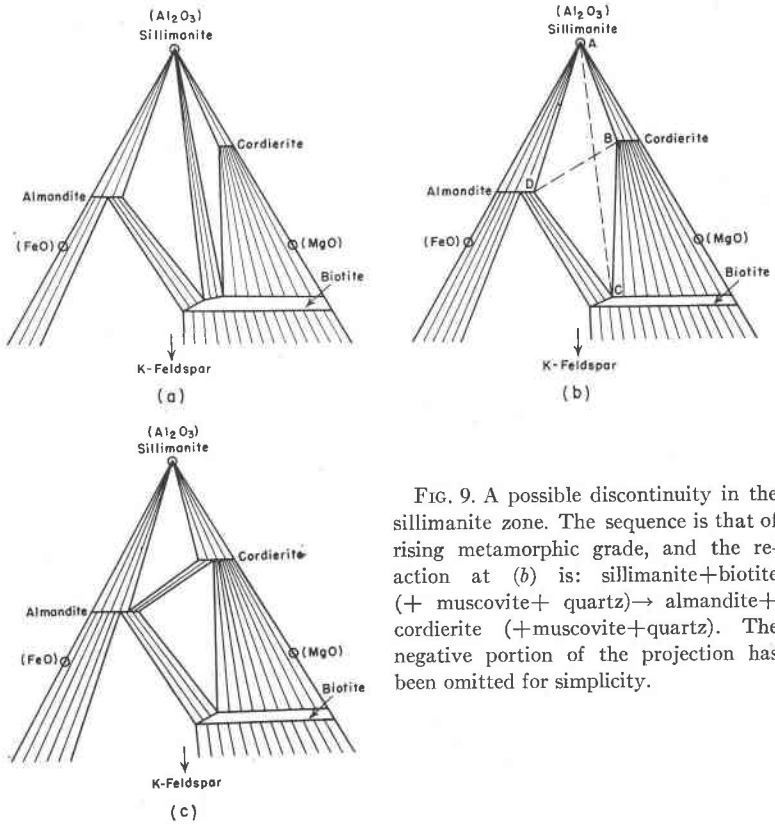
FIG. 9. A possible discontinuity in the sillimanite zone. The sequence is that of rising metamorphic grade, and the reaction at (b) is: sillimanite+biotite (+ muscovite+ quartz)→ almandite+ cordierite (+muscovite+quartz). The negative portion of the projection has been omitted for simplicity.

to such continuous variation in facies there will be discontinuities in facies involving changes in the basic topology of the projection. These may involve the appearance of a new phase, the disappearance of an old one, or a change in the compatible associations as in Fig. 9.

The discontinuities in facies are probably the most suitable changes upon which to draw isograds since they are independent, if observed at all, of local variation in the ratios of the critical components. In Fig. 9b all compositions in the quadrilateral A-B-C-D would show the discontinuity. An isograd based on the simple shift of the boundary of a three-phase field across some specific bulk composition, on the other hand, is clearly dependent on the composition selected as well as on the externally controlled variables: P, T and η.

A discontinuity in facies in this system represents conditions of either univariant or bivariant equilibrium. Where H_2O is gained or lost, as is commonly the case, the equilibrium is bivariant. The dependence of bivariant equilibria upon the externally controlled variables has been

discussed by the author in a previous paper (Thompson, 1955). Where H_2O is not actively involved the equilibrium is univariant. Examples of univariant equilibria would be a change from kyanite to sillimanite or a reaction such as: sillimanite+biotite (+quartz+muscovite)→almandite+cordierite (+quartz+muscovite). In the latter example almandite or cordierite but not both (barring extraneous components) may be present on the left hand side (Fig. 9a), and biotite or sillimanite, but not both, on the right hand side (Fig. 9c). This equilibrium is univariant because muscovite and biotite are the only hydrous phases involved as well as the only potassic phases. In both, to a first approximation, H_2O is equal to $2K_2O$, hence, no water is gained or lost in the above reaction.

A complete sequence of projections representing all changes from the chlorite zone to the sillimanite zone in a metamorphic area must clearly, on geometric grounds, involve many independent discontinuities in facies. Furthermore, the sequence determined in one area should not be taken as one that should necessarily be applicable to any other metamorphic terrane. A different path with respect to P, T and $\acute{\eta}$ is quite likely to pass through a different sequence of facies.

The number of possible facies is certainly large, even if we regard as topologically "the same" those which may be transformed into one another by continuous variation, and it is not possible to indicate them all without more knowledge than we now have of the compositions of coexisting minerals. Knowledge of the relative values of the ratio $MgO/(MgO+FeO)$ in coexisting pairs limits the topological possibilities and a partial listing in order of increasing tendency to concentrate FeO is:

(1) Cordierite
(2) Biotite
(3) Staurolite
(4) Almandite

Chlorite is probably more "siderophile" than cordierite and less so than biotite. Chloritoid is definitely more siderophile than biotite, chlorite, or cordierite, but is of uncertain status relative to staurolite and almandite. Even if it were known that chloritoid came between staurolite and almandite in the above series, however, the relative topology of these three phases would still be ambiguous, as the chloritoid composition could still lie on either side of the tie line joining the staurolite and garnet occurring with it. Inversions in siderophile tendency are unlikely owing to the near ideality of the substitution of Fe^{++} for Mg. Once the topologic relationships have been determined it will be possible, at least in principle, to establish the possible facies and clarify their sequential relations to one another. The author will present chemical data bearing on this matter in a subsequent paper.

REFERENCES

ALLEN, W. C., AND SNOW, R. B. (1955), The orthosilicate-iron oxide portion of the system CaO-"FeO"-SiO$_2$: *Jour. Amer. Ceram. Soc.*, **38**, 264–280.

BALK, R. (1953), Structure of graywacke areas and Taconic Range, east of Troy, New York: *Bull. Geol. Soc. Amer.*, **64**, 811–864.

BARROW, G. (1893), On an intrusion of muscovite-biotite gneiss in the south-east Highlands of Scotland: *Geol. Soc. London, Quart. Jour.*, **49**, 330–358.

BARROW, G. (1912), On the geology of lower Dee-side and the southern Highland border: *Geol. Assoc. Proc.*, **23**, 268–284.

BARTH, T. F. W. (1936), Structural and petrologic studies in Dutchess County, New York, Pt. II: *Geol. Soc. Amer. Bull.*, **47**, 775–850.

BOWEN, N. L. (1925), The mineralogical phase rule: *Jour. Wash. Acad. Sci.*, **15**, 280–284.

BOWEN, N. L., and ANDERSEN (1914), The binary system MgO-SiO$_2$: *Amer. Jour. Sci.*, 4th ser., **37**, 487–500.

BOWEN, N. L., AND SCHAIRER, J. F. (1932), The system FeO-SiO$_2$: *Amer. Jour. Sci.*, 5th ser., **24**, 177–213.

CLARKE, F. W. (1924), The data of geochemistry, fifth edition: U. S. Geol. Survey Bull. **770**, 841 pp.

ESKOLA, P. (1915), On the relation between chemical and mineralogical composition in the metamorphic rocks of the Orijärvi region: *Comm. Géol. Finlande*, Bull. **44**, 145 pp.

HARKER, A. (1939), Metamorphism, second edition, revised: Methuen, London, 362 pp.

HEALD, M. T. (1950), Structure and petrology of the Lovewell Mountain quadrangle, New Hampshire: *Geol. Soc. Amer. Bull.*, **61**, 43–90.

JAMES, H. L., AND HOWLAND, A. L. (1955), Mineral facies in iron- and silica-rich rocks: *Geol. Soc. Amer. Bull.*, **66**, 1580–1588.

JUURINEN, A. (1956), Composition and properties of staurolite: *Ann. Acad. Sci. Fennicae:* Ser. A-III, **47**, 53 pp.

OSBERG, P. H. (1952), The Green Mountain anticlinorium in the vicinity of Rochester and East Middlebury, Vt.: *Vermont Geol. Surv.*, Bull. **5**, 127 pp.

PHILIPSBORN, H. VON (1928), Zur graphischen Behandlung quarternär systeme: *N. Jahrb. f. Min. Geol. Paläont.* Beil-Bd. **57**, Abt. A. 973–1012.

THOMPSON, J. B. (1955), The thermodynamic basis for the mineral facies concept: *Am. Jour. Sci.*, **253**, 65–103.

TILLEY, C. E. (1925), Petrographical notes on some chloritoid rocks: *Geol. Mag.*, **62**, 309–318.

TURNER, F. J. (1948), Mineralogical and structural evolution of the metamorphic rocks: *Geol. Soc. Amer.* Memoir **30**, 342 pp.