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METAMORPHISM OF THE PELITIC SCHISTS IN THE BRYANT POND QUADRANGLE, MAINE

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ABSTRACT

Pelitic rocks in the Bryant Pond quadrangle, Maine, have been highly deformed and metamorphosed to sillimanite-bearing gneisses and sillimanite-microcline-bearing gneisses. It is proposed that the isograd indicating rocks with sillimanite and potash feldspar (orthoclase or microcline) be called the sillimanite-potash feldspar isograd. It would distinguish rocks in which this mineral pair coexists from rocks in which this pair is incompatible. This isograd is probably dependent upon the pressure, temperature, activity of water and the An content of the plagioclase in the rock. The minerals involved in the designation of the sillimanite-potash feldspar isograd are sillimanite, potash feldspar, muscovite, quartz and plagioclase, and they can be represented by the system $CaO\text{-}Na_2O\text{-}K_2O\text{-}Al_2O_3$ with H_2O mobile and quartz in excess. The following reaction takes place at the sillimanite-potash feldspar isograd: quartz+muscovite+plagioclase$\rightleftharpoons$sillimanite+soda-rich potash feldspar +more calcic plagioclase+H_2O.

The possibility of mapping continuous variations of the An content of the plagioclase is discussed; it is emphasized that this is possible only if the assemblage consists of sillimanite-potash feldspar-muscovite-plagioclase.

INTRODUCTION

The Bryant Pond quadrangle is in western Maine (Fig. 1) just south of Rumford. It is bounded by latitudes 44°15′ to 44°30′ and longitudes 70°30′ to 70°45′. This area was mapped by the writer during the summers of 1959–61. It consists of highly deformed and metamorphosed Ordovician (?) and Devonian strata. Large intrusive bodies belonging to the New Hampshire magma series, Billings (1955), underlie approximately one-third of the area. These intrusive bodies consist of quartz diorite, quartz monzonite and pegmatite.

The metamorphic rocks can be described in two groups, one consisting of pelitic or micaceous schists and gneisses, the other of calc-silicate granulites. The latter type is particularly abundant in the southern half of the area where it constitutes at least half of the metamorphosed strata. The pelitic rocks greatly predominate in the northern part of the quadrangle and also are common in the southern part. This paper will be concerned only with the metamorphic changes that have occurred in the pelitic rocks.

The pelitic rocks in the Bryant Pond area have been metamorphosed to the sillimanite and sillimanite-potash feldspar grades of metamorphism and an isograd (Fig. 2) has been mapped which shows the boundary between the two grades. A more precise location is presented on a geologic map by Guidotti (1963). Within the New England area, pelitic rocks in approximately similar grades of metamorphism have been treated by Heald (1950), Chapman (1952), Fisher (1955), Barker (1961, 1962) and Lundgren (1962). Various terms have been used to indicate the metamorphic change between those rocks which contain assemblages with sillimanite and potash feldspar and those assemblages with sillimanite but no potash feldspar. Such terms include "second sillimanite zone," "orthoclase isograd," "microcline isograd" and "microcline-sillimanite isograd." The first term has little to recommend it; the other three terms do not seem general enough. Inasmuch as this isograd is based upon the initial coexistence of sillimanite and a potash feldspar which can be either microcline or orthoclase, it would seem desirable to call it the sillimanite-potash feldspar isograd.

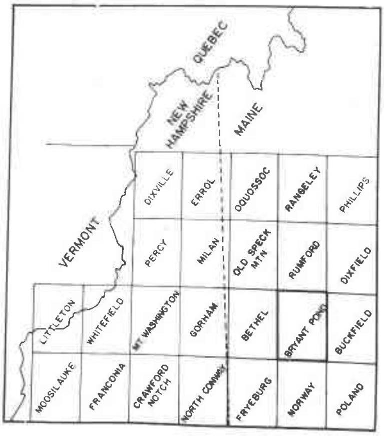

FIG. 1. Location of the Bryant Pond Quadrangle.

Most workers have approached similar rocks from the point of view that the change from sillimanite to potash feldspar+sillimanite-bearing assemblages can be represented by the following reaction:

(1) Muscovite+quartz$\rightleftharpoons$potash feldspar+sillimanite+H_2O.

Possibly the fact that most rocks with potash feldspar+sillimanite do not have muscovite present has led petrologists to assume the above reaction. Barker (1961, 1962), Fisher (1955), Heald (1950) and Chapman (1952) have noted that the potash feldspar is actually soda-rich perthitic microcline or orthoclase. Barker (1961, p. 1170) has not stated explicitly an alternative to equation (1) but his discussion does suggest the following reaction:

(2) Muscovite+potash-rich plagioclase+quartz$\rightleftharpoons$soda-rich microcline+sillimanite +H_2O.

In this reaction it is assumed that one is neglecting the calcic component of the plagioclase or dealing with a pure soda plagioclase.

The very fact that most workers have noted that the potash feldspar is soda-rich would seem to indicate that equation (2) merits further consideration. Moreover, it is likely that in pelitic rocks the plagioclase in equa-

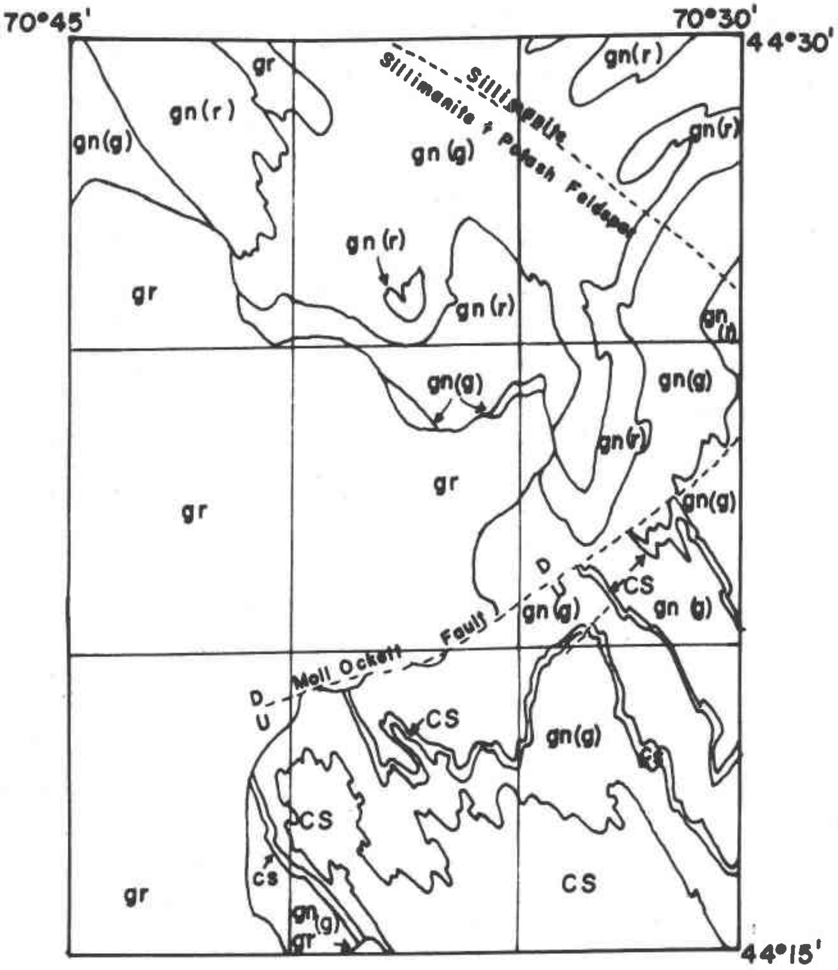

FIG. 2. Generalized geologic map of the Bryant Pond quadrangle, showing the location of the sillimanite-potash feldspar isograd.

gr—intrusive granitic rocks
gn(r)—migmatitic, rusty-weathering pelitic gneisses
gn(g)—migmatitic, grey, pelitic gneisses
cs—calc-silicate rocks

tion (2) tends toward at least An_{5-10} in the plagioclase series. Hence it would seem that an adequate treatment of the sillimanite-potash feldspar isograd should consider the components Na_2O and CaO for these almost certainly are involved in the reaction which marks the isograd in question.

The writer will describe the metamorphism of the pelitic rocks in the Bryant Pond quadrangle and try to show how the sillimanite-potash feldspar isograd can be expressed in the system CaO-Al_2O_3-Na_2O-K_2O-SiO_2-H_2O. An attempt will be made to show this isograd is dependent upon P, T, aH_2O and the An content of the plagioclase in the rock. The possibility of mapping isograds based upon the compositions of the plagioclase will be discussed also.

ACKNOWLEDGMENTS

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ASSEMBLAGES IN THE PELITIC ROCKS

The pelitic rocks in the Bryant Pond area range from biotite granulite[1] to very schistose migmatitic gneisses. The latter rock type is essentially an interlayering of coarse mica schists and bands of coarse-grained quartz and feldspar in varying amounts. It should be noted here that the writer is using the term "pelitic" to mean any rock derived from a clay-rich sediment. Again, this usage is in accord with that of Harker (1939).

The significant minerals in the pelitic rocks are biotite, muscovite, plagioclase, quartz, sillimanite, garnet and perthitic microcline. Quartz is present in all of the assemblages listed below. In general, all of the minerals mentioned above appear to be fresh and to have sharp contacts with each other. Any one of them can be found in direct contact with any other of them. Hence it would seem that they are coexisting in equilib-

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[1] Granulite is used here as a textural term following Harker (1939, p. 246).

brium. The only exception is that north of the isograd shown in Fig. 2, sillimanite and perthitic microcline do not occur together. Minor or accessory minerals in the pelitic rocks include tourmaline, zircon, apatite, pyrrhotite, retrograde chlorite, rutile and myrmekite. Table I presents the various assemblages found by the writer in the pelitic rocks of the Bryant Pond area. It is possible to obtain these assemblages throughout the area (with the exception of those containing sillimanite and microcline) merely by choosing a suite of rocks ranging from the biotite granulites to the very micaceous fraction of the migmatitic gneisses. One noteworthy aspect of these assemblages is that some of the rocks contain sil-

TABLE I.

Assemblages with *muscovite* and *quartz:*	
qtz-plag-micr-bio-musc-sill-garn	9
qtz-plag-micr-bio-musc-sill	8
qtz-plag-micr-bio-musc-garn	8
qtz-plag-micr-bio-musc	6
qtz-micr-bio-miusc-sill-garn	3
qtz-plag-bio-musc-sill-garn	32
qtz-plag-bio-musc-sill	36
qtz-plag-bio-musc-garn	7
qtz-plag-bio-musc	8
qtz-bio-musc-sill-garn	2
qtz-bio-musc-sill	2
qtz-bio-musc	2
Assemblages *without* muscovite:	
qtz-plag-micr-bio-sill-garn	2
qtz-plag-micr-bio-garn	5
qtz-plag-micr-bio-sill	2
qtz-plag-micr-bio	4
qtz-plag-bio-sill-garn	6
qtz-plag-bio-sill	1
qtz-plag-bio-garn	20
qtz-plag-bio	1

qtz = quartz
plag = plagioclase
micr = microcline
musc = muscovite
sill = sillimanite
garn = garnet
bio = biotite

limanite, perthitic microcline, and muscovite. In the assemblages reported by Barker (1961, 1962), Heald (1950) and Lundgren (1962), potash feldspar and sillimanite occur together but no muscovite is present. On the other hand, Fisher (1952, 1962), Fowler-Billings (1948), Chapman (1952) and Fisher (1941) do find muscovite in the same assemblage with potash feldspar and sillimanite. This point will be considered again.

It readily can be seen that all of the minerals, with the exception of biotite and garnet, listed in the assemblages shown in Table I can be represented in the system CaO-Na_2O-K_2O-Al_2O_3-SiO_2-H_2O. This system is essentially the same as that which has been investigated by many workers in connection with various problems related to granites.

DESCRIPTION OF MINERALS

The minerals to be described in this section are those which can be plotted in the system CaO-Na_2O-K_2O-Al_2O_3-SiO_2-H_2O. It will be shown later that the metamorphic changes which have occurred in the Bryant Pond area can be represented by changes in the mineralogy in this system.

Muscovite occurs as large megacrysts in the gneisses to the north of the Moll Ockett fault (Fig. 2). Commonly these megacrysts are parallel to the foliation of the rock but in some cases they lie at high angles to the foliation. Swarms of fibrolitic sillimanite is sometimes found in the muscovite. South of the Moll Ockett fault the muscovite does not occur as megacrysts and is always parallel to the foliation. In general, muscovite is more abundant in the pelitic gneisses to the north of the fault.

It has been pointed out by Eugster and Yoder (1955) and Yoder (1957) that the basal spacings of muscovite can be used to indicate the amount of Na^+ in the mineral. In general, it is found that the basal spacings in muscovite increase as the amount of Na^+ in the mineral decreases. Ca^{++} probably affects the basal spacings in a similar fashion but the amount is unknown. In addition, it is still uncertain whether or not the effect on the basal spacing due to a variation in the K/Na ratio is linear. However, Eugster and Yoder (1955) did assume such a straight-line relationship in order to obtain the muscovite side of the solvus between muscovite and paragonite.

Rosenfeld *et al.* (1958) have shown that the miscibility gap between coexisting muscovite and paragonite appears to narrow in rocks as the grade of metamorphism increases from the biotite to the kyanite zone of metamorphism. This is shown by a decrease in the basal spacings of muscovite and an increase in the basal spacing of the coexisting paragonite. Table II presents some of their data. However, from the experimental phase diagram for the subsolidus region of the muscovite-paragonite join by Eugster and Yoder (1955), it is apparent that the Na^+ content in muscovite will increase with temperature only as long as paragonite is present. When paragonite breaks down, the muscovite remaining will coexist with feldspars and become poorer in Na^+ as temperature increases. Eugster and Yoder point out that their work indicates that Na^+-bearing muscovite will break down before pure muscovite. Rosenfeld (1956) has indicated that paragonite breaks down within the kyanite zone. It appears that paragonite is always gone before sillimanite appears in pelitic rocks. Hence one would expect that the basal spacing in muscovite from rocks in the sillimanite grade of metamorphism will show a rapid increase.

TABLE II. DATA ON THE D-SPACINGS OF MUSCOVITE

A. Partial list of basal spacings (Å) for coexisting muscovite and paragonite from Rosenfeld *et al.* (1958).

	Zone	Muscovite	Paragonite	Difference
Pizzo Forno, Switz.	kyanite	9.888	9.647	0.241
Gassetts, Vt.	kyanite	9.918	9.640	0.278
East Jamaica, Vt.	staurolite	9.933	9.630	0.303
Plymouth, Vt.	garnet	9.948	9.644	0.304
Glebe Mt., Vt.	garnet	9.932	9.622	0.310
Pittsfield, Vt.	garnet	9.943	9.627	0.316
Ira, Vt.	biotite	9.975	9.623	0.352
Danby, Vt.	biotite	9.981	9.623	0.358

B. Basal spacings (Å) of muscovite in the staurolite and sillimanite grades of metamorphism in the Old Speck Mountain quadrangle, Maine, from Milton (1961).

OSM 25	9.914	OSM 32	9.950
OSM 431	9.925	OSM 104	9.956
OSM 382	9.942	OSM 395	9.964
OSM 473	9.945	OSM 264	9.966
OSM 505	9.948	OSM 21	9.978

C. Basal spacings (Å) of muscovite in the assemblage microcline-muscovite-quartz-biotite-sillimanite-plagioclase (An_{25}); Bryant Pond quadrangle, Maine.

Sample Number	Basal Spacing
(6) 6/21/61	9.982
(1) 8/21/61	9.984
(2) 8/25/61	9.982

Milton (1961, p. 154) has determined the basal spacings of some muscovite samples from rocks in the sillimanite and staurolite zones of metamorphism in the Old Speck Mountain quadrangle, which lies immediately northwest of the Bryant Pond quadrangle. Milton's data are given in Table II. It will be noted that some of the d-spacings are almost as great as those in the muscovites in the biotite zone reported by Rosenfeld *et al.* (1958).

The writer has determined the basal spacings of muscovite from three specimens in which the assemblage is quartz-biotite-muscovite-sillimanite-perthitic microcline-plagioclase (An_{25}). A Norelco *x*-ray diffractometer was employed with a scanning speed of $\frac{1}{4}°$/minute and thorium oxide as an internal standard. Using CuKα radiation and measuring 2θ for the 005 plane, the data presented in Table II were obtained.

By comparing the data presented in Table II, it is probably reasonable tentatively to state that the muscovite in the Bryant Pond quadrangle is more nearly pure muscovite than that found in the Old Speck Mountain area. In fact, this is to be expected inasmuch as the rocks in the Bryant Pond area are more highly metamorphosed. This point will be considered more fully in a later section.

An implication to be derived from the presence of potash-rich muscovite is that the Na^+ in the perthitic microcline must have come from some other source than the mere breakdown of muscovite. This point probably is applicable also to the other areas where the association soda-rich potash feldspar+sillimanite is present. In fact, the reports of Barker (1961, 1962), Heald (1950), Fisher (1955) and Chapman (1952) indicate that the potash feldspar is perthitic.

Plagioclase compositions have been determined in thin section by means of albite twinning and relief. In the biotite granulites the plagioclase tends to be more An-rich and ranges up to An_{50}. In the migmatitic gneisses the plagioclase tends to average quite close to An_{25}. This is true throughout the Bryant Pond quadrangle regardless of whether or not the pair microcline-sillimanite is present. This point will be considered again inasmuch as the writer believes that the composition of the plagioclase in a rock can affect the location of the sillimanite-potash feldspar isograd.

Microcline occurs both in the groundmass of the pelitic rocks and in pegmatitic intergrowths with quartz. The latter is the predominant mode of occurrence. In most cases the coarse microcline and quartz intergrowths occur as four to six-inch blebs and stringers; however, commonly they appear as anhedral to subhedral megacrysts. The coarse-grained microcline is seen to be perthitic even in hand specimen, while the microcline in the groundmass is not always observed to be perthitic even when viewed in thin section under high magnification.

TABLE III.

(a) Compositions of potash feldspar in rocks with sillimanite and potash feldspar.

(1) Heald (1950)—Orthoclase microperthite from porphyroblastic orthoclase gneiss. (LM6)

$(K^{0.74}Na^{0.21}Ca^{0.01}Ba^{0.01})_{0.97}Al_{1.10}Si_{2.93}O_8$

—Molecular composition in weight per cent:

$Or_{77}Ab_{21}An_1Cn_1$

(2) Barker (1962)—Microcline from a pegmatite at Sturbridge, Massachusetts.

82 weight per cent of $KAlSi_3O_8$

(b) Analyses of pelitic rocks with sillimanite and potash feldspar present.

(1) Heald (1950)—Lovewell Mountain quadrangle, N. H.

SiO_2 —62.04
Al_2O_3—18.29
Fe_2O_3— 0.33
FeO — 8.45
MnO— 0.22
MgO— 3.23
CaO — 0.45
Na_2O— 0.77
K_2O — 3.54

H_2O^+—0.99
H_2O^-—0.09
CO_2 —0.01
T_1O_2 —1.11
ZrO_2 —n.d.
P_2O_5 —0.08
SO_8 —n.d.
Cl —0.00
F —0.10
S —0.03
C —n.d.
less 0 for S and F—0.06

Total 99.67
S.G. 2.85

(LM6) Porphyroblastic orthoclase gneiss, Dakin Hill member, 0.1 mile south of the junction of Highways 10 and 123 in Marlow, Lovewell Mountain quadrangle. L. C. Peck, analyst.

(2) Lundgren (1962)—Southeastern Connecticut.

Chemical analyses [subscripts cations in 160 oxygen (Barth) cell] of sillimanite +orthoclase-bearing rock.

$K_{3.8}Na_{3.4}Ca_{1.1}Mg_{3.3}Mn_{0.1}Fe^{++}_{4.2}Fe^{+++}_{1.0}Al_{13.7}Ti_{0.6}Si_{60.2}(O_{152}OH_8)$

(3) Barker (1962) "typical gneiss"—Sturbridge, Mass.

SiO_2 —53.1
T_1O_2 — 1.2
Al_2O_3—24.1
Fe_2O_3— 1.4
FeO — 8.4
MgO— 3.7
C_aO – 1.5

Na_2O—1.7
K_2O —3.5
H_2O —1.4
P_2O_5 —0.06
MnO—0.10
CO_2 —0.05

Total 100.2

(c) Analyses of pelitic rock in the vicinity of the Bryant Pond area.

(1) Fisher (1955)—Bethel quadrangle, Maine.

Key:

1. Massive quartz-biotite-sillimanite gneiss from the intersection at Gilead, Maine, of U. S. Route #2 and the "Evans Notch Road." Analysis by L. C. Peck.
2. Wispy quartz-biotite-sillimanite gneiss from an elevation of 1590 feet on Morrison Brook in the town of Mason, Maine. Analysis by Eileen H. Kane.
3. Pyrrhotitic gneiss from 0.3 miles south of Little Lary Brook on the "Evans Notch Road" in Batchelders Grant, Maine. Analysis by Eileen H. Kane.

Chemical Analyses of Rocks

	1	2	3
SiO_2	62.69	62.68	61.95
Al_2O_3	18.17	17.74	17.89
Fe_2O_3	.45	1.07	2.80
FeO	6.91	5.46	4.79
MgO	2.70	2.02	2.43
CaO	.79	1.03	.94
Na_2O	1.56	1.59	.86
K_2O	3.53	4.07	3.20
H_2O^+	1.53	1.69	1.59
H_2O^-	.08	.11	.14
CO_2	.05	.02	.03
TiO_2	.98	1.00	1.20
ZrO_2	.00	.02	.00
P_2O_5	.08	.21	.02
Cl	.02	n.d.	n.d.
S	.02	.98	3.36
MnO	.16	.04	.05
BaO	.02	.05	.03
C	.10	.02	.10
	99.84	99.80	101.29
Minus oxygen for sulfur		.49	1.68
		99.31	99.61

Normative Minerals of Analyzed Rocks

Quartz	29.8	29.8	38.9
Orthoclase	20.6	24.1	19.0
Albite	13.1	13.6	7.4
Anorthite	3.9	4.2	4.7
Corundum	10.4	9.1	11.3
Hypersthene	17.7	11.6	6.0
Ilmenite	1.8	1.8	2.2
Magnetite	.7	1.7	.5
Apatite	—	.4	—
Pyrite	—	2.1	7.1
Hematite	—	—	2.6

A rather notable feature in the blebs, stringers and megacrysts of microcline is the outline of quartz grains. The quartz has very distinct, sharp boundaries rather than irregular, random shapes. In many specimens the quartz approaches the bipyramidal forms commonly seen in volcanic rocks.

METAMORPHISM AND GRAPHICAL RELATIONS

The pelitic rocks of the Bryant Pond area consist essentially of biotite, quartz, plagioclase, sillimanite, perthitic microcline, muscovite, and garnet. These minerals can be expressed adequately by the components CaO, K_2O, Na_2O, SiO_2, Al_2O_3, FeO, MgO and H_2O. Thompson (1957) has pointed out that pelitic rocks commonly have quartz present, and he has shown that quartz conveniently may be disregarded as a compositional variable. Moreover, Thompson (1955, 1957) has presented reasons for considering H_2O to be a completely mobile component and thus to be considered in terms of its chemical potential or activity. Hence it becomes an intensive variable much like P or T and is an externally controlled variable like P and T. Thompson (1957) thereupon described a very concise graphical method of describing the metamorphism of those pelitic rocks in which muscovite and quartz are present in all assemblages. The components graphically shown in his approach are MgO, K_2O, FeO and Al_2O_3. Barker (1961) has presented a modification of Thompson's approach by considering the same system with regard to those high-grade assemblages in which muscovite is absent but potash-feldspar is always present. In both methods the common rock-forming components CaO and Na_2O had to be neglected in order to obtain graphical facility. Hence the Na_2O content of the muscovite and potash feldspar and the CaO content of the garnets had to be completely neglected. Thompson (1957) has pointed out that, because of the disregard of CaO and Na_2O, more minerals may appear in an assemblage than theoretically allowed by the mineralogical phase rule. Green (1961), describing rocks in the system K_2O-MgO-FeO-Al_2O_3, has reported the presence of garnet in assemblages which thus appear to have too many phases present according to the mineralogical phase rule. A second major restriction imposed by the use of the above system is that it completely neglects the plagioclase phase in any of the reactions graphically depicted. With regard to the graphical illustration of the lower grades of metamorphism, Thompson (1957), this presents little problem as many of the reactions indicated are concerned with minerals other than the plagioclase—such as biotite, chlorite, staurolite, etc. However, in the higher grades of metamorphism this restriction becomes more serious as several of the critical reactions almost certainly involve plagioclase as well as the Na_2O content of the potash feldspar and possibly muscovite.

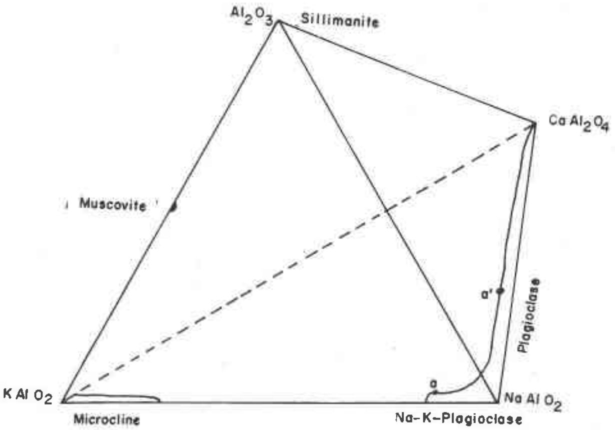

FIG. 3. Tetrahedron showing the minerals of pelitic rocks which can be plotted in the system Al_2O_3-CaO-K_2O-Na_2O with SiO_2 in excess and H_2O mobile.

This is indicated in particular by the fact that the potash feldspar in those rocks which contain the pair potash feldspar+sillimanite is soda-rich; Barker (1961, 1962), Heald (1950). Moreover, present indications are that muscovite becomes poorer in soda as the metamorphic grade increases above the lower limits of the sillimanite zone. Hence any proposed reaction to form potash feldspar by the breaking down of muscovite must find a source for the soda in the resulting potash feldspar. The most ready source is plagioclase. Finally, any soda-rich potash feldspar which does form cannot be represented adequately if Na_2O is neglected; its equilibrium relations with plagioclase can be represented only in a system which includes CaO also.

Inasmuch as the minerals involved in the definition of the sillimanite-potash feldspar isograde are sillimanite, muscovite, plagioclase, and perthitic microcline, the writer proposes that the system CaO, Na_2O, K_2O, Al_2O_3 be used to treat the metamorphism of the high-grade rocks in the Bryant Pond quadrangle. Quartz is present in all assemblages and thus may be neglected as a compositional variable. If we consider H_2O to be perfectly mobile, then the four phases listed above can be represented completely by the proposed components. Moreover, in these four phases extraneous components, such as FeO, MgO, Fe_2O_3, etc., will have little tendency to enter one phase in preference to another and thus stabilize it relative to the other phases.

The components CaO, Na_2O, K_2O, Al_2O_3 may be represented as the corners of a tetrahedron. Within this tetrahedron we may pick the points Al_2O_3-$CaAl_2O_4$-$NaAlO_2$-$KAlO_2$ and consider them to be the components of the phases under consideration. Figure 3 shows this new tetrahedron with the phases plotted in the appropriate places. The miscibility gap shown for the alkali feldspars is based upon the solvus experimentally determined by Tuttle and Bowen (1958). In Fig. 3, as well as the succeeding diagrams, the immiscibility gap is only qualitatively shown because no rocks with Ca-free plagioclase can be found in the Bryant Pond area. Fig. 4 shows the compatibilities in the sillimanite grade of metamorphism. If, for the present, we neglect $CaAl_2O_4$ and consider only the $KAlO_2$-$NaAlO_2$-Al_2O_3 face of the tetrahedron in Fig. 3, we may obtain the two diagrams shown in Figs. 5a and 5b. Figure 5a shows the compatibilities and assemblages which are commonly found in pelitic rocks in the sillimanite grade of metamorphism. Neglecting the $CaAl_2O_4$ found in the plagioclase, all of the indicated assemblages are common in the Bryant Pond quadrangle in the area northeast of the isograd shown in Fig. 2. The most notable aspect of this diagram is the mineral pair muscovite-albite. It is readily apparent that this pair should preclude the pair potash feldspar-sillimanite. This is a difficult point to demonstrate in rocks as the plagioclase is seldom or never pure albite but usually contains significant amounts of the anorthite molecule. This will be considered below. Figure 5b illustrates the change that probably occurs with an increase in metamorphic grade over that indicated in Fig. 5a. Such a change would be equivalent to what Thompson (1957) has called a discontinuous change, and it would define what the writer calls the sillimanite-potash feldspar isograd. Of course the particular

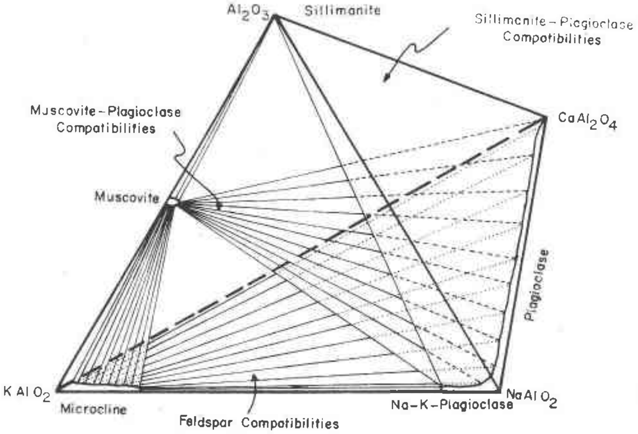

FIG. 4. Tetrahedron showing compatible minerals in the system Al_2O_3-$KAlO_2$-$NaAlO_2$-$CaAl_2O$, in the sillimanite grade of metamorphism. Note that the assemblage muscovite-plagioclase completely cuts out the assemblage sillimanite-microcline.

case in point neglects CaO. Most workers who have considered the coexistence of potash feldspar and sillimanite have considered the reaction given in equation (1):

(1) Muscovite+quartz$\rightleftharpoons$potash feldspar+sillimanite+H_2O.

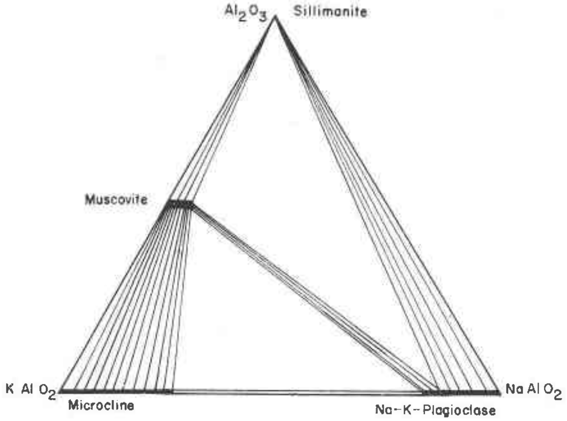

FIG. 5a. K_2O-Na_2O-Al_2O_3 face of tetrahedron of Fig. 4, showing compatibilities in the sillimanite grade of metamorphism.

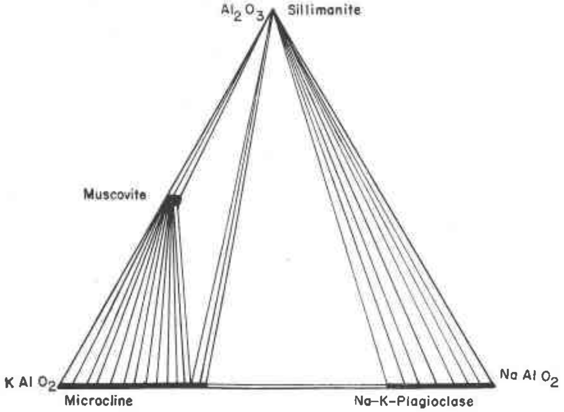

FIG. 5b. Compatibilities above the sillimanite+potash feldspar grade of metamorphism.

As noted previously, many workers have noted that the potash feldspar is soda-rich and commonly perthitic. Barker (1961) has emphasized this point. In order to take into consideration the soda which must be involved in the reaction that results in the initial coexistence of sillimanite and potash feldspar, it is probably more realistic to consider equation (2):

(2) Muscovite+potash-rich plagioclase+quartz$\rightleftharpoons$soda-rich microcline+sillimanite $+H_2O$.

If we now consider the effects of the CaO in the plagioclase indicated as pure albite in equation (2), we must return to the tetrahedral diagram shown in Fig. 3. The immediate question to be answered concerns the effect on equation (2) of the An content in the plagioclase. In general the presence of An in the plagioclase will raise the temperatures and pressures at which the reaction indicated will take place. This follows inasmuch as CaO can be regarded as a "contaminating" component in the albite with a concomitant stabilization of albite and the assemblages in which it can occur. Hence with a continued rise in the temperature, point "a" in Fig. 3 would migrate into the tetrahedron along the surface indicating the plagioclase compositions to some point such as "a'." The following equation would represent this reaction:

(3) Quartz+muscovite+sodic plagioclase (egAb_{95})$\rightleftharpoons$sillimanite+soda-rich microcline $+H_2O$+more calcic plagioclase.

Figure 6 shows the compatibilities that exist after the plagioclase compositions begin to become more calcic. A notable feature is the four-phase volume muscovite-sillimanite-microcline-plagioclase. It was noted earlier that this is a common assemblage in the Bryant Pond quadrangle. It also has been reported by Fowler-Billings (1949), Fisher (1955) and Chapman (1952). Other potential three-phase assemblages indicated in Fig. 6 are the following:

1. micr—sill—plag
2. musc—plag—sill
3. musc—micr—plag
4. musc—sill—micr.

All of these assemblages have been recorded in the Bryant Pond area. Barker (1961, 1962), Heald (1950) and Lundgren (1962) report the first assemblage. It readily can be seen that these workers may have been working in rocks which excluded muscovite for compositional reasons rather than those of metamorphic grade. Barker (1961) does note this possibility.

With a continued increase in metamorphism the plagioclase corner of the four-phase volume muscovite-plagioclase-microcline-sillimanite would be expected to move toward the $CaAl_2O_4$ corner of the tetrahedron. An interesting feature noted by Barker (1962) is that some of the plagioclase in his assemblage plagioclase-potash feldspar-sillimanite is zoned with the rims more calcic than the cores. This is the zoning relation that is to be expected in the light of equation (3). Possibly Barker has an example of this reaction interrupted before complete equilibrium could be attained. A limitation on the %An in the plagioclase obtainable by equation (3) is probably set by the final breakdown of nearly pure muscovite to sillimanite and potash feldspar. As yet this limit is unknown. This breakdown curve is undoubtedly dependent on the activity of H_2O in the system or rock. Experimental curves on the breakdown of muscovite have been determined by Segnit and Kennedy (1961) and are shown in Fig. 7.

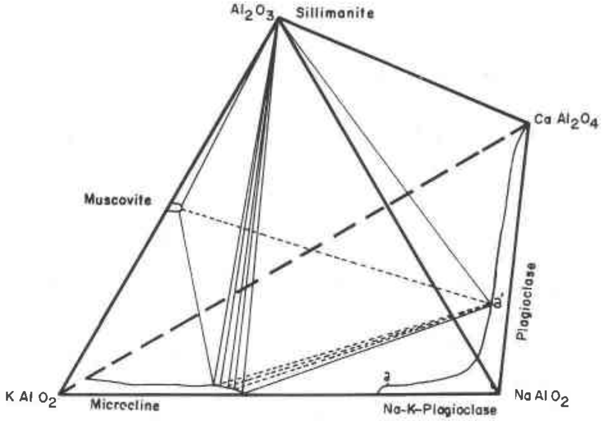

Fig. 6. Tetrahedron showing the coexistence of sillimanite and microcline as part of the 4-phase volume sillimanite-muscovite-microcline-plagioclase (composition ca. "a′"). Sillimanite+potash feldspar grade of metamorphism. At initial coexistence of sillimanite and microcline, point "a′" would be at "a" See Figs. 5a and 5b.

The preceding discussion should suffice to make it apparent that the sillimanite-potash feldspar isograd is certainly dependent upon the An content in the plagioclase as well as the temperature, pressure, and activity of H_2O, as pointed out by Barker (1962). This dependence upon the activity of H_2O is readily apparent from equation (3). The dependence upon the An content in the plagioclase may be seen from a consideration of Fig. 3. If the initial plagioclase composition were at point "a′," then the T, P, and aH_2O conditions necessary to effect equation (3) would be very likely quite different from those necessary when the initial plagioclase has a composition at "a." The required temperatures almost certainly would be higher than those necessary to effect reaction (2). Essentially we may consider the plagioclase corner of the four-phase volume muscovite-potash feldspar-sillimanite-plagioclase to be migrating along the $NaAlO_2$-$CaAl_2O_4$ edge of the tetrahedron in response to increased temperature and decreased a-H_2O. When this four-phase volume eclipses the point in the tetrahedron representing the bulk composition of the rock in question, that composition should then be expressed as the four phases at the corners of this volume. Finally, the four-phase volume might have the plagioclase corner move still closer to the $CaAl_2O_4$ corner of the tetrahedron. In such a case the four-phase volume could move past the bulk composition of the rock in question. This bulk composition then would be expressed as the assemblage sillimanite-sodic potash feldspar-plagioclase.

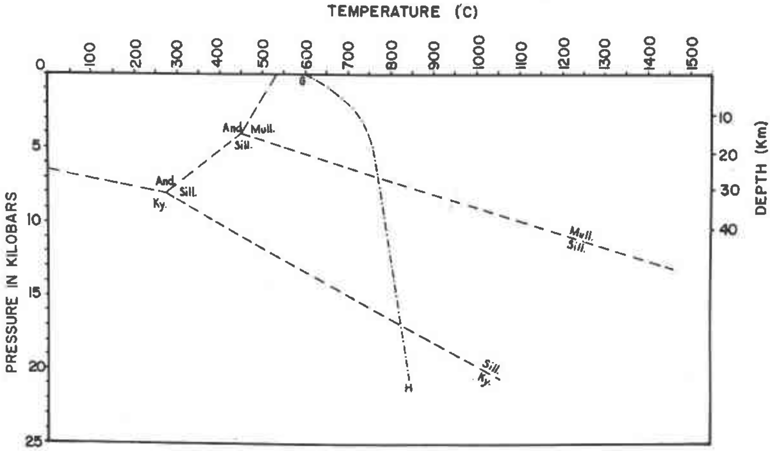

FIG. 7.

(1) Curves for aluminum silicates, andalusite, kyanite, sillimanite, and mullite. Clark *et al.* (1957), and Clark (1961)

(2) Curve GH for muscovite, Segnit and Kennedy (1961)
   (a) Below 5000 bars (in the presence of steam)
   muscovite+quartz$\rightleftharpoons$sanidine+sillimanite+water
   (b) Above 5000 bars (H_2O=that due to the breakdown of muscovite)
   muscovite+quartz$\rightleftharpoons$sillimanite+glass

From the preceding discussion the possibility emerges that one could potentially map isograds based upon the variation of the plagioclase in the four-phase assemblage muscovite-plagioclase-sillimanite-potash feldspar. This possibility exists only if all four phases are present. Thompson (1957) refers to such changes as "continuous variations." Obviously only extensive detailed work on the compositions of the plagioclase will determine the validity of this possibility.

If we again consider the pelitic rocks in the Bryant Pond area, we can clarify further the nature of the isograd shown in Fig. 2. The writer has found that in the rocks rich in alumina the plagioclase compositions are usually between An_{20} and An_{30} and that in most specimens they are near An_{25}. This seems to be true throughout the whole area regardless of the location relative to the isograd shown in Fig. 2. Hence those rocks with the assemblage sillimanite-muscovite-microcline-plagioclase (An_{25}) probably represent rocks which have been sufficiently metamorphosed to cause the plagioclase corner of the four-phase volume in Fig. 6 to have migrated to a point near that indicating An_{25}. This four-phase assemblage has not been found north of the indicated isograd. The reaction would be that given in equation (3). Essentially the first coexistence of microcline and sillimanite in these rocks represents metamorphic conditions of sufficient intensity to have caused the four-phase volume to have pivoted toward the $CaAl_2O_4$ corner sufficiently far to have eclipsed the bulk composition in terms of CaO, Al_2O_3, K_2O, Na_2O. This results in the four indicated components being expressed as muscovite-sillimanite-microcline-plagioclase (An_{25}). In the pelitic rocks under consideration the components listed above (except Al_2O_3) are held almost completely in the feldspar, muscovite and sillimanite. Some fraction of the total alumina in the rock of course is bound up in the biotite and garnet present. No chemical analyses of pelitic rocks in the Bryant Pond area are available. However, Table 2, taken from Fisher (1955), shows the analyses of several pelitic rocks from the Bethal area which are stratigraphically equivalent to several of the units in the Bryant Pond area and of similar metamorphic grade. It readily can be seen that these rocks are as high (or slightly higher) in CaO as most analyzed pelitic rocks.

In some respects the isograd shown in Fig. 2 may be considered to be the An_{25} isograd in rocks with the critical four-phase assemblage. Potentially this four-phase assemblage can be found for some distance north of the isograd if rocks sufficiently poor in CaO could be found. South of the isograd the plagioclase in the critical assemblage should become progressively more An-rich. Work is presently in progress to determine the validity of this conjecture.

COMPARISON WITH OTHER NEW ENGLAND AREAS OF SIMILAR METAMORPHIC GRADE

As mentioned above, several other workers in New England have described rocks with the pair sillimanite-potash feldspar. In those areas described by Barker (1961, 1962), Heald (1950) and Lundgren (1962) the potash feldspar+sillimanite rocks contain no muscovite except as a retrograde mineral after potash feldspar. In the Bryant Pond area muscovite is present as a primary phase. Barker (1961) pointed out the possibility that muscovite may still be stable after sillimanite and potash feldspar become stable together. He also mentions that the muscovite in this case would be more potassium-rich than the coexisting potash feldspar. Essentially he has described what is shown graphically in Figs. 5a and 5b. He states (p. 1170), "The pair sillimanite+sodic microcline (or orthoclase) may separate, in a compositional sense, the assemblages muscovite-sodic microcline (or orthoclase)-sillimanite and soda-saturated microcline (or orthoclase)-sodic plagioclase-sillimanite."

Both of these assemblages are present in the Bryant Pond area. He makes note that muscovite possibly could be stable in rocks with a higher K/Na ratio than those on which he was working. Table II gives analyses of some of the pelitic rocks in the area treated by Heald (1950) and Barker (1961).

There can be little doubt that, in general, rocks with the pair potash feldspar-sillimanite are of higher metamorphic grade than those with the pair muscovite-plagioclase. Heald (1950) has pointed this out in the Lovewell Mountain area. The pelitic rocks to the west of that area are below the sillimanite zone and successively rise to the sillimanite and then the sillimanite-potash feldspar isograd as they are traced to the east. A similar zoning exists in a northeast to southwest direction from the Dixfield quadrangle (K. Pankiwskyj, pers. comm.) into the Bryant Pond quadrangle in Maine.

The rocks in the Lovewell Mountain area and those near Sturbridge, Massachusetts, Barker (1962), may be free of muscovite for one or more of the following reasons:

(1) They are more highly metamorphosed with a resultant breakdown of the last potassium-rich muscovite.

(2) The overall composition of the rock may be too low in K_2O. (See Fig. 5b.)

(3) The metamorphic conditions may have been so dry that the hydrous mineral decomposed sooner than in the pelitic rocks of the Bryant Pond area.

The second suggestion may be ruled out by noting that the K/Na ratio (Table II) of the pelitic rocks in the Lovewell Mountain area and those from Sturbridge, Massachusetts, are at least as high as those in the Bethel area. Hence the first and third possibilities remain. The writer tends to favor the first reason inasmuch as the plagioclase coexisting with the sillimonite and potash feldspar in these other localities is somewhat more calcic than in the Bethel or Bryant Pond areas. Barker (1962) reports rims of calcic andesine to sodic labradorite on the plagioclase present in the pelitic rocks at Sturbridge, Massachusetts.

A notable feature in the sillimanite-potash feldspar-bearing rocks is the variation in the polymorph of potash feldspar which is present. Either perthitic microcline or perthitic orthoclase is present. This variation may be related to the temperatures attained during metamorphism or may be a function of the cooling history of the rock.

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