

Application of the muscovite–paragonite geothermometer to a staurolite-grade schist from Sulitjelma, north Norway

K. J. HENLEY¹

Department of Geology, University College, Gower Street, London, W.C. 1

SUMMARY. The occurrence of coexisting paragonite (containing 0.70 % CaO) and muscovite (containing 0.16 % CaO) in a staurolite-grade paragonite–muscovite–hornblende–garnet–biotite schist from Sulitjelma enables an estimate to be made of the temperature of recrystallization, using an extension, based on crystal chemistry considerations and available analyses of muscovites and paragonites from metamorphic rocks, of the experimentally determined solvus in the K–Na white mica system into the Ca–K–Na system. This temperature of recrystallization is approximately 550–70 °C and is consistent with the experimental data on the coexistence of staurolite and quartz in the system Fe–Al–Si–O–H (Richardson, 1968).

IN recent years paragonite has been recorded in an increasing variety of metamorphic rocks. It has commonly been found to coexist, at low to medium grades of metamorphism, with one or more of the following minerals: muscovite, chlorite, biotite, chloritoid, almandine, staurolite, and kyanite; and more rarely with andalusite, glaucophane, or actinolite (Harder, 1956; Zen and Albee, 1964; Guidotti, 1968). To the writer's knowledge, however, the only occurrences of paragonite coexisting with hornblende are those recorded by Banno (1960) from the Bessi district, Sikoko, Japan: Kyanite–zoisite–paragonite–hornblende–quartz; zoisite–epidote–paragonite–hornblende–quartz; zoisite–epidote–paragonite–hornblende–plagioclase–chlorite–quartz; garnet–paragonite–hornblende–epidote–plagioclase–quartz; and paragonite–muscovite–hornblende–epidote–quartz.

An occurrence of paragonite in rutile amphibolites of the Central Urals is recorded by Yakshin (1964), but the presence of paragonite is attributed to soda metasomatism and the paragonite–hornblende assemblage cannot be considered to be in equilibrium.

During a mineralogical investigation of the rocks of the Sulitjelma region, north Norway, the writer discovered a paragonite–muscovite–hornblende–garnet–biotite schist in a staurolite grade environment. Apart from the apparent rarity of paragonite coexisting with hornblende this particular assemblage is of interest in that it is only the third occurrence of paragonite recorded for Norway (Neumann, 1959), and the presence of muscovite coexisting with paragonite enables an estimate to be made of the temperature of recrystallization of the rock during staurolite grade metamorphism, using the experimentally determined muscovite–paragonite solvus of Iiyama (1964).

¹ Present address: The Australian Mineral Development Laboratories, Conyngham St., Frewville, South Australia 5063.

The geology and petrography of the Sulitjelma region have been extensively documented by Vogt (1927) and revised by Henley (1968, and in press), Mason (1966, 1967), Nicholson (1967), and Wilson (1968). The metasediments are mainly calcareous pelites, and constitute a 'western facies' of the Caledonian geosyncline, containing relatively more CaO and MgO and less Al_2O_3 and K_2O than the 'eastern facies' developed in Sweden (Vogt, 1927, pp. 219-40). The metamorphic grade increases from lower biotite zone in the eastern part of the area studied to kyanite zone in the west (based on assemblages in the occasional 'normal' aluminous pelitic schists), and in the western part of the area a thin bed of staurolite-garnet-mica schist is present.

In the calcareous pelites only one isograd is present and marks the first appearance of garnet or hornblende or both and probably calcic oligoclase (Henley, 1968, and in press). This isograd lies several kilometres to the east of the thin bed of staurolite schist. At grades lower than the garnet/hornblende isograd the calcareous pelites contain mainly quartz, biotite, and clinozoisite or calcite or both, all of which minerals may be present at higher grade coexisting with the garnet, hornblende, and oligoclase. Muscovite is generally present in the calcareous pelites as large porphyroblasts, which cut across the schistosity and most minor fold structures, and more rarely as sub-parallel oriented flakes defining the schistosity with biotite.

Immediately adjacent to the staurolite schist is a thin bed of garnetiferous schist with subhedral to euhedral garnet porphyroblasts up to 10 mm in diameter and smaller hornblende porphyroblasts, wrapped around by a schistose fabric of white mica and biotite. Interstitial coarse quartz, often strained, plagioclase, and minor rutile and ilmenite are the other minerals present. A 1-kg sample of this garnetiferous schist was collected for study and after crushing to 5-cm sized fragments and retaining one or two pieces for thin- and polished-thin-section preparation, the remainder were bulked and reduced to minus 100 mesh for chemical and mineralogical analysis.

Experimental procedures. The minerals were separated by a combination of heavy liquid and magnetic techniques and in all cases except one the mineral concentrates were better than 99 % pure. The exception was the white mica, which was analysed as a pure white mica concentrate, but was subsequently shown by X-ray diffraction to consist predominantly of paragonite with minor muscovite. Separation using a heavy-liquid density-gradient column (Sollas, 1891; Muller and Burton, 1965) showed that approximately 7 % of the white mica was muscovite. Further separation of a larger amount of the rock was carried out in order to obtain sufficient pure muscovite (and paragonite) for analysis. Ultimately a virtually pure paragonite concentrate (1.5 ± 1.5 % muscovite impurity) and muscovite concentrate (7.5 ± 1.5 % paragonite impurity) were produced, the intimate interleaving of the two white micas precluding further purification. The proportion of impurity in each white mica concentrate was estimated to the above limits of accuracy by X-ray diffraction.

Chemical analyses of the rock and minerals (except for alkalis) were carried out by an X-ray fluorescence method involving fusion of one part by weight of sample with four parts by weight of 1:1 Li_2CO_3 : $\text{Li}_2\text{B}_4\text{O}_7$, reducing the glass beads thus produced to minus 200 mesh in a tungsten-carbide mill, briquetting the powder, and

analysing the briquettes on a Phillips 12/12 Autrometer for SiO_2 , TiO_2 , Al_2O_3 , Fe (total), MnO, MgO, and CaO. A range of artificial oxide standards with compositions spanning the mineral and rock compositions were also prepared in the same way, and the accuracy of the analyses is considered to be $\pm 3\%$ relative. Alkalies were determined by flame photometry and are accurate to $\pm 2\%$ relative.

Mineralogical (modal) analysis of the host rock was obtained by quantitative separation of the minerals in a representative sample of minus 100 mesh crushed rock, using a combination of magnetic and heavy-liquid techniques, and grain counting; the accuracy is $\pm 3\%$ of the amount present.

Electron-probe microanalyses were carried out on the Microgeoscan in the Department of Mineralogy and Petrology, Cambridge, using analysed mineral standards and correcting for absorption, fluorescence, and atomic number effects. These analyses are accurate to $\pm 3\%$ relative. The X-ray diffraction pattern of the paragonite was obtained using Ni-filtered Cu radiation with quartz as an internal standard. Refractive indices were determined in sodium light, with an accuracy of ± 0.004 .

Host-rock. Chemical and mineralogical analyses of the host-rock (U.C.L. No. 64K-323) are given in table I, together with an average analysis of four different samples of the typical garnet-hornblende-mica schists from Sulitjelma. Compared to the average analysis of the typical schist, 64K-323 is enriched in FeO and MnO, leading to a very high proportion of garnet—16.6%—as compared to less than 4% for the average schist, and in Al_2O_3 and TiO_2 , leading to the formation of the Al_2O_3 -rich phase paragonite and of rutile in addition to the normal ilmenite. 64K-323 also has a high ratio of $\text{Na}/(\text{Na} + \text{K} + \text{Ca})$, which is reflected in the absence of clinozoisite and calcite, the lower proportion of biotite ($\sim 20\%$ as compared to 30–5% in the average schist), and the presence of the Na_2O -rich phase paragonite.

Garnet. Compositionally the large garnets present in 64K-323 are strongly zoned, although texturally they show only one apparent phase of growth (Harte and Henley, 1966; Henley, 1968). Inclusions in the garnets are mainly ilmenite and quartz and show S-shaped or linear arrangements such as are found in many of the garnets in the Sulitjelma schists. The garnets are almandine-rich (table I) and are zoned from an MnO-rich core (12.7% MnO) to an MnO-poor margin (1.1% MnO), with FeO and MgO increasing regularly from core to margin and CaO remaining practically constant. The MnO content of the core is one of the highest MnO contents of any garnet (core or margin) analysed from Sulitjelma and corresponds to nearly 30% of the spessartine molecule.

An analysis of a bulk garnet concentrate prepared from 64K-323 is given in table I (1c) and comparison with the electron-probe analyses (1a and 1b) indicates that the composition corresponds reasonably closely to the margin composition, suggesting either that only the marginal part of the garnet was concentrated during separation, or more probably, that the large volume of low-MnO marginal garnet overwhelmed the effect of the small volume of high-MnO garnet in the core on the bulk analysis.

TABLE I. Analytical data on the paragonite-muscovite-hornblende-garnet-biotite schist 64K-323, and an average analysis of four typical garnet-hornblende-mica schists from Sultijelma

	1a	1b	1c	2	3	4	5	6	7	8
SiO ₂	n.d.	n.d.	38.2	42.3	38.3	45.9	n.d.	58.0	62.5	Quartz
TiO ₂	n.d.	n.d.	0.32	0.35	1.24	0.3	n.d.	1.84	0.99	Biotite
Al ₂ O ₃	n.d.	n.d.	21.1	17.9	16.4	39.3	n.d.	18.2	16.2	Garnet
FeO*	24.8	30.3	30.5	14.5	15.2	0.7	n.d.	10.2	7.2	Paragonite
MnO	12.7	1.1	1.1	0.08	0.04	0.04	n.d.	0.41	0.14	Hornblende
MgO	1.6	4.0	4.2	8.9	14.5	0.02	n.d.	3.8	4.6	Oligoclase†
CaO	2.7	3.2	3.6	10.4	0.01	0.70	0.16	2.1	3.6	Muscovite
Na ₂ O	n.d.	n.d.	n.d.	2.21	0.32	6.81	1.29	1.7	1.7	Rutile
K ₂ O	n.d.	n.d.	n.d.	0.33	8.60	1.03	9.02	1.9	3.0	Ilmenite
				Atoms %	{ Na	27.0	5.3	17.6	41.3	30.0
					{ K	2.7	94.6	8.6	81.2	34.9
					{ Ca	70.3	0.1	4.9	1.2	35.1
				n or γ	1.795	1.615	1.600	—	—	—

		Atomic ratios to N Oxygen				
	1a	1b	2	3	4	5
Almandine	56.4	71.0	N	24	23	22
Spessartine	29.3	2.6	Si	6.08	6.25	5.71
Pyrope	6.5	16.7	Al ^{iv}	—	1.75	2.29
Grossular	7.9	9.6	Al ^{vi}	3.96	1.36	0.59
			Ti	0.04	0.04	0.14
			Fe	4.06	1.79	1.89
			Mn	0.15	0.01	0.01
			Mg	1.00	1.96	3.22
			Ca	0.61	1.65	0.00
			Na	—	0.63	0.09
			K	—	0.06	1.72
						0.17

All data refer to 64K-323 except analysis 7.

1. Garnet (a = core; b = margin; c = bulk concentrate).

2. Hornblende.

3. Biotite.

4. Paragonite.

5. Muscovite.

6. Host rock (64K-323).

7. Average of four typical garnet-hornblende-mica schists from Sultijelma.

8. Modal analysis of 64K-323.

* Total iron as FeO except in paragonite where as Fe₂O₃. † An ≈ 22.

Hornblende. Hornblende occurs as euhedral prisms showing almost colourless (α) to blue-green (γ) pleochroism. Electron-probe microanalysis established that the crystals were compositionally unzoned. The analysis (table I) shows that the hornblende is alumina- and soda-rich, and in fact it is the most soda-rich amphibole analysed from Sulitjelma, for of five other metasedimentary amphiboles analysed all contained between 1.4 % and 1.8 % Na_2O , and of six amphiboles analysed from metadolerites all contained less than 1.6 % Na_2O (Henley, 1968). The richness of the hornblende in soda is presumably associated with its coexistence with paragonite, since in the majority of the Sulitjelma schists the hornblende is not associated with such a soda-rich mineral.

Biotite occurs as pale to medium brown flakes, which, with paragonite and muscovite, define the schistosity. Compositionally the biotite is one of the most MgO -rich from the Sulitjelma metasediments, having a value for $100\text{Mg}/(\text{Fe}+\text{Mg}+\text{Mn}+\text{Ti})$ of 61.3 as compared to values between 26.8 and 61.7 for 25 other metasedimentary biotites from a variety of assemblages and metamorphic grades (Henley, 1968).

The soda content of the biotite from 64K-323 is not exceptionally high in comparison to other Sulitjelma biotites, for seven out of ten biotites analysed for Na_2O contain between 0.14 % and 0.31 % Na_2O and three contain between 0.33 % and 0.46 % Na_2O . This relatively small Na_2O content of biotite in 64K-323 is rather surprising in view of the richness of the coexisting hornblende in Na_2O and the much greater values of Na_2O that have been recorded for biotites in other metamorphic rocks (Deer, Howie, and Zussman, 1962).

Paragonite. An analysis of the paragonite is given in table I, and X-ray diffraction data in table II. The chemical analysis was obtained by recalculating the initial analysis of

TABLE II. X-ray powder diffraction data for paragonite from 64K-323

d	I/I_{100}	hkl †	d	I/I_{100}	hkl	d	I/I_{100}	hkl
9.615 Å	44	002	3.271 Å	9	024	2.418 Å	8	133,008‡
4.808	27	004	3.204	100	006	2.344	5	133,204‡
4.409	11	110,020	3.148	8	114	~ 2.24	*	040,221‡
4.389	14	111	2.908	7	025	2.175	3	135,204‡
~ 4.26	*	111	2.806	6	115	~ 2.13	*	222,028‡
4.035	2	022	2.691	5	116	2.091	4	043,135‡
3.847	4	112	2.553	6	200,130‡	1.923	24	0.0.10
3.652	3	023	2.526	13	131,202‡	1.604	6	0.0.12,2.0.10‡

* Intensity unknown due to interference with quartz line (internal standard).

† hkl values are taken from the indexed paragonite described by Zen, Ross, and Bearth (1964).

‡ Additional lines present.

The basal spacing of the muscovite from 64K-323 is 9.965 Å.

slightly impure (7 % muscovite) paragonite free of muscovite and using the alkali analyses obtained on the purified paragonite and muscovite. It can be seen from table I that the Sulitjelma paragonite approaches the ideal paragonite formula with 6 Si^{iv} , 2 Al^{iv} , and 4 Al^{vi} , but with $(\text{Na}+\text{K}+\text{Ca})^{\text{xii}}$ slightly less than two.

Muscovite. A partial analysis only of the muscovite is given in table I since insufficient material was separated for a full chemical analysis. Comparison of the alkali analyses of the paragonite and muscovite in 64K-323 shows that the paragonite contains significantly more CaO than the muscovite, a feature that seems characteristic of the few analyses of coexisting white micas (Albee and Chodos, 1965; Rosenfeld, Thompson, and Zen, 1958) and one that is explained by the closeness of ionic radii of Ca^{2+} (0.99 Å) and Na^+ (0.97 Å) as compared to K^+ (1.33 Å) (cf. the K–Na–Ca feldspars). This is discussed in more detail in the following section.

The muscovite–paragonite geothermometer

Knowing the composition of the coexisting paragonite and muscovite in 64K-323 enables an approximate minimum temperature of recrystallization to be obtained from the experimentally determined muscovite–paragonite solvus. However, there is some controversy in the literature as to the exact position of the solvus (Eugster and Yoder, 1955; Iiyama, 1964; Nicol and Roy, 1965; Popov, 1968) and the presence of significant amounts of calcium in the paragonite and muscovite from 64K-323 introduces a further complication since the experimental work has been carried out only on the pure K–Na system.

Experimental determinations of the muscovite–paragonite solvus. The earliest and perhaps most widely quoted experimental determination of the muscovite–paragonite solvus was by Eugster and Yoder (1955) who measured the *c* spacings of the muscovite and assumed a straight-line relation between the *c* spacings of the two end members. Due to the poor crystallization of paragonite in these experiments the solvus on the paragonite side was determined by using natural muscovite–paragonite assemblages and fixing their temperature of formation with the aid of the solvus for synthetic muscovite.

Eugster and Yoder's (1955) work was criticized by Nicol and Roy (1965) who failed to confirm the increasing substitution with temperature of Na^+ in muscovite and K^+ in paragonite found by the former authors. Nicol and Roy found that between 450 and 625 °C muscovite could accept up to 30 % Na^+ replacing K^+ with, however, no indication of increasing Na^+ substitution with temperature, and that paragonite could not accept more than 5 % K^+ replacing Na^+ .

In a detailed series of hydrothermal syntheses using NaCl–KCl solutions and pure synthetic muscovite (100 % K^+) and paragonite (100 % Na^+) as starting materials, Iiyama (1964) confirmed, with some modification, the increasing substitution of Na^+ in muscovite and K^+ in paragonite with increase in temperature found by Eugster and Yoder (1955). Iiyama's results differ from those of Eugster and Yoder in indicating a somewhat higher content of Na^+ in muscovite between 500 and 600 °C (Iiyama's experiments were carried out at temperatures between 500 and 650 °C) and a lower content of K^+ in paragonite below 550 °C—a rapid increase in K^+ in paragonite taking place between 550 and 570 °C.

Popov (1967 and 1968) synthesized muscovites and paragonites over the temperature range 350 to 500 °C using alumina–silica gel and excess NaCl–KCl solution (with

various $\text{Na}^+ / (\text{Na}^+ + \text{K}^+)$ ratios but with constant Cl^- content) such that the system was effectively open to Na^+ and K^+ . Popov's results show no progressive increase in the maximum Na^+ content of muscovite with increasing temperature, this maximum being 20 % Na^+ replacing K^+ at 350 and 500 °C. Paragonite was found to contain up to 25 % K^+ replacing Na^+ at 450 and 500 °C, up to 16 % K^+ at 400 °C, and virtually no K^+ at 350 °C.

Fig. 1 summarizes the experimental data of the various workers on the muscovite-paragonite solvus. It seems clear from both the experimental work of Eugster and Yoder (1955) and Iiyama (1964) and from the analysis of the c spacings of natural coexisting muscovites and paragonites (Zen and Albee, 1964) that there is a definite increase of Na^+ in muscovite and K^+ in paragonite with increasing temperature of crystallization, the solvus being markedly asymmetric and closing nearer the paragonite side.

A crystal structural explanation of this asymmetry, based on the lengths of the alkali-oxygen bonds, has been suggested by Burnham and Radoslovich (1964), who also showed that the change in average alkali-oxygen distance with $\text{Na}^+ - \text{K}^+$ substitution was non-linear. This non-linearity may explain the discrepancy between the results of Eugster and Yoder, who assumed a linear relation between c spacing and composition, and Iiyama, whose solvus was obtained without the use of such a correlation. The failure of the results of Nicol and Roy to agree with Eugster and Yoder and Iiyama must be attributed to non-equilibration, and Nicol and Roy (1965, p. 404) themselves emphasize the metastable nature of the early crystallized micas.

The results of Popov are in contradiction with all the other determinations of the muscovite-paragonite solvus in suggesting that paragonite can contain up to 25 % K^+ replacing Na^+ , more than the maximum replacement of K^+ by Na^+ in muscovite (20 % according to Popov). The reason for this discrepancy is not clear, although it may be due to the use of X-ray powder photography rather than the more sensitive X-ray diffractometry to detect the presence of small quantities of one mica in the presence of the other in the two-phase region. However, on crystal structural grounds it is most unlikely that K^+ can substitute to the extent of 25 % in paragonite, and available paragonite analyses (see below) and the work of Zen and Albee (1964) support this conclusion.

At present the best available experimental determination of the muscovite-paragonite solvus is probably that of Iiyama (1964), although unfortunately the solvus was only determined for temperatures above 500 °C, and therefore has limited value as a geothermometer. It is, however, applicable, after allowance for the presence of

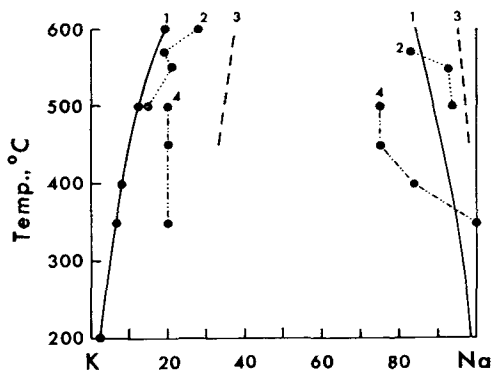


FIG. 1. Summary of the experimental determinations of the solvus in the K-Na white mica system. 1, Eugster and Yoder, 1955. 2, Iiyama, 1964. 3, Nicol and Roy, 1965. 4, Popov, 1968.

Ca²⁺ in the white micas, to the muscovite–paragonite assemblage from Sulitjelma, which recrystallized under staurolite grade conditions.

Intersubstitution of Ca²⁺, K⁺, and Na⁺ in natural white micas. No experimental data are available on the effect of Ca²⁺ substitution on the muscovite–paragonite solvus, but a reasonable picture may be obtained by considering the relative sizes and charges of the Ca²⁺, K⁺, and Na⁺ cations, and the available analyses of muscovite and paragonite.

On the basis of size and charge the replacement of K⁺ in muscovite by Na⁺ will be much greater than the replacement of Na⁺ in paragonite by K⁺, and the replacement of Na⁺ in paragonite by Ca²⁺ will be much greater than the replacement of K⁺ in muscovite by Ca²⁺. These predictions are in general borne out by available white mica analyses, where muscovites commonly contain 0.5–1.5 % Na₂O and less than 0.4 % CaO (approximately 6–20 % and less than 3 % replacement of K⁺ by Na⁺ and Ca²⁺ respectively), and paragonite commonly contains 0.5–1.5 % K₂O and 0.5–1.5 % CaO (approximately 4–12 % replacement of Na⁺ by each of K⁺ and Ca²⁺).

The intersubstitution of Ca²⁺, K⁺, and Na⁺ in natural white micas is illustrated in fig. 2, in which are plotted the more recent analyses of muscovites and paragonites from metamorphic and metasomatic rocks. The analyses plotted in fig. 2 do not suggest any regular pattern of replacement of K⁺ and Na⁺ by Ca²⁺ in white micas with changing metamorphic grade, and the absence of any correlation of replacement of Na⁺ by K⁺ in paragonites with grade is possibly due to insufficient data. There is a wide variation in the Na⁺ substitution in muscovites from any one metamorphic grade, as discussed for example by Butler (1967), but this is probably because most of the analysed muscovites do not coexist with paragonite and their compositions do not therefore represent the maximum Na⁺ substitution that can occur at a particular grade. The picture is further complicated by the possibility, suggested by McNamara (1965), of increased solid solution between phengites and sodic phengites as compared to Al-rich potassium and sodium white micas. Nevertheless, the data in fig. 2a do indicate that there is a general correlation of the Na⁺ content of muscovite with metamorphic grade, most muscovites from rocks of the chlorite and biotite zones and the blueschist facies containing less than 10 % Na⁺, most muscovites from garnet-zone rocks containing 5–15 % Na⁺, and most muscovites from staurolite, kyanite, and sillimanite-zone rocks containing greater than 15 % Na⁺.

Application of the geothermometer to the muscovite–paragonite assemblage from Sulitjelma. In the light of the available analyses of white micas and the crystal chemical factors already discussed it is possible to suggest the topology of the extension of the muscovite–paragonite solvus into the system margarite–muscovite–paragonite (Ca–K–Na). The extension of the solvus is illustrated diagrammatically in fig. 3, and in fig. 4 are plotted the muscovite and paragonite from 64K-323 together with the solvus data of Iiyama for the K–Na white micas and the tentative solvus isotherms based on fig. 3 extended into the Ca–K–Na system. It can be seen that the muscovite and paragonite give independent but mutually compatible temperatures of equilibration, within the limit of analytical error and the assumptions as to the topology of the

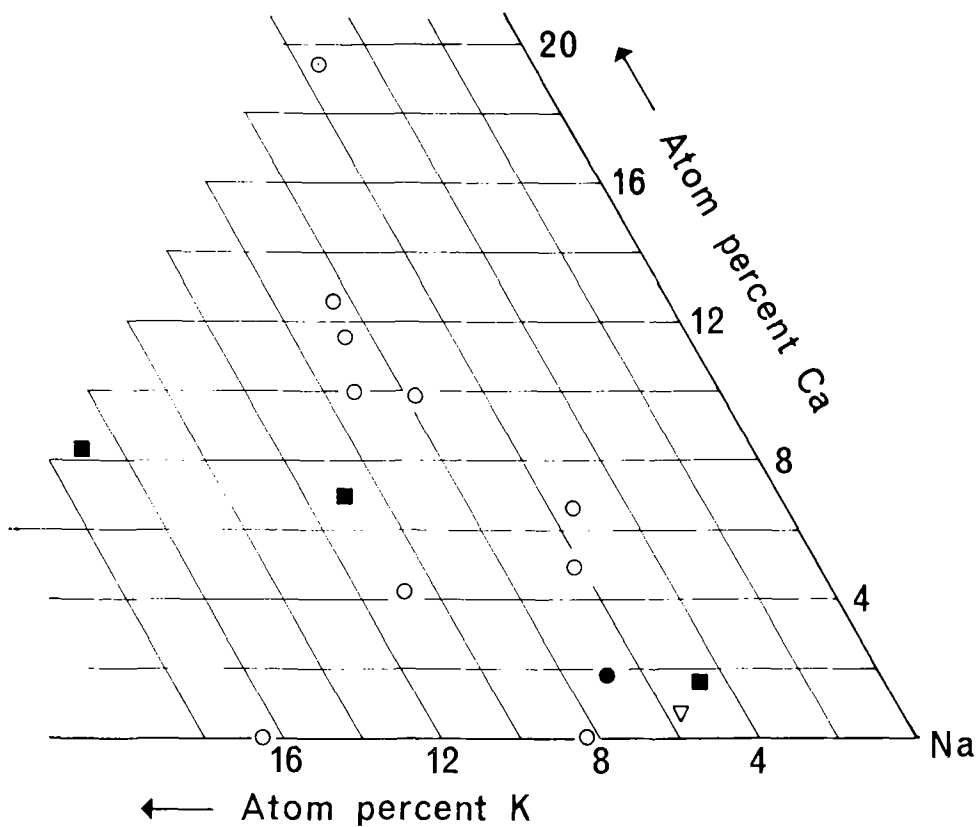
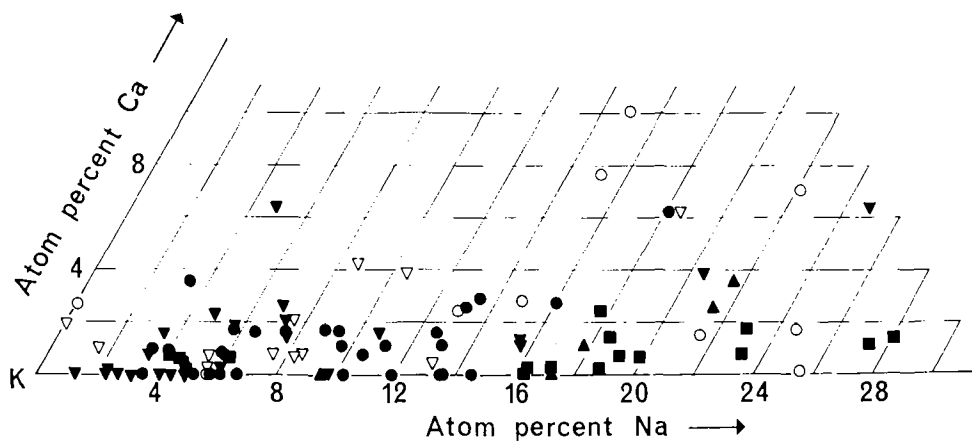
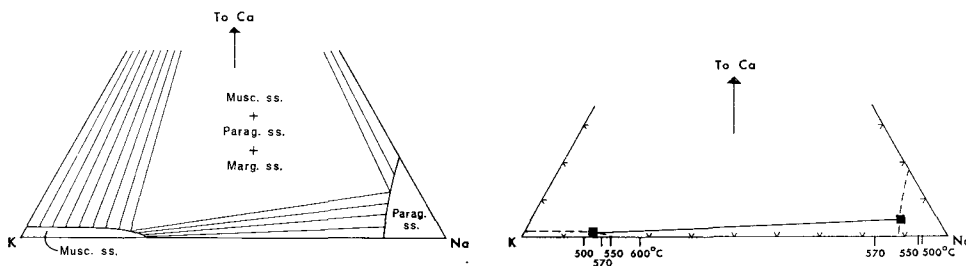


FIG. 2. Analyses of white micas from regionally metamorphosed rocks plotted in the system Ca-K-Na (margarite-muscovite-paragonite), (a) muscovites and phengites, (b) paragonites (including some of metasomatic origin). The symbols correspond to the metamorphic grade of the host-rock as follows: ∇ blueschist facies, \blacktriangledown chlorite and biotite zones, \bullet garnet zone, \blacksquare staurolite and kyanite zones, \blacktriangle sillimanite zone, \circ uncertain. Sources of the analyses are: Albee, 1965; Albee and Chodos, 1965; Banno, 1960; Belkovskii, 1966; Brown, 1967; Butler, 1967; Chinner, 1960; Dietrich, 1958; Ernst, 1963 and 1964; Harder, 1956; Henley, this paper; Hietanen, 1969; Hinterlechner-Ravnik, 1961; Hunziker, 1966; Hutton, 1940; Lambert, 1959; McNamara, 1965; Miyashiro, 1962; Rosenfeld, Thompson, and Zen, 1958; Saxena, 1966; Schaller and Stevens, 1941; Zen, Ross, and Bearth, 1964. A single analysis of a muscovite from a kyanite zone schist (Rosenfeld, Thompson, and Zen, 1958) plots outside fig. 2a, and has the co-ordinates $\text{Na/K/Ca} = 38.4/60.8/0.8$.

solvus in the Ca–K–Na system, namely 550–70 °C. The temperature indicated by the paragonite is not dependent to a great degree on the exact position of the proposed solvus since it is in the temperature range 550–70 °C that the large increase of K⁺ in paragonite takes place in the experimentally determined K–Na system (Iiyama, 1964).

It should be noted, however, that, in applying the experimental solvus to the white micas from 64K-323, the presence of minor oxides such as Fe₂O₃, TiO₂, MgO, and



FIGS. 3 and 4: Fig. 3 (left). Suggested topology of the extension of the muscovite–paragonite solvus into the Ca–K–Na system based on crystal chemistry considerations and available white mica analyses. Fig. 4 (right). Muscovite and paragonite from 64K-323 plotted in the Ca–K–Na system. The tentative solvus isotherms (dashed lines) are based on fig. 3 and points on the solvus for Ca-free muscovite and paragonite plotted in °C on the K–Na side of the triangle are from Iiyama (1964).

MnO in the white micas has been neglected, since the effect of these oxides on the solvus is unknown. Although the content of these oxides is very low in the paragonite (the muscovite was not analysed completely) the temperature of 550–70 °C must therefore be treated as approximate. However, the value of 550–70 °C, which represents the minimum temperature of recrystallization of rock 64K-323 during the Caledonian metamorphism, is consistent with the nearby occurrence of a staurolite–garnet–mica–quartz assemblage, since Richardson (1968) has shown experimentally that the assemblage staurolite–quartz is only stable between about 515 and 700 °C.

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Note added in proof: A summary of the results of a more recent determination of the muscovite-paragonite solvus than the four discussed in the present paper has been given by H. P. Eugster, A. L. Albee, A. E. Bence, J. B. Thompson, Jr., and D. R. Waldbaum (*Trans. Amer. Geophys. Union*, **4**, 351 (1969)). The chemical compositions of the coexisting white micas synthesized hydrothermally at 2 kb were obtained by electron-probe microanalysis and gave the following tentative mean values: 300 °C, $K_{92.7}Na_{7.3}$ and $Na_{98.1}K_{1.9}$; 400 °C, $K_{89.2}Na_{10.8}$ and $Na_{97.0}K_{3.0}$; 600 °C, $K_{74.8}Na_{25.2}$ and $Na_{89.4}K_{10.6}$. When plotted on fig. 1 these points define curves that agree closely with Iiyama's (1964) data, except that the sharp change in paragonite composition between 550 and 570 °C found by Iiyama is not present.

Additional experimental data on the stability of staurolite is given by G. Hoschek (*Contr. Min. Petr.* **22**, 208-32 (1969)). Using a starting mixture of chlorite and muscovite with $Mg/(Mg+Fe) = 0.4$, staurolite was synthesized under equilibrium conditions at 565 ± 15 °C at 7 kb and 540 ± 15 °C at 4 kb. The maximum stability of staurolite in the presence of quartz, muscovite, and biotite was established as 675 ± 15 °C at 5.5 kb and 575 ± 15 °C at 2 kb. All determinations were made under the conditions of the fayalite-magnetite-quartz buffer and the results are consistent with Richardson's (1968) data on the stability of staurolite in the system Fe-Al-Si-O-H.

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