Barium silicates in stratabound Ba–Zn mineralization in the Scottish Dalradian

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ABSTRACT. Barium feldspar and barian muscovite are major constituents of the Aberfeldy Ba–Zn mineralization. Celsian varies from equigranular to a platy habit in quartz-celsian rock and forms porphyroblasts in schist and marble. Hyalophane is less common. Barian muscovite is a major component of the schist in the mineralized zone. Celsian (> 80 % Cn) and/or hyalophane coexist with muscovite containing c.6 % Ba, and c.8.5 % Ba was measured in muscovite from one feldspar-free specimen. Cymrite separated from foliated quartz-celsian rock conformed to the formula $BaAl_2Si_2O_8 \cdot H_2O$. The rock textures reflect regional metamorphism, but it is believed that the barium silicates are ultimately authigenic in origin. The platy habit of much of the celsian may have been inherited from cymrite formed during the development of tectonic fabrics.

BARIUM silicate minerals are an important component of the Aberfeldy barium–zinc mineralization recently described by Coats et al. (1980). Such minerals are not common and their presence in considerable quantities at Aberfeldy is a significant new occurrence to place alongside other British occurrences such as in the manganese deposits at Rhiw, North Wales (Spencer, 1942; Campbell-Smith et al., 1949) and the harmotome present in base-metal bearing veins at Strontian (Gallagher, 1964) and Struy (Russell, 1946) in Scotland.

The barium silicates recorded at Aberfeldy in the present work are celsian, hyalophane, cymrite, and barian muscovite. In addition, a major part of the barium present occurs as the baryte from which the economic potential of the mineralization derives.

The mineralization is of stratabound type, hosted by graphitic quartz–muscovite schist of the Ben Eagach Schist formation, which is of Middle Dalradian (lower Cambrian) age (fig. 1). Coats et al. (1980) consider it to be of synsedimentary exhalative origin, the feldspathic rock representing authigenic precipitation of barium chert from Si–Al–Ba gel, while Ba-enriched schist represents incorporation of barium into clays during diagenesis.

Dalradian schists ⎫
Moine schists etc ⎭ Caledonian

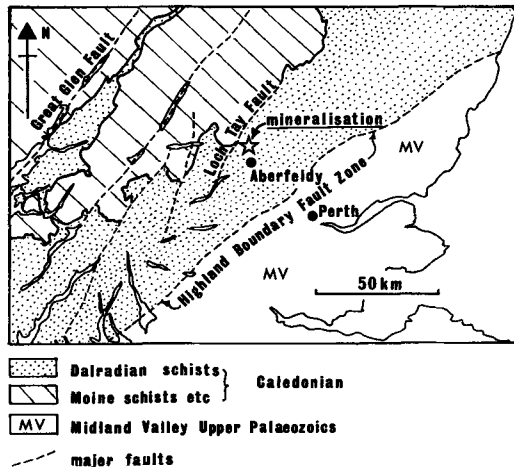MV Midland Valley Upper Palaeozoics

- - - major faults

FIG. 1. Outline map of the Central Highlands area of Scotland showing the location of the Aberfeldy mineralization.

The present paper describes the barium silicates and their occurrence.

Geology. The Aberfeldy mineralization comprises a zone of banded metal-rich metasediments including bands and lenses of massive baryte-rock. The sequence has been subjected to amphibolite-grade metamorphism during the Caledonian orogeny.

Fig. 2, based on Coats et al. (1981), illustrates the structure of the mineralized zone, showing its lensing character. The celsian-rich rocks contain between 5 and 25 % Ba (Coats et al., 1981), and it is clear that in the section in fig. 2 they account for a major part of the total barium present. However, on present evidence it is difficult to be more precise about the total celsian content of the mineralization beyond observing that celsian-rich rocks appear to be laterally more persistent and of greater total thickness than baryte rocks at least in the eastern and central parts of the mineralized zone.
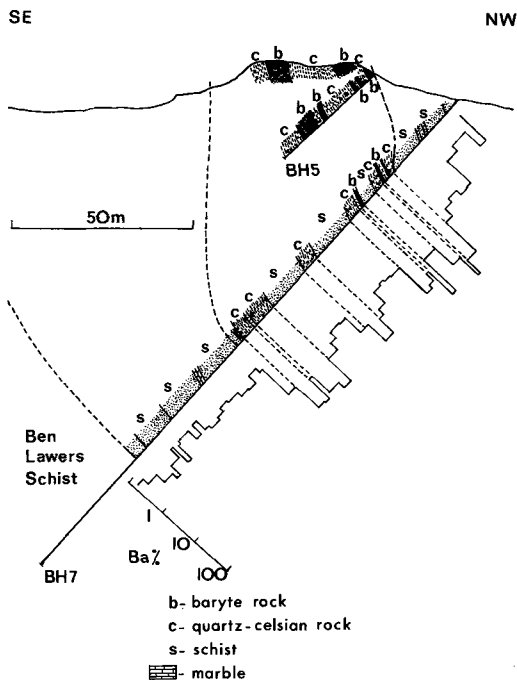
FIG. 2. Geological cross-section of the mineralized zone based on IGS Boreholes 5 and 7, with the corresponding log of Ba content for BH7 (adapted from Coats *et al.*, 1981).

As shown in fig. 2, the typical situation is for sharply defined bands of baryte-rock $\geqslant 1$ m in thickness to occur in quartz–celsian rock interbanded with other metalliferous lithologies. Additional sets of celsian-rich bands may be present, and the mineralized rocks are set in graphitic schist which also contains low but anomalous amounts of barium. Other lithologies include non-graphitic muscovite schist and bands of marble, both also frequently barium enriched.

Petrography. Quartz–celsian rock, present throughout the mineralized zone, varies from a massive cherty type to foliated, and is often rhythmically banded. Dolomite and muscovite are generally present, as is accessory rutile which occurs as minute euhedral crystals, typically as inclusions in celsian crystals. The sulphides pyrite, pyrrhotine, sphalerite, galena, and chalcopyrite occur in varying amounts and combinations. Banding is expressed by changes of mineral assemblage, including the presence of pyrite plus sphalerite laminae sometimes less than 2 mm thick. Changes in grain size and texture are also features of the banding.

The cherty type of quartz–celsian rock has a somewhat equigranular texture in which neither muscovite nor celsian crystals show a pronounced

preferred orientation (fig. 3a). The foliated type tends to be more quartzose than the cherty type, and its fabric is created by alignment parallel to the lithological banding of crystals of both muscovite and celsian. Here the celsian occurs as platy grains. Groups of such grains may share optical continuity as indicated by simultaneous optical extinction, and are thus single crystals evidently formed by equal-volume replacement of groups of earlier platy crystals. It is tempting to conclude that the precursor mineral was cymrite (see below) though the curved, extremely thin forms sometimes shown by these celsian grains are often suggestive of a mica.

Replacement of a platy mineral has led to some most unusual textures. Where, for instance, the platy precursor was a major constituent of the rock, celsian crystals may show an internal relict foliation created by trails of sub-microscopic inclusions which mark the original grain boundaries (fig. 3b). In another case the precursor formed a framework of randomly oriented grains, and in replacing this the celsian crystals have developed irregular branching forms. In other celsian-rich bands the feldspar occurs as relatively large, angular crystals in which earlier formed quartz and other minerals are preserved as trails of inclusions (fig. 3c), and it is suggested that these celsian crystals developed by a merging of smaller celsian crystals in rock originally of cherty aspect.

Celsian also occurs as porphyroblasts in marble and in brecciated carbonate-rich rocks in which individual celsian crystals may form whole fragments or large parts thereof. At one locality, coarse, euhedral celsian occurs in sulphide-rich irregular veinlets in massive dolomitic marble. This rock is also notable for the bottle-green colour of the celsian crystals. The feldspar itself is creamy-white, and the green colour is created by a ramifying network of chlorite alteration.

The possibility that the precursor to the platy celsian was cymrite ($BaAl_2Si_2O_8 \cdot H_2O$) is suggested by the presence of this mineral as a minor constituent of the foliated quartz–celsian rock. Although only located in two specimens to date, it is possible that cymrite is more widespread since it has a similar appearance to platy celsian in thin section, and its replacement by celsian would involve little more than loss of H_2O. It remains to be shown that cymrite can take up the extremely thin, curved habit indicated by the celsian in some specimens.

Barium feldspar is a minor constituent of the Ba-enriched muscovite schists, both graphitic and non-graphitic. In this situation hyalophane may be as common as celsian, though it is only a minor constituent of the more barium-rich rocks.
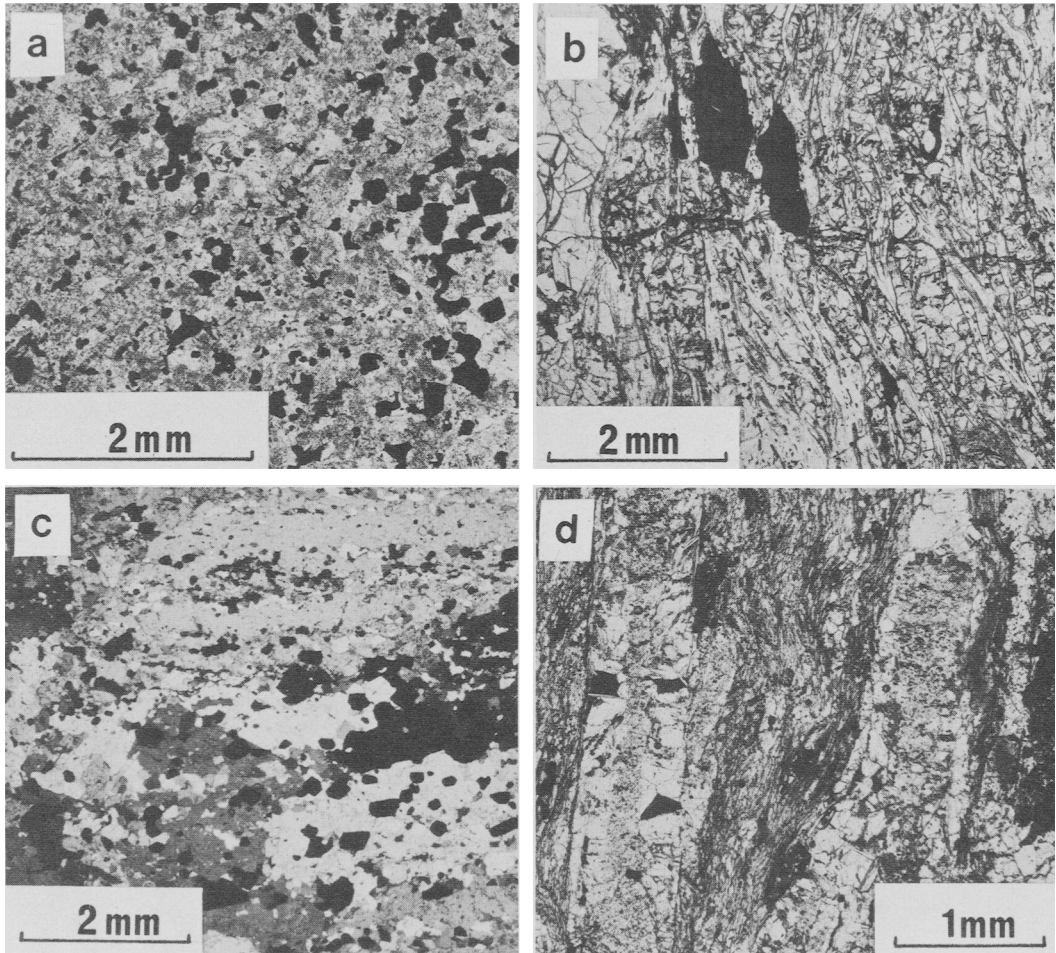
FIG. 3. Photomicrographs showing: (a) cherty rock in which the light material is celsian (IGS BH2); (b) foliated rock in which coarse celsian crystals have replaced a platy mineral (IGS BH5); (c) coarse celsian-rich rock with parallel trails of quartz and pyrite grains (IGS BH5); (d) composite bladed porphyroblasts in quartz-muscovite schist (IGS BH9).

The feldspars occur in the schists both as porphyroblasts and as irregular crystals interleaved with the mica, and the porphyroblasts may also have interleaved outgrowths. Where the schist is graphitic the feldspar crystals tend to contain graphitic granules, as does the accompanying mica.

In one specimen, celsian and hyalophane coexist in quartz–muscovite schist as composite porphyroblasts of complex internal structure (fig. 3d). The feldspars are intergrown (see Table I, analysis 22; Table II, analyses 8 and 9) and inclusions of quartz, pyrite and, uncommonly, baryte are concentrated into central zones of the porphyroblasts.

Muscovite in the schists and other mineralized rocks is very often barium enriched. The most Ba-rich muscovite observed was in a specimen of graphitic quartz-muscovite schist lacking any feldspar. In the initial absence of analytical data there was no reason to anticipate the presence of anomalous amounts of barium in the rock (see Grout and Gallagher, 1980). Bauer and Berman (1933) observed a pink body colour in barium-muscovite (oellacherite) from Franklin, New Jersey, but this has not been repeated in the present study.

It is worth noting that witherite and other barium minerals including sanbornite have not yet been reported from the Aberfeldy mineralization. In the case of witherite, this is perhaps surprising in view of the abundance of carbonate and baryte in the deposit, and the scope remains for the discovery of additional barium minerals.

Mineralogy. The barium feldspars mostly occur as optically uniform crystals in which cleavage and twinning are poorly developed, except for the coarser crystals in which cleavage and simple twins are not uncommon. Universal Stage examination of the coarse celsian crystals in one band indicated normal twins with (001) composition planes (Manebach-Law) and optic axial angles near 86° positive. Platy crystals may show straight extinction, presumably due to elongation in the (001) plane. Refractive index determinations on grains separated from three rocks gave the following results:

Specimen	n_α	n_β	n_γ	2V.*	2V.†	%Cn‡
BH2–7.2 m	1.585	1.590	1.595	89.73°	c.90°	96.2–78
BH10–13.3 m	1.585	1.589	1.594	96.14°	—	—
BH11–26.8 m	1.581	1.586	1.591	89.73°	—	92

* Calculated. † Measured. ‡Microprobe data.

Analyses were carried out by electron microprobe (Cambridge Instruments Microscan V) using wavelength-dispersive techniques and standards as described by Bowles (1975). Raw data were corrected using the programme of Mason *et al.* (1969). Results are given in Tables I and II and displayed in fig. 4.

The feldspar compositions plot near to a straight line on the Ba–K–Na diagram (fig. 4*a*) corresponding to a K/Na ratio near 4.26, but analyses from other localities scatter widely on this diagram. The reason for this constancy may relate to the over-all chemistry of the deposit. On a plot of Al *v.* Ba (fig. 4*b*) the feldspars plot close to the linear trend governed by the reaction $BaAl \rightleftharpoons (Na,K)Si$, reflecting the low abundance of other cations. Most analyses from the literature conform to this trend, though banalsite from the Rhiw mineralization (Campbell-Smith *et al.*, 1944) shows an excess of Al confirming that it is not a true feldspar (Deer *et al.*, 1962). Ca, Ti, Mn, and Mg are near the detection limits in both the celsian and the hyalophane. Fe_2O_3, however, is present in amounts up to 0.65 %, Fe^{3+} substituting for Al^{3+}. These barium feldspars thus form a chemically simple suite whose
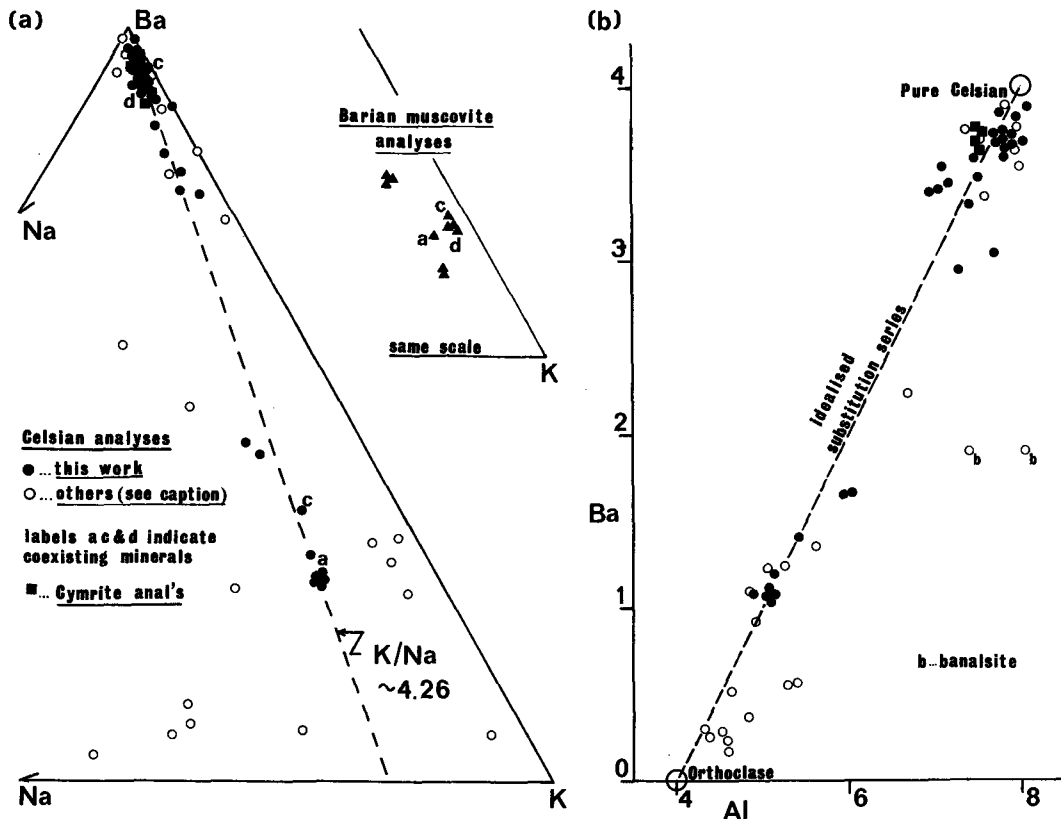

FIG. 4. (*a*) Ba–Na–K diagram showing barium feldspar and cymrite analyses plus (inset) barian muscovite analyses for the Aberfeldy mineralization (filled symbols) and other localities (open symbols); (*b*) Ba versus Al (32 oxygens) for barium feldspar and cymrite. Additional data from Spencer (1942), Yosimura (1939), and Deer *et al.* (1962).

Table I. Electron-microprobe analyses of celsian.

Analysis	1	2	3	4	5[1]	6[1]	7	8	9	10	11[2]	12	13
Specimen	--CZR3552E---			----CZR3530---		-CZR3934A-	--CZR3909B--		-------BH2 -7.5m-----			-------BH7 - 81.6m----	
SiO_2	31.80	37.20	31.07	32.68	35.48	37.32	35.78	32.64	34.10	34.07	33.19	34.50	33.05
Al_2O_3	27.67	28.56	28.35	28.04	24.84	24.49	24.42	27.27	26.01	27.26	27.11	25.71	26.79
TiO_2	-	-	-	-	0.07	nd	0.10	-	-	-	nd	0.09	0.05
Fe_2O_3*	0.28	0.65	0.36	0.46	0.06	0.03	0.12	-	-	-	-	-	-
MgO	nd	0.15	nd	nd	0.02	0.01	0.03	-	-	-	-	-	-
CaO	nd	0.02	nd	nd	0.01	nd	0.02	-	-	-	-	-	-
BaO	39.84	33.84	39.92	38.66	36.82	35.83	35.45	39.43	36.26	38.90	38.26	37.17	38.36
Na_2O	0.08	nd	nd	0.24	0.24	0.13	0.30	0.10	0.25	0.14	0.09	0.15	0.07
K_2O	0.31	1.18	0.24	0.71	0.59	0.62	2.14	0.33	2.76	0.73	0.45	0.95	0.57
Total	99.98	101.60	99.99	100.80	98.13	98.43	98.36	99.77	99.38	101.09	99.10	98.57	98.89

Formulae based on 32 oxygens.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Si	7.906	8.510	7.740	7.966	8.725	9.010	8.765	8.081	8.368	8.248	8.192	8.508	8.204
Al	8.107	7.700	8.323	8.055	7.199	6.969	7.050	7.957	7.524	7.780	7.884	7.172	7.836
Ti	-	-	-	-	0.013	0.0	0.018	-	-	-	0.0	0.016	0.008
Fe	0.052	0.112	0.067	0.084	0.011	0.005	0.022	-	-	-	-	-	-
	16.065	16.322	16.130	16.105	15.948	15.984	15.855	16.038	15.892	16.028	16.076	16.000	16.048
Mg	0.0	0.051	0.0	0.0	0.007	0.004	0.011	-	-	-	-	-	-
Ca	0.0	0.005	0.0	0.0	0.003	0.0	0.005	-	-	-	-	-	-
Ba	3.881	3.033	3.897	3.692	3.548	3.389	3.403	3.825	3.488	3.692	3.700	3.592	3.732
Na	0.039	0.0	0.0	0.113	0.114	0.061	0.142	0.048	0.120	0.064	0.044	0.072	0.032
K	0.098	0.344	0.076	0.221	0.185	0.191	0.669	0.104	0.864	0.224	0.140	0.300	0.180
	4.018	3.433	3.973	4.026	3.857	3.645	4.230	3.977	4.472	3.980	3.884	3.972	3.944

Molecular proportions.

	1	2	3	4	5	6	7	8	9	10	11	12	13
%Cn	96.6	89.8	98.1	91.7	92.2	93.1	80.8	96.2	78.0	92.8	95.3	90.3	94.6
%Ab	1.0	0.0	0.0	2.8	3.0	1.7	3.3	1.2	2.7	1.6	1.1	1.8	0.8
%Or	2.4	11.2	1.9	5.5	4.8	5.2	15.9	2.6	19.3	5.6	3.6	7.6	4.6

Analysis	14[2]	15	16	17	18	19	20	21	22
Specimen	----------BH 11 - 26.8 m------				----BH3-23,12m---		-BH8-143.6m----		BH9-28.6m
SiO_2	33.26	33.17	33.47	33.68	35.75	32.66	33.71	37.84	36.30
Al_2O_3	26.80	26.78	27.25	27.21	24.78	26.16	27.03	26.45	26.56
TiO_2	nd	nd	nd	0.02	-	-	-	-	-
Fe_2O_3*	0.03	0.06	0.04	0.06	-	-	-	-	-
MnO	0.05	nd	0.05	0.02	-	-	-	-	-
MgO	nd	nd	0.01	0.02	-	-	-	-	-
CaO	nd	nd	nd	nd	-	-	-	-	-
BaO	38.23	38.06	36.43	37.77	35.80	39.05	37.19	32.10	35.68
Na_2O	0.19	0.16	0.17	0.15	0.30	0.12	0.19	0.41	0.36
K_2O	0.65	0.84	0.51	0.54	1.19	0.21	0.58	2.12	1.65
Total	99.21	99.07	97.92	99.45	97.82	98.20	98.70	98.92	100.55

Formulae based on 32 oxygens.

	14	15	16	17	18	19	20	21	22
Si	8.215	8.206	8.240	8.236	8.772	8.220	8.276	8.852	8.608
Al	7.802	7.808	7.908	7.844	7.168	7.760	7.820	7.292	7.424
Ti	0.0	0.0	0.0	0.004	-	-	-	-	-
Fe	0.006	0.011	0.008	0.004	-	-	-	-	-
	16.023	16.025	16.156	16.088	15.940	15.980	16.096	16.144	16.032
Mn	0.010	0.0	0.012	0.004	-	-	-	-	-
Mg	0.0	0.0	0.0	0.0	-	-	-	-	-
Ca	0.0	0.0	0.0	0.0	-	-	-	-	-
Ba	3.700	3.689	3.516	3.620	3.444	3.852	3.580	2.944	3.316
Na	0.091	0.077	0.080	0.072	0.144	0.060	0.092	0.184	0.164
K	0.205	0.265	0.160	0.168	0.372	0.068	0.180	0.632	0.500
	4.006	4.031	3.768	3.864	3.960	3.980	3.852	3.760	3.980

Molecular proportions.

	14	15	16	17	18	19	20	21	22
%Cn	92.6	91.5	93.6	93.7	86.9	96.8	92.9	78.3	83.3
%Ab	2.3	1.9	2.1	1.9	3.6	1.5	2.4	4.9	4.1
%Or	5.1	6.6	4.3	4.4	9.5	1.7	4.7	16.8	12.6

Notes for Tables I, II, and III :

[1] Analyses by J.A.T. Smellie.

[2] Analyses previously given by Coats et al. (1980) and reproduced by permission of the Institute of Mining and Metallurgy.

* Total iron is expressed as Fe_2O_3

nd not detected.

- not analysed..

Details of the specimens and their sample localities are given by Coats et al. (1981).

Table II. Electron-microprobe analyses of hyalophane.　(Notes as for Table 1)

Analysis	1	2	3	4	5	6	7	8	9
Specimen	--------BH7-40.8m---------						-BH7-81.6m	--BH9 - 28.6m	
SiO_2	52.72	52.58	53.88	53.53	53.92	53.98	50.66	48.69	48.45
Al_2O_3	21.05	21.04	21.13	20.28	21.22	21.52	22.05	24.39	24.50
TiO_2	0.03	0.11	0.11	0.16	0.06	0.12	nd	-	-
Fe_2O_3*	0.04	0.04	0.02	0.12	0.03	0.07	nd	-	-
MgO	nd	nd	nd	nd	nd	nd	nd	-	-
CaO	0.02	0.01	0.01	0.01	nd	nd	nd	-	-
BaO	13.58	14.96	13.41	13.38	13.50	13.70	18.44	20.11	20.27
Na_2O	1.43	1.33	1.44	1.45	1.36	1.37	1.11	1.18	1.27
K_2O	9.11	8.68	9.08	9.24	9.15	9.09	7.71	6.22	5.71
Total	97.97	98.75	99.09	98.14	99.26	99.85	99.97	100.59	100.20

Formulae based on 32 oxygens

	1	2	3	4	5	6	7	8	9
Si	10.864	10.837	10.929	10.995	10.925	10.880	10.560	10.152	10.132
Al	5.112	5.111	5.052	4.908	5.067	5.112	5.416	5.992	6.040
Ti	0.004	0.017	0.017	0.024	0.009	0.018	0.0	-	-
Fe	0.004	0.006	0.003	0.016	0.005	0.011	0.0	-	-
	15.984	15.971	16.001	15.943	16.006	16.021	15.976	16.144	16.172
Ca	0.004	0.002	0.002	0.0	0.002	0.0	0.0	-	-
Ba	1.096	1.208	1.066	1.076	1.072	1.082	1.408	1.644	1.660
Na	0.572	0.531	0.566	0.576	0.534	0.535	0.448	0.476	0.516
K	2.396	2.282	2.350	2.420	2.365	2.337	2.052	1.656	1.524
	4.068	4.023	3.984	4.072	3.973	3.954	3.908	3.776	3.700
%Cn	27.0	30.0	26.8	26.4	27.0	27.4	36.0	43.5	44.9
%Ab	14.1	13.2	14.2	14.1	13.5	13.5	11.5	12.6	13.9
%Or	59.0	56.8	59.0	59.4	59.5	59.1	52.5	43.9	41.2

Table III. Electron-microprobe analyses of barian muscovite.　(Notes as for Table 1)

Analysis	1	2	3	4	5[2]	6	7	8[2]	9	10	11
Specimen	--BH7-36.7m---		--BH7-81.6m---		------BH8-135.0m-----			--BH11-26.8m-		-BH7-40.	
SiO_2	45.0	45.6	45.5	46.6	43.1	43.0	42.8	43.9	44.0	44.5	44.5
Al_2O_3	30.8	30.9	29.5	29.3	32.0	32.0	32.0	29.8	29.6	30.0	30.0
TiO_2	0.99	0.97	1.74	1.69	1.16	1.13	1.13	1.67	1.48	1.52	1.46
Fe_2O_3*	1.05	1.33	0.71	0.61	0.33	0.38	0.35	1.58	1.57	1.12	1.17
MnO	-	-	-	-	-	-	-	0.05	0.05	-	-
MgO	1.94	2.08	3.80	3.58	2.27	2.43	2.39	3.06	2.89	2.28	2.31
CaO	nd	0.02	nd	nd	nd	0.01	nd	0.01	0.02	0.01	0.01
BaO	3.94	4.03	6.40	5.96	8.17	8.25	7.93	5.71	5.89	5.92	6.07
Na_2O	0.45	0.45	0.15	0.16	0.45	0.44	0.46	0.14	0.21	0.34	0.37
K_2O	9.25	9.24	8.60	8.78	7.59	7.43	7.42	8.83	8.66	8.91	8.71
Cr_2O_3	-	-	-	-	-	-	-	0.06	0.04	-	-
Total	93.42	94.42	96.40	96.68	95.07	95.07	94.48	94.81	94.41	93.48	94.36

Formulae based on 22 oxygens

	1	2	3	4	5	6	7	8	9	10	11
Si	6.27	6.28	6.24	6.34	6.05	6.04	6.03	6.16	6.20	6.24	6.24
Al^{IV}	1.73	1.72	1.76	1.66	1.95	1.96	1.97	1.84	1.80	1.76	1.76
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al^{VI}	3.33	3.29	3.01	3.04	3.34	3.33	3.36	3.08	3.12	3.20	3.20
Ti	0.10	0.10	0.18	0.17	0.12	0.12	0.12	0.18	0.16	0.16	0.15
Fe	0.11	0.14	0.07	0.06	0.04	0.04	0.04	0.17	0.17	0.12	0.13
Mg	0.40	0.43	0.78	0.73	0.48	0.51	0.50	0.64	0.61	0.48	0.48
Y	3.94	3.96	4.04	4.00	3.98	4.00	4.02	4.07	4.06	3.96	3.96
Ca	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ba	0.22	0.22	0.34	0.32	0.45	0.45	0.44	0.31	0.33	0.33	0.33
Na	0.12	0.12	0.04	0.04	0.12	0.12	0.13	0.04	0.06	0.09	0.10
K	1.64	1.62	1.51	1.52	1.36	1.33	1.34	1.58	1.56	1.60	1.56
X	1.98	1.96	1.89	1.88	1.93	1.90	1.91	1.93	1.95	2.02	1.99

compositions may be adequately described by the molecular percentage of $BaAl_2Si_2O_8$ (% Cn).

Gay and Roy (1968) showed that the series $KAlSi_3O_8$–$BaAl_2Si_2O_8$ can exist as a more or less continuous substitution series, but that the c parameter of celsian is double that of hyalophane. They suggest that near the solidus of the series (high-T structural state) celsian is confined to 90–100 % Cn, whilst in the low-T structural state, corresponding to conditions prevalent at Aberfeldy, there is a composition gap between hyalophane (15–65 % Cn) and celsian (80–100 % Cn). The analyses presented here of celsian mostly fall above 80 % Cn while hyalophane falls in the range 25–40 % Cn, consistent with the presence of a substantial composition gap.

In general, the least-potassic celsian (> 90 % Cn) occurs in the most celsian-rich (K deficient) lithologies. Zoning of low-K celsian is not uncommon as reflected by the analyses in Table I, and may be oscillatory in nature. Fine compositional zones controlled by the symmetry of the crystals, as in fig. 5a, suggest a growth phenomenon. The Ba and K contents along a traverse of this crystal (fig. 5b) show that the composition varies abruptly from 78 % Cn to 95 % Cn in the area of oscillatory zoning (Table I, analyses 20 and 21). This particular crystal is cut by a late quartz vein which accounts for the break in the microprobe traverses.

A second type of zoning apparently involves replacement of low-K celsian by a more potassic variety. Fig. 6a shows part of a coarse crystal in which low-K celsian (97 % Cn; Table I, analysis 19) occurs as patches in more potassic celsian (87 % Cn; Table I, analysis 18). The probe traverses in fig. 6b show abrupt boundaries between the two celsian generations and indicate that the surrounding celsian is continuously zoned away from the K-poor patches. Irregular fluctuations evident in fig. 6b are due to micaceous inclusions in the feldspar.

Celsian which occurs in quartz-muscovite schist tends to be relatively potassic (80–90 % Cn) and may be intergrown with hyalophane as already
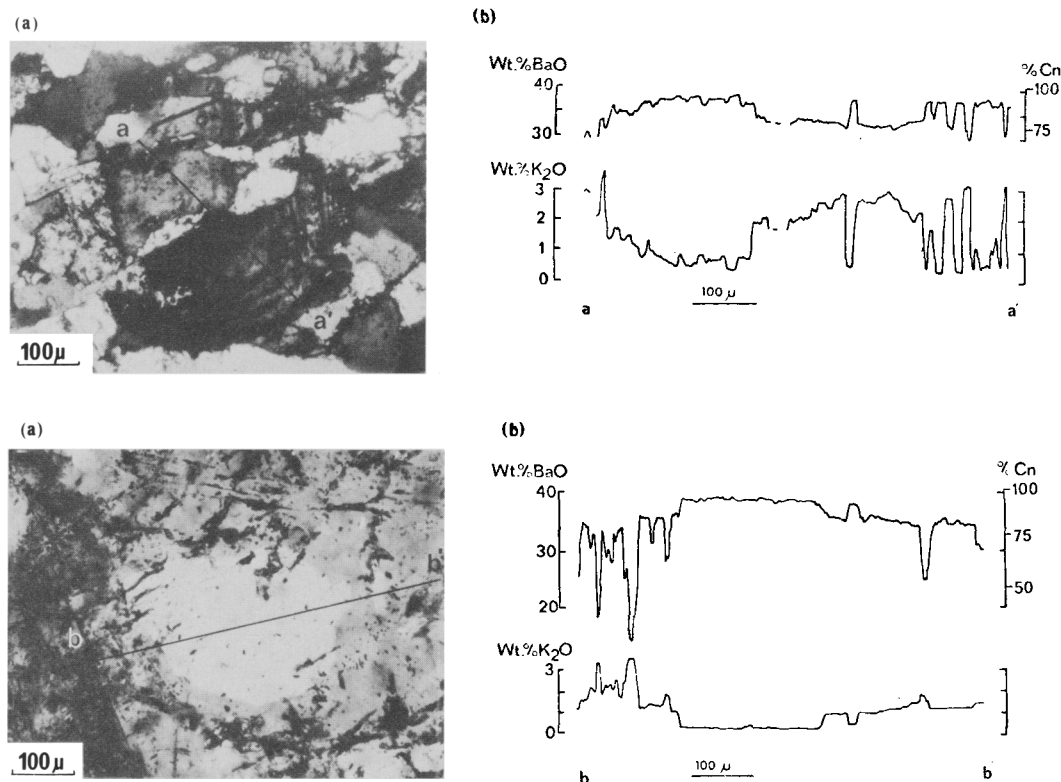
FIGS. 5 and 6. FIG. 5 (*top*). (*a*) Photomicrograph (crossed polars) of oscillatory zoning in celsian crystal; (*b*) microprobe beam traverse for Ba and K on line aa′, with approximate BaO, K_2O, and % Cn contents. FIG. 6 (*bottom*). (*a*) Photomicrograph (crossed polars) of part of a large celsian crystal in which patches of low-K celsian are set in more potassic feldspar; (*b*) microprobe beam traverse for Ba and K on line bb′, with approximate BaO, K_2O, and % Cn contents.

described. Analyses 22 in Table I and 8 and 9 in Table II represent coexisting celsian and hyalophane from a single composite porphyroblast in the thin section in which such intergrowth was observed.

Refractive index determinations of muscovite from three rocks gave the following results:

Specimen		n_α	n_β	n_γ	$2V_{\text{measured}}$
BH7-36.7 m	c.4% Ba	1.574	1.604	1.607	34.9°
BH7-40.3 m	c.6% Ba	1.585	1.609	1.610	30.3°
BH8-135.0 m	c.8% Ba	1.578	1.608	1.611	35.3°

Microprobe analyses of barium muscovite are given in Table III. BaO contents from 3.9% to 8.3% have been measured though within individual specimens the Ba level is relatively constant. Analyses of barian mica are rare in the literature though Bauer and Berman (1933) have reported a mica from Franklin, New Jersey, containing 9.89% BaO. In three feldspathic samples analysed (Table III) the muscovite consistently contained about 6% BaO, even though the feldspar varied from hyalophane to celsian. It may be that this represents an effective saturation level for muscovite in barian feldspathic rock at this metamorphic grade. The more Ba-rich muscovite could represent the case in which barian feldspar is absent and more Ba is retained metastably in the muscovite lattice.

Other elements detected in significant amounts include Na, Ti, Fe, and Mg. Ca was generally at or below detection level and despite the occurrence of fuchsite in some rocks from Ben Eagach (Coats et al., 1980) Cr levels in Ba-muscovite were less than 0.05%. The relationship between Na, K, and Ba in the muscovites is illustrated in fig. 4a where it is evident that the K/Na ratio is higher than in coexisting feldspar. It is interesting to note that the Ti present in muscovite, but not in feldspar, is possibly compensated for in a replacement relationship by the presence of rutile inclusions in the latter.

The incorporation of Ba into the muscovite lattice could occur by one of two substitution reactions:

$$Ba^{2+}(Mg,Fe)^{2+} \rightleftharpoons K^+ Al^{3+} \qquad (1)$$
$$Ba^{2+}Al^{3+} \rightleftharpoons K^+ Si^{4+} \qquad (2)$$
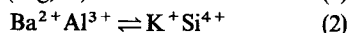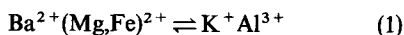
Reaction (1) is a combination of (2) and the common phengitic substitution of normal muscovite:

$$(Mg,Fe)^{2+}Si^{4+} \rightleftharpoons Al^{3+}Al^{3+} \qquad (3)$$

Inspection of the atomic formulae given in Table III indicate that reaction (1) cannot account alone for the observed amounts of Mg, Fe, and Ba, even allowing for the incorporation of Ti in the octahedral sites. Thus reactions (2) and (3) probably operate independently, the former governed prin-

cipally by exchange with feldspar. In general, the degree of phengitic substitution is comparable with that in Ba-free muscovites at similar metamorphic grades (cf. Butler, 1967).

Cell-parameters were determined for Ba-muscovite with approximately 8% BaO (Table III, analyses 5–7) from diffractometer and Guinier-Hägg measurements using CuK_α radiation ($\lambda =$ 1.54178 Å) and silicon as an internal standard. From twenty-four unambiguous reflections, least squares refinement gave the following results (D. Atkin, unpubl. results): $a = 5.205 \pm 0.002$, $b = 9.034 \pm 0.005$, $c = 19.963 \pm 0.007$ Å, $\beta = 95.79 \pm 0.04°$, V = 933.92 ± 0.76 Å^3, structural type $2M_1$. These are very close to that for standard $2M_1$ muscovite (JCPDS 6-263), but differ appreciably from results for the Franklin Ba-muscovite which has a $1M$ structure (Heinrich and Levinson, 1955). A Ba–V mica reported by Snetsinger (1966) and containing 2.9% BaO also has a $2M_1$ structure.

Cymrite was positively identified in only two specimens of the two hundred or so examined. It is a uniaxial-negative, colourless mineral of moderate relief and low birefringence. According to Kashayev (1966) it has a sheeted mica-like structure. In thin section it resembles celsian, thus its distribution may be wider than was observed. It was identified by X-ray diffractometry on grains separated from samples BH11–26.8 m (D. Atkin, unpubl. data). Further grains yielded the data $n_\omega = 1.611$ and $n_\varepsilon = 1.603$ which are in agreement with results given by Runnells (1964). Microprobe analyses of cymrite from this sample are shown in Table IV.

Various formulae have been proposed for cymrite. Runnells (1964) gives it as $Ba_2Al_5Si_5O_{19.5} \cdot 3.65H_2O$ and Aye and Strauss (1975) suggest $BaAlSi_3O_8 \cdot (OH)$. Carron et al. (1964) and Essene (1967), however, propose $BaAl_2Si_2O_8 \cdot H_2O$, which is essentially hydrated celsian, and the present analyses are in agreement with this, while also indicating slight solid solution with a $(K,Na)Al_2Si_2O_8 \cdot H_2O$ component. Other cations such as Ti, Fe, Mg, and Mn are low or below detection levels. The oxide deficits of 4 to 5% agree well with a theoretical H_2O content of 4.6%. The presence of H_2O rather than OH is indicated by an infrared transmission spectrum obtained for this cymrite (D. J. Bland, unpubl. data) which is also in agreement with the data of Carron et al. (1964).

In the sample BH11–26.8 m it is evident that both celsian and cymrite are compositionally very similar (fig. 4) and any reaction between them, as is proposed, would involve only H_2O loss or gain.

Discussion. The barium feldspars and muscovite are a product of metamorphic crystallization which post-dated formation of penetrative schistosity and

TABLE IV. *Electron-microprobe analyses of cymrite*

Analysis	1	2	3	4
Specimen	BH11–26.8 m			
SiO$_2$	32.97	32.55	31.75	32.71
Al$_2$O$_3$	25.08	24.83	24.50	24.88
TiO$_2$	0.10	0.03	0.13	0.18
Fe$_2$O$_3$*	0.06	0.06	0.14	0.03
MgO	n.d.	0.04	0.11	0.04
CaO	n.d.	n.d.	0.12	n.d.
BaO	36.84	35.78	36.07	37.37
Na$_2$O	0.19	0.20	0.12	0.19
K$_2$O	0.74	0.87	0.34	0.39
Total	95.98	94.36	93.28	95.79
Formula based on 8 oxygens.				
Si	2.100	2.101	2.083	2.096
Al	1.883	1.889	1.895	1.879
Ti	0.005	0.001	0.006	0.009
Fe	0.003	0.003	0.007	0.001
	3.991	3.994	3.991	3.985
Mg	0.0	0.004	0.011	0.004
Ca	0.0	0.0	0.008	0.0
Ba	0.920	0.905	0.927	0.938
Na	0.023	0.025	0.015	0.024
K	0.060	0.072	0.028	0.032
	1.003	1.006	0.989	0.998

* Total iron is expressed as Fe$_2$O$_3$.

crenulation cleavage. Atherton and Smith (1979) indicate the widespread presence of post-cleavage (post D$_3$) growth of plagioclase and other minerals in the Dalradian of Perthshire, and in view of its textural characteristics it is reasonable to equate the barium feldspar with this period.

Evidence apparently suggesting restricted Ba, Al, and K mobility during metamorphism is threefold. First, celsian pseudomorphs after a platy mineral may suggest muscovite replacement. Secondly, neoformation of euhedral porphyroblasts of celsian must involve local concentrating, and hence mobilization, of Ba and Al. Lastly, the presence of apparent growth and replacement zoning in celsian crystals suggest some mobility of barium and potassium during their formation.

No evidence of gross input of barium into the mineralized zone was reported by Coats et al. (1980), and any source of mobile barium must therefore have been already present. Baryte rock itself is not considered likely because no evidence has been found for reaction between baryte rock and other Ba-bearing rocks. The high thermal stability of baryte (e.g. Segnit and Gelb, 1970) given favourable fO_2-fS_2 conditions could explain its survival during amphibolite-grade metamorphism despite formation of a metamorphic fabric. It must

be concluded that the barium feldspar formed in rocks already enriched in Ba and that element mobility was at best very local. Similarly, Ba-muscovite is envisaged as having crystallized in more potassic, pelitic rocks originally enriched in Ba, this element occurring in clay minerals, zeolites or as very fine baryte grains (cf. Gurvich et al., 1979).

It is interesting to consider the possible role of cymrite in the petrogenesis. The mineral is known from little-metamorphosed black shales with chert (Soong and Olivecrona, 1975) and from strata-bound base-metal mineralization (Runnells, 1964; Aye and Strauss, 1975; D. Large, pers. comm.). Essene (1967) suggested that in barium-silicate lithologies at low metamorphic temperature and pressure the assemblage krauskopfite plus pyrophyllite could be stable, but with increasing temperature it would be replaced by cymrite plus quartz, while at still higher temperatures cymrite would give way to celsian. Granted that the quartz-celsian rock and schist at Aberfeldy were initially enriched in Ba during authigenesis-diagenesis, it is reasonable to suggest that cymrite was an important phase in these rocks during cleavage formation and that subsequent dehydration caused it to be almost completely replaced by celsian. This would account for the platy habit of much of the celsian whose within-grain compositional zonation only involves a degree of Ba–K segregation on an exceedingly local scale. It is thus not necessary to postulate general mobility of such relatively stable elements as Ba and K in rocks in which fine primary sulphide banding is preserved in detail.

Replacement of cymrite could also account for the feldspar interleaved with barian muscovite in the schist, and certain celsian porphyroblasts which show relict lamination. Such a hypothesis fails, however, to account for the more euhedral porphyroblasts in the schist and marble since there is no suggestion that they formed by replacement of cymrite. It is concluded that they represent growth of new crystals, and that this probably took place during the metamorphism. This is particularly apparent where coarse celsian in veinlets is concerned. However, it is also possible that some of this growth occurred at an earlier stage. Björlykke and Griffin (1973) described celsian growth by replacement of authigenic baryte crystals during diagenesis of shales in the Oslo graben. The suggestion might be that Ba-feldspar crystals in the schists at Aberfeldy have a similar origin. This would provide an explanation of the composite porphyroblasts depicted in fig. 3d which bear a textural resemblance to fragments observed in a quartzite specimen from Aberfeldy (CYR6, reported by Coats et al., 1981, Appendix III). These

are tabular fragments made up of a layer of quartz grains sandwiched between layers of baryte grains. Diagenetic replacement of the baryte in such fragment could yield composite feldspar 'porphyroblasts'. The presence of rare relict grains of baryte included in these porphyroblasts gives support to this mode of genesis.

The conclusion reached is that the apparent evidence of barium and potassium mobility during metamorphism is misleading and that the rocks developed for the most part by *in situ* metamorphic reactions. The cherty type of quartz-celsian rock is believed to have acquired its feldspar content early as evidenced by the lack of replacement texture from it. The foliated type is believed to have been cymrite-rich at one stage and to have initially developed from sediment containing a hydrous authigenic barium silicate such as harmotome.

Although this paragenesis appears to be unusual it is noted that celsian is associated with base-metal exhalative mineralization at Broken Hill (Segnit, 1946), Rosh Pinah in Namibia (Page and Watson, 1976) and other localities. In addition, an occurrence of cymrite and celsian in stratabound baryte mineralization at the Tom deposit in British Columbia has recently been reported (D. Large, pers. comm.), and it is possible that rocks of this type are more common than at present realized.

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