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The Pendennis peralkaline minette

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ABSTRACT. The Pendennis minette has an exceptionally high K_2O/Na_2O ratio and is strongly peralkaline. Its constituent minerals, which are described in detail, are sanidine, biotite, two carbonates (dolomite and ferroan magnesite), two amphiboles (riebeckite and a new variety, potassium magnesio-arfvedsonite), and quartz. The major and trace element composition of the minette indicates close affinities with the lamproitic lavas.

THE Pendennis minette occurs as a minor intrusion cutting the Devonian slates of the Gramscatho Beds on the foreshore at Pendennis Point in Falmouth, Cornwall. It is exposed for only a few tens of metres, mostly below high-tide level, but is the freshest and most accessible example of the handful of minette dykes which occur in various parts of SW England. The intrusion is tabular and varies in width and attitude, changing from an inclined sill to a vertical dyke in the short distance over which it is exposed (Hall, 1974). It is deeply eroded, in contrast to the resistant slates on either side, but despite its brown crumbly appearance at the surface it is perfectly fresh underneath.

The rock is fine-grained, with an average grain diameter of about 0.2 mm and some biotite flakes and feldspar laths up to 1 mm in length. The mineralogical composition is given below. The carbonate contents were measured directly by evolved gas analysis (Milodowski and Morgan, 1980) and the other minerals were calculated from the bulk composition of the rock and probe analyses of the individual minerals. The approximate weight percentage mode is:

Sandine	52	Magnesite	7
Biotite	13	Apatite	4
Quartz	12	Alkali amphiboles	1
Dolomite	10	Rutile	1

The accessory minerals which have been identified are baryte, chromite, haematite, ilmenite, hedenbergite, zircon, pyrite, a Cu sulphide, and a Cu-Fe sulphide. Magnetic and heavy-liquid separations were carried out in order to concentrate the minerals for identification and microprobe analysis.

A chemical analysis of the rock is given in Table I. Most major and trace elements were determined by plasma spectrometry, including the *RE* after an ion-exchange separation. The minette is essentially a basic igneous rock with a very high K_2O content. In many respects it is similar to other minettes, whose average composition is given in Table VII, but its K_2O/Na_2O ratio is more extreme and its Al_2O_3 content is lower. It is also rich in carbonate, which is interpreted here as an essential primary constituent and not as a result of secondary alteration. There is no petrographic evidence of secondary alteration; the country rocks are almost devoid of carbonates; there are no carbonate veins in either the minette or the country rocks; and the dolomite of the minette is zoned in the same way as the mica.

TABLE I. *Chemical analysis of the Pendennis minette* (*trace elements in ppm*)

		Norm			
SiO_2	50.69	Q	9.9	Ba	6306
TiO_2	1.58	Or	53.1	Ce	616
ZrO_2	0.26	Ks	0.4	Co	32
Al_2O_3	9.71	Ac	3.5	Cr	262
Fe_2O_3	3.06	Zr	0.4	Cu	117
FeO	3.37	Hy	7.7	Dy	8.2
MnO	0.13	Cc	6.1	Eu	6.5
MgO	6.07	Ms	8.1	Gd	18
CaO	5.28	Il	3.0	La	274
BaO	0.70	Mt	2.7	Li	96
SrO	0.27	Ap	4.1	Lu	0.3
Na_2O	0.47	H_2O	0.8	Nb	45
K_2O	9.22			Nd	264
P_2O_5	1.73			Ni	122
H_2O+	0.82			Pr	58
CO_2	6.91			Sc	18
				Sm	32
	100.27			Sr	2345
				V	128
				Y	36
				Yb	2.1
				Zn	99
				Zr	1894

The normative composition of the rock reveals its extremely peralkaline nature. Although the rock is oversaturated with silica, it is so deficient in alumina that potassium metasilicate appears as a normative constituent in addition to acmite. The peralkaline character is of course also revealed by the actual presence of alkali amphibole. In calculating this norm, it was necessary to make an allocation of CO_2 and MgO to magnesite because the CaO/CO_2 ratio was too low for all the CO_2 to be accommodated by normative calcite.

Mineralogy

Feldspar. Sanidine is the only feldspar in the rock. There is no plagioclase at all, not even as a perthitic intergrowth in the sanidine crystals. The analyses of the sanidine (Table II) show unusually low Na contents for igneous K-feldspar. There are two other notable features; richness in barium, and in ferric iron.

The high Ba is a natural consequence of the large amount of Ba in the magma, as indicated by the rock analysis. Although the BaO content of the feldspars is over 1 %, this corresponds to only 2 or 3 mole % celsian because of the high molecular weight of BaO. The substitution of divalent Ba for K is accompanied by a corresponding deficiency of Si below 3.00 in the cation proportions (per 8 oxygens) and the slight excess of Al(+Fe) over 1.00.

The contents of Fe are exceptionally and consistently high. The low proportions of Al (below 1.00) suggest that there is a genuine isomorphous substitution of Fe^{3+} for Al. Such a substitution requires either a high chemical potential of Fe^{3+} or a low chemical potential of Al, or both, during crystallization. At first sight, the high Fe_2O_3/FeO ratio of the rock analysis suggests that the oxidation state was the key factor, particularly since other magmas of similar composition with exceptionally high Fe^{3+}/Fe^{2+} ratios have also crystallized ferriferous sanidine. The wyomingites of the Leucite Hills in Wyoming (Carmichael, 1967) are a case in point. On the other hand, the low potential of Al may be equally significant. The rock is so peralkaline that the molecular proportion of Al_2O_3 is not only less than that of (K_2O+Na_2O), but less than that of K_2O alone. The atomic ratio of K : Al is 1 : 0.973, so that there is not enough Al to convert all the K into orthoclase or any other common K-bearing mineral, and substitution of Fe for Al provides the readiest means of enabling excess K to be accommodated within the normal rock-forming minerals.

In thin section the sanidine shows what appears to be zoning, in that the outer parts of individual crystals are infested with tiny and uniformly distributed haematite inclusions. It is possible that these are exsolution rather than alteration products. They are most abundantly present in the freshest rock samples, in which the feldspar is not otherwise altered, and are particularly conspicuous near the edges of feldspar crystals which are in contact with quartz (fig. 1). The quartz, mica, and fresh carbonates do not contain haematite inclusions of this kind.

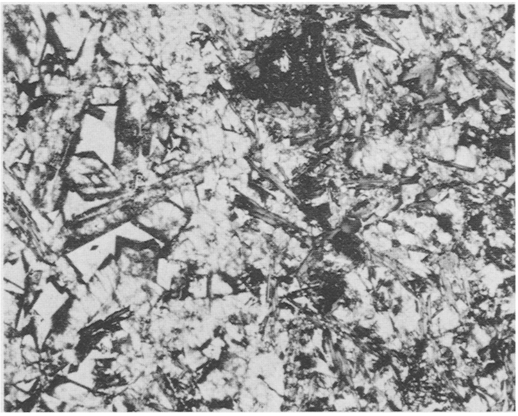

FIG. 1. Photomicrograph of the Pendennis minette in plane-polarized light (× 15). On the left-hand side of the picture are euhedral sanidines, dusted with minute inclusions of exsolved haematite near their rims, and enclosed by interstitial quartz. In the top centre of the picture is a large patch of anhedral ferroan magnesite (high relief, and darkened by limonitic alteration).

Micas. The mica in the Pendennis minette is brown and strongly coloured, and forms thin but very elongated flakes which are strongly zoned from pale centres to dark edges. Analyses of the micas are given in Table III. The pale centres of the flakes are phlogopite and the edges are Fe-rich biotite. The analyses given in the table are mostly of separated grains, and are over-representative of the Fe-rich compositions. It is only the outer 10% or so of most crystals which shows the strong darkening indicative of an Fe-rich composition, and the bulk of most crystals lies within the range that Deer *et al.* (1963) classify as phlogopite (Mg : Fe > 2 : 1). Nevertheless, even the phlogopitic cores of the crystals are as strongly coloured as the biotite in most other rocks, and would probably not be identified as phlogopite by optical examination alone. This strong colouring may be due to their relatively high Ti content, which is believed to be a factor in the coloration of biotite.

TABLE II. Electron microprobe analyses of sanidines from the Pendennis minette

	1	2	3	4	5	6	7	8	9	10
SiO_2	62.66	62.98	63.13	63.12	64.31	63.24	62.77	63.46	63.36	63.12
Al_2O_3	17.16	17.52	17.27	17.53	16.88	17.36	16.99	17.47	17.48	17.49
Fe_2O_3	2.48	2.35	2.30	1.98	3.05	2.18	2.72	2.02	1.87	2.22
CaO	0.00	0.00	0.00	0.10	0.00	0.10	0.19	0.14	0.00	0.06
Na_2O	0.70	0.76	0.66	0.68	0.66	0.50	0.63	0.50	0.69	0.41
K_2O	15.18	15.32	15.34	15.37	15.77	15.27	15.23	15.42	15.32	15.45
BaO	1.45	1.28	1.63	1.53	0.46	1.29	1.20	0.90	1.18	1.47
Total	99.63	100.21	100.33	100.31	101.13	99.94	99.73	99.91	99.90	100.22
Cations per 8 oxygens										
Si	2.959	2.953	2.963	2.959	2.977	2.967	2.960	2.970	2.970	2.960
Al	0.955	0.969	0.955	0.969	0.921	0.960	0.945	0.964	0.966	0.967
Fe	0.088	0.083	0.081	0.070	0.106	0.077	0.096	0.071	0.066	0.078
Ca	-	-	-	0.005	-	0.005	0.010	0.007	-	0.003
Na	0.064	0.069	0.060	0.062	0.059	0.046	0.058	0.046	0.062	0.037
K	0.915	0.916	0.918	0.919	0.931	0.914	0.916	0.921	0.916	0.924
Ba	0.027	0.023	0.030	0.028	0.008	0.024	0.022	0.016	0.022	0.027

TABLE III. Electron microprobe analyses of micas from the Pendennis minette

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	39.57	41.32	40.31	40.22	39.42	38.01	38.14	37.71	37.10	36.81	36.27	37.32
TiO_2	3.59	3.79	3.72	4.05	4.13	4.77	4.57	6.38	6.50	6.36	7.23	6.39
Al_2O_3	11.78	12.42	11.76	11.93	11.71	11.20	11.39	11.32	10.92	10.97	10.66	10.20
Cr_2O_3	0.50	0.42	0.67	0.00	0.07	0.00	0.05	0.01	0.16	0.03	0.08	0.05
FeO	5.30	5.60	5.51	6.36	7.09	12.67	15.59	17.88	18.05	18.66	20.16	20.36
MnO	0.06	0.00	0.01	0.05	0.05	0.19	0.22	0.26	0.19	0.24	0.32	0.13
MgO	22.77	23.34	22.89	22.29	21.79	17.17	15.11	13.13	12.53	12.35	10.50	10.80
CaO	0.00	0.06	0.17	0.09	0.04	0.01	0.10	0.00	0.06	0.06	0.02	0.16
Na_2O	0.42	0.41	0.41	0.26	0.26	0.00	0.53	0.38	0.30	0.10	0.60	0.36
K_2O	10.03	10.36	10.18	10.23	10.30	9.82	10.14	9.73	9.39	9.50	9.46	9.36
BaO	0.66	0.43	0.60	0.30	0.58	0.94	0.82	1.56	1.97	1.70	1.70	1.26
Total	94.68	98.15	96.23	95.78	95.44	94.78	96.66	98.36	97.17	96.78	97.00	96.39
Cations per 22 oxygens												
Si	2.874	2.886	2.882	2.888	2.864	2.864	2.864	2.822	2.824	2.818	2.801	2.879
Al	1.009	1.022	0.991	1.010	1.003	0.994	1.008	0.998	0.980	0.990	0.970	0.928
Ti	0.196	0.199	0.200	0.218	0.226	0.270	0.258	0.359	0.372	0.366	0.420	0.371
Cr	0.029	0.024	0.038	0.000	0.004	0.000	0.002	0.000	0.010	0.002	0.005	0.004
Fe	0.322	0.326	0.330	0.382	0.431	0.798	0.979	1.120	1.149	1.194	1.302	1.314
Mn	0.004	0.000	0.000	0.003	0.003	0.012	0.014	0.016	0.012	0.016	0.022	0.008
Mg	2.466	2.430	2.440	2.386	2.360	1.928	1.692	1.465	1.422	1.409	1.208	1.242
Ca	0.000	0.004	0.013	0.007	0.003	0.001	0.008	0.000	0.005	0.006	0.002	0.014
Na	0.058	0.055	0.057	0.036	0.036	0.000	0.077	0.054	0.044	0.015	0.090	0.054
K	0.930	0.923	0.928	0.938	0.954	0.944	0.972	0.930	0.912	0.928	0.932	0.921
Ba	0.019	0.012	0.017	0.008	0.016	0.028	0 024	0.046	0.058	0.051	0.052	0.038
Σtet.	3.883	3.908	3.873	3.898	3.867	3.858	3.872	3.820	3.804	3.808	3.771	3.807
Σoct.	3.017	2.979	3.008	2.989	3.024	3.008	2.945	2.960	2.965	2.987	2.957	2.939
Σint.	1.007	0.994	1.015	0.989	1.009	0.973	1.081	1.030	1.019	1.000	1.076	1.027

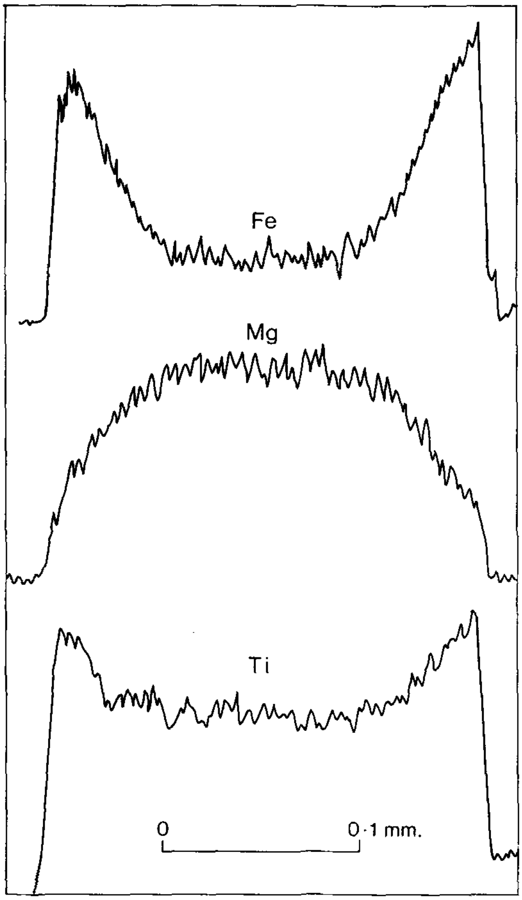

FIG. 2. Electron probe line-scan across a strongly zoned, euhedral biotite crystal.

A line-scan across a single mica crystal sectioned parallel to the cleavage (fig. 2) shows the magnitude of the compositional zoning. In addition to Fe, the margins of the crystals are also enriched in Ti, Mn, and Ba. In contrast, the margins are poorer than the cores in Cr as well as Mg. These variations follow the normal trends of trace element distribution during fractionational crystallization.

The Al contents of these micas are very low. When the cation proportions are calculated on the basis of 22(O), the sum of (Si + Al) falls below the ideal tetrahedral site occupancy of 4.00. There is thus no evidence of Al in octahedral sites, and a possibility that Fe may occupy some of the tetrahedral sites. This deficiency in Al is considered to be a reflection of the peralkaline magma composition. The Fe-rich margins of the biotite flakes (which presumably grew last) are more Al-deficient than the cores, suggesting that the peralkalinity of the melt increased as crystallization proceeded.

Amphiboles. Amphibole is a minor and inconspicuous constituent of the rock. It occurs in very small grains which almost always consist of an intergrowth with one or more of the other rock-forming minerals, including quartz, feldspar, mica, and carbonates, perhaps an indication of a replacive mode of crystallization. The amphibole is visibly heterogeneous, varying both in habit and colour. All the crystals have a short prismatic shape, but some have such an intense closely spaced cleavage as to have a virtually fibrous internal structure. Electron-probe examination shows that the fibrous amphibole is commonly intergrown with, or even largely replaced by, silica. This recalls the replacement of fibrous crocidolite by silica in the material known as tiger's eye. All the crystals are strongly pleochroic from blue (along the prism elongation) to a pale mauvy-grey (at right angles to the prism elongation), but some are much more highly coloured than others, the blue colour ranging from barely visible to intense. No distinction could be made optically between different amphibole varieties.

Probe analyses showed that although there is variation both between and within individual crystals, the compositions of the amphiboles cluster into two distinct and separate compositional ranges. One set of compositions may be classified as riebeckite, and the other set corresponds to a new, previously undescribed variety of amphibole for which an appropriate name is potassium magnesio-arfvedsonite. The electron probe analyses given in Tables IV and V were recalculated on the basis of Si + Ti + Al + Fe + Mn + Mg = 13.00 This basis was chosen in preference to using 23(O) or 24(O) because Fe^{2+}/Fe^{3+} and H_2O+ were not measured by the probe, and in minerals with high iron content the proportion of oxygen to cations is strongly dependent on the assumed oxidation state of the iron. In the case of the analyses given in Table IV (but not Table V) an assumption of 23(O) on a water-free, all-ferrous basis would lead to improbably high Si proportions of 8.1 to 8.3. It is therefore likely that an appreciable proportion of the iron in the riebeckites is in the ferric state.

The compositions of the alkali amphiboles may be compared with the following ideal end-member formulae (Leake 1978):

Magnesio-riebeckite	□	Na_2	$Mg_3\ Fe_2^{III}$	$Si_8O_{22}(OH)_2$
Magnesio-arfvedsonite	Na	Na_2	$Mg_4\ Fe^{III}$	$Si_8O_{22}(OH)_2$
K-magnesioarfvedsonite	K	Na_2	$Mg_4\ Fe^{III}$	$Si_8O_{22}(OH)_2$
K-richterite	K	Na Ca	Mg_5	$Si_8O_{22}(OH)_2$

The *A*-site in the crystal structure of amphiboles, which in most calcic amphiboles and in riebeckite remains empty, is occupied by Na in arfvedsonite and K in potassium richterite. The large cation summations of the recalculated analyses in Tables

IV and V range from 2.1–2.4 in the analyses identified as riebeckite, and from 2.9–3.2 in those identified as potassium arfvedsonite, with no examples in the range 2.4–2.9. In those crystals with fully occupied *A* positions (i.e. the arfvedsonites), the number of K atoms per formula unit ranges from 0.59 to 0.76, so that K must be the principal occupant of the *A* sites. Fig. 3 shows the amphibole compositions in terms of *A*-site occupancy.

Besides the main compositional hiatus there are several other chemical differences between the riebeckites and K-arfvedsonites. The latter are distinctly lower in Si, Al, and Fe, and higher in Ca, Mg, Mn, and Ti. The relationship between the K and Ti contents is shown in fig. 4.

Whereas riebeckite and arfvedsonite are well-established amphibole varieties, potassium arfvedsonite has only recently been reported. Velde (1975) described a potassium arfvedsonite near to the Fe end-member composition (under the name 'potassium riebeckite'), but no potassium magnesio-arfvedsonite has yet been reported. The only well-known amphibole variety to contain K as an essential constituent (i.e. as the principal occupant of the *A* structural site) is potassium richterite, but this is a Ca-bearing amphibole, and as can be seen from Tables IV and V the amphiboles in the Pendennis rock are essentially Ca-free.

Although the potassium magnesio-arfvedsonite is a new variety of amphibole, related amphiboles are known to occur in rocks of similar composition. The ultra-potassic basic lavas commonly contain potassium richterite, including those of the Leucite Hills, West Kimberley, and Jumilla (Sahama 1974); indeed this is the main occurrence of K-richterite. Other minettes have been found to contain normal non-potassian arfvedsonite, for example the Jersey minette described by Velde (1971), and the one reported occurrence of a potassium ferro-arfvedsonite (Velde, 1975) is in a lamproite. Two particular features of the Pendennis minette may have led to its particular amphibole composition: the high K/Na ratio (much higher than the Jersey rock) and the high carbonate content. Unlike the ultrapotassic lavas, the intrusive minette has retained its volatile constituents including CO_2 so that virtually all the Ca is tied up in carbonates and apatite, leaving almost no Ca for the amphiboles.

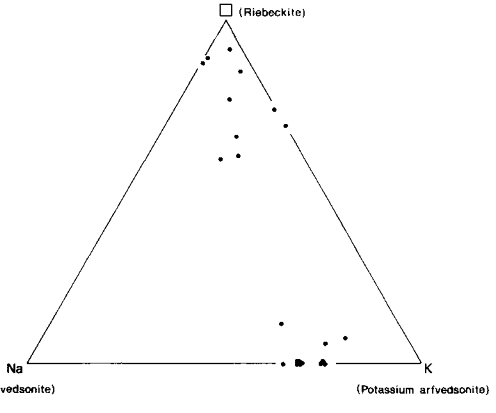

FIG. 3. Compositions of the alkali amphiboles (Tables IV and V) expressed in terms of *A*-site occupancy. In assigning cations to *A*- and *B*-sites it was assumed that the *B*-sites would be filled first by Ca and then by Na, and that any deficiency in (Ca+Na+K) below a total of 3.000 would correspond to *A*-site vacancies.

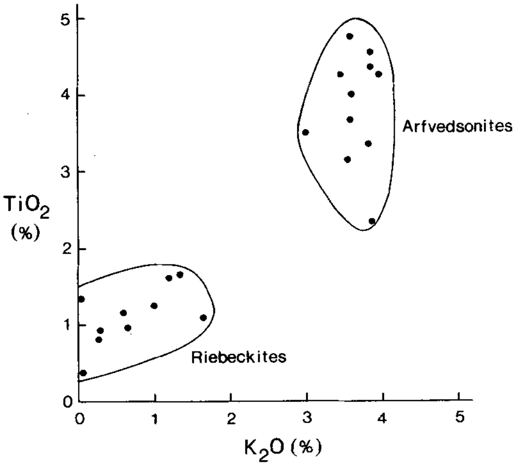

FIG. 4. Plot of K_2O against TiO_2 in the alkali amphiboles, showing the hiatus between riebeckite and arfvedsonite compositions.

Carbonates. The rock contains two carbonate minerals; dolomite and ferroan magnesite. In thin section these are indistinguishable, but electron-probe investigation suggests that they are distributed differently. The petrographic habits of carbonate are: (1) small well-formed crystals which are mainly surrounded by sanidine, against which they are euhedral—these may be either dolomite or magnesite; (2) interstitial grains, often associated with quartz, against which sanidine is euhedral—these appear to be dolomite; and (3) large irregular aggregates with no euhedral boundaries against any other mineral, possibly replacive—this carbonate is invariably magnesite. In slightly weathered samples of the rock, the ferroan magnesite is associated with a limonitic alteration product which enables it to be distinguished from dolomite, and on this basis it appears that magnesite is the major constituent of the large carbonate patches, whereas dolomite constitutes the majority of the other two habits.

Analysis of the carbonate minerals using the energy-dispersive electron probe presented special difficulties. Neither carbon nor oxygen could be determined directly, and the computer software of the energy-dispersive system which was used only allowed for the presence of one unanalysed element, normally oxygen. Thus corrections to the measured intensities could not be correctly calculated. This was overcome by using previously analysed samples of well crystallized dolomite, siderite and magnesite to obtain empirical ZAF correction factors, which were then applied to the intensity data to obtain the analyses quoted in Table VI.

The most interesting feature of the carbonate compositions is that the magnesites have a much higher Fe/Mg ratio than the dolomites (fig. 5). The dolomites are Mg-rich, approximating to $Ca(Mg_{0.9}\,Fe_{0.1})(CO_3)_2$. The magnesites are more

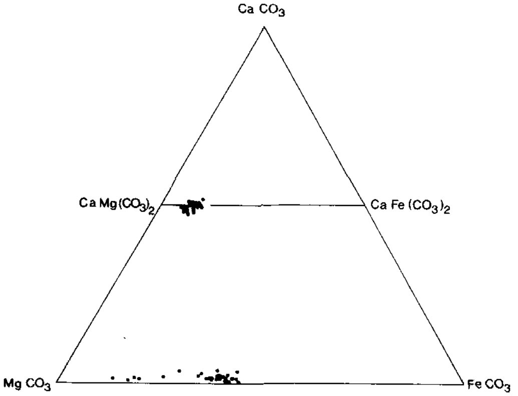

FIG. 5. Compositions of the carbonate minerals in terms of the principal end-members. Mn is included with the Fe component.

TABLE IV. Electron microprobe analyses of riebeckites from the Pendennis minette

	1	2	3	4	5	6	7	8	9	10
SiO_2	53.10	53.89	52.82	53.36	54.14	53.92	54.03	54.00	53.96	53.29
TiO_2	1.09	1.64	1.16	1.60	1.23	0.91	0.80	1.32	0.37	0.97
Al_2O_3	1.35	0.67	0.64	0.65	0.61	1.34	0.85	0.57	0.57	0.59
FeO	20.52	21.28	21.26	21.42	22.39	22.57	22.58	22.70	23.48	23.76
MnO	0.08	0.11	0.23	0.17	0.13	0.00	0.20	0.09	0.10	0.12
MgO	10.19	8.92	10.07	8.86	8.79	9.52	9.32	8.84	8.60	8.24
CaO	0.17	0.26	0.25	0.23	0.14	0.10	0.23	0.17	0.18	0.28
Na_2O	6.84	6.79	6.93	7.32	7.64	7.16	7.41	7.31	7.19	7.11
K_2O	1.64	1.33	0.60	1.19	1.00	0.29	0.28	0.01	0.06	0.64
Total	94.98	94.89	93.96	94.80	96.07	95.81	95.70	95.01	94.51	95.00
Cation proportions										
Si	7.852	8.044	7.855	8.010	8.023	7.854	7.930	7.987	8.021	7.966
Ti	0.121	0.183	0.130	0.181	0.137	0.099	0.089	0.147	0.041	0.108
Al	0.234	0.117	0.112	0.115	0.105	0.231	0.147	0.099	0.099	0.105
Fe	2.538	2.657	2.644	2.689	2.776	2.750	2.772	2.807	2.919	2.970
Mn	0.010	0.014	0.029	0.021	0.017	0.000	0.025	0.012	0.014	0.015
Mg	2.245	1.984	2.231	1.984	1.943	2.066	2.038	1.949	1.907	1.836
Ca	0.026	0.041	0.039	0.037	0.022	0.014	0.036	0.027	0.028	0.046
Na	1.959	1.965	1.999	2.130	2.195	2.021	2.108	2.095	2.073	2.062
K	0.309	0.254	0.114	0.228	0.188	0.054	0.052	0.002	0.012	0.123
Ca+Na+K	2.294	2.260	2.152	2.395	2.405	2.089	2.196	2.124	2.113	2.231

Total iron is given as FeO, and the cation proportions are calculated so that Si + Ti + Al + Fe + Mn + Mg = 13.000.

varied. Most of the magnesite is highly ferroan, approximating to $(Mg_{0.6}Fe_{0.4})CO_3$, but in areas of intense limonitic alteration the iron contents fall to about $(Mg_{0.9}Fe_{0.1})CO_3$. Evidently oxidation of the primary ferroan magnesite takes place by removal of Fe without the residual magnesium carbonate being dissolved away. Analyses 7 and 8 in Table VI are of magnesites associated with the limonitic alteration. The dolomites also show some zonation, with the outer parts of crystals being slightly more Fe-rich than the cores.

Discussion

Minette's compositions cover a very wide range, extending from undersaturated to oversaturated with respect to silica, and from peralkaline to peraluminous. The oversaturated, peralkaline nature of the Pendennis minette is rather unusual. The majority of minettes are subaluminous or peraluminous and although some are peralkaline the latter are not usually silica-saturated. It can be seen from Table VII that the peralkaline minettes (e.g. Pendennis, Sisco, Holsteinsborg) have not only a high (K+Na)/Al ratio but also a very much higher than average K/Na ratio.

The Pendennis minette is one of a large number of minette dykes of similar age (late Carboniferous or early Permian) which occur in a region stretching from the south-west of England to the north-west coast of Normandy. They are most abundant in the Channel Islands, and their average composition in Jersey (Table VII) also shows a tendency towards high K_2O and low Na_2O.

There is a less clear relationship between the Pendennis minette and the Permian lavas of the Exeter volcanic series, whose nearest exposures are about 100 km to the north-east. These may well be extrusive representatives of the same magmatic episode, and some of the lavas do share the high K_2O/Na_2O ratios and similar trace element characteristics, but in other respects they are quite

TABLE V. Electron microprobe analyses of arfvedsonites from the Pendennis minette

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	53.49	52.39	52.38	51.68	53.23	52.35	52.07	52.39	52.08	51.60	51.57
TiO_2	3.36	2.32	4.74	4.24	4.25	4.35	4.54	4.00	3.68	3.17	3.50
Al_2O_3	0.23	0.12	0.09	0.13	0.36	0.34	0.19	0.29	0.33	0.30	0.14
FeO	12.83	12.69	13.35	14.77	15.43	16.10	16.20	16.73	18.04	18.29	18.24
MnO	0.35	0.37	0.38	0.42	0.59	0.55	0.45	0.53	0.46	0.55	0.50
MgO	13.58	13.64	12.41	10.90	10.46	10.65	10.58	10.77	10.35	10.12	9.77
CaO	1.22	1.70	0.86	0.79	1.14	1.04	1.04	0.49	0.71	0.92	0.72
Na_2O	7.03	7.06	7.87	7.35	6.73	7.31	7.35	7.72	8.22	7.44	7.31
K_2O	3.81	3.87	3.58	3 47	3.96	3.85	3.85	3.61	3.59	3.53	2.99
Total	95 90	94.16	95.66	93.75	96.15	96.54	96.27	96.53	97.46	95.92	94.74
Cation proportions											
Si	7.942	7.962	7.915	8.001	8.061	7.929	7.925	7.899	7.861	7.875	7.924
Ti	0.376	0.265	0.539	0.494	0.484	0.496	0.520	0.454	0.417	0.364	0.404
Al	0.041	0.021	0.016	0.023	0.063	0.060	0.034	0.051	0.059	0.054	0.026
Fe	1.593	1.613	1.687	1.912	1.954	2.039	2.062	2.109	2.276	2.335	2.343
Mn	0.044	0.048	0.048	0.055	0.075	0.070	0.058	0.068	0.059	0.072	0.065
Mg	3.005	3.090	2.795	2.515	2.362	2.405	2.400	2.420	2.328	2.301	2.238
Ca	0.194	0.276	0.140	0.131	0.184	0.168	0.170	0.079	0.115	0.150	0.119
Na	2.024	2.081	2.305	2.206	1.977	2.146	2.168	2.258	2.406	2.201	2.179
K	0.722	0.751	0.691	0.685	0.765	0.744	0.747	0.695	0.691	0.688	0.585
Ca+Na+K	2.940	3.108	3.136	3.022	2.926	3.058	3.085	3.032	3.212	3.039	2.883

Total iron is given as FeO, and the cation proportions are calculated so that Si + Ti + Al + Fe + Fe + Mn + Mg = 13.000.

TABLE VI. Electron microprobe analyses of magnesites (1-8) and dolomites (9-15) from the Pendennis minette

	Weight %				Cation %			
	FeO	MnO	MgO	CaO	Fe	Mn	Mg	Ca
1	30.88	1.40	22.34	0.11	42.7	2.0	55.1	0.2
2	29.36	1.19	23.82	0.38	39.9	1.7	57.8	0.7
3	28.38	1.07	24.92	0.71	37.9	1.4	59.4	1.2
4	27.88	1.36	24.06	1.03	38.0	1.9	58.4	1.8
5	28.38	1.07	24.92	0.71	37.3	1.4	59.8	1.4
6	26.72	1.09	25.72	0.58	35.9	1.5	61.6	1.0
7	20.90	0.51	29.17	2.29	27.4	0.7	68.1	3.8
8	10.25	0.47	39.19	0.82	12.5	0.5	85.7	1.3
9	6.38	0.37	17.32	29.20	8.5	0.5	41.1	49.9
10	6.37	0.36	18.23	28.53	8.4	0.5	42.9	48.2
11	5.89	0.20	18.29	29.29	7.8	0.3	42.8	49.2
12	5.03	0.26	18.82	28.65	6.6	0.4	44.4	48.6
13	4.79	0.21	18.96	29.42	6.3	0.3	44.2	49.3
14	4.10	0.11	19.19	29.51	5.4	0.2	44.9	49.6
15C	5.12	0.18	18.33	29.60	6.8	0.2	43.0	50.0
15M	6.82	0.25	16.77	28.93	9.2	0.3	40.4	50.1

Dolomites 15C and 15M are from the centre and margin of the same crystal.

TABLE VII. Comparison of the Pendennis and other minettes

	1	2	3	4	5
SiO_2	50.69	52.84	51.17	56.23	49.60
TiO_2	1.58	1.10	1.36	1.14	4.15
Al_2O_3	9.71	12.30	13.87	12.06	8.64
Fe_2O_3	3.06	3.01	3.27	1.91	2.21
FeO	3.37	3.80	4.16	2.91	4.75
MgO	6.07	8.20	6.91	6.90	6.32
CaO	5.28	7.08	6.58	3.48	4.32
Na_2O	0.47	1.61	2.12	1.03	1.60
K_2O	9.22	6.82	5.49	10.00	10.03
P_2O_5	1.73	1.47	-	0.79	1.26
H_2O^+	0.82	1.64	2.42	1.56	1.12
CO_2	6.91	3.91	>1.32	0.41	2.93

1. Pendennis Point.
2. Jersey (average of 18 Hercynian minettes given by Lees, 1974).
3. All minettes (average of 64 analyses given by Métais & Chayes, 1963).
4. Sisco, Corsica (analysis no. 1 on p. 216 of Velde, 1967).
5. Holsteinsborg, Greenland (no. 5652 - the most potassic lamprophyre analysed by Scott, 1979).

different (Table VIII). The Exeter lavas are rich in Al_2O_3 and are not peralkaline, and those that are comparable to the minette in SiO_2 and alkali contents have much higher Fe/Mg ratios. There is a much closer resemblance between the Pendennis minette and some of leucite-bearing lavas (orendites and wyomingites) of the Leucite Hills in Wyoming and the West Kimberley district of Western Australia.

The role of CO_2 in lamproitic rock types is especially interesting. It is clear that a magma with the composition of the Pendennis minette could not retain its carbonate content if it were erupted at the surface. The decarbonation temperatures of the carbonates in this rock (magnesite 630 °C, dolomite 750 °C) are a long way below the likely solidus temperature at atmospheric pressure. An effusive equivalent of the Pendennis minette might therefore be expected to contain Ca-Mg-silicates in place of the dolomite and magnesite. If the chemical analysis of Table I is recalculated into a norm on a CO_2-free basis, the oversaturation in silica is almost eliminated (normative quartz is reduced to less than 0.5%). It may be predicted that some of the lamproitic lavas which are normatively and actually leucite- and nepheline-bearing might not have been so if their magmas had contained as much CO_2 as this minette, and if they had been emplaced under plutonic rather than volcanic conditions. It might well be that many apparently CO_2-poor lamproite lavas, including the orendites and the Exeter lavas whose compositions are shown in Table VIII, crystallized from a magma which was much more CO_2-rich than the erupted rocks suggest.

The origin of minettes has recently been reviewed by Bachinski and Scott (1979). They listed various lines of evidence for believing that minette magmas originate in the mantle and that crustal materials have not been involved in their development. Similar conclusions have been reached by other recent workers. The occurrence and composition of the Pendennis minette are consistent with this view. The terrain in which the Pendennis dyke is emplaced is built from a Palaeozoic sedimentary succession in which argillaceous compositions predominate. The Cornubian granites, which also intrude this terrain, have isotopic and chemical features indicative of derivation by crustal melting, and are exceptionally peraluminous. Despite this, and despite the presence in the minette of some argillaceous xenoliths, the minette magma remains peralkaline, and there seems no way that it could have remained so if it were derived from, or contaminated by, melt fractions of its exceptionally Al-rich surroundings.

It is not known whether minette can be a primary product of melting in the mantle. Various ways have been suggested by which minettes could be derived from more primitive magmas by crystal fractionation or liquid immiscibility. It is, however, likely that the peralkalinity of the Pendennis minette is a primary feature, because it could not be developed by fractionation of any of the mineral

TABLE VIII. Comparison of the Pendennis minette with the compositions of lamproitic lavas

	Pendennis minette		Exeter lavas		Leucite Hills lavas	
	Actual	CO_2-free	PV8	PV21	Orendite	Wyomingite
SiO_2	50.69	54.29	50.08	46.80	54.12	52.40
TiO_2	1.58	1.69	2.03	1.95	2.44	2.28
Al_2O_3	9.71	10.40	14.82	18.48	9.74	10.57
Fe_2O_3	3.06	3.28	11.61	13.87	3.42	3.05
FeO	3.37	3.61			0.80	1.44
MgO	6.07	6.50	3.02	3.27	7.74	6.78
CaO	5.28	5.66	3.93	0.43	3.69	4.57
BaO	0.70	0.75	0.57	0.06	0.53	0.78
Na_2O	0.47	0.50	1.23	0.26	1.24	1.32
K_2O	9.22	9.88	9.49	9.24	11.54	11.03
P_2O_5	1.73	1.85	2.47	0.28	1.40	1.74
CO_2	6.91	-	0.42	0.07	-	-

The analyses of the Exeter lavas are from Cosgrove (1972); the compositions of orendite and wyomingite are the averages of four analyses of each calculated by Sahama (1974).

TABLE IX. Comparison of the trace element contents (ppm) of Hercynian ultrapotassic rocks with basalts and kimberlites

	Tholeiitic *basalt*	Alkali *basalt*	Kimberlite	Pendennis minette	Exeter lava PV8	Jersey minettes
Ba	246	528	1000	6306	5146	6027
Ce	33	105	200	616	198	45
La	15	54	150	274	97	316
Li	7	12	25	96	-	66
Nd	19	49	85	264	58	196
Sr	328	530	740	2345	1079	2034
Zr	137	189	250	1894	872	647
Co	48	43	77	32	-	37
Cr	168	202	1100	262	-	574
Cu	90	85	80	117	33	50
Nb	13	69	110	45	30	21
Ni	134	145	1050	122	333	414
Sc	30	20	15	18	-	19
V	251	213	120	128	69	140
Y	28	33	22	36	39	93
Zn	100	108	80	99	51	-

Average trace element contents of basalts and kimberlites are from Wedepohl and Muramatsu (1979). Data for the Exeter lava and Jersey minettes are from Cosgrove (1972) and Lees (1974) respectively.

phases actually present in the rock, none of which has an atomic ratio Al/K greater than 1.0.

A widely favoured explanation for the origin of potassic mafic magmas is that they formed by melting of locally K-metasomatized mantle, generally assumed to have the mineralogy of a phlogopite-bearing lherzolite. Optimum conditions for the production of a peralkaline melt from such a material would be:

(1) The phlogopite in the source rock should have Al/K less than 1.0. Actual phlogopites from metasomatized xenoliths in kimberlite do not have this characteristic (Harte and Gurney, 1975), but exceptionally low Al/K ratios (< 1.0) are found in the phlogopites of the MARID suite xenoliths (Dawson and Smith, 1977).

(2) During partial melting the phlogopite in the source material should be consumed close to the solidus, while leaving aluminous phases such as garnet in the residue (at low degrees of partial melting). A low degree of partial melting and a garnetiferous residuum would also be an appropriate explanation for the steep, light *REE*-enriched rare earth pattern (fig. 6). The experiments of Eggler and Wendlandt (1978, fig. 68) on the melting of kimberlite suggest that the higher the total pressure, the more likely it would be for garnet to remain in the residue while phlogopite entered the melt.

The Pendennis minette, like the Exeter lavas and the Jersey minettes (Table IX), shows the typical trace element characteristics of ultrapotassic rocks, namely enrichment in such 'mantle-incompatible' elements as P, Ba, Sr, and *REE*. This is reflected in the abundance of minor and accessory minerals, including several percent of apatite, and the occurrence of baryte, which is unusual in an igneous rock, although it occurs in some kimberlites. The *RE* pattern, shown in fig. 6, is very strongly enriched in the light *RE* and shows only a slight negative

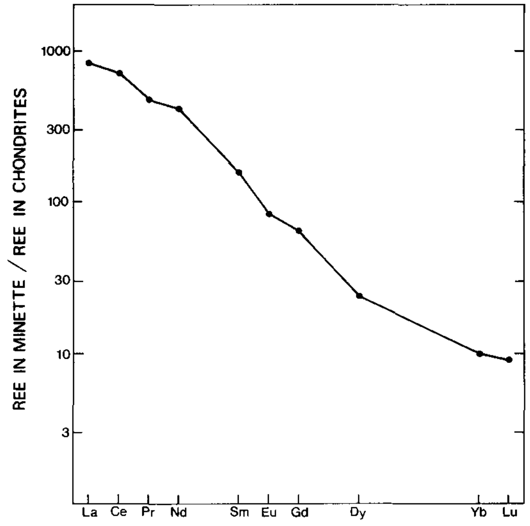

FIG. 6. Chondrite-normalized *RE* abundance pattern of the Pendennis minette.

Eu anomaly, if any. This is a very similar pattern to that found by Bachinski and Scott (1979) in New Brunswick minettes, and strongly resembles the light *REE*-enriched patterns of kimberlites and carbonatites.

The large-ion lithophile elements (Ba, Li, Sr, Zr, *REE*), which are enriched in alkali basalts compared with tholeiites, are enriched in the minette to an extreme degree. Some of the elements which are depleted in alkali basalts relative to tholeiites (Co, Sc, V) are more depleted in the minette. Wedepohl and Muramatsu (1979) have interpreted the progression of trace element concentrations from kimberlite to alkali basalt to tholeiite as a sequence reflecting increasing degree of partial melting in the mantle source material. For the large-ion lithophile elements the concentrations in the minette would imply an even smaller degree of partial melting than for kimberlite, but it is unlikely that this could be the only factor involved. Bachinski and Scott (1979) recently offered an explanation for the differences between minettes and the obviously related ultrapotassic lavas and kimberlites in terms of H_2O/CO_2 ratio during melting. They suggested that melting of K-metasomatized mantle might give rise to a minette magma if the H_2O/CO_2 ratio was high, but to the more undersaturated magmas (e.g. kimberlite, carbonatite) if the H_2O/CO_2 ratio was low. The high carbonate content of the Pendennis minette, and of those described by Scott (1979) from west Greenland, does not provide any support for such an explanation.

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