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Geochemistry of the Isles of Scilly pluton

M. STONE and C.S. EXLEY

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Four granite types, (1) Early inclusions, (2) Outer granite, (3) Inner granite, and (4) Late micrograntes and aplites, provide a time sequence in biotite and tourmaline bearing granites that shows progressive evolution in chemistry in terms of overall increase in a trace-alkali oxide/element suite (Li, Rb, Cs, F and Sn) and decrease in a femic suite (TiO_2, FeO, CaO, Zr, Sr, V, Ba, Ce, U and Th). Statistical comparison using Mann-Whitney tests and discriminant analysis clearly separates types 1, 2 and 3, but 3 and 4 have many features in common.

An origin by partial melting of metagreywacke and pelitic lower crust is consistent with the S-type characteristics and indicated by comparison with the other plutons of the batholith for which isotope data are available. Most of the biotite and much plagioclase is likely to be modified restite, whilst andalusite and accessory minerals are probably largely derived from source. 'Cleansing' by removal of these minerals during transit is considered to be responsible for most of the trend patterns and correlations in the femic suite of oxides/elements. The monazite LREE pattern (Carnmenellis) is followed broadly by both biotite and host rocks and, as in the case of the Carnmenellis granite, that in biotite is considered to reflect the REE pattern in the original anatectic melt or the metamorphosed source rocks undergoing melting, whilst flattening of the LREE slope results from removal of both biotite and monazite.

M. Stone, Department of Geology, University of Exeter, Exeter EX4 4QE.C.S. Exley, Department of Geology. University of Keele, Staffs STS 5BG.

Introduction

The Isles of Scilly are situated some 45km WSW of Land's End (GR SW0810-960 0500-180) and are composed almost wholly of granite. Maps published by the BGS (1/50000 Sheet 357/360, 1974), Jones (1963) and Dangerfield and Hawkes (1981) show an inner finer-grained granite surrounded by a more prominent outer coarser-grained granite (corresponding with types 2 and 3 below, respectively). Previously published work on the Isles of Sckilly pluton has been concerned solely with field relations and petrography. This paper sets out to supplement this earlier petrographic work with new chemical data, to compare rock types and examine variation patterns in an attempt to provide a basis for petrogenetic interpretation.

Four granite types coincide with those previously noted. (1) Medium-grained biotite-granite `enclaves' (ovoid inclusions of Barrow 1906; stage 1 of Osman 1928), petrographically similar to the enclosing outer granite, but having a finer-grained matrix, are commonly tabular, ovoid or rectangular in plan and range in size from several cm to over a metre across. Contacts with the host rocks are usually sharp but are sometimes blurred by a gradual increase in K-feldspar towards the margins. (2) An outer megacrystic biotite granite (G1 of Jones 1963; stage 2 of Osman) accounts for most of the exposed outcrop. Usually coarse-grained with small megacrysts of K-feldspar, it is grouped with the `outer' granite of the Carnmenellis pluton and the principal granite of the Bodmin Moor pluton by Dangerfield and Hawkes (1981). (3) A medium-grained central granite (G2 of Jones; stage 3 of Osman) is less megacrystic, has less biotite and commonly more tourmaline that the outer granite: it appears to be transitional into the latter on Tresco. According to Dangerfield and Hawkes (1981), this granite is the sole representative of its type in the Cornubian batholith. (4) Biotite microgranite sheets and dykes (stage 4 of Osman) containing biotite and/or tourmaline, and aplite dykes with or without pegmatite (stage 5 of Osman) cut the outer granite. The strong resemblance between many fine-grained granite veins and the inner granite, together with the rarity of such veins cutting the latter, led Barrow (1906) to suggest that most of the veins are contemporaneous with and a part of the inner granite, but Osman (1928) refers also to later microgranite and aplite. Field relations observed in this study and chemical similarity do not permit distinction between microgranites and aplites.

Chemical data - minerals

Biotite. Average microprobe analyses and formulae of biotites from the biotite granites (Table 1, cols 1-4) compare with those of other biotites in the Cornubian batholith (Stone *et al.* 1988). All have octahedral Al > I and Fe/(Fe+Mg) > 0.5, consistent with siderophyllite. With a formula Li content (Stone *et al.* 1988) between 0.5 and 1, these are lithian siderophyllites.

Table 1. Microprobe analyses of micas.

	Biotites				Muscovites			
Column	1	2	3	4	5	6	7	8
Rock	1	2	3*	4	1	2	3*	4
Wt%								
SiO_2	35.9	35.78	35.44	34.51	47.41	47.42	48.67	46.33
TiO_2	2.67	2.66	3.03	2.87	0.79	0.77	0.67	0.28
$Al2O_3$	20.12	20.01	19.85	20.39	34.25	33.75	35.39	35.04
tFeO	21.54	21.63	21.81	24.52	1.91	1.86	1.28	2.01
MnO	0.5	0.45	0.33	1.22	0.01	tr	nd	nd
MgO	4.74	4.29	5.46	1.93	1.05	0.94	0.72	0.47
CaO	0.02	0.01	nd	nd	0.02	tr	0.03	nd
Na_2O	0.03	0.07	0.07	nd	0.53	0.51	0.55	0.25
K_2O	9.41	9.3	9.22	9.05	9.93	9.85	9.42	10.06
Rb_2O	0.15	0.19	0.11	0.13	0.06	0.06	0.02	0.01
Cs_2O	0.04	0.07	0.04	nd	0.02	0.02	0.01	0.01
F	1.45	1.71	1.06	0.96	0.83	0.96	0.47	0.57
Cl	0.03	0.05	0.06	nd	nd	nd	nd	nd
Formulae based upon 22 oxygen atoms								
Si	5.524	5.551	5.445	5.439	6.263	6.309	6.31	6.21
AI(4)	2.476	2.449	2.555	2.561	1.737	1.691	1.69	1.79
A1(6)	1.173	1.212	1.039	1.225	3.595	3.597	3.72	3.749
Ti	0.309	0.312	0.351	0.34	0.078	0.075	0.067	0.029
tFe	2.771	2.805	2.803	3.231	0.201	0.207	0.139	0.225
Mn	0.065	0.059	0.043	0.163	0.001	--	--	--
Mg	1.087	0.981	1.25	0.454	0.206	0.184	0.137	0.095
Sum Y	5.403	5.369	5.486	5.412	4.082	4.063	4.063	4.098
Ca	0.003	0.001	--	--	0.003	--	0.004	--
Na	0.009	0.019	0.022	--	0.136	0.131	0.138	0.065
K	1.846	1.833	1.807	1.819	1.674	1.682	1.56	1.722
Rb	0.015	0.018	0.011	0.013	0.005	0.005	0.002	0.001
Cs	0.003	0.005	0.002	--	0.001	0.001	0.001	--
Sum X	1.873	1.875	1.842	1.833	1.819	1.819	1.705	1.787
F	0.708	0.839	0.515	0.48	0.345	0.404	0.195	0.243
n	16	34	13	3	13	17	7	4
N	3	5	2	1	3	5	2	1

nd - not detected; tr - trace.
n - number *of* points analysed, *N* - number *of* samples.
Al(4) and *Al(6)* refer to *A1* in tetrahedral and octahedral sites. tFeO - total iron as FeO: tFe - total iron in formula as Fe^{2+},
*- samples from transitional junction between granite types *2* and *3* on Tresco.

Biotites from granite types 1 and 2 are similar in composition (Table 1, cols 1 and 2), as also are those from the type 3 granite on the west side of Tresco (Table 1, col. 3). However, the latter have lower Rb_2O and F and, in this respect, resemble biotite from the type 4 granite (Table 1, col. 4). Biotite from the type 4 granite is markedly enriched in FeO and MnO, but depleted in MgO and F compared with biotites of granite types 1 and 2. High contents of Rb_2O and F and a good positive correlation between them are consistent with those of the trioctahedral micas of the batholith in general (Stone *et al.* 1988). The trend of octahedral A1 enrichment in biotites of the later terms, noted by Charoy (1986) in the Carnmenellis pluton and attributed by him to progressive increase in alumina activity, is not apparent here.

A comparison between the full analyses of five Carnmenellis biotites (from the outer granite) and two from the Isles of Scilly (one each from granite types 1 and 2) given in Stone *et al.* (1988, Table 2) shows that the latter are depleted in Li_2O, Rb, Cs and F, and enriched in Ba, Th and Zr relative to the former.

Muscovite. Average analyses of muscovites from these rocks (Table 1, cols 5-8) show a slight excess in the Y site and, like biotite, a deficiency in the X site. All muscovites are phengitic with tetrahedral R^{3+} between 1.7 and 1.8 and octahedral R^3+ between 3.6 and 3.75, hence a celadonite content of c. 10% (cf. Charoy 1986). The muscovites of granite types 1 and 2 (cols 5 and 6) are similar but differ from those in the finer-grained contact facies of granite type 3 (col. 7) in their low $A1_2O_3$ (and octahedral Al) and higher Rb_2O and F. The single microgranite specimen (Table 1, col. 8) has lower TiO_2, MgO, Na_2O and higher Fe/(Fe+Mg). Rb_2O and F are significantly correlated (r - +0.54).

Tourmaline. In all rock types this is schorl. The most significant correlation (r = -0.86) reflects a marked substitution of Fe by Mg, one that is much stronger than in the micas and reflects Fe enrichment and increased Fe/(Fe+Mn+Mg) in tourmaline of the later rocks compared with those of granite types 1 and 2 (Table 2). Values of Fe/(Fe+Mn+Mg) range from 0.59 to 0.78, typically lower than those in the Carnmenellis granite (Charoy 1986). Zoned tourmalines have pale-coloured cores and darker brown margins in thin section. The latter are enriched in TiO_2, tFeO, CaO and F, and usually Na_2O, and depleted in Al_2O_3 and SiO_2 compared with the former (Table 2). Occasional pale extreme outer rims show continued enrichment in FeO and F, enrichment in MnO, but depletion in TiO_2, Al_2O_3 and MgO.

K -feldspar. Microprobe analyses show a wide range in composition but little consistent variation with rock type. In general, K-feldspars from granite types 1 and 2 have higher BaO contents (> 0.05 to 0.33 wt%) than those from the later granite types (<0.05 wt%) consistent with overall whole rock data and with crystal chemical considerations. A wide range in Na_2O (0.97-1.93 wt%) reflects a formula range of 0.09 to 0.17 Na atoms (on basis of 8 oxygens), but as in the case of Rb, no consistent pattern is evident.

Table 2. Analyses of zoned tourmaline.

Column	1	2	3	4	5
Samples	-417-		-447		
	Pale brown core	Dark brown edge	Pale brown core	Dark brown edge	Pale straw rim
Wt%					
SiO_2	36.88	35.97	36.63	35.15	35.88
TiO_2	0.25	1.44	0.39	0.67	0.49
$A1_2O_3$	36.59	33.7	36.24	35.16	34.8
tFeO	9.81	10.51	10.83	11.6	12.77
MnO	0.2	nd	nd	nd	0.2
MgO	3.08	3.76	2.83	2.76	1.83
CaO	nd	0.27	0.27	0.3	0.21
Na_2O	1.59	2.34	1.75	1.92	1.8
F	0.27	0.57	0.45	0.56	0.74

nd - not detected

1 and 2. Type 2 granite (outer).
3, 4 and 5. Type 3 granite (inner).

Plagioclase feldspar. Alteration prevents analyses of plagioclase cores from type 1 granites, so that the most anorthite-rich composition, $Ab_{77}An_{23}$, is a minimum. A comparison between rock CaO values of granite types 1 and 2 and the very low P_2O_5 contents of type 1 indicate that its plagioclase has cores that are at least as anorthite rich as those in the type 2 granites ($Ab_{68}An_{32}$). The ranges shown by analysed points from granite types 3 and 4 ($Ab_{80}An_{20}$ to $Ab_{98}An_2$) reflect zoning from oligoclase cores to albitic margins, but with overall compositions of albite/ oligoclase (c. $Ab_{89}A_{11}$). A specimen (411) from the contact zone between granite types 2 and 3 has an average plagioclase composition of $Ab_{73}An_{27}$ suggesting that such rocks be included with type 2.

Chemical data - rocks

Inspection of the raw data (Table 3) suggests that, although the four granite types are distinct in terms of their relationships in the field, some samples are transitional in composition between types 2 and 3, and that one type 4 dyke cutting type 2 granite is richer in TiO_2, FeO, CaO, Zr, Ce, V, Th and Ba than the other microgranites and closer in composition to the type 2 granites. Q-mode cluster analysis (not illustrated), using these 8 oxides/elements, suggests some, but little, overlap in chemistry between granite types 1 and 2, whilst type 3 is clearly separated from these. The two fine/medium-grained biotite granite

Table 3. Average analyses of rock types and results of statistical tests.

Column	1	2	3	4	5	6	7
Rock Type	1	2	3	4	Mann-Whitney Tests		
					1&2	2&3	3&4
SiO_2	72.26	71.52	72.96	73.64	*	*	N
TiO_2	0.24	0.24	0.08	0.06	N	**	N
$A1_2O_3$	14.53	14.84	14.42	14.23	*	*	N
Fe_2O_3	0.49	0.53	0.57	0.28	N	N	*
FeO	0.95	1.02	0.36	0.59	N	**	N
MgO	0.33	0.36	0.17	0.24	N	*	N
CaO	0.95	0.81	0.54	0.48	*	**	N
Na_2O	3.54	2.94	3.28	3.29	**	*	N
K_2O	5.06	5.42	5.04	5.04	**	*	N
P_2O_5	0.14	0.23	0.24	0.22	**	N	N
F	0.11	0.24	0.16	0.17	**	N	N
As	0.11	9	7	1	N	N	N
Ba	709	420	251	241	*•	*	N
Ce	81	78	28	4	N	**	N
Cs	28	30	40	32	N	N	N
Ga	17	21	19	21	**	*	N
La	18	25	0	2	N	-	-
Li	260	293	206	166	*	*	N
Mn	228	236	263	212	N	*	N
Nb	13	12	13	14	N	N	N
Pb	35	37	42	30	N	N	*
Rb	430	441	472	498	N	*	N
Sn	9	9	12	12	N	N	N
Sr	111	108	48	27	N	**	**
Th	40	27	6	5	**	**	N
U	8	7	5	4	N	N	N
V	20	16	6	5	*•	**	N
Y	13	16	20	16	*	N	N
Zn	32	37	28	35	•	**	N
Zr	144	117	30	25	**	**	N
K/Rb	98.7	102.5	88.8	89.5			
Rb/Sr	4	4.3	11	23.6			
KZrX100/Ti	10	8.1	6.8	8			
n	19	22	7	8			

n is no. of samples in each rock type. Types 1, 2, 3 and 4 are early inclusions in 2, outer granite, inner granite and late microgranite/ aplite dykes respectively. Results of Mann-Whitney tests between types 1 and 2(col. 5), 2 and 3 (col. 6) and 3 and 4 (col. 7) indicated as follows: N = not significant, * and ** indicate rejection of the Null hypothesis at the 0.05 and 0.01 probability levels respectively.

samples from the west coast of Tresco, close to the transitional boundary between types 2 and 3 and originally collected as type 3, cluster with type 2 and are included in its average analysis (Table 3, col. 1).

Mann-Whitney tests between granite types 1 and 2 (inclusions and outer granite) reveal markedly significant differences (at p = 0.01) in Na_2O, K_2O, P_2O_5, F, Ba, Ga, Th, V and Zr, but similarities in Rb, La, Pb, As, TiO_2, Fe_2O_3, FeO, MgO, CaO, Ce, Cs, La, Li, Rb, Sri, Sr, U, Y and others (Table 3, col. 5). Similar tests between types 2 and 3 (Table 3, col. 6) reveal significant differences in several oxides/elements at the p = 0.05 level, but only TiO_2, FeO, CaO, Ce, Sr, Th, V, Zn and Zr at the p = 0.01 level. Types 3 and 4 (central granite and most microgranites) are chemically similar in many respects and differ at the p = 0.01 level only in Sr and Pb (Table 3, col. 7). As indicated earlier, one of the microgranites may be a minor intrusion derived directly from the outer granite, although it has a significantly lower Sr content than this granite.

Multiple discriminant analysis of all the data using the 'femic suite' of elements/oxides (TiO_2, FeO, CaO, Zr, Sr, V, Ba, Ce, U and Th) again significantly separates types 1, 2 and 3, with only two misclassified observations out of 48. This suggests that whatever petrogenetic linkage there may be between these types, they are statistically distinct at the present exposure level as far as the femic suite is concerned. However, types 3 and 4 cannot be discriminated, confirming conclusions reached above (Table 3, col. 7).

Chemical variation

An abridged correlation matrix (Table 4) reveals strong positive correlations and hence probable association between members of a "femic element/oxide" suite composed of TiO_2, FeO, CaO, Zr, Sr, Ba, V, Th and U. La and Ce are also associated with these oxides/elements. MgO is associated with CaO and, more weakly, with FeO, hence must be included although association with other members of the suite is weak. This suite of elements is broadly similar to a`femic suite' found in the Carnmenellis granite (Stone 1987, Table 3). The trace alkali elements, Sri and Mn are also quite strongly associated and form another suite (the 'trace-alkali suite') which shows stronger association than in the Carnmenellis granites. R-mode cluster analysis (not shown) also distinguishes these two principal groups of associated elements/oxides. However, unlike the association between F and the trace alkali elements observed in the Carnmenellis and other plutons, F is not strongly correlated with other elements.

Table 4. Pearson product moment correlation matrix of selected elements.

(a) Femic suite'

	TiO2	FeO	CaO	Zr	Sr	V	Ba	U
FeO	+0.798							
CaO	+0.653	+0.503						
Zr	+0.902	+0.698	+0.761					
Sr	+0.869	+0.654	+0.744	+0:910				
V	+0.839	+0.622	+0.618	+0.76	+0.703			
Ba	+0.552	+0.315	+0.538	+0.562	+0.455	+0.763		
U	+0.634	+0.423	+0.464	+0.617	+0.562	+0.551	+0.46	
Th	+0.798	+0.519	+0.595	+0.888	+0.0743	+0.671	+0.597	+0.699

(b) Trace-alkali suite'

	Rb	Mn	Cs	Sn
Mn	+0.638			
Cs	+0.313	+0.412		
Sn	+0.733	+0.606	+0.602	
Li	+0.528	+0.712	+0.263	+0.368

All values are significant at the p= 0.05 level (using t for rejection of the Null Hypothesis r = 0).
Values>+0.424 are significant at the p = 0.001 level.

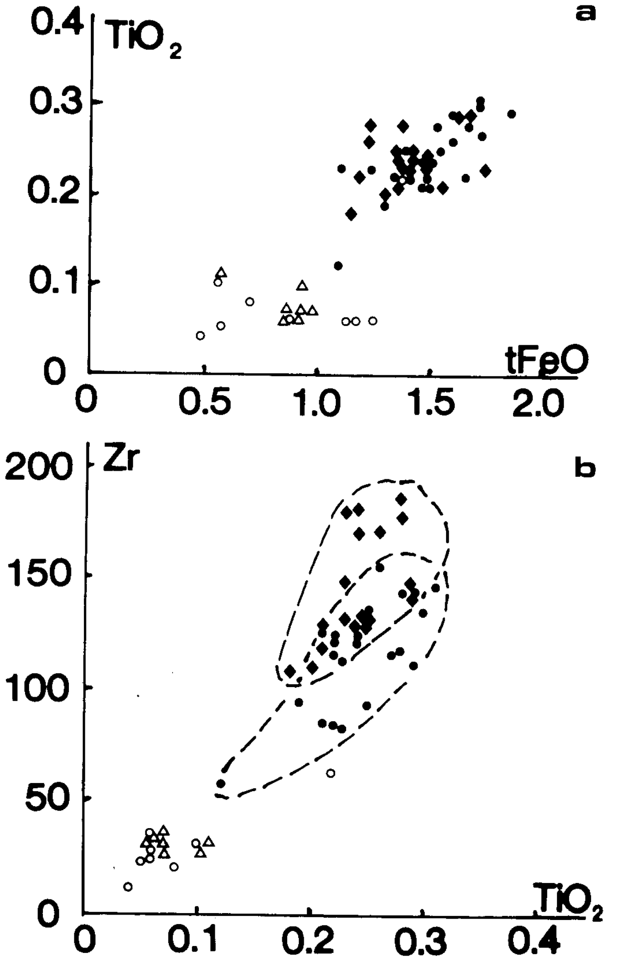

Figure 1. Variation between oxides/elements of the 'femic' suite. a. TiO_2 (wt%) - tFeO (total Fe as FeO, wt%).
b. Zr (ppm) - TiO_2 (wt%).
Symbols refer to granite types described in the text. Type 1 (early inclusions) - filled diamonds; type 2 (outer granite) - filled circles; type 3 (inner granite) - open triangles; type 4 (microgranites and aplites) - open circles. Note that one data point for a microgranite (specimen 407) lies well outside the field of type 4 granites in each figure.

Bivariate plots between more elements/oxides of the 'femic suite' (Fig. 1) also illustrate the close association within this group and have linear spreads of data points often arranged sequentially according to rock type about lines having positive slopes. Many of these plots, like TiO_2 - tFeO (Fig. la) and Zr-TiO_2 (Fig. 1b) exhibit wide ranges in values and largely discriminate types 1 and 2 on the one hand from 3 and 4 on the other. However, the clearest variation patterns are those in which rock type (placed in sequence 1-4) is plotted against mean. Examples like CaO, Zr, Rb/Sr and Zr/Ti, taken directly from the `one-way analysis of variance' output of the Minitab package (Fig. 2), show both the mean for each type and the 95% confidence limits about the mean (based upon Student's t statistic). CaO and Zr (Figs. 2a and b) behave like most other members of the `femic suite' in showing a decrease in the time sequence and, like Sr, V, Ba, Cc and Th clearly discriminate types 1 and 2 on the one hand from 3 and 4 on the other, but do not separate types 3 and 4. Rb/Sr (Fig. 2c) shows an overall increase in the sequence of rock types 1-4, although types 1 and 2 are almost identical: in the K/Rb pattern (not shown) types 1 and 2 are similar whilst 3 and 4, also similar, have markedly lower values (Table 3). These ratios are often taken as indices of fractionation and Fig. 2 suggests that granite types 1 and 2 had reached similar extents of differentiation, like the coarser-

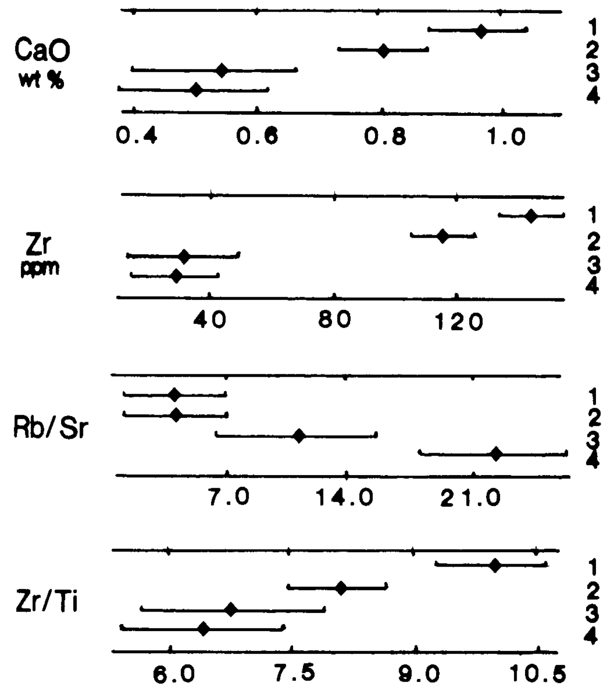

Figure 2. Variation diagrams showing means of CaO, Zr, Rb/Sr and Zr/Ti and 95% confidence limits (based upon pooled standard deviation) in the sequence of rock types 1-4. Taken directly from the Minitab output of oneway analysis of variance.

Table 5. REE analyses and other data.

Col.	1	4	6	7	8	9	10	11
Spec. No.	467	46S	448	466	CAV	467B	465B	021B
Type	1	2	3	4		1	2	
ppm								
La	43.45	40,14	5.67	1.S8	30.87	95.96	126.5	28
Ce	79.83	82.48	11.82	3.15	63.01	181.5	269.5	62
Pr	7.78	6.3	1.3	nd	7.48	18.34	26.72	7.3
Nd	29.75	35.12	S.14	1.14	26.83	70.07	114.6	23.7
Sm	4.68	6.01	1.6	0.42	5.3	10.21	17.19	4.69
Eu	0.68	0.84	0.27	0.08	0.75	0.44	0.8	0.13
Gd	3.25	3.85	1.61	0.34	3.63	7.84	11.42	3.5
Dy	1.99	2.26	1.99	0.52	2.32	4.76	5.12	1.5
Ho	0.38	0.43	0.36	0.09	0.38	0.87	0.92	0.33
Er	1.02	1.15	0.82	0.27	1.12	2.63	3.15	1
Yb	0.73	0.86	0.83	0.44	0.87	1.54	1.68	0.S0
Lu	0.12	0.13	0.12	0.07	0.13	0.22	0.26	0.1
Sum	176.3	181.8	31.5	8.1	142.7	394.4	577.8	133.1
Ce_N/ Yb_N	28.3	24.8	3.7	1.9	18.7	30.5	41.5	32.1
c	2.39	2.37	1.37	-0.19	2.24	2.74	2.89	2.21
m	-0.15	-0.13	-0.06	0.03	-0.12	-0.15	-0.14	-0.12
-r	0.999	0.997	0.949	-0.05	0.999	0.998	0.996	0.997

Column heading numbers correspond with those in Fig. 3. Nos. 1, 4, 6 and 7 are rock samples and 9 and 10 are biotites from the Isles of Scilly pluton. 8 is average rock (CAV) and 11 a biotite (021B) from the outer granite of the Carnmenellis pluton (Stone 1987). Linear regression parameters on the first six elements excluding Eu are given by c (intercept) and m (slope). -r is the negative correlation coefficient.

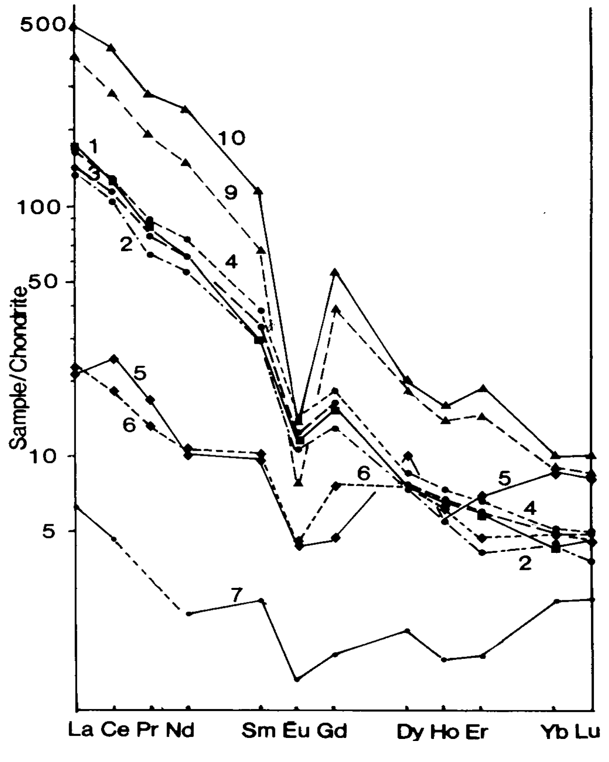

Figure 3. Chondrite normalised REE plot of rock and biotite samples from the Isles of Scilly pluton. Symbols: filled triangles - biotites (9) and (10); filled squares - type 1 granite (1); filled circles and dot-dash, large dashes and short dashes respectively - type 2 granites (2), (3) and (4); filled diamonds - type 3 granites (5) and (6); small filled circles - type 4 granite (7). Numbers in parentheses correspond with column heading numbers in Table 5.

grained granites of Carnmenellis (Stone 1987, Fig. 3d). Zr/Ti (Fig. 2d) shows a decrease in the sequences of types 1 to 3, in marked contrast with the pattern of constant Zr/Ti of Carnmenellis. Again, types 3 and 4 have similar means and spreads.

REE patterns

Whole rock and biotite REE data (Table 5), normalised using the chondrite values of Evensen *et al.* (1978) are plotted in Fig. 3. Most analyses were determined by the ICP method, but two, nos. 2 and 5 in Fig. 3, were determined by neutron activation.

Total REE show marked reduction in the later members of the emplacement sequence from granite types 1 to 4 (Table 5). The ratio Ce_N /Yb_N is a measure of the overall slope of the line joining the two elements labelled in the ratio, and shows a dramatic fall in the granite types 3 and 4 compared with types 1 and 2. The higher Ce_N /Yb_N ratios are roughly parallel with the Ce_N /Sm_N ratios (not shown): the highest is that of the single type 1 inclusion, then come the three type 2 granites followed by the two type 3 granites and finally, the single type 4 microgranite.

Actual slopes, obtained by regression of the logarithms of the normalised REE on atomic number for the first 6 analysed elements, i.e. La to Gd, but omitting Eu, are given in the row marked `m' in Table 5. These show a distinct fall in progressing from granite types I to 4. The data also show a reduction in the correlation coefficient (-r) as the slope diminishes and similarities in slope between host rocks and their biotites (nos. 1 and 4, and 9 and 10 respectively in Table 5 and Fig. 3). Biotite from the Carnmenellis outer granite (no. 11) has a similar but marginally lower slope (-0.12) which is identical with that of its host rock (no. 8).

Petrogenesis

Source. The occurrence of muscovite and commonly abundant K-feldspar megacrysts in these granites together with a strongly peraluminous character, high trace-alkali element content, high Rb/Sr, low K/Rb and high Sri and U contents, suggest an affinity with S-type granites (Chappell and White 1974) and hence, a predominantly lower crustal source, although no oxygen or strontium isotope data are currently available. However, it is unlikely that the source is markedly different from that of the other granites of the batholith and these have high $\delta^{18}O$ (Sheppard 1977), high initial Sr ratios (Darbyshire and Shepherd 1985) and Pb-isotope patterns (Hampton and Taylor 1983) that also point to lower crustal, largely pelitic or semipelitic, sources. The Dartmoor granite also contains primary/restite cordierite (Stone 1988), considered by White *et al.* (1986) to be clear evidence for a true S-type granite.

As in the Carnmenellis granites, andalusite is a common accessory mineral. Evidence considered elsewhere (Exley and Stone 1982; Stone 1987) suggests that andalusite and biotite (albeit modified) is undigested material derived from pelitic material in source rocks, although some contamination from wallrock during upward transport of magma is also likely. However, 'experiments involving partial melting of pelitic, semipelitic and granitoid rocks (Winkler 1976; Luth 1976) indicate that moderate extents of melting (say 30-40%) leave residues containing opaque ores, andalusite (or sillimanite), cordierite, garnet and much biotite and plagioclase. On the basis of REE modelling, Charoy (1986) suggested that the megacrystic outer biotite granite of the Carnmenellis pluton was derived by the partial melting (c. 30%) of Brioverian pelitic rocks. Such a source seems reasonable, although metagreywackes are commonly more abundant in orogenic belts and are likely to provide a more `fertile' source for granite magma (White and Chappell 1988) in the lower crust. Further, larger amounts of granitic melt can be expected from a feldspathic greywacke source than a pelitic one.

Xenoliths and contamination. There is little evidence of contamination at the present exposure level here or in the Carnmenellis pluton. As Jefferies (1985b) pointed out, marked assimilation of pelitic material (at the present level of exposure) would enrich granite in the REE, Zr and Th and, of this, there is no evidence. Most xenoliths and, as suggested above, andalusite, biotite and the more calcic cores of plagioclase are considered to be restite material, or derived from wall-rock in channelways or foundered blocks of country rock at depth (Bromley and Holl 1987).

The Type 1 granite inclusions are the earliest rocks of the complex and would seem to be fragments of an early, only slightly less differentiated granite than the present outer granite. Type 1 formed an initial crust subsequently broken up and incorporated in the outer granite at the time of its emplacement as a later magma pulse.

Fractionation. Almost continuous chemical variation within the sequence of rock types in the Carnmenellis pluton between members of the 'femic element/oxide' suite (i.e. TiO_2, FeO, MgO, CaO, Ba, Ce, La, Sr, Th and Zr) and their overall depletion in the time sequence outer granite, inner granite, microgranites, is believed to reflect progressive biotite and accessory mineral fractionation (Stone 1987). Despite some different abundances compared with the Carnmenellis granites, most of these oxides/elements are also associated (i.e. positively correlated) and show a similar depletion with time in the Isles of Scilly pluton. Thus, fractionation of biotite and the accessory minerals again provides the simplest explanation for these patterns. Clemens and Wall (1981) also considered that fractionation of early-formed biotite together with plagioclase explains chemical trends in many S-type granites. Comparison between the data of Table I of this paper and Table 2 in Stone (1987) reveals broadly similar TiO_2 and Zr trends and contents within the structurally equivalent granite types in each pluton (outer and inner granites and microgranites). However, some separation of Zr and Ti in the Isles of Scilly sequence (i.e. a change in Zr/Ti) may indicate different rates of fractionation of accessory minerals and biotite and/or more marked change with time of biotite composition than in the Carnmenellis pluton. Certainly, there is a wider composition range of Ti as well as SiO_2 in the biotites of the Isles of Scilly granites and, provided that the single microgranite biotite is typical, of FeO, MgO and MnO. There is no evidence for crystal fractionation in situ; this must have occurred either in a chamber below the presently exposed level or, more likely, in transit from the source region.

Magma rising from its deep crustal source would be composed of melt, primary crystals (mainly plagioclase + some quartz), restite (biotite, equilibrated with magma and perhaps containing some magmatic addition + An-richer plagioclase with later magmatic envelope + metamorphic minerals, sillimanite/andalusite, cordierite, garnet + refractory accessories, monazite, zircon, etc), and source 'xenoliths'. This would be expected to follow paths of weakness (deep fractures) to the present site of the pluton. Possible changes undergone by magma as it rose to form the present plutons include chemical re-equilibration of solid solution phases with the magma, fractionation ('cleansing') of early crystallization products and/or restite phases from melt, progressive disaggregation and dispersion of source xenoliths and wall-rock contamination.

Clusters of early crystallized minerals both on the walls of channelways and, perhaps, within the moving magma would be expected to trap restite material and interstitial melt. The latter, having an overall density less than the total solid phases would be expected to separate and join the main magmatic stream in the channelway. Progressive separation of crystals/restite from melt in this manner (cf. Sparks *et al.* 1984) provides a feasible mechanism of progressive fractionation with time to give the granite types observed in the Isles of Scilly and Carnmenellis plutons. In particular, this kind of mechanism avoids the problem of biotite fractionation by gravity in a viscous magma. Initial magmatic pulses would contain more biotite and accessory minerals and hence be richer in the 'femic' suite of oxides/elements and would have An-richer plagioclase than later terms; the latter would be progressively depleted in these mineral and with this, the `femic' oxide/element suite, as biotite and accessory' minerals were trapped in crystal mushes or crystallized early on the walls of the channelways.

Both decreasing K/Rb and increasing Rb/Sr, together with a general enrichment in the `trace alkali' suite (Table 3 and Fig. 2c) indicate progressive evolution of the granites in the sequence of types 1-4. However, even the earliest rocks (type 1 granite inclusions), are quite highly evolved, with trace alkali elements and Rb/Sr well above and K/Rb well below the values found in most granites including S-types, although the extent of evolution is less marked than in the Carnmenellis granites. Most Rb/Sr values for S-type granites in the Lachlan fold belt quoted by White and Chappell (1988) range from 1.2 to c. 4.0 although one selected sample has a value of 18.1. The earliest rocks in the Isles of Scilly pluton have an average Rb/Sr of 4.0 (Table 3). Aluminium Saturation Indices (ASI, see White and Chappell 1988) are c. 1.22 in granite types 2, 3 and 4 but only 1.11 in the type 1 granites. These ASI values broadly agree with those of the Lachlan S-type granites.

Markedly evolved granites, like those considered here, can suggest small extents of partial melting, but as pointed out by Pitcher (1987), there are problems "..in envisaging the physical extraction of small volumes of melt..", particularly in highly viscous S-type granite crustal melts that are likely to behave pseudoplastically. Crustal fusion events are more likely to produce quite large volumes of magma, perhaps involving up to 40% melting. Such magmas are capable of undergoing extensive fractionation between source and present site.

REE patterns. Several authors (e.g. Mittlefehldt and Miller 1983; Gromet and Silver 1983; Michael 1988) have shown that much of the REE pattern in granitoids is controlled by the mainly refractory accessory minerals. Jefferies (1985a) demonstrated that the accessory mineral suite, composed of monazite, zircon, uraninite, apatite and xenotime, accounts for almost all of the rock REE patterns in the Carnmenellis granite. Subsequent work by Stone (1987) suggested that the LREE pattern for biotite largely reflects the included monazite pattern. Part of the HREE pattern is believed to result from included zircon and tiny amounts of xenotime. In a similar manner, it is clear that much of the whole rock pattern, particularly for the LREE is controlled by the biotite pattern and hence, ultimately, the monazite pattern. The LREE slope for monazite obtained by regression as described above is -0.138. This is based upon the mean of three Carnmenellis monazites given by Jefferies (1985a). If we assume that this slope is close to that of the LREE slope of monazites in the early Isles of Scilly granites, it can readily be seen that both biotite and rock LREE slopes are governed very largely by the monazite pattern. Also, the marked negative europium anomaly reflects that in monazite rather than the effects of feldspar fractionation. It is suggested that biotite has included the accessory mineral suite in roughly the same proportions as it occurs in the whole rock at the time of metamorphism and anatexis and that the biotite represents restite material, subsequently modified in composition by equilibration with evolving magma as it rose in the crust. Evidence is provided by the close similarity between the LREE slopes for the Carnmenellis (and hence, the Isles of Scilly) outer granite and a sillimanite-bearing pelitic xenolith, believed to be source material, in the Carnmenellis outer granite (Jefferies 1985b). Thus, the decrease in the 'femic' suite of oxides/elements and total REE, together with the reduction in slope of the LREE is the result of both biotite and accessory mineral (monazite) fractionation (Miller and Mittlefehldt 1982; Stone 1987).

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