THE EARLY CORNUBIAN PLUTONS: A GEOCHEMICAL STUDY, COMPARISONS AND SOME IMPLICATIONS

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Each of the older Cornubian granite plutons (Isles of Scilly, Carnmenellis and Bodmin Moor) has its own structural and geochemical identity, but as a group they have some common geochemical characters, particularly amongst the `femic' element group, which separate them from the later plutons. Also, each pluton has a concentric (ring) structure, thereby differing from the more complex multiphase later plutons. Geochemical comparisons reveal broad similarities between the outer granites of all three plutons and between the inner granites of Carnmenellis and Bodmin Moor. The Isles of Scilly inner granite differs in texture and is related to the microgranite/aplite dykes which cut the outer granite. The latter has enclaves of poorly megacrystic medium-grained granite, possibly a disrupted outer skin having some chemical similarity with the host but also marked differences. Differentiation in each pluton ended with the emplacement of the microgranite dykes. The zoned Bodmin Moor pluton shows continuous emplacement of its coarse-grained granites whilst in the Carnmenellis granite there is a hiatus between emplacement of outer and inner granites, but the medium-grained central granite in the Isles of Scilly pluton shows more extreme differentiation to the microgranite stage. Both early and late plutons are associated with basic magmatism, although the former have more mantle component than, and were uncovered before emplacement of, the latter.

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INTRODUCTION

A geochemical hiatus occurs between the earlier (Isles of Scilly, Carnmenellis and Bodmin Moor) and later (Land's End, St Austell and Dartmoor) plutons of the Cornubian batholith (Stone, 1997). Differences include the steeper REE pattern (higher Ce_N/ Yb_N) (Darbyshire and Shepherd, 1985; Stone, 1995), higher e_{Nd} (Darbyshire and Shepherd, 1994) and more the aluminous nature of the former and the dominance of microgranite enclaves (ME) and slightly more basic composition in the latter (Stimac *et al* ., 1995). However, on the basis of field studies alone, Dangerfield and Hawkes (1981) recognised two groups of coarse-grained megacrystic granite that alternate along the batholith, a contrast that anticipates the division implied by both age determinations (Chen *et al.,* 1993; Chesley *et al.,* 1993) and the proposed geochemical dichotomy.

This study of the early pluton set aims to compare and discuss the geochemistry of the rock types and emplacement sequences, and to comment on aspects of their setting and genesis. It uses data summarised in Stone (1987) and Stone and Exley (1989) supplemented by data supplied by Dr Colin Exley for the Bodmin Moor pluton (summarised in Exley, 1996) and by Professor Bruce Chappell for both the Bodmin Moor and Carnmenellis plutons and differs from the former studies (Stone, 1995, 1997) by including the later terms and fuller data for the Bodmin Moor pluton.

Granite types are defined by grain size and amount and size of K-feldspar megacrysts (largely after Dangerfield and Hawkes, 1981) and by pluton. These are given in the following text and in the footnote to Table 1.

FIELD RELATIONS

Each of the Bodmin Moor (bd), Carnmenellis (cm) and Isles of Scilly (sc) plutons (the *sccmbd* set) has some kind of "ring" structure. In the Bodmin Moor pluton this is geochemically and petrographically a zoned structure from centre to margin, which shows decreases in Rb and Li and increases in modal biotite, normative anorthite and `femic' elements (Exley, 1996). An arbitrary boundary between outer [bdCGm(O)] and inner [bdCGm(I) granites is placed at a value of tFe_2O_3 + MgO = 1.8 wt%, which lies close to the biotite isopleth at *ca.* 3.5% (Exley, 1996). In addition, there are later fine-grained granites [bdmc].

	1	2	3	4	5	6	7	8	9	10
Pluton	bd	bd	bd	cm	cm	cm	sc	sc	sc	sc
Rock type	CGm(O)	CGm(I)	mc	CGm(O)	CGm(I)	mc	XMGm	CGm(O)	MG	mc
wt%										
SiO_2	71.31	7173	72.45	72.11	72.84	75.86	72.26	71.52	72.96	73.47
TiO_2	0.24	0.14	0.11	0.24	0.18	0.07	0.24	0.24	0.08	0.09
Al_2O_3	15.14	14.79	14.84	15.04	14.64	14.44	14.53	14.84	14.42	14.37
tFe_2O_3	1.93	1.32	1.15	1.6	1.47	1.08	1.55	1.5	0.97	1.04
MgO	0.4	0.24	0.16	0.43	0.39	0.13	0.33	0.36	0.17	0.22
CaO	0.75	0.56	46	0.92	0.68	0.57	0.95	0.81	0.54	0.52
Na_2O	2.79	281	2.6	3.06	3.19	3.75	3.54	2.94	3.28	3.25
K_2O	5.42	5.41	5.79	5.12	4.95	4.29	5.06	5.42	5.04	5.1
P_2O_5	0.22	0.19	0.23	0.24	0.23	0.26	0.14	0.23	0.24	0.22
ppm										
Ba	189	121	142	237	220	115	709	420	251	257
Ce	65	38	19	70	59	20	81	78	30	27
Cs	48	nd	nd	48	56	45	28	30	40	31
La	33	19	11	33	27	2	42	25	nd	19
Li	316	401	248	418	401	295	260	293	206	194
Mn	339	366	253	359	318	252	228	236	263	226
Nb	13	14	15	12	14	17	13	12	13	14
Pb	29	28	36	33	37	15	35	37	42	30
Rb	428	486	414	478	463	581	430	441	472	497
Sn	16	nd	nd	12	17	15	9	9	12	13
Sr	90	59	71	88	79	28	111	108	48	36
Th	14	nd	nd	15	7	3	40	27	6	7
U	11	nd	nd	13	9	13	8	7	5	4
V	16	8	6	15	12	4	20	16	6	6
Y	13	9	10	16	15	5	13	16	20	14
Zn	46	36	41	44	nd	18	nd	37	nd	27
Zr	88	57	48	109	74	25	144	117	30	34

sc, cm, bd = Isles of Scilly, Carnmenellis, Bodmin Moor plutons. CGm = coarse-grained with small megacrysts in outer (O) and inner (I) granites; MG = medium-grained mainly aphyric; XMGm = enclaves of medium-grained granite with small megacrysts; mc = combined aplites and microgranites.
Extreme values shown in bold type

Table 1. *Average chemical analyses of main granite types in each pluton.*

The outer [cmCGm(O)] and inner [cmMGm(I)] granites of the Carnmenellis pluton are petrologically and chemically distinct and correspond with the G1/G2 and G3 granites respectively of Ghosh (1934). Their sharp contact *(cf.* Ghosh, 1934; Dangerfield and Hawkes, 1981) appears to be joint-controlled and gives the appearance of a 'nested' pluton (Al Turki and Stone, 1978). These rocks are cut by microgranite and aplite dykes [collectively cmmc] and two outcrops of K-rich fine-grained granite [cmFG]. Deformed country rocks around bd and to a lesser extent around cm reveal some diapirism.

In the Isles of Scilly pluton, the outer granite [scCGm(O)] contains xenoliths of an earlier medium-grained granite with small megacrysts [scXMGm] apparently disrupted by the emplacement of the former (Stone and Exley, 1989). Its core is composed of medium-

(a) Classification

		Bodmin Moor			Original Carnmenellis			Isles of Scilly			
		CGm(O)	CGm(I)	mc	CGm(O)	CGm(I)	mc	XMGm	CGm(O)	MGM	mc
Bodmin	CGm(O)	35	0	0	3	1	0	0	1	0	0
	CGm(I)	1	12	0	0	1	0	0	0	0	1
	mc	0	1	2	0	0	0	0	0	0	1
Carnmenellis	CGm(O)	7	0	0	44	0	0	0	1	0	0
	CGm(I)	2	1	0	1	8	0	0	3	0	0
	mc	0	0	0	0	0	13	0	0	0	2
Is. of Scilly	XMGm	0	0	0	0	0	0	18	1	0	0
	CGm(O)	1	0	0	3	0	0	1	15	0	0
	MG(I)	0	0	0	0	0	2	0	1	6	1
	mc	0	0	0	0	0	1	0	0	1	5
Total		46	14	4	51	10	16	19	22	7	10
N		35	12	4	44	8	13	18	15	6	5
N^*		43	13	4	50	9	16	18	17	7	9
(b) D^2 values											
Bodmin	CGm(O)	0	12.5	20.5	5	5.8	36.4	26.9	7.9	33	28.2
	CGm(I)	12.5	0	3.5	14.7	3.9	8.7	34.2	17.8	10.5	5.3
	mc	20.5	3.5	0	25.5	8.6	12.1	42.8	23.3	9	8.3
Carnmenellis	CGm(O)	5	14.7	25.5	0	6.6	37.9	13.9	4.1	33.5	28.2
	CGm(I)	5.8	3.9	8.6	6.6	0	21.4	25.4	8.1	15.1	11.9
	mc	36.4	8.7	12.1	37.9	21.4	0	62.6	47.9	10.8	4.8
Is. of Scilly	XMGm	26.9	34.2	42.8	13.9	25.4	62.6	0	10.3	56.9	52.6
	CGm(O)	7.9	17.8	23.3	4.1	8.1	47.9	10.3	0	36.7	34.6
	MGM	33	10.5	90	33.5	15.1	10.8	56.9	36.7	0	3
	mc	28.2	5.3	8.3	28.2	11.9	4.8	52.6	34.6	3	0

Eight variables (TiO2, tFe2O3, MgO, CaO, Zr, Y, Sr and V). Abbreviations as in Table 1.
N = number of samples classified into correct rock type and pluton.
N^* = number of samples grouped into similar rock groups, e.g. outer granites of sc, cm and bd.

Table 2. *Discriminant analysis output.*

grained (1-2 mm grain diameters) mainly aphyric granite [scMG(I)] (Jones, 1963) which has both gradational and sharp contacts with the outer granite (Barrow, 1906) and contrasts texturally with the central granites of the other two early plutons. Aplite and microgranite dykes [scmc] cut the outer granite and appear to emanate from the inner core (Barrow, 1906; Stone and Exley, 1989).

DATA

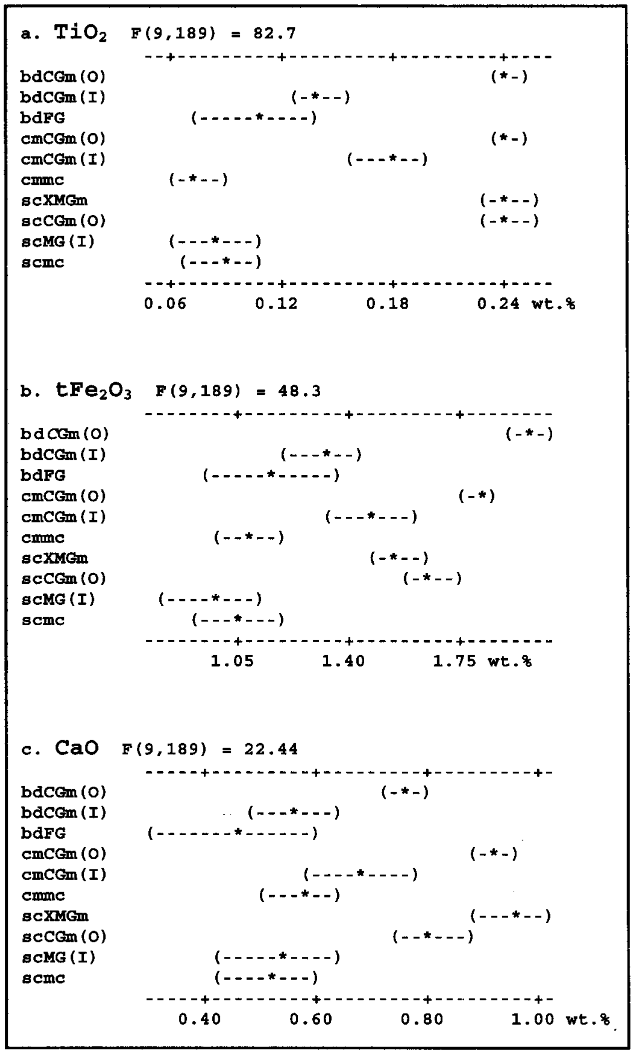
Although the Kolmogorov - Smirnov one sample test reveals some departures from the normal distribution (e.g. TiO_2, Nb, Sr, Rb, Ba and La), a comparison between the output from parametric and equivalent non-parametric tests shows similarity between means and medians, close Pearson and Spearman Rank correlation coefficients and similar output from the analysis of variance and the Mood and Kruskal-Wallis tests. The statistical procedures used here assume the normal distribution and give comparable information to the equivalent nonparametric methods.

Averages of granite types in each pluton (Table 1) show broad similarities between the outer granites, between the inner bd and cm granites and between the microgranites, although there are some clear differences within each group. Underlined values give bdCGm(O) [tFe_2O_3], cmmc [SiO_2, Rb] , scXMGm [Zr, Sr, V, Ba, La, Th] and scCGm(O) [Sr, Ba, Th] some distinctive features and individuality.

The correlation matrix (not shown) reveals strong association between the `femic' elements, especially TiO_2, tFe_2O_3, MgO, CaO, Zr, Sr and V. High positive correlations occur also between the trace alkali elements, Nb and Rb, Sn and both Rb and Cs, and Li and U. Similar patterns appear in previous studies (Stone, 1987; Stone and Exley, 1989, Table 4) and in bulk major element data *(cf.* Floyd *et al.,* 1993, Table 5.3).

F-values (variance ratio = between rock type variance/within rock type variance) for several femic elements are given in Figures 1 and 2. Al_2O_3 has a low value, as do Nb, Rb and Sn (not shown), whereas TiO_2, tFe_2O_3, MgO, CaO, Zr, Y, Sr, V, Ba, La, Ce and Th have much higher (highly significant) values than the other elements. Thus, large variations (higher F) as well as higher correlation coefficients occur in the "femic" suite of elements, i.e. those that go into biotite and associated accessory minerals and the anorthite component of plagioclase feldspar.

Computer output of means and confidence intervals for several constituents of the `femic' element suite shows correspondence between outer granites in TiO_2 (Figure la), MgO and V (Figure 2c) but other constituents, whilst similar, do not correspond exactly, e.g. CaO (figure lc) and Zr (Figure 2a) and a marked enrichment of tFe_2O_3 (Figure lb) in the Bodmin Moor outer granite and Sr (Figure 2b), Ba and Th enrichment in the Isles of Scilly outer granite. Likewise, there are relatively small differences between the inner granites of bd and cm in MgO, Zr (Figure 2a), Sr (Figure 2b) and V (Figure 2c). However, if the arbitrary boundary in bd is raised from tFe_2O_3 + MgO = 1.8 to over 2.0 (say, 2.3), the inner bd and cm granites become almost identical in TiO_2, tFe_2O_3, CaO, Zr, Y, Sr, V, La and Ce and the similarities between the outer granites remain close. The broad similarities between the outer granites, the inner bd and cm granites and the fine-grained rocks of each pluton accompany falling contents of femic constituents in the sequence outer granite 11 inner granite microgranite in both the bd and cm plutons. Also, as shown by Stone (1997), the differences between the outer *sccmbd* granites are less than those between the early and later plutons.

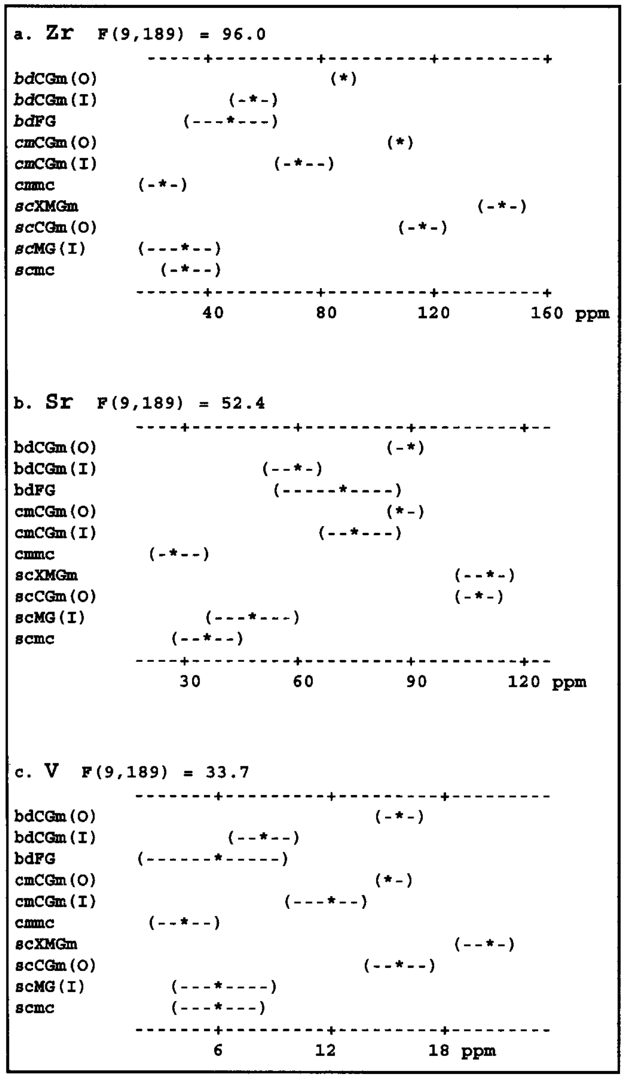


```
a. TiO2  F(9,189) = 82.7
           --+---------+---------+---------+----
bdCGm(O)                                  (*-)
bdCGm(I)                (-*--)
bdFG           (-----*----)
cmCGm(O)                                  (*-)
cmCGm(I)                     (---*--)
cmmc         (-*--)
scXMGm                                   (-*--)
scCGm(O)                                 (-*--)
scMG(I)      (---*---)
scmc          (---*--)
           --+---------+---------+---------+----
           0.06      0.12      0.18      0.24 wt.%


b. tFe2O3  F(9,189) = 48.3
           --------+---------+---------+--------
bdCGm(O)                                    (-*-)
bdCGm(I)               (---*--)
bdFG            (-----*-----)
cmCGm(O)                               (-*)
cmCGm(I)                   (---*---)
cmmc                 (--*--)
scXMGm                         (-*--)
scCGm(O)                          (-*--)
scMG(I)     (----*---)
scmc               (---*---)
           --------+---------+---------+--------
                 1.05      1.40      1.75 wt.%


c. CaO  F(9,189) = 22.44
           -----+---------+---------+---------+-
bdCGm(O)                        (-*-)
bdCGm(I)            (---*---)
bdFG       (-------*-------)
cmCGm(O)                                (-*-)
cmCGm(I)                 (----*----)
cmmc                 (---*--)
scXMGm                                  (---*--)
scCGm(O)                         (--*---)
scMG(I)          (-----*----)
scmc                 (----*---)
           -----+---------+---------+---------+-
              0.40      0.60      0.80      1.00 wt.%
```

Figure 1. *Means and 95% confidence intervals (—*—) for major oxides in wt. % (a) TiO_2 (b) tFe_2O_3 and (c) CaO. F(9,189) = F-value from the analysis of variance with 9 and 189 degrees of freedom (see text). Abbreviations in text and footnote of Table 1.*

Although bd and cm are broadly comparable, there are differences between these and sc (Figures 1 and 2). In the latter, the scXMGm-granite enclaves in the outer granite are enriched in CaO (Figure lc), Nb, Zr (Figure 2a), V (Figure 2c), Ba and Th compared with the host rock, although other elements have similar contents in both.

Such enclaves are absent from the exposed Carnmenellis and Bodmin Moor outer granites. The medium-grained Isles of Scilly central granite [scMG(I)] and the microgranites/aplites [scmc] have



```
a. Zr  F(9,189) = 96.0
            -----+---------+---------+---------+
bdCGm(O)                    (*)
bdCGm(I)           (-*-)
bdFG           (---*---)
cmCGm(O)                         (*)
cmCGm(I)               (-*--)
cmmc       (-*-)
scXMGm                                   (-*-)
scCGm(O)                          (-*-)
scMG(I)    (---*--)
scmc         (-*--)
           ------+---------+---------+---------+
                 40        80       120       160 ppm


b. Sr  F(9,189) = 52.4
           ----+---------+---------+---------+--
bdCGm(O)                         (-*)
bdCGm(I)              (--*-)
bdFG                   (-----*----)
cmCGm(O)                         (*-)
cmCGm(I)                   (--*---)
cmmc        (-*--)
scXMGm                                 (--*-)
scCGm(O)                               (-*-)
scMG(I)          (---*---)
scmc          (--*--)
           ----+---------+---------+---------+--
               30        60        90       120 ppm


c. V  F(9,189) = 33.7
           -------+---------+---------+---------
bdCGm(O)                        (-*-)
bdCGm(I)           (--*--)
bdFG       (------*-----)
cmCGm(O)                        (*-)
cmCGm(I)                (---*--)
cmmc        (--*--)
scXMGm                                 (--*-)
scCGm(O)                       (--*--)
scMG(I)       (---*----)
scmc          (---*---)
           -------+---------+---------+---------
                  6        12        18 ppm
```

***Figure** 2. Means and 95% confidence intervals (—*—) for trace elements in ppm (a) Zr, (b) Sr, (c) V. F as in Figure 1 and symbols as in the footnote to Table 1.*

closely similar compositions in all major elements and most trace elements (Figures 1a-c and 2a-c and Nb, Y, Ba, La and Th). This close comparison confirms their common genesis as indicated by Barrow (1906) and Stone and Exley (1989). In general, the composite fine-grained granites (bdmc, cmmc and scmc) are similar.

Bivariate plots, like TiO_2 *vs* tFe_2O_3 (Figure 3a) and Zr vs Sr (Figure 3b), reflect the high positive femic element correlations, clearly separate the outer, inner and microgranites, and group together most samples within each rock type. scMG(I) plots with the microgranites and scXMGm lies just off the main trend. On a multivariate level, factor analysis can simplify multivariate arrays by grouping variables into clusters: it uses here the correlation matrix and the variables shown in Figures 1 and 2 and MgO, Nb, Y, Mn, Ba and Ce. The first two factors give the element loadings shown in Figure 4a. High loadings of the `femic' elements on the positive end of the X-axis produce a cluster that forms a single `femic element' factor (variable). The other end of this axis is dominated by SiO_2, Nb and Rb (and, presumably, the other trace alkali elements, for which data are insufficient), whilst the Y-axis contains high loadings of P_2O_5 and Mn (on the negative Y-axis) and opposing Na_2O and K_2O. Factor scores of samples plotted on these axes (figure 4b) separate the fine-grained from the earlier coarse-grained granites, the scXMGm enclaves and to a large extent the outer and inner granites, whilst scMG(I) and scmc data points are interspersed. They also show the clear trend of diminishing 'femic' constituents with increasing SiO_2 and Rb (the negative X-axis) with time.

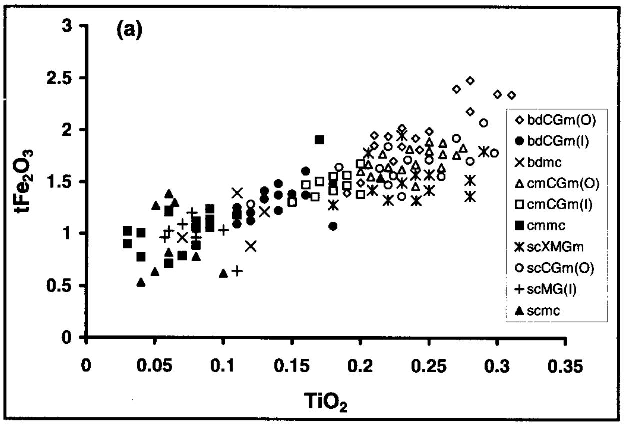


***Figure** 3. Bivariate plots (a) TiO_2 wt. % vs tFe_2O_3 wt. %; (b) Zr (ppm) vs Sr (ppm).*

Linear discriminant analysis in the Minitab package gives values of D^2 (squared distance between multivariate means of rock types/plutons; the lower the value, the closer the means and the greater the similarity), and classifies samples within each rock type. Values of D^2 are used here qualitatively; significance can be estimated, but is not included in the package and the calculation is considerable. Linear discriminant analysis using `femic' elements (Table 2) classifies correctly 80.4% of the samples, but when similar rock types are grouped, 91.5% of the samples are correctly classified. Similar results are obtained using all the major oxides plus the `femic' trace elements and Nb. Mahalanobis distances (D^2) between multivariate means (Table 2) show relatively close similarities between the outer granites and between the inner granites of cm and bd. Distances between me granites are broadly similar, but most striking is the close multivariate relationship between the sc inner granite and the microgranite dykes. These results confirm the evidence from univariate and bivariate plots at a multivariate level.

COMPARISON WITH THE LATER PLUTONS

As some comparisons have already been made (Stone, 1995, 1997), only an outline is given here. Dartmoor (dt), St Austell (sa) and the Land's End (le) plutons (the *lesadt* set) contain coarse-grained megacrystic (CGM) and poorly megacrystic (PM) granites and various fine-grained granites. In addition, most of the early (basic) microgranite enclaves (ME or type A of Exley and Stone, 1982) occur in the *lesadt* plutons: typically, these differ considerably from their host granites and appear to be unrelated and to contain a significant mantle component (Stimac et al., 1995; Stone, 1997).

The early granites are distinguished from the later granites in the sparsity of microgranite enclaves and in being more aluminous (Stimac *et al.*, 1995), in having steeper Ce_N/Yb_N slopes (Darbyshire and Shepherd, 1985; Stone, 1995) and higher e_{Nd} (Darbyshire and Shepherd, 1994), in their lower femic element content and smaller K-feldspar megacrysts. The femic elements clearly discriminate between the *lesadt* CGM- or PM- granites and the *sccmbd* CGm-/MGm- outer or inner granites (cf. Stone, 1997, Fig. 1 and 1995, Fig. 3). Bivariate (Zr *vs* Nb, Ba *vs* Rb and Ba *vs* Sr) and triangular (Ga-Nb-Zr, and Rb-Ba-Sr) plots in Manning (1998) also discriminate non-megacrystic (= CGm-granites herein) and megacrystic (= CGM granites herein) biotite granites. Although the end products of differentiation are similar, the earlier terms are quite different in petrography, texture and chemistry. The later CGM- and PM-granites bear no clear parental relationship to the *sccmbd* outer and inner granites at the present erosion level. Each granite set evolved separately and was emplaced at a different time. Also, the *lesadt* set contains tourmaline granites

(Manning, 1998) and recent work on the St Austell (Hill and Manning, 1987), Land's End (Powell *et al.,* 1999) and Dartmoor (Knox and Jackson, 1990) plutons reveals more complex plutonic histories than the *sccmbd* set.

DISCUSSION

The high variability in the oxides/elements of the 'femic' suite (those given in Figures 1 and 2, plus La, Yand Th) is shown by their highly significant F-values and high correlation coefficients. This variability, reflected in biotite contents and compositions and associated accessory minerals and tourmaline, combined with texture form the basis for most of the visual differences between the rock types.

The statistical results reveal some significant differences between the outer granites, but their textural and many geochemical similarities point to the initiation of each early pluton by the emplacement of a similar magma type at about the same time. The ultimate judgement in the geochemical comparison must be made at the multivariate level. Here, similarities in multivariate means and in classification (Table 2) together with the 'multi-element' (factor analysis) plot of Figure 4, group the outer granites as a single type (i.e. the Gm granites of Dangerfield and Hawkes, 1981). The inner granites of *bd* and *cm* are also geochemically similar: the similarity increases when the arbitrary boundary at tFe_2O_3 + MgO = 1.8 between the bd outer and inner granites is raised.

It could be argued that the granite enclaves [scXMGm] in the Isles of Scilly outer granite formed an original outer granite and that the present scCGm(O) is really the inner granite. The present central granite would then constitute an additional intrusion not present in the other two plutons. However, most of the plots in Figures 1 and 2 and the bivariate plots do not support this, whilst the results of discriminant and factor analysis make it quite clear that there is little relationship to the other rock types apart from some similarity between enclaves and host granite. The enclaves could be the remains of the initial stages of the emplacement of an evolving outer granite (Stone and Exley, 1989) or they could have been derived from an earlier part of the multiphase Cornubian batholith at a deeper level. In any case, this stage is not apparent in the Bodmin Moor and Carnmenellis plutons: tests between these enclaves and the outermost samples from bdCGm(O) reveal no similarity.

Despite some slight similarity between the medium-grained inner aphyric sc granite and the inner bd and cm granites (Table 2) the differences are greater than those between the latter two. Further, the close similarity between scMG(I) (in all figures and Table 2) and the microgranite dykes confirms the close genetic affinity shown by the field relations. If an intermediate stage of evolution had developed between scMG(I) and scCGm(O), it was not emplaced at the present erosion level. The contacts between scMG(I) and scCGm(O) are both gradational and sharp (Barrow, 1906), perhaps pointing to a short break. However, the associated microgranite/aplite dykes cut the latter and mark a later brittle phase and there is marked geochemical contrast between outer and inner granites, perhaps pointing to a larger hiatus.

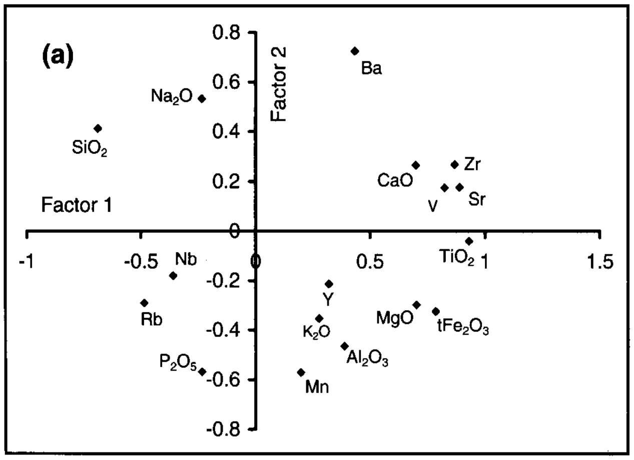


***Figure** 4. Factor analysis plots (a) factor loadings for the major oxides SiO_2, TiO_2, tFe_2O_3, MgO, CaO, Nap, K_2O, P_2O_5 and trace elments Nb, Zr, Y, Sr, Rb, V, Mn and Ba on the first two factors (which account for most of the variance); (b) plot of factor scores of samples on the axes of Figure 4a. For bdCGm(O), cmCGm(O), scXMGm and scCGm(O), a number of data points have been removed in order to reduce overcrowding.*

Several points arise from the structural, geochemical and the age differences between the *sccmbd* and *lesadt* pluton sets.

(i)Earlier gravity and seismic work (Bott *et al.,* 1970) suggests that below 10-12 km the batholith passes into a denser medium composed of residuum and stoped material. In contrast, Brooks *et al.* (1984) interpret a seismic reflector (R2), 10- 15 km deep, as a late Variscan southward-dipping thrust: this coincides with the base of the granite, as predicted from gravity modelling, but extends well beyond the northern limit of the batholith. However, a shallow tabular batholith is unlikely to be the repository for several types of granite, with associated mineralization, emplaced in two distinct sets separated by a 10Ma gap, unless the granites moved along the thrust (see below) or their displacement from an almost *in situ* root is small, despite possible pre-granite movement.

(ii)To allow sufficient depth for granite formation and emplacement, Shackleton *et al.* (1982) propose that the granites were generated some 150 km further south and were injected northwards " ... as a sheet-like body from which protrusions moved upwards diapirically and by stoping to form the separate exposed granite masses ...". However, there are several objections to this. Firstly, the décollement, above which the granite is shown to have been emplaced (Shackleton *et al*., 1982) occurs at only *ca.* 6 km depth in Germany: even if this depth were maintained, or, were increased to a mid-crustal level (to the position of R2 say), it is unlikely to be sufficient for marked differentiation and multiple emplacement, especially where large-scale stoping is envisaged (despite the model of Bromley and Holl, 1986, Fig. 8). Secondly, as Floyd *et al.* (1993) point out, it is unlikely that magma could travel this distance and be capable of rising in the crust to form the present plutons without solidifying. Thirdly, a 10+ Ma time gap between the two main periods of emplacement would require two periods of magma supply from the source and transport along the thrust.

(iii) The circular/ovoid shapes of the early plutons indicate that the present erosion surface cuts them at greater depth than the more irregular shapes of the later bodies, which lie closer to their roofs and have shallow-dipping roof contacts. The early plutons must have been emplaced at a (slightly) higher level. Further, Dartmoor was uncovered in the Upper Permian and is associated with contemporaneous vulcanicity (Scrivener, 1994; Awad *et al.,* 1997). This suggests that the early plutons were already uncovered at this time.

(iv) Interbedded lamprophyric and basaltic lavas in the Early Permian give ages of *ca.* 290Ma in the Bow Breccia and 282 Ma in the higher Thorveton Sandstone, corresponding with the ages of the Bodmin and Dartmoor granites respectively and point to a mantle driving force (heat engine) for both early and late plutons (Edwards *et al.,* 1997). Such evidence refutes (a) the idea of magma movement along a thrust and (b) the need for a radioactive heat engine, although this was probably also operative. Clasts in the Lower Permian sandstones have a ε_{Nd} value of ca. -6.9, close to the median Bodmin Moor granite value of -7.1, compared with those in the Upper Permian which have ε_{Nd}= -4.8, close to the median Dartmoor granite value of -4.7 (Edwards *et al.,* 1997). Such values point to a larger mantle component in the later plutons.

CONCLUSIONS

1. Apart from the initial emplacement of the minor scXMGm granite, the plutonic history of these early plutons began with the (partly diapiric) emplacement of coarse-grained small megacryst granites. Following this, there were differences in the evolution of each pluton. Bodmin Moor and Carnmenellis evolved similar inner granites, although the latter is finer-grained. However, in the former there is a continuous evolution between outer and inner granites, consistent with diapirism, whereas in the latter there is a hiatus in magma supply sufficient to produce a sharp, joint-controlled contact with the outer granite.

2. Further magmatic evolution in these plutons generated the micrograpites and aplites, which despite some differences, are broadly similar. A major difference in magma supply occurred in the Isles of Scilly pluton resulting in the evolution of an inner granite at the microgranite stage complete with microgranite dykes that penetrated the outer granite.

3. The early granites differ from the later set in their chemistry, petrography, and structure. The later granites are more complex multiphase bodies, whereas the early granites are fairly simple 'ring-type' structures.

4. A tabular batholith produced by movement along a thrust is inconsistent with two periods of emplacement separated by *c.* 10Ma.

5. The early plutons were unroofed before the onset of Dartmoor plutonism.

6. Associated basic magmatism produced the heat engine for both periods of granite magmatism, although the small mantle component is greater in the later plutonic event.

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