The Lundy granite: a geochemical and petrogenetic comparison with Hercynian and Tertiary granites

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Abstract

New chemical data show that the two main granite types (G1 and G2) cannot be discriminated, but that microgranite sheets/dykes (G3) are significantly different and more evolved, largely as a result of biotite, accessory mineral, and plagioclase fractionation. The Lundy granite is similar to other Tertiary granites of Scotland and Ireland, in age, setting, possible high-temperature mineralogy, relationship to basic magmatism, and *REE* patterns. These features and a highly evolved chemistry suggest derivation from an unexposed more 'primitive' granite that, in turn, had a basaltic parentage. However, similarities with the nearby S-type Hercynian granites, such as high aluminium saturation index (and normative corundum), high trace alkali, Nb, and F contents, low Zr, and high initial Sr ratio suggest a significant crustal component. The problem is resolved by proposing either mixing of silicic magma derived by strong fractionation of basaltic magma with anatectic magma from a pelitic/semi-pelitic crustal source, or fractionation of basaltic magma heavily contaminated by assimilated crustal material. Both origins would yield the high *REE* contents and flat *REE* patterns of a 'primitive' granite magma. Fractionation, perhaps of hornblende initially, and later, of biotite and accessory minerals together with feldspars, would produce the small volume of highly fractionated Lundy granite.

KEYWORDS: Lundy granite, geochemistry, petrogenesis, Cornubian granite, Tertiary granite.

Introduction

THE small island of Lundy lies off the north coast of Devon some 18 km NNW of Hartland Point (GR 22291279). It is composed mainly of granite, but folded sedimentary rocks occupy the extreme SE tip (Fig. 1), and both are cut by basic and felsic dykes. The sedimentary rocks comprise slates with some siltstones and fine-grained sandstones which are correlated lithologically with the Morte Slates (Upper Devonian) on the Mainland (Edmonds *et al.*, 1979).

Previous work includes that of Dollar (1941), Edmonds *et al.* (1979) and Dangerfield (1982). In the controversy over the age of the Lundy granite, several writers, including Davison (1932) and Dollar (op. cit.), considered that the Lundy granite was Hercynian, like its neighbours in the Cornubian batholith. Davison (op. cit.) compared the common occurrence of minerals like topaz, muscovite, tourmaline, and cassiterite in both the Lundy and Cornubian rocks. Others (e.g. McLintock and Hall, 1912) compared the occurrence of topaz and beryl in the Lundy granite with that in the Tertiary granites of Arran and the Mourne Mountains. Further similarities between the Lundy, North Arran, and Mourne Mountains granites are the common occurrences of miarolitic cavities and granophyric and myrmekitic textures.

Isotopic age determinations (K/Ar in minerals) by Dodson and Long (1962) and Miller and Fitch (1962) gave a Tertiary (Eocene) age of *c.* 52 Ma that has since been extended to *c.* 55 Ma (Fitch *et al.*, 1969) by the ^{40}Ar–^{39}Ar method, to 57 Ma (Institute of Geological Sciences, 1981) by a whole rock Rb:Sr isochron and to 53 ± 5 Ma by a mineral/whole-rock Rb:Sr isochron (Hampton and Taylor, 1983). Dolerite and trachyte dykes give a K–Ar age of *c.* 55 Ma (Edmonds *et al.*, op. cit.) confirming their previously accepted Tertiary age. A more recent age of one dyke by ^{40}Ar–^{39}Ar is 56.4 Ma (Mussett *et al.*, 1988).

The Lundy granite is associated with strong magmatic anomalies together with a strong positive gravity anomaly to the WNW of over

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+20 mgal above the regional gradient, suggesting the occurrence of underlying and nearby basic rocks and perhaps a Tertiary centre like those in W Scotland (Brookes and Thompson, 1973). Its Tertiary age and apparent association with basic magmatism clearly relate it to the other Tertiary granites that were involved in events associated with the opening and widening of the North Atlantic Ocean. Recent work indicates that the present 'Lundy Rhomboid' is an uplifted graben (Arthur, 1989) representing a composite pull-apart formed by sinistral faulting, that Tertiary sedimentation occurred within the graben, and that this was the site of emplacement of the 2.5–4 km thick Lundy igneous complex.

The aims of this paper are to provide the results of a more comprehensive study of the geochemistry of the Lundy granite in order to compare the granite types of Dollar (op. cit.), to relate data and variation patterns to those in the Cornubian granites, to compare briefly with data from other Tertiary complexes, and to examine the petrogenesis of the Lundy granite in the light of these comparisons and its tectonic setting.

Methods of analysis include X-ray spectrometry for most oxides/elements, flame spectrophotometry for Li, titration for FeO and an automated specific ion-electrode method for F, as outlined in Stone *et al.* (1988). Minerals were analysed by combined WD and ED methods on the Cameca electron probe at the Department of Geology, University of Manchester. *REE* were determined by ICP at the Department of Geology, Royal Holloway and Bedford New College.

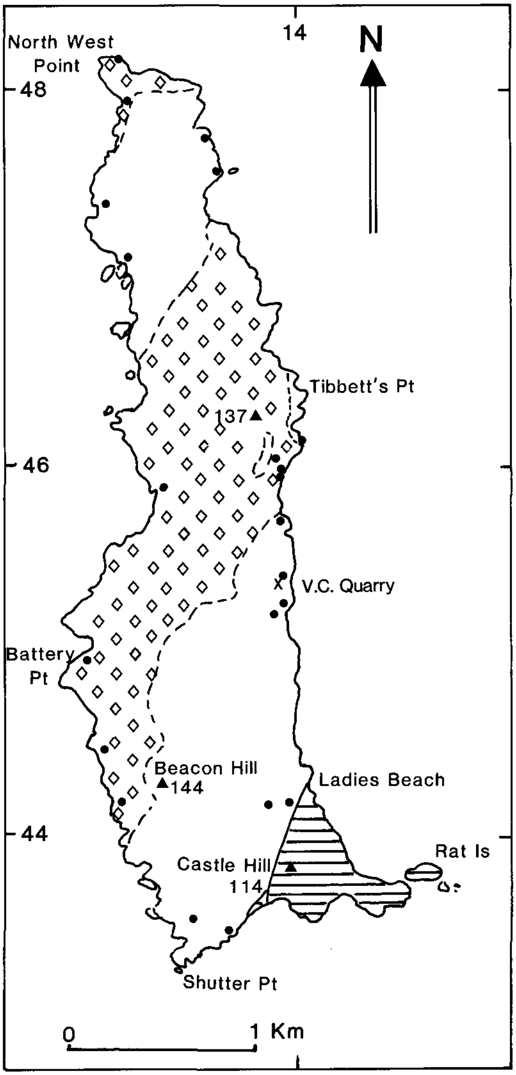

FIG. 1. Geological sketch map of Lundy (based upon Dollar, 1941). Granites: G1—blank; G2—open diamonds. Metasedimentary rocks—ruled. Dykes omitted. Numbers in margins refer to the national grid. Sample localities marked by filled circles.

Granite types and petrography

According to Dollar (1941), the coarse-grained granite that forms most of Lundy comprises two types, an earlier granite, G1, occurring as an irregular subhorizontal sheet which was lifted and fractured into blocks and intruded by the later granite, G2. The latter underlies G1 in the cliffs of the northern part of the island and at some localities in the south (Fig. 1).Both types are cut by microgranites (G3).

The main petrographic differences between G1 and G2 appear to be the occurrence of bipyramidal quartz grains in, and the finer-grained matrix of, the latter. The authors of the BGS Memoir (Edmonds *et al.*, 1979) considered that these criteria were not adequate to separate the two types although they referred to G2 as a megacrystic fine-grained variant which occurs as irregular pods and patches within G1 and suggested that these could represent pieces of the consolidated granite crust caught up in the advancing magma or granitized sedimentary material. Many samples collected from around the island for this study can be grouped into a coarser-grained granite corresponding with G1 and a granite with a finer-grained matrix which would correspond with G2 or its chilled margin, so that the textural differences and their broad distributions observed by Dollar appear to be correct, although it is possible that Dollar overestimated the extent of G2 by linking together isolated occurrences (Dangerfield, 1982). However, there are no obvious mineralogical differences between the two types and, in any case, it would be difficult to map them clearly.

Detailed petrographic accounts are given by Dollar (op. cit.), Shelley (1966), Edmonds *et al.* (op. cit.) and Dangerfield (1982): an outline only is given here. The coarse-grained granite (G1), like that from the V.C. Quarry (GR SS13904137) and elsewhere, contains white K-feldspar megacrysts (typically 1–3 cm long) with numerous inclusions of plagioclase (up to 2 mm) and plagioclase megacrysts, in a medium-grained (1–3 mm) groundmass of biotite, quartz, muscovite, topaz and plagioclase. According to Shelley (1966) and Edmonds *et al.* (1979) many of the K-feldspars are sanidine (small negative 2V), but the occurrence of coarse microperthite suggests orthoclase. Cores of plagioclase megacrysts are commonly altered: indeed 'In some examples, the core has embayed margins suggesting that the plagioclase was strongly corroded prior to the crystallization of further plagioclase or inclusion of quartz' (Shelley, op. cit.). Some specimens contain almandine garnet crystals measuring up to 6 mm in diameter, rimmed and veined by green biotite. A 'reaction' rim of quartz and mica commonly separates garnet from adjacent feldspar grains (Stone, 1988). The other principal granite, G2, has a finer-grained grey matrix (0.1–0.5 mm). Megacrysts of plagioclase (0.5–2 cm) are locally abundant, although usually subordinate to perthitic K-feldspar (typically *c.* 2 cm). Red-brown biotite and topaz occur in the groundmass, together with quartz, the feldspars, and muscovite, as do occasional anhedral garnets (2 mm). Zonal myrmekite and granophyric intergrowths, common in both G1 and G2, are described by Shelley (1966) who relates these phenomena to the crystallization history of the granites. Large quartz grains (3–8 mm across) sometimes provide evidence of late growth by replacement of feldspars in the form of septa and optically continuous patches of quartz in the feldspar.

Microgranite and aplite dykes and sheets (G3) are often weathered. Many are muscovite (±biotite) microgranites, forming steeply-dipping dykes some 2–20 cm or more in width. Others are associated with beryl-bearing pegmatite and layered biotite- and tourmaline-bearing rocks in the V.C. quarry and elsewhere. Dollar (1941) refers to the occurrence of Li-bearing white micas here, although there is no evidence that these rocks are significantly enriched in Li (Table 2; also Table 5 of Edmonds *et al.*, 1979). Occasional true aplites with saccharoidal texture and low mica contents occur as dykes.

Chemical data: minerals

Garnet from G1 and G2 is almandine having the approximate end member composition of $Alm_{81}Sp_{10}Pyr_4Gro_5$. Stone (1988) showed that these garnets have compositions fairly close to those in the Dartmoor granite at Sweltor and concluded that they were most likely derived from source rocks in the lower crust.

Biotite analyses and formulae calculated on the basis of 22 oxygen atoms are given in Table 1:additional analyses are given in Stone (1988). Differences between rock types are not marked. The most striking features are low TiO_2 and MgO and high tFeO (i.e. total iron as FeO), MnO, Rb_2O, Cs_2O, and F compared with many biotites elsewhere, e.g. those from the Caledonian granites in Scotland (e.g. Deer, 1937; Haslam, 1968; Stone, unpublished), although several features compare with biotites of the Cornubian granites (see below). With tetrahedral Al typically close to 2.5, octahedral Al lying within the range 1.6–2 and a tFe/(tFe+Mg) ratio near to 1, these biotites are Fe-rich siderophyllites.

Muscovite analyses (Table 1, cols 7 and 8) yield high tFeO, Rb_2O, and F and, usually, high MnO. Octahedral sites contain just over 4 atoms per formula unit but dodecahedral sites generally have <2 atoms per formula unit. However, with tetrahedral R^{3+} at *c.* 1.7 and octahedral R^{3+} close to 3.6 and high iron contents, these muscovites are clearly phengitic and contain between 10 and 20% of the celadonite component.

Pale brown, faintly pleochroic mica, described by Edmonds *et al.* (op. cit.) as 'probably phlogopite', is more likely to be either a slightly pleochroic, Fe-rich muscovite or partly bleached biotite, both of which are seen in thin section. Phlogopite is unlikely to co-exist with biotite or occur in rocks so markedly deficient in magnesium.

K-feldspar compositions range from $Or_{81}Ab_{19}$ to $Or_{88}Ab_{12}$ with a mean value of $Or_{83}Ab_{17}$: An contents lie in the range 0–0.4%. There is no clear evidence of zoning or difference between coarse granite types and microgranites.

Plagioclase compositions in the coarse granites range from $Ab_{81}An_{19}$ to $Ab_{99.5}An_{0.5}$. Much of this range represents variation observed in normal zoning. Most cores are altered so that core compositions could extend to considerably higher An contents. Bulk compositions lie just below the albite–oligoclase boundary (normative $Ab_{95}An_5$). Edmonds *et al.* (1979) refer to compositions in the range oligoclase to sodic andesine in the

Table 1. Microprobe analyses of micas in the Lundy granites

	<------ Biotite					------>	<-Muscovite	->
	1	2	3	4	5	6	7	8
Spec.No	768	769	778	780	785	762		
Type	G1	G1	G1	incl	G2	G3	Av.GC	Av.G3
wt.%								
SiO_2	36.77	35.84	35.82	36.11	37.02	33.30	46.36	46.66
TiO_2	0.49	1.17	1.81	1.92	1.04	0.40	0.02	0.05
Al_2O_3	23.37	22.16	20.92	20.74	21.08	22.73	32.41	33.42
tFeO	20.14	22.73	25.73	24.37	23.93	25.86	5.00	5.00
MnO	1.04	1.15	0.73	0.90	0.99	1.06	0.19	0.26
MgO	0.08	0.26	0.33	0.37	0.37	nd	0.05	nd
CaO	nd	0.02	nd	nd	nd	0.20	nd	0.02
Na_2O	0.47	0.13	0.41	0.30	0.17	nd	0.66	0.54
K_2O	9.30	9.30	9.12	9.26	9.21	9.20	9.75	8.83
Rb_2O	0.49	0.35	0.31	0.37	0.53	0.38	0.13	0.09
Cs_2O	0.08	0.04	0.02	0.08	0.24	0.12	nd	0.01
F	3.60	3.27	2.40	2.84	2.89	2.89	2.26	3.00
Cl	nd	0.02	0.04	nd	0.11	0.12	nd	nd
Total	95.83	96.44	97.64	97.26	97.59	96.26	96.83	97.88
-O=F,Cl	1.52	1.38	1.02	1.20	1.24	1.25	0.95	1.26
	94.31	95.06	96.62	96.06	96.34	95.01	95.90	96.42
Formulae on basis of 22 oxygen atoms								
Si	5.778	5.664	5.616	5.684	5.795	5.381	6.324	6.294
Al(4)	2.222	2.336	2.384	2.316	2.205	2.619	1.676	1.706
Al(6)	2.105	1.792	1.482	1.531	1.685	1.711	3.530	3.607
Ti	0.058	0.138	0.215	0.227	0.122	0.049	0.002	0.005
tFe	2.649	3.006	3.376	3.208	3.134	3.494	0.577	0.565
Mn	0.138	0.154	0.098	0.120	0.131	0.146	0.022	0.030
Mg	0.020	0.061	0.076	0.086	0.085	---	0.010	---
Sum Y	4.969	5.152	5.246	5.170	5.157	5.399	4.140	4.207
Ca	---	0.004	---	---	---	0.035	---	0.003
Na	0.143	0.041	0.126	0.090	0.052	---	0.173	0.140
K	1.865	1.875	1.824	1.859	1.839	1.896	1.699	1.520
Rb	0.050	0.036	0.031	0.037	0.053	0.039	0.012	0.008
Cs	0.005	0.003	0.001	0.005	0.016	0.008	---	0.001
Sum X	2.063	1.959	1.981	1.991	1.961	1.978	1.884	1.672
F	1.790	1.637	1.193	1.414	1.434	1.477	0.983	1.281
Cl	---	0.004	0.010	---	0.030	0.034	---	---
tFe/(tFe+Mg)	0.993	0.982	0.978	0.974	0.974	1.000		
n	6	9	6	5	5	1	11	11

nd = not detected. Al(4) and Al(6) are tetrahedral and octahedral Al respectively. G1, G2 and G3 as in Dollar, 1941. incl = inclusion of medium-grained granite in G1. Av.GC (col.7) is average in 6 samples of coarse-grained granite (G1+G2); Av.G3 is average of points in 2 microgranite samples. n = number of points analysed.

coarse granite. Zoning of plagioclase is less prominent in the microgranites: the range of compositions is $Ab_{94}An_6$ to $Ab_{99}An_1$ with an average close to $Ab_{95.5}An_{4.5}$, i.e. all within the albite range (normative $Ab_{98}An_2$). Average Or contents (omitted above) lie between 1 and 2% and are similar in both coarse-grained granites and micrograinites.

Chemical data: rocks

Average analyses of the coarse-grained granites G1 and G2, combined G1 and G2 and micrograinites, G3, are given in Table 2.Striking geochemical features in all granite types are high SiO_2, F, Nb, Rb, Ga, Cs, Sn, and Li and low TiO_2, MgO, Zr, Sr, K/Rb, and Ce/Y compared with average continental granite (Taylor, 1964). Kolmogorov-Smirnov one sample tests (Table 2, col. 6) show that the normal distribution can be accepted for all oxides/elements at the 0.01 probability level, so that parametric statistical tests are generally applicable. Average analyses of G1 and G2 (Table 2) are obviously similar, and comparison between them using t-tests (Table 2, col. 7) show no geochemical difference (Mann–Whitney tests yield the same results). However, there are marked differences between these coarser-grained rocks and the late micrograinites (Table 2, col. 8).

Geochemical association and variation. In the correlation matrix (Table 3), strongly positively correlated oxides/elements fall into two main groups, (A) TiO_2, FeO, CaO, Zr, Y, Sr, Ba, La, and Ce, together with Pb, Ni, and Cs and, in part, Li, V, and Zn, and (B) Na_2O, P_2O_5, F, Rb, Ga, Nb, and, in part, Li, Cs, and Mn. Group A occurs in most granitic sequences that have undergone some mafic and accessory mineral fractionation (cf. the 'femic suite/association' of Stone, 1987). Group B (a generally less well-associated 'felsic suite') also has some similarity with the 'trace alkali suites' in the Cornubian batholith, but dif-

Table 2. Chemical analyses of Lundy granites and results of statistical tests

	1	2	3	4	5	6	7	8
Spec.	G1	G2	Av GC	sd	G3	KS	<-t-test->	
							G1/2	GC/G3
Wt.%								
SiO_2	77.43	76.75	77.13	1.35	75.26	0.127	N	**
TiO_2	0.07	0.08	0.08	0.02	0.05	0.116	N	**
Al_2O_3	13.38	12.51	13.00	1.35	14.96	0.121	N	*
Fe_2O_3	0.28	0.31	0.29	0.07	0.26	0.101	N	N
FeO	0.83	0.93	0.87	0.16	0.66	0.161	N	**
MgO	0.04	0.02	0.03	0.03	0.04	0.248	N	N
CaO	0.40	0.42	0.41	0.08	0.28	0.155	N	**
Na_2O	3.45	3.38	3.42	0.16	4.06	0.262	N	N
K_2O	4.35	4.52	4.43	0.27	4.18	0.092	N	N
P_2O_5	0.05	0.07	0.06	0.02	0.12	0.175	N	*
F	0.29	0.25	0.27	0.08	0.37	0.147	N	N
ppm								
Nb	56	56	56	3.8	86	0.248	N	**
Zr	51	58	54	8.9	22	0.117	N	**
Y	54	57	55	5.3	29	0.168	N	**
Sr	9	10	9	3.8	2	0.148	N	**
Rb	478	475	477	62.5	580	0.126	N	*
Mn	367	381	373	91.7	342	0.096	N	N
Ba	83	113	96	52.1	21	0.158	N	**
La	14	17	16	3.5	4	0.129	N	**
Ce	33	35	34	5.5	9	0.127	N	**
U	11	9	10	3.4	10	0.147	N	N
Th	9	9	9	1.1	8	0.138	N	N
Pb	8	15	11	9.5	4	0.281	N	**
Ga	27	26	27	1.6	37	0.257	N	**
Zn	47	53	49	14.8	42	0.130	N	N
Cs	24	30	27	6.6	19	0.095	N	N
Sn	29	28	28	6.8	28	0.153	N	N
Li	259	284	270	84.0	238	0.123	N	*
K/Rb	77	79	78	9.1	61			
Rb/Sr	69	54	62	30.6	286			
Zr+/Ti	12	12	12	2.1	9			
n	9	7	16		6			

Cols 1- average G1: 2- av. G2: 3- av. G1+G2 (GC): 4- standard deviation of values in col. 3: 5- av. G3. Note very low Sr resulting in high Rb/Sr: 6- Kolmogorov-Smirnov statistic (KS); critical values are 0.280 and 0.330 at the 0.05 and 0.01 probability levels respectively: 7 and 8- results of t-tests between G1 and G2 and between total G1+G2 (GC) and G3 respectively: N = not significant: * and ** indicate rejection of the Null hypothesis at the 0.05 and 0.01 probability levels respectively: Zr+ = ZrX100. n = number of analyses.

fers here because Li and Cs have positive correlations with members of each group.

Simple bivariate plots between oxides/elements of Group A, hereafter referred to as the 'femic suite', show the expected linear arrays of data points that define regression lines having positive slopes. Zr *vs.* TiO_2 (Fig. 2*a*)and Y *vs.* Zr provide examples that show a marked decrease of the Lundy 'femic suite' in the later microgranites, but again do not separate G1 and G2.

Rare earth elements. A plot of Ce_N *vs.* Y_N (analysed by XRF and normalized using chondrite values in Wood *et al.*, 1979) in Fig. 2*b* compares with that of Fig. 2*a* and again illustrates the strong coherence between elements of the 'femic suite'. The regression line has a slope close to +2 implying only slight *LREE* enrichment and *REE* patterns that are (*a*) flat compared with those of many other granitoid suites and (*b*) similar to one another despite differences in actual abundances of total *REE*. *REE* data (Table 4) and chondrite-normalized plots (Fig. 3) reveal flat patterns and large europium anomalies. All the coarser granites have similar patterns and similar slopes in the *LREE* pattern. The single G3 sample has a much lower total *REE* than the coarse granite and a more convex upwards profile. Ce_N/Yb_N is <4 and Eu_N/Eu_N^* (where Eu_N^* is the value of Eu_N interpolated between Sm_N and Gd_N) is 0.24 to 0.08 in the coarse granite and <0.03 in the single G3 sample.

Rock patterns for the coarser granites are reflected in the flat biotite patterns, even to the slight Nd depression. The almandine pattern has a much higher total *REE* content and, as expected, a strong *HREE* enrichment, but with an anomalously high Er value, although the *LREE* end is parallel to the biotite and rock patterns.

Comparison with other Tertiary granites and Cornubian granites

Geological setting. The Cornubian batholith occurs in a Hercynian continental collision setting in which there is an absence of contemporary basic magmatism at the present exposure level. Accounts by Floyd (1972), Badham and Halls (1975), Mitchell (1974), Bromley (1975), and Floyd *et al.* (1983) give some idea of the differing interpretations of the nature of subduction and collision. On the other hand, the Tertiary centres were emplaced in attenuated crust associated with faulting that accompanied the opening of the North Atlantic (Bott and Watts, 1971; Dewey and Windley, 1988). Associated magmatic activity occurred mainly in the interval 63–52 Ma, mostly concentrated close to 59 Ma. Although acid magmatism followed basic in most cases, the latter occurred at intervals throughout (Mussett *et al.*, 1988).

The shallow thickness of the Lundy granite (*c.* 1.2 km according to Bott *et al.*, 1958) is consistent with present depths of the granites of Skye (Bott and Tuson, 1973) and Mull (Bott and Tantrigoda, 1987). Gravity surveys over central complexes typically reveal marked positive Bouguer anomalies that are nearly circular in plan. These, as in the case of the recently investigated Mull centre (Bott and Tantrigoda, op. cit.), are interpreted in terms of large cylindrical masses of underlying dense gabbroic or ultrabasic rocks (see Bott and Tuson, 1973), perhaps like those exposed on Skye and Rhum, emplaced by ring subsidence and stoping. It follows that basic magmas have played a major role in the development of central complexes, even though in centres such as Lundy, North Arran and the Mourne Mountains, granite predominates at the present exposure level. Fea-

Table 3. Abridged Pearson product moment correlation matrices

(a) 'Femic suite'

	TiO_2	FeO	CaO	Zr	Y	Sr	Ba	La	Ce
FeO	0.659	---	---	---	---	---	---	---	---
CaO	0.757	0.560	---	---	---	---	---	---	---
Zr	0.805	0.532	0.604	---	---	---	---	---	---
Y	0.720	0.523	0.562	0.954	---	---	---	---	---
Sr	0.664	0.124	0.499	0.769	0.742	---	---	---	---
Ba	0.769	0.278	0.562	0.750	0.681	0.917	---	---	---
La	0.763	0.535	0.484	0.862	0.886	0.788	0.739	---	---
Ce	0.828	0.546	0.675	0.934	0.944	0.790	0.753	0.911	---
Pb	0.630	0.151	0.515	0.662	0.605	0.646	0.727	0.629	0.637

(b) 'Felsic suite'

	Al_2O_3	Na_2O	P_2O_5	F	Nb	Rb	Mn	Ga	Cs
Na_2O	0.208	---	---	---	---	---	---	---	---
P_2O_5	0.026	0.066	---	---	---	---	---	---	---
F	0.157	0.579	0.382	---	---	---	---	---	---
Nb	0.566	0.676	0.636	0.467	---	---	---	---	---
Rb	0.244	0.736	0.664	0.732	0.683	---	---	---	---
Mn	-0.182	0.259	0.040	0.378	0.024	0.507	---	---	---
Ga	0.516	0.578	0.636	0.512	0.877	0.720	-0.007	---	---
Cs	-0.261	-0.059	-0.065	0.197	-0.189	0.151	0.527	-0.320	---
Li	-0.355	0.127	0.194	0.580	-0.183	0.436	0.638	-0.047	0.551

Critical values for rejection of the Null hypothesis (i.e. $r = 0$) are 0.413, 0.526 and 0.640 at the 0.05, 0.01 and 0.001 probability levels respectively.

tures like the occurrence of miarolitic cavities, bipyramidal quartz crystals (as in G2 of Lundy) that suggest paramorphs after high-temperature quartz, and evidence for higher-temperature alkali feldspar, together with the common lack or paucity of pegmatite in several Tertiary granites, support the idea of high-level emplacement (cf. Tuttle and Brown, 1958).

Direct evidence for the nature of emplacement of the Lundy granite is lacking. However, Arthur (1989) suggested that '... the dominant WNW–ESE pattern of dykes is inconsistent with the granite buoyantly uplifting the area overlying it ...' but that it is consistent with permitted emplacement in a pull-apart associated with sinistral faulting. Diapiric features are apparent in the North Arran granite (BGS 1:50 000 map of Arran and field mapping with student groups) and possibly on the northeast margin of the Mourne Mountains (Emeleus, 1982), although most of the latter granite, like the Western Red Hills of Skye (Thompson, 1969) and elsewhere, appears to have been emplaced passively, perhaps by ring dyke intrusion and cauldron subsidence.

Pearce *et al.* (1984) have used certain elements to discriminate composition fields in granitoids that correspond with tectonic setting. All groups considered here fall into the field of 'syn–collision granites' (syn–COLG) in a Rb *vs.* SiO_2 plot (not shown), although the Lundy granite plots with the composition field of the Cornubian granites and is separated from the Arran rocks. In the Nb *vs.* Y diagram (Fig. 4*a*), Arran and Lundy data points plot in the 'within plate granite' (WPG) field whilst Cornubian granite data points plot in the syn-COLG field, although the Dartmoor granite data points overlap into the WPG field. Lundy micrograntes have higher Nb but lower Y contents than their host granites. The Rb *vs.* (Nb + Y) plot (Fig. 4*b*) clearly separates all three groups. Cornubian rocks plot in the syn–COLG field, again with Dartmoor data points lying closer to the WPG boundary: Arran data points plot inside the WPG field, but the Lundy granite points fall on the WPG–syn-COLG boundary. Cornubian microgranites show a wider scatter than their associated host granites in both plots.

Mineralogy. Although almandine occurs both in the Lundy granite and the Cornubian batholith (Stone, 1988), other Al-rich accessory minerals like cordierite, sillimanite, and andalusite which occur in the latter have not been observed in the former. On the other hand, fayalite, clinopyroxene, amphibole/alkali amphibole, and titanite occur in some Tertiary granites (e.g. Mourne,

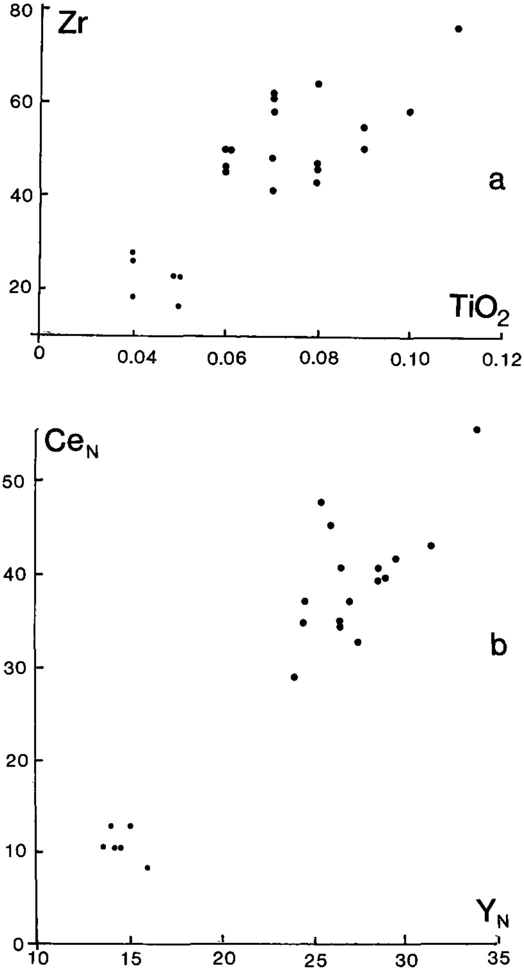

FIG. 2. Bivariate plots of Lundy granites. (*a*) Zr ppm *vs*. TiO_2 wt%; (*b*) Ce ppm *vs*. Y ppm, normalized using chondrite values in Wood *et al*. (1979). Granite (G1 and G2)—large filled circles; microgranite—small filled circles.

Skye, North Arran: Bell, 1982) but are not observed in the Lundy granite at the present exposure level.

Comparison between Lundy biotites (average G1, G2, and G3) and Cornubian and North Arran biotites are shown in Fig. 5. Similarities between Lundy and Cornubian biotites include high total Al (> 3.6), octahedral Al (although Lundy biotites have much more: Fig. 5*b*) and total iron as Fe (tFe) in the formulae. On the other hand, Lundy biotites have low Ti (Fig. 5*a*) and Mg together with high tFe/(tFe+Mg) (Fig. 5*c*) and high Mn compared with Cornubian biotites; also, F (Fig. 5*d*) and Rb tend to be higher than in the

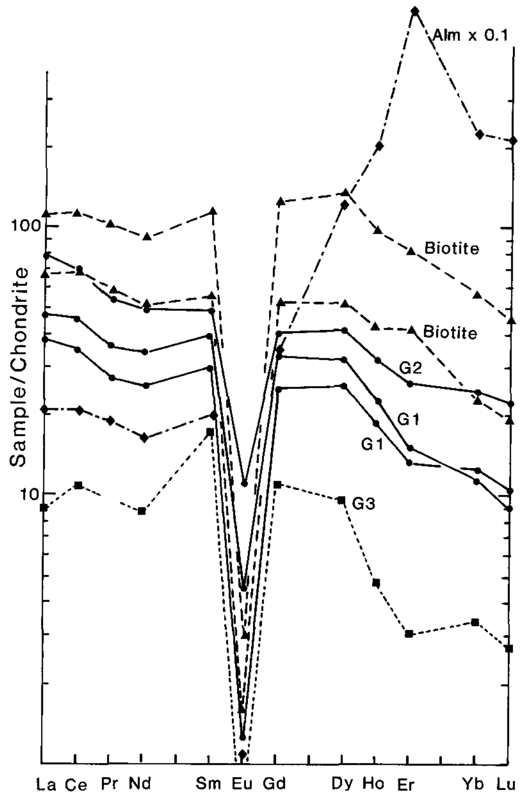

FIG. 3. Chondrite-normalized *REE* plot of Lundy samples using chondrite values of Evensen *et al*. (1978). G1 and G2 (filled circles) are the two main granite types of Dollar (1941); G3—microgranite (filled squares); biotites (filled triangles) and almandine (alm—filled diamonds) are labelled: almandine values are divided by 10.

latter. Biotites from the outer and inner members of the Tertiary Northern granite of Arran have much lower Al and octahedral Al (Fig. 5*b*) and higher tFe than Lundy and Cornubian biotites, whilst Ti, Rb, and F are similar to the latter (Fig. 5). Thus, while Cornubian and Lundy biotites are siderophyllites, with Lundy samples lying closer to the siderophyllite end-member of the eastonite–siderophyllite series than the Cornubian micas, the Arran biotites are mostly closer to annite in composition.

Muscovites from the Carnmenellis and Isles of Scilly plutons (Stone, unpublished; Stone and Exley, 1989) have much higher Ti and Mg and lower tFe, F, and commonly Rb than those in the Lundy granites. Indeed the high F contents of Lundy muscovites are remarkable and compare with those in zinnwaldite–albite–topaz pegmatites

Table 4. REE data for Lundy granites and minerals

	1	2	3	4	5	6	7
Sample	761	770	768	771	778B	772B	772G
	GC	GC	GC	G3	GC	GC	GC
La	19.95	11.72	9.01	2.20	16.50	27.70	50.59
Ce	44.86	29.31	22.68	7.00	43.65	73.40	132.59
Pr	5.20	3.47	2.65	<1.22	5.65	9.88	17.78
Nd	23.42	16.14	12.23	4.10	24.24	43.14	77.04
Sm	7.59	6.17	4.70	2.66	8.58	17.93	30.85
Eu	0.63	0.26	0.14	<0.08	0.09	0.17	0.65
Gd	8.40	6.81	5.15	2.29	10.85	25.79	70.14
Dy	10.62	8.25	6.61	2.47	13.54	34.48	320.52
Ho	1.95	1.29	1.06	0.27	2.43	5.54	115.73
Er	4.37	2.50	2.21	0.52	7.09	13.65	1078.80
Yb	4.11	1.92	2.09	0.57	3.85	9.39	374.26
Lu	0.57	0.23	0.27	0.07	0.50	1.15	54.71
tREE	131.31	88.07	68.80	22.15	136.97	262.22	2323.66
Ce_N/Yb_N	2.83	3.95	2.81	3.18	2.93	2.02	0.09
Eu_N/Eu_N^*	0.24	0.12	0.09	<0.03	0.03	0.02	0.04

tREE = total REE; subscript N refers to normalization using chondrite values in Evensen et al. (1978). Eu_N^* is the normalized europium value obtained by interpolation between Sm_N and Gd_N. GC = main granite (i.e. G1+G2); G3 = microgranite.

associated with the Tregonning granite (Stone, unpublished). Muscovite is uncommon in the other Tertiary granites.

Major and trace elements. Lundy and North Arran granites show broad similarities in several major elements, but marked differences in some trace and minor elements (Table 5), for example, higher P_2O_5, F, Nb, Rb, Cs, Li, U, Ga, and Sn and lower Zr, Y, Sr, Ba, La, and Ce in the Lundy rocks. Data for the later granites of the Mourne Mountains (Meighan *et al.*, 1984) have many of the features of the Arran rocks, but compare with Lundy in having high Rb, Rb/Sr, Cs, and U and low K/Rb (Table 5, cols 11 and 12). Indeed, in grouping the Tertiary granites, Thompson (1982) placed the Mourne Mountains G2 and Lundy G1 together as subalkaline leucogranites. The Cornubian type B granites (Exley and Stone, 1982) in the Isles of Scilly, Carnmenellis and Dartmoor plutons differ from the Lundy (and Arran) granites in many major oxides, e.g. SiO_2, TiO_2, MgO, CaO, and P_2O_5 and some trace elements such as Sr, Ba, and Y, although microgranite/aplite dykes (i.e. late differentiates) from the Carnmenellis and Isles of Scilly plutons are closer in composition to the Lundy and Arran granites in several respects (Table 5; Fig. 7). On the other hand, Cornubian megacrystic biotite granites and Lundy granites have broadly similar Al_2O_3, Mn, Rb, U, and Li. In fact both rock suites are enriched in the trace alkali elements and probably Sn and F compared with other Tertiary granites (Meighan, 1979; Walsh *et al.*, 1979; Thompson, 1982) and typical Caledonian granites (Stone, unpublished). Lundy and Cornubian granites also have similar K/Rb, Zr/Ti and aluminium saturation indices (ASI) of Zen (1986).

Variation patterns. In the Zr *vs*. TiO_2 plot (Fig. 6*a*), Arran samples show a trend towards the data points of the Lundy rocks, although the two Arran microgranites do not lie along this line. On the other hand, the Cornubian granites follow a trend that ends in a microgranite field coincident with the Lundy microgranites. Data points for some of the Mourne granites (Meighan *et al.*, 1984) occur close to Arran points but extend to much higher values of Zr: indeed, high Zr is a feature of most of the Tertiary granites and contrasts with the lower values found in the Lundy rocks. Similar patterns are shown by other pairs of 'femic suite' oxides/elements and also the plot of K/Rb *vs*. TiO_2 (Fig. 6*b*). In this, all three rock suites show a marked decrease in K/Rb (an index of differentiation?) with TiO_2. Despite having different slopes, the longer paths taken by Cornubian and Arran granites converge on the composition fields of the Lundy rocks. Note that the early granites have higher K/Rb in all cases and that the early Arran rocks have a higher K/Rb than the Lundy and Cornubian rocks, both of which have similar ranges and values. Average Mourne granite data points plot close to the Cornubian rocks and late differentiates plot in the composition fields of Lundy granites and microgranites.

Trends shown in the Minitab output of means and confidence intervals (Fig. 7) reveal the marked fractionation of the 'femic suite' oxides/elements. TiO_2 (Fig. 7*a*) and, particularly, Zr (Fig. 7*d*) show marked decreases in each of these rock suites: trends are more extreme in the Cornubian rocks, but, in the case of Zr, Cornubian differentiates are like the Lundy rocks. CaO (Fig. 7*b*) behaves similarly, and again, the more marked fractionation (of anorthite) is shown by the Cornubian rocks. The MgO pattern (Fig. 7*c*) shows little variation in the Tertiary rocks and marked trends in the Cornubian rocks: again the differentiates of the latter trend towards the low MgO contents of the former. Ce (Fig. 7*e*) and Y show decreases in later fractions, consistent with the *REE* patterns of later granitoid differentiates. Rb and F undergo marked increases in the later granite fractions of both Tertiary centres. There is enormous increase in Ga in the Lundy microgranites (G3): this is a highly significant jump that accompanies a marked increase alumina (Table 5), shown separately by all six microgranite samples. As expected, Sn is high in the Cornubian granites and appears to show a pro-

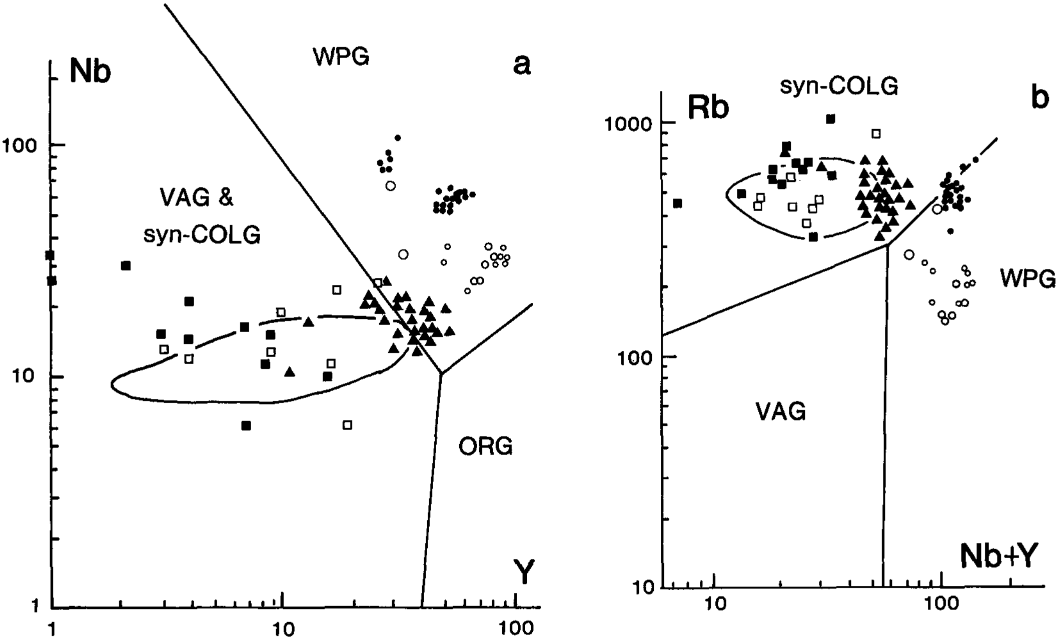

FIG. 4. Geochemical tectonic discriminant plots (after Pearce *et al.*, 1984). (*a*) Nb ppm *vs.* Y ppm; (*b*) Rb ppm *vs.* (Nb + Y) ppm. Straight lines separate fields of syn-collision granites (syn-COLG), within-plate granites (WPG) and orogenic granites (ORG) or volcanic arc granites (VAG). Isles of Scilly and Carnmenellis (outer) granite data points enclosed in solid lines. Symbols: Dartmoor megacrystic biotite granite—filled triangles; Isles of Scilly and Carnmenellis microgranite—open and filled squares respectively; Lundy granite and microgranite—small filled circles (the six microgranites form a distinct group in 4*a* but not 4*b*); Arran microgranite, outer (coarse) and inner (fine) granite—large, medium, and small open circles respectively.

gressive increase from W to E, but the Lundy values are so much higher that it is a truly stanniferous granite (Table 3). The ASI also increases in the later Lundy rocks (Fig. 7*f*) compared with the Cornubian rocks: both are clearly peraluminous, whereas the Arran granites (and later Mourne granites; Table 5) have values close to 1 and are metaluminous or subalkaline, but show no trends with time.

REE patterns. Ce_N/Yb_N for Lundy granites is <4 (although a sample of G1 in Meighan (1979) has a ratio of 9.7) compared with values >20 for most of the Cornubian coarse-grained biotite granites. Cornubian microgranites can have much lower values (commonly <8) that compare more closely with the Lundy ratios, but at lower values of total *REE*. Ce_N/Y_N ratios for Arran rocks (*c*. 1–4) compare with those of Lundy (0.5–2) and are much lower than those of Cornubian coarse biotite granites (typically 12–15). Likewise, Ce_N/Yb_N for Arran rocks (2.9 and 1.7 for outer and inner granites, respectively; data in Meighan, 1979) are comparable (Table 4).

The close similarity between biotite and host rock *REE* patterns in the Lundy samples compares with the similarities in the Carnmenellis (Charoy, 1986; Stone, 1987) and Isles of Scilly (Stone and Exley, 1989) samples, where both rock and biotite patterns mirror the accessory mineral patterns. Accessory minerals, mainly those included in biotite, were examined with the aid of a Philips 501B SEM fitted with a LINK Systems microanalyser. Most of the included accessory minerals in the Cornubian granite biotites are monazites, together with zircon, apatite, manganiferous ilmenite, and very little xenotime (cf. Jefferies, 1985). In the Lundy rocks, zircon occurs with readily identified xenotime and monazite. Tiny amounts of xenotime readily dictate the *HREE* abundances so that small changes in amounts of this mineral can markedly change the shape of the *REE* pattern. Indeed, the biotite pattern in these rocks is clearly the result of inclusions of monazite, zircon, and xenotime and, to a lesser extent, apatite. It follows from the similarity between biotite and rock patterns that the latter are also dictated by these accessory minerals. Clearly, as almandine is not observed as inclusions

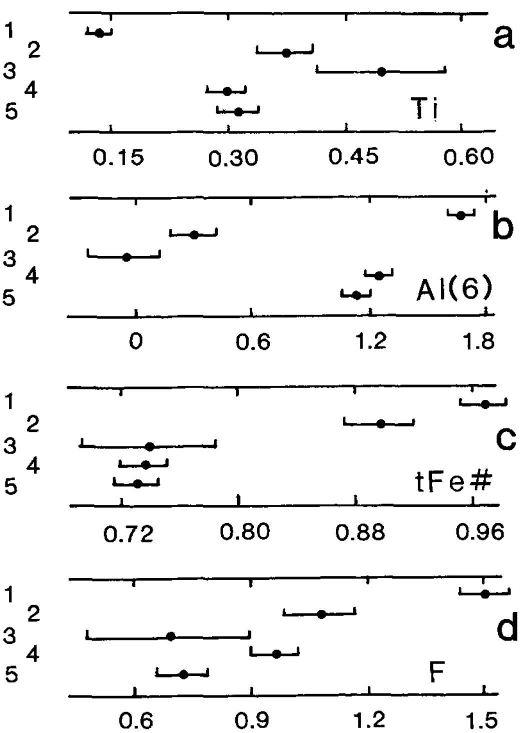

FIG. 5. Formula data for biotite, based on 22 oxygen atoms: means and 95% confidence intervals based upon pooled standard deviations: taken from the Minitab oneway analysis of variance output. (*a*) Ti; (*b*) Al(6)—octahedral Al; (*c*) tFe – tFe/(tFe + Mg) where tFe is total iron atoms as Fe^{2+}; d. F. 1, Lundy granite (all biotites); 2, Arran outer granite; 3, Arran inner granite; 4, Isles of Scilly outer granite; 5, Carnmenellis outer granite.

in biotite, its effect on the *HREE* is subordinated by that of xenotime. Also, it is possible that part of the almandine *REE* pattern is itself determined by tiny accessory mineral inclusions.

Discussion

Role of fractionation. Observed chemical trends are based upon samples collected at the present exposure level, so that breaks in continuity, both in the field and in the variation patterns in the Lundy and other rock suites, suggest that the processes causing variation took place below the present exposure levels. The broad patterns of variation referred to above (Figs. 6 and 7) are common to all the rock suites examined, and despite following different paths, end in microgranites that have many geochemical features in common and near-coincident bivariate composition fields. This suggests that the processes leading to the formation of later differentiates were similar in all cases.

Stone (1987) and Stone and Exley (1989) proposed that trends of decreasing 'femic suite' oxides/elements and falling *REE* patterns in the Cornubian rocks were consistent with biotite and accessory mineral fractionation. Such patterns are characteristic of most granites, including those that have earlier undergone hornblende/titanite/allanite/apatite fractionation. In the Lundy pluton, microgranites appear to be late differentiates resulting from biotite and accessory mineral fractionation.

The Cornubian biotite granites are quite highly fractionated rocks in terms of low K/Rb, high Rb/Sr, and low Zr, TiO_2 and other 'femic suite' constituents and associated microgranites are even more highly fractionated. In Figs 6*a* and *b*, the Lundy trend from coarse-grained biotite granite to microgranite is short compared with the Cornubian and North Arran trends implying that the earlier coarse-grained granite is almost as fractionated as the various microgranites. This is also shown by the high differentiation indices (*c*. 94), low normative anorthite (< 1.7), enrichment of Lundy biotite granites in the trace alkali elements, Nb, Sn, and F, and their low values of K/Rb and very high Rb/Sr which reflect the highly evolved nature of the earlier granite. Such highly fractionated rocks imply either very low degrees of melting of source rocks or, more likely, marked crystal fractionation at source or in transit to the present site.

Rare earth element patterns. The Ce_N/Yb_N ratios of the Lundy samples are similar to those of many other Tertiary granites, for which there is evidence of basaltic parentage (Thorpe *et al.*, 1977; Thorpe, 1978; Walsh *et al.*, 1979; Thompson, 1982; Walsh and Clarke, 1982), but their Eu anomalies are generally larger (numerically smaller), like those in the later granites of the Mourne Mountains (Meighan *et al.*, 1984).

The tendency for total *REE* to decrease in later granite differentiates, along with the 'femic suite', is a feature of the Lundy and Cornubian and other granites (e.g. Pankhurst, 1979) in which the trend in set by the fractionation of granite constituents that carry the *REE*: these may be earlier-formed crystals or restite. Marked differentiation of the Cornubian granites produced both a flattening of the *REE* pattern and lower total *REE*, whereas the flat Lundy *REE* pattern occurs in rocks with comparable total *REE* to the earlier Cornubian rocks. This could imply derivation of the presently exposed Lundy granites from earlier, more primitive, magma with a higher value of Ce_N/Yb_N and

Table 5. Tertiary and Hercynian granites

	1	2	3	4	5	6	7	8	9	10	11	12
	LGC	LG3	AO	AI	Amg	SC2	SCmg	CM1	CMmg	DT	MG2	MG3
Wt.%												
SiO_2	77.13	75.26	75.87	78.27	78.44	71.52	75.33	72.18	75.71	73.29	78.2-	76.9-
TiO_2	0.08	0.05	0.17	0.10	0.07	0.24	0.08	0.25	0.07	0.28	0.11	0.05
Al_2O_3	13.00	14.96	11.55	12.19	12.37	14.84	14.31	15.13	14.42	14.04	11.83	12.73
Fe_2O_3	0.29	0.26	0.87	0.59	0.46	0.53	0.28	0.45	0.56	0.85	0.25	1.09*
FeO	0.87	0.66	0.83	0.55	0.54	1.02	0.65	1.25	0.48	1.42	1.01	--
MgO	0.03	0.04	0.08	0.05	0.00	0.36	0.22	0.43	0.13	0.36	0.08	0.06
CaO	0.41	0.28	0.65	0.54	0.32	0.81	0.50	0.96	0.57	0.80	0.63	0.49
Na_2O	3.42	4.06	3.23	3.70	4.25	2.94	3.31	3.06	3.76	3.00	3.49	4.01
K_2O	4.43	4.18	4.93	4.74	4.84	5.42	5.01	5.09	4.29	5.12	4.76	4.43
P_2O_5	0.06	0.12	0.01	0.01	0.00	0.23	0.22	0.24	0.26	0.21	0.02	0.01
F	0.27	0.37	0.08	0.13	---	0.24	0.17	0.37	0.49	---	---	---
ppm												
Nb	56	86	29	31	50	12	14	12	18	17	--	--
Zr	54	22	190	138	168	117	29	110	25	127	136	164
Y	55	29	77	78	33	16	15	16	5	35	--	--
Sr	9	2	43	12	3	108	29	87	27	63	16	<5
Rb	477	580	160	206	353	441	508	492	604	509	424	665
Mn	373	342	260	183	193	236	226	339	259	407	--	--
Ba	96	21	922	185	37	420	259	259	111	228	21	<10
La	16	4	52	41	9	25	8	35	1	33	59	49
Ce	34	9	104	90	28	78	8	73	19	51	131	105
U	10	10	4	4	7	7	4	14	12	17	15	--
Th	9	8	13	15	23	27	6	14	3	30	52	--
Pb	11	4	23	25	35	37	30	34	15	31	--	--
Ga	27	37	17	18	23	21	21	21	23	17	--	--
Zn	49	42	49	35	36	37	38	42	48	40	--	--
Cs	27	19	2	4	10	30	31	50	46	51	17	--
Sn	28	28	6	7	11	9	13	12	15	16	--	--
Li	270	238	36	64	168	293	195	423	295	359	--	--
K/Rb	78	61	261	195	120	103	87	86	65	87	93	55
Rb/Sr	62	286	4	17	45	4	22	7	34	13	27	>133
Zr+/Ti	12	9	18	23	52	8	7	8	7	8	21	55
ASI	1.18	1.32	0.98	1.00	0.97	1.29	1.28	1.30	1.29	1.24	0.98	1.04
n	16	6	5	8	2	22	9	34	14	29		

* total Fe as Fe_2O_3; Zr+ = ZrX100; ASI = Aluminium Saturation Index; --- not determined or stated; n = no. of samples. Cols 1- LGC - Lundy granite (G1+G2): 2- Lundy microgranite (LG3): 3, 4 and 5- Arran outer (AO), inner (AI) granite and microgranite (Amg): 6 and 7- Isles of Scilly outer granite (SC2) and microgranite (SCmg); 8 and 9- Carnmenellis outer granite (CM1) and microgranite (CMmg); 10- Dartmoor coarse-grained granite (DT); 11 and 12- Mourne Mts granites G2 and G3 (Tables V and VI in Meighan et al., 1984).

much higher total *REE*. Certainly, the exposed Cornubian granites are unlikely to have provided such a source directly.

The principal carriers of *REE* in most granites are the accessory minerals monazite, zircon, apatite, xenotime, orthite, and titanite (Mittlefehldt and Miller, 1983; Gromet and Silver, 1983; Jefferies, 1985; Stone, 1987). Accessory mineral fractionation would result in a lowering of the *REE*, together with Th, P, etc. In monazite-rich rocks, fractionation of this mineral, often included, in part, in biotite and hence also reflecting biotite fractionation, would result in a fall in the *LREE*:*HREE* ratio (Miller and Mittlefehldt, 1982) and hence in Ce_N/Yb_N and Ce_N/Y_N, as in the case of Cornubian granites (Stone, 1987; Stone and Exley, 1989). In the Lundy rocks, Ce_N/Y_N and Ce_N/Yb_N are much lower and, on the basis of evidence given below, it is proposed that the flat *REE* patterns result from the presence of more xenotime than in the Cornubian rocks alongside monazite and zircon and, perhaps, almandine. Overall removal of these accessories in more or less the proportions in which they occur initially will merely drop the flat pattern to lower levels, as observed in Fig. 3. If biotite crystallized early or is restite material, it follows that the accessory mineral suite also crystallized early or is restite.

A plot of Sm_N *vs*. Ce_N/Yb_N (Fig. 8) of rocks and biotites from the Cornubian batholith and Lundy clearly suggests that biotite fractionation, and this also means accessory mineral fractionation, could have produced the trends towards late differentiates. This plot also suggests that the Cornubian and Lundy trends follow different paths. In the Lundy rocks, the Ce_N/Yb_N ratio remains almost constant with falling Sm_N (and total *REE*), whilst the Cornubian rocks show a fall in both variables. The latter is interpreted in terms of dominant monazite fractionation, the former of xenotime, monazite, and zircon (and some almandine) fractionation. The different trends again indicate that the Lundy rocks are unlikely to have

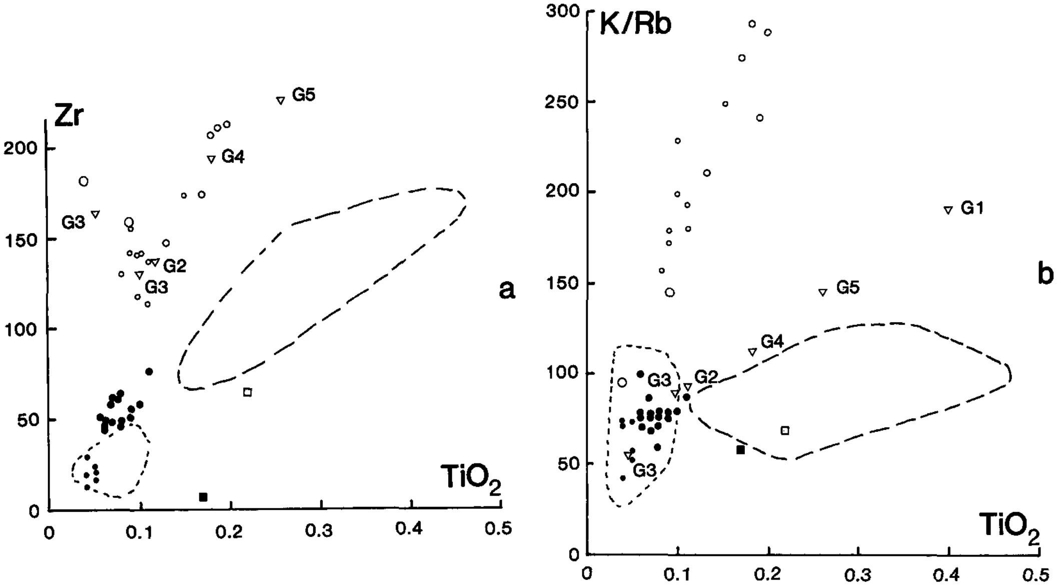

FIG. 6. Bivariate plots for Lundy, Arran, Mourne and Cornubian granite data. (*a*) Zr ppm *vs*. TiO_2 wt.%; (*b*) K/Rb *vs*. TiO_2 wt.%. Large dashes enclose field of Cornubian coarse-grained biotite granites (Dartmoor, Carnmenellis and Isles of Scilly); smaller dashes enclose field of Carnmenellis and Isles of Scilly microgranites. Large and small filled circles are data points for Lundy granite and microgranite respectively; large, medium, and small open circles are Arran microgranites, outer, and inner granites respectively; inverted open triangles are Mourne data points from Meighan *et al.* (1984, table V), numbers correspond with columns in this table.

arisen directly from Cornubian-type granites or granite magmas.

Evidence for crustal source. It follows from the previous discussions that the earlier emplaced and least fractionated rocks are more likely to carry signatures of source materials than their later fractionates. As in the Cornubian granites, the occurrence of muscovite (not necessarily primary), Al-rich biotite, K-feldspar megacrysts, a marked peraluminous character—high normative corundum (*c.* 2.2 in the main granite and >3.5 in the microgranites) and high ASI (*c.* 1.2 and 1.3, Table 5), a high trace alkali content, high Rb/Sr, low K/Rb and high Sn suggest that the Lundy granites belong to the S-type granitoids of Chappell and White (1974) and hence could have a prominent crustal source component. This is further supported by Sr (initial $^{87}Sr/^{86}Sr = 0.7194$) and Pb isotope data (Hampton and Taylor, 1983): this work also points to a source with high Rb/Sr (i.e. one not depleted in LIL elements) of late Proterozoic age. Cordierite in the Lundy granite is referred to by Dollar (1941) but has not been observed by the present writer: the occurrence of 'primary' cordierite would provide strong evidence of a true S–type granite (White *et al.*, 1986).

The high ASI values of the Lundy rocks and biotites roughly match those of the Cornubian batholith and the S-type granites of the Lachlan fold belt (White and Chappell, 1988) and provide further evidence for a crustal source component. Later rocks (G3) show a small increase in ASI implying either feldspar and biotite fractionation from a magma already enriched in Al or, perhaps, alkali loss via a late-stage magmatic vapour phase. However, the more primitive Tertiary granites are hornblende-bearing and fractionation of this mineral in metaluminous/subalkaline magmas and, indeed, once the ASI exceeds 1, feldspar fractionation, can produce peraluminous rocks (Zen, 1986). Thus, whilst high ASI often points to a crustal source, it can be produced by strong hornblende and feldspar fractionation and lead to the crystallization of 'primary' aluminous minerals.

Conclusions

In the light of comparison with the Tertiary granites of Scotland and Ireland, a good case can be made for the origin of the Lundy granite by strong differentiation of primitive granite magma, itself arising by differentiation of basaltic magma. Similarities are tectonic setting, indications of a

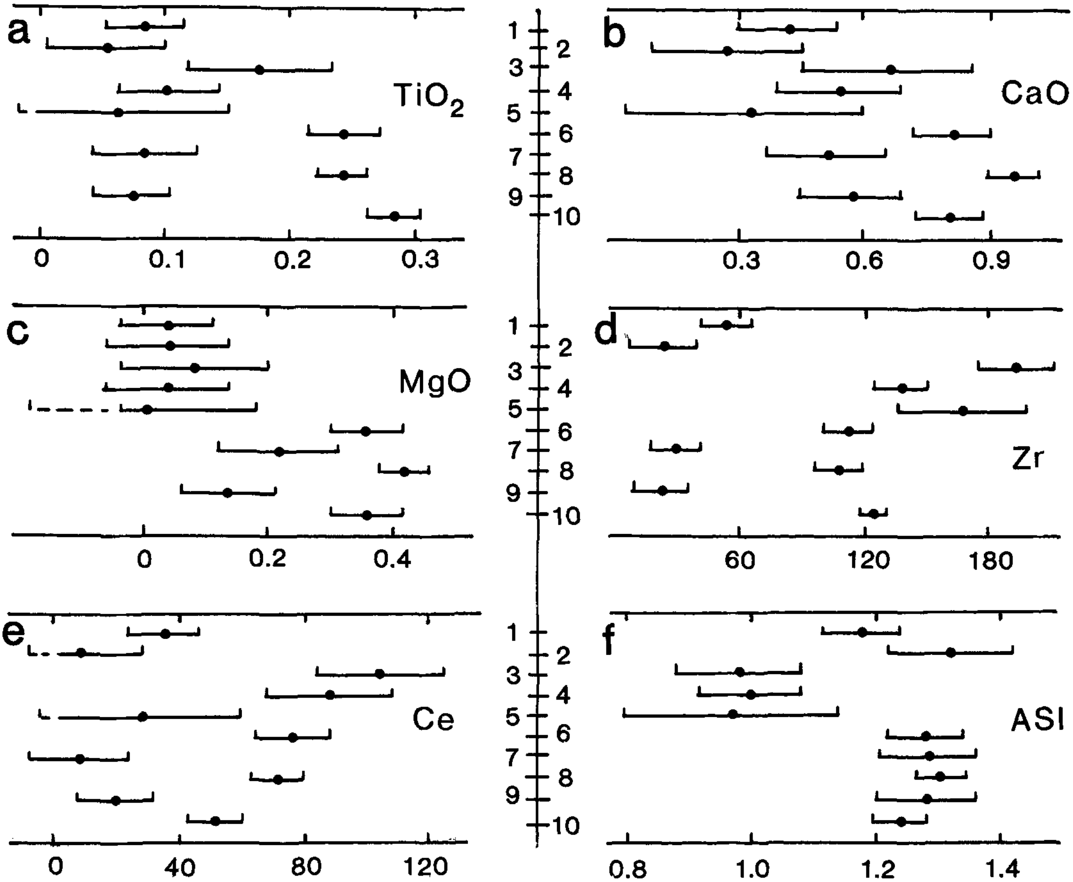

FIG. 7. Mean and 95% confidence intervals based upon pooled standard deviations for (*a*) TiO_2 wt.%; (*b*) CaO wt.%; (*c*) MgO wt.%; (*d*) Zr ppm; (*e*) Ce ppm; (*f*) aluminium saturation index (ASI). From Minitab as in Fig. 5. Bar lines extend to negative values at low means with large spreads and as a result of pooling the variance. 1, Lundy granite; 2, Lundy microgranite; 3, Arran outer granite; 4, Arran inner granite; 5, Arran microgranite (2 samples only); 6, Isles of Scilly outer granite; 7, Isles of Scilly microgranite; 8, Carnmenellis outer granite; 9, Carnmenellis microgranites; 10, Dartmoor granite.

former high-temperature mineralogy, close association with basaltic magmatism and hence mantle activity, high SiO_2 and low TiO_2, MgO and P_2O_5 contents, and flat chondrite-normalized *REE* patterns. Perhaps the precursor of the earlier granite on Lundy is not yet exposed: like the Mourne G1 granite, it could have features that relate it to differentiation from basic rocks. However, the S-type granite features listed above and many close similarities, such as the trace alkali, F, Nb, Sn, and U enrichments and low Zr, suggest an affinity with the Cornubian granites and, perhaps in part, a similar source.

The highly evolved nature of the Lundy granite could suggest direct derivation from a Cornubian-type granite magma by crystal differentiation or partial melting, but this is unlikely due to the different *REE* patterns, in particular, the markedly higher Ce_N/Yb_N ratios in the latter compared with the former, the very different 'biotite' fractionation trends in the Sm_N *vs.* Ce_N/Yb_N plot (Fig. 8), and the absence of large subsurface volumes of granite. Partial melting of small extent could produce the more highly evolved Lundy rocks, as these have many chemical similarities with the Cornubian late differentiates, but again, the *REE* abundances and patterns are not readily explained unless the *REE* and particularly, the *HREE* can be concentrated by some other mechanism. Also, there is always the problem of separating small amounts of partial melt from their host rocks to form larger bodies of granite (Pitcher, 1987;

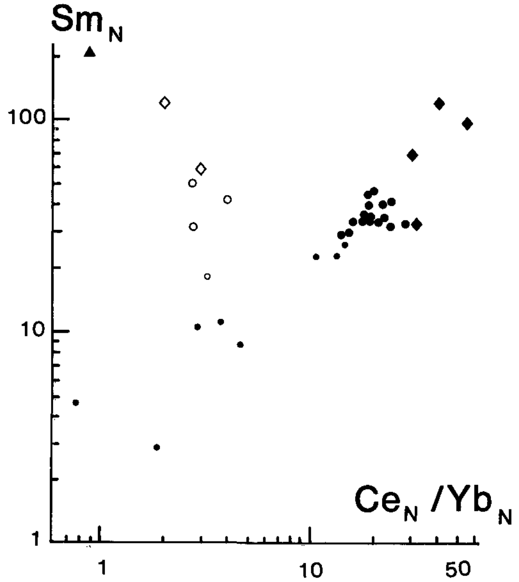

FIG. 8. Logarithmic plot of Sm_N *vs.* Ce_N/Yb_N (after Thorpe, 1978). All values have been chondrite-normalized as in Fig. 3. Carnmenellis and Isles of Scilly: coarse-grained biotite granite—large filled circles; microgranite—small filled circles; biotite—filled diamonds. Lundy; granite—large open circles; microgranite—small open circle; biotite—open diamonds; almandine—filled triangle.

Wickham, 1987), although the high F content of the micas and the presence of topaz in the Lundy granites point to the importance of F in the source of magma, which would reduce melt viscosity and aid coagulation of small packets of melt and their rapid upward movement.

Similar source rocks to those envisaged for the Cornubian granites, such as a pelitic/semipelitic (greywacke) source that had retained incompatible elements and not been involved in an earlier fusion event might provide suitable source material. On the basis of *REE* modelling, Charoy (1986) concluded that the Carnmenellis granite magma in the Cornubian batholith could have been derived by *c.* 30% melting of Brioverian source rocks. Such a source for the Lundy granite is consistent with presently available isotope data (Hampton and Taylor, 1983), but <30% melting would give Ce_N/Yb_N ratios of *c.* 20 or more and would not produce any *REE* pattern from which the Lundy rocks could have evolved unless there was a major input of *HREE*, or total *REE* followed by marked *LREE* fractionation to give a flat pattern. Only near total fusion would give *REE* patterns that approach those of the Lundy granite.

However, the high-temperature nature of the Lundy granite and its apparent close association with basic magmatism, could be consistent with near total melting, especially if metagreywacke predominated in the source region (White and Chappell, 1988). This would produce less-evolved magmas from which highly evolved granite could be generated by strong fractionation, but would only partly account for the flat *REE* patterns of the Lundy granite and, again, would produce much more subsurface granite than geophysical data indicate.

Clearly, the evidence for a basaltic parent of the Lundy granite is balanced by the many S-type granite characteristics that suggest, but do not prove, a crustal source. Differentiation of basaltic magma can produce granitic magma that would provide the initially high *REE* contents needed to explain the flat *REE* patterns (cf. Walsh and Clarke, 1982) and small volumes of high-level, high-temperature granite magma. However, basalt magmatism would also partially melt and incorporate local crustal rocks, so that marked contamination of the basalt parent by crustal material enriched in constituents associated with the Cornubian petrographic province or, perhaps, mixing of silicic magmas derived from both sources, could have provided many of the observed S-type characteristics. Such petrogeneses would also maintain the intermediate chemical properties that relate the Lundy granite to both the Cornubian and Tertiary granites and, for example, locate its composition field in the Rb *vs.* Nb + Y discriminant plot (Fig. 4*b*) between the Arran and Cornubian rocks on the boundary between the syn-collision and within-plate granite composition fields.

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