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PETROLOGICAL FEATURES OF THE BODMIN MOOR GRANITE, CORNWALL

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The coarse-grained granite of Bodmin Moor, although variable in texture, shows no evidence of more than one intrusive phase. Statistical examination of a large number of modal and chemical analyses reveals that it evolved *in situ* to produce a more mafic and K-rich outer zone surrounding a more felsic and Na-rich core. Fine-grained granite having affinities with the latter was intruded later, as were quartz-feldspar porphyry (elvan) dykes, at least one of which, however, has compositional similarities with the outer granite, and aplites. It is concluded that, although the Bodmin Moor pluton is one of the older Cornubian intrusions, it has one of the least complex genetic histories.

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INTRODUCTION

Lacking the grandeur of its eastern neighbour, Dartmoor, and the variety of rock types and commercial interest of its western neighbour, St Austell, the granite of Bodmin Moor superficially appears dull and uninteresting and this may account for the paucity of published research.

Accounts describing both coarse-grained and fine-grained varieties appear in the early Geological Survey memoirs (Reid *et al.,* 1910; Reid *et al.,* 1911) but apart from these and relatively specialised papers (e.g. Exley, 1961, 1965; Exley and Edmondson, 1993), the only notable work is that of Ghosh (1927). This author described the eastern part (covered by Geological Survey Sheet 337) and concluded that, as postulated by Brammall for Dartmoor (Brammall, 1926; Brammall and Harwood, 1932), the coarse-grained granite was intruded in two stages and was followed by the fine-grained variety. Subsequent work by both the present author and the Geological Survey (B.G.S. Sheets 336 and 337 and accompanying Technical Reports) has failed to find evidence of these two coarse-grained intrusions and several of Ghosh's criteria for distinguishing between them have not been observed.

A more up-to-date and comprehensive account of the granite cropping out in the western two-thirds of the pluton, included in Geological Survey Sheet 336, is due to be published (Exley in press).

COARSE-GRAINED GRANITE

The coarse-grained, megacrystic rock which predominates on Bodmin Moor falls into the Type B category of Exley and Stone (1982), the small megacryst variant of Dangerfield and Hawkes (1981) and the syenogranite and alkali-granite fields of Streckeisen (1976). The most distinctive variant is foliated and occurs round most of the margin of the western part of the outcrop and in patches a few hundreds of metres across within the interior of the exposure. Evidence from recrystallisation textures, strained quartz and feldspar, the development of chlorite and, in some localities, crushing of minerals shows that near the western contact much of the foliation is due to tectonic activity and it may well be linked to movement in the neighbouring Portnadler-St Teath fault system. Isopleths of Chayes' (1956) Index of Coarsness (IC number), derived from trend surface analysis of groundmass material, have higher values round the margin of the pluton, indicating finer-grained rocks there (Figure 2a) which, on field evidence, is unusual in Cornubia.

Composition

As well as the absence of internal intrusive boundaries, there appears to be no systematic regional variation in the composition of the pluton, although neighbouring outcrops may differ considerably. The problem is illustrated by Table 1 which shows that although what are here arbitrarily classed as 'outer' and 'inner' granites (as described below) have almost identical mean modal compositions, the ranges across individual mineral components are very wide. It seemed likely, therefore, that a statistical approach, involving large numbers of analyses, would be the best way to investigate the variation. Accordingly, 122 specimens were collected from sites within 500 m circles whose centres were 1500 m apart (Exley, 1963) and their analyses subjected to trend surface analysis by which local variations are smoothed out to reveal regional changes (Davis, 1973). All 122 specimens were modally analysed by point-counting at least 4000 points on thin sections of areas appropriate to their coarseness of grain (Chayes, 1956), and 52 were chemically analysed (Figure 1).

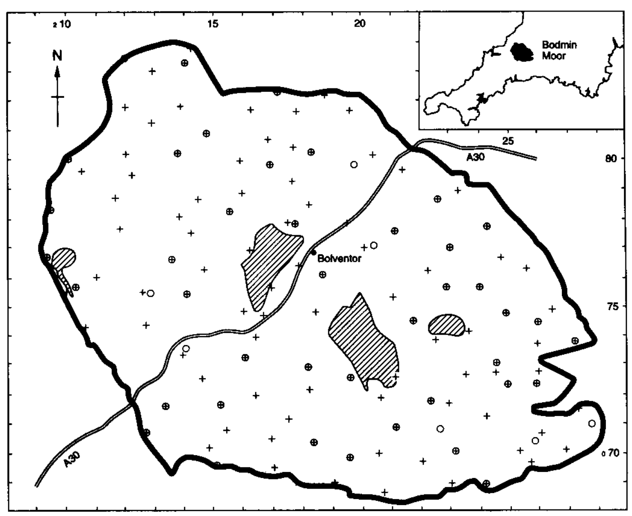

Figure 1. Bodmin Moor granite outcrop with locations of analysed specimens of coarse-grained granite. Crosses - modally analysed; circles - chemically analysed; Numerals at map margins are those of National Grid. (Some localities are no longer accessible because of reservoirs, etc.). Fine-grained granite shaded.

The component minerals are those customarily found in Comubian granites and have been described many times. The account of the Land's End granite in Booth and Exley (1987) will suffice to describe the Bodmin Moor minerals but the following additional points are noteworthy. *K-feldspar,* while always microperthitic orthoclase in megacrysts, may be either orthoclase or microcline in the groundmass, the former occupying an irregular area in the centre and south of the pluton with the latter nearly surrounding it (Exley and Edmondson, 1993). *Plagioclase* compositions range from An_{25-30} in the cores of crystals to An_5 in the rims. *Biotite* is much less plentiful than *muscovite,* and *apatite* is abundant and ubiquitous. *Fluorite* is present in trace amounts in some mineralised areas but *topaz* has not been seen.

As Figures 2b and 2c show, the important constituents biotite and andalusite have a distribution roughly concentric with the contact of the intrusion, the higher values being on the outside. Other values are less symmetrically disposed; tourmaline (Figure 2d) has its maximum in the south and west, although concentrations of 1% and less are approximately symmetrical, while the K-feldspar: plagioclase ratio has it maximum in the south-central area (Figure 2f) and the mafic index, while nearly concentric, increases to the north-east (Figure 2e).

Chemical compositions are given in Table 2 and are typical of Comubian high-level granites. In the absence of discernible divisions on the ground, two artificial boundaries have been drawn on an arbitrary basis in Figure 3. Figure 3a shows areas with less than 1.8% Fe_2O_3 + MgO and Figure 3b those with less than 2% normative anorthite. In each case there is a conspicuous central zone.

Various chemical constituents are plotted in Figure 4, from which it is evident that specimens from this central zone are different from those around it. In particular, lower values of FEM (Fe_2O_3 + MgO), TiO_2, Zr and Y and higher values of Rb are notable in the diagrams and lower mean values of Ce, La, Sr and Zr and higher values of Li are seen in Table 2.

	Coarse-grained 'Outer'	Coarse-grained 'Inner'	Fine-grained
N	72	50	10
	%	%	%
Quartz	32.8	35.2	33.2
	(24.3-42.8)	(25.5-42.9)	(29.4 -39.5)
K-feldspar	28	27.9	25.7
	(19.1-37.8)	(14.8-34.0)	(18.4-31.9)
Plagioclase	17.1	18.6	22.9
	(2.5 -22.8)	(8.7 -29.5)	(15.3-31.9)
Muscovite	7.7	9.3	7.9
	(4.5-17.2)	(4.7-15.9)	(3.9-12.8)
Biotite	4.3	3.6	2.5
	(1.1-8.5)	(0.5-6.6)	(0.5-5.3)
2y mica	1.0	1.0	0.8
	(0.1-3.3)	(0.1-2.7)	(0.1-2.7)
Clay	7.7	2.4	5.6
	(1.6-17.7)	(1.5-15.4)	(2.1-10.9)
Apatite	0.3	0.8	0.2
	(0.1-0.6)	(0.1-0.5)	(0.1-0.3)
Tourmaline	0.9	1.0	1.0
	(0-3.0)	(0-3.1)	(0-2.7)
Andalusite	0.1	Tr	0.1
	(0-0.6)	(0-0.1)	(0-0.2)
Ore	0.1	0.1	n.f.
	(0-0.5)	(0-0.3)	
Zircon	0.1	Tr	Tr
	(0-0.2)	(0-0.2)	(0.0.1)
Fluorite	Tr	Tr	n.f.
	(0-0.2)	(0-0.2)	
	100.1	99.9	99.9
Kspar:plag	1.15	1.35	0.9
Mafic index	13.5	14.8	11.6
Chayes' IC no.	28	27	99

For ratios, original Kspar calculated as observed Kspar + $^1/_2$ 2y mica and original plag as observed plag + clay. Tr = less than 0.005. n.f. = not seen.

TABLE 1
Mean modal compositions of Bodmin Moor granite with ranges in parentheses

FINE-GRAINED GRANITE

There are four main outcrops of fine-grained granite (Figure 1) in none of which are good contacts with the surrounding rock to be found, the nearest approach being an interdigitated mixture in an exposure approximately 2 km west of Bolventor. However, in all four localities coarse-grained boulders with fine-grained granite veins occur.

Composition

These rocks are non- or poorly-megacrystic and have more quartz, K-feldspar and muscovite and less biotite than the coarse-grained granite and their chemistry is accordingly enriched in SiO_2, K_2O, and P_2O_5 and impoverished in Fe_2O_3 MgO and CaO (Tables 1 and 2). They are associated with the 'inner' granites in the variation diagrams (Figure 4).

ELVANS

Quartz-feldspar porphyry dykes (elvans) occur in several places within the granite outcrop, chiefly in the south-western quadrant where they strike east-west or east-north-east - west-south-west. Their width is variable, about 10 m being the maximum, and they are traceable for distances ranging from 100-200 m to the exceptional 1-1.5 km along the strike. Their dips are consistently steeper than 70° and may be northerly or southerly. Most examples have good, chilled, rhyolitic margins which may be either stepped or interleaved with granite and they both coarsen and become megacrystic towards the middle. Flow textures are seen in places but multiple intrusions have not been identified.

Composition

The mineralogy of the elvans is similar to that of the granites with K-feldspar predominating among the megacrysts, followed by quartz and in some cases plagioclase. The largest megacrysts are 1-2 cm long and are set in a groundmass of 0.5-1 mm in which the dominant minerals are quartz, K-feldspar and muscovite. Plagioclase, biotite and tourmaline are less often found. A significant feature is the presence of multiple, intergrown grains of quartz, grains of intergrown quartz and K-feldspar, interpreted as fragments of granite, and corroded quartz.

Both modal and chemical compositions vary widely; the chemical composition of the dyke at Temple Tor, 4.7 km southwest of Bolventor, is given in Table 2 and the constituents plotted in Figure 4 are, apart from Zr, associated with those of the 'outer' granite. Zr concentrations being notable higher.

APLITES

Aplite and aplogranite veins, generally no more than one or two tens of centimetres wide, cut through both coarse- and fine-grained granites. They are allotriomorphic granular in texture and some are poorly megacrystic with crystals up to about 5 mm long set in a groundmass having grain diameters between 0.1 and 2 mm.

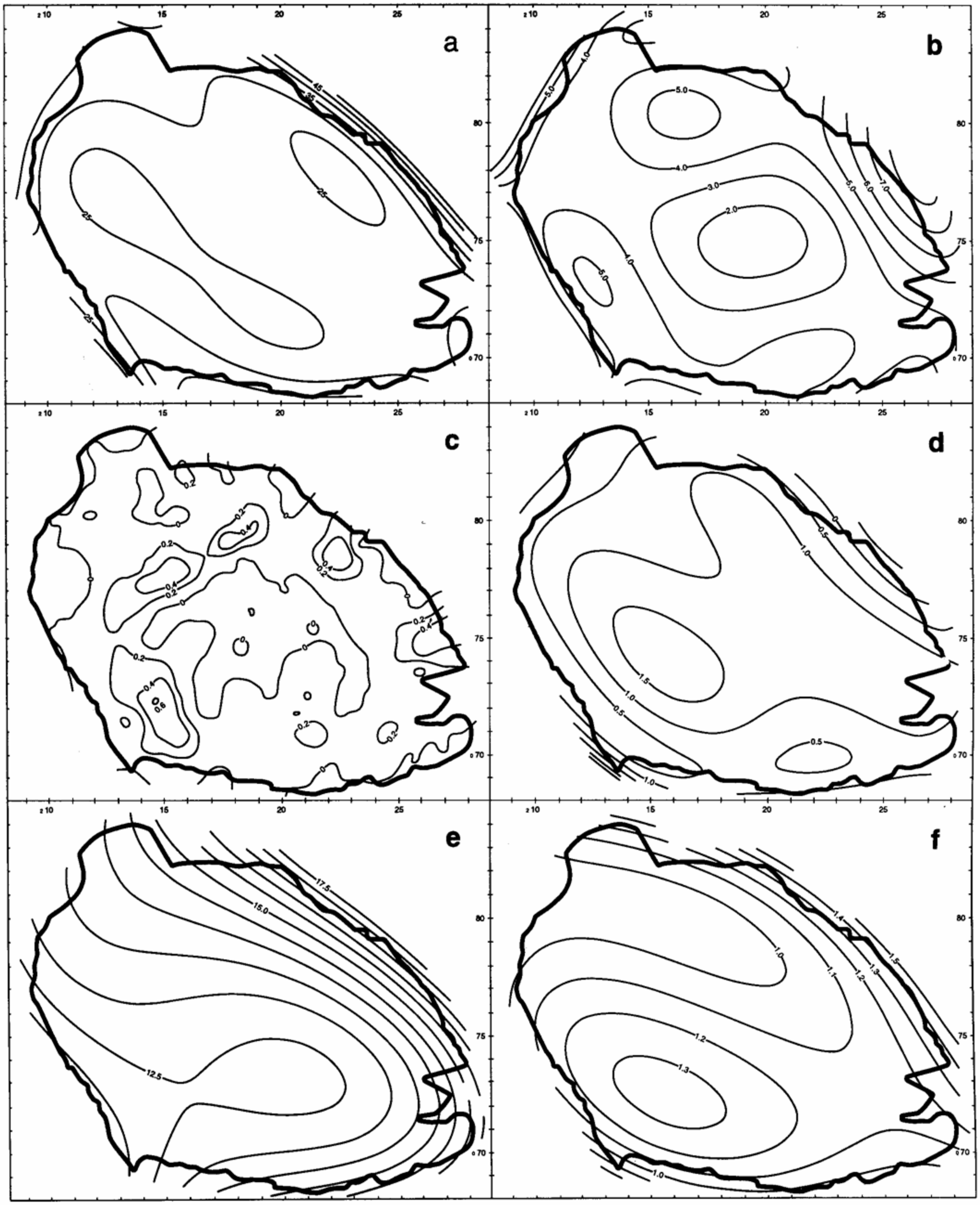

Figure 2. Isopleth maps from trend surface analyses of coarse grained granites. (a) Chayes' IC values; (b) % modal biotite; (c) % modal andalusite (raw data); (d) % modal tourmaline; (e) mafic index; (f) K-feldspar: plagioclase ratio.

Composition

The megacrysts include quartz, K-feldspar and plagioclase and the groundmass has these minerals plus biotite, muscovite and tourmaline. Table 2 points to a wide range of chemical composition in these rocks; the aplite points plotted in Figure 4 are from only one of the two specimens analysed, the concentrations of relevant elements from the other lying outside the parameters of the diagrams.

	Coarse-grained 'Outer'	Coarse-grained 'Inner'	Fine-grained	Temple Tor Elvan	Aplite
N	38	14	4	1	2
%					
SiO_2	71.16	71.73	72.45	71.51	74.4
	(70.17-72.85)	(70.20-74.43)	(71.30-73.21)		(74.40-74.79)
TiO_2	0.24	0.14	0.09	0.32	0.1
	(0.19-0.31)	(0.11-0.18)	(0.02-0.13)		(0.09-0.10)
Al_2O_2	15.26	14.79	14.84	15.14	14.53
	(13.78-16.08)	(13.95-16.81)	(14.45-15.30)		(14.21-14.85)
Fe_2O_3	2	1.32	1.15	2.14	0.9
	(1.53-2.48)	(1.07-1.60)	(0.88-1.85)		(0.77-1.03)
MnO	0.05	0.05	0.02	0.05	0.04
	(0.03-0.06)	(0.03-0.06)	(0.02-0.03)		(0.02-0.06)
MgO	0.41	0.24	0.16	0.09	0.02
	(0.21-0.51)	(0.17-0.39)	(0.02-0.25)		(0.008-0.03)
CaO	0.75	0.56	0.46	0.69	0.31
	(0.38-1.02)	(0.40-0.77)	(0.25-0.58)		(0.28-0.34)
Na_2O	2.74	2.81	2.6	2.2	3.02
	(2.07-3.37)	(2.62-3.20)	(2.10-2.98)		(2.75-3.29)
K2O	5.45	5.41	5.79	6.25	5.15
	(4.43-6.63)	(4.48-7.01)	(5.02-6.63)		(5.09-5.21)
PA	0.21	0.16	0.23	0.27	0.31
	(0.19-0.26)	(0.13-0.22)	(0.18-0.27)		(0.30-0.32)
H_2O^+	0.99	0.92	1.05	1.07	0.94
	(0.74-1.70)	(0.77-1.23)	(0.84-1.34)		(0.62-1.26)
p.p.m.					
Ba	189	121	142	316	39
	(117-246)	(74-249)	(96-186)		(33-44)
Ce	65	38	19	78	4
	(44-101)	(19-52)	(10-27)		(2-5)
Co	43	41	34	n.f.	n.f.
	(25-68)	(27-56)	(n.f.-55)		
Cr	14	10	14	19	16
	(7-23)	(5-15)	(8-30)		(15-16)
Cu	7	8	8	6	3
	(3-59)	(3-33)	(3-18)		
La	33	19	11	24	45
	(24-51)	(10-28)	(7-14)		(7-82)
Li	308	401	248	231	245
	(85-600)	(150-608)	(145-333)		(17-472)
Nb	14	14	15	13	10
	(11-17)	(9-17)	(13-19)		(2-19)
Ni	12	8	6	5	31
	(8-16)	(7-9)	(2-10)		(4-57)
Pb	30	28	36	32	234
	(20-50)	(21-40)	(25-51)		(19-449)
Rb	424	486	414	409	232
	(343-498)	(318-591)	(383-460)		(n.f.664)
Sc	4	3	2	n.f.	12
	(3-5)	(3-4)	(n.f.-2)		(n.f.-24)
Sr	90	59	71	122	16
	(58-105)	(32-71)	(41-106)		(11-21)
V	15	8	6	35	6
	(11-24)	(6-14)	(2-10)		(5-6)
Y	12	9	10	12	28
	(9-16)	(8-11)	(9-10)		(9-46)
Zn	46	36	41	38	44
	(29-99)	(23-53)	(33-55)		(34-54)
Zr	84	57	48	149	22
	(63-122)	(45-84)	(34-55)		(n.f.-43)
CALC	8.93	8.78	8.85	9.14	8.48
	(7.67-9.86)	(7.89-9.84)	(8.41-9.34)		(8.18-8.78)
FEM	2.37	1.57	1.31	2.23	0.94
	(1.81-3.01)	(1.26-1.81)	(0.90-1.62)		(0.78-1.06)
Q	32.46	34.01	34.18	33.4	37.33
	(27.74-38.92)	(28.33-38.90)	(31.70-35.56)		(35.96-38.69)
Or	32.53	32.87	35.14	37.48	30.84
	(27.40-41.95)	(29.03-41.95)	(30.87-39.99)		(30.54-31.13)
Ab	23.58	24.46	22.95	18.18	25.88
	(17.89-28.65)	(19.62-27.55)	(18.14-15.52)		(23.62-28.14)
An	2.44	1.63	0.95	0	0
	(1.81-3.01)	(1.26-1.81)	(0.90-1.62)		

Total iron as Fe_2O_3. n.f. = not detected. CALC = CaO + Na_2O + K_2O. FEM = Fe_2O_3 + MgO.

Table 2
Mean chemical compositions of Bodmin More granites (with ranges in parentheses)

DISCUSSION

Recent research has shown that the intrusion of the Cornubian batholith was a complex process extending over a considerable period and involving many intrusive phases. The plutons currently exposed cover a span of at least 25 m.a., although agreement as to their exact ages and cooling spans has not yet been reached. Nevertheless, it seems certain that the Bodmin Moor pluton is one of the oldest, with an emplacement age of the order of 290-288 m.a. B.P. and is exceeded only by that of Carnmenellis (Chen *et al.,* 1993; Chesley *et al.,* 1993; Clark *et al.,* 1993).

While it has long been known that, leaving aside 'basic microgranite inclusions', the Isles of Scilly and Carnmenellis outcrops include clearly separable coarse-grained facies, it has been argued lately that the Land's End granite also consists of two phases (Chen *et al.,* 1993) and St Austell has at least two (Hill and Manning, 1987; Bristow and Exley, 1994). The Dartmoor intrusion, too, has recently been described as consisting of 'outer' and `inner' facies generated either by the formation of a marginal cumulate (Ward *et al.,* 1992) or the intrusion of an inclusion-rich magma followed immediately by a more evolved inclusion-poor magma (Stone, 1995).

In contrast, the Bodmin Moor mass does not show these features and is evidently an example of a single intrusion which has crystallised inwards from its contacts so as to grade from a slightly more mafic and potassic outer facies perhaps resulting from contamination to a slightly more felsic and sodic core, both mineral and chemical variation following a conventional pattern during this differentiation. The distribution of a number of elements described by Edmondson (1972) was attributed to this process. The distribution is not, however, symmetrical (Figure 2) and the higher mafic index values in the north-east (Figure 2e) are in agreement with the increased density in that direction found by Bott *et al.* (1970), while the higher K-feldspar: plagioclase ratios occur where microcline is absent (Exley and Edmondson, 1993).

In the absence of decisive field evidence, the relationships between the fine-grained and coarse-grained granites are not absolutely clear, but the veining of the latter by the former and the data in Tables 1 and 2 and Figure 4 strongly suggest that the fine-grained granite formed a later intrusive fraction.

On the other hand, despite its intrusive relationships, the data from the Temple Tor elvan signify that it was derived, at least in part, from the 'outer' coarse-grained magma which enclosed and reacted with solid granite fragments as it rose (cf. Stone, 1968; Goode, 1973).

Although field relations suggest that the aplites are the last in the intrusive sequence and the chemical compositions of the two analysed (Table 2) imply that they are late differentiates, the range of compositions and lack of clear associations with both the main granites and the elvans make their origins uncertain.

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SiO_2 and H_2O^+ were analysed at Keele, respectively by Miss M. Aikin, using XRF, and Mr. D.W. Emley, using gravimetric, methods. All other elements were analysed by Dr. J.N. Walsh at King's College, London, using ICP spectrometry.

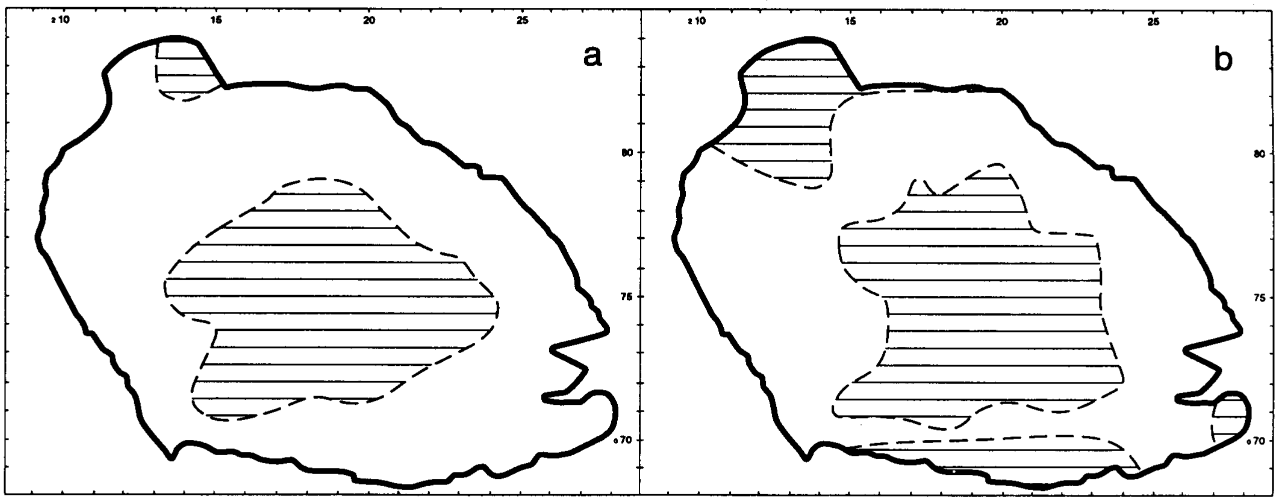

Figure 3. *Areas (shaded) with low values of some constituents. (a)* Fe_2O_3 *+ MgO less than 1.8%; (b) normative anorthite less than 2%.*

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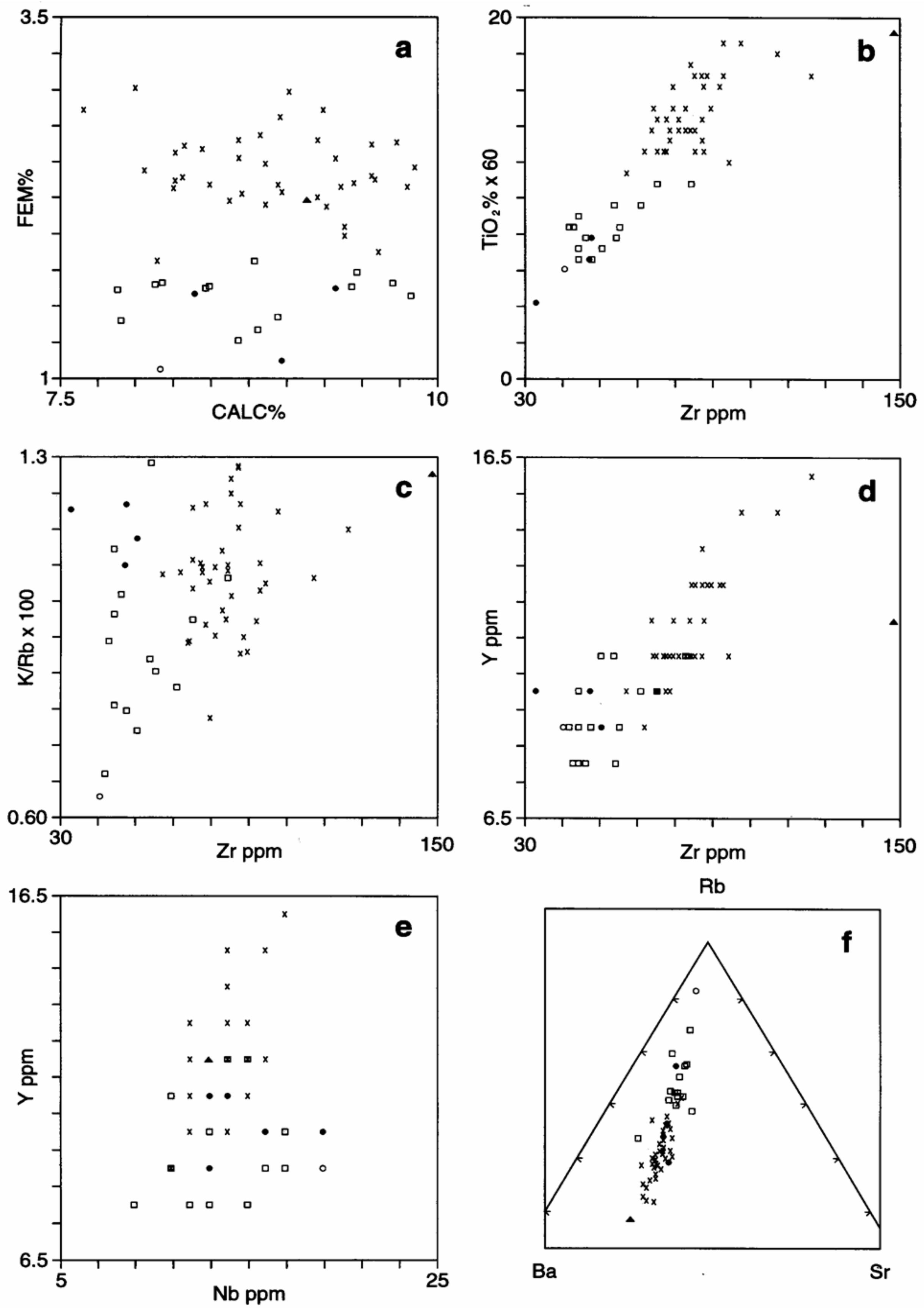

Figure 4. Variation diagrams of some chemical constituents. (a) FEM (Fe_2O_3 + MgO) vs CALC (CaO + Na_2O + K_2O); (b) TiO_2 x 60 vs Zr; (c) K/Rb x 100 vs Zr; (d) Y vs Zr; (e) Y vs Nb; (f) part of Rb-Ba-Sr diagram. Crosses - 'outer' granite; open squares - granite; filled circles -fine-grained; open circles - aplite; triangle - elvan.