Igneous Rocks of South-West England

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Chapter 5

The Cornubian granite batholith (Group C sites)

INTRODUCTION

The sites covered here are not only representative of the main megacrystic granites, but include many of the extreme variants typical of high-level, volatile-rich, calc-alkaline granites. They are shown in Figure 5.1 and are in approximately evolutionary order, the oldest granites first. Many, however exhibit late-stage or contact phenomena, so that this arrangement is fairly loose.

LIST OF SITES

Older granites, including some with xenoliths

C1 Haytor Rocks area (SX 758773)
C2 Birch Tor (SX 686814)
C3 De Lank Quarries (SX 101755)
C4 Luxulyan (Goldenpoint, Tregarden) Quarry (SW 054591)

Older granites in contact with metasediments

C5 Leusdon Common (SX 704729)
C6 Burrator Quarries (SX 549677)
C7 Rinsey Cove (Porthcew) (SW 593269)
C8 Cape Cornwall area (SW 352318)
C9 Porthmeor Cove (SW 425376)

Granite near contact between biotite- and Li-mica bearing varieties

C10 Wheal Martyn (SX 003556)
C11 Carn Grey Rock and Quarry (SX 033551)

Granites with Li-mica, topaz and fluorite

C12 Tregargus Quarry (SW 949541)

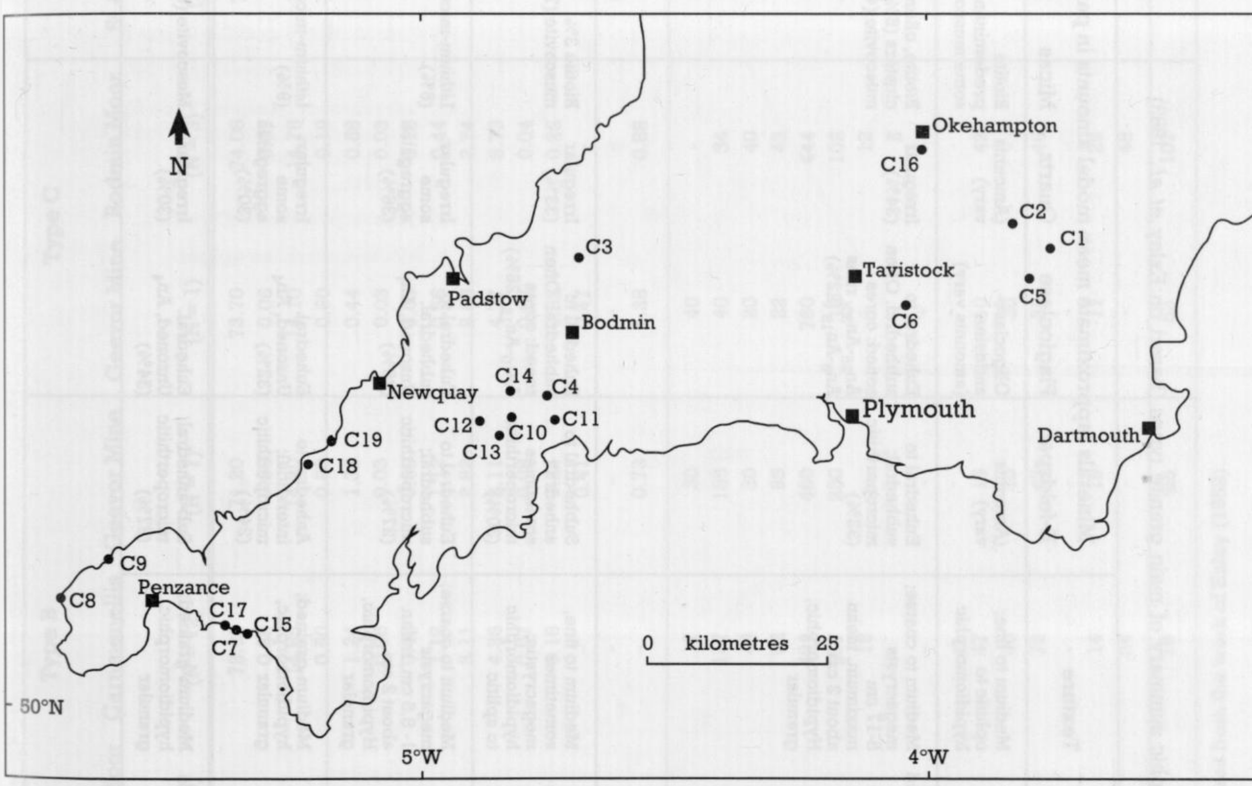


Figure 5.1 Outline map of south-west England showing the location of Group C sites.

Table 5.1 Petrographic summary of main granite types (based on Exley *et al.*, 1983)

Type	Description	Texture	Minerals (approximate mean modal amounts in parentheses)						Other names in literature
			K-feldspar	Plagioclase	Quartz	Micas	Tourmaline	Other	
A	Basic microgranite	Medium to fine; ophitic to hypidiomorphic	(Amounts vary)	Oligoclase-andesine (amounts vary)	(Amounts vary)	Biotite predominant; some muscovite	Often present	Hornblende, apatite, zircon, ore, garnet	Basic segregations (Reid *et al.*, 1912); Basic inclusions (Brammall and Harwood, 1923, 1926)
B	Coarse-grained megacrystic biotite granite	Medium to coarse; megacrysts 5-17 cm maximum, mean about 2 cm. Hypidiomorphic, granular	Euhedral to subhedral; microperthitic (32%)	Euhedral to subhedral. Often zoned: cores An_{25}-An_{30}, rims An_{8}-An_{15} (22%)	Irregular (34%)	Biotite, often in clusters (6%); muscovite (4%)	Euhedral to anhedral. Often zoned. 'Primary' (1%)	Zircon, ore, apatite, andalusite, etc. (total, 1%)	Includes: Giant or tor granite (Brammall, 1926; Brammall and Harwood, 1923, 1932) = big-feldspar granite (Edmonds *et al.*, 1968), coarse megacrystic granite (Hawkes and Dangerfield, 1978). Also blue or quarry granite (Brammall, 1926; Brammall and Harwood, 1923, 1932) = poorly megacrystic granite (Edmonds *et al.*, 1968), coarse megacrystic granite (mesocrystic type) (Hawkes and Dangerfield, 1978), coarse megacrystic granite (small megacryst variant) (Dangerfield and Hawkes, 1981). Also medium-grained granite (Hawkes and Dangerfield, 1978), medium granites with few megacrysts and megacrysts very rare (Dangerfield and Hawkes, 1981). Biotite-muscovite granite (Richardson, 1923; Exley, 1959). Biotite granite, equigranular biotite granite, and globular quartz granite (Hill and Manning, 1987).
C	Fine-grained biotite granite	Medium to fine, sometimes megacrystic; hypidiomorphic to aplitic	Subhedral to anhedral; sometimes microperthitic (30%)	Euhedral to subhedral. Often zoned: cores An_{10}-An_{15} (26%)	Irregular (33%)	Biotite 3%; muscovite (7%)	Euhedral to anhedral. 'Primary' (1%)	Ore, andalusite, fluorite (total, <1%)	Fine granite, megacryst-rich and megacryst-poor types (Hawkes and Dangerfield, 1978; Dangerfield and Hawkes, 1981)
D	Megacrystic lithium-mica granite	Medium to coarse; megacrysts 1- 8.5 cm, mean about 2 cm. Hypidiomorphic, granular	Euhedral to subhedral; microperthitic (27%)	Euhedral to subhedral. Unzoned, An_{7} (26%)	Irregular; some aggregates (36%)	Lithium-mica (6%)	Euhedral to anhedral 'Primary' (4%)	Fluorite, ore, apatite, topaz (total, 0.5%)	Lithionite granite (Richardson, 1923). Early lithionite granite (Exley, 1959). Porphyritic lithionite granite (Exley and Stone, 1964). Megacrystic lithium-mica granite (Exley and Stone, 1982)
E	Equigranular lithium-mica granite	Medium-grained; hypidiomorphic, granular	Anhedral to interstitial; microperthitic (24%)	Euhedral. Unzoned, An_{4} (32%)	Irregular; some aggregates (30%)	Lithium-mica (9%)	Euhedral to anhedral (1%)	Fluorite, apatite (total, 2%); topaz (3%)	Late lithionite granite (Exley, 1959). Non-porphyritic lithionite granite (Exley and Stone, 1964). Medium-grained, non-megacrystic lithium-mica granite (Hawkes and Dangerfield, 1978). Equigranular lithium-mica granite (Exley and Stone, 1982). Topaz granite (Hill and Manning, 1987)
F	Fluorite granite	Medium-grained; hypidiomorphic, granular	Sub-anhedral; microperthitic (27%)	Euhedral. Unzoned, An_{4} (34%)	Irregular (30%)	Muscovite (6%)	Absent	Fluorite (2%), topaz (1%), apatite (<1%)	Gilbertite granite (Richardson, 1923)

Table 5.2 *Average analyses of granites from the Cornubian batholith (after Exley et al., 1983)*

	Type B			Type C		Type D		Type E	Type F	Granite porphyry	Microgranite
	Bodmin Moor	Carnmenellis	Geevor Mine	Geevor Mine	Bodmin Moor	St Austell*	Cligga Head	Tregonning -Godolphin	St Austell*	Tregonning -Godolphin	Meldon micro -granite dyke, NW Dartmoor †
	(N = 10)	(N = 12)	(N = 7)	(N = 1)	(N = 3)	(N = 6)	(N = 2)	(N = 10)	(N = 5)	(N = 2)	(N = 1)
SiO_2	72.43	72.63	71.20	73.70	74.08	73.01	72.73	71.10	74.20	72.80	72.80
TiO_2	0.21	0.28	0.35	0.06	0.07	0.14	0.13	0.06	0.07	0.20	0.04
Al_2O_3	15.03	14.65	14.20	14.10	14.76	14.72	14.85	16.11	15.81	14.50	16.40
Fe_2O_3	0.32	0.50	0.80	0.60	0.19	0.47	0.34	0.35	0.08	1.85	0.84
FeO	1.48	1.24	1.38	0.44	0.86	0.74	0.94	0.81	0.17	1.21	
MnO	0.04	0.05	0.03	0.03	0.03	0.03	0.03	0.07	0.01	0.05	0.09
MgO	0.44	0.48	0.60	0.05	0.18	0.14	0.33	0.09	0.08	0.26	0.05
CaO	0.84	1.12	1.12	0.56	0.44	0.44	0.41	0.59	1.31	0.28	1.28
Na_2O	3.11	3.11	2.82	2.86	2.74	3.42	3.21	3.73	4.06	0.12	2.77
K_2O	5.06	4.36	5.11	4.77	5.73	5.36	5.03	4.84	4.66	7.66	3.95
Li_2O	0.06	0.07	0.08	0.07	0.04	0.18	0.11	0.27	0.01	0.03	0.94
P_2O_5	0.25	0.18	0.24	0.32	0.25	0.33	0.15	0.50	0.46	0.26	0.48
B_2O_3	-	-	0.41	0.47	-	-	0.27	0.14	-	-	-
F	-	-	-	-	-	(0.38)	0.38	1.22	(1.36)	-	1.40
H_2O	1.01	-	0.73	1.38	0.88	-	1.13	-	-	-	-
Nb		17	30	40		57		93	81	21	67
Zr	121	137	185	40	34	(50)	65	46	(11)	94	38
Y	41	48	30	20	40	-	-	10	-	18	-
Sr	94	92	95	22	43	41	175	61	64	34	47
Rb	419	462	480	760	444	982	695	1218	615	814	2293
Ba	196	397	230	15	102	(83)	150	204	(43)	699	197
La	31	16	-	-	12	8	-	~3	-	14	15
Ce	38	-	-	-	2	34	95	36	19	68	27
U	-	-	-	-	-	-	-	19	-	20	24
Th	-	-	-	-	-	-	-	22	-	31	-
Pb	46	47	15	10	42	-	-	16	-	6	5
Ga	-	40	30	30	-	-	40	40	-	20	35
Zn	62	72	45	35	48	-	103	48	-	45	31
Ge	-	-	-	-	-	-	-	11	-	4	11
Sn	23	14	19	17	29	-	40	36	-	71	14
Cs	28	34	-	-	48	-	-	127	-	33	223
K/Rb	100	78	88	52	107	45	60	33	63	78	14

* Values in parentheses from the work of Exley (1959)
† Total Fe as Fe_2O_3
Oxide values in weight %
Trace element values in ppm

Late differentiates

C13 St Mewan Beacon (SW 985534)
C14 Roche Rock (SW 991596)
C15 Megiliggar Rocks (SW 609266)
C16 Meldon Aplite Quarries (SX 567921)

Granite-porphyry (elvan) dyke

C17 Praa Sands (Folly Rocks) (SW 573280)

Mineralized granite

C18 Cameron (Beacon) Quarry (SW 704506)
C19 Cligga Head area (SW 738536)

LITHOLOGICAL AND CHEMICAL VARIATION

Summaries of the petrography and chemistry of the principal granite types of the batholith are given in Tables 5.1 and 5.2 (from Exley *et al.*, 1983) and descriptions of each type follow. Further details can be found in Exley and Stone (1982). Although widely used now, the classification of Streckeisen (1976) is not of much practical help in considering the Cornubian granites, because the differences which show their history and relationships consist of variation in the anorthite content of plagioclase, the kind of mica and the nature and amount of accessory minerals, none of which are parameters used by Streckeisen (1976). Still of limited value, but of more help, is the diagram of normative quartz–albite–orthoclase (Figure 5.2), while some important trace-element ratios for the various granite types are shown in Figure 5.3.

Type A: basic microgranite

This category is largely one of convenience as it embraces a range of types from diorite to granodiorite. They occur in nodules or rafts as enclaves within the present 'main' biotite granite to which they are precursors. Texturally, they are

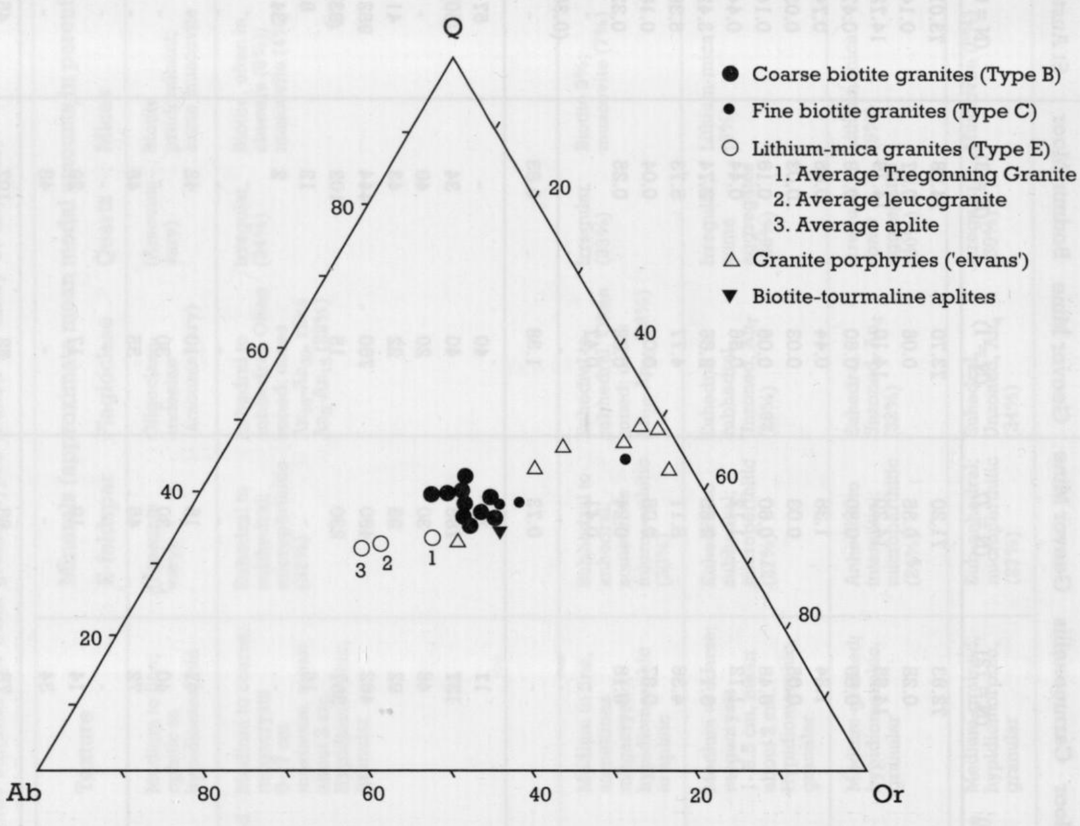


Figure 5.2 Normative quartz-albite-orthoclase (Q–Ab–Or) diagram (after Exley and Stone, 1982, Figure 23.2).

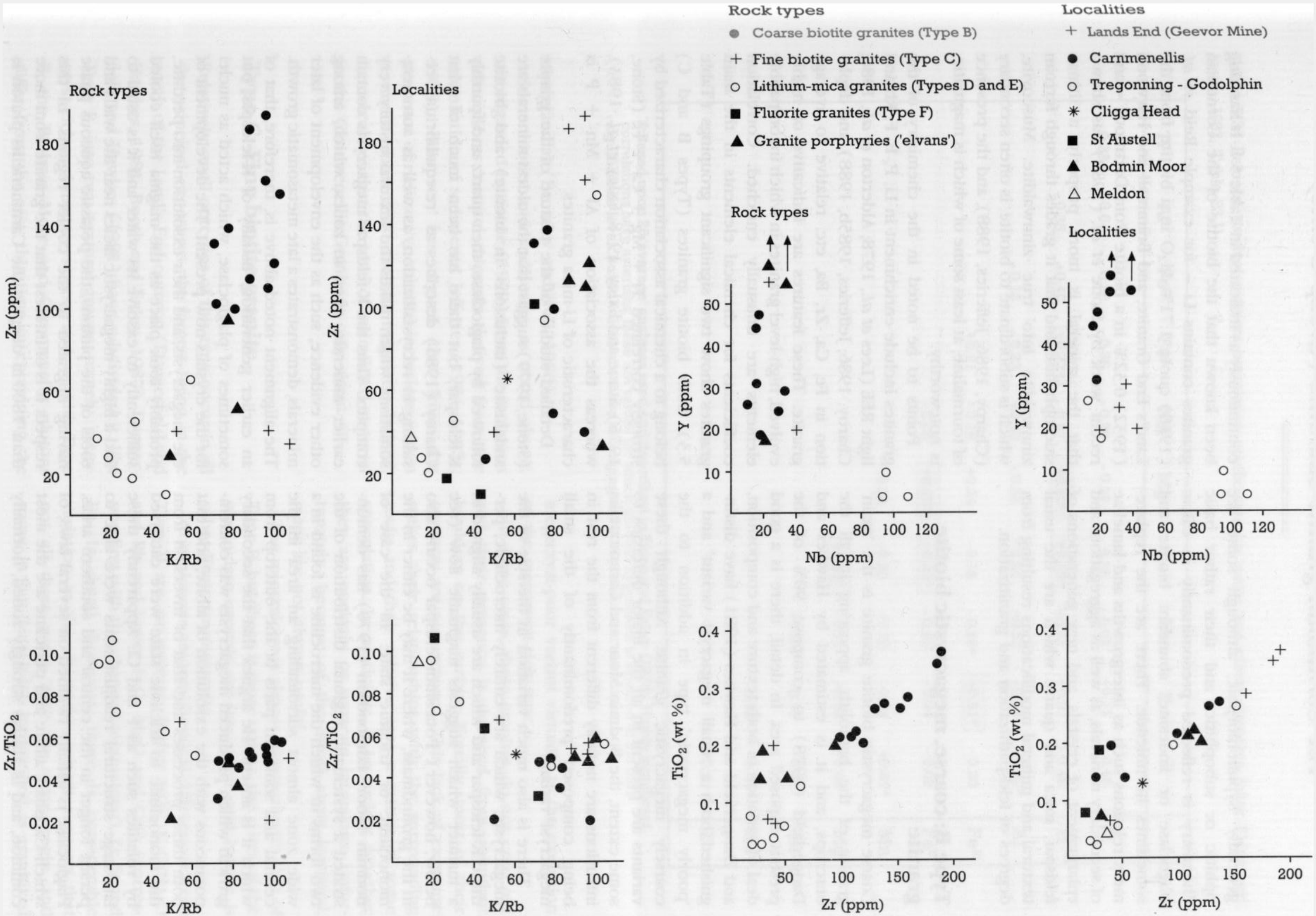


Figure 5.3 Variation diagrams for Zr–K/Rb, Zr/TiO_2–K/Rb, Nb–Y and Zr–TiO_2 in south-west England granite types and different plutons (after Exley *et al.*, 1983).

generally hypidiomorphic, although some are ophitic or subophitic, and their rather basic chemistry is reflected predominantly in calcic oligoclase or andesine, abundant biotite and sometimes hornblende. There are the replacement relations such as intergrowths and lamellae of secondary minerals, as well as aggregations and enlargement of crystals, and new generations of feldspar, mica and quartz which are the usual textural and mineral modifications resulting from degrees of feldspathization and granitization.

Type B: coarse, megacrystic biotite granite

Coarse megacrystic biotite granite is the 'main' granite of the batholith, appearing in all the outcrops, and it is estimated by Hawkes and Dangerfield (1978) to compose 90% of the present exposed area. In detail, there is a good deal of variation in both texture and composition, and Dangerfield and Hawkes (1981) have distinguished both a 'small megacryst variant' and a 'poorly megacrystic' type in addition to the coarsely megacrystic granite. Although these variants are present in all the major outcrops to some extent, the Bodmin Moor and Carnmenellis intrusions are notably different from the rest in being composed predominantly of the small megacryst variant.

There is also much variation in the size of the megacrysts, which are entirely microclinic, perthitic K-feldspar and which are usually aligned in a manner which suggests magmatic flow (see below, however). Potassium-feldspar occurs also in the groundmass, where it may be either in the monoclinic or triclinic state. In the case of Bodmin Moor, Edmondson (1970) has demonstrated a systematic regional distribution of the two forms in which the microcline is found in a wide zone almost surrounding an area in the central and southern parts of the outcrop from which it is absent. He argues that the secondary growth which produced megacrysts was contemporaneous with the exsolution of albite, and that both these processes and that of inversion from the monoclinic to triclinic state were catalysed by volatiles such as F and Cl. Apparently these late-stage structural readjustments were able to persist longer in the central and southern areas. Plagioclase is usually twinned on several laws, of which Carlsbad, albite and pericline are the most common, and is always strongly zoned, normally continuously as indicated in Table 5.1. It has long been known that the biotite of the Cornubian granites contains Li – for example Reid *et al.* (1910) quote 1.71% Li_2O in a biotite from the Land's End Granite, and Brammall and Harwood (1932) 0.32% in a biotite from Dartmoor – and recent work by Stone *et al.* (1988) has shown that the mineral is more properly a lithian siderophyllite and that it grades through ferroan zinnwaldite into true zinnwaldite. Muscovite, which is subordinate to biotite, is often secondary (Charoy, 1986; Jefferies, 1988), and the presence of tourmaline, at least some of which is magmatic, is noteworthy.

Points to be noted in the chemistry of the granites include enrichment in Li, P, B, F, Rb and light REE (Lees *et al.*, 1978; Alderton *et al.*, 1980; Charoy, 1986; Jefferies, 1985b, 1988), and depletion in Fe, Ca, Zr, Ba, etc. relative to average granite. These features are indicative of highly evolved, high-level granites in which incompatible elements are unusually enriched. Correlation coefficients for chemical elements in the main granites show two significant groupings (Table 5.3). Both biotite granites (Types B and C) belong to a chemical association characterized by strongly correlated Ti + Mg + Ca + Fe (Stone, 1975); Stone and Exley, 1978; Exley *et al.*, 1983), whereas the association of Al + Mn + P is characteristic of Li-mica granites.

Detailed studies of the texture of the granite (Stone, 1979) suggest that the oldest minerals are andalusite (inclusions in biotite) and biotite followed by plagioclase, then quartz and fourthly K-feldspar, but there has been much of what Charoy (1986) describes as 're-equilibrium' resulting in recrystallization, as well as autometasomatism, which makes the textural history very complex. Thus the K-feldspar megacrysts contain earlier minerals, often in zones, which, among other evidence, such as the envelopment of later minerals, demonstrates a late metasomatic growth. The alignment noted above is, therefore, that of an earlier generation, usually of K-feldspar but sometimes of plagioclase, which acted as nuclei for the crystals now present. The development of the megacrysts, and their exsolution into perthite, probably took place as the magma itself cooled sufficiently to exsolve its water and it is usual to find a highly megacrystic facies near the walls and roofs of the plutons, the potassic aqueous phase having migrated to the cooler regions. In this respect it is of interest that the granite from more than 1800 m deep in the Carnmenellis pluton is

Table 5.3 Pearson product moment correlation coefficients for major and minor elements (after Exley and Stone, 1982, Table 23.1)

Ti	Al	Fe^III	Fe^II	Mn	Mg	Ca	Na	K	P	
-0.33	-0.61	-0.28	-0.36	-0.26	-0.29	-0.26	-0.05	+0.11	-0.45	Si
	-0.35	+0.40	+0.77*	-0.27	+0.90*	+0.75*	-0.21	+0.07	-0.48	Ti
		-0.16	-0.23	+0.43	-0.33	-0.24	+0.33	-0.28	+0.72*	Al
			+0.21	-0.16	+0.34	-0.13	-0.69*	+0.61*	-0.20	Fe^III
				-0.04	+0.76*	+0.60*	-0.01	-0.04	-0.09	Fe^II
					-0.34	-0.20	+0.23	-0.29	+0.61*	Mn
						+0.67*	-0.11	+0.02	-0.46	Mg
							+0.24	-0.37	-0.40	Ca
								-0.92	+0.33	Na
									-0.21	K

* Based upon 26 'average' analyses used and described in Stone and Exley (1978). Highly significant correlations have asterisks: these are values for which the Null hypothesis is rejected at the 0.01 significance level. Boxed values are those belonging to the femic element association.

equigranular (Bromley and Holl, 1986).

Some biotite and andalusite, as noted above, are regarded by Stone (1979) from the inclusion principle as 'restite' minerals derived from the assimilation of sediments. Jefferies (1984, 1985a, 1988), however, has argued that from the presence of radioactive mineral inclusions within it, much biotite must itself be magmatic. Indeed, he calculates that the total of assimilated material in the Carnmenellis Granite is only about 4%.

Type C: Fine biotite granite

Relatively small outcrops of this type occur in all the principal exposures, the largest being in the north of the Land's End outcrop (Dangerfield and Hawkes, 1981; Booth and Exley, 1987). Dangerfield and Hawkes (1981) have subdivided it, like Type B, into two textural groups, namely, megacryst rich and megacryst poor and, as with Type B, the Bodmin Moor and Carnmenellis plutons differ from the rest, this time in containing the megacryst-poor variant virtually to the exclusion of the megacryst-rich type.

In some cases, these granites do not crop out and their presence is deduced from abundant boulders on the surface. Equally, most of their contacts are not exposed. This lack of exposure makes their relationships with the surrounding rocks and their relative ages a matter of some speculation. In particular, it is unclear whether they are enclaves or separate intrusions. Unfortunately, because of the small areas involved, maps are not always useful.

The mineralogy is almost identical with that of Type B, but there is more quartz, the cores of the plagioclase crystals are less calcic and biotite is subordinate to muscovite.

Conspicuous among chemical differences from Type B are, on average, higher SiO_2, K_2O/Na_2O and Rb and lower FeO, MgO and CaO (corresponding with the changed mineralogy), Zr, Sr and Ba. In detail, however, there is considerable variation in the chemistry, which suggests that not all these rocks have the same origin, and some, in fact, have been interpreted as granitized sedimentary rafts (Tammemagi and Smith, 1975; Hawkes, 1982). Even those of unquestioned igneous origin do not seem to have been derived by any straightforward process from Type-B granite.

Type D: Megacrystic Li-mica granite

This variety is unique to the central and extreme western parts of the St Austell outcrop and, as can be seen from Tables 5.1 and 5.2, it occupies an intermediate position between Types B and E in both modal and chemical composition. Its texture is generally like that of Type B, that is, coarse-grained and megacrystic, although it has considerable variation in the size and frequency of megacrysts and the nature of the matrix. It is much the most heavily kaolinized area in Cornwall and for this reason it has only recently been realized that some of this textural variation reflects the presence of several distinct intrusions (Manning and Exley, 1984; Hill and Manning, 1987).

The chief changes in mineral content, relative to Type B, are the presence of less K-feldspar, more plagioclase (which is substantially more albitic), zinnwaldite in place of biotite, and the appearance of both topaz and fluorite in small amounts. These changes are the manifestation of a reduction in the K_2O/Na_2O ratio, a substantial increase in Li_2O, a reduction in MgO, redistribution of Fe and Al, and an increased importance of B and F, all brought about by the intrusion of the Type-E granite which Type D surrounds. This aspect is discussed further below and in the site descriptions which follow.

Type E: Equigranular Li-mica granite

Type E is the representative of the second chief intrusive phase, dated at about 270 Ma BP. It is exposed in the St Austell (and Castle-an-Dinas), Tregonning and St Michael's Mount outcrops, but it may underlie much of the exposed biotite granite (Manning and Exley, 1984; Bristow *et al.*, in press).

A characteristic feature of its contact with the rocks that it has intruded is the development of a roof complex of banded aplite, pegmatite and leucogranite; these are a consequence of the high volatile content of Type-E magma which is believed to have been derived at depth by a complex differentiation and reaction process. This is discussed more fully below and in the appropriate site descriptions.

Like Type D, it is distinguished at once by the assemblage albite–zinnwaldite–topaz and, as Table 5.1 shows, it has a much higher proportion of plagioclase to K-feldspar than Type B. The plagioclase is nearly pure albite, and this rock type has an average of 9% zinnwaldite, no other mica and 3% topaz. Its texture is aphyric/equigranular. This mineralogy is highly unusual among British granites, but is well known in tin-bearing granites elsewhere, such as the Krušné hory Mountains (Erzegebirge) of Bohemia in the Variscan Saxothuringian Zone (Štemprok, 1986).

Chemically, the rock is distinguished by a relatively low K_2O/Na_2O ratio, high Li_2O, P_2O_5 and Ba and very high Rb. Along with Types D and F, it is characterized by the strongly correlated association of Al + Mn + P which marks it as fundamentally different from the biotite granites (Stone, 1975; Stone and Exley, 1978; Exley *et al.*, 1983).

Type F: Fluorite granite

This rock, like Type D, has so far been found only in the west-central part of the St Austell pluton east of the Fal Valley, where it occurs in pockets several hundreds of metres across within Type E. Texturally, it is identical with Type E, that is non-megacrystic and equigranular, but its mineral content differs sharply, with no iron-bearing minerals such as zinnwaldite and tourmaline being found. Correspondingly, its total Fe content is much lower. On the other hand, the F content is high (Table 5.2) and this is shown not only in the presence of topaz and fluorapatite, but also in 2% of purple fluorite which gives the rock its easily recognized character in hand specimen.

Like Type D, fluorite granite is now thought to have originated from the reactions induced by the emplacement of Type E which are discussed in the relevant site descriptions.

Other varieties

Many minor (in volumetric terms) granitic rock types are also found in south-west England, ranging from the granite porphyry (elvan) dykes already mentioned, through microgranite sheets, quartz–topaz and quartz–tourmaline rocks, to aplites and pegmatites. Most of these are highly specialized and are significant indicators of the evolution and chronology of the batholith. Details of their petrology are discussed in the various site descriptions.

PETROGENESIS

The granitic rock Geological Conservation Review sites described in this volume have been chosen to illustrate both the variety of types and their evolutionary history. The following section describes the various petrogenetic hypotheses developed over the years and how they relate to the rocks themselves.

Pre-1950 and the Dartmoor model

The questions of the linking of the granite outcrops at depth and the origins of the magmas from which they formed are inextricably entwined, but before the 1950s little appears to have been written about these matters. Two early and notable exceptions are De la Beche, the first Director of the Geological Survey, and W. A. E. Ussher. In his celebrated report of 1839, De la Beche was quite clear that a single granite mass underlay the individual 'protrusions' which he considered to be of the same age. Ussher (1892), in a fascinating paper full of detailed arguments about the relations between stratigraphy, structure and origins of both igneous rocks and sediments, took a similar view but also concluded that the granite '. . . resulted from the metamorphism of pre-existing rock of Pre-Devonian age . . .'.

Despite these contributions and a considerable body of knowledge derived from mining activities, the petrologists of the Survey, who wrote most of the pre-1920s accounts, confined themselves chiefly to detailed petrographical descriptions and notes on the field relationships of the different granite facies. We have, for example, Barrow (*in* Reid *et al.*, 1910) observing that there occur within the Bodmin Moor outcrop masses of finer granite 'which are clearly intrusive', and Flett and Dewey (*in* Reid *et al.*, 1912) describing the 'basic segregations' in the Dartmoor Granite. There is, however, practically no discussion of the origins of the magmas or much about the derivation of different granite varieties: argument being limited to such remarks as 'the structure is rather characteristic of the residual material of granite magmas that is forced up as veins through a large coherent intrusive mass' (Flett and Dewey (*in* Reid *et al.*, 1912) referring to micropegmatite in fine-grained granite on Dartmoor). The same authors mention that the fine granites 'belong undoubtedly to the same magma' (as the coarse granites) and summarize the relationship by the comment that 'Though of one geological date, the intrusion is made up of various injections, some finer-grained than others, but in no case do the later veins and masses appear to have been intruded after the earlier mass had cooled. They therefore blend and pass into each other at the margins in a very characteristic way'. Basic segregations are ascribed by these authors to the 'crystallization of scattered lumps of small size, before the crystallization of the rest of the magma'. Elvan dykes were accepted by the Survey officers as late intrusions, but again their origins were not discussed beyond suggestions that they too, derived from the same magma (for example, Flett, *in* Ussher *et al.*, 1909).

There was much more interest in the volatile-rich varieties than in the main granite types and the processes of 'tourmalinization', 'greisening' and 'kaolinization' were speculated upon by most authors in these years. It was clearly recognized that they resulted from unusually high concentrations of B, F, Cl and OH in the magma and that, while some B was incorporated into 'primary' tourmaline, the vein tourmaline and other mineralizing effects resulted from the passage of the concentrated residual volatile phases through consolidated, but fractured, rock. 'Pneumatolytic' and 'hydrothermal' are adjectives commonly used in the literature. Subsequent studies have enlarged upon this early thinking as more data, including those from experimental work, have been acquired. The basic concepts have not suffered substantial revision, however.

An interest in the origins of granite magmas themselves was starting to show itself in Britain at about the time of World War 1 when petrology was becoming strongly influenced by the work of N. L. Bowen and his demonstrations of the production of acid magma by differentiation from crystallizing basic magma. Not all geologists found this process entirely satisfactory, however, and some, probably with continental (and especially Scandinavian) experience, preferred to argue for metamorphic changes in pre-existing rock, followed by mobilization. One of these was Holmes (1916) who, in reviewing Bowen's paper on 'The later stages of the evolution of igneous rocks', pointed out that only a limited amount of granite could be produced by differentiation from basalt, and that, while the earliest granites probably originated in this way, younger ones must have arisen by refusion, especially of sediments which were themselves derived from granite. In effect, Holmes supported Ussher's concept of 1892 as far as Cornubian granite is concerned. The dichotomy between supporters of differentiation and those of metamorphism (or 'anatexis' or 'palingenesis') led to the 'granite controversy' of the 1940s and 1950s, in which Holmes, together with H. H. Read and D. H. Reynolds, were the leaders of the latter school of thought in Britain. All made direct reference to Cornubian granites. Holmes (1932) took further his arguments for refusion, using Brammall and Harwood's evidence of assimilation in the Dartmoor Granite in support. Read (1949) regarded the granites as the end members of his Granite Series, 'almost dead when they arrived at their present positions'. And Reynolds (1946) illustrated her account of the chemistry of the granitization processes by reference, *inter alia*, to features in the Dartmoor granites.

Between the two World Wars, more sophisticated and detailed work accompanied the development of improved laboratory techniques. In consequence, much more chemical information became available, enabling petrologists to pursue more fundamental problems. In a series of papers between 1923 and 1932, Brammall and Harwood examined many aspects of the Dartmoor Granite and its minerals, and discerned in it stages of evolution, although they published no map to show the distribution of the different types.

In 1927, Ghosh published a paper about the eastern part of Bodmin Moor, describing two stages of coarse-grained granite in addition to the fine-grained variety, and followed this in 1934 with a similar study of Carnmenellis in which he distinguished three types of coarse granite. The granites of St Austell were considered in 1923 by Richardson, who, for the first time, separated eastern and western intrusions and clarified the importance of the Li-bearing micas there. He also emphasized the importance of 'mineralizers' in the later stages, pointing out how they modified the mineralogy, particularly by removing iron.

The Isles of Scilly granites were identified as having nine stages of development (the principal ones corresponding with those of Dartmoor) by Osman (1928). Nothing, however, appears to have been written about the Land's End intrusion in this period.

Of all these authors, Brammall and Harwood (1932) were the ones who really developed a petrogenetic scheme. They rejected a straightforward Bowen-type differentiation origin on the grounds that there is too much granite for the amount of basalt required in the area, and that such a magma would be deficient in such elements for instance, as Sn, W and B. They preferred a palingenetic starting point like that of Ussher (1892) and Holmes (1916), with the latter of whom Brammall evidently discussed the matter.

Their scheme envisaged a partial melting of pelitic metasediment (of the sort exemplified on Leusdon Common) to produce a rather sodic magma; evidence included the nature of xenoliths, presence of garnet, etc. This magma was 'basified' by assimilated country rock and by differentiation to produce more K- and Fe-rich varieties on the one hand and more siliceous varieties on the other. Evidence of these processes is provided by detailed textural descriptions, chemical analyses and calculations of the balances obtained in various reactions. Of particular importance is the sequence of analyses made across the Dartmoor Granite contact at Burrator. The magma was not intruded in one batch, however, and Brammall and Harwood interpreted the facies found at Haytor Rocks as indicating an older more 'basic' magma intruded by a younger, inner, more 'acid' magma. The reciprocal processes of 'basification' are those of 'granitization' and Brammall and Harwood describe changes in the textures and compositions of country-rock xenoliths of various types (such as those from Birch Tor) in varying degrees of assimilation by the granite magma. Although strictly based on and calculated for Dartmoor, this scheme was widely applied by others to the remaining Cornubian granites.

Brammall and Harwood were equally conscious of the importance of volatiles, especially B, F and OH, in facilitating the movement of elements, altering the physicochemical environment and making possible the generation of varieties such as those rich in tourmaline, although, since Dartmoor lacks the extremely Li- and F-rich granites found at St Austell, they did not find it necessary to suggest the involvement of these in the kinds of major evolutionary process Richardson (1923) had described.

The scheme devised by Brammall and Harwood is what is called the 'Dartmoor model' at the beginning of this chapter. One of its remarkable features, reflecting the astuteness of its authors, is that from the start it contained the genetic concepts of both of the extremist schools involved in the granite controversy. It thus survived without serious criticism through the arguments of both 'magmatists' and 'transformists'.

As for alteration and mineralization, accounts published in these years start from the premise that the mobile constituents which brought them about, were initially present in the magma and were concentrated and released in the late stages of crystallization. The opinion of the Geological Survey is summarized by Reid and Flett (1907) in the Land's End Memoir (p. 54), where they say 'It is generally admitted that agents which occasioned these changes were vapours emanating from the granite at a time following its injection but anterior to its complete cooling and consolidation'. These vapours consisted mainly of water at a very high temperature. The occlusion of water in molten igneous magmas is a phenomenon of universal occurrence and needs no special explanation in this connection. But it is clear that the Cornish granite masses discharged not only steam, but other substances which have the power of profoundly modifying rocks when they penetrate them, especially at high temperature. Compounds of boron and fluorine were certainly present, as these elements are especially characteristic of the new minerals deposited (tourmaline, topaz, mica, fluorspar). Lithia and phosphoric acid are other substances which passed outward from the granite. Finally, most of the metalliferous ores may reasonably be ascribed to the same source. This is established beyond doubt for the tinstone, and is at least extremely probable for the uranium, tungsten, copper and iron ores. Perhaps the only ores in this area with a different origin seem to be those of silver–lead, zinc and some of the ironstones'.

Despite many papers on minerals and mining, there seems to have been little questioning of this general concept, or of where the magma acquired its relatively high concentration of B, halogen and metallic elements. At the same time, it is apparent that the importance of metasomatism was understood, although it was generally recognized only on a local scale, for example, in greisen-bordered veins, and not as a widespread, pervasive process.

One controversy did develop, however, and that concerned kaolinization which was recognized as a late, low-temperature process. The two schools of thought comprised those who believed, like Hickling (1908), that kaolinization was a consequence of deep weathering, and those like Collins (1878, 1887), Butler (1908) and the Geological Survey who saw it as a magmatic, hydrothermal process. Coon (1911, 1913) accepted both views, postulating an earlier, partial breakdown of feldspar by hydrothermal action, and a subsequent completion of the process by weathering. Given the confused field relations of altered and unaltered rock and the lack of sophisticated chemical techniques, these differences of opinion were bound to persist and in fact were not resolved for many years.

Post-1950, the St Austell model and minor rock types

Following a long quiescent period, research into the granites and their associated geology was resumed in the 1950s, by which time there had been great advances in geophysical and geochemical techniques, largely as a result of wartime developments.

In 1958, Bott, Day and Masson-Smith published the results of the first comprehensive geophysical survey of South-west England, establishing conclusively that the granite outcrops were protruberances from a batholith, as anticipated by De la Beche some 120 years earlier.

Although some modifications to the shape and extent of this have been made (for example, Bott and Scott, 1964; Bott *et al.*, 1970; Holder and Bott, 1971; Tombs, 1977), Bott *et al.*'s concept has not been seriously challenged. Doubts have persisted about the floor of the batholith, however, the lower-crustal sediments having much the same density and seismic velocity as granite and continuing without substantial variation down to the Moho. As noted previously (Chapter 2), a seismic reflector has been found at depths of 10–15 m (Brooks *et al.*, 1984) and it is now widely believed that this is caused by a southward-dipping thrust, an interpretation which accords with the nappe-and-thrust structure elucidated for the Cornubian Peninsula as a whole in recent years. Until the late 1970s, the main direction of granite research was towards classifying the relationships of the principal varieties, the question of the source of the early magma being no more soluble than it had been in the days of Brammall.

In the St Austell intrusion, Exley (1959) followed Richardson (1923) in separating eastern

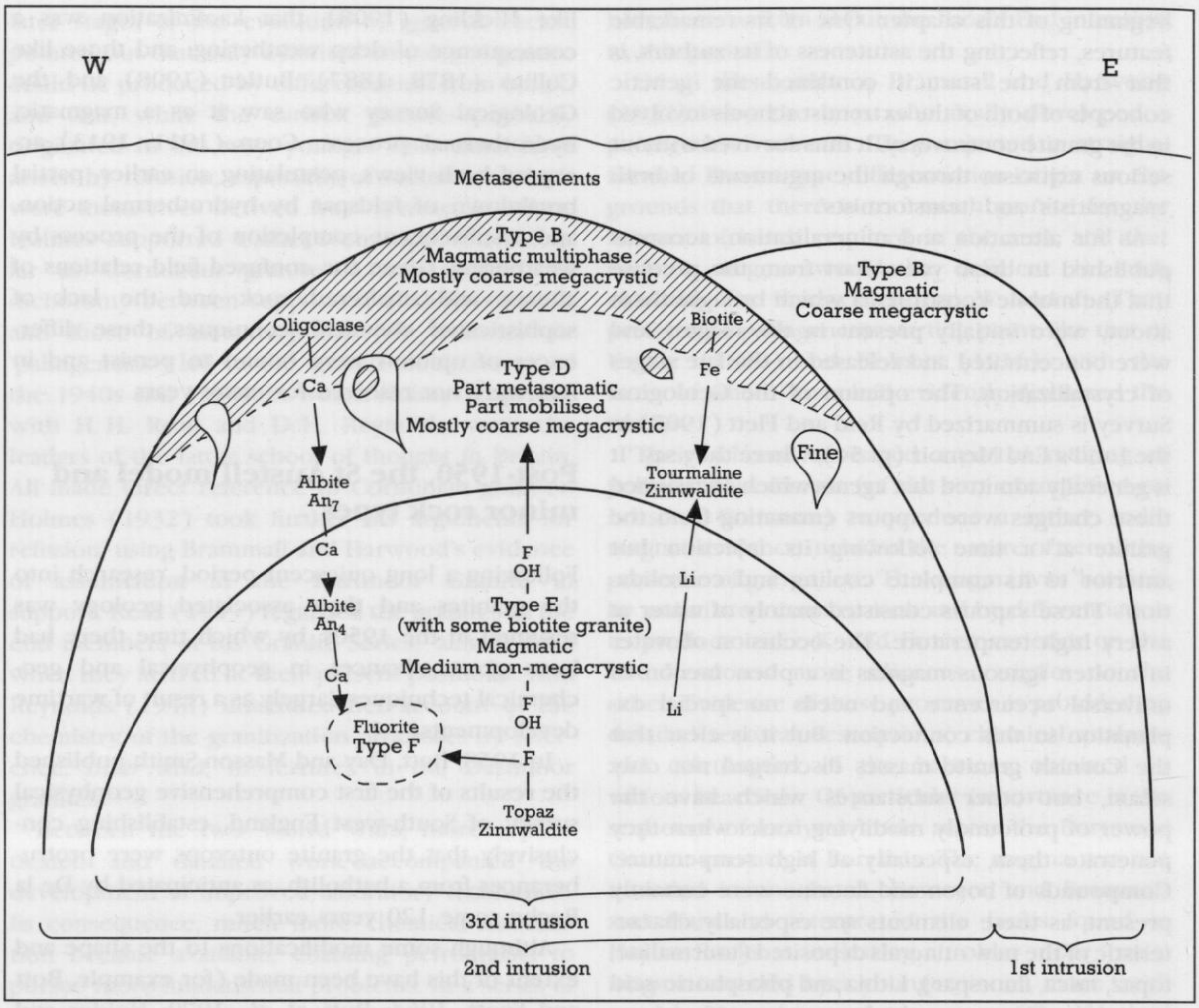


Figure 5.4 The St Austell model. Diagram showing the first intrusion of Type-B granite (Table 5.1) cut by multiphase second intrusion of biotite granite, with metasomatic aureole of Type D caused by intrusion of Type E.

and western intrusions and then went further by subdividing the western area into early and late Li-mica-bearing varieties and a fluorite-bearing variety. All these he considered to have been derived by differentiation from biotite granite magma. This view was later revised when it became clear that Exley's 'late lithionite granite' (now called the 'non-megacrystic Li-mica granite' (Type E) or, by Hill and Manning (1987) the 'topaz granite') was intrusive into biotite granite (Type B) which it had metasomatized to produce Li-mica (Table 5.1). The sequence has thus been reversed: much of the 'early lithionite granite' (Type D) now being recognized as late and referred to as the 'megacrystic Li-mica granite' and not magmatic in origin (Dangerfield *et al.*, 1980), although Bristow (in press) and Bristow *et al.* (in press) believe that a magmatic component is present. A further revision was made by Manning and Exley (1984) who ascribed the fluorite granite (Type F) to hydrothermal and metasomatic reactions accompanying the alteration of biotite granite to megacrystic Li-mica granite. The release of Ca from plagioclase, addition of F from topaz and redistribution of Li and Fe gave rise to fluorite in pockets of granite which were impoverished in mafic minerals (variations in nomenclature are listed in Table 5.1).

Owing to indifferent exposure and extensive alteration, the junction between the eastern and western intrusions and the extent of the metasomatic conversion of the latter into a Li-mica variety have never been precisely defined. Thus outcrops of biotite granite, although sometimes texturally different from that in the eastern intrusion, were known to occur in the western area. The confusion has been reduced to a large extent by Hill and Manning (1987), who have identified a number of granite types in the western area, indicating that, before being metasomatized, it was composed of a composite multiphase intrusion, the components of which themselves constitute an evolutionary, intrusive and metasomatic sequence. This consists of: biotite granite → equigranular biotite granite → globular quartz granite → tourmaline granite → aphyric granite → topaz granite. Exploration for, and expansion of, china clay workings have shown that substantial unmetasomatized bodies of biotite granite remain in the area. The magmatic history of the St Austell Granite, as it is now understood, is represented diagrammatically in Figure 5.4 and constitutes the 'St Austell model'.

The relationship between the biotite granite and the Li-mica granite magmas began to emerge when, shortly after Exley's early work on the St Austell granite, Stone carried out a detailed investigation of the small Tregonning–Godolphin Granite between the Carnmenellis and Land's End intrusions. Here, both biotite granite and non-megacrystic Li-mica granite occur together and Stone (1975) was able to establish that the latter had intruded the former. He deduced that the second magma had been derived at depth from biotite granite, the process envisaged consisting of the albitization of the plagioclase, the exchange of Li–Al for Mg–Fe to produce Li-mica from biotite, and the enrichment of the fluid phase (already widespread and F-rich) in K, leaving the rock richer in Na. At the depths and pressures considered probable, large volumes of melt could be generated in this way. Later experimental work by Manning (1979) on melts in the system Qz–Ab–Or with varying F contents, has shown that it is possible for magma of the required composition to be derived from volatile-rich bioite granite magma by differentiation.

The Li-mica granite of Tregonning is some 10 Ma younger than the neighbouring Carnmenellis Granite, just as the Castle-an-Dinas Li-mica granite near St Austell is 10 Ma younger than the nearby biotite granite. This fact, together with the widespread mineralization dated at about 280–270 Ma (Table 2.1), has led to the belief that the Li-mica granite intrusive phase was responsible for the main mineralization and that this type of granite is much more widespread than is indicated by the small outcrops in the St Austell and Tregonning areas. If this is correct, there seems to be no reason why both the evolutionary processes outlined above should not have operated, local conditions of temperature, pressure and volatile concentration being the determining factors.

None of the other granite outcrops show the range of varieties of the two described above, consisting predominantly of coarse-grained biotite granite (Type B) with inclusions (Type A) and small amounts of fine-grained granite (Type C), although Knox and Jackson (1990) have recently described an evolutionary suite of biotite granite intrusions from the southern marginal area of Dartmoor.

As far as the coarse-grained granite is concerned, suspicions that this was not composed of two or more varieties intruded separately began to emerge early in the post-war period. For example, Chayes (1955) demonstrated that the modes of Types 1 and 2 of Carnmenellis (described by Ghosh in 1934) were not statistically distinguishable, a conclusion reinforced by Al-Turki and Stone (1978) who also showed that some chemical differences were not significant. Ghosh's Type 3 was, however, significantly different from these. During the remapping of the Dartmoor Granite by the Geological Survey, Edmonds *et al.* (1968) became convinced that Brammall and Harwood's Giant and Blue granite varieties were not separate intrusions, but facies of the same rock. Likewise, Booth and Exley (1987) have noted variations in the coarse granite of Land's End, and it is the present author's opinion that the same feature is to be found on Bodmin Moor, although Ghosh (1927) regarded his Normal and Godaver varieties as having an intrusive relationship.

In all cases, the coarser, more striking megacrystic rock forms an envelope (usually incomplete) around a less obviously megacrystic core. Hawkes (*in* Edmonds *et al.*, 1968) refers to the two as the 'big feldspar granite' and the 'poorly megacrystic granite' and they formed the basis of the very useful field and mapping classification described by Hawkes and Dangerfield (1978). Owing to their mineral and chemical similarities, however, Exley and Stone (1982) preferred to regard them as variants of a single coarse-grained biotite granite, their Type B.

An explanation for the different textures as variants was first suggested by Stone and Austin (1961) and further discussions are to be found in Exley and Stone (1964), Booth (1968), Hawkes (*in* Edmonds *et al.*, 1968), Stone and Exley (1968) and Stone (1979, 1984, 1987). Essentially it is agreed by these authors that the textures associated with the K-feldspar megacrysts show them to be secondary and developed by autometasomatism around either earlier K-feldspar or, in some cases, plagioclase. Their presence in the marginal regions of the intrusions was due to the exsolution of OH in the cooler parts, thereby providing the medium for the movement and recrystallization of alkalis. Stone (1979, 1984, 1987) relates this stage of evolution to the transition between magmatic (solidus) and post-magmatic (subsolidus) reactions and to feldspar unmixing. In his 1987 paper, he also draws attention to small but significant differences between the 'trace-alkali suite' of elements (Li, Rb, Cs, F and SiO_2) in Ghosh's Types 1 and 2 granites, suggesting that this variation is due to late-stage redistribution (which would have the textural consequences just noted) and that Type 2 represents 'relict areas not affected by these changes'. It should be noted that some authors, notably Webb *et al.* (1985), Vernon (1986), Leat *et al.* (1987) and Jackson *et al.* (1989), argue for a magmatic origin of the megacrysts. This is a view with which the present author does not concur in the light of his own experience of the textural relations and distribution of these megacrysts.

The other chief granite variety is the fine-grained biotite granite (Type C) and modern opinions about this include both those which regard it as a late, intrusive differentiate and those which regard it as granitized sediment, as was noted above (Exley and Stone, 1982; Exley *et al.*, 1983; Hawkes, 1968, 1982; Stone and Exley, 1986; Tammemagi and Smith, 1975). There has also been work during recent years on some of the less-abundant types, especially leucogranite, aplite, pegmatite, quartz–tourmaline rock, quartz–topaz rock, granite porphyry (elvan) and explosion breccia. Discussions about these are included in the relevant site descriptions and are briefly summarized below.

Leucogranite, aplite and pegmatite

Given the high concentrations of volatile constituents and such elements as Li, well-developed pegmatites are surprisingly uncommon in Devon and Cornwall, although they occur in small patches, veins and pods quite frequently and in many cases are obviously the result of pockets in the magma where volatiles have been concentrated; probably in some cases they represent globules of an immiscible phase.

One of the most characteristic developments of pegmatite is in conjunction with aplite and leucogranite in the 'roof complexes' of the Tregonning Granite, the related sheets near Megiliggar Rocks, and the non-megacrystic Li-mica granite intrusion in the St Austell mass, but they also occur on a large scale at Meldon near the north-western margin of the Dartmoor Granite.

The textures and compositions of these rocks suggest that they, like the metasomatic facies of the main granites described earlier, originated by reactions spanning the super-solidus/subsolidus stages of magmatic crystallization. Leucogranite is regarded as a direct magmatic descendant, owing its composition to fractionation of calcic plagioclase and dark minerals, while aplite represents the Na-rich liquid fraction left when K was preferentially partitioned into vapour phase. This, in turn, caused recrystallization into pegmatite.

Quartz–tourmaline and quartz–topaz rock

Quartz–tourmaline rock occurs in association with most of the main granites in areas where B concentrations have been particularly high, for example, at Roche Rock north of the St Austell Granite and along the western margin of the Land's End Granite at Porth Ledden. The evidence points to a magmatic origin through the separation of an immiscible liquid phase.

Quartz–topaz rock is rather rarer and mostly seen in the St Austell area, especially at St Mewan Beacon. Its origin is not yet fully explained, but it seems not to be staightforwardly magmatic and includes a significant hydrothermal component.

These two rock types also belong to the late-magmatic and immediately post-magmatic stages.

Elvan dykes

Granite porphyry dykes, sometimes consisting of single, but often of multiple, intrusions are to be found throughout the peninsula and follow the main, approximately E–W-trending joint direction for the most part. Some of these rocks are of straightforward magmatic derivation from biotite granite magma, but many (such as that at Praa

Sands), contain evidence of a solid component incorporated by fluidization. These rocks are the youngest of the magmatic intrusions.

Explosion breccias

Spectacular developments of breccias made up of both igneous rocks and metasediments, and usually heavily mineralized, occur in a number of places in Cornwall. Most are in the central and western parts, as at Venton Cove near Marazion, and at Wheal Remfry in the west of the St Austell Granite. They have resulted from violent reduction of pressure as fissure systems above magmatic fluid concentrations reached the surface allowing the rocks to implode.

Source material and the 1980s model

Until good techniques for the analysis of radio-isotopes and trace- and rare-earth elements became established, it was impossible to say much about possible source rocks for the early magmas, or about the conditions under which they formed. Thus, detailed though they were, discussions such as those by Brammall and Harwood (1932) remained unsupported by what is now considered to be essential chemical evidence. The general nature of more modern data and the tenor of arguments based on them have been outlined in Chapter 2, including the proposition that these are 'S-type' granites (Chappell and White, 1974) We now need to add further details.

1. Table 5.2 shows that a number of trace elements and their ratios are not appropriate to primitive granites resulting from deep-seated magmatic differentiation, e.g. Nb, Y and Zr are relatively low and Rb, Ba and Sn are high.
2. Table 2.1 shows that the initial ratios of $^{87}Sr/^{86}Sr$ range from 0.7095 to 0.7140, which are crustal values.
3. Hampton and Taylor (1983) record Pb isotope ratios of $^{206}Pb/^{204}Pb$ from 18.363 to 18.499, $^{207}Pb/^{204}Pb$ from 15.614 to 15.655 and $^{208}Pb/^{204}Pb$ from 35.261 to 38.508; again these are crustal not subcrustal values.
4. Both the concentrations of the radio-elements U, Th and Zr and the rare-earth elements, and the ratio of light to heavy REE (shown by the steepness of the slope of the chondrite-normalized values in Figure 5.5) indicate that the magma was derived from a source already well differentiated and not from a basic magma, even if it were contaminated as suggested by Thorpe *et al.* (1986), Thorpe (1987) and Leat *et al.* (1987). Darbyshire and Shepherd (1985) show REE patterns for Dartmoor, Land's End, Bodmin Moor and Carnmenellis (Figure 5.5) and suggest that differences between the first two and the last two indicate either different degrees of partial melting or different source rocks. They agree that all are indicative of a metasedimentary source, however. Most work on REE has been carried out on the Carnmenellis Granite (Jefferies, 1984, 1985a; Charoy, 1986; Stone, 1987) and this confirms that these elements are carried in the main by the accessory minerals: apatite, zircon, monazite, xenotime, ilmenite and uraninite. There is some uncertainty as to the extent to which these minerals (and the biotite which frequently encloses them) are magmatic or derived from their sedimentary host rock as 'restite'. Jefferies (1984) regards them as chiefly magmatic and Stone (1987) as restitic. The issue is, in any case, complicated by some fractionation and later metasomatic redistribution of these elements (for example, Alderton *et al.*, 1980).
5. The highly aluminous nature of the granite and the occasional presence in it and its xenoliths of garnet, sillimanite, andalusite and cordierite, in addition to the chemical characters enumerated above, point clearly to a pelitic sedimentary source containing garnet, and Charoy (1986) has argued the case for material similar to Brioverian pelite.
6. The ammonium content of the granite ranges from 3–179 ppm with an overall average of 36 ppm and an average of 94 ppm for Bodmin Moor. These compare with a world's average of 27 ppm for granite and granodiorites and, since the source of ammonium is almost certainly organic matter in sediments, such high values are strongly indicative of contamination by sediment (Hall, 1988).

There remain, however, some anomalies, such as the sources of Sn, U, Cl and F which seems unlikely to have been available in any metasedimentary source in anything like the concentrations required to give rise to the quantities present in the granite. The only possible alternative source for these lies in the upper mantle where the heat

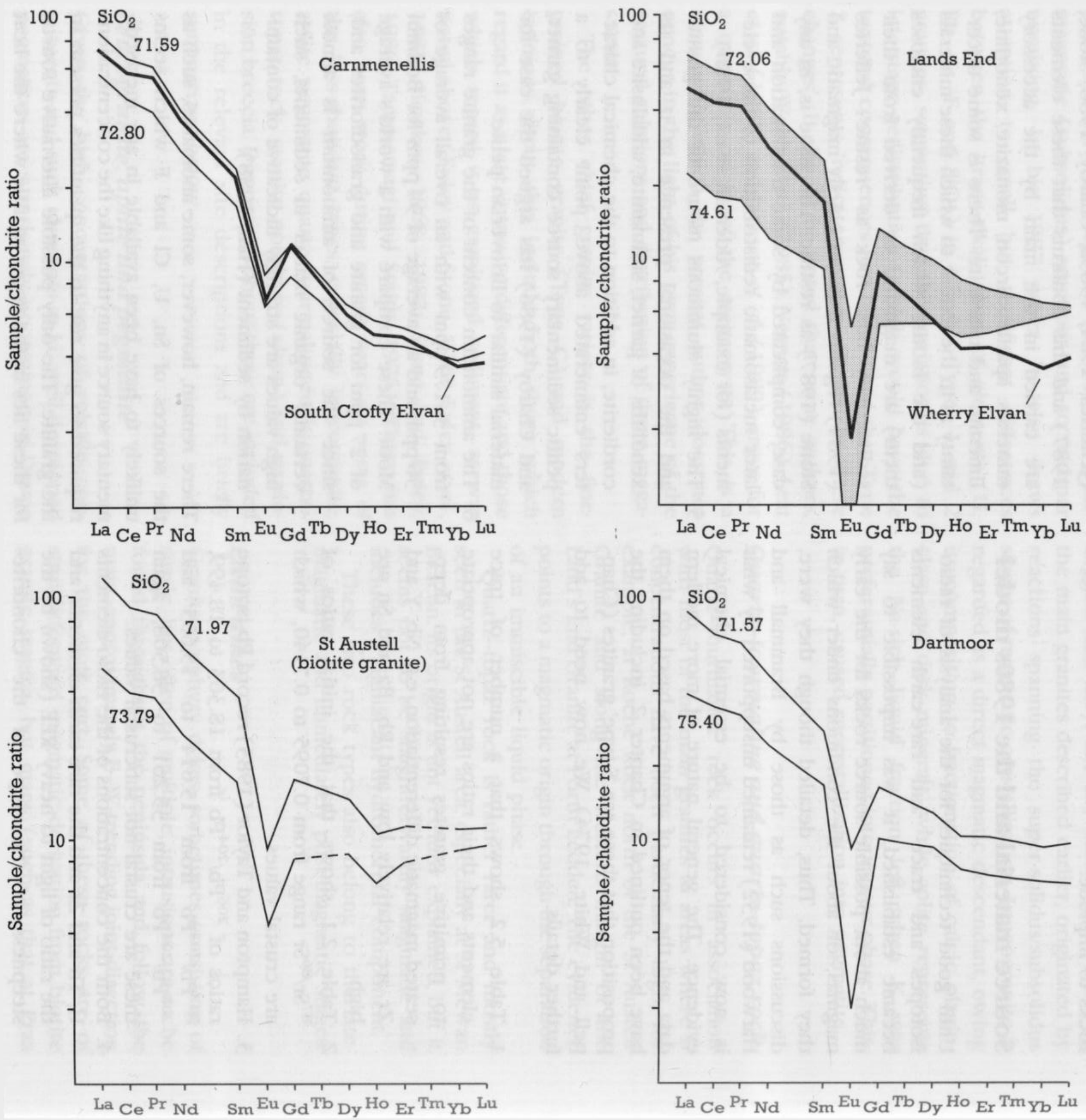


Figure 5.5 Chondrite-normalized REE profiles for Cornubian granites. Data for Land's End, Carnmenellis, Bodmin Moor and Dartmoor from Darbyshire and Shepherd (1985).

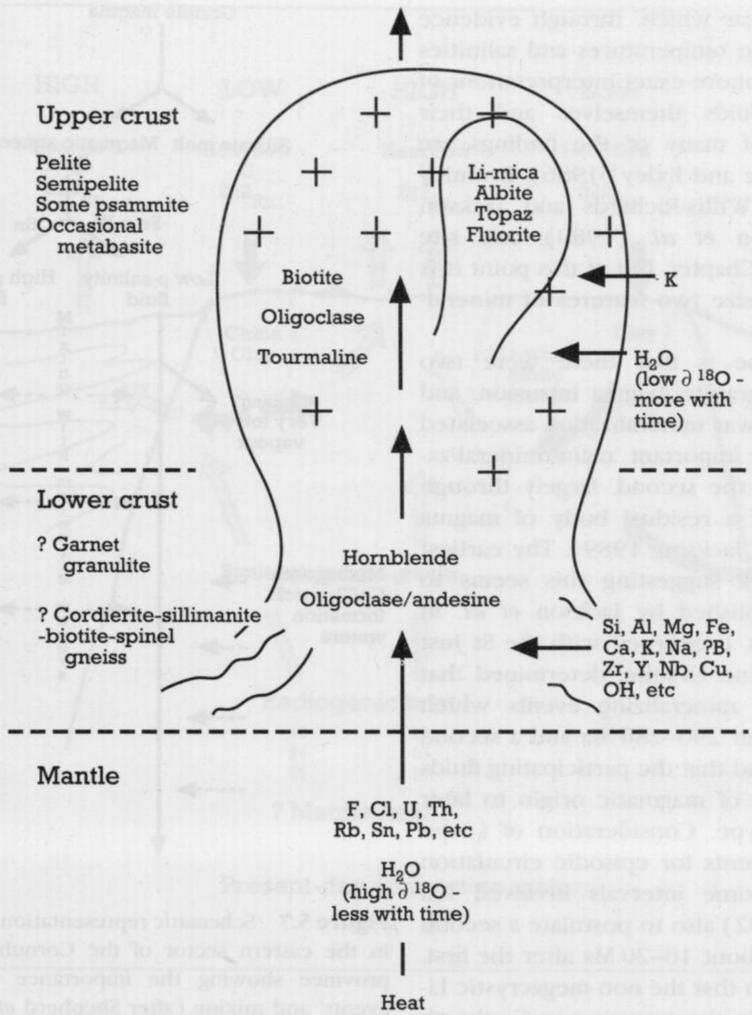


Figure 5.6 The 1980s model. Granitic magma generated in the lower crust (but with mantle components) and evolving both by assimilating upper-crustal constituents and differentiating Li-mica granite magma. Magma becomes increasingly hydrated by drawing in increasing quantities of meteoric water during ascent.

needed for partial melting must have also originated. The conclusion must be, therefore, that volatiles from high-level mantle rocks carried these components into the granite magma as it formed in the crust, and that their present distribution is a result of their partition into different phases as the magma evolved. Although aqueous, the amount of water in the magma at this stage must have been small, or the magma would not have been able to rise to high crustal levels; Charoy (1986) suggests something in the region of 3–5%. Most of the water which played so important a part in the later stages of evolution must have been acquired from the surrounding rocks.

The magmatic history accepted at present is demonstrated diagrammatically in Figure 5.6 and is put in the overall context in Table 2.2.

Mineralization and alteration – current views

As with magmatic origins and evolution, understanding of mineralization and alteration advanced little until it became possible to analyse trace elements and isotopes. In addition, however, the development of the heating/cooling microscope stage brought more useful results from the study of fluid inclusions than the crude and confusing technique of decrepitometry had done. As a result, in the late 1960s and 1970s experimental data started to appear which, through evidence from homogenization temperatures and salinities of inclusions, led to more exact interpretations of the mineralizing fluids themselves and their reactions. Details of many of the findings are summarized in Stone and Exley (1986), Bromley and Holl (1986), Willis-Richards and Jackson (1989) and Jackson *et al.* (1989), and site descriptions in this Chapter, but at this point it is necessary to emphasize two features of mineralization.

The first of these is that there were two principal stages of granite magma intrusion, and that although there was mineralization associated with both, the more important 'main' mineralization was related to the second, largely through the maintenence of a residual body of magma (Willis-Richards and Jackson, 1989). The earliest comprehensive work suggesting this seems to have been that published by Jackson *et al.* in 1982. These authors, concerned with the St Just area of the Land's End Granite, determined that there were several mineralizing events which included one at about 290–280 Ma and a second about 10 Ma later, and that the participating fluids changed from those of magmatic origin to later ones of meteoric type. Consideration of (*inter alia*) heat requirements for episodic circulation of fluids and the time intervals involved led Durrance *et al.* (1982) also to postulate a second magmatic event at about 10–20 Ma after the first. It was already known that the non-megacrystic Li-mica granite found in the intrusion in Gunheath clay pit near St Austell and in the Castle-an-Dinas Mine a short distance away had intruded biotite granite (Hawkes and Dangerfield, 1978; Dangerfield *et al.*, 1980), so that when the ages of these were found to be approximately 270 Ma BP (Darbyshire and Shepherd, 1985, 1987), it became clear that they represented the event in question. It is possible that the granite intrusions described by Knox and Jackson (1990) from southern Dartmoor also belong to this episode.

The second feature concerns the nature of the fluids which have been found to have a complex evolutionary history. The earliest stage in recognizing that they separated into different fractions followed the work of Jahns and Tuttle (1963) and Jahns and Burnham (1969) who described how partition of Na and K into liquid and vapour phases respectively gave rise to aplite and pegmatite formation, the process underlying the alkali metasomatism of the main granites, the formation of the leucogranite–aplite–pegmatite complexes and, at least partly, to pervasive greisening. Subsequently, however, Pichavant's experiments (1979) coupled with the field studies of Charoy (1979, 1981, 1982) demonstrated that, in B-rich magmas, an immiscible aqueous Si–K–B liquid could evolve to crystallize as rock types rich in tourmaline. Although it is possible that this phase could have carried several metals, Shepherd *et al.* (1985) argued that it too separated into two immiscible phases, one being of low density and low salinity, carrying some Sn and all the W, the other being of high density and high salinity and carrying most of the Sn. This is the pattern seen in the Dartmoor Granite mineral deposits; in the neighbouring country rocks immiscible liquids did not exsolve, but a meteoric water component became mixed with the magmatic component. This thinking is summarized in Figure 5.7.

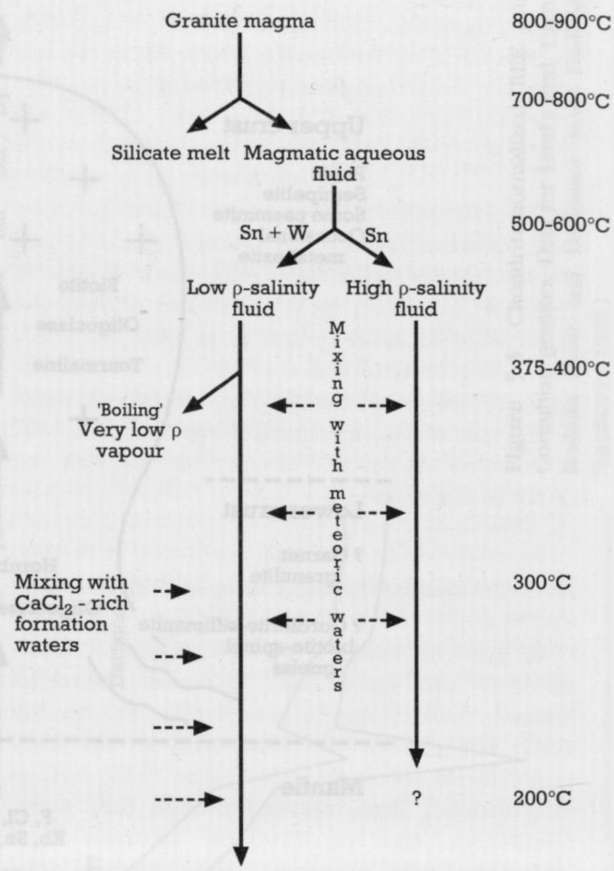


Figure 5.7 Schematic representation of fluid evolution in the eastern sector of the Cornubian metallogenic province showing the importance of 'immiscibility events' and mixing (after Shepherd *et al.*, 1985).

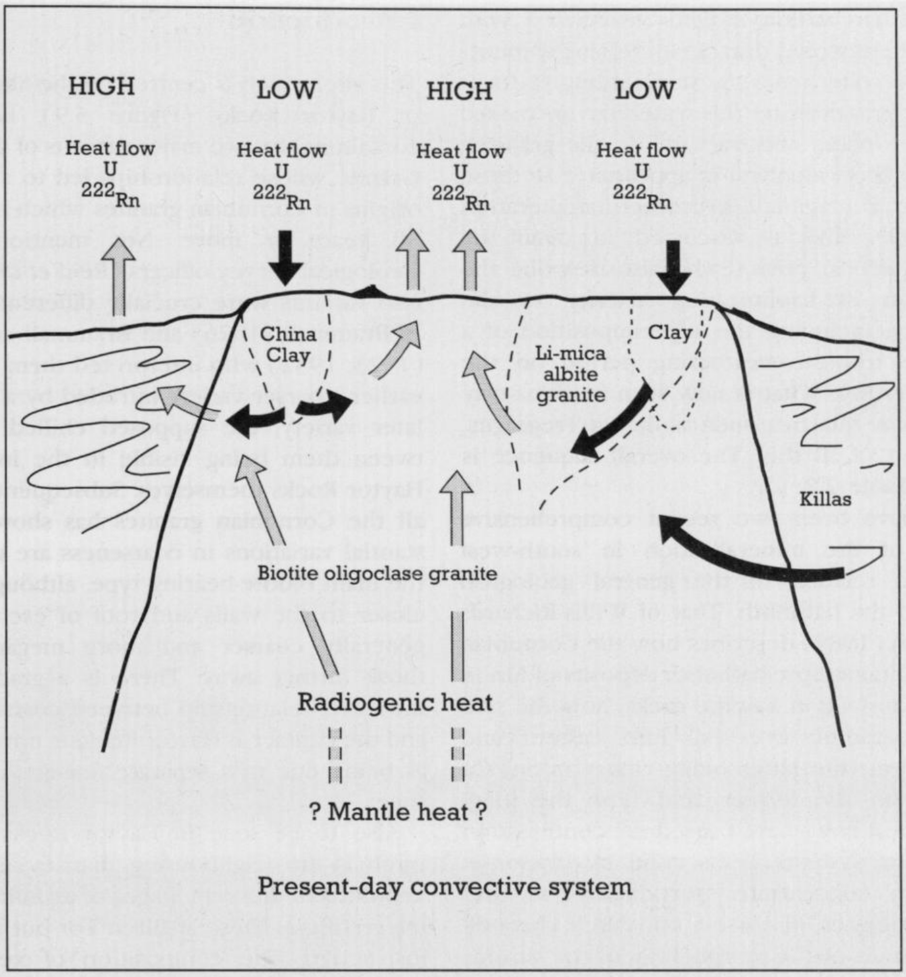


Figure 5.8 Diagrammatic representation of water circulation in Cornubian granite. Areas of low heat flow, U and ^{222}Rn concentration are associated with china clay and indicate draw-down; areas of high heat flow, U and ^{222}Rn concentration indicate uprise (based on Durrance *et al.*, 1982).

The separation of the immiscible fluids resulted in greatly increased internal pressures which disrupted the outer parts of the granites in some places, e.g. Wheal Remfry, west of St Austell. The consequent sudden drop in pressure not only generated a far-travelling vapour phase which could deposit minerals either in the main fracture system or pervasively, but also caused the implosion of the surrounding rocks to give rise to breccias. This happened twice, first in minor fashion at the end of the 280 Ma magmatism, and again at the end of the 270 Ma magmatism when it initiated the main mineralization and also increased the permeability of the granites, thus facilitating later alteration.

The discovery of the importance of meteoric water as a constituent of the mineralizing and altering solutions was made by Sheppard (1977), using stable isotopes and was confirmed by Jackson *et al.* (1982). It has had a profound effect on the understanding of these processes.

Sheppard (1977) showed that mica in greisens contained both magmatic and meteoric water, but that kaolinite contained only the latter. He thus supports the weathering origin of kaolinite mentioned above, but the absence of a deeply weathered mantle overlying the Cornubian rocks and the close relationship between kaolinization and the joint system, often beneath unaltered rock, still obstructed its acceptance by advocates of magmatic hydrothermal action. The dilemma was resolved by the publication of a paper by Durrance *et al.* (1982), who, following the ideas of Fehn *et al.* (1978), established the concept of convective circulation systems associated with granites. These would draw in increasing amounts of meteoric water from the surrounding rocks as well as the granites, and this water, having passed through the pores and fractures in the granites, produced effects identical in appearance to those resulting from magmatic hydrothermal alteration (Figure 5.8). This is discussed in detail by Bristow *et al.* (in press), who also describe the continuation of kaolinization activity to the present day, including the superimposition of a Palaeogene tropical weathering period on the earlier alteration. What is now seen in china-clay pits and some quarries, such as that at Tregargus, is the result of all this. The overall sequence is shown in Table 2.2.

There have been two recent comprehensive accounts of the mineralization in south-west England in relation to the general geological setting and the batholith. That of Willis-Richards and Jackson (1989) describes how the Cornubian orefield contained pre-batholith deposits of Mn in sediments and Cu in basaltic rocks, how the syn- and post-batholith ores fall into eastern and western areas, the latter being richer in Sn, Cu and Zn than the former, and how the long-sustained heat flows have caused the continuation of convective systems. The second, by Jackson *et al.* (1989), concentrates particularly on ore-forming processes, discussing both their chronology and details of the morphology of the various types of deposit. The nature of both main-stage and epithermal mineralizing fluids is considered in terms of their temperatures, salinities and flow as modelled by computer. These papers support the brief description given above but add much important detail to it.

C1 HAYTOR ROCKS AREA (SX 758773)

Highlights

This classic site contains the best exposure of variants of the coarse, megacrystic granite of Dartmoor, together with a later, intrusive, fine-grained granite sheet. Its coarse-grained granites enclose a variety of genetically significant xenoliths. It also provides excellent evidence of tourmalinization.

Introduction

This site, which is centred on the fine summit tor of Haytor Rocks (Figure 5.9), is unique in containing the two major variants of the Dartmoor Granite whose relationships led to a view of the origins of Cornubian granites which held sway for 30 years or more. Not mentioned by the Geological Survey officers (Reid *et al.*, 1912), the two variants were crucially different in the eyes of Brammall (1926) and Brammall and Harwood (1923, 1932) who interpreted them as an upper, earlier, coarser variety intruded by a lower, finer, later variety, the supposed chilled contact between them being visible in the lower part of Haytor Rocks themselves. Subsequent research in all the Cornubian granites has shown that substantial variations in coarseness are usual among the main biotite-bearing type, although the rocks closer to the walls and roof of each pluton are generally coarser and more megacrystic than those further away. There is a gradational, not intrusive, relationship between coarser and finer, and the contact at Haytor Rocks is now recognized as being due to a separate fine-grained intrusive sheet.

Also to be seen in Haytor Rocks (and more rarely in the neighbouring quarries) is a variety of xenoliths in different stages of assimilation; not as interesting as those at Birch Tor but nevertheless instructive. The composition of xenoliths was used by Brammall and Harwood (1932) in calculations of the modification of the earliest Dartmoor magma into the first of the main magmas; and a cordierite hornfels from Haytor Rocks was described by them in 1923 and a highly granitized 'basic inclusion' from the Haytor Quarry in 1932. Later work suggests that xenoliths are less important than was supposed (Stone and Exley, 1986; Bromley and Holl, 1986). The authors of the Survey Memoir (Reid *et al.*, 1912) described the Dartmoor Granite as being less boron rich than average in south-west England, but the presence in the Haytor Quarries, and in the boulders in the area, of tourmaline-bearing veins and nodular masses of tourmaline called 'suns' indicates that the boron content of the magma was relatively high nevertheless. Brammall and Harwood (1923, 1925, 1932) discussed the significance of this and, especially in their 1925 paper, separated what are now regarded as magmatic, autometasomatic and post-magmatic tourmaline generations. Although later research has modified their views in some details, it has

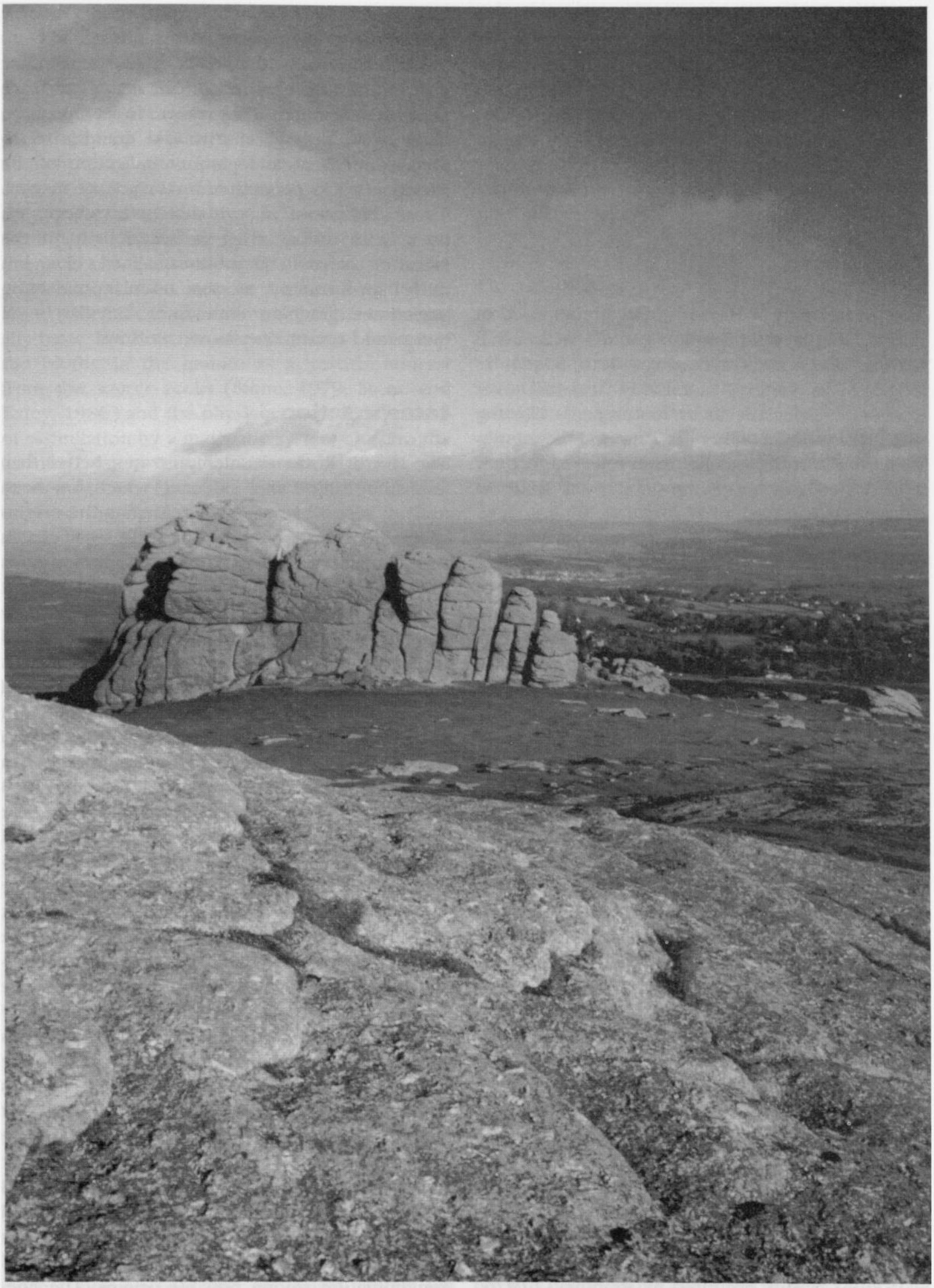


Figure 5.9 Haytor Rocks, exposing the coarse megacrystic granite of Dartmoor. The megacrystic character of the granite is visible in the foreground exposure. (Photo: S. Campbell.)

been based on work done elsewhere than Haytor and is described within this volume.

Haytor Rocks were classified as an excellent and 'type' example of 'summit tor' by both Linton (1955) and Gerrard (1974) and figured in photographs in both Linton's (1955) and Palmer and Neilson's (1962) papers.

Description

The greater part of Haytor Rocks is composed of coarse, megacrystic biotite granite with alkali feldspar megacrysts averaging 40 to 50 mm in length. This variety, commonly seen all over Dartmoor, especially in tor outcrops, is like the main granites of other masses in the south-western peninsula and has been referred to their Type B by Exley and Stone (1982) and Exley *et al.*, (1983).

The lower parts of the western and north-western faces of Haytor Rocks, however, are made up of fine-grained granite, devoid of megacrysts and with pronounced vertical columnar jointing. The contact between the two granites is sharp, although irregular, and dips gently but unevenly towards the south-west; the marginal zone of the lower granite being especially fine grained. Taking into account the exposures in a nearby abandoned cutting, the lower granite must be at least 10 m thick.

Two hundred and fifty metres to the NNW is a small unnamed quarry, while 450 m to the NNE are the much larger eastern Haytor Quarries. In these exposures the rock is not as coarse or as abundantly megacrystic, and this led Brammall and Harwood to the conclusion that there were two granite types, a view that they supported by chemical analyses. They believed that the type forming the upper part of Haytor Rocks and other tors in the vicinity was earlier, sheet like and less potassic. It was known as 'tor' or 'giant' granite. The type found in the quarries was thought to constitute an underlying intrusion into the giant granite, with its chilled contact phenomena visible in the lower part of Haytor Rocks. This later variety was supposed to be derived from the earlier at depth, it was more potassic and was called 'blue' or 'quarry' granite. Other examples of apophyses and sheets of blue granite in contact with giant granite are cited by Brammall (1926) and by Brammall and Harwood (1923), but none is so large and significant as that at Haytor, and it was recognized that the provenance of these minor intrusions was not always clear.

The xenoliths in the area vary in size, but are mostly less than about 0.5 m across and are generally rounded. They range in composition from basic, through diorite and grandiorite, to metasedimentary; and give an indication of the variety of rocks penetrated by the granite magma. Tourmalinization, in evidence everywhere, especially in the quarries, is occasionally in the form of narrow quartz–tourmaline veins but more spectacularly as the nodular masses – sometimes granular, sometimes acicular – of quartz and tourmaline known as 'suns'.

Interpretation

The Haytor Rocks site demonstrates, better than any other single site, evidence which has been used to support hypotheses regarding the origins of the Cornubian granites. The most significant is the presence of the two major granite variants thought by Brammall and Harwood to be distinct and separate intrusions. However, it is now realized that most of the chemical and textural variations in the coarser Cornubian granites is gradational and does not allow the separation of types which can be shown to be different statistically (for example, Chayes, 1955; Al-Turki and Stone, 1978); thus both Haytor variants can be accommodated in Exley and Stone's Type B granite or the 'coarse megacrystic' and 'coarse poorly megacrystic' varieties of Dangerfield and Hawkes (1981). Moreover, it is generally accepted that the fine-grained intrusion at Haytor Rocks is a large sheet later than, and independent of, the coarse granites in both the tors and the quarries. It has a significantly different composition, and is thus considered to belong to the Type C of Exley and Stone (1982) or 'fine poorly megacrystic' type of Dangerfield and Hawkes (1981). Although both field relations and trace element ratios suggest that some Type-C granites were derived from the Type-B magma (Exley *et al.*, 1983), variations in their chemistry indicate that others were not and that the process was not straightforward (Exley *et al.*, 1983; Stone and Exley, 1986). For example, describing fine-grained granite from a few miles to the north, Hawkes (*in* Edmonds *et al.*, 1968) included both chilling and contamination among possible origins. The fine-grained sheets noted by Brammall and Harwood do not all have the same origin, therefore.

It was postulated by Brammall and Harwood (1932) that the earliest magma was 'sodipotassic' and that it was modified and made increasingly potassic by the assimilation of xenolith material, particularly metasedimentary fragments, from the rocks through which it ascended, and, while concentrating attention on material from the contact at Burrator, on the west of Dartmoor, they quote an analysis from a Haytor xenolith in their paper. According to Reynolds (1946), the chemical changes resulting from assimilation and granitization make suspect Brammall and Harwood's identification of some xenoliths as originally basic. Furthermore, the derivation of much of the biotite in the granite as a 'restite' mineral from the source rocks (Stone, 1979; Stone and Exley, 1986) and the physicochemical difficulties of assimilation by a magmatic system close to the 'granite' system ternary minimum of Tuttle and Bowen (1958), (Bromley and Holl, 1986) have reduced the significance of xenoliths in modern views about the petrogenesis. Nevertheless, the presence of a wide variety of xenoliths, many of which are metasedimentary, gives these granites the aspect of Chappell and White's (1974) S-type, although relatively high concentrations of some metallic and halogen elements suggest the addition of some mantle components (Exley *et al.*, 1983; Stone and Exley, 1986). The Dartmoor petrogenetic model is put into historical context in the earlier part of this chapter.

A relatively high boron concentration in the Cornubian magmas played a very important role in late- and post-magmatic activity of various kinds including mineralization. By comparison with granites further west, such activity was restricted in the Dartmoor area: quartz–tourmaline veins and nodules such as are well displayed in the rocks around Haytor, provide excellent examples of the early stages of these phenomena. Brammall and Harwood (1925) suggested that there was a reciprocal relationship between the proportions of biotite and tourmaline, a suggestion supported by a deficiency of biotite in the rock surrounding some of the tourmaline 'suns' found in the Haytor Quarries. They argued that Fe, Mg and Ti were distributed in biotite, tourmaline, rutile, anatase and brookite or zircon according to the temperature of the magma, concentrations of B and extent of post-magmatic alteration (Brammall and Harwood, 1923, 1925, 1927).

This site contains the exposures which led Brammall and Harwood (1923, 1932) to believe that the finer-grained Dartmoor Granite was intrusive into earlier, coarser-grained variety, a belief which is not now accepted. It also contains examples of the xenoliths whose assimilation these authors considered to have played a crucial role in modifying the composition of the initial magma. Lastly, it contains a variety of veins and nodules which illustrate the effects of tourmalinization resulting from the high boron concentration in the magma.

Conclusions

The Haytor Rocks site constitutes an ideal area in which to examine textural and compositional variations in the earlier, main suite of Dartmoor granites in particular and in the Cornubian granites in general. Additionally, there is evidence for the way in which the magma was modified both by the incorporation of xenolithic constituents and by reaction with boron. Geomorphologically, the site is dominated by a classic example of a summit tor.

C2 BIRCH TOR (SX 686814)

Highlights

This site has an important display of varied xenoliths illustrating material thought to have influenced the final composition of the main Dartmoor Granite magma.

Introduction

The site is situated 8 km south-west of Moretonhampstead. It encloses Birch Tor itself, which contains xenoliths and rafts of precursors of the Dartmoor Granite and is adjacent to the remains of the open-cast workings of the Birch Tor and Vitifer tin mine.

One of the cornerstones of Brammall and Harwood's hypothesis (discussed earlier), regarding the composition of the main Dartmoor Granite was that it had been modified from its original 'sodipotassic' nature by assimilation of country rocks and older granites which it had intruded. They noted several areas, for example Haytor Rocks and Bellever Tor, in which evidence for this can be found, but one of the most important is Birch Tor which shows a particularly good range of xenoliths contained within their 'giant' or 'tor' variety of granite. Particular reference is made to the dark rock at the base of the tor, in Brammall's paper of 1926 (in which there is a field photograph) and in joint papers of 1923 and 1932 (in which there are chemical analyses, with a photomicrograph in the latter). There has been no serious dispute about Brammall and Harwood's evaluation of the origin and composition of these xenoliths at high levels in the granites, and a similar range is described from a few miles to the north by Hawkes (*in* Edmonds *et al.*, 1968). Reynolds (1946) has, however, questioned the identification of some as originally basic as a result of her calculations of the changes resulting from granitization. Stone (1979) and Stone and Exley (1986) have noted that some of the biotite in the granite is of 'restite', not xenolithic, origin and Bromley and Holl (1986) have shown that on geophysical, as well as geochemical grounds, assimilation at depth was probably very limited.

Description

Birch Tor is a low, extended tor with two main outcrops and conspicuous subhorizontal jointing. It is composed of coarse, megacrystic, biotite granite and contains a variety of xenoliths of different shapes, sizes and compositions. Some inclusions are rounded and others flat and subangular, but the most conspicuous is a sheet- or raft-like mass, some 7 m long and at least 3.5 m thick at the base of the south face of the western summit. This was illustrated by Brammall (1926) who described it as 'dark, blue-grey microgranite', and has been figured and analysed by Brammall and Harwood (1923; 1932) who also gave an analysis of a smaller xenolith. Many of these xenoliths look similar and are microgranodioritic or microdioritic; evidently they have undergone recrystallization as a consequence of entrapment in the granite magma.

Interpretation

The Dartmoor Granite was the subject of intensive investigation, especially by Brammall and Harwood between 1923 and 1932. For the most part, it consists of coarse-grained, megacrystic biotite granite, but the size and concentration of megacrysts is rather variable and, partly on this basis, Brammall and Harwood separated it into two intrusions: an earlier, coarser 'giant' or 'tor' variety and a later, finer 'blue' or 'quarry' variety. It has been proved subsequently that these textural features are gradational and both varieties are now included in the coarse-grained megacrystic or poorly megacrystic categories (of Dangerfield and Hawkes, 1981) and Type B (of Exley and Stone, 1982 and Exley *et al.*, 1983). Other intrusive varieties also occur and can be found around Birch Tor, but these are present in comparatively small amounts, all are younger and are not relevant in the present context.

The granite here is believed to have originated by lower crustal anatexis, much of its biotite being 'restite' material carried over from the source rocks which were probably more granodioritic than those in the contemporary upper crust (Stone and Exley, 1986). It is therefore an 'S-type' granite essentially (Chappell and White, 1974), and, as noted in Chapter 2 and the 'Petrogenesis' section above, shows appropriate chemical and mineral features. In Brammall and Harwood's view (1932), the initial magma was both acid and 'sodipotassic' or even sodic, and it became more basic and potassic by assimilating country rocks of overall argillaceous composition but which also contained dolerite, dioritic and granodioritic units. They based this argument on examination of this section and on chemical analyses from xenoliths found in the main granite and from a series of analyses across the granite/country rocks contact at Burrator.

Although, as has been said, Brammall and Harwood believed that some xenoliths were of originally basic composition, Reynolds (1946) pointed out that their present compositions are inappropriate to such a derivation when desilication and other changes are calculated, and that the xenoliths were more probably metasedimentary in origin.

Brammall and Harwood's concept has also been modified in three respects by more recent work (Hawkes, *in* Edmonds *et al.*, 1968; Exley and Stone, 1983; Exley *et al.*, 1983; Stone and Exley, 1986; Bromley and Holl, 1986). First there is the recognition that biotite is a derived or 'restite' mineral (Stone, 1979), and this has important implications with respect to the water content of the magma. Secondly, is the recognition that the feldspar megacrysts are a secondary phase and have developed as a result of potash metasomatism, sometimes on nuclei provided by plagioclase crystals. Brammall and Harwood saw the 'potassification' of the magma by xenoliths taking place in such a way that feldspars grew from the liquid as primary crystals, whereas the later workers, following the lead of Stone and Austin (1961), attribute them to the action of a later and separate K-rich aqueous phase. Thirdly, assimilation of much country rock is precluded by the composition of the magma, now known to be close to the 'granite' system's ternary minimum melt composition, and by the rapid rate of settling of xenoliths. Moreover, the observed density increase with depth in the batholith is consistent with a concentration of sunken xenoliths.

Brammall and Harwood were strongly influenced by the work of N. L. Bowen, whose important research, culminating in the publication of *The Evolution of the Igneous Rocks* in 1928, was coincident with much of their own. Hence, among other things, they emphasized the importance of assimilation and differentiation in modifying magma, and concluded that the latter was responsible for their second magma fraction (giving 'blue' granite) and subsequent fractions. At the time, however, many physicochemical controls of crystallization were still unrecognized, including the nature of the partitioning of elements between solid, liquid and gas phases, and it is this later knowledge that has led to revisions of Brammall and Harwood's interpretations.

Conclusions

This site contains an outcrop of coarse, megacrystic biotite granite containing xenoliths of various rock types. These have been taken to illustrate the kinds of material whose incorporation into the magma substantially modified the chemistry and mineralogy of the Dartmoor Granite. It exemplifies a significant part of a concept of petrogenesis which was sustained for many years and was a foundation of modern thinking.

C3 DE LANK QUARRIES (SX 101755)

Highlights

These quarries contain fresh, coarse-grained, poorly megacrystic biotite granite, characteristic of the Bodmin Moor intrusion, strongly foliated and jointed, and containing pegmatitic patches, minor granitic veins and xenoliths. They also incorporate typical Cornubian, fine-grained, megacrystic biotite granite and granite porphyry dykes ('elvans').

Introduction

The De Lank Quarries provide a rare opportunity to see really fresh, coarse, Cornubian biotite granite of the type classified by Dangerfield and Hawkes (1981) as the 'small megacryst variant'. This is typical of Bodmin Moor, much of Carnmenellis and the Isles of Scilly, but uncommon elsewhere. This rock type is often foliated and this feature is particularly conspicuous at De Lank. Although the officers of the Geological Survey (Reid *et al.*, 1910; Reid *et al.*, 1911) noted these features, they did not classify the rocks as a separate type, and the 'Godaver' type of Ghosh (1927), found in the extreme east of the pluton, is not distinguished by these criteria. Indeed, the present author's research indicates that the Godaver Type is a minor variant of the main granite.

Although subhorizontal jointing is characteristic of surface exposures, its change in frequency with depth cannot usually be seen: the deep quarries at De Lank provide an invaluable demonstration of such jointing. Similarly, although surface exposures often display such phenomena as xenoliths, pegmatitic segregations and small veins of later, intrusive granite, these are usually weathered and of poor quality compared with fresh examples found in the quarry.

A major occurrence of fine-grained, megacrystic biotite granite is found a short distance to the north of the site, and an apophysis of this, exposed in the De Lank River in the north-east corner of the site, is one of the very few of this type in a fresh condition in Devon and Cornwall.

The remains of three substantial outcrops of dykes of granite porphyry ('elvan') are also present; although the bulk of the central parts of these dykes has been worked out, unusually good specimens are available in the ends of the cuttings and the contact facies remain excellently preserved.

Description

The De Lank Quarries are part of a group, few of which are now working, on the western margin of the Bodmin Moor Granite about 9 km NNE of Bodmin. This granite mass is one of the major cupolas on the Cornubian batholith. For the most part, it is composed of the small megacrystic biotite granite (Type B, Table 5.1; Exley and Stone, 1982) which is well seen in the quarries, but it also has four small areas of fine-grained granite (Type C, Table 5.1; Exley and Stone, 1982), one of which is just to the north of De Lank. The mass as a whole has been dated by the Rb/Sr method at 287 ± 2 Ma BP (Darbyshire and Shepherd, 1985).

Within the main quarries, the granite contains abundant megacrysts, mostly about 10–20 mm in length; these are of orthoclase microperthite, while the potash feldspars of the groundmass include microcline (Edmondson, 1970). There is a conspicuous, nearly vertical, foliation with an approximately north–south strike which is emphasized by the megacrysts. Although foliation is not rare in Cornubian granites, it is seldom as strongly developed as it is here.

In addition to the main rock-forming minerals, De Lank Granite contains about 1% tourmaline, contrary to the Geological Survey's assertion (Reid *et al.*, 1910), and it is thus similar to the rest of the mass.

The rock is well jointed in several directions, the chief subvertical orientations being about 075° and 340° and close to the mean for the northern part of the outcrop, with subordinate joints between these. Dip directions and amounts are variable. Subhorizontal joints are most prominent in the topmost 20 m where they undulate in approximate conformity with the land surface, but the granite becomes very massive at depth.

The rock is cut by aplite and microgranite veins and sheets up to 0.10 m thick, which have strikes parallel with those of the joints. The rock also encloses veins and pockets of quartzo-feldspathic pegmatite, as well as xenoliths which are sometimes stretched into *schlieren*.

The quarry area is limited on the north by an ENE–WSW fault zone dipping towards the south and with easterly dipping slickensides. This fault, the surfaces of which are coated with tourmaline, is a major structural feature, being one of a number which separate the outcrop of the Bodmin Moor mass into large blocks (Exley, 1965), and it controls the course of the adjacent De Lank River. It also separates the De Lank and Hantergantick quarries, the granites of which have perceptibly different compositions. Although similar block faulting almost certainly exists in other Cornubian granite masses, it is not as well demonstrated as it is on Bodmin Moor.

North of the De Lank Quarries, centred on Lower Penquite, is an area of fine-grained granite (Type C), which has an outcrop about 1 km in diameter and a long, narrow apophysis leading south. The latter is exposed in the De Lank River, close to the fault mentioned above, and is clearly intrusive, while the presence of the main outcrop is revealed by boulders in the fields. This variety is younger than, and intrusive into, the coarse granite.

Immediately south of the northern working quarry at De Lank, two granite-porphyry dykes ('elvans') striking ENE–WSW, about 10 m thick, are exposed in road cuttings and quarries on both sides of the river, and there is a third in a quarry on the south-west side. Much of the rock has been removed, but the chilled margins and faces at the ends are accessible and show the distinctive features of this rock which is fine-grained and often megacrystic. It is not clear whether the De Lank elvans are all single intrusions or multiple like that at Praa Sands.

Interpretation

This site provides a superb example of typical Cornubian, coarse, small-megacrystic biotite granite which is extensive elsewhere only at Carnmenellis. Here, however, it has a strong tectonic foliation. There is well-developed jointing and pegmatitic patches which, together with minor granitic veins, illustrate the effects of late magmatic fractions. The exposure of typical Cornubian fine-grained megacrystic biotite granite and granite-porphyry dykes indicate subsequent intrusive phases, while xenoliths provide examples of material incorporated by the magma during its ascent. Opportunities to see all these phenomena, and their relationships within such a small area and in such a fresh state, are rare.

As is usual in batholiths, the separate intrusions which comprise that in Devon and Cornwall vary somewhat in age (Table 2.1). The oldest is Carnmenellis (290 ± 2 Ma) and the youngest Dartmoor and Land's End (280 ± 1 and 265 ± 2 Ma, reset) with St Austell and Bodmin Moor between these at 285 ± 4 and 287 ± 2 Ma respectively (Darbyshire and Shepherd, 1985).

Textures also vary between individual plutons, and while the granites of Dartmoor, the eastern (oldest) part of St Austell and Land's End have relatively large megacrysts, those of Bodmin Moor and most of Carnmenellis are relatively small, although abundant (Dangerfield and Hawkes, 1981). Since the development of large megacrysts is a feature of the upper and outer regions of Cornubian plutons, it is possible that their absence from the Bodmin Granite indicates a deeper level of erosion, as is suggested also by the regular shape of their outcrops.

The foliation often seen locally in the Cornubian granites seldom extends for more than a few metres and is frequently curved, sometimes showing 'swirls' reminiscent of eddies in liquids. They have often been ascribed to magma movement, and some may have originated in this way, although some of the minerals, especially the feldspar megacrysts, are subsolidus and must therefore owe their alignment to pre-existing structures. The foliation at De Lank is quite different, and textural relations and extensive strain in the quartz, which is largely segregated into bands, show that it has a deformation, not igneous, origin. It is clearly different from that seen, for example at Haytor Rocks, Luxulyan Quarry or near Cape Cornwall, and is presumed to be associated with movement along the neighbouring St Teath–Portnadler Fault system (Dearman, 1963).

It has been argued, in the 'Petrogenesis' section above, that the granites are predominately 'S-type' (Chappell and White, 1974), and one of the pieces of evidence for this is the nature of the xenoliths. Excellent examples of these, often seen now as *schlieren*, are present at De Lank and are of 'restite' origin, comprising largely biotite and andalusite.

The field relations of the fine-grained granite apophysis in the De Lank River indicate that it is intrusive, and suggest that the larger mass to the north, to which the apophysis is presumed to extend, is intrusive also. Unfortunately, the latter is not seen *in situ*, and it is possible that it may represent 'granitized' sedimentary raft material as has been suggested for some fine-grained granite on Dartmoor (Edmonds *et al.*, 1968; Hawkes, 1982) and in the Land's End intrusion (Tammemagi and Smith, 1975).

The elvan dykes, which are some 10 Ma younger than the main granites, are believed to represent a differentiate from a deeper-seated biotite granite magma which underwent considerable modification by ion exchange and was emplaced as a fluidized system which included fragments of the granite through which it had passed (Stone, 1968; Goode, 1973; Henley, 1972; 1974).

Conclusions

This site provides a superb example of typical Cornubian coarse biotite granite of the small-megacryst type typical of Bodmin, Carmenellis and Scilly. It shows strong foliation and xenoliths (see 'Birch Tor' conclusion), as well as typical Cornubian fine-grained megacrystic biotite granite and granite-porphyry dykes. Opportunities to see all these phenomena and their relationships within such a small area and in such a fresh state are rare.

C4 LUXULYAN QUARRY (GOLDEN POINT, TREGARDEN) (SW 054591)

Highlights

Luxulyan Quarry contains the coarse, megacrystic biotite granite of typical Cornubian type which forms the earliest variety in the complex magmatic sequence at St Austell. Its fresh xenoliths of pelitic and semipelitic sediment provide evidence about the origin of the magma, and there is also evidence of post-magmatic activity in the form of luxullianite *in situ*.

Introduction

Luxulyan Quarry (which has also been called Goldenpoint and Tregarden) is situated in typical Cornish granite of the St Austell mass, described in detail by Ussher *et al.* (1909); these authors, however, did not realize that there was a sharp distinction between this eastern rock and the granite types seen a few kilometres to the west. The differences were first recognized by Richardson (1923) and later Exley (1959), who both concluded that the Luxulyan Granite represented an earlier, separate intrusion which has subsequently been interpreted as a boss about 9 km across and dated, by the Rb/Sr method, at 285 ± 4 Ma BP by Darbyshire and Shepherd (1985). The boss was emplaced by stoping and subsidence, and xenoliths of the country rock, found in the quarry, have been used by Lister (1984) as evidence bearing on the origin of the magma.

The rest of the St Austell outcrop consists of a second, slightly larger, intrusion which, having been emplaced to the west of the Luxulyan Granite, was itself intruded by a magma of entirely different composition and was altered by a complex interchange of elements in a volatile-rich environment. The changes and mechanisms are noted in general terms in Chapter 2 and the 'Petrogenesis' section above, and in detail in the appropriate site descriptions. It is sufficient here to note that, although widespread in the western area, they have affected the Luxulyan area to only a moderate degree (Figure 5.4).

Among the few volatile-induced modifications, however, was the formation of luxullianite. This rock, described by Bonney (1877a), Flett *in* Ussher *et al.* (1909) and by Wells (1946), was known only from boulders until found *in situ* by Lister (1978, 1979a, with a contribution by Alderton (1979)). Lister (1979b) also used material from this site in her study of quartz-cored tourmaline.

Description

The granite at Luxulyan (Figure 5.10) has been described (Dangerfield and Hawkes, 1981) as 'coarse megacrystic' and as Type B (Table 5.1) (Exley and Stone, 1982). It is characterized by biotite and zoned oligoclase (An_{25-30}), and contains abundant K-feldspar megacrysts between 20 and 100 mm in length. These are generally aligned and commonly include zones (containing quartz, plagioclase and biotite) indicative of growth following a potassium-rich metasomatism process. Other minerals include muscovite, tourmaline and trace quantities of apatite, topaz, andalusite, fluorite, zircon and iron ore. The rock is closely comparable with the other coarse biotite granites of Cornwall and Devon and its mineralogy and chemistry show that, despite its early arrival in the St Austell sequence, it is a highly evolved, high-level variety (Table 5.2).

Evidence bearing upon the emplacement of this granite is seen in the abundant, rounded xenoliths, which are usually about 20 mm across, but range up to about 130 mm. These are mainly composed of quartz and abundant biotite, but sometimes contain andalusite. The majority have lost any foliation that they might have had, but

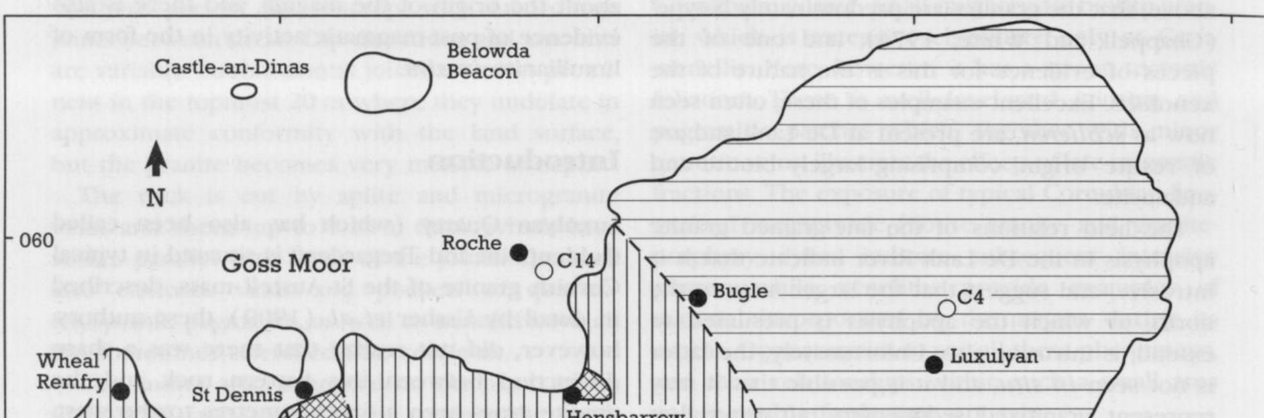


Figure 5.10 Map of the St Austell Granite outcrop, showing the chief granite types, localities mentioned in the text (filled circles) and the following sites: C4 = Luxulyan Quarry; C10 = Wheal Martyn; C11 = Carn Grey Rock; C12 = Tregargus Quarries; C13 = St Mewan Beacon; and C14 = Roche Rock.

have not yet been sufficiently 'granitized' to develop feldspar. They are clearly of pelitic or semipelitic origin and derived from the stoping of its walls by the magma. Fresh cordierite has been recorded from this quarry (Ussher *et al.*, 1909).

Luxullianite, an attractive rock composed of red K-feldspar, acicular tourmaline and quartz, and formerly used as an ornamental stone, occurs in often discontinuous, near-vertical sheets which sometimes anastomose. These strike approximately ENE–WSW, and are up to a metre or two in thickness. The jointing is both more extensive and less regular than in many Cornubian exposures, and some joints show evidence of post-magmatic activity in the form of reddening and veining by quartz and tourmaline. Sometimes, such tourmaline has cores of quartz or feldspar (Lister, 1979b). There are also small pods, up to 0.5 m in diameter, of pegmatite consisting of the chief minerals of the granite but mostly deficient in plagioclase. A major joint, with a veneer of tourmaline striking 070°, serves as the quarry wall beneath the crushing plant.

Kaolinization, not due primarily to weathering, is confined to a zone striking N–S and tapering downwards in width from about 10 m. This separates the north-eastern quarry from the rest of the site.

Interpretation

The granite at Luxulyan is typical of the eastern part of the St Austell outcrop, which, having been recognized as significantly different from the granite in the western part (Richardson, 1923; Exley, 1959), was interpreted by the latter as the first member of a magmatic differentiation series. This interpretation followed from its relative enrichment in Ca and Fe (exhibited in oligoclase and biotite) and impoverished in Na (in albite), Li (in zinnwaldite), B (in tourmaline) and F (in topaz) (Tables 5.1 and 5.2). Later work has shown, however, that much of the western granite has a similar texture to that in the east and a composition intermediate between the medium-grained Li-mica–albite–topaz granites (Type E, Table 5.1) and the biotite granite. Hence the present interpretation is that the first member of the western intrusion was also a biotite granite, much of which was metasomatized by incoming Li-mica–albite–topaz granite derived at depth (see Chapter 3 and the 'Petrogenesis' section of this Chapter). The first importance of the Luxulyan site therefore lies in its exposure of the rock held to be the earliest in both hypotheses.

Theories about the derivation of the Cornubian granite magma agree that it resulted essentially from partial melting of a lower crustal source. However, the extraordinary enrichment of the batholith, relative to average granites, in such elements as Sn, W and Cu, Li, Sr and Ba, U and Th and B and F have led to speculation as to whether their provenance was middle or lower crustal or subcrustal (Simpson *et al.*, 1976, 1979; Watson *et al.*, 1984), and to what extent they were incorporated either from already enriched crustal material or from some subcrustal source. A study of xenolith material, some of which came from Luxulyan Quarry, has suggested that Sn, W, U and Ta were not derived from pelitic sediments, that V, Ba, Sr, Cu and Zn might have been, and that some elements which could easily have escaped from the magma (for instance, Li, Th and F) were in fact retained and concentrated in biotite-rich xenoliths. Those elements not derived from assimilated sediments must have been magmatic. Luxulyan xenoliths are thus of importance in the petrogenetic history of the Cornubian granites (Lister, 1984).

Granitic rocks generally similar to luxullianite have been found in various parts of south-west England, and it is agreed, from textural evidence, that they were formed by the post-magmatic alteration process described as 'tourmalinization'. Flett (in Ussher *et al.*, 1909), however, when contrasting luxillianite with the tourmalinite of the Roche Rock 6–7 km to the WNW, observed that 'In luxullianite the process of metasomatic replacement has stopped at the half-way stage'. There has also been disagreement over the nature of the replacement and the original mineralogy. Thus, Bonney (1877a) thought that brown tourmaline had replaced biotite, but both Flett (1909) and Wells (1946) believed that biotite had never been present, brown tourmaline occurring instead. Again Bonney thought that acicular, blue, secondary tourmaline formed from feldspar, but Flett and Wells considered that it replaced both feldspar and brown primary tourmaline. Lister's (1978) examination of the first *in situ* luxullianite to be described makes it clear that biotite and primary tourmaline coexist, and that secondary tourmaline came from a hydrothermal generation and did not involve the breakdown of the primary crystals. However, the chemical changes between unaltered granite and luxullianite described by Lister (1978) differ from earlier suggestions, principally in showing a decrease in SiO_2 and an increase in K_2O and, following a discussion by Alderton (1979), she agreed that probably there had been a combined process of tourmalinization and K-feldspathization. It is worth noting as Charoy (1982) points out, that there is 'tourmalinization and tourmalinization', and that Lister and Alderton were not comparing like with like. As for tourmaline in veins, Lister (1979b) noted that some from this quarry contained cores of 'polycrystalline quartz and/or feldspar' and attributed this to skeletal growth resulting from undercooling of the tourmalinizing melt.

Regarding other alteration processes, Luxulyan is typical of the eastern St Austell area in showing only minor greisening and kaolinization, although it is interesting that the kaolinized zone in the quarry is of the wedge shape, described by Bristow (1977) as characteristic of such zones found throughout the Cornubian granites, although often on a much larger scale and at such a depth that this shape is revealed only when the zones are worked or from boreholes.

The biotite granite at Luxulyan is typical of Cornubian granites, and is enriched in elements such as Sn, W, Cu, Li, Sr, Ba, U, Th, B and F. It is uncertain to what extent these were contributed by crustal or mantle sources, but research on biotite in xenoliths from Luxulyan suggests that Sn, W and U (as well as Ta) did not come from sediments and were thus not crustal, that B, Sr and Cu (and also V and Zn) could have done so, and that magmatic Li, Th and F were trapped and thus concentrated in the biotite in xenoliths.

A similar type of granite formed the major part of a second intrusion to the west, but this was metasomatized to give the albite–Li-mica–topaz variety now present.

Luxullianite from the quarry has shown that there are two generations of tourmaline in these rocks, that tourmaline and biotite are not necessarily mutually exclusive and that the tourmalinization process may be accompanied by K-feldspathization.

Conclusions

Luxulyan Quarry provides an exceptional opportunity to examine the typical Cornubian biotite granite in a locality close to the succeeding lithium- and volatile-rich rocks of the St Austell complex of intrusions. The site shows xenoliths here consisting of metamorphosed, muddy sedimentary rocks. It is thought that the incorporation of these rock fragments has made a significant contribution to the final chemistry of the granite. The nearby village gives its name to the rock type luxullianite. This rock, made up of red feldspar, quartz and the dark mineral tourmaline (a complex boron-bearing aluminium silicate), was formed by alteration of the original St Austell Granite by hot fluids associated with the final phases of granite magmatic activity, which, flowing out from the solidifying granite, chemically altered and recrystallized the minerals which made up the granite and the rocks around it.

C5 LEUSDON COMMON (SX 704729)

Highlights

Migmatization is very rare in association with Cornubian granites, and Leusdon Common probably shows the best available example. Exposures here, which are mostly of boulders, show mixtures of granite and metasediment in intimate relationship resulting from mobilization and plastic flow. They come from the roof and the uppermost wall of the Dartmoor intrusion, which is composed of coarse biotite granite.

Introduction

Leusdon Common is a small area of gorse-covered ground some 6 km north-west of Ashburton. Exposed on its southern slopes are small, separated outcrops and boulders of the country rocks of the Dartmoor Granite, illustrating the nature of the uppermost wall or lower roof of the intrusion, together with a narrow apophysis of fine-grained granite. Brief accounts of the rocks are given by Reid *et al.* (1912) and Dearman (1962).

Description

The main body of the granite underlying the high ground at Leusdon is coarse-grained megacrystic biotite granite (Dangerfield and Hawkes, 1981; Type B, Table 5.1; Exley and Stone, 1982), of which the finer variety mentioned above is derivative. It too is megacrystic, at least in its uppermost 0.10 m, and it is *in situ*. It has given rise to spotted hornfelses at its contact, whereas the country/contact rocks found elsewhere on the site have a much more migmatitic aspect which is most unusual for Cornubian granite contacts. Cordierite is plentiful in the metamorphic rocks. Some boulders are composed of intermixed granite and sediment, and in other cases xenoliths in all stages of assimilation occur, some still showing original sedimentary banding and some being aligned. The granite in these cases is fine grained and varies from veins a centimetre or two thick to narrow, thread-like apophyses. These veinlets are often contorted and may penetrate into the metasediment, causing fragments to spall off. The metasediments also are often contorted.

Interpretation

These exposures exemplify some of the complex relationships between magma and country rocks involved in the emplacement by stoping of granite magmas. Although the mechanical effects are perhaps better shown at some Cornish contacts, for instance at Rinsey Cove, migmatization in such places is absent, as it is at two other Dartmoor roof contacts at Sharp Tor and Standon Hill. Neither is it prominent at the Burrator wall contact, although Brammall and Harwood (1932) referred to it in describing the changes brought about in Dartmoor Granite magma by the assimilation of Devonian metasediments.

The process of migmatite formation requires a combination of high temperature, high pressure and high volatile (especially water) content; it is, therefore, not commonly associated with high-level, relatively cool granites such as those in Cornubia, and there is no pattern in its occurrence here. The conclusion is that it took place in small, restricted regions near the upper parts of intrusions, where heat and water were locally concentrated, and that it may also have been connected with the potassium metasomatism which produced the megacrystic outer granites. Migmatization itself is of little consequence in the assimilation process discussed by Brammall and Harwood (1932), but the ramification of mobile granitic vein material, whether magmatic or migmatitic, was the chief stoping mechanism by which blocks of country rock were prised off to be engulfed by, and incorporated into, the granite magma.

Conclusions

There is no better site than Leusdon Common for the study of the complex relations between intrusion and country rock resulting from a combination of stoping and migmatization during emplacement of a Cornubian granite magma.

C6 BURRATOR QUARRIES (SX 549677)

Highlights

Burrator Quarries contain a rare contact between Dartmoor Granite and Upper Devonian sediments, showing slight mobilization, tourmalinization and vein intrusion. As the site of early investigation of compositional relationships between granite and country rocks, it is important in the development of hypotheses about the origins of Cornubian granites.

Introduction

This pair of small quarries lies 3 km east of Yelverton and 300 m south-west of the dam at Burrator Reservoir. It is one of the few places where the coarse, megacrystic biotite granite of Dartmoor can be seen in contact with the Devonian country rocks. This contact was a key feature in the evidence used by Brammall and Harwood (1932) in their petrogenetic study of the Dartmoor Granite, for they were able, by a series of analyses taken across it, to draw conclusions about the effects of assimilation on the granite magma. The significance of assimilation is now seen differently in the light of experimental work on the 'granite system', and more recent observations (Stone, 1979; Stone and Exley, 1986; Bromley and Holl, 1986; Bromley, 1989), but the changes discussed by Brammall and Harwood remain unchallenged.

Description

The country rocks on the west of the Dartmoor mass are essentially pelites and semipelites of Famennian age belonging to the Kate Brook Formation of the 'Kate Brook Tectonic Unit', the autochthonous component of the complex nappe

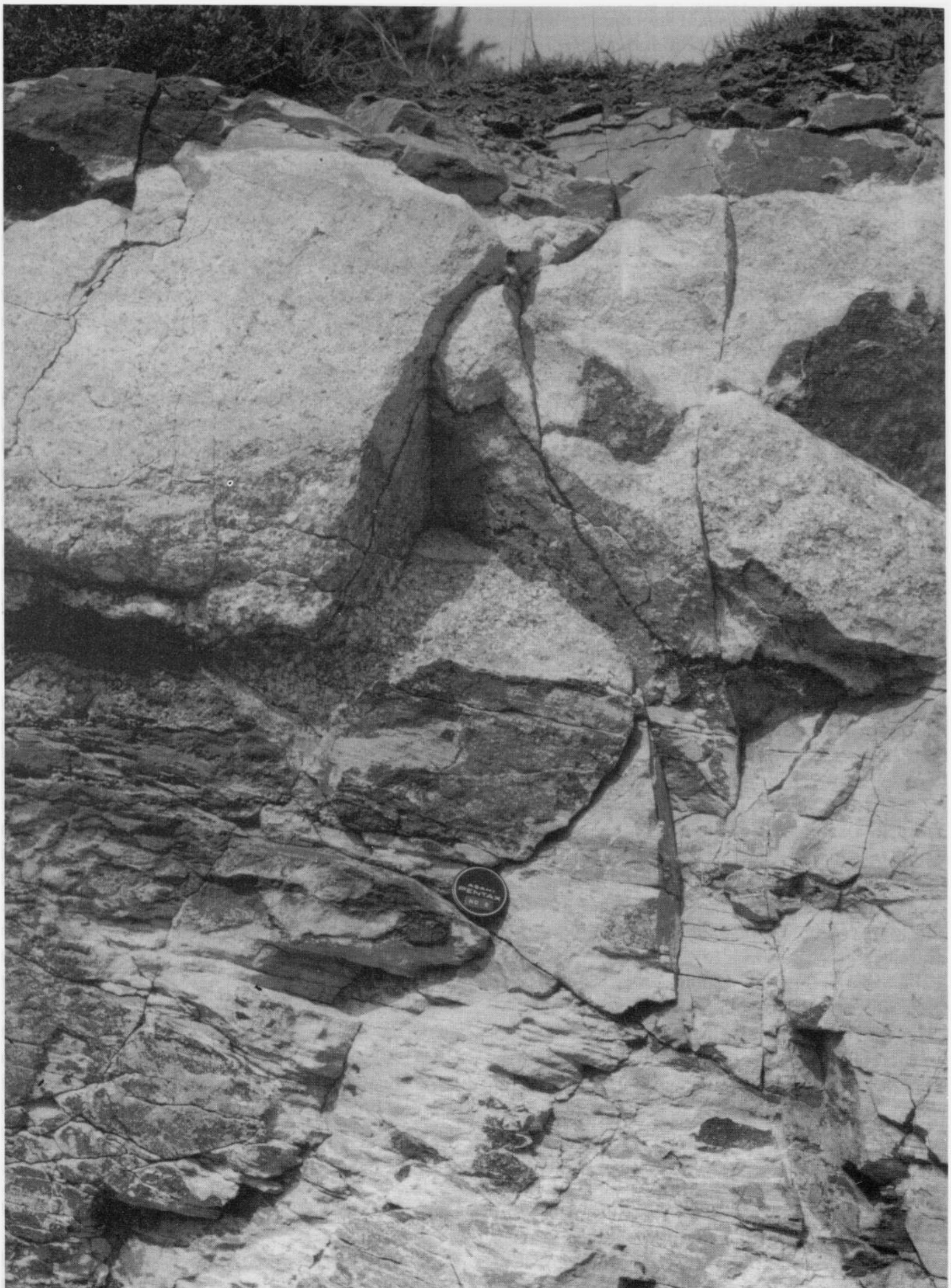


Figure 5.11 Contact between Dartmoor Granite and Devonian slates, re-exposed after face cleaning by the Nature Conservancy Council in 1980. (Photo: M.J. Harley.)

structure found between the Dartmoor and Bodmin Moor granites (Isaac *et al.*, 1982; Isaac, 1985). These basinal sediments were first regionally metamorphosed to slaty rocks, and subsequently thermally metamorphosed by the granite. At Burrator they are spotted and banded cordierite- and andalusite-bearing hornfelses with a conspicuous flat-lying cleavage and extensive tourmalinization. Corundum, found in the Land's End contact aureole at Priest's Cove, has not been reported from here, and the tourmaline is chiefly a patchy yellow-brown and blue-green variety. The presence of much biotite probably indicates a degree of potassium metasomatism, and, certainly, the movement of potassium is recorded by the occurrence of perthitic feldspar close to the contact. Fine-grained granite and siliceous veins up to 0.3 m wide occur within the hornfelses, both concordantly and discordantly.

The contact itself, illustrated by Brammall and Harwood (1932), although very irregular, is sharp, and it shows evidence of some mobilization of the metasediments with attendant segregation of felsic and mafic constituents (Figure 5.11); Brammall and Harwood described this as a 'migmatic zone' although there is much less evidence of mobilization than at Leusdon Common (discussed above).

Tourmalinization has affected not only the contact hornsfelses but also the outer parts of the intrusion, and the granite in both quarries is considerably reddened by this process, especially adjacent to joints.

Interpretation

The Dartmoor Granite was emplaced at about 280 Ma BP, as dated by the Rb/Sr method (Darbyshire and Shepherd, 1985) making it the youngest Cornubian intrusion except for Land's End, and most of the rock is coarse grained and megacrystic, although a non- or poorly megacrystic variety also occurs. These were called 'giant' and 'blue' granite respectively by Brammall and Harwood (1923), who argued that the latter was intruded into the former: it has subsequently been recognized that the variation is gradational (Dangerfield and Hawkes, 1981; Hawkes, 1982), with both types corresponding with the Type B (Table 5.1) of Exley and Stone (1982) and Exley *et al.* (1983). It is often the case that the coarse and megacrystic nature of the granite persists right to its contact with the country rocks, as, for example, near Cape Cornwall, and this is seen in the Burrator Quarries, although the number of megacrysts is rather few and the crystals are only about 50 mm in length.

Brammall and Harwood (1932) published analyses from a sequence of 'shales' at Burrator as the contact was approached (over a distance of about 5 m) and used these, in conjunction with 'fresh' granite, to demonstrate both the chemical exchanges consequent upon intrusion and the effects upon the granite magma of the assimilation of xenoliths. In particular they concluded that the earliest of the Dartmoor magmas was 'acid' and was 'basified' by contamination at the same time as it was undergoing differentiation. The analyses remain valid and, in general terms, this view is still held, the earliest magma being envisaged as lower crustal and palingenetic in origin (see 'Petrogenesis' section above). It then rose through a pile of sediments and basic volcanics to its final high-level position where it consolidated in an essentially passive fashion, as the locally undeformed rocks show. However, it is now believed that some minerals, especially biotite, were derived from the source rocks, and that at low crustal levels the physicochemical condition of the magma prevented substantial assimilation (Stone, 1979; Bromley and Holl, 1986; Stone and Exley, 1986; Bromley, 1989) of the sort envisaged by Brammall and Harwood. The introduction of potassium from sediments was part of Brammall and Harwood's thesis, but it is now thought that late-magmatic potassium metasomatism was facilitated by an aqueous phase, and that the megacrystic texture was a consequence of this (Stone and Austin, 1961; Hawkes *in* Edmonds *et al.*, 1968; Exley and Stone, 1982; Exley *et al.*, 1983; Stone and Exley, 1986).

Although the assimilation of metasediment is not now regarded as being as important as Brammall and Harwood believed, the changes in the rocks at Burrator Quarries, and their interpretation by these authors, continue to be important to the understanding of the effects of Cornubian granite intrusion on the country rocks and the alterations which can result from assimilation.

Conclusions

This site is important both as a locality where contact phenomena of the Dartmoor (and, by implication, other Cornubian) Granite can be seen and as a place where classic work on

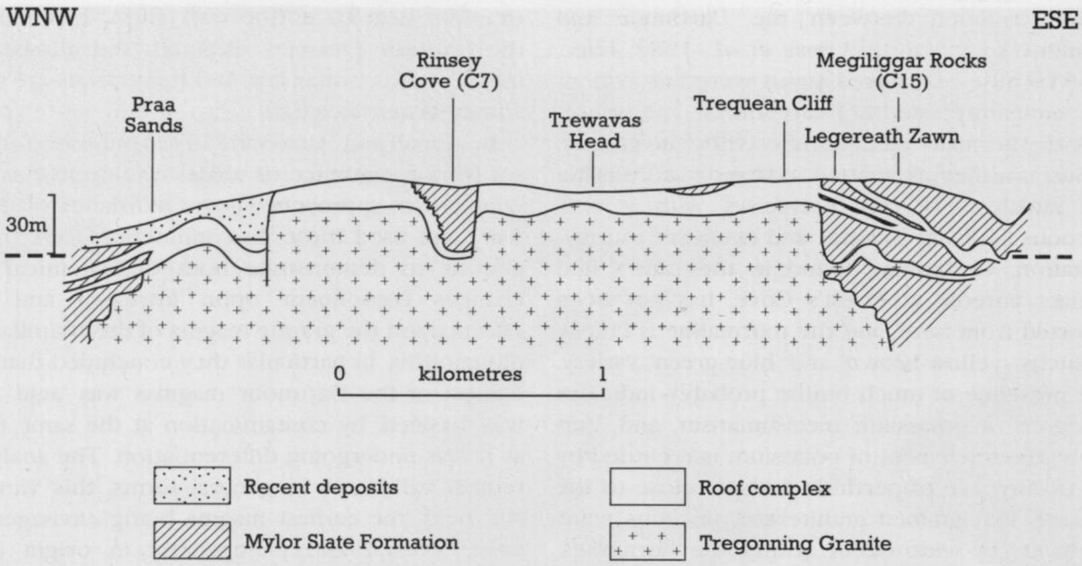


Figure 5.12 Diagrammatic section across the Tregonning Granite, based on coastal exposures, showing the location of sites at Rinsey Cove (C7) and Megiliggar Rocks (C15) (after Exley and Stone, 1982, figure 21.2).

Cornubian granite genesis was carried out. Although the conclusions from this work have been modified by subsequent findings, the data and principles still stand.

C7 RINSEY COVE (PORTHCEW) (SW 593269)

Highlights

This site has a unique section through a pelitic roof pendant in a granite pluton. Its late-stage and metasomatic minerals and textures in the granite and country rock, reflect the influence of magmatic volatile constituents.

Introduction

There are several places where contacts between Cornubian granites and their country rocks can be seen, but this section (Figure 5.12) through a roof pendant is unique. Not only do its margins show stepped contacts, xenoliths and granite apophyses, demonstrating the emplacement of the Tregonning Granite by stoping, but the granite itself, a lithium-mica-bearing variety, has developed a roof complex of leucogranite, pegmatite and aplite associated with a coarse-grained facies at the contact. Together with extensive tourmalinization, these features demonstrate the effects of volatiles such as OH, F and B during crystallization as they became progressively concentrated close to a nearby impermeable envelope.

A detailed field description and petrography was given by Hall (1930), general accounts of the petrogenesis are included in Exley and Stone (1982) and Exley *et al.* (1983), and details of the origin of the Li- and F-rich granite come from Stone (1975, 1979, 1984). The origin of the roof complex has been explained by Stone (1969), Bromley and Holl (1986) and Badham (1980).

Description

Rinsey Cove, or Porthcew, is on the south coast of Cornwall immediately to the east of Rinsey Head and about 4 km north-west of Porthleven. The Tregonning–Godolphin Granite pluton, which meets the coast here, is composed of two variants; the more northerly Godolphin facies consisting of fine-grained, megacrystic biotite granite (Type C, Table 5.1; Exley and Stone, 1982), while the southern Tregonning facies, exposed in the coast section, is made up of medium-grained, non-megacrystic lithium-mica–albite–topaz granite (Type E, Table 5.1; Stone, 1975; Stone and Exley, 1982). This has developed a local megacrystic facies and banding which, unlike that in western parts of the Bodmin Moor

Granite, is not tectonic in origin, and which is parallel with the contact with the roof, visible on the west side of Rinsey Head and in the cliffs on both sides of the cove. This contact is sharp and dips seaward at about 30°, the granite immediately beneath it being somewhat coarser than average and having a sheet complex of lithium-mica leucogranite–aplite–pegmatite just below.

Tourmalinization is common in xenoliths which are found in all stages of assimilation, and acicular tourmaline appears on the underside of the country rocks near the cliff top at the eastern side of Rinsey Cove.

The rocks which make up the roof and pendant, which occupy most of the Cove, are Mylor Slate Formation metasediments which, although predominantly dark and pelitic, contain semipelite and psammite and thus have a striped or banded appearance. The place of the Mylor Slate Formation in a wider context of stratigraphy and structure has been discussed by Leveridge *et al.* (1984) and Leveridge and Holder (1985). The rocks also contain numerous quartz veins, both contorted and cross-cutting, much of the silica for which seems to have been derived from the mobilization of quartz within the rocks by the compression and heat of metamorphism. The local structure, better seen here than at many contacts, consists of recumbent folds, on the limbs of which are minor folds resulting from an earlier deformation. There are two cleavages, of which the more striking (originally termed S_2 but now redesignated S_3 to correspond with the regional chronology) is subhorizontal and undisturbed by the granite (Stone and Lambert, 1956; Stone, 1966).

In addition to being folded, the metasediments have been thermally metamorphosed to spotted hornfelses, with the development of cordierite, andalusite (locally chiastolite) and, through metasomatism, tourmaline. Corundum, present in the Land's End metasediments at Priest's Cove, has not been found, and migmatization, like that associated with the Dartmoor Granite at Burrator and Leusdon Common, is absent.

On the west side of Rinsey Cove, the contact dips towards the Cove at 20–30°, cutting across the flat-lying cleavage, but is 'stepped' along joints in units from 0.5 to 4 m high, demonstrating emplacement of the granite by stoping and subsidence; disorientated xenoliths and apophyses of granite show how the magma penetrated the killas and prised blocks away. Coarse granite and aplite–pegmatite layers up to 3-m-thick are present. At the head of the cove, a cave has been eroded along the contact which here shows evidence of having been faulted and mineralized. The eastern contact is nearly vertical and may be either intrusive or faulted. The main body of the granite has a medium-grained texture almost up to the contact where there are 1-m-thick pegmatite and pegmatitic patches nearby. A smaller, elliptical pendant or large xenolith about 15 m across and also accompanied by pegmatitic patches is exposed between tide marks on the shore a few metres to the south.

Interpretation

It is considered that the magma producing the Tregonning Granite evolved from the Godolphin magma as a consequence of the deep-seated separation of a fluorine- and OH-rich fraction and ion exchange to enrich the Tregonning magma in Li, Na and Al at the expense of Fe, Ca and Mg. Biotite was thus replaced by zinnwaldite, and plagioclase became more albitic. This process is demonstrated elsewhere in the St Austell mass (discussed below, Tregargus Quarries). The sheets of the roof complex at Rinsey indicate the building up of a later, volatile-rich residuum under a relatively impermeable roof. The lithium-mica leucogranite represents a direct continuation of magmatic melt evolution, whereas the aplite represents a crystallized silicate liquid, and the pegmatite replaces aplite which was metasomatized by a K-rich aqueous fluid (Stone, 1969; Manning, 1982; Exley and Stone, 1982; Exley *et al.*, 1983; Manning and Exley, 1984; Pichavant and Manning, 1984). The roof complexes of other granites, for instance Land's End (seen near Cape Cornwall and Porthmeor Cove), are much simpler because of the absence of the lithium-mica granite component, while the related sheets of Megiliggar Rocks, a short distance to the south-east, are both thicker and more complex. The difference between aplitic and pegmatitic textures could, however, equally be a result of pressure variations following successive openings of the rock initiated by the movement of foundering blocks, as suggested by Bromley and Holl (1986). Badham (1980) combined features of both these explanations, accepting the variations in fluid compositions but emphasizing the importance of physical conditions in determining textures. The lithium-bearing micas from the Tregonning Granite and its leucogranite sheets, whose exact compositions were uncertain for many years, have now been identified as zinnwaldite and lepidolite respectively (Stone *et al.*, 1988).

The only other exposures of this type of granite are found in the western part of the St Austell mass, but in this case they are intruded into granite. Moreover, the roof complex, seen only in china clay pits in the vicinity of Hensbarrow Beacon, has not developed as distinctive a display of leucogranite, aplite and pegmatite as that at Rinsey Cove.

Conclusions

This site shows outstanding sections through the upper part of one of the plutons of the Cornubian Granite mass and its junction with the older sedimentary rocks which it has intruded, baked and altered. Here may be seen evidence of how the granite was emplaced when still molten rock, by the undermining and dislodgement of blocks of the surrounding rocks by forcefully penetrating joints and fissures (a process called stoping), followed by subsidence of blocks into the magma. Blocks thus prised off from the country-rock walls and a possible hanging mass of baked sediments are seen to be surrounded by granite. In time, the molten granite would have assimilated the blocks, but here they have survived because the granite cooled and solidified before this could happen. The site has a well-developed roof complex, the upper-formed product of the granite magma. Although still of granite composition, the component pegmatite, aplite and leucogranite of the complex differ in detail from one another and from the earlier-crystallized granite as a result of losing some constituents of early crystals, increased concentration of volatiles, and interactions between the constituents.

C8 CAPE CORNWALL AREA (SW 352318)

Highlights

The Cape Cornwall area shows a stoped contact between metasediments and Land's End Granite, which shows evidence of being a two-stage intrusion. Greisen-bordered mineral veins, sapphire in thermally metamorphosed country rock and evidence of potassium metasomatism of granite and metamorphic aureole also occur here with late-stage veins, pipes and pods of pegmatite and quartz–tourmaline, and a quartz–tourmaline contact facies, all resulting from a concentration of a volatile-rich phase at the granite margin.

Introduction

Although the cliff and beaches immediately north and south of Cape Cornwall have become, in recent years, famous exposures for demonstrating both contact and late-stage igneous phenomena of the Land's End Granite mass, very little has been published on the area. The Land's End Granites as a whole were described in the Geological Survey Memoir by Reid and Flett (1907), with a revision, following publication of a new 1:50 000 map in 1984, by Goode and Taylor (1988); the latter, which contained little petrological discussion, is supplemented by an 'Open File' report (Goode *et al.*, 1987) in which there is substantially more detail. A specific study was made by Booth (1966), followed by a note on the granites' relations with the 'granite system' (Booth, 1967) and a paper by Booth and Exley (1987). Most of these contain passing references to the Cape Cornwall area, but van Marcke de Lummen (1986) used material from both Priest's Cove and Porth Ledden in his study of the crystallization sequence in the granites.

Charoy (1979, 1981, 1982) has quoted examples from Porth Ledden in his work on late-stage phenomena, especially tourmalinization, and Lister (1979b) has included specimens from both Priest's Cove and Porth Ledden in her investigations into quartz-cored tourmaline crystals. At least part of this tourmalinization, which Manning (1981) and Pichavant and Manning (1984) thought might have been due to a complex hydrothermal/metasomatic process, may be related to the 270 Ma BP intrusive phase noted in Chapter 2 (Bristow *et al.*, in press). Duddridge (1988) has argued that at least some tourmaline must be metasomatic.

Description

Cape Cornwall is situated on the west coast of the Penwith Peninsula about 2 km WNW of St Just; the cliffs and beach immediately to the north and south of the Cape exhibit a variety of

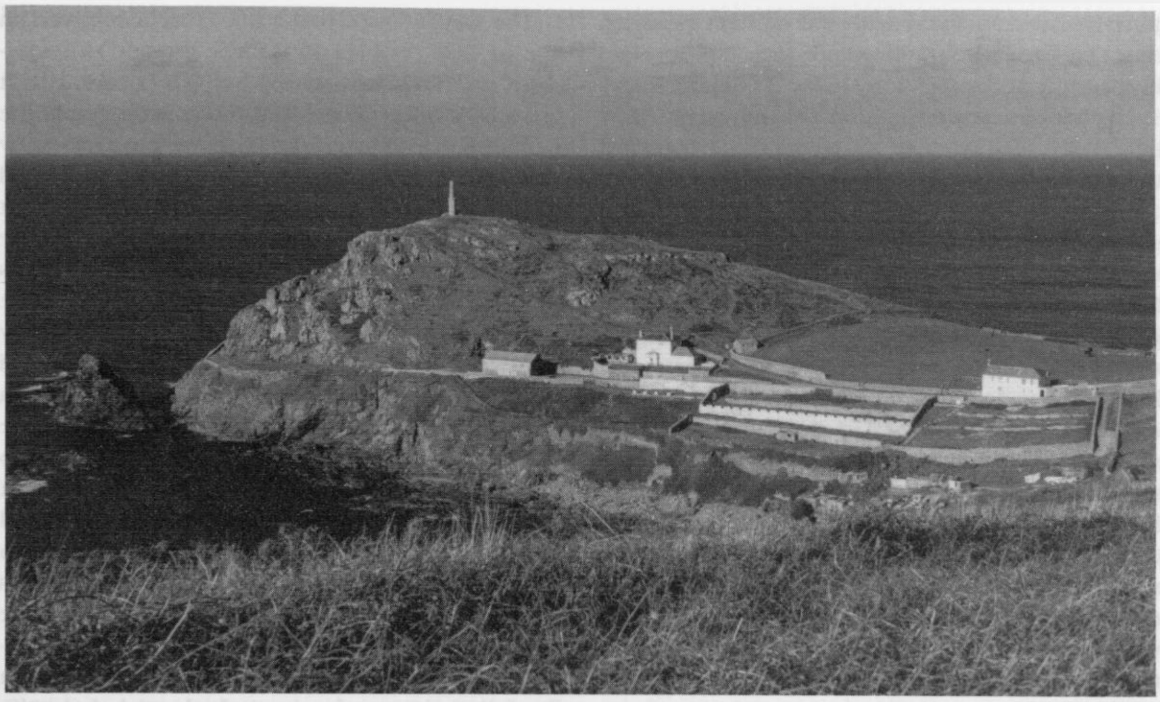


Figure 5.13 The headland of Cape Cornwall which exposes contacts between Land's End Granite and adjacent metasediments. (Photo: S. Campbell.)

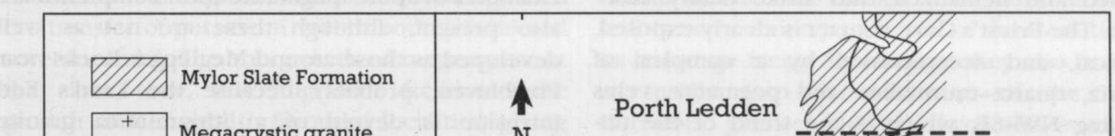


Figure 5.14 Geological sketch map of the Cape Cornwall area (site C8).

phenomena associated with the contact between the Land's End Granite and the Mylor Slate Formation metasediments ('killas') (Figure 5.13). Such phenomena are typical of Cornubian granites, but it is seldom that so many are displayed together in so small an area and can be related to one another so directly (Figure 5.14).

The country rocks are originally mudstones with subordinate sandstones, and these have been folded and metamorphosed into hard, splintery, grey, banded hornfelses, in which andalusite, chiastolite, cordierite, corundum and tourmaline have been identified. Corundum is of special interest, being unusual in Cornubian contact rocks and occurring as the variety sapphire in some exposures in the cliffs above Priest's Cove. Mobilization of the silica has produced extensive convoluted quartz bands and veins in the metasediments and, while these are typical of granite contacts throughout Cornwall and Devon, it is worth noting that there is no migmatization of the sort seen at Leusdon Common on Dartmoor (C5).

The contacts in Priest's Cove and near the stream at the northern end of Porth Leddon are faulted and hematized, and strike nearly east–west. The Priest's Cove contact is clearly exposed, vertical, and accompanied by a complex of quartz, quartz–tourmaline and pegmatite veins striking NW–SE, which is the trend of the tin-bearing veins formerly worked in the area. The breccia at this contact, formerly regarded as a result of faulting, is interpreted by Badham (1980) as 'a small breccia pipe formed during stoping'. Movement during and shortly after emplacement is usual in the Cornubian granites and, as here, often provided pathways for mineralizing solutions. Some of the quartz–tourmaline veins have dark, greisen borders a few centimetres wide.

The contact running down the cliff and across the beach in Porth Ledden is, in contrast, not faulted. Large K-feldspar megacrysts, both close to the contact itself and in isolated exposures presumed to be in an eroded roof pendant or large zenolith, provide examples of potassium metasomatism of the hornfels.

There is no evidence of more than slight disturbance of the country-rock structures as a result of intrusion, and granite emplacement must have taken place principally by stoping and subsidence; the step-like contacts which can result from this process, although discernible, are not well seen in this area and are better displayed at Rinsey Cove.

The Land's End Granite mass has been given an age of 268 ± 2 Ma BP (Rb/Sr method) (Darbyshire and Shepherd, 1985) but this is seriously at odds with mineral ages and the general age of the batholith and is thought to have been reset by mineralization (Table 5.1). Alternatively, it could relate to the later major intrusive phase at about 270 Ma. In the Cape Cornwall area, the granite contains many xenoliths of killas, and it is variable in both composition and texture. The main variety is a medium-grained and poorly megacrystic biotite granite (Dangerfield and Hawkes, 1981; Booth and Exley, 1987); this is a subdivision of the Type B of Exley and Stone (1982) shown in Table 5.1. It has megacrysts up to 40 mm long, but in some places it is almost aphyric, and elsewhere it contains veins and patches of a distinctly coarser variety. In Porth Ledden, a very coarsely megacrystic facies occurs close to the contact with the killas, where there is a pronounced parallelism between the megacrysts and the contact. This is quite different from the foliation seen, for example, in and about the De Lank Quarries on Bodmin Moor where there has been a strong tectonic influence. Good examples of aplite–pegmatite roof–complexes are also present, although these are not as well developed as those around Megiliggar Rocks near Porthleven, probably because the Land's End intrusion is devoid of a lithium-mica granite phase like that of Tregonning.

On the granite side of the Porth Ledden contact there is a lens of quartz–tourmaline rock which extends northwards from about halfway along the beach at the foot of the cliff. In some places this is subhorizontally banded and it passes downwards into aphyric, medium-grained granite. Within the main granite at the southern end, there are orbicular patches with tourmaline-rich rims and feldspathic cores which contrast with the pegmatitic pods, pipes and veins with tourmaline cores occurring in Priest's Cove. Some tourmaline is 'cored' (Lister, 1979b).

Many veins and apophyses of granite intrude the country rocks, their strikes often being controlled by the joint pattern; complexes of such veins are present in both Priest's Cove and Porth Ledden. The range of veins includes pegmatite (a notable one in Porth Ledden has curved feldspar crystals; '*stockscheider*'), medium-grained granite, aplogranite, microgranite and aplite. Some are relatively rich in tourmaline; some have a variety of textures including a development of pegmatite along their hanging-wall contacts.

Interpretation

The evidence of the veining and breaking up of medium-grained by coarse-grained granite suggests that in this area the Land's End magma was intruded in two pulses, the second following closely after the first had started to consolidate.

Together, these intrusions tilted the Mylor metasediments and thermally metamorphosed them to the equivalent of the anthophyllite–cordierite subfacies (examples of which are seen to the north of Porth Ledden at Kenidjack), with the development of sapphire locally as in Priest's Cove. Again, this is a rare phenomenon. The granites also sent out various veins and apophyses and incorporated fragments of country rock.

The remaining features, such as veins and pods of pegmatite and quartz–tourmaline, were dependent on the effects of volatile phases which became concentrated close to the granite–killas contact, as is usual in Cornubian rocks (although not so well displayed), but exceptional among British granites in general, presumably as a result of their lower volatile content. Thus the early concentration of water, particularly as it migrated to outer, cooler regions, would have accomplished the transfer of potassium within both granite and aureole, and led to the growth of megacrysts. At the same time, this migration facilitated the growth of feldspars in favoured localities, giving rise to pegmatitic bands, pipes and pods. Along with this aqueous phase was boron, which was concentrated enough in some places to form early, disseminated tourmaline within both granite and killas, although most of the tourmaline growth followed later, perhaps being linked with the 270 Ma BP intrusive episode (Chapter 2). In some places, such as at Wheal Remfry in the western lobe of the St Austell Granite mass, and at the Priest's Cove contact, the boron-rich fluid built up enough pressure to brecciate the confining rock (Allman-Ward *et al.*, 1982; Bromley and Holl, 1986; Halls, 1987; Bromley, 1989), but in others, for instance, Roche Rock and here at Porth Ledden, its effect was to cause pervasive tourmalinization (Bristow *et al.* in press). The fluid itself was probably a boron- and silica-rich component of the magma which separated either completely and formed areas of massive tourmalinite, or partially to form spots and patches (Badham, 1980; Charoy, 1979, 1981, 1982; and see 'Petrogenesis' section). The mechanism of separation was at least partly metasomatic, although complex (Manning, 1981; Pichavant and Manning, 1984): the precise process and effect in a particular case depending largely on physical conditions such as pressure, temperature and concentration gradients (Badham, 1980).

The cored-tourmaline crystals studied by Lister (1979b) were collected from near-vertical pegmatite veins and contained cores of polycrystalline quartz. Lister concluded from her examinations of the textures, chemical analyses and crystal growth mechanisms that they were formed by the supercooling of the tourmaline-bearing liquid. This would be a consequence of the sudden release of volatiles or of chilling, both of which could cause cooling below the normal crystallization temperature and thus instability at the 'crystal–fluid interface' and growth of unusual crystals. It is another effect of the high volatile content of Cornubian magmas. The greisen-bordered veins, some of which contained metallic minerals such as cassiterite and chalcopyrite, were emplaced last of all at about 270 Ma BP, that is, around 10 Ma after the intrusion of the main granite (Jackson *et al.*, 1982).

The exposures in the Cape Cornwall vicinity are outstanding, both as examples of the contact of the Land's End Granite mass with its metasedimentary country rock, and of the evolution of its late-stage facies. By analogy, they also provide an insight into the evolution of the other Cornubian granites and that of volatile-(especially boron-)rich granites in general.

The contact indicates that the granite was emplaced passively, by stoping, while K-metasomatism, the presence of pegmatites, extensive tourmalization and mineral veins show that the residual fluids of the magma were enriched in K (at least to begin with) and in B and a number of metallic elements. Depending on temperature and the extent of fracturing, these were able to penetrate both granite and killas and, because of good exposure, they illustrate how such processes must have operated in other granites of similar composition.

Conclusions

Both as examples of the contact of the Land's End Granite mass, its metamorphosed sedimentary country rocks, and of the evolution of its late-stage facies, the exposures in the Cape Cornwall vicinity are outstanding. These late-stage rocks include granitic rocks such as veins, pipes and pods of pegmatite and quartz–tourmaline rocks formed from volatile-rich solutions working their way to and crystallizing at the margins of the granite. Minerals also formed in the surrounding altered sedimentary rocks as a result of the influx of the late-magmatic fluids, and these include tourmaline and sapphire. By analogy, they also provide an insight into the evolution of the other Cornubian granites and that of volatile-(especially boron-)rich granites in general.

C9 PORTHMEOR COVE (SW 425376)

Highlights

This site uniquely exposes two satellite 'mini plutons' of the Land's End Granite showing development of a roof complex in biotite granite and a sequence of granitic dykes.

Introduction

This locality is about 3 km WSW of Zennor on the north-west coast of the Penwith Peninsula. It is one of several places where Land's End Granite can be seen in contact with its country rocks but is distinguished by the presence, on the eastern side of the Cove, of two small granite cupolas which have presumably arisen from the main intrusion. These are the only recorded examples in south-west England, of well-exposed, complete 'mini-plutons'.

Most references to the locality are very brief (Reid and Flett, 1907; Booth, 1966; Hall, 1974; Hall and Jackson, 1975; Exley and Stone, 1982; Booth and Exley, 1987; Goode and Taylor, 1988), the only comprehensive account thus far being that of Stone and Exley (1984), who describe the more accessible intrusion and its associated dykes; and also suggest a chronology, drawing attention to the evolution of its roof complex of interbanded leucogranite and pegmatite by differentiation. Bromley and Holl (1986) argue that the magma was emplaced after the foundering of a block of country rock, the overlying pegmatite/aplite complex developing through pressure changes as the block sank in stages.

Description

The country rocks at Porthmeor Cove are hard, grey, pelitic hornfelses of the banded Mylor Slate Formation which are sometimes spotted; these overlie a massive metadolerite sill some 20–25 m thick. The whole succession dips at about 20° to the north. The more northerly of the two cupolas on the eastern side of the cove, containing angular xenoliths and sending out apophyses, is visible in the cliffs but is inaccessible. The more southerly cupola, measuring about 19 m by 15 m, can easily be examined and displays several component rock types and a complex history (Figure 5.15).

It is an angular body, both in plan and in section, whose emplacement was controlled by the joints in the country rocks. All contacts are sharp and the roof is slightly domed. The main granite body is of megacrystic biotite granite (Dangerfield and Hawkes, 1981; Type B, Table 5.1; Exley and Stone, 1982; Exley *et al*., 1983), but an aphyric, slightly banded granite occupies the central parts. A typical Cornubian leucogranite/pegmatite complex, 0.60–0.70 m thick, underlies the roof and this demonstrates the concentration of late-magmatic volatiles there and thus a considerable degree of differentiation *in situ*.

Three important dykes are associated with the cupola in addition to the vein complexes at the two seaward corners. The youngest dyke, composed of tourmaline microgranite, cuts through the cupola from north-west to south-east and then turns to the east-north-east, merging with a second dyke for a few metres before continuing into the hornfelses. A dyke of intermediate age, about 0.50 m thick and of megacrystic granite, arises directly from the cupola at its south-eastern corner and runs north-east into the country rocks. About 8 m from the pluton it cuts and displaces the oldest, 0.3 m thick, dyke which is of leucogranite (Figure 5.16). On the south side of its convergence with the youngest dyke, it forms a veneer on the steep cliff face and then joins an underlying leucogranite/aplite complex, only seen at low water. Bromley and Holl (1986) state that the top of a 'huge arrested xenolith' is visible at the lowest tides; this has not been confirmed by an examination at low-water spring tides, and rock relations appear to be more complicated than these authors suggest.

Interpretation

The complexity of rock relations at the base of the pluton does not invalidate Bromley and Holl's proposition that the subsidence of a large xenolith

Figure 5.15 Small granite cupola emplaced in pelitic hornfelses of the Mylor Slate Formation. Porthmeor Cove, Cornwall. (Photo: R.A. Cottle.)

Figure 5.16 Later dyke of megacrystic granite cutting and displacing an earlier leucogranite dyke. Porthmeor Cove, Cornwall. (Photo: R.A. Cottle.)

gave the opportunity for magma to move into the resulting cavity, decompression causing the volatiles to exsolve and the depleted magma to crystallize as aplite. Above this, the volatile-rich fluid would have cooled and solidified as pegmatite, and cycles of 'foundering, decompression and arrest' thus would have produced a banded complex.

The main Land's End Granite, which also has a roof complex of leucogranite, aplite and pegmatite over megacrystic biotite granite, has an exposed contact towards the head of the cove, but it is separated from the cupola by a fault. Roof complexes are well known in south-west England, and another occurs at Porth Ledden, but they become even more spectacular where lithium-mica granite is associated with them as in the sheets adjacent to the Tregonning intrusion and seen at Megiliggar Rocks (Stone, 1969, 1975).

It is significant that despite a degree of differentiation sufficient to produce pegmatite, there is no development of lithium–mica–albite–topaz granite at Porthmeor and Porth Ledden, suggesting that this variety (Type E, Table 5.1, found only at Tregonning–Godolphin and St Austell) does not evolve directly, and at high levels, from biotite granite magma (Exley *et al.*, 1983).

It appears that the main Land's End Granite pluton was intruded, tilting its envelope of sediments and sills to the north, and developed a roof complex through volatile concentration. Either this complex, or a closely related one, then gave rise to the earliest dyke, which is of leucogranite, at Porthmeor. The Porthmeor cupola, composed of biotite granite like the main Land's End intrusion, was subsequently passively emplaced by stoping, sent out the second dyke, also of megacrystic biotite granite, and developed its own roof complex. Finally, the third dyke, of tourmaline microgranite whose source is not seen, was intruded through all the older rocks (Hall and Jackson, 1975; Stone and Exley, 1984). The small cupola therefore repeats the cycle in the main granite in which the build-up of volatiles, principally B, F and OH, during crystallization caused the formation of rocks impoverished in Fe, Ca and Na but enriched in minerals, such as tourmaline, containing these volatiles. The partitioning of some elements between residual silicate magma and OH-rich vapour determined the formation of leucogranite, usually fine grained, or pegmatite. Where jointing provided lines of weakness, the magma from the cupola penetrated to form the second dyke; the last dyke, again following the jointing but younger than the others, represents a last stage in the granite evolution in the area.

Conclusions

Here there occur two domed granite masses (cupolas), one of which is a composite intrusion, made up of an outer (older) coarse-grained granite and a younger component forming the core of the intrusion. The top of the cupola is formed of a capping mass of rock, less than one metre thick, of two types – one coarsely crystalline (pegmatite) and the other finer grained and pale coloured (aplite/leucogranite) above the main mass of the biotite granite. Such rocks have been associated with the final volatile-rich (boron- and water-rich) granite magma, differentiation, cooling and solidification in place at the top of the granite mass. Pegmatite/aplite roof complexes are usually developed from Cornubian Li-mica–albite–topaz granite magmas, but the Porthmeor Cove example is a rare and instructive example of development from biotite granite. This exposure also shows the unusual emplacement of a satellite pluton after the main intrusion, and a clear sequence of related granitic dykes.

C10 WHEAL MARTYN (SX 003556)

Highlights

This site is exceptional in that it contains relatively fresh Li-mica granite, generated by metasomatic alteration of biotite granite, which forms the greater part of the western intrusion at St Austell and provides the main source of china clay.

Introduction

As described in the 'Petrogenesis' section of this chapter, the St Austell Granite comprises two main intrusions. That in the east is centred on Luxulyan and consists of coarse-grained biotite granite (Type B, Table 5.1), while that in the west is chiefly made up of megacrystic granite of variable grain size (mostly coarse) and characterized by the Li-mica zinnwaldite (Type D, Table

5.1). Formerly thought to have been a magmatic differentiate, this latter granite is now considered to have resulted from the metasomatic alteration of large parts of an earlier biotite granite by an intruding Li-mica granite magma (Richardson, 1923; Exley, 1959; Hawkes and Dangerfield, 1978; Dangerfield *et al.*, 1980). Other varieties within the western intrusion include the Li-mica granite product of the crystallization of this magma and fluorite granite derived from it (respectively Types E and F, Table 5.1; Manning and Exley, 1984; Hawkes *et al.*, 1987; and Figure 5.4). There are also small remnant patches of biotite granite, suggesting that the western intrusion was multiphase, and these have been interpreted as constituting a sequence of fractions of magma representing stages in the cooling history (Hill and Manning, 1987; Bristow *et al.*, in press).

The western intrusion is the area in which kaolinization has been most intense and from which the great majority of china clay is extracted, so that fresh examples of the original rocks are hard to find; the Wheal Martyn site provides these rare examples. The nearby china-clay pits of Greensplat, seen from the China Clay Museum's viewing point, demonstrate the severity of the alteration and show the manner of working china-clay rock.

Description

The Wheal Martyn site is roughly in the middle of the St Austell Granite outcrop, about 3 km north of St Austell. It is towards the eastern side of the second, western intrusion which has a diameter of about 11 km and is centred just to the north-east of St Dennis. Its northern part underlies the Lower Devonian metasediments and the superficial deposits of Goss Moor (Figure 5.10).

The excavation at Wheal Martyn contains relatively fresh Type-D granite (Table 5.1). In this, there are rather few megacrysts of subhedral feldspar, 10–15 mm long; rounded composite quartz grains 5–7 mm in diameter; and tourmaline needles up to 5 mm long, all set in a groundmass with an average grain size of 1–2 mm. Flakes of pale-brown Li-mica, identified as zinnwaldite by Stone *et al.* (1988) are also visible. It is probable that this rock would be classified as 'globular quartz granite' by Hill and Manning (1987). There is also a small patch of fine-grained biotite granite (Type C, Table 5.1), suggesting that in this area some fine-grained granite was emplaced relatively early.

Interpretation

Following the intrusion of a biotite granite (Type B, Table 5.1) boss in the east, a series of biotite-bearing granites, variable in texture, was emplaced on its western side. Owing to its coarse, megacrystic texture and its composition (Type D, Table 5.1), which includes albite (An_7) and Li-mica, the bulk of this rock was thought to be a magmatic differentiate from the main biotite granite magma (Exley, 1959). However, the realization that the non-megacrystic Li-mica granite (Type E, Table 5.1) was intrusive into megacrystic rocks led Dangerfield *et al.* (1980) to conclude that the surrounding Type-D granite had originally been biotite granite (Type B) and that it had been metasomatized. This conclusion is now widely accepted, although Bristow *et al.* (in press) consider that some is of magmatic origin. The metasomatism was achieved in the presence of an aqueous fluorine-rich fluid, by introducing lithium which replaced iron to form zinnwaldite, and sodium which replaced calcium in oligoclase to give albite: adjustments in other constituents balancing these changes. Surplus calcium was combined with fluorine into fluorite, and surplus iron, together with boron, crystallized as tourmaline. The introduction of the lithium, sodium and some of the fluorine and water, was effected by the intrusion of the Type-E magma which had separated at deeper levels from biotite granite magma with which it had undergone some ion exchange. The rock, formed directly from this magma, is now seen as a non-megacrystic Li-mica granite (Type E), containing patches of fluorite granite (Type F) in the Nanpean area and near Hensbarrow (Stone, 1975; Dangerfield *et al.*, 1980; Exley and Stone, 1982; Manning, 1982; Exley *et al.*, 1983; Manning and Exley, 1984).

An early form of alteration resulting from the presence of OH- and F-rich fluids was a pervasive greisening which attacked the K-feldspar, replacing it by a secondary white mica and quartz. The extent of this is very variable and the granite at this site shows it to a limited degree.

The whole area surrounding the site has been affected by intensive kaolinization. This was a consequence of Cretaceous or Palaeogene subaerial weathering initiated by hot water circulating through the joint system in the granite (Exley, 1959, 1964; Sheppard, 1977; Durrance *et al.*, 1982; Exley and Stone, 1982; Exley *et al.*, 1983; Manning and Exley, 1984; Bristow *et al.*, in press). That closely spaced joints produced pervasive kaolinization can be seen in many clay pits, including those visible from the Museum viewing area, as can also the relationship between this process and tourmaline veins and greisen-bordered veins. The latter provide evidence for the movement of late fluids through the solidified granite and for the way in which these replaced the feldspar in the joint walls with aggregates of mica and quartz – an identical process to that seen in the body of the rock and noted above. Where they occur, ore minerals are usually found in greisen-bordered veins of this type. (See also the 'Petrogenesis' section of this chapter and the description of Tregargus Quarries.)

Conclusions

This site provides a rare exposure of relatively fresh, metasomatically originated, megacrystic Li-mica granite, which is one of the main varieties of the St Austell outcrop.

C11 CARN GREY ROCK AND QUARRY (SX 033551)

Highlights

This site is one of the few showing granite intermediate in character between that of the two main St Austell intrusions.

Introduction

Carn Grey Rock and its adjacent quarry lie 3.5 km to the north-east of St Austell, beside the road to Trethurgy. They lie in the contact zone between the first and second intrusions of the St Austell mass (Figure 5.10). The more western of these, much of which is now characterized by Li-mica, cuts the eastern biotite granite along a zone extending roughly between Carclaze and Bugle and in the direction of Roche. It has been thought, variously, that this rock is of direct magmatic origin or to have been metasomatically produced from biotite granite (Richardson, 1923; Exley, 1959; Hawkes and Dangerfield, 1978; Dangerfield *et al.*, 1980; Manning and Exley, 1984; Hawkes *et al.*, 1987; and also the 'Petrogenesis' section above). The western intrusion does contain some biotite granite, however, and is variable in texture, suggesting that its origins are not simple (Hill and Manning, 1987; Bristow *et al.*, in press). Some biotite granite is found close to the presumed intrusive contact, indicating a degree of complexity there (discussed below). Although situated on the eastern side of this contact, Carn Grey Rock resembles the western types of (Li-mica) granite in respect of its texture, sodic plagioclase, high tourmaline content and low biotite content.

Description

The granite at Carn Grey Rock is medium- to coarse-grained and rather poorly megacrystic, with megacrysts up to 40 mm in length, and quartz in rounded aggregate grains. In thin section it shows many features indicative of re-crystallization, such as strain, zoning and inter-growth in minerals. Its composition is that of biotite granite from the eastern intrusion, except that it has less biotite and calcic plagioclase and more tourmaline. The biotite is very pale, and Richardson (1923) believed that both biotite and 'lithionite' (zinnwaldite) were present; the optical properties of these micas are similar, however, and they are unlikely to coexist as discrete phases. Indeed, Leech (1929) disagreed with Richardson and considered the Carn Grey Granite to be a distinct type, comparing it with that of Merrivale on Dartmoor. Carn Grey Rock is a rather 'flat' tor, about 4 m high, with well-developed subhorizontal jointing which is also seen in the quarry below, where it shows an antiformal structure. It is believed that this site was the source of many standing stones and menhirs in the St Austell district.

Interpretation

The first of the St Austell intrusions, which has a centre near Luxulyan and a diameter of about 9 km, is made up of coarse-grained granite with biotite, zoned oligoclase (An_{25-30}) and potash feldspar megacrysts (Type B, Table 5.1; Exley and Stone, 1982). The second, which was intruded across the western edge of the first, is centred near St Dennis, and is about 11 km in diameter.

Most of it contains zinnwaldite (Stone *et al.*, 1988), albite (An_7) and potassium feldspar megacrysts, but is generally not as strikingly megacrystic as the first intrusion and has a variable texture which includes some fine-grained rock and, in addition, pockets of biotite granite (Manning and Exley, 1984; Hill and Manning, 1987; Bristow, in press; Bristow *et al.*, in press). The zinnwaldite-bearing rock is Type-D granite (Table 5.1; Exley and Stone, 1982). Originally thought to be a member of a differentiated magmatic sequence (Richardson, 1923; Exley, 1959), much of this rock is now considered to be the result of metasomatism of biotite granite by the intrusion of a late-magmatic differentiate from biotite granite magma. This brought in lithium and sodium, and the resultant rock can be seen in its solid state in the Nanpean area and near Hensbarrow Beacon as a non-megacrystic Li-mica granite with albite (An_{0-4}) and topaz (Type E, Table 5.1). Its origins are discussed in the 'Petrogenesis' section above and in relation to Tregargus Quarries.

In most of the western area (see Figures 5.4 and 5.10), an aqueous, F-rich fluid exchanged Li and Na for Fe in biotite and Ca in oligoclase. The Fe not used in the resulting zinnwaldite, combined with B to form tourmaline, and Ca not retained in albite combined with B to form fluorite. Fluorite granite (Type F, Table 5.1) occurs in pockets within the Type-E granite in the Nanpean area (Manning, 1982; Exley and Stone, 1982; Exley *et al.*, 1983; Manning and Exley, 1984; Hawkes *et al.*, 1987).

The contact between the two main intrusions is not exposed, and severe kaolinization makes field relations difficult to interpret, but biotite granite has been reported from several localities in the western area (Richardson, 1923; Bray, 1980; Allman-Ward *et al.*, 1982; Hill and Manning, 1987), and the evidence seen so far suggests that the contact is an irregular zone rather than a plane. Although the texture of the Carn Grey Rock is typical of the western intrusion, its composition is intermediate between the eastern (Type B) and the western (Type-D) granites, and it seems to represent the easternmost point to which the metasomatism penetrated and a case where the changes were not complete.

Carn Grey is an important site, providing one of the fresh exposures in the south-west of the eastern St Austell intrusion. It has textural and compositional characteristics and a geographical position which suggest that it provides a link between the main original rock types of the eastern and western intrusions, where partial alteration by Li, Na and F, brought in by the youngest intrusion, can be seen. Successive intrusions and subsequent Li metasomatism do not occur in any of the other Cornubian granite masses.

Conclusions

Carn Grey is an important site, providing one of the rare fresh exposures in the south-west of the eastern St Austell granite intrusion. The site lies in the contact area of the first and second granite intrusions which make up the St Austell mass. Texturally, the granite here has the characteristics of the medium- to coarse-grained megacrystic (with larger crystals, to 40 mm) western granite, but the chemical/mineral composition approaches that of the eastern granite. It therefore has characteristics and a position which suggest that it might provide a link between the chief rocks of the eastern and western intrusions.

C12 TREGARGUS QUARRIES (SW 949541)

Highlights

Tregargus Quarries are unusual in that they contain the two late-magmatic variants (non-megacrystic lithium–mica–topaz granite and fluorite granite) of the St Austell sequence; examples of late- and post-magmatic mineralization and alteration are developed.

Introduction

The Tregargus Quarries (Figure 5.10) are sited in fluorite granite which contains patches of non-megacrystic Li-mica–albite–topaz granite (Types E and F, Table 5.1). These facies, which are surrounded by megacrystic Li-mica–albite–topaz granite (Type D, Table 5.1), are part of the western intrusion of the St Austell mass recognized by Richardson (1923), Exley (1959), and others subsequently. This intrusion was emplaced alongside an earlier biotite granite boss centred on Luxulyan (Figure 5.10), a distinction not identified by the early Geological Survey work (Ussher *et al.*, 1909). The western intrusion was originally biotite granite also, but it was largely metasomatically altered by the incoming Li-mica–albite–topaz granite magma (Hawkes and Dangerfield, 1978; Dangerfield *et al.*, 1980; Hawkes *et al.*, 1987), which had itself been generated from biotite granite at depth (Stone, 1975; Manning and Exley, 1984; Pichavant and Manning, 1984).

Fluorite granite ('china stone' or 'Cornish stone') such as that at Tregargus, was thought by Ussher *et al.* (1909) and Howe (1914) to be an intermediate stage in the breakdown of granite to china clay, but Coon (1913a, 1913b) regarded it as a late variety modified by circulating water. Exley (1959) believed it to be the youngest member in a differentiation sequence, but the current view (Manning and Exley, 1984); Pichavant and Manning, 1984) is that it is a by-product of the complex metasomatic processes by which the Li-mica–albite–topaz granite altered its biotite granite host.

Post-magmatic greisening and tourmalinization are seen in the veins of the quarries, and there is considerable early kaolinization. The last process has given rise to much controversy. One school of thought, exemplified by Hickling (1908) and Sheppard (1977), argued that it resulted from extensive deep weathering, but a second (for example, Collins, 1878, 1887, 1909; Butler, 1908; Ussher *et al.*, 1909; Howe, 1914; Exley, 1959, 1964, 1976) held that it was due to hydrothermal fluids of magmatic origin. A third, currently popular thought, attributes kaolinization to a combination of processes of both kinds (Coon, 1911, 1913a, 1913b; Tomkeieff, discussion in Exley, 1959; Bristow, 1977; Durrance *et al.*, 1982; Bristow *et al.*, in press).

All of these evolutionary concepts are put into historical context in the 'Petrogenesis' section of this chapter.

Description

The Tregargus Quarries are just under 1 km north-west of St Stephen, a village 7 km west of St Austell, and are towards the southern limit of an elliptical area, roughly 3.5 km from north to south and 1.25 km from east to west, which, for convenience, is here called the Nanpean area (Figure 5.10). Within it occur two of the four main varieties of St Austell Granite (Exley, 1959; Exley and Stone, 1982; Exley *et al.*, 1983; Manning and Exley, 1984) which have been extensively worked for china stone, the latter formerly being used as a flux in pottery manufacture.

In the Nanpean area most of the rock contains lithium-mica (zinnwaldite – Stone *et al.*, 1988), albite and topaz. Its texture is not megacrystic, and it encloses irregular patches, up to 400 m across and at least 70 m deep, of fluorite granite. The latter have rapidly transitional, non-intrusive contacts with the former, which the fluorite granite resembles in texture and composition apart from having no iron-bearing minerals (the mica is muscovite) and an average of 2% fluorite (Table 5.1). The two most important areas are immediately west of Nanpean and around Tregargus.

The rock in the Nanpean area escaped the potassium metasomatism which gave rise to large feldspar megacrysts elsewhere in the St Austell mass, but they do show, in varying degrees, greisening, tourmalinization and kaolinization. The first is both pervasive through the rock, but restricted to the replacement of some of the K-feldspar, and localized, where it occurs as true greisen borders a few centimetres thick alongside quartz and quartz–tourmaline veins. Tourmalinization, although pervasive in other places, having produced much (4%) tourmaline within the megacrystic Li-mica granite (Type D, Table 5.1), is localized in veins at Tregargus.

Kaolinization, and its relationship to joints and faults, is best seen in the non-megacrystic Li-mica granite, the fluorite granite largely remaining fairly fresh, although, where it has been affected, it used to be graded from fresh 'hard purple' to altered 'soft white' by quarrymen before being sold for pottery making (Exley, 1959; Keeling, 1961).

The predominant rock at the Tregargus Quarries is fluorite granite, and all grades of china stone occur, although not much 'hard purple'. The non-megacrystic Li-mica granite (Type E, Table 5.1; locally known as shellstone) is to be found in irregular areas, no larger than a few square metres, but in such a way that the relationships between the two types may be seen. All the rock has been altered and veined in the manner described above. Among less-usual minerals found in the quarries are autunite, gilbertite and löllingite.

Interpretation

As has been indicated in the 'Petrogenesis' section, the St Austell Granite, which is unique in Britain, has had a more complicated evolution than the other Cornubian granite masses, starting with the intrusion of a boss of coarse-grained megacrystic granite characterized by biotite and zoned oligoclase (An_{25-30}) (Type B, Table 5.1; Exley and Stone, 1982), centred on Luxulyan. Subsequently, a second intrusion was emplaced to its west, cutting across both the earlier granite and its metamorphic aureole. The second intrusion also consisted of biotite granite, and it is thought to have included several facies (Hawkes and Dangerfield, 1978; Manning and Exley, 1984; Hill and Manning, 1987). The later intrusion, however, did not rise as far as the first so that a large, but thin, area of its thermally metamorphosed Lower Devonian roof still remains north of St Dennis, penetrated by granite in several places (Figure 5.10).

Much of the biotite in the second intrusion has been replaced by lithium-mica (now known to be zinnwaldite; Stone *et al.*, 1988), and the four main varieties of St Austell Granite were thought at one time to constitute a magmatic differentiation series of biotite granite (Type B) → megacrystic Li-mica granite (Type D) → non-megacrystic Li-mica granite (Type E) → fluorite granite (Type F) (Richardson, 1923; Exley, 1959). However, subsequent work has shown that this is not the case. It is now believed that, as a consequence of fluorine and water concentration, a residual 'magma' separated at depth from the biotite granite magma and that this contained relatively high concentrations of Li and Na rather than Fe and Ca, similar to the state of affairs in the Tregonning–Godolphin area in west Cornwall (Stone, 1975; Manning, 1982; Pichavant and Manning, 1984). This residual magma intruded the second St Austell boss to give the non-megacrystic Li-mica–albite–topaz granite now seen in the Nanpean area (and also near Hensbarrow Beacon; see Figure 5.10). Under the influence of highly volatile fluids (particularly of fluorine and water) emanating from this intrusion, biotite and oligoclase of the earlier rocks were altered. Iron was replaced by Li to give zinnwaldite, and Ca was replaced by Na to give albite (An_7); other adjustments, especially of Al, took place concurrently and gave rise, *inter alia*, to topaz. Excess Ca combined with F to produce fluorite, and hence local patches of fluorite granite, and excess Fe combined with B to form tourmaline (Manning and Exley, 1984; Pichavant and Manning, 1984). The megacrystic Li-mica granite (Type D, Table 5.1) in most of the western intrusion is thus interpreted now as a metasomatic aureole of the Nanpean (Type-E) Li-mica granite.

Some mineralization was associated with the intrusion of the coarse biotite granites in Devon and Cornwall, but the main period followed about 10 Ma later, at about 270 Ma BP (Jackson *et al.*, 1982). It is believed, on field and other evidence, to have been consequent on the intrusion of the Li-mica–albite–topaz granite (Manning and Exley, 1984; Darbyshire and Shepherd, 1987; Bristow *et al.*, in press). The existence of both pervasive and vein-concentrated greisening and tourmalinization throughout the western intrusion attest to the circulation of volatiles, especially water, F and B, and to a sequence of metasomatism, alteration and replacement continuing through the late-magmatic and into the post-magmatic stages (Figure 5.4).

The fact that kaolinization is often found beneath unaltered rocks and to great depths effectively seemed to have ruled out weathering as a cause, until Sheppard (1977) described stable isotope ratios which indicated clearly that meteoric water was of the greatest importance. This led to a revival of interest (Bristow, 1977) in a combined magmatic/hydrothermal and weathering mechanism such as had been proposed by Hickling (1908), Coon (1911, 1913a, 1913b) and, more positively, by Tomkeieff (discussion *in* Exley, 1959). These authors envisaged an initial hydrothermal alteration, breaking down feldspar to mica and increasing porosity, followed by weathering to complete the process. The recognition of convection cells, circulating meteoric water driven by radiogenic heat (Figure 5.8), and the probability of such activity during the Mesozoic and Cenozoic (Durrance *et al.*, 1982), has enabled a detailed chronology of the intrusion–mineralization–kaolinization continuum to be built up (Bristow, 1987; Bristow *et al.*, in press; Table 2.2). During this, the original magmatic water was progressively replaced by meteoric water from the country rocks, bringing elements which, at appropriate temperatures, formed the various mineral deposits and finally brought about low-temperature processes such as kaolinization which have continued through to the present. Evidence of all the chronological stages of Table 2.2, except stages 1 and 2, is present at Tregargus.

Conclusions

This site contains the only examples now readily accessible of the two youngest varieties of the chief members of the St Austell suite. The granite here originally contained the dark mica biotite, but because of concentrations of certain elements in the final granite magma and its associated solutions, reactions were set up which converted the original mineral composition and produced a different granite enriched in new elements, including lithium and fluorine. Formerly variously attributed to hydrothermal alteration and magmatic differentiation, the Li-mica–albite–topaz granite is now thought to have been derived from a late-stage magma originating at depth, and the fluorite granite to have been the result of complex metasomatic exchanges with earlier biotite granite. Also to be seen are greisen and quartz–tourmaline veins and kaolinized rock. These have spatial relationships with both the fracture system and fresh rock which show that they have resulted from solutions, now known to be largely of meteoric origin, which have travelled up from deeper levels and penetrated the walls of the fractures.

C13 ST MEWAN BEACON (SW 985534)

Highlights

This site displays a rare exposure of quartz–topaz–tourmaline rock of hydrothermal origin, formed immediately under the metamorphic rocks of the granite roof.

Introduction

St Mewan Beacon is situated on the southern margin of the St Austell Granite, 3 km WNW of St Austell and just outside the Blackpool china-clay pit (Figure 5.10).

The St Austell Granite was emplaced in three episodes, the second of which cuts across the first, near St Dennis (Figure 5.4). Both the first and the second consist of megacrystic biotite granite of typical Cornubian type (Type B, Table 5.1; Exley and Stone, 1982). A third intrusion of Li-mica–albite–topaz granite (Type E, Table 5.1) was emplaced within the second boss, and this is now exposed between St Dennis and St Stephen and near Hensbarrow Beacon. It is believed to have been derived from biotite granite at depth (see 'Petrogenesis' section and site descriptions) and upon emplacement to have metasomatized much of the second intrusion, albitizing the oligoclase, converting biotite to zinnwaldite and introducing topaz. It is this type of granite (Type D, Table 5.1) which is adjacent to St Mewan Beacon. Accompanying and following these intrusions, the introduction of boron gave rise to extensive tourmalinization which preceded greisening, metalliferous mineralization and kaolinization (Manning and Exley, 1984).

Field relations, textures and composition have, in the past, been used to suggest either a 'pneumatolytic' (Ussher *et al.*, 1909) or 'magmatic' (Collins and Coon, 1914) origin for the rocks of the Beacon, but Manning (1981) and Pichavant and Manning (1984) have concluded, from fluid-inclusion and other experimental data, that the rock was formed by complex hydrothermal processes.

Description

The rocks exposed at St Mewan make up a line of low crags along the south-facing slope. Storage tanks now occupy a small quarry at the western end, from which rock was formerly taken to pave grinding mills for china stone.

For the most part, the rocks are equigranular, fine- to medium-grained and made up of quartz and topaz with subordinate tourmaline, but banded quartz–tourmaline rock occurs in the southern side of the quarry, the banding dipping at about 40° to the south. The suite forms a contact facies between the main part of the granite, which is very kaolinized here, and its country rock consisting of tourmalinized pelites, semipelites and psammites of the Lower Devonian Meadfoot Group (Collins and Coon, 1914).

Interpretation

In addition to the quartz, topaz and tourmaline, the rocks of the Beacon contain accessory muscovite (sometimes as a replacement for topaz), apatite and opaque ore. The proportions of the main minerals vary to give rocks which may be very quartz- or tourmaline-rich, especially near the margins of the outcrop, but the average composition is about 60% quartz, 25% topaz and 15% tourmaline. They therefore fit into the St

Austell sequence after the main intrusions and metasomatism, and before the main post-magmatic tourmalinization (between Stage III and Stage IIIb of Table 2.2). However, not only are these unusual rocks very hard, but experiments on melting relations and fluid-inclusion composition suggest that they are too refractory to have been produced from a straightforward magmatic melt, although they could have crystallized in equilibrium with saline hydrothermal fluid at about 620°C (Manning, 1981). The latter would link them to the hydrothermal (i.e. high-temperature, low-pressure) mineralization stage; occasional exposures of comparable rocks are found in clay workings and mines, although these are seldom long-lived enough and accessible enough to be examined. Manning (1981) concludes that 'multi-stage and complex processes' were involved, but that more work is required on stability relations in highly saline systems containing B, F and OH in order to advance knowledge of these systems and processes further. The commencement of such work is reported in Pichavant and Manning (1984), where it is concluded that in the H_2O-saturated system Q_z–Ab–Or–H_2O added B partitions into the vapour phase while added F partitions into the melt, and that added B effects little change in the minimum melt compositions.

St Mewan Beacon provides a rare chance to see an unusual topaz-rich rock of high-temperature hydrothermal origin arising in the change from late- to post-magmatic conditions and providing a link in the evolutionary continuum. It is unlikely to have crystallized from an ordinary melt, and is probably the result of interaction between magma and a volatile phase rich in F, B and OH.

Conclusions

St Mewan Beacon consists of an igneous rock made up predominantly of the minerals: quartz, tourmaline and topaz, believed to have formed within the topmost portion (roof) of part of the St Austell granite intrusion. It has been suggested that it formed by the modification of solidifying granite magma by hot (hydrothermal) solutions containing fluorine, boron and water, through the alteration and reorganization of the chemistry and mineral content of the crystallizing granite. The fluids were a legacy of the waning igneous activity which formed the Cornubian granites. The site provides a rare chance to see an unusual rock of high-temperature origin arising in the change from late- to post-magmatic conditions and providing a link in the evolutionary continuum.

C14 ROCHE ROCK (SW 991596)

Highlights

Roche Rock is a unique site within an intrusion of quartz–tourmaline rock which was formed either from a boron-rich differentiated magmatic fluid or from a complex late-magmatic hydrothermal process.

Introduction

Roche Rock (Figure 5.10) is a lenticular, craggy outcrop, rising to a height of 20 m above its lower slopes and surmounted by a ruined chapel (Figure 5.17). It is on the southern outskirts of the village of Roche, about 8 km NNW of St Austell. The rock itself is entirely made up of quartz and black tourmaline (schorl) in varying proportions, is generally rather friable and sometimes distinctly vuggy. Its origin has been ascribed variously to magmatic (Power, 1968; Charoy, 1981, 1982) and hydrothermal/metasomatic (Flett, *in* Ussher *et al.*, 1909; Wells, 1946) processes. Manning (1981) regarded it as probably being due to the latter, but as a result of much more complex reactions than previously recognized. It is likely that these are related to those responsible for breccia formation and mineralization in other places and they are associated with the 270 Ma BP intrusive phase (Chapter 2; Allman-Ward *et al.*, 1982; Bromley and Holl, 1986; Halls, 1987; Bromley, 1989; Bristow *et al.*, in press).

Description

There is nothing to add to the simple field observations noted above, beyond saying that in hand specimen most of the tourmaline is in short prisms, although some is acicular, with needles up to 40 mm long, and radiating 'suns' are not uncommon. Although the total outcrop has been mapped as an elliptical area about 600 m by 300 m, an area of about 250 m by 100 m is fully exposed at this site.

The average grain size is seen to be 1–2 mm and both quartz and tourmaline are usually sub-

Figure 5.17 The craggy outcrop of Roche Rock consists of quartz–tourmaline (schorl) rock. Roche Rock, Cornwall. (Photo: R.A. Cottle.)

to anhedral, with sutured or indented margins, and the tourmaline is yellow brown with patches and zones of blue.

Interpretation

The school of thought favouring hydrothermal origin, based its conclusions primarily on textural evidence (Flett, *in* Ussher *et al*., 1909; Wells, 1946), apparent replacement of one mineral by another being common and tourmaline often being found in veins and other obviously post-magmatic situations. Hence the Roche Rock tourmalinite came to be regarded as the tourmalinized end-member in a sequence, starting with granite and in which luxullianite was an intermediate stage. Power (1968), however, in a general study of south-west England tourmaline, discovered clear differences between blue-green acicular tourmaline of the kind usually found in veins, and regarded as hydrothermal, and the brown prismatic tourmaline found in the body of the granites and considered to be primary and, at latest, late magmatic. This established the Roche Rock tourmalinite as magmatic.

Quartz–tourmaline rocks and tourmalinites are not rare in Cornwall; in addition to the Roche Rock (which is outstanding), there is an example at Porth Ledden, and such rocks are often uncovered in china-clay workings and mines. Charoy (1981, 1982), noting the experimental work of Pichavant (1979), ascribed all these to the separation of immiscible boron- and fluorine-rich magmatic fluid, accompanied by alkalis and silicon, in the late stages of Cornubian granite crystallization (see 'Petrogenesis' section above). Bearing in mind the results of other laboratory experiments on relatively simple granite systems incorporating boron and fluorine, Manning (1981) suspected that the process was more complex than this, especially in view of a tendency towards highly saline fluid inclusions in the minerals, and that the process may be multistage. Like quartz–topaz–tourmaline rocks such as that at St Mewan Beacon, with which he associated them, Manning thought that tourmalinite might have followed closely on magmatic crystallization, but saw a need for more experimental work, particularly on stability relations in systems with high salinity and containing B, F and OH. Some preliminary results of such work are reported by Pichavant and Manning (1984); these suggest that B and F can depress the magmatic freezing temperature of the granite system to 650°C at 1 kbar, and that the effect of F is greater than that of B in altering minimum melt compositions.

The second intrusive phase of the batholith at about 270 Ma BP (see Chapter 2) brought with it much boron and resulting tourmalinization. Frequently, this produced both explosive and implosive reactions which caused extensive brecciation by building up high internal pressure, which was suddenly released by fracturing to the surface, as at Wheal Remfry in the west of the St Austell mass (Allman-Ward *et al.*, 1982; Bromley and Holl, 1986; Halls, 1987; Bromley, 1989). It seems probable, however, that where violent rupturing of the rocks did not occur, intense tourmalinization, with both primary and secondary generations of tourmaline, took place in areas of high boron concentration. Roche Rock could well be an example of this (Bristow *et al.*, in press).

Conclusions

Roche Rock is probably the largest and certainly the best exposed quartz–tourmaline rock in Cornwall and perhaps in the country. It affords a unique site for the examination of this late granitic facies *in situ*. The origin of this distinctive rock has been variously attributed to its being the last product of the magma crystallized from a residual granite melt, particularly rich in boron to form so much of the mineral tourmaline, or, alternatively, as the product of changes wrought by hot solutions charged with boron left over from the magmatic phase during which the granites of Cornwall were formed (see St Mewan Beacon).

C15 MEGILIGGAR ROCKS (SW 609266)

Highlights

This is the only well-exposed site which shows contacts between lithium-mica granite and pelitic hornfels, sheets of leucogranite, aplite and pegmatite developed from a late-stage granitic roof complex, and unusual minerals.

Introduction

This site (Figure 5.12) includes both cliffs and foreshore over a length of about 1 km below Tremearne Farm, just over 2 km north-west of Porthleven. Within it are the eastern contact of the Tregonning part of the Tregonning–Godolphin Granite with its country rocks and a series of granitic sheets developed from the intrusion as an extension of its roof complex.

The mixed sediments of the Mylor Slate Formation are strongly folded, cleaved and veined in a manner typical of the Cornish 'killas'; the local structures have been discussed by Stone and Lambert (1956) and Stone (1966, 1975) and the regional setting of the Mylor Slate Formation by Holder and Leveridge (1986). The sediments have been thermally metamorphosed into cordierite- and andalusite-hornfelses near the granite.

The granite (Type E, Table 5.1; Exley and Stone, 1982) is thought to have originated at depth by a complex exchange process. As described earlier ('Petrogenesis' section), this was facilitated by an F-rich phase and involved the replacement of Fe–Mg in biotite by Li–Al to produce zinnwaldite, and the albitization of plagioclase. In the opinion of Stone (1975 *et seq.*), this occurred in solid biotite granite, which was then remobilized as Type-E magma, while Manning (1982) considers that it could have been part of a process of magmatic differentiation (Stone, 1975, 1984; Manning, 1982; Exley and Stone, 1982; Exley *et al.*, 1983; Manning and Exley, 1984; Pichavant and Manning, 1984). Either way, this variety of granite is exposed elsewhere only in the St Austell outcrop.

From the eastern contact, a series of sheets of pegmatite, aplite and leucogranite, changing from one to another both vertically and laterally, cuts through the cliffs and along the beach (Figure 5.18). Stone (1969, 1975) and Exley and Stone (1982) have ascribed the varied rock types to the contrasted partioning of elements between discrete liquid and vapour phases, but Bromley and Holl (1986) have suggested that these phases themselves arose from pressure variations triggered by the opening of cavities by subsidence of country rock. Badham (1980) argued that temperature variation controlled the development of the various rock types. The sheets are characteristically lithium rich, and Stone (1984) and Stone *et al.* (1988) believe that some of the lepidolite in these late rocks may have been magmatic, rather than metasomatic like most of the Li-mica in the region. Many unusual minerals occur here, among them amblygonite (Stone and George, 1979) and triplite (George *et al.*, 1981).

Description

The country rocks at Megiliggar Rocks are banded, light and dark grey and buff psammites, semipelites and pelites of the Mylor Slate Formation which have been deformed twice (first into minor upright and overturned folds and then into major recumbent folds) and cleaved, as has been explained in the account of the nearby Rinsey Cove site. These features are typical of the killas of Cornwall and are particularly well seen in these cliffs. Close to the granite, the metasediments have been baked and are now spotted hornfelses with cordierite and andalusite. Corundum, however, has not been reported as it has at Priest's Cove.

The neighbouring granite intrusion consists of a northern, fine-grained, megacrystic biotite granite (Dangerfield and Hawkes, 1981; Type C, Table 5.1, Exley and Stone, 1982), which is called the Godolphin Granite (after Godolphin Hill), and a southern, medium-grained, non-megacrystic lithium-mica- and topaz-bearing granite (Type E, Table 5.1) named after Tregonning Hill. The latter component is exposed in the cliffs.

Its eastern contact with the Mylor Slate Formations can be seen at the eastern end of Trequean Cliff, especially on the shore, and across the head of Legereath Zawn. In both localities it is sharp and without significant marginal change in the texture of the granite. It is almost vertical, although tourmalinization streaks (*'schlieren'*) and a thin pegmatite occur within the granite at the first locality and there are sheets and veins of granites of different types at the base of the cliffs and in stacks at the second.

Presumably owing to the steepness of the contact, a sheeted roof complex is not well-developed here, but from Legereath Zawn eastwards there is a series of granitic sheets of similar compositions to those found in the roof complex above the eastern end of Rinsey Cove. These sheets dip gently towards the south-east, vary in

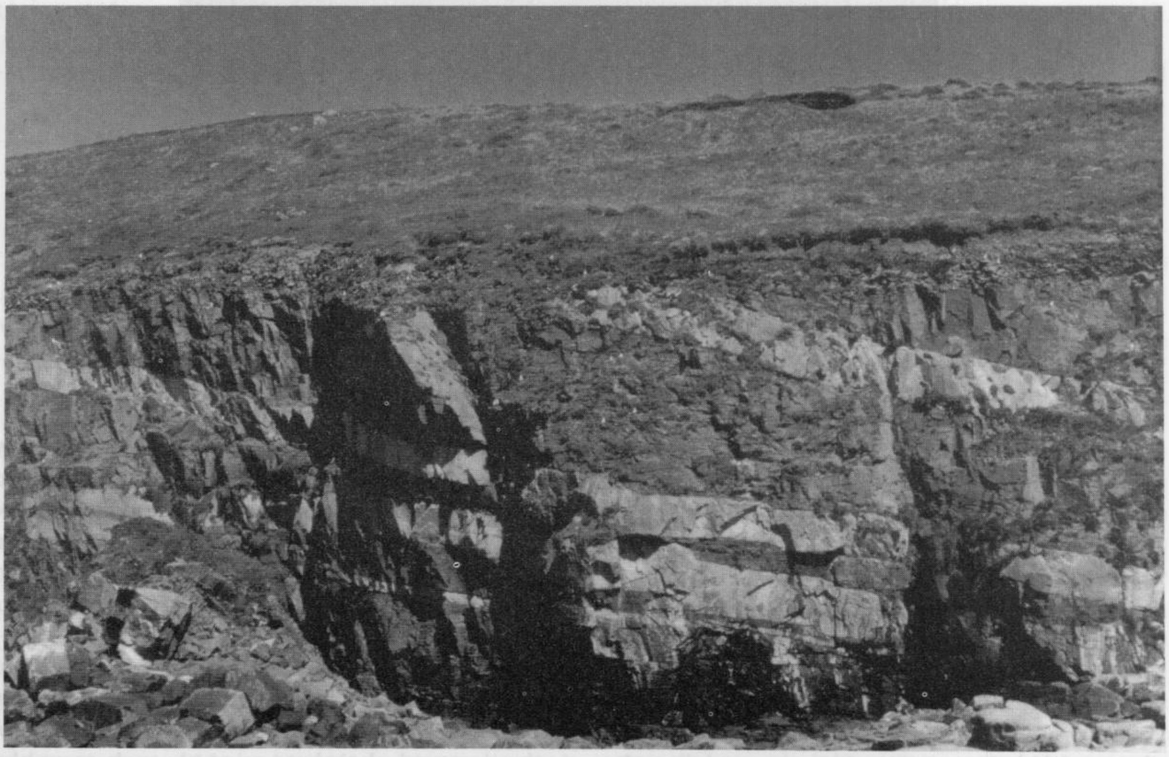


Figure 5.18 Pegmatite–aplite–granite sheets cutting Mylor Slate Formation metasediments in the cliffs at Legereath Zawn, near Tremearne Par. Megiliggar Rocks, Cornwall. (Photo: C.S. Exley.)

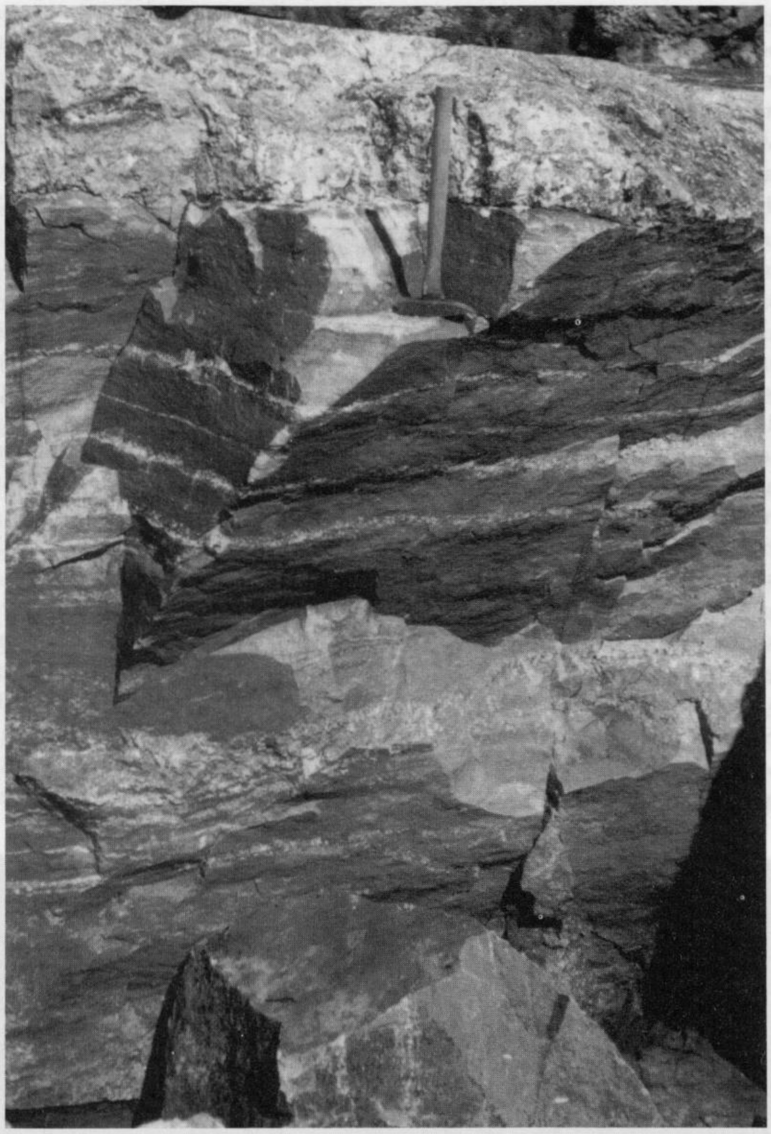


Figure 5.19 Pegmatite–aplite–granite layering in one of the granitic sheets. Megiliggar Rocks, Cornwall. (Photo: C.S. Exley.)

thickness from 0.10 m to 3 m approximately, and both coalesce and split on occasion. They cut across the cleavage in the Mylor metasediments.

The chief rock types in the sheets are pegmatites (Figure 5.19), aplites and lithium-mica leucogranites, and these types change from one to another with distance from the main granite. Pegmatites are especially well developed under pelite 'roofs', even where these are provided by xenoliths, of which there are many in various stages of detachment, disorientation and digestion. The most-complicated single outcrop is that forming Megiliggar Rocks and, here and nearby, all variations of texture are present, from narrowly banded 'line rocks' to pegmatites 0.10–0.15 m thick, together with a wide range of compositions. Some rocks are 'graded' in respect of grain size and/or tourmaline content, and have uneven bases. Many quasi-sedimentary features occur (Figure 5.20).

The occurrence at Megiliggar of blue-green apatite crystals up to 30 mm long is well known (although they are far from common); that of other unusual phosphate minerals such as amblygonite (Stone and George, 1979) and triplite (George *et al.*, 1981) less so.

Figure 5.20 Pegmatite–aplite–granite boulder on Tremearne Beach, demonstrating the quasi-sedimentary character of the igneous layering. Megiliggar Rocks, Cornwall. (Photo: C.S. Exley.)

Interpretation

The Tregonning Granite is believed to have derived from biotite granite at depth, by the separation of a fluorine- and water-rich fraction of the magma as described earlier for Rinsey Cove and in the 'Petrogenesis' section. The origin of the pegmatite–aplite–leucogranite sheets lay in the high volatile concentrations in this new magmatic fraction, which contained high concentrations of such elements as Mn, P, Sn, Ga and Ge along with the OH, F and B. The Li-mica leucogranite would seem to have been the direct continuation of the magmatic process, but the eventual partitioning of Na into the silicate melt and K into aqueous vapour, gave rise to aplite, and by reaction with the aplite, metasomatic pegmatite respectively (Stone, 1969; Exley and Stone, 1982). The development of the vapour phase could have resulted from sudden pressure changes as blocks of country rock subsided to make way for the magma; repetition of such movements would produce alternating aplite and pegmatite (Bromley and Holl, 1986). Badham (1980) did not distinguish between vapour and liquid phases, but argued that the separation and crystallization of leucogranite at higher temperatures was followed by the separation and crystallization of distinct aplite and pegmatite fluids at lower temperatures and subsequent diffusive alteration.

The rock types and mineralogies of the sheets in this complex are much more varied than those found at other places, such as Porthmeor Cove, because of the presence of Li, P and F in the Li-mica granite magma.

The Megiliggar Rocks section exhibits the only well-exposed series of leucogranite–aplite–pegmatite sheets developed from a lithium-mica granite, and allows detailed examination of these unusual late-stage facies and their relationships with each other, their parent granite and their host metasediments. They have developed as a result of the concentration of volatile constituents under an impermeable roof of metasediment and the partitioning of elements from residual magma between liquid and vapour phases. In the only other exposures of Type-E granite, the contacts are with other granites and the roof complexes are relatively poorly developed.

Conclusions

The Megilligar Rocks section exhibits the only well-exposed series of sheets of aplite, pegmatite and leucogranite developed from a lithium-mica granite. They comprise sheet-like offshoot intrusions from the main granite mass, are the last representatives of igneous activity locally, and are among the last products of the declining igneous activity that had formed the massive granite masses of Devon and Cornwall. The emplacement of this main body of magma had already folded and baked the surrounding (older) sedimentary rocks. The site allows detailed examination of these unusual late-stage granitic facies and their relationships with each other, their parent granite and their host, metamorphosed, sedimentary rocks.

C16 MELDON APLITE QUARRIES (SX 567921)

Highlights

Meldon Quarries is a classic site which contains a unique, late-stage aplitic dyke with a variable texture and composition, and a very wide range of unusual minerals both within the dyke and in associated veins. There has been metasomatism of semipelitic and calcareous sediments by elements introduced in association with the dyke.

Introduction

This site is about 4 km south-west of Okehampton, and comprises two small quarries in the Meldon 'Aplite' Dyke and adjacent metasediments, together with much older quarries in nearby calcareous metasediments. It is famous for the variety of lithium-, beryllium-, boron-, fluorine-, sulphur- and rare-element-bearing minerals occurring in both the dyke, which has a unique composition (Edmonds *et al.*, 1968), and the metasediments (Worth, 1920; Dearman and Butcher, 1959; Kingsbury, 1961, 1964, 1970; Mackenzie, 1972; Chaudry and Howie, 1973, 1976; Hawkes, 1982; von Knorring and Condliffe, 1984).

The dyke was intruded into the Carboniferous Lower Culm sediments lying within the metamorphic aureole of the Dartmoor Granite mass. These form steep, overturned folds (Dearman and Butcher, 1959; Edmonds *et al.*, 1968), which are now thought to be linked with the northward thrusting of a nappe from the south (Selwood and Thomas, 1984). The mineralogy of these metasediments varies not only with their original composition and its modification by thermal metamorphism, but also with the degree to which they suffered metasomatism associated with the intrusion of the dyke.

Description

The Meldon Dyke is probably at least 3 km long, running north-east from Sourton Tors to the Meldon Railway Quarry (Worth, 1920; Hawkes, 1982), but outcrops are intermittent, and thickness is variable both along the strike and vertically. The dyke often splits into smaller veins and apophyses and does not always reach the present surface. In the larger of the two quarries on the site, south of the Red-a-Ven Brook, the dyke is about 20 m wide at the lowest level, but it separates into several branches at higher levels, where the thickest member is some 10 m thick. The dip is about 50° to the south-east. In the smaller quarry, on the north side of the brook, the dyke is made up of several branches, the thickest being only about 4 m. In the Railway Quarry, 500 to 600 m away, only thin stringers of aplite are found (these thicknesses refer to those in the former working faces).

The dyke is parallel with and about 1.5 km distant from the margin of the main Dartmoor Granite intrusion, and it is of the same age, i.e. about 280 Ma (Darbyshire and Shepherd, 1985). It is not quite parallel with the strike of the aureole metasediments, and cuts obliquely across the junction between the Meldon Chert Formation and the underlying Meldon Shales-and-Quartzite Formation, both of which are of Lower Culm Measures (Namurian) age (Dearman, 1959; Dearman and Butcher, 1959). The structure of this area is complex, consisting of a pair of antiforms overturned against the granite to the south-east and separated by a shallow, asymmetrical synform. The antiforms occur in the Meldon Shales-and-Quartzite Formation, the Meldon Chert Formation forming the core of the intervening synform. Formerly thought to be an overturned fold (Dearman, 1959; Dearman and Butcher, 1959; Edmonds *et al.*, 1968), the structure has been reinterpreted from evidence along strike by Selwood and Thomas (1984), who believe the Meldon Shales-and-Quartzite Formation and part of the overlying Crackington Formation to be allochthonous and to have been thrust into their present positions as a nappe from the south, before the intrusion of the dyke. The remaining Crackington Formation was subsequently thrust up from the north. All of the beds have north-westerly dips at various angles, however, and the aplite is situated on the south-easterly limb of the synform where a fault has developed and the dip of the metasediments is about 30°.

The Meldon Shales-and-Quartzite Formation was originally composed of interbedded mudstones and siltstones with, towards the top, a volcanic sequence of spilitic and keratophyric agglomerates and tuffs, and an uppermost group of shales and quartzites. The sedimentary nature of the pyroclastic deposits is emphasized by Dearman and Butcher (1959). As a consequence of thermal metamorphism by the granite, these rocks have been hornfelsed, the semipelitic varieties being characterized by biotite, chiastolite and andalusite, and the metavolcanic rocks by amphibole, pyroxene and garnet.

The Meldon Chert Formation originated as a series of bedded limestones and cherts (hence the old term 'Meldon Calcareous Group') whose relationships are well seen in the bank of the West Okement River in the north-west corner of the site. Depending on composition, they have been thermally metamorphosed into more-or-less pure marbles and 'calc-flintas', the latter predominating, with the development of wollastonite and grossularite. However, it is not possible entirely to separate purely thermal from metasomatic effects in the vicinity of the dyke and many other minerals occur in the metasediments. They include axinite, andradite, idocrase, hedenbergite, hornblende and tourmaline.

The aplite itself is a predominantly fine grained, equigranular rock with euhedral to subhedral laths of albite, anhedral orthoclase, quartz and a small amount of lepidolite. It is considerably more sodic, less potassic and less siliceous than the average Dartmoor Granite and these features, combined with the presence of lithium, were said by Edmonds *et al.* (1968) to make it unique in Britain. The chief accessory minerals, amounting to about 5%, are topaz and elbaite. The last mineral is usually pale green, but often has pink zones suggestive of the rubellite which is present in later hydrothermal veins and their metasomatized aureoles. The dyke is mostly white and consists of albite, quartz and pinkish lepidolite. There are, however, bluish marginal facies containing quartz, albite and accessory orthoclase, tourmaline, apatite and colourless lepidolite. There are also patches of a coarser brown rock, with an increased quartz and pink or brown lepidolite content and tourmaline, topaz, fluorite and apatite. It often shows mineral banding (Chaudry and Howie, 1976) and also includes streaks and pockets of pegmatite in which orthoclase is a significant phase and, in addition to the rock-forming minerals already named, such species as petalite, fluorite and apatite occur.

Chaudry and Howie (1973) have separated the pegmatites into two types, one containing albite and elbaite, and the other containing topaz and petalite. The lepidolite in the pegmatites is of a lower-temperature variety than that in the aplite proper (Chaudry and Howie, 1973), and there are resemblances to lepidolites found at Megiliggar Rocks (Stone *et al.*, 1988). Many other minerals occur, either sporadically as accessories or in a more concentrated fashion along joints, in veins or in drusy cavities. Axinite is particularly well developed in cross-cutting 'reaction veins' (Mackenzie, 1972). Lithium-bearing varieties include, in addition to the micas, amblygonite and spondumene; and beryllium-bearing species include not only beryl, but also beryllonite, chrysoberyl, eudidymite, milarite, rhodizite and bavenite. There are also the zeolites heulandite and stilbite, the clay montmorillonite, the boron-bearing species datolite, and others such as pollucite (caesium), palygorskite, prehnite and columbite (niobium). Moreover, the late sulphide mineralization, which was extensively developed in the area of the nearby Red-a-Ven Mine, has given rise to the presence (especially in the metasediments) of pyrite, chalcopyrite, pyrrhotite and arsenopyrite.

Interpretation

This site illustrates both the normal development of an aplitic dyke associated with a granite in the metamorphic aureole, and the unusual concentration of minor elements and volatile constituents characteristic of the Cornubian batholith. As with the aplites of the Tregonning Granite roof complex, so well seen at Rinsey Cove and Megiliggar Rocks, the Meldon Aplite formed at a late stage when Li, Be, Rb, B, F and OH were highly concentrated, and it provided a route by which S compounds could travel out of the parent granite at a later stage. While no direct link between the dyke and the Dartmoor Granite has yet been identified, clearly there was one; it may still exist at depth or it might have been broken by tectonic activity.

The relations between aplite and pegmatite and their dependence on the partitioning of K into an aqueous phase and Na into a silicate liquid phase, have been noted in other site descriptions, for example, Megiliggar Rocks. These are all roof complexes, however, whereas the Meldon Dyke, showing similar phenomena, has developed away from the granite body.

There have been virtually no recorded discussions as to why and how the aplite magma, with its remarkable composition and range of unusual mineral phases, should have developed so locally and asymmetrically with respect to the main granite. It seems certain that it evolved in a cusp on the side of the batholith where volatiles were concentrated. It was noted in the 'Petrogenesis' section that mineralization and lithium enrichment are thought to be associated with a second major intrusive event at about 270 Ma and the resemblance between the Meldon Aplite and the Rinsey Cove and Megiliggar aplites and pegmatites strongly suggests that it belongs to this episode. Although no conclusive evidence of the 270 Ma event has been found on Dartmoor, and, as stated above, the Meldon Dyke has been dated at 280 Ma, Knox and Johnson (1990) have described post-main granite intrusions including fine- to medium-grained leucocratic topaz- and tourmaline-granite from the Lee Moor area.

The site demonstrates the metasomatic development of minerals carrying the various elements noted above and the sequential crystallization of some of them in various rock types, both igneous and metamorphic. Minerals with such elements as Be tend to precede those with Li, Rb, B and F, while those with much OH, such as zeolites and clays, are the youngest. Although groups of these minerals are to be found commonly elsewhere in the mineralized zone of the batholith, nowhere else is there so wide a variety in so small an area.

Conclusions

Here a steeply dipping igneous intrusion, the Meldon Aplite Dyke, 20 m wide at its maximum, cuts through the baked sedimentary rocks which surround the Dartmoor Granite. The aplite, a fine-grained, pale-coloured granitic rock consisting normally of the minerals quartz and feldspar, was intruded at the end of the last major phase of igneous activity in this part of Britain, between 280 and 270 million years ago. Like the main Dartmoor Granite mass, the aplite baked and chemically altered the surrounding rocks into which it was injected: thus the chemical changes wrought by the granite were overprinted by further metamorphism imposed by the dyke. The aplite, which was one of the final products of the magmas which had formed the granites of the south-west peninsula, was responsible for a uniquely diverse suite of minerals both within itself, and through the reactions of the penetrative hot solutions which flowed outward from it, with the surrounding metamorphosed sediments.

C17 PRAA SANDS (FOLLY ROCKS) (SW 573280)

Highlights

This site contains fresh exposures of an unusually large granite-porphyry dyke with evidence of multiple intrusion, chilled margins and flow banding. Microscopic features provide evidence for a complex emplacement mechanism involving solid, liquid and gas phases.

Introduction

Praa Sands is a 1.5 km long beach between Marazion and Porthleven. The site (Figure 5.12) is at its western end (Folly Rocks) and consists of a major granite-porphyry ('elvan') dyke, and its country rocks which are Mylor Slate Formation metasediments. The structure of the dyke, the main body of which has a narrow, banded, chilled margin outside an even narrower non-banded rock, has led Stone (1968) to postulate that it was a multiple intrusion, and that its textures and chemistry showed it to have contained liquid magma, solid fragments and a gas phase, all of which interacted. This explanation of the mechanism, although more complex than the simple magmatic intrusion suggested by Reid and Scrivenor (1906), was supported by Goode (1973). Henley (1972, 1974), following a study of other elvan dykes, pointed out their potassium enrichment, and Exley and Stone (1982), Exley *et al.* (1983) and Stone and Exley (1986) gave accounts of their possible derivation. They have been dated at about 269 Ma BP by the Rb/Sr method (Hawkes *et al.*, 1975).

Description

The country rocks at this site are folded and cleaved black and grey Mylor Slate Formation pelites with numerous contorted quartz veins, and they have been hardened by contact metamorphism for a few centimetres adjacent to the dyke. This dips at about 80° to the north-east and, by analogy with other dykes in Cornwall, has an Rb/Sr age of 269 ± 8 Ma (Hawkes *et al.*, 1975). The dyke is about 18 m wide overall and strikes approximately 128°, which is parallel with the local mineral veins but divergent from the general trend seen inland. Such large, multiple intrusions are unusual in south-west England.

Three rock types are discernible, the first being a banded, very fine-grained felsitic variety which forms an outer selvedge some 0.30 m wide. This rock contains rounded megacrysts of quartz and alkali feldspar up to about 1 mm in diameter. Within this selvedge, on both sides of the dyke, is a zone about 0.15–0.20 m wide in which the rock is again fine grained but not noticeably banded. This also includes rounded quartz and feldspar megacrysts but these are rather sparsely distributed. Finally, separated from the second variety by a very narrow zone in which the grain size increases markedly but gradationally, there is the main, central body of the dyke which, although relatively coarse, is still microcrystalline. Here, quartz and alkali feldspar megacrysts are common, the latter being mostly subhedral, sometimes zoned, and aligned subparallel with the contacts. There are also rather rounded, fine-grained, poorly megacrystic xenoliths. In thin section, the rock is seen to contain fragments of granite and compound crystals of quartz and alkali feldspar, as well as broken xenocrysts of quartz and feldspar.

Interpretation

Stone (1968) believed that the outer, felsitic rock constituted the first phase of a two-stage intrusion, the main central part being a second phase with either fine-grained chilled margins or a progressively intruded magma filling a slowly opening fissure, as suggested earlier by Reid and Scrivenor (1906), and giving a rock of increasing coarseness. The textures of all these granite-porphyry types show evidence of reaction and recrystallization of early-formed mineral phases and xenocrystic and probably xenolithic fragments as well. Chemically, the Praa Sands elvan is both potassium rich and has a high K:Na ratio; this led Stone (1968) to propose that there had been extensive ion exchange among the components of the fluid phase which must have been present at the time of its emplacement to effect both alteration and recrystallization of minerals. Moreover, such a fluid phase probably provided the medium for transportation of both solid and magmatic particles in a fluidized system. Goode (1973) supports this view, adding that, in general, Cornish elvans also show evidence of having drilled channels for themselves by their own hot gases (gas coring) and having brecciated the adjacent rocks during intrusion.

Exley and Stone (1982), Exley *et al.* (1983) and Stone and Exley (1986) argue, from detailed chemical and other evidence, that the granite-porphyry magma might have been derived from biotite granite magma of the type which supplied the main batholith rocks. This evidence includes enrichment in K and Rb, impoverishment in Na, and a statistical clustering with granite types B and C.

A number of elvan dykes in the Perranporth area were examined by Henley (1972, 1974), but these are not as well exposed as that at Praa Sands. Nevertheless, Henley was able to conclude, from both textural and chemical features, that elvans solidified from a magma that was already enriched in potassium as a consequence of leaching of sodium and silicon from pre-existing solid granite by late-magmatic fluids. Such aqueous residual fluids, rising rapidly from deep-seated reservoirs because of fracturing, might be stable only with K-feldspar and mica, and would incorporate fragments of granite and corroded crystals from it. An interesting feature of this concept is its dependence on a sufficient time interval between the main period of granite crystallization and dyke emplacement to permit erosion of the granite and stress relief, thus allowing deep fracturing. On the evidence then available, Henley put this at 55–75 Ma, but it is now thought to be nearer 20 Ma (Table 2.1).

The Praa Sands elvan is a very important, fresh exposure of a granite-porphyry dyke intruded in stages by a combination of magmatic intrusion and fluidization processes and deriving from both differentiated magma, developed at depth and K-rich, and incorporating solid granite broken from the walls of the fissures through which the gas-charged material passed.

Intrusions of this type are most commonly associated with volcanic activity and are known in many parts of the world. In the case of Cornubia, they are either very late-tectonic or even post-tectonic and may indicate links with volcanoes of which there are now no traces, except, perhaps, the rhyolites of the Withnoe–Kingsand area of south-east Cornwall (Cosgrove and Elliott, 1976; see Chapter 6).

Conclusions

Here is exposed a remarkable example of one of the last products of the major igneous phase which affected south-west England around 270 million years ago. After the major granite masses of Dartmoor, St Austell, etc., smaller vertical or steeply dipping sheets (dykes) of granite porphyry ('elvans') were emplaced. The elvan dyke at Praa Sands is 18 m across, and is remarkable in that it was formed by the injection of more than one magma into an opening fracture. Its outer portion, which baked the surrounding rocks, shows banding indicating the movement of the molten rock through the fissure. The central part of the dyke is coarse grained and contains fragments of older rocks (xenoliths) broken off from rocks at deeper levels by the rising magma. It has been suggested that the fissure which hosts the dyke continued to open to make this two-phase injection of magma possible. Between the central and outer rock types is a zone made up of a third rock produced by the reaction between the gas-charged later magma and the earlier outer melt. The Praa Sands Dyke is an important one for the study of the processes of igneous intrusion and reactions between magmas with different chemical and physical natures.

C18 CAMERON (BEACON) QUARRY (SW 704506)

Highlights

This quarry contains the only surface exposure of the St Agnes Granite contact, with rare pervasive greisening, which is possibly unique in Britain. There is also replacement and telescoped ore mineral paragenesis.

Introduction

Cameron (or Beacon) Quarry is situated about 800 m WNW of St Agnes Beacon on the north coast of Cornwall, and is the only place where the St Agnes Granite contact, with the country rock of Upper Devonian hornfels, is exposed at the surface. Together with the Cligga Head Granite, 5 km to the north-east, this granite forms a small cusp on a northerly prolongation of the Cornubian batholith (Bott *et al.*, 1958; Tombs, 1977).

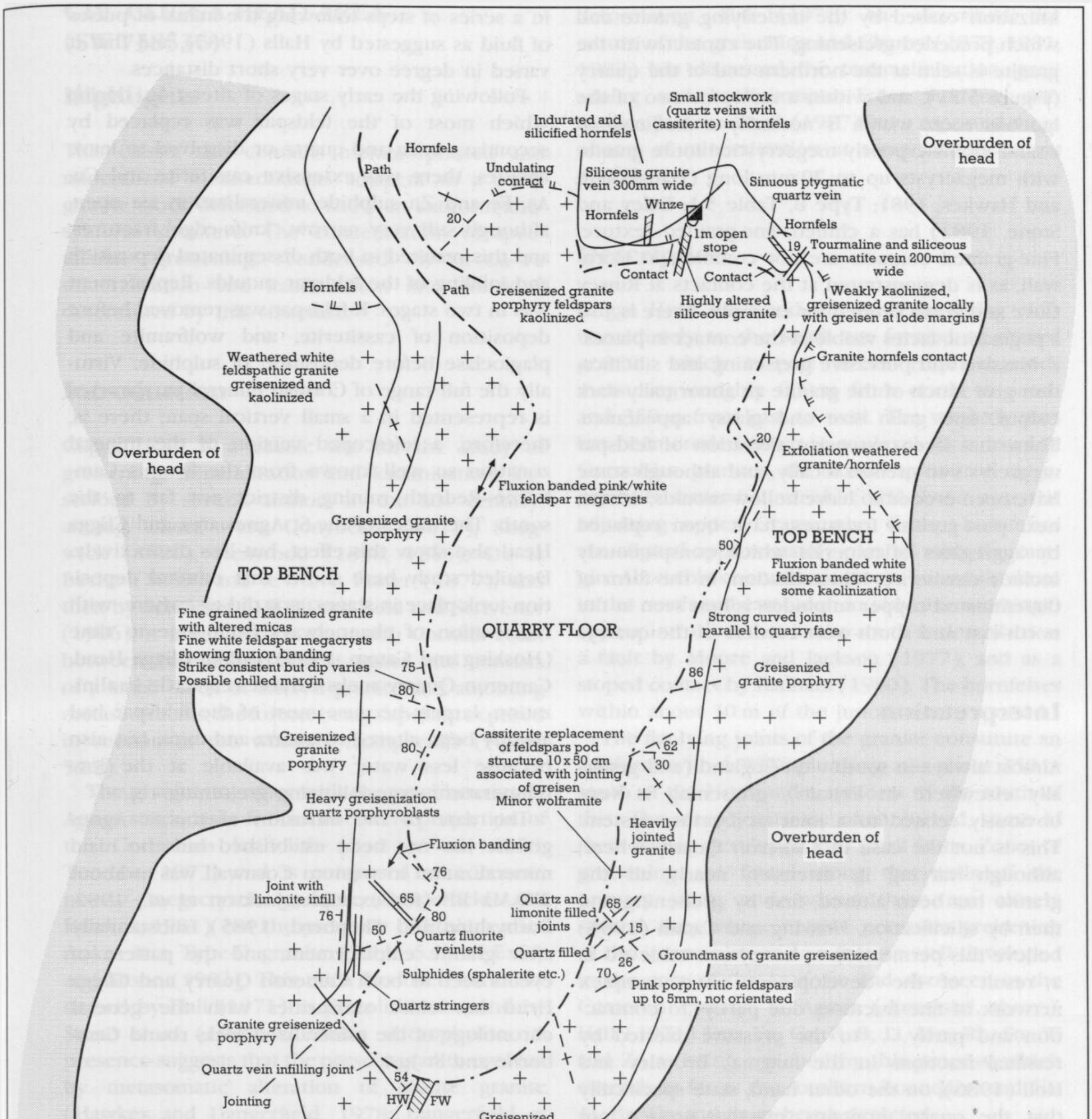
At the contact between the sedimentary rocks and the biotite granite, the pelites have been metamorphosed to spotted hornfelses, and the granite has a fine-grained margin with some pegmatitic patches.

The main interest in the quarry lies in the widespread, pervasive greisening, which is very rare; silicification; the development of disseminated cassiterite and sulphide mineralization. Reid and Scrivenor (1906) described some of the replacement phenomena, and Hosking (1964) and Hosking and Camm (1985), who give a full description of the quarry (Figure 5.21), proposed a complex paragenesis in which the relations between greisening and mineralization are examined in detail. They ascribe these features to permeation of the granite by fluids moving through it along a network of 'knife-edge' and microscopic fissures. Bromley and Holl (1986) consider the fracture system to be unrelated to the greisening, the impermeable cover of the granite cusp being more important in giving rise to a 'ponding' effect.

Description

The country rocks round Cameron Quarry are the semipelitic and psammitic Porthtowan Formation (formerly the Ladock Beds, a subdivision of the more extensive Upper Devonian Gramscatho Group), and although the psammites at the contact show little obvious signs of alteration, loose fragments on the ground surface show that thermal metamorphism has caused spotting of the hornfelses, with andalusite developed in pelitic bands. These features are additional to tourma-

Figure 5.21 (Opposite) Detailed map of Cameron Quarry (after Hosking and Camm, 1985).



Small stockwork (quartz veins with cassiterite) in hornfels
Indurated and silicified hornfels
Hornfels
Path
Undulating contact
Siliceous granite vein 300mm wide
Sinuous ptygmatic quartz vein
Overburden of head
Hornfels
Winze
Hornfels
1m open stope
Tourmaline and siliceous hematite vein 200mm wide
Contact
Contact
Weakly kaolinized, greisenized granite locally with greisen at lode margins
Hornfels
Path
Greisenized granite porphyry feldspars kaolinized
Highly altered siliceous granite
Granite hornfels contact
Weathered white feldspathic granite greisenized and kaolinized
Overburden of head
Exfoliation weathered granite/hornfels
Fluxion banded pink/white feldspar megacrysts
Greisenized granite porphyry
TOP BENCH
TOP BENCH
Fluxion banded white feldspar megacrysts some kaolinization
Fine grained kaolinized granite with altered micas
Fine white feldspar megacrysts showing fluxion banding
Strike consistent but dip varies
Possible chilled margin
QUARRY FLOOR
Strong curved joints parallel to quarry face
Greisenized granite porphyry
Greisenized granite porphyry
Cassiterite replacement of feldspars pod structure 10 x 50 cm associated with jointing of greisen
Minor wolframite
Heavy greisenization quartz porphyroblasts
Heavily jointed granite
Overburden of head
Fluxion banding
Joint with limonite infill
Quartz and limonite filled joints
Quartz fluorite veinlets
Quartz filled
Groundmass of granite greisenized
Sulphides (sphalerite etc.)
Pink porphyritic feldspars up to 5mm, not orientated
Quartz stringers
Granite greisenized porphyry
Quartz vein infilling joint
Jointing
HW
FW
Replacement of feldspars and pyritization
Greisenized granite porphyry
N
TOP BENCH
Overburden of head
0
metres
20
Joints, direction and dip

linization caused by the underlying granite and which preceded greisening. The contact with the granite is seen at the northern end of the quarry (Figure 5.21), and within a metre or two of the igneous rock, which is normally a medium- to coarse-grained, poorly megacrystic biotite granite with megacrysts up to 20 mm long (Dangerfield and Hawkes, 1981; Type B, Table 5.1; Exley and Stone, 1982) has a chilled, fine-grained texture. Fine-grained contacts are not common in Cornwall, as is demonstrated at the contacts at Rinsey Cove and Porth Ledden for example. There is also a pegmatitic facies visible at the contact in places.

Massive and pervasive greisening and silicification give much of the granite an abnormally dark colour, fine grain size and glassy appearance. There has been extensive alteration of feldspar megacrysts to greisen locally, and although some have been eroded to leave hollow moulds, others, near post-greisen fractures, have been replaced by aggregates of minerals which conspicuously include cassiterite. Mineralization, in the form of disseminated copper sulphides, is best seen in the north-east and south-west corners of the quarry.

Interpretation

Almost always in south-west England (and generally elsewhere in Britain), greisening is very obviously related to a joint or fracture system. This is not the case in Cameron Quarry where, although varying in intensity, nearly all the granite has been altered, first by greisening and then by silicification. Hosking and Camm (1985) believe this permeation to have been achieved as a result of the development of a complex network of fine fractures due partly 'to contraction and partly ... to the pressure exerted by residual fractions in the magma'. Bromley and Holl (1986), on the other hand, state specifically that the quarry contains 'massive greisen not related to penecontemporaneous fractures' and presume that 'the greisening solutions were ponded beneath the impermeable carapace of tourmalinized hornfelses'. There seems to be no reason why both should not be right if the 'network of fine fractures' is on a scale approaching the microscopic and regarded as distinct from the usual type of megascopic joint system. It is certain, however, that mineralization took place in a series of steps following the influx of pulses of fluid as suggested by Halls (1987), and that it varied in degree over very short distances.

Following the early stages of alteration, during which most of the feldspar was replaced by secondary mica and quartz or dissolved to leave cavities, there was extensive cassiterite and Cu, As, Fe and Zn sulphide mineralization via open, although still very narrow, 'knife-edge' fractures, and this resulted in both disseminated deposition and infilling of the feldspar moulds. Replacement was in two stages: K-feldspar was removed before deposition of cassiterite, and wolframite and plagioclase before deposition of sulphide. Virtually the full range of Cornish mineral parageneses is represented in a small vertical span; there is, therefore, a telescoped version of the mineral zonation so well known from the famous Camborne–Redruth mining district not far to the south. The mines of the St Agnes area and Cligga Head also show this effect, but less distinctively. Detailed study here shows that mineral deposition took place in stages, as it did elsewhere, with reactivation of channelways from time to time (Hosking and Camm, 1985). Unlike Cligga Head, Cameron Quarry rocks exhibit very little kaolinization, largely because most of the feldspar had already been altered to quartz and mica, but also because less water was available at the low temperature stage following greisening.

The date of the intrusion of the St Agnes granite has not been established but the main mineralization in western Cornwall was at about 270 Ma BP (for example, Jackson *et al.*, 1982; Darbyshire and Shepherd, 1985), substantially after granite emplacement; and the pattern of events seen at both Cameron Quarry and Cligga Head has close similarities with the general chronology of the mineralized areas round Camborne and St Just.

Conclusions

This is a unique site in which can be seen the widespread effects of greisening, silicification and intense mineralization in a 'telescoped' succession in which the effects are superimposed rather than in distinct zones, all less closely related to jointing than is normal.

C19 CLIGGA HEAD AREA (SW 738536)

Highlights

This classic site contains metamorphosed and mineralized metasediments adjacent to a small granite stock deformed to show an antiform-and-synform structure. The concentration of spectacular greisening, condensed W–Sn–Cu–Fe mineralization and kaolinization into zones is determined by this structure.

Introduction

Cligga Head is a classic site for the study of greisening, mineralization and kaolinization. Described by several authors in the last century, among whom were Conybeare (1817), Sedgwick (1820), Henwood (1838, 1843), De la Beche (1839) and le Neve Foster (1877), and then by Scrivenor (1903) and Reid and Scrivenor (1906), it is situated on the north Cornish coast between Perranporth and St Agnes, and consists of a small stock of altered granite and adjoining metasediments, the former being superbly exposed in section in the westerly facing cliffs (Figure 5.22).

The granite, together with the neighbouring St Agnes stock, rises from a northerly projection of the Cornubian batholith (Bott *et al.*, 1958; Toombs, 1977) and is composed of a coarse, poorly megacrystic granite (Dangerfield and Hawkes, 1981), but the presence of lithium mica makes it a Type-D granite (Table 5.1) of Exley and Stone (1982). This mica has been variously named by Hall (1971) as protolithionite, and by Stone *et al.* (1988) as lithian siderophylite; its presence suggests that the present granite evolved by metasomatic alteration of biotite granite (Hawkes and Dangerfield, 1978; Dangerfield *et al.*, 1980; Exley and Stone, 1982; Exley *et al.*, 1983; Manning and Exley, 1984; Stone and Exley, 1986, Hawkes *et al.*, 1987). Charoy (1981) considers the albite was derived from original oligoclase by hydrothermal alteration. There is disagreement as to the nature of the granite's southern contact (Moore and Jackson, 1977; Badham, 1980).

The granite has been deformed in a way not seen elsewhere in south-west England, and Moore and Jackson (1977) have related the distribution of alteration and mineralization zones to this deformation. Hall (1971) has described the nature of the greisening and Charoy (1979, 1981, 1982) has discussed the tourmalinization, greisening and kaolinization. From fluid-inclusion studies, Jackson *et al.* (1977) have reported three phases of mineralization at temperatures below 400°C.

Description

Cligga Head itself and the westerly facing cliffs immediately to the south are formed of altered granite, which is part of an elliptical stock measuring roughly 600 m from north to south and 350 m from east to west. The westerly part has been eroded down to sea-level. As is usual in Cornubian granites, the concentration of megacrysts is somewhat variable, and those near the adjoining upper Gramscatho Group hornfelses are aligned approximately parallel with the margin. All visible contacts are steep, but while those in the north and east (seen in old mine workings) appear intrusive, that in the south is described as a fault by Moore and Jackson (1977), and as a stoped contact by Badham (1980). The hornfelses within about 30 m of the junctions are spotted.

The flat-lying joints of the granite constitute an antiform with a WSW-plunging axis about 350 m south of the Head and a synform to the south of this. The steep joints are often curved, some of them having developed into small faults. Zones of greisening are found along the walls of the primary joints and, where these are closely spaced, they merge to give pervasive greisening of the intervening rock, a feature well developed in the core of the antiform and also seen in the Cameron Quarry, St Agnes (discussed above). Hall (1971) lists Fe, Ca, F, B, Li, Mn, Rb, Sn, W and Zn as being enriched by this process, which extends as far as the southern boundary; and Na, Al, Ba, Cu and Sr as being depleted.

The mineral assemblage wolframite–cassiterite–arsenopyrite–molybdenite–mispickel, associated with a quartz gangue, also follows the joints, although some of the veins are transgressive. There are two intensely mineralized zones: one situated about 200 m south of Cligga Head (this is some 130 m wide) and the second at the southern boundary (up to 30 m wide). Iron staining is conspicuous in the vicinity of the latter. Zones of extreme kaolinization are also present in these areas, although the whole stock has been kaolinized to some extent. The adjacent

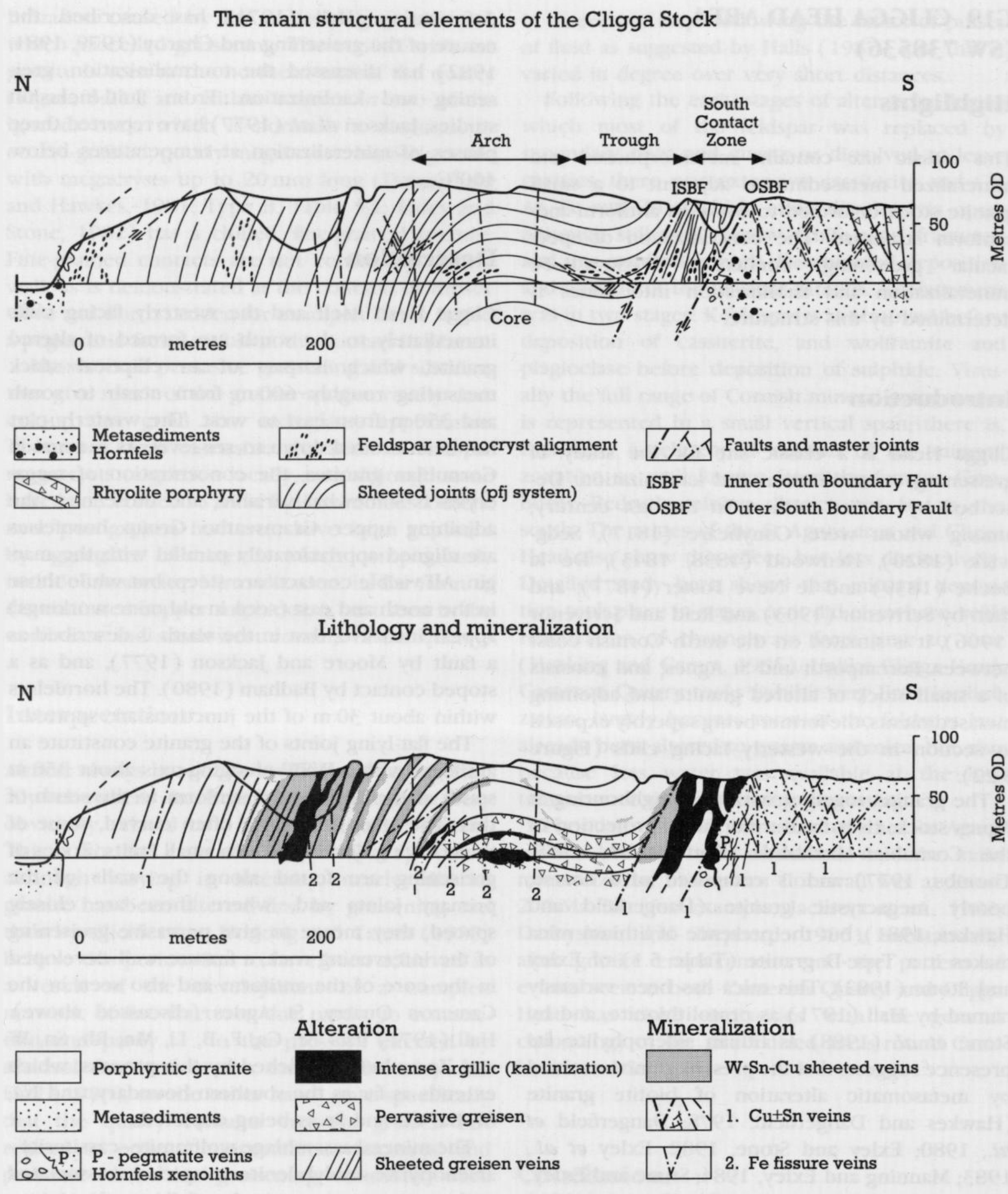


Figure 5.22 Coastal section of the Cligga Head Granite, site C19 (after Moore and Jackson, 1977).

'killas' has also been affected locally by these processes.

About 100 m south of the spotted hornfelses of the southern contact, two narrow, steeply dipping outcrops of granite-porphyry containing chalcopyrite, and believed to converge at about sea-level, strike roughly north-east inland from Hanover Cove.

Interpretation

The granite at Cligga appears, like that in the central parts of the St Austell mass, to have been a biotite granite which has been metasomatized. Apart from the lithium-rich nature of the mica, Charoy (1981) points out that the present albite has been derived from earlier oligoclase. This alteration is thought to have been brought about by a complex exchange process induced by a Li- and F-rich differentiated magma which substituted Na, Al and Li for Ca, Fe and Mg, as described in the 'Petrogenesis' section and under Tregargus Quarries. The Li-bearing mica now present has been identified as protolithionite (Hall, 1971; Charoy, 1981) or lithian siderophyllite close to zinnwaldite in composition (Stone *et al.*, 1988). The implication is that Type-E granite (Table 5.1), which brought about metasomatism, could be present in the batholith nearby.

As explained earlier in this chapter, the crystallization of the granite magma gave rise to hydrothermal fluids capable of causing metasomatism and producing pegmatites, aplites, metalliferous mineralization and eventually kaolinization. The origin of the water in these fluids was increasingly meteoric and decreasingly magmatic with time and they were associated with two periods of granite intrusion, at 290 Ma and 270 Ma BP. From the Li-rich nature of the Cligga Head Granite, it is evident that the mineralization here belongs to the second period and it therefore corresponds with the 'Main mineralization' described from the St Just area of Land's End by Jackson *et al.* (1982).

According to Moore and Jackson (1977) the development of the undulating 'floor' joints and subvertical joints and faults resulted from stress in a NNW–SSE direction, first synkinematically due to magmatic pressure and then cooling, and secondly, post-kinematically from the relaxation of stress, while Halls (1987) argues for a successsion of hydrothermal pulses. These controlled the distribution of both hydrothermal alteration and mineralization (Figure 5.22), the wide-ranging mineral assemblage indicating a condensed or telescoped sequence in which mineralized zones overlap instead of being separate, like that at Cameron Quarry but not to the same degree. The work of Jackson *et al.* (1977) led them to conclude that mineralization took place in three stages. The first was itself a two-stage process; the earlier, at a T_h range of 400–280°C, deposited cassiterite and wolframite and the later, with a T_h range of 320–240°C, deposited sulphides of Sn, Cu, As, Zn, Fe, Bi and Mo. The hydrothermal fluids involved were of low salinity (2–12 equiv. wt. % NaCl) and might also have caused the greisening. The second stage, post-faulting, resulted in quartz–hematite and quartz–pyrite–chalcopyrite assemblages from fluids with a T_h range of 260–210°C and a narrower range of low salinities (3–9 equiv. wt. % NaCl); and the final stage, leaving iron hydroxides, was effected at T_h of 150 to <70°C from fluids with salinities as low as 1–3 equiv. wt. % NaCl. Jackson *et al.* suggest that the minimum depth of formation of these deposits was 400 m, and that the last fluids might have played a part in the kaolinization process which, at similar temperatures, subsequently broke down the feldspar.

It is interesting that the salinities recorded by Jackson *et al.* (1977) are lower than those measured in the Main Mineralization of the Land's End area by Jackson *et al.* (1982) at 10–20 (and locally 40) equiv. wt. % NaCl, and that the depth of cover at 400 m minimum compares with 2800 for Land's End. Cligga Head Granite is a small granite, peripheral to the main batholith, and, as Jackson *et al.* (1982, Figure 2) suggest, salinities in the flanks of the intrusion tend to be lower than those in the main body. Jackson *et al.* (1977) do not date the later episodes of mineralization at Cligga but, by analogy with Land's End (Jackson *et al.*, 1982), they probably include Mesozoic and Cenozoic events.

Charoy (1979, 1981, 1982) has used the Cligga Head Granite in his studies of all three of the 'traditional' alteration processes in Cornwall. As regards greisening, he agrees in essence with Jackson *et al.* (1977) about the temperature and salinity of the altering fluids but, in addition, lays emphasis on the difficulties in drawing firm conclusions about processes and changes in areas where there has been repeated and successive alteration. While Hall (1971) was firm about the changes at Cligga Head, he also emphasized the difficulties in making comparisons. Charoy (1981) pointed out the importance of a shallow depth and relatively open physicochemical system in interpreting a complex site like Cligga Head. Charoy regards the tourmaline at Cligga as 'a true magmatic phase', unlike those at Porth Ledden and Roche Rock, which were a consequence of an unmixed, B-rich, late- or post-magmatic liquid giving rise to a secondary mineral. Kaolinization he regarded as a low-temperature continuation of the earlier hydrothermal processes, again agreeing with Jackson *et al.* (1977).

Conclusions

Like the St Agnes Granite, the Cligga Head Granite mass is a comparatively small projection from the Cornwall–Devon granite (the Cornubian batholith). The flat-lying joints in the granite show that it is folded and all the main joints have been affected by greisenization (see Cameron Quarry above). Cligga Head is an ideal location for the study of this process as well as metalliferous mineralization and kaolinization. The last process, the decomposition of the granite and the transformation of its feldspar crystals to the clay mineral kaolinite, was brought about by the action of the youngest and coolest of the fluids persisting from the magmatic phase which generated the granite. So here may be seen mineral veins with greisen borders and intervening zones of kaolinized granite. The full range of these phenomena, typical of south-west England, is available on this site.