
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 758 773]

C2 Birch Tor [SX 686 814]

C3 De Lank Quarries [SX 101 755]

C4 Luxulyan (Goldenpoint, Tregarden) Quarry [SX 054 591]

Older granites in contact with metasediments

C5 Leusdon Common [SX 704 729]

C6 Burrator Quarries [SX 549 677]

C7 Rinsey Cove (Porthcew) [SW 593 269]

C8 Cape Cornwall area [SW 352 318]

C9 Porthmeor Cove [SW 425 376]

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

C10 Wheal Martyn [SX 003 556]

C11 Carn Grey Rock and Quarry [SX 033 551]

Granites with Li-mica, topaz and fluorite

C12 Tregargus Quarry [SW 949 541]

Late differentiates

C13 St Mewan Beacon [SW 985 534]

C14 Roche Rock [SW 991 596]

C15 Megiligar Rocks [SW 609 266]

C16 Meldon Aplite Quarries [SX 567 921]

Granite-porphyry (elvan) dyke

C17 Praa Sands (Folly Rocks) [SW 573 280]

Mineralized granite

C18 Cameron (Beacon) Quarry [SW 704 506]

C19 Cligga Head area [SW 738 536]

(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)
K-feldspar ophitic to hypidiomorphic (Amounts vary)	Plagioclase (Amounts vary)	Quartz (Amounts vary)	Micas (Amounts vary)
		Tourmaline (Amounts vary)	Other (Amounts vary)
		Other names in literature	A Basic microgranite Medium to fine; Biotite predominant; some muscovite Often present Hornblende, apatite, zircon, ore, garnet Basic segregations (Reid <i>et al.</i> , 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 <i>et al.</i> , 1968), coarse megacrystic granite (Hawkes and Dangerfield, 1978). Also blue or quarry granite (Brammall, 1926; Brammall and Harwood, 1923, 1932) = poorly megacrystic granite (Edmonds <i>et al.</i> , 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	Carmenellis	Geevor Mine	Geevor Mine Bodmin Moor	St Austell* Cligga Head	Tregonning	St Austell*	Godolphin	Tregonning	Godolphin 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 ₂ O ₃	15.03	14.65	14.20	14.10	14.76	14.72	14.85	16.11	15.81	14.50	16.40
Fe ₂ O 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 ₂ O	3.11	3.11	2.82	2.86	2.74	3.42	3.21	3.73	4.06	0.12	2.77
K ₂ O	5.06	4.36	5.11	4.77	5.73	5.36	5.03	4.84	4.66	7.66	3.95
Li ₂ O	0.06	0.07	0.08	0.07	0.04	0.18	0.11	0.27	0.01	0.03	0.94
P ₂ O ₅	0.25	0.18	0.24	0.32	0.25	0.33	0.15	0.50	0.46	0.26	0.48
B ₂ O ₃			0.41	0.47			0.27	0.14		-	
F						(0.38)	0.38	1.22	(1.36)	-	1.40
H ₂ O	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 Fe₂O₃

Oxide values in weight %

Trace element values in ppm

The Cornubian granite batholith (Group C sites)

Lithological and chemical variation

Summaries of the petrography and chemistry of the principal granite types of the batholith are given in (Table 5.1) and (Table 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 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 microclitic, 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 equigranular (Bromley and Holl, 1986).

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

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

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 SiO₂, K₂O/Na₂O 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 (Table 5.1) and (Table 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 KruAne 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 material of granite magmas that is forced up as 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 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 'laolinization' 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 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 biotite 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-Divas 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 SiO₂) 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 Megiligar 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 straightforwardly 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 radioisotopes 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 $^{87}\text{Sr}/^{86}\text{Sr}$ range from 0.7095 to 0.7140, which are crustal values.
3. Hampton and Taylor (1983) record Pb isotope ratios of $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.363 to 18.499, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.614 to 15.655 and $^{208}\text{Pb}/^{204}\text{Pb}$ 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 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 decrepitemetry 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 maintenance 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 leuogranite–aplite–pegmatite complexes and, at least partly, to pervasive greisenization. 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).

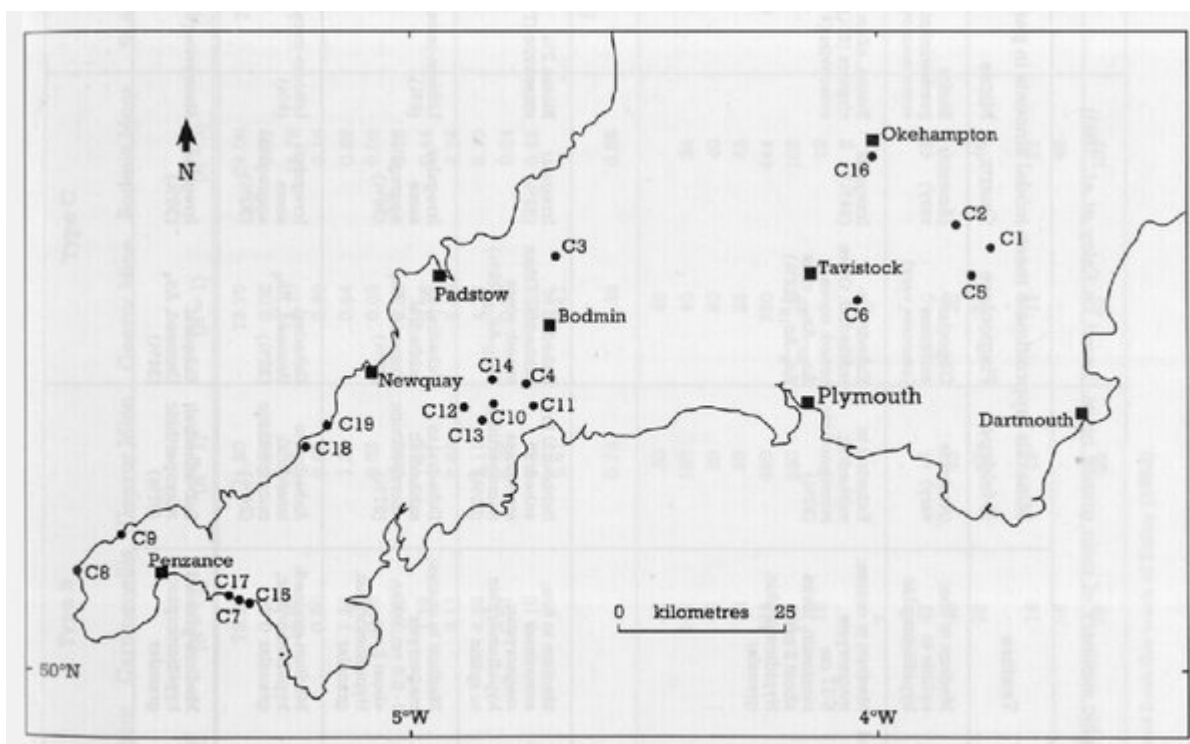
The separation of the immiscible fluids resulted in greatly increased internal pressures which disrupted the outer parts of the granites in some places, e.g. Wheal Remfry, west of St Austell. The consequent sudden drop in pressure not only generated a far-travelling vapour phase which could deposit minerals 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.

[References](#)



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

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 (Stammall and Harwood, 1923, 1924)
B	Coarse-grained megacrystic biotite granite	Medium to coarse; megacrysts 5-17 cm maximum, mean about 5 cm. Hypidiomorphic, granular	Euhedral to subhedral; micropertitic (32%)	Euhedral to subhedral. Often zoned; cores $An_{10}-An_{20}$, rims An_2-An_{11} (25%)	Irregular (34%)	Biotite, often in clusters (6%); muscovite (4%)	Euhedral to anhedral. Often zoned. Primary (1%)	Iron, ore, apatite, andalusite, etc. (total, 1%)	Includes: Giant or tor granite (Stammall, 1926; Stammall and Harwood, 1923, 1932) = big feldspar granite (Edmonds et al., 1968), coarse megacrystic granite (Hawkes and Dangerfield, 1978). Also blue or quartz granite (Stammall, 1926; Stammall 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 variety) (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, 1967).
C	Fine-grained biotite granite	Medium to fine, sometimes megacrystic; hypidiomorphic to ophitic	Subhedral to anhedral; sometimes micropertitic (30%)	Euhedral to subhedral. Often zoned; cores $An_{10}-An_{11}$ (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 5 cm. Hypidiomorphic, granular	Euhedral to subhedral; micropertitic (27%)	Euhedral to subhedral. Unzoned, An_4 (26%)	Irregular; some aggregates (36%)	Lithium-mica (6%)	Euhedral to anhedral. Primary (4%)	Fluorite, ore, apatite, topaz (total, 0.5%)	Lithionic granite (Richardson, 1923). Early lithionic granite (Exley, 1959). Porphyritic lithionic granite (Exley and Stone, 1964). Megacrystic lithionic-mica granite (Exley and Stone, 1962)
E	Equigranular lithium-mica granite	Medium-grained; hypidiomorphic, granular	Anhedral to interstitial; micropertitic (24%)	Euhedral. Unzoned, An_4 (32%)	Irregular; some aggregates (30%)	Lithium-mica (9%)	Euhedral to anhedral (1%)	Fluorite, apatite (total, 2%); topaz (3%)	Late lithionic granite (Exley, 1959). Non-porphyritic lithionic granite (Exley and Stone, 1964). Medium-grained, non-megacrystic lithium-mica granite (Hawkes and Dangerfield, 1978). Equigranular lithium-mica granite (Exley and Stone, 1964). Topaz granite (Hill and Manning, 1967)
F	Fluorite granite	Medium-grained; hypidiomorphic, granular	Sub-anhedral; micropertitic (27%)	Euhedral. Unzoned, An_4 (34%)	Irregular (30%)	Muscovite (6%)	Absent	Fluorite (2%), topaz (1%), apatite (<1%)	Gilbertite granite (Richardson, 1923)

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

	Type B			Type C		Type D		Type E	Type F	Granite porphyry	Microgranite
	Bodmin Moor	Carmenellis	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 = 5)	(N = 2)	(N = 10)	(N = 5)	(N = 2)	(N = 1)
SiO ₂	72.43	72.63	71.30	73.70	74.09	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 ₂ O ₃	15.03	14.65	14.30	14.10	14.75	14.72	14.85	14.11	15.81	14.50	16.40
Fe ₂ O 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	0.89	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	0.45	0.60	0.05	0.15	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	1.25
Na ₂ O	3.11	3.11	2.82	2.86	2.74	3.42	3.21	3.73	4.06	0.12	2.77
K ₂ O	5.06	4.36	5.11	4.77	5.73	5.36	5.05	4.84	4.66	7.66	3.95
Li ₂ O	0.06	0.07	0.06	0.07	0.04	0.18	0.11	0.27	0.01	0.03	0.94
P ₂ O ₅	0.25	0.18	0.24	0.32	0.23	0.33	0.15	0.50	0.46	0.28	0.48
B ₂ O ₃	-	-	0.41	0.47	-	-	0.27	0.14	-	-	-
F	-	-	-	-	-	(0.36)	0.36	1.22	(1.36)	-	1.40
H ₂ O	1.01	-	0.73	1.38	0.88	-	1.13	-	-	-	-
Nb	-	17	30	40	-	57	-	93	81	21	47
Zr	121	137	185	42	34	(50)	65	46	(11)	94	38
Y	41	48	30	20	40	-	-	10	-	18	-
Sr	94	92	95	23	43	41	175	61	84	34	47
Rb	419	452	480	760	444	982	695	1218	615	814	2293
Ba	196	397	230	15	102	(63)	180	204	(43)	699	197
La	31	16	-	-	12	5	-	-3	-	14	15
Ce	38	-	-	-	2	34	95	38	19	65	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
Ce	28	34	-	-	48	-	-	127	-	33	223
K/Rb	100	78	88	52	107	45	60	33	63	78	14

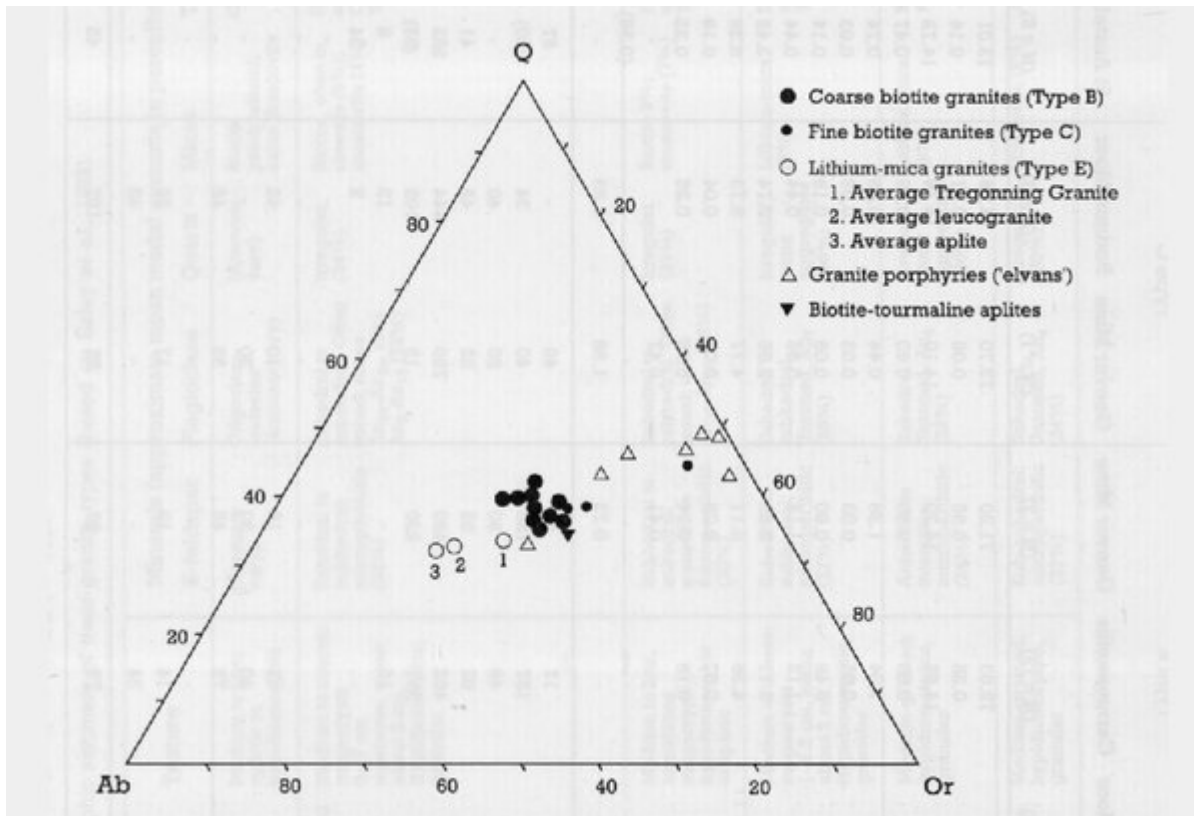
* Values in parentheses from the work of Eddy (1969)

† Total Fe as Fe₂O₃

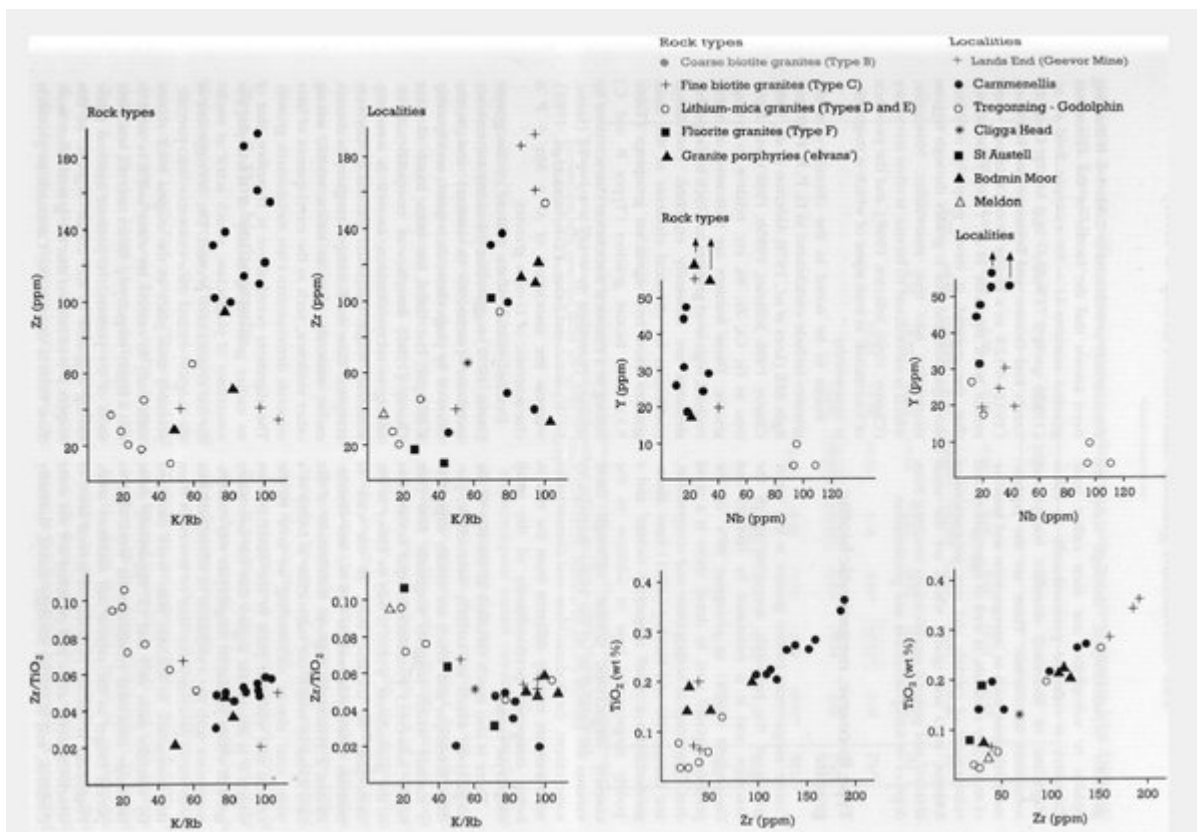
Oxide values in weight %

Trace element values in ppm

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



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



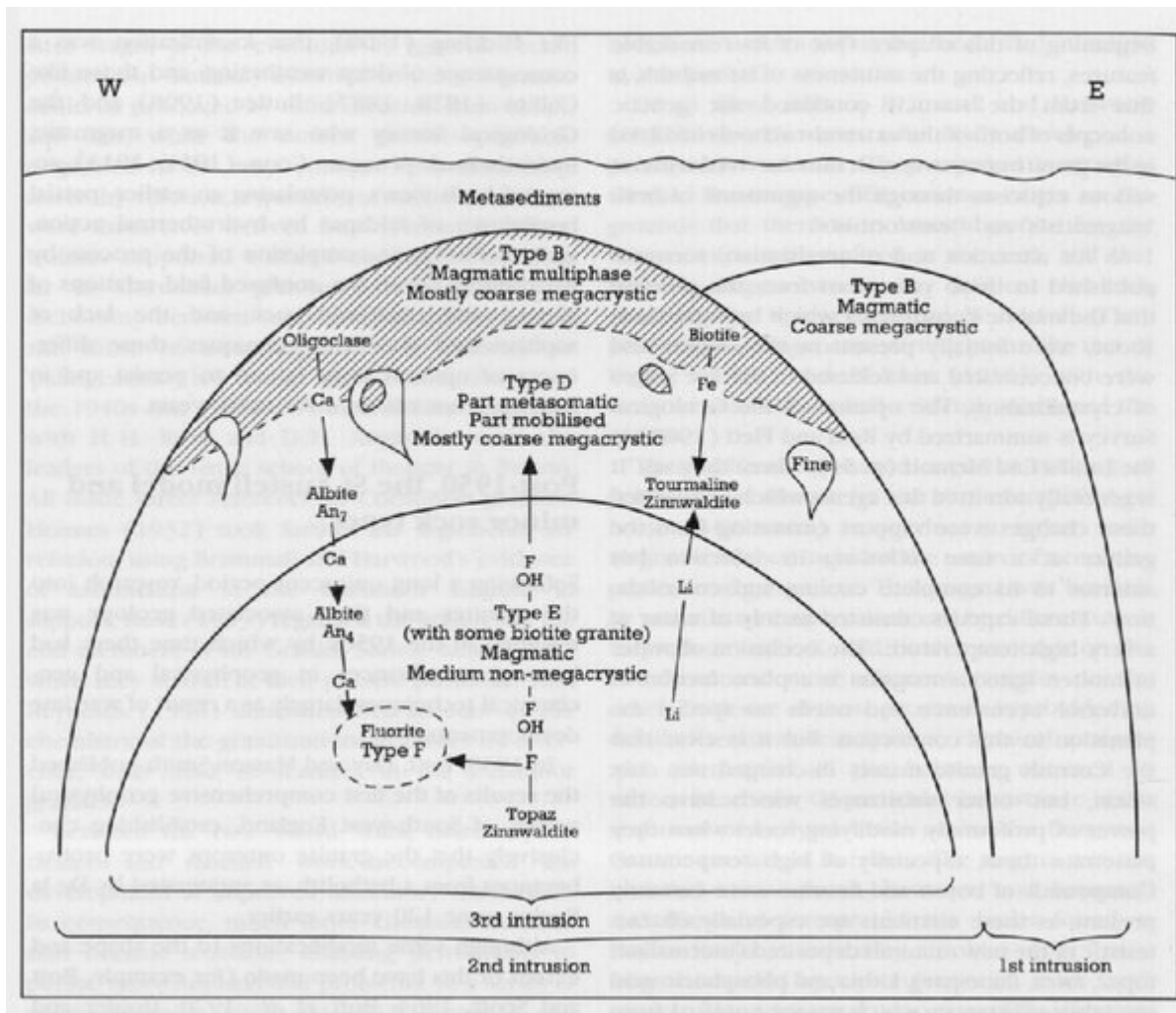
(Figure 5.3) Variation diagrams for Zr—K/Rb, Zr/TiO₂—K/Rb, Nb—Y and Zr—TiO₂ in south-west England granite types and different plutons (after Exley et al., 1983).

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 ^I
					-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.

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

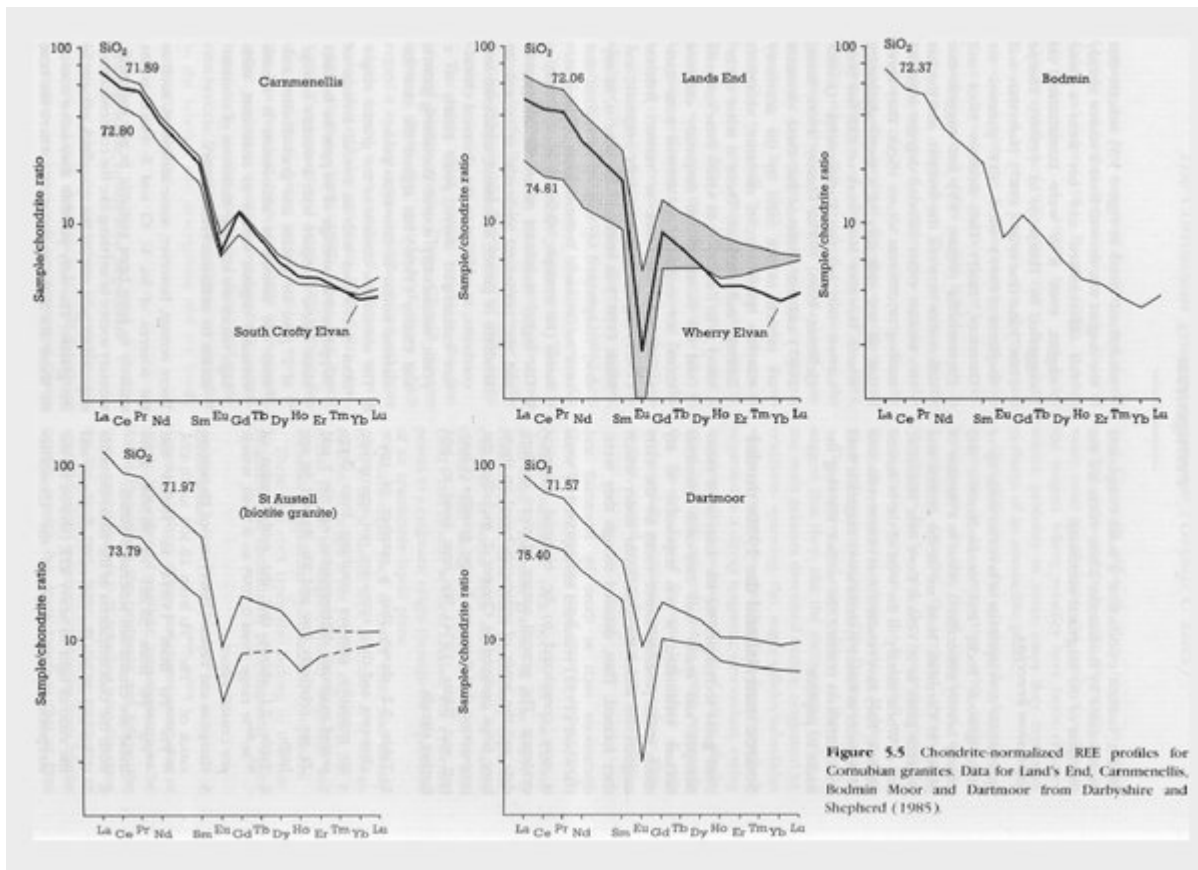
Boxed values are those belonging to the ferric element association.



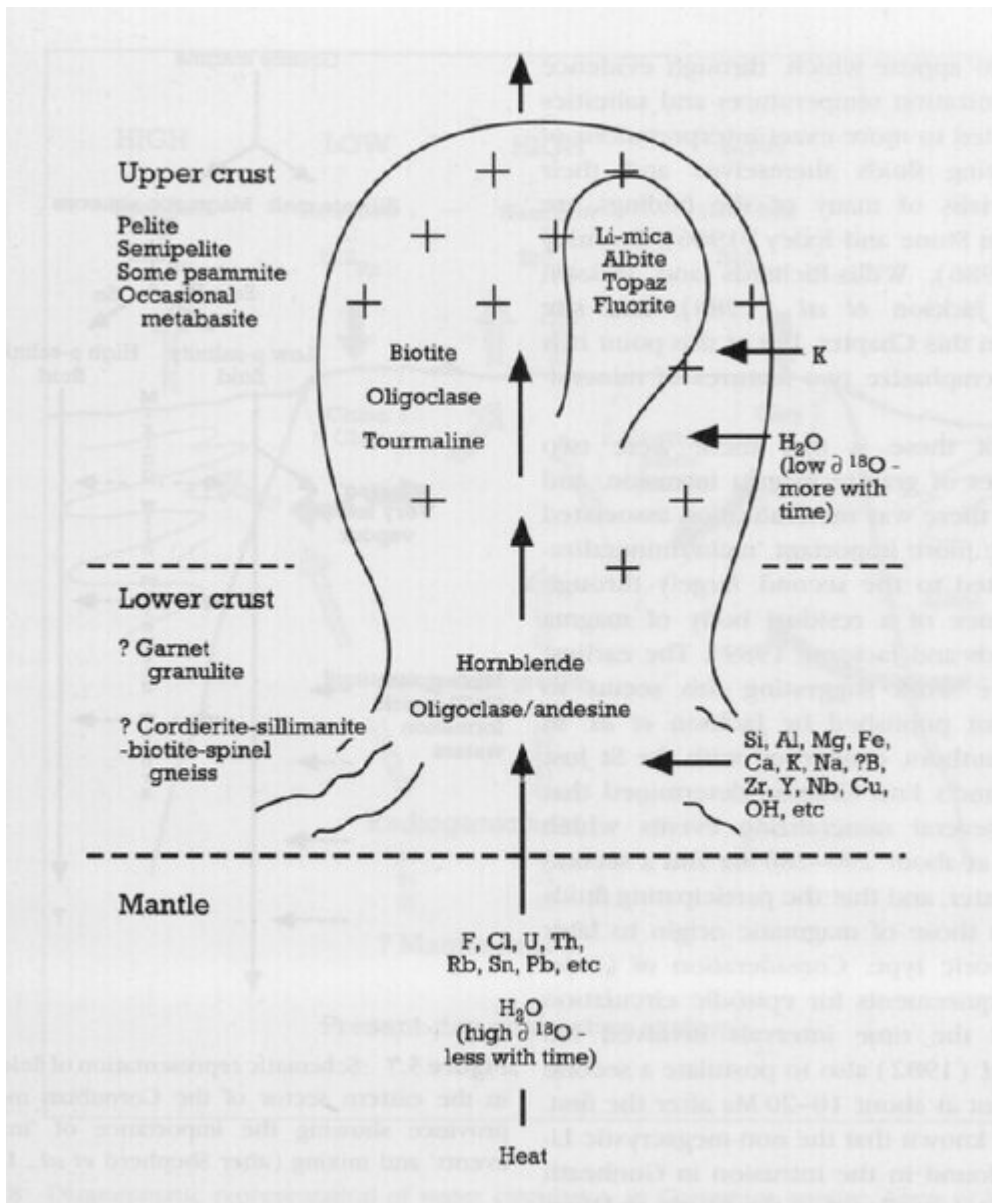
(Figure 5.4) The St Austell model. Diagram showing the first intrusion of Type-B granite (Table 5.1) cut by multiphase second intrusion of biotite granite, with metasomatic aureole of Type D caused by intrusion of Type E.

Intrusive phase	Outcrop and granite type	Rb-Sr age (Ma)	Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio	Comments
Major	Dartmoor (B)	280 ± 1	0.7101 ± 0.0004	-
	Bodmin Moor (B)	287 ± 2	0.7140 ± 0.0002	Mineral age
	St Austell (B)	285 ± 4	0.7095 ± 0.0009	-
	Carnmenellis (B)	290 ± 2	0.7130 ± 0.0020	Mineral age
	Tregonning (E)	280 ± 4	0.71498 ± 0.00381	Highly evolved, lithium-rich
	Land's End (B)	268 ± 2	0.7133 ± 0.0006	Mineralization re-set age
Minor	Hemerdon Ball	304 ± 23	0.70719 ± 0.01025	Heavily mineralized
	Kit Hill	290 ± 7	0.70936 ± 0.00228	-
	Hingston Down	282 ± 8	0.71050 ± 0.00119	-
	Castle-an-Dinas	270 ± 2	0.71358 ± 0.00122	Later intrusion re-set age
	Carn Marth	298 ± 6	0.70693 ± 0.00207	-
	Dykes	Meldon 'Aplite'	279 ± 2	0.7098 ± 0.0017
Brannel Elvan		270 ± 9	0.7149 ± 0.0031	Re-analysed
Wherry Elvan		282 ± 6	0.7120 ± 0.0025	Re-analysed
Mineral veins	South Crofty	269 ± 4	-	-
	Geevor	270 ± 15	0.7122 ± 0.0012	-

(Table 2.1) Ages and initial Sr isotopic ratios of granitic rocks from the Cornubian batholith (data from Darbyshire and Shepherd, 1985, 1987)



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

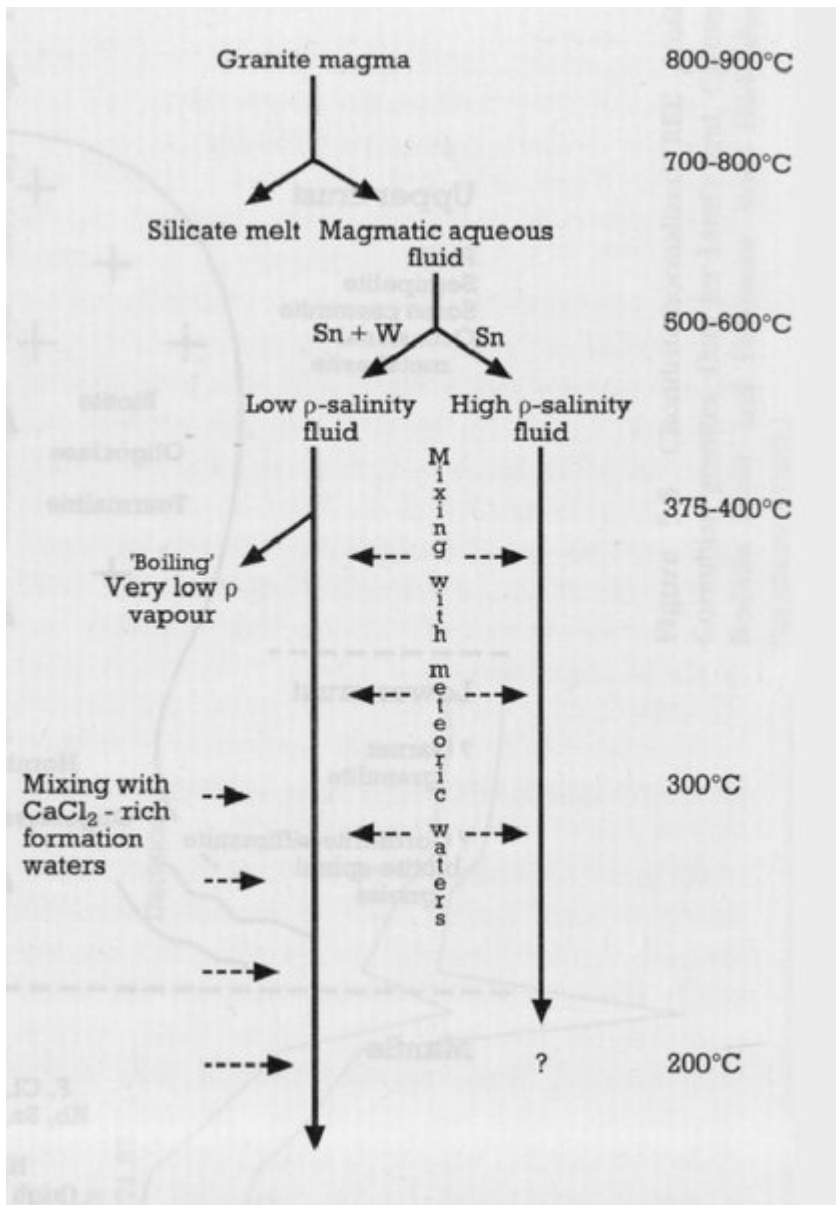


(Figure 5.6) The 1980s model. Granitic magma generated in the lower crust (but with mantle components) and evolving both by assimilating upper-crustal constituents and differentiating Li-mica granite magma. Magma becomes increasingly hydrated by drawing in increasing quantities of meteoric water during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

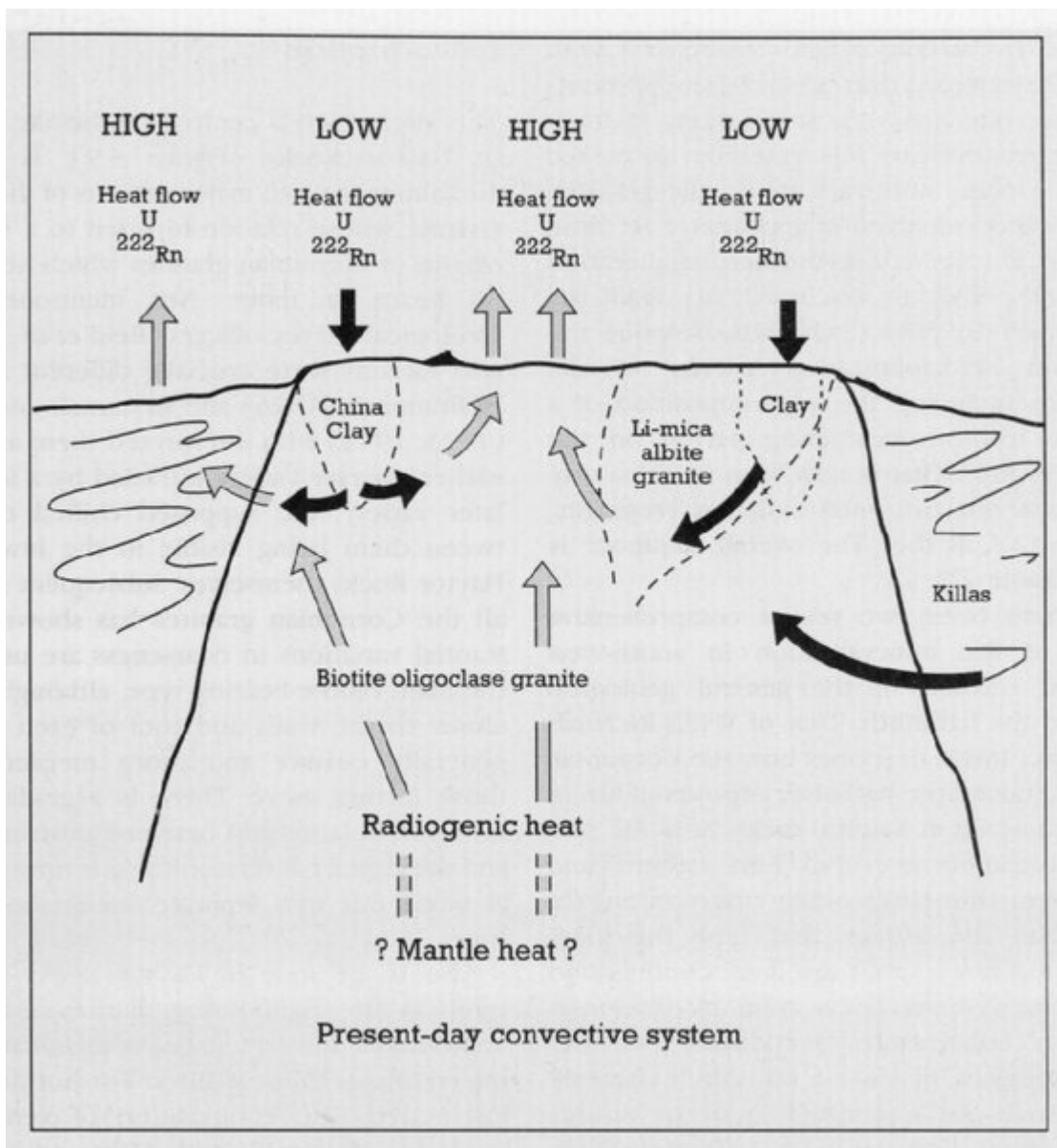
Stage	Process	Age (millions of years) *	Depth (km)	Temperature (°C)	Salinity of fluids	Source of heat	Direction of least stress	Main changes in mineralogy			Associated metaliferous mineralization	Comments
								Feldspar	Quartz	Mica		
I	Emplacement of biotite granite, forming main batholith	280-285	7.3	500-600	-	Magmatic	Variscan (E-W)	-	-	-	-	Biotite granite which now forms eastern part of the St Austell granite
II	First phase of post-magmatic alteration and mineralization	285-275	2-3	500-700	Moderate	Magmatic	Initially E-W, then N-S	Limited greisenization alongside veins	-	-	Se, W	Early greisenization and mineralization e.g. Carlinian-Duress (W)
IIIa	Emplacement of evolved lithium rich granites and biotite granites in western part of St Austell granite	275-250	2-3	500-600	-	Magmatic	N-S	-	-	-	-	Granites belonging to this phase may underlie much of the batholith. Granites hydraulically fractured
IIIb	First part of second phase of post-magmatic alteration and mineralization	275-270	7.2	450-380	Moderate	Mainly magmatic, some radiogenic	N-S or NW-SE	Greisenization: converted to quartz, mica and topaz by F-rich fluids. Tourmalinization: replaced by tourmaline	Repeatedly fractured and fractures associated by fresh growths of quartz	Some re-crystallization, biotite loses iron which is taken up by tourmaline growth	Se, W, Cu	Main phase of metaliferous mineralization
IIIc	Emplacement of felsitic dykes	275-270	7.2	400-500	Moderate	Magmatic	N-S	-	-	-	Se, W, Cu	Further input of magmatic heat
IV	First phase of argillic alteration and NW-SE or N-S quartz-kalinite veins and faulting	270-260	7.1.2	350-300	Moderate to high	Mainly radiogenic, possibly some magmatic or mantle heat	E-W	Na feldspar: altered to amethyst-like assemblage, little kaolinite K feldspar: altered to illite, maybe some amethyst	Free silica released by argillification, forms overgrowths on quartz and now iron-stained non-tourmaline bearing lodes (NW-SE and N-S)	Much iron liberated from biotite which is carried out of the granite to form iron lodes. Some mica hydrated to gibberite	Fe/U/Pb/Zn	Note: Salinity, lack of kaolinite and change in stress direction. Low temperature metaliferous mineralization
Quiescent period?												
V	Second phase of argillic alteration. Main period of kaolinization (Deep Mesozoic supergene alteration?)	260 to present	0.2-1.5	50-150	Low	Radiogenic	Variable E-W or N-S, later becoming vertical	Na feldspar: altered readily to kaolinite K feldspar: altered less readily to kaolinite Smectite: altered readily to kaolinite	Free silica released by argillification, forms overgrowths on quartz and some minor quartz veins	Some iron liberated from biotite, not carried out of the granite so colour matrix. In areas of intense kaolinization mica/illite altered to kaolinite	Fe/U (minor)	Note: Fresh water and main episode of kaolinite formation. Isostatic uplift may have played a part
VI	Early Tertiary Chemical weathering (also Mesozoic?)	25-60	0.0-0.3	20-50	Low	High surface temperature	Vertical	Altered kaolinite, illite Eocene/Oligocene weathering	Some solution of silica from quartz grains	Some iron liberated from biotite, not carried out of the granite so colour matrix. In areas of intense kaolinization mica/illite altered to kaolinite	-	Tertiary weathering matrix is source of material for ball clays and associated sediments

* Radiometric dates from Bray (1980), and Darbyshire and Shephard (1985, 1987)

(Table 2.2) Main evolution and alteration stages of the St Austell Granite (after Bristow et al., in press)



(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).