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AMPHIBOLE-RICH POLYCRYSTALLINE CLOTS IN CALC-ALKALINE GRANITIC ROCKS AND THEIR ENCLAVES

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Abstract

The presence of amphibole-rich polycrystalline aggregates (clots) of millimetric size is a widespread feature of calc-alkaline granitic rocks and related microgranular enclaves. A petrological study of these clots, including field relationships, textures, mineral chemistry, and compositional zoning has been carried out to constrain possible origins and petrogenetic significance. The two plutons chosen, the Quintana pluton in the Hercynian belt of Iberia and the Strontian pluton in the Caledonides of Scotland, differ in age and tectonic setting. In both, amphibole-rich clots are present in microgranular enclaves and in the host granitic rocks. The clots are generally zoned. The margin is rich in amphibole, but with significant proportions of biotite and plagioclase, normally intergrown with other minerals of the groundmass. The interior is dominantly composed of multiple crystals of amphibole in mutual contact showing a typical granoblastic texture. Individual crystals there show compositional zoning. In general terms, the core is actinolite, and the rim, magnesian hornblende. This "reverse" zoning can be explained by a complex reaction with early pyroxene. This reaction probably took place in two stages, one producing magnesian hornblende in equilibrium with the melt, and the other producing actinolite in the solid state, from reaction of pyroxene armored by early hornblende. The origin of the pyroxene precursors to these amphibole clots is not well constrained by this study, but the prismatic form of these clots in the enclaves does suggest that those preserved in enclaves were originally idiomorphic magmatic phenocrysts, whereas those in the host granite could also have a restitic origin.

Keywords: granite, clot, amphibole, calc-alkaline, magma mixing, restite, Quintana pluton, Spain, Strontian pluton, Scotland.

Sommaire

La présence d'agrégats millimétriques polycristallins riches en amphibole est répandue dans les roches granitiques calco-alcalines et les enclaves microgrenues qu'elles contiennent. Nous avons étudié ces agrégats, leurs relations de terrain, leurs textures, et la composition et la zonation de leurs minéraux, afin de placer des limites sur leur origine et leur signification pétrogénétique. Les deux suites plutoniques choisies, Quintana (ceinture hercynienne ibérique) et Strontian (Calédonides d'Ecosse) diffèrent dans leur âge et leur contexte tectonique. Aux deux endroits, les agrégats riches en amphibole sont présents dans les enclaves microgrenues et dans les roches granitiques hôtes. Ces agrégats sont zonés, en général. La bordure est enrichie en amphibole, mais contient une proportion importante de biotite et de plagioclase, normalement en intercroissance avec les autres minéraux de la pâte. L'intérieur est surtout composé d'une multitude de cristaux d'amphibole dont les contacts définissent une texture granoblastique. Les cristaux individuels sont zonés. En général, le coeur est fait d'actinote, et la bordure, de hornblende magnésienne. Cette zonation "inversée" peut s'expliquer au moyen d'une réaction complexe avec un pyroxène précoce. La réaction aurait eu lieu en deux stades, le premier donnant une hornblende magnésienne en équilibre avec le magma, l'autre produisant l'actinote à l'état solide, par réaction du pyroxène recouvert de hornblende précoce. L'origine du pyroxène précurseur à ces agrégats riches en amphibole n'est pas bien définie par nos résultats, mais la forme prismatique de ces agrégats dans les enclaves fait penser qu'il s'agissait au départ, dans ces cas du moins, d'un phénocristal magmatique idiomorphe. Ceux du granite hôte pourraient aussi être un matériau "restitique".

(Traduit par la Rédaction)

Mots-clés: granite, agrégats, amphibole, calco-alcalin, mélange de magmas, restite, pluton de Quintana, Espagne, pluton de Strontian, Écosse.

INTRODUCTION

Mafic clots (millimetric aggregates of mafic minerals) are remarkably common features of calc-alkaline tonalites and granodiorites of widely varying age and tectonic setting (*e.g.*, Presnall & Bateman 1973, Vernon 1983, Cantagrel *et al.* 1984, Zorpi *et al.* 1989, Castro 1990, Castro *et al.* 1991a). In I-type granitic rocks, these clots are most commonly amphibole-rich. Their origin has been variously attributed to restite, accidental xenoliths, cognate xenoliths, remnants of mingled magmas, mineral cumulates, polycrystalline pseudomorphs of phenocrysts, and crystal agglomerations, with effects of recrystallization where appropriate. A knowledge of the origin of such clots is most desirable, as their presence is generally taken as a sure indication of one or other of these petrogenetic processes, and their normally homogeneous distribution over a pluton or plutonic unit is taken as evidence of the widespread extent of that process. It is very difficult, however, to design field or petrographic tests to choose among these models; indeed, if recrystallization of clots has occurred, the ultimate origin may be more obscure. In volcanic rocks, clots of similar form but rather different composition also may occur, and have even been inferred to control the composition of calc-alkaline series (Scarfe & Fujii 1987). Interpretation of textures in plutonic rocks is less well constrained owing to the possible modifications by recrystallization during slow cooling. Thus, for this study we have adopted an approach that places most emphasis on mineral compositions and their patterns of zonation.

In comparing within-clot and between-clot compositional and textural variations, we find the combination of back-scattered electron imagery (BEI) and electron-microprobe analysis to be particularly useful. Whereas some important textural features are visible using normal polarized-light petrographic techniques, others that are controlled solely by bulk composition are only revealed by BEI (a *Z*-contrast technique: Lloyd 1987). Thus BEI can guide the points for analysis particularly efficiently and disclose textures and compositional characteristics that would otherwise only become apparent only with a high density of spot electron-microprobe analyses.

MODELS FOR THE ORIGIN OF CLOTS

The literature on amphibole-rich clots in granitic rocks is quite extensive. Here, we attempt to summarize the models for their origin in terms of end-member processes, combinations of which may be possible.

1. Restite: a patch of mafic phases survives the melting process and is transported along with the magma, either unmodified or after recrystallization in equilibrium with the host magma. Presnall & Bateman (1973) interpreted clots in the Sierra Nevada batholith to be indicators of the presence of solid material (restite fraction) carried up from depth by the granitic magma (Chappell *et al.* 1987).
2. Crystal cumulate: an accumulation of melt-precipitated mafic phases becomes entrained and dispersed through the magma body.
3. Mafic remnants of mingled magmas: remnants from the quenching and dynamic disruption of mafic magma in a lower-temperature felsic magma during magmatic flow.
4. Disaggregated enclaves: a cluster of attached mafic minerals forms by the chemical or mechanical disaggregation of a mafic enclave (either cognate or accidental xenolith).
5. Pseudomorphs: phenocrysts recrystallize into a cluster of secondary minerals (Vernon 1983, Mazzone *et al.* 1987).

In several of the above cases, it may be appropriate to consider that there has been a precursor phase, such as pyroxene, that recrystallizes to an amphibole-dominated assemblage. This precursor is required for the formation of clots by the replacement of phenocrysts, but could also occur in the other models where the early-formed mafic phase was pyroxene that later reacted with melt, or fluid, to form a new assemblage dominated by amphibole.

GEOLOGICAL SETTING

The two plutons chosen for this study are the Strontian pluton in the Scottish Caledonides and the Quintana pluton of the Spanish Hercynian (Fig. 1). Their common features include: (a) mineralogical and bulk chemical compositions (metaluminous) typical of I-type plutons, (b) the dominance of granodiorite, (c) abundant microgranular enclaves of diorite and tonalite composition, and (d) the presence of abundant amphibole-rich clots.

The Caledonian pluton of Strontian

The Strontian pluton (Fig. 1B) intruded Moine Proterozoic metasedimentary and meta-igneous rock at 425 Ma (Rogers & Dunning 1991) during the Caledonian orogeny in northern Britain. The metasediments were regionally metamorphosed to the sillimanite zone of a kyanite–sillimanite sequence (Winchester 1974), and these were overprinted by an asymmetrical metamorphic aureole that reaches cordierite – K-feldspar assemblages at the contact. The asymmetry is attributed to a gradient in the regional metamorphic isograds at the time of emplacement (Ashworth & Tyler 1973). Emplacement of the pluton was passive, in part controlled by contemporaneous movements on the Great Glen Fault (Hutton 1988a, b).

The pluton is internally zoned (Fig. 1B), with an outer nonporphyritic granodiorite (ONPG), inside which is the outer porphyritic granodiorite (OPG), and an inner core of granite (IG). These plutonic members are easily

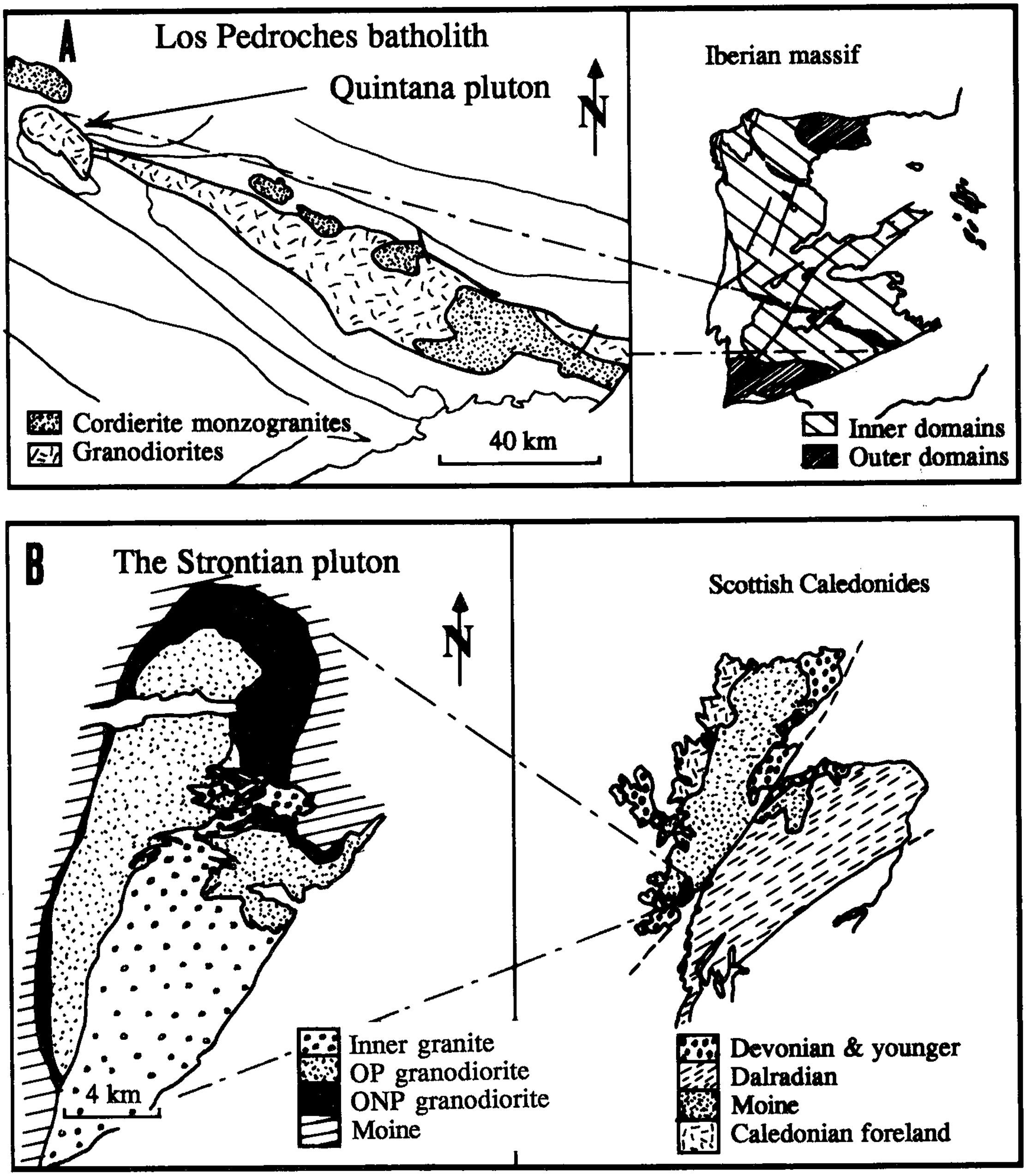


FIG. 1A, B. Geological sketch and regional setting of the two granitic plutons chosen for study. A. The Quintana pluton (Spain). B. The Strontian pluton (Scotland).

mapped in the field. The names used here are those of the IUGS classification (Streckeisen 1976) applied to the "tonalite", "porphyritic granodiorite", and "biotite granite", respectively, of the earlier investigators (MacGregor & Kennedy 1932, Sabine 1963, Munro 1973). Detailed petrographic descriptions may be found in these papers. The boundary between the ONPG and the OPG is a transition over about 10 metres, whereas the OPG–IG boundary is quite sharp. The outer members of the pluton are host to some large bodies of "appinite", hornblendite – diorite series rocks that show lobate and crenulate liquid–liquid contacts indicating contemporaneous intrusion. Enclaves of microdiorite aspect are abundant in the ONPG and OPG, locally occurring as swarms of apparently disaggregated synplutonic dykes. The ONPG and OPG are characterized by abundant amphibole-rich clots aligned within the plane of foliation; the idiomorphic crystals of amphibole grew randomly. The Sr isotope initial ratios for the pluton are about 0.7053–0.7060 for the ONPG and OPG, 0.7068–0.7072 for the IG, 0.7051–0.7066 for the enclaves, and 0.7056–7060 for the appinites (Halliday *et al.* 1979, Hamilton *et al.* 1980, Holden *et al.* 1987).

The Hercynian pluton of Quintana

The Quintana pluton (Fig. 1A) is part of the Los Pedroches batholith, one of the largest granitic batholiths of the Iberian massif. It was emplaced as an elongate body parallel to the NW–SE trend of regional structures, at the southern branch of the Central Iberian Zone (Julivert *et al.* 1974). The pluton was emplaced at high levels into Upper Paleozoic metasediments, and emplacement took place after the first phase of Hercynian deformation, and probably during the second phase, which was dominated in this sector of the chain by intracontinental shear movements (Castro 1985, 1986). Full descriptions and a petrogenetic interpretation were recently presented by Castro (1990).

The pluton is a medium-grained biotite hornblende granodiorite. Several facies are identified on the basis of their amphibole content (normally 0–5%) and color index. However, these facies do not show any regular distribution within the pluton, and the pluton is considered to be essentially unzoned on a broad scale. Mafic microgranular enclaves are abundant (1–5%) and more-or-less evenly distributed over the pluton. Three types of enclave were classified by Castro (1990) as: (a) porphyritic tonalite enclaves (PTE), (b) hornblende–plagioclase diorite enclaves (HPDE), and (c) transitional enclaves (TRE) that have features of both PTE and HPDE. Petrographic descriptions of these types are also given in Castro (1990).

Clot-bearing rocks in the Strontian and Quintana plutons

In both plutons, amphibole-rich clots tend to be preferentially concentrated in the more mafic granitic facies and also in certain types of microgranular enclave.

Granitic rocks. At Strontian, amphibole-bearing clots are abundant in the ONPG. They are also present, however, with somewhat lesser abundance, in both the OPG and ONPG facies of the pluton. It is important to note that the ONPG, which is richest in clots, has few crystals of idiomorphic amphibole, whereas in the porphyritic granodiorites, the modal proportion of idiomorphic amphibole to clots is approximately 9:1. On the basis of whole-rock geochemical studies (including clots but not enclaves; Stephens *et al.*, in prep.), the difference between the two facies is more textural than compositional. The boundary between the ONPG and the OPG is transitional along the Loch Sunart section of the northerly part of the pluton (Fig. 1B). There is an inverse correlation between the abundances of idiomorphic amphibole and mafic enclaves, except where there are swarms of enclaves.

At Quintana, there is no preferential distribution of the clot-rich facies, which appear in domains richer in amphibole. Most of the amphibole occurs in clots, with only a minor proportion of isolated idiomorphic crystals. In general, the Quintana granodiorite is more biotite-rich in comparison with the Strontian rocks, in which amphibole dominates over biotite. In both plutons, there is an appreciable correlation between the abundances of enclaves and clots. That the enclave-rich facies are also richer in clots perhaps indicates a common genetic relationship between enclaves and clots. The same correlation has been observed in other calc-alkaline granitic bodies such as the Central System batholith of Spain (Castro *et al.* 1991b), and the Sierra Nevada batholith of California (Presnall & Bateman 1973).

Enclaves. In general, and certainly in the two plutons considered here, not all mafic, microgranular enclaves contain amphibole-rich clots. Clots are particularly associated with the so-called transitional enclaves (TRE) of the Quintana pluton (Castro 1990), where clots represent more than 10% by volume of the enclave. A similar type of enclave is also common in Strontian and other Caledonian plutons (*e.g.*, the Criffell pluton, as described by Holden *et al.* 1987). Characteristics of these enclaves are: (1) a fine-grained matrix, (2) the presence of plagioclase megacrysts having a resorbed core, and (3) the presence of amphibole in the form of clots varying in abundance between 5% and 30% by volume. The fine-grained matrix of these enclaves typically has a serial texture and comprises biotite, plagioclase laths, quartz, amphibole, acicular apatite and other accessory minerals including titanite, zircon and opaque minerals. Poikilitic quartz is a feature of many tonalitic enclaves (Castro *et al.* 1991c) and synplutonic dikes in zones of magma interaction (Castro *et al.* 1991a), suggesting a complex history of crystallization. The two other types of enclaves (porphyritic tonalites, PTE and hornblende–plagioclase diorites, HPDE) are poorer in amphibole clots. Amphibole-rich enclaves (HPDE type), with modal amphibole approaching 90%, are present in both plutons, but are more abundant in the Strontian pluton; clots are less abundant in this type. The PTE have few if any clots; these enclaves are particularly abundant in the Quintana granodiorite but are very scarce at Strontian, generally supporting the correlation noted between amphibole content of the host granite and the abundance of amphibole-rich enclaves.

Textural Features of Amphibole Clots

Amphibole-bearing clots, as described from batholiths from a wide variety of orogenic settings, appear to be remarkably similar in their textural and compositional characteristics. We have studied these features in both the Strontian and Quintana plutons.

Size

Amphibole clots vary from less than 1 mm up to a few cm, but with an even grain-size for the individual crystals of amphibole. However, the dominant size ranges from 2 to 8 mm (Figs. 2, 3); we note a correspondence between size of the clots and the average grain-size of the rock. In fine-grained enclaves, clots are typically smaller than those of the coarser-grained host granite, but in both cases, unusually large clots (> 10 mm) may be present.

Shape

In undeformed granitic rocks, amphibole-rich clots typically have a round shape, whereas in deformed rocks, including the marginal facies and enclaves of the Strontian pluton (Hutton 1988b), amphibole-rich clots

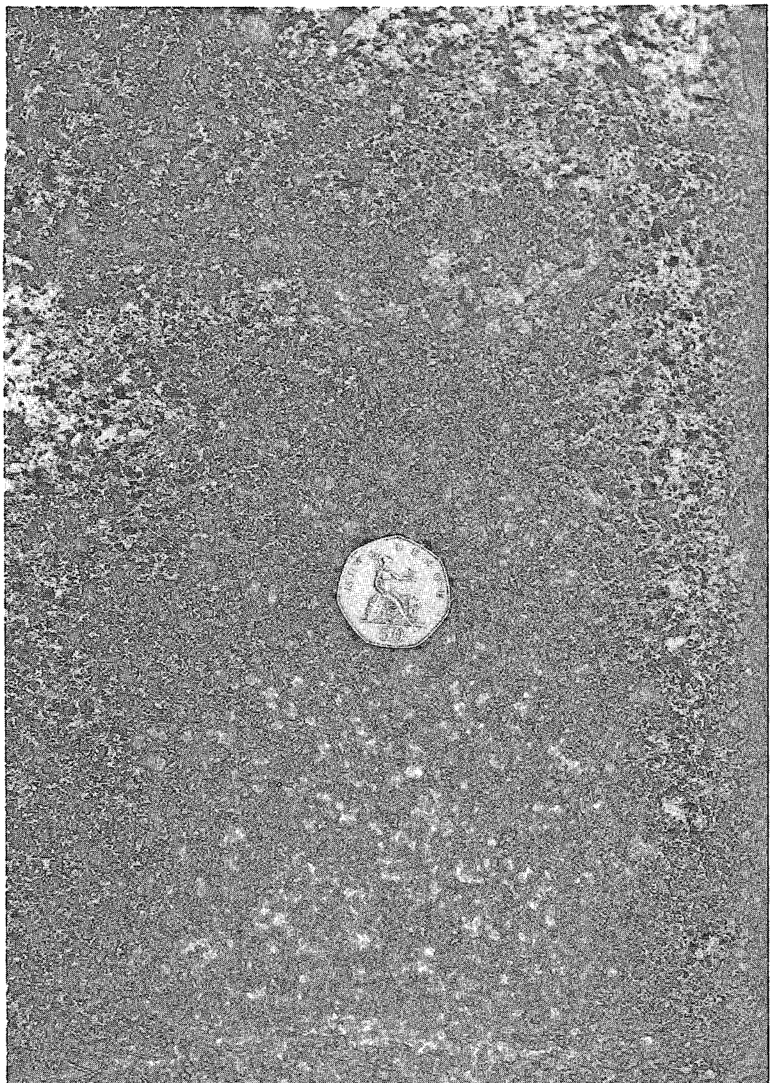


Fig. 2. Aspect of a clot-bearing tonalite of the Strontian pluton. Note the homogeneous size of the clots (darker spots).

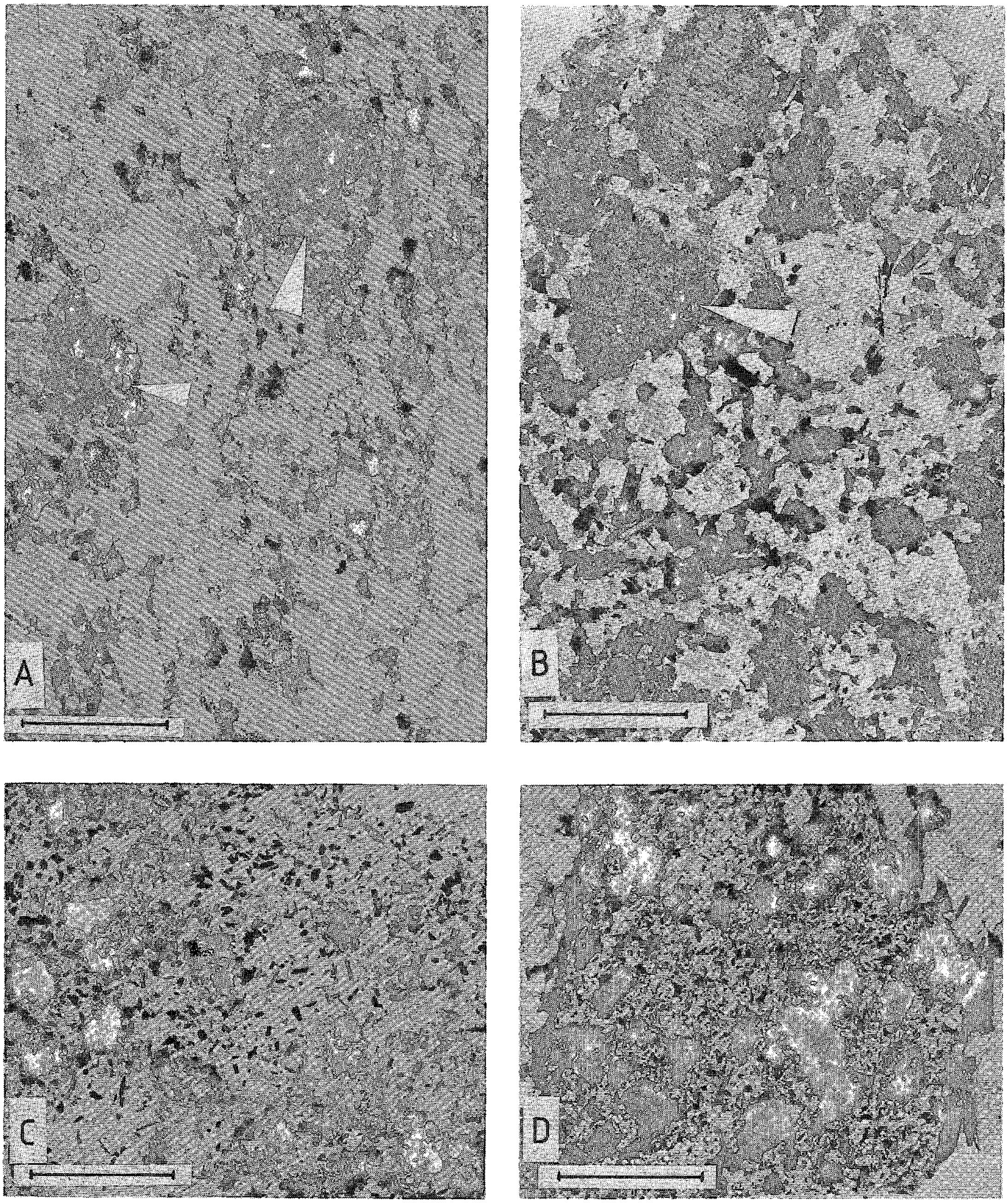


FIG. 3. Comparisons between shape and size of amphibole clots in different rock types of the Strontian and Quintana plutons. A and C are the Quintana granodiorite and related tonalitic enclaves, respectively. B and D are the Strontian tonalite and related enclaves, respectively. Note the compositional zoning in the clots of B; the lighter core is richer in actinolite. Scale bar = 6 mm.

have ellipsoidal shapes, with the principal axis aligned parallel to other deformation-related structures in the rock. In the case of deformed rocks, the absence of intracrystalline deformation in the latest mineral phases (quartz and K-feldspar) suggests that clots were deformed when the rock was in a magmatic state. The absence of any kind of intracrystalline deformation in the amphibole of these oriented clots may indicate that some recrystallization may have occurred either during, or after, magmatic flow. The fact that the textures of these clots do not correspond to those generally attributed to magmatic processes (as illustrated below) makes it difficult to interpret the history of clots. Specifically, it is not possible to demonstrate that they formed from the crystallization of a silicate melt during laminar magmatic flow.

Occasionally, amphibole clots show approximately prismatic shapes; this feature is most commonly seen in clots within mafic enclaves, whereas the clots of host granites tend to be more irregular, and generally rounded. The prismatic shape is conspicuous in the TRE of the Quintana granodiorite (Fig. 3C) and in similar enclaves of the Strontian pluton. A comparison between clot shape in enclaves and in related granitic rocks is shown in Figure 3. This feature may be indicative of pseudomorphism of early ferromagnesian silicates (pyroxene, olivine), as described by Vernon (1983) and Zorpi *et al.* (1989).

Texture

A major difficulty with the interpretation of textures of amphibole-rich clots is that they do not exhibit the texture typical of serial crystallization in magmatic rocks. Most clots are characterized by a granoblastic-like texture in which individual grains display near-120° triple junctions (Fig. 4). This texture is widespread in the core of the clots, in which amphibole alone is present. Toward the rim, plagioclase or biotite or both may be present together with amphibole. In these marginal domains, the texture is serial, and plagioclase and biotite fill interstices between idiomorphic crystals of amphibole (see below, Fig. 9A). This sequential, apparently magmatic, texture is best developed in the outermost parts of the clots, in which amphibole is intergrown with other minerals of the groundmass, namely biotite, plagioclase and quartz. Generally, this concentric zoning of texture is reflected in a weak optical zoning of amphibole, with the marginal amphibole having deeper pleochroic colors than amphibole in the core.

Relationships with other minerals

Biotite, plagioclase, quartz, titanite and opaque minerals are commonly present in modal quantities each less than 5% in amphibole-rich clots. Plagioclase typically shows an intergranular texture, indicating that it formed as a late-crystallizing phase. The composition of this plagioclase is similar to that of plagioclase in the host granite. These crystals are normally zoned, with the more albitic, external bands contouring amphibole crystals. However, lobate amphibole–plagioclase contacts also are present, suggesting simultaneous growth. Similar intergranular textures are shown by biotite crystals close to the rim of the clots. However, biotite may exhibit triple junctions with amphibole, suggesting simultaneous growth in the solid state. Most biotite occurs near the rim, in part encircling the clot and intergrown with the outermost amphibole crystals, and overlaps in the crystallization sequence with the groundmass plagioclase and quartz. Quartz and opaque minerals are found as inclusions in amphibole, with quartz occurring as very small vermicular-like grains typical of symplectitic intergrowths. Opaque minerals are principally sulfides (pyrite and chalcopyrite), except in a few cases where probable chrome-rich spinel was qualitatively identified with the electron microprobe. Apatite and intergranular titanite are common phases in amphibole-rich clots. Apatite typically has an acicular habit and appears as inclusions in amphibole within the outer parts of clots.

TABLE 1. REPRESENTATIVE ELECTRON–MICROPROBE DATA ON AMPHIBOLE FROM THE QUINTANA GRANODIORITE AND RELATED ENCLAVES

Rock type	PT encl.	PT encl.	PT encl.	TR encl.	TR encl.	Granod.	Granod.
Sample	C-2	C-2	C-2	C-3	B-3	D-1	D-1
Analysis	10	12	37	22	4r	31.928	19
Description	Clot	Clot	Clot	Matrix	Clot	Clot	Matrix
SiO2 wt%	50.66	51.16	50.94	50.61	48.68	47.13	49.83
TiO2	0.51	0.47	0.48	0.62	0.79	0.95	0.45
Al2O3	3.56	3.49	3.57	4.17	5.34	5.92	4.12
Cr2O3	0.04	0.04	0.09	0.2	0.14		0.06
FeO	10.34	7.57	8.51	11	11.75	12	10.7
Fe2O3 *	2.79	5.87	5.73	2.35	2.9	2.24	2.69
FeOt	12.85	12.85	13.66	13.12	14.36	14.01	13.12
MnO	0.47	0.63	0.55	0.47	0.48	0.48	0.42
NiO	0.03	0.04	0.05		0.02		
MgO	14.41	14.61	14.66	14.01	13.23	12.04	13.69
CaO	11.68	10.86	11.48	11.8	11.89	11.1	11.34
Na2O	0.73	0.64	0.65	0.62	0.95	0.88	0.82
K2O	0.3	0.3	0.28	0.4	0.52	0.6	0.31
TOTAL	95.52	95.66	96.98	96.24	96.69	93.35	94.42
Structural formulae (O=23)							
Si	7.491	7.495	7.412	7.443	7.205	7.216	7.463
Al (IV)	0.509	0.505	0.588	0.557	0.795	0.784	0.537
Σ (T)	8	8	8	8	8	8	8
Al (VI)	0.113	0.098	0.025	0.167	0.137	0.285	0.191
Ti	0.057	0.051	0.053	0.069	0.088	0.11	0.05
Cr 3+	0.004	0.004	0.01	0.023	0.016		0.007
Fe 3+ *	0.311	0.651	0.63	0.26	0.324	0.258	0.303
Fe 2+	1.281	0.933	1.041	1.355	1.456	1.538	1.342
Mn	0.059	0.078	0.067	0.058	0.061	0.063	0.053
Ni	0.003	0.004	0.005		0.002		
Mg	3.175	3.191	3.178	3.07	2.919	2.748	3.056
Σ (C)	5.003	5.01	5.009	5.001	5.003	5.001	5.002
R2+	0.003	0.01	0.009	0.001	0.003	0.001	0.002
Ca	1.851	1.705	1.79	1.859	1.885	1.821	1.82
Ba							
Na (M4)	0.147	0.285	0.2	0.14	0.112	0.178	0.178
Σ (B)	2	1.99	1.99	2	2	2	2
Na (A)	0.062	-	-	0.037	0.161	0.084	0.059
K	0.056	0.055	0.053	0.076	0.097	0.118	0.059
Σ (A)	0.118	0.055	0.053	0.112	0.259	0.202	0.117
Total cations	15.118	14.952	15.035	15.112	15.259	15.202	15.117
% An in Plag.	26.65	30.06		38.54		21.68	20.41

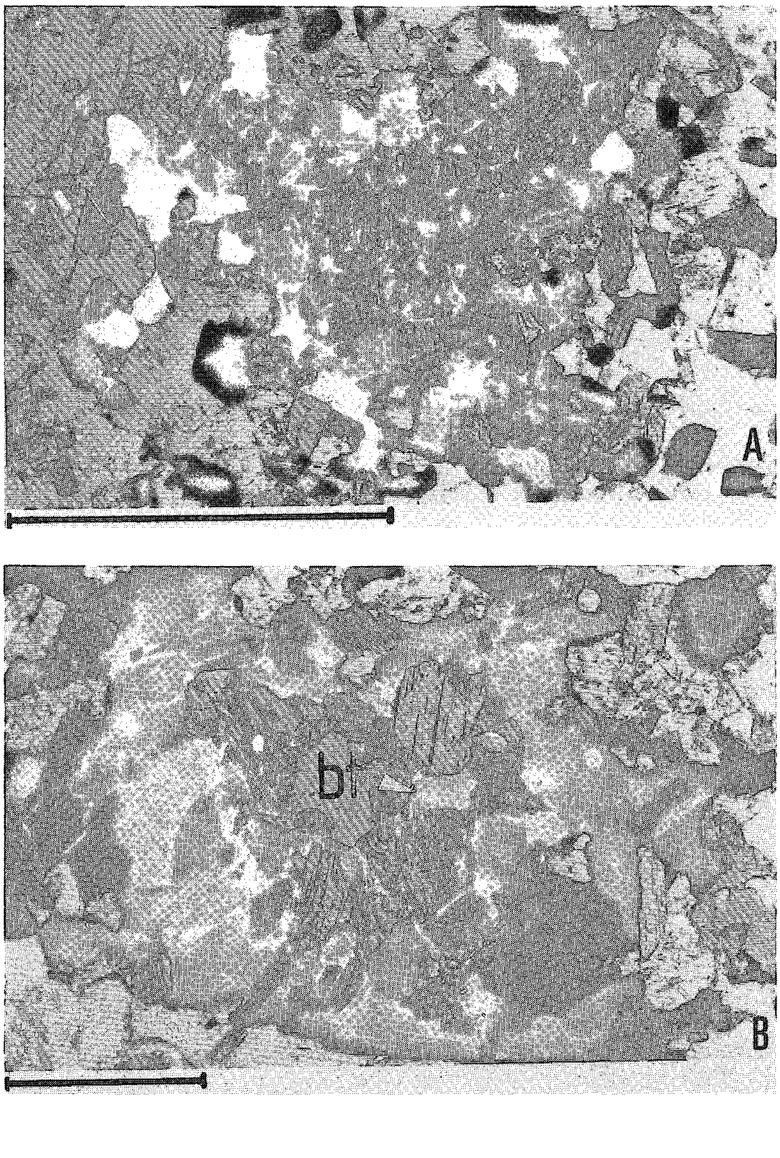
*) Calculated (see text)

MINERAL CHEMISTRY

Silicate phases in clots were analyzed by electron microprobe (JEOL JCXA733 Superprobe) at the University of St. Andrews, with more than 500 point analyses performed. Analyses were carried out using a beam current of 20 nA and an acceleration potential of 15 kV. Reference standards were a combination of pure metals and silicate minerals; the ZAF procedure was used to correct apparent concentrations. Back-scattered electron imaging (BEI) was used to reveal features of compositional zoning in amphibole, and textural and reaction relationships between amphibole and contiguous phases.

Amphibole compositions

Representative results of analyses are listed in Tables 1 and 2. Structural formulae were calculated on the basis of 23 oxygen atoms, with recalculation of ferric iron based on the maximum per formula unit (pfu) to satisfy stoichiometry (Robinson *et al.* 1982), with the ideal total of cations set at 13 (exclusive of Ca, Na and K). Amphibole compositions, including those from clots and idiomorphic crystals in both host rocks and enclaves, display a wide range of Si pfu, from 6.8 to 7.8 as shown in the IMA classification (Fig. 5; Leake 1978). In most cases, the amphibole is magnesian hornblende and actinolitic hornblende; pargasitic hornblende only ap-



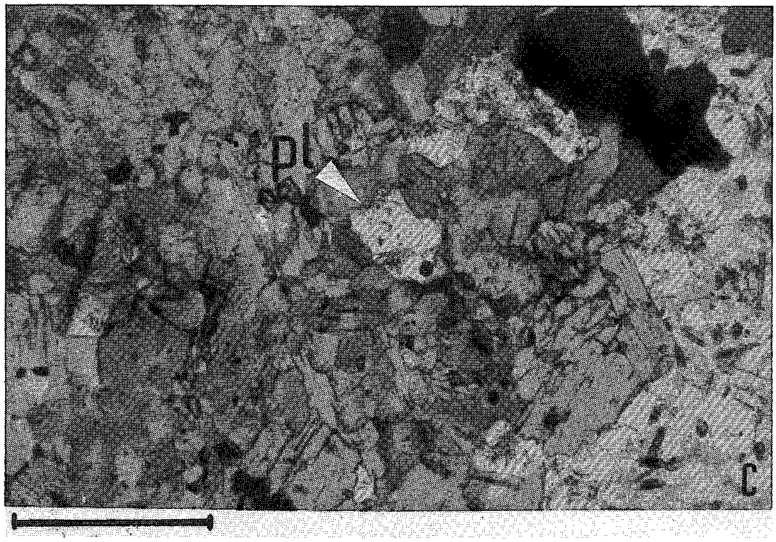


FIG. 4. Textural relationships in several amphibole-rich clots from microgranular enclaves of the Quintana granodiorite. A. The minerals at the edge are intergrown with minerals of the fine-grained matrix. B. Polygonal packing, with abundant triple junctions between different amphibole crystals and between amphibole and biotite (arrow). C. Intergranular texture is displayed by plagioclase (arrow) near the edge of the clot. Scale bar corresponds to 3 mm in A, and 1 mm in B and C.

pears in the Strontian pluton in the core of idiomorphic crystals.

Complex coupled substitutions between various cations in different amphibole sites are common. Their identification is possible using simple schemes (Czamanske & Wones 1973, Blundy & Holland 1990) in which any amphibole composition is related to the tremolite (Tr) end-member. Charge compensation due to the introduction of Al in tetrahedral sites may be balanced in various ways, the most common in natural and synthetic amphiboles being incorporation of alkalis in the *A* site (Blundy & Holland 1990). This is the edenite (Ed)-type substitution, formulated as:

$$\mathrm{Si} + \square_A = {}^{IV}\mathrm{Al} + \mathrm{Na}_A$$

Another common way of achieving charge balance is by incorporation of octahedrally coordinated Al in substitution of divalent cations in M1–M3 sites. This is the tschermakite (Ts)-type substitution, formulated as:

$$\mathrm{Si} + R^{2+}_{(M1\text{–}M3)} = {}^{IV}\mathrm{Al} + {}^{VI}\mathrm{Al}$$

Figures 6 and 7 show cation plots used to identify these coupled substitutions. Ed-type substitution is dominant in the amphiboles, as evidenced by the good correlation between tetrahedrally coordinated Al and alkalis in the *A* site, for amphibole from both the Strontian and Quintana plutons. This plot also shows compositional differences between amphibole within the host granodiorite and within enclaves of the Quintana pluton (Fig. 7B). However, analogous differences are not found in the amphibole crystals from the Strontian pluton (Fig. 6B). It must be noted that there is a smaller difference in bulk composition between enclaves and host in the Strontian pluton (both are tonalites) compared with the Quintana pluton.

The linear correlation between ^{IV}Al and other tetravalent and trivalent cations (Figs. 6A, 7A) is better in amphibole from Strontian than in that from Quintana, but in both cases correlations are less significant than for the Ed-type substitution. This indicates that other coupled substitutions involving hornblende (Hbl), pargasite (Prg) and tschermakite (Ts) are rather less important than the Ed-type substitution in determining amphibole composition in these two plutons. Combinations of these substitutions are shown [Fig. 8, based on Blundy & Holland (1990)]. The dominant compositional vector for both plutons starts from the Tr end-member and moves toward a position intermediate between Ed and Prg but rather closer to Ed. The dominant substitutions are similar for the amphibole compositions of clots from enclaves and host granite in both plutons. Granitic rocks and related enclaves are similar in overall bulk composition, but the PT conditions (mainly P) during crystallization were different. The Quintana pluton was emplaced at shallower levels than the Strontian pluton.

Total Al content is strongly dependent on T, as demonstrated by Blundy & Holland (1990), but balanc-

TABLE 2. REPRESENTATIVE ELECTRON-MICROPROBE DATA ON AMPHIBOLE FROM THE STRONTIAN GRANITIC ROCKS AND RELATED ENCLAVES

Rock type	Tonalite	Enclave	Enclave	Tonalite	Tonalite	Enclave	Enclave	Enclave	Enclave	Enclave	Hybrid	Hybrid
Sample	SR2	SR2	SR2	SR4	SR4	SR6	SR6	SR6	SR6	SR6	SR5	SR5
Analysis	8	15	29	34	41	4 (core)	5 (rim)	19 (core)	26 (rim)	36	23 (core)	24 (rim)
Description	Idiom.	Idiom.	ncl. Plag	Idiom.	Rim clot	Clot	Clot	Clot	Clot	Rim clot	Clot	Clot
SiO2 wt%	50.70	47.78	47.48	48.00	48.45	52.99	48.49	55.02	50.94	45.32	55.38	51.84
TiO2	0.30	1.04	0.96	1.06	0.96	0.22	0.75	0.10	0.46	1.24	0.10	0.50
Al2O3	4.53	6.62	6.05	6.66	6.16	2.72	5.89	1.38	4.42	7.88	1.32	3.73
Cr2O3	-	0.01	0.06	0.06	0.03	-	0.05	-	0.10	0.01	0.03	0.07
FeO	8.54	9.54	10.11	10.70	9.97	6.88	9.19	6.49	8.01	11.18	6.18	7.79
Fe2O3 *	4.63	5.08	4.04	4.42	4.38	4.61	4.92	3.80	4.73	4.51	3.03	3.32
MnO	0.37	0.29	0.35	0.40	0.31	0.35	0.36	0.38	0.28	0.28	0.20	0.32
NiO	-	-	0.02	0.04	0.03	-	0.02	0.14	0.07	0.05	0.09	0.08
MgO	15.33	13.60	13.74	13.31	13.77	16.64	14.27	17.69	15.50	12.34	18.68	16.64
CaO	11.95	11.16	11.78	11.71	11.69	11.73	11.67	11.85	11.76	11.43	12.44	12.24
Na2O	0.91	1.44	1.11	1.19	1.03	0.56	1.21	0.35	0.82	1.51	0.32	0.74
K2O	0.36	0.76	0.62	0.68	0.57	0.22	0.58	0.09	0.31	0.80	0.09	0.34
TOTAL	97.62	97.31	96.33	98.22	97.34	96.92	97.39	97.28	97.39	96.55	97.84	97.62
Structural formulae (O=23)												
Si	7.319	7.004	7.041	6.999	7.086	7.596	7.083	7.800	7.344	6.778	7.784	7.426
Al (IV)	0.681	0.996	0.959	1.001	0.914	0.404	0.917	0.200	0.656	1.222	0.216	0.574
Σ (T)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al (VI)	0.090	0.147	0.099	0.145	0.148	0.056	0.098	0.030	0.095	0.168	0.003	0.056
Ti	0.033	0.114	0.107	0.116	0.105	0.024	0.082	0.010	0.050	0.139	0.010	0.054
Cr 3+	-	0.001	0.006	0.007	0.004	-	0.006	-	0.011	0.002	0.004	0.008
Fe 3+ *	0.505	0.562	0.452	0.486	0.484	0.500	0.543	0.407	0.515	0.509	0.321	0.359
Fe 2+	1.035	1.174	1.257	1.309	1.223	0.828	1.127	0.772	0.969	1.402	0.728	0.935
Mn	0.045	0.036	0.044	0.049	0.038	0.043	0.044	0.046	0.035	0.036	0.024	0.038
Ni	-	-	0.003	0.004	0.003	-	0.002	0.015	0.008	0.006	0.010	0.009
Mg	3.298	2.972	3.038	2.892	3.002	3.554	3.106	3.738	3.331	2.750	3.913	3.552
Σ (C)	5.006	5.007	5.007	5.010	5.008	5.005	5.009	5.019	5.014	5.012	5.012	5.012
R2+	0.006	0.007	0.007	0.010	0.008	0.005	0.009	0.019	0.014	0.012	0.012	0.012
Ca	1.849	1.753	1.872	1.829	1.831	1.802	1.826	1.800	1.817	1.831	1.873	1.879
Na (M4)	0.145	0.240	0.121	0.161	0.161	0.156	0.165	0.095	0.170	0.157	0.087	0.109
Σ (B)	2.000	2.000	2.000	2.000	2.000	1.963	2.000	1.914	2.000	2.000	1.972	2.000
Na (A)	0.109	0.169	0.198	0.174	0.132	-	0.176	-	0.061	0.282	-	0.097
K	0.067	0.142	0.118	0.127	0.106	0.040	0.108	0.016	0.056	0.153	0.015	0.062
Σ (A)	0.176	0.311	0.316	0.301	0.238	0.040	0.284	0.016	0.117	0.435	0.015	0.159
Total Cation	15.182	15.318	15.323	15.311	15.246	15.008	15.293	14.949	15.131	15.447	14.999	15.171
% An in Plag	16.17		21.50							20.80		

*) Calculated (see text)

ing of charges by coupled substitutions depends more on component activities than PT conditions. Ed-type substitution is dominant in amphibole crystallized in equilibrium with plagioclase, the norm in calc-alkaline magmas.

Compositional zoning in the clot amphiboles

A significant feature of the clots is the presence of discontinuous, regular and sector zoning in the amphiboles. There exists a compositional gap of about 5% SiO_2 and 2% MgO (see Table 2). Geometrically, the compositional zoning appears in three different situations: (1) core zoning, (2) oscillatory zoning, and (3) patchy zoning. In all three cases, the compositional differences are very similar, and the boundary between adjacent zones is sharp.

Zoning in the core is displayed by the amphibole grains displaying a granoblastic texture, in the central part of the clots (Figs. 9A, B). Cores have an actinolitic composition richer in Mg and Si and poorer in Al, Fe, and alkalis, than the rim, which is hornblende in composition. The shape of actinolitic core is more or less irregular, but generally follows the external shape of the zoned crystals. Figure 10A is a compositional profile of a zoned crystal in a clot within the Strontian NPG. Zoning, although revealed as being sharp by BEI (Figs. 9A, B), does not appear to be sharp in terms of the Mg/(Mg+Fe) ratio, indicating either that this parameter was not important in the primary zonation or that

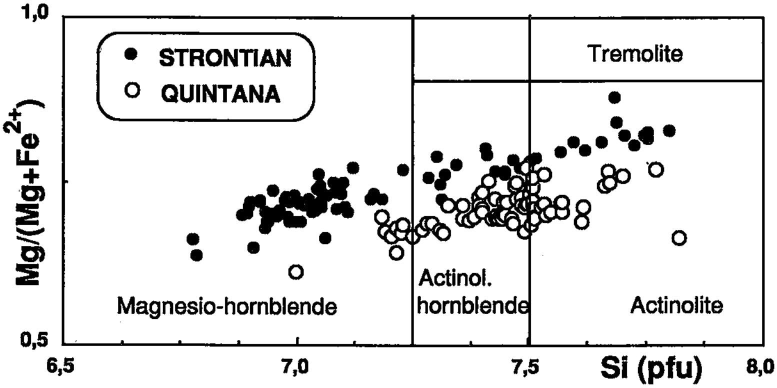


FIG. 5. Leake's (1978) classification diagram showing the amphiboles of the Strontian and Quintana plutons.

subsequent re-equilibration affected the distribution of Fe and Mg. The compositional vector on the substitution triangle (Fig. 10B) is coincident with the general vector displayed by the amphibole grains (Fig. 8), suggesting that zoning is controlled by magmatic processes. The zoned crystal of Figure 10 can be taken as representative of all the zoned crystals of amphibole, as the same compositional relationships were found in many analyzed cases in both the Strontian and Quintana plutons. If zoning is related to magmatic crystallization, a problem arises in explaining the apparent sequence of actinolite to hornblende, the reverse of that normally observed, which suggests that the activities of silica and the alkalis decreased as crystallization proceeded. The granoblastic-like texture also is not a primary magmatic feature. Many amphibole grains in clots were found to have oscillatory zoning near the edge, and this feature is more common in idiomorphic crystals of amphibole texturally intergrown with biotite (Fig. 9A). The zoning consists of several alternating continuous bands of

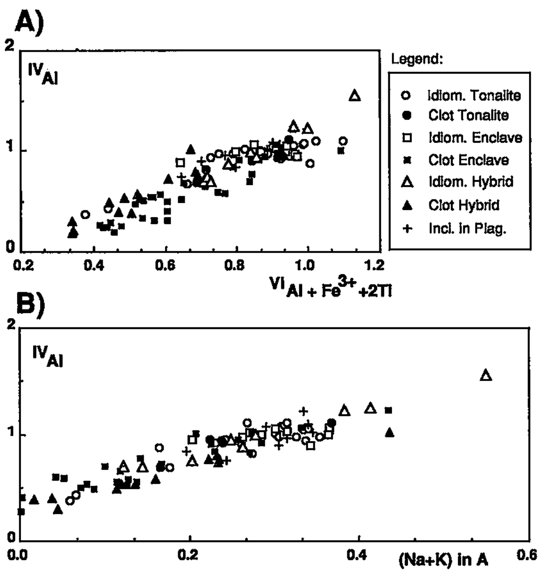


FIG. 6. Cation plots for the Strontian amphiboles. Compositions from clots and other textural situations are included in order to make comparisons. The grouping in the alkalis *versus* ^{IV}Al plot (B) is better than in the octahedral sites *versus* ^{IV}Al plot (A), indicating the dominance of the edenite-type substitution.

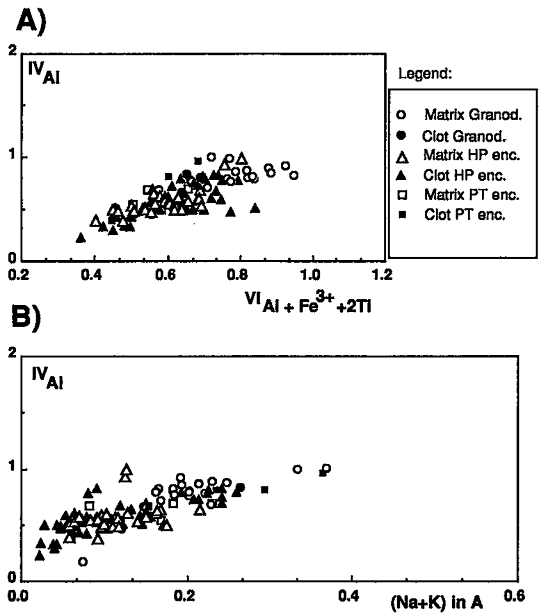


FIG. 7. Cation plots for the amphibole compositions at Quintana. Compositions from clots and other textural situations are included in order to make comparisons. The grouping in the alkalis *versus* ^{IV}Al plot (B) is better than in the octahedral sites *versus* ^{IV}Al plot (A).

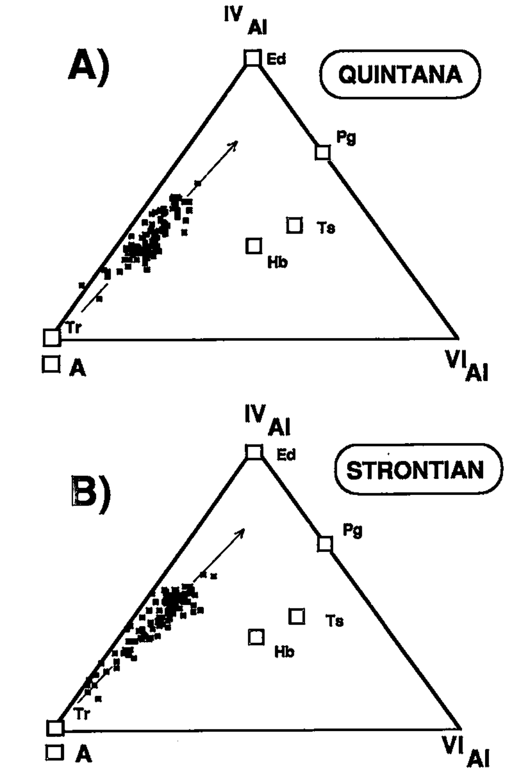
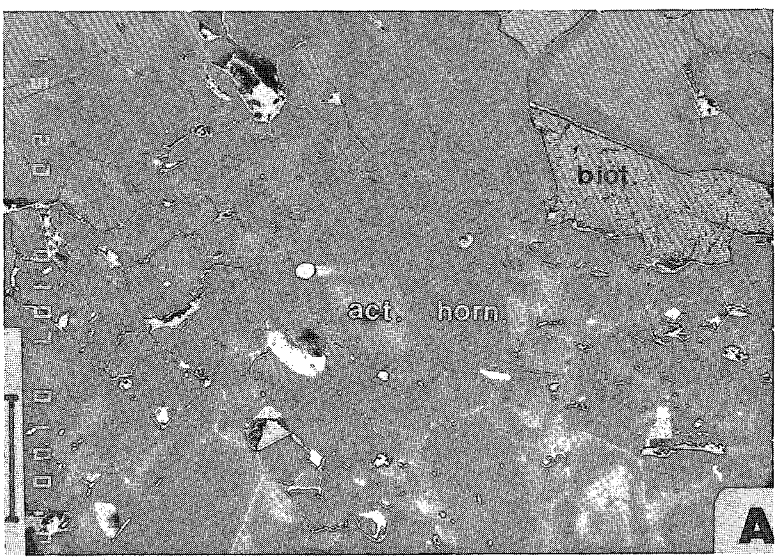


FIG. 8. Triangular plot for the amphiboles of Quintana (A) and Strontian (B) showing the substitution vector, dominated by a combination of Ed and Pg.

actinolite and hornblende. Occasionally, actinolite also forms irregular lamellae in hornblende; this is the patchy zoning referred to above and shown in Figure 9C. The association of actinolite lamellae with quartz inclusions may be accidental in this case, and they are unrelated in most cases.

Amphibole–biotite relationships

Biotite is the most abundant subordinate phase in the clots that we have studied. Indeed, some clots contain only biotite. These are very abundant in the biotite granodiorites and related enclaves of the Central System batholith of Spain (Castro *et al.* 1991b). Many clots rich in amphibole have a marginal zone rich in biotite; biotite may show complex textural relationships with amphibole crystals inside the clots (Figs. 4B, 9A). Biotite may show a granoblastic-like texture, with triple junctions involving biotite and amphibole (Fig. 4B), which suggests that they recrystallized in equilibrium, with no apparent signs of reaction. Elsewhere, biotite shows reaction textures with amphibole in both directions, that is Bt reacts to Amp and Amp reacts to Bt, the latter being very common near the margin of the amphibole clots. Finally, biotite appears to fill interstices between the amphibole grains (Fig. 9A). Biotite in these different textural forms was analyzed with the electron microprobe, and representative compositions are presented in Tables 3 and 4. The most significant feature is the rather homogeneous composition of the biotite (Fig. 11). Biotite from the Strontian pluton has a larger Mg/(Mg+Fe) ratio (Mg#) than biotite from the Quintana pluton. This difference may be related to the slightly more mafic composition of the Strontian bulk rocks. It is not possible to distinguish biotite from



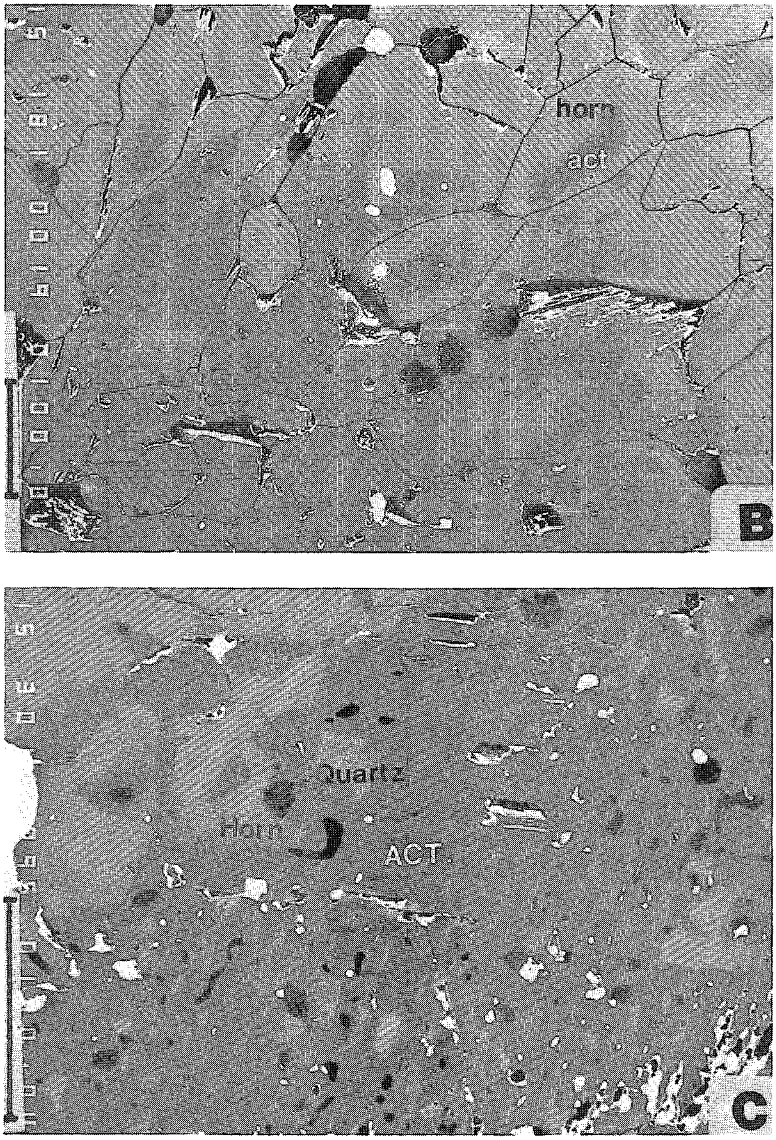


FIG. 9. Back-scattered electron images (BEI) of representative amphibole clots from the rocks studied. Three types of zoning are displayed: core zoning (A,B), oscillatory zoning (A) and patching zoning (C). The darker zones are richer in actinolite. Note the triple junctions and the intergranular biotite in A. The zoned crystal at the center of A also shows oscillatory zoning near the rim. A compositional traverse across the labeled crystal in B is shown in Fig. 10. A comes from a clot in an enclave of the Quintana pluton. B and C come from clots in the Strontian tonalite. Scale bar = 100 μm.

different textural occurrences in either the Strontian or Quintana plutons, which suggests that re-equilibration has extensively affected this mineral, or that this parameter is not sensitive to paragenetic environment. Biotite–amphibole pairs were analyzed from the margins of clots, in order to compare the respective Mg# and to estimate the average partition coefficient, expressed as $(X^{Mg}/X^{Fe})_{Bt}/(X^{Mg}/X^{Fe})_{Amp}$ (after Speer 1987).

Figure 12 is an AFM plot for these biotite–amphibole pairs. In the Strontian pluton, there are no significant differences between the slopes of tie lines corresponding to pairs from the margins of clots compared with pairs from idiomorphic amphibole in contact relationship with biotite. This strongly suggests that at least the marginal part of the clot crystallized in equilibrium with amphibole of the host rock. The calculated D is approximately

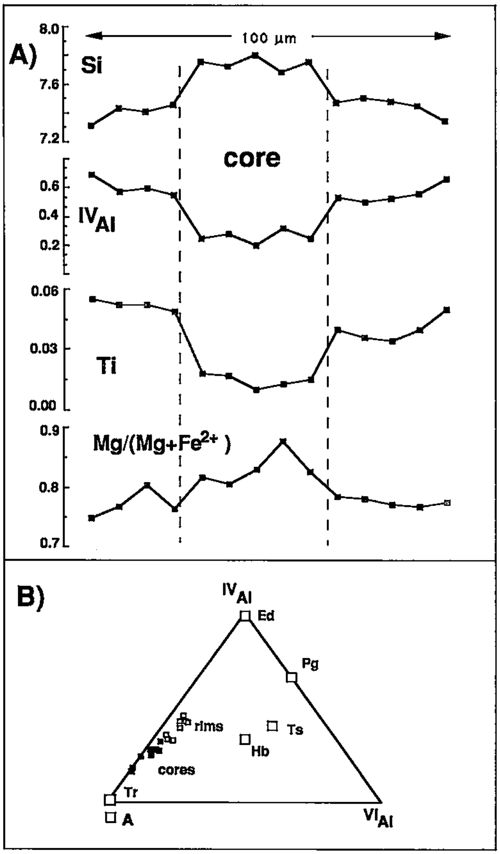


FIG. 10. A. Cation plots showing variations along a traverse in an amphibole crystal from the clot of Fig. 9B. Note the discontinuous zoning involving Si, ^{IV}Al and Ti and the more gradual variation in Mg#. B. The triangular substitution plot showing that zoning in the core is dominated by an edenite-type coupled substitution.

0.86 for the Quintana pluton and 0.92 for the Strontian pluton. These values are within the range of normal values for calc-alkaline granitic rocks as reported by Speer (1987). If the uniform compositions displayed by biotite indicate extensive re-equilibration, then the *D* values may be unrelated to conditions of magmatic equilibrium. The observed differences in the *D* values between the two plutons may be explained by differences in the intensive variables (*e.g.*, the greater depth of emplacement of the Strontian pluton) and may not be primarily related to differences in the bulk composition of the respective magmas. Speer (1987) suggested that the calculated *D* depends on the mineral assemblage and bulk composition, with *D* increasing toward more felsic compositions. In our case, although the differences in bulk composition are quite small, this correlation is reversed, with lower *D* values in the more felsic composition (Quintana).

Amphibole–plagioclase relationships

Plagioclase and amphibole are normally the most abundant felsic and mafic phases, respectively, in intermediate calc-alkaline plutonic rocks. Both may crystallize over a wide range of T (see Blundy & Holland 1990) and may record physicochemical changes during magma evolution. Many of the amphibole clots studied contain plagioclase as a subordinate phase. Mutual relationships between amphibole and plagioclase are important for recognition of whether clots have a magmatic origin and whether the amphibole–plagioclase thermometer (Blundy & Holland 1990) is applicable. Plagioclase normally occurs in these clots as an interstitial phase showing lobate contacts with amphibole. These features are indicative of simultaneous crystallization, and thus geothermometric applications are appropriate. Figure 13 shows compositions of selected pairs (Tables 1 and 2) plotted in a graphical solution of the Blundy & Holland (1990) thermometer. The selected pressures, 1 kbar for the Quintana pluton and 3 kbar for the Strontian pluton, are based on

TABLE 3. REPRESENTATIVE ELECTRON–MICROPROBE DATA ON BIOTITE FROM THE QUINTANA GRANODIORITE AND RELATED ENCLAVES

Rock type	PT encl.	PT encl.	PT encl.	TR encl.	Granod.	Granod.
Sample	C-2	C-2	C-2	B-2	D-1	D-1
Analysis	30	32	34	3	2	3
Description	Amph. clot	Amph. clot	Amph. clot	Matrix	Matrix	Amph. clot
SiO2 wt%	37.11	37.37	36.83	37.18	36.37	37.29
TiO2	3.50	3.73	3.83	3.37	4.24	3.79
AL2O3	13.57	14.16	13.88	13.77	14.04	13.66
FeOt	17.18	17.34	17.07	18.22	18.65	18.20
Cr2O3	0.13	0.06	0.14	0.07	-	-
MnO	0.32	0.26	0.2	0.33	0.25	0.34
NiO	0.12	0.04	0.03	0.08	-	-
MgO	12.56	12.47	12.36	12.43	11.41	12.12
CaO	-	-	-	-	0.02	0.04
BaO	0.06	0.18	0.07	-	0.70	0.30
Na2O	0.17	0.11	0.12	0.10	0.11	0.12
K2O	9.25	8.57	9.09	9.11	9.42	9.59
TOTAL	93.98	94.28	93.61	94.63	95.21	95.45
Structural	formulae (O = 22)					
Si	5.70	5.69	5.67	5.69	5.59	5.68
Al (IV)	2.30	2.31	2.33	2.31	2.41	2.32
Z site	8.00	8.00	8.00	8.00	8.00	8.00
Al (VI)	0.16	0.23	0.18	0.17	0.13	0.14
Ti	0.40	0.43	0.44	0.39	0.49	0.43
Cr	0.02	0.01	0.02	-	-	-
Fe2+	2.21	2.21	2.20	2.33	2.40	2.32
Mn	0.04	0.03	0.03	0.04	0.03	0.04
Ni	0.01	-	-	0.01	0.00	-
Mg	2.88	2.83	2.83	2.83	2.61	2.75
Y site	5.71	5.73	5.7	5.77	5.67	5.68
Ca	0.01	0.03	0.01	-	-	0.01
Ba	0.05	0.03	0.04	-	0.04	0.02
Na	-	-	-	0.03	0.03	0.03
K	1.81	1.66	1.78	1.78	1.85	1.86
X site	1.87	1.72	1.83	1.81	1.92	1.92
TOTAL CAT.	15.58	15.46	15.53	15.58	15.59	15.61

TABLE 4. REPRESENTATIVE ELECTRON-MICROPROBE DATA ON BIOTITE FROM THE STRONTIAN GRANITIC ROCKS AND RELATED ENCLAVES

Rock type	Enclave	Enclave	Tonalite	Tonalite	Hybrid	Hybrid
Sample	SR2	SR6	SR4	SR4	SR5	SR5
Analysis	14	8	26	33	3	32
Description	Idiom. amph.	Amph. clot	Plag. incl.	Idiom. amph.	Idiom. amph.	Amph. clot
SiO2	37.69	36.47	37.29	37.81	38.48	37.61
TiO2	3.41	3.34	3.52	3.60	4.04	3.73
AL2O3	14.12	14.29	14.62	14.32	14.48	14.63
FeOt	16.88	16.81	17.98	17.38	14.96	15.07
Cr2O3	0.03	0.01	-	0.15	0.25	0.04
MnO	0.18	0.26	0.23	0.14	0.17	0.14
NiO	0.02	0.02	-	0.02	-	-
MgO	13.70	13.16	12.21	13.42	14.64	14.55
CaO	0.01	0.10	0.02	0.01	0.09	0.07
Na2O	0.10	0.08	0.10	0.14	0.12	0.03
K2O	9.79	9.27	9.68	9.71	9.54	9.73
TOTAL	95.93	93.80	95.65	96.69	96.80	95.60
Structural formulae (O=22)						
Si	5.66	5.60	5.64	5.64	5.65	5.61
Al (IV)	2.34	2.40	2.36	2.36	2.35	2.39
Z site	8.00	8.00	8.00	8.00	8.00	8.00
Al (VI)	0.16	0.19	0.25	0.15	0.16	0.18
Ti	0.39	0.39	0.40	0.40	0.45	0.42
Fe2+	2.12	2.16	2.27	2.17	1.84	1.88
Cr	-	-	-	0.02	0.03	0.01
Mn	0.02	0.03	0.03	0.02	0.02	0.02
Ni	-	-	-	-	-	-
Mg	3.06	3.01	2.75	2.98	3.21	3.23
Y site	5.75	5.78	5.71	5.75	5.71	5.74
Ca	-	0.02	-	-	0.01	0.01
Na	0.03	0.02	0.03	0.04	0.03	0.01
K	1.88	1.82	1.87	1.85	1.79	1.85
X site	1.91	1.86	1.90	1.89	1.83	1.87
TOTAL CAT.	15.66	15.64	15.60	15.63	15.54	15.61

estimates of their respective depths of emplacement deduced from aureole assemblages (Ashworth & Tyler 1973). Many amphibole–plagioclase pairs indicate subsolidus temperatures for both plutons. In the Quintana pluton, mineral pairs from the margin of clots are not significantly different from other textural occurrences in the same rock. In the Strontian pluton, mineral pairs within the amphibole clots show the same trends as idiomorphic crystals of amphibole in contact with plagioclase either in enclaves, host tonalites and hybrid rocks. These similarities suggest that plagioclase and amphibole in the clots crystallized under similar conditions and in equilibrium with other amphibole–plagioclase pairs of the groundmass, where their magmatic origin is unambiguous on textural grounds. However, plagioclase only appears near the margin of the amphibole clots. Consequently, the interpretation of a magmatic origin may not be applicable to the inner parts of the clots, at least not as simple precipitates from a melt.

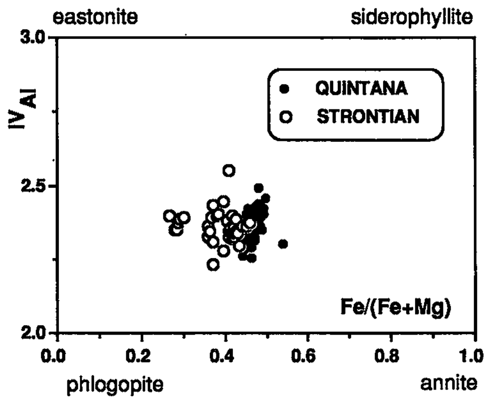


FIG. 11. ^{IV}Al *versus* Fe ratio diagram for biotite related to the amphibole-bearing rocks of Strontian and Quintana. Note the nearly homogeneous composition for both plutons.

Comparisons with amphibole in the host rock

Amphibole in textural types other than clots has been analyzed in order to compare clots with apparently normal magmatic parageneses in the same rock. These comparisons are made using the substitution diagrams (Figs. 6, 7). The differences between amphibole in clots and that in idiomorphic crystals are not particularly

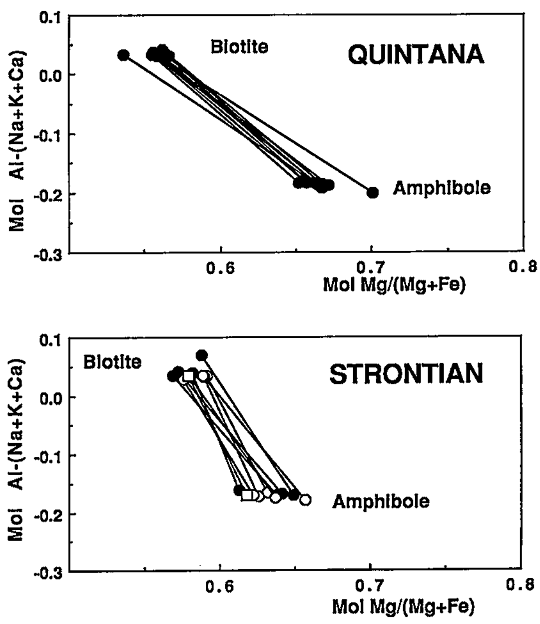


FIG. 12. AFM plots (Speer 1987) showing several biotite–amphibole pairs from the marginal zone of amphibole-rich clots (full circles). Pairs of idiomorphic amphibole in contact with biotite inclusions also are shown for the Strontian tonalites (open circles) and related enclaves (open squares).

large. All the analytical data from different samples are grouped together in this diagram. For reasons of clarity, comparisons are made using data from one particular sample from the Strontian pluton (SR4), including an enclave and the host tonalite. Figure 14 shows compositions of amphibole from clots and of idiomorphic crystals within this sample. In diagrams showing Mg# *versus* ^{IV}Al and Ti *versus* ^{IV}Al, compositions of the clot amphibole vary differently within enclaves and within the host rock, and both are distinct from the idiomorphic amphibole in the host granodiorite. Cores, rims and idiomorphic amphiboles of the enclaves show wide variations, whereas compositions of amphibole from similar occurrences in the host granodiorite are tightly grouped. If re-equilibration during slow cooling affected amphibole compositions, then it is clear that it was more effective in the host tonalite than in the enclave (which probably crystallized earlier and more rapidly, as suggested by the fine-grained matrix and the presence of acicular apatite). However, the core-to-rim compositional trend for amphibole within the clots differs from that for amphibole in clots within enclaves, and both differ from the trend for idiomorphic amphiboles in the host tonalite (Fig. 14). These trends might reflect differences in original composition of the magmas. If this is so, then the amphibole in clots within the host granodiorite and the enclaves probably crystallized from different magmas and in equilibrium with different melts prior to the mingling event that formed the enclaves (Holden *et al.* 1987). This conclusion assumes that the amphibole in clots crystallized from a melt phase; however, there is an alternative possibility, that the amphibole is not a primary precipitate from melt, but a reaction product of an earlier ferromagnesian phase. Idiomorphic crystals of amphibole probably crystallized later than the inner parts of the clots.

DISCUSSION

Any model for the origin of amphibole-rich clots in the Strontian and Quintana tonalite and granodiorite plutons must account for certain general features of clots hosted by granite or by enclave. In both cases, a critical factor in interpreting the clot-forming process is whether actinolite in such tonalite–granodiorite rocks and dioritic enclaves is magmatic in origin, as proposed by Pe-Piper (1988), or whether it formed in the subsolidus after calcic pyroxene, as conventionally interpreted (*e.g.*, Chivas 1981). We have observed oscillatory zoning in actinolite, which might favor a magmatic origin, though the evidence is equivocal, as such zoning might be inherited from similar zoning in a precursor calcic pyroxene. Helz (1982) observed that tremolite–actinolite is absent from all experimental runs in metaluminous systems. She attributed this finding to the inability of Al-poor amphibole to coexist with liquids of normal (10–25%) Al_2O_3 content.

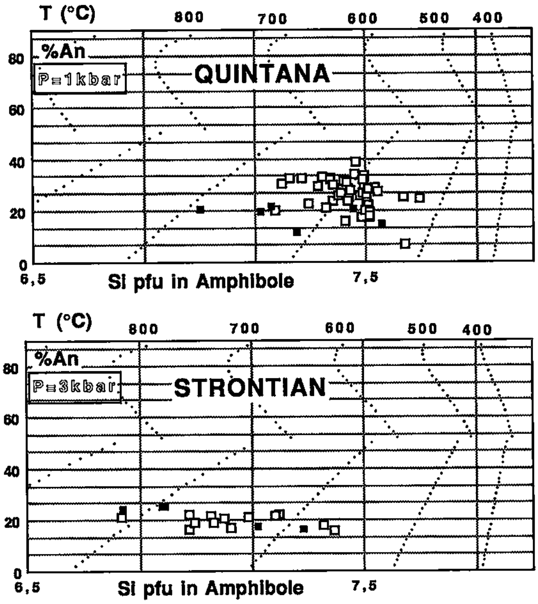


FIG. 13. Graphical solutions to the plagioclase–amphibole thermometer (Blundy & Holland 1990) for 1 kbar (Quintana) and 3 kbar (Strontian). The analyzed pairs around clots from enclaves are plotted as open squares, and the host granitic rocks as full squares.

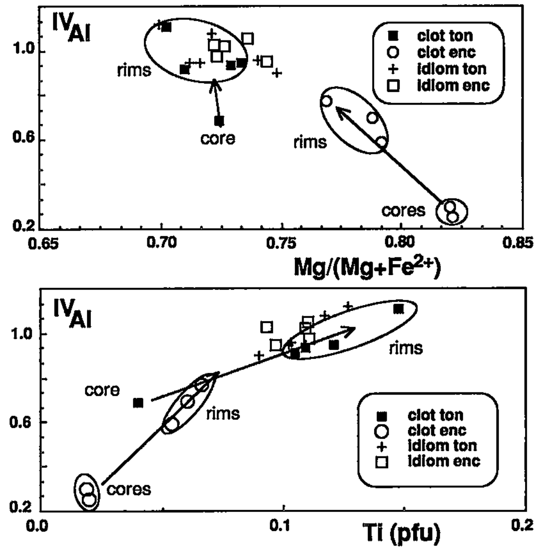


FIG. 14. Cation plots showing core–rim relationships in zoned amphiboles from enclaves and host tonalites of the Strontian pluton (from a single sample).

The constraints we consider most important to any model of clot formation are:

a) The dimensions of clots are more or less comparable with the long axes of the larger prismatic amphibole crystals in the host rocks.

b) The distribution of clots through a magmatic unit in the host granite is relatively uniform. There are no zones where clots are more numerous.

c) Texturally, the interior and outer margin of clots are distinct. The interior is dominantly composed of multiple crystals of amphibole in mutual contact. The margin also is amphibole-rich, but with significant proportions of biotite and plagioclase, and virtually no quartz or alkali feldspar. An idiomorphic (prismatic) outline of clots is observed only in the enclaves, whereas the outline of clots in the granitic matrix is always irregular.

d) Individual crystals of amphibole in the interior of a clot tend to be zoned. The core of these crystals is low in Al (actinolitic), whereas the rim is a calcic amphibole similar in composition to the idiomorphic crystals in the host granitic rock. The amphibole in the margin of clots is a calcic amphibole indistinguishable from that of the host rock.

The textural and compositional differences between the interior of a clot and its outer margin strongly suggest that they have distinct histories of crystallization.

Origin of clot interiors

The interior of the clots is characterized by multiple individual grains of amphibole, in mutual contact, each having an actinolitic core surrounded by a rim of more normal calcic amphibole similar in composition to that of idiomorphic amphibole in the host rock. If the actinolitic core precipitated directly from a magma, it must have been in equilibrium with a liquid of different composition than the magma that presently hosts the clots. Alternatively, the actinolitic core may be a product of reaction of pyroxene with magma, fluid, or of adaptation to changed P–T conditions. The problem is to determine the origin of the pyroxene and to explain why individual grains preserved these distinct cores and developed a rim of calcic amphibole in magmatic equilibrium with the host while also developing a granoblastic texture.

The observed compositional zoning is the reverse of that anticipated for magmatic crystallization. According to Wones (1981), Cawthorn (1976), and Allen & Boettcher (1978), the silica content of an amphibole increases sympathetically with that of the host magma. Cawthorn (1976) also observed that an amphibole tends to be richer in Ti than its host magma, but the core of our amphibole is relatively depleted in Ti compared to the rim. Both features suggest that the actinolitic core probably did not crystallize from a magma of similar composition to the present host-rock.

Pyroxene precursors to the clot cores are a likely rationalization of these features:

(a) Early pyroxene phenocrysts in tonalitic–granodioritic magma may be expected before the H_2O activity increased sufficiently to stabilize amphibole. Calcic pyroxene cores to phenocryst amphiboles are commonly observed, though it must be stated that this is not the case for the two plutons in this study.

(b) Mafic and intermediate magmas containing pyroxene phenocrysts have been reported as mingling and mixing with more silicic magmas (*e.g.*, Castro *et al.* 1991a). Survival of pyroxene crystals as grains and networks would leave these minerals in a new compositional and thermal environment, which may lead to extensive re-equilibration. A variant of this proposal might include pyroxenes formed by the disruption of mafic igneous enclaves, themselves incorporated in the granitic magma by processes of magma mingling (Stephens *et al.* 1991).

(c) Pyroxene will dominate the mineral assemblage of a mafic restite after partial melting of a typical I-type source (Rutter & Wyllie 1988). Entrainment and transport in the magma of such restite are regarded by some workers as important features of I-type granites (*e.g.*, Chappell *et al.* 1987).

Whatever the origin of inferred pyroxene in the magma, such pyroxene, on entering the stability field of hornblende, will react with melt to produce an amphibole in equilibrium with that crystallizing from the melt. This process of crystal–melt re-equilibration will be most effective on the rim of crystals in contact with melt, and perhaps along some grain boundaries. Contemporaneously, the magma will precipitate new amphibole most rapidly on appropriate sites of nucleation, and a mass of amphibole crystals in the form of a clot might represent a favorable substrate in this regard. If the rate of this amphibole-accretion process is considerably more rapid than the process of crystal–melt re-equilibration, then the effectiveness of the latter will rapidly diminish as the clot becomes armored by a new cycle of amphibole growth. The net effect might be to arrest the re-equilibration of pyroxene grains with melt, leaving a pyroxene core surrounded by a hornblende rim.

The most difficult problem in explaining these characteristics of clots is to account for the actinolitic core to granoblastic crystals within the clot interiors. In our first model for re-equilibration, we assume that:

$$\text{pyroxene} + \text{melt}_1 \rightarrow \text{hornblende} + \text{melt}_2.$$

The low aluminum content of the pyroxene favors the formation of actinolite in the solid state in a reaction isolated from melt, such as:

$$\text{pyroxene} + \text{fluids (OH, ...)} \rightarrow \text{actinolite}.$$

Such a reaction may occur once the pyroxene is isolated from melt by the armoring of the clot by hornblende crystals.

The second model regards the interior of a pyroxene-rich clot as isolated from contact with the melt and is based on the observation that hydrogen diffuses through silicate melt and along grain boundaries much more rapidly than all other elements (Goldsmith 1987). It is proposed that a hypothetical precursor clinopyroxene grain isolated within a clot reacts with hydrogen to form an actinolitic amphibole and some iron, according to the model reaction:

$$\underset{\text{cpx}}{4Ca_{0.5}Mg_{0.75}Fe_{0.75}Si_2O_6} + 2H \rightarrow \underset{\text{amph}}{Ca_2Mg_3Fe_2Si_8O_{22}(OH)_2} + Fe$$

Goldsmith (1987) proposed that Al/Si interdiffusion in albite is facilitated by hydrogen hopping and suggested that the extent of equilibration may be as much dependent on the availability of hydrogen as on time. In an analogous way, we propose that the above reaction dominates while the supply of protons is large compared with other cations. The rate of H^+ diffusion in pyroxene crystals is very high, and this will not limit the rate of the reaction (Skogby & Rossman 1989). However, as the more sluggishly diffusing Al and other cations become available at the grain boundaries, then equilibration of the actinolite with the more aluminous amphibole of the host magma may take place, according to:

$$\underset{\text{low-Al amphibole}}{Ca_2Mg_3Fe_2Si_8O_{22}(OH)_2} + 2Al \rightarrow \underset{\text{aluminous amphibole}}{Ca_2Mg_3Fe_2Si_6Al_2O_{22}(OH)_2} + 2Si$$

Thus the actinolite represents a transient state and intermediate stage between the precursor pyroxene and the hornblende of the host magma, and is preserved only to the extent that the kinetic control on the availability of other cations allows. This model could explain the texture of individual grains of the clot interior. Complete reaction with protons transforms the whole grain to actinolite, whereas with mass transfer within the clots taking place dominantly by grain-boundary diffusion, equilibration with aluminous amphibole of the magma takes place *inward* from the grain margin. This process might be prevented from going to completion either by new melt-precipitated growth on the clot exterior, choking off access to the clot interior, or by loss of energy from the system in a cooling pluton, reducing the rates of diffusion to ineffective levels.

Origin of the clot margins

Characteristics of the margin of the clots are entirely consistent with crystallization from the host magma. The compositions of amphibole, biotite and plagioclase do not differ from those in the host granitic rock, and textures are magmatic. It seems that the clot as a whole may have acted as a suitable substrate for nucleation during the early and main stages of crystallization. Late-stage minerals such as quartz and alkali feldspar are not abundant amongst the minerals making up the clot margins. Clots in the enclaves are distinct from those in the host granitic rocks in tending to maintain a prismatic shape indicative of an origin by pseudomorphic replacement of pyroxene. Enclaves in the Strontian pluton have been shown to have formed from exotic magmas of mantle derivation (Holden *et al.* 1987), probably as networks of mafic and other high-T phases resulting from quenching of a mafic magma in a felsic granitic magma (Stephens *et al.* 1991). These networks formed coherent structures in which the pyroxenes reacted in a local environment to give amphibole.

Conclusions

Our study of mafic clots in two plutons has revealed some apparently general characteristics of amphibole-dominated clots. The clots are zoned, with an interior comprising multigrain polygranular aggregates of amphibole surrounded by an amphibole–biotite–plagioclase assemblage forming a continuous margin. The interior grains are themselves zoned from an actinolitic core to a calcic amphibole rim.

We conclude that the clots are primarily the products of reactions with pyroxene occurring in a metaluminous magma precipitating calcic amphibole. Two possible origins are proposed: (a) Pyroxene re-equilibrated with the melt to form calcic amphibole in equilibrium with calcic amphibole crystals growing in the host, and new amphibole also grew with plagioclase and biotite at margins. When this marginal growth choked off access of the melt to clot interiors, the remaining cores of pyroxene reacted in the solid state to form actinolitic amphibole, presumably in the presence of a fluid phase. (b) Pyroxene in the clot interiors was isolated from melt, and grain-boundary diffusion of protons from the melt promoted recrystallization of pyroxene to actinolite. Later, the more sluggish diffusion of Al and other components brought about partial re-equilibration with the more aluminous amphibole crystallizing from the melt. This re-equilibration was prematurely arrested when growth of amphibole, plagioclase and biotite at the clot margins choked off access, or when diffusion ceased to be an effective method of mass transfer for thermodynamic reasons.

The origin of the precursor pyroxene crystals is not obvious from this study. Possibilities include original phenocrysts, or derivation through the mingling of the granodioritic magma with more basic magma, or they may simply have been restitic from the source. Their uniform distribution is consistent with either an origin as phenocryst or a restite, whereas their granoblastic texture favors a restitic origin.

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