

Cordierite in felsic igneous rocks: a synthesis

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Abstract

Cordierite is a characteristic mineral of many peraluminous felsic igneous rocks. A combination of T - P - X parameters, which overlap the stability conditions for felsic magmas, control its formation. Critical among these parameters are relatively low T , low P , and typically high ($Mg+Fe^{2+}$), Mg/Fe^{2+} , A/CNK , $a_{Al_2O_3}$, and f_{O_2} . Spatial and textural information indicate that cordierite may originate in one of three principal ways in felsic igneous rocks: Type 1 Metamorphic: (a) xenocrystic (generally anhedral, many inclusions, spatial proximity to country rocks and pelitic xenoliths); (b) restitic (generally anhedral, high-grade metamorphic inclusions); Type 2 Magmatic: (a,b) peritectic (subhedral to euhedral, associated with leucosomes in migmatites or as reaction rims on garnet); (c) cotectic (euhedral, grain size compatibility with host rock, few inclusions); (d) pegmatitic (large subhedral to euhedral grains, associated with aplite-pegmatite contacts or pegmatitic portion alone); and Type 3 Metasomatic (spatially related to structural discontinuities in host, replacement of feldspar and/or biotite, intergrowths with quartz). Of these, Type 2a (peritectic) and Type 2c (cotectic) predominate in granitic and rhyolitic rocks derived from fluid-undersaturated peraluminous magmas, and Type 2d (pegmatitic) may be the most common type in fluid-saturated systems.

KEYWORDS: cordierite, pinite, granite, aplite, pegmatite, rhyolite, migmatite, restite, xenocryst, metamorphic, magmatic, metasomatic.

Introduction

CORDIERITE occurs as a characteristic, usually accessory, phase in many types of felsic peraluminous extrusive and intrusive igneous rocks (rhyolites, granitoids, pegmatites). Such rocks commonly have high A/CNK (> 1.1) [$A/CNK = \text{mol. } Al_2O_3 / (\text{CaO} + \text{Na}_2O + \text{K}_2O)$], $^{87}\text{Sr}/^{86}\text{Sr}_i$ (> 0.7075), and $\delta^{18}\text{O}$ ($> +10 \text{‰}_{\text{SMOW}}$). In these rocks, cordierite shows a wide range of distribution both relative to contacts with country rocks, and to contacts between internal facies in felsic igneous bodies. It also exhibits a variety of coexisting mineral assemblages and textures (grain sizes, grain shapes, and relationships with the coexisting phases, such as inclusions, intergrowths, and reactions). The principal question concerning the presence of cordierite in felsic igneous rocks is not whether this mineral is diagnostic of a particular genetic type of granite (White, 1989), but how it formed. In general terms, the answer is relatively straightforward. Like any other mineral, cordierite is a predictable thermodynamic entity in temperature (T)-pressure (P)-composition (X) space, a space that

overlaps considerably with that of felsic magmas. Simply stated, cordierite nucleates as a result of changes in T - P - X that drive the chemical system into the cordierite stability field. But what are the spatial and textural criteria that reveal the environment of formation? This paper reviews the occurrences of cordierite in felsic igneous rocks, and presents a comprehensive classification for understanding its origins.

Cordierite composition and structure

Cordierite is an orthorhombic tectosilicate with the general formula: $X_{0-1}M_2T_9O_{18}$, where $X = \text{H}_2\text{O}$, CO_2 , Ar , Xe , Na , K occupying large channels parallel to the c -axis created by the pseudo-hexagonal rings (Armbruster and Bloss, 1982); $M = \text{Mg}^{2+}$, Fe^{2+} (with possibly some Li^+) in octahedral co-ordination; and $T = \text{Al}_4\text{Si}_5$ (with possibly some Be^{2+}) in tetrahedral co-ordination. Cordierite has a structure similar to that of beryl, forming prismatic crystals commonly showing a prominent (001) parting, and it may develop simple, lamellar, or cyclic twinning. Indialite

is the high-temperature hexagonal polymorph, with a continuum of Al–Si ordering linking it to cordierite (Miyashiro, 1957).

T–P–X framework

The stability region of cordierite occupies a discrete part of *T–P–X* space that embraces both the normal metamorphic and igneous domains (Fig. 1). In this overlap lies the dilemma — is any given cordierite grain metamorphic or igneous? In practice, the problem is even more complicated, because a cordierite could have both metamorphic and igneous growth histories, or be entirely metasomatic. Figure 1 shows a schematic *T–P* stability field for cordierite, including many of the important bounding reactions discussed subsequently in this paper. In reality, the bounding reactions are zones, rather than lines, as a consequence of extensive solid solution in most of the phases, and the boundaries also shift their positions in *T–P* space as a function of other chemical parameters. Favourable compositional (*X*) conditions include high values for

$\Sigma(\text{Mg}+\text{Fe}^{2+})$, Mg/Fe^{2+} , A/CNK , $a_{\text{Al}_2\text{O}_3}$, and f_{O_2} relative to cordierite-free granitic rocks (Clemens and Wall, 1988; Zen, 1989; Patiño Douce, 1992). (The rare occurrence of sekaninaite ($\text{Fe} > \text{Mg}$) as large crystals in pegmatite (Staněk, 1954, 1991) represents an exception to the condition of high Mg/Fe). Additional tests of mineral assemblage, texture, chemical partitioning, and phase equilibrium constraints combine to determine whether cordierite is cognate or foreign to its host felsic igneous rock (Clarke, 1981b).

In a related connection, Gordillo (1984) used cordierite–garnet pairs in migmatites, and Fang and He (1985) used the same coexisting phases in granites and volcanic rocks, to estimate magmatic *T–P* conditions, with varying degrees of success depending on the extent of (re)equilibration between cordierite and garnet.

Formation of cordierite

The following sub-sections classify cordierite in felsic igneous rocks into three genetic types —

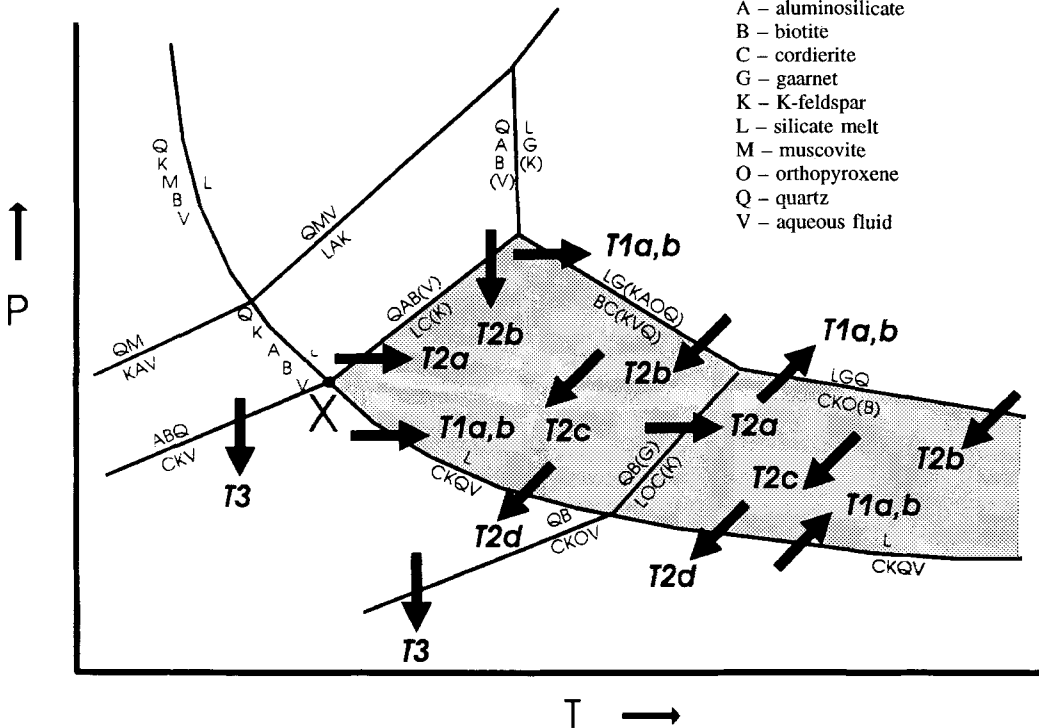


FIG. 1. Schematic petrogenetic grid for cordierite in felsic magmas. The shaded region indicates the stability region of cordierite in association with felsic silicate melts. Arrows refer to types of reactions producing cordierite. Precise location of reactions depends on compositional parameters of the system, and most univariant boundaries are in reality divariant zones. Sources: Hensen and Green, 1973; Green 1976; Abbott and Clarke, 1979; Grant, 1985; Vielzeuf and Holloway, 1988; Clemens and Wall, 1988; Jones and Brown, 1990.

metamorphic, magmatic and metasomatic (Table 1). The organization of the types is from foreign (Types 1a,b) to cognate (Type 2), and from melt–solid reactions (Types 1a,b and 2a-c), to melt–solid–vapour reactions (Type 2d), to solid–vapour reactions (Type 3). The selected examples attempt only to provide clarity of illustration; Zen (1988) describes further examples.

Metamorphic — formation as the result of solid–solid reactions

Type 1 Metamorphic: (a) Xenocrystic. The former, and mistaken, notion that cordierite was an exclusively metamorphic mineral led to the venerable interpretation that all cordierite in felsic igneous rocks was xenocrystic. Indeed, granitic magmas commonly intrude low- to medium-grade meta-

morphic rocks of semi-pelitic to pelitic compositions, and incorporation of cordierite-bearing fragments of these country rocks into the invading magmas is almost inevitable. Particularly in those cases where cordierite in the pluton concentrates near the contact with the country rocks, or in regions with high contents of pelitic xenoliths, the spatial evidence for a xenocrystic origin is strong. Ideally, such cordierite grains have poikiloblastic textures, and show some textural evidence of their disequilibrium with the melt phase (corrosion, euhedral epitaxial overgrowth) (Vernon and Collins, 1988). In reality, however, the original habit, types of inclusions, and chemical composition of the xenocrystic cordierite may be highly variable.

Brammall and Harwood (1932) used a xenocrystic explanation for some of the cordierites in the Dartmoor granite, and D'Amico *et al.*, (1981)

TABLE 1. Characteristics of cordierite types

Type	Origin	Ideal spatial and textural characteristics
1a (Fig. 2)	Xenocrystic L ⁻ , Crd ⁻ (at least initially)	Spatial correlation between cordierite in granite and cordierite in country rocks and/or enclaves; anhedral to euhedral grain shapes; small (mm) grain size
1b (Fig. 3)	Restitic L ⁺ , Crd ⁺ or L ⁺ , Crd ⁺	Textural features consistent with high-grade metamorphic origin, but ranging to cordieritites; in clots with, or with inclusions of, fibrous sillimanite, spinel, foliated biotite; other textural characteristics transitional between Type 1a above and Type 2c below
2a (Fig. 4)	Peritectic Magmatic (F) L ⁻ , Crd ⁺ , S ⁻	Most readily identified spatially in leucosomes (and/or melanosomes) of migmatites; early cordierites may have rounded quartz inclusions in core; larger (cm) grain size; as degree of partial melting increases, indistinguishable from Type 2c below
2b (Fig. 4)	Peritectic Magmatic (T) L ⁻ , Crd ⁺ , S ⁻	Characteristic of rapidly ascending melts (aplites, rhyolites); occurring as reaction rims on garnet, with or without inclusions of biotite and/or orthopyroxene — if reaction complete, then possibly indistinguishable from Type 2c below
2c (Fig. 5)	Cotectic Magmatic L ⁻ , Crd ⁺ , S ⁺	Ubiquitous; euhedral grain shapes, few inclusions, grain size compatibility with host rock (whether fine-grained rhyolite or aplitite, or coarse-grained granite)
2d (Fig. 6)	Fluidic-Magmatic L ⁻ , V ^{+/-} , Crd ⁺	Large (cm–m) grain size; anhedral to euhedral grains associated with aplitite-pegmatite contacts, miarolitic cavities, and/or pegmatitic cores
3 (Fig. 7)	Subsolidus Metasomatic V ^{+/-} , S ⁻ , Crd ⁺	Euhedral grain to anhedral clots; distribution along structural weaknesses in granite; commonly within leucocratic biotite-free haloes; possible pseudographic intergrowths with quartz

Notes

- Abbreviations: Crd — cordierite; L — silicate melt; S — other solid phases; V — aqueous fluid phase; + phase increasing in modal abundance as reaction proceeds; - phase decreasing in modal abundance as reaction proceeds.
- Exceptions to practically every textural criterion, and late-stage reactions of cordierite with the magma and/or subsolidus reactions with fluids, combine to diminish the usefulness of textural evidence as a reliable criterion to infer the origin of cordierite.

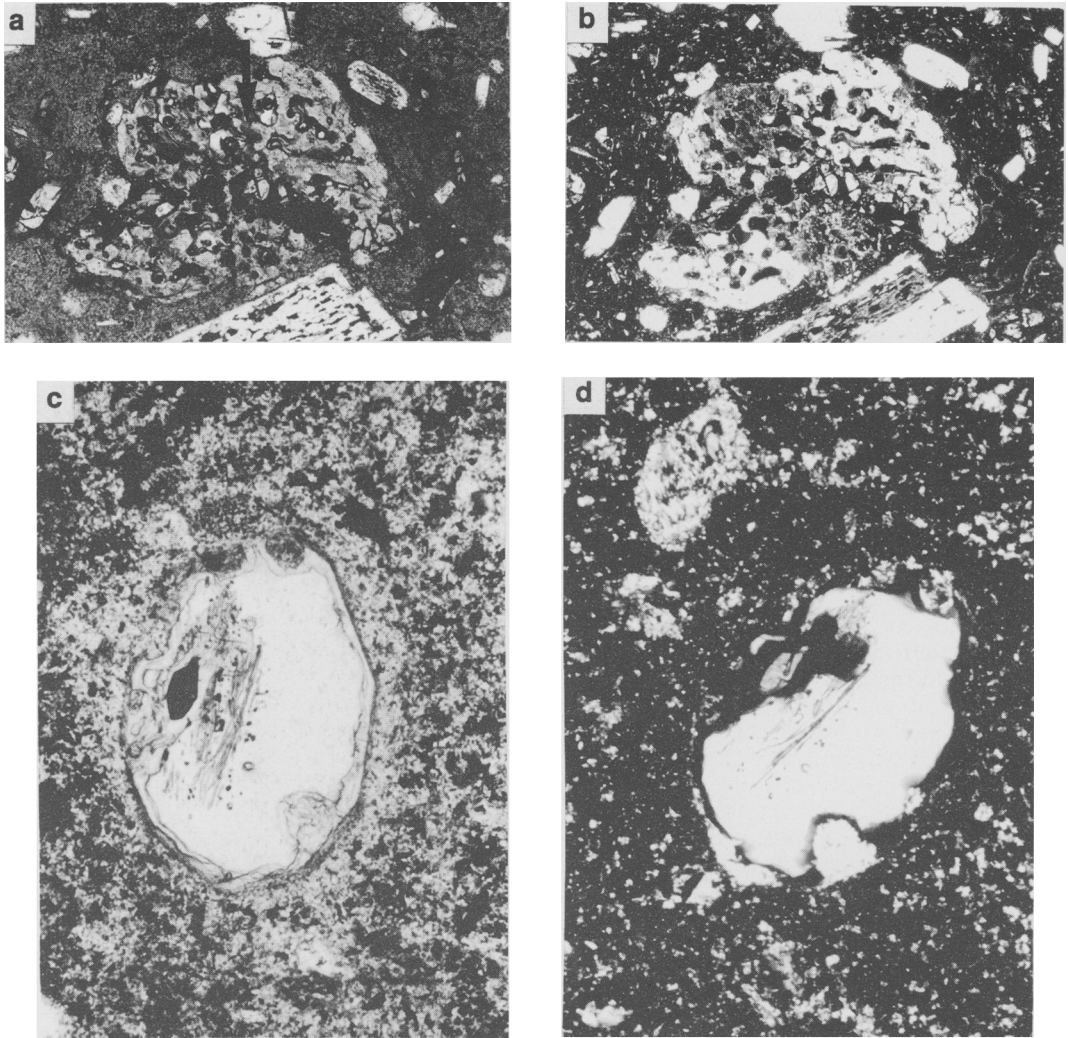
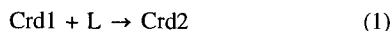


FIG. 2. Type 1a xenocrystic cordierites and Type 1b restitic cordierites. (a,b) Sample LIP-2. Type 1a xenocrystic cordierite, 2 mm across, in plane-polarized light (ppl) and crossed nicols (xn), respectively, from rhyolite lava flow, Lipari, Aeolian Islands. Note anhedral shape, relict sector twinning, and vermicular inclusions of iron-rich glass (arrow, medium gray in ppl and black in xn) produced as the cordierite melted. (c,d) Type 1b restitic cordierite (in ppl and xn, respectively) with inclusions of sillimanite in microgranite from the Petite Kabylie Massif, northern Algeria (photographs courtesy of S. Fourcade).

determined that much of the cordierite in the peraluminous granites of the Calabrian arc is xenocrystic. Maillet and Clarke (1985) recognized a textural and compositional gradation from metamorphic to xenolithic to magmatic cordierite and made a case for metamorphic seed crystals for cordierites of the South Mountain Batholith. Barker (1987) interpreted anhedral cordierites in a rhyolite from Lipari as xenocrysts from the disaggregation of

pelitic xenoliths (Fig. 2a,b), although some cordierites at the margins of xenoliths have grown in a reaction relationship between the melt and the xenolith. Ugidos and Recio (1993) cite the strong correlation between the modal abundance of cordierite in granites of the Central Iberian Massif, and the proximity of cordierite-rich country rocks and enclaves, as evidence for a xenocrystic origin for the cordierite present in the granites.

How can metamorphic cordierites become xenocrysts in a granitic melt? The combination of heating of an enclave leading to melting along its grain boundaries, and differential thermal expansion of the minerals of the xenolith or country rock, may result in disaggregation of the xenolith (Ugidos, 1988, 1990; Ugidos and Recio, 1993). Thus, cordierites of metamorphic origin may be released into a silicate melt and, in general, they would be out of chemical equilibrium with that melt. Their subsequent history then depends on the degree to which they are out of equilibrium with the magma, and on the chemical kinetics of the new environment. Xenocrystic cordierite may disappear rapidly in a high-temperature, well-mixed, relatively fluid metaluminous melt, survive largely unmodified in a near-solidus, static, viscous peraluminous melt, or grow in a highly peraluminous melt. Expressed as a simple equation,



where Crd1 is the original metamorphic cordierite, L is the silicate melt phase, and Crd2 is the re-equilibrated cordierite in the melt. Crd2 is almost certainly different in size, shape, and chemical composition compared with Crd1.

Type 1 Metamorphic: (b) Restitic. Wall *et al.* (1987) described some general principles for recognizing restitic material. Chappell *et al.* (1987) presented the specific case for the occurrence of restite in granitic rocks and discussed its implications. In simple terms, restite minerals are those that comprise the refractory residua of partial melting. Given that partial melting is the rule in magma generation, restite always exists, somewhere. Whether that refractory restite remains largely *in situ* after a partial melting event, or ascends with the magma, is still an open question. In this paper I make the theoretically important (but practically difficult) distinction between restitic cordierite that was present in the source rocks before partial melting began (Type 1b), and magmatic peritectic cordierite that appears only as a result of the melt-producing reaction (Type 2a below). In Type 1b, modal cordierite in the anatectic system may increase or decrease as melting proceeds, whereas in Type 2a, modal cordierite first nucleates as melting takes place and increases during the initial stages of partial melting. Any magma that was in equilibrium with cordierite as a restite phase in the region of partial melting is itself saturated in cordierite, and is likely to remain saturated in cordierite during its ascent, whether or not it is accompanied by entrained restite, and whether or not the melt becomes contaminated with typical upper crustal country rocks.

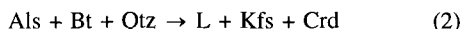
Examples of Type 1b restitic cordierite include: anhedral cordierite with fibrolite inclusions in a

dacite from Cerro del Hoyazo in SE Spain (Zeck 1970, 1992); subhedral cordierite with inclusions of sillimanite from the Petite Kabylie Massif, northern Algeria (Fig. 2c,d) (S. Fourcade, pers. comm., 1993); zoned cordierites in rhyolites of the Cerberean Cauldron, SE Australia (Birch and Gleadow, 1974); clots of Crd-Bt-Sil in a granite (Morin and Turnock, 1975); anhedral Type B cordierites with inclusions of biotite and/or sillimanite and spinel in the Strathbogie batholith (Phillips *et al.*, 1981); cordierite-bearing leucosomes in highly aluminous Qtz-Pl-Kfs-Crd-Grt-Sil-Ilm-Gr gneisses from central Massachusetts (Tracy and Robinson, 1983); anhedral cordierite from the subsolidus protolith (coexisting with newly nucleated magmatic cordierite grains) in the leucosomes of the Kelly's Mountain migmatites of Nova Scotia (Jamieson, 1984); and Type B cordierite in the Violet Town volcanics of SE Australia (Clemens and Wall, 1984).

Cordierites (rocks predominantly consisting of cordierite) constitute an important subset of the monomineralic rock problem in igneous petrology. Such unusual bulk rock compositions arise either by concentrating the chemistry to make the minerals, or by concentrating the minerals to make the chemistry. Ugidos (1988, p. 131) described the cordierites of the Central Iberian Massif as the residues of partial melting and re-equilibration, and concluded that the cordierite composition is the product of removal of a granitic component from a pelitic source rock in which "Leucogranites and cordierites...represent melt and residue, respectively". In this scenario, it is not surprising that such cordierites may also occur in the complementary granitic magma.

Magmatic — formation as the result of solid-melt reactions

Type 2 Magmatic: (a) Peritectic (T↑). This category includes cordierite that appears only as the result of a melt-producing reaction in response to rising temperature. In other words, cordierite is not part of the subsolidus mineral assemblage at the onset of partial melting, but it appears as melting begins in a peritectic reaction such as



Spatially, this cordierite may form along the contact between pelitic xenoliths and melt (Fig. 3a), or associate with the melt phase (initially as leucosomes) rather than the refractory residuum (restite) (Fig. 3b). These cordierites have no subsolidus metamorphic history, and thus could possibly be euhedral and free of inclusions. Other reactions, most of which are dehydration melting reactions (Hensen and Green, 1973; Green 1976; Abbott and Clarke, 1979; Hoffer and Grant, 1980; Grant 1985; Vielzeuf

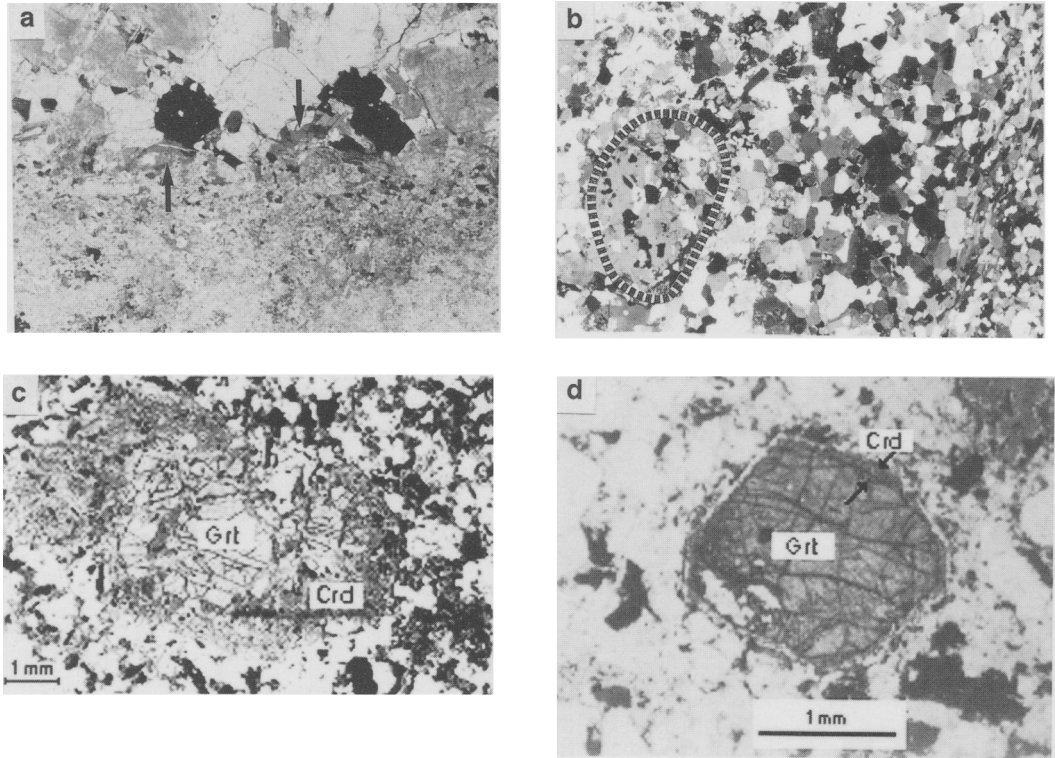
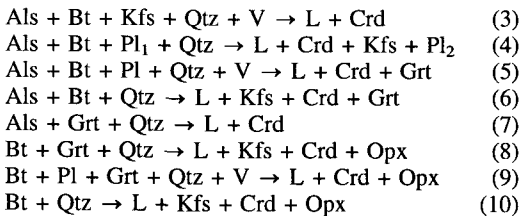


FIG. 3. Type 2a and Type 2b peritectic magmatic cordierites. (a) Sample L83-L51(A). Concentration of Type 2a cordierite (arrows) along the contact between semi-pelitic xenolith (lower part of photograph) and host granite, South Mountain batholith (field of view 8 mm wide). (b) Sample KM82. Large (6 mm) reaction cluster of Type 2a cordierite, biotite, and opaque oxides in leucosome of Kelly's Mountain gneiss. Normal grain size of mesosome evident on right side of photograph. (c) Garnet with reaction rim of Type 2b cordierite in Velay granite (after Weber *et al.*, 1985). (d) Garnet with reaction rim of Type 2b cordierite in Violet Town volcanics (after Clemens and Wall, 1984).

and Holloway, 1988; Clemens and Wall, 1988; Jones and Brown, 1990), which may account for the appearance of cordierite during melting of pelitic and semipelitic rocks, are:



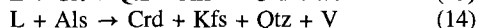
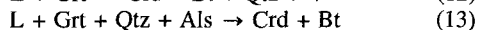
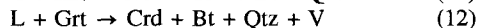
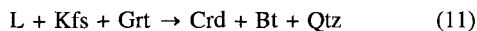
For example, Ellis and Obata (1992) used reaction (3) to account for the formation of melt in the migmatite at Cooma, SE Australia, under conditions of $T = 670\text{--}730^\circ\text{C}$ and $P_{\text{H}_2\text{O}} = 3.5\text{--}4.0$ kbar.

Cordierite produced by any of the above reactions is magmatic because it owes its existence entirely to

the presence of a silicate melt phase. The close association between peraluminous source rocks and the appearance of cordierite during melting explains the intimate association between cordierite and peraluminous felsic igneous rocks. This statement does not diminish the importance of other mechanisms for producing peraluminous granites (fractionation of hornblende from metaluminous melts, contamination, vapour-phase transfer; Clarke 1981a; Halliday *et al.*, 1981), nor other ways in which cordierite may form (this paper). And perhaps among all of these cordierite-producing peritectic reactions, Equation 2 involves the most common phases as a starting assemblage; it takes place at the lowest temperature, and is thus probably one of the most important reactions producing cordierite in felsic igneous rocks.

Type 2 Magmatic: (b) Peritectic ($T\downarrow$ and/or $P\downarrow$). A second type of peritectic magmatic reaction occurs in

which cordierite appears in response to falling temperature and/or pressure. Figure 1 shows that drops of pressure across several reaction boundaries can produce cordierite, possibly as reaction rims on other phases (particularly garnet and aluminosilicate) in rapidly ascending magmas, or even in isobarically cooling granites. Some reactions are:



Examples of this type, in which cordierite occurs as a reaction rim on garnet, include: Velay granite (Weber *et al.*, 1985) (Fig. 3c); Violet Town volcanics (Clemens and Wall, 1984) (Fig. 3d); Strathbogie

batholith (Phillips *et al.*, 1981); and Bavarian Forest (Propach and Gillessen, 1984). That many of these reactions (11–14) may go to completion, especially in the case of isobaric cooling, could explain the relative scarcity of this type of cordierite. The cordierite so produced, may be indistinguishable from Type 2c cordierites below.

Type 2 Magmatic: (c) cotectic — fluid undersaturated. In theory, at least, the overlap between the stability fields of cordierite and granitic magmas suggests that cordierite can nucleate directly from a silicate melt. The problem is to distinguish this type from all the others (xenocrysts, restites, peritectic magmatic). Whereas a non-descript, anhedral to euhedral cordierite megacryst in a granitic rock may have a number of possible origins, an inclusion-

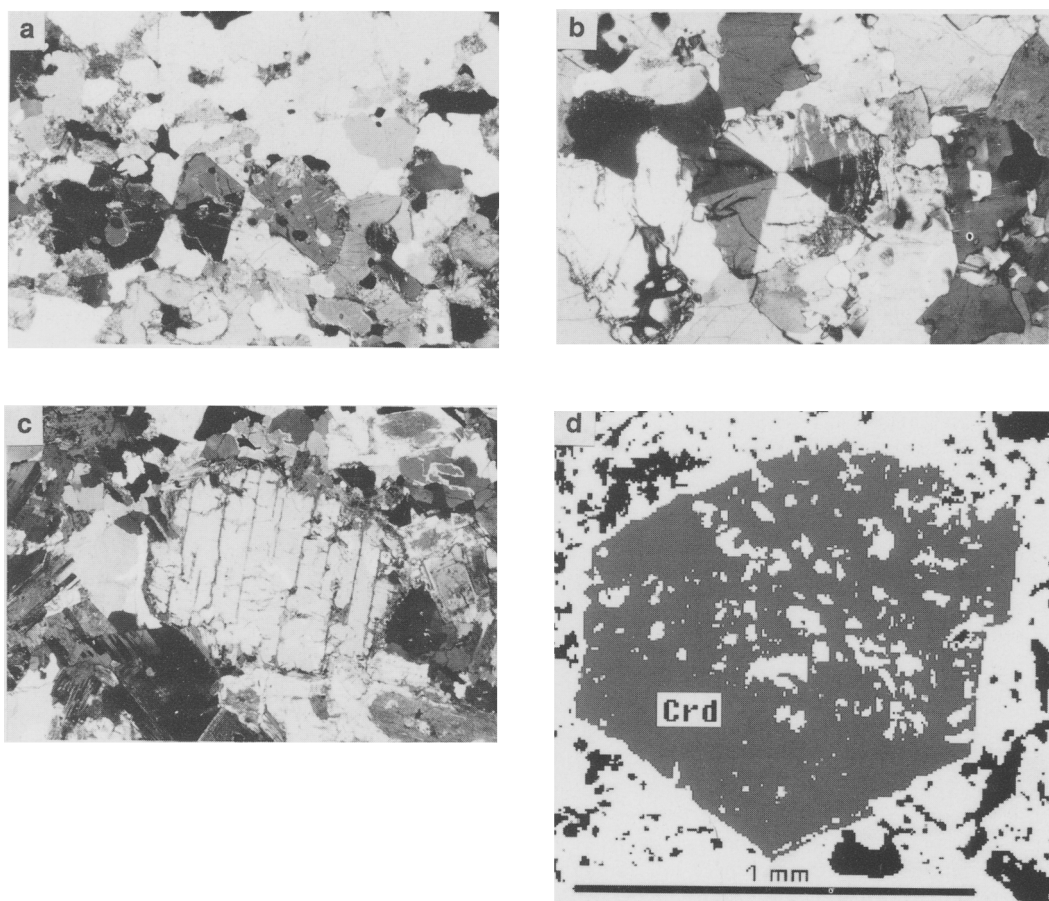
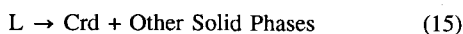


FIG. 4. Type 2c cotectic magmatic cordierites. (a) Sample KM79-043e. Euhedral sixling, 2 mm in diameter, in leucosome of Kelly's Mountain migmatite. (b) Sample 103-A5. Euhedral sixling, 0.5 mm in diameter, in South Mountain batholith aplite. (c) Sample D15-0056. Large (8 mm) subhedral prismatic cordierite with good (001) parting in Musquodoboit batholith, Nova Scotia. (d) Euhedral microphenocryst in Violet Town volcanics (after Clemens and Wall, 1984).

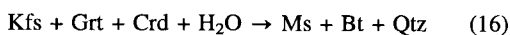
free, anhedral to euhedral cordierite, in textural equilibrium with quartz and feldspars in an aplite or rhyolite bearing no evidence of contamination, is much less problematic. If any cordierite is magmatic cotectic, this type should be.

Examples include euhedral cordierite sixlings from the Kelly's Mountain migmatite (R. A. Jamieson, pers. comm., 1993) (Fig. 4a) and from an aplite in the South Mountain batholith (M. A. MacDonald, pers. comm., 1993) (Fig. 4b); the Musquodoboit batholith, Nova Scotia (Fig. 4c); euhedral cordierite without any spatial relationship either to the contacts of the Halifax Pluton or the abundance of xenoliths (MacDonald and Horne, 1988); the Dartmoor granite (Brammall and Harwood, 1932); euhedral cordierite in peraluminous granite plutons of the southern Appalachians (Speer, 1981); Type A cordierite in the Strathbogie batholith (Phillips *et al.*, 1981); and Type A euhedral cordierite phenocrysts in the Violet Town volcanics (Clemens and Wall, 1984) (Fig. 4d).

Nucleation of cordierite in the magmatic cotectic environment is simply a case of the silicate melt reaching saturation in cordierite through changes in T , P , or X (reaching an appropriate chemical composition, favoured by high A/CNK, high $\Sigma(\text{Mg}+\text{Fe}^{2+})$, and generally low $f_{\text{H}_2\text{O}}$, by some process such as fractional crystallization). With a large field of overlap between the stability fields of cordierite and granitic melts in T - P space, and with cordierite stable down to the solidus temperature in most cases, the reaction must approximate



Zen (1989) identified the critical reaction involving several AFM minerals as



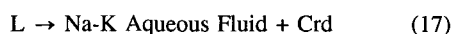
The addition of water to the left side of the equation converts 'dry' Crd \pm Grt-bearing granites to 'wet' two-mica granites; in other words they are compositional equivalents except for the amount of water. This is a first-order approximation to the differences between exotic Crd-Grt granites and common Bt-Ms (two-mica) granites.

Type 2 Magmatic: (d) cotectic — fluid saturated. Zen (1989) noted the association of cordierite with water-undersaturated granitic melts. Indeed, in many cordierite-bearing plutons, cordierite belongs to the early stages of crystallization prior to saturation in an aqueous vapour phase. The occurrence of cordierite in pegmatites, however, limits the usefulness of the generalization that cordierite necessarily signifies 'early and dry'; it may also mean 'late and wet'.

Cordierite can occur in small pegmatitic 'sweats' in cordierite-bearing granulite facies rocks (Thomson, 1989) or in large zoned pegmatites

associated with peraluminous granites (Fig. 5a-c). Individual cordierite crystals may range in size from millimetres to metres, and they commonly occur near the quartz-rich cores of the pegmatites (Heinrich 1950; Goad and Černý, 1981; Povondra *et al.*, 1984). Their widespread occurrence in pegmatites, commonly in association with other characteristic peraluminous minerals such as aluminosilicates, spinel, corundum, tourmaline, dumortierite, topaz, beryl, pyrophyllite and diasporite, suggests conditions highly favourable for nucleation in the fluid-saturated magmatic system. But is the role of the super-critical aqueous fluid phase as a medium for precipitation, or is it as an agent to modify the silicate melt composition?

Deduced origins for cordierite in pegmatites include xenocrystic (Schumacher, 1990), direct crystallization from the pegmatitic fluid locally contaminated by Al and Mg from biotite gneisses (Gordillo *et al.*, 1985), and direct crystallization from the pegmatitic melt phase as a result of alkali loss (Goad and Černý, 1981). Excluding cordierite of demonstrably foreign origin, the common thread linking other occurrences appears to be a change in the bulk chemical composition of the fluid-magmatic system, resulting from extensive Rayleigh distillation of alkalis into the highly mobile and fugitive fluid phase. In this case, the residual silicate melt may experience a considerable increase in A/CNK with alkali loss resulting in its somewhat unexpected saturation in cordierite. A general equation is:

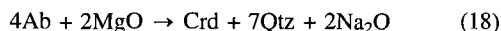


Although $a_{\text{H}_2\text{O}} \approx 1$, the formation of cordierite occurs because loss of K from the silicate melt makes the formation of biotite unlikely. The role of the aqueous fluid phase is significant in two respects: it abruptly raises the A/CNK of the melt, and it facilitates chemical migration of elements to produce the large cordierite crystals characteristic of some pegmatites (Heinrich, 1950). This fluid-loss process for the formation of cordierite probably explains the zones of cordierite in pegmatites better than a magmatic cotectic (Type 2c) process, as might occur in the type of pegmatitic system envisaged by London (1992).

Metasomatic — formation as the result of solid-fluid reactions

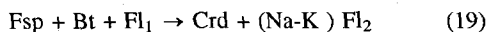
Type 3: metasomatic — subsolidus. Only two types of cordierite can occur in association with a felsic silicate melt (Type 1 metamorphic and Type 2 magmatic, described above). However, another variety occurs so intimately with granites and pegmatites that it requires discussion here. Černý *et*

al. (1967), and Černý and Povondra (1967), described fracture-controlled 'chains' of cordierite crystals cutting across the primary internal zoning of pegmatites of west Moravia (Fig. 6*a*). Černý and co-workers suggested that this cordierite is the product of the reaction



in which the source of the MgO could be closed system within the pegmatite (autometasomatic), or open system (originating from the MgO-rich serpentinite wall rocks). Note that this reaction potentially yields cordierite-quartz intergrowths. In another example, Didier and Dupraz (1985) described nodules (1–10 cm) of poikilitic

(poikiloblastic?) cordierite containing inclusions of quartz in the Velay granite of the Massif Central. The nodules concentrate along structural discontinuities in the host granite and are surrounded by leucocratic (biotite-free) zones (Fig. 6*b*). Didier and Dupraz speculated that CO₂-rich fluids at near-solidus temperatures exploit structural weaknesses in the granite and promote formation of cordierite. Although they did not attempt to write the reaction, it must be similar to



The leucocratic haloes around the cordierite nodules attest to the consumption of biotite from a volume of rock larger than currently occupied by the nodule.

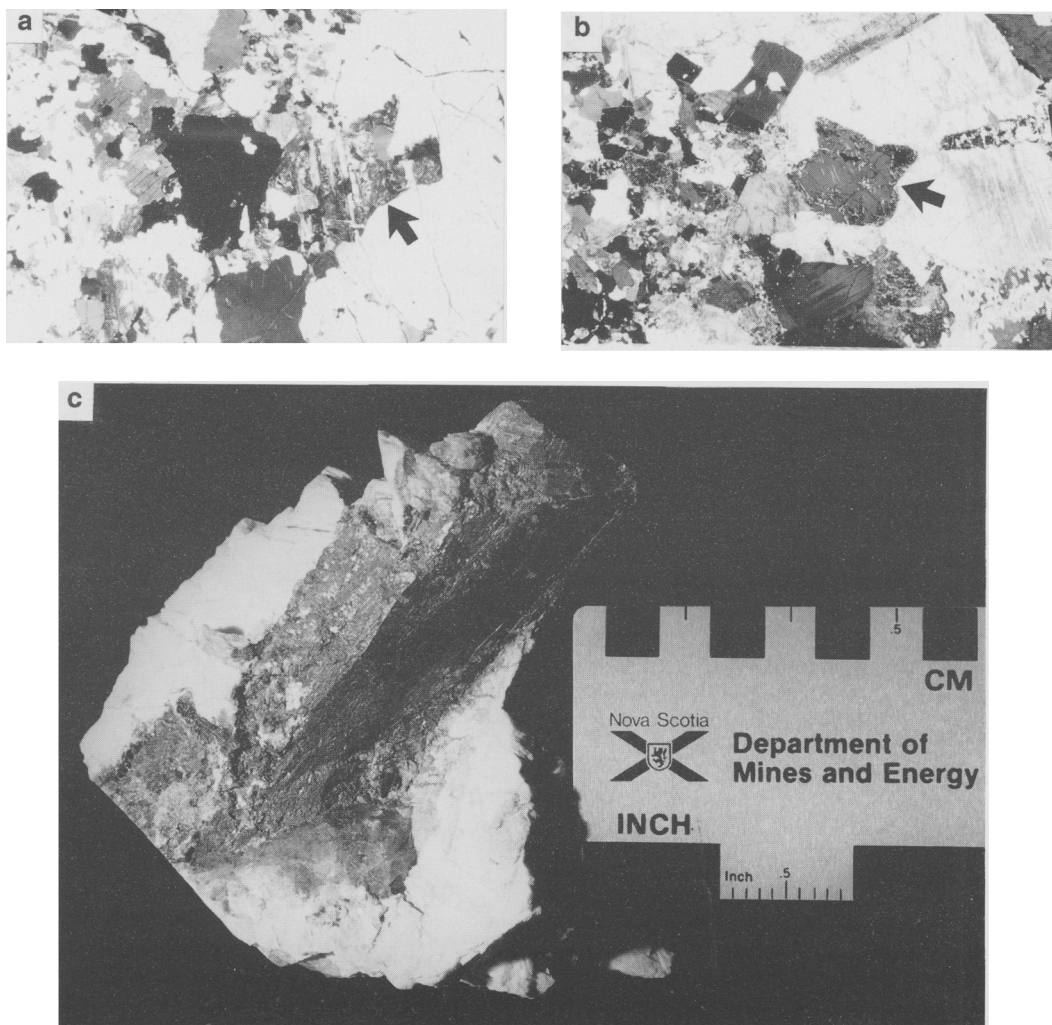


FIG. 5. Type 2d pegmatitic cordierites. (*a, b*) Samples D15-0640 and 103-P7. Anhedrous cordierites (arrows) growing from an aplite-pegmatite contact into the coarse-grained pegmatite, South Mountain batholith (widths of photos 8 mm and 18 mm, respectively). (*c*) Large euhedral cordierite from pegmatite, South Mountain batholith.

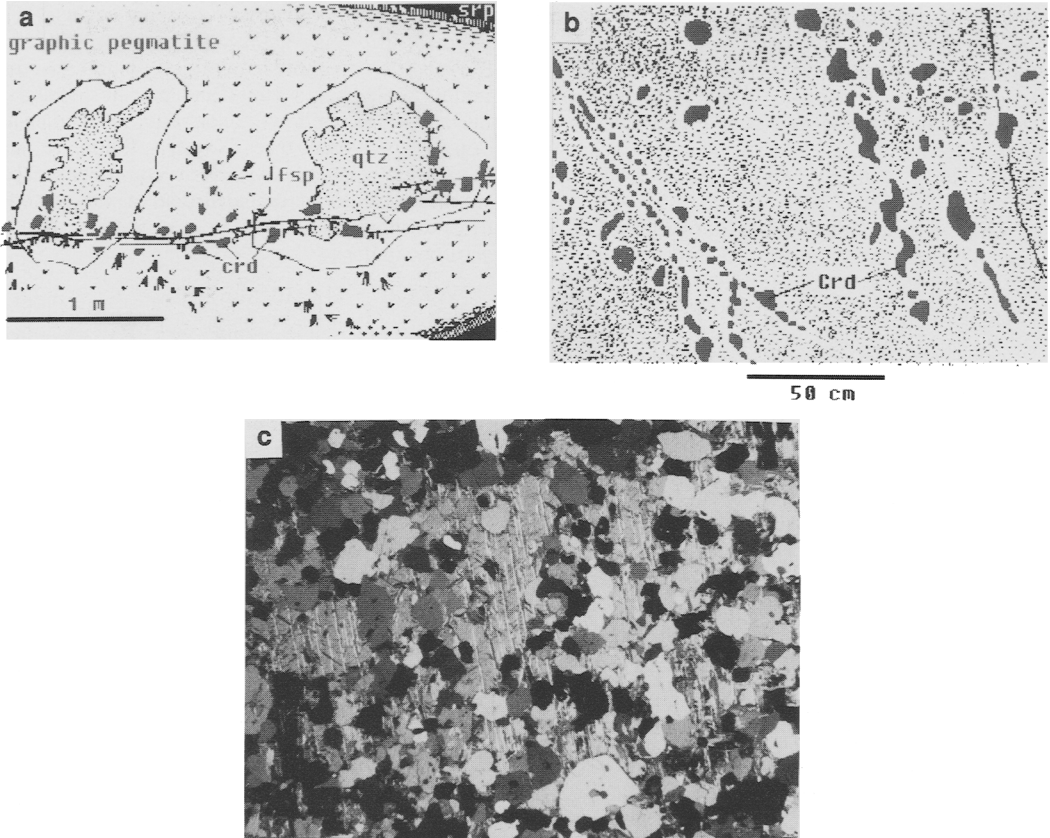
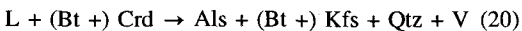


FIG. 6. Type 3 metasomatic cordierites. (a) Euhedral and ovoid cordierites associated with cross-cutting fracture in the Vezna pegmatite (after Černý and Povondra, 1967). (b) Cordierite pods associated with microshears in the Intres granite, Massif Central (after Didier and Dupraz, 1985). Note the leucocratic, biotite-free haloes around each cordierite. (c) Sample M79-085. Metasomatic cordierite, with (001) parting and rich in anhedral quartz inclusions, in aplitic, Musquodoboit batholith, Nova Scotia (width of photo 12 mm).

Type 3 metasomatic cordierite may not be particularly common, but because it is secondary, it may occur anywhere in the felsic igneous system; all that is required for its formation is fluid, feldspar, and a source of Fe-Mg (e.g. in an aplitic, Fig. 6c).

Breakdown of cordierite

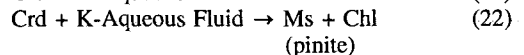
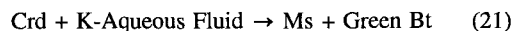
Cordierite crystals in felsic igneous rocks are rarely pristine or euhedral, making assignment of their origin into Types 1–3 difficult. Again, in simple terms, elimination of cordierite begins whenever it leaves its own T – P – X stability field. This departure may occur above the appropriate ‘granite’ solidus in a reaction such as



e.g. as occur in the Musquodoboit batholith (Abbott

and Clarke, 1979), in the Bavarian Forest (Propach and Gillessen, 1984), and at Cooma (Ellis and Obata, 1992). The occurrence of cordierite with a corona of andalusite and biotite is a useful general geobarometer because such a reaction must occur at pressures greater than X (Fig. 1), however the position of X is not independent of compositional parameters in P – T space, although it probably should be less than 4 kbar.

Other reactions to eliminate cordierite may occur under subsolidus conditions with reactions such as:



The irony of these breakdown processes is that they are complementary to those that produce Type 2d cordierites; in other words, the same fluids that are

indirectly responsible for the formation of cordierite in aplite-pegmatite systems may destroy Types 1a-2c cordierite elsewhere in the same pluton. Unfortunately, these processes not only degrade the textural and chemical features that permit determination of the origin, but also they may proceed to the point where even the prior existence of cordierite cannot be easily recognized. Figure 7 illustrates several types of cordierite breakdown reactions.

Problematic cases

Several different types of problem arise with reliance on this spatial-textural classification of cordierite in felsic igneous rocks: (1) various types of alteration (say, to 'pinite') may obscure genetic relationships; (2) absence of chemical parameters, particularly trace element profiles, and knowledge of the chemical compositions of cordierite and their coexisting

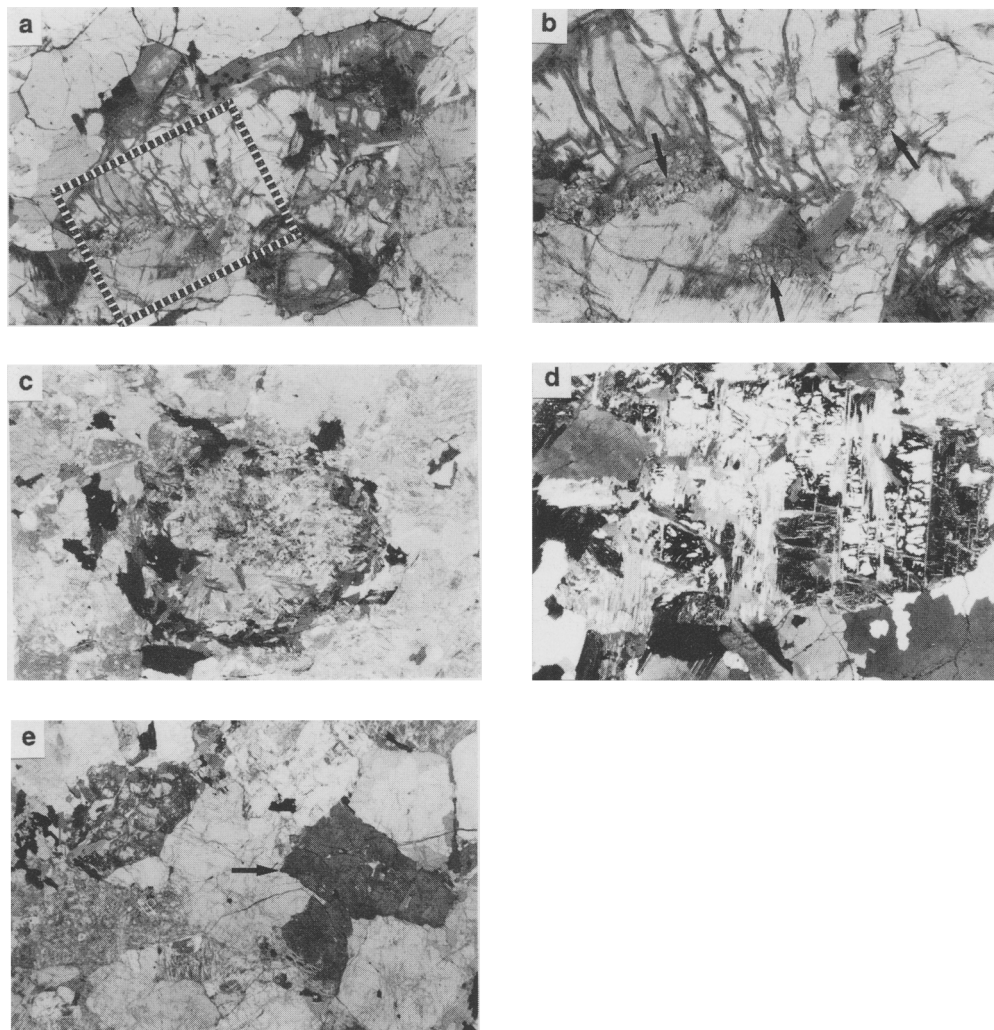


FIG. 7. Cordierite breakdown reactions. (a) Sample D15-0560. Cordierite \rightarrow Andalusite + Biotite. Anhedronal grain of cordierite partially broken down to a mixture of biotite and granular andalusite, Musquodoboit batholith (width of photo 7 mm). (b) Detail of (a) showing andalusite (arrows). (c) Sample M79-032. Cordierite \rightarrow Biotite. Anhedronal grain of cordierite, 8 mm long, with wide reaction rim of biotite, Musquodoboit batholith. (d) Sample D15-0439. Arrested reaction Cordierite \rightarrow Muscovite + Chlorite (Pinite), Musquodoboit batholith (original grain 9 mm long). (e) Sample D15-0545. Completed reaction Cordierite \rightarrow Muscovite + Chlorite (Pinite), South Mountain batholith (grain with arrow 7 mm long).

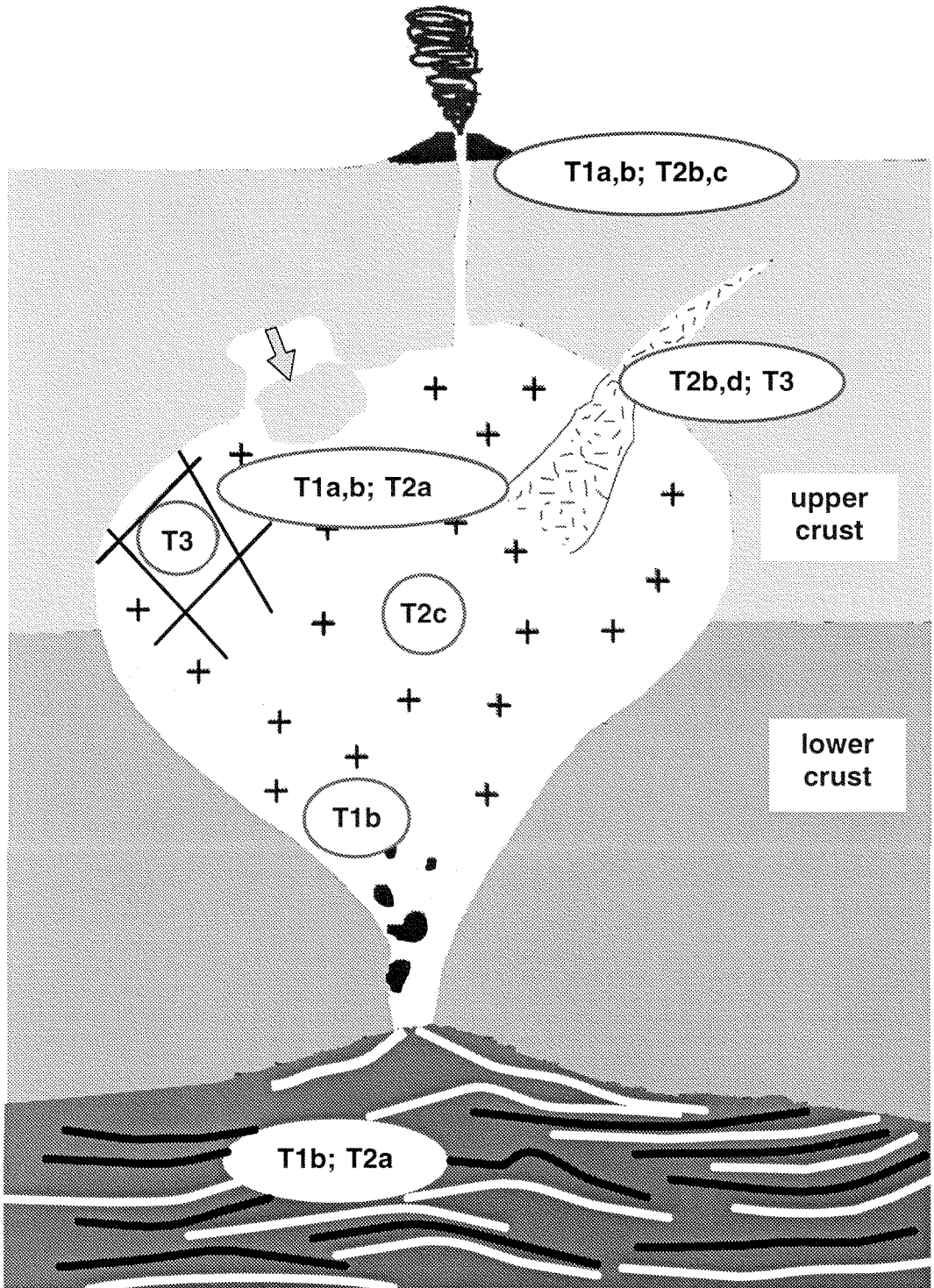


FIG. 8. Cross-section showing overlapping environments of cordierite occurrences in felsic igneous rocks.

phases, both of which may yield useful information about attainment of equilibrium, zoning, growth history, and P - T conditions of formation, restricts the usefulness of this classification; (3) random sections of cordierite grains may not reveal diagnostic features such as inclusions of sillimanite or spinel; (4) a potentially large variety of cordierite xenocrysts, ranging from anhedral and poikiloblastic to possibly euhedral and inclusion-free (in fact, all of Types 1-3), greatly complicates the simple two-fold (xenocrystic, restitic) model presented here; and, most importantly (5) several types of cordierite can cross physical and, therefore, classificatory boundaries (for example, a Type 2a magmatic peritectic cordierite, formed in a melting reaction, may become a Type 2c magmatic cotectic cordierite after more extensive melting, or a Type 1a metamorphic xenocrystic or Type 1b metamorphic restitic cordierite may also become the core of a later Type 2c magmatic cotectic cordierite).

Nevertheless, spatial and textural relations have much to offer toward a first-order interpretation of the occurrence of cordierite in felsic igneous rocks.

Summary and conclusions

The type of analysis of cordierite types presented in this paper (i.e. classification on spatial and textural criteria, definition of T - P - X space, examination of reactions, relation to genetic types) is easily adaptable to any AFM mineral (Bt, Ms, Crd, Als, Grt, etc.) in peraluminous igneous rocks (in fact, to any mineral in any rock). The types are probably similar, the T - P - X spaces are different but overlap to some extent, and the reactions have both theoretical and experimental validity.

Partial melting of pelitic material under high pressure in the middle to lower crust probably results in the formation of peraluminous granitic melts in equilibrium with garnet, not cordierite (Green 1976; Vielzeuf and Holloway, 1988). Ascent brings those melts into the stability field of cordierite. Alternatively, partial melting of pelitic material under lower pressures in the middle to upper crust results, in many cases, in the formation of cordierite in the same peritectic reaction that forms the peraluminous melt phase.

In practice, the xenocrystic mechanism of cordierite formation must occur, however it is probably not the most important process. True restitic cordierite is probably rare in large, high-level granite plutons, owing partly to the mechanical problem of entraining significant amounts of dense restite over vertical distances of 10-20 km, and partly to the fact that restitic cordierite is unlikely to occur at $P > 6$ kbar (≈ 20 km). Occurrences of pegmatitic and metasomatic cordierite represent

volumetrically small special cases. Probably the single most important reason for the occurrence of cordierite in peraluminous felsic igneous rocks is the multitude of cordierite-producing melting reactions in pelitic and semi-pelitic rocks, however magmatic cordierites are an almost inevitable crystallization product of these peraluminous magmas as they ascend into the upper crust. Figure 8 demonstrates the high degree of spatial overlap of the various cordierite types in a single hypothetical pluton.

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