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GARNET-FORMING AND GARNET-ELIMINATING REACTIONS IN A QUARTZ DIORITE INTRUSION AT CAPO VATICANO, CALABRIA, SOUTHERN ITALY

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Abstract

Late Hercynian peraluminous granitoids (quartz diorite, tonalite, and granodiorite) intrude amphibolite–granulite-facies country rocks in the Capo Vaticano area, Calabria, southern Italy. Small (1 cm in diameter) grains of garnet occur in kinzigitic gneisses and amphibolites in the country rocks, but they are rare to absent in the intrusive rocks, except for one quartz diorite pluton that contains up to 15% modal garnet. Field relations, textural relations, compositional ranges, and chemical zonation profiles of the garnet grains indicate how these grains nucleated, grew, and eventually disappeared. Within the quartz diorite pluton, garnet occurs in metasedimentary enclaves, particularly in the leucosomes associated with their apparent partial melting, suggesting a formation reaction of the type: Pl + Bt + Crd + Als + Pl + Qtz $\rightleftharpoons$ L + Grt ± Kfs. This reaction may or may not have begun with pre-existing nuclei of garnet in the metasedimentary rocks. With subsequent disintegration and assimilation of these enclaves into the magma, the garnet grains occur as large (up to 4 cm diameter), discrete, euhedral crystals, apparently in chemical equilibrium with the melt fraction. Most garnet associated with metasedimentary material, or isolated in the quartz diorite, has similar Mn profiles (higher concentrations in the cores and rims than between the core and rim). Elsewhere in the quartz diorite, garnet crystals occur as irregular grains with a wide corona of biotite and tschermakite, suggesting an elimination reaction of the type: Grt + L $\rightarrow$ Bt + Ts. Although garnet grains in other granitoid rocks may be entirely of xenocrystic or magmatic origin, their occurrence in the Capo Vaticano quartz diorite demonstrates formation principally through a melting reaction in metasedimentary enclaves. The later elimination of this garnet occurs at a peritectic reaction resulting from open-system assimilation of the anatectic melt and garnet in the larger body of quartz dioritic magma.

Keywords: garnet, xenolith, magmatic, quartz diorite, partial melting, tschermakite, Capo Vaticano, Calabria, Italy.

Sommaire

Une suite de roches granitiques hyperalumineuses (diorite quartzifère, tonalite et granodiorite) a été mise en place dans des roches hôtes recristallisées dans le facies amphibolite – granulite dans la région de Capo Vaticano, en Calabre, Italie. De petits grains de grenat (1 cm de diamètre) sont présents dans le gneiss kinzigitique et l'amphibolite des roches hôtes, mais ils sont rares, voire même absents dans les roches intrusives, à l'exception des roches d'un petit pluton de diorite quartzifère, qui contient jusqu'à 15% de grenat par volume. Les relations de terrain, les textures, l'ensemble des compositions et le profil des cristaux zonés révèlent certains détails à propos de la nucléation, la croissance, et la disparition de ces cristaux. Au sein du pluton de diorite quartzifère, le grenat se trouve dans des enclaves métasédimentaires, et particulièrement dans le leucosome, résultat apparent de la fusion partielle. Sa présence suggère une réaction du genre Pl + Bt + Crd + Als + Pl + Qtz $\rightleftharpoons$ L + Grt ± Kfs. Cette réaction pourrait (ou non) avoir débuté avec des nucléus de grenat dans les enclaves métasédimentaires. Avec la désintégration et l'assimilation éventuelle de ces enclaves dans le magma, les grains de grenat apparaissent sous forme de cristaux idiomorphes distincts et grossiers (jusqu'à 4 cm) qui seraient en équilibre chimique avec la fraction liquide. La plupart des cristaux de grenat associés au matériau métasédimentaire, ou isolés dans la diorite, font preuve d'un profil semblable dans la répartition du Mn (teneur plus élevée dans le coeur et la bordure que dans les parties intermédiaires). Ailleurs dans la diorite quartzifère, les cristaux de grenat se présentent en grains irréguliers ayant une couronne volumineuse de biotite et de tschermakite, ce qui témoignerait d'une réaction du type Grt + L $\rightarrow$ Bt + Ts. Quoique les grains de grenat dans les autres massifs granitiques pourraient bien avoir une origine entièrement xénocristique ou magmatique, leur présence dans la diorite quartzifère de Capo Vaticano démontre un mode de formation par réaction de fusion des enclaves métasédimentaires. La disparition éventuelle du grenat impliquerait une réction péritectique découlant de l'assimilation en système ouvert du liquide anatectique et du grenat dans le volume plus important de magma dioritique quartzifère.

(Traduit par la Rédaction)

Mots-clés: grenat, xénolithe, magmatique, diorite quartzifère, fusion partielle, tschermakite, Capo Vaticano, Calabre, Italie.

Introduction

Garnet can occur in both metaluminous and peraluminous granitoid rocks, but usually only as an accessory phase. Its stability is a complex function of temperature and pressure (Abbott & Clarke 1979, du Bray 1988, Green 1977, Clemens & Wall 1981), and many compositional parameters, including Al-oversaturation, Mn content, $f(H_2O)$, $f(O_2)$, and $f(F)$ (Abbott 1981, Clarke 1981, Miller & Stoddard 1981, Zen 1988, 1989). As a result, the origins of garnet in granites include: *restitic* (Stone 1988), *xenocrystic* (Allan & Clarke 1981, Pattison *et al.* 1982, Plimer & Moazez-Lesco 1980), *anatectic* (Clark & Lyons 1986, Hogan & Dickenson 1986, Hartel *et al.* 1990), *primary magmatic* (Miller & Stoddard 1981, du Bray 1988), *fluido-magmatic* (Baldwin & von Knorring 1983, Manning 1983), *metasomatic* (Calzetti & Zeda 1980, Kontak & Corey 1988), and even *postmagmatic metamorphic* in some varieties of orthogneiss.

In the Capo Vaticano area, some of the basement rocks (kinzigitic gneisses and amphibolites), and many of the granitoid rocks (quartz diorite, tonalite, and granodiorite), contain garnet in highly variable modal proportions (up to 15 volume %), and with variable textural features and chemical compositions (Rottura *et al.* 1986, 1991, 1993). In this paper, we examine the range of garnet types in both the granitoid rocks and their xenoliths, and compare their occurrence, textures, and compositions with garnet from the kinzigitic (bt–sil–grt) gneisses and amphibolitic basement rocks to determine the history of garnet formation at Capo Vaticano. In some of the granitoid rocks, the garnet grains have extensive coronas of biotite and amphibole. We contend that most of the garnet formed during melting of paragneiss xenoliths, and that magma mixing resulted in a reaction relationship which then began to eliminate the garnet.

Geological Setting

The Capo Vaticano Promontory belongs to the Calabrian Arc, an Alpine belt of stacked nappes linking the Apennines and the Maghrebian chain of Sicily (Fig. 1). Within this arc is a segment of the Hercynian of southwestern Europe that contains metamorphosed (very low grade to granulite facies) basement rocks of Paleozoic to Precambrian age (*e.g.*, Amodio Morelli *et al.* 1976, Scandone 1982). The Late Hercynian (*ca.* 295 Ma) Capo Vaticano granitoids intrude this basement, and crop out discontinuously beneath a Miocene–Quaternary cover over an area of *ca.* 270 km^2. Their modal compositions include quartz diorite, tonalite, and granodiorite, and their chemical compositions range from metaluminous to peraluminous.

In the S. Maria – Ioppolo area, quartz diorite occurs in a fault block (Fig. 1), but elsewhere in the region quartz diorite forms a marginal facies of the granitoid plutons (Caggianelli & Di Florio 1989). Two types of quartz diorite occur in this area: the first type is dominantly plagioclase-rich (An_{47-57}, 64 vol. %), with interstitial biotite, quartz, magnesian cummingtonite – tschermakite pairs, and minor accessories, and the second type consists of small biotite-rich (45 vol. %) masses and pods occurring mainly in the tonalites, with plagioclase (An_{46-60}; *ca.* 40 vol. %), minor quartz, and magnesian cummingtonite – magnesian hornblende intergrowths (Rottura *et al.* 1990). The first type of quartz diorite contains centimeter- to

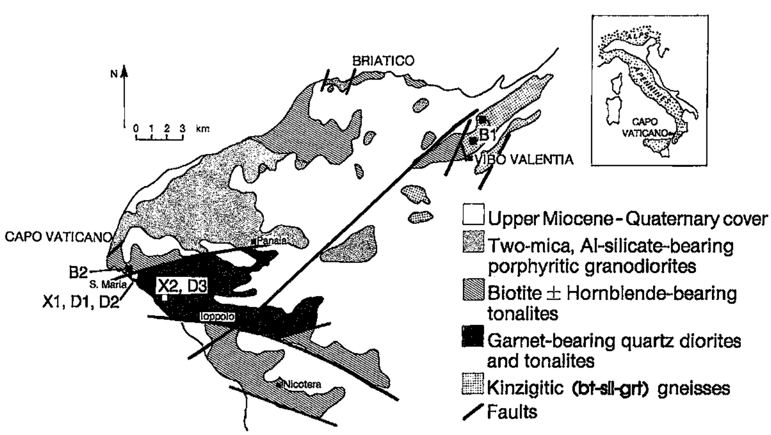

FIG. 1. Geological map of the Capo Vaticano area showing the distribution of basement rocks, granitoid plutons, and sampling localities.

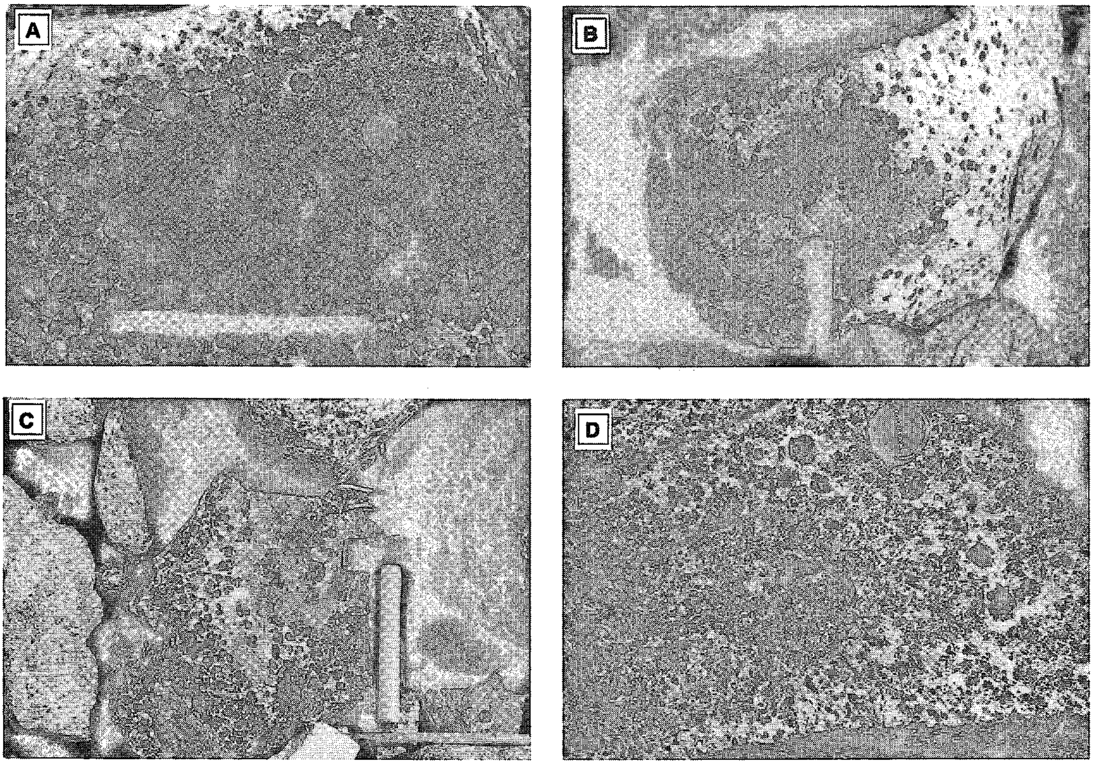

FIG. 2. Field occurrences of garnet in the Capo Vaticano area. A. Necklace of garnet grains around a metapelitic xenolith in quartz diorite at locality X1. B. Isolated euhedral garnet grains spalling off xenolith into melt phase at locality X1. C. Garnet-rich leucosomes in pelitic xenoliths at locality X1. D. Garnet with leucocratic halo in melt fraction containing strongly reacted enclaves at locality X2.

meter-sized xenoliths of amphibolite and metapelitic (40% pl, 24% bt, 12% qtz, 3% crd, <3.5% sil, <4% and, <3% st; Fig. 2) xenoliths related to the upper part of the Serre lower crustal section (Maccarrone *et al.* 1983, Schenk 1984, 1989).

Abundant large crystals of garnet occur in the plagioclase-rich quartz diorite, commonly in close spatial association with the metapelitic xenoliths. The grains of garnet in the quartz diorite are normally euhedral, but some have a corona of biotite and amphibole; those in the metapelitic xenoliths generally have a leucocratic halo of plagioclase with minor quartz and biotite.

TEXTURAL CLASSIFICATION OF GARNET

On the basis of sample location and textural type, seven types of garnet occur in the Capo Vaticano area (Table 1): two belong to the basement rocks (B1, B2), two occur in metapelitic xenoliths in the quartz diorite host (X1, X2), and three occur as isolated grains in the quartz diorite without accompanying xenoliths (D1, D2, D3).

Figure 3 shows hand specimens and photomicrographs of each type of garnet. The garnet grains in the kinzigitic gneisses and amphibolite are generally subhedral and contain few inclusions, whereas those associated with the quartz diorite, either in xenoliths or as isolated crystals, are subhedral to euhedral and commonly have more inclusions in their core than in their rim. Inclusions in garnet of the basement rocks are anhedral; inclusions in garnet of the xenoliths and quartz diorite are commonly lobate.

CHEMICAL CHARACTERISTICS OF THE GARNET

Analytical technique

Garnet compositions were determined by combined wavelength- (Mn) and energy-dispersion analysis (all other elements) on a JEOL733 electron microprobe using an accelerating voltage of 15 kV, a beam current

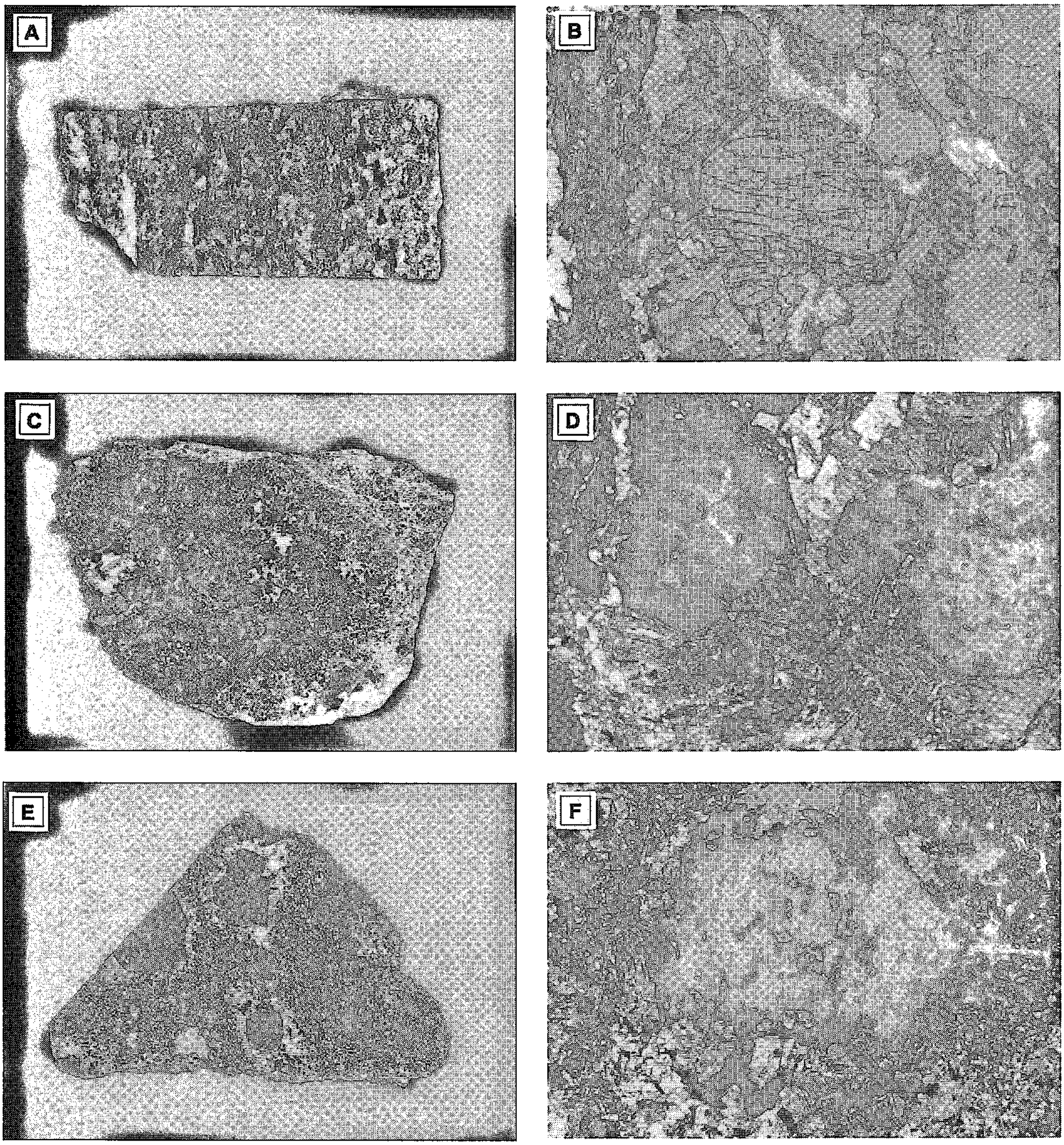

FIG. 3. Hand-specimen photographs and photomicrographs of garnet types at Capo Vaticano. Refer to Table 1 for detailed descriptions. A, B. Kinzigite (locality B1). C,D. Amphibolite (locality B2). E.F. Metapelite (locality X1).

of 12 nA, and counting times of 10–20 seconds. Precision on MnO determinations was ±0.03% absolute at the 1 wt% level.

Chemical compositions of garnet

Table 2 presents some typical garnet compositions, and Figure 4A shows that all grains of garnet from the Capo Vaticano region are almandine-rich. Figure 4B shows that garnet compositions in the kinzigitic gneiss (B1) and amphibolite (B2) basement rocks do not overlap, and thus represent independent lithological sources. Garnet grains associated with the metapelitic xenoliths (X1, X2) generally show extensive compositional variation, much of which is internal zoning within individual crystals (Fig. 4C). Garnet occurring as separate crystals in the quartz diorite (D1, D2, D3) also show extensive compositional variation related

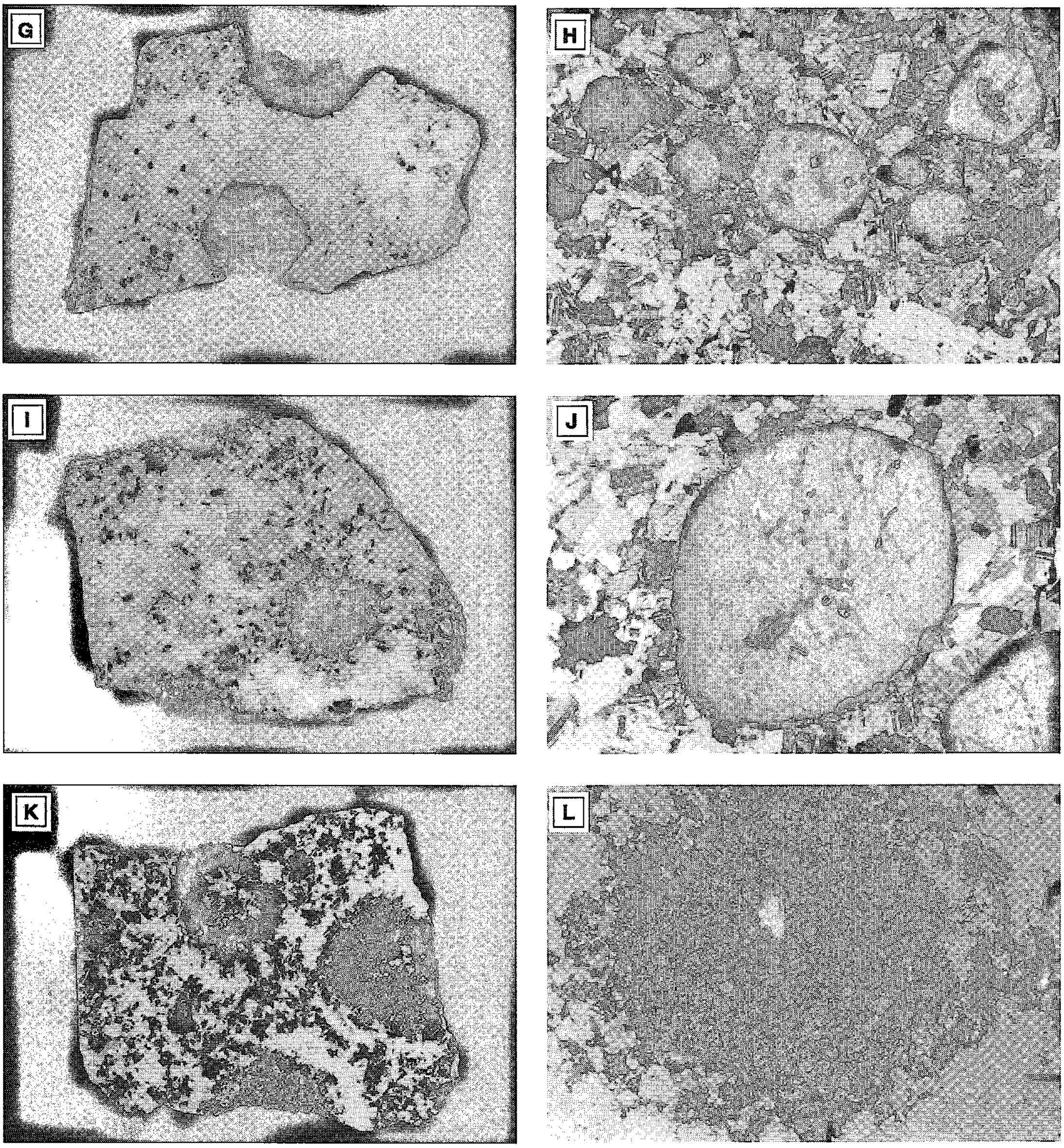

FIG. 3 (continued). G,H. Euhedral garnet in quartz diorite (locality D1). I,J. Garnet with biotite rim in quartz diorite (locality D2). K,L. Garnet with reaction rim of biotite and tschermakite (locality D3). All hand-specimen photographs taken at the same scale (nearly complete garnet in G is 2.5 cm in diameter).

mainly to internal zoning in individual grains (Fig. 4D). The few Mn-poor unzoned grains of garnet in quartz diorite (D1, D2) could be derived from basement rocks, or they could just represent sections through outer parts of zoned grains that do not intersect the Mn-rich core. The Ca–Mn-poor parts of all zoned grains of garnet in the xenoliths and quartz diorite (X1, X2, D1) overlap in composition with those from the basement rocks (B1, B2), but these low-Ca–Mn compositions are not found in the *core* of the garnet grains, such that basement garnet is not likely the *nucleus* for garnet in the quartz diorite. Two groups of garnet grains (D2, D3) have compositions that do not overlap with B1 garnet grains at the Mn-poor end; if they ever had such Mn-poor compositions, then either homogenization or loss of the Mn-poor rim through reaction has occurred. However, the high-Mn cores of D3 garnet grains suggest that

TABLE 1. CLASSIFICATION AND CHARACTERISTICS OF GARNET FROM THE CAPO VATICANO AREA

Field Label Map Location	Sample Numbers	Petrological Description (mineral abbreviations after Kretz 1983)	Profiles	General Style of Chemical Zoning C = Core, M = Midway to Rim, R = Rim U = U-shaped profile, W = W-shaped profile G = Gradual, S = Serrated MF = MgO/(MgO+MnO+FeO) (wt.%)
KINZG B1	CV:9-1, 9-2-1, 9-2-2 K:1, 2	kinzigitic (bt + sil + grt) paragneiss from Vibo Valentia and near S. Pietro di Bivona (Fig. 3A,B); inclusions of bt, pl, and qtz in grt	11	MnO(U,G): C 0.5, M 0.75, R 1.0 MF(G): C 0.3, R 0.25 (Fig. 5A)
AMPHB B2	CV:9-6-1, 9-6-2	garnet-bearing amphibolite from a fault zone at Capo Vaticano (Fig. 3C,D); inclusions of plagioclase and opaques	7	MnO: C 2.5, R 0.15 MF: C 0.25, R 0.10 (Fig. 5B)
TMGMX X1	CV:601, 605, G12, G20, G25a, G25b, G26, G29, 9-7-3, 9-7-4, 9-7-9	garnets associated with metapelitic xenoliths at Torre S. Maria beach (Fig. 3E,F); inclusions of bt, crd, and qtz concentrated in core and concentric in rims	14	MnO(W,S): C 0.5 R 1.0 MF(S): C 0.28 R 0.15 (Fig. 5C)
PIGMX X2	CV:G1A, G1B, G2, G3, G4, G5, G8, G10A, G10B	garnet-rich leucosomes in migmatitic metasedimentary xenoliths on Panaia - Ioppolo road; lobate inclusions of pl, bt, qtz	13	MnO(W,S): C 1.1, M 0.9, R 2.0 MF(U,G): C 0.15 R 0.25 (Fig. 5D)
TMGQD D1	CV:G11, G15, G18, G22, G23, 9-7-7, 9-7-12	isolated euhedral garnets in quartz diorite at Torre S. Maria beach (Fig. 3G,H); some grains nearly free of inclusions, others with lobate pl, bt, opaques	11	MnO(W,S): C 2.0, M 1.1, R 3.0 MF(S): C 0.33 R 0.15 (Fig. 5E)
TMGRB D2	CV:9-7-1	isolated garnets with biotite rims in quartz diorite at Torre S. Maria beach (Fig. 3I,J)	3	MnO(W,S): C MF(S): C 1.5, M 1.0, R 2.5
PIGRA D3	CV: G6, G7AA, G7AB, G7C, 89-8A	isolated garnets with amphibole rims in quartz diorite on Panaia - Ioppolo road (Fig. 3K,L); inclusions of bt, pl, qtz	9	MnO(W,S): C 4.0, M 2.0, R 4.0 MF(S): C 0.25 R 0.15 (Fig. 5F)

homogenization did not occur even at magmatic temperatures.

Table 3 shows the results of a multivariate discriminant function test for chemical similarity among the seven garnet groupings. If garnet compositions from each of the sample populations (B1, B2, X1, *etc.*) were unique, all data would fall on the diagonal from upper left to lower right. Instead, those that fall off the diagonal represent grains that have closer chemical affinities with some other population. Input data for the discriminant function analysis were the concentrations of FeO, MnO, MgO, and CaO, transformed by

TABLE 2. AVERAGE COMPOSITIONS OF GARNET FROM THE CAPO VATICANO AREA

Sample	All	All	G25a	G25a	G15	G15	G15	G7a	G7a	G7a
Type	B1	B2	X1	X1	D1	D1	D1	D3	D3	D3
Position	-	-	Core	Rim	Core	Mid.	Rim	Core	Mid.	Rim
n	70	45	9	3	11	11	5	11	7	7
SiO_2	38	37	37	36	37	38	38	37	38	37
TiO_2	0	0	0	0	-	-	-	-	-	-
Al_2O_3	22	21	21	21	21	22	22	21	22	21
FeO_T	32	32	31	34	31	31	31	29	31	32
MnO	1	2	1	2	2	2	2	4	2	5
MgO	6	5	7	4	6	6	6	6	6	4
CaO	1	2	2	2	2	2	2	3	2	2
Total	100	99	99	99	100	100	100	100	101	100

Electron-microprobe data (wt. %)

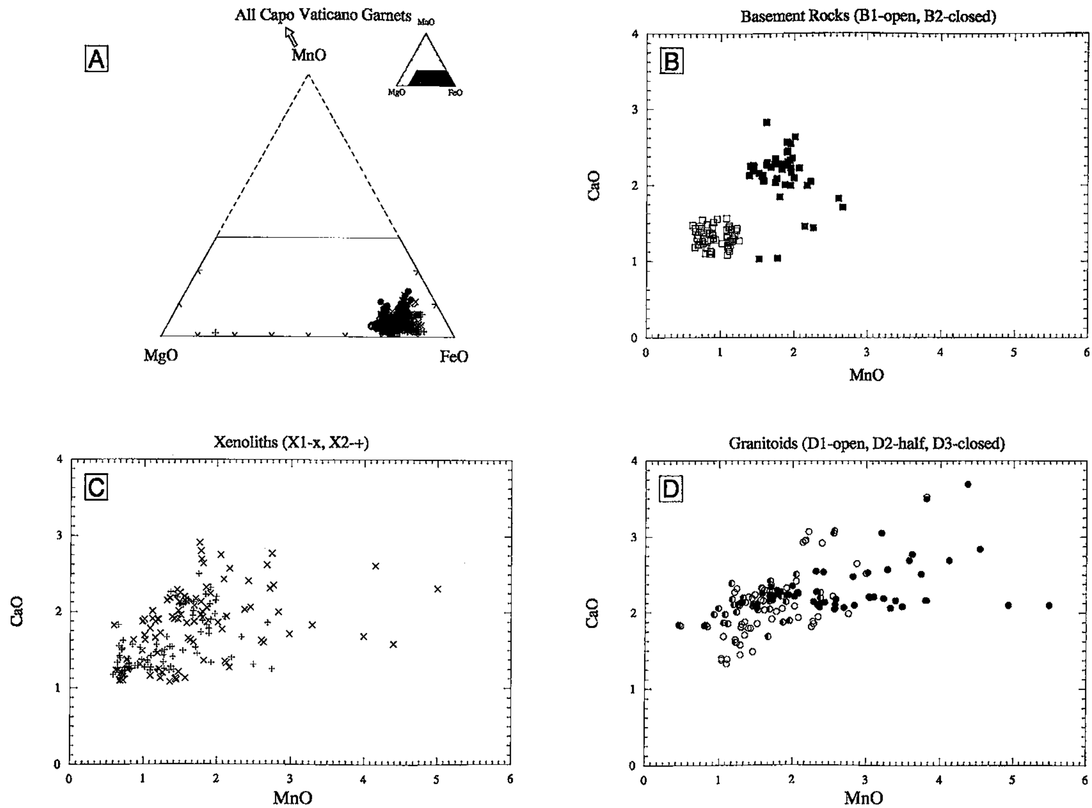

FIG. 4. Chemical compositions (in wt. %) of the seven types of garnet. Garnet grains in the basement rocks form discrete groups; much of the compositional variation in garnet grains in the xenoliths and granitoid rocks is due to internal zoning within single crystals.

the expression ln[(Oxide wt%)/(100–SiO_2)] to compensate for closure and any possible non-normal distributions. The results show the following: (i) the garnet from kinzigitic rocks (B1) is distinctive in the Capo Vaticano area; (ii) the compositions of garnet from amphibolitic basement (B2) also represent a reasonably distinctive grouping, but some of its members have compositions that classify in other groups; (iii) the garnet grains closely associated with xenoliths at Torre S. Maria (X1) do not form a clearly definable population, but rather resemble the X2 and D1 groups: (iv) the garnet grains associated with xenoliths (X2) along the Panaia – Ioppolo road form a reasonably distinct group, although they have strong affinities with B1, B2, and X1; (v) isolated grains of garnet in the quartz diorite (D1) at Torre S. Maria represent a reasonably distinct population, but with about half its members classifying in other groups; (vi) the samples of garnet grains with reaction rims of biotite in the quartz diorite (D2) overlap strongly with D1; and (vii) the isolated grains of garnet with amphibole coronas from the Panaia – Ioppolo road (D3) also form a reasonably distinctive group, but have strong affinities to the other isolated grains of garnet in the granitoid hosts (D1, D2). In general, discriminant function analysis only correctly classifies 49.5% of the Capo Vaticano garnet grains (only 41.2% not including the

TABLE 3. RESULTS OF DISCRIMINANT FUNCTION ANALYSIS

Predicted Group Membership

Field Classification	B1	B2	X1	X2	D1	D2	D3	Total	% Correct
B1	68	0	0	2	0	0	0	70	97
B2	4	32	1	1	1	3	3	45	71
X1	8	11	9	20	34	5	15	102	9
X2	13	17	11	50	4	0	0	96	52
D1	8	8	4	3	39	6	14	82	48
D2	1	7	2	0	10	2	4	26	8
D3	0	5	0	0	7	7	35	54	65
Total	102	80	27	76	95	23	71	475	

distinctive B1 group), suggesting strong similarities among the others and indicating possible common origins.

Compositional profiles across the garnet

Compositional profiles for garnet from the basement rocks (Figs. 5A,B) show weak smooth zonation in Mn. Garnet grains from all other associations (xenoliths at localities X1 and X2, and all quartz diorite samples at localities D1 and D3) show various degrees of "normal" zoning, from a Mn-rich core to Mn-poor intermediate positions, and then "reverse" zoning toward a Mn-rich rim (Figs. 5C–F). (As mentioned above, the absolute concentration of Mn in the "core" depends on whether the polished thin section passes through the body center of the crystal.) Also important is the serrated Mn pattern that characterizes many of the grains associated with the quartz diorite. These serrated and "W-shaped" Mn profiles, together

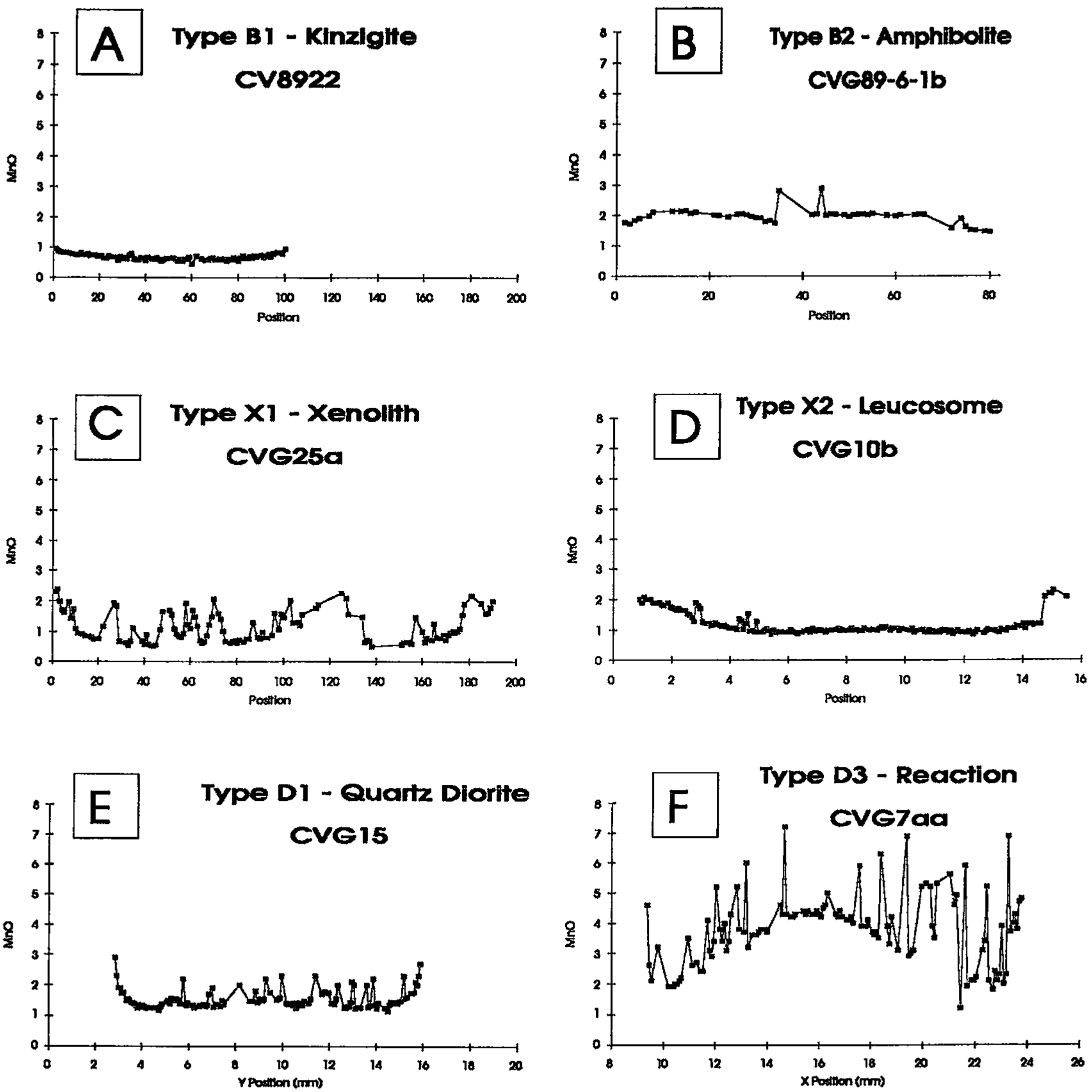

FIG. 5. Typical rim-to-rim chemical zonation profiles (in wt. %). A. Kinzigite (B1). B. Amphibolite (B2). C. Metapelite (X1). D. Garnet-rich leucosome (X2). E. Euhedral garnet in quartz diorite (D1). F. Garnet with reaction rim of biotite and tschermakite (D3). Spacing between analysis points on the compositional profiles is 0.1 mm, except where interrupted by alteration, cracks, or inclusions. Refer also to abbreviated chemical data in Table 1.

with the textural similarity of inclusions in the cores, indicate that many of these grains associated with the quartz diorite have a similar history, and suggest a common origin, as discussed below.

Evolutionary Histories of the Capo Vaticano Garnet Types

Garnet in the metamorphic rocks

Garnet occurring in the kinzigitic gneisses is almandine-rich, with low Mn and Ca contents. The grains show a large homogeneous core, with a narrow zoned rim (Figs. 5A,B), and a systematic variation in the stratigraphic sequence of metapelites, from magnesium-rich compositions at the base (X_{Mg} = 0.38) to more iron-rich compositions at the top (X_{Mg} = 0.19) (Schenk 1990). In the metabasites intercalated with the kinzigitic gneisses, garnet ($Alm_{60}Prp_{33}Grs_7$) occurs in association with anthophyllite (Ioppolo *et al.* 1978), whereas garnet and hornblende are mutually exclusive. Figure 5 and Table 3 show that the garnet of the kinzigitic gneisses (B1), and that of the amphibolites (B2), are compositionally distinct from garnet in the granitoid rocks, and thus garnet in the granitoid rocks is unlikely to represent xenocrysts derived from the basement rocks.

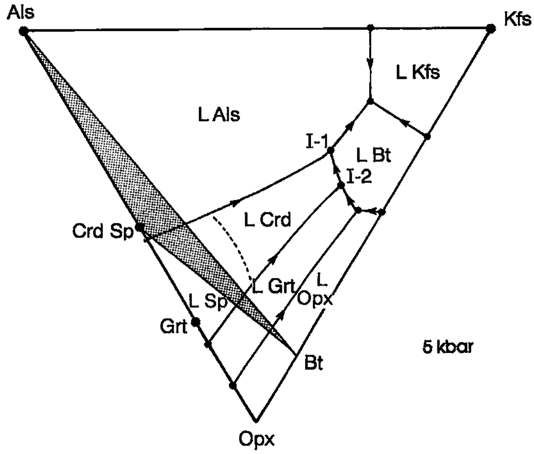

FIG. 6. Relationship in the pseudoternary system Als–Kfs–Opx (after Vielzeuf & Holloway 1988). Garnet appears as a product of melting of the metapelitic xenoliths at invariant point I–2 (see text for detailed explanation). The shaded area defines all bulk compositions with the assemblage Als–Bt–Crd that approximate the initial garnet-free assemblage in the metapelitic xenoliths before melting.

Garnet grains with "W-shaped" Mn profiles

Figure 6 is the experimentally determined, pseudoternary phase diagram at 5 kbar under conditions of $X_{Mg} \approx 0.5$, excess H_2O, and saturation in quartz (Vielzeuf & Holloway 1988). The metasedimentary xenoliths at Capo Vaticano probably had a primary regional metamorphic assemblage of Pl + Bt ± Qtz ± Als ± Crd. The number of phases now present depends on the bulk compositions and the degree of reaction, but plagioclase and biotite invariably are present. Heating of the initially garnet-free metasedimentary enclaves by the quartz diorite magma may have produced some melt and eliminated Als by the reaction Bt + Als + Qtz $\rightleftharpoons$ Crd ± Kfs + L at invariant point I–1 (Fig. 6). With further heating, the composition of the liquid would migrate along the L + Crd + Bt cotectic to invariant point I–2, where garnet first appears by the reaction Bt + Crd + Qtz $\rightleftharpoons$ Gnt ± Kfs + L. If the melt fraction were still low at this stage, or if the original metasedimentary assemblage were Als-free, the early garnet may contain many inclusions and show a pattern of normal zoning. This main melting reaction at I–2 probably lies close to the fluid-absent invariant point (Vielzeuf & Holloway 1988): Pl + Bt + Crd + Als + Qtz $\rightleftharpoons$ L + Grt ± Kfs, located at 850°C and 5 kbar in a plagioclase-free system.

With further melting, further growth of garnet, and eventual disintegration of the metapelite, the garnet grains became surrounded by the *local* anatectic melt, and their euhedral outlines (*e.g.*, Fig. 3E) suggest that they were in chemical equilibrium with this silicate melt. Furthermore, their reverse zonation outward to a more Mn-rich rim suggests either continued growth from a melt as Mn/(Mg+Mn+Fe) increased in the evolving local melt (Fig. 5) (Allan & Clarke 1981, Miller & Stoddard 1981), equilibration at lower temperature, competition for Fe–Mg with some later-stage phase such as biotite, or some combination of these causes.

The distinctive serrated Mn profiles of many of the grains of garnet in the xenoliths and quartz diorite may be the result of local breakdown of Mn-bearing phases (such as Mn-rich ilmenite; see reaction 3 of Patiño Douce & Johnston 1991) during melting, producing a short-lived flux of Mn (depending on diffusivity and permeability in the increasing melt phase) that the nearby growing garnet readily consumed. Of interest, too, is the failure of the host quartz diorite magma to homogenize these serrations.

Destruction of the Capo Vaticano garnet

Just as the formation of garnet is a complex function of T–P–*X*, so is its incipient elimination at sample localities D2 and D3. Falling temperature, or ascent of the magma and decreasing pressure, may take the bulk composition out of the stability field of garnet in T–P space (Fig. 4 of Clemens & Wall 1981). Likewise, fractional crystallization may change the bulk composition of the magma so that it evolves beyond the stability field of garnet in *X* space. In practice, these three factors may be inseparable.

Garnet grains at D2 have a thin corona of biotite (Figs. 3I–J), and those at D3 have a wider reaction rim of biotite + tschermakite (Figs. 3K–L). Plimer & Moazez-Lesco (1980) have described a similar occurrence in Iran of (xenocrystic) garnet grains replaced by biotite and amphibole. The question now becomes: why are these minerals the reaction products? Perhaps with falling temperature and increasing $f(H_2O)$, a retrograde reaction in D2 occurred to produce biotite. This may be, in part, the reverse of the prograde reaction that produced garnet initially: L + Grt ± Kfs $\rightleftharpoons$ Pl + Bt + Crd + Qtz, with L + Grt $\rightleftharpoons$ Bt dominating the reaction. The tschermakite rim on garnet grains at the D3 locality may result from a continuation of the above reaction. The appearance of biotite already suggests increasing $f(H_2O)$ in the melt, and this production of biotite consumes limited potassium from the quartz diorite magma. Thus, with high $f(H_2O)$, low K_2O, and high CaO, the garnet–melt reaction may change to produce a highly aluminous calcic amphibole instead: L + Grt $\rightleftharpoons$ Ts, again emphasizing only the dominant components. Figure 7 permits a comparison of coexisting Grt–Bt(–Ts) assemblages in the country rocks, xenoliths, and quartz diorite.

The schematic summary of the phase relations (Fig. 7F) offers two possibilities for the elimination of the garnet. First, closed-system fractional crystallization of the magma [decreasing 100*MgO/(MgO+MnO+FeO, temperature, and perhaps pressure] drives the melt from a cotectic equilibrium L + Bt + Grt to a peritectic L + Grt $\rightleftharpoons$ Bt + Ts, but the reaction

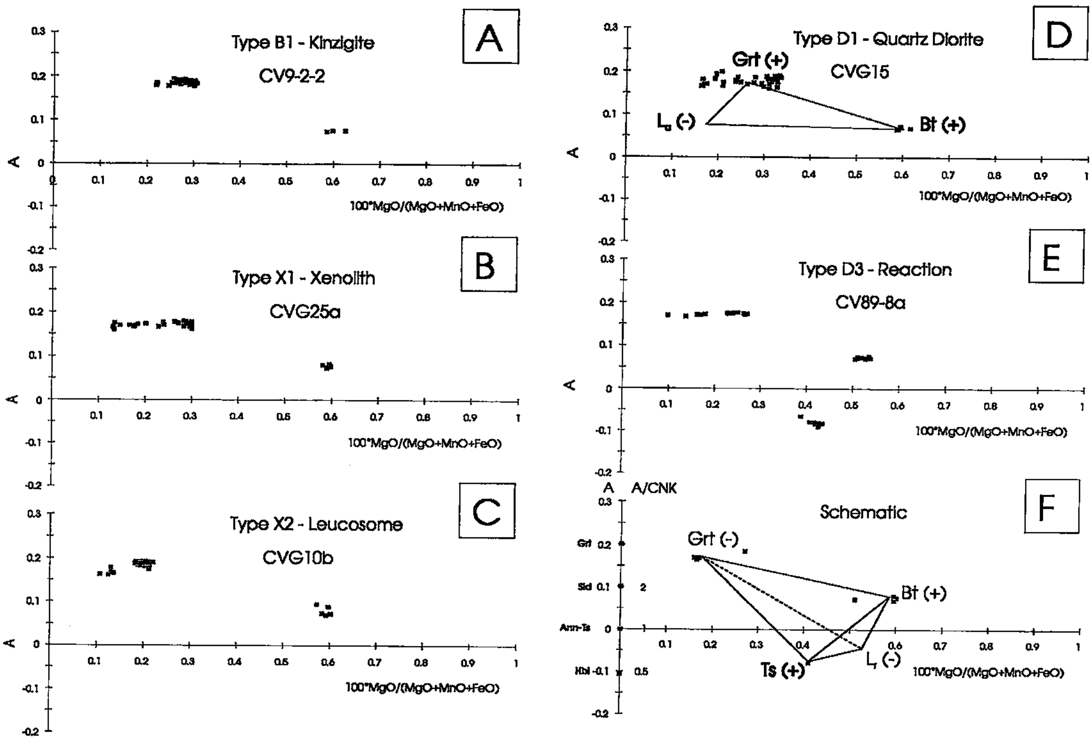

FIG. 7. Comparison of garnet–biotite(–tschermakite) assemblages in Capo Vaticano metamorphic and igneous rocks. Mineral compositions for kinzigite (B1) are distinct from those in the reacting xenoliths (X1, X2) and cotectic quartz diorite (D1). A reaction relationship of the type L_r + Grt $\rightleftharpoons$ Bt + Ts in the quartz diorite (D3) replaces cotectic crystallization $L_a \rightleftharpoons$ Bt + Grt in the anatectic melt from the xenoliths (D1). The estimated composition of the anatectic melt (L_a) is peraluminous and has a higher Fe/Mg ratio than its coexisting solid phases, whereas the estimated composition of the reacting quartz dioritic melt (L_r) is metaluminous and has a lower, more primitive, Fe/Mg ratio. A: mol (Al_2O_3 – CaO – Na_2O – K_2O).

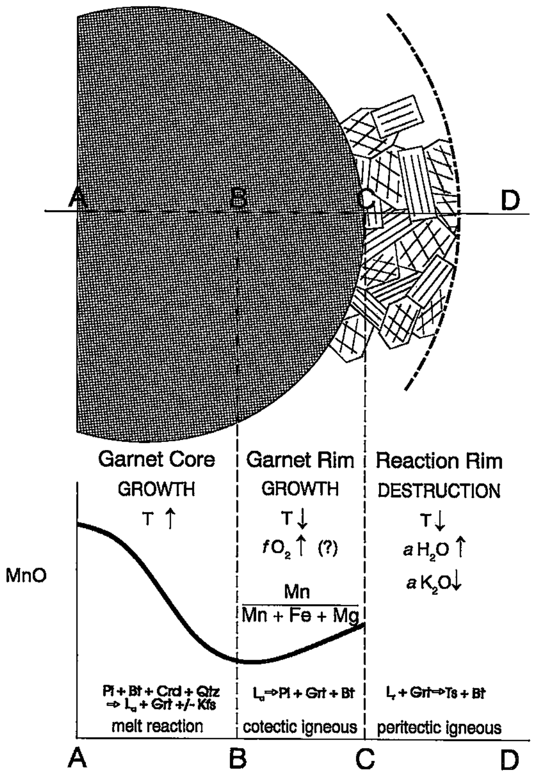

FIG. 8. Schematic profile through a typical D3 garnet. The grain shows normal zoning from the core to about half way to the rim, representing largely solid-state growth, then reverse zoning out to the rim, representing peritectic or cotectic growth in equilibrium with a silicate melt phase. The corona of biotite and tschermakite probably represents a peritectic relationship in which the garnet reacts with a metaluminous quartz dioritic magma.

does not proceed to completion because the products rim the garnet. What makes this mechanism unlikely is that the normal course of closed-system fractional crystallization drives metaluminous melts toward *increasing* A/CNK, with the elimination of amphibole and the *appearance* of the characteristic minerals of peraluminous granitoids (garnet, aluminosilicates). A second possible mechanism to account for the destruction of garnet is an open-system interaction between the clearly peraluminous melt produced by heating of the xenoliths and the *regional* metaluminous melt (quartz diorite) that provided the heat. As long as the peraluminous melt with its contained garnet did not mix extensively with the metaluminous melt, the grains of garnet retained their euhedral outline. However, when the peraluminous melt began to mix with the more voluminous quartz diorite magma, the crystals of garnet began to react. The trend in garnet morphologies in the sequence D1 → D2 → D3 reflects progressive interaction with the quartz diorite magma, *i.e.*, D1 represents no interaction, D2 shows the initial stages of degradation of the garnet grains, and D3 shows an advanced interaction. Figure 8 summarizes a possible history of a D3 garnet.

SUMMARY AND CONCLUSIONS

Garnet in granitoid rocks may be restitic, xenocrystic, magmatic, anatectic, fluido-magmatic, or metasomatic, spanning a wide range of cognate or foreign, and primary or secondary, origins. At Capo Vaticano, the field relations (spatial association of garnet grains with metasedimentary xenoliths, and the close association of garnet with former pods of melt or leucosomes) suggest that many grains of garnet originated in a melting reaction such as: Pl + Bt + Crd + Qtz ⇌ L + Grt ± Kfs. The Mn- and inclusion-rich cores suggest that nucleation of garnet began with rising temperature when the melt fraction was very low. The Mn-poorer and largely inclusion-free intermediate zones and rims are consistent with continued growth from the anatectic melt with falling temperatures. The Mn-rich rim on many grains of garnet in the granitoid rocks suggests late-stage growth as concentrations of Mn increased relative to Fe and Mg in the residual magmas. Some apparently unzoned grains in the quartz diorite may be xenocrysts from the kinzigitic gneisses or the amphibolites. Coronas of biotite, and biotite + tschermakite, around garnet grains, particularly from locality D3, suggest a reaction relationship between early garnet and a metaluminous quartz diorite melt to eliminate the garnet from the equilibrium mineral assemblage.

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