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Synmetamorphic veining: origin of andalusite-bearing veins in the Vedrette di Ries contact aureole, Eastern Alps, Italy

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ABSTRACT Discordant andalusite–biotite–quartz-bearing veins occur in the contact aureole of the Vedrette di Ries pluton (Italian Eastern Alps), never outside the area of contact metamorphic andalusite development. Andalusite veins are found only within andalusite-bearing hornfelses, and vein biotite occurs wherever host-rock garnet is partially replaced by biotite. Veins formed during contact metamorphism, synchronously with the crystallization of andalusite and biotite within host rocks. Their pegmatitic structure and their orientation suggest that vein parageneses crystallized within fluid-filled cavities that opened by hydraulic fracturing.

A mechanism of *synmetamorphic veining* is proposed to explain rock failure and subsequent mineral deposition within veins. During hydrofracturing induced by dehydration reactions in response to heating in the aureole, fissures were immediately filled with locally derived fluids. The lack of large-scale flux, together with high fluid pressures required by hydrofracturing, suggest fluid in the cavities was a virtually stagnant, passive medium, and that mass-transport toward fractures was driven by intergranular diffusion. Because temperature and P_f values within veins are similar to those in the host rock, vein assemblages are interpreted as the stable, high-T side of reactions taking place within pelitic schists, at the time when fractures opened. Once nucleation of product phases occurred, chemical components released by dissolution of reactant minerals were driven to precipitation sites by chemical potential gradients. Since nucleation was favoured at the strained grains of vein walls, andalusite and biotite simultaneously grew in vein and host rock.

The proposed genetic model contrasts with generally adopted metasomatic mechanisms for the genesis of Al_2SiO_5-bearing veins, in not requiring large fluid/rock ratios or a highly 'aggressive' fluid composition. The mechanism of synmetamorphic veining may be particularly useful in the interpretation of vein occurrences in medium- and deep-crustal rocks which have undergone extensive devolatilization.

Key words: andalusite veins; diffusion; Italian Eastern Alps; synmetamorphic veining; Vedrette di Ries pluton.

INTRODUCTION

Kyanite-, sillimanite- and andalusite-bearing veins and segregations are relatively common in various metamorphic terranes, suggesting that aluminium is a mobile element. Veins that cross-cut foliation or layering are often pegmatitic, indicating that a fluid-filled cavity was sealed by the precipitation of vein minerals from the fluid. Almost all the occurrences of Al_2SiO_5-bearing discordant veins have been interpreted as the result of a process called infiltration metasomatism (Kerrick, 1990), by which veins would arise from non-equilibrium interaction between the host rock and a pervading fluid. In this model, minerals in the host rock would be dissolved, their components transported by advection into the fracture and finally reprecipitated to form vein minerals, due to fluid oversaturation. In the infiltration metasomatism process, the driving force for mass transfer and mineral precipitation is attributed mainly to the fluid pressure difference (Walther & Orville, 1982) or to temperature gradients between the fracture and the host rock (e.g. Yardley, 1986).

Although there is a lack of experimental data at metamorphic $P–T$ conditions, and the nature of the Al-complexing solutions is not yet clear, the solubility of Al_2SiO_5 in aqueous fluids is considered to be very low (Walther & Wood, 1984). There is also a general belief that the production of veins by infiltration metasomatism requires large fluid volumes and/or highly 'aggressive' fluid compositions: very large fluid/rock ratios have been calculated from single-pass flow models which extrapolate quartz and Al_2SiO_5 solubilities to metamorphic conditions (discussion and references in Yardley, 1986; Kerrick, 1988; Thompson & Connolly, 1992). In the case of andalusite-bearing veins in contact aureoles, the large fluid volumes required are traditionally considered to result from the

large-scale advective/convective circulation of magmatic or metamorphic fluids that accompany the intrusion of granitoid plutons.

The importance of devolatilization reactions taking place during contact metamorphism, and their possible control on the veining mechanism, has either been rejected (Yardley, 1986; Philippot & Selverstone, 1991) or received little attention in the past, especially from the metasomatic model perspective. The reactions in the host rock have been considered merely as a fluid source (Kerrick, 1988), that can eventually cause rock fracturing. Fluid production by devolatilization of country-rocks has been taken into account in recent numerical modelling of fluid flow during contact metamorphism (Hanson, 1992). Results have shown that fluid circulation is prevented if rock permeabilities are $<0.1–100\,\mu D$, a reasonable range for crustal rocks at depths >6–10 km (Connolly & Thompson, 1989). It is thus possible that some contact aureoles, or part of them, may behave as relatively closed systems, and the fluid presence is essentially related to the dehydrating/decarbonating country rocks. Formation of veins in a similarly 'closed' system would not be consistent with the model of infiltration metasomatism, and would necessitate an alternative explanation for the precipitation of 'insoluble' minerals.

Based on the example from the Vedrette di Ries aureole, this study proposes a synmetamorphic model for the genesis of some andalusite-bearing veins, which do not exhibit metasomatic or hydrothermal signatures and are interpreted to be coeval with contact metamorphism. According to this model, fracturing, mineral deposition and vein assemblages are essentially controlled by devolatilization reactions in the adjacent host pelite.

GEOLOGICAL FRAMEWORK

The Vedrette di Ries (Rieserferner) pluton is a granodioritic–tonalitic body of Oligocene age (Bellieni *et al.*, 1981). It is a product of the late-Alpine magmatism in the Eastern Alps, south of the Tauern Window (Fig. 1). The pluton intruded the polymetamorphic Austroalpine crystalline basement, creating an E–W-trending antiformal structure in the enveloping country rocks: the contact is essentially concordant at a large scale, being almost parallel to the metamorphic layering in the country rocks. The emplacement and cooling of the pluton was not

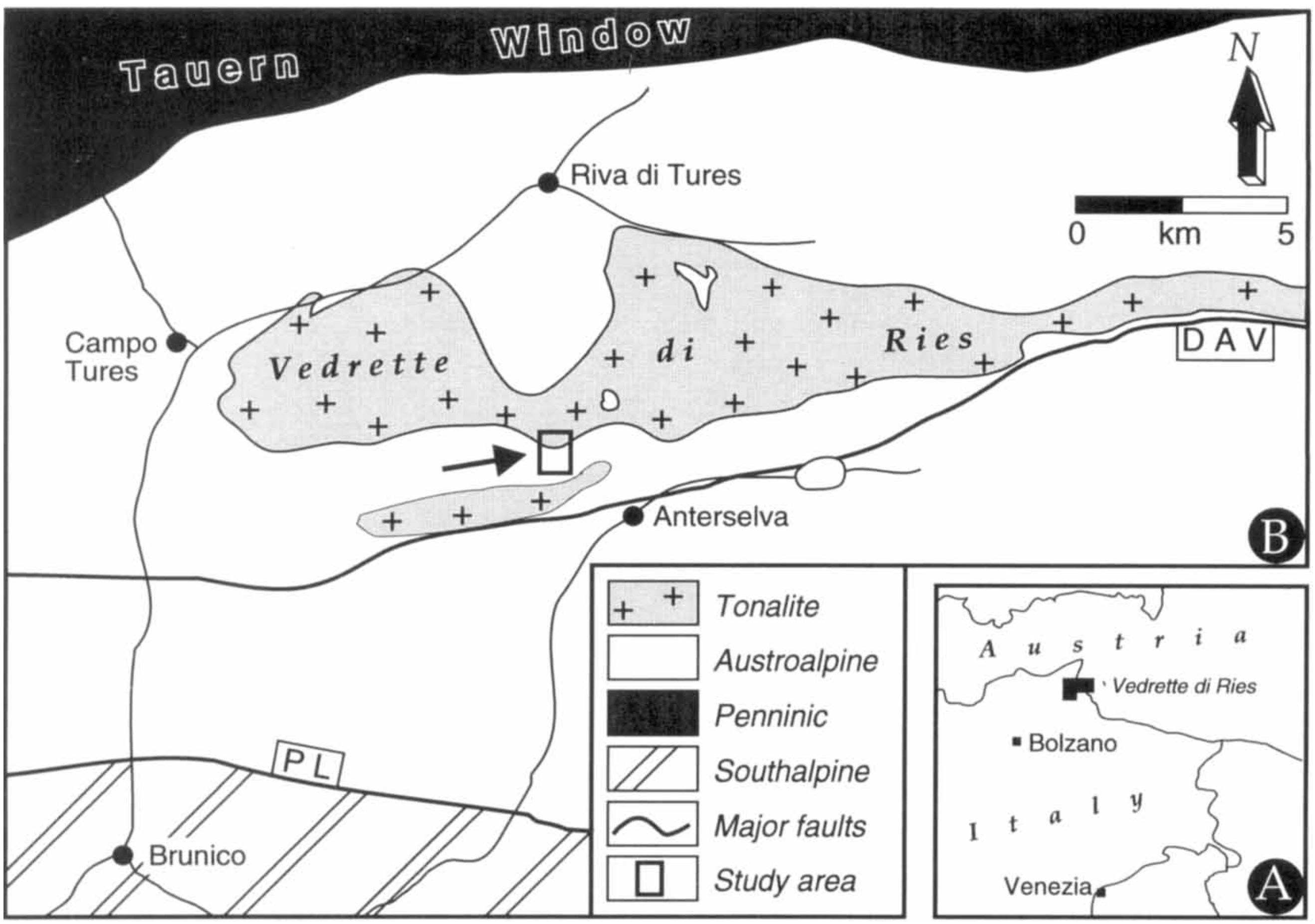


Fig. 1. Location (a) and geological sketch map (b) of the Vedrette di Ries intrusive and adjacent basement units. DAV, Deferegger–Anterselva–Valles line; PL, Periadriatic lineament. Arrow indicates the area of Forcella Valfredda, enlarged in Fig. 2.

associated with significant hydrothermal activity: pegmatites are very rare and restricted to the immediate vicinity of the contact, and there are no ore deposits.

Pelitic and semipelitic schists, aplitic–pegmatitic orthogneiss layers and minor metabasite and metacarbonate pods form the country rocks to the pluton. These rocks suffered a complex tectono-metamorphic evolution with early Palaeozoic, Variscan and polyphase Alpine metamorphic events (references quoted in Cesare, 1992a). The last regional metamorphism is the late-Alpine event or 'Tauern metamorphism', which developed under greenschist facies and was accompanied by strong deformation. The Tauern metamorphism retrogressed former amphibolite facies metapelites to Qtz–Pl–Ms–Chl ± Bt-bearing schists and mylonites containing relicts of garnet, staurolite, acicular sillimanite and kyanite.

The Tauern metamorphism pre-dates intrusion of the Vedrette di Ries pluton, which produced a contact aureole affecting the polymetamorphic basement. Pelitic schists and hornfelses typically contain staurolite, andalusite, acicular and prismatic sillimanite and minor cordierite as contact metamorphic phases (Cesare, 1992b). Evidence for syndeformational contact metamorphism is lacking: undeformed andalusite and staurolite porphyroblasts have a random orientation and overgrow the earlier mylonitic foliation. None of the deformation phases and lineations recognized by Mager (1985) have been definitely related to the pluton emplacement. Although the penetrative schistosity clearly developed before intrusion, the elongate shape of the pluton implies that the stress field with subhorizontal E–W σ_3 (see below) was present during contact metamorphism.

The aureole ranges in width from a few hundred metres to more than 1 km in the southern Forcella Valfredda area (Mager, 1985). The andalusite-bearing veins have been studied in this latter area, where the contact aureole is wider and better exposed. Cesare (1992b) divided the aureole into five mineralogical zones. In order of decreasing distance to the tonalite the zones are: biotite, staurolite–andalusite, staurolite–fibrolite, garnet–fibrolite and K-feldspar–sillimanite. Chlorite is widespread in the biotite zone, and is progressively consumed until it completely disappears a few metres before the And–Sil isograd. The progressive loss of chlorite suggests that andalusite growth was probably accompanied by dehydration of the metapelites. The zonal sequence of contact metamorphism is consistent with type 2bii in the facies series scheme of Pattison & Tracy (1992), which would indicate metamorphic pressures in the range 2.5–3.5 kbar. This barometric interval is consistent with the calculations of Cesare (1994), which give a minimum pressure of 2.5 kbar.

ANDALUSITE VEINS

Schists outcropping in the southern aureole of the Vedrette di Ries pluton contain several vein generations distinguished by mineralogical composition. The following discussion considers only those veins which are discordant with respect to the pervasive regional foliation, indicating that they are younger than (or contemporaneous with) Alpine deformation. Quartz veins, tonalite dykes and tourmaline-bearing granitic pegmatite are quite common, but they occur only within 50 m of the contact.

Andalusite-bearing veins are much less abundant, but are widespread and occur up to 1 km from the tonalite. These were originally reported by Mager (1985), who regarded them as the result of late magmatic activity. The veins are thin, parallel-sided, filled fractures, generally straight and in parallel sets. They are orientated at a high angle to the south-dipping foliation, and are not folded, implying that major ductile deformation did not affect the area during or after the vein formation. The fine-grained pegmatitic structure and the euhedral shape of andalusite crystals indicate crystallization within fluid-filled fissures.

Two outcrops with abundant veins in the area of Forcella Valfredda (Fig. 2) were chosen for further investigation. Outcrop 1 is in the staurolite–andalusite zone, 800 m from the intrusion; outcrop 2, in the garnet–fibrolite zone, is closer to the pluton. Figure 2 shows the distribution of the different Al_2SiO_5 polymorphs in the area, and the relationship between vein occurrence and andalusite presence within schists. Andalusite is widespread throughout the area, even at outcrop 2 and closer to the intrusion, but here it shows partial to total replacement by acicular or prismatic sillimanite, as a result of the prograde evolution during contact metamorphism. It is relevant to the following discussion to note that most of the vein occurrences shown in Fig. 2 (with the exceptions of outcrops 1 and 2) consist of single, thin veinlets. Therefore, the vein/host rock volumetric ratio is extremely low.

At *outcrop* 1, host rocks are pelitic hornfelses and schists containing quartz, plagioclase, andalusite, staurolite, biotite, ilmenite and graphite (± garnet ± chlorite). They preserve the older penetrative planar foliation dipping south and a well-developed E–W subhorizontal stretching lineation. This lineation has the same orientation as fold axes B4 and B6 of regional deformation (Mager, 1985), which pre- and post-date the intrusion, respectively.

Andalusite veins are very thin, usually <1 cm and no longer than 1 m. They contain quartz and andalusite in equal amounts, with variable biotite, and rare plagioclase and/or white mica. Biotite, which may reach up to 30%, is directly correlated to the abundance of garnet in the immediately adjacent host rocks.

At *outcrop* 2, the country rocks are pelitic hornfelses, composed of quartz, plagioclase, biotite, muscovite, acicular and prismatic sillimanite, garnet, ilmenite and graphite, with abundant relicts of andalusite.

Veins are larger and more abundant, and may in some cases reach a few metres in length and up to 5 cm in thickness. Some veins are adjacent to dykes of tonalite and tourmaline-bearing pegmatite, in which andalusite never occurs, but are not physically connected to them. Pegmatite dykes post-date the andalusite-bearing veins.

Veins are discordant, their direction being quite random, but always very steep. In places, they are curved

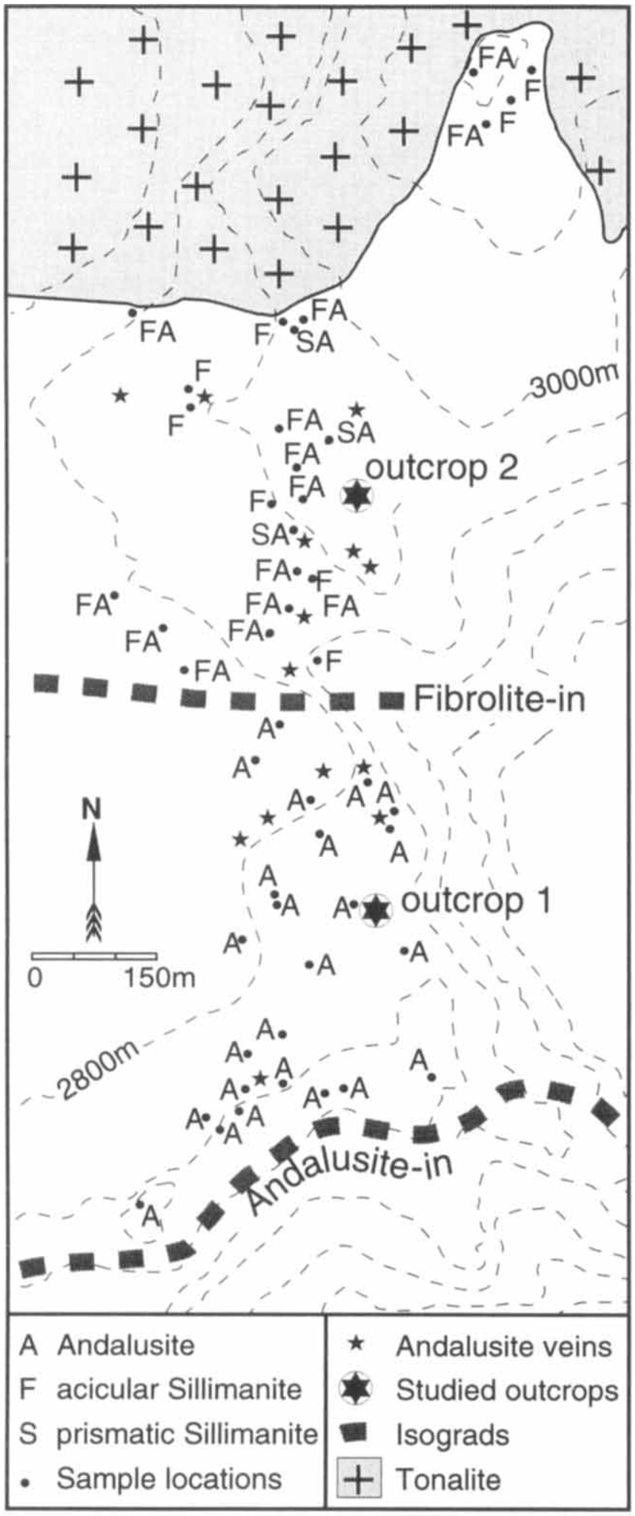
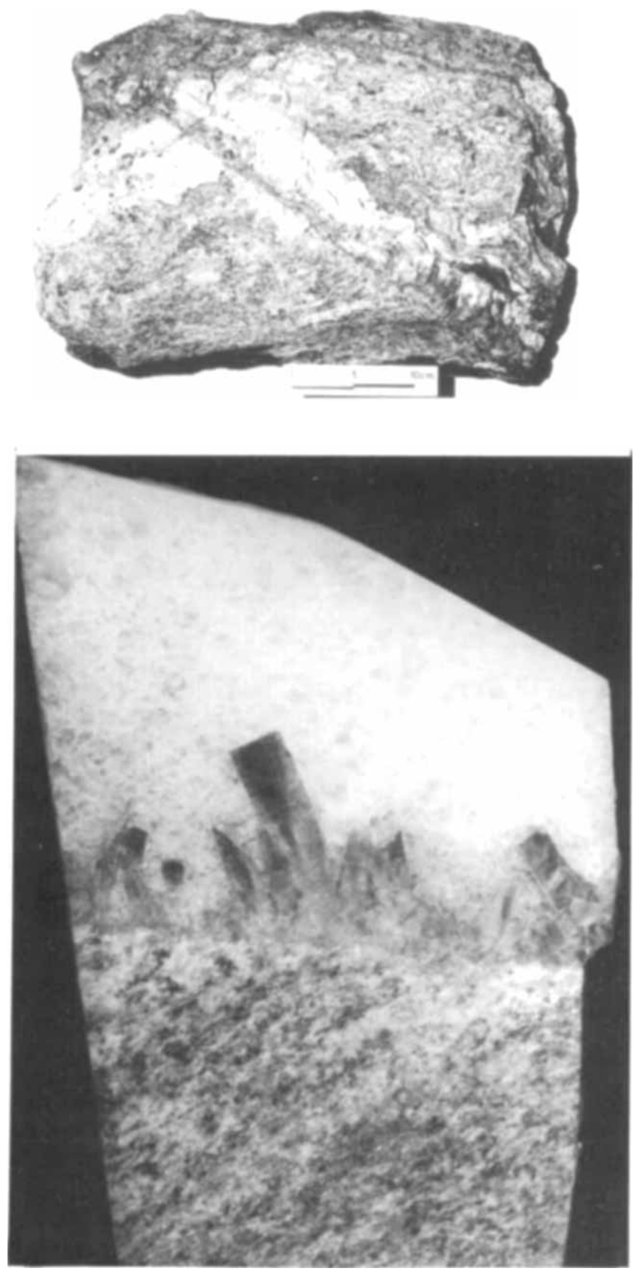


Fig. 2. Occurrences of andalusite-bearing veins and distribution of the Al_2SiO_5 polymorphs in the southern Vedrette di Ries aureole. Intrusive contact drawn after Mager (1985); isograds after Cesare (1992a).



(b)

Fig. 3. Andalusite–quartz veins at outcrop 2: (a) thick vein perpendicular to the foliation orientation within host rock; (b) polished surface showing euhedral andalusite crystals which cluster at the straight vein wall; they exhibit concentric zoning with Fe-enriched darker areas (see text for details). Width of view = 25 cm.

towards weaker layer-parallel surfaces or boudin necks, indicating that the development and orientation of fractures was locally controlled by rock anisotropies. There are two end-member types of andalusite-bearing pegmatitic vein at outcrop 2: biotite-absent, quartz-rich veins (the larger ones, Fig. 3a), and biotite-rich, quartz-poor veins. In the first type, euhedral andalusite crystals generally project from the vein walls into the quartz-rich inner zone (Fig. 3b) as isolated prisms (up to 3 cm in length) or rosette aggregates. The second type occurs within garnet-bearing host rocks (Fig. 4); coarse-grained

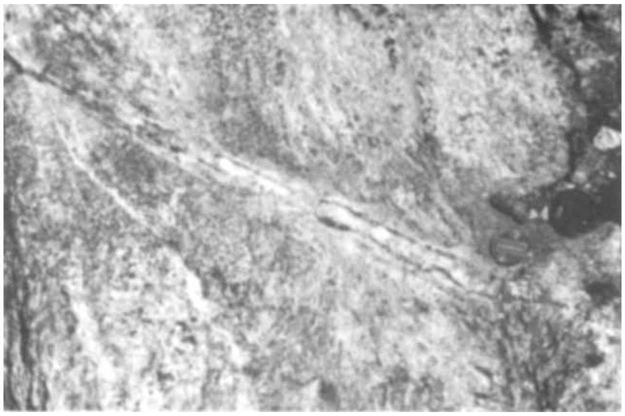


Fig. 4. Biotite–andalusite–quartz vein at outcrop 2. Biotite forms the black continuous layer at both vein walls, and may fill the whole fracture at its tip (lower left). Dark spots in the country rocks are partial to complete pseudomorphs of biotite after garnet. Width of view = 0.5 m

biotite is located at the vein walls, but also occurs in the central portion of the veins, alone or associated with andalusite.

The veins show a mineralogical zoning with andalusite and biotite abundant at vein borders, whereas quartz is dominant at the centre. Plagioclase concentrations (up to 2 cm in thickness) have been observed at the walls of a few veins (Fig. 5), within more gneissic host rocks.

All of the andalusite-bearing veins occur within those parts of the aureole in which andalusite crystallized during contact metamorphism (cf. Fig. 2), and are always hosted by andalusite-bearing rocks. Where veins occur in non-pelitic lithologies (e.g. pegmatitic gneiss or quartzite), they do not contain andalusite or biotite. In the few cases where veins cross-cut different lithologies, there is a different mineral assemblage in each part. The general relationships among mineralogy of veins and that of host rocks are sketched in Fig. 6.

Fig. 5. Biotite–andalusite–quartz vein at outcrop 2: the white rim adjacent to the vein mainly consists of plagioclase (see text for discussion). Country rock contains dark, round, biotite pseudomorphs after garnet (arrowheads). Width of view = 1 m.

Veins are subparallel along a N–S vertical orientation at outcrop 1, and subvertical with a random direction at outcrop 2 (Fig. 7). Their orientation can be consistently related to the stress field generated by the emplacement of the underlying tonalite (see Paterson *et al.*, 1991), that gives a subvertical σ_1. In particular, the N–S vein directions at outcrop 1 are concordant with the marked elongation of the pluton, which defines the E–W direction of minimum principal stress in the schists.

MICROTEXTURES AND MINERAL CHEMISTRY

Outcrop 1

The grain size of vein minerals is everywhere coarser than in the host rock. Andalusite is generally undeformed and forms euhedral crystals, but it may occur as skeletal grains in the thinner veins. Close to the walls andalusite poikiloblasts contain abundant quartz inclusions, and individual crystals often extend into the host rock without optical discontinuity. Pink pleochroic cores are common, both in vein and in host-rock andalusite. In some thin (mm-sized) veinlets, andalusite crystals are continuous from one wall to the other, and are deformed, showing undulose extinction. Together with the deflection of foliation of the country rocks in the vicinity of the vein, this is the only evidence for a weak shear displacement along the vein during (or after) crystallization of andalusite.

Andalusite and biotite are generally intergrown in biotite-bearing veins (Fig. 8), indicating synchronous crystallization. Biotite flakes are perpendicular to the walls and apparently nucleated on them. Biotite is coarser in veins than in neighbouring schists, and is clearly grown *inside* a fracture, not in the wallrock. Figure 8 shows the close relationship between the schist mineralogy and the vein assemblage: biotite occurs in veins wherever the adjacent rock contains garnet partially replaced by biotite. Microstructural evidence indicates that the alteration of garnet to biotite can be ascribed to contact metamorphic effects (Cesare, 1992a). Another important feature observed in Fig. 8 are euhedral andalusite porphyroblasts with a thin graphite rim in the host-rock matrix. This is clear evidence for the lack of andalusite dissolution within the rock adjacent to the vein.

Plagioclase is generally absent within veins. When it occurs, it is located at the vein walls as thin granoblastic layers, whose grain size is generally fine and comparable with that in the host rock. These plagioclase-rich border zones have also been observed at outcrop 2. Tourmaline and apatite, which occur in the hornfelses, are totally absent within veins.

Outcrop 2

Vein mineral assemblages and textures are very similar to those at outcrop 1, but veins are larger and their zoning is more conspicuous. Euhedral andalusite, which clusters at

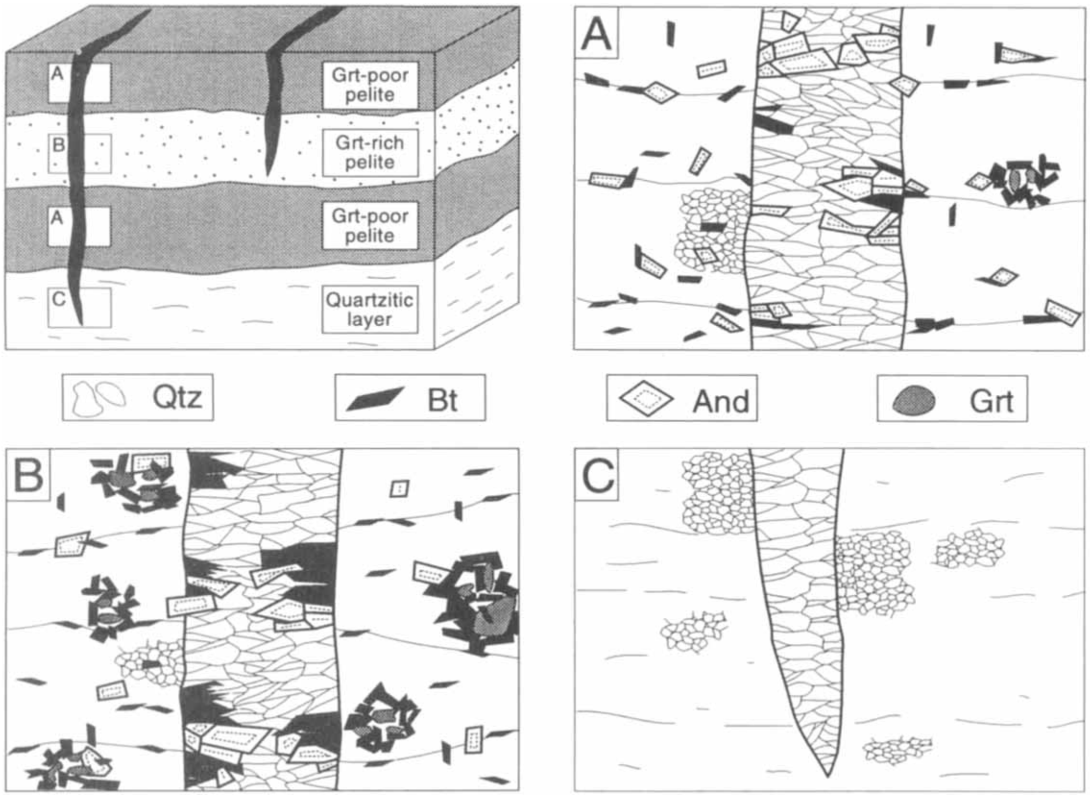


Fig. 6. Schematic diagram summarizing meso- and microstructural observations on the andalusite-bearing veins of the Vedrette di Ries aureole. Veins that formed in a layered rock (upper left) comprising metapelites and quartzite display a variable mineralogy, depending on the composition of the adjacent host rock. A, B and C represent observed mineral composition and texture of veins in three end-member host-rock lithologies, respectively garnet-poor pelite, garnet-rich pelite and quartzite.

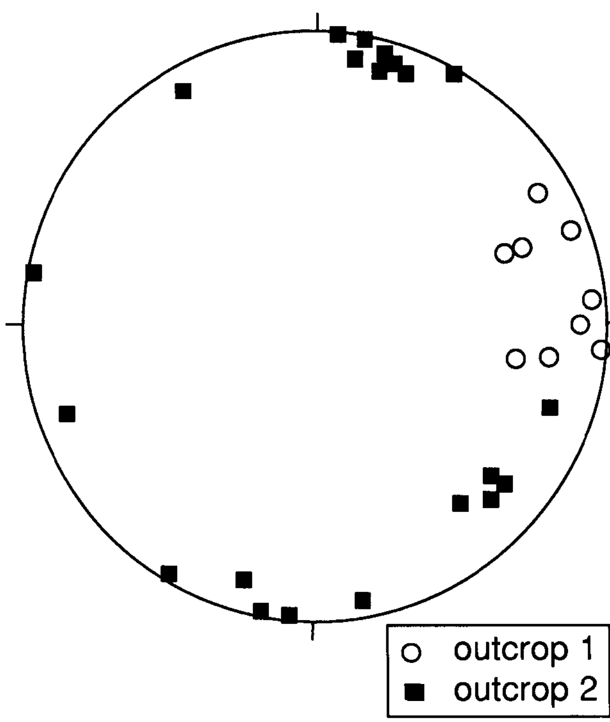


Fig. 7. Projection of the poles of vein surfaces (lower hemisphere). All of the veins are planar and have a subvertical orientation.

the border of the veins, increases in grain size towards the quartz-rich core (Fig. 9); it commonly displays concentric zoning with pink pleochroic cores. Andalusite shows partial to complete replacement by prismatic sillimanite or prograde white mica; the latter is in turn overgrown by acicular sillimanite. Both these pseudomorph textures have also been observed in the adjacent host rocks, and suggest that after veining during the initial stages of contact metamorphism, veins and their host rocks reached temperatures exceeding the And = Sil phase boundary. This inference is supported by occurrences of thin sillimanite veinlets that cross-cut andalusite-bearing veins (Fig. 10).

Biotite may be the main constituent of veins, its abundance being once again correlated with the occurrence of garnet within the adjacent hornfelses. In some veins, biotite fills the whole fracture, with large (1 cm across) flakes intergrown with quartz and andalusite (Fig. 10). Chloritization of biotite, as well as alteration of andalusite to sericite, sometimes occurs at some vein walls where narrow retrograde shear zones are localized.

Mineral chemistry

Minerals from two samples of andalusite-bearing veins, one from each outcrop, were analysed in both veins and in host rocks with a CAMECA SX50 electron microprobe at

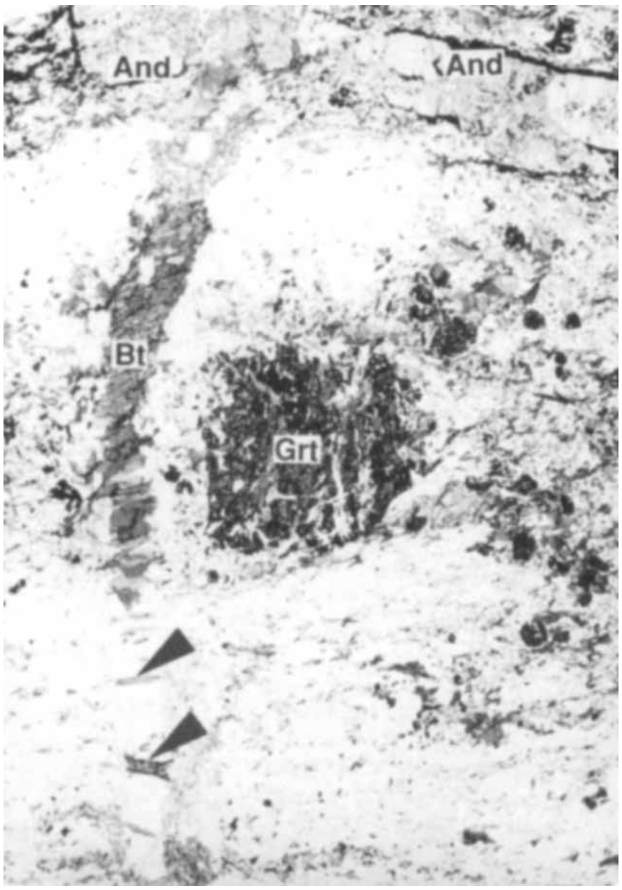


Fig. 8. Photomicrograph of a biotite-rich, andalusite-bearing veinlet of outcrop 1. Biotite (Bt) fills the vein with large flakes (arrowheads), while in the country rock garnet (Grt) is partially altered to biotite. Andalusite (And) occurs both in vein and in the host rock, where euhedral crystals are coated by a graphite film. This indicates lack of dissolution of andalusite in the rock adjacent to the vein. Plane-polarized light, width of view = 15 mm.

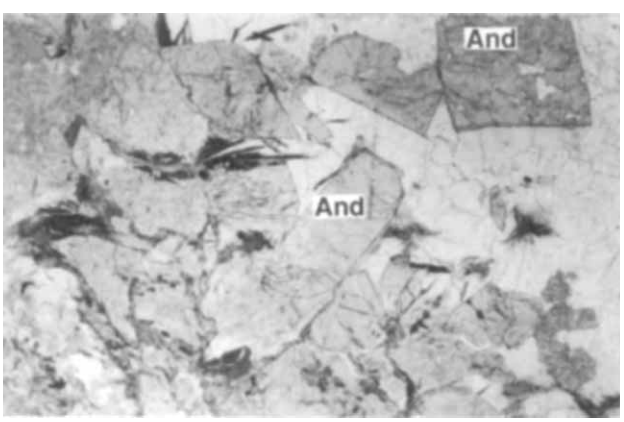


Fig. 9. Photomicrograph of an andalusite-rich, biotite-bearing vein of outcrop 2. Clusters of anhedral andalusite occur at the wall of the vein, while the quartz-rich core contains larger, isolated, euhedral crystals (upper right). Plane-polarized light, width of view = 20 mm.

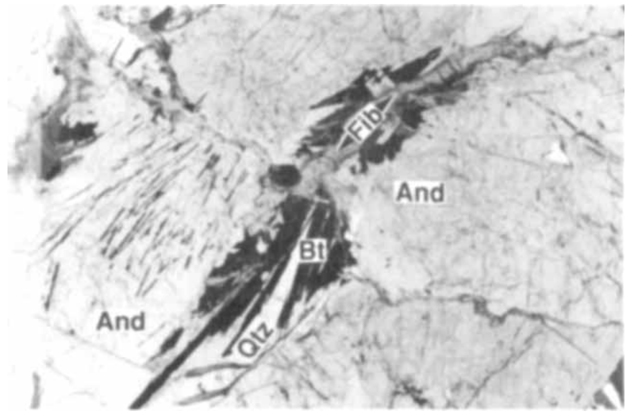


Fig. 10. Intergrowth of biotite (dark), andalusite and quartz in vein from outcrop 2. Small biotites occur within andalusite, whereas larger biotite crystals are embedded with quartz (Qtz). Acicular sillimanite (Fib) veinlets cross-cut andalusite and biotite. Plane-polarized light, width of view = 9 mm.

the Institute of Mineralogy and Petrography of the ETH, Zürich. Apart from routine elements, Cl and F were measured in biotite. Table 1 lists the average chemical composition of andalusite, biotite and plagioclase.

Minerals from vein and host rock of the same sample have practically the same composition. Andalusite generally contains low Fe_2O_3, which reaches up to 1 wt % in the pink pleochroic cores of crystals. Biotite has very low F and Cl contents, which combined with the low salinity of the synmetamorphic fluid inclusions in the veins (B. Cesare & L. Hollister, unpubl. data), suggest that the fluid was not chloride-rich. Biotite from the sample closer to the contact (VR553, outcrop 2) has higher Ti and X_{Fe} values than at outcrop 1, indicating that these rocks reached higher temperatures in the amphibolite facies (Guidotti, 1984). Plagioclase is weakly inhomogeneous, without distinct zoning patterns, and the compositional variations are similar in both vein and host rock. The composition of 'vein' plagioclase at outcrop 1 (VR550) has been obtained from analyses of the feldspar-rich border zone described above. This portion may not actually belong to the vein, as discussed the next section.

A MODEL OF FORMATION

A mechanism of *synmetamorphic veining* is proposed to account for the processes of fracture opening, migration of matter and precipitation of minerals.

Vein opening: timing, mechanism and fluid behaviour

The similar prograde evolution of andalusite in vein and host rock of outcrop 2, as well as the systematic relationship between biotite presence in veins and biotite pseudomorphs after garnet in the adjacent schists, indicate that veins formed during the contact metamorphic event, *before* the crystallization of sillimanite. At that time the

Table 1. Chemical composition of andalusite, biotite and plagioclase from vein and adjacent host rock at outcrop 1 (sample 550) and 2 (sample 553).

Sample	550	550	553	553
n	3	3	13	4
Location	host	vein	host	vein
Andalusite				
SiO_2	36.87 ± 0.13	37.47 ± 0.38	36.88 ± 0.45	37.19 ± 0.78
TiO_2	0.03 ± 0.00	0.06 ± 0.04	0.02 ± 0.02	0.03 ± 0.05
Al_2O_3	62.60 ± 0.48	62.45 ± 0.40	62.13 ± 0.54	62.47 ± 0.20
Fe_2O_3	0.25 ± 0.03	0.41 ± 0.17	0.25 ± 0.04	0.38 ± 0.19
MnO	0.01 ± 0.02	0.00 ± 0.00	0.00 ± 0.01	0.00 ± 0.02
MgO	0.04 ± 0.01	0.14 ± 0.11	0.04 ± 0.02	0.06 ± 0.06
Total	99.80 ± 0.49	100.53 ± 0.40	99.33 ± 0.37	100.13 ± 0.81
Cations on the basis of 5 oxygens and all Fe^{3+}				
Si	1.00 ± 0.00	1.01 ± 0.00	1.00 ± 0.01	1.00 ± 0.01
Ti	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Al	2.00 ± 0.00	1.98 ± 0.02	1.99 ± 0.02	1.99 ± 0.02
Fe^{3+}	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Mn	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Mg	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Sample	550	550	553	553
n	30	17	16	30
Location	host	vein	host	vein
Biotite				
SiO_2	35.80 ± 0.54	35.78 ± 0.75	35.21 ± 0.56	34.42 ± 0.81
TiO_2	1.61 ± 0.14	1.81 ± 0.14	1.92 ± 0.29	2.20 ± 0.22
Al_2O_3	19.46 ± 0.57	19.50 ± 0.35	19.88 ± 0.40	19.90 ± 0.38
FeO	19.11 ± 0.56	19.11 ± 0.50	21.50 ± 0.65	20.86 ± 0.50
MnO	0.07 ± 0.04	0.08 ± 0.02	0.15 ± 0.02	0.15 ± 0.03
MgO	9.35 ± 0.40	9.30 ± 0.22	7.93 ± 0.31	7.90 ± 0.22
Na_2O	0.22 ± 0.06	0.21 ± 0.07	0.21 ± 0.03	0.32 ± 0.10
K_2O	8.87 ± 0.18	8.79 ± 0.24	8.96 ± 0.23	8.93 ± 0.23
F (range)	0–0.02	0–0.01	0.04–0.17	0.02–0.07
Cl (range)	0–0.02	0–0.02	0.04–0.07	0.04–0.07
Total	94.56 ± 0.56	95.13 ± 0.67	95.93 ± 0.78	94.92 ± 0.72
Cations on the basis of 22 oxygens and all Fe^{2+}				
Si	5.46 ± 0.05	5.44 ± 0.05	5.37 ± 0.05	5.31 ± 0.06
Ti	0.19 ± 0.02	0.21 ± 0.02	0.22 ± 0.03	0.26 ± 0.03
Al	3.50 ± 0.08	3.51 ± 0.04	3.57 ± 0.06	3.62 ± 0.05
Fe^{2+}	2.44 ± 0.08	2.43 ± 0.08	2.74 ± 0.10	2.69 ± 0.09
Mn	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.00
Mg	2.13 ± 0.10	2.11 ± 0.05	1.80 ± 0.07	1.82 ± 0.05
Na	0.07 ± 0.02	0.06 ± 0.02	0.06 ± 0.00	0.10 ± 0.03
K	1.73 ± 0.05	1.71 ± 0.05	1.74 ± 0.04	1.76 ± 0.05
F	0–0.011	0–0.003	0.022–0.081	0.010–0.036
Cl	0–0.005	0.001–0.006	0.009–0.018	0.012–0.019
X_{Fe}(range)	0.50–0.57	0.52–0.55	0.58–0.65	0.58–0.62

Sample	550	550	553	553
n	14	16	6	28
Location	host	vein	host	vein
Plagioclase				
X_{An}	0.38–0.48	0.39–0.52	0.17–0.27	0.18–0.24

P–T conditions were within the stability field of andalusite ($T = 500 \pm 50°$C, Cesare, 1992a), and schists were undergoing further heating. Furthermore, the presence of euhedral andalusite crystals at the vein walls, partly in the vein and partly in the host rock, together with the lack of dissolution of host-rock andalusite, suggests growth of andalusite in veins and host rocks was coeval. Hence, mineral precipitation in veins was *synmetamorphic*: it was synchronous with metamorphic reactions taking place in the host rock at the time of vein formation.

Brittle failure of a rock may occur according to either extensional shear or hydraulic extension fracturing (see Sibson, 1990, for a detailed overview of vein-related structures). Hydraulic extension fracturing (hydrofracturing) requires elevated fluid pressures and low deviatoric stress (Phillips, 1972; Sibson, 1990), and generates fractures perpendicular to σ_3. It occurs when the fluid pressure (P_f), exceeds the sum of minimum stress (σ_3) and tensile strength of the rock (τ_0), according to the failure condition (see also Nishiyama, 1989):

$$P_f \geq \sigma_3 + \tau_0.$$

In the studied example, the hydrofracturing model is consistent with the orientation of veins (Fig. 7) with respect to the stress field induced by the underlying tonalite. Since the typical features of shear fracturing (e.g. *en-echelon* arrangements of veins and conjugate fractures, displacement parallel to vein surfaces and/or bending of cleavage) are minimal, it can be concluded that the main mechanism of vein opening was hydrofracturing. The lack of interconnected veins and the absence of hydrothermal activity in the aureole suggest a local fluid source. Chemical components to form vein minerals are also considered to be of local origin, given the very strong control of host-rock composition on vein mineralogy. Hydrofracturing was caused by fluid release during devolatilization reactions: decrease in modal chlorite and white mica, which is recorded proceeding upgrade within the andalusite zone of the aureole (Cesare, 1992a), is clear evidence that host-rock metapelites were undergoing dehydration during andalusite formation. Combining the above data with the textural observation of biotite pseudomorphing garnet, the equilibrium

$$\text{Grt} + \text{Chl} + \text{Ms} = \text{And} + \text{Bt} + \text{Qtz} + H_2O \quad (1)$$

can be proposed as one plausible dehydration reaction in the hornfelses, capable of producing the vein mineral assemblage. Due to disequilibrium features and occurrence of abundant relicts in the polymetamorphic metapelites, the model reaction might not be the one actually occurring, and could be modified by introducing kyanite and/or staurolite.

Opening of fissures in the rock generates a sudden increase in the volume available for the fluid phase and a consequent drop in pore pressure. Fractures become a source for local pressure gradients which immediately drive fluids along permeable pathways (e.g. foliation planes) into the open cavities, filling them. However, to keep a vein open, fluid pressure in the vein must be equal to σ_3: after a rapid initial fluid flow toward the cavity, a condition of mechanical stability among fracture and host rock will be attained. Unless further fluid release promotes more hydrofracturing and crack propagation to create a continuous network (Nishiyama, 1989; Brenan, 1991), pressure gradients and permanent flow will be inhibited (Brenan, 1991; Canals *et al.*, 1993). Frequent occurrences of isolated, thin, andalusite-bearing veins in the studied aureole, and the lack of interconnected vein networks are additional observations against large-scale fluid circulation. Furthermore, regimes of lithostatic fluid pressure can be predicted by calculated emplacement depth of about 10 km

(Cesare, 1994), and by the density of the earliest fluid inclusions within veins (B. Cesare & L. Hollister, unpubl. data).

Mass transfer and mineral deposition

After the initial, transient flow, fluid can be considered as virtually stagnant, acting as a passive medium (Rubie, 1986, Philippot & Kienast, 1989), in thermal and mechanical equilibrium with the surrounding rocks. Moreover, chemical equilibrium can also be assumed, considering theoretical models (Walther & Wood, 1984), and the equal parageneses and mineral chemistry in vein and host rock. Evidence for 'aggressive' fluid compositions (Klein, 1976; Kerrick, 1988) is also absent: (i) low F and Cl concentrations in the fluid are suggested by the compositions of the micas and by the absence of tourmaline and apatite within veins; (ii) fluid inclusion study of the same veins indicates that the vein-filling fluid was a low-salinity, water-rich C–O–H fluid in equilibrium with graphite (B. Cesare & L. Hollister, unpubl. data). Given the above scenario, crystallization of vein minerals was simply controlled by heterogeneous mineral reactions in the host rock (e.g. reaction 1).

Nucleation of product phases (andalusite, biotite and quartz) is favoured on the strained minerals at vein walls (Spry, 1969; White, 1975; Lasaga, 1981; Carlson, 1989); once nuclei form, concentration and chemical potential gradients between reactants and products are established (Lasaga, 1986; Ridley & Thompson, 1986; Kerrick *et al.*, 1991), and transfer of chemical components, continuously provided by dissolving reactants, is activated. Thus, the driving force for mineral deposition in veins is the free-energy difference between reactants and products of a metamorphic reaction. The synmetamorphic veining mechanism implies synchronous growth of andalusite in vein and host rock; from this viewpoint growth of andalusite and biotite within veins is comparable with that of porphyroblasts, according to the mechanism suggested by Ramberg (1952, p. 214) for diffusion-controlled veins. Because of the presence of an intergranular network filled with stagnant fluid released by dehydration reactions, mass transfer from adjacent host rock to the vein occurs via intercrystalline diffusion, which can be very effective, and dominant during metamorphism (Rubie, 1986; Walther & Wood, 1984; Ridley & Thompson, 1986). Since the fracture is filled with fluid that allows faster diffusion, growth of vein minerals is also faster and grain size coarser (Fyfe *et al.*, 1978); this explains the pegmatitic vein texture. Qualitative relationships between the abundance of reactant phases in the pelites at lower grades, and modal distribution of andalusite and biotite within veins and host rock, suggest maximum diffusion distances of about 100 cm for the formation of the studied veins.

Because intergranular diffusion is the mass-transfer process during synmetamorphic veining, diffusion halos around veins can be expected (Carlson, 1989). The plagioclase-rich border zones that sometimes occur at vein margins can be interpreted as diffusion halos. The fine grain size of plagioclase, compared with the coarser vein minerals, suggests these enrichment zones are part of the host rock and probably represent the refractory residue that did not take part in the reaction and was depleted of the chemical components diffusing into the vein. Conversely, such an explanation is not applicable to the biotite-rich zones, which are located within the veins, and cannot be interpreted as the 'selvages' of Keller (1968), Klein (1976) and Kerrick (1990, p. 344), i.e. as residual portions of metasomatically depleted country rocks.

DISCUSSION

Synmetamorphic veining: requirements and products

The model proposed for the genesis of veins at Vedrette di Ries requires only devolatilization reactions to occur in a low-permeability rock body, heat transfer from the cooling intrusive being the ultimate driving force (Ridley, 1986). Considering that heat transfer is also typical of regional metamorphism, the model is likely to be applicable to other geological settings within the medium to lower crust (Hanson, 1992). Contact metamorphism is usually considered to occur at shallow depth under $P_f \leq P_l$ conditions; however, the level of emplacement of the Vedrette di Ries pluton seems deep enough to permit lithostatic values for fluid pressure (Connolly & Thompson, 1989). High P_f conditions are also in agreement with numerical modelling of fluid behaviour during contact metamorphism and dehydration (Furlong *et al.*, 1991).

Synmetamorphic veining requires devolatilization to cause hydrofracturing and formation of an intergranular stagnant fluid network, and vein walls to act as preferential nucleation sites for reaction products. Mass transfer processes are diffusion-controlled, and growth of the product assemblage of dehydration is coeval in vein and host rock. The result of such a process is a pegmatitic vein whose mineral paragenesis is the same as that developed in the host rock, and with orientation and phenomenology typical of hydrofracturing. High strain, infiltration of externally derived fluids, or highly 'aggressive' fluid compositions are not required by the model. Similarly, depletion halos at vein walls may be present but only if diffusion is the rate-controlling step in the process. Thus, the extent of the chemical differences between vein and adjacent host rock is not dependent on the process, but on the relationship among starting bulk composition and reaction stoichiometry. This suggests the mechanism of synmetamorphic veining cannot be considered metasomatic, and is instead comparable either with metamorphic differentiation as defined by Eskola (1932) or with lateral segregation (Yardley, 1986; Yardley & Bottrell, 1992).

Solubility of Al_2SiO_5: advection vs. diffusion

Al_2SiO_5-bearing veins have always represented a problem to petrologists, mainly because of the extremely low solubility of Al_2SiO_5 in aqueous fluids. Thus, the transport

of considerable amounts of aluminium in discordant veins has been explained by appealing to interaction between rocks and large volumes of advecting fluids, often chloride-rich (Gresens, 1967). Advective mass transport has been considered the only plausible mechanism capable of transporting relatively insoluble compounds, the contrasting process of diffusion metasomatism being applied only to segregation formed by replacement of a pre-existing rock (Kerrick, 1990).

However, in many circumstances, large-scale flows around contact aureoles may not be geologically feasible (Hoernes *et al.*, 1991), or even possible (Furlong *et al.*, 1991; Hanson, 1992). When this is the case, fluids interacting with rocks should be internally derived from devolatilization reactions, and their pressure could increase to exceed lithostatic pressure (Rubie, 1986). These fluids would essentially escape from the production domains, whereas the possible influx of magmatic or external fluids would be limited only to the retrograde path in the thermal history of the aureole. This means that the approach of fluid pressure to lithostatic values (which allows the possibility of hydrofracturing) is incompatible with the development of large-scale fluid circulation, since the former requires low permeabilities (Thompson, 1987). As a consequence, the 'tectonic pumping' model (Fyfe *et al.*, 1978), considered the most active in focusing fluid into veins (Kerrick, 1990, p. 339) is poorly applicable to veins formed by hydrofracturing, and to the present case study, so that these vein occurrences need alternative explanations.

Considering that any Al_2SiO_5-forming reaction releases Al from dissolving reactants, and that widely spaced porphyroblasts of andalusite and kyanite are a common feature of metapelites, it is clear that Al is indeed mobile (at least for several centimetres), and its transport does not necessarily require large fluid/rock ratios. Thus, if a situation where Al_2SiO_5 is *produced* (and not dissolved) is considered, the problem of insolubility is overcome. As long as effective mass transport is maintained (in the present case by intercrystalline diffusion), Al_2SiO_5, as well as any other mineral (e.g. rutile, omphacite, garnet; Philippot, 1987) can be transported and precipitated in veins. This process actually operates, regardless of mineral solubilities, in all metamorphic rocks undergoing heterogeneous reactions.

CONCLUSIONS

Andalusite–biotite–quartz-bearing veins at Vedrette di Ries have been interpreted as a product of *synmetamorphic veining*. Such a process is able to integrate several scattered inferences about vein formation in other localities: veining during metamorphism (Heinrich, 1986; Philippot, 1987), in the absence of strain or pervasive fluid flux (Vidale, 1974); hydrofracturing mechanism (Yardley, 1983; Heinrich, 1986); equal mineral assemblage in vein and host rock (Philippot & Selverstone, 1991; Vidale, 1974); local source for material or fluid; lack of wallrock alteration (Heinrich, 1986; Yardley & Bottrell, 1992); synchronous growth of minerals in vein and host rock (Stout *et al.*, 1986; Yardley *et al.*, 1980). Accordingly, the process of synmetamorphic veining may be applicable to vein occurrences where vein and country-rock parageneses are similar and where there is no evidence for large-scale infiltration; it may also prove particularly useful to explain the presence of veins with pegmatitic structure in dehydrated rocks (e.g. eclogitic veins). Re-consideration of the genesis of some Al_2SiO_5-bearing veins that at present do not have an interpretation, e.g. Ky–Qtz–St–Ms–Pg veins at Pizzo Forno (Keller, 1968) or Ky–Qtz–Omp veins in the Lepontine Alps (Heinrich, 1986), might highlight the important role of synmetamorphic veining.

It is important to keep in mind, however, that the genetic model proposed in this study is only one end-member veining process, which is added to those of infiltration metasomatism (Kerrick, 1990) and syndeformation veining (Misch, 1969; Philippot, 1987; Yardley & Bottrell, 1992). Although in some geological scenarios synmetamorphic veining may be proved to be the only mechanism taking place, it is very likely, as suggested by Kerrick (1990, p. 311), that more than one, or all the end-member processes simultaneously operate during formation of most veins. Only an accurate analysis of veins and related host rocks, including structural, petrographic and petrological studies, can distinguish which dominant process prevailed.

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