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P-T-deformation paths of Variscan metamorphism in the Austroalpine basement: controls on geothermobarometry from microstructures in progressively deformed metapelites

by *Bernhard Schulz*[1]

Abstract

Pre-Upper-Ordovician units (metapsammopelite-amphibolite-marble unit AMU, metapsammopelite unit MPU) interlayered with Upper Ordovician granitoids, and early-Palaeozoic sequences (Thurntal complex TC) occur with foliation-parallel lithological contacts and parallel structures to the south of the Tauern Window in the Eastern Alps. The units suffered a common Variscan deformation history. In metapelites, syn- and postcrystalline-rotated garnets enclose plagioclase and micas. Garnet, plagioclase, micas, staurolite and kyanite occur both together and separated in microlithons which are surrounded by the main foliation S_2. These microstructures are assigned to a progressive foliation-forming non-coaxial shearing D_1–D_2 and provide criteria for contemporaneous mineral growth and for mineral equilibria. Different garnet zonation trends (increasing *X*Mg, systematic variation of *X*Ca) and correlated chemical variations in biotites and plagioclases in the lithological units are interpreted to be the product of continuous reactions. Following the microstructural criteria, P and T for successive stages of syndeformational garnet growth were calculated with conventional cation-exchange and net-transfer geothermobarometers. The shapes of syn-D_1–D_2 P-T paths are similar and characteristic within each unit, but different shapes of P-T paths for each unit and different P_{max} and T_{max} suggest a metamorphic zonation in the basement. Shapes and spatial array of the P-T paths are interpreted in terms of syndeformational burial and partial uplift of the units by a progressive overstacking process during an early-Variscan continental collision.

Keywords: metapelites, microstructures, mineral chemistry, P-T-deformation paths, Variscan orogeny, Austroalpine basement, Eastern Alps.

Introduction

The quantitative reconstruction of pressure-temperature-time-deformation (P-T-t-d) paths from metamorphic rocks is an important contribution to understand the thermotectonic processes in orogenic belts. One basic approach toward this end depends on the assumption of phase equilibrium throughout the microstructural domain of interest and allows P-T conditions to be quantified at some point of a rocks metamorphic history by conventional cation-exchange and net-transfer geothermobarometry. A second approach, the Gibbs method, involves the determination of changes in P and T relative to reference conditions and numerically relates compositional zoning in minerals to equilibrium changes in state (P, T, and chemical potentials), on the assumption that zoning resulted from continuous and/or discontinuous reactions among the minerals that now constitute the assemblages (SPEAR, 1989; HAUGERUD and ZEN, 1991). However, this latter method provides only as much information, as the variance of the assemblages allows. Apart from knowledge about the assemblages present during garnet growth (FROST and TRACY, 1991), the Gibbs monitoring of quadravariant systems requires assumptions about the behaviour of a component, especially the *X*Ca of plagioclase (SPEAR and SELVERSTONE, 1983). For this reason, initial results from another method which considers both garnet zonation and conventional geo-

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thermobarometry in combination with microstructural studies in metapelites, are promising (e.g. TRIBOULET and AUDREN, 1985; AUDREN et al., 1987; AUDREN and TRIBOULET, 1993; ST-ONGE, 1987; SCHULZ, 1990; 1993a; TERRY and FRIBERG, 1990). When continuous reactions among garnet, mica, plagioclase, staurolite, aluminosilicates and quartz are considered in such rocks, each step of garnet chemical evolution or zoning represents a finite temporal (Δt) and spatial domain of equilibration with other minerals of the assemblage. Moreover, when coexistent minerals (e.g. mica and plagioclase) are preserved as inclusions or within a microstructural domain ("local equilibrium"), and when their chemical compositions are known, successive P and T or P-T changes for consecutive stages of garnet growth can be evaluated directly by conventional geothermobarometry (PERCHUK et al., 1985; TRIBOULET and AUDREN, 1985; ST-ONGE, 1987).

In metapelites of the Austroalpine basement to the south of the Tauern Window, microstructures of synmetamorphic foliation-forming progressive deformation provide criteria for ascertaining contemporaneous growth of zoned garnets and successive micas and plagioclases in aluminosilicate-bearing assemblages, and for defining a chronological range of successive time intervals of mineral equilibrium. By a combination of the microstructural evolution and the systematic variations of related mineral chemistries, it was possible to calculate individual syndeformational P-T paths from 13 samples and to precisely constrain the tectonometamorphic evolution of the lithologic units.

Structural evolution in the Austroalpine basement

Several pre-Alpine lithologic units appear in N–S profiles of the Austroalpine basement to the south of the Tauern Window (Fig. 1, 7h–n). A structurally lower metapsammopelite-amphibolite-marble unit (AMU) and an upper monotonous metapsammopelitic unit (MPU) are both of pre-Palaeozoic origin and are interlayered by Upper Ordovician granitoids (BORSI et al., 1973; HAMMERSCHMIDT, 1981; CLIFF, 1980). To the south, presumably early-Palaeozoic (Ordovician to early-Devonian) sequences of the Thurntal complex (TC) bear porphyroids (acid metavolcanics) of supposed Upper Ordovician age (SCHÖNLAUB, 1979; HEINISCH and SCHMIDT, 1984). In palaeogeographic reconstructions of the pre-Alpine arrangement of the units (e.g. SCHÖNLAUB, 1979; 1992; NEUBAUER, 1988; LOESCHKE, 1989), the pre-Upper-Ordovician continental crust (AMU and MPU) intruded by the Upper Ordovician granitoids is situated to the N of a NE–SW striking passive continental margin (TC and other phyllitic sequences) with early-Palaeozoic sedimentation, acid volcanism and basic magmatism. Both palaeogeographic zones can be assigned to the northern margin of Gondwana (FRISCH et al., 1990; VON RAUMER and NEUBAUER, 1993).

To the north of the late-Alpine Defereggen-Antholz-Vals line (DAV, Fig. 1b) and in northern parts of the basement, early-Alpine K–Ar muscovite ages of 100 Ma and around 80 Ma, late-Alpine Rb–Sr biotite isochrons ranging from 15 to 28 Ma and Alpine-Variscan "mixing ages" give evidence of an Alpine partial overprinting of the pre-Alpine basement (BORSI et al., 1978; STÖCKHERT, 1985; HOKE, 1990; SCHULZ et al., 1993). Relic pre-Alpine foliation (S_2) and F_3 folds are truncated by late-Variscan pegmatites in the southern parts of the AMU (BORSI et al., 1980; STÖCKHERT, 1985; HOKE, 1990).

Rb–Sr mica ages of around 300 Ma (BORSI et al., 1978) occur to the south of the DAV. In the metasediments of the MPU, a dominant pre-Alpine foliation S_2 (pure quartz layers are considered to represent an older foliation S_1) is axial-planar to isoclinal F_2 folds. F_2 fold axes run parallel to a mineral lineation (L_2). In metabasites (amphibolites and eclogitic amphibolites) L_2 is defined by preferentially-oriented amphibole, zoisite and clinopyroxene. Lineation-parallel

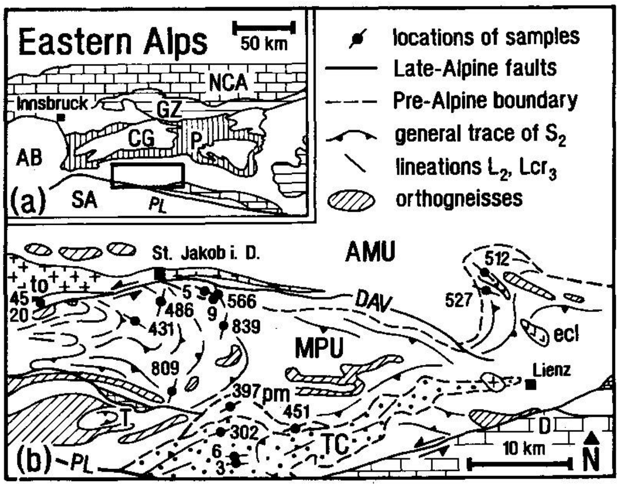

Fig. 1 Geological setting to the south of the Tauern Window. AB = Austroalpine basement; AMU = metapsammopelite-amphibolite-marble unit; DAV = Defereggen-Antholz-Vals line; ecl = eclogitic amphibolites; KV = Kalkstein-Vallarga line; MPU = metapsammopelitic unit; PL = Periadriatic Lineament; pm = phyllitic micaschists of the metapsammopelitic unit MPU; T = Permotrias of Kalkstein; TC = Thurntal complex; to = late-Alpine tonalite;

elongated calcsilicate-gneiss bodies (SCHULZ, 1988b) and sheath folds F_2 with long axes parallel to L_2 in paragneisses, as well as asymmetric K-feldspar augen in orthogneisses signal a considerable non-coaxial and progressive deformation (D_1–D_2) with a shearing direction parallel to L_2 during the generation of the main foliation S_2 (SCHULZ, 1988a). Orientations of L_2 are variable due to later overprinting, but in southern parts of the MPU, and in the TC, this lineation runs uniformly ENE–WSW (Fig. 1b), with several shear sense criteria suggesting a top-to-WSW directed movement during D_1–D_2 (SCHULZ, 1990, 1991). Linear-planar fabrics in the Upper Ordovician granitoids, now orthogneisses, are parallel to S_2–L_2 of the metasedimentary host rocks and give evidence that D_1–D_2 is post-Upper-Ordovician in age (STÖCKHERT, 1985; GUHL and TROLL, 1987; SCHULZ, 1988a). F_2 folds and S_2 were refolded and overprinted at all scales by open to tight F_3-folds and crenulations Lcr_3 whose axes are oriented mostly parallel to L_2. The F_3-folds with steeply plunging axes in some regions of the MPU are minor structures of large-scale syn- and antiforms, called "Schlingen" structures (SCHMIDEGG, 1936; SCHULZ, 1988a).

In the Thurntal complex (TC), isoclinal folding of S_1 quartz layers is accompanied by formation of an axial-planar main foliation (S_2). F_2 fold axes are parallel to a mineral lineation L_2 of amphibolites, porphyroids and phyllitic micaschists. Asymmetric K-feldspar augen structures in porphyroids and syncrystalline-rotated plagioclase and garnet in phyllitic micaschists point as well to a non-coaxial and progressive deformation (D_1–D_2) with a shearing sense parallel to L_2 (SCHULZ, 1991). As is similarly observed in AMU and MPU units, S_2 and F_2 were overprinted by tight to open F_3 folds and crenulations Lcr_3 whose axes are parallel to L_2. Two generations of shear-band foliations, S_4 with top-to-NE directed extensional movement and S_5 with NW to W directed movement of the hangingwall, occur in southern parts of the MPU and in the TC (SCHULZ, 1988a; 1990; 1991) and complete the pre-Alpine structural evolution of the basement.

Parallel orientations of S_2–L_2, F_3 and Lcr_3, S_4 and S_5 in MPU and TC indicate a common pre-Alpine deformation history of both units. A lithological transition between the units is foliation-parallel and shows overprinting by S_4 and S_5 structures. Early interpretations (SASSI and ZANFERRARI, 1972) favoured a former transgressive overlap of the greenschist-facies Thurntal sequences upon the amphibolite-facies MPU, but the supposed "basal conglomerates" turned out to be mylonites of the later overprinting of the lithological contact (HEINISCH and SCHMIDT, 1984) and until now no evident proof of a post-Upper-Ordovician "Caledonian" angular unconformity in the basement to the south of the Tauern Window exists (SCHULZ et al., 1993). Therefore the parallel structures and common deformation history alongside the different metamorphism and protolith ages of MPU and TC represent a major geological problem of the pre-Alpine evolution in the Austroalpine basement.

Microstructural relationships in metapelites

Microstructures were studied in sections parallel to (XZ) and perpendicular (YZ) to L_2 and Lcr_3 ($\hat{=}$ X) of 850 metapelite samples from the AMU, MPU and TC sequences (Fig. 1b, 7h–n) in order to find precise approaches for geothermobarometry. Garnet, staurolite and kyanite (e.g. samples 527, 486, 431, 809) and garnet with staurolite (sample 839) dominate in the MPU. There, staurolite enclosing garnet is frequently observed, but inclusions of staurolite inside garnet have not been found yet. Garnet with fibrolitic sillimanite (samples 5, 9) occurs in the upper parts of the AMU. Samples from the AMU (No. 20, 45) in the thermal aureole around the late-Alpine Rieserferner tonalite bear pre-Alpine garnet and early staurolite. Andalusite with late staurolite in these samples crystallized during a late-Alpine contact metamorphism along the pluton (SCHULZ, 1993b). No staurolite nor aluminosilicates are found in phyllitic micaschists (pm) in southern parts of the MPU (samples 397, 451) and in the Thurntal complex (samples 3, 302).

In micaschists and phyllitic micaschists the most obvious structure in XZ-sections is an anastomosing trace of foliation S_2, defined by mica. S_2 surrounds lens-shaped microlithons or low-strain zones with garnet 1–6 mm in diameter, plagioclase, mica, staurolite and aluminosilicate (Fig. 2). Microlithons sometimes preserve crenulations of S_1. Apart from inclusions without preferential orientation (Figs 2 d, f, m), garnets in all lithotectonic units display internal foliation S_1i by heavy minerals, opaques, quartz, mica and plagioclase, or as observed in the MPU, doubly spiral-shaped pressure shadow inclusion trails ("snowball garnet", Figs 2 h–k, n, o). Microstructures like planar S_1i oriented discordant to (Figs 2 c, e, p) and in some cases lining up with the external S_2 (Fig. 2 t), continuously curved S-shaped S_1i-trails lining up (Fig. 2 r) or discontinuous with S_2 (Figs 2 g, l, s), and the doubly spiral-shaped pressure shadow inclusion trails (SCHULZ, 1990, 1991, 1992a) are interpreted to indicate syncrystalline garnet rota-

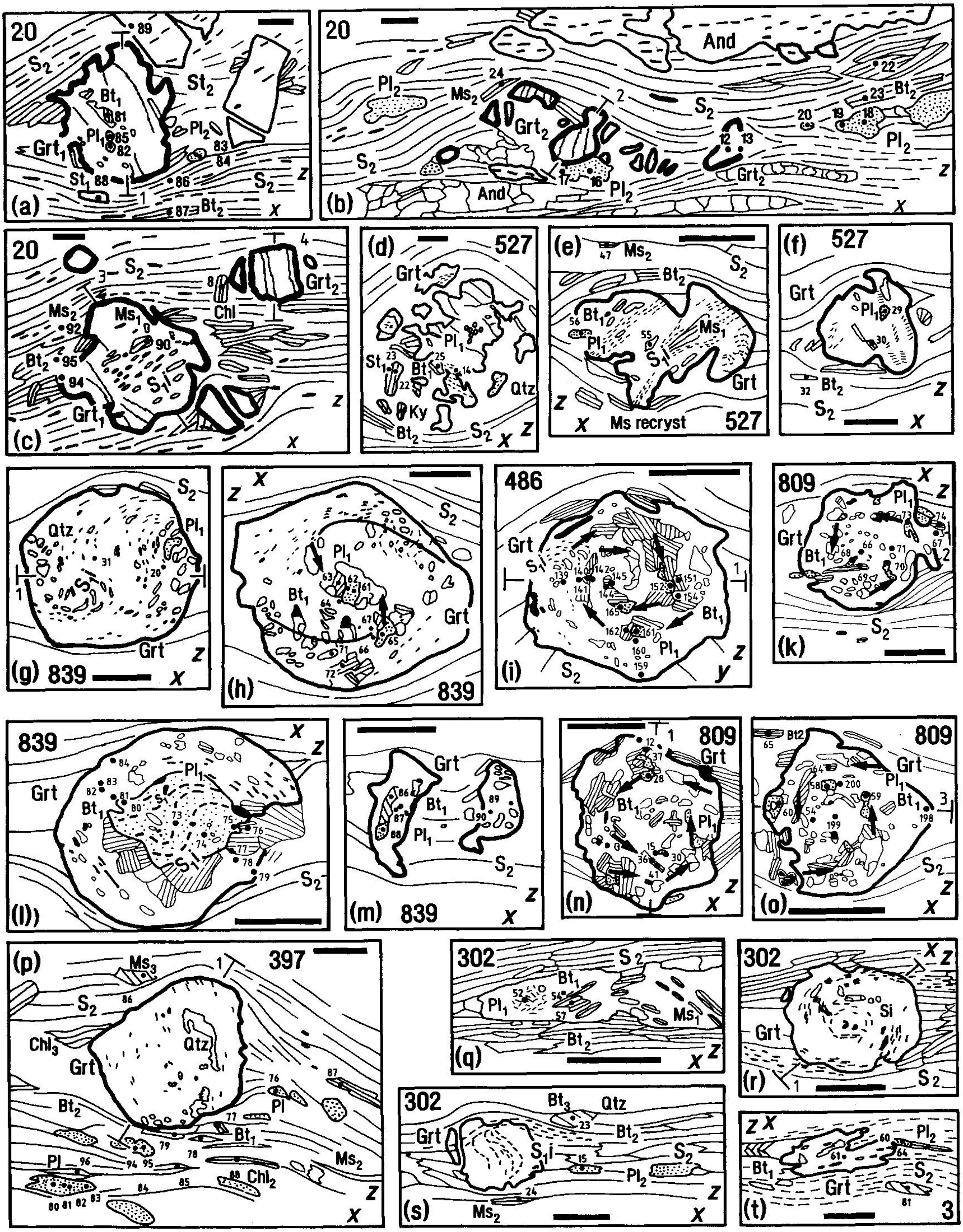

Fig. 2 Microstructures in metapelites and locations of selected microprobe analyses. Scale bar is 0.5 mm. The sections are oriented parallel (XZ) or perpendicular (YZ) to the lineation L_2 or Lcr_3. For garnet zonation profiles see figure 4. Sample 20 (a–c) is from the metapsammopelite-amphibolite-marble unit (AMU), samples 527, 839, 486,

tion (= rotation during growth), following the arguments of PASSCHIER et al. (1992) in an ongoing discussion (BELL et al., 1992). No uniform rotation sense of the porphyroblasts has been observed in XZ sections, but in most samples and in all lithological units, garnet rotation axes parallel to the Y-direction indicate a dominant non-coaxial deformation component with a shearing direction parallel to X and a top-to-SW sense of movement during the formation of S_2 (SCHULZ, 1988c; 1990, 1991, 1992a).

Planar S_1i in garnets inside microlithons represents an early stage D_1 of deformation. Foliation S_2, wrapping the microlithons and surrounding the porphyroblasts, is related to a later stage of deformation (D_2). Consequently, the different internal structures preserved in the syncrystalline-rotated garnets are interpreted as successive incremental steps of a D_1–D_2 deformation with progressive character (SCHULZ, 1990). Porphyroblast-S_1i – matrix-S_2 relationships allow the relative timing of crystallization of each mineral with reference to the successive foliations of progressive deformation to be ascertained (e.g. SPRY, 1969; VERNON, 1978; BELL et al., 1986). The porphyroblasts of syn-D_1–D_2 or pre/syn-S_2 assemblages respectively are situated inside microlithons or are elongated within S_2. As is best observed in YZ-sections, porphyroblasts of the post-S_2 assemblages overgrew crenulation folds (Lcr_3) of S_2.

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809 (d–o) represent the metapsammopelitic unit (MPU), sample 397 (p) belongs to the phyllitic micaschists of the MPU and samples 302, 3 (q–t) are from the Thurntal complex (TC).

(a) First generation garnet (Grt_1) enclosing biotite (Bt) and albitic plagioclase (Pl). Staurolite $_1$ (St_1) of probably pre-Alpine age appears in foliation S_2. Post-S_2 staurolite $_2$ and andalusite (And) are related to late-Alpine contact metamorphism.

(b) Microlithon with broken garnet $_2$ in contact with plagioclase and microlithons with isolated garnet and plagioclase.

(c) Large first generation garnet with planar S_1i in the core and a limpid rim. Second generation garnet bears no inclusions.

(d) Microlithon with garnet enclosing albitic plagioclase in the core. Staurolite $_1$, kyanite $_1$ and biotite $_1$ appear near to the garnet rim.

(e) Postcrystalline-rotated garnet with planar S_1i by biotite, muscovite, albitic plagioclase and quartz, situated discordant to external S_2.

(f) Garnet enclosing albitic plagioclase and mica without preferential orientation.

(g) Syncrystalline-rotated garnet with S-shaped inclusion trails of S_1i. Note differently curved hinges of S_1i trails on each side of the porphyroblast. Rotation axis is parallel to Y, signalizing porphyroblast rotation during non-coaxial deformation with a shearing sense parallel to X.

(h) Syncrystalline-rotated garnet with doubly pressure shadow spiral by mica, plagioclase and quartz. Arrows and lines indicate the trace of the inclusion spiral. S_1i trails by opaques and quartz cross-cut the spiral with sharp hinges. Rotation axis of the garnet is parallel to Y.

(i) Syncrystalline-rotated garnet with a doubly pressure shadow spiral. Arrows point to the center of the spiral. S_1i by opaques cross-cuts the spiral with sharp hinges. As an exception, the rotation axis of the garnet is oriented parallel to X.

(k, n, o) Syncrystalline-rotated garnets with doubly pressure shadow spirals. Rotation axes are oriented parallel to Y and indicate porphyroblast rotation by non-coaxial deformation with a shearing sense parallel to X.

(l) Garnet enclosing mica and large plagioclase with S-shaped S_1i trails of syncrystalline rotation. This plagioclase appears to coexist with the garnet of figure 2g.

(m) Small broken garnet bearing biotite, plagioclase and quartz without preferential orientation.

(p) Large garnet in phyllitic micaschists of the MPU. S_1i by opaques and quartz is discordant to S_2. Elongated plagioclase in the microlithons is sharply marked albite in the core surrounded by zoned oligoclase (An 15–18%) in the rim.

(q) Microlithon in phyllitic micaschists of the TC, with zoned plagioclase enclosing first generation biotite and muscovite.

(r) Syncrystalline-rotated garnet with curved Si by opaques and quartz, lining up with external S_2. Rotation axis of the garnet is parallel Y, suggesting rotation by shearing parallel to X.

(s) Garnet core with slightly curved S_1i which is discordant to inclusion trails in the rim. Elongated small plagioclase appears in S_2.

(t) Post-S_2 garnet with Si lining up with S_2. Crenulated S_1 by mica is situated in a microlithon to the left.

According to the microstructural observations in the metapelites of AMU and MPU, where early staurolite and kyanite occur inside microlithons whereas late staurolite and kyanite overgrow crenulation folds Lcr_3 of S_2, the following successive mineral assemblages can be derived and summarized (SCHULZ, 1988a; 1990; 1993a, 1993b): Early syn/post-S_1 garnet + biotite + muscovite + plagioclase are followed by later syn-S_2 garnet + biotite + muscovite + plagioclase + staurolite ± kyanite and post-S_2 staurolite + biotite + muscovite + plagioclase ± kyanite or sillimanite or andalusite. In the phyllitic micaschists of the MPU and the TC, the assemblage is garnet + biotite + muscovite ± chlorite + plagioclase (SCHULZ, 1991).

Microstructural criteria for mineral equilibria

When compositional zoning of garnets in metapelites is a product of continuous reactions within low-variance assemblages (THOMPSON, 1976; TRZCIENSKI, 1977; TRACY, 1982), the chemical evolution of the porphyroblasts reflects a time sequence of more or less continuous growth. Thus, apart from knowledge about the present aluminosilicate, for application of available garnet-biotite Fe-Mg-exchange geothermometers and garnet-plagioclase Ca-net-transfer geobarometers, analyses from biotites and plagioclases which correspond to early (= core) and successively later (= towards rim) stages of the garnet growth are required. The main problem is the preservation of these minerals in the course of later stages of metamorphism and deformation. A synmetamorphic foliation-forming progressive deformation of metapelites isolates structural sites like microlithons, low-strain zones and porphyroblasts, in which minerals of earlier deformational and metamorphic stages in most cases resist later re-equilibration and dissolution (BELL, 1981; BELL et al., 1986, 1992). From the Austroalpine metapelites, different microstructural criteria (labelled 1 to 6) for synchronous mineral growth or for mineral equilibrium for corresponding time intervals Δt in course of such progressive deformation can be assessed and summarized (SCHULZ, 1990; 1991; 1993a; 1993b):

Minerals of pressure shadow spirals in syncrystalline-rotated porphyroblasts ("snowball garnets") probably provide the most reliable record of temporally coexisting phases (criterion 1, Fig. 3a). Following the models of SCHONEVELD (1977), these minerals are interpreted to have crystallized in the pressure shadows almost at the same time as they were successively enclosed by garnet rotating during its growth, and will give a syndeformational record of mineral equilibria.

Correspondingly, when successive foliations S_1 and S_2 were produced during progressive deformation, mica and plagioclase associated with S_1 and enclosed in syn- and/or postcrystalline-rotated garnet can be related to an early stage, and syn-S_2 mica and plagioclase to a later stage of porphyroblast growth (criterion 2, Figs 3 b, c).

Similarly, this can be used when inclusions without preferential orientation occur at different sites (core, intermediate zone, rim) in garnet (criterion 3), and indicate a static growth of the porphyroblast without rotation (Figs 3 b, c). The work of ST-ONGE (1987) has shown the accuracy of this criterion which is useful for broad application (e.g. TERRY and FRIBERG, 1990; SCHULZ 1992b; AUDREN and TRIBOULET, 1993). However, this criterion appears to be less reliable as criterion 2 because the inclusions may predate the garnet growth or may be matrix intergrowths.

Furthermore, when no inclusions occur inside garnet, cores of zoned plagioclase and S_1-biotite within the same microlithon can be interpreted to be in equilibrium with garnet core. Rims of plagioclase, unzoned plagioclase and cores of S_2-biotite may correspond to garnet rim when garnet shows "prograde zonation" (ROBINSON, 1991) (criterion 4, Fig. 3d). The contemporaneous growth of garnet, plagioclase and biotite appears to be less well defined by this criterion as by syn- and postcrystalline-rotated porphyroblasts or by garnets with inclusions, and the question arises what portion of the zoned plagioclase, core or not, was actually in equilibrium with zoned garnet core. This criterion avoids possible effects of diffusive re-equilibration in garnet inclusions.

As criteria 1 to 4 can be applied to garnet, plagioclase and mica within the same microlithon, a similar use of these criteria appears to be possible when the minerals occur isolated in equivalent microstructural positions within different microlithons (criterion 5, Fig. 3e). However, the latter criterion must regarded with some caution due to the possible (but rarely observed) formation of successive generations of microlithons (AUDREN, 1987; AUDREN and TRIBOULET, 1993) with temporally and chemically different generations of the same phase in the course of a progressive deformation.

Furthermore, in YZ-sections perpendicular to crenulations of the main foliation (S_2), core-rim zonations of postdeformational porphyroblasts, occurring in contact or not, can provide a confident additional microstructural criterium for mineral equilibrium (criterion 6, Fig. 3f).

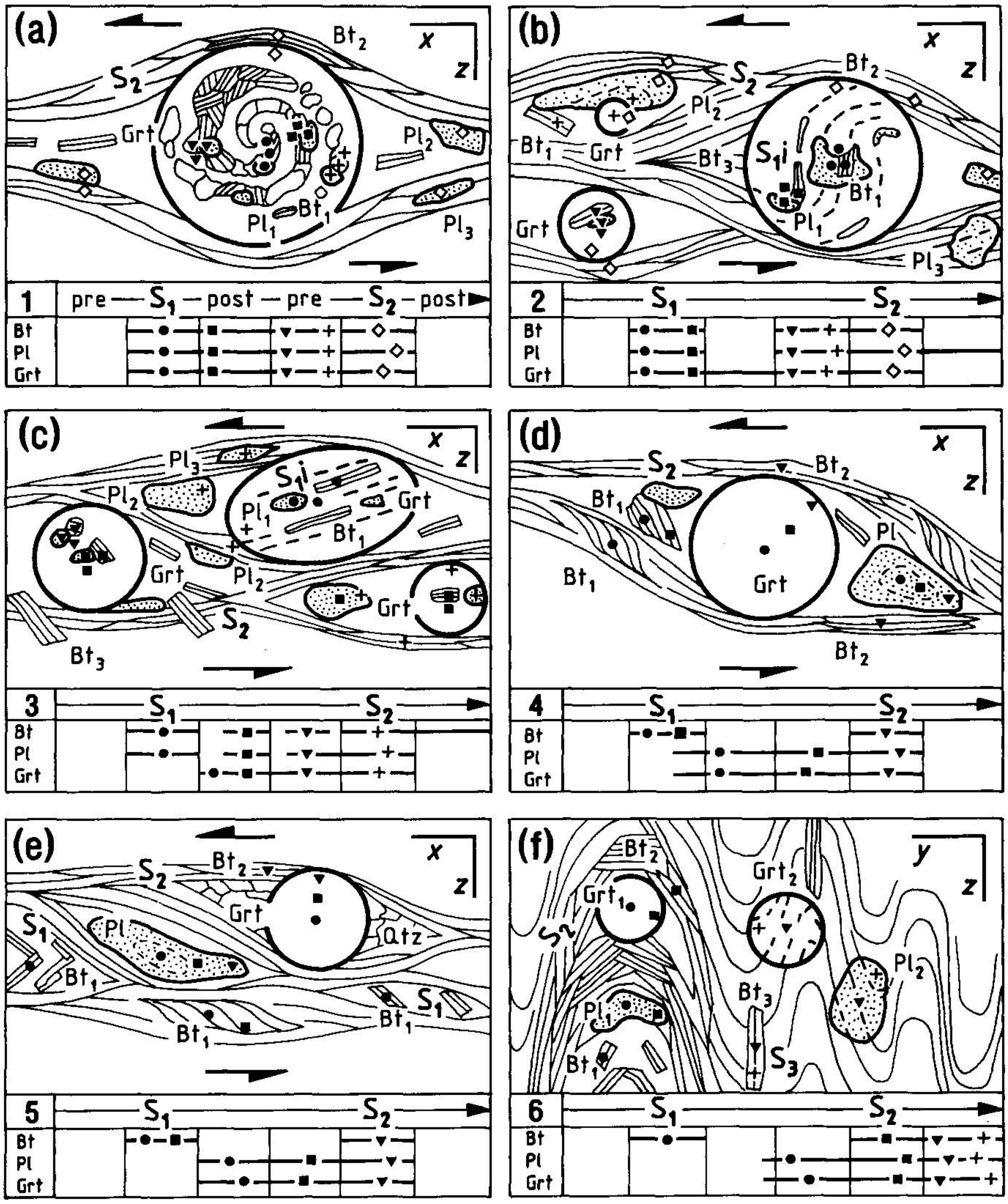

Fig. 3 Microstructural criteria for contemporaneous mineral growth and mineral equilibria of garnet (Grt), biotite (Bt) and plagioclase (Pl) in XZ and YZ sections of deformed metapelites. Staurolite and aluminosilicates are not shown. Schematic and synoptic view, compiled from observations in metapelites of the Austroalpine basement (Fig. 2). Arrows signalize non-coaxial deformation component. Marked mineral pairs are interpreted to have grown contemporaneously and to represent "local equilibrium", the marks in a similar manner indicate proposed locations for microprobe analyses (see text). Mineralogical-microstructural schemes display relative temporal and structural positions of the mineral pairs in reference to foliations S_1 and S_2 of progressive non-coaxial deformation. Marks refer to the mineral pairs and corresponding mineral compositions to be used for geothermobarometry. Arrows indicate the time axis.

(a) Criterion 1: syncrystalline rotated garnet with doubly pressure-shadow inclusion spirals (see Figs 2 h–k, n, o).

(b) Criterion 2: syncrystalline rotated garnet with S_1i and inclusions (see Figs 2 g, l).

(c) Criterion 3: postcrystalline-rotated garnet with biotite and plagioclase inclusions arranged as S_1i in microlithon (see Figs 2 c, e), and statically grown garnet bearing inclusions without preferential orientation (see Figs 2 a, d, f, m).

(d) Criterion 4: garnet without inclusions, together with zoned plagioclase and/or biotite $_1$ in a microlithon surrounded by S_2 (see Figs 2 b, d).

(e) Criterion 5: garnet, zoned plagioclase and biotite $_1$ separately occur in different microlithons (see Figs 2 b, p–s).

(f) Criterion 6: syn-S_2 garnet $_1$, plagioclase $_1$ and biotite $_1$ occur in separated microlithons surrounded by S_2. Post-S_2 garnet $_2$, plagioclase $_2$ and biotite $_3$ postdate crenulation folds of S_2, the latter criterion was not found in and applied to the listed samples.

The criteria of successive mineral equilibria in progressively deformed metapelites listed here are not complete, and further cases may occur. As is outlined in many papers dealing with microstructures in metapelites (e.g. VERNON, 1978; BELL et al., 1986; BELL et al., 1992; PASSCHIER et al., 1992), microstructural observations are uncertain, ambiguous, subjective, dependent on the orientations of the thin slices, and the interpretations appear to be afflicted with prejudices. An independent control of the observations and interpretations appears to be possible and necessary by mineral chemistry analysis.

Mineral-chemical evolution in metapelites

Microprobe analyses (800 points, for the data see SCHULZ, 1990; 1991; 1993a; 1993b; unpublished data) were taken from 13 selected metapelite samples. Micas are represented by analyses from their cores and sometimes from cores and rims, while zoned plagioclases were controlled by a few analyses from cores to rims. In order to avoid the analysis of possible retrograde re-equilibration effects by cation diffusion (TRACY et al., 1976), only cores of mica inclusions in garnet and no immediate grain boundaries were considered. The chemical evolution of the garnets has been characterized by zoning profiles with 7 to 25 analyses from several porphyroblasts in each sample; sometimes the profiles are oriented perpendicular within one porphyroblast. Garnets with complex internal microstructures of syn- and postcrystalline rotation display similar circular or elliptic zonations as porphyroblasts without such inclusions. Effects of diffusional homogenization in garnet cores and random re-equilibration of rims by retrograde exchange reactions (ROBINSON, 1991) are not observed (Fig. 4).

Garnet compositions were plotted in spessartine-grossular-pyrope (Sps-Grs-Prp) and in Mg/(Mg + Ca + Fe + Mn) versus Ca/(Mg + Ca + Fe + Mn) (MARTIGNOLE and NANTEL, 1982) diagrams (Fig. 5). These plots are necessary for deducing the most complete chemical evolution trend of the garnets from a given sample, as single garnet profiles may have not got the early core, single porphyroblasts within one sample can display zonation gaps near to the rims (Figs 4 a, g), and some porphyroblasts may show only a part of the complete chemical evolution of garnets in a sample (Figs 4 b–d, g, i, k, l). The complete and characteristic evolution trend of the garnets in each sample can be summarized in synthetic *X*Mg-*X*Ca-*X*Fe-*X*Mn core-rim zonation profiles (Fig. 6).

In garnets from the AMU (sample 20) and the MPU (samples 527, 839, 486, 809) an increasing *X*Mg from cores to rims is accompanied by strong Ca variations (Figs 4 a, e–h, l, p–s, 6 a, e–h). This general trend is predated by decreasing *X*Mg in sample 45 (Figs 5 b, m, 6 b) and interrupted by a slight decrease-increase of *X*Mg in samples 20, 527, 839, 486 and 809 (Figs 5 a, e–h, 6 a, e–h). Samples 5 and 9 display only decreasing *X*Ca (Figs 5 c, d, n, o, 6 c, d). In the other samples, despite their different microstructures and kilometres of distance in between, the variation of *X*Ca, at first a decrease then an increase and finally a decrease again, are similar and independent from occurrence or microstructural positions of aluminosilicates (SCHULZ, 1990; 1992a; 1993a; 1993b). It is concluded that this variation of grossular in the garnet profiles has been induced by a general geological effect which affected the lower parts of the basement. Garnets from phyllitic micaschists (samples 397, 451) in the upper part of the MPU display increasing *X*Mg with constant *X*Ca (Figs 5 i, t, 6 i) whereas constant *X*Mg is accompanied by increasing *X*Ca from cores to rims in garnets from metapelites of the TC (Figs 5 k, u, 6 k).

Following the microstructural criteria outlined above (Fig. 3) for the analyses of biotites and plagioclases which correspond to defined successive stages of the garnet growth, different chemical trends of these minerals are observed: Biotites are only slightly zoned as has been emphasized by PIGAGE and GREENWOOD (1982). The *X*Mg of successive biotites slightly decrease in samples 20, 527, 839, 486, 809 (Figs 6 a, e–h) and increase in samples 45, 9, 5, (Figs 6 b–d) when *X*Mg of garnets increase during D1–D2. Increasing *X*Mg of biotite with increasing grade have been observed from different samples in metamorphic zones (e.g. THOMPSON, 1976; LANG and RICE, 1985). From successive biotites in single samples from one zone, increasing as well as decreasing *X*Mg of biotites with increasing *X*Mg of garnet can be stated (ST-ONGE, 1987). This is possible as the K_D for Fe–Mg exchange between garnet and biotite merely trends toward 1 with *X*Mg garnet approximating *X*Mg biotite at increasing T (YARDLEY, 1989). In plagioclases, *X*Ca evolves oppositely directed to *X*Ca garnet variation in samples 20, 45, 486, 809, 397, 451 (Figs 6 a, b, e–i). Similarly directed Ca evolution trends with decreasing *X*Ca in garnet and plagioclases occur in samples 5 and 9 (Figs 6 c, d). This different behaviour may be explained by changing mineral abundance along specific P-T trajectories (SPEAR et al., 1990). For a next step of interpretation and following these observations, it appears to be useful to correlate the deformation and microstructural evo-

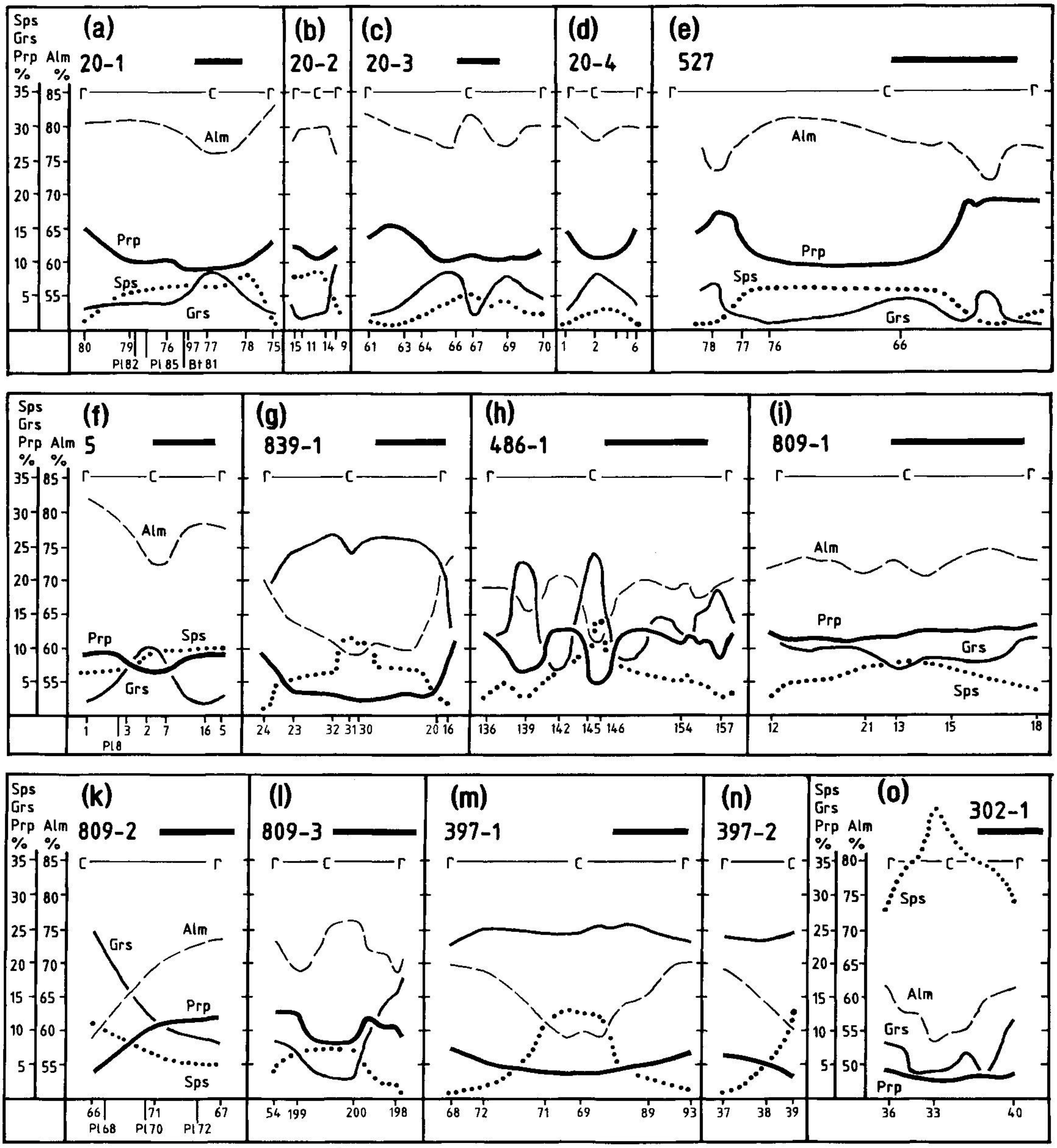

Fig. 4 Chemical profiles from garnets (see Fig. 2) in spessartine (Sps), grossular (Grs), pyrope (Prp) and almandine (Alm) contents, expressed in %. Scale bar is 1 mm. Numbers are selected analyses in figures 2, 5, 6. c = core; r = rim.

lution of the metapelites in course of D_1–D_2 to the continuous/discontinuous chemical record of minerals within the assemblages in order to calculate P and T of equilibria and to define P-T-deformation paths (AUDREN and TRIBOULET, 1989).

Geothermobarometry

The garnet-bearing assemblages in the metapelites appear in a divariant field which is bounded by a garnet-forming continuous reaction at low temperatures and a staurolite-producing continuous reaction at high temperatures (SPEAR and CHENEY, 1989), the changes in mineral chemistry can be explained by further continuous reactions inside this field. Increasing *X*Mg of zoned garnet is characteristic of a metamorphism prograde in temperature whereas increase and decrease of *X*Ca in the garnets signalize coeval relative increase and decrease of pressure (MARTIGNOLE and NANTEL, 1982; SPEAR et al., 1990; ROBINSON, 1991). As is indicated by the microstructures and garnet zonation trends, assemblages with staurolite and kyanite in the central part of the MPU possibly crystallized at increasing T and decreasing P by reactions

garnet + chlorite + muscovite =
staurolite + biotite + H_2O
or
garnet + biotite + Al_2SiO_5 + H_2O =
staurolite + muscovite + quartz

(SPEAR and CHENEY, 1989). Discriminative and corresponding reaction structures were not observed.

Temperatures were calculated from the garnet-bearing assemblages by several garnet-biotite Fe–Mg exchange geothermometers (THOMPSON, 1976; HOLDAWAY and LEE, 1977; HODGES and SPEAR, 1982; GANGULY and SAXENA, 1984; PERCHUK and ARANOVITCH, 1984). Several garnet-plagioclase-aluminosilicate-quartz Ca net-transfer geobarometers (NEWTON and HASELTON, 1981; GANGULY and SAXENA, 1984; PERCHUK et al., 1985; KOZIOL and NEWTON, 1988) and the garnet-biotite-muscovite-plagioclase geobarometer of GHENT and STOUT (1981) were used to estimate the corresponding pressures. The minimal and maximal results from all applied geothermobarometers for a given garnet-biotite-(muscovite)-plagioclase pair enclose a P-T field encompassing the disagreement among all the calibrations and garnet solid-solution models and defining the global error of the calculations in a rigorous way (TRIBOULET and AUDREN, 1985; SCHULZ, 1990; 1993a). For each sample, these calibrations have been applied to mineral pairs of simultaneous crystallization in course of progressive deformation D_1–D_2, as defined by the microstructural criteria listed in figure 3. A relative temporal range of the P-T fields is given by the core-rim zonations of the garnets, the relative position of inclusions in the garnets and the microstructural position of the minerals in relation to S_1, S_1i and S_2 foliations (Fig. 2). All P-T fields line up and characterize a syndeformational (D_1–D_2) P-T path for each sample.

In detail, successive mineral pairs from garnets with doubly pressure shadow spirals in the samples 486 and 809 (Figs 2 i, k, n, o) allowed to calculate successive P and T which define the metamorphic evolution for the complete period of garnet growth by criterion 1 (Fig. 3a). For sample 839, only an intermediate part of the evolution was estimated from a garnet with a doubly pressure shadow spiral (Fig. 2h). Calculation of the early part of this P-T path, was possible from combination of core and rim of a garnet with S-shaped S_1i (Fig. 2g) with core and rim of a plagioclase with equivalent S_1i and biotites (criterion 5, Fig. 3e), both enclosed in another garnet (Fig. 2l). The final stage of this path has been obtained from inclusion pairs (criterion 3) in another porphyroblast (Fig. 2m). For sample 20, P and T of an early stage were calculated from early garnet core inclusions (criterion 3, Fig. 2a). P-T data for intermediate and final stages of metamorphism has been estimated from mineral pairs within the same (criterion 4, Fig. 2b) and in different microlithons (criterion 5, Figs 2 b, c) bearing second generation garnets and corresponding plagioclases. Pressures and temperatures for the internal parts of garnets in sample 527 were calculated from inclusion pairs (criteria 2 and 3, Figs 2 d–f). Marginal parts of the garnets in combination with S_2-biotites and enclosed or adjacent unzoned plagioclases (criteria 3, 4, 5) led to the final segment of the P-T path (SCHULZ, 1993a). Similarly, P and T were estimated from cores and rims of garnets in the samples 5 and 9. Due to lacking inclusions in the garnets of samples 397, 451 and 302, the application of criterion 5 (Figs 2 p–s) was necessary for P-T estimates from garnet cores and rims. The lines in the P-T diagrams of figures 7 a–g display the mean evolution trends, given by the successive P-T fields which were calculated from each sample.

Discussion of uncertainties

Two assumptions of equilibrium, (1) that heterogeneous equilibrium was achieved and preserved within a given volume of rock, (2) that Fe–Mg exchange between garnet and biotite as well as Ca net-transfer from garnet to plagioclase ceased equilibrating at the same time, are critical to the Gibbs method and to conventional thermobarometry (HAUGERUD and ZEN, 1991). When these basic assumptions are accepted, uncertainties upon P-T paths calculated from zoned minerals arise from quantitative systematic error (microprobe analyses, thermodynamic data) and from qualitative error such as the combination of possibly inappropriate mineral pairs, possible changes of the garnet profiles by diffusion at high temper-

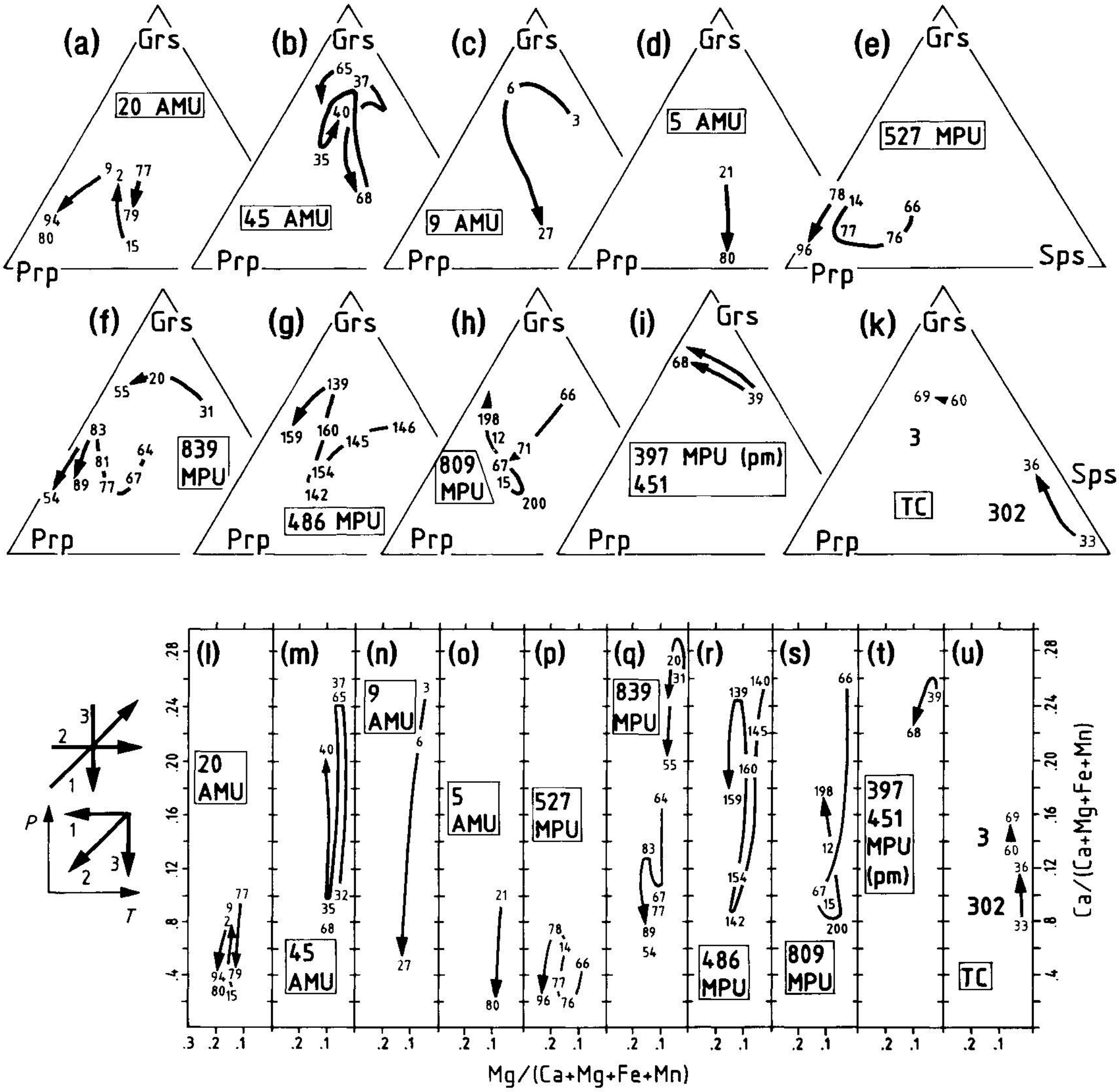

Fig. 5 Evolution of compositions of syn-D_1–D_2 garnets in metapelite samples (large numbers) from the metapsammopelite-amphibolite-marble unit (AMU), the metapsammopelitic unit (MPU), phyllitic micaschists (pm) of the MPU and the Thurntal complex (TC) of the Austroalpine basement. Arrows show core-rim trends, small numbers refer to characteristic analyses within the trends (see Fig. 4 for zonation profiles).
(a–k) Garnet compositional trends in spessartine-grossular-pyrope (Sps-Grs-Prp) coordinates.
(l–u) Garnet compositional trends in XMg versus XCa coordinates (Martignole and Nantel, 1982) refer to tectonic history: isobaric cooling (1), cooling/unloading (2) and isothermic unloading (3).

atures, possible re-equilibration of mica inclusions in garnet, or lacking information on the assemblages coexistent with the garnet cores.

Due to poorly understood activity/composition relationships (Ashworth and Evirgen, 1985) and a possible strong deviation from ideality (Ghent and Stout, 1981) in plagioclase with low anorthite contents at low temperatures, it is possible that pressure estimates from garnet and albitic plagioclase, as in samples 20 and 527 (Figs 6 a, e), may be doubtful and too high. Comparison of P-T estimates for maximal pressures from the garnet-plagioclase-aluminosilicate and garnet-biotite-muscovite-plagioclase barometers for sample

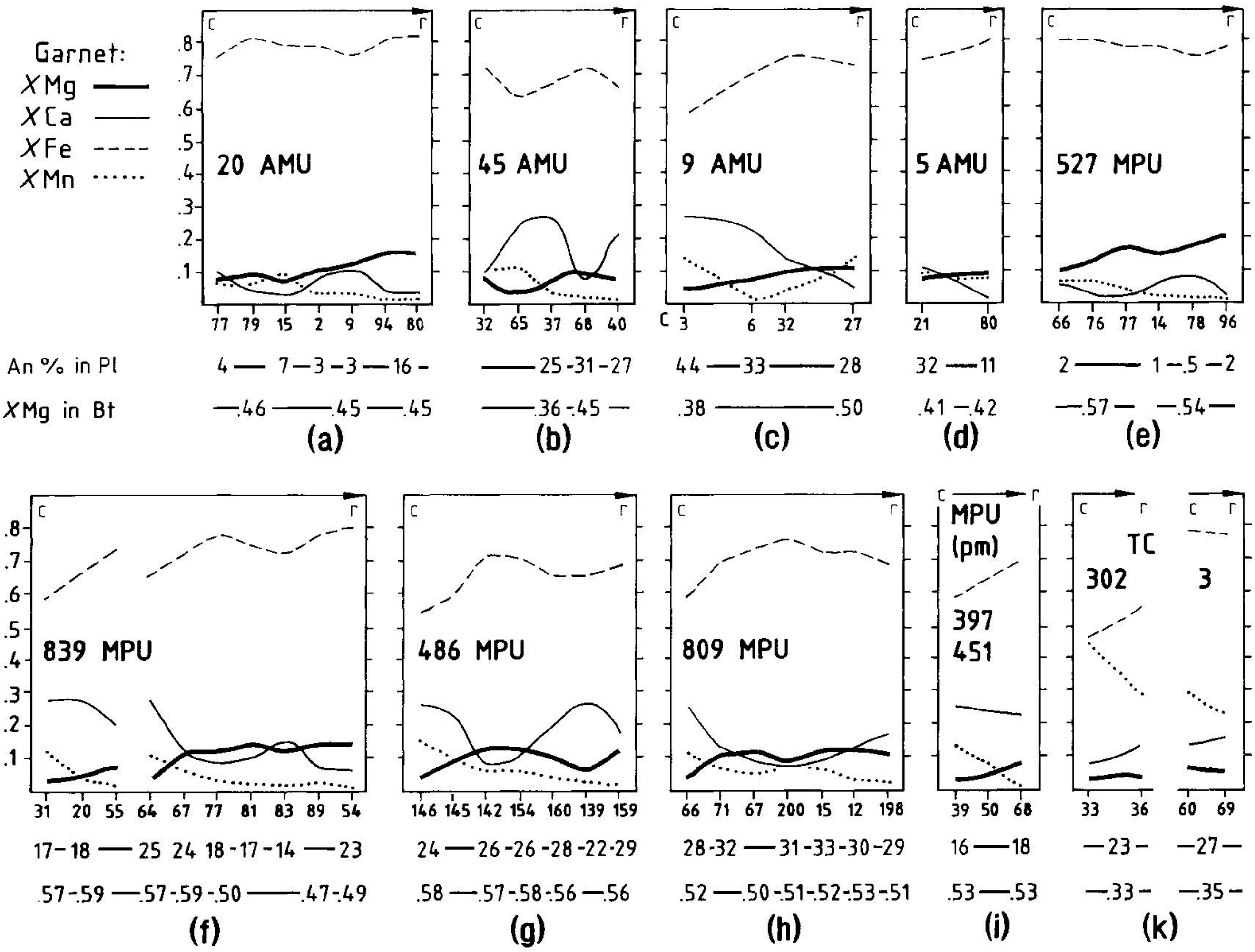

Fig. 6 (a–k) Synthetic garnet zonation profiles in *X*Mg, *X*Ca, *X*Mn, *X*Fe (Xn = n/(Mg + Ca + Mn + Fe), compiled and derived from core-rim (c, r) zonation profiles (Fig. 4). Small numbers refer to characteristic analyses in figures 2, 4, 5 of several porphyroblasts in each sample. Compositions of corresponding plagioclases and biotites (according to the microstructural criteria of Fig. 3) are expressed in An % and in *X*Mg = Mg/(Mg + Fe) respectively.

527 indicate that mean values fit well with independent pressure and temperature estimates from an eclogitic amphibolite (sample 512, Figs 1b, 7b) nearby (Schulz, 1992a; 1993a).

Qualitative errors, especially possible changes of chemical profiles in the interior of garnets by internal diffusion (Spear, 1988; 1991; Spear et al., 1990; Robinson, 1991), are difficult to assess. When the zonation profiles of figure 4 are compared, similar zonation trends (Figs 5, 6) are observed from different locations within porphyroblasts with different sizes and from several porphyroblast generations within a given sample. This provides no hints to possible internal diffusive changes in the garnets.

Slow rates of post-entrapment volume diffusion in plagioclases will preserve original compositions of inclusions inside garnets (St-Onge, 1987). The only effective means of equilibration is for early plagioclase to dissolve partially or completely, and for new plagioclase of a different composition to grow (Spear et al., 1990). No textural signs of a retrograde albitization of initially anorthite-richer plagioclase and of coexisting oligoclase and albite (Ashworth and Evirgen, 1985) were found in the investigated samples. A possible re-equilibration of biotite inclusions by local cation exchange with garnet (Spear, 1991), retrograde net-transfer garnet resorption (Robinson, 1991) or by exchange with the matrix along small cracks (Loomis, 1983), is difficult to exclude or to prove. Detailed studies (e.g. St-Onge, 1987; Audren and Triboulet, 1993) in rocks which suffered equivalent and higher temperatures, have shown slight systematic compositional changes of biotite inclusions in dependence of their positions inside the garnets, and provide an argument that these compositions are representative for the time of entrapment. In the Austroalpine micaschists, different compositions of biotites in different microstructural sites, enclosed or not, give evidence that no unwelcomed overall homogeneous re-equilibration of the micas has been achieved. Furthermore, it is possible to check this problem by comparing the compositions of inclusions with the data from minerals in equivalent microstructural positions according to the criteria of figure 3.

Due to a supposed continuous recrystallization of micas in foliation planes during a progressive deformation, the chemical compositions of the phyllosilicates are related to a final increment of each local foliation-forming deformation only (TRIBOULET and AUDREN, 1985; DEMPSTER, 1992) and establish a discontinuous structural/chemical record, which is sometimes difficult to be correlated to appropriate successive steps of the continuous chemical record of garnets and plagioclases, especially when inclusions are lacking. For this reason, the most reliable criteria for simultaneous crystallization is given by syncrystalline-rotated "snowball" garnets with numerous inclusions (Fig. 2a) when several criteria are joined in a given section.

Furthermore, following the microstructural observations in the lower basement parts, the presence of aluminosilicate(s) in the assemblage coexistent with garnet cores and throughout the whole period of garnet growth is questionable, but possible when the AFM relationships of phases in single samples are taken into account. Possibly, pre-existent aluminosilicate has been completely obscured by transformation to white mica. For this case, results from garnet-plagioclase-aluminosilicate-quartz barometers for early stages of garnet growth will give maximal pressures (FROST and TRACY, 1991). However, the corresponding results from the garnet-biotite-muscovite-plagioclase calibration in each case confirmed the relative as well as the actual P-T trends (SCHULZ, 1992a; 1993a; 1993b).

These possible uncertainties discussed above may seriously affect the accuracy of absolute P-T estimates (HODGES and MCKENNA, 1987). Therefore, for further detailed interpretation it appears to be convenient to take into account mainly relative P-T variations. A calculation of P-T values from characteristic analyses out of the garnets chemical trends will provide a less faulty relative P-T evolution due to the easiest controllable and measurable garnet zonations and the potentially minor serious effects of diffusion upon interior parts of the profiles. This has been shown by SPEAR and RUMBLE (1986) by garnet profile simulation based on the Gibbs method. The dependence of a calculated P-T path on garnets *X*Ca and *X*Mg evolution is intensified, when corresponding micas and plagioclases have only slight compositional variations as in samples 397, 451, 302, 3 (Figs 6 i, k), or when *X*Mg in biotite and *X*Ca in plagioclase evolve oppositely directed to the corresponding *X*Mg and *X*Ca variations in garnets (samples 20, 45, 527, 839, 486, 809, Figs 6 a, b, e–h). The effect is reduced when the compositional trends evolve with similar direction (samples 9, 5, Figs 6 c, d). Thermobarometric calculations for given steps of garnet evolution with mineral pairs in contact or not in contact, defined by alternative microstructural criteria (Figs 2, 3), or calculations with micas and plagioclases of different compositions, yielded no significant changes of the obtained relative P-T trends. This is as well true for samples 9 and 5, where barometry using plagioclase with similarly directed strong *X*Ca variation as in the garnet, confirmed the relative pressure variation semiquantitatively given by garnets decreasing *X*Ca. Summing up, the shapes or the relative $\Delta P/\Delta T$ trends of P-T paths obtained by using conventional geothermobarometry in that way, appear to be robustly preserved when uncertainties about corresponding plagioclase and biotite are considered.

P-T-deformation paths of Variscan continental collision in the Austroalpine basement

Following the garnets *X*Mg and *X*Ca evolution trends in the upper parts of the AMU and in the lower parts of the MPU, the corresponding P-T paths generally display increasing temperatures (400 to 680 °C) and coeval strong pressure variations with maximum pressures ranging from 10 to 15 kbar (Figs 7 a–e). Results from eclogitic amphibolites (sample 512, Fig. 7b, see above), amphibolites (sample 566, Fig. 7a), and data from STÖCKHERT (1985) and HOKE (1990) from adjacent parts of the basemet (S, H in Figs 7 a, b) independently confirm the maximal pressures and temperatures calculated from the metapelites (SCHULZ, 1990; 1992a; 1993a). P-T estimates from Mg-poor and Ca-rich garnet cores indicate an early greenschist-facies metamorphism at intermediate to high pressures in the MPU. A subsequent high-pressure amphibolite/eclogite-facies stage followed by a high-temperature medium-pressure amphibolite-facies stage was calculated from Mg-rich outer parts of the garnets. Samples 9 and 5 from the upper parts of the AMU and bearing fibrolitic sillimanite obviously recorded only an early stage of this evolution. In some samples (486, 809), continuous zonation trends in

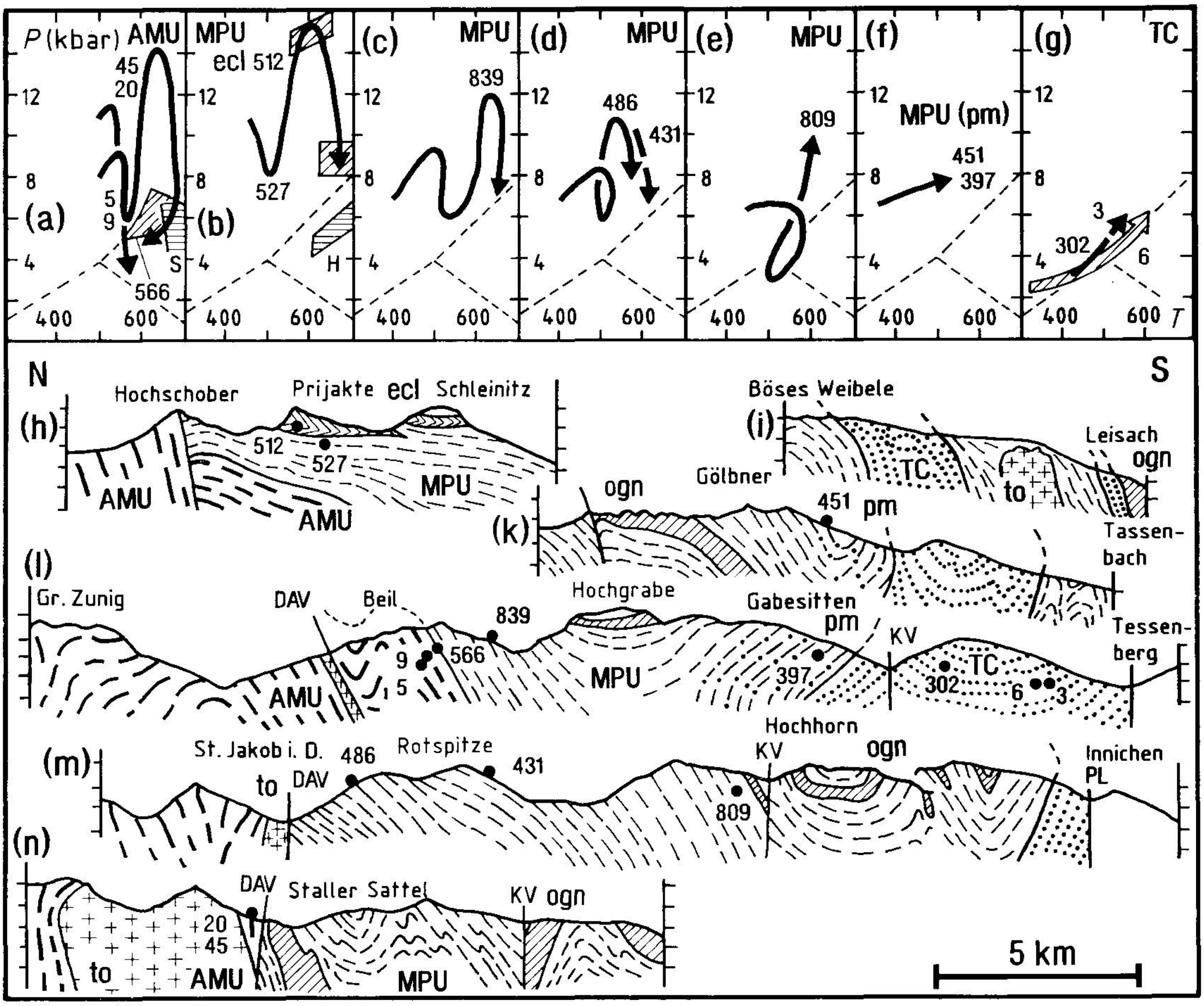

Fig. 7 (a–g) Syn-D_1–D_2 P-T-deformation paths from the Austroalpine basement, arranged in a N–S profile from lower to upper basement parts, compiled from SCHULZ (1990: samples 839, 486, 431, 566; 1991: samples 3, 6, 302; 1992a: sample 809; 1993a: samples 527, 512; 1993b: samples 20, 45, and unpublished data: samples 5, 9, 451, 397), see figures 1b, 7h–n for sample locations. S = P-T data from STÖCKHERT (1985) for the AMU in the Tauferer valley to the west; H = P-T data from HOKE (1990) from the MPU in the Kreuzeckgruppe to the east. Diagonal hatching marks P-T data from metabasites.
(h–n) N–S directed geological profiles arranged from east (h) to west (n) from the Austroalpine basement and sample locations. The profiles are compiled from SCHMIDEGG (1936; 1937), SENARCLENS-GRANCY (1964), TROLL et al., 1976; BORSI et al. (1978), BEHRMANN (1990) and SCHULZ (1991).

garnets with "snowball" microstructures clearly signal that the pressure decrease and re-increase which separates the greenschist- and amphibolite-facies stages, is syndeformational (D_1–D_2), and that both stages were passed by a single and continuous P-T loop. The P-T paths from the samples display individual but sometimes similar shapes. Absolute P and T of the paths are different and point to a metamorphic zonation of the basement.

P-T paths from the phyllitic micaschists (samples 397, 451) in upper parts of the MPU show no significant pressure variation but a nearly isobaric temperature increase (400–550 °C) at 7–8 kbar from upper greenschist-facies to amphibolite-facies conditions (Fig. 7f). Phyllitic micaschists of the TC recorded conditions of 570 °C at around 6 kbar. Geothermobarometry on amphibolites (Fig. 7g) completes the general trend of this prograde P-T evolution and indicates that lower amphibolite-facies has been attained by a temperature-dominated and slightly anticlockwise P-T evolution in this unit (SCHULZ, 1991).

As is indicated by microstructures and the mineral chemical evolution of the samples, the prograde metamorphism evolved contemporaneously with the deformation (D_1–D_2) and the formation of the main foliation (S_2) of the rocks. A considerable part of the final uplift/heating in the lower parts of the basement (samples 20, 527, 839, 486) is syndeformational to D_1-D_2 and therefore was not controlled by isostasy or erosion alone. These sections of the uplift paths from lower parts of the basement passed conditions of anatectic melting (STÖCKHERT, 1985; HOKE, 1990). Garnets in the upper parts of the MPU and in the TC recorded no segment of the uplift path. For all studied samples, P-T conditions of the further syn-D_3, -S_4 and -S_5 history are poorly defined by petrological data, and the retrograde paths may have the general clockwise shapes of isostatic/erosional uplift/cooling as modelled by ENGLAND and THOMPSON (1984). Post-S_2 staurolite + kyanite assemblages in the MPU and fibrolitic sillimanite in the AMU (samples 9, 5) indicate that the retrograde paths have passed the corresponding stability fields (SCHULZ, 1990). Microstructures of the progressive foliation-forming deformation (D_1–D_2) allowed to control mineral chemistry evolution as well as geothermobarometry. Therefore we observe syndeformational P-T evolutions through time from each location and no random pattern of metamorphic field gradients (SCHUMACHER et al., 1990) has been obtained. Deformation D_1–D_2 affected both metabasites and Upper Ordovician granitoids interlayered with the metapelites, and mica cooling ages in southern parts of the basement range around 300 Ma (BORSI et al., 1978). Hence a post-Upper-Ordovician to pre-late-Variscan age, or an early-Variscan age, of the syn-D_1–D_2 metamorphism can be assumed.

Apart from the pre-collisional palaeogeographic arrangement and different protolith ages, a model for the Variscan tectonometamorphic evolution of the basement units should consider on one hand their common deformation by progressive non-coaxial shearing D_1–D_2, and on the other hand their different metamorphism which is obvious from different prograde P-T paths' shapes and actual P_{max} and T_{max}. The individual syndeformational P-T paths indicate that the units sufferred their prograde metamorphism not at the same place and possibly have not passed P_{max}, T_{max} at the same time. Characteristic shapes of the P-T deformation paths in combination with the metamorphic zonation of the basement, given by different P_{max}/T_{max} and the spatial arrangement of the paths, allow an interpretation by comparison with numerical thermotectonic models. A general process of collisional burial, thickening

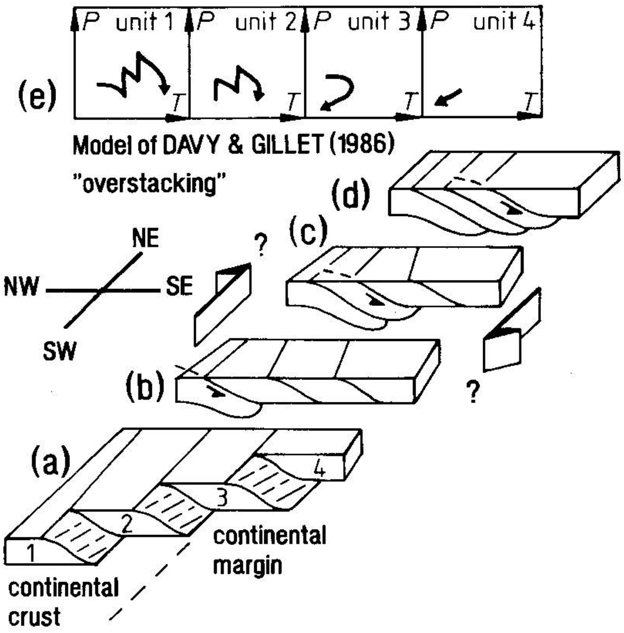

Fig. 8 Model of the early-Variscan tectonometamorphic evolution in the Austroalpine basement to the south of the Tauern Window, as derived from the numerical P-T model for a collisional overstacking process (DAVY and GILLET, 1986).
(a) Pre-collisional palaeogeographic arrangement. Numbers of future tectonic units refer to figure 8e.
(b–d) Successive southwards progressing overstacking of the units 1–4, the stacking is accompanied by a considerable dextral? orogen-parallel movement component.
(e) Numerical P-T models for tectonic units 1–4 involved in an overstacking process, after DAVY and GILLET (1986). See text for further explanation and compare with actual P-T paths from the basement in figure 7a–g.

and uplift of crust is indicated by the mostly clockwise and sometimes only partly anticlockwise paths (ENGLAND and THOMPSON, 1984; THOMPSON and ENGLAND, 1984). Over and above that, due to the synmetamorphic deformation D_1–D_2, it is possible to explain this process by a model of tectonic stacking of crustal-scale nappes. Modelling of crustal thickening by successive understacking and overstacking of crustal units (DAVY and GILLET, 1986) yielded individual P-T paths for each involved unit and discriminative different shapes of paths for each stacking mode. Following these simulations, an overstacking process can be derived for the early-Variscan tectonothermal evolution of the basement (SCHULZ, 1990). The P-T paths from lower basement parts display significant pressure variations as has been modelled for the lower tectonic units (Fig. 8e, units 1 and 2).

Such pressure variations were not found in the phyllitic micaschists of the upper MPU and in the TC, as in the upper units of the model (Fig. 8e, units 3, 4). Accordingly, during a presumably early stage of the Variscan collision, units of a northern pre-Upper-Ordovician continental crust (AMU and MPU) were reworked by high-pressure metamorphism and coeval shearing D_1–D_2 (Figs 8 b, c). Later, in the course of the beginning uplift of the rocks, the overstacking process with deformation D_1–D_2 may have continuously progressed towards the south and caused a more temperature-dominated metamorphism of the early-Palaeozoic passive continental margin represented by the TC (Fig. 8d). In the southern parts of the basement a synmetamorphic movement direction with possible top-to-WSW transport during D_1–D_2 is subparallel to the palaeogeographic and lithological zonation. This can be interpreted by an oblique geometry during the stacking process (ELLIS and WATKINSON, 1987) with a predominant orogen-parallel dextral? movement component (Figs 8 a–d). A subsequent common late-Variscan cooling/uplift of the welded units then probably evolved in a dextral transpressional system of NW–SE directed compression with deformations D_3, D_4 and D_5 (SCHULZ et al., 1993). That way, correlation of microstructural and mineral chemical data yielded an array of P-T-deformation paths which permits the deciphering of a complex Variscan tectonometamorphic evolution and provides new ideas to the solution of geological problems of the pre-Alpine history in the Austroalpine basement.

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References

ASHWORTH, J.R. and EVIRGEN, M.M. (1985): Plagioclase relations in pelites, central Menderes Massif, Turkey. II. Perturbation of garnet-plagioclase geobarometers. J. Metamorphic Geol., 3, 219–229.

AUDREN, C. (1987): Evolution structurale de la Bretagne méridionale au Palaeozoïque. Mém. Soc. Géol. Géol. Minéral. Bretagne, 31, 365 pp.

AUDREN, C., FEYBESSE, J. L., TEGYEY, M. and TRIBOULET, C. (1987): Relations entre déformations et cristallisations et chemins "P.T.t.d" des micaschistes polyphasés d'Echassières. Modèle d'évolution géodynamique. Géologie de la France, 2–3, 43–45.

AUDREN, C. and TRIBOULET, C. (1989): Pressure-temperature-time-deformation paths in metamorphic rocks and tectonic processes, as exemplified by the Variscan orogeny in South Brittany, France. In: DALY, J. S., CLIFF, R. A. and YARDLEY, B.W.D. (eds). Evolution of Metamorphic Belts, Geol. Soc. Spec. Publ. No. 43, 441–446.

AUDREN, C. and TRIBOULET, C. (1993): P-T-t-deformation paths recorded by kinzigites during diapirism in the western Variscan belt (Golfe du Morbihan, southern Brittany, France). J. Metamorphic Geol., 11, 337–356.

BEHRMANN, J.H. (1990): Zur Kinematik der Kontinentkollision in den Ostalpen. Geotekt. Forsch., 76, 1–180.

BELL, T.H. (1981): Foliation development: the contribution, geometry and significance of progressive bulk inhomogeneous shortening. Tectonophysics, 75, 273–296.

BELL, T.H., RUBENACH, M.J. and FLEMING, P.D. (1986): Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partitioning during foliation development. J. Metamorphic Geol., 4, 37–67.

BELL, T.H., JOHNSON, S.E., DAVIS, B., FORDE, A., HAYWARD, N. and WILKINS, C. (1992): Porphyroblast inclusion-trail orientation data: eppure non son girate!. J. Metamorphic Geol., 10, 295–307.

BORSI, S., DEL MORO, A., SASSI, F.P., VISONA, D. and ZIRPOLI, G. (1980): On the existence of Hercynian aplites and pegmatites in the lower Aurina Valley (Ahrntal, Austrides, Eastern Alps). N. Jb. Miner. Mh., 1980, 501–514.

BORSI, S., DEL MORO, A., SASSI, F.P. and ZIRPOLI, G. (1973): Metamorphic evolution of the Austridic rocks to the south of the Tauern Window (Eastern Alps): radiometric and geopetrologic data. Mem. Soc. Geol. Ital., 12, 549–571.

BORSI, S., DEL MORO, A., SASSI, F.P., ZANFERRARI, A. and ZIRPOLI, G. (1978): New geopetrologic and radiometric data on the Alpine history of the Austridic continental margin south of the Tauern Window. Mem. Ist. Geol. Min. Univ. Padova, 32, 1–17.

CLIFF, R.A. (1980): U–Pb isotopic evidence from zircons for lower Palaeozoic tectonic activity in the Austroalpine nappe, the Eastern Alps. Contrib. Mineral. Petrol., 71, 283–288.

DAVY, P. and GILLET, P. (1986): The stacking of thrust slices in collision zones and its thermal consequences. Tectonics, 5, 913–929.

DEMPSTER, T.J. (1992): Zoning and recrystallization of phengitic micas: implications for metamorphic equilibration. Contrib. Mineral. Petrol. 109, 526–537.

ELLIS, M. and WATKINSON, A.J. (1987): Orogen-parallel extension and oblique tectonics: The relation between stretching lineation and relative plate motions. Geology 15, 1022–1026.

ENGLAND, P.C. and THOMPSON, A.B. (1984): Pressure-temperature-time paths of regional metamorphism I. Heat transfer during the evolution of regions of thickened continental crust. J. Petrol., 25, 894–928.

FRISCH, W., MÉNOT, R.-P., NEUBAUER, F. and VON RAUMER, J.F. (1990): Correlation and evolution of the Alpine basement. Schweiz. Mineral. Petrogr. Mitt. 70, 265–285.

FROST, B.R. and TRACY, R.J. (1991): P-T paths from zoned garnets: some minimum criteria. Am. J. Sci., 291, 917–939.

GANGULY, J. and SAXENA, S.K. (1984): Mixing properties of aluminosilicate garnets: constraints from natural and experimental data, and applications to geothermo-barometry. Amer. Mineral., 69, 88–97.

GHENT, E.D. and STOUT, M.Z. (1981): Geobarometry and geothermometry of plagioclase-biotite-garnet-muscovite assemblages. Contrib. Mineral. Petrol., 76, 92–97.

GUHL, M. and TROLL, G. (1987): Die Permotrias von Kalkstein im Altkristallin der südlichen Deferegger Alpen (Österreich). Jb. Geol. B.-A., 130, 37–60.

HAMMERSCHMIDT, K. (1981): Isotopengeologische Untersuchungen am Augengneis vom Typ Campo Tures bei Rain in Taufers, Südtirol. Mem. Ist. Geol. Min. Univ. Padova, 34, 273–300.

HAUGERUD, R.A. and ZEN, E.A. (1991): An essay on metamorphic path studies or Cassandra in P-T-τ-space. In: PERCHUK, L.L. (ed.). Progress in Metamorphic and Magmatic Petrology. Cambridge University Press, 323–348.

HEINISCH, H. and SCHMIDT, K. (1984): Zur Geologie des Thurntaler Quarzphyllits und des Altkristallins südlich des Tauernfensters (Ostalpen, Südtirol). Geol. Rdsch. 73, 113–129.

HODGES, K.V. and MCKENNA, L.W. (1987): Realistic propagation of uncertainties in geologic thermobarometry. Amer. Mineral., 72, 671–680.

HODGES, K.V. and SPEAR, F.S. (1982): Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. Amer. Mineral., 67, 1118–1134.

HOKE, L. (1990): The Altkristallin of the Kreuzeck Mountains, SE Tauern Window, Eastern Alps – basement crust in a convergent plate boundary zone. Jb. Geol. B.-A., 133, 5–87.

HOLDAWAY, M.J. and LEE, S.M. (1977): Fe–Mg cordierite stability in high-grade pelitic rocks based on experimental, theoretical and natural observations. Contrib. Mineral. Petrol., 63, 175–198.

KOZIOL, A.M. and NEWTON, R.C. (1988): Redetermination of the anorthite breakdown reaction and improvement of the plagioclase-garnet-Al_2SiO_5-quartz geobarometer. Amer. Mineral., 73, 216–223.

LANG, H.M. and RICE, J.M. (1985): Geothermometry, geobarometry and T-X(Fe–Mg) relations in metapelites, Snow Peak, Northern Idaho. J. Petrol., 26, 889–924.

LOESCHKE, J. (1989): Lower Palaeozoic volcanism of the Eastern Alps and its geodynamic implications. Geol. Rdsch., 78, 566–616.

LOOMIS, T.P. (1983): Compositional zoning of crystals: A record of growth and reaction history. In: SAXENA, S.K. (ed.). Kinetics and equilibrium in mineral reactions. Springer Verlag New York, 1–60.

MARTIGNOLE, J. and NANTEL, S. (1982): Geothermobarometry of cordierite-bearing metapelites near the Morin anorthosite complex, Grenville province, Quebec. Canad. Mineral., 20, 307–318.

NEUBAUER, F. (1988): Bau und Entwicklungsgeschichte des Rennfeld-Mugel- und des Gleinalm-Kristallins (Ostalpen). Abh. Geol. B.-A., 42, 1–137.

NEWTON, R.C. and HASELTON, H.T. (1981): Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer. In: NEWTON, R.C., NAVROTSKY, A. and WOOD, B.J. (eds). Thermodynamics of minerals and melts. Springer Verlag New York, 131–147.

PASSCHIER, C.W., TROUW, R.A. J., ZWART, H.J. and VISSERS, R.L.M. (1992): Porphyroblast rotation: eppur si muove?. J. Metamorphic Geol., 10, 283–294.

PIGAGE, L.C. and GREENWOOD, H.J. (1982): Internally consistent estimates of pressure and temperature: the staurolite problem. Amer. J. Sci., 282, 943–969.

PERCHUK, L.L. and ARANOVITCH, L.Y. (1984): Improvement of garnet-biotite geothermometer: correction for fluorine content in biotite. Dokl. Acad. Sci. USSR, 277, 471–475.

PERCHUK, L.L., ARANOVITCH, L.Y., LAVRENTEVA, I.V., GERASIMOV, V.Y., FEDKIN, V.V., KITSUL, V.I., KARSAKOV, L.P. and BERDNIKOV, N.V. (1985): Precambrian granulites of the Aldan shield, eastern Siberia, USSR. J. Metamorphic Geol., 3, 265–310.

VON RAUMER, J.F. and NEUBAUER, F. (1993): Late Precambrian and Palaeozoic evolution of the Alpine basement – an overview. In: VON RAUMER, J.F. and NEUBAUER, F. (eds). The pre-Mesozoic geology of the Alps. Springer Verlag Heidelberg, 623–636.

ROBINSON, P. (1991): The eye of the petrographer, the mind of the petrologist. Amer. Mineral., 76, 1781–1810.

SASSI, F.P. and ZANFERRARI, A. (1972): Il significato geologico del Complesso de Thurntaler (Pusteria), con particolare riguardo alla successione di eventi metamorfici prealpini nel basamento austridico dell'Alpi Orientali. Boll. Soc. Geol. Ital., 91, 533–557.

SCHMIDEGG, O. (1936): Steilachsige Tektonik und Schlingenbau auf der Südseite der Tiroler Zentralalpen. Jb. Geol. B.-A., 86, 115–149.

SCHMIDEGG, O. (1937): Der Triaszug von Kalkstein im Schlingengebiet der Villgrater Berge (Osttirol). Jb. Geol. B.-A., 87, 111–132.

SCHONEVELD, C. (1977): A study of some typical inclusion patterns in strongly paracrystalline-rotated garnets. Tectonophysics, 39, 453–471.

SCHÖNLAUB, H.P. (1979): Das Paläozoikum in Österreich. Abh. Geol. B.-A., 33, 1–124.

SCHÖNLAUB, H.P. (1992): Stratigraphy, biogeography and palaeoclimatology of the Alpine Paleozoic and its implications for plate movements. Jb. Geol. B.-A., 135, 381–418.

SCHULZ, B. (1988a): Deformation und Metamorphose im ostalpinen Altkristallin südlich des Tauernfensters (südliche Deferegger Alpen, Österreich). Schweiz. Mineral. Petrogr. Mitt., 68, 397–406.

SCHULZ, B. (1988b): Quarz- und Mikrogefüge zonierter Kalksilikatgneis-Körper im ostalpinen Altkristallin (südliche Deferegger Alpen, Österreich). Erlanger geol. Abh., 116, 117–122.

SCHULZ, B. (1988c): Mikrogefüge in Paragneisen des ostalpinen Altkristallins südlich der Defereggen-Antholz-Vals-Linie (Osttirol, Österreich). Mitt. Österr. Geol. Ges., 81, 245–253.

SCHULZ, B. (1990): Prograde-retrograde P-T-t-deformation path of Austroalpine micaschists during Variscan continental collision (Eastern Alps). J. Metamorphic Geol., 8, 629–642.

SCHULZ, B. (1991): Deformation und Metamorphose im Thurntaler Komplex (Ostalpen). Jb. Geol. B.-A., 134, 369–391.

SCHULZ, B. (1992a): Pre-Alpine high-pressure metamorphism in the Austroalpine basement: P-T-t-deformation paths from samples to the south of the Tauern Window. Zbl. Geol. Paläont. Teil 1, 1992, 93–103.

SCHULZ, B. (1992b): P-T path interpretation from garnets in the Moldanubian diaphthorite zone to the west of Waldthurn (Bohemian Massif, NE Bavaria). Mineralia slovaca, 24, 339–347.

SCHULZ, B. (1993a): Mineral chemistry, geothermobarometry and pre-Alpine high-pressure metamorphism of eclogitic amphibolites and mica schists from the Schobergruppe, Austroalpine basement, Eastern Alps. Mineral. Mag,, 57, 189–202.

SCHULZ, B. (1993b): Microstructural evolution of metapelites during pre-Alpine and Alpine deformation and metamorphism (Austroalpine basement to the north of the Staller Sattel, Eastern Tyrol, Austrian Alps). Jb. Geol. B.-A. (in press).

SCHULZ, B., NOLLAU, G., HEINISCH, H. and GODIZART, G. (1993): Austroalpine basement complex to the south of the Tauern Window. In: VON RAUMER, J.F. and NEUBAUER, F. (eds). The pre-Mesozoic Geology in the Alps. Springer Verlag Heidelberg, 493–512.

SCHUMACHER, J.C., HOLLOCHER, K.T., ROBINSON, P. and TRACY, R.J. (1990): Progressive reactions and melting in the Acadian metamorphic high of central Massachusetts and southwestern New Hampshire, USA. In: ASHWORTH, J.R. and BROWN, M. (eds). High-temperature metamorphism and crustal anatexis. Unwin Hyman London, 199–234.

SENARCLENS-GRANCY, W. (1964): Zur Grundgebirgs- und Quartärgeologie der Deferegger Alpen und ihrer Umgebung. Z. dt. geol. Ges., 116, 502–511.

SPEAR, F.S. (1988): Metamorphic fractional crystallization and internal metasomatism by diffusional homogenization of zoned garnets. Contrib. Mineral. Petrol., 99, 507–517.

SPEAR, F.S. (1989): Relative thermobarometry and metamorphic P-T paths. In: DALY, J.S., CLIFF, R.A. and YARDLEY, B.W.D. (eds). Evolution of Metamorphic Belts, Geol. Soc. Spec. Publ. No. 43, 63–81.

SPEAR, F.S. (1991): On the interpretation of peak metamorphic temperatures in light of garnet diffusion during cooling. J. Metamorphic Geol., 9, 379–388.

SPEAR, F.S. and CHENEY, J.T. (1989): A petrogenetic grid for pelitic schists in the system SiO_2–Al_2O_3–FeO–MgO–K_2O–H_2O. Contrib. Mineral. Petrol., 101, 149–164.

SPEAR, F.S., KOHN, M.J., FLORENCE, F.P. and MENARD, T. (1990): A model for garnet and plagioclase growth in pelitic schists: implications for thermobarometry and P-T path determinations. J. Metamorphic Geol., 8, 683–696.

SPEAR, F.S. and RUMBLE, D. (1986): Pressure, temperature, and structural evolution of the Orfordville Belt, West-Central New Hampshire. J. Petrol., 27, 1071–1093.

SPEAR, F.S. and SELVERSTONE, J. (1983): Quantitative P-T paths from zoned minerals: theory and tectonic applications. Contrib. Mineral. Petrol., 83, 348–357.

SPRY, A. (1969): Metamorphic textures. Pergamon Press Oxford, 350 pp.

STÖCKHERT, B. (1985): Pre-Alpine history of the Austridic basement to the south of the western Tauern Window (Southern Tyrol, Italy) - Caledonian versus Hercynian event. N. Jb. Geol. Paläont. Mh., 1985, 618–642.

ST-ONGE, M.R. (1987): Zoned poikiloblastic garnets: P-T paths and synmetamorphic uplift through 30 km of structural depth, Wopmay orogen, Canada. J. Petrol., 28, 1–21.

TERRY, M.P. and FRIBERG, L.V.M. (1990): Pressure-temperature-time path related to the thermotectonic evolution of an Early Proterozoic metamorphic terrane, Black Hills, South Dakota. Geology, 18, 786–789.

THOMPSON, A.B. (1976): Mineral reactions in pelitic rocks. Am. J. Sci., 276, 401–454.

THOMPSON, A.B. and ENGLAND, P.C. (1984): Pressure-temperature-time paths of regional metamorphism II: their inference and interpretation using mineral assemblages in metamorphic rocks. J. Petrol., 25, 929–955.

TRACY, R.J. (1982): Compositional zoning and inclusions in metamorphic minerals. In: FERRY, J.M. (ed.). Characterization of metamorphism through mineral equilibria. Mineral. Soc. Amer. Rev. in Mineralogy, 10, 355–397.

TRACY, R.J., ROBINSON, P. and THOMPSON, A.B. (1976): Garnet composition and zoning in the determination of temperature and pressure of metamorphism, central Massachusetts. Amer. Mineral., 61, 76–775.

TRIBOULET, C. and AUDREN, C. (1985): Continuous reactions between biotite, garnet, staurolite, kyanite-sillimanite-andalusite and P-T-time-deformation path in micaschists from the estuary of the river Vilaine, South Brittany, France. J. Metamorphic Geol., 3, 91–105.

TROLL, G., FORST, R., SÖLLNER, F., BRACK, W., KÖHLER, H. and MÜLLER-SOHNIUS, D. (1976): Über Bau, Alter und Metamorphose des Altkristallins der Schobergruppe, Osttirol. Geol. Rdsch., 65, 483–511.

TRZCIENSKI, W.E. (1977): Garnet zoning – product of a continuous reaction. Canad. Mineral., 15, 250–256.

VERNON, R.H. (1978): Porphyroblast-matrix microstructural relationships in deformed metamorphic rocks. Geol. Rdsch., 67, 288–305.

YARDLEY, B.W.D. (1989): An introduction to metamorphic petrology. Longman Scientific & Technical, 248 pp.

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