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Pre-Alpine tectonometamorphic evolution in the Austroalpine basement to the south of the central Tauern Window

by *Bernhard Schulz*[1]

Abstract

The Austroalpine basement between the central Tauern Window and the Drauzug Permo-Mesozoic is composed of mainly psammopelitic pre-Upper-Ordovician units (Altkristallin) and pelitic- volcanosedimentary Early-Palaeozoic sequences (Thurntaler Complex). Metabasites occur in different groups. Geochemical signatures of enriched N-MORB and MORB of divergent plate boundary settings, and of transitional to alkaline OIB of a within-plate setting have been identified. A separate group of hornblende-plagioclase gneisses with basaltic to andesitic compositions follows a calc-alkaline evolution trend and displays trace element ratios attributed to subduction-related magmatism. Long-lasting Precambrian to Early-Palaeozoic continental extension, possibly triggered by subduction activity, could have been an appropriate geodynamic setting. A brief period of Upper-Ordovician acid magmatism was probably related to crustal anatexis involving subcrustal components. The Thurntaler Complex was thrusted into southern and upper parts of the Altkristallin. Both units show similar and parallel post-Upper-Ordovician structures S2 and F2 of non-coaxial shearing followed by folding F3 and later formation of shear bands. In parts of the Altkristallin, an eclogitic event was followed by high-temperature amphibolite-facies metamorphism with partial anatexis. Medium-pressure amphibolite-facies metamorphism is observed in Altkristallin phyllitic mica schists adjacent to the Thurntaler Complex. The Thurntaler Complex underwent epidote-amphibolite-facies metamorphism. All these metamorphic stages are related to the Variscan orogeny. Metapelite garnet XMg–XCa–XMn zonation trends were used (a) to distinguish among different basement units, (b) to reconstruct syndeformational P-T paths and (c) to discriminate among pre-Alpine and Alpine metamorphism in northern parts of the basement. Parallel and similar structures, but different metamorphism and P-T path shapes in the southern Altkristallin and the Thurntaler Complex can be explained by a pre-Carboniferous progressive crustal stacking which first reworked the Altkristallin to the NW and then affected the phyllitic Palaeozoic sequences to the SE.

Keywords: Austroalpine basement, Eastern Alps, metabasite geochemistry, tectonics, garnet zonation, P-T path, Variscan orogeny.

Geological setting

Although many structures, mineral assemblages and radioisotopic compositions were obscured by Alpine overprinting, a multi-stage pre-Alpine metamorphic and magmatic evolution has been reconstructed from the Austroalpine basement in the Eastern Alps. An increasingly complex puzzle of basement units with individual geological histories and provenance has been revealed by recent studies (Pohl, 1984; Frisch et al., 1984; 1987; 1990; Becker et al., 1987; Hoinkes and Thöni, 1993; Neubauer and Frisch, 1993; von Raumer and Neubauer, 1993).

In this paper, the Austroalpine basement to the south of the central Tauern Window is discussed. The northern border of the area studied is marked by the Alpine Austroalpine-Penninic suture along the Penninic Matreier Zone. Structures and lithology of the basement can be traced further to the west and to the east across the Ahrn and Isel rivers (Fig. 1). Late-Alpine tectonic lines subdivide the basement. The W–E trending Defereggen-Antholz-Vals line (DAV) is characterized by a north-to-south ductile-brittle transition of deformation in the western part. Brittle deformation is observed in the eastern part of the shear zone. Possibly, the line continues to the east across the Isel

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river; but its location has not yet been specified there. In the western part, the DAV line separates a northern block with Alpine metamorphism, ductile overprinting and radiometric cooling ages, from a southern block lacking pervasive Alpine ductile deformation. Regional distribution of late-Alpine radiometric cooling ages from 15 to 28 Ma in the northern block contrast late-Variscan mica ages in the southern block. This has been explained by a considerable component of vertical movement predating and/or accompanying sinistral strike-slip displacement along the shear zone. Furthermore, increasingly older mica cooling or "mixed" ages (15–80 Ma) towards the east indicate a deeper erosional level of the northern block to the west (BORSI et al., 1978; HOFMANN et al., 1983; KLEINSCHRODT, 1987).

Brittle Alpine deformation is observed along the Kalkstein-Vallarga (KV) fault system (BORSI et al., 1978; GUHL and TROLL, 1977; 1987). The Alpine brittle northern Drauzug fault (SPRENGER and HEINISCH, 1992; BAUER and BAUER, 1993) marks the southern border of the basement described here. Relics of the anchi- to epizonal Permo-Mesozoic cover of the basement are found in the southern brittle part of the DAV (Trias of Staller Alm), along the KV (Permotrias of Kalkstein), to the west of Sillian and immediately to the north of the Periadriatic Lineament. The intrusion of the Oligocene (30 Ma) Rieserferner tonalite coincided and was lasted out by movement along the DAV. Contact metamorphic aureoles with mineral zones are developed in the basement metapelites around the Rieserferner, Zinsnock and Lienz (Pölland) plutons (PROCHASKA, 1981; MAGER, 1985a; KREUTZER, 1992; CESARE, 1994). Apatite fission-track ages in the basement are continuously younger from the south to the north (20.5 to 8 Ma). The data provide no hints to post-Oligocene vertical displacement located at the Defereggen-Antholz-Vals line (GRUNDMANN and MORTEANI, 1985).

Pre-Alpine tectonostratigraphic units

The Austroalpine basement complex between Tauern Window and Drauzug is divided in two principal lithologic associations of metamorphic rocks, the basement s. str. or the "Altkristallin", and the "phyllitic sequences". Four lithological subunits which possibly represent former pre-Palaeozoic sedimentation zones, are distinguished in the Altkristallin (Fig. 1): To the north, a metapsammopelite-amphibolite-marble unit (AMU) is composed of biotite gneiss and garnet mica schist series (BIANCHI, 1934; DAL PIAZ, 1934). The biotite gneiss series contain ortho-augengneisses, amphibolites and marbles. Orthogneisses are lacking in the garnet mica schists. To the south of the Defereggen-Antholz-Vals line, a monotonous metapsammopelite unit (MPU) with orthogneisses prevails. In the southern parts of this sequence, phyllitic mica schists (pmMPU) with orthogneisses form a metamorphic and structural transition to the phyllitic sequences of the Thurntaler Complex (TC).

METAPSAMMOPELITE-AMPHIBOLITE-MARBLE UNIT (AMU):

The subunits of the metapsammopelite-amphibolite-marble unit strike W–E. Biotite gneisses and diaphthoritic micaschists with partly chloritized metabasites and several mylonitic ortho-augengneisses form the immediate hanging wall of the Austroalpine-Penninic suture. The metabasites in this zone are hornblendites, amphibolites, garnet-amphibolites and a sequence of light, banded plagioclase-amphibolites and hornblende-plagioclase gneisses. This presumably metavolcanic sequence in the eastern part of the AMU occurs with variable thickness of several tens to hundreds of meters between two orthogneiss layers (SENARCLENS-GRANCY, 1964; BEHRMANN, 1990; SCHÖNHOFER, 1997). Chloritic garnet-muscovite-micaschists, sometimes with a phyllonitic structure, and garnet-muscovite-gneisses, both rarely intercalated by m-thick amphibolites, are called "Cima-Dura-phyllites" in the western part (DAL PIAZ, 1934; BAGGIO et al., 1971; HAMMERSCHMIDT, 1977; BUTTURINI et al., 1995). These mica schists separate the northern from a southern biotite gneiss sequence. A microcline-bearing ortho-augengneiss (Sand in Taufers / Campo Tures) is extending tens of kilometers from the Ahrn valley to the east (MAGER, 1981; HAMMERSCHMIDT, 1981). Metabasites in the biotite gneisses are mostly small lenses of amphibolites, garnet amphibolites, hornblende garben gneisses and biotite hornblendites with several meter thickness and extension. To the south of the Rieserferner/Vedrette di Ries Massif, a 200-m-thick banded sequence of foliated and folded metabasites (Schwarze Wand / Croda Nera) outcrops (FRIZZO, 1981; MAGER, 1985a). To the east, a 100-m-thick complex of amphibolites interlayered by dm-thick marble horizons can be mapped to the south of Matrei (SENARCLENS-GRANCY, 1964; SCHÖNHOFER et al., 1997). Marbles occur in dm- to m-thick layers as well as in a 100 m thick body to the north of Erlsbach in the Defereggen valley. Calcsilicate-gneisses form dm-thick bands.

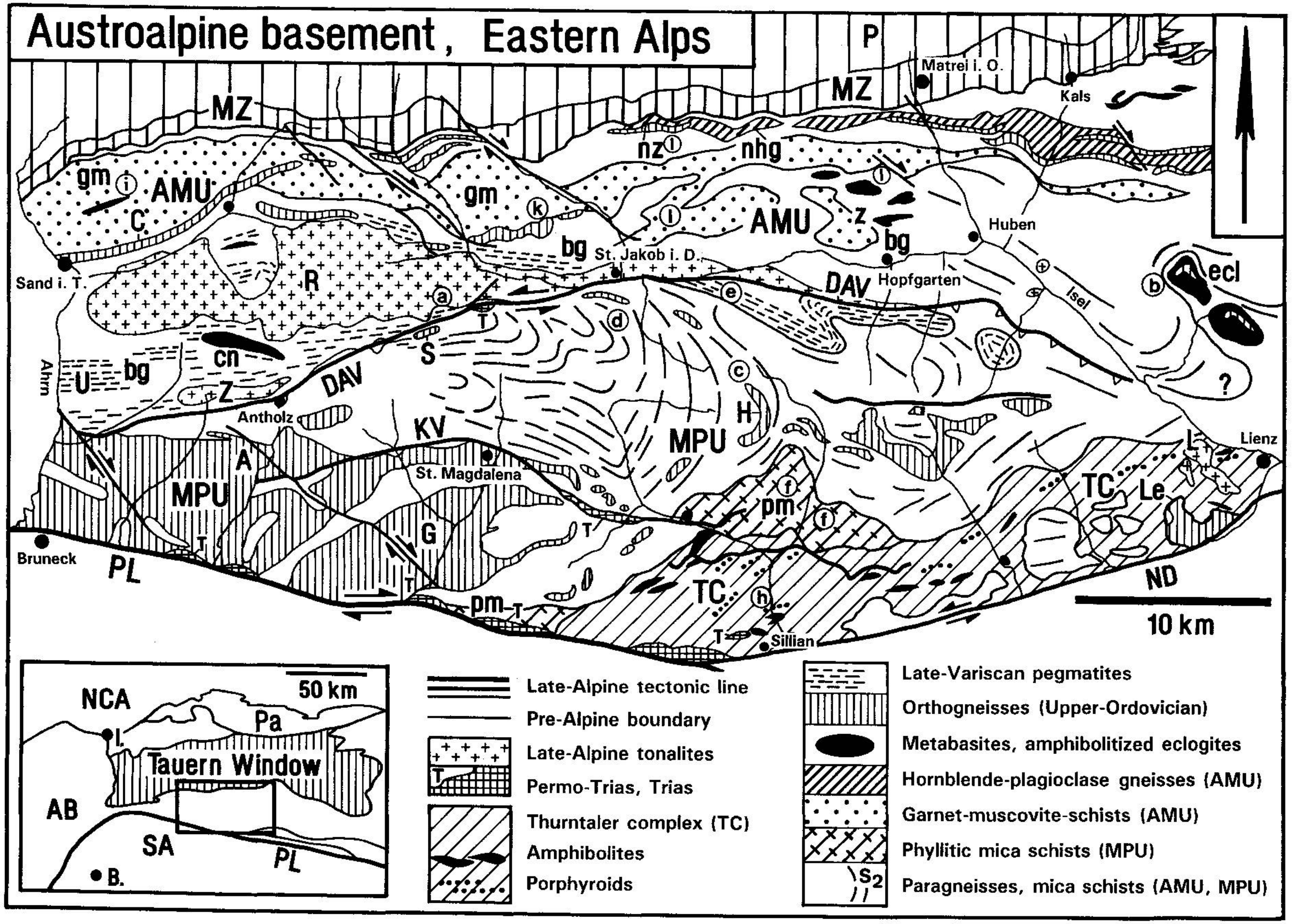

Fig. 1 Geological sketch map of the Austroalpine basement to the south of the central Tauern Window. Encircled letters a–h refer to sample locations of garnet zonation trends in figure 3. A orthogneiss of Antholz; AB Austroalpine basement; AMU metapelite-amphibolite-marble unit; bg biotite gneisses; C orthogneiss of Sand i. T. (Campo Tures); cn metabasites of Croda Nera; DAV Defereggen-Antholz-Vals line; ecl amphibolitized eclogites of the Schobergruppe; G orthogneiss of Gsies (Casies); gm garnet-muscovite schists (AMU); KV Kalkstein-Vallarga line; L tonalite of Lienz; Le orthogneiss of Leisach; MPU metapsammopelitic unit; MZ Matreier Zone; NCA Northern Calcareous Alps; nhg northern hornblende-plagioclase gneisses; nz northern zone (AMU); P Penninic unit; PL Periadriatic Lineament; pm phyllitic mica schists of the MPU; R Rieserferner tonalite; S orthogneiss of Staller Sattel; SA South-Alpine; T Permo-Trias and Trias; TC Thurntaler Complex; U Late-Variscan pegmatites of Uttenheim (Villa Ottone); z metabasites of Zunig; Z Zinsnock tonalite. Compiled from SANDER, 1925; BIANCHI et al., 1930; SENARCLENS-GRANCY, 1964; 1972; KROL, 1974; TROLL et al., 1980; HAMMERSCHMIDT, 1981; MAGER, 1985b; GUHL and TROLL, 1987; BEHRMANN, 1990; KREUTZER, 1992; SCHULZ, 1988c; 1991; 1994b; SCHULZ et al., 1993; SCHÖNHOFER, 1997; and references cited therein.

Aplitic and pegmatitic rocks are interlayered with the biotite gneisses at the southern border of the sequence. At Uttenheim/Villa Ottone, Ahrn Valley), muscovite pegmatites bearing tourmaline and garnet, and a kilometer-scale muscovite-granite body outcrop. According to STÖCKHERT (1987), these pegmatitic rocks have REE poor bulk chemistry and can be derived from small-scale lit-par-lit intrusions of water-rich acid melts which were produced by partial anatexis of the host rocks in lower parts of the crust. In fact, in southern parts of the biotite gneiss sequence, migmatites are present (STÖCKHERT, 1985; MAGER, 1985a; SPAETH, 1993). A further pegmatite-rich zone with garnet-sillimanite-biotite bearing metapelitic host rocks is found immediately to the south of the Defereggen-Antholz-Vals line between St. Jakob in Defereggen and the Isel Valley. These W–E striking pegmatitic zones seem to form the uppermost part of the AMU and the lowermost part of the MPU unit respectively and could be related to a pre-Alpine tectonic lineament.

METAPSAMMOPELITIC UNIT (MPU)

To the east, in the Schobergruppe, the "Hangendkomplex" (CLAR, 1927; TROLL and HÖLZL, 1974; TROLL et al., 1976; 1980; BEHRMANN, 1990; SPAETH, 1991) concordantly overlies the AMU ("Liegendkomplex") along a pre-Alpine foliation-parallel contact, marked by a variable lithology. Foliated amphibolitized eclogites and microcline orthogneisses are interlayered in the basal part of the Hangendkomplex. The latter may be assigned to the lower parts of the monotonous metapsammopelitic unit MPU prevailing in the central part of the basement. Between the Isel Valley and St. Jakob i. Def. a foliation-parallel contact is observed between the MPU and the AMU with biotite paragneisses, metabasites, marbles and the pegmatites. To the west of St. Jakob, the MPU and AMU units are divided by the Defereggen-Antholz-Vals line. A several kilometer-thick monotonous metapsammopelitic sequence of banded quartzitic gneisses, paragneisses and mica schists constitutes the major part of the MPU in the southern Deferegger Alps (SCHMIDEGG, 1936; SENARCLENS-GRANCY, 1964; SCHULZ, 1988a). Interlayered thin amphibolites show no textural evidence of former eclogite assemblages. Thin layers of marbles, graphitic gneisses and quartz-feldspar gneisses are rarely found. Calcsilicate-gneisses form cigar- and tongue-shaped bodies extending parallel to a stretching lineation. The sequence is concordantly interlayered by several km-scale orthogneiss bodies which differ in grain size, mode and fabric (BORSI et al., 1973; 1978).

PHYLLITIC MICA SCHISTS (PMMPU)

Mica schists containing garnet but no staurolite outcrop in southern parts of the MPU (Fig. 1). They show smaller grain sizes compared to the MPU mica schists, and locally bear a shearband foliation. Contacts between the phyllitic mica schists and the MPU s. str. are transitional and no definitive lithological border can be mapped or defined. Orthogneisses are found in both units. The border between the phyllitic mica schists and the Thurntaler Complex is foliation-parallel and structurally concordant but marked by different lithologies, grain sizes and mineral modes (KREUTZER, 1992).

THURNTALER COMPLEX (TC)

The Periadriatic Lineament cuts the Thurntaler Complex to the west; to the east this basement unit continues in the southern parts of the Kreuzeck-Gruppe. To the north, the MPU s. str. sequences and the phyllitic mica schists are found structurally above, as well as below the Thurntaler Complex rocks. To the south, orthogneisses and paragneisses were thrusted upon the Thurntaler Complex (KREUTZER, 1992). However, even where the original orientation of the Thurntaler Complex-Altkristallin contact has been obscured by thrusting and faulting, it is generally presumed that the Altkristallin rocks represent the lower tectonostratigraphic unit. Quartzphyllites and phyllitic mica schists are interlayered by amphibolites, epidote-amphibolites, chlorite schists, quartzites, graphite phyllites and rare calcite and dolomite marbles. In the lower parts of the sequence, porphyroid schists and gneisses occur with the metabasites (KROL, 1974; HEINISCH and SCHMIDT, 1984; SPAETH and KREUTZER, 1990; KREUTZER, 1992; NEUBAUER and SASSI, 1993). The metabasites are volcanogenic tholeiitic rocks and occasionally bear stratiform CuS- and Sb-W-mineralizations. Porphyroid schists and gneisses are interpreted as meta-tuffites. They have alkali-rhyolitic, rhyolitic and dacitic compositions and probably were deposited in a marine environment (HEINISCH and SCHMIDT, 1976; 1984).

Geochronological data from the acid magmatic rocks provide time markers for a subdivision of the pre-Alpine and Alpine evolution of the Altkristallin. Orthogneisses yielded Rb–Sr whole-rock isochrons of 445 ± 24 Ma (Sand in Taufers, HAMMERSCHMIDT, 1981), 439 ± 20 Ma (Wangenitzsee, BRACK, 1977), 434 ± 4 Ma and 436 ± 17 Ma (Antholz, BORSI et al., 1973; SATIR, 1975). U–Pb isotopic data from zircons in tonalitic and leucogranitic orthogneisses to the east of the Winkeltal gave evidence for primary zircon formation at 443 and 427 Ma (CLIFF, 1980). These radiometric data are interpreted to date the intrusion of granitoid bodies at Upper-Ordovician times into the Altkristallin host rocks. Aplitic and pegmatitic rocks in the AMU and MPU units produced Rb–Sr whole-rock ages of 262 ± 5 Ma (Uttenheim, BORSI et al., 1980) and 266 ± 6 Ma (Cliff pers. comm. in HOKE, 1990) which are considered to date their intrusion during Late-Variscan times. The granodioritic-tonalitic plutonic bodies of Rieserferner-Zinsnock and Lienz (Pölland) intruded around 30 Ma (BORSI et al., 1979). Rb–Sr and K–Ar mica cooling ages in ortho- and paragneisses to the south of the DAV vary from 260 to 310 Ma (BORSI et al., 1973; 1978; SATIR, 1975). In the basement to the west of Hopfgarten in Defereggen, a sharp boundary between southern Late-Variscan and northern Late-Alpine (30–16 Ma) mica cooling ages is marked by the DAV. In contrast, to the east of the Isel Valley a more or less continuous S–N transition from Late-Variscan to Early-Alpine ages with "mixing ages" exist (TROLL, 1978; see HOKE, 1990 for data compilation). No radiometric or biochronological ages are available from the Thurntaler Complex. SASSI and ZANFERRARI (1972), HEINISCH and SCHMIDT (1976; 1984) and SCHÖNLAUB (1979) presumed an Ordovician to Early-Devonian age of deposition of the acid, basic volcanic and sedimentary rocks by lithological and geochemical comparison with less metamorphosed Early-Palaeozoic sequences of the Eastern Alps. Geochemistry and structures of the porphyroids in the Thurntaler Complex are similar to dated Upper-Ordovician porphyroids elsewhere in the Austroalpine and they are considered to be the volcanic equivalents of the Upper-Ordovician granitoids in the adjacent Altkristallin (PECCERILLO et al., 1979; SCHÖNLAUB, 1979; HEINISCH, 1981; MAZZOLI and SASSI, 1992; KREUTZER, 1992).

Geochemistry of metabasites and acid meta-magmatites

No geochemical or genetic linkages between the Upper-Ordovician acid magmatism and the basic magmatism in the Austroalpine basement to the south of the central Tauern Window have been demonstrated yet (PECCERILLO et al., 1979; HEINISCH, 1981; KREUTZER, 1992; MAZZOLI and SASSI, 1992). Geochemical data from the Croda Nera metabasites and from thin amphibolites in the MPU are still lacking. Based on this incomplete data, one can distinguish four groups of basic magmatites in the Altkristallin.

The amphibolitized eclogites of the Prijakt area in the Schobergruppe are a homogeneous metabasite group. Whole-rock compositions are tholeiitic and systematic element correlations are attributed to fractional crystallization processes. Peculiar "saw-tooth" like trends of REE in Zr-REE coordinates possibly indicate discontinuous cyclic magmatic fractionation (SCHULZ, 1995a). High field-strength element abundances and element ratios like Ti/V are in the range of present-day MORB. Compared to N-MORB, the large ion lithophile elements Rb, Sr, K, Ba are slightly enriched (Fig. 2a). REE patterns are slightly enriched in LREE when compared to N-MORB, with Ce_N/Yb_N ranging from 1.4 to 3.2 at 10–50 times chondrite abundances (Fig. 2b). Slightly negative Eu and positive Ce anomalies are obvious. Both LIL and LRE elements enrichments reflect a "crustal or subduction component" during melt formation. Furthermore, $(Tb/Ta)_N$ from 0.93–3.31 and $(Th/Ta)_N$ between 1.38 and 2.50 are not typical of enriched N-MOR basalts in a continental rift setting but are considered as a sign of of a back-arc basin magmatism (THIÉBLEMONT et al., 1994).

Consistent variation trends of high field-strength and rare earth elements allow two groups of metabasites to be distinguished in the AMU (GODIZART, 1989). Group 1 metabasites are low in incompatible elements and their Zr/Y, Zr/Nb and Ti/V ratios show affinities to MORB. The REE patterns are LREE-depleted to flat with La_N/Yb_N = 0.5–1.1. Group 2 metabasites have transitional to alkaline compositions similar to OIB. Compared to group 1 metabasites they are significantly enriched in HFSE and LREE and depleted in the HREE. The REE patterns are fractionated with La_N/Yb_N = 14.6–19.6. (Fig. 2 c–f). The two groups cannot be related to each other by simple magmatic fractionation processes or different degrees of partial melting. Generation of group 1 metabasites from a LREE-depleted mantle source in a divergent plate boundary setting, and generation of group 2 metabasites from an enriched mantle source in a within-plate setting may explain the geochemical signatures (GODIZART, 1989). According to KREUTZER (1992), the metabasites in the eastern part of the Thurntaler Complex can be characterized as tholeiitic within-plate basalts. Alkaline composi-

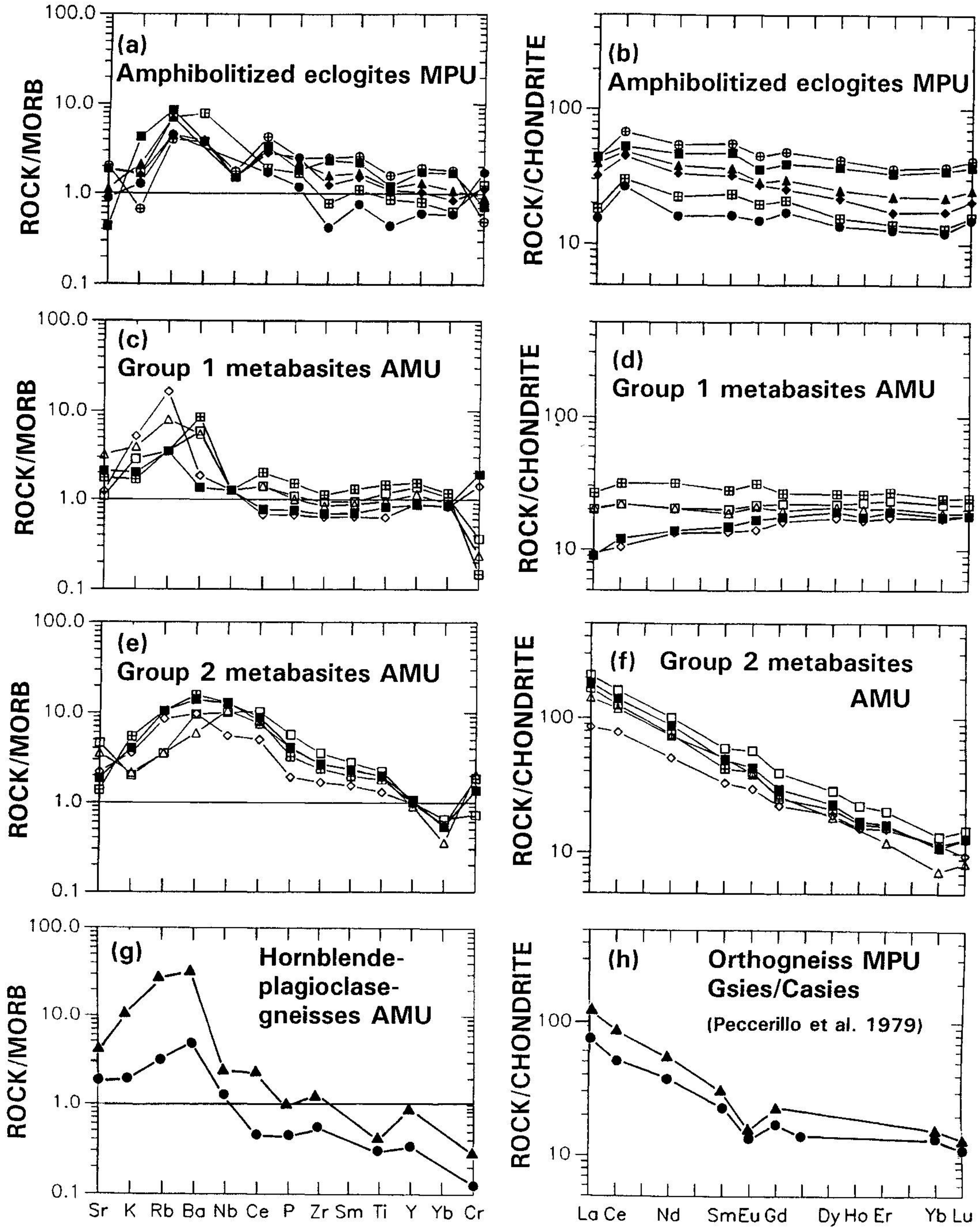

Fig. 2 Geochemistry of metabasites (normalized to data of PEARCE and THOMPSON in ROLLINSON, 1993). (a), (c), (e), (g) MORB-normalized variation diagrams. (b), (d), (f), (h) Chondrite-normalized REE pattern. Further analyses from rock groups in (g) and (h) range between the plotted samples. AMU = metapsammopelite-amphibolite-marble unit; MPU = metapsammopelitic unit.

tions of some diaphthoritic chlorite-albite schists there were caused by element mobility during retrogression.

Element absolute abundances and systematic correlations signal a magmatic provenance of the hornblende-plagioclase gneiss sequence in the northern part of the AMU. The compositions vary from basaltic to andesitic, arranged in a calc-alkaline evolution trend. In Ti–Zr, Ti–V, Cr–Y coordinates, the analyses form homogeneous groups within the discriminative fields of volcanic arc basalts and arc tholeiites or follow trends from island arc tholeiites to calc-alkaline basalts. The subduction-related element ratios in these rocks are obvious. Sr, K, Rb, Ba are 5–50 times enriched when compared to MORB. Ce, P, Zr are in the range of MORB whereas Ti, Y, Cr are depleted. The MORB-normalized element patterns and other HFSE and LIL element ratios differ from the other metabasites and acid orthogneisses of the Altkristallin (Fig. 2g). Following the preliminary data from 20 XRF analyses (SCHÖNHOFER, 1997), the hornblende-plagioclase gneiss sequence appears as a previously geochemically unrecognized separate group of former magmatic rocks.

PECCERILLO et al. (1979) and MAZZOLI and SASSI (1992) found fractionated LREE and poorly fractionated HREE in the Casies (Gsies) orthogneiss in the southern part of the MPU. More acidic samples show a higher HREE fractionation. A small negative Eu anomaly occurs (Fig. 2h). Geochemical signatures of the Casies orthogneisses are similar to Upper-Ordovician metagranitoids elsewhere in the Austroalpine basement and show the character of a continental plutonic province. The acid plutonic rocks with a calc-alkaline affinity can be related to an unique magmatic cycle. A brief period of widespread crustal anatexis in the basement appears as the most appropriate process for explaining the geochemical and petrographic data. However, a subcrustal component of the protoliths by a direct mantle contribution or the incorporation of mantle-derived crustal material is suggested by the initial $^{87}Sr/^{86}Sr$ data (BORSI et al., 1973; SATIR, 1975; MAZZOLI and SASSI, 1992). The granitoids in the Altkristallin are geochemically similar to the metavolcanic rocks (porphyroids) of the phyllitic sequences (PECCERILLO et al., 1979; HEINISCH, 1981; MAZZOLI and SASSI, 1992). This has been confirmed for the porphyroids of the eastern Thurntaler Complex. The acid rocks are high-K calc-alkaline meta-rhyolites similar to post-collisional magmatites. Zircon morphology studies show a provenance from anatectic crustal magma (KREUTZER, 1992).

Due to lacking geochronological data from the metabasites, speculations about the relative temporal relationships among the metabasite groups and the acid magmatites are based on the structural and geochemical observations only. Occurrence of both tholeiitic within-plate basalts and porphyroids in a "bimodal" volcanic sequence in the lower (Ordovician?) parts of the Thurntaler Complex, provides an argument for a contemporaneous acid and basic magmatism. However, the Thurntaler tholeiitic metabasites contrast the widespread Silurian-Devonian within-plate alkali-basalts of the Austroalpine Palaeozoic sequences (e.g. LOESCHKE, 1989). The latter have been attributed to a long-lasting extensional process with thinning of continental crust and subsidence of marginal basins (LOESCHKE and HEINISCH, 1993). In the Altkristallin part, intrusive structural relationships among basic and acid magmatic rocks are generally obscured as both rock types were affected by strong deformation. Amphibolites are observed in xenoliths within acid orthogneisses (PECCERILLO et al., 1979). Therefore, at least a part of the metabasite groups is of pre-Upper-Ordovican origin. Based on geochemistry, the hornblende-plagioclase gneisses, Prijakt and group 1 tholeiitic metabasites may represent early stages, and the alkaline group 2 rocks a later stage of a complex magmatic evolution. Progressive continental extension by incipient rifting, initiated by a subduction process operating far away appears as a speculative geodynamic scenario for the basic magmatism.

Pre-Alpine structural evolution

Based on the Late-Variscan Rb–Sr mica cooling ages, structures of pre-Alpine ductile deformation can be expected to the south of the Defereggen-Antholz-Vals line. In the metasediments of the MPU, a dominant pre-Alpine foliation S2 (pure quartz layers are considered to represent an older foliation S1) is axial-planar to isoclinal F2-folds. F2 fold axes run parallel to a mineral lineation L2. Lineation-parallel elongated calcsilicate-gneiss bodies and sheath folds F2 with long axes parallel to L2 in paragneisses, asymmetric K-feldspar clasts in orthogneisses and syncrystalline-rotated garnets in metapelites are structures of non-coaxial and progressive deformation D1–2. Kinematic indicators signalize a shearing direction parallel to L2 during the generation of the main foliation S2 (SCHULZ, 1988a; 1988b). Linear-planar fabrics in the Upper-Ordovician granitoids, now orthogneisses, are parallel to S2–L2 of the metasedimentary host rocks (STÖCKHERT, 1985; GUHL and

TROLL, 1987; SCHULZ, 1994a). This indicates a common post-Upper-Ordovician foliation-forming deformation. F2 folds and S2 were refolded and overprinted at all scales by open to tight F3-folds and crenulations Lcr3 whose axes are oriented mostly parallel to L2. Micas are recrystallized in the F3 crenulations. F3-folds with steeply plunging axes in the Staller Sattel region to the south of the DAV are minor structures of kilometre-scale syn- and antiforms, called "Schlingen" (SCHMIDEGG, 1936). A Late-Variscan minimum age of these structures is given by the mica cooling ages to the south of the DAV. In the AMU immediately to the north of the DAV, the pre-Alpine foliation S2 and the F3 folds are cross-cut by the pegmatites, defining as well a Late-Variscan minimum age of the D3 structures (STÖCKHERT, 1987). In the Thurntaler Complex (TC), isoclinal folding of S1 quartz layers was accompanied by formation of an axial-planar main foliation S2. F2 fold axes are parallel to a mineral lineation L2 of amphibolites, porphyroids and phyllitic mica schists. Asymmetric K-feldspar augen structures in porphyroids and syncrystalline-rotated plagioclase and garnet in phyllitic mica schists point to a non-coaxial and progressive deformation (D1–2). In southern parts of the MPU, and in the TC, the lineation runs uniformly ENE–WSW, with several shear sense criteria suggesting a top-to-WSW directed movement during D1–2 (SCHULZ, 1991; KREUTZER, 1992). As in the AMU and MPU units, S2 and F2 were overprinted by tight to open F3 folds and crenulations Lcr3. Several structural studies have confirmed that orientations of S2–L2 and F3 structures are parallel in the MPU and the northern TC (SCHMIDEGG, 1937; HEINISCH and SCHMIDT, 1984; SCHULZ, 1991; KREUTZER, 1992). Occasionally, discordant orientations of these fabrics are observed along the southern TC-MPU contact (KREUTZER, 1992). Two generations of shear band foliations, S4 with top-to-NE directed extensional movement, mapped mainly in the MPU phyllitic mica schists, and S5 with NW to W directed movement of the hangingwall, affected both MPU and TC and overprinted the contact between the units (HEINISCH and SCHMIDT, 1984; SCHULZ, 1991; KREUTZER, 1992). Pervasive dynamic recrystallization of quartz is characteristic within the shear bands. This has not been observed in the Alpine deformed Permotriassic sandstones of Kalkstein (GUHL and TROLL, 1987) and to the west of Sillian. Therefore a Variscan age appears probable for shear bands and the older structures.

P-T-paths of Variscan metamorphism

The highest grade of the pre-Alpine metamorphism has been observed in migmatitic biotite gneisses to the south of the Rieserferner tonalite. Metabasites in this region bear brown Mg-hornblende coexisting with bytownite, or clinopyroxene + garnet assemblages. P-T estimates by garnet-clinopyroxene equilibria and the amphibole geothermobarometer of COLOMBI (1989) yielded temperatures of 650–750 °C at 5–7 kbar (BELLIENI and VISONA, 1981; MAGER, 1985a; GODIZART, 1989; SCHULZ, 1995b). STÖCKHERT (1982) described anatectic melting in initially K-feldspar-free metapelites, starting by a K-feldspar-absent reaction producing liquid and aluminiumsilicate at elevated pressures, and later generation of K-feldspar and sillimanite from muscovite and quartz. Temperatures above 650 °C at 6 ± 1 kbar were reached during the anatexis (STÖCKHERT, 1985). This high-temperature event post-dated the pre-Alpine foliation S2 as is evident from a metablastic postdeformational growth of the related minerals.

Amphibolitized eclogites of the Schobergruppe give evidence of a high-pressure stage in parts of the Austroalpine basement. Pyrope- and grossular-rich garnets (Prp 15–20%, Grs 27–25%) coexisting with preferentially oriented omphacite (Jd 35–42%), albite (An 7–9%) and rutile equilibrated at 550–650 °C / 14–16 kbar when garnet-clinopyroxene-plagioclase equilibria are considered. Post-eclogitic assemblages in the metabasites enclose extremely fine-grained symplectites and coarse-grained amphibole and plagioclase replacing omphacite. The post-eclogitic pargasitic hornblendes with Al^{IV} 2.4, Al^{VI} 1.21 and Na_{M4} 0.61 (p.f.u.) mantle and enclose the garnets (SCHULZ, 1993a). Conditions of around 700 °C / 9 kbar for the post-eclogitic event have been estimated by amphibole equilibria (e.g. TRIBOULET, 1992). As a mineral lineation marked by omphacite and amphibole in the amphibolitized eclogites is parallel to the stretching lineation L2 of intercalated orthogneisses, a post-Upper-Ordovician age of the corresponding non-coaxial deformation D1–2, as well as of the coeval eclogitic then medium-pressure amphibolite-facies stages can be concluded.

Metapelites of the MPU to the south of the DAV bear amphibolite-facies assemblages with garnet + biotite + muscovite + chlorite + plagioclase + quartz + staurolite + kyanite. Staurolite and kyanite occur in two generations, with early staurolite and kyanite inside microlithons surrounded by S2, and late staurolite and kyanite postdating S2 and crenulation folds Lcr3. Samples from nearby locations can show post-S2 staurolite predating the crenulation folds F3 as well as staurolite postdating folds F3. In most cases, garnets are enclosed by staurolite. This is interpreted as an evolution from early pre/syn-S2 staurolite-out assemblages toward later syn/post-S2 and post-F3 staurolite-in assemblages (SCHULZ, 1990; 1993a; 1993b). Fibrolitic sillimanite and biotite replacing garnet are observed in biotite schists in the vicinity of the Late-Variscan pegmatites. Assemblages in the phyllitic mica schists of the MPU are garnet + biotite + muscovite + chlorite + plagioclase + quartz. Lacking aluminosilicates and staurolite in these assemblages may be due to inadequate bulk rock compositions or a lower grade of metamorphism compared to the MPU s. str. rocks. Phyllitic mica schists of the TC bear assemblages with garnet + biotite + muscovite + chlorite + plagioclase + quartz (SASSI and SPIESS, 1992). Conditions of the epidote-amphibolite-facies in the Thurntaler Complex are further indicated by assemblages with magnesio-hornblende and tschermakite + al-

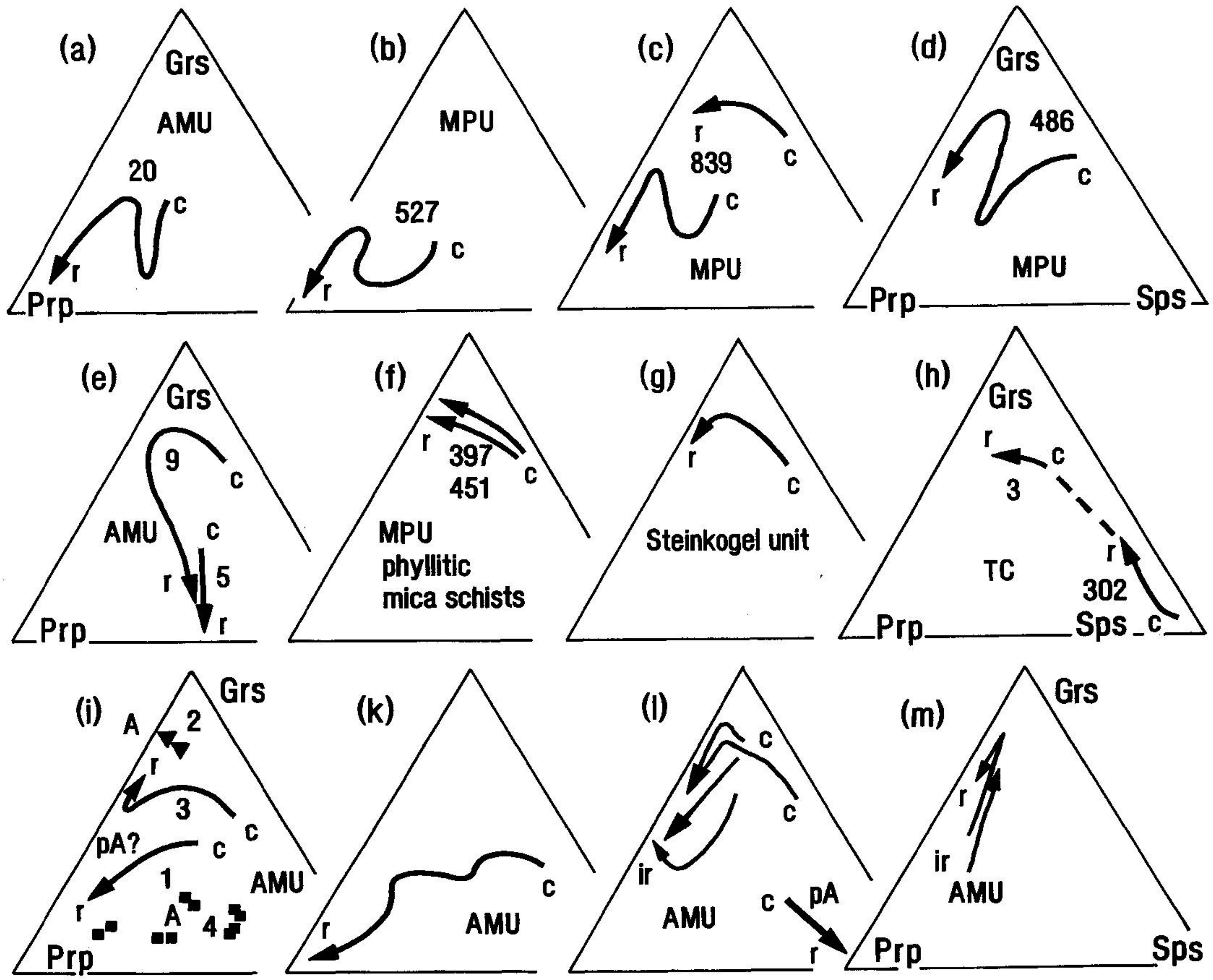

Fig. 3 Comparison of garnet zonation trends in metapelites of the amphibolite-marble unit (AMU), metapsammopelitic unit (MPU), phyllitic mica schists of the MPU (MPUpm); Thurntaler Complex (TC), and the Steinkogel unit to the north of the Tauern Window (S). Core (c) to rim (r) trends in grossular-pyrope-spessartine (Grs-Prp-Sps) trends. Numbers are samples or zonation trends. See figure 1 for sample locations (a)–(l). (a) Mica schist to the north of the DAV at Staller Sattel. (b) Ky-St-Grt mica schist adjacent to amphibolitized eclogites. (c), (d) Southern DefeSouthern Deferegger Alps. (e) Biotite mica schists with fibrolitic sillimanite. (f) Phyllitic mica schists. (g) Steinkogel mica schists for comparison. (h) Phyllitic mica schists from the Thurntaler Complex (References for (a)–(h) in SCHULZ, 1992; 1993a; 1993b; 1994b; 1995b. (i) Western Cima Dura unit (garnet muscovite schists): Trends 1 (pre-Alpine, pA?) and 2 (Alpine, A) after BUTTURINI et al. (1995); Trend 3: SCHULZ (unpublished data); Trend 4: Late-Alpine contact metamorphism in the Rieserferner aureole (CESARE, 1991). (k) Garnet-muscovite schists to the north of St. Jakob (SCHULZ, 1995b); (l), (m) Garnet-muscovite schists and biotite gneisses of the AMU (SCHÖNHOFER, 1997).

bite + plagioclase (up to An 27%) + epidote + chlorite + titanite + quartz in the amphibolites (SCHULZ, 1991; 1995b).

Compositional growth zonations of metapelite garnets can be understood as a product of continuous reactions within low-variance assemblages (e.g. TRACY, 1982; SPEAR, 1993). In the Austroalpine basement, similar garnet zonation trends are observed from locations kilometers apart and from samples slightly differing in microstructures, mineralogy and mode. This provides arguments that not local or metasomatic processes but general changes in P-T triggered the reactions. The growth zonations therefore should represent a primary characteristic property of a lithotectonic unit. Garnet zonations can be used for the evaluation of P-T paths (HAUGERUD and ZEN, 1991; SPEAR, 1993). Pyrope (XMg) and grossular (XCa) variations reflect relative changes in temperatures and pressures in reactions involving biotite and plagioclase respectively. Spessartine (XMn) variations monitor the garnet growth process as they are controlled by Rayleigh fractionation. Therefore the garnet compositional zonations were compared in grossular-pyrope-spessartine coordinates.

Garnets from mica schists near to the Prijakt amphibolitized eclogites, from the AMU of the Staller Sattel region and from the MPU to the south of the DAV with Late-Variscan cooling ages, show similar core-rim zonation trends with increasing pyrope and marked grossular variations (Fig. 3 a–d, zonation profiles are detailed in SCHULZ (1993b p. 309; 1993a p.197; or 1995b p. 50, 58, 67). This provides an argument for a pre-Late-Variscan age of the garnet crystallization even in basement regions with Alpine overprinting and mica cooling ages, or with mixed ages as in the Schobergruppe.

Syndeformational (D1–2) P-T paths of the pre-Alpine metamorphism have been reconstructed from the garnet-bearing assemblages. Garnet-biotite cation exchange thermometers, garnet-plagioclase- aluminosilicate-quartz and garnet-biotite-muscovite-plagioclase net transfer barometers were used. Several calibrations of the thermo-barometers were applied on mineral pairs defined by microstructural criteria. The general presumptions and uncertainties of the method, detailed descriptions of the microstructural/mineral-chemical definition of mineral pairs, and treatment of the thermobarometric data are given in SCHULZ, 1990; 1993b; 1995b pp. 8–40; publication SCHULZ 1995b can be obtained from the author). The shapes of these P-T paths are strongly dependent on the garnets XCa–XMg zonation trends. P-T paths in the AMU and in the lower parts of the MPU generally display increasing temperatures (400 to 680 °C) and coeval strong pressure variations with maximum pressures ranging from 10 to 15 kbar within the kyanite stability field (Fig. 4 a, b). P-T estimates from Mg-poor and Ca-rich garnet cores indicate an early greenschist-facies stage at medium pressures in the MPU. A subsequent amphibolite/eclogite-facies stage at higher pressures, followed by a high-temperature medium-pressure amphibolite-facies stage was calculated from Mg-rich outer parts of the garnets. Amphibolitized eclogites and adjacent kyanite-staurolite-garnet mica schists with coexisting garnet and albitic plagioclases recorded equivalent eclogitic conditions and an amphibolite-facies overprint. The similarity of the garnet zonation trends and P-T-path shapes (Fig. 3 a–d, 4 a, b) in the Prijakt area with Alpine mica ages and partial recrystallization, and in the regions with Variscan cooling ages, provide arguments for a Variscan age of the eclogite and amphibolite-facies stages of metamorphism. Continuous zonation trends in garnets with "snowball" microstructures clearly signal that the pressure decrease and reincrease separating the prograde greenschist- and amphibolite-facies stages, is syndeformational (D1–2), and that both stages were passed on a single and continuous P-T loop. Absolute P and T of the paths are different and point to a metamorphic zonation of the basement. Inter- and intramineral microstructures of the metapelite garnets indicate a syndeformational (syn-D1–2) growth of the porphyroblasts during formation of S2–L2. As D1–2 and S2–L2 postdate the intrusion of the granitoids, now orthogneisses, this metamorphism should be post-Upper-Ordovician. The Late-Variscan mica ages date the cooling and provide a minimum age for the amphibolite-facies stage.

Garnets in the phyllitic mica schists of the MPU are rich in grossular and display simple zonation trends without reversals of Ca (Fig. 3f). Correspondingly, the P-T paths show no significant pressure variation but increasing temperatures (400–550 °C) at 7–8 kbar from upper greenschist-facies to amphibolite-facies conditions (Fig. 4c, SCHULZ, 1995b, p. 70). It is interesting to note that equivalent garnet zonation trends and P-T estimates have been described from the Austroalpine Steinkogel mica schists above the Innsbrucker Quarzphyllit to the north of the Tauern Window (Figs 3g, 4c). In contrast to the MPU unit, garnets in phyllitic mica schists of the TC display increasing XCa toward the rims (Fig. 3h). These rocks recorded maximal conditions of 570 °C at around 6 kbar (Fig. 4d, SCHULZ, 1991; 1995b p. 73). Geothermobarometry with amphibole equilibria

(COLOMBI, 1989; TRIBOULET, 1992) on metabasites nearby confirms the data with a prograde P-T evolution from low-pressure greenschist facies to the lower amphibolite-facies along a temperature-dominated path.

As was outlined above, garnet XCa–XMg zonation trends in combination with geothermobarometry provided important arguments to distinguish the MPU phyllitic mica schists in the Altkristallin. The zonations further support a Variscan age of the eclogitic and amphibolite-facies stages in regions with Alpine overprint. In a similar manner, garnet zonations can be used to identify a second metamorphism related to a further orogenic overprint (e.g. KARABINOS, 1984). PURTSCHELLER et al. (1987) argued that sharp changes in metapelite garnet growth zonation profiles from the southern Oetztal basement were caused by an eo-Alpine lower grade overprinting of a higher grade Variscan metamorphism. Therefore, in a new study, metapelite garnet zonations were checked in northern parts of the AMU. There, an overprinting of the basement by Alpine foliations and folds has been recognized from radiometric and structural data (HAMMERSCHMIDT, 1981; HOFMANN et al., 1983; STÖCKHERT, 1984; 1985; MAGER, 1985a; SCHÖNHOFER, 1997).

From similar garnet zonation trends in amphibolites and phyllonitic garnet-muscovite schists in the western Cima Dura unit, BUTTURINI et al. (1995) concluded that zoned garnets with intermediate Ca contents crystallized during Variscan metamorphism and persisted during Alpine greenschist-facies overprinting (Fig. 3i, trend 1). In the same region, zoned garnets with Ca-richer compositions have been analyzed (Fig. 3i, trend 3; Schulz, unpublished data). An equivalent zonation in garnet predating the Alpine main foliation

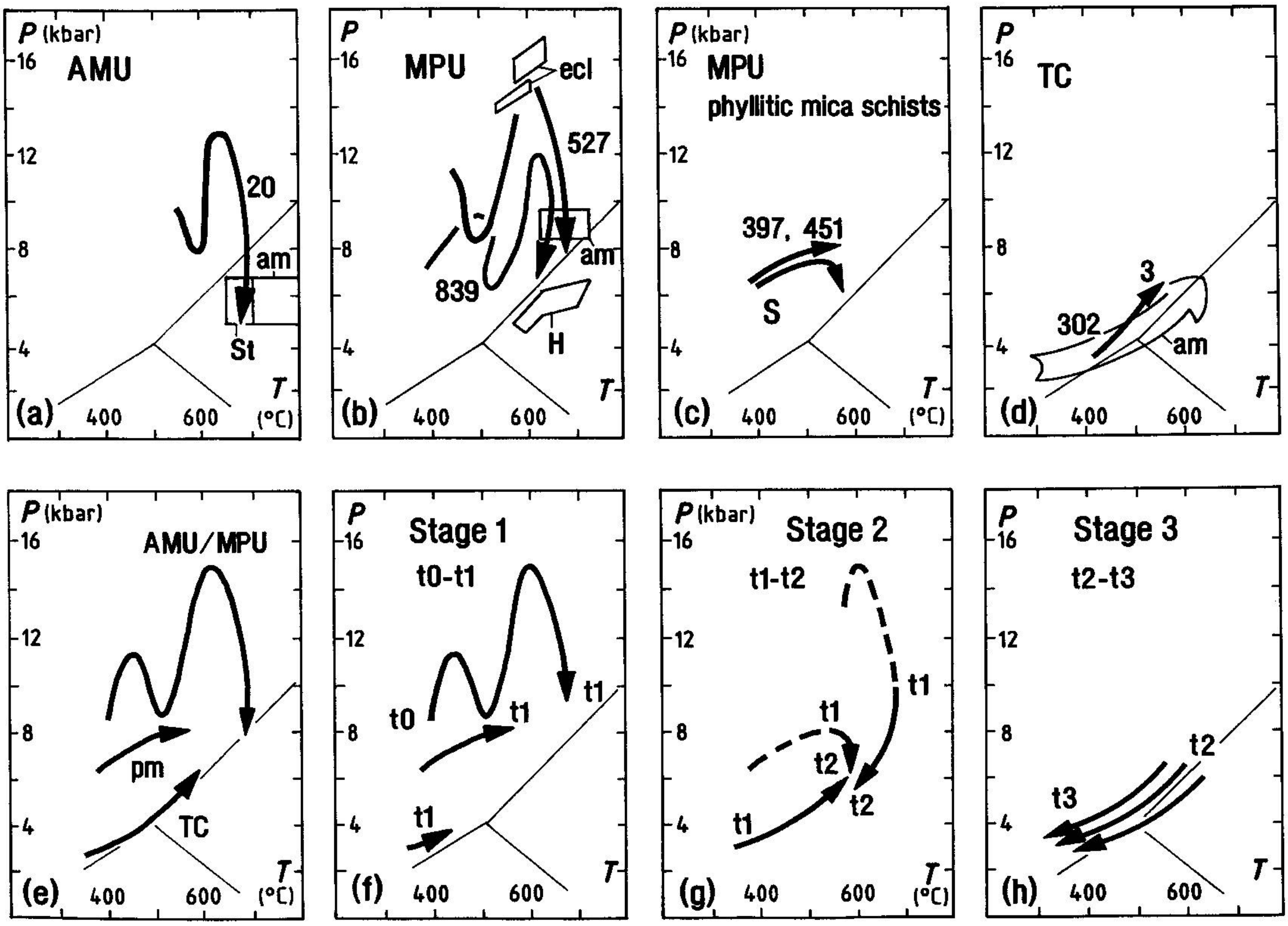

Fig. 4 (a)–(d) Variscan syn-D1–2 P-T paths from garnet metapelites (black arrows) and metabasites (am, ecl) of the Austroalpine basement units AMU (amphibolite-marble unit), MPU (metapsammopelitic unit), phyllitic mica schists of the MPU and TC (Thurntaler Complex) to the south of the central Tauern Window, and related units. Data from SCHULZ (1991; 1993a; 1993b), STÖCKHERT (1987) (St), HOKE (1990) (H), Steinkogel unit (S). Numbers refer to samples and zonation trends in figure 3. (e) Summarized Variscan P-T paths from (a)–(d). (f) Syn-D1–2 stage 1 of evolution from t0 (post-Upper-Ordovician) to t1. (g) Syn-D1–2 stage 2 from t1 to t2 with welding of the units at t2. (h) Post-D1–2 stage t2–t3 (Late-Variscan mica ages) of common uplift-cooling of the units.

S3 (Fig. 3k) has been found in eastern parts of the Cima Dura sequence (SCHULZ, 1995b p. 82). Unzoned Ca-rich garnets with high Ca contents (Fig. 3i, trend 2) can be distinguished from these zoned intermediate-Ca and high-Ca porphyroblasts and were labelled as "Alpine" by BUTTURINI et al. (1995). Unzoned garnets with low Ca (Fig. 3i, trend 4) in the AMU have been assigned to the Late-Alpine contact metamorphism around the Rieserferner tonalite (CESARE, 1991), or could be retrograded pre-Alpine porphyroblasts (Fig. 3l, trend pA). Zoned high-Ca garnets are widespread in the eastern part of the AMU (SCHÖNHOFER, 1997). Some of the porphyroblasts display strongly increasing Ca-contents in the narrow rims (Fig. 3l, m). When compared with the Alpine trend 2 garnets in figure 3i, this could be interpreted as an Alpine overprint or alteration. Garnet zonations can be compared in a profile from the AMU to the south of the DAV with Late-Variscan mica cooling ages (location e in Figs 1, 3e) toward the Austroalpine-Penninic boundary (via locations l in Figs 1, 3l) with ductile Alpine overprinting. No significant differences of the zonation trends nor marked discontinuities in the central parts of the zonation profiles are observed. Furthermore, geothermobarometry with the zoned intermediate-Ca and high-Ca garnet bearing assemblages yielded maximal temperatures around 550 °C (BUTTURINI et al., 1995; SCHULZ, 1995b) at pressures of 6–8 kbar (SCHÖNHOFER, 1997). These temperatures considerably exceed previous estimates (450 °C) for an Alpine event in the western part of the AMU (STÖCKHERT, 1984; 1985), and in the Penninic units to the north (DACHS, 1990). This provides arguments that the garnets even in northern parts of the AMU crystallized during a pre-Alpine metamorphism and that Alpine overprinting appears to be restricted to small marginal zones of the porphyroblasts. Whatever, previous interpretations of the garnets as products of an Early-Alpine metamorphism in the northern AMU (SCHULZ, 1995b) should be revised in the light of the new data. The situation in this part of the basement is further complicated by two successive stages of early then late Alpine structural reworking. Deformed and statically annealed fabrics to the west of the Ahrn Valley are considered as early Alpine (pre-Oligocene) (STÖCKHERT, 1984; KLEINSCHRODT, 1987). The existence of such pre-Oligocene structures even in southern parts of the AMU is further indicated by a fine-grained mylonitic foliation of Late-Variscan pegmatites discordant with and cut by the Oligocene Rieserferner tonalite (SCHULZ, 1994a).

Discussion of the pre-Alpine evolution

The intrusion of the Upper-Ordovician granitoids into the Altkristallin and the deposition of their, probable, volcano-clastic equivalents in the Palaeozoic phyllitic sequences, provides a correlatable time marker within the basement. Thus, it is convenient to distinguish a pre-Upper-Ordovician and a post-Upper-Ordovician history. The granitoids, generated by crustal anatexis (PECCERILLO et al., 1979; MAZZOLI and SASSI, 1992) represent the final stage of a pre-Upper-Ordovician evolution of which structures are preserved inside rare, unconformably interlayered xenoliths in the orthogneisses (BORSI et al., 1973; 1978). A palaeogeographic/palaeotectonic subdivision of the pre-Alpine basement in the Alpine orogen into a northern Helvetic-Moldanubian terrane, an intermediate Penninic-Austroalpine mobile belt and a southern Noric terrane has been proposed (VON RAUMER and NEUBAUER, 1993). When the Alpine tectonic displacements are considered (RATSCHBACHER and FRISCH, 1993), the Penninic basement with Early-Palaeozoic island-arc and back-arc settings (FRISCH et al., 1993) has been situated to the NW of the Austroalpine Altkristallin during pre-Alpine times. Within this frame and according to pre-collisional palaeogeographic reconstructions (HEINISCH, 1986), the Altkristallin to the south of the Tauern Window represents a "Panafrican" pre-Upper-Ordovician continental crust, situated to the NW of a Palaeozoic passive continental margin, of which sediments and volcanics are found in the Thurntaler Complex. Although some of the metabasites in the basement discussed here can be seen in a context of a Palaeozoic progressive continental extension by incipient rifting, the Prijakt amphibolitized eclogites and the hornblende-plagioclase gneisses display geochemical signatures of subduction-related magmatism. On the other hand, further toward the southeast, the Palaeozoic passive continental margin represented by the phyllitic zones and weakly metamorphic Palaeozoic sequences was part of the northern margin of Gondwana (SCHÖNLAUB, 1993).

Despite the clear two-stage subdivision of the pre-Alpine history in the basement by the Upper-Ordovician acid magmatism, the temporal assignment of tectono-metamorphic events in the Altkristallin and Thurntaler Complex is controversial: A "Caledonian" age of the amphibolite facies stage in AMU and MPU as well as a direct relation between this metamorphism and the Upper-Ordovician acid magmatism by crustal anatexis have been proposed (PURTSCHELLER and SASSI, 1975; BORSI et al., 1978; SASSI et al., 1987).

Following these early interpretations, the post-Upper-Ordovician (Variscan) deformation of the granitoids should have taken place under low-pressure greenschist facies conditions and at a high geo-thermal gradient of > 30 °C/km. Cooling after this metamorphism led to Late-Variscan mica ages in the Altkristallin (BORSI et al., 1978). An important argument for this interpretation are the generally concordant structures but apparently significantly different conditions of metamorphism in Altkristallin and Thurntaler Complex. This implies a model of early amphibolite facies metamorphism of the Altkristallin followed by a transgressive deposition (proposed by SASSI and ZANFERRARI, 1972) or tectonic emplacement (HEINISCH and SCHMIDT, 1984) of the Thurntaler Complex, and a later common deformation under greenschist facies conditions.

However, as reported above, other authors found strong evidence that amphibolite facies assemblages in the AMU and MPU are partly younger than the post-Upper-Ordovician main foliation S2 or even postdate crenulation folds F3 which deformed S2 (CLIFF, 1980; HEINISCH and SCHMIDT, 1984; STÖCKHERT, 1985; SCHULZ, 1988a). Further arguments for a post-Upper-Ordovician tectono-metamorphism of both Altkristallin and Thurntaler Complex arise from an interpretation of the syndeformational (D1–2), thus post-Upper-Ordovician P-T paths reconstructed from metabasites and garnet-bearing metapelites. These P-T paths indicate: 1) "polymetamorphism" in parts of the AMU and MPU along complex P-T-loops with eclogite then subsequent amphibolite-facies high-temperature conditions; 2) a more or less continuous metamorphic zonation with decreasing P_{max} and T_{max} towards upper parts of the MPU; 3) the existence of a separate Altkristallin unit (phyllitic mica schists of the MPU) with a comparably simple P-T path at medium pressures, and 4) an individual P-T evolution passing the epidote-amphibolite facies in the Thurntaler Complex. The minimum ages of all these P-T evolutions are defined by the late-Variscan mica cooling ages. However, contrasting the well-preserved prograde paths, parts of the uplift and retrograde paths are still poorly constrained by petrological data.

Apart from the pre-collisional palaeogeographic arrangement and different protolith ages, a model for the Variscan tectono-metamorphic evolution of the basement units should consider 1) their common deformation by progressive non-coaxial shearing D1–2, then folding D3 and shear-band formation (D4, D5), and 2) the different shapes of their prograde P-T paths with different 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 did not pass P_{max}, T_{max} at the same time. Due to the relatively small vertical distances and the lack of large-scale shear zones between the lithostratigraphic units it appears unlikely that the eclogitic stage in the Altkristallin and P_{max}-T_{max} in the Thurntaler Complex are contemporaneous events. It is more convenient to presume an early eclogitic event, then an amphibolite-facies high-temperature stage in the Altkristallin, and a later metamorphism in the Thurntaler Complex, like the two-stage models of SASSI and ZANFERRARI (1972), BORSI et al. (1978), or SASSI et al., (1985). However, pre-syn-S2 prograde P-T paths both in Altkristallin and Thurntaler Complex, and parallel S2 and post-S2 structures are apparently inconsistent with such a two-stage evolution. This contrast could be explained, when an early formation of S2 in the Altkristallin and a successively later formation of S2 in the Thurntaler Complex during a progressive tectonic process affecting both units, are assumed.

P-T paths from AMU, MPU, phyllitic mica schists and Thurntaler Complex can be labelled with absolute and relative time markers t0–t1–t2–t3. The absolute time markers t0 and t3 are provided by the Upper-Ordovician intrusion ages of the granitoids and the Late-Variscan mica cooling ages. A relative time marker t1 approximates the time of T_{max} in the AMU/MPU, P_{max} in the phyllitic mica schists and the beginning of metamorphism in the Thurntaler Complex. Relative time marker t2 then can be placed on the retrograde AMU/MPU path, post-T_{max} of the phyllitic mica schists and P_{max}-T_{max} of the Thurntaler Complex (Fig. 4e). Deformation D1–2 was progressive in course of t0–t1–t2. During a first step t0–t1 of the evolution, AMU/MPU underwent their prograde, then high-pressure eclogitic, then high-temperature amphibolite-facies metamorphic stages until they reached T_{max} at uplift. The burial of the phyllitic mica schists started later compared to AMU/MPU (Fig. 4f). A second stage t1–t2 of the evolution then can be characterized by beginning uplift-cooling of the AMU/MPU units, the P_{max} to T_{max} metamorphism of the phyllitic mica schists and the burial and prograde metamorphism of the Thurntaler Complex. The Early-Palaeozoic phyllitic sequences and the Altkristallin units tectonically merged at about t2, still syn-D1–2, and at temperatures markedly above 500 °C but below T_{max} in the Altkristallin (Fig. 4g). The third stage t2–t3 of the evolution is a common uplift-cooling of the welded units, accompanied by D3–D4–D5 (Fig. 4h).

When compared to numerical models (e.g. ENGLAND and THOMPSON, 1984; DAVY and

GILLET, 1986), the clockwise shapes of the syndeformative P-T paths in combination with their spatial arrangement and different P_{max}/T_{max} are indicators of a collisional stacking with crustal burial, thickening and uplift. Accordingly, during a presumably early stage of a Variscan continental collision, units of a northern pre-Upper-Ordovician continental crust (AMU and MPU) were stacked and reworked by high-pressure metamorphism and coeval shearing D1–2. Later, in the course of the beginning uplift of the rocks, the crustal stacking process with deformation D1–2 continuously progressed towards the south and caused a more temperature-dominated metamorphism of the early-Palaeozoic passive continental margin represented by the TC.

Structural data indicate a tectonic movement subparallel to the lineation L2 and a top-to-WSW transport during D1–2 in both MPU and TC. This direction is subparallel to the former palaeogeographic and lithological zonation of the units. Such a geometrical arrangement is explained by a NE–SW directed predominant orogen-parallel dextral? transcurrent movement component accompanied by shortening in NW–SE direction during an oblique collision (ELLIS and WATKINSON, 1987). Both movement components led to a top-to-WSW directed thrusting in course of the collision. The subsequent common Late-Variscan cooling/uplift of the welded units probably evolved also in a dextral transpressional system of NW–SE directed compression with deformations D3, D4 and D5 (SCHULZ, 1995b). This Variscan tectonometamorphic evolution in the Austroalpine basement to the south of the central Tauern Window was part of the Palaeozoic continental collision of Gondwana and Baltica, as outlined by NEUGEBAUER (1989).

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