Variscan and Alpine metamorphism in the Austroalpine Basement to the south of the Tauern Window

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Abstract. The metamorphic rocks in the Austroalpine Basement to the south of the Tauern Window show a variety of foliations $S_{V1}$, $S_{V2}$, $S_{V3}$, $S_{V4}$, $S_{V5}$. They are caused by the Variscan deformation and amphibolite-facies metamorphism as it is concluded from Upper Carboniferous mica cooling ages as well as Carboniferous and Permian monazite ages. The Alpine overprint results in greenschist-facies (locally amphibolite-facies) metamorphism and deformation with foliations $S_{A1}$, $S_{A2}$, $S_{A3}$. An Eo-Alpine overprint is documented by monazite ages around 100 Ma and a first foliation $S_{A1}$ of Permian pegmatites. Late-Alpine structures are related to sinistral shearing along the Defereggen-Antholz-Vals line (DAV) which divides the Austroalpine Basement into a northern ductile and a southern brittle Alpine deformed block.

Introduction

A major part of the Alpine orogen consists of pre-Mesozoic basement units which recorded a polyphase tectonic and metamorphic evolution.

The Austroalpine Basement to the south of the Tauern Window is subdivided into four lithological groups (Fig.1). Between the southern margin of the Central Tauern Window and the major faults of the Periadriatic Lineament and towards the hangingwall one can distinguish the (1) Northern-Defereggen-Petzeck Group (NDPG); (2) Durreck Muscoviteschist Group (DMG); (3) Defereggen Group (DG) and the (4) Thurnthal Phyllite Group (TPG) (Schulz and Bombach 2003).
Fig. 1. Lithological units in the Austroalpine basement to the south of the central Tauern Window, Eastern Alps (modified after Schulz et al. 2006). A Antholz/Anterselva muscovite orthogneiss; BQ Brixen Quartzphyllite; CA Carnic Alps; CNSg Croda Nera Subgroup (metabasites); CT Campo Tures orthogneiss; DAV Defereggan-Antholz-Vals line; DG Defereggan Group (monotonous metapsammopelites); DMG Durreck Muscoviteschist Group; EW Engadine Window; H Hochgrabe biotite orthogneiss; IQ Innsbruck Quartzphyllite; J Kristeinerl biotite orthogneiss; KC Koralpen Crystalline; KV Kalkstein-Vallarga line; MSg Michelbach Subgroup (amphibolites); MZ Matreier Zone (Penninic); NDF Northern Drauzug fault; NDPG Northern-Defereggan-Petzeck Group; NCA Northern Calcareous Alps; P Penninic Upper Schieferhuelle; PG Palaeozoic of Graz; PGZ Palaeozoic of Greywacke Zone; PL Periadriatic Lineament; PSp Priajkt Subgroup (eclogitic amphibolites and hornblende-gneisses); R Rieserferner tonalite; RSg Rotenkogel Subgroup (hornblende-gneisses, orthogneisses); SA Southern Alps; T Permo-Trias and Trias; TPG Thurmtaler Phyllite Group; TSg Torkogel Subgroup (amphibolites); Z Zinsnock tonalite.

The Northern-Defereggan-Petzeck Group consists of meta-psammopelitic rocks with interlayered meta-quartzites and marbles. Within the NDPG four metabasic subgroups appear with different geochemical characteristics (Priajkt, Rotenkogel, Torkogel, Michelbach and Croda Nera Subgroup). Monotonous garnet-muscoviteschists and garnet-muscovite-quartzitic gneisses are the main rock types in the Durreck Muscoviteschist Group. This unit occurs within the NDPG. The Deferegg-
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The Thurntaler Phyllite Group overlies the DG along a partly overturned pre-Alpine contact (Heinisch and Schmidt 1984; Schulz 1991; Kreutzer 1992). It consists of quartzphyllites and phyllitic micaschists which are interlayered by amphibolites, epidot-amphibolites, chlorite schists, quartzites, graphite phyllites and rare marbles.

The W-E trending Defereggen-Antholz-Vals line (DAV) is a shear zone which subdivides the Austroalpine Basement into two major blocks. As the NDPG and the DMG appear to the north of the DAV the Defereggen Group and the Thurntaler Phyllite Group occur to the south of the DAV. The shear zone shows a sinistral offset and an uplift of the northern block in transpressional regime with NE-SW-directed compression. In the northern block Early- and Late-Alpine ductile deformation overprinted earlier structures. In the southern block a Variscan ductile deformation and an Alpine brittle overprinting are observed.

**Methods**

For the distinction of the Variscan and Alpine metamorphism and deformation it is necessary to study the macrotectonical features of the metamorphic and metamagmatic rocks like foliation, lineation and shear sense indicators. Microtectonical observations are possible by studying thin sections which show typical metamorphic mineral assemblages and their deformation in XZ- or in YZ-sections of finite strain. This microtectonical setting is important for reconstructing the relative sequence of deformation and the metamorphic facies as well as for determining the age of metamorphic events by K-Ar, Rb-Sr dating of mica and electron microprobe (EMP) dating of monazite.

**Variscan deformation and metamorphism**

Pre-Alpine (Variscan) ductile deformation is observed primarily to the south of the Defereggen-Antholz-Vals Line. Paragneisses and micaschists of the Defereggen Group show sporadic cm-thick monomineralic quartz-layers which are considered to represent a foliation $S_{V1}$. These $S_{V1}$-quartz-layers became subjected to a deformation $D_{V2}$. The quartz-layers were deformed into isoclinal folds $F_{V2}$ during deformation $D_{V2}$. The main foliation $S_{V2}$ of the rocks is axial-planar to the $F_{V2}$ folds. Among the congruent and isoclinal $F_{V2}$ folds occur strongly non-cylindrical sheath folds (cm to dm scale) with strongly curved fold axes (Schulz 1988b). They appear in quartz-, biotite-plagioclase- and calcisilicategneisses as well as in marbles. Calcisilicategneiss bodies also show these tongue-like structures of $D_{V2}$. Upper Ordovician magmatites (now orthogneisses) got their first main foliation and
stretching lineation which is parallel to \(S_{V2}\) in the metasedimentary rocks also during \(D_{V2}\) (Stöckhert 1985). For this reason the main foliation to the south of the DAV should have a Post-Upper-Ordovician age.

During \(D_{V3}\) the \(S_{V2}\) and \(F_{V2}\) structures were refolded and overprinted by \(F_{V3}\) folds whose fold axes and crenulation fold axes \(L_{V3}\) are oriented mostly parallel to \(L_{V2}\) and the \(F_{V3}\) fold axes. The axes of the \(F_{V3}\) folds are steeply plunging in some regions and are minor structures of large-scale syn- and antiforms, named as “Schlingen” structures (Schmidegg 1936). In the eastern and southern parts of the Defereggen Group a more gentle WSW or ENE plunging of the linear structures prevails. A similar orientation of \(L_{V2}/S_{V2}\) linear-planar fabrics and of \(F_{V3}\) fold axes as in the DG is observed in the adjacent Thurntaler Phyllite Group (Schulz 1991).

In phyllitic micaschists of the DG in the East a shear band foliation \(S_{V4}\) with top-to-NE-transport cuts the older \(S_{V2}\) and bends this fabric sigmoidally (Schulz 1988a). The lithological contact between DG and TPG (labelled Markinkele-Line to the W) was overprinted by mylonitic shear bands \(S_{V5}\) with NW to W or S directed movement (Heinisich and Schmidt 1984; Schulz 1991; Kreutzer 1992). \(S_{V4}\) and \(S_{V5}\) shear bands show typical dynamic recrystallisation of quartz.

In the DG the typical paragenesis of micaschists is biotite + muscovite + chlorite ± garnet ± staurolite ± kyanite ± oligoclase + quartz. As staurolite and kyanite crystallize after garnet, staurolite encloses the garnet. Furthermore staurolite and kyanite occur partially in microclithons enclosed by \(S_{V2}\). Both minerals overgrow also \(F_{V3}\) crenulation folds post-deformatively. Cuts parallel to the crenulation linear show asymmetric S-shaped bended internal foliations \(S_{V1i}\) and doubled inclusions spirals in garnets. This indicates a syndeformative growth during simultaneous rotation of porphyroblasts by dominant simple shear. The sheath folds and calcisilicategneiss bodies were also shaped by simple shear during \(D_{V2}\). The garnets show growth zonations with increasing \(X_{Mg}\) and a systematic variation of \(X_{Ca}\) from core to rim (Schulz 1995). Thermobarometrical studies (Fig.2) point to maximal \(p-T\)-conditions of 630°C/6 kbar for Mg rich rims of Ca-variable garnets (Schulz et al. 2001). Depending on the zonation also lower temperatures and pressures occur there. In garnets of phyllitic micaschists to the south of the DG the \(X_{Mg}\) increases whereas the \(X_{Ca}\) is constant. This causes \(p-T\)-conditions with increasing temperatures from 400 to 500°C and pressures from 6 to 7 kbar. Staurolite and kyanite are absent in this part of the unit.

Garnets of the Thurntaler Phyllite Group show S-shaped bended internal foliations with syndeformative growth and rotated porphyroblasts just as in the Defereggen Group. There occur furthermore postdeformative unzoned garnets which overgrow \(S_{V2}\). Thermobarometrical investigations (Fig.2) of Schulz et al. (2001) result in an increasing temperature and pressure from 420°C/4 kbar to 500°C/5 kbar for crystallization of syndeformative garnets. The postdeformative garnets crystallize at 530°C/6 kbar.

In amphibolites of the TPG, continuously zoned amphiboles recorded prograde \(p-T\)-paths from 300°C/2 kbar to 600°C/6 kbar (Schulz 1991). The thermobaromet-
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Ric data signalize minor differences between the DG and the TPG in respect of maximum temperature of metamorphism but major differences in respect of pressure conditions (Fig.2). The p-T-data of the Defereggen and the Thurntaler Phyllite Group characterise a Variscan metamorphism. This is evident from Upper Carboniferous mica cooling ages (Borsi et al. 1978; Schuster et al. 2001). An other argument for a Variscan (resp. Pre-Alpine) metamorphism is given by the already mentioned pervasive dynamic recrystallization of quartz in S_v4 and S_v5 shear bands which are not observed in Alpine deformed Permo-Triassic sandstones of Kalkstein (Guhl and Troll 1987). Moreover the Upper-Ordovician magmatites were subject to D_v2.

Variscan metamorphism is also proved to the north of the DAV. The already mentioned S_v1 quartz layers occur as sheared off hinges of isoclinal F_v2 folds. These folds lie within the axial-planar foliation S_v2. Garnets from the Durreck Muscoviteschist Group affect in remaining S_v2 main foliation or isolated in micro-lithons. The inclusion spirals show no connection to the external foliation. They are assumed as remnants of S_v1. The S_v2 foliation in muscoviteschists is partially overgrown by garnet. This indicates a crystallization of garnet seams after D_v3. Either the garnet grew during a static Late-Variscan or during the Alpine metamor-

Fig.2. Left: p-T paths of metapelites to the south of the DAV. Black arrows show p-T paths reconstructed from zones garnets (Grt) in micaschists from the Defereggen Group (DG), from phyllitic micaschists of the Defereggen Group (DGpm) and the Thurntaler Phyllite Group (TPG). P-T data and p-T path from amphibolites in the TPG with zoned amphiboles are marked by crosses and a grey arrow. Right: p-T-conditions to the north of the DAV. Black arrows show p-T paths reconstructed from zoned garnet (Grt) in micaschists and paragneisses of the North-Deferegge-Petzeck Group. Crosses mark p-T conditions derived from amphiboles (Am) in metabasites from the basement and the Penninic unit. The grey arrow displays a p-T path from eclogitic amphibolites of Schobergruppe. Black and grey symbols show pre-Alpine (Variscan) p-T conditions. Green symbols show Alpine p-T conditions (con = late-Alpine contact metamorphism (con) along the Rieserferner; Ms = early-Alpine p-T conditions from decussate white mica). Modified after Schulz et al. 2006.
phism. In paragneisses and amphibolites of the northern NDPG coarse grained muscovite and biotite as well as amphibole form $S_{V2}$. The crystallization of garnet in metapelites and tschermakite in amphibolites is correlated with the formation of $S_{V1}$ and $S_{V2}$ foliations under prograde conditions within the amphibolite facies. After Schulz et al. (2001) the crystallization of garnet seams (post $D_{V2}$) is assign to the Variscan metamorphism. The garnets are continuously zoned with increasing $X_{Mg}$ from core to rim. An Alpine overprint with a new growth of garnet would have caused prominent varieties in the zonation profiles.

The pressure-temperature-paths (Fig. 2) of the eclogitic amphibolites within the Prijakt Subgroup show a prograde metamorphic evolution from 550-600°C/14 kbar to 600-650°C/15 kbar (Schulz 1993). Amphiboles out of the eclogitic amphibolites display a retrograde evolution from 730°C/10 kbar to 600°C/6 kbar (Schulz et al. 2005). The authors mentioned above state maximal temperatures 650°C/7 kbar and maximal pressures of 650°C/7 kbar for metapelites of the NDPG. Both the metapelites and the eclogitic amphibolites show p-T-conditions of amphibolite facies.

The question concerning dominant Variscan or Alpine metamorphism north to the DAV arises also with respect to the eclogitic amphibolites of the Prijakt Subgroup. Micaschists associated to the eclogitic amphibolites contain monazite which occurs often with staurolite. The Th-U-Pb-dating of these monazites by electron microprobe analysis yielded mostly Variscan (350-320 Ma) and Peronian (290-260 Ma) ages (Schulz et al. 2005). One sample contains monazite grains at the age of 95 ± 11 Ma, whereas also Peronian monazites occur. Another sample shows a change from Pre-Alpine to Eo-Alpine ages from core to rim. However, the majority of monazites crystallized during a Pre-Alpine (Variscan-Peronian) metamorphism. The Eo-Alpine age indicates a low grade Alpine overprint of the dominant Variscan metamorphic rocks.

**Alpine deformation and metamorphism**

The Austroalpine Basement to the north of the Defereggen-Antholz-Vals line is mainly characterized by ductile Alpine deformation. The Variscan $S_{V2}$ foliation within the NDPG and DMG is overprinted by the first Alpine deformation $S_{A1}$. A second foliation $S_{A2}$ is parallel to $S_{A1}$. $S_{A2}$ is the axial-planar foliation of $F_{A2}$ folds and dips steeply to moderate to SSE. Within the DMG also N dipping directions occur. $S_{A2}$ is locally folded by $F_{A3}$. Furthermore ECC-type-foliations $S_{A3}\text{ECC}$ as well as mylonitic foliations $S_{Amyl}$ occur on the northern margin of the DAV.

Garnets in micaschists of the DMG show typical double circular inclusion figures in cuts parallel to the lineation respectively rotation axis. This is ascribed to a passive rotation of older garnets during the Alpine deformation. Sigma shaped pressure shadows of garnets in $S_{A2}$ domains indicate a top-to-west transport. Variscan and Alpine deformation and metamorphism to the north of the DAV can be distinguished by pegmatites intruded mostly parallel to $S_{V2}$. The pegmatites intruded both to the north (e.g. Prijakt Subgroup of the NDPG) and the south of
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The 262 ± 5 Ma old Permian pegmatites (Borsi et al. 1980) to the south of the DAV are overprinted in a cataclastic to pseudotachylitic manner (brittle deformation) whereas the pegmatites to the north of the DAV show incomplete to complete foliation (ductile deformation). This deformation took place after the Permian intrusion. Therefore it must be an Alpine deformation age ($S_{A1}$). Schönhofer (1999) proved a top-to-west transport during the first Alpine deformation on the basis of alignments of quartz c-axes.

 Dating of muscovite yielded early Alpine K-Ar ages (100 and 80 Ma), dating of biotite yielded late Alpine Rb-Sr ages (15 to 28 Ma) (Borsi et al. 1978, Stöckhert 1985). Furthermore Alpine-Variscan mixing ages occur there. These mixing ages in combination with the datings and microtectonic observations show an Alpine overprinting of the pervasively Variscan deformed rocks of the Austroalpine basement. The Alpine influence also was provided by Schulz et al. 2006 on the basis of monazite dating (95 ± 11 Ma).

The metamorphism and deformation took place under greenschist-facies-conditions (Fig.2). The amphibolite facies with maximal temperatures of 500°C and pressures of 4 kbar was attained locally (calculated on the basis of amphibolites of the Penninic Unit, Schulz et al. 2006).

The intrusion of the Oligocene (30 Ma, Borsi et al. 1979) Rieserferner tonalite pluton along the western DAV caused a contact metamorphism (Fig.2) with maximal conditions of 620°C/3 kbar (Schulz 1994). Contact metamorphic blasts like andalusite, sillimanite and staurolite are observed. The original foliation survived as layered anisotropy.

**Geodynamic model**

A geodynamic model of the Variscan deformation and metamorphism (Fig.3) is presented in Schulz et al. 2006. The Variscan orogeny begins with the collision of Gondwana terranes (and later Gondwana itself) with Laurussia during Devon and Carbon. Furthermore the subduction of Palaeotethys begins. The associated poly-metamorphism can be explained by a "overstacking" model (Schulz 1990, Schulz 1995, Schönhofer 1999). During an early phase of the Variscan metamorphism the northern crustal segments underwent burial and subsequent uplift. This resulted in high pressure amphibolite-facies conditions. The process of burial and uplift progressed toward the south and included the units in the hangingwall. The DG and TPG are therefore characterized by lower maximal pressures. The subsequent late Variscan uplift of the rocks took place at a dextral transpression system with NW-SE directed compression. Indications are given by „Schlingen“ structures $F_{V3}$ and the $S_{V4}$ und $S_{V5}$ shear bands.

Postcollisional pegmatites intruded in the Variscan orogen during the Permian. The Permian monazite ages and crystallization of andalusite in metapelites nearby the pegmatites signalize re-increasing temperatures at low pressures during the
general decompression path. Altogether, the post-Variscan evolution is dominated by crustal extension and thinning, followed by the Mesozoic sedimentation.

In the course of subduction of the European under the Adriatic plate the Alpine orogeny took place (Upper Cretaceous – Paleogene). To the south of the present Tauern Window the Deferegggen-Antholz-Vals line developed. The block to the north of the sinistral DAV was uplifted at the oblique reverse fault relatively to the southern block (Borsi et al. 1978, Schulz 1989). The vertical displacement amounts 5 km to the W, 2 – 3 km at the Staller Sattel and < 1 km to the E. The horizontal displacement amounts 30 km (Schulz 1989). The uplift caused an erosional exposure of the late-Alpine ductile deformation structures in the northern block.

Fig. 3. Top: Variscan continental collision with crustal thickening by tectonic stacking of lithotectonic units in the southern part of the Variscan orogen. High-pressure amphibolite-facies metamorphism occurs in structurally lower tectonic units. Centre: to the right: ongoing subduction of Palaeotethys; uplift and extension with intrusion of Permian pegmatites in distinct basement units; sedimentation of Permian and Mesozoic cover rocks; to the left: Jurassic opening of Penninic ocean and separation of the Adriatic Plate. Bottom: Late stage of Alpine continental collision with accretion of Penninic units at the base of the Austroalpine nappes. Subsequent late-Alpine intrusions (Rieserferner) are associated with shear zone activity along the Deferegggen-Antholz-Vals line (DAV). The non-metamorphic Permo-Mesozoic sedimentary cover is preserved e.g. along the DAV. Modified after Schulz et al. (2006).
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