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EXPLANATORY NOTES TO THE MAP: METAMORPHIC STRUCTURE OF THE ALPS METAMORPHIC EVOLUTION OF THE EASTERN ALPS

by

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1. Introduction

The Eastern Alps are the product of two orogenies, a Cretaceous orogeny followed by a Tertiary one (FROITZHEIM et al., 1996). The former is related to the closure of an embayment of the Neotethys ocean into Apulia (Meliata ocean), the latter is due to the closure of the Alpine Tethys oceans between Apulia and Europe.

The result of the orogenic movement is a complex nappe stack, which is built up from north to south and from bottom to the top by the following units (Plate 1 in SCHMID et al., 2004): The proximal parts of the Jurassic to Cretaceous European margin built up the northern Alpine foreland and the Helvetic nappes, whereas the distal margin is represented by the Subpenninic nappes. The Penninic nappes comprise the Piemont-Ligurian and Valais ocean (Alpine Tethys) and the Briançonnais Terrain. Apulia consists of the northern Austroalpine nappes and the Southern Alpine unit (STAMPFLI & MOSAR, 1999). Remnants of the Neotethys embayment occur as slices within the eastern part of the Austroalpine nappe stack. Both orogenic events are accompanied by regional metamorphism of variable extent and P-T conditions. The Cretaceous (Eo-Alpine) metamorphism effects mainly the Austroalpine Nappes, the Penninic domain by the Tertiary metamorphism, some units of the Lower Austroalpine Nappes show signs of both events.

2. Metamorphic evolution of the Eastern Alps

2.1. Geological Framework of the Eastern Alps

In the Eastern Alps (Plate 1 in SCHMID et al., 2004) the Jurassic to Cretaceous European margin is represented by the Helvetic and Ultrahelvetic Nappes composed of Mesozoic sedimentary series and by the Subpenninic nappes consisting of orthogneisses with remnants of roof pendants (Altes Dach), Paleozoic metasediments and a transgressive Mesozoic cover. The Helvetic and Ultrahelvetic Nappes built up the northern foothills of the orogen, whereas the Subpenninic Nappes occur in the Tauern Window in the south.

The Penninic nappes are present along the northern margin of the Alps and within the Lower Engadin Window, Tauern Window, and Rechnitz Window Group. Cretaceous ophiolitic fragments overlain by Cretaceous to Tertiary (Lower Engadine Window) calcareous schists as well as flysch sediments (Rhenodanubian flysch) of the Valais ocean form the Lower Penninic Nappes. The eastern oftshoots of the Middle Penninic Nappes reach until the Lower Engadine Window. They consist of a continental basement with a Mesozoic cover. The Upper Penninic Nappes (Piemont-Ligurian ocean) are characterised by slices of subcontinental mantle and oceanic crust in connection with Jurassic radiolarites and Cretaceous to Tertiary calcareous schists.

The Austroalpine nappes are composed of crustal material with a complex Phanerozoic history. They can be subdivided in a Lower and an Upper Austroalpine unit. The former shows a remarkable reworking related to the opening and closure of the Piemont-Ligurian and Valais ocean, whereas the internal structure of the latter is due to the closure of the Tethys embayment. Coming from the north the Upper Austroalpine unit is built up by Mesozoic sedimentary sequences of the Northern Calcareous Alps, Paleozoic metasediments and metavolcanics of the Graywacke zone and the crystalline basement units with remnants of Paleozoic and Mesozoic metasediments. The crystalline basement can be subdivided into four parts: The lowermost Silvretta-Seckau nappe system is predominantly consisting of a deeply eroded Variscan metamorphic crust with a partly preserved Mesozoic cover (NEUBAUER et al., 1999a, NEUBAUER, 2002). The overlying Wölz-Koralpe nappe system is built up exclusively by pre-Mesozoic rocks and represents an extruding metamorphic wegde. Above this wedge the Ötztal-Bundschuh and the Gurktal-Drauzug nappe system are present. To the south of the Periadriatic lineament the Southern Alpine unit is located. The nappe systems above the wedge as well as the Southern Alpine unit are composed of crystalline basement, Paleozoic metasedimentary rocks and Permo-mesozoic cover sequences.

Nearly all nappe units contain metasedimentary sequences and/or metabasaltic rocks of Mesozoic age. During the Alpine tectonometamorphic events prograde assemblages formed in these rocks, defining the grade of the Alpine metamorphic imprints. However, large parts of the Austroalpine nappes, especially those of the Wölz-Koralpe nappe system lack prograde sequences, but show complex polyphase microstructures. It is not always easy to distinguish between several metamorphic events, which reach sometimes similar conditions. Therefore, due to missing geochronological data, different individual metamorphic events including the Variscan or Permian event, were sometimes mixed up in the older literature.

2.2. Pre-alpine metamorphic history of the Austroalpine Unit

In the Austroalpine unit two regional Palaeozoic metamorphic imprints are well documented. In the Penninic and Subpenninic unit of the Eastern Alps only one is known up to now and this one is restricted to the basement of the Tauern Window.

2.2.1. Variscan tectonometamorphic event

Pre-Alpine metamorphic basement units are exposed within different continental microplates of the Eastern Alps: the Subpenninic, Penninic, Austroalpine and Southalpine units. They show varriable metamorphic imprints due to the variety of metamorphic facies and age of metamorphism. These imprints are interpreted to result from accretion of various units to the active Laurasian continental margin.

The Variscan metamorphic event was induced by the collision of Africa, Baltica, Laurentia and intervening microplates (TAIT et al., 1997). A collision related LT/HP imprint occurred prior to 350 Ma. The thermal metamorphic peak was reached at about 340 Ma at medium pressure conditions. Typical Variscan cooling ages are about 310 Ma (MILLER & THÖNI; 1995, NEUBAUER et al. 1999a; THÖNI, 1999).

The Subpenninic basement exposed within the Tauern Window is largely overprinted by Variscan migmatite-grade metamorphism associated with intrusions of Variscan granites. Rare eclogites of Silurian age predate migmatite formation. The Austroalpine basement units vary in metamorphic grade and timing of metamorphism ranging from greenschist to granulite facies conditions. Only a Variscan greenschist metamorphic overprint is recorded in the eastern part of the Southalpine unit.

2.2.2. Permo-Triassic tectono-thermal event

The Permo-Triassic imprint reflects lithospheric extension after the late Variscan orogenic collapse. It may be due to the anticlockwise rotation of Africa and the southern part of the Apulian microplate with respect to Eurasia and the northern part of the Apulian microplate and caused extension within the Austroalpine and South Alpine realm. Accompanied thinning of the lithosphere resulted in a high temperature metamorphic imprint (HT/LP) (SCHUSTER et al., 2001). The Permo-Triassic imprint is widespread in the Austroalpine unit (Fig. 1) and affects pre-Permian rocks of different metamorphic grade (HABLER & THÖNI, 2001; SCHUSTER et al., 2001). Well preserved Permo-Triassic metamorphic rocks occur in the Gurktal-Drauzug nappe system between the southern border of Alpine metamorphism (SAM, HOINKES et al. 1999) and the Periadriatic Lineament, as well as in the western part of the Silvretta-Seckau nappe system. Similar lithologies with an Eo-Alpine overprint of different grade are present in the Wölz-Koralpe nappe system.

Areas with well preserved Permo-Triassic HT/LP lithologies south of the SAM

Well preserved Permo-Triassic HT/LP assemblages occur within more or less complete sections of Permo-Triassic crustal fragments up to c. 15 km structural depth. They comprise of a upper and middle continental crust and their Permo-Triassic sedimentary cover sequencies with intercalations of Lower Permian quartz-porphyries. In the crust a continous increase of the metamorphic grade up to high amphibolite facies lithologies with local anatexis can be identified by

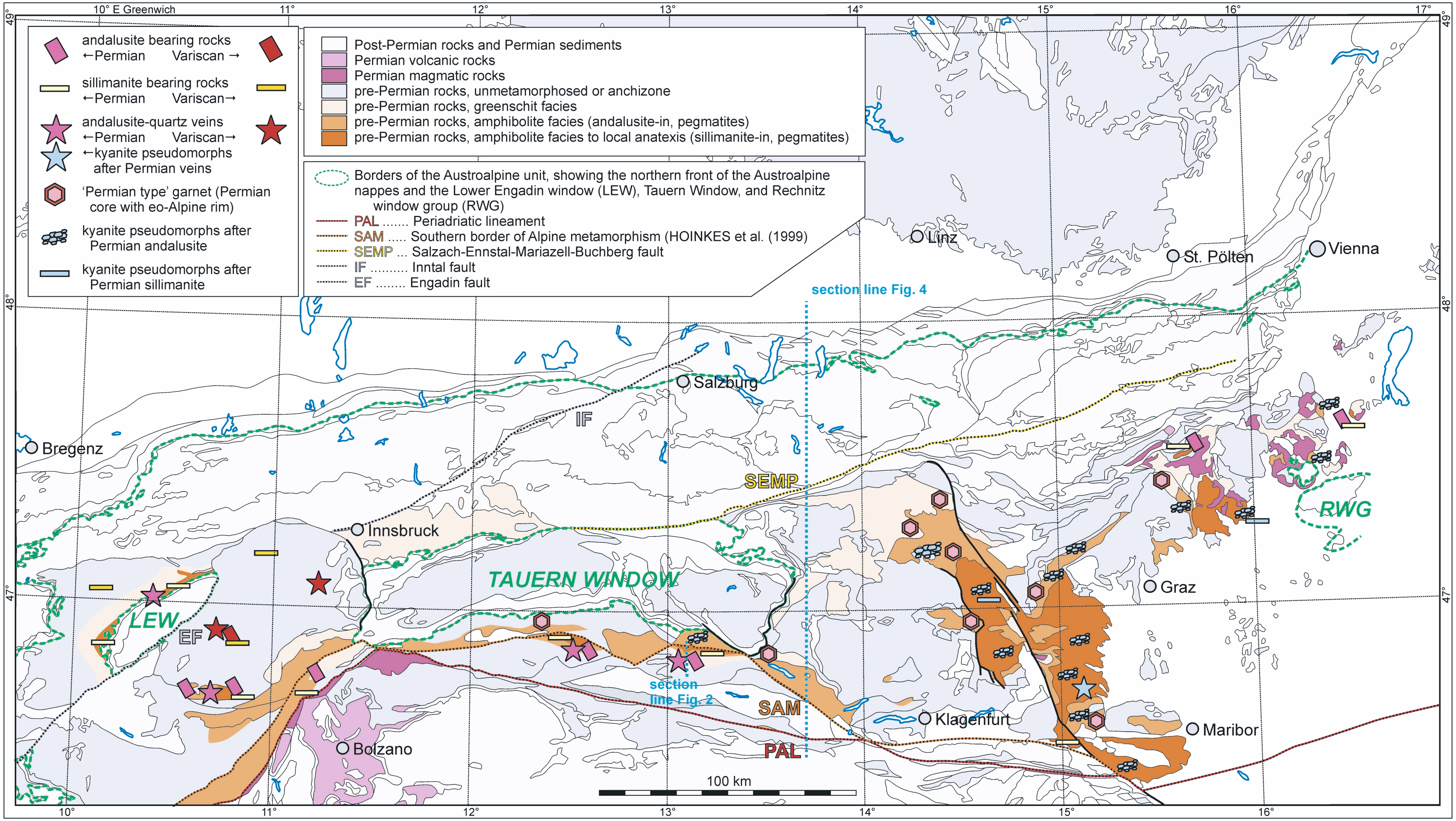

Fig. 1

Tectonic map of the Eastern Alps showing the distribution of the Permo-Triassic metamorphic imprint. Additionally the section lines of the transsects in Fig. 2 and Fig. 4 are given.

decreasing cooling ages, different HT/LP assemblages and the occurrence of Permian magmatic rocks. The structurally deepest parts are outcropping along Tertiary structures, e.g. along the Defereggen-Antholz-Vals fault, the Ragga-Teuchl fault or the thrust plane along the northwestern margin of the Lower Engadin Window.
One of the most complete sections is preserved in the Kreuzeck and Goldeck Mountains (Fig. 2). In this profile a Permo-Triassic event is overprinting Variscan metamorphic rock sequences of different metamorphic grade. In the tectonic higher units (south of the profile shown in Fig. 2), white mica Ar-Ar ages of ~310 Ma reflect post-Variscan cooling. The Variscan structures and assemblages are well preserved. In the upper part of the Strieden Complex post-deformation mica growth with respect to the Variscan structures can be observed, the white mica Ar-Ar ages range from 290 in the south to 260 Ma in the north. Below a zone with andalusite bearing lithologies occurs (HOKE, 1990). Andalusite, forming up to several centimetres large porphyroblasts, is frequently found within layers of Al-rich metapelites (24.9-26.9 wt% Al_2O_3) with a low X_{Mg} (0.19-0.23). Together with plagioclase and coarse-grained biotite flakes andalusite is overgrowing the Variscan microfabrics and porphyroblasts of staurolite and garnet. Andalusite is formed by the breakdown of chlorite (Chl + Ms ⇔ And + Bt + Qtz + H_2O) and paragonite (Pg + Qtz ⇔ Ab + And + H_2O). Furthermore, there are lithologies where staurolite is present only as small and dismembered inclusions with identical optical orientation within the andalusite porphyroblasts. In this case the andalusite growth is due to the breakdown of staurolite (St + Ms + Qtz ⇔ And + Bt + H_2O). Coarse-grained veins with mineral assemblages of Qtz + And + Ms ± Pl ± Ilm are crosscutting the Variscan foliation of the andalusite-bearing schists. Within these veins andalusite idioblasts up to 20 cm in length occur. Within deformation zones they are ductily deformed and fibrolitic sillimanite was growing within highly sheared areas. Ar-Ar muscovite ages of the andalusite-zone are in the range of 200-230 Ma.

In the lowermost part of the andalusite-zone isolated pegmatites appear, whereas pegmatites are frequent in the sillimanite-zone below. In metapelites sillimanite occurs within biotite-rich layers and as millimetre-sized patchy pseudomorphs, which often contain relics of garnet or staurolite covered by quartz. Locally plagioclase porphyroblasts up to 1 cm in size are growing. With structural depth the content of muscovite is decreasing. In the lowermost part anatectic mobilisates composed of Qtz + Pl + KFsp ± Bt ± Sil are present. Obviously sillimanite is formed by the successive breakdown of paragonite (Pg + Qtz ⇔ Ab + Sil + H_2O), staurolite, garnet (Grt + Ms ⇔ Sil + Bt + Qtz + H_2O) and muscovite (Ms + Qtz ⇔ Sil + L). Together with the continuous change in the mineralogy a syn-metamorphic foliation becomes more prominent with structural depth. In the lowermost part the Variscan mineral assemblages and microstructures are nearly totally annealed. The pegmatites exhibit magmatic assemblages of Kfsp + Pl + Qtz + Ms + Turm ± Grt. Most of them are concordant or slightly discordant with a weak ductile deformation. Some are folded by the syn-metamorphic schistosity. Magmatic crystallisation ages of the pegmatites yielded 260-285 Ma. The pegmatites are obviously related to the HT/LP event, because they occur only in the lowermost andalusite-zone and within the sillimanite-zone. Additionally spodumene-bearing pegmatites are known. Typical Ar-Ar muscovite ages of the sillimanite zone are ~190 Ma.
In the NKFMASH grid (SPEAR, 1993) the following assemblages characterise the Permo-Triassic imprint (Fig. 3): And + Bt + Ms + Pl (500-570°C, < 0.35 GPa), Sil + Bt + Ms + Pl (550-650°C, 0.3-0.45 GPa), Sil + Bt + Pl + melt (> 650 °C, < 0.45 GPa).

These assemblages define an elevated metamorphic gradient of ~40°C/km. According to the age data on the synmetamorphic pegmatites the metamorphic peak occurred at ~270 Ma. After 270 Ma. the rock pile was not exhumed but cooled down to heat flow contitions of ~25°C/km, which was reached at ~190 Ma (SCHUSTER et al., 2001).

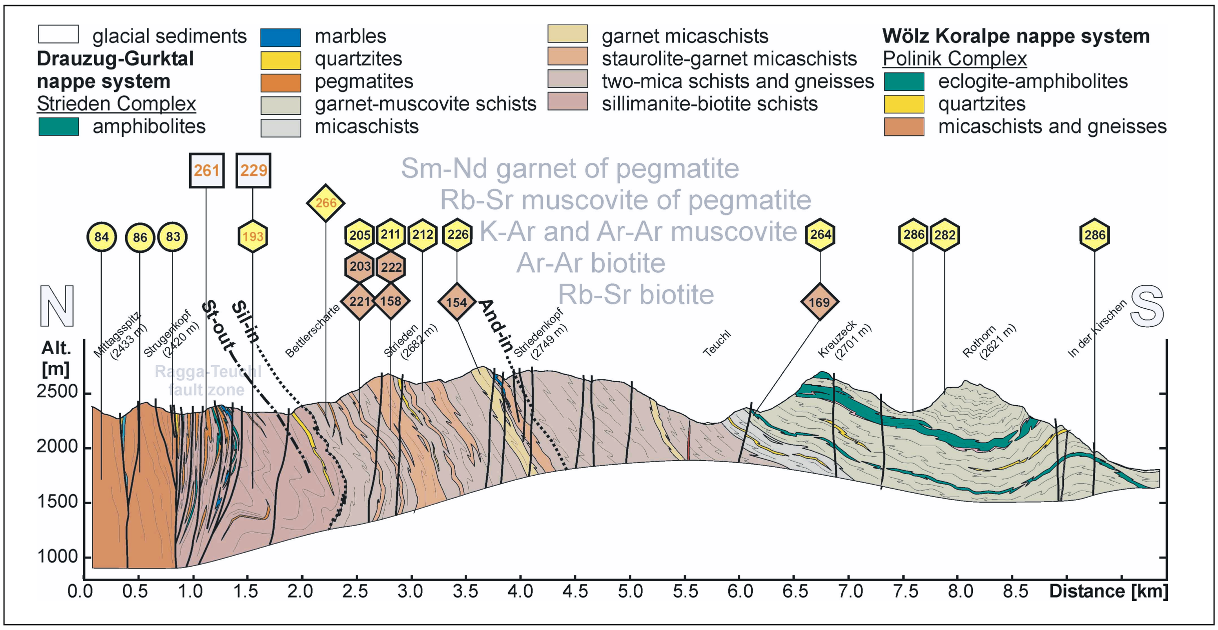

Fig. 2

Transsect through the Kreuzeck mountains (Carinthia/Austria). The Polinik Complex to the north of the Tertiary Ragga-Teuchl fault zone experienced an eclogite and high-amphibolite facies imprint during the Eo-Alpine thermal event. Typical K-Ar muscovite cooling ages are about 85 Ma. The Strieden Complex to the south of the fault zone is characterised by an anchizonal to lowermost greenschist facies Eo-Alpine imprint. Therefor the Permo-Triassic thermal imprint can be studied. In the structural lowermost part sillimanite is the typical alumosilicate phase, whereas above andalusite can be found. Ar-Ar muscovite ages show increasing values towards the top.

Permo-Triassic HT/LP lithologies north of the SAM

In the western part of the Eastern Alps a Permian to middle Cretaceous diastathermal metamorphism has been reported. During Permian and lower Triassic times a high heat flow caused a near surface geothermal gradient of ~70°C/km and burial temperatures up to 300°C (FERREIRO-MÄHLMANN, 1995, 1996).

Within the Wölz-Koralpe Nappe system the units with the highest Eo-Alpine metamorphic grade also exhibit the most intense Permo-Triassic imprint. The latter can be identified by the occurrence of Permian garnet cores within polyphase garnet crystals, characteristic kyanite aggregates pseudomorphosed after andalusite and sillimanite, and by the occurrence of Permian magmatic rocks like pegmatites (SCHUSTER & FRANK, 2000; THÖNI & MILLER, 2000), gabbros (MILLER & THÖNI, 1997), and granites (MORAUF, 1980).

The Wölz Complex is mainly formed by garnet-micaschist with intercalations of amphibolites and marbles. In some areas garnet porphyroblasts with optically and chemically distinct cores and younger rims occur. The cores are idiomorphic, almandine-rich and poor in grossular ($alm_{0.73}sps_{0.08}pyr_{0.09}grs_{0.09}$). They have a pinkish colour and contain inclusions of margarite ($ma_{0.83}pa_{0.13}ms_{0.04}$), paragonite ($pa_{0.92}ma_{0.06}ms_{0.02}$), muscovite ($ms_{0.91}pa_{0.09}ma_{0.00}$), epidote, quartz and ilmenite.

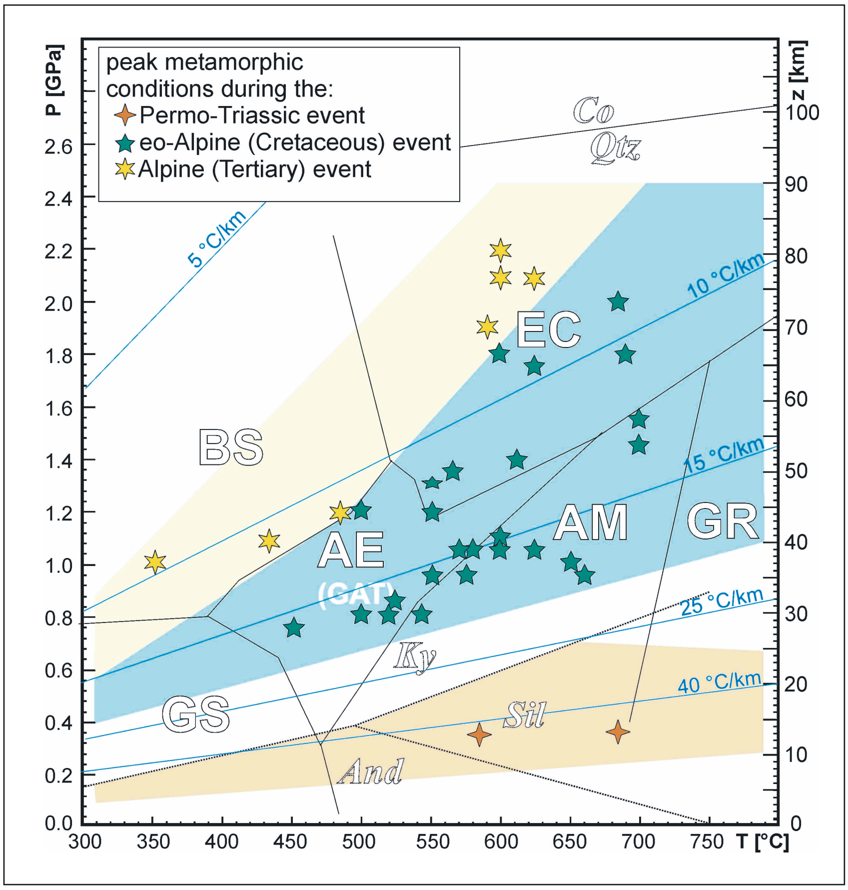

Fig. 3
Diagram showing the peak metamorphic P-T data referred in the text. The Permo-Triassic, Eo-Alpine and Alpine metamorphic event are characterised by different geothermal gradients during the metamorphic peak.

The core of one garnet yielded a well defined Sm-Nd crystallisation age of 269 ± 4 Ma and hence a Permian age of formation. Based on the coexistence of white mica phases during the growth of the garnet core, upper greenschist facies conditions at low pressures can be estimated (SCHUSTER & FRANK, 2000). Also from other units of the Wölz-Koralpe Nappe system garnet cores yielded Permian formation ages in the range of 265-285 Ma (THÖNI, 1999). They prove a metamorphic imprint of at least upper greenschist facies conditions for these areas.

In the Strallegg Complex the transformation of Permian andalusite and sillimanite-bearing assemblages into kyanite-bearing gneisses can be observed. This unit is composed of biotite-rich micaschists and migmatic gneisses, scarce amphibolites and intercalations of fine-gained granitic orthogneisses and pegmatites. Similar as in the Strieden Complex the andalusite and sillimanite-bearing lithologies contain relics of Variscan garnet and staurolite. They show mineral assemblages of Sil + And + Kfsp + Bt + Pl and also cordierite has been reported. Based on observations from TÖRÖK (1999) two sillimanite generations occur: the older developed by the breakdown of paragonitic mica by the reaction Pg + Qtz ⇔ Sil + Ab + H_2O. This sillimanite is present as inclusions within andalusite. The latter formed by the reaction St + Ms + Qtz ⇔ And + Bt + H_2O at lower pressures (Fig. 3). A younger sillimanite generation occurs within extensional shear bands and between boudinaged andalusite porphyroblasts. Metamorphic peak conditions reached 640-710 °C at 0.22- 0.38 GPa (DRAGANITS, 1998; TÖRÖK, 1999). The granites and pegmatites represent syn-metamorphic intrusions with respect to the HT/LP event. They are crosscutting the schistosity defined by the HT/LP assemblages, but they are also deformed by syn-metamorphic structures. The age of the HT/LP imprint is defined by Sm-Nd garnet isochrone ages of metasedimentary and magmatic rocks in the range of 263-286 Ma.

The Eo-Alpine transformation of the alumosilicate starts with the formation of distinct kyanite crystals along the edges and within cracks. Finally andalusite and sillimanite are totally replaced by fine-grained kyanite aggregates. These pseudomorphs are very typical even when they are affected by a strong deformation later on.
The Saualpe-Koralpe Complex consists of various kyanite-bearing micaschists and paragneisses with intercalated marbles, eclogites and amphibolites. Rocks of magmatic origin are (meta-)gabbros and frequent pegmatite gneisses. The present day metamorphic and structural behaviour is the result of the Eo-Alpine tectonothermal event, which reached eclogite and subsequent amphibolite facies conditions (see below). Relics of an amphibolite facies Permian HT/LP imprint are frequent kyanite pseudomorphs after andalusite and sillimanite, similar to those in the Strallegg Complex. Further Permian garnet cores and Permian pegmatites have been identified. The latter are interpreted as vein mobilisations from the host rocks (THÖNI & MILLER, 2000). Further gabbroic rocks yielded Permian crystallisation ages in the range of 240-285 Ma (MILLER & THÖNI, 1997; THÖNI, 1999). However, the most impressive relics of the HT/LP event are up to half a meter long kyanite pseudomorphs after chiastolithic andalusite from metapelites and idiomorphic kyanite pseudomorphs after andalusite within pre-existing andalusite-quartz veins. HABLER & THÖNI (2001) calculated metamorphic conditions of 590 ± 20°C at 0.38 ± 0.1 GPa for the HT/LP imprint. They used relic assemblages preserved within garnet cores from metapelites. A summary of the Permian imprint in the Austroalpine unit was published by SCHUSTER et al. (2001).

2.3. Alpine metamorphic history

In the Eastern Alps Alpine tectonometamorphism is triggered by two independent plate tectonic events:

1) **The Eo-Alpine (Cretaceous) metamorphic event** is widespread within the Austroalpine unit. It is related to the continental collision following the closure of an embayment of the Tethys ocean. The latter opened in Triassic to Jurassic times in the southeast of the Austroalpine unit (STAMPFLI & MOSAR, 1999) and was closed in Upper Jurassic to Cretaceous times. The geometry during the closure of this embayment is not well understood yet. However, recent investigations argue that the northern part of the Austroalpine unit formed the tectonic lower plate, whereas the southern parts and the north-eastern margin of the Southalpine unit acted as the tectonic upper plate during the continental collision following the disapearance of the oceanic embayment (SCHMID et al., 2004). The peak of the Eo-Alpine metamorphic event was reached at about 100 Ma, the youngest cooling ages reach 65 Ma (FRANK et al. 1987a; THÖNI, 1999).
2) **The Tertiary Alpine metamorphic event** is due to the closure of the Jurassic to early Tertiary Briançonnais and Valais oceans (Alpine Tethys). According to WAGREICH (2001) the re-arrangement of the Penninic-Austroalpine border zone from a passive to an active continental margin began at about 120 Ma. From that time on the oceanic lithosphere and slices from the northern margin of the Austroalpine unit (Lower Austroalpine units) were subducted towards the south below (Upper) Austroalpine units. The Tertiary event reached blueschist facies conditions in some Mesozoic parts of Penninic windows and some units of the Lower Austroalpine (Tarntal nappe). Eclogite facies conditions occur only in a narrow zone of the Tauern Window.

After the thermal peak at about 30 Ma (BLANKENBURG et al., 1989) uplift and cooling is recorded by K-Ar and Ar-Ar ages on white micas and fission track ages on zircon and apatite (LUKSCHEITER & MORTEANI, 1980; GRUNDMANN & MORTEANI (1985); FÜGENSCHUH et al., 1998).

2.3.1. Eo-Alpine (Cretaceous) metamorphic event

In the Lower Austroalpine nappes the Eo-Alpine metamorphic imprint is expressed by a retrograde overprint on pre-Alpine metamorphic rock series and a prograde metamorphic imprint in Mesozoic cover sequences. During the retrogressive overprint the assemblage Chl + Ab + Ms + Qtz was stable in the basement rocks, indicating lower greenschist facies conditions. For the northern part of the Wechsel nappe MÜLLER et al. (1999) proposed temperatures of 350°C, whereas SLAPANSKY & FRANK (1987) estimated 350-400°C for the Radstadt nappe system.

In the Upper Austroalpine unit the Eo-Alpine metamorphic imprint shows a generally north-south orientated zonation, which is disrupted by Tertiary faults. Coming from the north the Eo-Alpine metamorphic conditions increase with structural depth from diagenetic up to greenschist facies conditions from the Northern Calcareous Alps down into the Silvretta-Seckau nappe system. Within the lower part of the overlying Wölz-Koralpe nappe system the metamorphic grade is increasing upwards from lower greenschist facies at the base to eclogite and high amphibolite facies in the central part. In the upper part it is decreasing upwards again to epidote-amphibolite or greenschist facies conditions at the top. The latter trend is continuing in the overlying Ötztal-Bundschuh and Drauzug-Gurktal nappe systems, where anchizonal or diagenetic conditions can be found in the tectonically uppermost units (Fig. 4). In the following chapter general outlines on this metamorphic zoning are given, whereas more detailed information on the metamorphic imprint of the individual units is given in HOINKES et al. (1999). Units, referred in here, are shown in a map by SCHUSTER et al. (2001, Fig. 1).

The metamorphic grades given for the Northern Calcareous Alps are based on illite-crystallinity data, coalification ranks and conodont alteration indices (CAI) (FERREIRO-MÄHLMANN, 1995; 1996; KRALIK & SCHRAMM, 1994; GAWLIK et al. 1994). Palygorskite occurs within unmetamorphosed sediments, whereas paragonite, margarite, pyrophyllite and paragonite/muscovite mixed layer minerals were formed during the Eo-Alpine thermal imprint (KRALIK et al., 1987). There is an overall southward increase of the metamorphic grade, with diagenetic conditions in the Bajuvaric and northern Tirolic nappe system, to upper anchizonal conditions and lowermost greenschist facies in the southern part of the Tirolic nappe system. This seems to be more complicated by local trends. For example, in the western part of the Northern Calcareous Alps lowermost greenschist faces is reported from the tectonic uppermost Krabachjoch Nappe (KÜRMANN, 1993) and on the other hand, along the southeastern margin of the Northern Calcareous Alps the conditions are decreasing upwards from upper anchizonal conditions within the Permoscythian metasediments of the Tirolic nappes to diagenetic conditions in the uppermost Schneeberg nappe (Juvavic Nappe system). GAWLICK et al. (1994) reported the distribution of conodont alteration indices (CAI) for large parts of the Northern Calcareous Alps. Based on this data also a Jurassic thermal event can be recognised. The highest indices up to CAI 7 can be found in the Juvavic nappe system (FRISCH & GAWLICK, 2003).

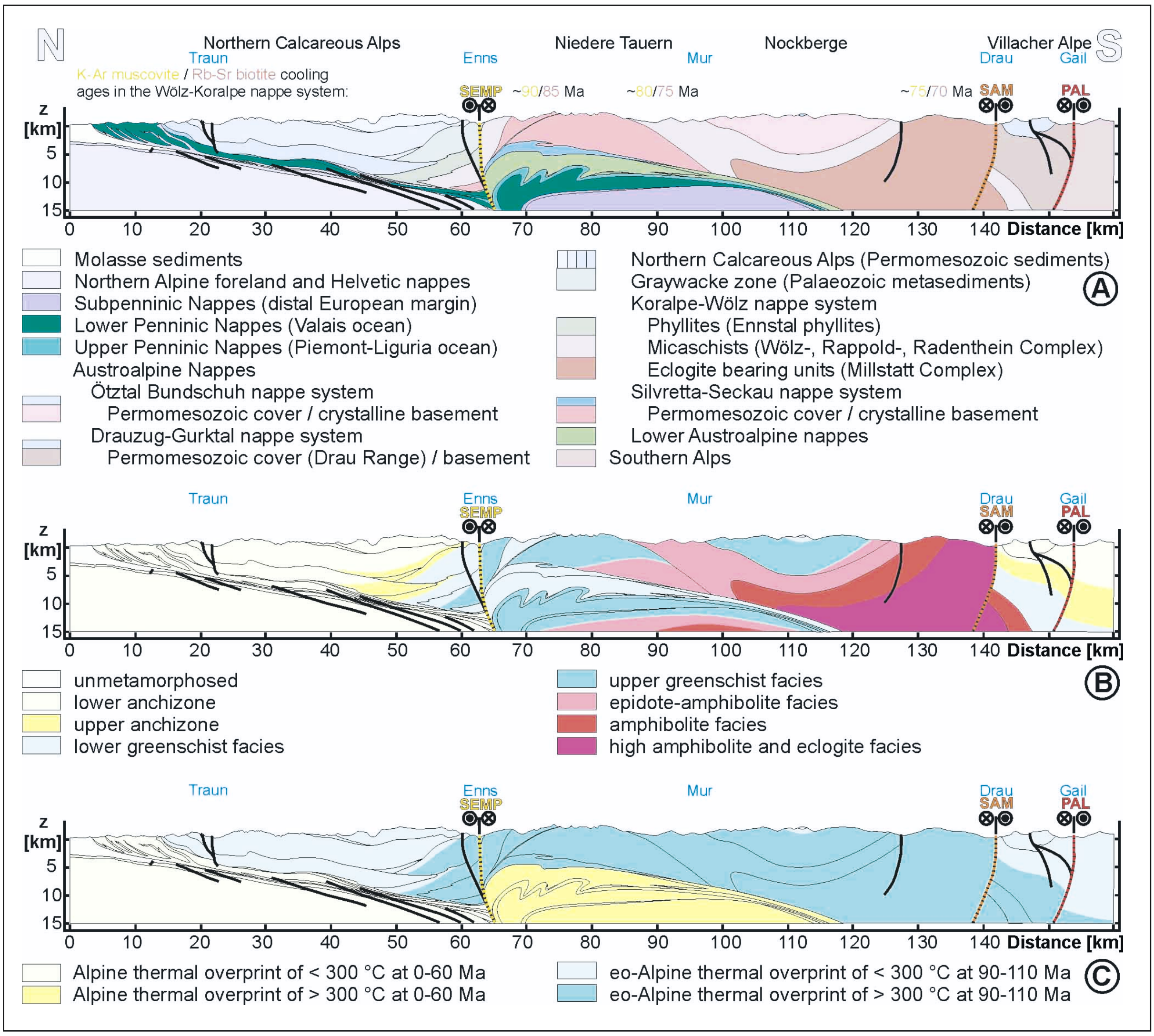

Fig. 4
Schematic transect through the eastern part of the Eastern Alps. The transects show the main tectonic units in (A), the metamorphic grade in (B) and the age distribution of the metamorphic imprint based on HANDY & OBERHÄNSLI (2004) in (C).

In the Noric, Silbersberg and Veitsch nappe of the Greywacke zone lower greenschist facies conditions are proved by illite crystallinity data, the grade of graphitisation and the occurrence of chloritoid. Only for some areas along the border to the Silvretta-Seckau nappe system temperatures of up to 500°C, indicating upper greenschist facies conditions, are reported. For these areas the local appearance of Eo-Alpine garnet is described by RATSCHBACHER & KLIMA (1985). In the Silvretta-Seckau nappe system high anchizonal to upper greenschist facies conditions have been reached along the northern margin. In the west, in the pre-Alpine amphibolite facies metamorphic rocks of the Silvretta Complex Variscan and Permo-Triassic K-Ar and Ar-Ar muscovite cooling ages are still preserved and even the Rb-Sr isotopic system in biotite is not totally reset. For this reason only anchizonal or lowermost greenschist facies conditions have been inferred as maximum conditions. On the other hand, in the Troiseck-Floning Komplex towards the east some biotite ages are totally reset and lower greenschist facies conditions are proved by the growth of Eo-Alpine biotite and chloritoid.

The highest conditions and an internal southward increase of the metamorphic grade are determined for the central part. In the north transgressive Permian metasediments on top of the Seckau Complex are characterised by the assemblage Ms + Ctd + Chl + Qtz, indicating upper greenschist facies conditions (500°C at 0.8 GPa). In this area Variscan Ar-Ar hornblende ages are still preserved. Towards the south epidote-amphibolite facies conditions of 550-600°C at 0.9-1.0 GPa and the total reset of the hornblende ages has been observed (FARYAD & HOINKES, 2001; 2003).
In the northern, tectonically lower part of the Wölz-Koralpe nappe system, the metamorphic grade is increasing upwards. Assemblages of Ms/Pg + Chl + Qtz ± Bt ± Grt ± Ep (Ennstal Phyllites) are typical for the northernmost part. The Wölz Complex above is characterised by prograde assemblages of predominantly micaschist (Grt ± St ± Ky ± Ab + Ms/Pg + Bt + Qtz ± Chl) with intercalations of amphibolites and marbles. An internal gradient is indicated by the distribution of staurolite and the local breakdown of staurolite by the reaction St + Qtz ⇔ Ky + Grt + H_2O. The amphibolites are variable and include massive amphibolites as well as mica-rich hornblende garben-schists (Ca-Amp + Grt + Ms/Pg + Pl + Chl ± Ep ± St ± Ky). Besides pure calcitic marbles also dolomitic marbles with assemblages of Cc + Dol + Qtz + Tr occur. According to FARYAD & HOINKES (2003) the metamorphic conditions in the uppermost parts of the unit reach 600-650°C at 1.0-1.1 GPa. From the same authors similar conditions have been reported for the overlying Rappold Complex. However the prograde breakdown of staurolite is very typical in the latter unit. For the Grobgneiss Complex in the eastern part of the Eastern Alps Eo-Alpine metamorphic upper greenschist facies and epidote amphibolite facies conditions of 550°C at 0.9 GPa have been determined (KOLLER et al., 2004). Somewhat higher conditions of ~560°C at 1.3 GPa were reported for the overlying Strallegg Complex (DRAGANITS, 1998; TÖRÖK 1999).
The central part of the Wölz-Koralpe nappe system is characterised by eclogite-bearing (Grt + Omp + Ca-Amp + Ep/Zoi +Ru + Qtz + Phe) units. Peak conditions for the easternmost Sieggraben Complex are 710°C at 1.5 GPa (NEUBAUER et al., 1999b; PUTIS et al., 2000). Variable results are reported for the Saualpe-Koralpe Complex (600°C at 1.8 GPa. (MILLER, 1990); 685°C at 2.0 GPa (MILLER & THÖNI, 1997); 700°C at 1.8 GPa (STÜWE & POWELL, 1995); 700°C at 1.6 GPa (GREGUREK et al., 1997); 690°C at 1.8 GPa (FARYAD & HOINKES, 2003). These widespread results may be due to the fact that the Saualpe-Koralpe complex consists of several subunits which might have reached different depths during the Eo-Alpine collisional event. Towards the west, conditions of c. 600°C at 1.1 GPa have been determined for the Millstatt and Polinik Complexes (HOINKES et al., 1999) whereas 550°C at 1.2 GPa were measured for the westernmost occurrence in the Texel mountains (HOINKES et al., 1991). All the eclogite-bearing units show a subsequent overprint at (high-)amphibolite facies conditions.
Decreasing metamorphic conditions are characteristic in the upper part of the Wölz-Koralpe nappe system: On top of the Saualpe-Koralpe Complex the metamorphic grade is decreasing from amphibolite facies conditions of 570°C at 1.05 GPa within the garnet-micaschists (Grt + Ky+ St ± Ctd + Ms/Pg + Qtz+ ± Chl) of the Plankogel Complex (GREGUREK et al., 1997) to greenschist facies conditions in the micaschists above. Towards the west investigations yielded 600°C at 1.1 GPa for the Radenthein Complex (KOROKNAI et al., 1999) and 580°C at 1.05 GPa for the Schneeberg Complex (KONZETT & HOINKES, 1996), which are composed of lithologies very similar to those of the Wölz Complex.
In general the P-T-t paths in the lower part of the Wölz-Koralpe nappe system show a pronounced heating after the metamorphic peak, whereas those from the central and upper part are characterised by isothermal decompression.

In the Ötztal-Bundschuh and Gurktal-Drauzug nappe systems the upward decrease in the metamorphic grade is continuing. In the west the metamorphic grade is decresing from epidote-amphibolite facies conditions along the southeastern margin of the Ötztal Complex to anchizonal conditions in the northwest. The same trend is visible in the transgressive Mesozoic cover. The epidote amphibolite facies is indicated by the occurrence of an Eo-Alpine garnet. Towards the north the occurrence of chloritoid defines the area of upper greenschist facies conditions. Further to the north the formation of stilpnomelane and a second generation of phengitic white mica within metagranitoides indicates a LT/HP imprint (< 300°C at c. 0.5 GPa). In the overlying Steinach Nappe high anchizonal conditions can be expected by coalification ranks.
The Bundschuh Complex is very similar to the Ötztal Complex. In its tectonic lowermost part amphibolite facies conditions of 600°C at 1.05 GPa were determined by KOROKNAI et al. (1999), whereas the conditions are decreasing to (lower)-greenschist facies conditions below and in the transgressive Mesozoic cover (SCHUSTER & FRANK, 2000). Assemblages of Ms + Chl ± Grt + Ab + Bt + Ep + Czoi + Cc + Dol suggest upper greenschist facies conditions in the Paleozoic sequences of the overlying Murau nappe. The pre-Alpine medium grade rocks of the Ackerl nappe and the Paleozoic metasediments of the uppermost Stolzalpen nappe show lower greenschist facies and anchizonal conditions. According to the fact that the latter unit experienced a similar metamorphic grade during the Variscan event, the detailed distribution of the Eo-Alpine anchizonal and lower greenschist facies imprint is not known (HOINKES et al., 1999). The late Carboniferous cover sequences of the Stolzalpen nappe show an anchizonal imprint, indicated by pyrophyllite, paragonite/muscovite mixed layer minerals and paragonite (SCHRAMM, 1982).
Within the Austroalpine units to the south of the SAM (HOINKES et al. 1999) (Fig. 1) the metamorphic grade is decreasing upwards. Greenschist facies conditions have been reached only in the northern part of the Goldeck mountains, whereas anchizonal conditions can be expected for the main part of the crystalline basement. This is mostly based on Rb-Sr biotite ages, which yield Eo-Alpine ages in the northern Goldeck mountains (DEUTSCH, 1988) and partial reset or unaffected pre-Alpine ages in the other areas. Based on illite-cristallinity and vitrinite reflection data anchizonal or diagentic conditions occur within the Mesozoic cover sequences of the Drau Range (RANTITSCH, 2001; RANTITSCH & RAINER, 2003)

The observed Eo-alpine metamorphic zoning of the Austroalpine unit can be explained as follows: Based on a number of geochronological data (THÖNI, 1999) the pressure peak occurred at 100 ± 10 Ma. These data include Ar-Ar ages on fine fractions of white mica and whole rocks of low grade metamorphic rocks from tectonically high levels, as well as Sm-Nd garnet isochron ages on high-pressure rocks. Prior to 100 Ma shortening within the Austroalpine realm was compensated by W-NW directed (RATSCHBACHER, 1986) thrusting in the brittle tectonic wedge of the upper part and ductile deformation in the lower part of the crust. The northern part of the Austroalpine nappe stack, including the Northern Calcareous Alps, the Greywacke zone and the northern part of the Silvretta-Seckau nappe system, as well as the southern part of the Austroalpine unit comprising the Ötztal-Bundschuh and Gurktal-Drauzug nappe systems were substantially formed by this event. During the metamorphic peak their principal present day relations within the Austroalpine nappe stack were established. For this reason this units exhibit an upright metamorphic zoning.

After 100 Ma the deeply buried, highly metamorphosed and partly eclogite-bearing nappes of the Wölz-Koralpe nappe system were exhumed. In the area to the east of the Tauern Window their exhumation is due to NW-N directed thrusting (e.g. KROHE, 1987) in the lower part and by SE-directed normal faulting in the upper part of the nappe system. This post-peak metamorphic tectonic caused the inversion of the peak metamorphic grade in the lower part of the Wölz-Koralpe nappe system (Fig. 5). Therefor the Wölz-Koralpe nappe system has been defined as an extruding metamorphic wedge by SCHMID et al. (2004). Towards the west the eclogite-bearing units are outcropping in a back folding structure of the wedge. As only the upper limb of the back fold structure is visible, an upright metamorphic zoning can be observed in the field (Fig. 4).
In general, the metamorphic cooling ages of the Eo-Alpine metamorphic event show an interference of two trends. Firstly, within the nappe piles formed prior to the metamorphic peak the oldest Eo-Alpine cooling ages are younger than the metamorphic peak (< 110 Ma) and decrease downward in the section. The second trend shows younger ages towards the south within the units of the metamorphic wedge (Wölz-Koralpe nappe system). In the northern, lower part of the wedge Ar-Ar muscovite ages and Rb-Sr biotite ages are c. 90 Ma and 85 Ma respectively. In the southern part and also in the back fold structure cooling ages of ~75 Ma (Ar-Ar muscovite) and ~70 Ma (Rb-Sr biotite ages) have been measured (Fig. 4A).

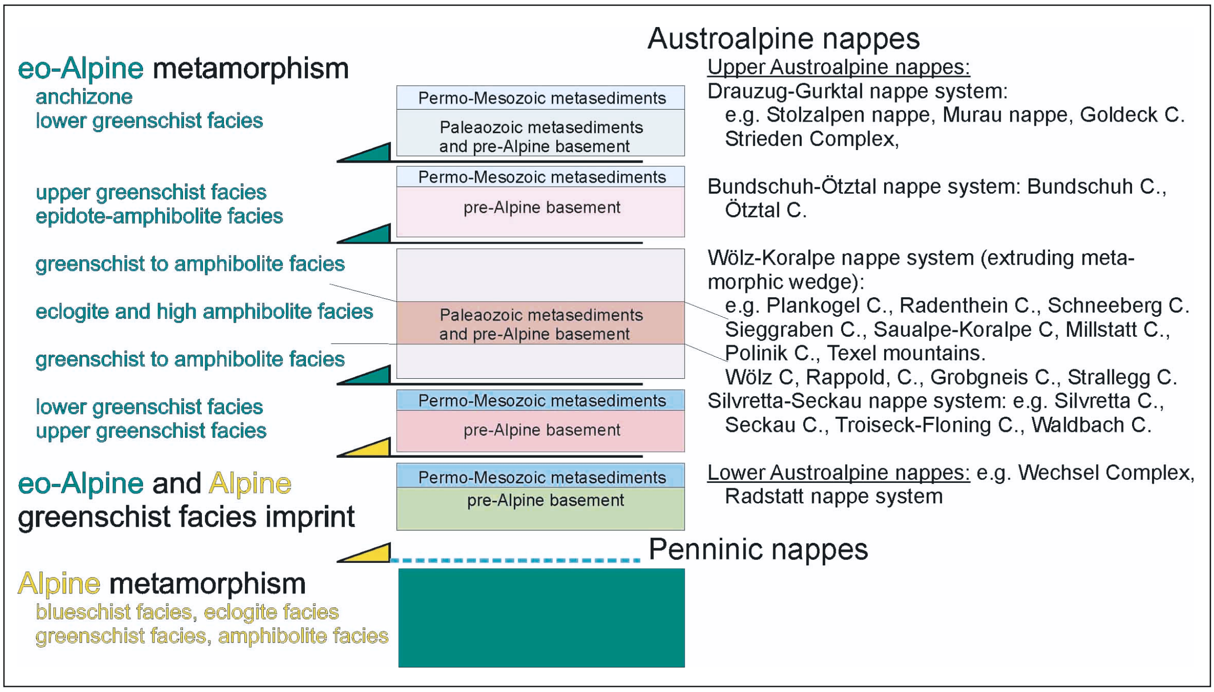

Fig. 5

Schematic nappe stack of the SE part of the Eastern Alps with the metamorphic evolution. Further the posible correlation to individual Austroalpine nappes from the western part of the Eastern Alps are show together with their metamorphic evolution.

2.3.2. The Tertiary Alpine metamorphic event

The Tertiary metamorphism is restricted to the Penninic Zone including the Suppenninic nappes and its immediate neighboring units, i.e. parts of the Lower Austroalpine unit (DINGELDEY et al., 1997, LIU et al., 2001) and the Austroalpine units just southwest of the Tauern Window (BORSI et al., 1978).

The Penninic nappes, widely distributed in the Western and Central Alps, can be followed along a series of windows across the whole range of the Eastern Alps. These are, from the W to the E the Lower Engadin Window (LEW), the Tauern Window (TW) and a group of small windows at the eastern margin of the Alps called the Rechnitz Window Group (RWG) (HÖCK & KOLLER, 1989; KOLLER & HÖCK, 1990). The Rhenodanubian Flyschzone is also ascribed to the Penninic realm (e.g. OBERHAUSER, 1995).
Stratigraphically, the metamorphics in the Penninic zone range form the Late Proterozoic(?) to the Paleogene. Pre-Mesozoic rocks are restricted to the TW and to small fragments at the basement of the Tasna nappe in the LEW (FLORINETH & FROITZHEIM, 1994). Mesozoic rocks, such as Triassic quartzites, marbles and dolomites as well as Jurassic and Cretaceous phyllites, micaschists, calcareous micaschists and other metasediments, ophiolites and non-ophiolitic volcanics occur throughout all Penninic windows. The upper stratigraphic boundary of the Mesozoic to Cenozoic sequences is still under discussion. Late Cretaceous and Paleogene sediments are proven from the LEW (OBERHAUSER, 1995), Early Cretaceous from the TW (REITZ et al., 1990) and the RWG (PAHR, 1980). The occurrence of Late Cretaceous and Tertiary sediments in the more easterly windows is questionable.
The Radstadt nappe system in the northeast of the Tauern Window is built up by slices of pre-Alpine amphibolite facies rocks and Mesozoic cover sequences. An Alpine lower greenschist metamorphic imprint is indicated by prograde assemblages in the Mesozoic rocks and retrogression within the basement.

2.3.2.1 Lower Engadine Window

Situated between the Eastern and Central Alps, the Lower Engadine Window forms an antiform trending NE-SW (KLÄY, 1957). It exposes a stack of Penninic nappes, overlain and framed by Austroalpine nappes. The Lower Engadine Window can be subdivided into several distinct units (CADISCH et al., 1968; TRÜMPY, 1975; OBERHAUSER, 1980); from top to base they are as follows.
The **Arosa zone** is a highly tectonized ophiolite-bearing unit (RING et al., 1990) with an ophiolite sequence mostly of serpentinites, gabbros and basalts (HÖCK & KOLLER, 1987) of the Piemont-Ligurian ocean. It is coverd by a sequence of radiolarian cherts, pelagic limestones, black shales of Hauterivian-Aptian age (WEISSERT & BERNOULLI, 1985) and flysch. The Arosa zone in the eastern part of the Grisons continues southward into the Platta nappe with similar chemical and paleogeographic features (DIETRICH, 1976; FRISCH et al., 1994). It is likely to be correlative with the Matrei zone in the Tauern Window (FRISCH et al., 1987) that was interpreted as part of an imbricated thrust stack formed by the overriding of the Austroalpine units. According to Ring (1992) the Matrei zone can be compared to an accretionary prism.
The metamorphism of the ophiolites is twofold; an older HT oceanic metamorphism can be separated from a younger HP metamorphism. Evidence for the former comes from the replacement of gabbroic clinopyroxenes by amphiboles (pargasite, magnesio hornblende to actinolite) formed at relatively high temperatures. This together with some metasomatic changes of the bulk geochemistry (mainly Na enrichment) and some local strong oxidation argues for this hydrothermal event. Remnants of the E-W striking oceanic high temperature deformation planes in the gabbros show commonly formation of black amphibole in their vicinity indication of H_2O infiltration. The cores of these amphiboles in the altered gabbros contain still high Cl contents up to 4000 ppm.

In the hyaloclastites and pillow breccias the hydrothermal influence of the oceanic metamorphism causes locally ~E-W striking epidote-rich veins. The same event causes locally an intensive oxidation, defined by the dark red color of some hyaloclastite layers.

The Tertiary Alpine metamorphic grade of the Idalp ophiolite sequence belongs to the LT conditions at the transition between greenschist and blueschist facies with 0.7-0.9 GPa at ~350°C. The mineral assemblages are defined by pumpellyite + chlorite + albite. The pumpellyite of the metagabbro is Mg-rich, the green pumpellyite of the diabases with a $Fe_{tot}/(Fe_{tot}+Al)$ range between 0.11-0.15. Prograde replacement to epidote is rare. In the metabasite locally a high phengitic micas with an Si of 3.6 pfu were found.

The **Tasna nappe** is a continuous sedimentary sequence from the Permo-Triassic to the late Cretaceous, locally associated with slices of continental basement (WAIBEL & FRISCH, 1989). The Lias-Cretaceous sequence is composed mainly of turbidites with associated debris flows and pelagic limestones. However, recent studies in the Tasna nappe basement (FLORINETH & FROITZHEIM, 1994) revealed a preserved transition from the continental crust of the Briançonnais terrane to the oceanic crust of the Valais ocean. The metamorphic conditions belong to the lower greenschist facies.

The **Ramosch Zone** represents the transition between a continental unit (Briançonnais) and an oceanic (Valais) unit (FLORINETH & FROITZHEIM, 1994). The main unit is of a serpentinized peridotite-body associated with ophicarbonates and serpentinite breccias (VUICHARD, 1984). Metagabbros are lenticular within and adjacent to the serpentinite body. Directly underlying the serpentinite along an Alpine, top-north directed thrust fault, pillow basalts represent a part of the Valais ocean (FROITZHEIM et al., 1996). Further a huge mass of Bündnerschiefer, forming the deepest units of the Lower Engadine Window, with up to 10 km of calcschists interbedded with shales and quartzites (HITZ, 1995). It grades upward into flysch deposits that are lithologically very similar to the Bündnerschiefer and are dated as Late Cretaceous to Eocene (ZIEGLER, 1956). Some mafic bodies are intercalated within the schists particularly in the core of the window. These bodies are mainly composed of pillow basalts and hyaloclastites associated with metaradiolarites, where geochemical criteria suggest an oceanic basement (DÜRR et al., 1993). This unit is the remnant of the northern Penninic ocean, the Valais basin (FRISCH, 1976; TRÜMPY, 1980; STAMPFLI, 1993).

In Bündnerschiefer and associated metabasites of the LEW two units displaying distinct metamorphic have been reported by BOUSQUET et al. (1998, 2002). The structurally lower unit (Mundin unit) has a clear HP-LT history, whereas in the upper unit (Arina unit) no obvious HP-LT mineral assemblages were found.

In the Mundin unit blueschist metamorphic conditions are exclusively found in the central part of the window forming the core of a late anticline. These conditions are characterized by the occurrences of (Fe,Mg)-carpholite in metasediments (GOFFÉ & OBERHÄNSLI, 1992; OBERHÄNSLI et al., 1995). In the core of the Mundin unit antiform, carpholite appears as relicts. For the Mundin unit, P-T estimates range between 1.1-1.3 GPa for a temperature around 350-375°C (BOUSQUET et al., 2002). Indication of the LT-HP metamorphic assemblages in the metabasites are rare and occur mainly in samples which unterwent prior an oceanic metamorphism. Glaucophane (BOUSQUET et al., 1998) and Na-pyroxene were found in metabasites. The Na-pyroxene assemblages are partly replaced by riebeckite or Mg-riebeckite. Also aragonite was found as a relict in the Na-pyroxene bearing assemblages, partly or strongly replaced by calcite.

In the Arina unit, evidence for HP metamorphism is scarce. However, crossite and lawsonite occur in metabasites (LEIMSER & PURTSCHELLER, 1980), and Mg-pumpellyite in association with chlorite, albite, and phengite occur in metapelites. The P-T conditions calculated by BOUSQUET et al. (1998) range around 0.6 GPa, 300°C.

2.3.2.2. Tauern Window

The oldest rocks in the TW are found in a volcano-sedimentary sequence comprising ophiolites, island arc volcanics and associated sediments of Late Proterozoic to Paleozic age (Habach Group). A part of this sequence underwent pre-Mesozoic metamorphism, partly migmatisation and was intruded by Variscan granitoids. According to the tectonic classification of SCHMID et al. (2004) the Paleozoic sequences belong to the Subpenninic nappes.

The post-Variscan sequences start with Permo-Triassic quartzites, middle Triassic limestones and dolomites and upper Triassic sandstones and shales. The Triassic rocks are overlain by shales, marls and shaly limestones of Jurassic to Early Cretaceous age (Bündnerschiefer Group). Locally, sandstones, breccias and arcoses occur. Associated with the sediments are ophiolites and other basic intrusions and volcanics. The youngest sediments proven so far are of Early Cretaceous age. Comparison with lithologically similar sediments in the LEW and the Penninic realm in the Western Alps suggests the occurrence of younger sediments.

Tectonically two nappes are generally delineated (FRISCH, 1976): the lower Venediger nappe (Subpenninic nappes according to SCHMID et al. (2004)) comprising most of the pre-Mesozoic rocks and relatively little Mesozoic sediments and volcanics and the higher Glockner nappe (Lower Penninic nappes according to SCHMID et al. (2004) including most of the Triassic rocks, the Bündnerschiefer and the ophiolites. Both nappes were later folded forming a huge anticline with an axis following approximately the main ridge of the Alps. Apart from the pre-Mesozoic metamorphism three episodes of metamorphic events were recognized: an eclogite event, a blueschist metamorphism, and the final greenschist to amphibolite facies metamorphism. The eclogitisation affects only a relatively small strip mainly at the southern escarpment of the TW, the blueschist metamorphism is more widely distributed but restricted to the ophiolites, their immediate cover and the areas tectonically below. The Tertiary greenschist to amphibolite facies metamorphism can be seen in all rocks of the TW.

Two metamorphic events are recognizable in all Penninic windows where the older is regarded as a HP/LT metamorphism and the younger as Barrovian type. Only in the TW an earlier eclogite metamorphism is recorded with a retrograde evolution path, entirely different from the rest of the Penninic metamorphics of the Eastern Alps.

The most conspicuous eclogite assemblages are found in metabasic rocks but some original basalt - sediment interfaces are still preserved. Consequently some metasediments exhibit high-pressure mineral assemblages (FRANK et al., 1987b; FRANZ & SPEAR, 1983). Inclusions in the eclogitic mineral assemblage in the metabasites indicate a greenschist to amphibolite facies event prior to the eclogitisation (MILLER, 1977; DACHS, 1986; DACHS et al., 1991).

The P-T conditions of the formation of eclogite are fairly well established within the analytical error and the errors of the different geobarometers used. The eclogitized metabasics and metasediments passed through a mantle/crust segment in a depth of 70 km (possibly 85 km according to STÖCKHERT et al., 1997). With T_{max} around 600- 630°C and P ~1.9-2.2 GPa (HOSCHEK, 2001) they formed at a very low geothermal gradient of 7-9°C/km, typical for subduction zones.

It should be noted here that only the structurally lowest part of the Mesozoic sediments and volcanics below the ophiolites underwent the eclogite metamorphism.
Whereas the P-T conditions are well constraint no dating of the eclogites is available yet. If the Ar-Ar age data of ZIMMERMANN et al. (1994) are valid for the blueschist event, the eclogites formed prior to the Eocene/Oligocene boundary. ZIMMERMANN et al. (1994) estimate the age of mica formation related to the eclogites between 40 and 50 Ma.
By contrast to the eclogite assemblages, which are well preserved, the minerals formed during the blueschist event survived only rarely. They can be traced by some individual mineral relicts and by pseudomorphs. The most conspicuous relics from this stage are pseudomorphs after lawsonite. Some jadeite poor omphacites coexisting with albite rich plagicolase derived from the decompositon of a more jadeite rich omphacite also represents the blueschist facies. Occasionally blue amphiboles such as glaucophane and/or crossite are preserved and probably barroisitic amphiboles. Associated with this stage and possibly also with the eclogite event are high Si phengite with Si = 3.30-3.40 pfu. In extreme cases the Si content may reach 3.65 pfu (ZIMMERMANN et al., 1994). From that data FRANK et al. (1987a) estimated the conditions of blueschist formation as T = 400-450°C and P around 0.9 GPa. ZIMMERMANN et al. (1994) calculated 1.0 GPa at 400°C. The blueschist event is neither well constraint in respect to the P–T path, nor in respect to age dating. The data by ZIMMERMANN et al. (1994) suggest for the TW an age of late Eocene - early Oligocene for the formation of the blueschist assemblages. Again the low thermal gradient of 10-13°C/km suggests a subduction related environment.
At the southern rim of the TW the zone of Matrei (Upper Penninic nappes according to SCHMID et al., 2004) consists of various lithologies including serpentinites and metabasites. Below the serpentinites thin horizons of blueschist assemblages in basaltic to ophicarbonate lithologies were found recently in several localities (KOLLER & PESTAL, 2003). This assemblage contains blue amphiboles or an older alkali pyroxene (up to 20% Jd), and stilpnomelane together with albite. In some cases a replacement to bluisch-green amphiboles is common.

2.3.2.3. Rechnitz Window Group

At the eastern end of the Alps close to the Austrian-Hungarian border several small Penninic windows occur below the Lower Austroalpine nappes. All these windows comprise huge masses of Mesozoic metasediments and locally some ophiolites. The lithology consists of a several km thick sequence of metasediments with calcareous micaschists, quartz-phyllites, graphite phyllites, rare breccias and few horizons of rauhwackes. Within the ophiolitic section remnants of oceanic metamorphism occur together with various degrees of oxidation. This event can be traced in most of the metagabbros and ophicarbonates, as well as in some metabasalts (KOLLER, 1985).

Blueschist facies event

Within the ophiolitic sequence remnants of a HP/LT event are widespread. Typical minerals are alkali pyroxenes, glaucophane or crossit, rare pseudomorphs of lawsonite, high-Si phengite, Mg-rich pumpellyite, stilpnomelane, hematite and rutile. At high Fe^{3+} contents in metabasites alkali pyroxene+hematite and rutile occur. No clear high pressure assemblage can be defined for the metabasalts containing only rare relics of blue amphibole, stilnomelane and pseudomorphs after lawsonite. High-Si phengite is also observable in metabasaltes and common in metasediments. For the blueschist facies event KOLLER (1985) calculated temperatures of 330-370°C at a minimum pressure of 0.6-0.8 GPa.

Low-pressure greenschist event

The high-pressure event is followed by a common greenschist overprint forming the general assemblages (metabasalts, metasedimentes). From the north to the south, there is a slight increase in temperature observable, which can be defined by following mineral isogrades: (1) Disappearance of metastable stilpnomelane and Mg-pumpelleyite in the northern part of the Rechnitz Window, (2) first appearance of green biotite in the northern part of the Bernstein Window, and (3) the first appearance of garnet in metapelites is restricted to the southernmost outcrops of the Penninic units.

No reliable age dating exists from the high pressure event. The greenschist event is dated by K-Ar ages of muscovite in the range of 22-19 Ma (FRANK in KOLLER, 1985). Fission-track ages were reported by DUNKL & DEMÉNY (1997) for zircon from 21.9-13.4 Ma and for apatite from 7.3-9.7 Ma. Furthermore the Penninic rocks of the RWG are overlain by non-metamorphosed sediments of Miocene and Pliocene age (PAHR, 1980).

2.3.2.4. Lower Austroalpine

2.3.2.4.1. Radstadt nappe system

The Lower Austroalpine nappes of the "Radstädter Tauern" form the NE rim of the Tauern Window (TOLLMANN, 1977; HÄUSLER, 1987). They contain the tectonically highest quartzphyllite nappes with an inverse layering and different Permo-Mesozoic sequences, as the Hochfeind, Lantschfeld, Pleisling and Kesselspitz nappes. Well defined modern P-T path investigations on the Alpidic metamorphic evolution are still missing.

In the basement the Alpidic metamorphic event defines a retrograde evolution. The first geochronological results obtained by SLAPANSKY & FRANK (1987) on white micas (K-Ar and Ar-Ar ages) revealed a decreasing age from the uppermost nappe (~100 Ma) to the base (~50 Ma). More recent studies by LIU et al. (2001) confirm the general trend, giving Cretaceous ages in the upper Radstadt nappes and Paleogene age in the lower Hochfeind nappe. Similar ages were obtained by DINGELDEY et al. (1997) from the Reckner nappe.

The metamorphic evolution of the Permo-Mesozoic sediment sequences can be defined by the assemblage of phengite + chlorite and without forming biotite. Only locally also chloritoid and kyanite were mentioned by VOLL (1977). Temperatures of 450°C and pressures of at least 0.3 GPa have been assumed by SLAPANSKY & FRANK (1987). In general there is an increase of metamorphic conditions towards to the south.

2.3.2.4.2. Tarntal Nappes

The Lower Austroalpine Nappes cover the Penninic rocks of the TW also at the NW (Tarntal mountains). According to TOLLMANN (1977) the tectonic succession consists in the NW of the Tauern Window of three individual nappes. From the base to the top they are the Innsbruck quartzphyllite nappe, the Hippold nappe and the Reckner nappe.

The Innsbruck quartzphyllite nappe consists of various phyllites with rare diabases and quartz-porphyries, further carbonate (calcite, dolomite and magnesite) lenses. The top of this sequence is formed by Permo-Triassic sediments. By contrast, the Hippold and Reckner nappe are built up by a huge variety of partly fossil bearing Mesozoic sediment sequences ranging from Skyth to Malm ages (ENZENBERG, 1967; ENZENBERG-PRAEHAUSER, 1976). The top of the Reckner nappe is formed by the serpentinites and blueschists of the Reckner complex (DINGELDEY et al., 1997).

For both, the Reckner and the Hippold nappe a Tertiary HP/LT event in the range of ~350°C and ~1.0 GPa has been reported by DINGELDEY et al. (1997). Typical minerals of this event are alkalipyroxenes, Mg-rich pumpellyite, stilpnomelane and high Si phengite. The Penninic meta-sediments adjoining the Hippold nappe exhibit only intermediate pressure conditions (0.6-0.7 GPa).
This high pressure event was followed by a classical greenschist paragenesis with blue amphiboles replacing the alkalipyroxenes, low-Si muscovites, epidote, green biotite instead of stilpnomelane. Only a LP/LT event was found in the underlying Innsbruck Quartzphyllite nappe (~400 °C and < 0.4 GPa).
Ar-Ar-measurements on high-Si phengites from the Reckner nappe recorded ages around 50 Ma. In the underlying Hippold nappe and in the adjoining Penninic "Bünderschiefer" the high-Si phengites define ages between 44-37 Ma (DINGELDEY et al., 1997). Only rejuvenisation of Variscan micas and no clear Alpidic $^{40}Ar/^{39}Ar$ plateau ages were found in the Innsbruck Quartz-phyllite nappe.

2.3.2.4. Correlation of the Penninic Windows of the Eastern Alps
The subsequent greenschist to amphibolite facies event has its lowest Tmax with 350°C in the LEW. In the RWG a T_{max} of 450°C is recorded and in the TW between 500-550°C. T_{max} is combined with a pressure of 0.2-0.4 GPa in the LEW, 0.3-0.4 GPa in the RWG and 0.6-0.8 GPa, locally reaching up to 1.0 GPa in the TW approaching a geothermal gradient of 20-35°C/km, typical for a Barrovian type metamorphism. It is coeval with the total disappearance of the Penninic zone beneath the Austro-Alpine nappes. This metamorphic stage was reached shortly after 30 Ma and is further recorded by cooling ages down to 16 Ma. Similar cooling ages are reported from the RGW, the scarce data from the LEW record probably the onset of the low grade metamorphism. The cooling and exhumation in the TW and RWG can be followed through fission track studies of apatites down to 4 and 7 Ma respectively (FÜGENSCHUH et al., 1998).

3. Conclusions

The distribution of the metamorphic facies zones in the Eastern Alps is mainly controlled by the northwards transport of the Austroalpine nappes. They show a Cretaceous metamorphism and are thrusted over the Penninic domains with Tertiary metamorphism (Fig. 4). The latter are exposed in the Eastern Alps only as tectonic windows.

The ***Eo-Alpine (Cretaceous) metamorphic event*** is widespread within and restricted to the Austroalpine unit. It is related to the continental collision following the closure of an embayment of the Tethys ocean during late Jurassic to Cretaceous times. Recent investigations indicate that the northern part of the Austroalpine unit forms the tectonic lower plate. The southern parts and the north-eastern margin of the Southalpine unit acted as the tectonic upper plate during the continental collision following the disappearance of the oceanic embayment (SCHMID et al., 2004). In the Austroalpine nappes the Eo-Alpine metamorphic event overprints Variscan and/or Permo-Triassic metamorphic rocks as well as Permo-Mesozoic sedimentary sequences. The peak of the Eo-Alpine metamorphic event was reached at about 100 Ma, the youngest cooling ages are recorded at 65 Ma (THÖNI, 1999).

The metamorphic conditions reached sub-greenschist and greenschist facies in the northern part of the Austroalpine. To the south, in the Wölz-Koralpe nappe system the conditions increase upwards up to eclogite facies in the middle part of the nappe system (Fig. 5). In its upper part of the Wölz-Koralpe nappe system and in the overlying units the metamorphic degree is decreasing again until sub-greenschist facies. This zoning indicates a transported metamorphism at least in the Wölz-Koralpe nappe system.

The ***Tertiary Alpine metamorphic event*** is due to the closure of the Jurassic to early Tertiary Briançonnais and Valais oceans (Alpine Tethys). According to WAGREICH (2001) the re-arrangement of the Penninic-Austroalpine border zone from a passive to an active continental margin starts at about 120 Ma. From that time on the oceanic lithosphere and slices from the northern margin of the Austroalpine unit (Lower Austroalpine units) were subducted towards the south below (Upper) Austroalpine units. The Tertiary event reaches blueschist facies conditions in some Mesozoic parts of Penninic windows and some units of the Lower Austro-alpine (Tarntal nappe). Eclogite facies conditions followed by a blueschist event occur only in a narrow zone of the Tauern Window. The thermal peak ranges from greenschist to amphibolite facies, the latter was only reached in the central part of the Tauern Window. After the thermal peak at about 30 Ma (BLANKENBURG et al., 1989) uplift and cooling is recorded by K-Ar and Ar-Ar ages on white micas and fission track ages on zircon and apatite (LUKSCHEITER & MORTEANI, 1980; GRUNDMANN, & MORTEANI, (1985); FÜGENSCHUH et al., 1998). In the lower nappes of the Lower Austroalpine units the Tertiary Alpine metamorphism over-prints the Cretaceous metamorphic event.

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