Introduction to the Geology of the Eastern Alps

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1 Introduction

The Alpine orogen formed during the convergence of the African and European plates, which was a more or less continuous evolution since Cretaceous times. The geology of the Alpine –Mediterranean area is complex, however, because of the existence of more than one oceanic realm and several plates between Africa and Europe, as well as the interplay between shortening processes and lateral movements. This makes it difficult to determine the plate tectonic arrangement through time (HANDY et al., 2010). Models of Alpine tectonics have developed rapidly during recent decades, mainly as a result of modern structural, stratigraphic, petrological and geochronological investigations which, together with deep reflection seismic profiling and tomographic studies, have provided new insights into the present-day structures. Contrasting interpretations on the evolution of the Alpine orogen still remain, however, further complicated by the use of different nomenclatures.

This summary of the geology of the Alps is based on the tectonic interpretation by SCHMID et al. (2004) and on the review of Alpine metamorphic history by OBERHÄNSLI (2004) together with the literature cited therein.

In a geographical sense the Alps are divided into the Southern Alps (to the south of the Periadriatic lineament), the Eastern Alps, the Central Alps, and the arc of the Western Alps (Fig. 1). These subdivisions are each dominated by different paleogeographic elements that were incorporated at different stages in the Alpine tectonic evolution, resulting in distinct geological structures and a specific geomorphology.

In the following an overview on the plate tectonic and tectonic units of the Alps and an introduction in the different metamorphic cycles is given.

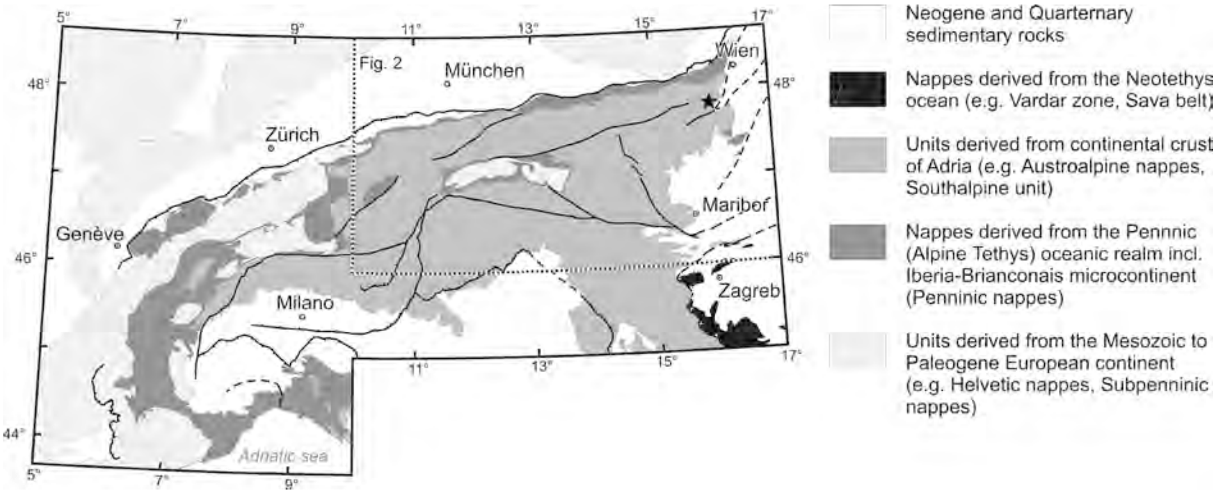

Figure 1: Map of the major paleogeographic and tectonic units in the Alps according to SCHMID et al. (2004).

2 Plate tectonics

The Alpine orogen is subdivided into plate tectonic units reflecting the Mesozoic to Paleogene paleogeography. From north to south, respectively from bottom to the top the Eastern Alps are formed by the following paleogeographic elements (Figs. 1, 2):

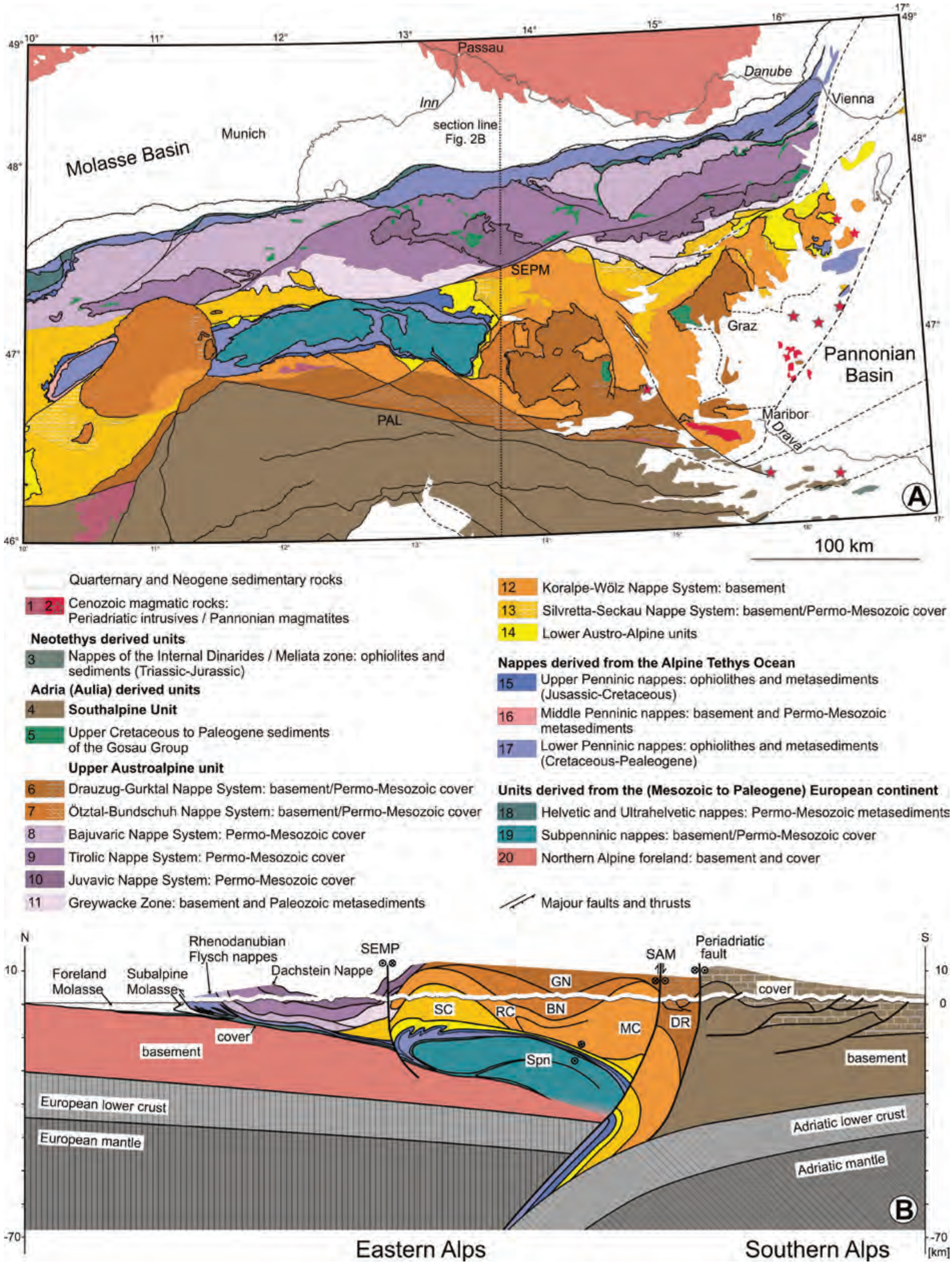

Figure 2: (A) Tectonic map of the Eastern Alps according to the nomenclature in SCHMID et al. (2004). The numbers of the units refer to the text. (B) Section through the Easter Alps according to SCHMID et al. (2004). GN…Gurktal nappe, DR…Drau Range, BN…Bundschuh nappe, RC…Radentherin Complex, MC…Millstatt Complex, SC…Schladming Complex, SEMP…Salzach-Ennstal-Mariazell-Puchberg fault, SAM…Southern border of Alpine Metamorphism (according to HOINKES et al., 1999), PAL…Periadriatic lineament.

The Mesozoic to Paleogene European continent is represented by the Helvetic, Ultrahelvetic and Subpenninic nappes. Relics of the former Penninic Ocean (Piedmont-Ligurian and Valais Ocean) are the overlaying Lower and Upper Penninic nappes which form the Rhenodanubian Flysch belt and the Penninic nappes of the Engadin, Tauern and Rechnitz Window. The Middle Penninic nappes present in the Engadine Window are the remnant of the Iberian-Brianconnais microcontinent. In the western part of the Alps this microcontinent separated the Penninic Ocean into the Piedmont-Ligurian and Valais oceanic basin. Above the Austroalpine and separated by the Periadriatic lineament (PAL) the Southalpine unit is situated. Both derived from the continental crust of the Adriatic plate. Remnants of the Neotethys oceanic realm (Meliata, Hallstatt, Vardar Ocean) occur in a few outcrops in the easternmost part of the Eastern Alps (MANDL & ONDREJICKOVA, 1993).

The Penninic oceans opened in Jurassic and Early Cretaceous times and were closed during the Alpine – Late Cretaceous to Paleogene – collisional event. Europe acted as the lower and the Adriatic plate as the tectonic upper plate. The Penninic oceanic suture zone can be traced all along the mountain belt. The eo-Alpine event is due to an intracontinental subduction zone within the recent Austroalpine unit (STÜWE & SCHUSTER, 2010). The subduction started in the Early Cretaceous (Valanginian; ca. 135 Ma), whereas maximum burial depth and peak metamorphic conditions were reached in the early Late Cretaceous (Turonian; ca. 92 Ma, THÖNI, 2006). During this event parts of the Austroalpine unit were in a lower plate position, whereas other parts were in an upper plate position.

The Neotethys Ocean formed an embayment into the Adriatic plate. Oceanic crust was formed during the westward propagation of the ocean in Triassic (Meliata), Jurassic (Vardar Ocean) and also in Cretaceous times (USTASZEWSKI et al., 2009). However, intraoceanic subduction processes and the emplacement of ophiolite nappes onto the Adriatic margin are documented since the Middle Jurassic. These nappes are widespread in the Dinarides but it seems that outlayers of these nappes were also present in the eastern part of the Eastrern Alps. Today all these outlayers are completely eroded, but redeposited material is present in the Upper Cretaceous sediments of the Gosau Group (SCHUSTER et al., 2007).

3 Description of the tectonic units of the Eastern Alps

This description of the tectonic units of the EasternAlps is based on the map and sections published by SCHMID et al. (2004). From bottom to top (from N to S, or NW to SE, respectively) the Alps are built up by the following tectonic units (Figs. 2, 3)

3.1 Units derived from the (Mesozoic to Paleogene) European continent

The European continent consists of a deeply eroded Variscan (Late Devonian to Carboniferous) metamorphic continental crust, rich in plutonic rocks (north of the Alpine front), covered by Carboniferous to Eocene sedimentary sequences (20). This crust is still in contact with its lithospheric mantle; it dips beneath the Alps and contains the Late Eocene to Neogene Molasse basin which is the northern peripheral foreland basin of the orogen. The External massifs represent windows in the European plate within the Western and Central Alps. They comprise basement rocks and Late Carboniferous to Cretaceous cover sequences. The Helvetic and Ultrahelvetic nappes (18) are a thin-skinned fold and thrust belt formed exclusively of detached cover sequences. At the northern margin of the Central Alps they cover wide areas, whereas in the Eastern Alps they are present only as thin slices. The Subpenninic nappes (19) represent the distal European margin, forming ductilely deformed basement and cover nappes which lost contact with their lithospheric mantle and served as the basement for the Helvetic nappes. They form the Gotthard, Travetsch and Adula nappes in the Central Alps and also, contrary to many earlier publications, the Venediger and Modereck nappe system in the Tauern Window of the Eastern Alps. This interpretation is based on the conclusion that the crustal material of the Venediger nappe system was not separated from the European margin by an oceanic basin (e.g. FROITZHEIM et al., 1996;

KURZ et al., 2001). The eclogitic Subpenninic basement units (Adula nappe, Cima Lunga nappe and Eclogite Zone in the Tauern Window) contain material derived from the Penninic ocean and developed in a subduction and accretion channel (ENGI et al., 2001; KURZ & FROITZHEIM, 2002).

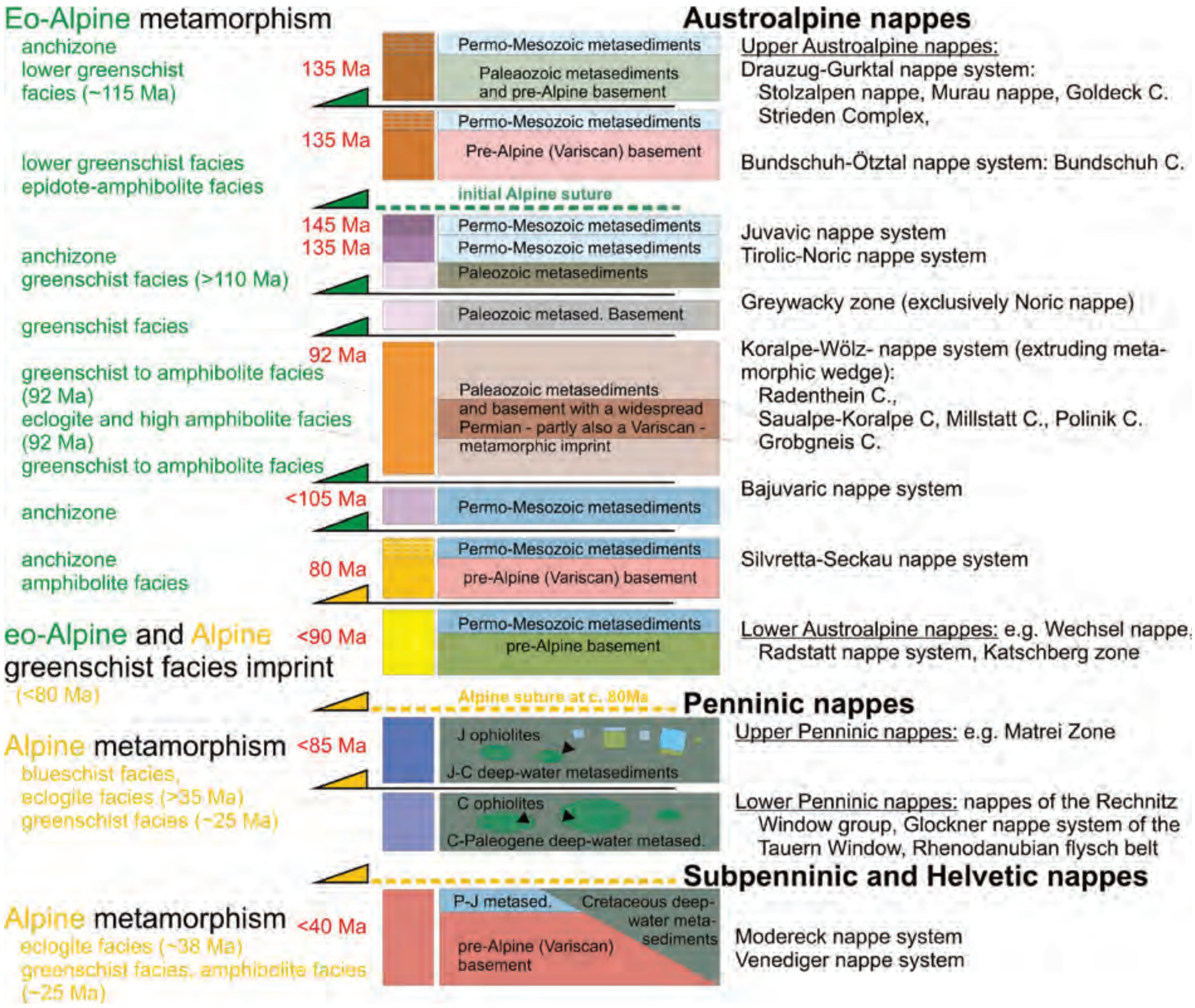

Figure 3: Block diagram showing the majour tectonic units of the Eastern Alps. In the left coloum the metamorphic grade during the eo-Alpine (Cretaceous) and Alpine (Cenozoic) events and the time of peak metamorphism is given. The red numbers indicate the time of incooperation into the Alpine orogenic wedge.

3.2 Penninic nappes

The Penninic nappes comprise three paleogeographic elements: the Piedmont-Ligurian ocean, the Brianconnais microcontinent and the Valais ocean.

The Piedmont-Ligurian ocean opened in Late Jurassic times. Its initial sea-floor formed by exhumation of the subcontinental mantle of the Adriatic plate (FROITZHEIM & MANATSCHAL, 1996). These mantle rocks are overlain by Jurassic radiolarites, aptychus limestones and Cretaceous calcareous turbiditic metasediments. The Brianconnais microcontinent was a part of the European distal margin until it was cut off by the opening of the Valais ocean in Cretaceous times. The Valais oceanic crust comprises Cretaceous ophiolites overlain by Cretaceous to Eocene calcareous turbiditic metasediments. Towards the east the Valais ocean merged into the Piedmont-Ligurian ocean, thus forming a single oceanic basin in the east (e.g. STAMPFLI, 1994; FROITZHEIM et al., 1996). Although this situation in the east makes any subdivision of the Piedmont-Ligurian from the Valais basin there somewhat artificial (KURZ et al., 2001), characteristic successions, analyses of the source areas of the clastic sedimentary successions and the age and chemical characteristics of the ophiolitic rocks allow the differentiation of elements from the northern or southern part of this joint oceanic basin.

The Penninic nappes can be subdivided into the Upper, Middle and Lower Penninic nappes, whereby each consists mainly of one of the paleogeographic elements mentioned above.

The Lower Penninic nappes (17) consist predominantly of material from the Valais oceanic province and from the northern parts of the joint oceanic basin in the east. The Lower Penninic nappes make up large parts of the Central Alps and the central part of the Lower Engadine Window. The lower nappes of the Rhenodanubian flysch zone, which are present along the northern margin of the Eastern Alps, represent a continuation of the Central Alpine Valais basin sediments into the Eastern Alps (KURZ et al., 1998); they comprise Cretaceous flyschoid sediments deposited in a basin along the European margin. The Glockner nappe system of the Tauern Window, as well as the nappes of the Rechnitz Window Group, consisting of calcareous flyschoid metasediments and metaophiolites, is thought to be a southern continuation of the lower nappes of the Rhenodanubian flysch zone.

The Middle Penninic nappes (16) are mainly derived from the Brianconnais microcontinent and are common in the Western and Central Alps. The easternmost nappes include material from the Brianconnais microcontinent and are represented by the Tasna nappe of the Lower Engadine Window.

Rocks derived from the Piedmont-Ligurian ocean and the accretionary wedge along the southern margin of the oceanic basin towards the Adriatic microcontinent make up the Upper Penninic nappes (15). They are widespread in the Western and Central Alps. In the Eastern Alps the Upper Penninic nappes form the uppermost tectonic elements in the Engadine and Tauern windows (e.g. the Arosa Zone, the Matrei Zone, and the Reckner Complex). In the northern part of the Eastern Alps the Ybbsitz klippen belt (DECKER, 1990) is a remnant of the Piedmont-Ligurian ocean, containing the typical sequence of serpentinites, Jurassic radiolarites and aptychus limestones. It is in contact with the Kahlenberg nappe of the Rhenodanubian flysch zone, which is also interpreted to be an Upper Penninic nappe (FAUPL & WAGREICH, 1992).

3.3 Adriatic microcontinent

The Adriatic microcontinent consists of a Cadomian continental crust (NEUBAUER, 2002) with Paleozoic metasedimentary sequences and with magmatic rocks related to rifting and subduction processes lasting until the Carboniferous. During the Variscan orogeny large parts of this crust were affected by metamorphic overprints and synorogenic magmatism. Post-orogenic Permian to Carboniferous sediments were deposited locally. In the Permian these units were affected by lithospheric extension expressed by basaltic magmatic underplating, intense acidic magmatism and related high-temperature / low-pressure (HP/LT) metamorphism. More than 3 km of Permo-Mesozoic sediments were subsequently deposited on top of the thermally subsiding microcontinent, which formed a broad carbonate shelf towards the Meliata ocean in the southeast and, from the Jurassic onwards, was bordered to the north by a passive continental margin facing towards the Piedmont-Ligurian ocean. In the Eastern Alps the Adriatic microcontinent is represented by the Austroalpine and Southalpine units, being separated by the Periadriatic lineament.

The Austroalpine unit forms a complex nappe stack of crustal material which can be subdivided into Lower and Upper Austroalpine units. The Lower Austroalpine unit (14) formed the continental margin towards the Piedmont-Ligurian ocean and was affected by extension and nappe stacking during the opening and closing of this oceanic realm, respectively. It overlies the Penninic nappes of the Eastern Alps. The Upper Austroalpine unit represents an eo-Alpine nappe pile. Its lowermost unit is the Silvretta-Seckau nappe system (13) consisting of a basement with a dominating Variscan metamorphic imprint and remnants of Permian to Triassic cover sequences. During the eo-Alpine event it was overprinted by sub-greenschist to amphibolite facies conditions.

To the north the Silvretta-Seckau nappe system is overlain by the nappes of the Greywacke zone (11), which consists of greenschist facies metamorphic Paleozoic sequences, and the Juvavic (8), Tirolic (9) and Bajuvaric (10) nappe systems. The latter form the Northern Calcareous Alps, comprising unmetamorphosed to lowermost greenschist facies metamorphic Permian to Mesozoic sediments deposited on the shelf facing originally towards the Neotethys ocean, with the sequences of the Juvavic nappe system representing the most distal shelf towards the oceanic basin.

To the south the Silvretta-Seckau nappe system is overlain by the Koralpe-Wölz nappe system (12) which represents an eo-Alpine metamorphic extrusion wedge. Its Permian to Mesozoic cover was completely stripped off during an early phase of the eo-Alpine orogenic event (Lower Cretaceous) and it therefore consists exclusively of polymetamorphic basement nappes with a Permian to Triassic HT/LP and an eo-Alpine LT/HP metamorphic overprint (SCHUSTER et al., 2004).

The Ötztal-Bundschuh nappe system (7) shows a similar lithological composition as the Silvretta-Seckau nappe system, but is positioned on top of the Koralpe-Wölz nappe system. The overlying Drauzug-Gurktal nappe system (6) is made up of a Variscan metamorphic basement, anchizonal to greenschist facies Paleozoic metasedimentary sequences and by unmetamorphosed Permian to Triassic sediments (RANTITSCH & RUSSEGGER, 2000). Within the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems the eo-Alpine metamorphic grade decreases upwards from amphibolite facies at the base to diagenetic conditions at the top of the nappe pile.

The Upper Cretaceous to Paleogene sediments of the Gosau Group (5) represent syn- to postorogenic sediments with respect to the eo-Alpine orogenic event (FAUPL & WAGREICH, 2000).

The Southalpine unit (4) shows minor deformation localized along its margins. Its major part is in contact with a subcontinental lithosphere; this contact is visible at the surface in the Ivrea Zone in the Western Alps. The Southalpine unit is considered to be a southern external retro-arc orogenic wedge within the Alpine orogenic system (e.g. SCHMID et al., 1996). In the southeast the Southalpine unit continues into the External Dinarides.

3.4 Meliata unit

The Meliata unit (3) of the Eastern Alps contains remnants of the Neotethys (Meliata) oceanic basin. These include serpentinites, basic volcanic rocks and deep water Triassic sediments, redeposited in Jurassic metasediments. These rocks can be correlated with those from the Meliata zone in the Western Carpathians (MANDL, 2000). The Meliata zone occurs as tiny klippen within the eastern part of the Eastern Alps between the Tirolic and Juvavic nappe systems of the Austroalpine unit. They show a sub greenschist facies metamorphic imprint but no indications of subduction-related HP/LT metamorphism. Material from the Meliata oceanic basin is also present as detritus in Cretaceous sediments of Austroalpine units (FAUPL & WAGREICH, 2000) and in the Haselgebirge, an evaporite tectonite at the base of the Juvavic nappe system (SCHORN et al., 2013).

3.5 Eocene to Miocene magmatism

The Periadriatic intrusions (1) comprise calkalkaline tonalities, granodiorites and granites, and minor alkaline basaltic dikes. They are (Eocene to) Oligocene in age and related to the break-off of the Alpine Tethys oceanic lithosphere from the distal European margin (DAVIS & VON BLANKENBURG, 1995). Their intrusion is closely associated with contemporaneous strike-slip movements along the Periadriatic lineament.

The Pohorje pluton west of Maribor is not belonging to the Periadriatic intrusives sensu strictu. It is Miocene in age and related to the Pannonian magmatism (2) in the course of the extensional tectonics which leads to the development of the Pannonian basin (FODOR et al., 2008).

4 Distribution and timing of metamorphism within the Eastern Alps

In the following chapter a brief summary of the metamorphic events of the Eastern Alps is given. In the Eastern Alps four major metamorphic cycles can be recognized since Paleozoic time.

4.1 Variscan collisional event (Upper Devonian to Carboniferous)

The Variscan event is induced by the Upper Devonian to Carboniferous collision of Gondwana, Laurussia and the intervening plates (e.g. Avalonia), during the accretion of the Pangea supercontinent (KRONER & ROMER, 2013).

Age data of about 380 Ma are the oldest remnants of the Variscan event within the Eastern Alpines (HANDLER et al., 1997). A collision-related LT/HP imprint occurred prior to 350 Ma (MILLER & THÖNI, 1997) and the thermal metamorphic peak was reached at about 340 Ma at medium pressure conditions (c. 25° C/km). During exhumation the sillimanite stability field at a mean geothermal gradient of 35° C/km was crossed in the medium to high grade units (TROPPER & HOINKES, 1996). Typical Variscan cooling ages are in the range of 310-290 Ma (THÖNI, 1999). Due to the reworking in the Alpine tectonometamorphic cycle not much is known about the tectonic style of the Variscan orogene within the present day Eastern Alps. In general the recent Austroalpine nappes were located near the southern margin of the Variscan orogen. Top to the south-directed ductile shearing was recognized in the some of the basement units and Variscan thrust tectonics within Palaeozoic sequences is proved (FLÜGEL & NEUBAUER, 1984).

4.2 Permian extensional event

The Permian event in the Alps followed in the wake of the Variscan tectonic evolution. Lithospheric extension affected the recent Austroalpine, Southalpine and also Western Carpathian realm and caused magmatism and metamorphism. The onset of the Permian event may be considered as when crustal thickness decreased below normal, and thus cannot be related to gravitational collapse of the Variscan orogen.

Evidence for active thinning in Permian time is the formation of grabens, intense magmatic activity and high temperature metamorphism (SCHUSTER & STÜWE, 2008). The metamorphic imprint reached a geothermal gradient of up to 45° C/km. Peak metamorphic conditions were reached at about 280-260 Ma and were accompanied by the formation of pegmatitic veins in upper amphibolites facies metamorphic rocks. After that the continental crust was not exhumed and the lithosphere cooled down slowly to the steady state geotherm of c. 25° C/km at about 200 Ma.

4.3 Alpine collisional event (Cretaceous to Neogene)

The convergence between the African, Adriatic and Eurasian Plate since Lower Cretaceous time caused shortening in the Alpine realm. This leads to the formation of the Alpine orogenic belt by “tectonic progradation” (FRISCH, 1979) from south to north. This process started with an intracontinental subduction within the Austroalpine unit in the Lower Cretaceous (KURZ & FRITZ, 2003; SCHUSTER, 2003) which was followed by the Upper Cretaceous-Eocene subduction of the Piedmont-Ligurian and Valais ocean and prograding continental collisional events that continued until recent times. This mechanism produced high-pressure metamorphism in different tectonic units, decreasing in age from south (internal) to north (external). A brief summary of this evolution is given below. Detailed reviews of the metamorphic conditions and the timing of metamorphism in the individual units, together with maps showing the distribution of the metamorphic grade, are given by FREY et al., (1999) and OBERHÄNSLI (2004) (Fig. 4).

In Early Cretaceous time (c. 135 Ma) a southeast-directed subduction zone developed which was at least in part situated within the continental crust of the Adriatic plate (e.g. JANAK et al. 2004; SCHUSTER & STÜWE, 2008). Along this subduction zone the Upper Austroalpine nappes formed an orogenic wedge which was continuously growing during the Cretaceous. During this tectonic event - which is referred as the Eo-Alpine tectonometamorphic event -

the northwesternmost part of the Adriatic plate, represented by the main part of the Austroalpine nappes, acted as the tectonic lower plate, whereas the main part of the Adriatic plate including some Austroalpine nappes and the recent Southalpine unit were parts of the upper plate. Today the Eo-Alpine suture is obscured by Cenozoic tectonics. Nappe stacking related to the initial eo-Alpine subduction was W- to NW- directed. Large parts of the sedimentary sequences of the Austroalpine unit were stripped off from their basement, which was buried and metamorphosed up to eclogite facies conditions. Geochronological data suggest peak metamorphic conditions of the high-P metamorphic event at about 92 Ma (THÖNI, 2006) and a subsequent medium pressure overprint during exhumation of the high pressure rocks. In the eastern part of the Eastern Alps exhumation of the deeply buried units occurred by N- or

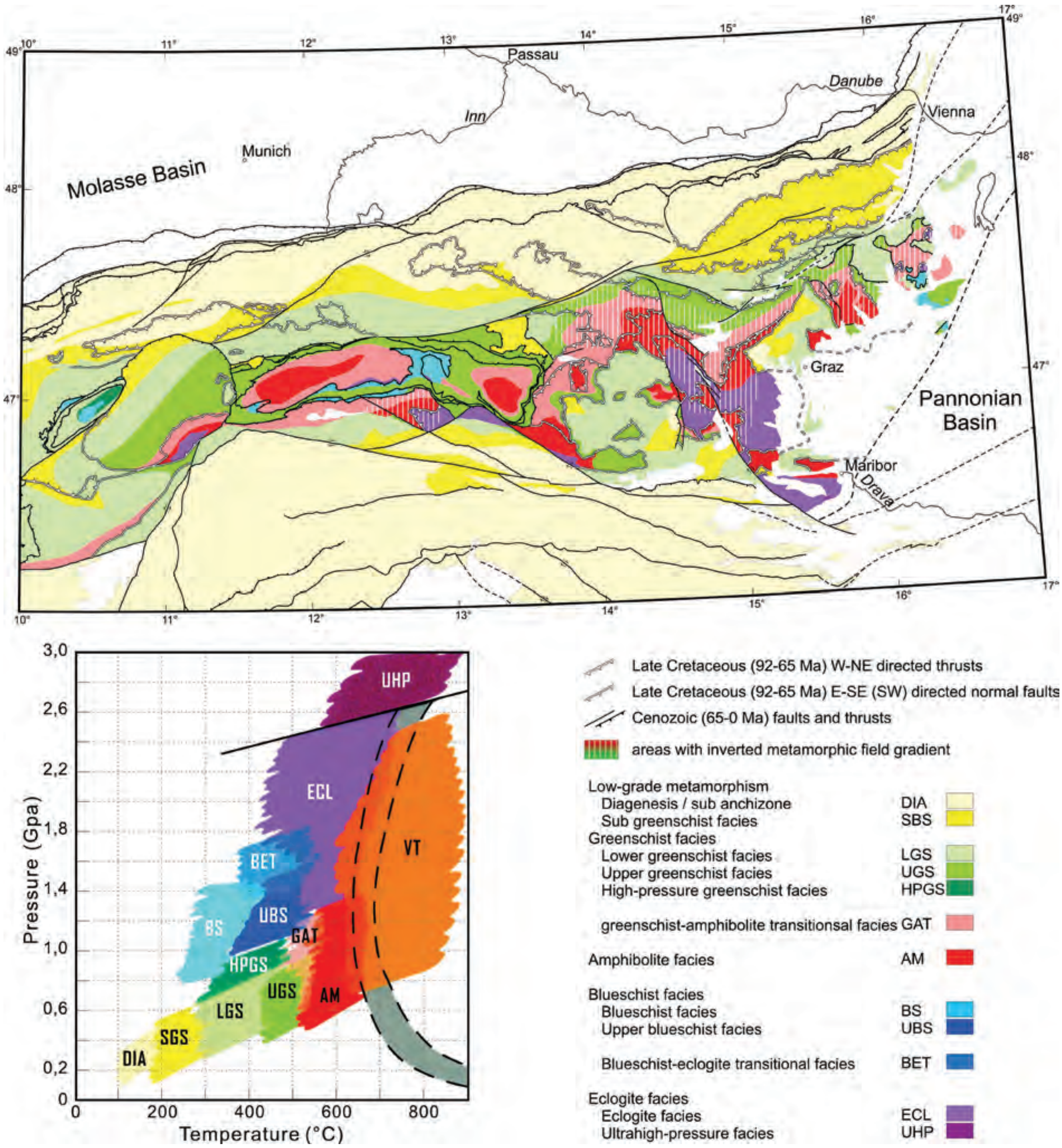

Figure 4: Map of the Eastern Alps showing the distribution of the Alpine metamorphic imprint according to OBERHÄNSLI (2004). Additionally areas with an inverted metamorphic field gradient and the most important Cretaceous and Cenozoic structures are given.

NW- directed thrusting and S- to SE- directed extensional tectonics. During this process a metamorphic extrusion wedge formed. The latter shows a lower part with an inverted metamorphic field gradient and an upper part with an upright metamorphic field gradient. Cooling ages are in the range of 90 to 70 Ma (HOINKES et al., 1999; THÖNI, 1999).

Ongoing subduction of the lithospheric plate caused the entrance of the Penninic oceanic domain into the subduction zone at about 85 Ma and after the closure of the ocean the European continent entered the subduction zone in the Paleogene at about 45 Ma (SCHMID et al., 2013). These processes are referred to as the Alpine event, which is the mayor event in the Western Alps. It resulted in the formation of the Penninic, Subpenninic and Helvetic nappes. In the Eastern Alps the Alpine event caused a LT/HP metamorphism in the Penninic and Subpenninic nappes at c. 40 Ma (THÖNI, 1999) and medium pressure overprint at about 30-25 Ma. Typical cooling ages are in the range of 25 to 15 Ma (LUTH & WILLINGSHOFER, 2008). Exhumation of these units is related to E-W extension since Miocene time. It caused the formation of the Engadine, Tauern and Rechnitz Windows. Adjacent to the windows the Austroalpine unit shows a structural and very-low to low grade Alpine metamorphic overprint (HOINKES et al., 1999).

Subsequent exhumation of the underlying Penninic and Subpenninic nappes within windows (GENSER & NEUBAUER, 1989; FÜGENSCHUH et al., 1997) and lateral extrusion of the orogene in the Miocene (RATSCHBACHER et al., 1989) generated a system of normal and strike slip faults. These faults have a major influence on the recent morphology and are responsible for the exhumation of the Saualpe-Koralpe Complex in the Pohorje region. Depressions like the Styrian, Knittelfeld and Klagenfurt basin developed along these faults. The major strike-slip faults are the Periadriatic lineament, Inntal, Salzach-Ennstal-Mariazel-Puchberg or the Lavanttal fault.

5 Geology of the Nockberge area

In the section from Villach up to the Königsstuhl a complex eo-Alpine nappe pile composed of different crystalline units as well as Palaeozoic and Mesozoic metasediments is preserved (Fig. 5). This section is a key area for the understanding of the eo-Alpine history of the Austroalpine unit. It is under discussion for a long time and was one major argument for the subdivision of the Austroalpine by TOLLMANN (1977). It bears important informations on the plate tectonic arrangement and the exhumation history in the western part of the Austroalpine unit.

From SSW to NNE, respectively from bottom to the top the following units are present:
The Millstatt Complex is bordered to the southwest by the Mölltal fault. The dominant lithology are monotonous metapelites and metapsammites, which are dipping to the north. Only in the lowermost part they sometimes contain two generations of staurolite, kyanite and garnet. Also calcsilicate rocks and massive marbles with intercalation of amphibolite lenses occur in this southern part. Within the lowermost amphibolite layers, relic eclogite bodies are present. Pegmatites of Permian age are common in the whole unit (SCHUSTER et al., 2001).

The pre-Alpine history of the Millstatt Complex is not well constrained. However, a Permian low-P event is indicated by the occurrence of Permian pegmatites and textures similar to those in units where a Permian low-P event is proved. Peak eo-Alpine metamorphic conditions reached ~1.38 GPa and 630 ± 20° C estimated from garnet-clinopyroxene thermometer and jadeite contents in omphacite (HOINKES et al., 1999). Reaction textures of the eclogite assemblages reflect decompression with a change from constant to decreasing temperatures during the exhumation of the Millstatt Complex.

In the overlying, north dipping, Radenthein Complex the most abundant lithologies are white mica-rich, garnet-bearing micaschists. Garnets are up to several centimeters in size, kyanite- and/or staurolite are present especially in biotite-bearing schists. Frequent are amphibole-garnet-plagioclase schists, mica-bearing amphibolites and marbles. A large magnesite body had been of economic interest. The microtextures and the chemical zoning indicate one prograde metamorphic imprint except in one locality where garnet contains older cores. Peak metamorphic temperatures are in the range of 550-600°C at pressures of 0.6-1.0 GPa (SCHIMANA, 1986; KOROKNAI et al., 1999; KAINDL & ABART, 2002). Sm-Nd garnet isochron ages of an amphibolite yielded c. 100 Ma (SCHUSTER & FRANK, 1999), K-Ar and Rb-Sr ages determined on micas and whole rock samples are in the range of 78 to 125 Ma. These data prove an eo-Alpine age of observed assemblages (BREWER, 1969; HAWKESWORTH, 1976; SCHIMANA, 1986).

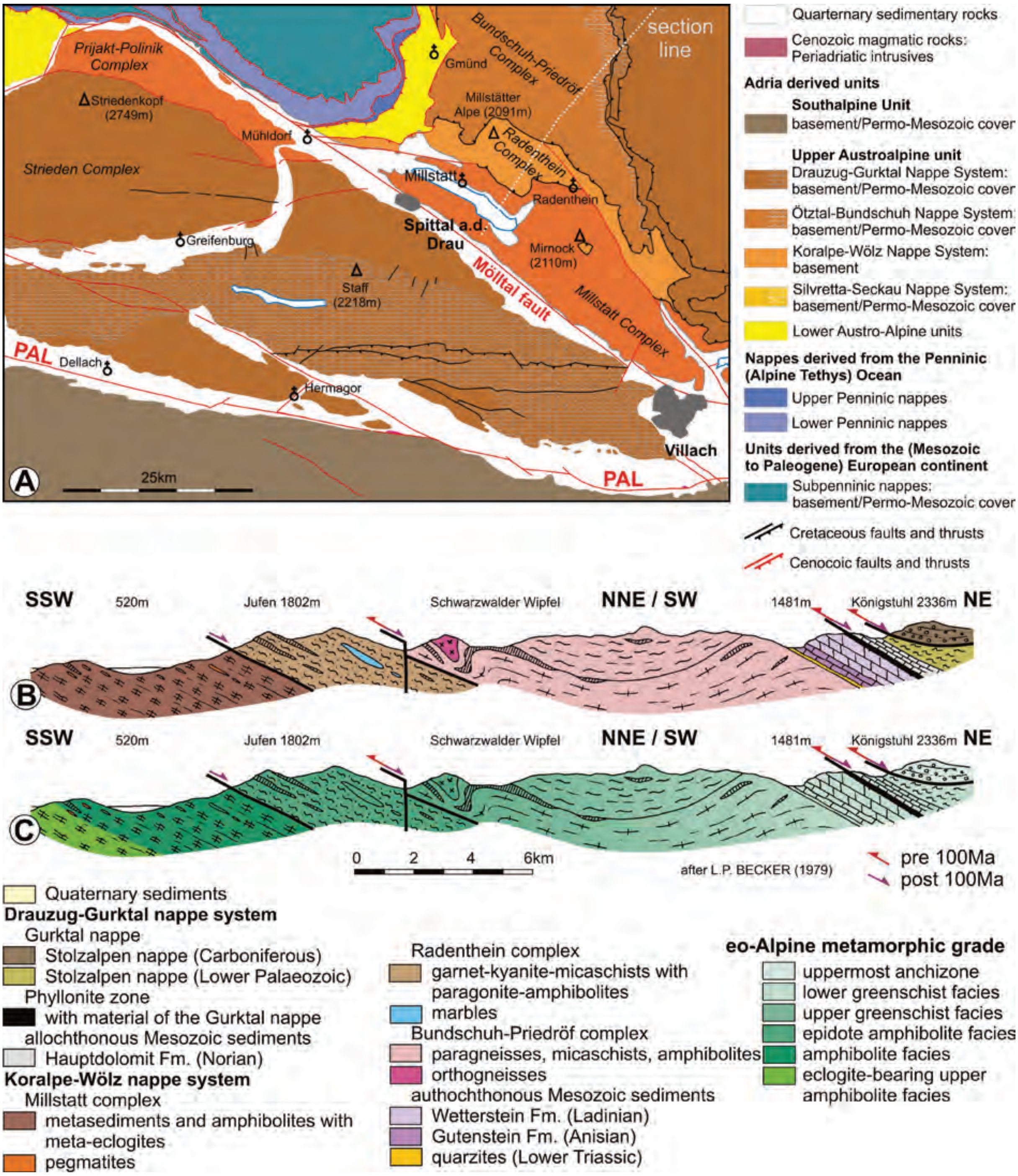

Figure 5: (A) Tectonic map of the western part of Carinthia. (B, C) Section trough the western part of the Nockberge area showing the geologic units and the distribution of the eo-Alpine metamorphic grade.

The Bundschuh Complex is overlying the Radenthein Complex with an eo-Alpine thrust contact (SCHUSTER & FRANK, 1999). Its lower part consists of fine-grained paragneisses with some intercalations of felsic biotite-free orthogneisses and amphibolites (Priedröf paragneisses, Bundschuh orthogneisses). Micaschists and interlayered amphibolites are restricted to the uppermost part of the unit in the center of a large scale gentle syncline structure. The Priedröf paragneisses contain a mineral assemblage of garnet + biotite + plagioclase (albite and oligoclase) + muscovite + quartz. In the micaschists additional staurolite and pseudomorphs after staurolite (rarely containing chloritoid) may be present. Garnets are very characteristic in the whole unit. In the paragneisses they have an average grain-size of less than 0.5 mm, whereas in the micaschists they are up to 2 cm in diameter. Optically an inclusion-rich, often idiomorphic core can clearly be distinguished from an inclusion-free rim. The cores are compositionally homogenous with low CaO contents of 3-5 wt%. Their age is presumed to be Variscan, because Variscan Rb-Sr ages (c. 350 Ma) were determined on muscovites of orthogneisses from the uppermost part of the unit (FRIMMEL, 1986). In the rim the CaO content is much higher (6-8 wt%), FeO, MgO and also XMg is lower. Based on the regional metamorphic history this garnet generation is eo-Alpine in age. Eo-Alpine metamorphic conditions reached up to 600 °C and 1.0 GPa in the lowermost parts in the south and greenschist facies conditions below the transgressive Mesozoic unit.

The Mesozoic Stangalm Unit is unconformalbly transgressing onto the pre-Alpine syncline structure. The lowermost part consists of Permian to Early Triassic quarzites. Above Anisian carbonates and Carnian phyllitic schists are preserved (TOLLMANN, 1977). A phyllonite horizon, composed of highly sheared Paleozoic and Mesozoic rocks marks the border to the overlying Pfannock unit (nappe). The Pfannock orthogneiss, which is very similar to the Bundschuh orthogneisses (FRIMMEL, 1988) forms the stratigraphically deepest part. It is transgressed by Carboniferous to Permian clastic sediments. Continuing Mesozoic carbonates and schists reach up to the Rhaetian Kössen Formation. The sediments show a lower greenschist facies metamorphic imprint.

The uppermost tectonic position is hold by the Gurktal nappes (Murau, Stolzalpen, Ackerl nappe; NEUBAUER & PISTOTNIK, 1984). The latter comprises clastic metasediments with some intercalations of carbonates and metatuffitic layers, which were deposited in Lower Palaezoic times. During the Variscan tectonothermal event they experienced a greenschist facies metamorphic imprint. After that Carboniferous sediments of an intramontane basin (KRAINER, 1984) and Permo-Mesozoic sediments were deposited on top. During the eo-Alpine event the whole sequence suffered anchizonal to lower greenschist facies metamorphic conditions.

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