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Objekttyp: **Article**

Zeitschrift: **Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie**

Band (Jahr): **79 (1999)**

Heft 1: **The new metamorphic map of the Alps**

PDF erstellt am: **24.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-60197

SCHWEIZ. MINERAL. PETROGR. MITT. 79, 41–62, 1999

Pre-Alpine metamorphism of the Eastern Alps

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Abstract

Basement successions are exposed within three different continental domains constituting the Eastern Alps, i.e. the Penninic, Austroalpine and Southalpine units. These were variably overprinted by a variety of metamorphic facies ranging from medium-pressure greenschist-facies to migmatite conditions, and to high-pressure eclogite facies metamorphic conditions during various tectonothermal events including the Late Cadomian, Caledonian and Variscan orogenies.

The Penninic basement exposed within the Tauern window is largely overprinted by Variscan amphibolite facies metamorphism associated with intrusions of Variscan granites. Silurian eclogites predate migmatite formation.

The Austroalpine basement units vary in metamorphic grade and timing of metamorphism. Lower Austroalpine units along the eastern margins of the Alps record 1) Devonian high-pressure metamorphism overprinted by Variscan greenschist metamorphic condition in the Wechsel unit, and 2) early Variscan amphibolite facies metamorphic conditions later locally overprinted by granulite facies conditions within the Kirchberg-Stuhleck unit. Middle Austroalpine units are polymetamorphic and were largely overprinted by amphibolite facies metamorphic conditions during Variscan orogeny subsequent to distinct earlier (Ordovician, Silurian and/or Early Carboniferous) metamorphic events. Early Variscan eclogites (max. c. 27 kb, 730 °C) were locally recorded from the Ötztal basement. Silurian to Devonian medium-grade metamorphism is also locally reported from northeastern Upper Austroalpine units. The Upper Austroalpine unit and Lower Austroalpine Quartzphyllite units generally record late Variscan greenschist metamorphic overprint similar to that recorded in Southalpine units.

The different timing and the different features of the pre-Alpine metamorphic evolution are interpreted to result from accretion of various units to the active Laurasian continental margin. Variscan metamorphism of the Eastern Alps is an expression of final Himalayan-Tibetan-type continental plate collision.

Keywords: Variscan metamorphism, pre-Variscan metamorphism, polymetamorphism, Eastern Alps, collisional orogeny, extension, high-pressure metamorphism.

1. Introduction

The Eastern Alps largely expose pre-Alpine metamorphic and plutonic Austroalpine and Penninic basement units (Figs 1, 2). Large portions were penetratively overprinted by Alpine (Cretaceous and/or Tertiary) metamorphism. The Austroalpine and Penninic tectonic units display a complex internal structure which originated from Cretaceous and Cenozoic tectonic processes. Alpine tectonometamorphic overprint resulted in variable retrogression, but also in progressive metamorphism, or overprint in similar metamorphic grade (see HOINKES et al., 1999, this volume, for review). These relationships, and the often missing intercalation of Permian to Mesozoic cover sequences gave rise to longlasting discussions on the timing and nature of peak metamorphic conditions in many portions of the Austroalpine basement in the Eastern Alps. The discussion now appears to be solved for the Cretaceous age of the eclogite-facies metamorphism and its evolution to

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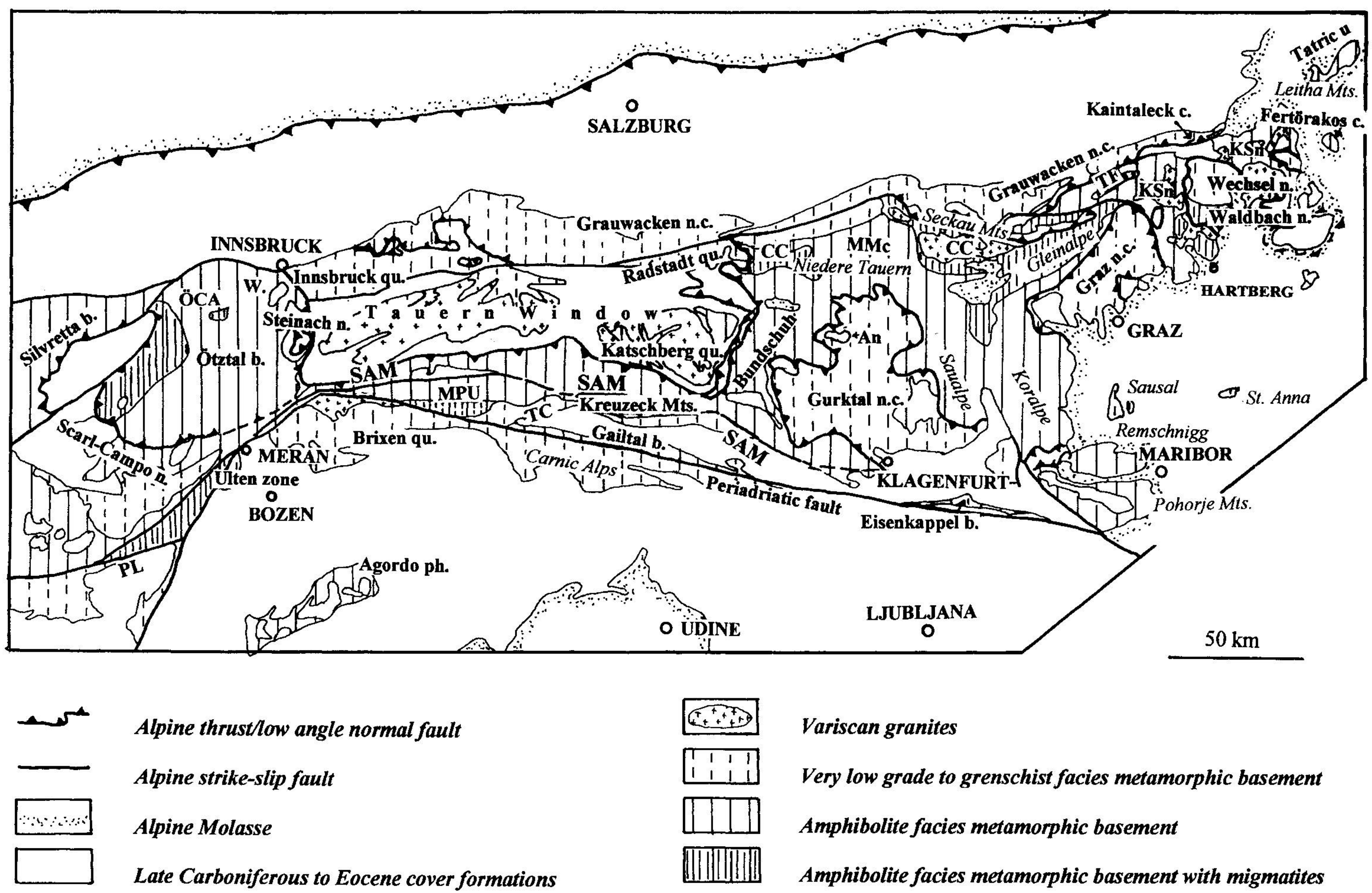

Fig. 1 Distribution of intensity of pre-Alpine metamorphism in Austroalpine and Penninic basement units in the Eastern Alps. Legend: An – Ackerl nappe, b. – basement; c. – complex; CC – "Core complex"; DAV – Defreggen-Antholz-Vals fault; KSn – Kirchberg-Stuhleck nappe; MMc – Micaschist-Marble complex; MPU – Micaschist-Paragneiss unit; n. – nappe; P – Peio fault, ph. – phyllite; PL – Periadriatic fault; qu. – quartzphyllite; SAM – southern limit of Alpine metamorphism; TC – Thurntal complex; TF – Troiseck-Floning; u. – unit; W. – Winnebach migmatite.

medium-pressure amphibolite-facies within the southern (Middle) Austroalpine basement (FRANK, 1987; MILLER and THÖNI, 1995; THÖNI and JAGOUTZ, 1992). However, geochronologic results (U–Pb zircon, Rb–Sr whole rock and mineral ages) revealed a large variety of scattered ages, ranging from c. 500 to 240 Ma, for metamorphism and respectively post-metamorphic cooling within various basement units, specifically of the Middle Austroalpine basement (see reviews by SASSI et al., 1985; and FRANK et al., 1987). These ages were often regarded as ambiguous. However, recent geochronologic results obtained by a wide variety of methods confirmed older results and revealed further details on the extent and timing of the pre-Alpine metamorphism within the Eastern Alps.

This review updates some older compilations on pre-Alpine metamorphism in the Eastern Alps (SASSI et al., 1985; BECKER et al., 1987; FRANK et al., 1987; GRUNDMANN, 1989; HOINKES and THÖNI, 1993; MAGGETTI and FLISCH, 1993; NEUBAUER and FRISCH, 1993; NEUBAUER and SASSI, 1993; SASSI and SPIESS, 1993; SASSI et al., 1995; SCHULZ et al., 1993) where also references to older literature can be found. The review mainly discusses field relationships of metamorphic sequences to their fossil content and to enclosed plutonic sequences, the metamorphic facies, and geochronologic age constraints for the distribution of pre-Alpine metamorphic facies as shown on the "Map of pre-Alpine Metamorphism" (see enclosure to this volume). Time scale follows recent calibrations proposed by GRADSTEIN and OGG (1996). Mineral abbreviations follow BUCHER and FREY (1994). The review spans metamorphic processes from Early Paleozoic to Permian, because some pre-Alpine metamorphic sequences were exhumed due to ongoing post-Variscan rifting. Only limited P-T estimates are available. These are compiled in table 1 and represented graphically in figure 3. Representative and significant geochronologic data were compiled in table 2.

Timing and petrologic features of the pre-Alpine metamorphic effects recorded in the various basement units occurring in the Eastern Alps may be classified in four different typologies. Consequently, four typologies of basement units may be envisaged (Fig. 1):

– typology A: mostly fossiliferous Ordovician to early Late Carboniferous sedimentary units which were affected by only low-grade Variscan (e.g. 330–300 Ma) metamorphism;

– typology A': units in which a medium- to high-grade Variscan metamorphism is only recognizable;

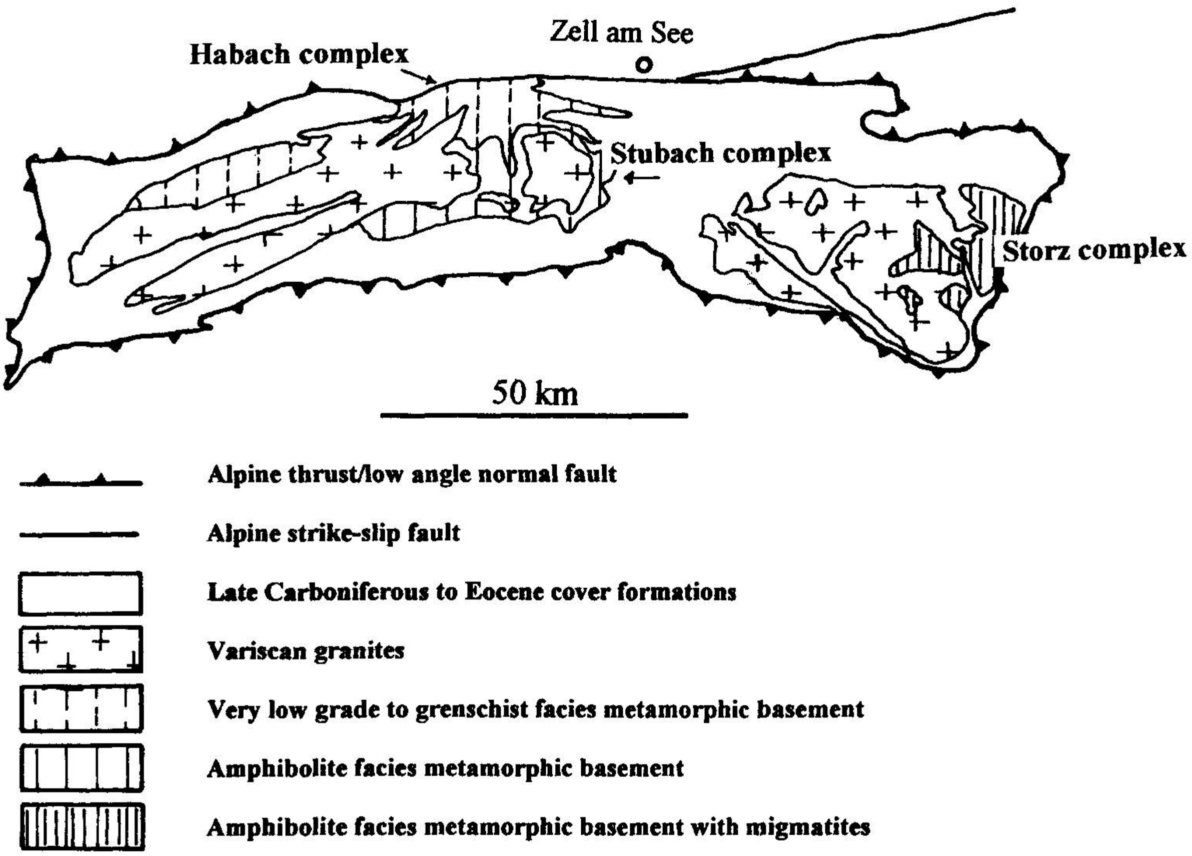

Fig. 2 Simplified geological map of basement units exposed within the Tauern window. For location, see figure 1.

– typology B: units which also were affected by Silurian-Devonian metamorphism;

– typology C: units where polymetamorphism is proven, which includes a high-grade Ordovician event ("Caledonian") overprinted by a Variscan event ranging from low- to medium-grade.

For clarity sake, tectonic units are discussed according to their present-day tectonic positions from base to top, and the appropriate or assumed typology is explicitly reported in the titles of the sections below.

2. Penninic basement of the Tauern window (typology B)

Penninic basement units are preserved within epidote-amphibolite-facies metamorphic conditions within the Habach complex, and within amphibolite-facies metamorphic conditions in the Storz, respectively Stubach complexes (e.g., GRUNDMANN, 1989; VAVRA and HANSEN, 1991; Fig. 2). All units are intruded in a variable degree by Variscan granites, which are now overprinted to the "Central Gneisses" due to Cenozoic tectonothermal events. Consequently, widespread migmatite formation in the Storz and Stubach complexes is related to Variscan granite intrusions. Local eclogites, preserved within the southeastern (DROOP, 1983) and southern central Tauern window (ZIMMERMANN and FRANZ, 1989), predate Variscan upper amphibolite-facies metamorphism. Eclogites of the central southern Tauern window were dated at 418 ± 18 Ma (U–Pb zircon), 415 ± 18 Ma (laser ablation ICP-MS) and 421 ± 16 Ma (Sm–Nd) (VON QUADT et al., 1997). DROOP (1983)

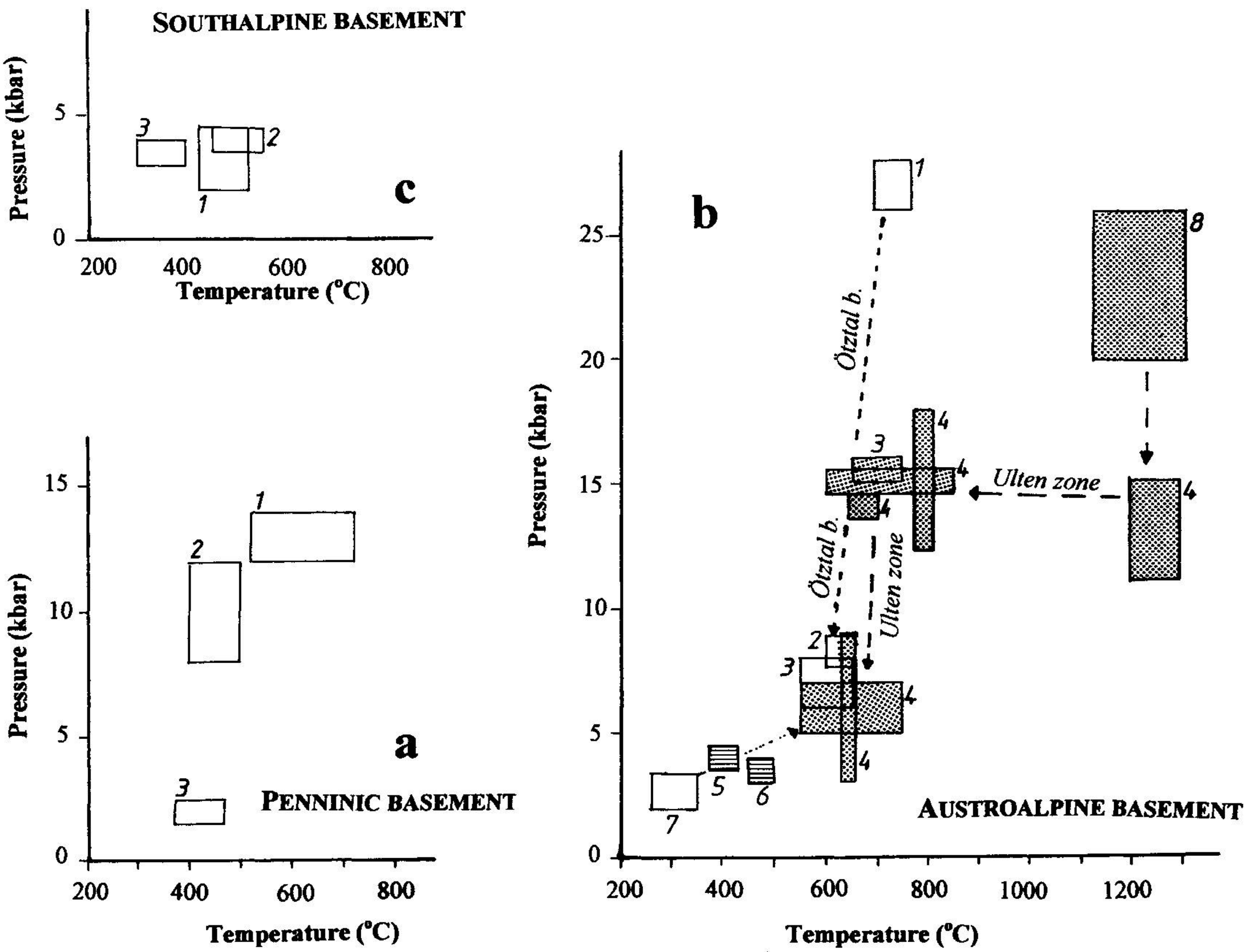

Fig. 3 P-T estimates of Penninic, Austroalpine and Southalpine units. Note anomalous low temperature/pressure gradients for the Penninic, Ötztal and Ulten zone basement. This is explained by metamorphism within a subduction zone. Sources of data: a: 1 – DROOP (1983), 2 – ZIMMERMANN and FRANZ (1989), 3 – KOLLER and RICHTER (1984). b: 1 – MILLER and THÖNI (1995), 2 – HOINKES et al. (1997), 3 – TROPPER and HOINKES (1996), 4 – GODARD et al. (1996), 5 – SASSI and SPIESS (1992), 6 – SASSI and ZANFERRARI (1972), 7 – SCHULZ (1991), 8 – OBATA and MORTEN (1987). Stippled – Ulten zone; horizontal hatching – quartzphyllite units.

Tab. 1 Pre-Alpine metamorphism in the Eastern Alps: geothermobarometry.

Rock unit	P-T conditions	Applied method	Reference
Penninic basement, Tauern window:			
eclogite	620 ± 100 °C, > 12 kbar	gt-cpx-thermometry, jd-content	DROOP (1983)
eclogite	400–500 °C, 8–12 kbar	gt-cpx-thermometry, jd-content	ZIMMERMANN and FRANZ (1989)
metarondingite	420 °C, 2 kbar	petrogenetic grid	KOLLER and RICHTER (1984)
Lower Austroalpine nappe complex:			
Fertörakos complex: *paragneiss*	600–660 °C, 6.7–8.9 kbar	mineral assemblage	TÖRÖK (1998)
Innsbruck *quartzphyllite*	c. 400 °C, 4 kbar	TWEEQU	DINGELDEY et al. (1997)
	c. 450 °C, 3–4 kbar	petrogenetic grid and b_0 of muscovite	SASSI and SPIESS (1992)
Middle Austroalpine nappe complex:			
Kreuzeck/Strieden unit: *paragneiss*	c. 650 ± 100 °C, 5.5 ± 1.5 kbar	sillimanite, mineral assemblage	HOKE (1990)
Zone S of DAV fault (S Tauern w.) *migmatitic paragneiss/micaschist*	650–750 °C, 5–7 kbar	anatexis, muscovite-out	SCHULZ (1995)
	c. 650 °C, 6 ± 1 kbar		STÖCKHERT (1985)
migmatitic paragneiss/micaschist	600–650 °C, 6–7 kbar	petrogenetic grid	SASSI and ZANFERRARI (1972)
	c. 670 °C, 7,5 kbar	petrogenetic grid and anatexis	MORETTI (1995)
Ötztal basement c.: *eclogite*	730 °C, 27 kbar	gt-cpx-thermom., jadeite-barom.	MILLER and THÖNI (1995)
paragneiss	570–640 °C, 5.8–7.5 kbar	TWEEQU	TROPPER and HOINKES (1996)
orthogneiss	630 °C, 6.5–8 kbar	phengite geobarometry	HOINKES et al. (1997)
Pohorje: *eclogites and ultrabasites*	HP stage: c. 750–800 °C, 30 kbar, coronite stage: c. 650–700 °C, 8 kbar	petrogenetic grid	HINTERLECHNER et al. (1991a,b)
Upper Austroalpine nappe complex:			
Steinach *quartzphyllite*	c. 450–500 °C, 3.5 kbar	petrogenetic grid and b_0 of muscovite	SASSI and MENEGAZZO (1971) SASSI and SPIESS (1992)
Austroalpine units along Periadriatic fault			
Ulten Zone: *garnet peridotite*	20–25, max. 28 kbar,	mineral assemblage of lherzolite	OBATA and MORTEN (1987)
garnet peridotite	1120–1300 °C	cpx-, opx composition	GODARD et al. (1996)
garnet peridotite	1150–1240 °C,	garnet exsolution in opx	GODARD et al. (1996)
eclogite	12.5–15.4 kbar	kelyphite formation	GODARD et al. (1996)
eclogite	769–802 °C, 12.2–17.9 kbar	gt-cpx-thermometry, jd-barometry	HAUZENBERGER et al. (1996)
migmatitic paragneiss	630–660 °C, 3–9 kbar	TWEEQU, Gt-bio	HAUZENBERGER et al. (1996)
	700 ± 50 °C, > 15 kbar		
	600 ± 50 °C , 6–8 kbar		
Thurntal *quartzphyllite*	300 °C, 2.5 kbar, 600 °C, 6 kbar	mafic mineral assemblage	SCHULZ (1990)
	c. 450–500 °C, 3.5 kbar	petrogenetic grid and b_0 of muscovite	SASSI and ZANFERRARI (1972) SASSI and SPIESS (1992)
Gailtal quartzphyllite	c. 450–500 °C, 3.5 kbar	petrogenetic grid and b_0 of muscovite	SASSI and SPIESS (1992)
Southalpine unit			
Brixen quartzphyllite	420–520 °C, 2–4.5 kbar	garnet-biotite thermometry, mineral assemblage	RING and RICHTER (1994)
	zoneography from ca. 350 to 520 °C, 3.5–4 kbar	petrogenetic grid and b_0 of muscovite	MAZZOLI and SASSI (1988)
Sarentino/Sarthein quartzphyllite	c. 500 °C, 4 kbar	petrogenetic grid and b_0 of muscovite	CARDIN et al. (1985)
Recoaro quartzphyllite	Ca. 350 °C, 3.5 kbar	petrogenetic grid and b_0 of muscovite	SASSI et al. (1974)

Tab. 2 Pre-Alpine metamorphism in the Eastern Alps: representative geochronologic age data concerning.

Rock unit	Applied methods	Age (Ma)	Reference
Penninic basement			
eclogite	U–Pb zircon (laser abl., ICP)	415 ± 18	v. QUADT et al. (1997)
	Sm–Nd	421 ± 16	v. QUADT et al. (1997)
	U–Pb zircon	313 ± 4	v. QUADT (1992)
	U–Pb titanite	282 ± 2	EICHHORN et al. (1995)
Lower Austroalpine nappe complex:			
Fertörakos complex: *paragneiss*	Ar–Ar muscovite		FRANK et al. (1996)
Kirchberg-Stuhleck nappe: *orthogneiss*	K–Ar biotite	328 ± 13, 320 ± 12	BALOGH and DUNKL (1994)
orthogneiss	Rb–Sr muscovite	424 ± 10, 231 ± 8	SCHARBERT (1990)
Middle Austroalpine nappe complex:			
Gleinalm-Rennfeld: *paragneiss*	Conventional U–Pb zircon	450–425	NEUBAUER et al. (1998)
trondhjemite	Conventional U–Pb zircon	363–353	NEUBAUER et al. (1998)
Troiseck-Floning: *garnet micaschist*	Rb–Sr muscovite	332 ± 3, 284 ± 3, 273 ± 3	HANDLER (1994)
Bundschuh *orthogneiss*	Rb–Sr muscovite	352 ± 4	FRIMMEL (1986)
Anterselva-Casies: *orthogneiss*	Rb–Sr whole rock isochron	434 ± 4	BORSI et al. (1973)
	Rb–Sr muscovite	308–294	BORSI et al. (1973)
	Rb–Sr biotite	299–286	BORSI et al. (1973)
Anterselva-Casies: *paragneiss/micaschist*	Rb–Sr whole rock isochron	497 ± 38	BORSI et al. (1973)
	Rb–Sr biotite	294–280	BORSI et al. (1978)
Villa Ottone: *pegmatite/aplite gneiss*	Rb–Sr whole rock isochron	262 ± 5	BORSI et al. (1980b)
Ötztal b.: Winnbach *migmatite*	U–Pb zircon evaporation	490 ± 9	KLÖTZLI-CHOWANETZ et al. (1997)
Ötztal basement: *orthogneiss*	Rb–Sr whole rock isochron	448 ± 14	BORSI et al. (1980a)
Stubai basement: *orthogneiss*	Rb–Sr whole rock isochron	425 ± 43	BORSI et al. (1980a)
Ötztal basement: *eclogite*	Sm–Nd WR-gt	373 ± 20, 359 ± 18	MILLER and THÖNI (1995)
Ötztal basement: *metapelite*	Sm–Nd WR-gt	343 ± 2 – 331 ± 3	HOINKES et al. (1997)
Ötztal basement: *various orthogneisses*	Rb–Sr muscovite	327–292	THÖNI (1981), HOINKES and THÖNI (1993), BORSI et al.. (1980a)
	Ar–Ar muscovite	312 ± 1 – 305 ± 1	HOINKES et al. (1997)
	K–Ar muscovite	317–297	THÖNI (1981), HOINKES and THÖNI (1993)
	Rb–Sr biotite	301–272	HOINKES and THÖNI (1993)
	K–Ar biotite	316–272	BORSI et al. (1980a) HOINKES and THÖNI (1993)
Ötztal: *paragneiss*	Rb–Sr muscovite	326 ± 23	BORSI et al. (1980a)
	Rb–Sr biotite	324–300	BORSI et al. (1980a)
Upper Austroalpine nappe complex:			
Kaintaleck m. c.: *hornblende gneiss*	conventional U–Pb zircon	c. 510, c. 390	NEUBAUER and FRISCH (1993)
orthogneiss, aplite, pegmatite	Rb–Sr muscovite	390 ± 4, 375 ± 4, 354 ± 3	HANDLER (1994)
orthgneiss, paragneiss, aplite	Ar–Ar muscovite	375 ± 0.4, 264 ± 0.8	HANDLER et al. (1999)
Southalpine unit:			
Carnic Alps: *sericite marble*	K–Ar muscovite	282 ± 8	LÄUFER et al. (1997)
Brixen quartzphyllite complex	Rb–Sr muscovite	314 ± 5	HAMMERSCHMIDT and STÖCKHERT (1987)
	K–Ar muscovite	316 ± 8	
	Ar–Ar muscovite	319 ± 5.5	
	Rb–Sr biotite	314 ± 5	
Brixen quartzphyllite complex	Rb–Sr biotite-Kfs-WR isochron	321 ± 1	DEL MORO et al. (1984)
	Rb–Sr muscovite-garnet-WR isochron	354 ± 10	DEL MORO et al. (1980)
Agordo quartzphyllite complex	Rb–Sr whole rock isochron	347 ± 17	CAVAZZINI et al. (1991)

and ZIMMERMANN and FRANZ (1989) reported metamorphic conditions of c. 8 and > 12 kbar and 450–620 °C for these eclogites.

Variscan migmatization is closely related to the intrusion of the precursor rocks of present Central Gneiss. Locally, andalusite can be found (GRUNDMANN, 1989). Metarodingites contain mineral assemblages for which P-T conditions of c. 420 °C and 2 kbar have been estimated (KOLLER and RICHTER, 1984). From southeastern regions Variscan garnet-staurolite-kyanite assemblages were reported by DROOP (1981). VON QUADT (1992) reported U–Pb lower intercept ages for zircons of 314 +4/–3 Ma and 301 ± 3 Ma, indicating Variscan metamorphism. A local Permian thermal overprint (for previous literature see FRANK et al., 1987) has also recently been confirmed by an U–Pb titanite age of 282 ± 2 Ma (EICHHORN et al., 1995).

In summary, pre-Alpine metamorphism within the Tauern window appears to have been polyphase: 1) Silurian high-pressure metamorphism, 2) Variscan metamorphism, related to Variscan granite intrusions (c. 330–300 Ma), and 3) Permian thermal overprint, probably localized along distinct shear zones (FRANK et al., 1987).

3. Austroalpine units

3.1. INTRODUCTION

For the internal subdivision of Austroalpine units we follow, for simplicity, the divsion in Lower, Middle, and Upper Austroalpine units which resulted from Cretaceous nappe stacking and subsequent Late Cretaceous extension (DALLMEYER et al., 1998), the latter being prominent along the Middle/Upper Austroalpine nappe contacts. The Lower Austroalpine units include a number of independent nappes, tectonically overlain by Middle Austroalpine units. The latter form a backbone extending from western to close to the eastern margin of the Eastern Alps. The Middle Austroalpine units are overlain by Upper Austroalpine units which are exposed as tectonic klippens above, and along the northern margins of Middle Austroalpine units. To the south of a tectonic fault system (including, from west to east, the Peio-, Jaufen-, Deffreggen-Antholz-Vals-(DAV), Strieden- and Keutschach faults, all together constituting the "SAM" = Southern limit of Alpine Metamorphism) and north of the Periadriatic fault, Austroalpine units are exposed, which do not fit into the tectonic structure applicable in the north as outlined above. Consequently, these units are discussed separately.

3.2. LOWER AUSTROALPINE UNITS (TYPOLOGY B)

3.2.1. Tatric units

In the transition zone from the Eastern Alps to the Carpathians, the basement complex of the Leitha Mountains is exposed. This belongs rather to the Western Carpathians than to the Alps because of a distinct facies of Permo-Mesozoic cover formations (Fig. 1). The basement is composed of paragneiss, staurolite-bearing micaschist, quartzitic biotite phyllite, and greenschist which include carbonatic layers (TOLLMANN and SPENDLINGWIMMER, 1978; WESSELY, 1962). The paragneiss and micaschist are intruded by plutons which include two-mica granite, granodiorite and leucogranite, similar to the Bratislava pluton exposed within the Little Carpathians. The phyllite is correlated by TOLLMANN and SPENDLINGWIMMER (1978) to the Lamac Formation of the Little Carpathians. In the Little Carpathians, the age of metamorphism is probably Devonian, constrained by a Rb–Sr mineral isochron of 380 ± 20 Ma (CAMBEL and KRAL, 1989). The Bratislava pluton yielded a Rb–Sr biotite age of 347 ± 4 Ma (CAMBEL and KRAL, 1989).

3.2.2. Wechsel/Waldbach nappes

The Wechsel and Waldbach nappes form two different tectonic units exposed within the Wechsel window and some further windows towards the east, close to the eastern margin of the Alps. The metamorphic evolution of the basement within the Wechsel nappe has been resolved during recent years (MÜLLER, 1994; MÜLLER et al., 1999). The Wechsel nappe basement mainly comprises albite-chlorite-mica gneiss with lense-shaped intercalations of mafic rocks (Wechsel Gneiss Complex) and phyllites constituting the Wechsel Phyllite complex. The gneiss displays a complex evolution recorded in inclusions within late-stage albite porphyroblasts. A mineral zonation, which records the transition from greenschist-facies in the north to epidote-amphibolite-facies metamorphic conditions towards south, is observed within the Wechsel window. However, the metamorphism has been accompanied by polyphase folding, suggesting an approximately north-south shortening within the present geographic framework. Phengitic white mica is common, both as inclusions within albite porphyroblasts, and within the matrix (MÜLLER et al., 1999). Rb–Sr and $^{40}Ar/^{39}Ar$ white mica ages range from c. 378 to c. 325 Ma, and are interpreted to record Devonian peak conditions of pressure-dominated metamorphism. Paragonite from the matrix records late Variscan $^{40}Ar/^{39}Ar$ ages (c. 245 Ma: MÜLLER et al., 1999). No record of penetrative Alpine ages has been found, except along shear zones (e.g., along the upper margins of the Wechsel gneiss complex towards the overlying Wechsel phyllite complex).

The Wechsel Phyllite complex comprises a polyphase fabric with typical greenschist-facies mineral assemblages recorded within mafic, tuffaceous rocks and slates. $^{40}Ar/^{39}Ar$ ages for paragonite of c. 270–240 Ma indicate a Permian age for the tectonothermal activity. Rb-Sr mineral isochrons (white mica – chlorite – whole rock) of the Wechsel Slate, and low-temperature increments of $^{40}Ar/^{39}Ar$ stepwise heating experiments are at c. 250 Ma (MÜLLER et al., 1999). These ages may proof activity along the ductile fault mentioned above during Permian extension with ongoing subsidence and/or thermal influence by Permian volcanism.

The Waldbach complex is a basement unit formed within upper amphibolite-facies metamorphic conditions and mostly overprinted by Alpine (Cretaceous) upper greenschist-facies metamorphic conditions. Typical pre-Alpine mineral assemblages within mafic rocks are green hornblende + oligoclase + garnet + zoisite ± titanite. The metapelitic rocks comprise garnet + white mica + quartz. The pre-Alpine metamorphic overprint reached amphibolite-facies metamorphic conditions, and locally partial melting occurred (FAUPL, 1972). No geochronological data are available from the Waldbach unit. Pegmatites and some mafic-intermediate intrusions are crosscutting through an amphibolite-facies foliation (AMANN, 1994).

3.2.3. Fertörakos complex

The Fertörakos complex in westernmost Hungary has been correlated to the Wechsel gneiss unit by some authors (e.g. KOVAC and SVINGÖR, 1981; KOSA and FAZEKAS, 1981), and to the Grobgneiss Serie by others (e.g. KISHAZI, 1977). This complex consists of granitic gneisses, acidic metarhyolites and acidic metavolcanoclastites, paragneisses and micaschists, amphibolites, phyllitic rocks and marbles, displaying a complex metamorphic evolution and a large variety of metamorphic conditions, from a migmatite-sillimanite stage to a kyanite-staurolite stage, followed by an andalusite + chloritoid greenschist-facies metamorphic overprint (LELKES-FELVARI et al., 1984). Based on mineral assemblages and exchange thermobarometry TÖRÖK (1998) reported c. 600–660 °C and 6.7–8.9 kbar for the peak P-T conditions. The relationships between the different rock types, as well as the complex metamorphic evolution, are difficult to interpret, also because of poor outcrops and many tectonic complications.

A Rb–Sr age of a pegmatitic white mica is at c. 354 Ma (KOVAC and SVINGÖR, 1981). Recent Rb–Sr dating of muscovite from gneisses recorded 339 ± 4 Ma and 287 ± 3 Ma, and $^{40}Ar/^{39}Ar$ muscovite ages slightly older than c. 300 Ma (FRANK et al., 1996).

3.2.4. Kirchberg-Stuhleck nappe

The Kirchberg-Stuhleck nappe extends from the eastern margins of the Alps towards west and northwest, where this unit is overriden by Middle and Upper Austroalpine nappe complexes. The basement is termed Grobgneiss complex or Raabalpen crystalline complex (west of the Wechsel window) or Eselsberg complex (east of the Wechsel window) (e.g., TOLLMANN, 1978; PAHR, 1980; NEUBAUER and FRISCH, 1993).

Only the southern portion of the Kirchberg-Stuhleck nappe is overprinted by Alpine medium-grade metamorphism (DALLMEYER et al., 1998). Therefore, well-preserved basement units are exposed within northern areas. The Grobgneiss complex is composed of migmatitic paragneiss (Strallegg gneiss), micaschist (Tommer schist), phyllonite (Mürztal and Birkfeld quartzphyllites), and minor intercalations such as talc schist, clinopyroxene-bearing amphibolite, quartzite, kyanite-bearing quartzite and tourmalinite (CORNELIUS, 1952; KOLLER and WIESENEDER, 1981; PEINDL, 1990; NEUBAUER et al., 1992). The age of deposition is uncertain, but predates intrusions of various, widely distributed Carboniferous granites.

The main metamorphic event is a pre-Alpine migmatitization of metapelites in southern and central areas, and pre-Alpine amphibolite-facies metamorphic conditions within the stability field of staurolite in northern areas (Tommer mica-schist).

The Strallegg gneiss (exposed to the southwest of the Wechsel window) is a migmatitic, locally alumosilicate-bearing (andalusite, sillimanite), biotite-rich paragneiss with a stromatitic foliation (e.g., KOLLER and WIESENEDER, 1981). Boudinage of the stromatitic foliation caused accumulation of leucosome in the boudin necks (PEINDL, 1990) which indicates synkinematic anatexis.

Although the Alpine overprint regionally reached variable greenschist to amphibolite-facies metamorphic conditions, the pre-Alpine mineral assemblages are well-preserved in some areas (WIESENEDER, 1961; KOLLER and WIESENEDER, 1981; MOREAU, 1981; MOYSCHEWITZ, 1995). Some stages of pre-Alpine metamorphism can be recognized because of the relationship with Carboniferous and Permian intrusions (PEINDL, 1990). A first stage of metamorphism predates Carboniferous intrusions and is responsible for partial melting in metapelites. The peak metamorphic conditions were reached after the intrusion of the muscovite-biotite granites by progressive decomposition of muscovite in granites to K-feldspar and sillimanite (PEINDL, 1990). Therefore, the peak metamorphic conditions which can be described as localized granulite-facies (see below), took place after intrusion of the first generation of two-mica granites between Early Carboniferous and Permian (for details, see NEUBAUER, 1988b; PEINDL, 1990; NEUBAUER et al., 1992).

The time of the migmatitization is unknown, probably it coincides with the time of the intrusion of the Carboniferous two-mica granites. Chilled margins in the granites and granite-dykes are missing, which is an argument for a higher temperature of the country rocks (migmatites). Arguments for a pressure of about 4 kbar at the time of the anatexis/intrusion are (PEINDL, 1990): (1) the existence of sometimes slightly corroded magmatic muscovite in the two-mica granites (according to HYNDMAN (1985) the lower stability limit for muscovite in granitic melts is 4 kbar), and (2) the existence of pseudomorphs of Alpine kyanite after Variscan andalusite in a contact aureole of the Variscan Wullmenstein granite (exposed north of Hartberg; PEINDL, 1990).

Clinopyroxene-bearing amphibolites are associated with migmatites. Textural relationships indicate progressive replacement of green by brown hornblende and finally by clinopyroxene.

A temperature rise follows the crystallization of the granites, which causes prograde replacement of magmatic muscovite by sillimanite + K-feldspar + quartz. Rare small green patches in the granites are interpreted to represent small frozen melt inclusions which formed along grain boundaries (PEINDL, 1990).

Before Triassic, but at latest at the Permian/Triassic boundary the Wullmenstein granodiorite intruded. Muscovites are slightly corroded by the melt but they do not show any sign of a temperature rise following the crystallization of the magma.

Due to the strong overprint by Alpine metamorphism, it is impossible until now to recognize the Variscan retrograde metamorphic P-T-path. Permo-Mesozoic sediments in the northern part of the Raab Alps proof the uplift of the Raabalpen complex at the end of the Variscan metamorphic evolution.

3.3. LOWER AUSTROALPINE NAPPE COMPLEX (TYPOLOGY A)

3.3.1. Katschberg, Radstadt and Innsbruck Quartzphyllite Units

Fossil-bearing quartzphyllites of Silurian to Early Devonian depositional age occur in several independent nappes of the Lower Austroalpine units (e.g., NEUBAUER and SASSI, 1993, for review). Petrographic data generally indicate lower and upper greenschist-facies metamorphic conditions, which were prooven now in some of these areas to be Late Variscan according to $^{40}Ar/^{39}Ar$ dating of white mica. DINGELDEY et al. (1997) reported a disturbed $^{40}Ar/^{39}Ar$ spectrum with a minimum age of metamorphism of c. 250 Ma, and, consistent with SASSI and SPIESS (1992), c. 400 °C and c. 4 kbar as conditions of metamorphism for the Innsbruck quartzphyllite. Consequently, most index minerals shown by HOSCHEK et al. (1980) appear to record Late Variscan mineral growth.

Similarly, mineral parageneses of the Radstadt and Katschberg quartzphyllites are variable (metapelite: Ms + Ab + Chl ± Grt; mafic rocks: Qtz + Ab + Chl + Ep + Ttn ± Bt ± Act; e.g., EXNER, 1989, 1996; GENSER, 1992) and may depict lower to higher greenschist-facies for peak metamorphic conditions. Marginal portions of the Radstadt quartzphyllite are incompletely retrogressed within lower greenschist-facies metamorphic conditions along semiductile shear zones (GENSER and KURZ, 1996). GENSER and WIJBRANS (in review) reported two single grain $^{40}Ar/^{39}Ar$ muscovite ages of c. 240 Ma from the Katschberg quartzphyllite constraining a Late Permian age of cooling following greenschist-facies metamorphism. The geological significance of this age remains uncertain.

3.4. MIDDLE AUSTROALPINE UNITS

The Middle Austroalpine units comprise a number of pre-Alpine basement units which were metamorphosed within mostly medium-grade conditions and deformed together during the Variscan orogeny. Southern sectors were overprinted by Alpine medium-grade, northern sectors by Alpine low-grade metamorphic conditions.

The Middle Austroalpine units of central eastern sectors, east of the Tauern window, contain several lithotectonic units, from top to base (Fig. 1): (1) the Micaschist-Marble complex (mainly exposed in the Niedere Tauern), (2) the Speik complex (exposed in the Gleinalpe), (3) the "Core complex", (1) to (3) together constitute the Muralpen units, (4) the Kor-Saualpe Eclogite-Gneiss complex (sometimes also referred to as the Koriden complex, and (5) the Kor-Saualpe Micaschist group (the latter two units are exposed in the Koralpe and Saualpe: Fig. 1).

3.4.1. Muralpen units (various typologies)

The Core complex is exposed within the center of structural domes beneath the Speik and Micaschist-Marble complexes in the area east of the Tauern window, e.g. within the Gleinalpe-Rennfeld mountains, northern segments of the Troiseck-Floning, the Seckauer Tauern, the Bösenstein and the Schladminger Tauern, which are part of the Niedere Tauern (Fig. 1).

In all these areas, the Core complex consists of strongly foliated biotite plagioclase paragneisses ("Biotite plagioclase gneiss complex"), mylonitic plagioclase metagranitoid ("fine-grained orthogneisses"), and huge masses of various amphibolites including mylonitic banded amphibolites (e.g., FRANK et al., 1976; NEUBAUER, 1988a). These strongly foliated sequences are intruded by a layered tonalite suite (NEUBAUER, 1988a) and granitic and granodioritic plutons. The latter include a sheet-like augen gneiss, forming the hangingwall boundary of the Core complex. All plutonic rocks are deformed under amphibolite-facies metamorphic conditions, too.

Structural relationships indicate that the Core complex, the Speik complex and the Micaschist-Marble complex share a common Variscan thermal history which overprints earlier tectonothermal events in the Core complex.

The so-called "Caledonian" thermal event can be inferred only for the Core complex, where U–Pb zircon lower intercept data between 450 and 425 Ma have been reported from the augen gneiss within a metatonalite suite, and the garnet amphibolite. In addition, zircons from paragneiss plot close to the discordia of this age (NEUBAUER and FRISCH, 1993; NEUBAUER et al., in press).

The superposition of the Speik complex on top of the Core complex as well as the superposition of both by the Micaschist-Marble complex seems to predate the common migmatitization that overprinted all three units. Micaschists are often detached from the Speik and Core complex. An intrusion relationship of the augen gneiss protoliths and pegmatites within the Micaschist-Marble complex is assumed because of field relationships and similar Rb–Sr ages (NEUBAUER, 1988a). One of the augen gneiss layers is discordant to the country rocks in the Speik complex: it climbs in southwesterly direction through the Speik complex and also reaches the lowermost parts of Micaschist-Marble complex. In the continuation, pegmatite swarms occur, suggesting a possible genetic relationship between pegmatite and augen gneiss protoliths. Because of the early Carboniferous age of the augen gneiss, a Variscan top-to-the-southwest shear is supposed for Variscan thrusting (NEUBAUER, 1988 a, b). A large Variscan ophiolite nappe (emplacement of the Speik complex) was postulated, therefore, by NEUBAUER (1988a). The peak metamorphic conditions are assumed to reach upper amphibolite-facies metamorphic conditions, including formation of migmatites during early Carboniferous. Metamorphic overprint was associated with deformation, therefore only less deformed portions monitor the pre-Alpine metamorphic conditions best. The Gleinalm core complexes, also exposed within the Troiseck-Floning-Zug, Seckau and Schladming cores, generally expose migmatites with a complex metamorphic history that interfers with various intrusions of different age. The best studied example is the Gleinalpe region where precursor rocks of acidic, heavily deformed granodioritic orthogneisses intruded before 500 Ma (HAISS, 1991), and were followed by intrusions of the precursor rocks of some granitic orthogneisses at c. 440–420 Ma (SCHARBERT, 1981; NEUBAUER and FRISCH, 1993) and by many mafic to acidic intrusions of Variscan age (c. 360–330 Ma; NEUBAUER and FRISCH, 1993, for review). The 440–420 Ma age of granitoid intrusion was associated with migmatite formation in country rocks. A second stage of migmatite formation was associated with above mentioned Variscan nappe stacking. The present metamorphic state of northern sectors of the Muralpen units was obviously established during Variscan metamorphism as indicated by Variscan white mica ages (Rb–Sr and $^{40}Ar/^{39}Ar$) within the Troiseck-Floning (HANDLER, 1994; DALLMEYER et al., 1998). Cretaceous amphibolite-facies metamorphic conditions were only reached in southern sectors of the Gleinalpe region (NEUBAUER et al., 1995).

3.4.2. Kor-Saualpe Eclogite-Gneiss complex (uncertain typology)

The Kor-Saualpe Eclogite-Gneiss complex exposed in the Koralpe, Saualpe and Pohorje mountains consists of a thick package of kyanite-bearing paragneiss which includes major lenses of eclogites and amphibolitic eclogites (Fig. 1). Other intercalations are rare relics of metagabbros, marbles, manganese quartzites, calcium silicate rocks, and widespread pegmatites. The eclogites are derived from two sources: kyanite-bearing eclogites are derived from gabbros (clinopyroxene cumulates), kyanite-free eclogites from N- to E-type MOR basaltic liquids (e.g., MILLER and THÖNI, 1997). THÖNI and JAGOUTZ (1992) found a Permian age for one of the gabbroic protoliths and an Alpine age of eclogite metamorphism. One of the pegmatites within a retrogressed eclogite yielded a Permian Rb–Sr whole rock age (S. SCHARBERT, cited in GÖD, 1989). Coarse-grained pegmatitic muscovites of pegmatites in paragneissic country rocks yielded numerous Rb–Sr ages in the range of 250–220 Ma (MORAUF, 1981) indicating partial resetting during Alpine metamorphic overprint in amphibolite-facies metamorphic conditions. Intra-Permian ages have been found also in Rb–Sr thin slab data of the mylonitic "Plattengneis" (FRANK et al., 1983) now confirmed by LICHEM et al. (1997).

The pre-Alpine history remains uncertain although recent U–Pb zircon data indicate Variscan zircon growth (HEEDE, 1997). Most workers agree that a metamorphic complex with low-pressure characteristics (andalusite occurrence) was intruded by numerous pegmatites in late Variscan times (e.g., MORAUF, 1980; FRANK et al., 1983). Low-pressure metamorphism was recently dated as Permian (SCHUSTER and THÖNI, 1996; LICHEM et al., 1997) and was likely associated with Permian mafic and pegmatitic intrusions into middle to shallow levels of the crust (THÖNI and JAGOUTZ, 1992; MILLER and THÖNI, 1997).

3.4.3. Micaschist Group of Koralpe and Saualpe (typology A')

The eclogite-bearing Gneiss group of the Koralpe and Saualpe is overlain by a number of lithotectonic complexes which are collectively referred to as Micaschist group. This includes the Plankogel complex with ophiolitic remnants, and several micaschist and amphibolite units. Since a long time (e.g., KLEINSCHMIDT et al., 1976; KLEINSCHMIDT, 1979), two stages of medium-grade metamorphism were known within these rocks because of the textural relationships of two staurolite generations and the presence of two Al-silicates (andalusite paramorphs, kyanite). The older staurolite was interpreted to record pre-Alpine metamorphic conditions. No conclusive age dating was done within these units, so that the exact age of pre-Alpine medium-grade metamorphism remains unknown.

3.4.4. Bundschuh-Einach complex (typology B)

In the area between the Tauern window and the Gurktal nappe complex, the Micaschist-Marble complex (here locally termed Aineck complex) is overlain by the Einach-Priedröf complex comprising paragneisses and the Bundschuh orthogneiss. Northern sectors of the Micaschist-Marble complex contain relics of, and pseudomorphs after staurolite. The Bundschuh orthogneiss differs strongly from other Austroalpine orthogneisses because of its high amount of muscovite and the unusual high Sr initial isotopic ratio of 0.738, and because of the Silurian to Devonian Rb–Sr whole rock model age and a Rb–Sr muscovite age of 354 ± 4 Ma (HAWKESWORTH, 1976; FRIMMEL, 1986, 1988).

3.4.5. Kreuzeck-Goldeck mountains (typologies A and A')

Southern sectors of the Kreuzeck-Goldeck mountains comprise well-preserved pre-Alpine basement units (SCHNEIDER et al., 1993; REIMANN and STUMPFL, 1985). Metamorphic overprint generally increases from south to north. Very low-grade units are preserved in the southeastern Goldeck Mountains (the Goldeck Mts. represent the eastern extension of the Kreuzeck Mts.; Fig. 1), greenschist-facies metamorphic units along an east-west extending zone along the southern Goldeck-Kreuzeck mountains, and amphibolite-facies metamorphic units along central sectors of the Kreuzeck mountains. The amphibolite-facies metamorphic unit was correlated to the Strieden unit by HOKE (1990). The boundary between the Strieden unit and the low-grade unit was examined in western sectors, where it is represented by a mylonite zone (Strieden shear zone), which was formed within upper greenschist-facies metamorphic conditions (NEUBAUER, unpubl. data). The conditions of pre-Alpine amphibolite-facies metamorphism within the Strieden unit were estimated, based on the presence of sillimanite and metapelite mineral assemblages, with 5.5 ± 1.5 kbar and 650 ± 100 °C by HOKE (1990). K–Ar biotite (BREWER, 1969) and muscovite ages (c. 300 Ma) proof a late Variscan metamorphic overprint on these units (see summary of age data in HOKE, 1990).

3.4.6. Austroalpine units south of the Tauern window (various typologies)

Austroalpine basement units to the south of the Tauern window are divided by the E-trending Defreggen-Antholz-Vals (DAV) fault (= SAM to the south of the Tauern window) into a northern block which is strongly overprinted by combined Cretaceous and Cenozoic metamorphic events, and a southern, Variscan block (BORSI et al., 1978).

The northern block includes the so-called Cima Dura phyllite, which is an Alpine phyllonitic unit (MAZZOLI et al., 1993, 1994). The southern block includes a structurally deeper micaschist/paragneiss unit and, tectonically separated, the overlying Thurntal quartzphyllite unit. The pre-Alpine age of metamorphism in the micaschist/paragneiss unit is constrained by numerous biotite Rb–Sr cooling ages in micaschists, falling in the range of 280–294 Ma. However, some values in the range of 260–200 Ma display a local, partial, Alpine rejuvenation related to tectonized levels (BORSI et al., 1978). A Rb–Sr whole rock age of 497 ± 38 Ma was obtained by BORSI et al. (1973) from the micaschist/paragneiss sequence, and was interpreted as the age of the first metamorphism. This age was a source of discussions among the authors, also due to the complex petrologic situation related to the Variscan metamorphism.

New data on all three units were presented by SCHULZ et al. (1993), and SCHULZ (1990, 1997). The northern unit (AMU - amphibolite-metapelite-marble unit according to Schulz, 1990, 1997) includes gneisses and eclogites for which SCHULZ (1997) argued for a pre-Alpine age of formation consistent with previous authors. However, LINNER (1995) reported preliminary Sm–Nd whole rock ages interpreted to represent a Cretaceous age of eclogite-facies metamorphic conditions. This would be in line with Cretaceous K–Ar ages for phengite reported from this unit (BORSI et al., 1978; STÖCKHERT, 1984). The Metapelite unit exposed to the south of the DAV fault includes migmatites for which P-T conditions of 650 °C and 6 ± 1 kbar were deduced (STÖCKHERT, 1985), confirmed by SCHULZ (1997), who reported 650–670 °C and 5–7 kbar.

The Uttenheim-Villa Ottone pegmatite yielded Rb–Sr whole rock ages of 262 ± 5 Ma (BORSI et al., 1980b) and 266 ± 6 Ma (CLIFF, pers. comm. in HOKE, 1990), interpreted to date the age of pegmatite-formation, and also to represent the minimum age of migmatization in adjacent areas.

3.4.7. Ötztal basement complexes (typology C)

The Ötztal basement consists of a widely distributed paragneiss complex, the Central Amphibolite and the Micaschist complexes including the Schneeberg, Laas, and Ortler complexes in the hangingwall. The Central Amphibolite includes partly retrogressed eclogite which were derived from gabbro (MILLER and THÖNI, 1995; SPIESS, 1991). The conditions of eclogite metamorphism were recently estimated to be at c. 730 °C and 27 kbar (MILLER and THÖNI, 1995). Sm–Nd garnet-whole rock ages proof a Variscan age of the eclogite metamorphism (c. 373 ± 20 and 359 ± 18 Ma; MILLER and THÖNI, 1995).

The paragneisses include variable lithologic members which were intruded by Late Ordovician granites. They record pre-Alpine polymetamorphism with a mineral zonation shown by distribution of alumosilicates sillimanite, andalusite and kyanite (PURTSCHELLER, 1969). VELTMAN (1986) reported 600–750 °C and c. 8 kbar for the sillimanite zone, and 570–650 °C and 6 kbar for the northern kyanite zone. In the andalusite zone of the western Ötztal basement, TROPPER and HOINKES (1996) reported garnet growth during pressure release with equilibrium P-T conditions at the rims between 570–640 °C and 5.8–7.5 kbar. The age of garnet growth was determined by the Sm–Nd method with a range from 343 ± 2 and 331 ± 3 Ma (SCHWEIGL, 1995; HOINKES et al., 1997). Together, the basement rocks were deformed within amphibolite-facies metamorphic conditions.

More and more evidence for pre-Late Ordovician metamorphic events has been found in limited areas: the northern part within the Winnebach migmatite and in the northwestern part. SÖLLNER and HANSEN (1987), CHOWANETZ (1990) and KLÖTZLI-CHOWANETZ et al. (1997) presented evidence for a pre-Variscan age of migmatite formation. In some regions pre-Variscan Rb–Sr and $^{40}Ar/^{39}Ar$ mineral ages are preserved (BERNHARD et al., 1996; HOINKES et al., 1997). However, a regional survey displayed that Variscan muscovite Rb–Sr and K–Ar ages are preserved over large sectors of the Ötztal basement units (THÖNI, 1981, 1986; DEL MORO et al., 1982; HOINKES and THÖNI, 1993; for data, see Tab. 2). These are related to regional cooling following amphibolite-facies metamorphic conditions.

3.4.8. Scarl-Campo nappes (various typologies)

Only a few recent data are available from the basement of the Scarl-Campo nappes. Consequently, the review follows the description of

HOINKES and THÖNI (1993). The basement of the Scarl-Campo nappes was largely affected by pre-Alpine medium-grade metamorphism due to the occurrence of staurolite in micaschists (BERTOLO, 1996; SEGATO, 1997), associated with paragneisses, amphibolites (e.g., POLI, 1989) and marbles (Laas marbles); these sequences grade in southern sectors into the low-grade Martell quartzphyllite. Locally, kyanite was reported from biotite-plagioclase paragneiss. The sequences include the Scarl orthogneiss for which a Rb–Sr age of 336 ± 7 Ma was reported (THÖNI, 1981). Rb–Sr and K–Ar ages of coarse-grained white mica range between 296 and 223 Ma. The Martell "granite" is an inhomogeneous, vein-type aplitic-pegmatitic leucogranite for which a Rb–Sr whole-rock age of 271 ± 3 Ma was reported (BOCKEMÜHL, 1988). This leucogranite intruded into a partly retrogressed unit in which garnet, staurolite, biotite were found (BOCKEMÜHL, 1988). Retrogression is due to Cretaceous overprint.

3.5. AUSTROALPINE BASEMENT UNITS ALONG THE PERIADRIATIC FAULT

3.5.1. Peridotites and granulites of the Pohorje Mts. (uncertain typology)

A thick sequence of kyanite-bearing paragneisses and micaschists occurs in the Pohorje mountains. Together with a unit characterized by the presence of marbles, quartzites and amphibolites, both units make up the country rocks in which the Alpine granodiorite-tonalite Pohorje body is injected (ALTHERR et al., 1995). Within the paragneiss sequence granulites, eclogites and garnet peridotites (including partly serpentinized dunites and harzburgites) occur (HINTERLECHNER-RAVNIK, 1982, 1988; HINTERLECHNER-RAVNIK and MOINE, 1977). This basement unit is situated immediately north of the Periadriatic Lineament, similarly to other Austroalpine pre-Alpine granulitic and HP ultramafic rocks (e.g. Ulten zone: see below).

Recent studies on the Pohorje eclogites and meta-ultrabasites by HINTERLECHNER-RAVNIK et al. (1991 a, b) show a decompressional polymetamorphic evolution. The HP stage represents the oldest event, older than foliated pegmatite and aplite veins of probably Variscan age. The low-pressure stage is of Alpine age.

Kyanite-bearing eclogites accompanying typically the garnet-peridotites suggest a similarity to the eclogite-bearing Kor-Saualpe Eclogite-Gneiss complex (HINTERLECHNER-RAVNIK, 1982, 1988). VISONÁ et al. (1991) refer the major ultrabasic body to an original layered gabbro body, and point out a N-MORB affinity for the protolith of the eclogites.

The age of the protoliths and the age of metamorphism is uncertain. The garnet peridotite and granulite have a similar tectonic position to the garnet peridotites and granulites of the Ulten zone for which a Variscan age of metamorphism is constrained by geochronological data (see below).

3.5.2. Eisenkappel and eastern Gailtal basement (uncertain typology)

A small tectonic segment of crystalline basement rocks occurs immediately north of the Periadriatic line in the eastern Karawanken (Eisenkappel basement: EXNER, 1972; FANNINGER, 1978). It consists of a schist-paragneiss sequence, which was intruded by the Karawanken pluton. The sequence mainly consists of biotite-plagioclase paragneiss, with intercalations of graphite-rich quartzites and gneisses, amphibolites and microcline orthogneiss (EXNER, 1972; VON GOSEN, 1989). The age and metamorphic history has not been investigated yet.

The Karawanken granite pluton is mainly composed of granite and subordinate granodiorite, quartzdiorite, diorite and gabbro, with veins of granodiorite, pegmatite, aplite and lamprophyre. The age of the pluton is badly constrained. A K–Ar amphibole age (252 ± 9 Ma; CLIFF et al., 1974) and a Rb–Sr biotite age (232 ± 9 Ma; SCHARBERT, 1975) suggest late Permian cooling of the Karawanken granite after intrusion. Recently, THÖNI (pers. comm.) measured a Rb–Sr whole rock isochron of 206 ± 10 Ma.

The contact aureole was petrologically investigated by MONSBERGER et al. (1994). The following mineral reactions in metapelites defining five metamorphic zones approaching the contact were observed:

(1) Chl + Ms + Qtz = Crd + Bt + H_2O
(2) Chl + Ms = Crd + Bt + And + H_2O
(3) Ms + Qtz = Kfs + And + H_2O
(4) Bt + And + Qtz = Crd + Kfs + H_2O
(5) Kfs + Pl + Qtz + H_2O = melt

From zone (1) to zone (5) a temperature increase from 520 °C (2 kbar) to 690 °C (2 kbar) is implied by the reaction sequence.

Granite, diorite and augen gneiss which are comparable to metagranitoids of the eastern Karawanken occur also as tectonic lenses along shear zones in the eastern Gailtal crystalline (EXNER, 1985).

3.5.3. Gailtal Metamorphic complex (typology A)

The Gailtal Metamorphic complex (Gailtal basement in Fig. 1) extends between the Drauzug and the Periadriatic fault. The eastern and southern part represents a quartzphyllite unit which remained within upper greenschist-facies metamorphic conditions. This situation is different in the western and northern sectors, where medium-grade metamorphic units occur. Both units are separated by an Alpine greenschist-facies ductile shear zone (BECKER et al., 1987; UNZOG, 1989). Beside garnet, staurolite, kyanite, and sillimanite were reported from metapelite and paragneiss of these sectors of the Gailtal Metamorphic complex (PAULITSCH, 1960; PURTSCHELLER and SASSI, 1975; HEINISCH, 1987).

3.5.4. Ulten complex

The Ulten zone exposes migmatitic gneisses and ultramafic rocks including garnet peridotite and other ultramafics (MARTIN et al., 1993; GODARD et al., 1996). HAUZENBERGER et al. (1996) and HÖLLER and HOINKES (1996) found a two-stage metamorphic evolution recorded in eclogites. Based on garnet-clinopyroxene thermometry and jadeite contents in omphacite, they found c. 700 ± 50 °C and > 15 kbar for peak metamorphic conditions. Subsequent decompression and regional equilibrium took place at c. 6–8 kbar and 600 ± 50 °C. OBATA and MORTEN (1987) reported spinel peridotites that formed at conditions of 25–20 kbar and c. 1200 °C, and garnet peridotite metamorphic conditions at c. 800 °C and 20 kbar. GEBAUER and GRÜNENFELDER (1978) reported U–Pb zircon ages of 332–326 Ma within these rocks.

3.6. UPPER AUSTROALPINE UNITS (MOSTLY TYPOLOGY A)

Upper Austroalpine basement units occur along northern margins of the Eastern Alps and in a number of independent klippens. Latter include the Steinach nappe, Gurktal nappe complex and its outliers in the Sausal, Remschnigg, and St. Anna regions (as well as subsurface basement exposures below the Styrian basin: FLÜGEL, 1988), and the Graz nappe complex. The Grauwacken and Gurktal nappe complexes include distinct medium-grade basement complexes. With the exception of the Steinach nappe, where Alpine overprint is minor (e.g., FÜGENSCHUH, 1995), all other complexes show polymetamorphic very low- to low-grade metamorphic conditions within a similar range during late Variscan and Alpine times. Clear proof for pre-Alpine metamorphism in them can only be derived in conjunction with textural studies below the post-Variscan unconformities. The presence of less deformed Late Carboniferous to Permian cover sequences indicates both (1) the grade of Variscan metamorphism and (2) the Late Variscan age of metamorphism within fossiliferous Early Paleozoic to early Late Carboniferous sedimentary sequences.

3.6.1. Graz nappe complex (typology A)

The entire Graz nappe complex and its extension beneath the Styrian Neogene basin (FLÜGEL, 1988) is composed of Silurian to early Late Carboniferous (Westfalian A) sedimentary sequences which were obviously overprinted during two metamorphic stages, e.g., Variscan and Cretaceous metamorphic events. The Variscan metamorphism is only proved by the presence of incompletely resetted K–Ar ages of muscovite (FRANK et al., 1987). This may be correlated with a metamorphic zonation ranging from upper greenschist to amphibolite-facies conditions present in the eastern/lower nappes within the Graz nappe complex. Part of these mineral assemblages may indicate a Cretaceous metamorphic overprint, too (FRANK, 1987). However, no post-Variscan cover sequences are present on the basement units of the Graz nappe complex.

3.6.2. Gurktal nappe complex (typology A)

The Gurktal nappe complex (GNC) comprises three Alpine nappes: (1) the structurally lower Murau nappe consisting of Late Silurian to early Middle Devonian sedimentary sequences; (2) the upper Stolzalpe nappe with Ordovician to early Late Carboniferous sedimentary sequences unconformably overlain by Westfalian C-D to Permian cover sequences (NEUBAUER and SASSI, 1993); and (3) the Ackerl nappe. Both, Murau and Stolzalpe nappes are polymetamorphic, i. e. they record similar Late Variscan and Cretaceous greenschist-facies metamorphic conditions. In a few cases (western and central sectors of the GNC), the Variscan grade and age of the low-grade metamorphism is indicated by a gap in metamorphic conditions between basement and Late Carboniferous cover rocks within the Stolzalpe nappe. Here, the basement comprises lower to medium greenschist-facies mineral parageneses with Chl + Ab + Ep ± Act ± Bt in mafic rocks. Preliminary results of $^{40}Ar/^{39}Ar$ muscovite age dating range between c. 315–310 Ma for the western GNC (NEUBAUER and HANDLER, unpublished results). Cover sequences are within very low-grade metamorphic conditions according to vitrinite reflectance data (RANTITSCH, pers. comm.).

The Alpine Ackerl nappe comprises two distinct pre-Alpine basement sequences which have been penetratively deformed under different metamorphic conditions. The Ackerl Micaschist unit, in a footwall tectonic position, comprises garnet-bearing micaschists, albite-chlorite rich micaschists and granites. The only diagnostic mineral assemblage (Grt + Phe + Ab + Qtz) may indicate high-pressure/low-grade metamorphic conditions. The Ackerl Gneiss unit, in the hanging wall tectonic position, comprises gneisses with the Bt + Olg + Qtz + Ms + Grt + St assemblage, indicating clear evidence for the lower amphibolite facies metamorphic imprint. Both units are separated by a ductile shear zone that formed under upper greenschist-facies metamorphic conditions. $^{40}Ar/^{39}Ar$ white mica ages of a 310–300 Ma show similar late Variscan postmetamorphic cooling of both units (DALLMEYER et al., 1996). Consequently, the Alpine overprint was minor, and did not exceed lower greenschist-facies metamorphic conditions.

3.6.3. Grauwacken nappe complex (Noric group: typology A; Kaintaleck nappe: typology B and C)

The eastern Grauwacken nappe complex (GWNC) comprises several Alpine nappes which contain pre-Alpine basement units. These are essentially the Kaintaleck nappe with the Kaintaleck metamorphic complex, and the Noric Group that extends towards the western GWNC.

The Noric Group is unconformably overlain by the Permian to Paleogene sediments of the Northern Calcareous Alps. Consequently, the presence of Variscan low-grade metamorphic imprint can be proven in it by the presence of ductile metamorphic fabrics, although detailed studies on the intensity of metamorphism are missing. Evidence for "late Variscan" tectonothermal activity in the source areas adjacent to Carboniferous and Permian clastic cover sequences is indicated by $^{40}Ar/^{39}Ar$ ages of c. 310–303 Ma which have been reported for detrital mica within these units (HANDLER et al., 1997).

The Kaintaleck nappe of the eastern Grauwacken zone comprises a number of various basement lithologies that generally record, in contrast with the surrounding units, medium-grade metamorphic conditions. Lithologies vary from paragneiss, garnet micaschist, amphibolite, marble and serpentinites to a few concordant trondhjemite gneiss lenses (common within some amphibolites) and granitic aplite gneiss (common in some paragneisses). Detailed studies of metamorphic conditions are scarce except for some amphibolites (Ritting type amphibolite). These appear to originate from eclogite, and represent symplectitic garnet-amphibolite now retrogressed to epidote amphibolite. Extensive geochronological work was carried out including U–Pb zircon, and Rb–Sr and $^{40}Ar/^{39}Ar$ mineral dating. U–Pb zircon ages suggest two different ages at c. 520–500 Ma, and c. 390 Ma (NEUBAUER and FRISCH, 1993). The latter event is also constrained by the presence of aplite with a U–Pb upper intercept age of c. 363 Ma. Rb–Sr and $^{40}Ar/^{39}Ar$ white mica ages range from c. 413 to 360 Ma, therefore constraining a Caledonian event (HANDLER, 1994; HANDLER et al., 1999).

3.6.4. Steinach nappe

The Steinach nappe comprises garnet-bearing phyllites, mafic schists, ferrigeneous dolomites and magnesites, and includes tectonic lenses of garnet micaschists with relics of staurolite (SASSI and MENEGAZZO, 1971; FRIZZO and VISONÁ, 1981). The garnet is rich in spessartine component, the average b cell parameter is low (SASSI and SPIESS, 1992). SASSI and MENEGAZZO (1971) suggested lower greenschist-facies metamorphic conditions which affected these sequences before deposition of the overlying unmetamorphic Nösslach Conglomerates (Westfalian-Stefanian).

4. Southalpine unit (typology A)

Basement rocks of the Southalpine unit of the Eastern Alps are exposed extending from the Karawanken through the Carnic Alps to the Brixen quartzphyllite area along the Periadriatic fault, in the Valsugana-Agordo area along the Valsugana thrust fault, and further to the south on the Recoaro area (SASSI et al., 1995).

Fossiliferous Ordovician to early Late Carboniferous basement rocks of the Karawanken and Carnic Alps are within very low-grade to subordinately low-grade metamorphic conditions according to vitrinite reflectance and illite crystallinity data (RANTITSCH, 1993, 1997; LÄUFER, 1996; LÄUFER et al., 1997). The age of metamorphism largely remains uncertain. The stronger metamorphic overprint in the Eder nappe of the eastern Carnic Alps helps to define a polymetamorphic unit with Variscan low-grade conditions overprinted by a little weaker Cretaceous, and still weaker Oligocene metamorphic overprint. K–Ar muscovite ages are c. 282 ± 8 Ma which are the same as recently found within similar rocks by the $^{40}Ar/^{39}Ar$ method (LÄUFER et al., 1997).

Towards west, the Variscan metamorphism prevails and appears to increase from very low-grade to low-grade conditions (ÁRKAI et al., 1995; SASSI et al., 1995), reaching the almandine greenschist-facies metamorphic conditions in the Sarntaler-Brixen area (SASSI and ZIRPOLI, 1989).

Biostratigraphic data are only available for the Agordo phyllites, where acritarch assemblages were found, referable to the time range Late Cambrian to Early Tremadocian (SASSI et al., 1985; KALVACHEVA et al., 1986). These acritarch-bearing phyllites gave a Rb–Sr whole rock isochron age of c. 350 Ma (CAVAZZINI et al., 1991), consistent with other radiometric age values previously obtained by other authors (review in SASSI et al., 1995).

5. Concluding remarks

As pointed out in the introduction, the data presented from the Eastern Alps indicate (1) a different metamorphic history in terms of timing, degree, and nature of the metamorphic evolution and (2) that major portions are characterized by a polymetamorphic pre-Alpine history. Four types of basement units may be distinguished according to their pre-Alpine metamorphic history, here reported in a chronological order.

(i) Units recording a "Caledonian" metamorphism with variable Variscan overprint (typology C): Units with polyphase amphibolite facies metamorphism, including Ordovician anatexis, and virtually lacking Silurian-Devonian thermal overprint, as for instance in the Ötztal basement. These units are in part overprinted by late Variscan medium- to low-grade metamorphism. Cooling of these units occurred during late Variscan times as suggested by consistently uniform Rb–Sr and K–Ar ages between c. 315–295 Ma.

(ii) Units recording a Silurian-Devonian metamorphism (typology B): The Penninic basement and some Lower, Middle and Upper Austroalpine basement complexes record Silurian-Devonian

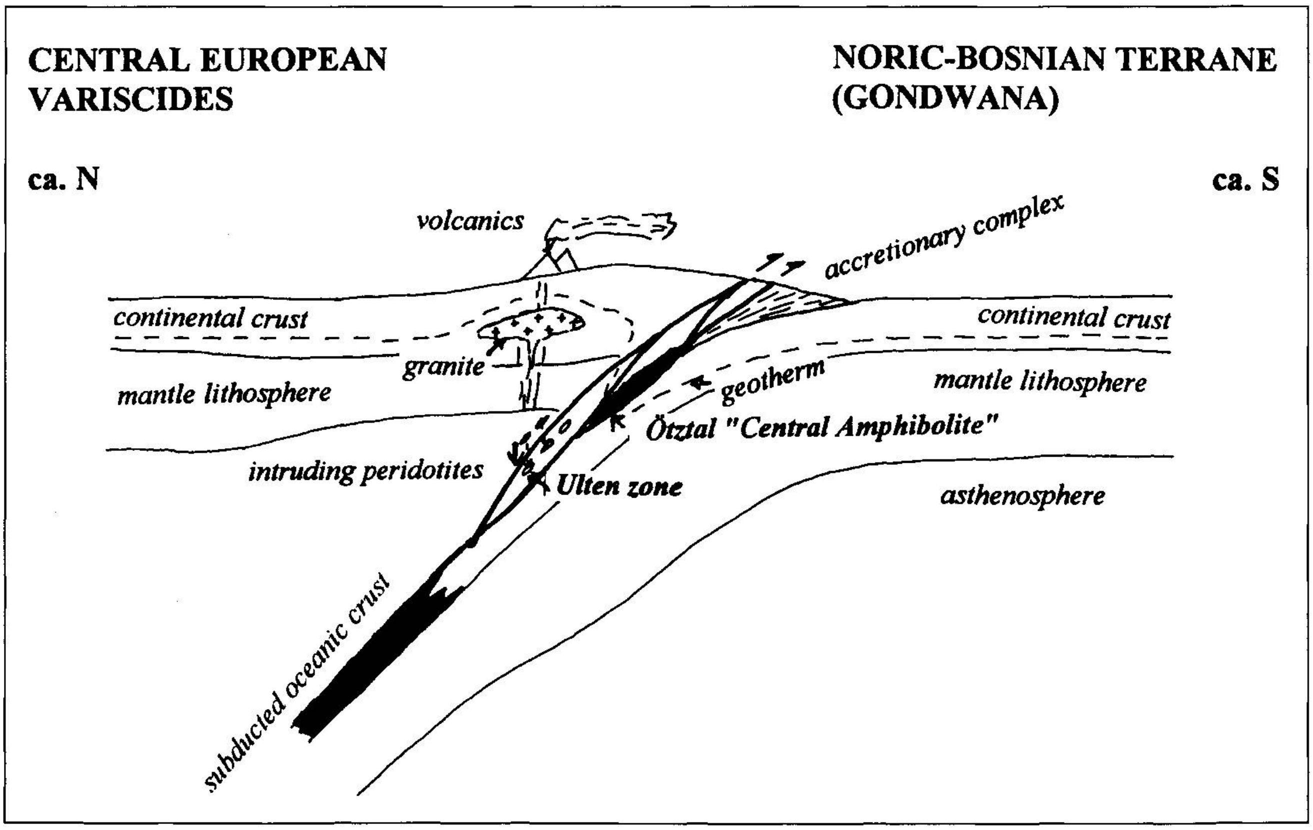

Fig. 4 Schematic model for explanation of Variscan P-T evolution of basement units exposed in the Eastern Alps. The Noric-Bosnian terrane corresponds to fossil-bearing pre-Late Carboniferous, Austroalpine and Southalpine units exposed in the Eastern Alps. These are interpreted to have collided with metamorphic units which were accreted to the southern margin of Central European Variscides (e.g., NEUBAUER and VON RAUMER, 1993).

metamorphism in the Penninic units including eclogite metamorphism. This history contrasts with the tectonothermal history of the Noric Group. Consequently, units with this history were considered to represent an active continental margin along which subducted units were accreted during mid-Paleozoic times.

(iii) Units only recording low-grade Variscan metamorphism (typology A): The Noric group with fossiliferous, very low- to low-grade, metamorphic units with a late Variscan metamorphic overprint. According to the fact that continuous fossil-bearing sections reaching early Namurian, locally Westfalian A (e.g., within the Paleozoic of Graz: EBNER, 1978), the age of the low-grade metamorphic overprint cannot be earlier than c. 320–310 Ma. This is in accordance with the observation that mainly late Variscan Rb–Sr and K–Ar mineral ages in the interval from 315–300 Ma (Tab. 2), were reported from these units. Furthermore, the weak metamorphic overprint was associated with nappe stacking which is also well-constrained by biostratigraphic data of the same age interval.

(iv) Units where only a medium- to high-grade Variscan metamorphism has been recognized (typology A'): These include the basement of Kirchberg-Stuhleck nappe, major portions of the Middle Austroalpine unit as exposed e.g. in the Kreuzeck mountains, and the Ackerl nappe.

The data support models which explain the Variscan history of Alpine basement units as a result of continent-continent collision between Gondwana-derived continental elements (units of typologies A, A', C) and northern portions of Central European Variscides and Fennosarmatia (Fig. 4). Evidence for these models include Silurian-Devonian (typology B) and Early Variscan eclogites, as a result of high-pressure metamorphism during subduction of continental and possible oceanic elements (Ötztal Central Amphibolite: MILLER and THÖNI, 1995), and Silurian-Devonian metamorphism as a result of accretion processes (e.g., VON RAUMER and NEUBAUER, 1994) when these units came into a lower plate tectonic position (Fig. 4). The uniform late Variscan tectonothermal overprint affected Ordovician to early Late Carboniferous passive continental margin sequences and are explained to record final Variscan continent-continent collision (e.g., NEUBAUER, 1988b). The incorporation of mantle rocks into the continental crust may be explained by incorporation of sinking garnet peridotites into the subducted continental rocks of the Ulten zone according to a recently published model of BRUECKNER (1998). Continental crust and peridotites have subsequently been exhumed together. Exhumation of subducted continental crust may be driven by buoyancy as recently demonstrated by means of analogue modelling by CHEMENDA et al. (1997).

More and more evidence for a separate Permian metamorphic event is found in various units. This is constrained by Sm–Nd garnet-whole rock ages as well as by Rb–Sr and K–Ar cooling ages (Tab. 2). In some areas, pegmatites appear to be associated with Permian-age metamorphic rocks. Pegmatite and local gabbro intrusions, local migmatite formation, and the scattered record of andalusite suggest a temperature-dominated event. This appears to record magmatic underplating due to a heat input by gabbros. Consequently, the Permian low pressure / high temperature metamorphism can be explained by ongoing post-Variscan extension due to rifting as already postulated earlier for western Southalpine and Austroalpine units (DAL PIAZ, 1993; SILETTO et al., 1993).

Acknowledgement

The manuscript resulted from discussion with many colleagues including Wolfgang Frisch, Dieter Gebauer, Hans Genser and Jürgen von Raumer. We appreciate suggestions to an earlier version of the manuscript by Rudolf Hänny and by an anonymous reviewer. The work of FN/RH and GH has been supported by grants of the Austrian Research Foundation (FWF grants P7405, 8652, 9918 to FN, grants S4705, S4708 to GH) which are gratefully acknowledged. FPS acknowledges support from Italian CNR and MURST.

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Manuscript received July 8, 1998; revision accepted December 16, 1998.