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Variscan orogeny in the Eastern Alps and Bohemian Massif: How do these units correlate?

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10 Figures and 2 Tables

Abstract

Basement units of the Eastern Alps and their lateral extension within the Carpathian arc and Dinarides (Alpine-Carpathian-Dinaride belt: ACD) include the principal suture zone of the southern branch of the European Variscides with generally ca. southward-, Gondwana-directed shortening. This contrasts with the Bohemian Massif (BM) where shortening was directed towards NNE, forming a syntaxis and orocline of the Variscan orogen due to indentation of the paleo-Alpine indenter into the combined Cadomian/Saxothuringian/Brunovistulian blocks. Both the ACD and BM basement units comprise continental fragments with a distinct pre-Carboniferous history. In the Bohemian Massif, the Moravo-Silesian block was overridden by the Gföhl terrane after consumption of the Raabs oceanic tract. The principal stage of deformation at highest P-T conditions was short (ca. 345-340 Ma) and also led to exhumation of hot mantle slabs along the suture, which contributed heat to partially remelt the continental orogenic wedge.

In the ACD belt, "externally" located, mainly medium-grade metamorphic units ("Variscan peri-Mediterranean metamorphic belt") overrode the internally located, peri-Apulian, fossil-bearing Noric-Bosnian terrane. Along the suture, remnants of Silurian-Devonian orogenic crust is preserved, which formed during a long-lasting Early Paleozoic period of subduction. The Variscan boundaries between these units of the ACD belt were entirely reactivated during Alpine tectonic processes. Consequently, the Carboniferous geodynamic evolution of the ACD belt comprises the following tectonic processes, due to continent-continent plate collision: (1) The consumption of pre-Carboniferous oceanic basins is inferred by the presence of ophiolitic sequences that subducted to depths corresponding to 27 kb (ultra-high pressure metamorphic conditions) ca. at the Devonian/Carboniferous boundary. (2) Tonalite-dominated suites intruded contemporaneously and formed above a subduction zone (e.g., the Helvetic "Cetic massif" and the Rennfeld layered suite within the Middle Austroalpine units). The Gondwana-derived Noric-Bosnian terrane was flexured during the subsequent late Early Carboniferous continental plate collision and a synorogenic flysch basin formed. Both thick-skinned and thin-skinned thrusting and A-subduction of the underplate continental crust developed during the early Late Carboniferous. Plate collision brought together the Gondwana-derived Noric-Bosnian terrane with tectonic elements that accreted along the Laurussian leading edge, north of the subduction zone during the Silurian and Devonian. Oblique continent-continent collision resulted in high surface uplift, large-scale exhumation of amphibolite-grade metamorphic crust and its denudation during ongoing transpressional or transtensional processes. Indentation by Gondwanian fragments ("Paleo-Alpine indenter") resulted in orocline formation within eastern and western sectors of the Variscides and the development of conjugate ductile shear zones. Contemporaneous rapid exhumation and associated cooling is evidenced by exclusively (Late) Carboniferous $^{40}Ar/^{39}Ar$ ages of detrital white mica recorded within Late Carboniferous molasse-type basins. These relationships suggest that at least the upper levels of the orogenic crust (>12 km) were entirely removed during orogenic processes prior to, and contemporaneous with, the formation of molasse-type intra-orogenic and peripheral foreland basins.

Introduction

The Carboniferous development of both extra-European Variscides, as exposed in the Bohemian Massif (BM), and in the Alpine-Carpathian-Dinarides belt (ACD) is crucial for the evolution of the Variscan orogenic belt. During this period, a more than 1000 km wide orogenic belt was formed, which reflects accretion and subsequent shortening of a number of terranes between Laurussia and Gondwana. However, there is no consensus on the presence and location of the principal suture zone (e.g., FRANKE, 1989; MATTE, 1986; FRANKE et al., 1995), which may have originated from the closure of one or several oceanic basins. Data from the basement within the Alpine-Carpathian belt may provide additional insights into the evolution of the Variscan belt, because basement units of this orogen differ in part from those exposed in the extra-Alpine Variscides (e.g., NEUBAUER and VON RAUMER, 1993; VON RAUMER, 1998).

The tectonic evolution of the Variscan orogenic belt of Central Europe is related to the amalgamation of various continental structural elements previously situated between Baltica and Gondwana during the Devonian and Late Carboniferous (e.g., MATTE, 1986, 1991; FRANKE, 1989; FRANKE et al., 1995). Several crustal units with contrasting pre-Variscan histories (Cadomian, Caledonian) are presently distributed within the Variscan orogenic belts of Central Europe (e.g., FRANKE, 1989; FRANKE et al., 1995).

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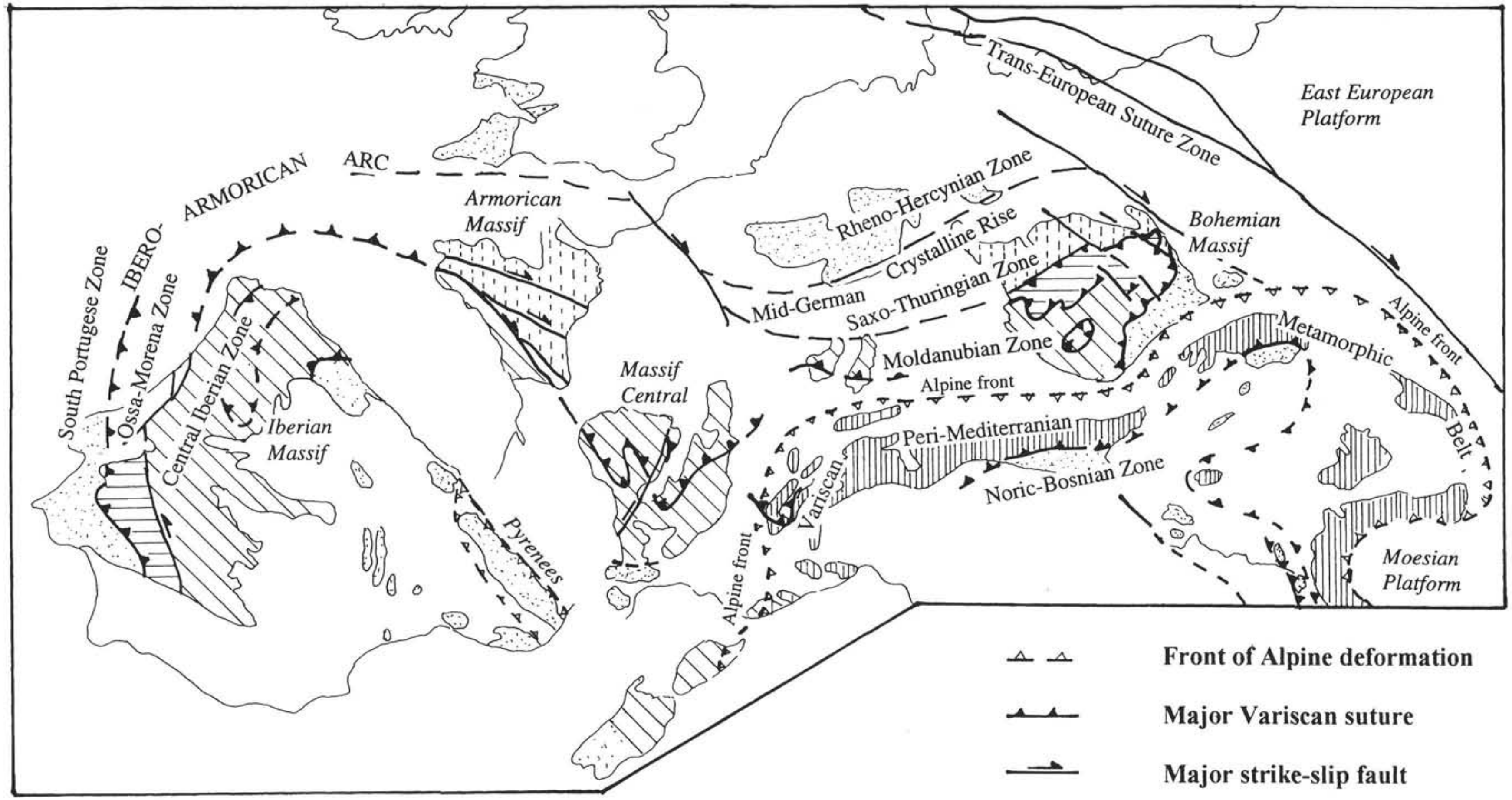

Fig. 1
Simplified map displaying main Variscan units in Central and Western Europe and the Alpine-Carpathian belt, as well as the Ibero-Armorican and Moravo-Silesian/Saxo-Thurigian oroclines (strongly modified after MATTE, 1986 and FRANKE, 1989). The Moravo-Silesian zone comprises the eastern Bohemian massif.

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The Eastern Alps largely expose pre-Alpine metamorphic and plutonic Austroalpine and Penninic basement units (Fig. 1). 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 during Cretaceous and Cenozoic tectonic processes. Alpine tectonometamorphic overprint of basement units resulted in variable retrogression, as well as in progressive metamorphism or in similar metamorphic grade (FREY et al., 1999; HOINKES et al., 1999). Cretaceous eclogite metamorphism and medium-pressure amphibolite facies within the southern (Middle) Austroalpine basement are widespread (FRANK, 1987; THÖNI and JAGOUTZ, 1992; FREY et al., 1999; HOINKES et al., 1999; THÖNI, 1999). Geochronology (U-Pb zircon, Rb-Sr, Sm-Nd whole rock and mineral ages and K-Ar and ^{40}Ar/^{39}Ar mineral ages) revealed a large variety of scattered ages, ranging from ca. 500 Ma to 240 Ma for metamorphism and post-metamorphic cooling within various basement units respectively, specifically of the Middle Austroalpine basement (see reviews by FRANK et al., 1987; NEUBAUER et al., 1999a; THÖNI, 1999). These ages were obtained by a wide variety of methods, confirmed older results and revealed further details on the extent and chronology of the pre-Alpine metamorphism and plutonism within the Eastern Alps (NEUBAUER et al., 1999a; THÖNI, 1999).

Aside from geochronology, many new sedimentological and petrological data have been accumulated during the last years, which support new ideas for the Carboniferous tectonic evolution of the Eastern Alps and Bohemian Massif. The question now is raised if there exists a major Carboniferous suture in the Eastern Alps and their lateral extension in the Carpathians. The new data suggest the presence of an ophiolitic suture and provide evidence of calc-alkaline magmatic belts which formed from the Devonian onwards to the Devonian/Carboniferous boundary, and of the subduction and subsequent eduction of both ophiolites and continental crust during the Carboniferous. The present review mainly discusses field relationships of metamorphic sequences to their fossil content and to plutonic sequences enclosed within these, the metamorphic facies and geochronological age constraints for the distribution of pre-Alpine metamorphic facies (as shown on the "Map of pre-Alpine Metamorphism": FREY et al., 1999) and to compare this evolution with that of the southern Bohemian Massif. The time scale follows recent calibrations proposed by GRADSTEIN and OGG (1996).

Bohemian Massif

Introduction

The eastern sectors of the Variscan orogen in Europe comprise the Moldanubian and Moravo-Silesian zones of the central Bohemian Massif (Figs.1, 2). The Moldanubian zone has been interpreted to represent a root zone for the high-grade metamorphic nappes, which were thrust onto both northwestern foreland (Saxo-Thuringian zone) and southeastern foreland units (Moravo-Silesian zone; FRANKE et al., 1995; DVORÁK, 1995; HÖCK, 1995). The southeastern Bohemian Massif was consolidated during oblique continental collision; the nature and location of the plate boundary between these continental blocks has been the subject of controversy (e.g., MATTE, 1986; MATTE et al., 1992; FRANKE, 1989; SCHULMANN et al., 1991; FRITZ and NEUBAUER, 1993). The tectonostratigraphic succession is characterized by several metamorphic nappes in internal orogenic portions, which have been delaminated at relatively deep crustal levels. By contrast, external portions were assembled within shallow crustal levels. The age of final emplacement of the nappes is indicated by the deposition of Visean flysch successions (e.g., FRANKE, 1989; DVORÁK, 1995) and the syn- to post-transport cooling history of the nappe complex (DALLMEYER et al., 1992). Intrusions of large granitoid bodies and steep conjugate shear zones postdate the nappe assembly (e.g., BRANDMAYR et al., 1995; FINGER et al., 1997). The most important geochronological data constraining the ages of protoliths, metamorphism and granite intrusions are compiled in Table 1. Major extensive and complete compilations can be found in FRITZ et al. (1997) and KRÖNER et al. (2000). These include: (1) Data interpreted to reflect protolith ages of magmatic rocks or depositional ages of sedimentary rocks; and (2) data which record the last post-metamorphic cooling of the nappe assembly. Data are interpreted to control protolith ages cluster between ca. 700 Ma and 500 Ma and include magmatic rocks and gneisses from the Moravo-Silesian Nappe Complex (SCHARBERT, 1977; SCHARBERT and BATIK, 1980; VAN BREMEN et al., 1982; MORAUF and JÄGER, 1982), as well as magmatic rocks from lower tectonostratigraphic levels within the Moldanubian nappe complex (FRANK et al., 1990). Very low ^{87}Sr/^{86}Sr ratios of both Moravian and Moldanubian marbles have been interpreted by FRANK et al. (1990) as evidence for Proterozoic sedimentary ages. These data contrast with Paleozoic protolith ages obtained from the Granulite and Gföhl nappes. Questionable Rb/Sr whole rock ages of c. 490-470 Ma have been interpreted either to represent primary magmatic ages or to date HT-granulite metamorphic isotopic equilibration (ARNOLD and SCHARBERT, 1973; FRANK et al., 1990).

Moravo-Silesian parautochthon and nappe complex

The southeastern Bohemian Massif exposes the Moravo-Silesian zone with several stratigraphic elements, which include: 1) A Cadomian basement complex with migmatite-grade metamorphic rocks (Deblin Group) and Cadomian granitoids (Brno and Thaya batholiths); 2) a Silurian to Early Carboniferous shallow water and pelagic sedimentary sequence; 3) the Carboniferous infilling of the Silesian trough with Early Carboniferous syn-orogenic Culm-type flysch and a Late Carboniferous molasse-type sequence; and 4) the metamorphic Moravian nappe complex, which mainly includes Cadomian tectonic elements that have been affected by Variscan amphibolite to greenschist facies metamorphism and associated ductile deformation during nappe stacking (for data compilations, see SCHULMANN, 1990; DVORÁK, 1995; FINGER et al., 1989, 1995; HÖCK, 1995; SCHULMANN et al., 1994, 1995; FRITZ et al., 1997).

Moldanubian nappe complex

The Moldanubian nappe complex is tectonically separated from units of the footwall Moravian nappe complex by the "Micaschist zone". It is composed of several major

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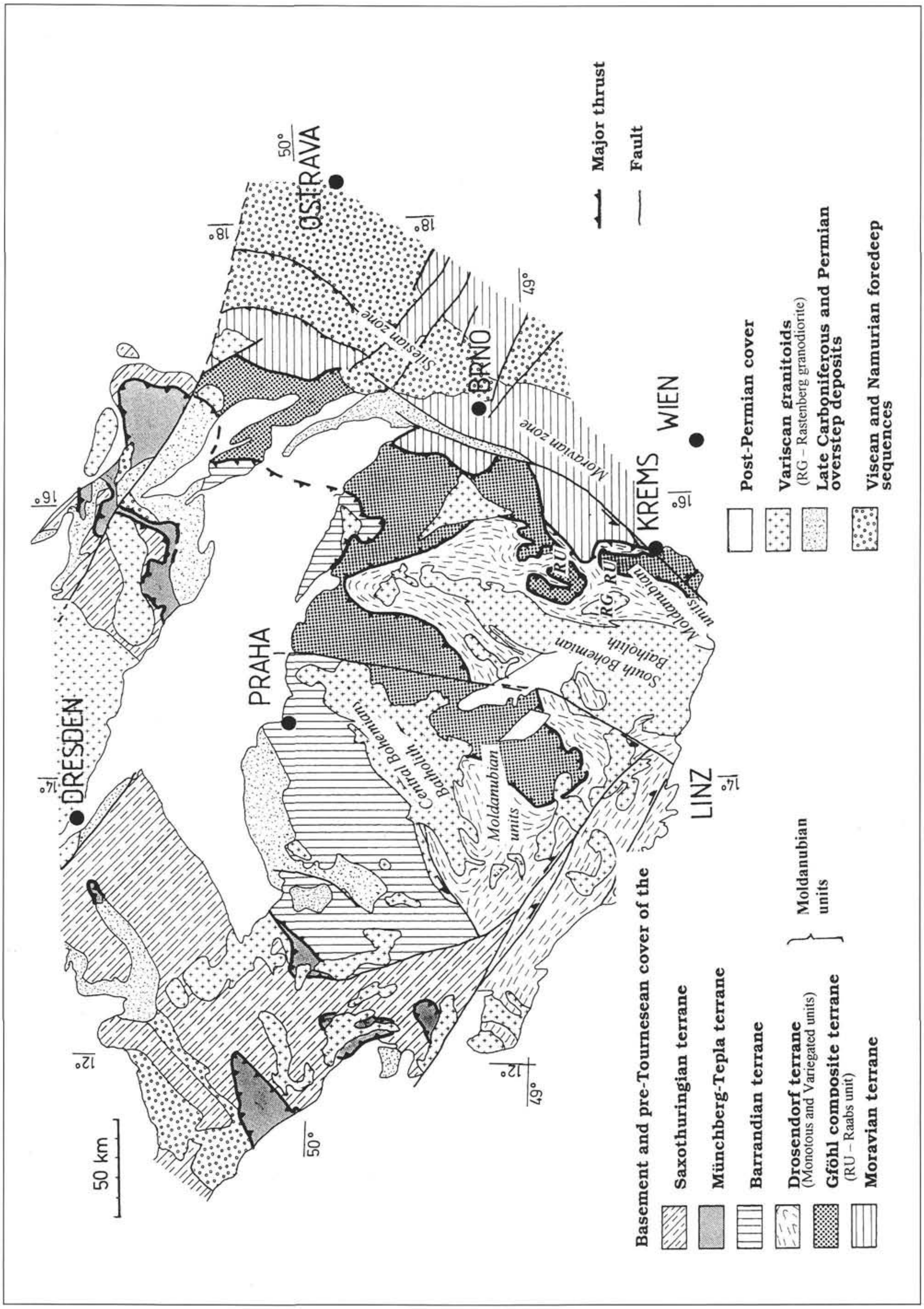

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Table 1
Selected geochronological data constraining the age of protolith formations and metamorphism in major tectonic units of the southern Bohemian massif. For further references, see Finger et al. (1997), Fritz et al. (1997), Kalt et al. (2000) and Kröner et al. (2000). Abbreviations: evap. – evaporation technique; l. i. – lower intercept; u. i. – upper intercept; WR – whole rock; z. – zircon.

Tectonic unit Lithology	**Method**	**Age (Ma)**	**Interpretation**	**Reference**
Moravian parautochthon:				
Brno/Tisnov diorite	U-Pb zircon	584 ± 4	intrusion	van Breemen et al. (1982)
Brno/Tisnov diorite	Ar-Ar amphibole	596-587	postintrusional cooling	Fritz et al. (1997)
Thaya pluton	Rb-Sr WR	551 ± 6	intrusion	Scharbert and Batik (1980)
Moravian nappe complex:				
various gneisses	Ar-Ar amphibole	341	postmetamorphic cooling	Dallmeyer et al. (1992)
	Rb-Sr muscovite	326	postmetamorphic cooling	Morauf and Jäger (1982)
	Ar-Ar muscovite	331-325	postmetamorphic cooling	Dallmeyer et al. (1992)
Variegated Series:				
Dobra gneiss	SHRIMP U/Pb z.	1377 ± 10	protolith formation	Friedl (1997)
Dobra gneiss	U-Pb zircon	1328 ± 34	protolith formation	Friedl (1997)
Dobra gneiss	U-Pb monazite	336 ± 3	metamorphism	Friedl (1997)
Spitz gneiss	U-Pb zircon u. i.	651 ± 16	protolith formation	Friedl (1997)
various gneisses/schists	Ar-Ar amphibole	334-329	postmetamorphic cooling	Dallmeyer et al. (1992)
various gneisses/schists	Ar-Ar muscovite	331-325	postmetamorphic cooling	Fritz et al. (1997)
Monotonous Series:				
paragneiss	U/Pb monazite u. i.	339 ± 2	metamorphism	Friedl (1997)
leucosome, mesosome	U-Pb monazite	326-322	metamorphism	Kalt et al. (2000)
migmatite	U-Pb monazite	323-322	metamorphism	Kalt et al. (2000)
amphibolite	Ar-Ar amphibole	322-316	postmetamorphic cooling	Kalt et al. (2000)
migmatite	Ar-Ar biotite	313-312	postmetamorphic cooling	Kalt et al. (2000)
Raabs ophiolite and related units:				
plagiogranite	U-Pb zircon	428 ± 6	protolith formation	Finger and von Quadt (1995)
amphibolite	U-Pb zircon	359 ± 6	protolith formation	Friedl (1997)
Gföhl nappe complex of the southeastern Bohemian massif				
ultramafic rocks	Sm-Nd	354-329	post-emplacement cooling	Becker (1997a)
granulite	Sm-Nd	337-327	post-metamorphic cooling	Becker (1997a)
granulite	U/Pb monazite	340 ± 4	metamorphism	Friedl (1997)
granulite	U/Pb monazite	341 ± 2	metamorphism	Friedl (1997)
Gföhl nappe, Cesky Krumlov (west of the South Bohemian batholith):				
granulite	SHRIMP U/Pb z.	339.8 ± 2.6	peak of metamorphism	Kröner et al. (2000)
Variscan granites:				
Rastenberg granodiorite	U-Pb zircon evap.	353 ± 9	intrusion	Klötzli and Parrish (1997)
Rastenberg granodiorite	U-Pb zircon	338 ± 2	intrusion	Klötzli and Parrish (1997)
Rastenberg granodiorite	U-Pb monazite	324 ± 3	intrusion	Friedl (1997)
Weinsberg granite	U-Pb monazite	328 ± 5	intrusion	Friedl (1997)
Weinsberg granite	U-Pb monazite	323 ± 4	intrusion	Friedl (1997)
Eisgarn granite	U-Pb monazite	327 ± 4	intrsuion	references in Finger et al. (1997)
Lamprophyre I, II	Ar-Ar biotite	322, c. 315	cooling after emplacement	Neubauer et al. (1999)
Freistadt granodiorite	U-Pb monazite	302 ± 2	intrusion	reference in Friedl et al. (1997)

structural units, each with distinct metamorphic evolution and different protolith ages (Fuchs and Matura, 1976; Arnold and Scharbert, 1973; van Bremen et al., 1982; Kröner et al., 1988, 2000; Frank et al., 1990; Kalt et al., 2000; also see data compilations in Finger et al., 1995; and Fritz et al., 1997). The "Monotonous Series" is exposed along the structural base of the Moldanubian nappe complex. It consists largely of migmatitic paragneisses (Fuchs and Matura, 1976; Linner, 1996) together with local eclogites. A Late Proterozoic age has been assumed for this sequence (Kröner et al., 1988; Frank et al., 1990). Structurally overlying tectonostratigraphic units include the "Bunte Serie" ("Variegated Series"), composed of acidic gneiss at the base (Dobra gneiss with a protolith age of 1377 Ma: Friedl, 1997) and followed by layers of micaschists, marbles, quartzites, amphibolites and the Rehberg amphibolite.

← Fig. 2
Simplified tectonic map of the Bohemian Massif (modified from Dallmeyer et al., 1992).

The uppermost units of the Moldanubian nappe complex (Gföhl gneiss and the Granulite nappes) are thought to form a coherent Gföhl "terrane" with Paleozoic protolith ages (e.g., Arnold and Scharbert, 1973; Franke, 1989). These units are tectonically separated from the Variegated Series and locally from the Monotonous Series by an ophiolite-like assembly, termed the Raabs unit (Finger and Quadt, 1995; Fritz, 1995, 1996; Höck et al., 1997). A U-Pb zircon of 428 ±6 Ma of plagiogranite suggest a Silurian age of protolith formation within the Raabs unit (Finger and von Quadt, 1995). The Raabs unit is considered equivalent to the Letov-

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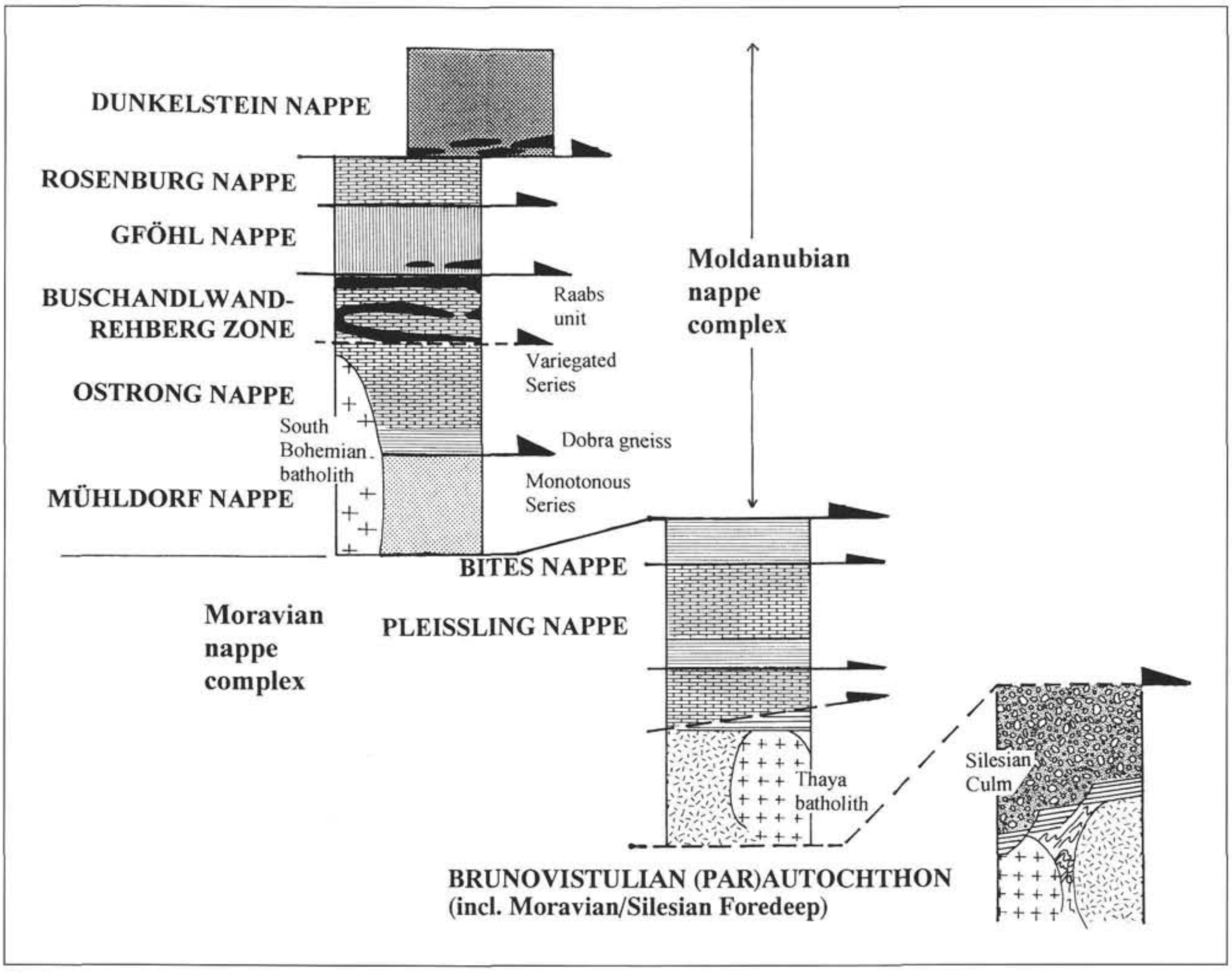

Fig. 3
Tectonostratigraphy of units exposed in the southeastern Bohemian Massif.

ice Formation exposed north of the Svratka dome (MISAR et al., 1984). The Gföhl gneiss and granulites represent lower crustal rocks with mantle structural units in basal portions and acidic gneisses of Paleozoic protolith ages (ARNOLD and SCHARBERT, 1973; FRANK et al. 1990; CARSWELL and JAMTVEIT, 1990; CARSWELL, 1991; FRIEDL, 1997).

Syn- and postorogenic magmatic suites

The Moldanubian nappe complex is intruded by large plutonic suites, which were recently discussed by FINGER et al. (1997 and references therein). Rare Group I granitoids comprise ca. 370 to 340 Ma old granitoids formed above a subduction zone. Group II syn-orogenic S-type granites were formed at ca. 340 Ma in the southeastern Moldanubian nappe complex as a result of migmatization. Group III granitoids compose the main suites/largest volumes and include S-type and high-K I-type granitoids formed between ca. 340 and 310 Ma (e.g., South and Central Bohemian batholiths; KLÖTZLI and PARRISH, 1996; Fig. 2). In the southeastern Bohemian Massif, the Rastenberg granodiorite, Weinsberg and Eisgarn granites represent the most prominent members of this group. Nappe boundaries are cut by these granitoids, which indicates that the intrusion of these Group III granites postdates nappe stacking.

Lamprophyric dykes occur along two major trends. An earlier ESE-trending dyke swarm transects both Moldanubian and Moravian units postdating peak conditions of metamorphism within these units. An ^{40}Ar/^{39}Ar biotite age of ca. 322 Ma from an unmetamorphic, southeastern sector of that dyke swarm constrains a late Early Carboniferous age of intrusion (NEUBAUER et al., 1999b). The second, NNE trending Waldviertel dyke swarm is slightly younger (ca. 320-315 Ma) postdating semiductile/ductile deformation. The formation of these lamprophyres relates to partial remelting of the subducted lithosphere.

Finally, group IV/V granitoids are late-stage leucogranites with Late Carboniferous to Permian ages, which often occur close to major strike-slip faults.

Tectonic evolution

Classical models explaining the Variscan orogeny in the southeastern Bohemian Massif illustrate the present situation as being due to eastward-directed thrusting of upper plate Moldanubian units onto a Moravo-Silesian foreland (e.g., TOLLMANN, 1982; FUCHS and MATURA, 1976; WEBER and DUYSTER, 1990; CIZEK and TOMEK, 1991). RAJLICH (1990), SCHULMANN (1990), SCHULMANN et al. (1991, 1995), FRITZ and NEUBAUER (1993) and FINGER and STEYRER (1995)

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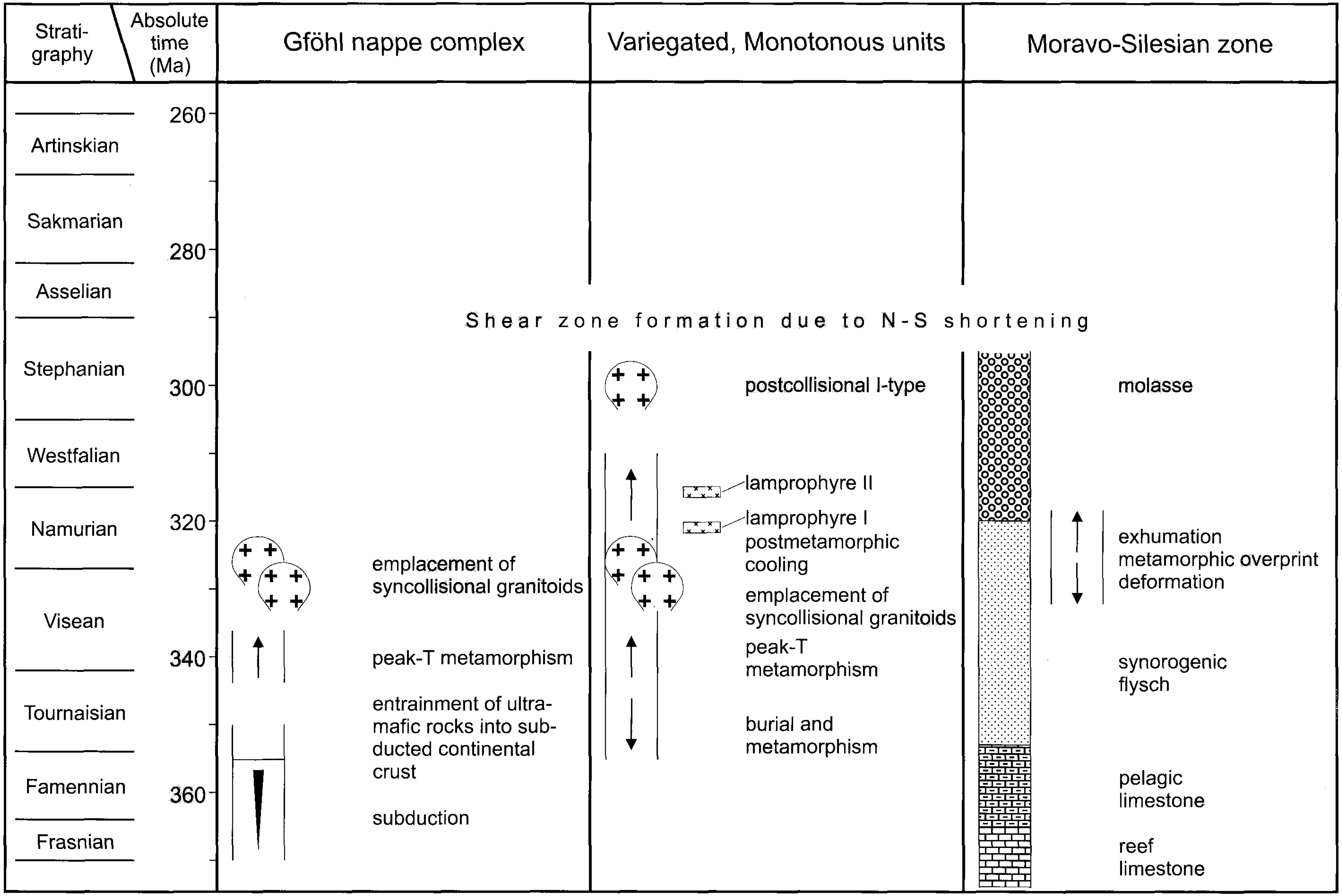

Fig. 4
Evolutionary diagram displaying the tectonic evolution from the Late Devonian to Early Permian of basement units of the southeastern Bohemian Massif.

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proposed a different model, based on geochronological, petrological and structural characteristics. This new model involves a late Proterozoic (Cadomian) composite terrane including Moravo-Silesian foreland units, the Moravian nappe complex and the Moldanubian Variegated and Monotonous Series. This terrane accreted to an early Paleozoic (Caledonian) terrane (Gföhl composite terrane) during and subsequent to the closing of an oceanic domain, which is now represented by vestiges preserved in the Letovice and Raabs units (Fig. 4a, b) (FINGER and STEYRER, 1995; FRITZ, 1995, 1996; HÖCK et al., 1997).

Kinematic models involving purely orthogonal collision along major tectonic boundaries have been replaced by those which document a polyphase evolution with major lateral displacements (e.g., SCHULMANN 1990; WEBER and DUYSTER, 1990; SCHULMANN et al., 1991; MATTE et al., 1992; FRITZ and NEUBAUER, 1993). By contrast, the model of an overall dextral transpression resulted in a clockwise displacement path (FRITZ and NEUBAUER, 1993) with orogen-parallel, NNE-directed crustal thickening. Paleomagnetic data from the Moravo-Silesian zone suggest a ca. 90° clockwise rotation of the Moravo-Silesian block during the Early Carboniferous and therefore, orocline formation (TAIT et al., 1996). Moldanubian granitoids were pervasively remagnetized during Late Carboniferous/Early Permian cooling (REISINGER et al., 1994). Subsequent exhumation is considered to have been achieved by orogen-parallel and orogen-perpendicular displacements. The Svratka and Thaya domes appear to have developed over ramp anticlines during thrust propagation (FRITZ and NEUBAUER, 1993; FRITZ et al., 1997). Orogen-parallel strike-slip faults accomodated transpression. East-vergent imbrication occurred in a pericollisional flysch basin simultaneously with the formation of extensional structures along boundaries of the Svratka and Thaya domes.

The age of nappe assembly is constrained by the deposition of Visean syncollisional flysch (DVORÁK, 1989, 1995), which records sedimentation onto the foreland during loading of the upper plate. ^{40}Ar/^{39}Ar white mica and hornblende ages of ca. 325-320 Ma within Moldanubian and Moravian nappe complexes have been interpreted to date relatively rapid cooling associated with upward nappe translation to shallow crustal levels (DALLMEYER et al., 1992).

Variscan orogenic activity in the southeastern area has been documented by VAN BREMEN et al. (1982), SCHULMANN (1990), DALLMEYER et al. (1992), BRANDMAYR et al. (1995), SCHULMANN et al. (1991), STIPSKA and SCHULMANN (1995), URBAN and MÍSAR (1995), BECKER (1996, 1997a, b), FRIEDL (1997), KALT et al. (2000) and KRÖNER et al. (2000), among others. Sm/Nd mineral ages from garnet-bearing mantle peridodites within basal portions of the granulite nappe have been interpreted to date the age of maximum metamorphic pressure conditions between ca. 370 and 340 Ma (CARSWELL and JAMTVEIT, 1990; BECKER, 1996; 1997a; ROBERTS and FINGER, 1997; FRIEDL, 1997; MEDARIS et al., 1998). Exhumation of ultramafic rocks was very rapid as petrological data indicate (e. g., MEDARIS et al., 1990).

Available geochronological data suggest a late Variscan age for the structural assembly of the Moldanubian and the Moravian nappe complexes (MATTE et al., 1992; FRANK et al. 1990; CARSWELL and JAMTVEIT, 1990; DALLMEYER et al., 1992). A lower age limit for Variscan deformation is given by 340-360 Ma Sm-Nd ages of garnet peridotites in the granulite klippe (CARSWELL and JAMTVEIT, 1990), which are interpreted to date the high pressure metamorphism. Nearly all U/Pb zircon and monazite and Sm-Nd mineral ages are within 345-340 Ma (Table 1). These ages constrain uniform metamorphic peak P-T conditions of ca. 10-11 kbar and 700-750 °C (PETRAKAKIS, 1997 and references therein; Fig. 5a). Uniform 340-325 Ma old ^{40}Ar/^{39}Ar ages of hornblende and white mica from the Moravian and Moldanubian nappe assembly have been interpreted to date rapid cooling from 500 °C through 350-400 °C (MATTE et al, 1992; DALLMEYER et al., 1992; BRANDMAYR et al., 1995; FRITZ et al., 1997). These ages are compatible with the stratigraphic ages of sedimentary successions in the Moravo-Silesian sedimentary foreland basin.

Geological relations in the eastern parts of the Bohemian Massif suggest that the succession of structural and tectonothermal events can be divided into three distinct chronological groups, including: (1) Localized decollement zones; (2) penetrative nappe-internal structures; and (3) structures which affected the entire nappe complex. It appears that the structural evolution was initiated during maintenance of peak metamorphic conditions and continued under retrograde metamorphic conditions during exhumation and cooling.

At the Late Carboniferous to Early Permian boundary major strike-slip systems formed. These compose major WNW-trending dextral ductile shear zones (e.g., Central Bohemian, Pfahl and Donau shear zones) and NNE-trending sinistral shear zones and faults (Rodl shear zone and Diendorf fault) (HANDLER et al., 1991; BRANDMAYR et al., 1995; 1999; PITRA et al., 1999). Together these form a conjugate system indicating ca. N-S shortening due to indentation. Indentation suggests the presence of a northward moving indenter in the area of the future Alps (NEUBAUER and VON RAUMER, 1993; BRANDMAYR et al., 1995).

The Eastern Alps

Introduction

Basement units in the Eastern Alps are widely exposed in the Southalpine, Austroalpine and Penninic continental units of the Eastern Alps. These units were variably overprinted by Cretaceous (Austroalpine) and Tertiary (Penninic) metamorphic events ranging from very low grade to eclogite-grade conditions (FREY et al., 1999; HOINKES et al., 1999; NEUBAUER et al., this volume). Furthermore, Austroalpine basement units were largely affected by Cretaceous nappe stacking, subsequent extension and associated ductile deformation. For the purpose of this review, we distinguish five units with a significantly different Late Devonian/Carboniferous tectonic evolution (as already introduced by NEUBAUER, 1988, and FRISCH and NEUBAUER, 1989):

1) the Helvetic basement ("Cetic massif"), as reconstructed from olistolitic blocks;
2) Penninic units, which record a Silurian eclogite-grade metamorphism and Carboniferous granite intrusions;
3) Austroalpine Silurian/Devonian metamorphic complexes nearly unaffected by subsequent Variscan tectonothermal processes;

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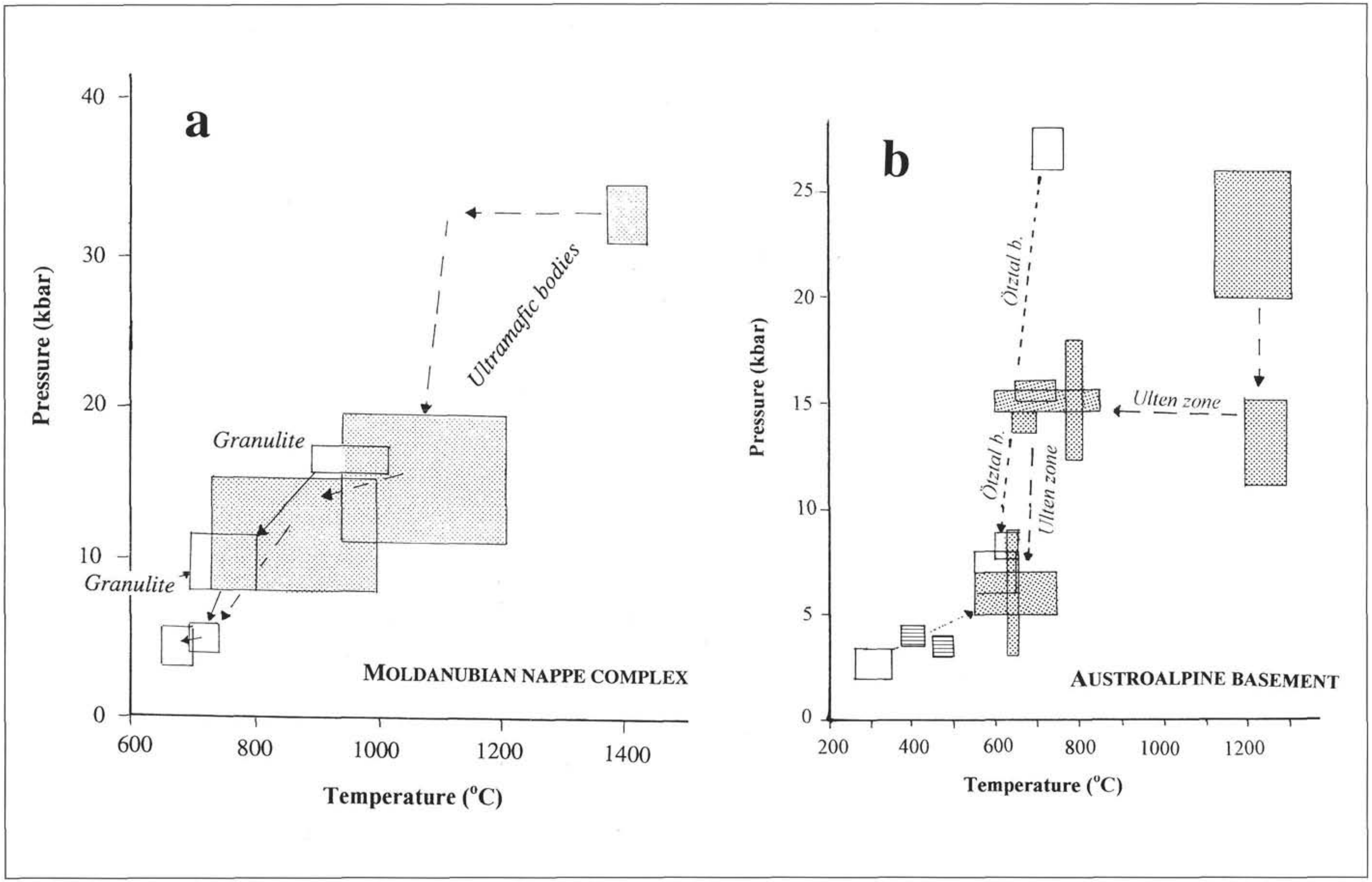

Fig. 5
Variscan P-T of Moldanubian units and Austroalpine basement units. a – P-T path of upper Moldanubian units (granulites and ultramafic rocks; mainly after Becker, 1997b; for data sources see Carswell and O'Brien, 1992; Petrakakis, 1997, Fritz et al., 1997 and O'Brien and Carswell, 1993; Becker, 1997b). b – Variscan P-T path of Austroalpine units (Ötztal basement and Ulten zone; modified from Neubauer et al., 1999a; for data sources, see Neubauer et al., 1999a).

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4) the Austroalpine/Southalpine Noric terrane (the Noric-Bosnian terrane, if considered for the ACD) with conformable Early Paleozoic to early Late Carboniferous sedimentary sequences. These generally show a Variscan very low-grade to low-grade metamorphic overprint; and
5) Austroalpine Carboniferous mostly high-grade metamorphic complexes.

Furthermore, we shall discuss Carboniferous overstep sequences. Sediment deposition within most of them started during the Westfalian, except the Veitsch and Nötsch units, which comprise Early Carboniferous sequences.

A simple sketch with various Austroalpine tectonostratigraphic units is shown in Figs. 6, 7 and an evolutionary diagram displaying the development of all major Eastern Alpine basement units is shown in Fig. 8. The most important geochronological data constraining the ages of protoliths, metamorphism and granitoid intrusions of major Alpine basement units are compiled in Table 2. Recent detailed summaries of these data can be found in FINGER et al. (1997), NEUBAUER et al. (1999a) and THÖNI (1999).

Helvetic basement ("Cetic massif")

The Helvetic basement of the Western Alps is widely exposed, in contrast to the Eastern Alps, where it forms only some major blocks/olistolites within Cretaceous flysch sequences. However, detailed work has allowed reconstructions of the so-called Cetic massif (e.g. FRASL and FINGER, 1988). Basement rocks mainly comprise a quartzdiorite-tonalite-granodiorite suite with I-type characteristics. THÖNI (1991) reported Devonian Rb-Sr whole rock (378±50 Ma), biotite (365±7–358±6 Ma) and K-feldspar ages (371±1 Ma). Together with petrological and geochemical information, these ages argue for the existence of a Middle to Late Devonian magmatic arc, due to subduction of oceanic lithosphere along the present southern margin of the Bohemian Massif, the northern margin of the Alps, respectively.

Penninic basement of the Tauern window

Penninic basement units of the Tauern window are preserved within epidote-amphibolite metamorphic conditions within the Habach complex and migmatite/amphibolite-grade conditions in the Storz and Stubach complexes, respectively (e.g., GRUNDMANN, 1989; VAVRA and HANSEN, 1991; Fig. 2). All are intruded to a variable degree by the Variscan granites, having been transformed into the Central Gneiss by Cenozoic tectonothermal events. Consequently, migmatite-grade metamorphism is supposed to relate to Variscan granite intrusions. Local eclogites preserved within the southeastern (DROOP, 1983) and southern central Tauern window (ZIMMERMANN and FRANZ, 1989) predate Variscan migmate-grade metamorphism. Eclogites of the central southern Tauern window were dated at 418±18 Ma (U-Pb zircon), 415±18 Ma (U-Pb zircon, laser ablation ICP-MS) and 421±16 Ma (Sm-Nd on garnet-whole rock) (VON QUADT et al., 1997). DROOP (1983) and ZIMMERMANN and FRANZ (1989) reported metamorphic conditions of 8 to >12 kbar and 450-620 °C for these eclogites.

Granite suites (now the Central Gneiss) intruded in the period between 320-300 Ma (FINGER and STEYRER, 1990; HÖCK, 1993; FINGER et al., 1997). These are interpreted to result from various sources constraining a number of tectonic events where I-type, subduction-related sources appear to be the most prominent ones. Variscan migmatization is closely related to the intrusion of precursor rocks of the present Central Gneiss. Locally, andalusite can be found (GRUNDMANN, 1989). Metarodingite contains mineral assemblages for which P-T conditions of ca. 420 °C and 2 kbar have been estimated (KOLLER and RICHTER, 1984). In the southeastern regions Variscan garnet-staurolite-kyanite assemblages were reported by DROOP (1983). VON QUADT (1992) reported U-Pb lower intercept zircon ages of 314 +4/-3 Ma and 301±3 Ma for Variscan metamorphism. A local Permian thermal overprint has also recently been confirmed by an U-Pb titanite age of 282±2 Ma (EICHHORN et al., 1995; for previous literature see FRANK et al., 1987).

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 (ca. 330-300 Ma) and 3) Permian thermal overprint, probably localized along distinct shear zones.

Silurian-Devonian metamorphic complex (Wechsel and Kaintaleck Complexes)

Two Austroalpine units record well-constrained evidence of Silurian to Devonian tectonometamorphic processes. These are the Wechsel Gneiss and Kaintaleck complexes.

The Wechsel Gneiss Complex is exposed within the Wechsel window, close to the eastern margin of the Alps. This unit comprises albite-chlorite-mica gneiss with lense-shaped intercalations of mafic rocks formed within a supra-subduction environment. The gneiss displays a complex metamorphic history recorded in inclusions within late-stage albite porphyroblasts. A metamorphic mineral zonation can be observed within the Wechsel window, which indicates the transition from greenschist facies metamorphic conditions in the N to epidote amphibolite facies towards the S. Metamorphism has been accompanied by polyphase S-directed folding suggesting an approximately N-S compression 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 ca. 378 to ca. 325 Ma and are assumed to record Devonian peak conditions of pressure-dominated metamorphism. Paragonite from the matrix records late Variscan ^{40}Ar/^{39}Ar ages (ca. 245 Ma: MÜLLER et al., 1999). No Alpine ages have been found except from new white mica which crystallized in shear zones, such as along the upper margins of the Wechsel Gneiss complex towards the overlying Wechsel Slate complex. The Wechsel Slate complex comprises a polyphase fabric with typical greenschist facies mineral as-

Fig. 6 →
Simplified tectonic map of the basement units exposed in the Eastern Alps (modified from NEUBAUER et al., 1999a). Legend: An – Ackerl nappe; b. – basement; c. – complex; CC – "Core" complex; DAV – Defreggen-Antholz-Vals fault; KSn – Kirchberg-Stuhleck nappe; MMc – Micaschist-Marble complex; n. – nappe; ph. – phyllite; qu. – quartzphyllite; SAM – southern limit of Alpine metamorphism; TF – Troiseck-Floning; u. – unit; W. – Winnebach migmatite.

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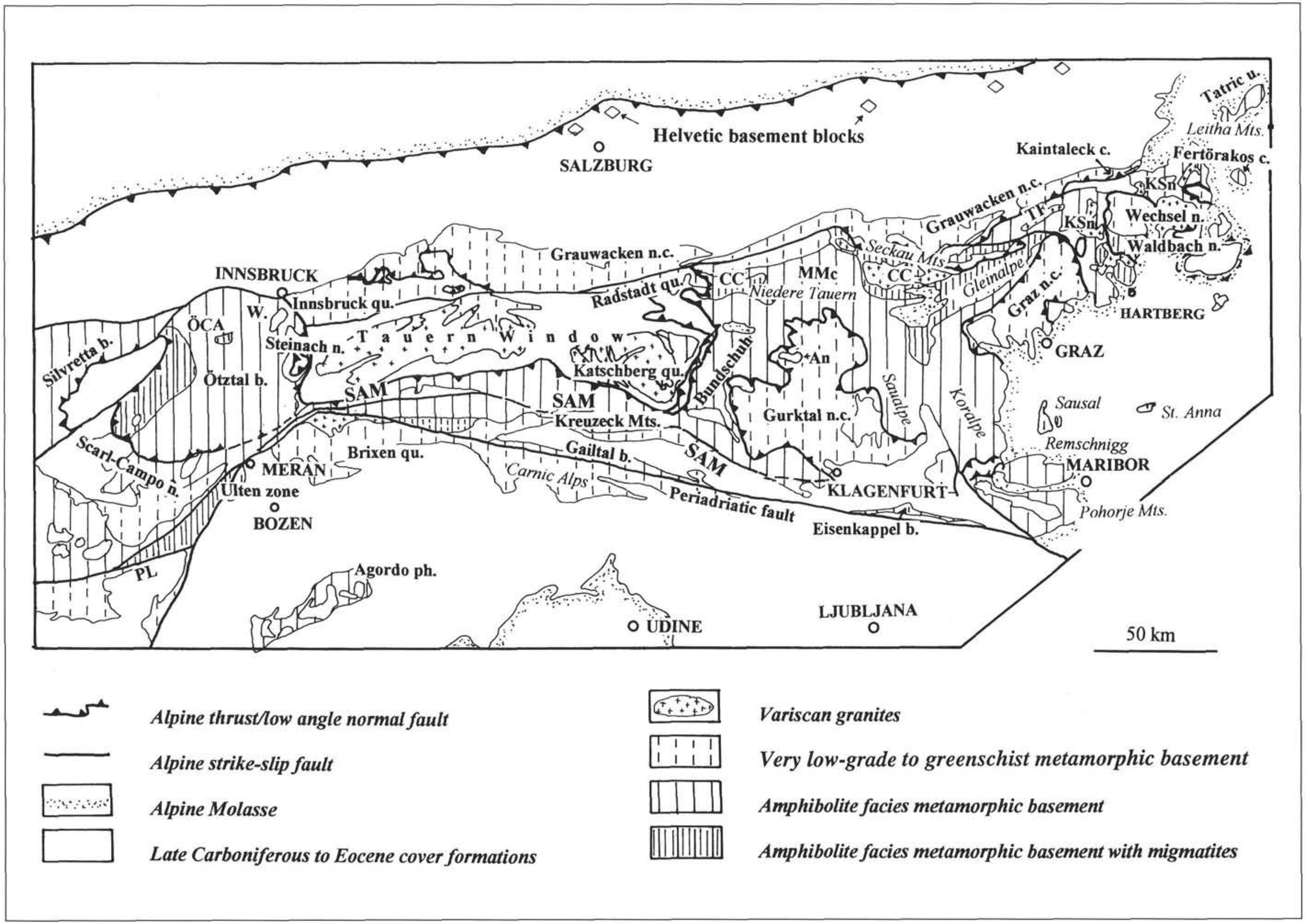

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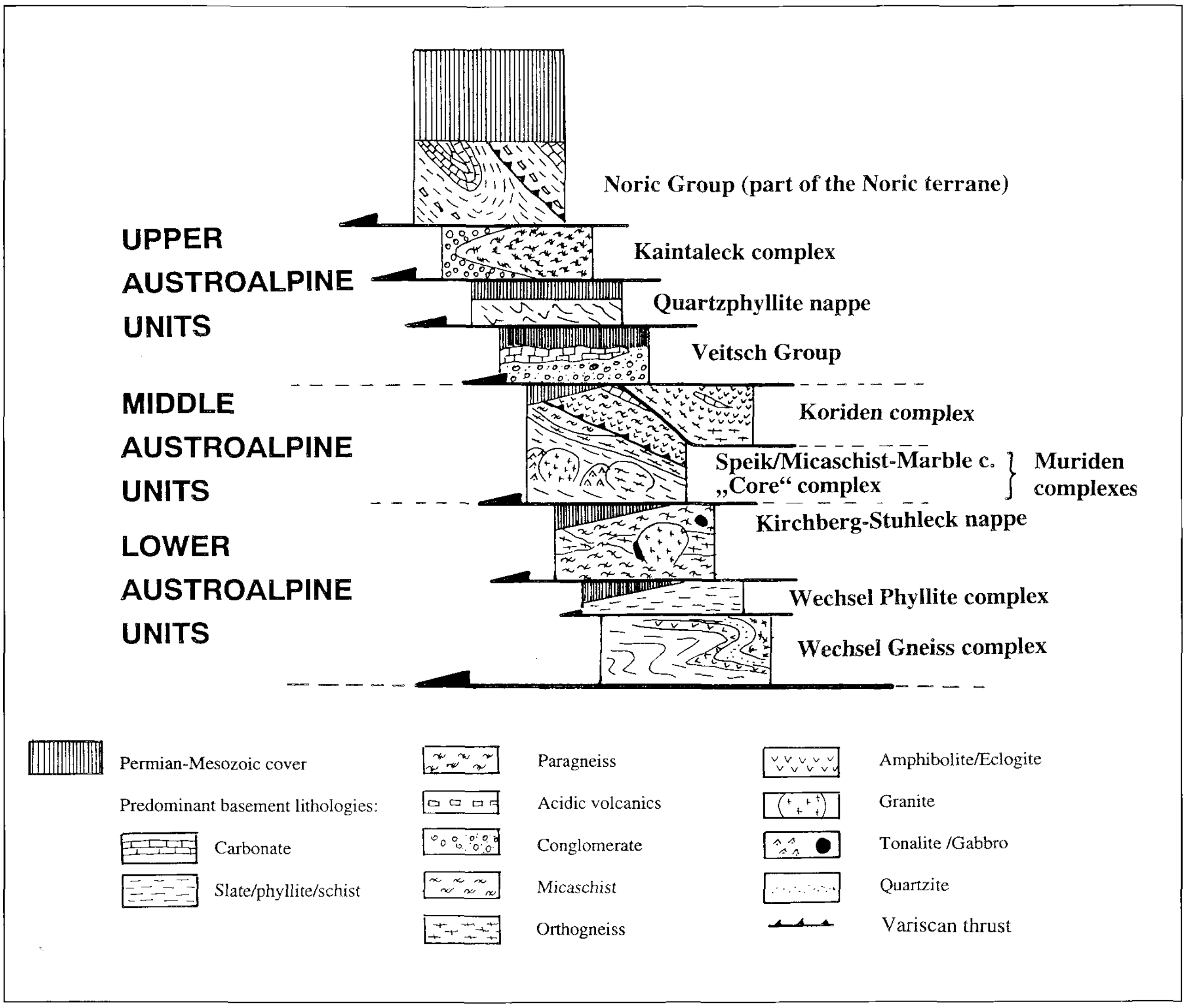

Fig. 7
Tectonostratigraphy of Austroalpine units exposed in the Eastern Alps.

semblages recorded within mafic, tuffaceous rocks and slates. An ^{40}Ar/^{39}Ar paragonite age of ca. 270-240 Ma gives evidence of a Permian age of tectonothermal activity. Rb-Sr mineral isochrons (white mica – chlorite – whole rock) of the Wechsel Slate and ^{40}Ar/^{39}Ar age spectra first increments are at ca. 250 Ma. These ages may provide proof of activity along the ductile fault mentioned above during Permian extension and/or thermal influence by Permian volcanism.

The Kaintaleck Metamorphic Complex (NEUBAUER et al., 1994) is represented by a number of individual units, which have been imbricated tectonically within the Graywacke zone of the Austroalpine nappe complex during Alpine nappe stacking. Although most of these units do not exceed a thickness of a few tens of meters and a length of a few hundred meters, they can be traced over more than 100 km at the same tectonic position along strike of the orogen (Fig. 5). This basement complex comprises medium-grade amphibolite, migmatitic paragneiss and garnet-micaschist. The foliation of these rocks is clearly cut by some pegmatites and aplitic gneisses. An U-Pb zircon age of ca. 390 Ma from a paragneiss constrains a Devonian age of metamorphism (NEUBAUER and FRISCH, 1993). Recently Rb-Sr and ^{40}Ar/^{39}Ar age dating has been carried out on amphibole and white mica, which appear now as porphyroblastic relics within a matrix, which formed within Alpine greenschist facies metamorphic conditions (HANDLER, 1994; HANDLER et al., 1999). Amphiboles revealed disturbed ^{40}Ar/^{39}Ar age spectra, due to the incorporation of extraneous argon components and mineral zonation. Rb-Sr analyses carried out on garnet-micaschist whole-rock vs. constituent white mica pairs yielded ages of c. 400 Ma. ^{40}Ar/^{39}Ar analyses from white mica of the same lithologies record staircase type Ar-release patterns with ages of ca. 200-250 Ma recorded in low-temperature steps, which consistently increase to ages of ca. 375 Ma in high-temperature gas release steps. The older age is also recorded in a well defined Ar-plateau for white mica, which was separated from a discordant pegmatite. These ages are interpreted to indicate the age of cooling of the Kaintaleck Metamorphic Complex below respective closure temperatures, e.g., below ca. 450 °C at ca. 375 Ma, thus indicating a penetrative Devonian tectonometamorphic event. This is further constrained by ^{40}Ar/^{39}Ar analytical data from white mica, which

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Table 2
Selected geochronological data constraining the age of protolith formation and metamorphism in major tectonic units of the Eastern Alps. For further references, see Neubauer and Frisch (1993), Neubauer et al. (1999a) and Thöni (1999). Abbreviations: gt – garnet; l. i. – lower intercept; metam. – metamorphism; mu – muscovite; WR – whole rock.

Tectonic unit Lithology	Method	Age (Ma)	Interpretation	Reference
Helvetic unit:				
granitoids	Rb-Sr	367 ± 24	protolith formation	Thöni (1999)
K-feldpar, biotite	Rb-Sr	358-371	cooling after intrusion	Thöni (1991)
Penninic basement of the Tauern window:				
eclogite	U-Pb zircon	415 ±18	HP metamorphism	von Quadt et al. (1997)
eclogite	Sm-Nd	421 ± 6	HP metamorphism	von Quadt et al. (1997)
Granatspitz metagranite	U-Pb zircon	330-320	protolith formation	references in Finger et al. (1997)
Hochalm metatonalite	U-Pb zircon	314 ± 7	protolith formation	references in Finger et al. (1997)
Venediger metatonalite	U-Pb zircon	290 ±10	protolith formation	references in Finger et al. (1997)
Wechsel Gneiss complex:				
gneiss	Rb-Sr phengite	376-360	peak conditions of metam.	Müller et al. (1999)
gneiss	Ar-Ar phengite	c. 354	postmetamorphic cooling	Müller et al. (1999)
Kaintaleck complex:				
paragneiss	U-Pb zircon	c. 390	peak conditions of metam.	Neubauer and Frisch (1993)
paragneiss	Ar-Ar muscovite	379-375	postmetamorphic cooling	Handler et al. (1999)
pegmatite	Ar-Ar muscovite	364 ± 0.8	postemplacement cooling	Handler et al. (1999)
Noric terrane; Austroalpine quartzphyllite units:				
quartzphyllite	K-Ar biotite	c. 300	postmetamorphic cooling	references in Neubauer et al. (1999a)
Noric terrane, Southalpine units:				
Southalpine basement	Rb-Sr gt-WR-mu	354 ± 10	peak conditions of metam.	references in Neubauer et al. (1999a)
	Rb-Sr muscovite	314	postmetamorphic cooling	
	K-Ar, Ar-Ar mu	319-316	postmetamorphic cooling	
	Rb-Sr biotite	321-314	postmetamorphic cooling	
Kirchberg-Stuhleck nappe:				
metatonalite	Rb-Sr WR	343 ± 20	protolith formation	references in Neubauer and Frisch (1993)
Grob gneiss	Rb-Sr WR	338 ± 12	protolith formation	
two-mica granite gneiss	Rb-Sr WR	326 ± 11	protolith formation	
two-mica granite gneiss	Rb-Sr WR	243 ± 17	protolith formation	
Muriden complexes:				
Orthogneiss	Rb-Sr WR	432 ± 16	protolith formation	Scharbert (1981)
Rennfeld tonalite	U-Pb zircon	353-363	protolith formation	Neubauer and Frisch (1993)
trondhjemite	U-Pb zircon	c. 353	protolith formation	Neubauer and Frisch (1993)
metagranite	Rb-Sr WR	354 ± 16	protolith formation	Scharbert (1981)
metagranite	Rb-Sr WR	331 ± 7	protolith formation	Scharbert (1981)
pegmatite	Rb-Sr muscovite	329 ± 12	postemplacement cooling	Scharbert (1981)
Koriden complex:				
metagabbro	Sm-Nd minerals	275 ± 18	protolith formation	Thöni and Jagoutz (1992)
pegmatite (St. Radegund)	Rb-Sr WR	313 ± 18	protolith formation	references in Neubauer and Frisch (1993)
pegmatite	Rb-Sr muscovite	277-244	postemplacement cooling	
Ötztal basement:				
metagabbro	Sm-Nd WR-gt	373-359	HP metamorphism	Miller and Thöni (1995)
eclogite	Sm-Nd WR-garnet	343-331	peak conditions of metam.	Hoinkes et al. (1997)
micaschist	Rb-Sr white mica	327-292	postmetamorphic cooling	references in Thöni (1999) and Neubauer et al. (1999a)
orthogneiss	K-Ar, Ar-Ar mu	317-297	postmetamorphic cooling	
orthogneiss	Rb-Sr biotite	301-272	postmetamorphic cooling	
orthogneiss	K-Ar biotite	316-272	postmetamorphic cooling	
Ulten zone:				
ultramafic rocks	U-Pb zircon	336-332	metamorphism	Gebauer and Grünenfelder (1978)
garnet-lherzolite	Sm-Nd	c. 340	metamorphism	Thöni (1999)
paragneiss	Sm-Nd WR-gt	351 ± 1	metamorphism	Hauzenberger et al. (1996)

was separated from an orthogneiss boulder of a transgressive conglomerate that unconformably covers the Kaintaleck complex. Once again, the Ar-release plot records a staircase type release pattern, however consistent ages of ca. 380 Ma are recorded in the high-temperature release steps (Handler et al., 1997). Together these data indicate a dominant Early-Variscan (Caledonian) metamorphic event, which markedly contrasts with the evolution of the underlying Carboniferous metamorphic basement units (Handler et al., 1999).

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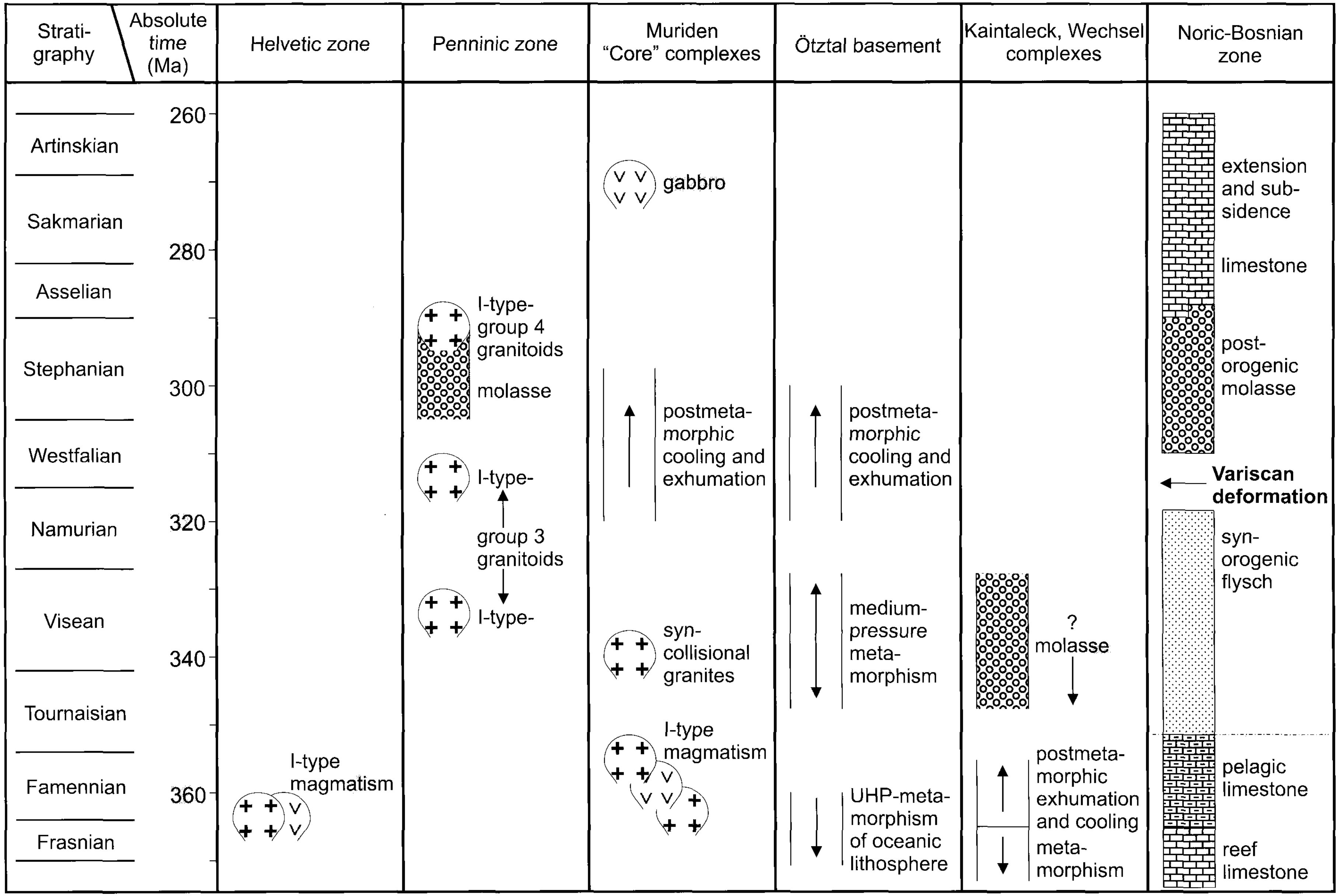

Fig. 8
Evolutionary diagram displaying tectonic evolution from Late Devonian and Early Permian of basement units in the Eastern Alps.

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Noric terrane

The Noric terrane comprises all well-studied early Paleozoic to early Late Carboniferous sedimentary sequences of the Austroalpine and Southalpine units (for the occurrences of the latter in Austria, see Schönlaub and Histon, this volume). The sedimentary sequences are believed to record Silurian to Devonian formation and Early Carboniferous destruction of a passive continental margin. These sequences are conformably overlain by Early Carboniferous synorogenic flysch successions (e.g., the Hochwipfel/Dimon (flysch) Group of the Southalpine unit; LÄUFER et al., 1993). These are considered to represent the synorogenic infilling of a flexural basin, which formed during convergence and loading by incoming thrust sheets (e.g., NEUBAUER, 1988; NEUBAUER and SASSI, 1993). A similar flysch sequence is known from the Gurktal nappe complex. In further occurrences (Graz Paleozoic, Graywacke Zone), mainly shales are recorded, which may represent more distal portions of similar basins (EBNER, 1978; SCHÖNLAUB, 1982). Together these clastic sequences indicate that final deformation of the Early Paleozoic to early Late Carboniferous successions was not prior to Late Namurian to Westfalian A (EBNER, 1978; SCHÖNLAUB, 1982; SCHÖNLAUB and HISTON, this volume). A Variscan top S to SSE displacement is known from the Southalpine basement (RING and RICHTER, 1994) and several sectors of the Noric terrane (see below). A special overstep sequence is represented by Nötsch and Veitsch units (for locations, see Fig. 5), which comprise Early Carboniferous marine molasse-type and Late Carboniferous terrestrial conglomerates and coal seams (RATSCHBACHER, 1987; KRAINER, 1993). Therefore, the Nötsch/Veitsch units constrain the presence of a pre-Early Carboniferous basement unit, as is also indicated by Devonian detrital mica ages (HANDLER et al., 1997).

The Westfalian Auernig Group in the Southalpine unit unconformably overlies these successions and therefore constrains a Westfalian late A/B age of Variscan deformation there. The Auernig Group comprises cyclic marine-terrestrial successions within changing depositional environments (KRAINER, 1992, 1993; FORKE in PILLER, this volume). The cyclicity is related to worldwide eustatic sea-level changes. By contrast, many local exposures of terrestrial conglomerates, including anthracite seams, have been reported within the Austroalpine domain (KRAINER, 1993, and references therein; SACHSENHOFER, this volume).

Basement rocks of the Southalpine unit of the Eastern Alps are exposed from the Karawanken through the Carnic Alps to the Brixen quartzphyllite area to the south of the Periadriatic fault and in the Valsugana-Agordo and Recoaro areas (SASSI and SPIESS, 1993; SASSI et al., 1995).

Fossiliferous Ordovician to early Late Carboniferous basement rocks of the Karawanken and Carnic Alps are overprinted by very low-grade to subordinately low-grade metamorphic conditions (RANTITSCH, 1997; LÄUFER et al., 1997). The age of metamorphism remains largely uncertain. The stronger metamorphic overprint in the Eder nappe of the eastern Carnic Alps is supposed to represent a polymetamorphic unit with Variscan low-grade conditions overprinted by a slightly weaker Cretaceous, and even weaker Oligocene, metamorphic overprint. K-Ar muscovite ages are 282±8 Ma, which are similar to those 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 (SASSI and SPIESS, 1993; SASSI et al., 1995), reaching the almandine greenschist facies in the Sarntal-Brixen area (SASSI and ZIRPOLI, 1989; HAMMERSCHMIDT and STÖCKHERT, 1987).

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, and SASSI et al., 1995, for review). Petrographic data generally indicate lower and upper greenschist facies metamorphic conditions, which have been proved 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 which constrains a minimum age of metamorphism of 250 Ma, and, consistent with SASSI and SPIESS (1993), ca. 400 °C and ca. 4 kbar as conditions of metamorphism for the Innsbruck quartzphyllite. Similarly, mineral parageneses of the Radstadt and Katschberg quartzphyllites are variable (e.g., EXNER, 1989, 1996; GENSER, 1992) and may depict lower to higher greenschist facies for peak metamorphic conditions. Marginal portions along semiductile shear zones are incompletely retrogressed within lower greenschist facies conditions. GENSER and KURZ (1996) and GENSER and WIJBRANS (in review) report two single grain $^{40}Ar/^{39}Ar$ muscovite ages of ca. 240 Ma from the Katschberg quartzphyllite, constraining a Late Permian age of formation or cooling within greenschist grade metamorphism. Details are not yet known as no P-T estimate of Katschberg quartzphyllite exists.

The Graz nappe complex is composed of Silurian to early Late Carboniferous (Westfalian A) sedimentary sequences, which were obviously overprinted during two Variscan and Cretaceous metamorphic events. The Variscan metamorphism is indicated 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 within the eastern/lower nappes of the Graz nappe complex. However, post-Variscan cover sequences in the Graz nappe complex are missing.

The Gurktal nappe complex (GNC) comprises three Alpine nappes. Proceeding from bottom to top these are the Murau, Stolzalpe and Ackerl nappes. The Stolzalpe nappe includes Middle Ordovician to Early Carboniferous successions, which are unconformably overlain by Westfalian A/B conglomerates. Both Murau and Stolzalpe nappes are polymetamorphic and record Late Variscan and Cretaceous metamorphism with a similar grade of greenschist facies metamorphic conditions. In a few cases (western and central sectors of the Stolzalpe nappe), the Variscan grade and age of the low-grade metamorphism is indicated by a gap of metamorphic conditions between basement and Late Carboniferous cover rocks. The basement comprises lower to medium greenschist facies mineral parageneses here with chlorite + albite + epidote ± actinolite ± biotite in mafic rocks. Preliminary $^{40}Ar/^{39}Ar$ muscovite ages from mylonites range between 315-310 Ma and constrain a Late Variscan age of ductile top-WSW shear within the the Stolzalpe basement (NEUBAUER and HANDLER, unpublished results).

The Alpine Ackerl nappe consists of two distinct pre-Alpine basement sequences, which have been penetrative-

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ly deformed under variable metamorphic conditions during Variscan thrusting. The Ackerl Micaschist unit is in a footwall tectonic position and comprises garnet-bearing micaschists, albite-chlorite rich micaschists and granites. The only diagnostic mineral assemblage (garnet + phengitic white mica + albite + quartz) may indicate high pressure/low grade metamorphic conditions. The Ackerl Gneiss unit in the hanging wall tectonic position is composed of gneisses with the biotite-oligoclase-quartz-muscovite-garnet-staurolite assemblage that shows clear evidence for the medium-grade medium-pressure metamorphic overprint. 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 (NEUBAUER and DALLMEYER, unpubl. results).

The Noric Group is unconformably overlain by the Permian to Paleogene sediments of the Northern Calcareous Alps. Consequently, the presence of Variscan low-grade metamorphism might be indicated by ductile metamorphic fabrics, although detailed studies on the intensity of metamorphism do not exist. Evidence for "late Variscan" tectonothermal activity in the source areas adjacent to Carboniferous and Permian clastic sequences is indicated by ^{40}Ar/^{39}Ar ages of ca. 320-303 Ma, which have been reported for detrital mica within Permian clastic sequences (HANDLER et al., 1997; PANWITZ et al., 2000).

Carboniferous metamorphic complexes

Major exposed basement units, which were strongly metamorphosed during the Variscan, Carboniferous cycle, are the Kirchberg-Stuhleck nappe, the Middle Austroalpine units east of Tauern window (Muriden/Koriden complexes), the Middle Austroalpine Ötztal basement and the Ulten zone exposed to the west of the Tauern window (Fig. 5). We shall discuss only those four units which bear significant evidence for specific Carboniferous tectonic processes.

The **Kirchberg-Stuhleck** nappe extends from the eastern margins of the Alps towards W and NW, where this unit is overriden by Middle and Upper Austroalpine nappe complexes. The "Grobgneis" 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 (KOLLER and WIESENEDER, 1981; PEINDL, 1990; NEUBAUER et al., 1992). The age of deposition is uncertain, but predates intrusions of voluminous Carboniferous granites.

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

Although the Alpine overprint regionally reached variable greenschist to amphibolite facies metamorphic conditions, the pre-Alpine mineral assemblages are well-preserved in some areas (KOLLER and WIESENEDER, 1981; NEUBAUER et al., 1992; PEINDL, 1990; MOYSCHEWITZ, 1994; BERKA et al., 1998; DRAGANITS, 1998; TÖRÖK, 1998). Some stages of pre-Alpine metamorphism may be recognized because of the relationship to Carboniferous and Permian intrusions (PEINDL, 1990). A first stage of metamorphism predates Carboniferous intrusions and reached partial melting in metapelites and metagreywackes. The peak metamorphic conditions were reached after the intrusion of the muscovite-biotite granites by progressive decomposition of muscovite from granites to potash feldspar and sillimanite, indicating local granulite facies conditions (PEINDL, 1990). A temperature rise followed the crystallization (dehydration) of the granites, which caused prograde replacement of magmatic muscovite by sillimanite + K-feldspar + quartz. Rare small green patches in the granites resulted from small frozen melts along grain boundaries (PEINDL, 1990). Age dating of andalusite-bearing migmatites indicate a Permian age (ca. 243 Ma). Permo-Mesozoic sediments in the northern part of the Raab Alps give proof of the exhumation of the Raabalpen complex at the end of the Variscan tectonometamorphic cycle in accordance with late Variscan ^{40}Ar/^{39}Ar mineral cooling ages (FRANK et al., 1996; MÜLLER et al., 1999).

Middle Austroalpine units comprise a number of pre-Alpine basement units that were metamorphosed within mostly medium-grade metamorphic conditions and deformed together during the Variscan orogeny. The southern sectors were overprinted by Alpine medium-grade, the 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 bottom (Fig. 1): (1) The Micaschist-Marble complex, (2) the Speik complex, (3) the "Core" complex, (1) to (3) together forming the Muralpen units (or **Muriden complexes**), (4) the Kor-Saualpe Eclogite-Gneiss complex (sometimes also referred to as the **Koriden complex**) and (5) the Kor-Saualpe Micaschist group.

The "Core complex" consists of strongly foliated biotite plagioclase paragneisses, a mylonitic plagioclase orthogneiss and huge masses of various amphibolites, including banded amphibolites (e.g., FRANK et al., 1976) of generally mylonitic appearance (NEUBAUER and FRISCH, 1993 and references therein). These strongly foliated sequences are intruded by the Rennfeld tonalite suite (NEUBAUER and FRISCH, 1993) and granitic and granodioritic plutons, including a sheet-like augen gneiss at the top boundary of the "Core complex". Field 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 is evidenced only in the "Core complex", where U-Pb zircon lower intercept data of between 450 and 425 Ma were reported from the augen gneiss within a metatonalite suite and the garnet amphibolite. In addition, paragneiss zircons are close to the discordia of this age (NEUBAUER and FRISCH, 1993).

The Rennfeld tonalite suite intruded at ca. 360-355 Ma (NEUBAUER and FRISCH, 1993). The suite consists of a wide range of magmatic rocks, including ultramafic rocks, gabbro, tonalite and granite, which form a layered intrusion. These rocks are considered to result from subduction of oceanic lithosphere at the Devonian/Carboniferous boundary.

The superposition of the Speik complex on top of the "Core" complex, as well as the superposition of both by the

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Micaschist-Marble complex, seem to predate the peak metamorphic conditions of pre-Alpine metamorphism, although the 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. One of the augen gneiss layers is discordant with the country rocks in the Speik complex: it climbs in a southwesterly direction through the Speik complex and also reaches into the lowermost parts of Micaschist-Marble complex. In the continuation, pegmatite swarms occur, suggesting a possible genetic relationship. Because of the early Carboniferous age of the augen gneiss, a Variscan top to the SW shear is supposed for Variscan thrusting (NEUBAUER, 1988).

A large Variscan ophiolite nappe was therefore postulated by NEUBAUER (1988). The peak metamorphic conditions are assumed to have reached the stability field of staurolite during Early Carboniferous times. Metamorphic overprint was associated with deformation, so that only the less deformed portions better monitor the pre-Alpine conditions. The Gleinalm core complexes, also exposed within the Troiseck-Floning-Zug, Seckau and Schladming cores, generally consist of migmatites with a complicated metamorphic history that interfere with various intrusions of different ages. The best studied example is the Gleinalm region where acidic, heavily deformed granodioritic orthogneisses intruded before 500 Ma (HAISS, 1991). These were followed by intrusions of the precursor rocks of some granitic orthogneisses at 440-420 Ma (SCHARBERT, 1981; NEUBAUER and FRISCH, 1993) and by many mafic to acidic intrusions of Variscan age (ca. 360-330 Ma; NEUBAUER and FRISCH, 1993, and SCHERMAIER et al., 1997, for reviews). The present state was obviously created during Variscan metamorphism, as Variscan mineral ages (Rb-Sr and Ar-Ar) within the Troiseck-Floning Zug suggest (HANDLER, 1994; DALLMEYER et al., 1998). Cretaceous amphibolite facies conditions were only reached in southern sectors of the Gleinalm region.

The Kor-Saualpe Eclogite-Gneiss complex outcropping 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. 5). Other intercalations are rare relics of metagabbros, marbles, manganese quartzites, calcium silicate rocks and widespread pegmatites. For the purpose of Late Paleozoic evolution, only two facts have to be mentioned: The eclogites were partly derived from Permian metagabbros. Furthermore, pegmatites of Permian age and a Permian low-pressure metamorphism are common (SCHARBERT cited in GÖD, 1989). 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 conditions. Intra-Permian ages have also been found 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 (see HEEDE, 1997, for details). Most researchers agree that a metamorphic complex with low pressure characteristics (andalusite stability) was intruded by numerous pegmatites in late Variscan times (e.g., MORAUF, 1980; FRANK et al., 1983). A reasonable scenario suggests that low pressure metamorphism was associated with Permian intrusions of mafic melts and pegmatitic melts into middle to shallow levels of the crust (SCHUSTER and THÖNI, 1996).

The **Ötztal basement complexes** consist 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 eclogites, which were derived from gabbros (MILLER and THÖNI, 1995; SPIESS, 1991). The conditions of eclogite metamorphism were recently estimated to be at ca. 730 °C and 27 kbar. Sm-Nd garnet-whole rock ages provide evidence of a Variscan age of the eclogite metamorphism (ca. 373±20 and 359±18 Ma; MILLER and THÖNI, 1995).

The paragneisses include variable lithologies, 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. VELTMAN (1986) reported 600-750 °C and ca. 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 temperatures and pressures at the rims between 570-640 °C and 5.8 and 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 (HOINKES et al. 1997). Together the data reveal that basement rocks were deformed within Variscan amphibolite facies metamorphic conditions.

Increasing evidence for pre-Late Ordovician metamorphic events was found in limited areas: The northern part within the Winnebach migmatite and in northwestern sectors of the Ötztal basement. 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 showed 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 Table 2). These are related to regional cooling, following Variscan amphibolite facies metamorphic conditions.

The **Ulten zone** exposes migmatitic gneisses and ultramafic rocks, including garnet peridotite and other ultramafics (MARTIN et al., 1993; HÖLLER and HOINKES, 1996). HAUZENBERGER et al. (1996) and GODARD et al. (1996) found a two-stage metamorphic evolution recorded in eclogites. Based on garnet-clinopyroxene thermometry and jadeite contents in omphacite, they found ca. 700±50 °C and >15 kbar for peak metamorphic conditions. Subsequent decompression and regional equilibrium took place at ca. 6-8 kbar and 600±50 °C. OBATA and MORTEN (1987) reported spinel peridotites that formed at conditions of 25-20 kbar and ca. 1200 °C and garnet peridotite metamorphic conditions at ca. 800 °C and 20 kbar. GEBAUER and GRÜNENFELDER (1978) reported U-Pb zircon ages of 332-326 Ma within these rocks. Recently, NIMIS and MORTEN (2000) interpreted the collage of various ultramafic rocks with variable metamorphic P-T conditions as entrained within migmatized crustal rocks within a subduction zone.

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Discussion

The data from both BM and ACD belts reveal that in both sectors of the Variscides similar processes occurred at the same time, but affected different continental units. Furthermore, the general direction of tectonic transport is basically N-directed in the BM and S- to SW-directed in Alpine basement units (Figs. 9, 10). These relationships suggest that BM and ACD represent different sectors of a double-vergent orogen, which formed between two different continental foreland blocks during the course of the Carboniferous. The Cetic massif, as well as Penninic units with Devonian to Early Carboniferous subduction-related plutonic suites, may have been located along southern, distal margins of the BM block and argue for the presence of a major subduction zone there separating BM and Alpine basement units.

The southeastern BM massif records Carboniferous final consumption of the oceanic lithosphere and the subsequent collision of the (Cadomian) Moravo-Silesian block (Brunovistulian microplate) with the Gföhl terrane. Mantle rocks where exhumed along the suture zone, together with subducted portions of the overlying rocks. In this sense, the entire Gföhl terrane (upper Moldanubian units), as it is exposed now, may represent part of the subduction zone which partially remelted due to entrainment of hot lithospheric mantle slabs into the subduction zone (BRUECKNER, 1998; BRUECKNER and MEDARIS, 1998; MEDARIS et al., 1998). The Moldanubian orogenic wedge was thermomechanically extremely weak, deformed within migmatite-grade metamorphic conditions and allowed rotation of the stiff foreland crust. The thermal imprint on Moravo-Silesian foreland units came from Moldanubian units (HÖCK, 1995). All the major Group III granitoids may record the same melt event (FINGER

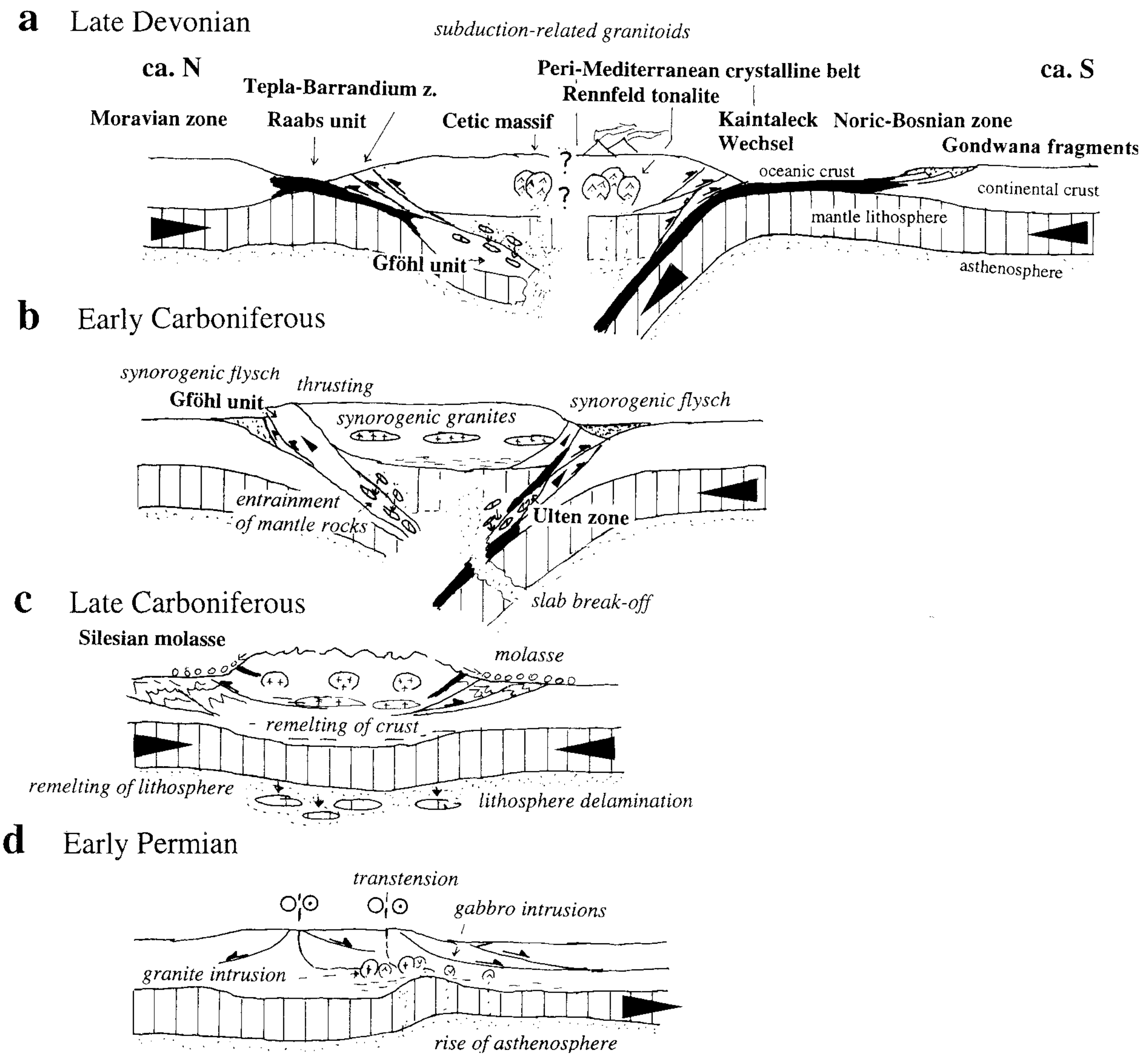

Fig. 9
Stages of tectonic evolution of Central Europe. a – Late Devonian; b – Visean; c – Late Carboniferous; d – Early Permian.

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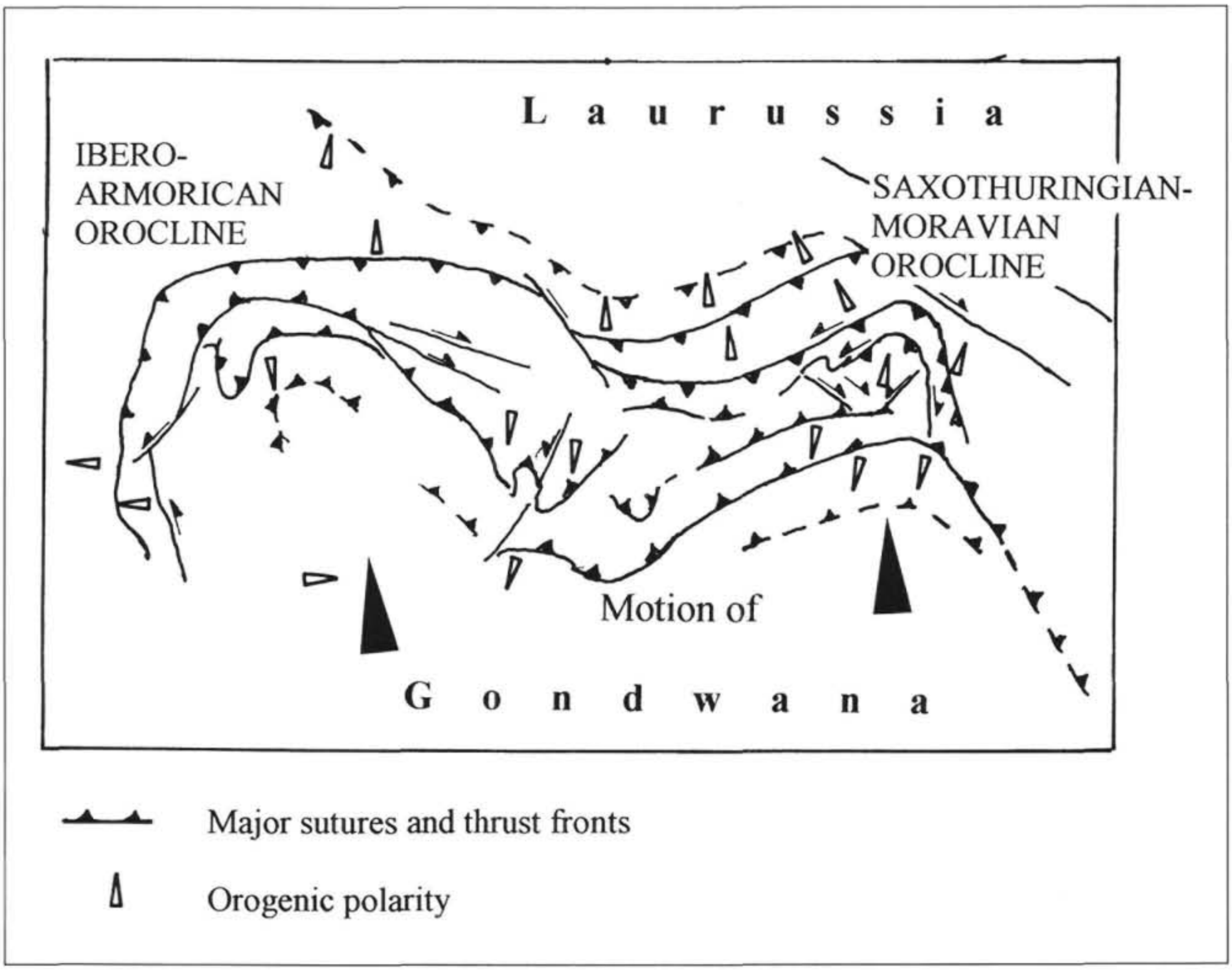

Fig. 10
Model of the late Variscan indenter forming the Ibero-Amorican and Saxothuringian-Moravian oroclines.

et al., 1997) during the plate collision. The Late Carboniferous to Early Permian system of conjugate shear zones records a continuation of N-S shortening and exhumation and contemporaneous cooling of the BM orogenic crust. As the Alpine indenter was located to the south of it, this closely matched the tectonic evolution there.

In the Alpine basement units, the data are in accordance with, and support models which explain the Variscan history of Alpine basement units as a result of continent-continent collision between Gondwana-derived continental elements and northern portions of Central European Variscides and Fennosarmatia. Evidence includes Silurian-Devonian and Late Devonian/Early Carboniferous (Early Variscan) eclogites, which are considered to result from (ultra-)high-pressure metamorphism during subduction of oceanic and continental elements, and the Silurian-Devonian metamorphism within various continental basement units as result of accretion processes (e.g., VON RAUMER and NEUBAUER, 1994). The uniform late Variscan tectonothermal overprint affected Ordovician to early Late Carboniferous passive continental margin sequences and is thought to record the final Variscan continent-continent collision (e.g., NEUBAUER, 1988).

The data mentioned above suggest that the basement units of the Eastern Alps and their lateral extension within the Carpathian arc and Dinarides include the principal suture zone of the southern branch of the European Variscides (for recent geochronological and kinematic data from Carpathians, see FRITZ et al., 1992; DALLMEYER et al., 1996, 1997, 1999; LIÉGEOIS et al., 1996; IANCU et al., 1998; DRAGANESCU and TANAKA, 1999). Basement units comprise continental fragments with a distinct pre-Carboniferous history, including a different metallogeny (EBNER et al., this volume). Among these, "externally" located, mainly medium-grade metamorphic units ("Variscan peri-Mediterranean metamorphic belt") and the "internally" located, peri-Apulian fossil-bearing Noric-Bosnian terrane are the most prominent ones (e.g., FLÜGEL, 1990). The boundary between these latter units was entirely reactivated during Alpine tectonic processes. However, increasing evidence suggests the presence of a Carboniferous suture between these units, including ophiolites, high-pressure rocks and tectonically incorporated mantle rocks (Ulten zone).

The Carboniferous geodynamic evolution of Alpine basement units reveals a succession of subsequent tectonic processes, due to continental plate collision following the consumption of an intervening ocean basin. (1) The consumption of a pre-Carboniferous oceanic basin is inferred by the presence of ophiolitic sequences, which have been subducted to depths corresponding to 27 kb (ultra-high

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pressure metamorphic conditions) at the Devonian/Carboniferous boundary. (2) The intrusions of I-type tonalites were contemporaneous with ultra-high pressure metamorphic conditions. These suites formed above a subduction zone (e.g., the Cetic massif and the Rennfeld tonalite suite within Middle Austroalpine units). (3) The Gondwana-derived Noric-Bosnian terrane was flexured during subsequent late Early Carboniferous continental plate collision. A synorogenic flysch basin extending from the Montagne Noire via the Alps and the Carpathian/Dinarides interface to Chios/Karaburun formed during that time. (4) Both thick-skinned and thin-skinned thrusting, including A-subduction of the underplate continental crust, developed during the early Late Carboniferous. (5) The tectonic emplacement of mantle slices (Ulten zone) within the subducted crust due to slab break-off and their joint exhumation also occurred within this time interval.

Plate collision brought together Gondwanian tectonic elements (Noric-Bosnian terrane) with tectonic elements which were accreted along the northerly adjacent, Laurussian leading edge of the subduction zone during the Silurian and Devonian (Figs. 9, 10). Their accretion is well-documented by geochronologic data of metamorphic rocks like eclogites exposed in the Eastern Alps and Southern/Eastern Carpathians (e. g., IANCU et al., 1998). Oblique continent-continent collision resulted in high surface uplift, large-scale exhumation of the amphibolite-grade metamorphic crust and its denudation during ongoing transpressional processes. Indentation by Gondwanian fragments ("Paleoalpine indenter") resulted in orocline formation within eastern and western sectors of the Variscides (Fig. 10). Contemporaneous rapid exhumation and associated cooling is evidenced by exclusively Variscan, Late Carboniferous to Early Permian $^{40}Ar/^{39}Ar$ ages (ca. 330 to 290 Ma) of detrital white mica recorded within Late Carboniferous to Early Permian molasse-type basins, both in the BM and ACD belts (HANDLER et al., 1997; PANWITZ et al., 2000; SCHNEIDER et al., 2000; CAPUZZO, HANDLER, MADER and NEUBAUER, unpublished data). These relationships suggest that at least upper levels of the orogenic crust, which was >12 km, as a the argon retention temperature (ca. 350-400 °C) in white mica indicate, were entirely removed during orogenic processes prior to, and contemporaneous with, the formation of molasse-type intra-orogenic and peripheral foreland basins. These basins are considered to have formed within an orogen-wide transpressional/transtensional shear belt (MUTTONI et al., 1996; VON RAUMER, 1998 with references). Structures related to extensional collapse are widespread, similar to other sectors of West European Variscides (e. g., MÉNARD and MOLNAR, 1988; MALAVIELLE, 1993; FAURE, 1995; KROHE, 1996).

Growing evidence for a separate Permian event is found in various units of the Alps, as well as in the Bohemian Massif. In the Alps, this is constrained by Sm-Nd garnet-whole rock ages, as well as by Rb-Sr and K-Ar cooling ages (Table 2). In some areas, pegmatites appear to be associated with these. 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 transtensional rifting.

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