Alpine metamorphism of the Eastern Alps

SCHWEIZ. MINERAL. PETROGR. MITT. 79, 155–181, 1999

Alpine metamorphism of the Eastern Alps

by *Georg Hoinkes*[1], *Friedrich Koller*[2], *Gerd Rantitsch*[3], *Edgar Dachs*[4], *Volker Höck*[5], *Franz Neubauer*[6] and *Ralf Schuster*[7]

Abstract

The metamorphic overprint of the Eastern Alps during Alpine times shows significant differences between the two main tectonic units, the Penninic and the Austroalpine, in terms of pressure, temperature, time and tectonic evolution. The Penninic units are characterized by mainly oceanic rocks and fragments of continental polymetamorphic basement and metasedimentary cover which underwent high-pressure metamorphism of low geothermal gradients between c. 7–13 °C/km typical for a subduction zone. This metamorphism caused eclogite formation at maximum crustal depths of about 70 to 85 km (18 to 25 kbar at 600 °C) which is restricted to the Tauern Window and subsequently the formation of blueschists at 10 to 15 kbar and 400 to 450 °C in the Tauern Window and 6 to 8 kbar at ~ 350 °C in the Engadine and Rechnitz Windows. The dominant rock-forming mineral assemblages however are due to a subsequent greenschist to amphibolite facies overprint. In the Engadine and Rechnitz Window only lower greenschist facies conditions of ~ 350–450 °C at ~ 2–4 kbar are recorded whereas in the Tauern Window a concentric metamorphic zonation reaching a maximum of 7 kbar at ~ 550–600 °C in the centre is observed. For the Tauern Window the geothermobarometric results indicate a discontinuous two-stage PT-loop. The age of this metamorphic evolution of the Penninic realm is well known for the late greenschist to amphibolite facies event which took place shortly after 30 Ma and is recorded by cooling ages and fission track studies. The exact age of the high-pressure event is still unknown. The oldest calculated age for the onset of Alpine metamorphism in the Tauern Window however is 62 Ma (Christensen et al., 1994) which is older than the proposed age of eclogite formation in the Central Alps reported by Gebauer et al. (1992) but coincides with Eocene Ar/Ar-ages reported by Zimmermann et al. (1994) for the Tauern Window.

The Lower Austroalpine unit, the paleogeographic link between the Penninic units and the Austroalpine continental plate shows a metamorphic evolution similiar to that of the Penninic realm. In the Lower Austroalpine units adjacent to the western Tauern Window a high-pressure event in the range of ~ 10 kbar and ~ 350 °C was overprinted by greenschist facies conditions of ~ 4 kbar and 400 °C during Eocene times, whereas east of the Tauern Window thorough PT-estimates are still missing. In the Lower Austroalpine units at the eastern end of the Alps a different metamorphic evolution is recorded with greenschist- to amphibolite facies conditions of 8–9 kbar and 500–550 °C, reflecting higher geothermal gradients than in the Penninic high-pressure event, and characterized by Cretaceous mineral ages of ≤ 80 Ma.

Cretaceous ages have also been recorded for the Middle Austroalpine units that represent the polymetamorphic basement and sedimentary cover of the continental plate below which the Penninic units were subducted. The Alpine metamorphic overprint increases from north towards the south from lower greenschist to amphibolite facies. Locally preserved relic eclogite facies conditions of 12 kbar and 550 °C in the west (Ötztal Alps) and 18–20 kbar and

[1] Institut für Mineralogie-Kristallographie und Petrologie, Universität Graz, Universitätsplatz 2, A-8010 Graz, Austria. <georg.hoinkes@kfunigraz.ac.at>
[2] Institut für Petrologie, Universität Wien, Geozentrum, Althanstrasse 14, A-1090 Wien, Austria. <Friedrich.Koller@univie.ac.at>
[3] Institut für Geowissenschaften, Montanuniversität Leoben, A-8700 Leoben, Austria. <rantit@unileoben.ac.at>
[4] Institut für Mineralogie, Universität Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria. <Edgar.Dachs@sbg.ac.at>
[5] Institut für Geologie und Paläontologie, Universität Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria. <Volker.Hoeck@sbg.ac.at>
[6] Institut für Geologie und Paläontologie, Universität Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria. <Franz.Neubauer@sbg.ac.at>
[7] Institut für Geologie, Universität Wien, Geozentrum, Althanstrasse 14, A-1090 Wien, Austria. <a8608424@unet.univie.ac.at>

700 °C in the east (Koralpe) represent geothermal gradients of around 20 °C/km. The subsequent amphibolite facies overprint is interpreted as due to uplift and exhumation after a collisional episode in a subduction regime. The reason for this could be a continent-continent collision at the western end of the Tethys in the late Cretaceous due to the closure of the Hallstatt-Meliatta ocean basin about 100–90 Ma in age, predating the sedimentation of the late Cretaceous Gosau group sediments. The Upper Austroalpine and Southalpine sediments of the Alpine sedimentation cycle starting in the late Carboniferous/Permian however are slightly effected by very low- to low-grade metamorphism with decreasing intensity from north to south, due to internal thrusting in the course of a collisional tectonic environment at the western end of the Tethys during Jurassic/Cretaceous times.

Keywords: polymetamorphism, high-pressure metamorphism, Cretaceous, Cenozoic, collisional orogeny.

1. Introduction

Metamorphism of Cretaceous and Cenozoic age overprinted large portions of the central zone of the Eastern Alps. Because of the overprint of fossil-bearing Mesozoic sedimentary sequences the metamorphism observed within the Penninic units is certainly of Alpine age. In contrast, rocks of the Austroalpine units of the Eastern Alps mainly represent pre-Mesozoic crystalline basement with varying pre-Alpine and Alpine metamorphic grade and Mesozoic to Tertiary sedimentary cover rocks showing a weak Alpine metamorphic imprint. The great extent of Alpine metamorphism of the crystalline basement was long overlooked because thorough geochronological and petrological investigative techniques were not available. With their subsequent development, efforts have been made to unravel the Alpine metamorphic history by numerous research groups. A preliminary report on the new results on Alpine metamorphism of the Penninic and Austroalpine units of the Eastern Alps carried out by Austrian research groups was published in a book edited by FLÜGEL and FAUPL (1987). At present, new data on age and grade of metamorphism of the Austroalpine units constrain the importance of the Alpine orogeny restructuring the pre-Mesozoic crystalline basement. Areas of basement exposed in the Eastern Alps, which lack Alpine metamorphism turned out to be the exception and well-known eclogites of the Austroalpine basement have been dated as Alpine formations. In this paper, we summarize the state of the art concerning the Alpine metamorphism of the Penninic and Austroalpine units from the Eastern Alps. The sections covering the Penninic realm and the Lower Austroalpine nappes were written by F. Koller, V. Höck and E. Dachs (parts of the Tauern Window chapter), the section covering the Austroalpine realm was written by G. Hoinkes with the exception of the Austroalpine Paleozoic and Mesozoic cover units and the Southern Alps which was written by G. Rantitsch. The entire chapter of Alpine Metamorphism of the Eastern Alps was compiled by G. Hoinkes. The distribution of Cretaceous and Palaeogene-age metamorphic facies is shown on the "Map of Alpine Metamorphism 1 : 500 000" (see enclosure) to which we refer.

2. Penninic tectonic units

The Penninic tectonic units, widely distributed in the Western and Central Alps can be found within a series of windows along the whole range of the Eastern Alps. From the W to E, these are the Lower Engadine Window (LEW), the Tauern Window (TW) and a group of small windows at the eastern margin of the Alps referred to as the Rechnitz Window Group (RWG) (HÖCK and KOLLER, 1989; KOLLER and HÖCK, 1990; see Fig. 1). The Rhenodanubian Flyschzone is also ascribed to the Penninic realm (e.g. OBERHAUSER, 1995), but is not considered here in terms of metamorphism.

Stratigraphically, the metamorphic rocks in the Penninic realm range from the Late Proterozoic(?) to the Palaeogene. Pre-Mesozoic rocks are restricted to the TW and to small fragments at the base of the Tasna nappe in the LEW (FLORINETH and FROITZHEIM, 1994). Mesozoic rocks, such as Triassic quartzites, marbles and dolomites, as well as Jurassic and Cretaceous phyllites, mica schists, calcareous mica schists and other metasediments, ophiolites and non-ophiolitic volcanics occur throughout all Penninic windows. The upper stratigraphic boundary of the Mesozoic to Cenozoic sequences is still under discussion. Late Cretaceous and Palaeogene sediments are found in the LEW (OBERHAUSER, 1995), Early Cretaceous in the TW (REITZ et al., 1990) and the RWG (PAHR, 1980). It has not been ascertained whether Late Cretaceous and Tertiary sediments occur in the more easterly windows.

2.1. LOWER ENGADINE WINDOW

The Penninic sequences of the LEW, located at the Swiss-Austrian border, are surrounded and overlain by different Austroalpine nappes. These are the Silvretta crystalline basement in the north, the Ötztal crystalline basement in the east and southeast and the Scarl unit in the south. The LEW itself can be divided into different internal nappes (OBERHAUSER, 1980; TRÜMPY, 1972). The deepest unit is the Pfunds Zone which contains the huge mass of the central "Bündnerschiefer". This unit is covered by the zone of Roz-Champatsch, Pezid, and Ramosch thought to be of Northpenninic origin. The next higher unit is the Tasna nappe with a base of pre-Alpine crystalline rocks (OBERHAUSER, 1980; FLORINETH and FROITZHEIM, 1994). The highest unit is the Arosa Zone, believed to be of Southpenninic origin (TRÜMPY, 1972; TOLLMANN, 1977; OBERHAUSER, 1980).

Most of the individual nappes consist of various carbonate-rich metasediments, mainly turbidites, sandstones and pelitic sediments of Mesozoic to Palaeogene age. Radiolarites are restricted to the ophiolites. In addition, the nappes of Pfunds, Ramosch and Arosa commonly contain well preserved fragments of oceanic crust. The ophiolites of the Pfunds and Arosa Zone consist of harzburgites at their base, while the Ramosch

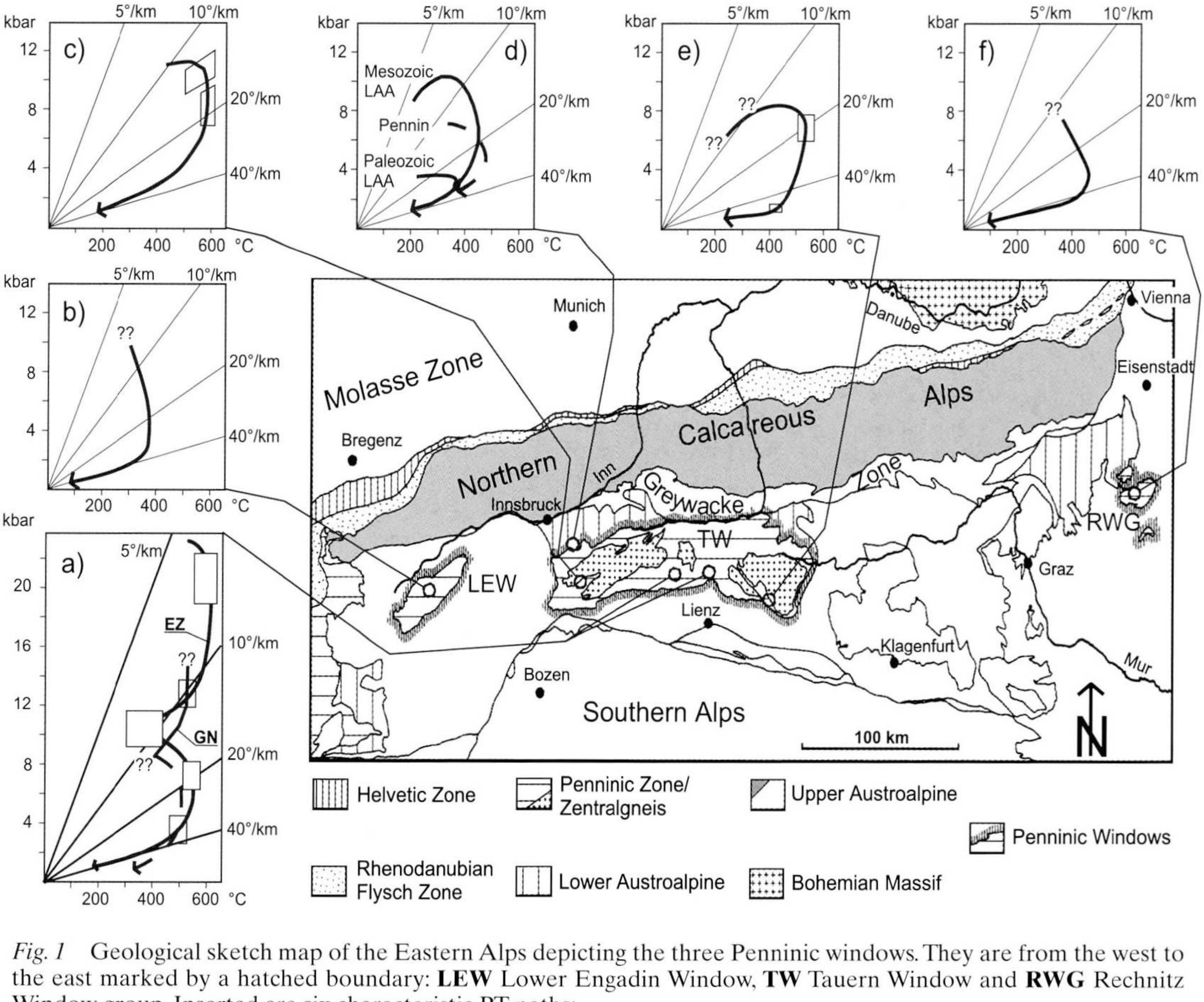

Fig. 1 Geological sketch map of the Eastern Alps depicting the three Penninic windows. They are from the west to the east marked by a hatched boundary: **LEW** Lower Engadin Window, **TW** Tauern Window and **RWG** Rechnitz Window group. Inserted are six characteristic PT paths:
a: Tauern Window eclogites (ZIMMERMANN et al., 1994; STURM et al., 1997);
b: Lower Engadin Window (OBERHÄNSLI, 1994; KOLLER et al., 1996);
c: Western Tauern Window (SELVERSTONE et al., 1984);
d: Lower Austroalpine Nappe, Tarntal Mts. (DINGELDEY et al., 1997)
e: Tauern Window (DROOP, 1985);
f: Rechnitz Window Group (KOLLER, 1985).

For references see text.

zone is dominated by lherzolitic compositions. All these fragments of oceanic crust exhibit traces of an ocean-floor metamorphism (KOLLER and HÖCK, 1990; KOLLER et al., 1996; OBERHÄNSLI et al., 1995).

2.1.1. High-pressure event

The Alpine metamorphic overprint begins with a poorly documented HP/LT event. It is recorded mainly in the metabasites exposed at different localities by the following minerals:

- lawsonite in metabasites from several localities in the northeastern part of the window (LEIMSER, 1977; LEIMSER and PURTSCHELLER, 1980; STÖCKHERT et al., 1990);
- rare blue amphiboles with compositions ranging from glaucophane to crossite from parts of the central window (OBERHÄNSLI et al., 1995) and from the NE part (LEIMSER, 1977);
- inclusions of Fe–Mg-carpholite in quartz from metasediments below the Piz Mundin ophiolite (OBERHÄNSLI et al., 1995);
- high-pressure phengites (Si up to 3.45 p.f.u.) from various metasediments (OBERHÄNSLI et al., 1995; STÖCKHERT et al., 1990).

So far, relatively few P and T estimates exist for this event, all of which lie around 300–350 °C and > 3 kbar (LEIMSER and PURTSCHELLER, 1980; KOLLER and HÖCK, 1990; KOLLER et al., 1996). STÖCKHERT et al. (1990) suggest pressures of 6 to 7 kbar from high density primary fluid-inclusions in vein quartz. For the Piz Mundin area, pressures are estimated > 6 kbar based on the carpholite composition (OBERHÄNSLI, 1994).

2.1.2. Low-grade metamorphism

The thermal peak of the metamorphic overprint is characterized by greenschist-facies assemblages. In the metabasic rocks pumpellyite is only rarely replaced by epidote, while stilpnomelane is common especially in the Tasna granite and is not replaced by green biotite. Using the compositions of preserved Mg-rich pumpellyite, temperatures were estimated to be in the range of ~ 350 °C at correspondingly low pressures of ≤ 3 kbar (KOLLER et al., 1996). OBERHÄNSLI (1994) relates the HP/LT event to the Meso-Alpine collisional stage, but there are no reliable mineral ages available for this event. A few K–Ar age data in the range of 34–30 Ma from < 2 μm fractions of muscovite have been published for the thermal event (THÖNI, 1981). The best constrained PT-path and geodynamic model to date have been published by OBERHÄNSLI (1994). The PT-path is characterized by a geothermal gradient of ~ 10 °C/km for the HP/LT event, followed by the thermal peak at ~ 30 Ma (Fig. 1b).

2.2. TAUERN WINDOW

The oldest rocks in the TW form a volcano-sedimentary sequence consisting of ophiolites, island arc volcanics and associated sediments of Late Proterozoic to Palaeozoic age (Habach Formation of FRASL, 1958). A part of this sequence underwent pre-Mesozoic metamorphism, including migmatisation in parts, and was intruded by Variscan granitoids (transformed to "Central Gneiss Cores" by the Alpine orogeny).

The post-Variscan sequence begins with Permo-Triassic quartzites, middle Triassic limestones and dolomites and Late Triassic sandstones and shales (Keuper). The Triassic rocks are overlain by shales, marls and shaly limestones of Jurassic to Early Cretaceous age (Bündnerschiefer Formation). Locally, sandstones, breccias and arkoses occur. Ophiolites and non-ophiolitic basic intrusions and volcanics are associated with the sediments. The youngest sediments known so far are of Early Cretaceous age (KLEBERGER et al., 1981; REITZ et al., 1990).

Tectonically, two nappes are generally delineated (FRISCH, 1976): the lower Venediger Nappe with most of the pre-Mesozoic rocks (Central Gneiss + "Lower Schieferhülle" = intruded polymetamorphic basement plus Permian to Mesozoic cover), and the higher Glockner Nappe ("Upper Schieferhülle") including most of the Triassic rocks, the Bündnerschiefer and the ophiolites. KURZ et al. (1998b) introduced the Rote Wand-Modereck nappe complex between both major units. All three nappes were later folded into a huge anticline with an axis approximately following the main ridge of the Alps (for a more detailed discussion of the Penninic nappe pile and its kinematic evolution see e.g. KURZ et al., 1996, and KURZ et al., 1998b).

Apart from pre-Mesozoic metamorphism, three Alpine metamorphic events have been recognized. These are an eclogite facies event, a blueschist facies metamorphism, and the final greenschist to amphibolite facies overprint, referred to as "Tauernkristallisation" by SANDER (1912). The eclogites are concentrated in a relatively small strip at the southern escarpment of the TW (Grossvenediger area, Eclogite Zone, sandwiched between Venediger and Glockner Nappe). They may also be found as strongly retrogressed relics in structurally lower parts of the

Glockner Nappe (Grossglockner region, CORNELIUS and CLAR, 1939). While it appears that eclogite facies metamorphism is restricted to these particular areas, the entire nappe pile has undergone blueschist facies metamorphism, followed by the Tertiary greenschist to amphibolite facies metamorphism which is the dominant metamorphic imprint in all rocks of the TW.

2.2.1. Eclogite event

i) Eclogite Zone (EZ) – southern Grossvenediger area

The most conspicuous eclogite assemblages are found in EZ-metabasic rocks south of the Grossvenediger. Original basal-sediment contacts are still preserved, and consequently the intercalated metasediments show high-pressure mineral assemblages as well (MILLER, 1977; FRANZ and SPEAR, 1983; DACHS, 1986; SPEAR and FRANZ, 1986). Inclusions in the cores of eclogite garnets such as Ep, Chl, Pg, Phe, Qtz, Ab, Fe–Bar etc., and Lws(?)-pseudomorphs in garnets from the metasediments indicate an epidote-amphibolite/blueschist facies event prior to the eclogite facies metamorphism (MILLER 1977; HOLLAND, 1979; DACHS 1986; DACHS et al., 1991). The following mineral assemblages are found in high pressure rocks of the EZ:

in eclogites: $Omp(Jd_{50})$ + $Grt(Prp_{37})$ + Rt + Qtz ± Ky ± Tlc ± Zo/Ep ± Pg ± Phe ± MgCld ± Dol (MILLER, 1977; HOLLAND, 1979; FRANK et al., 1987a), in synmetamorphic veins: Qtz + Ky + Omp ± MgCld ± Tlc ± Chl ± Zo/Ep ± Rt ± Ap ± Carb (FRANK et al., 1987a; THOMAS and FRANZ, 1989),

in marbles: Cal + Qtz ± $Omp(Jd_{30-32})$ ± Dol ± Tr ± Di ± Zo ± Ky ± Phe(Si = 3.32–3.47 p.f.u.) ± Pg ± Mrg (FRANZ and SPEAR, 1983; DACHS, 1986; SPEAR and FRANZ, 1986),

in metapelites: Phe(Si up to 3.47 p.f.u.) + $Grt(Prp_{24-35})$ + Qtz ± $Omp(Jd_{42-54})$ ± Pg ± Tlc ± Zo ± Ky ± Cld ± Dol ± Zn–St (DACHS, 1986; SPEAR and FRANZ, 1986).

Further to the east, eclogite relics ($Omp(Jd_{45})$ + $Grt(Prp_{10}Grs_{20}Sps_3)$ + Pg + Bar + Zo/Ep + Phe + Dol ± Qtz) can be traced to the Dorfertal valley north of Kals in an equivalent tectonic position between Venediger and Glockner Nappe.

Using the Fe/Mg distribution between coexisting clinopyroxenes and garnets in EZ-eclogites, temperatures between 550 and 650 °C were calculated (580–650 °C for pressures near 20 kbar, HOLLAND, 1979; 550–570 °C for P = 10 kbar, FRANK et al., 1987a). Based on coexisting Omp + Dol + Qtz + Ky + Pg, HOLLAND (1979) derived peak pressures of 19.5 ± 2.5 kbar and a_{H_2O} ~ 1 for the eclogite formation. Similar pressures close to 20 kbar were calculated by FRANK et al. (1987a) from the reactions:

Pg = $Omp(Jd_{50})$ + Ky + H_2O and Chl + Ky = MgCld(64) + Tlc at water activity ~1.

Comparable PT estimates were also reported from siliceous dolomites by FRANZ and SPEAR (1983; T = 600 °C, P = 18–25 kbar), calcareous mica schists by SPEAR and FRANZ (1986; T = 590 ± 20 °C, P = 19 ± 2 kbar) and for metapelites by DACHS (1986; T = 600 °C, P = 21 kbar). More recently, higher pressures up to 25 kbars were published by STÖCKHERT et al. (1997). The role of the fluid phase during subduction-zone metamorphism of the EZ was discussed by SELVERSTONE et al. (1992) and GETTY and SELVERSTONE (1994). Meso- and microfabrics, as well as possible mechanisms relevant for the exhumation of the EZ were studied by e.g. BEHRMANN and RATSCHBACHER (1989), and recently by KURZ et al. (1998a).

The eclogitic assemblages were subsequently overprinted by a younger blueschist event followed by the greenschist to amphibolite facies metamorphism (Tauernkristallisation). Corresponding breakdown reactions have been reviewed by MILLER (1977), FRANZ and SPEAR (1983), DACHS (1986) and SPEAR and FRANZ (1986).

ii) Grossglockner area

In the Grossglockner area, eclogites occur as strongly retrogressed relics in greenschists that belong to the structurally lower parts of the Glockner nappe. They contain the assemblage $Omp(Jd_{35-50})$ + $Grt(Prp_{11}Grs_{23}Sps_3)$ + Zo/Ep + Qtz + Rt ± Pg ± Dol ± Phe. STURM et al. (1997) calculated minimum pressures of ~ 13 kbar and temperatures around 530 °C (garnet-clinopyroxene thermometry) for their formation, demonstrating that at least the structural lower parts of the Glockner Nappe experienced eclogite facies conditions.

2.2.2. Blueschist event

Whereas the eclogite assemblages are locally well preserved despite a multiple overprint, the minerals formed in the blueschist event have survived only rarely. The best preserved remnants are found in the vicinity of the eclogite zone.

The most conspicuous relics from this stage are the pseudomorphs after lawsonite reported from various lithologies within the TW (e.g. FRY, 1973; HÖCK, 1974, 1980; MILLER, 1974, 1977; HOLLAND, 1979; RAITH et al., 1980; DROOP, 1985; SELVERSTONE and SPEAR, 1985). The composition of the pseudomorphs is variable and depends on the lithology of the host rocks. In basites, the pseudomorphs consist mainly of Czo/Ep, Ab, Chl, Act, Bt, in calcareous rocks, of Zo/Czo, Cal, Ab, Chl ± Pg, Mrg, Qtz (particularly as lawsonite-shaped euhedral relics in garnet). Despite a systematic search, no relics of lawsonite itself have been found so far in the TW. Some jadeite-poor omphacites, embedded in a symplectite of Ab + Hd + Act, also represent the blueschist facies (HOLLAND and RAY, 1985). Occasionally, blue amphiboles such as glaucophane and/or crossite, as well as barroisitic amphiboles are preserved. Associated with this stage and possibly also with the eclogite event are high-Si phengites with Si = 3.30–3.40 p.f.u. In extreme cases, the Si content may reach 3.5–3.7 p.f.u. in dolomite marbles (ZIMMERMANN et al., 1994). Using these data FRANK et al. (1987a) estimated the conditions of blueschist formation as T = 400–450 °C with P around 9 kbar. ZIMMERMANN et al. (1994) have summarized the PT-conditions of the blueschist stage as follows: Venediger Nappe: P < 13–15 kbar in the Central Gneiss Cores, T = 450–520 °C and P > 10 kbar in the Lower Schieferhülle; T < 450 °C (possibly < 300 °C, HOLLAND and RICHARDSON, 1979) and P = 10–15 kbar in the EZ; Glockner Nappe: T < 420–450 °C and P > 10 kbar.

2.2.3. Greenschist to amphibolite facies event

This metamorphic event has affected all rocks within the TW. A region of greenschist facies metamorphic rocks can be clearly differentiated from an amphibolite facies region. Corresponding mineral isograds run approximately parallel to the outline of the TW and are more or less concentrically arranged, such that metamorphic grade increases from the periphery towards the interior of the window (western TW: MORTEANI and RAASE, 1974; BERNOTAT and MORTEANI, 1982, HOERNES and FRIEDRICHSEN, 1974; HOSCHEK, 1980a; central TW: BICKLE and POWELL, 1977; RAITH et al., 1977; FRANK et al., 1987a; DACHS, 1990; eastern TW: DROOP, 1981, 1985); HÖCK (1980) presents distribution maps of Alpine minerals for the whole TW. The boundary between greenschist- and amphibolite-facies areas can be mapped in gneisses and metabasites by the first occurrence of oligoclase (An_{15-25}) coexisting with albite ($An_{<5}$). In both lithologic types, oligoclase appears at the same stage. In pelitic assemblages, garnet can serve as an index mineral appearing shortly before the income of oligoclase in the basic and gneissic assemblages e.g. of the Grossglockner region (FRANK et al., 1987a). In addition, the increase in metamorphic grade from the northern and southern rims towards the centre of the TW is also indicated by the amphibole compositions that change from actinolitic at low grades to magnesio-hornblende in the medium grade areas (FRANK et al., 1987a). The Mg-contents of calcite coexisting with dolomite also increase with metamorphic grade in the Bündnerschiefer (BICKLE and POWELL, 1977; DACHS, 1990). Pelites in the south-east TW show a clear metamorphic zonation from a relatively low-grade peripheral zone characterised by garnet + chlorite + biotite and garnet + chlorite + chloritoid AFM assemblages (garnet + chlorite zone) through a narrow transitional chloritoid + biotite zone to a relatively high-grade zone characterised by garnet + staurolite + biotite ± kyanite (staurolite + biotite zone) centred on the Hochalm Dome (DROOP, 1981; DROOP and HARTE, 1995). Kyanite occurrences begin in the high-T areas of the greenschist facies and Zn-poor staurolite is restricted to the highest metamorphic grades in the western and eastern TW (HÖCK, 1980; DROOP, 1981, 1985; SELVERSTONE et al., 1984; KRUHL, 1993); Zn-rich staurolite is also present in quartz-micaschists of the EZ (SPEAR and FRANZ, 1986).

The calcareous metasediments are variable in composition and mineralogy. They include voluminous calcareous mica schists (with minerals such as Cal, Dol, Phe, Pg, Mrg, Chl, Cld, Zo, Grt, Bt, Qtz), carbonate-quartzites (Cal, Dol, Tr/Act, Zo, Phe, Chl, Qtz) and impure marbles (containing Cal, Dol, Tr/Act, Di, Ep/Zo, Chl, Phe, Qtz). In the central part of the TW, biotite is very rare in most calcareous mica schists, while in the western and southwestern part biotite is fairly common (HOSCHEK, 1980, 1984). Thus, the simplified multisystem $CaO–MgO–Al_2O_3–SiO_2–H_2O–CO_2$ with six-phase mineral assemblages such as Mrg + Zo + Chl + Cal + Dol + Qtz or Grt + Zo + Chl + Cal + Dol + Qtz describes well the metamorphic evolution for the central part of the TW. These assemblages form isobaric invariant points in a TX_{CO_2} diagram and can serve as isograds in the field with 480 °C for the first and 510 °C at 6 kbar for the second invariant point (HÖCK and HOSCHEK, 1980; FRANK et al., 1987a; DACHS et al., 1991). In the western part, a simplified marly rock system including K_2O was used by HOSCHEK (1980 a, b) to describe phase relations in the calcareous Bündnerschiefer. Based on the appearance of Bt + Cal and Bt + Zo + Cal, corresponding isograds were mapped and temperatures around 550 °C at a pressure of 6 kbar, and relatively low X_{CO_2} derived as the appropriate physical conditions for the carbonate-rich rocks in the amphibolite-grade zone. The distribution of Fesulfides in graphite-free and graphite-bearing calcareous rocks of the western TW in response to metamorphic grade was addressed by HOSCHEK (1984).

Fluid inclusions were studied in quartz, epidote and other minerals from gneisses, amphibolites, mica schists and garbenschists from the western TW (LUCKSCHEITER and MORTEANI, 1980; SELVERSTONE et al., 1984; SELVERSTONE and SPEAR, 1985) and recently from quartz crystals in Alpine fissures. All data indicate that the cooling path of the greenschist- to amphibolite facies event passed through a T interval of 430–500 °C and P between 2 and 4 kbar.

Available PT data show that the Alpine metamorphic evolution cannot be described by a single PT loop (FRANK et al., 1987a; DACHS et al., 1991; ZIMMERMANN et al., 1994). Eclogites, originally formed at ~ 20 kbar and ~ 600 °C, first cooled to blueschist facies conditions (Fig. 1a). Following this, the eclogite path joined the loop for the ophiolites and all rocks structurally below in the Lower and Upper Schieferhülle, which reached their T_{max} between 450 to 550 °C (> 600 °C in the eastern TW according to DROOP, 1985) at pressures between 5–7 kbar (e.g. HOSCHEK, 1982; SELVERSTONE et al., 1984; SELVERSTONE and SPEAR, 1985; DROOP, 1985; DACHS, 1990), cooling down later to 375–400 °C at 2–4 kbar as indicated by the fluid inclusions (Fig. 1a-e).

2.2.4. Geochronology and deformation

Prior to 1985, age dating of the metamorphism mainly involved Rb/Sr and K/Ar dating of biotites and muscovites. A comprehensive review of the data up to 1987 is given by FRANK et al. (1987b), indicating that most of the cooling of Tauernkristallisation took place at < 30 Ma (Oligocene to Miocene). The biotite ages (Rb/Sr and K/Ar) gave lower ages than muscovites (Rb/Sr and K/Ar) from the same rocks (BLANCKENBURG et al., 1989; CLIFF et al., 1985, REDDY et al., 1993). The former cluster in the eastern TW between 15 and 24 Ma, the latter between 21 and 30 Ma, and in the western part around 13 Ma and 15–20 Ma respectively. The lower ages are interpreted as cooling ages following the greenschist- to amphibolite-grade metamorphism. Some of the Upper Oligocene ages from the structurally lowest parts are interpreted as approximating the metamorphic climax (CLIFF et al., 1985). Few ages, mainly in the western part of the TW (SATIR, 1975) and in the northeastern corner (PEER and ZIMMER, 1980), are older than 30 Ma (Eocene/Oligocene boundary).

More recent studies, using $^{40}Ar/^{39}Ar$ dating, confirmed the Eocene/Oligocene ages for Si-rich phengites (ZIMMERMANN et al., 1994) from the Lower Schieferhülle, the EZ and a few from the Upper Schieferhülle. Most of the analysed micas are associated with the blueschist event. ZIMMERMANN et al. (1994) argue that blueschist facies metamorphism took place between 36 and 32 Ma with the cooling of the subsequent greenschist to amphibolite facies event occuring after 27 Ma according to a minimum age obtained from a phengite in the Upper Schieferhülle. INGER and CLIFF (1994) obtained Rb–Sr phengite ages of 29 ± 1 Ma from the same area (EZ and Upper Schieferhülle). They interpret their data as representing rehomogenization of Sr isotopes throughout both units related to reheating to T_{max} of the Tauernkristallisation. It is noteworthy that DINGELDEY et al. (1997) reported higher ages from calcareous mica schists from the Upper Schieferhülle with $^{40}Ar/^{39}Ar$ ages between 42–38 Ma from phengites in Bündnerschiefer, which have experienced the greenschist facies event only.

A different method was used by CHRISTENSEN et al. (1994) to determine the growth rate and age of garnets in two garnet-bearing mica schists from the Upper and the Lower Schieferhülle, respectively. Measurement of the Rb–Sr isotopes at individual segments of single garnets from the Upper Schieferhülle revealed an age of 35 Ma for the core and 30.5 to 31 Ma for the rim. The oldest age measured in the core of a garnet from the Lower Schieferhülle yielded 55 Ma, the youngest 32 Ma. Extrapolating from the calculated growth rate they inferred the onset of garnet crystallisation as old as 62 Ma. This is the oldest reliable age reported from the TW regarding the onset of the Alpine metamorphism.

Fission tracks in apatites record a very late stage of exhumation with rocks passing through a temperature interval of approximately 100–120 °C. This varies in the western TW from 5–10 Ma with a systematic increase in ages obtained from the mineral zones in the core towards the rim of the TW (GRUNDMANN and MORTEANI, 1985; GRUNDMANN, 1987; FÜGENSCHUH, 1995). An extensive study in the eastern TW by STAUFENBERG (1985) gave fission track ages comparable with those from the western TW with a tendency towards slightly older ages.

The eclogite deformation within the Eclogite Zone occurred under prograde and retrograde metamorphic conditions. KURZ et al. (1988a) described NNE-directed shear during burial, and subsequent N-directed nappe emplacement under decompressional blueschist facies metamorphic conditions. The later event is consistent with regional N-directed nappe stacking within the eastern Tauern window (GENSER, 1992; KURZ et al., 1988b). Regional peak metamorphic conditions were associated with static mineral growth within central sectors of the Tauern window and formation of a new foliation associated with exhumation in peripheral, upper and lateral, sectors of the Tauern window. W-directed shear deformation prevails in the interior. Furthermore, retrogressive greenschist facies metamorphic overprint is related to confining low-angle normal faults and sinistral strike-slip zones (KURZ et al., 1988b, and references cited therein; WANG and NEUBAUER, 1998).

2.3. RECHNITZ WINDOW GROUP

At the eastern end of the Alps, close to the Austrian-Hungarian border, several small Penninic windows are exposed below the Variscan basement of the Lower Austroalpine nappes. From north to south they are the Möltener window, Bernstein window, Rechnitz window, and Eisenberg window. All these windows consist of huge masses of Mesozoic metasediments and some ophiolites. The metasediments consist of a several km thick pile of calcareous mica schists, quartz-phyllites, graphite-phyllites and locally breccias and few horizons of rauhwackes. Within the ophiolitic section, relics of oceanic metamorphism and various degrees of oxidation have been documented in most of the metagabbros, in some of the metabasalts and in the ophicarbonates (KOLLER, 1985).

2.3.1. Blueschist facies event

Within the ophiolitic sequence, remnants of a HP/LT event are widespread. Typical minerals are sodic pyroxenes, glaucophane or crossite, rare pseudomorphs of lawsonite, high Si-phengite (up to 3.5 p.f.u.), Mg-rich pumpellyite with a $Fe^{tot}/(Fe^{tot}+Al)$-ratio of 0.03–0.06 or epidote, stilpnomelane, hematite and rutile. No clear high-pressure assemblage can be defined for the metabasalts which contain only rare relics of blue amphibole, stilpnomelane and pseudomorphs after lawsonite. High-Si phengite is also present in metabasalts and common in metasediments. In general, very few data from the sedimentary rocks exist. KOLLER (1985) defines temperatures of 330–370 °C at a minimum pressure of 6–8 kbar for this high-pressure event.

2.3.2. Low-pressure greenschist event

The high-pressure event is followed by a widespread greenschist overprint. Prograde reactions have led to the breakdown of pumpellyite to the assemblage Grs + Chl in rodingites and to Czo + Chl + Act in metaleucogabbros. The Fe-rich Na-pyroxene is replaced by low-pressure riebeckite/magnesioriebeckite. Stilpnomelane is replaced by green biotite and lawsonite by epidote. From north to south, there is a slight increase in temperature. This can be defined by the following mineral zones: (1) disappearance of metastable stilpnomelane and Mg-pumpellyite in the northern part of the Rechnitz window, (2) first appearance of green biotite in the northern part of the Bernstein window, and (3) the first appearence of garnet in metapelites which is restricted to the southernmost outcrops of the Penninic units.

2.3.3. Radiometric age data and PT-path

No reliable ages have been obtained for the high-pressure event. Greenschist facies metamorphism has been dated by K/Ar from muscovite at 22–19 Ma (FRANK in KOLLER, 1985). Fission-track ages of 21.9–13.4 Ma have been reported by DUNKL and DEMENY (1997) for zircon and of 7.3–9.7 Ma for apatite. The Penninic rocks of the RWG are overlain by unmetamorphosed sediments of Miocene and Pliocene age (PAHR, 1980). The best constrained PT-path, according to KOLLER (1985), is shown in figure 1f.

Blueschist metamorphism within the Rechnitz window group was associated with static mineral growth. These fabrics were overprinted by formation of a regional foliation due to internal nappe stacking which evolved under greenschist facies metamorphic conditions. RATSCHBACHER et al. (1990) described a regional E–W directed stretch and regional pure shear deformation due to subvertical shortening. Late-stage, ductile low-angle normal faults formed along upper margins during exhumation consistent with above mentioned Early Neogene fission-track zircon ages.

2.4. COMPARATIVE METAMORPHIC EVOLUTION OF THE PENNINIC UNITS

Two metamorphic events are recognizable in all Penninic windows of the Eastern Alps. The older event is regarded as HP/LT metamorphism and the younger event of Barrovian type regional metamorphism. An earlier eclogite event with a retrograde evolution path different from the rest of the Penninic metamorphic rocks has been recorded in the TW only.

The eclogite facies metabasites and metasediments passed through a mantle/crust (?) segment at a depth of 70 km (possibly 85 km according to STÖCKHERT et al., 1997). With T_{max} of around 600 °C, they formed under conditions characterized by a very low geothermal gradient of 7–9 °C/km typical for subduction zones (Fig. 1a). If the $^{40}Ar/^{39}Ar$ data of ZIMMERMANN et al. (1994) reflect the blueschist event, then the eclogite formation has to predate the Eocene/Oligocene boundary. For many years it was believed to have taken place during the Cretaceous but positive evidence for this is missing. U/Pb zircon dating of eclogites in the Central Alps (GEBAUER et al., 1992) indicates that at least some eclogites were formed close to the Eocene/Oligocene boundary. Whether this also applies to the Tauern eclogites remains speculative.

For the eclogite, the HP/LT blueschist event represents a stage of cooling and uplift from 70–85 km to 35–40 km (Fig. 1a). This coincides with the subduction of other sediments and metavolcanics lying structurally above the eclogite-bearing units to the same depth and heating to 400–450 °C indicating a low thermal gradient of 10–13 °C/km within a subduction-zone environment.

The HP/LT remnants in the LEW and RWG record somewhat lower pressures and temperatures compared to the TW, but also indicate a subduction zone with a low thermal gradient around 10–12 °C/km. In the LEW, it is mostly the deeper parts (North Penninic metasediments) that are metamorphosed under blueschist facies conditions. For the ophiolites, evidence of a HP/LT metamorphic event is missing. In the RWG, the ophiolites have been affected by the blueschist event, but the metasediments above and below have not yet been studied. Therefore, the question of whether the blueschist event is synchronous throughout the Pennninic realm in the Eastern Alps and its areal extent remains an unsolved problem.

P-T modelling has shown that regional temperature conditions should be of Palaeogene age because of thermal conductivity and equilibration (GENSER et al., 1996). The subsequent greenschist to amphibolite facies overprinting has its lowest T_{max} at 350 °C in the LEW. In the RWG, a T_{max} of 450 °C is recorded and T = 500–600 °C in the TW. T_{max} is coupled with pressures of 2–4 kbar in the LEW, 3–4 kbar in the RWG and 5–7 kbar in the TW reflecting a geothermal gradient of 20–35 °C/km, which is typical for Barrovian type regional metamorphism (Fig. 1a,c,e,f). It coincides with the subduction of the Penninic zone beneath the Austroalpine nappes. This metamorphic stage occurred shortly after 30 Ma and is further recorded by cooling ages down to 16 Ma. Similar cooling ages are reported from the RGW. In contrast, the data from the LEW probably record the onset of the low-grade metamorphism. The cooling and exhumation in the TW and RWG have been recorded by apatite fission track studies to 5 and 7 Ma respectively.

In the TW, the only window where metamorphic zones are properly mapped (HOERNES and FRIEDRICHSEN, 1974), the originally subhorizontal isograds were tilted probably as result of the late compression and thinned close to the eastern and western margin by late extensional faults along the Austroalpine/Penninic boundary (SELVERSTONE, 1988; GENSER and NEUBAUER, 1989; FÜGENSCHUH et al., 1998). The isograds approximately image the late dome-like structure of the Tauern window.

3. Austroalpine realm

The Austroalpine unit represents the continental crust to the south of the Penninic ocean and subduction zone. Within the Eastern Alps it comprises (1) the high-grade, partly polymetamorphic basement of Proterozoic to Palaeozoic age and (2) the low- to very low-grade metasedimentary cover nappes of Palaeozoic and Mesozoic age which are arranged in parallel E–W-trending chains with increasing age from north to south. From west to east, the Austroalpine basement consists of a continuous zone of medium- to high-grade metamorphic rocks which are separated from the Southern Alps by the Periadriatic lineament. Interpretation of metamorphism in the basement is complicated by pre-Alpine metamorphic overprints of dominantly Carboniferous age (in the western and central Eastern Alps) and of Permian age (mainly in the eastern parts of the Eastern Alps). Alpine metamorphism is restricted to the northern part of this zone. There is an increase in grade of Cretaceous metamorphism from north to south until it is suddenly truncated along a tectonic line marking the southern limit of Alpine Metamorphism (for which we suggest the abbrevation SAM). SAM is situated in the southern basement units close to, but still north of, the Periadriatic lineament. From west to east, SAM is represented by the Pejo-, Passeier–Jaufen-, Deffreggen–Antholz–Vals-, Zwischenbergen–Wöllatratten-, Ragga–Teuchl-, Siflitz-, Viktring-fault zones. The basement blocks north of the SAM were affected by Cretaceous and partly also Tertiary metamorphism to varying extent. Western sections of SAM represent a zone of important, mostly Oligocene sinistral strike-slip displacement with an oblique-slip normal fault component, the eastern sectors (east of the Isel fault) a zone of Late Cretaceous sinistral strike-slip shear with a subordinate normal component.

To the north of SAM a structural division into Lower, Middle and Upper Austroalpine structural units can be applied. To the south of SAM, this subdivision becomes meaningless. We use the terms Lower, Middle and Upper Austroalpine nappe complexes for simplicity.

However, as shown below, the structural boundaries of these nappe complexes also represent a break in Cretaceous metamorphic conditions. These mainly include (1) superposition of Middle Austroalpine eclogite facies metamorphic units onto greenschist to amphibolite facies Lower Austroalpine units; and (2) superposition of amphibolite facies Middle Austroalpine metamorphic units on greenschist facies Upper Austroalpine units. The lower contact is suggested to represent a late-stage out-of-sequence thrust, the upper contact a regional late Cretaceous low-angle normal fault.

3.1. LOWER AUSTROALPINE NAPPE COMPLEX

The Lower Austroalpine Nappe surrounds the Penninic rocks of the Tauern Window in the NW (Innsbruck Quartzphyllite and Tarntal mountains) and in the NE (Radstadt nappe complex) and the Penninic units at the eastern end of the Alps (Rechnitz Window Group).

3.1.1. Innsbruck Quartzphyllite and Tarntal mountains

According to TOLLMANN (1977) the tectonic succession in the NW of the Tauern window consists of three individual nappes. From the base to the top they are the Innsbrucker Quartzphyllite nappe, the Hippold nappe and the Reckner nappe.

The Innsbrucker Quartzphyllite nappe comprises various phyllites with rare diabases, metarhyolites and carbonate lenses. The top is formed by Permo-Triassic sediments. In contrast, the Hippold and Reckner nappes consist of various and partly fossil-bearing Mesozoic sediments ranging from Skythian to Malm (ENZENBERG, 1967; ENZENBERG-PRÄHAUSER, 1976; HÄUSLER, 1988). The top of the Reckner nappe is formed by the serpentinites and blueschists of the Reckner complex (DINGELDEY et al., 1997).

For both Reckner and Hippold nappes a Tertiary HP/LT event (Fig. 1d) in the range of ~ 350 °C and ~ 10 kbar has been reported by DINGELDEY et al. (1997). Typical minerals of this event are alkali pyroxene (< $Jd_{37}Ac_{50}$), Mg-rich pumpellyite, stilpnomelane, high-Si phengite (< 3.65 p.f.u.). This high pressure event was followed by a greenschist paragenesis with blue amphiboles replacing the alkali pyroxenes, low-Si muscovites (3.05–3.17 p.f.u.), epidote, green biotite instead of stilpnomelane. Only a LP/LT event (~ 400 °C and < 4 kbar) was found in the underlying quartzphyllite nappe (Fig. 1d).

$^{40}Ar/^{39}Ar$-measurements on high-Si phengites from the Reckner nappe recorded ages around 50 Ma. In the underlying Hippold nappe and in the adjoining Penninic Bündnerschiefer the high-Si phengites yielded ages between 44 and 37 Ma (DINGELDEY et al., 1997). All $^{40}Ar/^{39}Ar$ data from the quartzphyllite nappe appear to demonstrate rejuvenation of Variscan micas and no clear Alpine $^{40}Ar/^{39}Ar$ plateau ages have been found.

3.1.2. The Radstadt nappe complex

The Lower Austroalpine nappes of the "Radstädter Tauern" form the NE rim of the Tauern Window (TOLLMANN, 1977; HÄUSLER, 1987). They comprise a Variscan basement and various Permo-Mesozoic cover sequences. These are from S to N the Speiereck, Hochfeind, Lantschfeld, Pleisling and Kesselspitz which are normally layered, whereas the uppermost quartzphyllite nappe exhibits inverse layering. Modern PT-path investigations on the Alpine metamorphic evolution have yet to be done.

Large pre-Mesozoic remnants are found in the crystalline of Tweng (basement of the Lantschfeld nappe) and in the quartzphyllite nappe. They are all characterized by a conspicuous retrograde evolution. BECKE (1909) applied the term "diaphthoresis" for the first time to the crystalline rocks of Tweng, which show low-grade overprint of pre-Alpine amphibolite facies metamorphism. The characteristic Alpine mineral is stilpnomelane (EXNER, 1971). In the quartzphyllite nappe most of the white micas yield still Variscan K/Ar ages, in contrast to the biotite with strongly rejuvenated Rb/Sr and K/Ar ages (SLAPANSKY and FRANK, 1987). SLAPANSKY and FRANK (1987) estimated the Alpine metamorphic conditions as 350–400 °C.

The Alpine metamorphic evolution of the Permo-Mesozoic sedimentary sequences can be defined by the assemblage of phengite + chlorite without newly formed biotite. VOLL (1977) described local chloritoid and kyanite from the quartzphyllite nappe. In the Hochfeind nappe, further to the south, MEIXNER (1978) described, besides stilpnomelane, Mn-minerals such as braunite, piemontite or spessartine in slightly metamorphosed radiolarites. Temperatures of 450 °C and pressures of > 3 kbar have been deduced by SLAPANSKY and FRANK (1987). Metamorphic conditions generally increase towards the south.

Summing up, the Permo-Mesozoic Lower Austroalpine nappes suffered a low-grade, possibly Cretaceous metamorphism. K/Ar ages of white micas (fine fractions) are only slightly rejuvenated in the northern part, while in the southern part Tertiary ages are more common (SLAPANSKY and FRANK, 1987).

3.1.3. Lower Austroalpine nappes at the eastern end of the Alps

The Lower Austroalpine Unit at the eastern end of the Alps can be divided into two different nappes, both containing pre-Alpine basement and an individual Permo-Mesozoic sedimentary cover. The lower nappe is named the Wechsel nappe, tectonically overlain by the higher Stuhleck-Kirchberg nappe, also known as "Grobgneis" nappe (TOLLMANN, 1977). Both nappes show an independant metamorphic evolution. They were thrusted onto the Penninic units of the RWG as seen in the borehole Maltern 1 (PAHR, 1975).

The Wechsel nappe is build up by the Wechsel gneiss and rare garnet-bearing micaschists, by the Wechsel phyllites and by Permo-Mesozoic sedimentary rocks (TOLLMANN, 1977). The typical Variscan Wechsel gneiss is characterized by a retrograde Alpine metamorphic overprint. The Wechsel phyllites (of possible Carboniferous to Permian sedimentation age) comprise various types of phyllites, including graphite phyllites. According to MÜLLER (1994) the main metamorphism of the Wechsel gneiss is defined by an Early Variscan high-pressure event. The Alpine metamorphic conditions are in lower greenschist facies with temperatures of 350 °C in the northern part (MÜLLER, 1994); a temperature increase towards the south is possible, but not well documented. Cretaceous $^{40}Ar/^{39}Ar$ white mica ages were determined from shear bands within the Wechsel gneiss (86 Ma), from the Wechsel phyllite (82.1 Ma) and from Early Triassic quartzites (MÜLLER, 1994; DALLMEYER et al., 1998).

The Stuhleck-Kirchberg or "Grobgneis" nappe consists of a pre-Alpine basement with syncollisional Variscan granites and garnet-, staurolite-, andalusite- and sillimanite-bearing micaschists. The basement is covered by the thick Permo-Mesozoic sedimentary sequences of the Semmering system (TOLLMANN, 1977). The Alpine metamorphic evolution ranges from greenschist facies in the north (ca. 350–400 °C) to amphibolite facies in the south. Alpine amphibolite facies metamorphism is documented by entirely recrystallized amphibolites, the presence of staurolite and kyanite in metapelites and Cretaceous K–Ar and Rb–Sr muscovite-ages (PEINDL, 1990; REINDL, 1989; MOYSCHEWITZ, 1994). Leucophyllites, which represent mylonitic former orthogneisses are common. "Blastomylonites" and chloritoid-bearing micaschists were described by LELKES-FELVARI et al. (1984) in western Hungary. Replacement textures of andalusite by (1) chloritoid, staurolite and white mica and (2) kyanite are reported by SCHUSTER (pers. com.) from the Strallegg gneisses and temperatures of 530 °C are estimated. The talc mining site Rabenwald was investigated by MOINE et al. (1989) who derived pressures of 8–9 kbar from phengite barometry at 500–550 °C. For the Sopron area near the Austrian-Hungarian border DRAGANITS (1996) postulates metamorphic conditions of ~ 550 °C and 9.5 kbar from replacement textures of pre-Alpine staurolite by eo-Alpine chloritoid, kyanite and phengitic white mica. From garnet-bearing orthogneisses of the Grobgneiss nappe in Western Hungary (Sopron area) peak metamorphic pressure conditions of 12 kbar at 450–500 °C are reported by TÖRÖK (1996, 1998). $^{40}Ar/^{39}Ar$ white mica ages are Cretaceous (81–71 Ma; MÜLLER, 1994; DALLMEYER et al., 1998) for mylonites in the "Grobgneis" and for Semmering quartzites. Fission track ages of 80–70 Ma for zircon and 30–80 Ma for apatite were reported by DUNKL (1992) for the Sopron unit suggesting Late Cretaceous to Palaeogene postmetamorphic cooling.

3.2. MIDDLE AUSTROALPINE NAPPE COMPLEX

3.2.1. Silvretta-, Scarl-Campo- and Ötztal Basement

In the westernmost Silvretta-, Scarl-Campo- and Ötztal-blocks the Alpine overprint is characterized by an increasing grade from NW towards SE ranging from very low-grade in the Silvretta and northern Ötztal blocks to low-grade in the Scarl-Campo block and medium-grade in the southern Ötztal block. This continuous increase in metamorphic grade is indicated by the Cld-in isograd crossing the Austroalpine basement area west of the Tauern window from Innsbruck in the NE to the Bernina area in the SW (PURTSCHELLER, 1969, THÖNI, 1981). North of the Cld-isograd a late formation of stilpnomelane and a second generation of phengitic white mica (3.5 Si/p.f.u.) in metagranitoids are indicative of a low-temperature (< 300 °C) – high-pressure (5 kbar) type Alpine metamorphism. South of the Cld-isograd increasing metamorphic temperature and pressure is indicated in the southern Ötztal block by an Alpine staurolite-in isograd (HOINKES, 1981), a KFMASH equilibrium assemblage of St + Ky + Grt + Bt + Chl + Ms with equilibrium conditions of c. 600 °C and 7 kbar, and phengitic white mica in metagranitoids (max. Si = 3.4/p.f.u.) indicating pressures of 10 kbar at 600 °C. In the southernmost Ötztal basement relics of eclogite assemblages in metabasites (omphacites with Jd_{40}) formed at minimum pressures of 11.5 kbar. The typical assemblage comprises *Ca-Amp* (Mg-hornblende) + Omp(Jd_{40}) + Grt(Alm_{70}) + Ep/Zoi + Rt + Qtz ± Phe. Characteristic textures are reaction rims of Al-rich amphiboles (sadanagaites) between Grt and Omp and partial to complete symplectitic replacement of Omp to Jd-poor Cpx + Pl and sometimes hornblende. Phengite is only preserved as relics and usually replaced by a Bt + Pl intergrowth. The geothermobarometric results from the eclogite assemblage and the symplectite assemblage in eclogites and the chemical zonation of phengites in metagranitoids are consistent with a clockwise PT-loop from 550 °C / 12 kbar to 600 °C / 5 kbar and finally 300 °C / 3 kbar (Fig. 2a) (HOINKES et al., 1991).

The main arguments for an eo-Alpine overprint with metamorphic grade increasing from very low-grade to eclogite facies are mineral age data presented by SCHMIDT et al. (1967), THÖNI (1981, 1986); FRANK et al. (1987a); HOINKES et al. (1991) and reviewed by THÖNI (1999, this volume). K/Ar- and Rb/Sr-ages of white mica and biotite are rejuvenated from Variscan ages in the NW of the Ötztal basement to eo-Alpine ages in the SE where thin-slab isochrons also result in Cretaceous ages. A range of 100 to 70 Ma obtained from thin slabs, white micas and biotite are interpreted in terms of a thermal climax close to 100 Ma. An uplift/exhumation-rate of 1 to 2 mm/a was calculated from the age data for the period between the Turonian and the Campanian. The preceeding P-climax is not very well constrained, but a Rb/Sr phengite age of 143 Ma from an eclogite assemblage is tentatively interpreted as the age of eclogite formation (HOINKES et al., 1991).

Laas Complex

The southern Ötztal basement is characterized by a narrow zone, a few kilometres wide, of a metacarbonate-rich basement. Since metacarbonates are otherwise rare in the Ötztal basement, this zone is distinguished by a special name. The index mineral of the siliceous carbonates is tremolite but in a few cases relic diopside partially replaced by tremolite can still be recognized. Whether this is an indication of polymetamorphism or is caused by PT changes during a single eo-Alpine metamorphic evolution is not clear. However, polymetamorphism in terms of a Variscan diopside formation followed by eo-Alpine tremolite formation is more plausible in this part of the Austroalpine basement, since diopside has never been found in the monometamorphic Schneeberg complex.

3.2.2. Schneeberg Complex

The Schneeberg Complex is a zone of texturally monometamorphic metapelites, metacarbonates and metamarls which forms a complex structure of several narrow synclines within the Ötztal basement exactly at the transition to the Laas complex. The lowermost units of this sequence however show indications for a two-stage garnet growth.

The dominant monometamorphic character of the Schneeberg complex is an additional argument for the eo-Alpine age of high-pressure metamorphism in the polymetamorphic Ötztal basement since Rb/Sr muscovite ages of c. 90 Ma clearly prove an eo-Alpine age of the metamorphism of the Schneeberg complex. The index mineral assemblages in the three lithologies are:

Grt + St + Ky + Pl ± Bt ± Chl in the paragonite- and muscovite-bearing metapelites (HOINKES, 1981), Qtz + Cal + Dol + Tr + Tlc and Qtz + Cal + Dol + Tr in marbles (HOINKES, 1983) and Ca-Amp + Grt + Pl + Ep + Chl ± St ± Ky in white mica-bearing amphibolites. Hornblende-garbenschists containing white mica and aluminosilicates and paragonite-amphibolites seem to be the precursor rocks of the eclogites further to the south (KONZETT and HOINKES, 1996). Pressure conditions of 9 to 12 kbar at 580 °C were derived by KONZETT and HOINKES (1991) for the white mica and aluminosilicate-bearing amphibolites. Symplectitic reaction rims of either Mrg + Ab + Chl or Mrg + Ab + Bt between white micas and *Ca-Amp* are again indicative for pressure release. A similar occurrence of paragonite-amphibolites and eclogites along an increasing metamorphic gradient is also observed in the Radenthein Complex and Millstatt basement east of the Tauern Window (TEIML et al., 1995).

3.2.3. Middle Austroalpine basement south of the Tauern Window

To the east of the Southern Ötztal basement, in the Austroalpine basement block bordered by the Penninic Tauern Window to the north and the DAV line to the south, BORSI et al. (1978) have reported mainly Tertiary Rb/Sr-biotite ages ranging between c. 20 and 50 Ma but also three Cretaceous ages between 82 and 95 Ma. Hence eo-Alpine metamorphism and a significant thermal effect from the Penninic realm in the Tertiary is evident for this Austroalpine block close to the Tauern Window. However, the interpretation of the mineral assemblages in terms of Alpine or pre-Alpine formation is still debated (SASSI et al., 1978; STÖCKHERT, 1985; SCHULZ et al., 1995; SCHULZ, 1997). Key petrological observations in metapelites include the stable occurrence of a second generation of kyanite and staurolite as well as phengitic white micas (SASSI, 1978) and hence very much resemble the petrological features of the southern Ötztal basement. However, eclogites have not been observed until now in this part of the Austroalpine basement. STÖCKHERT (1985) derived pressures and temperatures of c. 6 kbar and 600 °C which he allocated to the Variscan event but instead these probably represent Alpine conditions of either Cretaceous or Tertiary age.

Further to the east, several occurrences of relic eclogites within the Austroalpine basement are known from the Schober group (CLAR, 1927; LINNER et al., 1996), the Polinik unit of the northern Kreuzeck group (ANGEL, 1930; HOKE, 1990) and the Millstatt complex (STRAUSS, 1990; TEIML et al., 1995). The eo-Alpine age of the metamorphism affecting the Schober group is now well constrained by mineral dating of eclogite phases by LINNER (1995), LINNER et al. (1996) and LINNER (in prep.). Sm/Nd ages of garnet and WR and Rb/Sr ages of phengites from eclogites range between 115 and 80 Ma. Mineral assemblages of the eclogites are similar to those of the Polinik unit and the Millstatt complex and comprise Grt + Omp + Ca–Amp + Ep/Zoi + Rt + Qtz ± Phe. Rather high pressures of 16 to 19 kbar at 625 °C were derived for the Schober group eclogites and slightly lower pressures of 9 to 11 kbar at 650 °C for the enclosing metasediments (LINNER, in prep.). Metamorphic conditions of 11 kbar and 600 °C were proposed by HOKE (1990) for the eclogite formation of the Polinik unit and 12 to 13 kbar at 600 °C by TEIML et al. (1997) for the Millstatt basement (Fig. 2b). The eclogites are embedded in a metamorphic matrix of mainly quartzofeldspatic gneisses and schists of amphibolite facies with kyanite as the stable Al_2SiO_5 polymorph coexisting with staurolite. The Millstatt complex is similar to the Laas complex of the southern Ötztal basement in terms of lithologies and polymetamorphism. Massive tremolite-bearing marbles with relic diopside from a pre-Alpine metamorphic episode are present in both basement blocks as well as numerous barren pegmatites. The polymetamorphic Millstatt complex carries a monometamorphic metapelitic sequence which may be compared with the Schneeberg complex of the southern Ötztal basement. This is the *Radenthein complex* representing a zone of coarse-grained hornblende garbenschists and kyanite-garnet schists as part of the *Wölz complex,* the dominant Austroalpine unit to the north of the Millstatt complex and east of the Tauern Window. Cretaceous ages of amphibolite facies metamorphism were reported from the basement (DEUTSCH, 1988) and the Radenthein Complex (SCHIMANA, 1986) by Rb-Sr-garnet dating.

3.2.4. Middle Austroalpine basement east of the Tauern Window

This area is dominated by the *Wölz complex* comprising the area between the Enns and Palten valleys to the north and the Mur valley to the south from the line Schladming–Spital in the west to the line Rottenmann–Judenburg in the east. It covers the *Schladming- and Seckau crystalline basement* which represent lower tectonic units of the Austroalpine basement. Immediately to the east of the Tauern Window it carries tectonically the polymetamorphic *Bundschuh crystalline basement* which very much resembles the Ötztal basement to the west of the Tauern Window (FRIMMEL, 1986, 1988). Further east, the *Glein- and Stubalpen complex* represent the transitions to the tectonically highest basement nappes of the *Kor- and Saualpe* further to the south. The whole basement complex described above together with the Millstatt complex experienced a common eo-Alpine metamorphic event with increasing grade from north to south that partly obliterated tectonic boundaries but which may usually be recognized by lithological and petrological differences. Geochronological investigations by FRANK et al. (1987b) demonstrated the widespread Cretaceous metamorphic overprint of the Austroalpine basement east of the Tauern Window. The metamorphic imprint of the Gleinalpen complex is dated by $^{40}Ar/^{39}Ar$-hornblende and white mica ages ranging between 95 and 84 Ma (NEUBAUER et al., 1995; DALLMEYER et al., 1996). Together with zircon fisson track ages of 61 Ma an average cooling rate of 9 °C/Ma is calculated. The eo-Alpine metamorphic conditions continuously increase from north to south from low-grade to high-grade, ending up with regional eclogite facies conditions at the SAM. Along this metamorphic gradient white-mica-bearing hornblende garbenschists and paragonite amphibolites occur at epidote-amphibolite facies conditions in the Radenthein complex. High-pressure amphibolite facies conditions of 11 kbar, 600 °C (KOROKNAI et al., 1996) and 9 kbar, 570 °C (TEIML and HOINKES, 1996) were obtained from metapelites and metabasites of the Radenthein complex. Most metapelites, however, equilibrated at lower P and T conditions of 6 kbar and 550 °C (SCHUSTER, pers. com.). The petrologic data show that the Austroalpine basement areas immediately east and west of the Tauern Window are remarkably similar in terms of metamorphic evolution and the tectonostratigraphic sequences. In the eastern part of the Wölz complex polymetamorphic textures in garnet have been observed and dated; Sm/Nd ages of 269 Ma from a garnet core and 94 Ma from a rim have been interpreted as primary growth ages (SCHUSTER and THÖNI, 1996). The eastern Wölz complex again shows increasing metamorphic conditions towards the south. The medium-grade equilibrium assemblage in metapelites comprises St + Ky + Grt in a muscovite- and paragonite-bearing matrix (ABART und MARTINELLI, 1991) and is thought to represent the eo-Alpine conditions. The rare occurrence of reaction rims of garnet replacing staurolite in the southern Wölz complex is indicative either of the transition to high-grade eo-Alpine metamorphic conditions or of

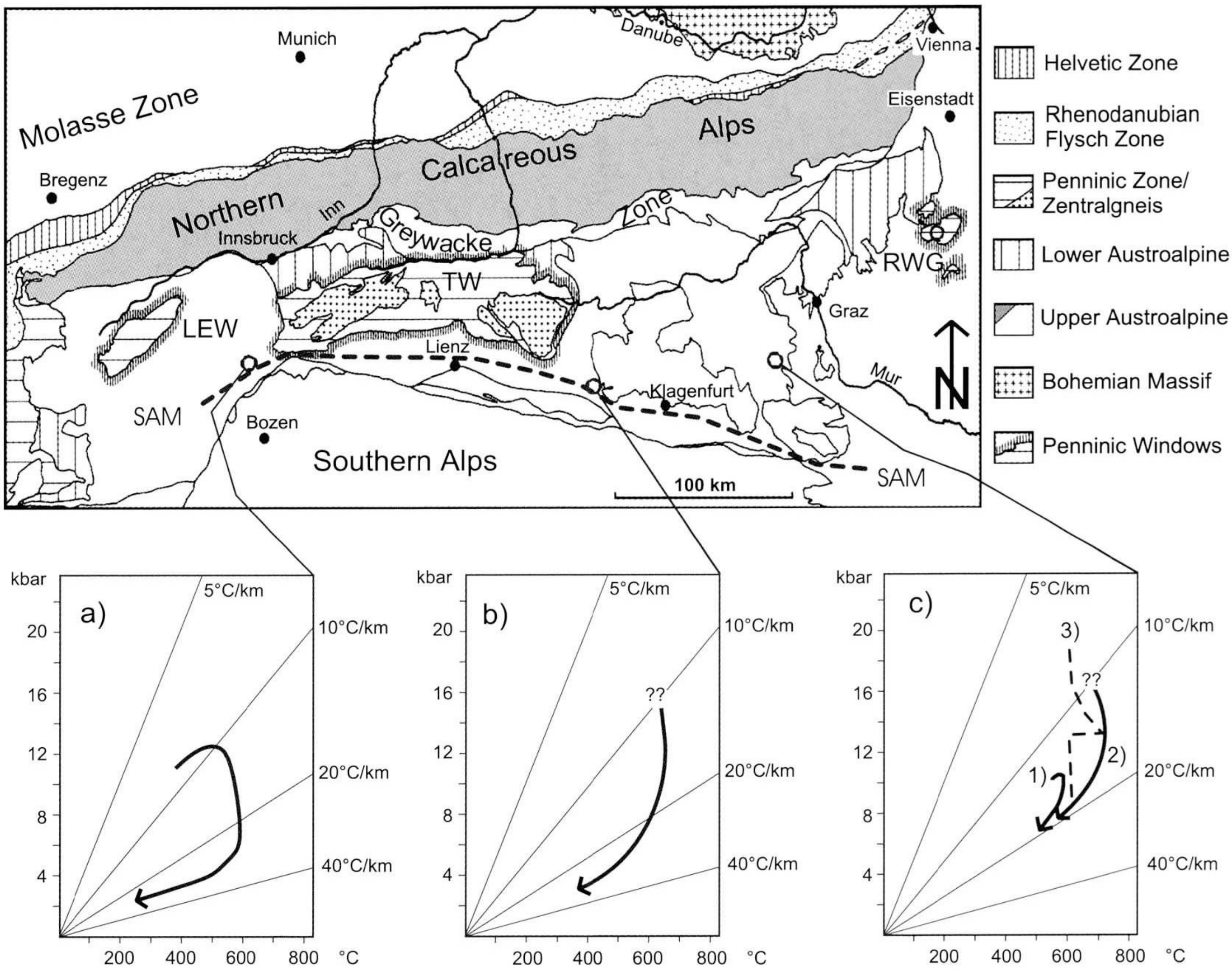

Fig. 2 Geological sketch map of the Eastern Alps and three characteristic PT paths for the
a) Southern Ötztal basement (HOINKES et al., 1991),
b) Millstatt basement (TEIML, 1996),
c) Koralpe: 1) Plankogel unit, 2) Koralm unit (GREGUREK et al., 1997); 3) Koralm "Plattengneis" (STÜWE and POWELL, 1995).

relic pre-Alpine high-grade assemblages. Metabasites locally exhibit garben textures and metacarbonates contain tremolite but a thorough petrologic and geothermobarometric examination of the Wölz complex is still required. Interestingly these garnet corona textures around staurolite are also observed a few kilometres to the south in the Gleinalpen complex at the northern border of the Koralpe complex (locality Gaberl, LICHEM et al., 1996). Until now it is not known if we are dealing with textures due to a single metamorphic event or polymetamorphism. Micaschists of the Wölz Complex appear as tectonic windows within the Koralpe basement further to the south, indicating that the Wölz Complex occupies a lower tectonic position than the Koralpe basement.

3.2.5. Middle Austroalpine Sau- and Koralpe

Garnet-bearing metapelites throughout the Sau- and Koralpe contain similar KFMASH mineral assemblages with kyanite and staurolite as the index phases. Staurolite is rather scarce with the exception of a few samples with abundant staurolite. Garnets generally appear to be monometamorphic, with continuous chemical zonation patterns, but may also exhibit complicated patterns due to a polyphase growth. In the "Plattengneis", a massive mylonitic gneiss, an older generation of clasts (Grt, Ky, Or) is typically embedded in a well foliated fine-grained recrystallized matrix. Staurolite is not present in the Plattengneis and kyanite typically forms elongated lenses of recrystallized grains. Another typical texture indicating polyphase metamorphism outside the mylonite zone is formed by rectangular aggregates of recrystallized kyanite representing pseudomorphs after andalusite. Concerning the metabasites the Kor- and Saualpe is well known as the type locality of eclogite. The term "eclogite" was first applied by HAÜY (1822) to garnet-pyroxene-zoisite-bearing metabasites from the localities Kupplerbrunn and Pricklerhalt of the Saualpe. Investigations by BECK-MANNAGETTA (1961); HERITSCH (1973); MILLER und FRANK (1983); MILLER et al. (1988); MILLER (1990); THÖNI and JAGOUTZ (1992) and others demonstrated the key function of these rocks for the geologic history of the Eastern Alps. The first eo-Alpine Sm/Nd-dates of eclogite facies metamorphism, ranging between 93 and 150 Ma, were reported by THÖNI and JAGOUTZ (1992) from a Koralpe metagabbro (locality Bärofen). In contrast to the eclogite occurrences of Cretaceous age from the other Austroalpine units described above, where relic magmatic textures are lacking, the Koralpe eclogites show textural evidence for gabbroic protoliths. Gabbros occur as isolated bodies in the quartzo-feldspathic country rocks and exhibit gradational transitions from primary magmatic assemblages in the cores to eclogite facies metamorphic assemblages in the rims. Magmatic ages, derived from the primary assemblages, are Permian (THÖNI and JAGOUTZ, 1992; MILLER and THÖNI, 1997), hence the high-pressure metamorphism must be an Alpine event. The high-pressure assemblages were overprinted by amphibolite facies conditions during the eo-Alpine PT-evolution and hence are only partially preserved. Moderate T-conditions of c. 600 °C at 18 kbar were reported by MILLER (1990) for some Sau- and Koralpe eclogites. The metamorphism of the Koralpe eclogites was reinvestigated by GREGUREK et al. (1997) who deduced PT conditions of 15–16 kbar and 700 °C for the southern Koralpe (Fig. 2c). Decreasing pressure and temperature conditions of eclogite formation in the Koralpe complex towards the north were demonstrated by LICHEM et al. (1996) and are consistent with the general metamorphic pattern of the Austroalpine basement. An eo-Alpine high-pressure history was also documented in the enclosing metapelites indicating that the whole basement shared a common high-pressure history. Sm/Nd garnet-whole rock dating of micaschists from the Saualpe complex resulted in a range of ages from 88.5 to 94 Ma; surprisingly high pressures of c. 20 kbar at 685 °C were derived by THÖNI and MILLER (1996) for these micaschists. Similar conditions of 18 kbar at 700 °C were derived by STÜWE and POWELL (1995) for metapelites of the Koralpe. Most metapelites and metabasites of the Austroalpine basement, however, equilibrated at much lower PT conditions corresponding to the amphibolite facies, but still within the kyanite stability field during exhumation. GREGUREK et al. (1997) report a continuous clockwise PT loop and conditions of 8 kbar, 630 °C for the final equilibration in metapelites outside the mylonite zone and 10 kbar, 700 °C in amphibolites (Fig. 2c). In contrast STÜWE and POWELL (1995) present evidence for a discontinuous three-step PT path from modal proportions of an average metapelite resembling the Plattengneis: a heating step to 700 °C during pressure release, an isobaric cooling step at 14 kbar to 600 °C and finally isothermal decompression followed by pressure release and cooling during exhumation (Fig. 2c). This is probably a typical PT path for the mylonitic gneisses but cannot be extrapolated to less deformed gneisses for which a clockwise PT path from eclogite to amphibolite facies conditions is derived (GREGUREK et al., 1997).

3.2.6. Plankogel unit

The micaschist-rich Plankogel unit in the southern Koralpe complex experienced lower metamorphic conditions than the rest, and may also be distinguished by a metapelitic and metabasic lithology similar to the Wölz complex but occuring in a higher tectonic position. In the Plankogel unit micaschists and amphibolites occur together with lenses of serpentinite, indicating a tectonic emplacement. This zone can be traced westwards into the southern Saualpe complex. The typical mineral assemblage of the paragonite-rich micaschists is Cld + St + Ky + Grt + Chl + Qtz (KLEINSCHMIDT and RITTER, 1976; HERITSCH and MÖRTL, 1977) and represents pressure and temperature conditions of 10.6 kbar, 570 °C (GREGUREK et al., 1997). The metabasites of the Plankogel unit never show indications of eclogite assemblages which is in contrast to the Kor- and Saualpe complex in the footwall. It is therefore concluded that both units were put together after the eo-Alpine pressure peak at medium-grade conditions. Permian Sm/Nd-ages of garnet cores and eo-Alpine rims from the Plankogel unit (LICHEM et al., 1997) indicate a similar metamorphic evolution to that suggested for the Wölz complex (SCHUSTER and THÖNI, 1996).

3.2.7. Sieggraben unit

East of the Sau-, Kor-, Glein- and Stubalpen complexes mainly lower levels of Austroalpine units and Penninic units appear. From top to bottom, the Middle Austroalpine *Sieggraben unit* represents a relic of the highest tectonic level, comparable to the Sau-/Koralpe complexes. It rests as a tectonic klippe on the Lower Austroalpine *Semmering* system (Grobgneis nappe) and *Wechsel nappe* representing the tectonostratigraphic sequence down to the Penninic units, partly present as tectonic windows. The eo-Alpine metamorphic age of the Sieggraben units is well constrained by $^{40}Ar/^{39}Ar$ plateaux ages of hornblende (136 and 108 Ma) and white mica (78–77 Ma). In the Sieggraben unit, which is interpreted as tectonic melange at the very eastern end of the Eastern Alps, relic eclogites very much resemble the Austroalpine units further to the west; their similar metamorphic conditions of 14–16 kbar and 670–750 °C (NEUBAUER et al., in prep.) are indicative of a large-scale compression and subduction regime within the Austroalpine plate during the Cretaceous.

3.3. UPPER AUSTROALPINE BASEMENT AND COVER UNITS

The general architecture of the upper Austroalpine units is characterized by a Variscan basement of early Palaeozoic to middle Carboniferous sediments and post-Variscan (late Carboniferous to Tertiary) cover sequences. This building style has been successfully used to date relatively the observed metamorphic overprint. However, during the Alpine cycle, the Graz Palaeozoic and the Carboniferous of Nötsch lost their post-Variscan cover sequences, so that the age of the decisive metamorphic overprint in these units remains uncertain.

The effects of polyphase very low- to low-grade tectonometamorphism have been studied in several papers. At the beginning of the 1970's clay mineralogical studies resulted in a first outline of the metamorphic zonation within the Northern Calcareous Alps including the Graywacke Zone as its primary basement (see KRALIK et al., 1987 for full references), in the Gurktal nappe complex (FRANK and RIEHL-HERWISCH, 1972; SCHRAMM et al., 1982; VON GOSEN et al., 1987) and in the Drau Range (NIEDERMAYR et al., 1984). Subsequently, these data were completed by coalification data (GAUPP and BATTEN, 1985; SACHSENHOFER, 1987; KRUMM et al., 1988; PETSCHICK, 1989; HEINRICHS, 1993; FERREIRO MÄHLMANN, 1994; RANTITSCH et al., 1996), geochronological data (KRALIK, 1983; NEUBAUER et al., 1987; HANDLER, 1994; KRALIK and SCHRAMM, 1994; DALLMEYER et al., 1996, 1998), conodont color alteration index (CAI) data (GAWLICK et al., 1994; LEIN et al., 1997; NEUBAUER and FRIEDL, 1997) and fluid inclusion data (RANTITSCH et al., 1997).

The Graz Palaeozoic was studied by combining data on clay mineralogy, coalification and conodont alteration indices by HASENHÜTTL and RUSSEGGER (1992), RUSSEGGER (1992, 1996) and HASENHÜTTL (1994). A similar approach was used to investigate the metamorphic overprint of the Carboniferous of Nötsch (RANTITSCH, 1995b).

Significant progress in understanding the thermal processes leading to very low-grade metamorphism within the Eastern Alps was achieved mainly by an approach of combining data of different methods. Problems in the reconstruction of the Mesozoic thermal history arise from a polyphase tectonothermal history including late Carboniferous to Permian (late- to post-Variscan) extensional tectonics (e.g. VAI, 1991), Alpine thrusting in the middle Cretaceous to early Tertiary (e.g. NEUBAUER, 1994; GENSER et al., 1996) and finally, from the lateral escape of large crustal blocks towards the east (e.g. KÁZMER and KOVÁCS, 1985; RATSCHBACHER et al., 1991). Locally, thermal events in the early Tertiary influenced the metamorphic history of basement rocks in the vicinity to the Periadriatic Lineament (SACHSENHOFER, 1992; RANTITSCH, 1997; SACHSENHOFER et al., submitt.).

In the uppermost tectonic units of the Alps (Upper Austroalpine and Southalpine) the intensity of metamorphism at the base of the Alpine sedimentation cycle (starting in the late Carboniferous/Permian) decreases from north to south (RANTITSCH, 1997). On the basis of structural and geochronological data, DALLMEYER et al. (1998) explain metamorphism within this nappe assembly as an effect of internal thrusting, initiated at c. 100–90 Ma (predating the sedimentation of Gosau Group sediments) by the closure of the Meliata-Hallstatt ocean.

3.3.1. Steinach nappe

Within the Steinach nappe, Alpine very low-grade conditions were attained as recorded by the presence of Late Carboniferous anthracite. FÜGENSCHUH (1995) reported Late Cretaceous zircon cooling ages.

3.3.2. Gurktal nappe complex

The mineral assemblage of quartz, muscovite, chlorite, albite ± garnet, biotite, epidote, clinozoisite, calcite, dolomite in the structurally low Murau nappe suggests Alpine greenschist facies metamorphism with maximum temperatures of 460–500 °C during Cretaceous metamorphism (KOROKNAI et al., 1998).

According to RANTITSCH and RUSSEGGER (in prep.) and KOROKNAI et al. (1998) the very low- to low-grade metamorphism in the Gurktal nappe complex is related to the loading of thrust sheets and to shear heating along fault planes, producing diagenetic to higher anchizonal illite crystallinities and anthracitic to meta-anthracitic coal ranks in the Late Carboniferous cover sequences (Stangnock Formation) of the structurally high Stolzalpe nappe (RANTITSCH and RUSSEGGER, in prep.). In this sequence SCHRAMM et al. (1982) described pyrophyllite, paragonite/muscovite mixed layer minerals and paragonite.

CAI values within Ordovician to early Carboniferous sediments of the Gurktal nappe complex vary from 5 to 8. Low values occur in eastern sectors, high values in northeastern and southwestern sectors (NEUBAUER and FRIEDL, 1997).

3.3.3. Graz Palaeozoic

The structurally low Schöckl nappe and the Kalkschiefer nappe of the Graz Palaeozoic are characterized by epizonal illite crystallinities, meta-anthracitic to semi-graphitic coal ranks and CAI values of 5–7, whereas in the Laufnitzdorf nappe meta-anthracitic coal ranks, anchizonal illite crystallinities and CAI values of 4–6½ are found. FRITZ (1988) reported Cretaceous K–Ar white mica ages from mylonites which formed along thrust surfaces. The structurally higher Hochlantsch nappe displays a meta-anthracitic to semi-graphitic organic maturation, anchi- to epizonal illite crystallinities and CAI values of 3–7. In the south of the Graz Palaeozoic the structurally high Rannach nappe shows low-volatile bituminous to semi-graphitic coal ranks, diagenetic to epizonal illite crystallinities and CAI values of 4½–8. The occurrence of paragonite is restricted to the Schöckl nappe, while pyrophyllite occurs in the eastern part of the Rannach nappe (RUSSEGGER, 1992, 1996; HASENHÜTTL and RUSSEGGER, 1992; HASENHÜTTL, 1994).

Due to the problems of distinguishing between Variscan and Alpine metamorphism, two contrasting models are given. In the northern part of the Graz Palaeozoic, HASENHÜTTL (1994) interprets metamorphic gaps at internal thrust planes as indicators of a synsedimentary rift-related metamorphic event. In the southern part of the Graz Palaeozoic, there is no metamorphic hiatus along internal thrusts. Therefore, RUSSEGGER (1992, 1996) explains the metamorphic data in terms of Alpine events. In this model, early Cretaceous thrust-related heating and a subsequent rise in heat flow during late Cretaceous extensional tectonics were responsible for maximum burial temperatures of c. 250 °C in the structurally high Rannach nappe.

In the eastern and structurally lower part of the Graz Palaeozoic phyllites are exposed which grade eastwards into phyllitic micaschists. They are characterized by a mineral zonation with the income of biotite, chloritoid and garnet towards the east and by Cretaceous Rb–Sr and K–Ar white mica ages (ESTERLUS, 1985).

3.3.4. Graywacke Zone

Analysis of illite crystallinity indicates that low-grade metamorphic conditions were attained during Alpine orogenic events. Chloritoid, paragonite, pyrophyllite, margarite and paragonite/muscowite mixed-layer minerals have been found as critical metamorphic minerals (KRALIK et al., 1997 and references therein). "Graphite" which is mined within Westphalian sediments of the eastern Graywacke Zone (Sunk/Trieben, Kaisersberg) is characterized by microscopic and X-ray investigations as semi-graphite (SACHSENHOFER and RANTITSCH, 1997; RAITH, submitt).

Radiometric dating demonstrates that the peak temperature of Alpine low-grade metamorphism in the eastern Graywacke Zone did not exceed 450 °C (HANDLER, 1994; NEUBAUER et al., 1994; HANDLER et al., 1997; DALLMEYER et al., 1998). According to SCHRAMM (1977, 1982) two events of similar intensity have to be postulated.

3.3.5. Northern Calcareous Alps

In the western and middle part of the Northern Calcareous Alps there is a general north-to-south- and east-to-west increase in the metamorphic overprint (PETSCHICK, 1989), documented by diagenetic to epizonal illite crystallinities and coalification ranks between the lignite stage and the meta-anthracite stage (KRALIK et al., 1987; PETSCHICK, 1989; KÜRMANN, 1993; FERREIRO MÄHLMANN, 1994). In this segment, PETSCHICK (1989) and FERREIRO-MÄHLMANN and PETSCHICK (1995) proposed a (pretectonic) Permian to middle Cretaceous diastathermal metamorphism with burial temperatures up to 300 °C, a syntectonic thermal event during early Cretaceous to Turonian times with burial temperatures of c. 250 °C (cf. KÜRMANN, 1993), and a posttectonic thermal event in the early Tertiary.

In the northeastern part of the Northern Calcareous Alps an eastward increase in the thermal overprint is indicated by sub-bituminous to high-volatile-bituminous Carnian (Lunz) coals, indicating maximum burial temperatures of c. 170 °C (SACHSENHOFER, 1987). In the Northern Calcareous Alps paragonite, margarite, pyrophyllite and paragonite/muscovite mixed-layer minerals are found as critical metamorphic minerals, whereas palygorskite occurs in unmetamorphosed sediments (KRALIK et al., 1987).

In the Juvavic nappe system extremely high ranks of conodont alteration indices (up to CAI 7) are explained by GAWLICK and KÖNIGSHOF (1993), GAWLICK et al. (1994) and GAWLICK and HÖPFER (1996) with a tectonic burial of internal parts in an accretionary wedge before the early Jurassic to early Cretaceous, inducing burial temperatures of 350–490 °C (from calcite-dolomite thermometry). SPÖTL et al. (1996) reported $^{40}Ar/^{39}Ar$ ages of c. 142–140 Ma for authigenic feldspar formed at c. 240 °C. These ages are consistent with both Rb–Sr and K–Ar sericite ages (KRALIK, 1983) and recent apatite fission track ages which are within the same age range (SCHWEIGL, 1997). The significance of this age group is uncertain but appears to be related to ongoing burial of the Northern Calcareous Alps.

The lower thermal overprint in the tectonically deeper Tirolic unit is explained by a younger (early Cretaceous) metamorphic event penetrating the Northern Calcareous Alps from the south, induced by crustal thinning combined with fluid circulation (KRALIK et al., 1987; KRALIK and SCHRAMM, 1994). HEJL and GRUNDMANN (1989) and SCHWEIGL (1997) reported similar apatite fission track ages of c. 140 Ma from the same region. These ages suggest that no thermal effect later than Late Jurassic affected northern sections of the Calcareous Alps.

3.3.6. Austroalpine units between SAM and Periadriatic fault

A weak thermal overprint is found in all units between SAM and the Periadriatic fault.

The metamorphic conditions within the Carboniferous of Nötsch (anchizonal illite crystallinities and anthracitic coal ranks) are explained by RANTITSCH (1995b) with Alpine peak conditions of c. 260 °C and 6 km subsidence. The Alpine anchizonal metamorphic overprint in the basal (Permian to Scythian) strata of Drau Range is documented by anchizonal illite crystallinities and semi-anthracitic coal ranks (NIEDERMAYR et al., 1984; RANTITSCH, 1995b, 1997; RANTITSCH et al., 1996). In late Triassic sediments, bituminous-stage coal ranks, diagenetic illite crystallinities and CAI values of 1½ to 2½ indicate that the metamorphic overprint in the Drau Range ceases within the Carnian (NIEDERMAYR et al., 1984; RANTITSCH et al., 1996; LEIN et al., 1997). There is a slight increase in the rank of organic maturation towards the west. Paragonite/muscovite mixed-layer minerals, paragonite and pyrophyllite are described by NIEDERMAYR et al. (1984) as metamorphic minerals in Permian to Scythian sediments.

In the North-Karawanken Range diagenetic (smectite-rich) illite/muscowite, high-volatile bituminous coal ranks and CAI values of 1½ in late Triassic sediments (LEIN et al., 1997; RUSSEGGER and RANTITSCH unpubl. data) indicate a thermal overprint corresponding to the eastern segment of the Gailtal Alps.

Based on thermal modeling, maximum temperatures of c. 220 °C in the Permian to Scythian basal strata and c. 130 °C in the Carnian level have to be assumed within the eastern segment of the Gailtal Alps (RANTITSCH, 1995b). Hydrocarbons in ore minerals of the Bleiberg Pb–Zn deposit and in authigenic quartzes of the Lienz Dolomiten Range indicate a hyperthermal event (130–180 °C) of migrating condensate-like hydrocarbons, affecting late Triassic carbonates during the middle Cretaceous to early Tertiary (RANTITSCH et al., 1997).

3.4. RELATIONSHIP BETWEEN METAMORPHISM AND DEFORMATION

The relationship between metamorphic overprint and deformation within Austroalpine units is complex. Cretaceous eclogites within the Middle Austroalpine are ductilely deformed within eclogite facies and subsequent amphibolite facies metamorphic conditions during exhumation from deep to shallow crustal levels (e. g., within the Kor-Saualpe region; NEUBAUER, 1991). Middle Austroalpine units with Cretaceous-age amphibolite facies metamorphic rocks as exposed in the Schneeberg, Ötztal, Radenthein and Kor-Saualpe regions are often well-recrystallized under static conditions during peak temperature conditions. These units are overprinted by retrogressive shear zones that developed along upper and lower margins of individual tectonic units (e.g., NEUBAUER et al., 1995; KOROKNAI et al., 1999; FROITZHEIM et al., 1997; FÜGENSCHUH et al., 1998). The boundaries between Middle to Upper Austroalpine units generally represent ductile low-angle normal faults and transtensive sinistral strike-slip faults. Low-grade metamorphic Upper Austroalpine units were ductilely deformed within greenschist metamorphic conditions (DALLMEYER et al., 1998). The corresponding foliation is considered to be the result from nappe stacking (RATSCHBACHER, 1986).

4. Southern Alps

The Carnic Alps, part of the Southern Alps, have been studied using clay mineralogy, coalification of organic matter, microthermometry on fluid inclusions, thermal modeling and radiometric dating (ÁRKAI et al., 1991; SCHRAMM, 1991; DALLMEYER and NEUBAUER, 1994; RANTITSCH, 1992, 1993, 1995a, 1997; SASSI et al., 1995; LÄUFER, 1996; LÄUFER et al., 1997).

Within the Carnic Alps the metamorphic overprint is exposed in a continuous north-to-south trending metamorphic section and ranges from the lower anchizone to the epizone, corresponding to semi-anthracitic to semi-graphitic coal ranks (ÁRKAI et al., 1991; SASSI et al., 1995; RANTITSCH, 1993, 1997). The metamorphic zonation is disturbed by shear zones related to the strike-slip movement of the Periadriatic Lineament. The Alpine metamorphic overprint shows the same intensity as the Variscan event (RANTITSCH, 1993, 1995a, 1997; LÄUFER et al., 1997). The temperature-sensitive mineral pyrophyllite is present in the whole anchizone. Paragonite occurs in epizonal and meta-anthracitic pre-Variscan samples, and in high anchizonal and semi-anthracitic post-Variscan samples. Kaolinite and pyrophyllite form the mineral paragenesis in the post-Variscan Auernig Group (RANTITSCH, 1997). Based on thermal modeling and fluid inclusion data RANTITSCH (1997) proposes Alpine peak conditions of c. 270 °C and a burial of 4–6 km. In the structurally lowest nappe of the Carnic Alps (Eder Nappe) $^{40}Ar/^{39}Ar$ and K–Ar ages suggest a two-stage, Cretaceous and Tertiary, history (LÄUFER et al., 1997). High-temperature fluid inclusion phases enclosed in extensional veins (RANTITSCH, 1993, 1997) may be related to one of these events.

5. Gosau basins

From the Late Cretaceous Gosau basins on top of the Northern Calcareous Alps, SACHSENHOFER (1987) reports coalification data of Coniacian to Santonian coals, corresponding to the sub-bituminous stage of organic maturation. A significantly higher coalification is attained in the Muttekopf Gosau basin (up to the medium-volatile bituminous stage; PETSCHICK, 1989). At the northeastern margin of the Kainach Gosau basin, which unconformably overlies the Graz Palaeozoic, vitrinite reflectance ranges from the sub-bituminous stage to the high-volatile bituminous stage. This coalification range and Rock Eval T_{max} data indicate maturation levels ranging from the beginning to the peak stage of oil generation (SACHSENHOFER et al., 1995), implying maximum burial temperatures of 140 °C.

6. Concluding remarks

Alpine metamorphism is evident in almost all tectonic units of the Eastern Alps. Significant metamorphic temperatures and pressures of low- to medium-grade conditions are restricted to the Penninic units and lower parts of the Austroalpine thrust mass. The Austroalpine thrust mass, however, may be divided into two E–W-trending units: a major northern unit with southwards increasing metamorphic overprint and a minor southern unit lacking significant Alpine metamorphism. Both units are separated by a tectonic fault-zone (SAM) parallel to the Periadriatic Lineament.

Alpine metamorphism of both tectonic units, the Penninic and the Austroalpine, is characterized by a "clockwise" PT-evolution from an early high-pressure event of partly eclogite facies conditions through a pressure release event of amphibolite or greenschist facies conditions to a final retrogressive stage. The most effective metamorphic overprint was the intermediate-pressure release stage, thoroughly obliterating the primary high-pressure assemblages in most of the rocks.

The age of metamorphism is significantly different in the Penninic and the Austroalpine units. The high-pressure event in the Penninic and Lower Austroalpine units is probably of Eocene/Oligocene age. It postdates the Upper Cretaceous metamorphism of the Middle Austroalpine units. It is generally expected that the metamorphism of the Penninic units was caused by the subduction (sensu lato) of the Penninic realm below the continental lithosphere to the south which is now represented by the Austroalpine unit. The high-pressure metamorphism of Upper Cretaceous age within the Austroalpine unit indicates collisional tectonics prior to the subduction of the Penninic realm. A currently discussed model is the opening of a small ocean basin (Hallstatt-Meliatta) at the western end of the Tethys which continues towards the west as a zone of extension with a high geothermal gradient in Jurassic times. Magma generation and high-temperature metamorphism in the eastern parts of the Eastern Alps may be indicators for this tectonic environment in the Austroalpine lithosphere. The opening of the Penninic ocean further to the north may have caused the closure of the Hallstatt-Meliatta ocean basin during the Cretaceous leading to compressional tectonics, crustal thickening and metamorphism in the Austroalpine lithosphere. The high-pressure rocks formed in this event were transported upwards by strike-slip thrusting along the SAM, now limiting the Austroalpine basement with significant Alpine metamorphic overprint to the south.

Acknowledgements

We gratefully acknowledge financial support by several grants of the Austrian Research Foundation (FWF). Grants include P5150-GEO, P9686-GEO, P11368-GEO to GH and P8652-GEO and P9918-GEO to FN and many other grants to other persons especially in the course of the S15-project. Thanks are also due to Giles Droop and Christine Miller for their thorough reviews and constructive criticism which very much helped to improve the manuscript.

References

ABART, R. and MARTINELLI, W. (1991): Variszische und alpidische Entwicklungsgeschichte des Wölzer Kristallins (Steiermark, Österreich). Mitt. Ges. Geol. Bergbaustud. Österr., 37, 1–14.

ANGEL, F. (1930): Gesteine der Kreuzeckgruppe (Kärnten). Mitt. Naturwiss. Ver. Steiermark 67, 7–35.

ÁRKAI, P., SASSI, R. and ZIRPOLI, G. (1991): On the boundary between the low- and very low grade South-Alpine basement in Pustertal: X-ray characterization of white mica in metapelites between Dobbiaco (Toblach, Italy) and Leithen (Austria) (Eastern Alps). Memorie di Scienze Geologiche, 43, 293–304.

BECK-MANNAGETTA, P. (1961): Zur Deutung der Eklogite im Koralpenkristallin (Zentralalpen). Tschermaks Min. Petr. Mitt., 7, 437–450.

BECKE, F. (1909): Über Diaphthorite. Tschermaks Min. Petr. Mitt., 28, 17–23.

BEHRMANN, J.H. and RATSCHBACHER, L. (1989): Archimedes revisited: a structural test of eclogite emplacement models in the Austrian Alps. Terra Nova 1, 242–252.

BERNOTAT, W.H. and MORTEANI, G. (1982): The microcline/sanidine transformation isograd in metamorphic regions: Western Tauern Window and Merano-Mules-Anterselva complex (Eastern Alps). Am. Mineralogist, 67, 45–53.

BICKLE, M.J. and POWELL, R. (1977): Calcite-dolomite geothermometry for iron-bearing carbonates. The Glockner Area of the Tauern Window, Austria. Contrib. Mineral. Petrol. 59, 281–292.

BLANCKENBURG, F.V., VILLA, I.M., BAUR, H., MORTEANI, G. and STEIGER, R.H. (1989): Time calibration of a PT-path from the Western Tauern Window, Eastern Alps: the problem of closure temperatures. Contrib. Mineral. Petrol., 101, 1–11.

BORSI, S., DEL MORO, A., SASSI, F.P., ZANFERRARI, A. and ZIRPOLI, G. (1978): New geopetrologic and radiometric data on the Alpine History of the Austridic continental margin south of the Tauern Window (Eastern Alps). Mem. Ist. Geol. Mineral. Univ. Padova, 32, 1–19.

CORNELIUS, H.P. and CLAR, E. (1939): Geologie des Grossglocknergebietes (I. Teil). Abh. Zweigst. Wien, Reichsst. f. Bodenforsch. (Geol. Bundesanstalt) 25, 1–305.

CHRISTENSEN, J.N., SELVERSTONE, J., ROSENFELD, J.L. and DEPAOLO, D.J. (1994): Correlation by Rb–Sr geochronology of garnet growth histories from different structural levels within the Tauern Window, Eastern Alps. Contrib. Mineral. Petrol., 118, 1–12.

CLAR, E. (1927): Ein Beitrag zur Geologie der Schobergruppe bei Lienz in Tirol. Mitt. Naturwiss. Ver. Steiermark, 63, 72–90.

CLIFF, R.A., DROOP, G.T.R. and REX, D.C. (1985): Alpine metamorphism in the south-east Tauern Window, Austria: 2. Rates of heating, cooling and uplift. J. metamorphic Geol., 3, 403–415.

DACHS, E. (1986): High-pressure mineral assemblages and the breakdown-products in metasediments south of the Grossvenediger, Tauern Window, Austria. Schweiz. Mineral. Petrogr. Mitt., 66, 145–161.

DACHS, E. (1990): Geothermobarometry in metasediments of the southern Grossvenediger area (Tauern Window, Austria). J. metamorphic. Geol. 8, 217–230.

DACHS, E., FRASL, G. and HOINKES, G. (1991): Mineralogisch-petrologische Exkursion ins Penninikum des Tauernfensters (Grossglockner Hochalpenstrasse/Südliches Grossvenediger Gebiet) und in das

Ötztalkristallin (Timmelsjoch/Schneebergerzug). Eur. J. Mineral., 3, Beiheft 2, 79–110.
DALLMEYER, R.D. and NEUBAUER, F. (1994): Cadomian $^{40}Ar/^{39}Ar$ apparent age spectra of detritial muscovite from the Eastern Alps. J. Geol. Soc., London, 151, 591–598.
DALLMEYER, R.D., NEUBAUER, F., HANDLER, R., FRITZ, H., MÜLLER, W., PANA, D. and PUTIS, M. (1996): Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole rock data. Eclogae geol. Helv., 89, 203–227.
DALLMEYER, R.D., HANDLER, R., NEUBAUER, F. and FRITZ, H. (1998): Sequence of thrusting within a thick-skinned tectonic wedge: evidence from $^{40}Ar/^{39}Ar$ and Rb/Sr ages from the Austroalpine Nappe Complex of the Eastern Alps. J. Geol., 106, 71–86.
DEUTSCH, A. (1988): Die frühalpidische Metamorphose in der Goldeck-Gruppe (Kärnten) – Nachweis anhand von Rb-Sr-Altersbestimmungen und Gefügebeobachtungen. Jb. Geol. Bundesanstalt Wien, 131, 553–562.
DINGELDEY, CH., DALLMEYER, R.D., KOLLER, F. and MASSONNE, H.-J. (1997): P-T-t history of the Lower Austroalpine Nappe Complex in the "Tarntaler Berge" NW of the Tauern Window: implications for the geotectonic evolution of the central Eastern Alps. Contrib. Mineral. Petrol., 129, 1–19.
DRAGANITZ, E. (1996): Kristallingeologische Neubearbeitung des südlichen Ödenburger Gebirges, Burgenland (Österreich). Unpubl. M. Sc. Thesis, Univ. Vienna, 151 pp.
DROOP, G.T.R. (1981): Alpine Metamorphism of Pelitic Schists in the South-East Tauern Window, Austria. Schweiz. Mineral. Petrogr. Mitt., 61, 237–273.
DROOP, G.T.R. (1985): Alpine metamorphism in the south-east Tauern Window, Austria: 1. P-T variations in space and time. J. metamorphic Geol., 3, 371–402.
DROOP, G.T.R. and HARTE, B. (1995): The effect of Mn on the phase selections of medium-grade pelites: constraints from natural assemblages on petrogenetic grid topology. J. Petrology, 36, 1549–1578.
DUNKL, I. (1992): Final episodes of the cooling history of eastern termination of the Alps. In: NEUBAUER, F. (ed.): ALCAPA Field Guide – The Eastern Central Alps of Austria. IGP/KFU Graz, 137–139.
DUNKL, I. and DEMENY, A. (1997): Exhumation of the Rechnitz Window at the border of the Eastern Alps and Pannonian Basin during Neogene extension. Tectonophysics, 272, 197–211.
ENZENBERG, M. (1967): Die Geologie der Tarntaler Berge (Wattener Lizum), Tirol. Mitt. Ges. Geol. Bergbaustud., 17, 5–50.
ENZENBERG-PRAEHAUSER, M. (1976): Zur Geologie der Tarntaler Berge und ihrer Umgebung im Kamm Hippold-Kalkwand (Tuxer Voralpen, Tirol). Mitt. Ges. Geol. Bergbaustud., 23, 163–180.
ESTERLUS, M. (1985): Kristallisationsgeschichte und Strukturprägung im Kristallin E des Grazer Paläozoikums. Unpubl. Ph. D. Thesis Formal-Naturwiss. Fak. Univ. Wien, 205 pp.
EXNER, CH. (1971): Stilpnomelan im Gneis der Radstädter Tauern – Der Karinthin, F. 64, 219–224.
FERREIRO MÄHLMANN, R. (1994): Zur Bestimmung von Diagenesehöhe und beginnender Metamorphose-Temperaturgeschichte und Tektogenese des Austroalpins und Südpenninikums in Vorarlberg und Mittelbünden. Frankfurter geowiss. Arb., Serie C, 14, 1–498.
FERREIRO MÄHLMANN, R. and PETSCHICK, R. (1995): Illit-Kristallinität, Vitrinitreflexion und Maturitätsmodellierungen: Tektonische Fallstudien aus der Lechtal- und Silvretta-Decke. In: AMANN, G., HANDLER, R., KURZ, W. and STEYRER, H.P. (eds): 6. Symposium Tektonik-Strukturgeologie-Kristallingeologie, Erweiterte Kurzfassungen, Salzburg (Universität Salzburg), 112–115.
FLORINETH, D. and FROITZHEIM, N. (1994): Transition from continental to oceanic basement in the Tasna nappe (Engadin window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. Schweiz. Mineral. Petrogr. Mitt., 74, 437–478.
FLÜGEL, H.W. and FAUPL, P. (1987): Geodynamics of the Eastern Alps. Deuticke, Wien.
FRANK, W. and RIEHL-HERWISCH, G. (1972): Der Metamorphosehiatus zwischen Magdalensbergserie und Oberkarbon in Mittelkärnten (Umgebung des Christophberges). Anz. Österr. Akad. Wiss., math.-naturwiss. Kl., 108, 139–140.
FRANK, W., HÖCK, V. and MILLER, CH. (1987a): Metamorphic and tectonic history of the central Tauern Window. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke, Wien, 34–54.
FRANK, W., KRALIK, M., SCHARBERT, S. and THÖNI, M. (1987b): Geochronological Data from the Eastern Alps. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke, Wien, 272–281.
FRANK, W., HOINKES, G., PURTSCHELLER, F. and THÖNI, M. (1987c): The Austroalpine Unit West of the Hohe Tauern: The Ötztal-Stubai-Complex as an example for the Eoalpine metamorphic evolution. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke, Wien, 179–183.
FRANZ, G. and SPEAR, F.S. (1983): High pressure metamorphism of siliceous dolomites from the central Tauern Window, Austria. Am. J. Sci., 283–A, 369–413.
FRASL, G. (1958): Zur Seriengliederung der Schieferhülle in den mittleren Hohen Tauern. J. Geol. Bundesanstalt Wien, 101, 323–472.
FRIMMEL, G. (1986): Isotopengeologische Hinweise für die paläogeographische Nachbarschaft von Gurktaler Decke (Oberostalpin) und dem Altkristallin östlich der Hohen Tauern (Österreich). Schweiz. Mineral. Petrogr. Mitt., 66, 193–208.
FRIMMEL, G. (1988): Metagranitoide am Westrand der Gurktaler Decke (Oberostalpin) – Genese und paläotektonische Interpretation. Jb. Geol. Bundesanstalt Wien, 131, 575–592.
FRISCH, W. (1976): Ein Modell zur alpidischen Evolution und Orogenese des Tauernfensters. Geol. Rundsch., 65/2, 375–393.
FRITZ, H., NEUBAUER, F. and RATSCHBACHER, L. (1991): Compression versus extension in the Paleozoic of Graz (Eastern Alps, Austria). Zbl. Geol. Paläont., 1, 173–203.
FROITZHEIM, N., CONTI, P. and VAN DAALEN, M. (1997): Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and IST significance for tectonics of the Eastern Alps. Tectonophysics, 280, 267–293.
FRY, N. (1973): Lawsonite pseudomorphed in Tauern greenschist. Min. Mag., 39, 121–122.
FÜGENSCHUH, B. (1995): Thermal and kinematic history of the Brenner area (Eastern Alps, Tyrol). Ph. D. Thesis, ETH Zürich, 224 pp.
FÜGENSCHUH, B., SEWARD, D. and MANCKTELOW, N. (1998): Exhumation in a convergent orogen: the western Tauern window. Terra Nova, 9, 213–217.

GAUPP, R. and BATTEN, D.J. (1985): Maturation of organic matter in Cretaceous strata of the Northern Calcareous Alps. N. Jb. Geol. Paläont. Mh., 1985: 157–175.

GAWLICK, H.-J., KRYSTYN, L. and LEIN, R. (1994): Conodont colour alteration indices: Paleotemperatures and metamorphism in the Northern Calcareous Alps – a general view. Geol. Rundsch., 83, 660–664.

GAWLICK, H.-J. and HÖPFER, N. (1996): Die mittel- bis früh-oberjurassische Hochdruckmetamorphose der Hallstätter Kalke (Trias) der Pailwand – ein Schlüssel zum Verständnis der frühen Geschichte der Nördlichen Kalkalpen. Schriftenr. Dt. Geol. Ges., 1, 30–32.

GAWLICK, H.-J. and KÖNIGSHOF, P. (1993): Diagenese, niedrig- und mitteltemperierte Metamorphose in den südlichen Salzburger Kalkalpen – Paläotemperaturabschätzung auf der Grundlage von Conodont-Color-Alteration-Index-(CAI-)Daten. Jb. Geol. Bundesanstalt Wien, 136, 39–48.

GEBAUER, D., GRÜNENFELDER, M., TILTON, G., TROMMSDORFF, V. and SCHMID, S. (1992): The geodynamic evolution of garnet-pyroxenites and eclogites of the Alpe Arami and Cima di Gagnone (Central Alps) from Early Proterozoic to Oligocene. Schweiz. Mineral. Petrogr. Mitt., 72, 107–111.

GENSER, J. (1992): Struktur-, Gefüge- und Metamorphoseentwicklung einer kollisionalen Plattengrenze: Das Beispiel des Tauernostrandes (Kärnten, Österreich). Ph. D. Thesis, Faculty of Sciences, University of Graz, 379 pp.

GENSER, J. and NEUBAUER, F. (1989): Low angle normal faults at the eastern margin of the Tauern window (Eastern Alps). Mitt. Österr. Geol. Ges., 81, 233–243.

GENSER, J., VAN WEES, J.D., CLOETINGH, S. and NEUBAUER, F. (1996): Eastern Alpine tectono-metamorphic evolution: constraints from two-dimensional P-T-t modeling. Tectonics, 15, 584–604.

GETTY, S.R. and SELVERSTONE, J. (1994): Stable isotopic and trace element evidence for restricted fluid migration in 2 GPa eclogites. J. metamorphic Geol. 12, 747–760.

VON GOSEN, W., PISTOTNIK, J. and SCHRAMM, J.-M. (1987): Schwache Metamorphose in Gesteinsserien des Nockgebietes und im Postvariszikum des Karawankenvorlandes (Ostalpen, Kärnten). Jb. Geol. Bundesanstalt Wien, 130, 31–36.

GREGUREK, D., ABART, R. and HOINKES, G. (1997): Contrasting Eoalpine P-T evolutions in the southern Koralpe, Eastern Alps. Mineral. Petrol. 60, 61–80.

GRUNDMANN, G. (1987): Hebungsraten im Tauernfenster, abgeleitet aus Spaltspurendatierungen von Apatiten. Mitt. Österr. Miner. Ges., 132, 103–116.

GRUNDMANN, G. and MORTEANI, G. (1985): The young uplift and thermal history of the Central Eastern Alps (Austria/Italy), evidence from apatite fission track ages. Jb. Geol. Bundesanstalt Wien, 128, H.2, 197–216.

HANDLER, R. (1994): $^{40}Ar/^{39}Ar$ and Rb–Sr mineral dating within a complex polymetamorphic terrain: the northeastern Alps, Austria. Ph. D. Thesis, University of Graz, 143 pp.

HANDLER, R., DALLMEYER, R.D. and NEUBAUER, F. (1997): $^{40}Ar/^{39}Ar$ ages of detrital white mica from Upper Austroalpine units in the Eastern Alps: evidence for Cadomian and contrasting Variscan sources. Geol. Rundsch., 86, 69–80.

HASENHÜTTL, CH. (1994): Eine Wärmegeschichte des Grazer Berglandes. Inkohlung, Illitkristallinität, Tonmineralogie und Conodont Colour Alteration Index im nördlichen Teil des Grazer Deckenkomplexes (Grazer Paläozoikum, Österreich). Ph. D. Thesis, Univ. Graz, 165 pp.

HASENHÜTTL, CH. and RUSSEGGER, B. (1992): Niedrigstgradige Metamorphose im Grazer Paläozoikum. Jb. Geol. Bundesanstalt Wien, 135, 287–297.

HÄUSLER, H. (1987): The northern Austroalpine margin during the Jurassic: breccias from the Radstädter-Tauern and the Tarntaler Berge. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke: Wien, 103–111.

HAÜY, R.J. (1822): Traité de minéralogie, 2nd ed., 2, 594 pp., Paris (Bachelier).

HEINRICHS, C. (1993): Sedimentpetrographische Untersuchungen zur Hochdiagenese in der Kössen-Formation (Obere Trias) der westlichen Ostalpen und angrenzenden Südalpengebiete. Bochumer Geol. u. Geotechn. Arb., 40, 1–206.

HEJL, E. (1997): "Cold spots" during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics, 272, 159–173.

HEJL, E. and GRUNDMANN, G. (1989): Apatit-Spaltspurendaten zur thermischen Geschichte der Nördlichen Kalkalpen, der Flysch- und Molassezone. Jb. Geol. Bundesanstalt Wien, 132, 191–212.

HERITSCH, H. (1973): Die Bildungsbedingungen von alpinotypem Eklogitamphibolit und Metagabbro, erläutert an Gesteinen der Koralpe, Steiermark. Tschermaks Min. Petr. Mitt., 19, 213–271.

HERITSCH, H. and MÖRTL, J. (1977): Die Bildungsbedingungen eines Disthen-Chloritoid-Staurolith-Granatglimmerschiefers mit wesentlichem Paragonitgehalt von der Rosshütte, südliche Koralpe. Mitt. naturwiss. Ver. Steiermark, 107, 15–23.

HÖCK, V. (1974): Lawsonitpseudomorphosen in den Knotenschiefern der Glocknergruppe (Salzburg-Kärten, Österreich). Karinthin, 71, 110–119.

HÖCK, V. (1980): Distribution maps of minerals of the Alpine metamorphism in the penninic Tauern window, Austria. Mitt. Österr. Geol. Ges., 71/72, 1978/1979, 119–127.

HÖCK, V. and HOSCHEK, G. (1980): Metamorphism of calcareous metasediments in the Hohe Tauern, Austria. Mitt. Österr. Geol. Ges., 71/72, 99–118.

HÖCK, V. and KOLLER, F. (1989): Magmatic evolution of the Mesozoic ophiolites in Austria. Chem. Geol., 77, 209–227.

HOERNES, S. and FRIEDRICHSEN, H. (1974): Oxygen isotope studies on metamorphic rocks of the western Hohe Tauern area (Austria). Schweiz. Mineral. Petrogr. Mitt., 54, 769–788.

HOINKES, G. (1981): Mineralreaktionen und Metamorphosebedingungen in Metapeliten des westlichen Schneebergerzuges und des angrenzenden Altkristallins (Ötztaler Alpen). Tschermaks Min. Petr. Mitt., 28, 31–54.

HOINKES, G. (1983): Cretaceous metamorphism of metacarbonates in the Austroalpine Schneeberg complex, Tirol. Schweiz. Mineral. Petrogr. Mitt., 63, 95–114.

HOINKES, G., KOSTNER, A. and THÖNI, M. (1991): Petrologic constraints for Eoalpine eclogite facies metamorphism in the Austroalpine Ötztal basement. Mineral. Petrol., 43, 237–254.

HOINKES, G., LICHEM, CH. and TEIML, X. (1997): High pressure metamorphism in the Austroalpine basement. Terra nova, 9, Abstr. suppl., 1, 14–15.

HOKE, L. (1990): The Altkristallin of the Kreuzeck Mountains, SE Tauern Window, Eastern Alps – Basement crust in a convergent plate boundary zone. Jb. Geol. Bundesanstalt Wien, 133, H. 1, 5–87.

HOLLAND, T.J.B. (1979): High water activities in the generation of high pressure kyanite eclogites of the Tauern Window, Austria. J. Geol., 87, 1–27.

HOLLAND, T.J.B. and RICHARDSON, S.W. (1979): Amphibole zonation as a guide to the evolution of metamorphic conditions. Contrib. Mineral. Petrol., 70, 143–148.

HOLLAND, T.J.B. and RAY, N.J. (1985): Glaucophane and pyroxene breakdown reactions in the Pennine units of the Eastern Alps. J. metamorphic Geol., 3, 417–438.

HOSCHEK, G. (1980a): Phase relations of a simplified marly rock system with application to the western Hohe Tauern (Austria). Contrib. Mineral. Petrol, 73, 53–68.

HOSCHEK, G. (1980b): The effect of Fe-Mg substitution on phase relations in marly rocks of the western Hohe Tauern (Austria). Contrib. Mineral. Petrol., 75, 123–128.

HOSCHEK, G. (1982): Alpidische Metamorphosebedingungen in Metasedimenten der westlichen Hohen Tauern. Jahresbericht 1980 Hochschulschwerpunkt S15, 33–35.

HOSCHEK, G. (1984): Alpine metamorphism of calcareous metasediments in the Western Hohe Tauern, Tyrol: mineral equilibria in COHS fluid. Contrib. Mineral. Petrol., 87, 129–137.

INGER, S. and CLIFF, R.A. (1994): Timing of metamorphism in the Tauern Window, Eastern Alps: Rb–Sr ages and fabric formation. J. metamorphic Geol., 12, 695–707.

KÁZMÉR, M. and KOVÁCS, S. (1985): Permian-Paleogene paleogeography along the eastern part of the Insubric-Periadriatic Lineament system: evidence for continental escape of the Bakony-Drauzug unit. Acta geol. Hungarica, 28, 71–84.

KLEBERGER, J., SÄGMÜLLER, J. and TICHY, G. (1981): Neue Fossilfunde aus der mesozoischen Schieferhülle der Hohen Tauern zwischen Fuschertal und Wolfbachtal (Unterpinzgau/Salzburg). Geol. Paläont. Mitt. Innsbruck, 10/9, 275–288.

KLEINSCHMIDT, G. and RITTER, U. (1976): Geologisch-petrographischer Aufbau des Koralpenkristallins südlich von Soboth/Steiermark-Kärnten (Raum Hühnerkogel-Laaken). Carinthia II, 86, 57–91.

KOLLER, F. (1985): Petrologie und Geochemie des Penninikums am Alpenostrand. Jb. Geol. Bundesanstalt Wien, 128, 83–150.

KOLLER, F. and HÖCK, V. (1990): Mesozoic ophiolites in the Eastern Alps. In: MALPAS, J., MOORES, E.M., PANAYIOTOU, A. and XENOPHONTOS, C. (eds): Ophiolites, Oceanic Crustal Analogues, Proceedings of the Symposium "TROODOS 1987", 253–263.

KOLLER, F., DINGELDEY, CH. and HÖCK, V. (1996): Exkursion F: Hochdruckmetamorphose im Recknerkomplex/Tarntaler Berge (Unterostalpin) und Idalm-Ophiolith/Unterengadiner Fenster. Mitt. Österr. Miner. Ges., 141, 305–330.

KONZETT, J. and HOINKES, G. (1991): High pressure metamorphism in the Austroalpine Schneeberg Complex and adjacent Ötztal basement rocks. Terra abstr., 3, 88.

KONZETT, J. and HOINKES, G. (1996): Paragonite-hornblende assemblages and their petrological significance: an example from the Austroalpine Schneeberg Complex, Southern Tyrol, Italy. J. metamorphic Geol., 14, 85–101.

KOROKNAI, B., NEUBAUER, F. and GENSER, J. (1996): Metamorphic and tectonic evolution of the Austroalpine Units at the Western margin of the Gurktal Nappe Complex, Eastern Alps. In: AMANN, G., HANDLER, R., KURZ, W. and STEYRER, H.P. (eds): 6. Symposium Tektonik-Strukturgeologie-Kristallingeologie, Erweiterte Kurzfassungen, Salzburg (Universität Salzburg), 223–226.

KOROKNAI, B., NEUBAUER, F., GENSER, J. and TOPA, D. (1999): Metamorphic and tectonic evolution of the Austroalpine units at the western margin of the Gurktal Nappe Complex, Eastern Alps. Schweiz. Mineral. Petrogr. Mitt., 79/2, in press.

KRALIK, M. (1983): Interpretation of K–Ar and Rb–Sr data from fine fractions of weakly metamorphosed shales and carbonate rocks at the base of the Northern Calcareous Alps (Salzburg, Austria). Tschermaks Min. Petr. Mitt., 32, 49–67.

KRALIK, M., KRUMM, H. and SCHRAMM, J.-M. (1987): Low grade and very low grade metamorphism in the Northern Calcareous Alps and in the Greywacke Zone: illite-crystallinity data and isotopic ages. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Wien, Deuticke, 164–178.

KRALIK, M. and SCHRAMM, J.-M. (1994): Illit-Wachstum: Übergang Diagenese-Metamorphose in Karbonat- und Tongesteinen der nördlichen Kalkalpen: Mineralogie und Isotopengeologie (Rb–Sr, K–Ar und C–O). Jb. Geol. Bundesanstalt Wien, 137, 105–137.

KRUHL, J.H. (1993): The P-T-t development at the basement-cover boundary in the north-east Tauern Window (Eastern Alps): Alpine continental collision. J. metamorphic Geol., 11, 31–47.

KRUMM, H. (1984): Anchimetamorphose im Anis und Ladin (Trias) der Nördlichen Kalkalpen zwischen Arlberg und Kaisergebirge – ihre Verbreitung und deren baugeschichtliche Bedeutung. Geol. Rundsch., 73, 223–257.

KRUMM, H., PETSCHICK, R. and WOLF, M. (1988): From diagenesis to anchimetamorphism, Upper Austroalpine sedimentary cover in Bavaria and Tyrol. Geodinamica Acta, 2, 33–47.

KÜRMANN, H. (1993): Zur Hochdiagenese und Anchimetamorphose in Permotrias-Sedimenten des Austroalpins westlich der Tauern. Bochumer geol. u. geotechn. Arb., 41, 1–328.

KURZ, W., NEUBAUER, F. and GENSER, J. (1996): Kinematics of Penninic nappes (Glockner Nappe and basement-cover nappes) in the Tauern Window (Eastern Alps, Austria) during subduction and Penninic-Austroalpine collision. Eclogae geol. Helv., 89/1, 573–605.

KURZ, W., NEUBAUER, F. and DACHS, E. (1998a): Eclogite meso- and microfabrics: implications for the burial and exhumation history of eclogites in the Tauern Window (Eastern Alps) from P-T-t paths. Tectonophysics, 285, 183–209.

KURZ, W., NEUBAUER, F., GENSER, J. and DACHS, E. (1998b): Alpine geodynamic evolution of passive and active continental margin sequences in the Tauern Window (Eastern Alps, Austria, Italy). Geol. Rundsch., 87, 225–242.

LÄUFER, A.L. (1996): Variscan and Alpine tectonometamorphic evolution of the Carnic Alps (Southern Alps) – Structural analysis, illite crystallinity, K–Ar and Ar–Ar geochronology. Tübinger Geowissenschaftliche Arbeiten, 26, 1–102.

LÄUFER, A.L., FRISCH, W., STEINITZ, G. and LOESCHKE, J. (1997): Exhumed fault-bounded Alpine blocks along the Periadriatic lineament: the Eder unit (Carnic Alps, Austria). Geol. Rundsch., 86, 612–626.

LEIMSER, W. (1977): Untersuchungen zur Petrographie und Metamorphose der Gesteine des Unterengadiner Fensters. Ph. D. Thesis, Naturw. Fak., Univ. Innsbruck, 137 pp.

LEIMSER, W. and PURTSCHELLER, F. (1980): Beiträge zur Metamorphose von Metavulkaniten im Pennin des Engadiner Fensters. Mitt. Österr. Geol. Ges., 71/72, 129–137.

LEIN, R., GAWLICK, H.-J. and KRYSTYN, L. (1997): Paläogeographie und tektonische Herkunft des Drauzuges – Eine Diskussion auf der Basis von Fazies- und Conodont Colour Alteration Index (CAI)-Untersuchungen. Zbl. Geol. Paläont. Teil I, 1996: 471–483.

LELKES-FELVARI, G., SASSI, F.P. and VISONA, D. (1984): Pre-Alpine and Alpine developments of the Austridic basements in the Sopron area (Eastern Alps, Hungary). Rend. Soc. Ital. Mineral. Petrol., 39, 593–612.

LICHEM, CH., GREGUREK, D. and HOINKES, G. (1996): Alpidische Metamorphosegradienten im Koralmkristallin. In: AMANN, G., HANDLER, R., KURZ, W. and STEYRER, H.P. (eds): 6. Symposium Tektonik-Strukturgeologie-Kristallingeologie, Erweiterte Kurzfassungen, Salzburg (Universität Salzburg), 253–254.

LICHEM, CH., HOINKES, G. and GREGUREK, D. (1997): Polymetamorphism of the Austroalpine Koralm Basement: New evidence for a permian event. Terra Nova 9, Abstr. Suppl. 1, 489.

LINNER, M. (1995): Das ostalpine Kristallin der südwestlichen Schober-Gruppe mit den frühalpidischen Eklogiten im Bereich Prijakte–Alkuser See–Schleinitz. In: Geologie von Osttirol, Arbeitstagung der Geol. Bundesanstalt 1995, 15–21.

LINNER, M., RICHTER, W. and THÖNI, M. (1996): Eo-Alpine eclogites in the Austroalpine basement S of the Tauern Window: Geochemistry of eclogites and interlayered metasediments. J. Conf. Abstr., 1, 363.

LUCKSCHEITER, B. and MORTEANI, G. (1980): Microthermometrical and chemical studies of fluid inclusions in minerals from Alpine veins from the Penninic rocks of the central and western Tauern Window (Austria/Italy). Lithos, 13, 61–77.

MEIXNER, H. (1978): Alpine Kluftminerale und Tauernmetamorphose im Radiolarit (Unteralm) der Hochfeindgruppe, südl. Radstädter Tauern, Salzburg. Karinthin, F. 79, 62–64.

MILLER, CH. (1974): On the metamorphism of the eclogites and high grade blueschists from the Penninic terrane of the Tauern Window, Austria. Schweiz. Mineral. Petrogr. Mitt., 54, 371–384.

MILLER, CH. (1977): Chemismus und phasenpetrologische Untersuchungen der Gesteine aus der Eklogitzone des Tauernfensters, Österreich. Tschermaks Min. Petr. Mitt., 24, 221–277.

MILLER, CH. (1990): Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria. Schweiz. Mineral. Petrogr. Mitt., 70, 287–300.

MILLER, CH. and FRANK, W. (1983): Das Alter der Metamorphose von Metabasiten und Eklogiten in Kor- und Saualpe. Jber. 1982, Hochschulschwerpunkt S 15, 229–236.

MILLER, CH., STOSCH, H.-G. and HOERNES, ST. (1988): Geochemistry and origin of eclogites from the type locality Koralpe and Saualpe, Eastern Alps, Austria. Chem. Geol., 67, 103–118.

MILLER, CH. and THÖNI, M. (1997): Eo-Alpine eclogitisation of Permian MORB-type gabbros in the Koralpe (Eastern Alps, Austria): new geochronological, geochemical and petrological data. Chem. Geol., 137, 283–310.

MOINE, B., FORTUNE, J.P., MOREAU, P. and VIGUIER, F. (1989): Comparative mineralogy, geochemistry, and conditions of formation of two metasomatic talc and chlorite deposites: Trimouns (Pyrenees, France) and Rabenwald (Eastern Alps, Austria). Econ. Geol., 84, 1398–1416.

MORTEANI, G. and RAASE, P. (1974): Metamorphic plagioclase crystallization and zones of equal anorthite content in epidote-bearing, amphibole-free rocks of the western Tauernfenster, Eastern Alps. Lithos, 7, 101–111.

MOYSCHEWITZ, G. (1995): Variszische und alpidische Entwicklung des südwestlichen Raabalpen- und des Kulmkristallins, Unterostalpin, Steiermark. Ph. D. Thesis, Univ. Graz.

MÜLLER, W. (1994): Neue geochronologische und strukturgeologische Daten zur geodynamischen Entwicklung des Semmering- und des Wechsel-Gebietes (Niederösterreich). Unpubl. M. Sc. Thesis, Univ. Vienna, 267 pp.

NEUBAUER, F. (1988): The Variscan orogeny in the Austroalpine and Southalpine domains of the Eastern Alps. Schweiz. Mineral. Petrogr. Mitt., 68, 339–349.

NEUBAUER, F. (1991): Kinematic indicators in the Koralm and Saualm eclogites, Eastern Alps. Zentralbl. Geol. Paläont. Teil 1, 1991, 139–155.

NEUBAUER, F. (1994): Kontinentkollision in den Ostalpen. Geowissenschaften, 12, 136–140.

NEUBAUER, F., FRISCH, W. and HANSEN, B.T. (1987): New data on the evolution of the Austroalpine basement: a U/Pb zircon study. Terra Cognita, 7, 93.

NEUBAUER, F., HANDLER, R., HERMANN, S. and PAULUS, G. (1994): Revised lithostratigraphy and structure of the Eastern Graywacke Zone (Eastern Alps). Mitt. Öster. Geol. Ges., 86, 61–74.

NEUBAUER, F., DALLMEYER, R.D., DUNKL, I. and SCHIRNIK, D. (1995): Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics, 242, 79–98.

NEUBAUER, F. and FRIEDL, G. (1997): Conodont preservation within the Gurktal nappe complex, Eastern Alps. Zbl. Geol. Paläont. Teil I, 1996, 227–289.

NIEDERMAYR, G., MULLIS, J., NIEDERMAYR, E. and SCHRAMM, J.-M. (1984): Zur Anchimetamorphose permoskythischer Sedimentgesteine im westlichen Drauzug, Kärnten-Osttirol (Österreich). Geol. Rundsch., 73, 207–221.

OBERHÄNSLI, R. (1994): Subducted and obducted ophiolites of the Central Alps: Paleotectonic implications deduced by their distribution and metamorphic overprint. Lithos, 33, 109–118.

OBERHÄNSLI, R., GOFFÉ, B. and BOUSQUET, R. (1995): Record of a HP-LT metamorphic evolution in the Valais zone: Geodynamic implications. In: LOMBARDO, B. (ed.): Studies on metamorphic rock and minerals of the Western Alps. Boll. Mus. Reg. Sc. Nat. Torino, 13/2, 221–240.

OBERHAUSER, R. (1980): Das Unterengadiner Fenster. In: OBERHAUSER, R. (ed.): Der Geologische Aufbau Österreichs, Springer-Verlag Wien-New York, 291–299.

OBERHAUSER, R. (1995): Zur Kenntnis der Tektonik und der Paleogeographie des Ostalpenraumes zur Kreide-, Paleozän- und Eozänzeit. Jb. Geol. Bundesanstalt Wien, 138, 369–432.

PAHR, A. (1975): Neue Erkenntnisse zur Geologie der Rechnitzer Schieferinsel und deren Konsequenzen für den Antimonitbergbau. Berg- u. Hüttenmänn. Mh., 120, 492–495.

PAHR, A. (1980): Die Fenster von Rechnitz, Bernstein und Möltern. In: OBERHAUSER, R. (ed.): Der Geologische Aufbau Österreichs, Springer-Verlag Wien-New York, 320–326.

PEER, H. and ZIMMER, W. (1980): Geologie der Nordrahmenzone der Hohen Tauern (Gasteiner Ache bis Saukarkopf–Grossarltal). Jb. Geol. Bundesanstalt Wien, 123, 411–466.

PEINDL, P. (1990): Variszische und alpidische Entwicklungsgeschichte des südöstlichen Raabalpenkristallins (Steiermark). Ph. D. Thesis, Univ. Graz, 252 pp.

PETSCHICK, R. (1989): Zur Wärmegeschichte im Kalkalpin Bayerns und Nordtirols (Inkohlung und Illitkristallinität). Frankfurter geowiss. Arb. Serie C, 10, 1–259.

PURTSCHELLER, F. (1969): Petrographische Untersuchungen an Alumosilikatgneisen des Ötztaler-Stubaier Altkristallins. Tschermaks Min. Petr. Mitt., 13, 35–54.

RAITH, M., HÖRMANN, P.K. and ABRAHAM, K. (1977): Petrology and metamorphic evolution of the Penninic ophiolites in the western Tauern Window (Austria). Schweiz. Mineral. Petrogr. Mitt., 57, 187–232.

RAITH, M., MEHRENS, C. und THÖLE, W. (1980): Gliederung, tektonischer Bau und metamorphe Entwicklung der penninischen Serien im südlichen Venediger-Gebiet, Osttirol. J. Geol. Bundesanstalt Wien, 123, 1–37.

RAITH, J.G. and VALI, H. (1998): Fibrous chlorite and muscovite from the Kaisersberg graphite mine, Styria, Austria. Canadian Mineralogist (in print).

RANTITSCH, G. (1992): Reflexionsmessungen an Graptolithen im Silur und Unterdevon der Karnischen Alpen. Jb. Geol. Bundesanstalt Wien, 135, 299–316.

RANTITSCH, G. (1993): Zur Wärmegeschichte der Karnischen Alpen. Ph. D. Thesis, Graz University of Graz, 173 pp.

RANTITSCH, G. (1995a): Coalification and graphitization of graptolites in the anchizone and lower epizone. Intern. J. Coal Geology, 27, 1–22.

RANTITSCH, G. (1995b): Niedrigstgradige Metamorphose im Karbon von Nötsch (Österreich). Jb. Geol. Bundesanstalt Wien, 138, 433–440.

RANTITSCH, G. (1997): Thermal history of the Carnic Alps (Southern Alps, Austria) and its paleogeographic implications. Tectonophysics, 272, 213–232.

RANTITSCH, G., RUSSEGGER, B. and EBNER, F. (1996): Maturität und Tonmineralogie der Raibler Schichten des Drauzuges (Ostalpen, Österreich). In: Sediment 96. 11. Sedimentologentreffen. Kurzfassungen der Vorträge und Poster. Wien (Universität Wien), 140.

RANTITSCH, G., RUSSEGGER, B., SACHSENHOFER, R.F., JOCHUM, J. and SCHROLL, E. (1997): Hydrocarbon-bearing fluid inclusions in the Drau Range (Eastern Alps, Austria): Implications for the genesis of the Bleiberg Pb–Zn deposit. In: PAPUNEN, H. (ed.): Mineral deposits: research and exploration. Where do they meet? Proceedings of the 4th Biennial SGA Meeting., Rotterdam (Balkema), 567–569.

RANTITSCH, G. and RUSSEGGER, B.: Thrust-related very low grade metamorphism within the Gurktal Nappe Complex (Eastern Alps), in prep.

RATSCHBACHER, L., BEHRMANN, J.H. and PAHR, A. (1990): Penninic windows at the eastern end of the Alps and their relation to the intra-Carpathian basins. Tectonophysics, 172, 91–105.

RATSCHBACHER, L., FRISCH, W., LINZER, H.-G. and MERLE, O. (1991): Lateral extrusion in the Eastern Alps. Part 2, structural analysis. Tectonics, 10, 257–271.

REDDY, S.M., CLIFF, R.A. and EAST, R. (1993): Thermal history of the Sonnblick Dome, south-east Tauern Window, Austria: Implications for heterogeneous uplift within the Pennine basement. Geol. Rundsch. 82, 667–675.

REINDL, H. (1989): Das westliche Raabalpenkristallin. Ph. D. Thesis, Univ. Graz, 235 pp.

REITZ, E., HÖLL, R., HUPAK, W. and MEHLTRETTER, CH. (1990): Palynologischer Nachweis von Unterkreide in der Jüngeren (Oberen) Schieferhülle des Tauernfensters (Ostalpen). Jb. Geol. Bundesanstalt Wien, 133, H.4, 611–618.

RUSSEGGER, B. (1992): Diagenese bis niedriggradige Metamorphose im südlichen Grazer Paläozoikum (Steiermark, Österreich). Ph. D. Thesis, Univ. Graz, 180 pp.

RUSSEGGER, B. (1996): Niedrigst- bis niedriggradige Metamorphose im südlichen Grazer Paläozoikum (Ostalpen). Jb. Geol. Bundesanstalt Wien, 139, 93–100.

SACHSENHOFER, R.F. (1987): Fazies und Inkohlung mesozoischer Kohlen der Alpen Ostösterreichs. Mitt. Österr. Geol. Ges., 80, 1–45.

SACHSENHOFER, R.F. (1992): Coalification and thermal histories of Tertiary basins in relation to late Alpidic evolution of the Eastern Alps. Geol. Rundsch., 81, 291–308.

SACHSENHOFER, R.F., CURRY, D.J., HORSFIELD, B. and RANTITSCH, G. (1995): Characterization of organic matter in late Cretaceous black shales of the Eastern Alps (Kainach Gosau Group, Austria). Org. Geochem., 23, 915–929.

SACHSENHOFER, R.F. and RANTITSCH, G. (1997): Das Inkohlungsbild österreichischer Kohlenlagerstätten und Temperaturgeschichten alpiner und ausseralpiner Sedimentbecken. In: WEBER, L. (ed.): Handbuch der Lagerstätten der Erze, Industrieminerale und Energierohstoffe Österreichs. Archiv f. Lagerstättenforschung, Geol. Bundesanstalt Wien, 19, 503–514.

SACHSENHOFER, R.F., JELEN, B., HASENHÜTTL, CH., DUNKL, I. and RAINER, TH. (submitt.): Thermal history of Tertiary basins in Slovenia (Alpine-Dinaride-Pannonian junction). In: TARI, G. (ed.): Extreme Miocene extension in the Eastern Alps/Pannonian basin transitional zone. Geol. Soc. America Spec. Vol.

SANDER, B. (1912): Über einige Gesteinsgruppen des Tauernwestendes. Jb. k.k. geol. Reichsanst., 62, H. 2, 219–287.

SASSI, F.P., BORSI, S., DEL MORO, A., ZANFERRARI, A. and ZIRPOLI, G. (1978): Contributions to the geodynamic interpretations in the Eastern Alps. In: CLOSS, H., ROEDER, D. and SCHMIDT, K. (eds): Apennines, Hellenides. Schweizerbart'sche Verlagsbuchhandlung Stuttgart, 154–160.

SASSI, R., ÁRKAI, P., LANTAI, C. and VENTURINI, C. (1995): Location of the boundary between the metamorphic Southalpine basement and the Paleozoic sequences of the Carnic Alps: illite "crystallinity" and vitrinite reflectance data. Schweiz. Mineral. Petrogr. Mitt., 75, 399–412.

SATIR, M. (1975): Die Entwicklungsgeschichte der westlichen Hohen Tauern und der südlichen Ötztalmasse auf Grund radiometrischer Altersbestimmungen. Mem. Ist. Geol. Min. Univ. Padova, 30, 84.

SCHIMANA, R. (1986): Neue Ergebnisse zur Entwicklungsgeschichte des Kristallins um Radenthein (Kärnten, Österreich). Mitt. Ges. Geol. Bergbaustud. Österr., 33, 221–232.

SCHMIDT, K., JÄGER, E., GRÜNENFELDER, M. and GRÖGLER, N. (1967): Rb/Sr- und U/Pb-Altersbestim-

mungen an Proben des Ötztalkristallins und des Schneebergerzuges. Eclogae geol. Helv., 60, 529–536.
SCHRAMM, J.-M. (1977): Über die Verbreitung epi- und anchimetamorpher Sedimentgesteine in der Grauwackenzone und in den Nördlichen Kalkalpen (Österreich) - ein Zwischenbericht. Geol.-Paläont. Mitt. Innsbruck, 7, 3–20.
SCHRAMM, J.-M. (1982): Zur Metamorphose des feinklastischen Permoskyths im Ostabschnitt der Nördlichen Kalkalpen (Ostösterreich). Verh. Geol. Bundesanstalt Wien, 1982, 63–73.
SCHRAMM, J.-M. (1991): The Permian-Triassic of the Gartnerkofel-1 core (Carnic Alps, Austria): Illite crystallinity in shaly sediments and its comparison with pre-Variscan sequences. Abh. Geol. Bundesanstalt Wien, 45, 69–78.
SCHRAMM, J.-M., VON GOSEN, W., SEEGER, M. and THIEDIG, F. (1982): Zur Metamorphose variszischer und postvariszischer Feinklastika in Mittel- und Ostkärnten (Österreich). Mitt. Geol. Paläont. Inst. Univ. Hamburg, 53, 169–179.
SCHULZ, B. (1997): Pre-Alpine tectonometamorphic evolution in the Austroalpine basement of the central Tauern Window. Schweiz. Mineral. Petrogr. Mitt., 77, 281–297.
SCHULZ, B., NOLLAU, G., HEINISCH, H. and GODIZART, G. (1995): Austro-Alpine basement complex to the south of the Tauern Window. In: VON RAUMER, J.F. and NEUBAUER, F. (eds): Pre-Mesozoic Geology in the Alps. Springer, Berlin, Heidelberg, 495–514.
SCHUSTER, R. and THÖNI, M. (1996): Permische Granate: Indizien für eine regionale permische Metamorphose im südlichen Ostalpin. In: AMANN, G., HANDLER, R., KURZ, W. and STEYRER, H.P. (eds): 6. Symposium Tektonik - Strukturgeologie - Kristallingeologie, Erweiterte Kurzfassungen, Salzburg (Universität Salzburg), 389–391.
SCHWEIGL, J. (1997): Kinematik der zentralen Nördlichen Kalkalpen (Ostalpen). Ergebnisse strukturgeologischer, sedimentologischer, stratigraphischer, geochemischer Untersuchungen und Spaltspurendatierung. Unpubl. Ph. D. Thesis, University of Salzburg, 259 pp.
SELVERSTONE, J. (1988): Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing history of the Tauern Window. Tectonics, 7, 87–105.
SELVERSTONE, J. and SPEAR, F.S. (1985): Metamorphic P-T paths from pelitic schists and greenstones from the south-west Tauern Window, Eastern Alps. J. metamorphic Geol., 3, 439–465.
SELVERSTONE, J., SPEAR, F.S., FRANZ, G. and MORTEANI, G. (1984): High-pressure metamorphism in the SW Tauern Window, Austria: P-T paths from hornblende-kyanite-staurolite schists. J. Petrology, 25, 501–531.
SELVERSTONE, J., FRANZ, G., THOMAS, S. and GETTY, ST. (1992): Fluid variability in 2 GPa eclogites as an indicator of fluid behavior during subduction. Contrib. Mineral. Petrol. 112, 341–357.
SLAPANSKY, P. and FRANK, W. (1987): Structural evolution and geochronology of the northern margin of the Austroalpine in the northwestern Schladming crystalline (NE Radstädter Tauern). In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke, Wien, 244–260.
SPEAR, F.S. and FRANZ, G. (1986): P-T evolution of metasediments from the Eclogite Zone, south-central Tauern Window, Austria. Lithos 19, 219–234.
SPÖTL, C., KRALIK, M and KUNK, M.J. (1986): Authigenic feldspar as an indicator of paleo-rock/water interactions in Permian carbonates of the Northern Calcareous Alps, Austria. J. Sed. Res., 66, 139–146.
STAUFENBERG, H. (1985): Hebungs- und Abkühlungsgeschichte des östlichen Tauernfensters und seiner ostalpinen Umrahmung, abgeleitet aus Apatit-Spaltspurenaltern. Ph. D. Thesis Technische Universität München, 78 pp.
STÖCKHERT, B. (1985): Pre-Alpine history of the Austridic basement to the south of the western Tauern window (southern Tyrol, Italy) - Caledonian versus Hercynian event. N. Jb. Geol. Paläont. Mh., 618–642.
STÖCKHERT, B., MASSONNE, H.-J. and NOWLAN, E.U. (1997): Low differential stress during high-pressure metamorphism: The miscrostructural record of a metapelite from the Eclogite Zone, Tauern Window, Eastern Alps. Lithos, 41, 103–118.
STÖCKHERT, B., RÖSNER, G., KÜSTER, M., HEIDER, M., GRUNDLACH, K. and RICHTER, D.K. (1990): High-pressure metamorphism of Mesozoic sediments in the Lower Engadine Window, Eastern Alps. Terra Abstracts, 2, 34.
STRAUSS, H. (1990): Kristallisations- und Deformationsgeschichte des Altkristallins nordwestlich von Villach. Ph. D. Thesis, Univ. Graz.
STURM, R., DACHS, E. and KURZ, W. (1997): Untersuchung von Hochdruckrelikten in Grüngesteinen des Grossglocknergebietes (zentrales Tauernfenster, Österreich): Erste Ergebnisse. Zbl. Geol. Paläont. 1997 (H. 3/4), 345–363.
STÜWE, K. and POWELL, R. (1995): PT paths from modal proportions: application to the Koralm Complex, Eastern Alps. Contrib. Mineral. Petrol., 119, 83–93.
TEIML, X. (1996): Die Gesteine der Millstätter Serie - petrologische und geothermobarometrische Untersuchungen. Dipl. Arb., Univ. Graz, 198 pp.
TEIML, X., HOINKES, G. and KONZETT, J. (1995): Joint occurrence of eclogites and white mica-amphibolites in the Austroalpine Basement (Eastern Alps). Terra Nova, 7, Abstr. suppl., 1, 318.
TEIML, X. and HOINKES, G. (1996): Der P-T-Pfad der Millstätter Serie und ein Vergleich mit dem südlichen Ötztal-Stubai-Kristallin. Mitt. Österr. Min. Ges., 141, 228–229.
THOMAS, S. and FRANZ, G. (1989): Kluftminerale und ihre Bildungsbedingungen in Gesteinen der Eklogitzone/Südvenediger-Gebiet (Hohe Tauern, Österreich). Mitt. Österr. Geol. Ges. 81 (1988), 189–218.
THÖNI, M. (1981): Degree and evolution of the Alpine metamorphism in the Austroalpine unit W of the Hohe Tauern in the light of K/Ar and Rb/Sr age determinations on micas. Jb. Geol. Bundesanstalt Wien, 124, 111–174.
THÖNI, M. (1986): The Rb–Sr thin slab isochron method - an unreliable geochronologic method for dating geologic events in polymetamorphic terrains? - Mem. Sci. Geol., 38, 283–352.
THÖNI, M. (1999): A review of geochronological data from the Eastern Alps. Schweiz. Mineral. Petrogr. Mitt. 79, 209–230.
THÖNI, M. and JAGOUTZ, E. (1992): Some new aspects of dating eclogites in orogenic belts: Sm–Nd, Rb–Sr and Pb–Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia/Styria, SE Austria). Geochim. Cosmochim. Acta, 56, 347–368.
THÖNI, M. and MILLER, CH. (1996): Garnet Sm–Nd data from the Saualpe and the Koralpe (Eastern Alps, Austria): chronological and P-T constraints on the thermal and tectonic history. J. Metamorphic Geol. 14, 453–466.

TÖRÖK, K. (1996): High pressure / low temperature metamorphism of the Köhegy gneiss, Sopron (W-Hungary); Phengite barometry and fluid inclusions. Eur. J. Miner., 8, 917–925.
TÖRÖK, K. (1998): Magmatic and high-pressure metamorphic development of orthogneisses in the Sopron area, Eastern Alps (W-Hungary). N. Jb. Miner. Abh. 173, 69–91.
TOLLMANN, A. (1959): Der Deckenbau der Ostalpen auf Grund der Neuuntersuchung des zentralalpinen Mesozoikums. Mitt. Ges. Geol. Bergbaustud., 10, 1–62.
TOLLMANN, A. (1977): Geologie von Österreich, Band 1. Wien, Deuticke, 766.
TRÜMPY, R. (1972): Zur Geologie des Unterengadins. In: Komm. Schweiz. natf. Ges. zur wiss. Erforschung d. Nationalparks: Ergebnisse der wissenschaftlichen Untersuchung im Nationalpark, 13, 71–87.
VAI, G.B. (1991): Paleozoic strike-slip rift pulse and paleogeography in the circum-Mediterranean Tethyan realm. Paleogeography, Paleoclimatology, Paleoecology, 87, 223–252.
VOLL, G. (1977): Seriengliederung, Gefügeentwicklung und Metamorphose in den Nördlichen Radstädter Tauern zwischen Forstau- und Preunegg-Tal. In: BÖGEL, H. (ed.): Geodynamics and geotraverses around the Alps. Abstract, 2, Salzburg.
WANG, X. and NEUBAUER, F. (1998): Orogen-parallel strike-slip faults bordering metamorphic core complexes: the Salzach-Enns fault zone in the Eastern Alps, Austria. J. Struct. Geol., 20, 799–818.
ZIMMERMANN, R., HAMMERSCHMIDT, K. and FRANZ, G. (1994): Eocene high pressure metamorphism in the Penninic units of the Tauern Window, Eastern Alps: evidence from ^{40}Ar–^{39}Ar dating and petrological investigations. Contrib. Mineral. Petrol, 117, 175–186.

Manuscript received July 6, 1998; revision accepted January 8, 1999.