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Objekttyp: **Article**

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

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

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

PDF erstellt am: **05.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-60206

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SCHWEIZ. MINERAL. PETROGR. MITT. 79, 209–230, 1999

A review of geochronological data from the Eastern Alps

by *Martin Thöni*[1]

Abstract

Within both of the major tectonostratigraphic units of the Eastern Alps (the Penninic and the Austroalpine complexes) the oldest ages (U–Pb on zircon) have been determined from intermediate or mafic meta-igneous rocks that indicate crystallisation of various magmatic protoliths during the Latest Proterozoic (650–600 Ma). In the Austroalpines, intense magmatic activity is constrained by U–Pb, Sm–Nd and Rb–Sr ages for the time span of 610–420 Ma. The magmas were emplaced into metasediments with a Middle Proterozoic (c. 1.6 Ga) mean crustal residence age. These Late Proterozoic–Early Palaeozoic rock-forming processes are related to rifting, as well as collisional-orogenic events.

The "Zentralgneise" of the Hohe Tauern represent Carboniferous intrusions (336–308 Ma). The medium- to high-grade mineral parageneses and correlated structures of major parts of the Austroalpine "Altkristallin" (e.g. Ulten, Ötztal, Schladming subunits) are also Variscan in age. An early, c. 350 (± 10) Ma old HP event is preserved in metabasites of the central Ötztal area. In the same basement unit, the thermal peak in Grt – St – Ky ± Sil ± And gneisses was reached at 330 ± 10 Ma. Regional cooling (below 500 °C) began at about 310 (± 10) Ma.

Permo-Triassic rift-related events were recently confirmed by ages from various igneous assemblages (c. 290–240 Ma). This magmatic activity is related to extensional processes, mantle upwelling and initial rifting in the southeastern Austroalpine realm, which was probably accompanied by a metamorphism of low-P type (andalusite) in the continental crust.

Alpine subduction, metamorphism and deformation of the basement probably commenced during the Jurassic and culminated in the internal Austroalpines during Middle Late Cretaceous times (c. 100 ± 10 Ma), with peak PT conditions of 20 kbar and 600–700 °C, followed by rapid, near-isothermal decompression and exhumation, nappe thrusting and cooling (90–65 Ma).

Following Austroalpine nappe imbrication and NW-directed thrusting, subduction of the southern Penninics below the Austroalpines reaches eclogite facies conditions during NS compression, at 20 kbar / 600 °C. However, a Late Cretaceous vs Eocene age for this subduction-related high-P metamorphism is still under discussion. Maximum temperatures in deeper tectonic levels of the Tauern window were attained during the late stages of Penninic nappe imbrication and continental collision, i.e. during exhumation, some 30 ± 5 Ma ago. Mica cooling and apatite fission track ages in these areas are in the range of 30–15 and 10–5 Ma, respectively. In the Austroalpines, the post-Cretaceous metamorphic imprint is only local and weak. Cooling below 300 °C was mostly accomplished by Paleocene times. Tertiary (mainly Oligocene) intrusions and dykes are almost unaffected by metamorphism.

Keywords: Eastern Alps, geochronology, magmatic history, metamorphism, crustal evolution, Austria.

1. Introduction

Polymetamorphic Austroalpine basement rocks (AAB) cover by far the greater part of the central Eastern Alps. Hence, these units are of prominent importance for the reconstruction of both pre-Alpine and Alpine tectonic histories. The metamorphic grade in these rock series is mostly within the amphibolite facies, but reaches, at the most, the transition to the granulite facies. Eclogite facies rocks, however, also occur in several places. The strong thermal and tectonic imprint undergone by considerable portions of the AAB during Alpine plate convergence and nappe stacking has only been recognized during the last twenty years, since geochronology became an important analyt-

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ical tool. However, the evolution in time of some important tectonometamorphic events in the AAB are still poorly known.

The Alpine, i.e. autochthonous Permo-Mesozoic cover of this basement is very rudimentarily preserved, since it has largely been removed, tectonically and/or by erosion. The paleogeographic position, derivation and, especially, the time of decoupling from its former substratum of what forms now the huge nappe pile of the Northern Calcareous Alps (NCA) ranges among the most fundamental questions concerning the tectonometamorphic evolution of the Eastern Alps.

During the later stages of plate convergence and final continental collision, AAB units were emplaced as nappes onto oceanic sediments and pre-Alpine basement units of the former Penninic ocean. Initiation and duration of this subduction of the Penninic units (PE), which are exposed along the central axis of the Alpine chain in the Engadine, Tauern and Rechnitz windows, are also still a matter of vivid discussion and represent one of the basic geochronological problems within the framework of the Alpine orogeny.

Since the publication of the first radiometric data from the Eastern Alps, more than 30 years ago (FLÜGEL, 1964; LAMBERT, 1964), the amount of geochronological information has grown enormously. It is the aim of the present paper to review some of the geochronological material from the Eastern Alps, with special emphasis on the more recent data sets. Both major tectono- and lithostratigraphic units, the Penninics and the Austroalpines, are considered with respect to their pre-Alpine as well as their Alpine evolution.

2. Review of age results

2.1. HELVETIC ZONE S.L.

Within the allochthonous Gresten Klippen belt between Salzburg and Vienna, a tectonic unit analogous to the Helvetic zone s.l. in eastern Switzerland, huge crystalline boulders occur, embedded in a wildflysch-like matrix of Paleogene age. The exotic blocks are of tonalitic to granodioritic composition and most of them have largely preserved their magmatic texture, but have undergone very low- to low-grade- alteration (prehnite, pumpellyite) to a varying extent. Interpretation of the tectonic derivation and position of these exotics is in debate. FRASL and FINGER (1988) suggest a connection with the "Cetic Massif", a hypothetical basement block adjoining the Moldanubian zone to the south, and now underlying the Eastern Alps.

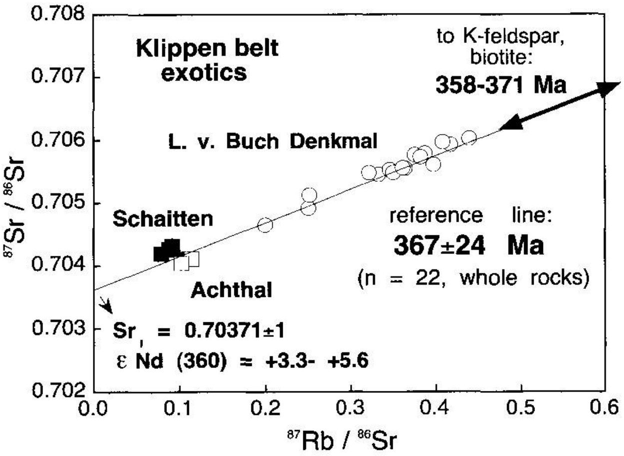

Fig. 1 Rb–Sr isochron diagram for different whole rocks of the Gresten Klippen belt, between Salzburg and Vienna. Data points for L. von Buch Denkmal, Schaitten, Achthal and St. Gilgen are shown (THÖNI, unpubl. data).

Rb–Sr whole rock data from different localities of this Klippen belt (Leopold von Buch memorial, Schaitten, Achthal, St. Gilgen) exhibit a very distinct composition, which is fairly different from most granitic rocks s.l. from the Alpine belt, as well as from the Variscan belt to the north. Low Rb, high Sr contents are in line with a fairly unradiogenic, but uniform Sr isotope composition (Fig. 1) as well as with other major and trace element data (FRASL and FINGER, 1988). Twenty-two whole rock data points from three localities (L. v. Buch memorial, Schaitten, Achthal) yield a Rb–Sr regression age of 367 ± 24 Ma and a very low ^{87}Sr/^{86}Sr initial ratio of 0.70371 ± 2 (Fig. 1). Including an apatite sample, the result is 362 ± 18 Ma, Sr_i = 0.70374 ± 8. The overall primitive character of the rocks is visible from the low initial Sr isotopic composition, compatible with a clearly positive ε Nd (360 Ma) of between +3.0 and +5.6 (5 samples; THÖNI, unpubl. data). Three Rb–Sr biotite ages range between 358 ± 6 and 365 ± 7 Ma, whereas one K-feldspar whole rock isochron lies at 371 ± 1 Ma (Fig. 1; THÖNI, unpubl. data). These data may be interpreted as cooling ages of the igneous assemblages. As a whole, the Sr and Nd data point to crystallisation of the magmatic assemblages in an I-type magmatic belt, probably between the Bohemian massif and the Alpine (Penninic) basement, during the early Variscan cycle.

2.2. PENNINIC REALM

Metamorphosed deep water sediments and ophiolites of the Penninic ocean are exposed in three tectonic windows, forming the Engadine, Tauern and the Rechnitz window group (HÖCK and KOLLER, 1989). Two main tectonostratigraphic units are discerned within the Tauern window (cf. FRISCH et al., 1993), which also exposes the deepest structural units of the Eastern Alps:

a) The "Lower Schieferhülle" (LS), which is the polymetamorphic pre-Mesozoic and parautochthonous Permo-Mesozoic cover to the Zentralgneis. This LS, consisting of "Altkristallin" plus volcanosedimentary units (Habach formation), was intruded during Variscan time by the granitic to granodioritic-tonalitic magmas that now form the Central Gneiss Cores ("Zentralgneise"). Migmatites are also known from this unit.

b) The allochthonous "Upper Schieferhülle" (US), which represents the metamorphosed oceanic realm between Europe and the Adria related parts (i.e. Austroalpines), is composed of pelitic schists, calcschists and greenstones, as well as the "Eclogite zone" of the Hohe Tauern.

2.2.1. Pre-Mesozoic ages

The oldest ages determined so far in the Tauern window were obtained on zircons (U–Pb, Sm–Nd) from eclogitic amphibolites of the LS. The upper concordia intercept yielded an age of 657 + 14/–15 Ma, whereas a Sm–Nd isochron age lies at 644 ± 12 Ma (von QUADT, 1992). These overlapping ages were interpreted as giving the time of crystallisation of the mafic to ultramafic magmatic protoliths. Isotopic evidence for a Late Proterozoic to Early Cambrian primary age was recently also published for the polyphase scheelite (tungsten) mineral deposit in the Felbertal, central Tauern window (EICHHORN et al., 1997, and references therein).

One further magmatic event within the LS Habach formation was postulated on the basis of U–Pb zircon results, as close to 540 Ma (539 + 9/–12 Ma; von QUADT, 1992). Recent conventional and laser ablation microprobe (LAM-ICP-MS) U–Pb analyses gave also evidence for a 488 ± 12 Ma magmatic event in the pre-Variscan basement of the LS. A 420–415 Ma old event was additionally proven, for the first time, by U–Pb and Sm–Nd results on zircons and garnet from the eclogitic amphibolites of the LS, which was interpreted as a Silurian metamorphic overprint (VON QUADT et al., 1997).

Age information on the crystallisation and emplacement of the Zentralgneis protoliths is somehow ambiguous. Several Rb–Sr whole rock "isochrons" gave Permian ages. HAWKESWORTH (1976, with references) published a Rb–Sr whole rock regression line for a composite granodioritic-tonalitic suite from the southeastern Tauern window with an age of 279 ± 9 Ma (Sr_i = 0.70577 ± 14). A similar Rb–Sr age of 283 ± 28 Ma (Sr_i = 0.7088 ± 24) was also reported for eight migmatite samples from the western part, which was suggested to constrain the "Hercynian metamorphic climax" (SATIR and MORTEANI, 1982). U–Pb dating of zircons, however, gave considerably older ages, in the range of 336-308 Ma (data compilation in FINGER et al., 1993, Tab. 1; EICHHORN et al., 1997). These older ages were interpreted as giving the time of magmatic crystallisation of the gneiss protoliths, implying that the Rb–Sr system might have been partly disturbed by post-magmatic fluid activity and deformation processes (CLIFF, 1981).

2.2.2. Alpine era

Isotopic age constraints on the Penninic ophiolites from the Eastern Alps (HÖCK and KOLLER, 1989) are scarce. A Sm–Nd whole rock (186 ± 12 Ma) and one ^{40}Ar–^{39}Ar biotite age (187 ± 1.4 Ma) were recently published for the "Lower Austroalpine" Reckner ultramafic-mafic suite, at the northwestern edge of the Tauern window (MEISEL et al., 1997; DINGELDEY et al., 1997). A Pl-Cpx pair (plagioclase is strongly saussuritized) from a gabbro of the Idalpe (Engadine window) gives an age of 182 ± 31 Ma and an initial ε Nd value of +8.3 (KOLLER and THÖNI, unpubl. data). Though badly defined, this date could also be interpreted as giving a hint that Penninic ocean floor formation was probably occurring since the Lower Jurassic.

Petrographic-petrological studies have revealed three Alpine metamorphic stages within the Tauern rocks: an eclogite facies stage, reaching conditions of c. 20 kbar at 550–630 °C, was followed by a blueschist event and then by a greenschist to lower amphibolite facies overprint during exhumation (KURZ et al., 1998, with literature). It was argued for a long time, that subduction of the Penninic ocean below the Austroalpines was already active during the Cretaceous and that the eclogite assembages could therefore be eo-Alpine in age (FRANK et al., 1987a).

Up to now, however, the eo-Alpine age for the US eclogites has not been proven directly by geochronologic results. ZIMMERMANN et al. (1994) constrained the blueschist event to between 32 and 36 Ma, using $^{40}Ar/^{39}Ar$ data of high-Si, phengitic micas. By applying exhumation rates of 2–10 mm/a (for 35 km of total exhumation), the authors inferred a possible time for the early high-P event between c. 40–50 Ma, i.e., during the Eocene. CHRISTENSEN et al. (1994), on the other hand, argued on the basis of Rb–Sr garnet growth studies in LS and US rocks, that the thermal maximum in the western Tauern window was reached around 30 Ma and that the high-P stage in the LS is constrained by the initiation of garnet growth "to before 62 Ma" (CHRISTENSEN et al., 1994).

Rb–Sr ages on white mica (and some U–Pb ages on titanite and allanite) from the SE part of the Tauern window gave evidence that peak metamorphic conditions of the last (post-high-P), greenschist facies event was reached at 30–28 Ma in this area (INGER and CLIFF, 1994). Younger mica ages, down to 23 Ma, trace zones of localized ongoing deformation during cooling (INGER and CLIFF, 1994).

Mica ages (Rb–Sr on biotite and K–Ar on white mica) younger than c. 25 Ma are generally taken as cooling ages, although this Tertiary "Tauern metamorphism" may have reached its thermal maximum at somewhat different times in the different tectonic levels exposed today (see CLIFF et al., 1985, for review). VON BLANCKENBURG and VILLA (1988) argued in favour of a differentiated, but young, postkinematic (20–18 Ma) crystallisation history on the basis of K–Ar and ^{40}Ar–^{39}Ar data of garbenschiefer amphiboles. Differential cooling is indicated by apatite fission track ages, which show that in the central and western area temperatures fell below c. 120 °C only some 10–5 Ma ago (GRUNDMANN and MORTEANI, 1985; see also data compilation by HEJL and WAGNER, 1991; FÜGENSCHUH et al., 1997; DUNKL et al., 1998), whereas in the eastern part of the Tauern window these ages range up to 23 Ma (STAUFENBERG, 1987).

Few age results are available from the Engadine window, where, in general, Alpine metamorphism reached only pumpellyite to greenschist facies conditions. Recent structural and petrological investigations, however, revealed a more complex situation, with a deeper high-P unit (12 kbar / 375 °C) being bounded by a large-scale shear zone from an upper tectonic unit with considerably lower PT conditions (7 kbar / 325 °C; BOUSQUET et al., 1998, in press). Four K–Ar ages on white mica rich fine fractions (< 2µ) from Bündnerschiefer-like samples range between 38.6 ± 2.3 and 26 ± 3 Ma, possibly indicating that the central, deeper parts of the window cooled later than the more external, higher levels (THÖNI, 1981). Alternatively, the older age could also reflect the presence of some inherited or excess argon.

2.3. AUSTROALPINE REALM

2.3.1. Austroalpine basement units

2.3.1.1. Polymetamorphic metasediments ("Altkristallin") – Proterozoic mean crustal residence ages and zircon inheritance

Polymetamorphic paragneisses and micaschists represent the most wide-spread rock type of the AAB. From several lines of evidence, it is clear that the age of the last sedimentation for considerable portions of this "Altkristallin" is probably pre-Cambrian, since it forms some kind of matrix within which younger meta-igneous rocks were emplaced.

Figure 2 shows a plot for some 30 whole rock data points of metasedimentary "Altkristallin" samples in an ε Nd (t = 0) vs time diagram. The analyses include samples from the Ötztal, the Ultental unit, Schobergruppe, Wölz micaschists, the Saualpe and the Koralpe. Additionally, two data points from the metasedimentary sequences of the Schneeberg and the Radenthein area are also shown. Except for these two latter samples, most of the remaining data (n = 24) define a mean age (Depleted Mantle Nd model age, T Nd DM) of 1.59 ± 0.1 Ga. Only two garnet-staurolite-rich samples from the Saualpe show significantly higher Nd model ages up to 2.2 Ga. The ε (0) Nd values are uniformly low, ranging between –10 and

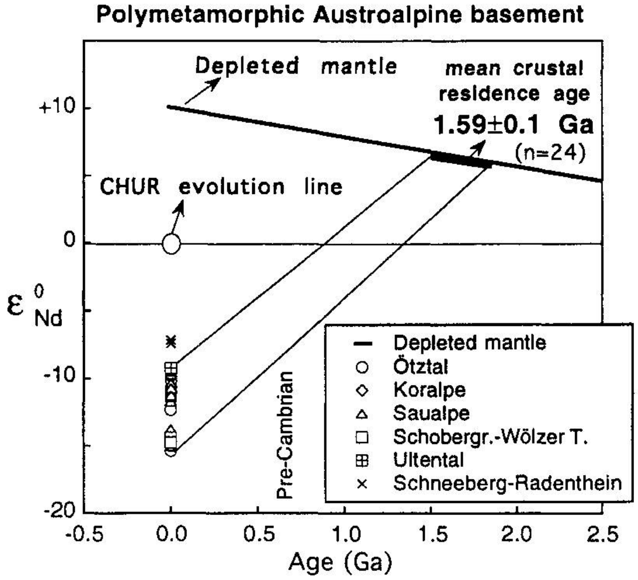

Fig. 2 Nd evolution for polymetamorphic metasedimentary AAB "Altkristallin" rocks. Most samples show a Mid-Proterozoic crustal residence age.
Data from: THÖNI and JAGOUTZ (1992), THÖNI and MILLER (1996), MILLER and THÖNI (1997), HOINKES et al. (1997), LINNER (unpubl. data), THÖNI (unpubl. data).

–15. Comparable Nd DM model ages have recently also been mentioned by VON QUADT and FINGER (1996).

At present, information from U–Pb analysis of zircons regarding the protolith age of these metasediments is scarce. KLÖTZLI-CHOWANETZ et al. (1997) mention zircon ages of 2.44 Ga. A two-point discordia through a strongly discordant zircon fraction yielded even an upper intercept age of 3.66 Ga for the oldest components present in zircons of the migmatized paragneisses from the Winnebach area in the northern Ötztal basement. U–Pb upper intercept zircon ages of 1.5–1.9 Ga have already been published by GRAUERT (1969) and up to 2.3 Ga by SÖLLNER and HANSEN (1987).

2.3.1.2. Late Proterozoic to Early Palaeozoic igneous activity and migmatisation – the Cadomian-Caledonian events

One striking difference between the western (Ötztal, Silvretta) and southeastern sections (Saualpe, Koralpe) of the AAB is the abundant occurrence of Early Palaeozoic meta-igneous rocks in the west, whereas in the southeastern parts such rocks are unknown.

Zircons from diorites from the *Silvretta* yielded an U–Pb age of 609 ± 3 Ma (SCHALTEGGER et al., 1997). A Pb–Pb evaporation age of 568 ± 6 Ma was determined for a mafic member of the "older orthogneisses" of the Silvretta by MÜLLER et al. (1995). Evidence for Cadomian magmatic or metamorphic protoliths is also given by ^{40}Ar–^{39}Ar ages (640–580 Ma) of detrital muscovite from various parts of the Eastern Alps (DALLMEYER et al., 1996, with literature).

From the *Ultental* ultramafics (peridotites of the Nonsberg area; OBATA and MORTEN, 1987; NTAFLOS et al., 1993) a strongly scattering Sm–Nd regression line for seven whole rock samples yields an "age" of 523 ± 67 Ma and an initial (523 Ma) ε Nd value of +5.4 ± 0.8. Nd isotopes, however, are positively correlated with Sr isotopes, whereas the present-day ^{187}Os/^{188}Os isotopic composition is within range of the contemporary mantle (NTAFLOS and THÖNI, in prep.) as well as within average of the silicate earth (MARTIN, 1991). In addition, a c. 410 Ma old event has also been preserved in large garnets (unpubl. Sm–Nd data). Thus, a polyphase pre-Variscan evolution for these mantle rocks is documented by the different isotopic systems (NTAFLOS and THÖNI, in prep.).

In the *Ötztal* unit, the oldest known protolith ages of mafic rocks are defined by Pl-Cpx pairs in gabbros of MORB affinity from the central Ötztal metabasite zone (Sm–Nd; MILLER and THÖNI, 1995) as well as by different varieties (whole rock Rb–Sr) of the Klopair diorite-tonalite gneiss in the Reschen pass area (SCHWEIGL, 1995). The data are concentrated in the time interval of 520–530 Ma. Similar ages were reported for zircons (U–Pb and Pb evaporation data, 520–540 Ma) of metabasic rocks (SCHALTEGGER et al., 1997; POLLER, 1997), oceanic plagiogranites and the "older orthogneisses" (MÜLLER et al., 1996) from the nearby *Silvretta* basement. In the *Gleinalpe,* a Cambrian Rb–Sr whole rock regression age was published for the so-called bimodal acidic-mafic suite by FRANK et al. (1976).

The dominant meta-igneous rocks of the Ötztal basement are of granitic composition. This suite includes muscovite- as well as biotite-rich assemblages, but only few pyroxene- and amphibole-bearing metagranites. The latter occurrences were interpreted as products of partial melting during ocean crust extraction, which also incorporated smaller amounts of continental material during emplacement. The time of protolith formation of these so-called Tieftal gneisses is defined by a Sm–Nd sphene-whole rock isochron and Pb–Pb zircon evaporation data at 485 ± 3 Ma (BERNHARD et al., 1996). Interestingly, this age is identical with SHRIMP and conventional U–Pb data (481 ± 9 Ma) mentioned for zircons of metagabbroic eclogites from the central Ötztal by GEBAUER and SÖLLNER (1993). Two stages of gabbro intrusion (537 and 470 Ma) were also reported for the Silvretta (POLLER, 1997).

For the majority of the Ötztal metagranitoids the age of magma formation and emplacement is still controversial. Single whole rock Rb–Sr model ages for the highly fractionated muscovite metagranites (using 0.710 as initial ^{87}Sr/^{86}Sr ratio) scatter mostly between 470 and 420 Ma, but in strongly deformed varieties even younger (Variscan) ages may be found (SCHWEIGL, 1995). Rb–Sr whole rock regression using a vast literature data set (see THÖNI, 1986; HOINKES et al., 1997, for review) give age results of 443 ± 5 and 435 ± 11 Ma, respectively. An apatite-whole rock Sm–Nd age for one of these orthogneisses lies at 455 ± 8 Ma (HOINKES et al., 1997). Rb–Sr whole rock isochron (MAGGETTI and FLISCH, 1993) and U–Pb zircon ages (GRAUERT and ARNOLD, 1968; GRAUERT, 1969) close to 440 Ma for ortho- and augengneisses are known also from the Silvretta (the so-called "younger orthogneisses"), from the Altkristallin south of the Tauern window (BORSI et al., 1973; BRACK, 1977; CLIFF, 1980; HAMMERSCHMIDT, 1981) and from the Seckau crystalline (SCHARBERT, 1981).

Combined Sr–Nd isotopic and geochemical studies of the Ötztal othogneisses support the

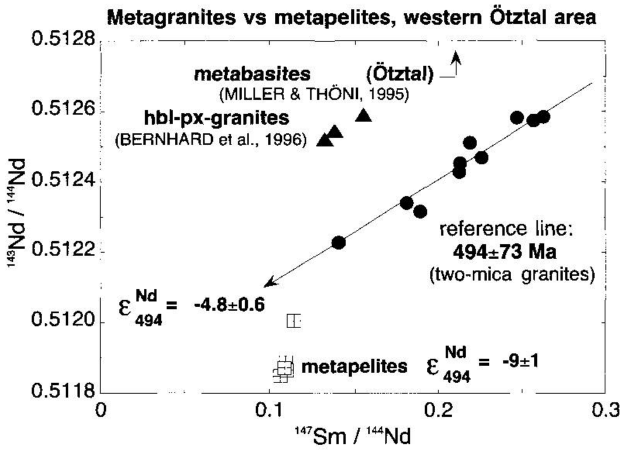

Fig. 3 Whole rock analyses from metagranites and metapelites of the western Ötztal basement in a Sm–Nd isochron diagram. The $\varepsilon_{Nd}(494)$-signature for 10 highly differentiated two-mica granites is distinctly different from the one of encasing metapelites at this time (–4.8 ± 0.6, compared with –9 ± 1). This shows that the "S-type" Ordovician metagranites are not derived exclusively, but largely, from metasediments by crustal "anatexis". Data from: HOINKES et al. (1997), modified, and BERNHARD et al. (1996).

largely crustal origin for both muscovite- and biotite-dominated suites. Both orthogneiss groups may, however, not be genetically related in a strict sense. Also, there is weak evidence from a 494 ± 74 Ma Sm–Nd whole rock errorchron (HOINKES et al., 1997) that the actual age of emplacement of these metagranites could be somewhat older than hitherto suggested from the 440 Ma Rb–Sr isochrons of muscovite-rich orthogneisses (cf. SCHMIDT et al., 1967; SCHARBERT and SCHÖNLAUB, 1980). The mean ε Nd value (at 494 Ma) ranges at –4.8 ± 0.6, compared with a mean of –9 ±1 for the encasing metapelites at this time (Fig. 3).

2.3.1.3. Ages related to the Variscan cycle

Variscan magmatism in the Austroalpines is not very intense, but is nontheless known from several places, represented largely by granitic to granodioritic plutonism. Rb–Sr whole rock isochron data have been published from the following areas: Silvretta (366–361 Ma, 351 Ma; GRAUERT, 1969, 1981), Scarl basement (336 ± 7 Ma; THÖNI, 1981), the Bundschuh crystalline (381 ± 30 Ma; HAWKESWORTH, 1976), the Seckau mountains (354 ± 16 Ma; SCHARBERT, 1981), the Stubalpe (331 ± 25 Ma; JUNG, 1982) and the Lower Austroalpine "Grobgneis" (augengneiss) of the Semmering unit (338 ± 12 Ma; SCHARBERT, 1990).

In areas with a weak Alpine metamorphic overprint, like the northwestern Ötztal basement, mineral dates called "Variscan" show a wide range of ages, spanning more than 100 Ma, from c. 390 down to c. 270 Ma (Figs. 4, 5). In addition, it has been plausibly demonstrated that, in special lithologies, the pre-Variscan isotopic clocks were not always reset during this event, since "Caledonian" Rb–Sr ages (435–474 Ma) have been varyingly preserved in coarse-grained white micas from migmatites (CHOWANETZ, 1991), pegmatites (SCHWEIGL, 1995) and orthogneisses (HOINKES et al., 1997). Figure 5 gives a summary for mica K–Ar and Rb–Sr as well as garnet Sm–Nd data from Alpine very-low- to low-grade areas. Three Sm–Nd garnet-whole rock ages from mica schist, where garnet has varyingly reacted to sillimanite and biotite, lie at 343 ± 2, 335 ± 4 and 331 ± 3 Ma (HOINKES et al., 1997). It is also evident from figure 5 that ages measured for systems/minerals with lower closure temperatures, e.g. biotite Rb–Sr and K–Ar and white mica K–Ar, are concentrated in the time range 310–270 Ma. Mica ages close to 300 Ma have long been known also from the Sivretta basement (GRAUERT, 1969; SPIESS, 1987) and the Phyllitgneiszone (THÖNI, 1981). Recent Pb–Pb and U–Pb results on staurolite (FREI et al., 1995) and zircon (LIEBETRAU et al., 1996) from the Silvretta, however, claim a prograde PT path and a metamorphic peak close to 300 Ma. "Variscan cooling ages" are also known from the Schladming crystalline (SLAPANSKY and FRANK, 1987; see also HEJL, 1984).

One further accumulation of ages is observed on figure 5, between c. 375 and 340 Ma. These data represent either garnet-whole rock and mineral-mineral Sm–Nd ages from basic eclogites (MILLER and THÖNI, 1995) or Rb–Sr ages from coarse-grained phengitic mica from orthogneisses (THÖNI, 1986; SCHWEIGL, 1995). "Early Variscan" (375–350 Ma) Rb–Sr and ^{40}Ar–^{39}Ar ages have also been documented for (partly phengitic) white mica from the Bundschuh orthogneisses (FRIMMEL, 1986), the Lower Austroalpine Semmering-Wechsel unit (MÜLLER, 1994) and other basement units at the front of the northeastern central Alps (DALLMEYER et al., 1996; cf. SCHMIDT and FRANK, 1998).

From the Ultental basement, a Sm–Nd garnet-whole rock age of 351 ± 1 Ma was measured for a highly metamorphosed paragneiss, whereas a garnet-whole rock age from a boudinaged orthogneiss lies at 399 ± 1 Ma (HAUZENBERGER et al., 1996). Two Sm–Nd garnet-whole rock ages from amphibole-bearing lherzolites (the "fine-grained type", OBATA and MORTEN, 1987) occurring within the high-grade metamorphic crustal rocks are close to 340 Ma (NTAFLOS and THÖNI, in prep.), in accordance with a strong imprint in

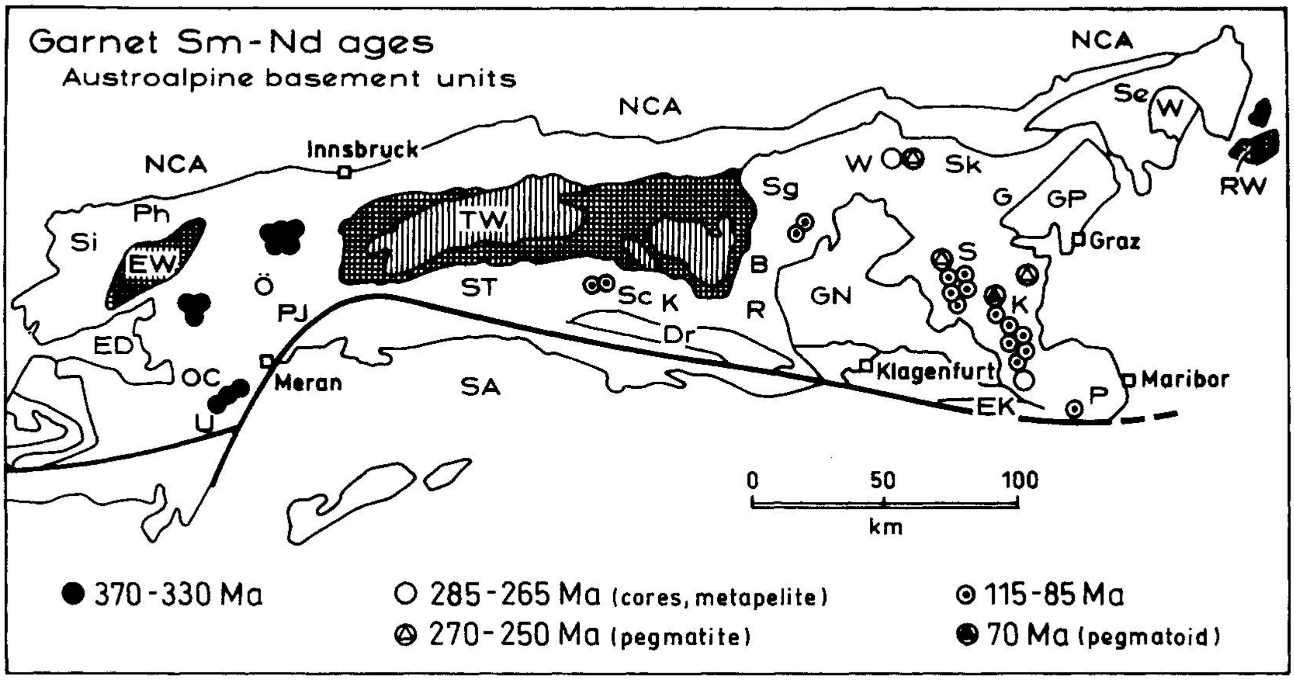

Fig. 4 Distribution of garnet Sm–Nd ages from the Austroalpine basement units (AAB) in the Eastern Alps. Also shown are local names for the most important tectonic-lithostratigraphic units as used in the text.
Si = Silvretta; Ph = Phyllitgneiszone; Ö = Ötztal; PJ = Penser Joch crystalline; ED = Engadine Dolomites; OC = Ortler-Campo basement; U = Ultental; ST = basement units to the south of the Tauern window; Sc = Schober; K = Kreuzeck; Dr = Drauzug; R = Radenthein; B = Bundschuh; Sg = Schladming; W = Wölz; Sk = Seckau; G = Gleinalpe; SeW = Semmering-Wechsel unit; GP = Graz Palaeozoic; S = Saualpe; K = Koralpe; GN = Gurktal nappe; EK = Eisenkappel intrusives; P = Pohorje; SA = Southern Alps; NCA = Northern Calcareous Alps; TW = Tauern window; EW = Engadine window; RW = Rechnitz window group.
Data from: MILLER and THÖNI (1995), HOINKES et al. (1997), HAUZENBERGER et al. (1996), NTAFLOS and THÖNI (data in prep.), LINNER (data in prep.), TEIMEL et al. (data in prep.), SCHUSTER and THÖNI (1996), THÖNI and JAGOUTZ (1992), THÖNI and MILLER (1996), HABLER and THÖNI (1998), MILLER and THÖNI (1997), LICHEM et al. (1997), THÖNI and MILLER (data in prep.).

these mantle rocks during Variscan times, as inferred from U–Pb zircon data (332, 336 Ma; GEBAUER and GRÜNENFELDER, 1978).

2.3.1.4. Rift-related Permo-Triassic events

From the eastern part of the Austroalpine basement units, a number of Rb–Sr and Sm–Nd whole rock and mineral dates have been obtained that strongly support a Permian event of regional importance. Some data are summarized on figure 6. Most stem from magmatic minerals, such as Sm–Nd analyses of plagioclase-clinopyroxene pairs from gabbros (THÖNI and JAGOUTZ, 1992; MILLER and THÖNI, 1997) and of garnet from pegmatites (THÖNI and MILLER, 1996; SCHUSTER and THÖNI, 1996; HABLER and THÖNI, 1998), as well as Rb–Sr results of core domains from cm-sized muscovites from pegmatites (MORAUF, 1981; JUNG, 1982), but include also a whole rock isochron (Rb–Sr, Wolfsberg granite gneiss; MORAUF, 1980). In addition, U–Pb zircon data from different meta-igneous rocks have been published. PAQUETTE and GEBAUER (1991) mention a U–Pb age of 299 ± 11 Ma for zircons from the Koralpe plattengneiss; the authors interpreted this date as a magmatic crystallization age from a former volcanodetrital sequence. A Permian to Permo-Triassic protolith age, as derived from Sm–Nd mineral isochrons for the Koralpe metabasites (THÖNI and JAGOUTZ, 1992; MILLER and THÖNI, 1997) was recently also derived from U–Pb analysis of zircons for some of the most important eclogite occurrences in the Saualpe. The protolith age suggested on the basis of these data is c. 285–240 Ma (HEEDE, 1997). For the famous spodumene-pegmatite at Weinebene, Koralpe, an U–Pb zircon age of 240 ± 1.5 Ma (multigrain, upper intercept) was published (HEEDE, 1997).

Extensive Permian pegmatite activity is documented also in the western Austroalpines. A well defined Rb–Sr whole rock isochron of 271 ± 2 Ma includes samples from the Pustertal area (Ahrntal; BORSI et al., 1980), the Matsch unit in the southern Ötztal basement and from the Martell "granite" in the Ortler-Campo basement (BOCKEMÜHL, 1988, with literature; see also GRAUERT et al., 1974). The good fit of all these data points to a common origin of the pegmatite melts (Sr_i = 0.71494 ± 7; 27 samples).

The wide-spread tholeiitic to andesitic dykes (HELLERMANN FURRER, 1992; PURTSCHELLER and RAMMLMAIR, 1982) from the Silvretta and Ötztal basement are suggested to be also of "Late Variscan" age, although no conclusive geochronological data exist so far (cf. HARRE et al., 1968; HELLERMANN FURRER, 1992).

Recently, the first Permian age results have been obtained from metamorphic rocks of the AAB. Two cm-sized garnet cores of polymetamorphic mica schists from the *Wölzer Tauern* and from the Plankogel series of the southern *Koralpe* gave Sm–Nd ages of 269 ± 3.5 (SCHUSTER and THÖNI, 1996) and 285 ± 1 Ma (LICHEM et al., 1997), respectively. Overall, the data shown on figure 6 encompass the time span 285–240 Ma (Permian to Early Triassic). An early, possibly Permo-Triassic thermal event was also independently inferred from vitrinite reflectance studies in former AAB cover rocks (FERREIRO MÄHLMANN and PETSCHICK, 1996).

Igneous rocks from near the Periadriatic lineament S of the Koralpe give similar Permotriassic age results. A Sm–Nd isochron (plagioclase, two clinopyroxene fractions and the whole rock)

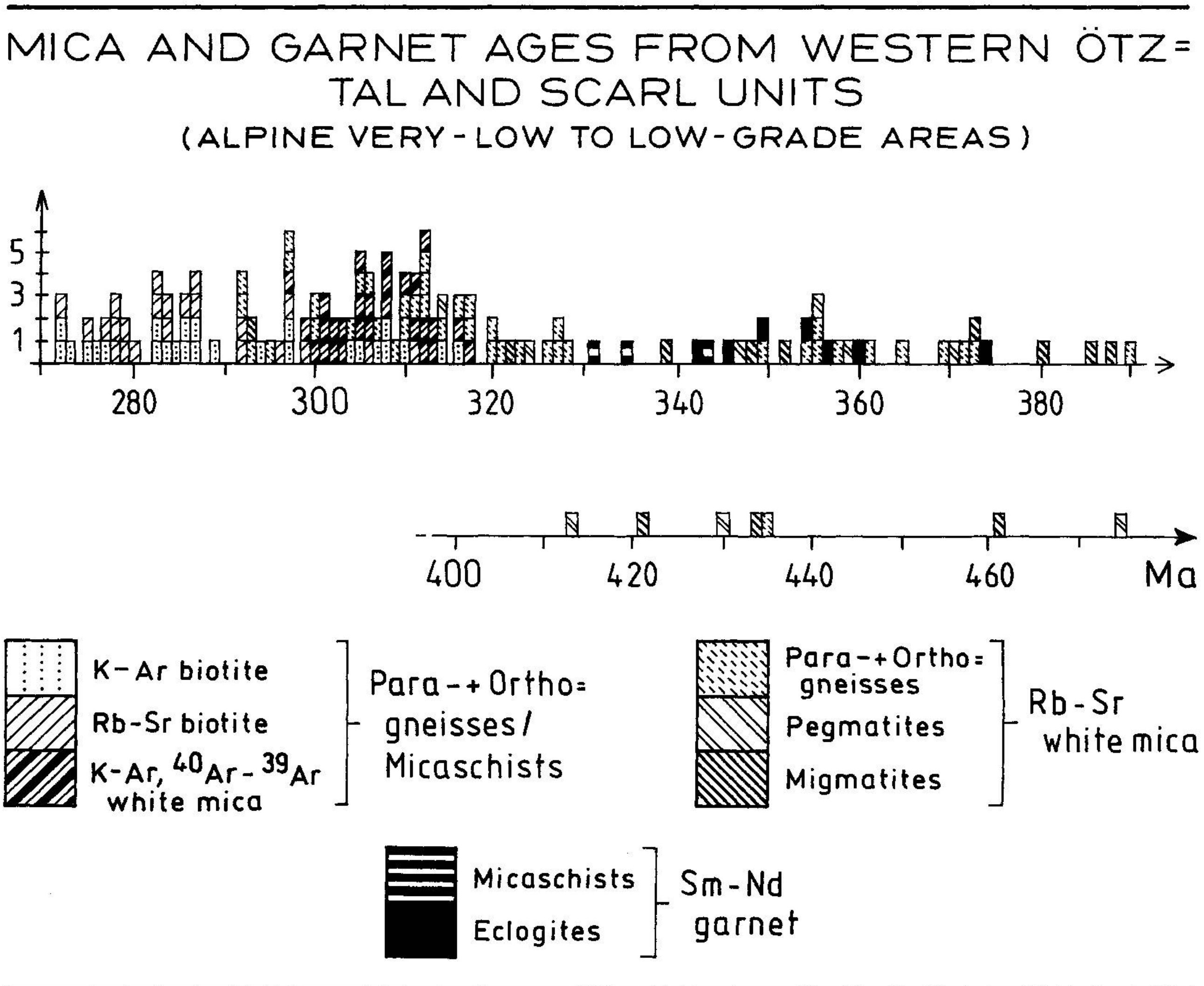

Fig. 5 Mica and garnet age data from the Alpine very-low to low-grade parts of the western Ötztal and Scarl units allow to recognize the following age groups: a) pre-Variscan (probably "Caledonian") ages that were incompletely reset during the Variscan cycle (micas from migmatites and pegmatites); b) Variscan high-P ages (c. 375–340 Ma); Variscan medium-low-P/high-T ages (c. 340–330 Ma); Variscan cooling ages and/or slightly rejuvenated Variscan cooling ages (< 310 Ma).
Data from: THÖNI (1980, 1981, 1986), CHOWANETZ (1991), THÖNI and MILLER (1995), SCHWEIGL (1995), HOINKES et al. (1997).

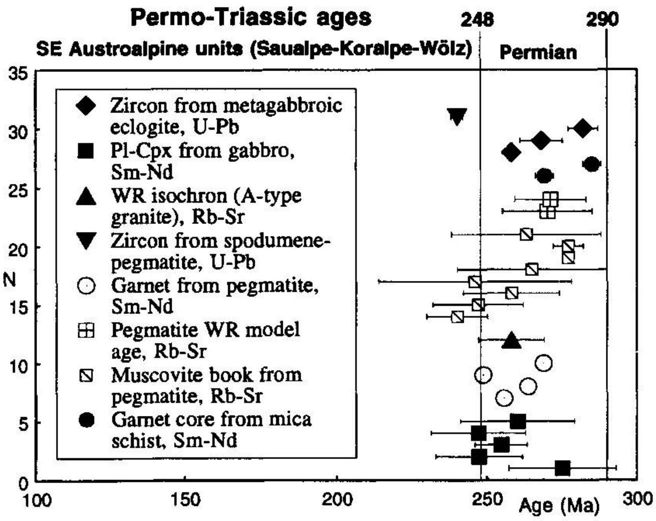

Fig. 6 Permo-Triassic age results of meta-igneous assemblages are widely distributed in the southeastern AAB and provide evidence for intense magmatic activity at this time. Mantle upwelling, initial rifting and low-P metamorphism may have governed these crustal segments at this time.
Data from: MORAUF (1980, 1981), JUNG (1982), FRANK et al. (1983), THÖNI and JAGOUTZ (1992), THÖNI and MILLER (1996), SCHUSTER and THÖNI (1996), LICHEM et al. (1997), MILLER and THÖNI (1997), HEEDE (1997). The two whole rock Rb–Sr model ages (SCHARBERT, unpubl. data) and one Pl–Cpx Sm–Nd isochron (gabbro from Eisenkappel; THÖNI, unpubl. data) represent unpublished data.

of a gabbro from near Eisenkappel gave an age of 260 ± 19 Ma and an initial ε Nd (260 Ma) of +3.6; the corresponding Sr isotope ratio is 0.7029 (THÖNI, unpubl. data, and Fig. 6). Somewhat younger ages have been published for sphene and amphibole (U–Pb age 230 ± 5 Ma, K–Ar ages 244 ± 8 and 244 ± 9 Ma; LIPPOLT and PIDGEON, 1974; CLIFF et al., 1975) as well as biotites (Rb–Sr, 216–238 Ma; LIPPOLT and PIDGEON, 1974; SCHARBERT, 1975; MONSBERGER, unpubl. data) for intermediate or acidic members of this same Eisenkappel magmatic suite. Late Carboniferous-Permian (300–280 Ma) Rb–Sr whole rock isochron ages are also known for some of the largest "old" Periadriatic granodioritic intrusions, in the Brixen-Kreuzberg (Bressanone-Monte Croce) area (BORSI et al., 1972).

2.3.1.5. Cretaceous high-P event, metamorphism and exhumation

MORAUF (1980, 1982) was the first to postulate an intense Cretaceous ("eo-Alpine") metamorphism for the southeastern part of the Austroalpine basement. On the basis of Rb–Sr data on 3T white micas from the Wolfsberg metagranite MORAUF (lit. cit.) also stated, that this eo-Alpine event was probably of a pressure-dominated type. The age of initial cooling for this metamorphism was defined at close to 80 Ma.

The recognition that the plattengneiss of the central-southern Koralpe, a several kilometres thick high-T mylonite sheet, is a product of the Alpine evolution, also shed more light on the grade of metamorphism and intensity of Alpine deformation within the so-called pre-Alpine basement (FRANK et al., 1983; KROHE, 1987). Intercalations of eclogite lenses within the plattengneiss with a N–S trending mineral orientation, identical to that in the plattengneiss proper, led some workers to conclude that parts of the Koralpe were metamorphosed at eclogite facies conditions during Alpine times (MILLER and FRANK, 1983).

More recently, several geochronological data sets have been published that clearly support an Alpine eclogite facies metamorphism for both *Koralpe* and *Saualpe*, and most probably also for the Pohorje Mts. in Slovenija (THÖNI and JAGOUTZ, 1992; THÖNI and MILLER, 1996; MILLER and THÖNI, 1997; LICHEM et al., 1997; THÖNI, unpubl. data). The material analysed includes both high-P assemblages from basic eclogites as well as high-P garnet data from metapelites adjoining the famous eclogite type-locality, probably Kuppler-

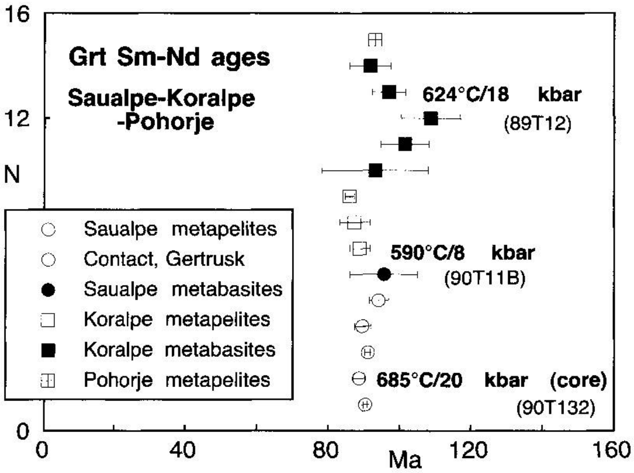

Fig. 7 Garnet Sm–Nd ages from metabasic eclogites and metapelites from the Saualpe-Koralpe-Pohorje area constrain the final stage of Cretaceous high-P metamorphism close to 100–90 Ma. The data also give evidence that the time distance between P max and T max is in the order of only some 10 Ma, or less.
Data from: THÖNI and JAGOUTZ (1992), THÖNI and MILLER (1996), MILLER and THÖNI (1997), LICHEM et al. (1997). The garnet date from the Pohorje Mts is unpublished (THÖNI, unpubl. data).

brunn-Prickler Halt, in the Saualpe (Haüy, 1822). P-T conditions for the Koralpe and Saualpe eclogites are close to 20 kbar / 600–650 °C (Miller, 1990; Miller and Thöni, 1997).

Figure 7 gives a review of the Koralpe and Saualpe Sm–Nd garnet ages. Only data that are believed to be geochronologically meaningful are presented. It is clear from figure 7 that eclogite facies metamorphism in these areas is Cretaceous in age and that HP-peak metamorphic conditions might have prevailed down to c. 100 ± 10 Ma (overall age range: 115–85 Ma). Data from other minerals or isotopic systems from this area give similar or somewhat younger age results (see also Manby and Thiedig, 1988; Morauf, 1980; Thöni, data in prep.).

Recently, a number of U–Pb data on zircons from different rock types from the Saualpe have been published (Heede, 1997). For one sample, Heede gives a date of 184 ± 10 Ma, interpreted as the possible time of eclogite formation. A second date of 130 ± 3 Ma, determined on zircons from kyanite-staurolite-schists, which form part of the eclogite host rocks, is interpreted as indicating early stages of subduction of the Penninic units below the Austroalpine.

According to new isotopic data (Thöni, unpubl. data, and Fig. 7) it is probable that this Alpine high-P metamorphic belt extends from the southern Koralpe-Saualpe into the *Pohorje mountains* of Slovenija. Garnets from mylonitic mica schists very similar to those of the Saualpe eclogite host rocks (Thöni and Miller, 1996) yielded Sm–Nd ages close to 100 Ma. Idiomorphic staurolite in these rocks partly still overgrows young shear bands, thus documenting high temperatures during early stages of Cretaceous exhumation. Eclogites with geochemical and mineralogical characteristics very similar to those of the Koralpe (Thöni, unpubl. data) are, besides ultramafics, also known from the Pohorje (Hinterlechner-Ravnik, 1982). Their age, however, is not yet proven by geochronological data.

Alpine high-P metamorphism was also reported from several other parts of the Austroalpine basement further to the west. Linner (1995, and 1997, pers. com.) gave P-T conditions for the *Schobergruppe* eclogites of 1.6–1.9 kbar and 625 ± 20 °C, with ages for the high-P minerals in the range of 115–85 Ma. Somewhat lower conditions of 9–12 kbar / 500–550 °C were published for the eclogite stage in the *Kreuzeckgruppe* (Hoke, 1990) and in the Radenthein-Bundschuh area (Schimana, 1986; Teimel et al., data in prep.). In the *Texelgruppe* (southern Ötztal basement), the existence of Cretaceous eclogites was postulated on the basis of petrological data from the eclogites proper (minimum pressure 12 kbar; Hoinkes et al., 1991) and indirectly also by structural and geochronological data from the eclogite host rocks (an Ar/Ar age for paragonitic mica yielded 84.5 ± 1.6 Ma; Konzett and Hoinkes, 1996).

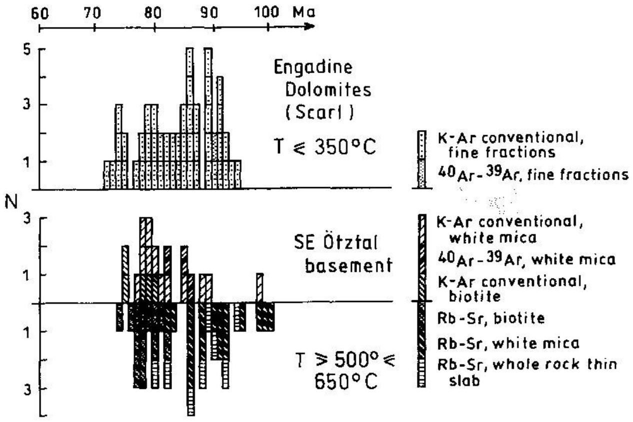

Fig. 8 Histogram showing the close coincidence of K–Ar, ^{40}Ar–^{39}Ar and Rb–Sr ages of micas, mica-rich fine fractions and Rb–Sr thin slab isochron ages of two areas with strikingly different Alpine metamorphic grade: the southern Ötztal basement vs the Scarl metasediments (Engadine Dolomites). The thermal climax is suggested to have occurred close to 90 Ma (cf. Fig. 9). Cooling below 300 °C was accomplished before 70 Ma.
Data from: Thöni (1988), modified.

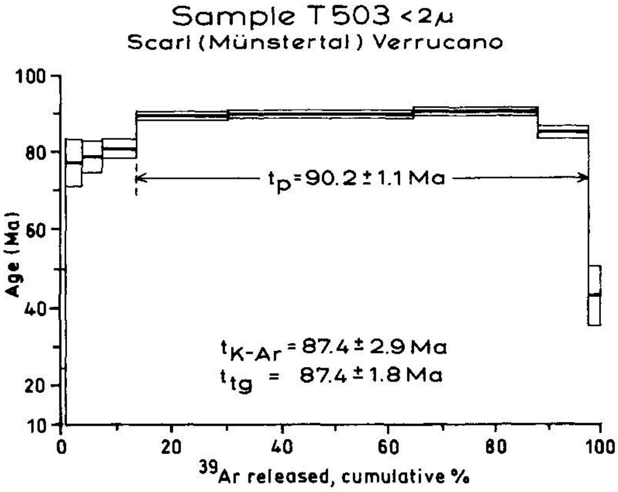

Fig. 9 The 90.2 ± 1.1 Ma plateau age for a < 2 μ white mica-rich fine fraction of the Permoscythian from the Engadine Dolomites (near Tschierv, Val Müstair; see Thöni, 1980) is interpreted as giving the time of mica crystallisation close to the thermal peak of eo-Alpine metamorphism.
Data from: Thöni and Miller (1987).

Mineral ages spanning the time interval of c. 90 to 70 Ma are most wide-spread all over the Austroalpine units of the Eastern Alps and have generally been interpreted to reflect Cretaceous cooling (FRANK et al., 1987; NEUBAUER et al., 1995; cf. PAAR and KÖPPEL, 1978). For the *southern Ötztal* and *Scarl* units, two areas that suffered strongly contrasting Alpine heating, it was argued that the thermal climax of the Cretaceous metamorphism was reached close to 90 Ma (Fig. 8). From the eo-Alpine highest grade areas, the Koralpe and Saualpe, localized young (90, 70 Ma) pegmatoid activity is also documented by U–Pb and Sm–Nd data for the late stages of exhumation (HEEDE, 1997; THÖNI et al., 1997). However, such 90–70 Ma age numbers may also be explained by ongoing deformation and recrystallization processes at distinct levels, during initial exhumation. This has to be analysed by much more detailed combined structural-geochronological-petrological work in the future. DALLMEYER et al. (1998) proposed a model where thrusting within a tectonic wedge was accompanied by ductile deformation that commenced some 100–90 Ma ago in the uppermost structural levels. Some of the Upper Cretaceous, 90–70 Ma K–Ar and Rb–Sr ages from brittle to ductile high-strain zones of the southern Ötztal, Scarl and Silvretta units (THÖNI, 1988) were also interpreted as giving the time of deformation-induced (re-)crystallization, related to distinct deformation phases during exhumation, including thrusting as well as late extensional tectonics, locally with the formation of pseudotachylites (see SCHMID and HAAS, 1989; FROITZHEIM et al., 1994, 1997; SÖLVA et al., 1998).

2.3.1.6. Post-Cretaceous ages

In general, the post-Cretaceous thermal imprint in the Austroalpine basement is weak and largely restricted to the vicinity of the Tauern window. The regional distribution of apatite fission track ages even shows, that large areas of the central Eastern Alps cooled to below 100 °C already in Late Cretaceous to Early Eocene times, and were never heated again (HEJL, 1997; FÜGENSCHUH et al., 1997).

Oligocene-Miocene biotite Rb–Sr ages have been measured for a considerable portion of the AAB to the south of the western Tauern window (BORSI et al., 1973). This zone with young ages seems to correlate with the Miocene deformation and thermal imprint in the weakly metamorphic Permo-Mesozoic sequence of Mauls–Penser Joch (FRANK et al., 1977), to the south of the Jaufen fault further west (SPIESS, 1995). Biotite Rb–Sr ages close to 20 Ma have also been measured from the Pohorje polymetamorphic metasediments (THÖNI, unpubl. data).

Time analysis of the numerous ductile-brittle fault zones has just begun and will without doubt contribute considerably to the understanding of post-Cretaceous kinematics in the Eastern Alps (RATSCHBACHER et al., 1991). For instance, for the Peio and Jaufen faults in the southern Ortler-Campo and Ötztal units, combined ^{40}Ar–^{39}Ar stepwise-heating, laser-ablation and Rb–Sr (microsampling) dating revealed a polyphase deformation history along the faults with ages close to 17–19, 35–36 and a range of ages between 52 and 80 Ma (MÜLLER et al., 1997).

A rather extensive magmatic activity has been recognized in the southern AAB and along the Periadriatic lineament in Oligocene times, with a concentration of ages around 30 Ma. To this group of mostly tonalitic intrusives belong the Rieserferner (Vedrette di Ries; 30 ± 3 Ma Rb–Sr whole rock age, BORSI et al., 1978a), the Rensenspitze (BORSI et al., 1978b) and possibly also the Eisenkappel tonalite as well as the intrusive stock of the Pohorje (cf. SCHARBERT, 1975; FANINGER, 1976).

Extensive alkali-basaltic to shoshonitic dyke magmatism has been documented for the time span c. 32–24 Ma from the AAB along the southeast corner of the Tauern window (K–Ar, Rb–Sr; DEUTSCH, 1984) and from the Ortler-Cevedale area (biotite Rb–Sr ages, 32–31 Ma; DAL PIAZ et al., 1988).

2.3.2. Post-Variscan Austroalpine cover sequences

2.3.2.1. Autochthonous (meta-)sediments

Isotopic ages from the relictic Permo-Mesozoic Austroalpine cover were mostly measured on fine fractions (< 2 µ) from Permoscythian rocks by the conventional K–Ar technique; few ^{40}Ar–^{39}Ar and Rb–Sr data are also available. In the Scarl-Umbrail-Ortler area, the age results span the time 99–74 Ma, with a clear concentration of the data from the more northwesterly, lowest-grade area close to 90 Ma (Fig. 8, and THÖNI, 1981). One ^{40}Ar–^{39}Ar result from such a Verrucano sample shows a fairly well-defined plateau with an age of 90.2 ± 1.1 (Fig. 9). Since the contribution of relictic detrital components in the analyzed sample did obviously not affect the age result, such 90 Ma ages were tentatively interpreted as crystallization ages of white mica below the effective blocking temperature of the K–Ar system in this mineral. Hence these numbers would approximate the thermal peak during prograde metamorphism of the Permo-Mesozoic metasediments. Biotite Rb–Sr ages from the higher grade Mesozoic rocks in the Brenner area are close to 80 Ma (data compilation in Thöni, 1981, 1983, and Fig. 8).

Much younger K–Ar ages in the range of 15–22 Ma were measured on fine fractions from the Permo-Mesozoic sequence of Mauls-Penser Joch (Frank et al., 1977).

2.3.2.2. Northern Calcareous Alps

A number of conventional K–Ar and Rb–Sr data on fine fractions (mostly of submicron size) have been compiled for the basal, more southerly parts of the NCA and the Northern Greywacke Zone between Arlberg Pass and Vienna by Kralik et al. (1987). The rock series were metamorphosed at very low- to low-grade conditions only, as shown by a vast set of illite crystallinity data. Ages scatter widely, from > 150 to < 70 Ma, but at least in the area S of Salzburg, a Lower Cretaceous, 140–120 Ma age group is predominant. These latter results are assigned to isotopic exchange during early eo-Alpine circulation of warm fluids and heat transfer, following supposed long-lasting crustal thinning during the Mesozoic (Kralik et al., 1987; cf. Ferreiro Mählmann and Petschick, 1996). ^{40}Ar–^{39}Ar ages in the range of 150–120 Ma were recently also reported from the basal parts of the eastern NCA (Schmidt and Frank, 1998). The K–Ar ages for two alkali-amphiboles from metavolcanics associated with the Permoscythian sequences of the NCA near Salzburg range between 118 ± 9 and 103 ± 9 Ma (Jäger in Kirchner, 1980). K–Ar and Rb–Sr ages in the range of 130–115 Ma have also been published from shear zone rocks of the weakly metamorphic series of the Graz Palaeozoic (Fritz, 1988).

A mean K–Ar age of 102 ± 2 Ma was given for the intrusion of primitive alkaline, mantle-derived melts, forming the Ehrwaldite dykes in the Lechtal nappe (western NCA). The rocks show almost no post-magmatic alteration and it was argued that post-intrusion ambient temperatures did not significantly exceed 120 °C (Trommsdorff et al., 1990).

3. Data interpretation and discussion

3.1. PRE-ALPINE HISTORY

The *pre-Cambrian* geodynamic history of the AAB is largely hidden due to involvement of the material into an unknown cycle of erosion, resedimentation and possibly also tectonometamorphic activities. Available U–Pb data on zircons as well as Nd DM model ages, however, demostrate clearly that protolith material with primary ages of up to > 3 Ga was involved in its formation. The ^{147}Sm/^{144}Nd ratios for most of the analyzed metasedimentary AAB rocks (see Fig. 2) are close to 0.11, a value typical for old continental crust. In combination with the relatively narrow range of the model ages close to 1.6 ± 0.1 Ga, this isotopic system points to a well-mixed source of the pre-Cambrian sedimentary protolith material. However, as long as SHRIMP zircon data are not available and the nature of the protolith is not known, the significance of such Proterozoic-Archean "ages" may not be discussed in full detail, because of the generally complex problems regarding zircon inheritance, multipe zircon growth and recrystallisation as well as Sm–Nd DM model age interpretation of polymetamorphic crustal rocks (Arndt and Goldstein, 1987; Liew and McCulloch, 1985; Pidgeon, 1992; Mezger and Krogstad, 1997; Vavra et al., 1997). Thus, it is at present not clear, whether the close concordance of the 1.6 Ga Nd model ages reflects a discrete period of crustal growth or whether these data are merely indicative for the provenance of the metasediments from a well-mixed source. In general, the data support the frequently observed behaviour of the different isotopic systems, where t U–Pb > t Sm–Nd DM > t Rb–Sr. It has been argued, on the basis of Rb–Sr and ^{40}Ar–^{39}Ar data, that the age of the last sedimentation for some of the polymetamorphic AAB metasediments is in the range of c. 650–600 Ma, or younger (e.g. Grauert, 1969; Dallmeyer et al., 1996).

From *Late Proterozoic to Early Cambrian* time onwards, U–Pb and Sm–Nd ages give evidence of wide-spread magmatic activity for both AAB as well as the pre-Variscan basement of the Tauern window. Whereas the AAB units to the west of the Tauern window consist of a number of basement blocks with rather similar Phanerozoic evolutions, the areas further to the east show a more complex, still partly unclear tectono-stratigraphic and magmatic-metamorphic history (e.g. Neubauer and Frisch, 1993). At least two tectonic mega-units (the Muriden and the Koriden nappe complexes) with fairly different Alpine tectonometamorphic evolution may be discerned in these eastern areas.

A heterogeneous evolution, with intense magmatic activities in both oceanic, partly MORB-related, as well as continental environments is recognized for Late Proterozoic (650–550) to Ordovician times in the AAB (e.g., the "older orthogneisses" in the Silvretta; Schaltegger et al., 1997). Island-arc and back-arc crustal segments also characterize the geotectonic settings of the pre-Variscan Tauern window (VAVRA and FRISCH, 1989). Individual ocean basins containing volcanic arcs and rifted microcontinents may have characterized the paleogeographic situation between the two megacontinents Gondwana and Laurasia for more than 150 Ma (650–470 Ma). The final stages of the Early Palaeozoic orogenic cycle, frequently called "Caledonian", are indicated by an extensive S-type magmatism. It is not clear, however, whether the wide-spread 460–430 Ma Rb–Sr whole rock ages reflect the time of emplacement of the melts, or, alternatively signal open system behaviour during high-grade "Caledonian" metamorphism, subsequent to melt emplacement (HOINKES et al., 1997; see also SCHARBERT and SCHÖNLAUB, 1980).

When considering metamorphic mineral parageneses in a strict sense, the timing of *pre-Variscan metamorphic events* in the basement is entirely speculative. The Winnebach migmatite (Ötztal) is one of the very few examples for which the existence of pre-Variscan, probably Ordovician-Silurian ("Caledonian") high-grade metamorphism can be postulated from (up to 461 Ma old) Rb–Sr ages on white mica and U–Pb ages (490 ± 9 Ma) of a distinct zircon population, which characterizes the neosome parts of this migmatite (KLÖTZLI-CHOWANETZ et al., 1997).

Metamorphic mineral ages from Alpine low-grade basement areas are generally *Variscan*, spanning a wide time range of more than 100 Ma (Fig. 5). The terms "Early" and "Late" Variscan, often found in the literature, are not used here, since "Late Variscan" would include also Permo-Triassic extensional events.

Presently available radiometric evidence implies a high-P evolution stage for the time interval of approximately 370–340 Ma, for at least some areas of the AAB. Peak pressures for the Ötztal metabasites are very close to the coesite field, requiring deep subduction of these Early Palaeozoic oceanic crustal fragments in Late Devonian / Early Carboniferous time (MILLER and THÖNI, 1995). This is in close agreement with data and interpretations given for the evolution of the European Variscan crust (e.g. BECKER, 1997). The question remains, however, whether high-P assemblages and encasing low-P parageneses shared a common early history in deep crustal/mantle levels.

Typical mineral parageneses from the metasedimentary pre-Alpine AAB continental crust contain sillimanite and/or andalusite. In paragneisses from the western Ötztal basement all three aluminum silicate polymorphs are present, as well as staurolite and garnet. TROPPER and HOINKES (1996) inferred decreasing pressures during garnet growth, with a possible loop leading from the kyanite into the sillimanite and then into the andalusite stability field, and late garnet breakdown within the stability field of staurolite. Garnet (partly with sillimanite-biotite rims) from these assemblages yields Sm–Nd ages of 343–331 Ma (HOINKES et al., 1997), obviously indicating a stage of decompression and/or exhumation, at temperatures of up to 640 °C. In some areas of the AAB the subsequent crystallisation of Variscan andalusite (and probably also of late staurolite and zircon, cf. FREI et al., 1995; LIEBETRAU et al., 1996) could tentatively be placed in the time interval 330–300 Ma. This evolution may, therefore, be characterized by decompression rather than reflecting a prograde part of a PT path (FREI et al., 1995), but nonetheless, temperatures at this time were still high enough, to allow crystallization of staurolite and andalusite. A short-lived and young Variscan metamorphism (FREI et al., 1995) is, however, in contrast to a rather long-lasting PT path and slow cooling model, as proposed by MAGGETTI and FLISCH (1993) and HOINKES et al. (1997) for the whole Variscan cycle. Successive blocking of isotopic systems in micas started about 310 (± 10) Ma ago (Fig. 5), closely resembling the history of the European Variscides. Ages younger than 300 Ma may reflect slow cooling, but may also be related with further extensional orogenic collapse, crustal extension and probably slight reheating (open behaviour of isotopic systems) during the Lower Permian. Alternatively, a weak Alpine reheating could additionally have caused slight Ar and Sr loss in biotite, thus being responsible for ages as young as 270 Ma (Fig. 5).

3.2. ALPINE EVOLUTION

Data from other, more southeasterly parts of the AAB require other models to explain the Late Palaeozoic age pattern in that there is no direct evidence for regional cooling during the Permian. In the Eastern Alps, up to recent years it was not uncommon to interpret metamorphic mineral "ages" in the range of c. 260 to less than 200 Ma as so-called "mixed ages", i. e. as Variscan (or older) ages that were incompletely reset during Alpine tectonothermal events, and thus as numbers without strict geochronological meaning (e.g. FRANK et al., 1987b).

Age data from meta-igneous parageneses document wide-spread magmatic activity during the Permian to Early Triassic (c. 290–240 Ma; Fig. 6). Some of these rocks give important clues as to the geotectonic setting of the magmatic sources via

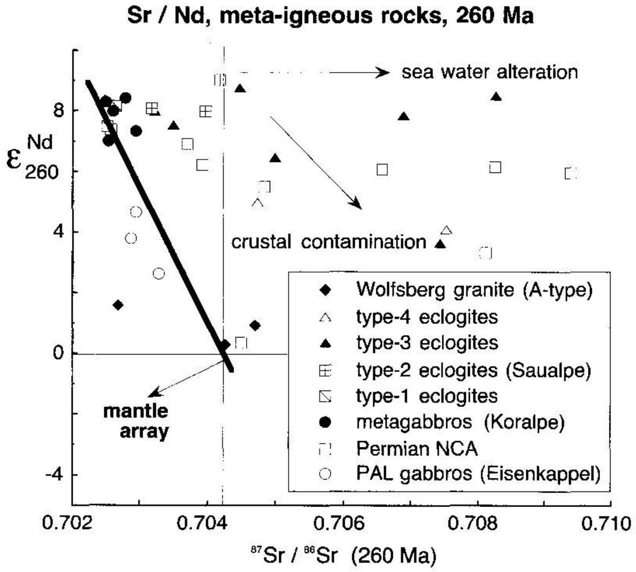

Fig. 10 Initial Nd and Sr isotope compositions for meta-igneous rocks from the southeastern AAB demonstrate that some of the magmatic protoliths were derived from a reservoir characterized by long-term depletion in LILE. Secondary influence may be due to late-magmatic sea water alteration as well as crustal contamination during emplacement and/or to the infiltration of metamorphic fluids.
Data from: Thöni and Jagoutz (1992), Miller and Thöni (1997), and Thöni (unpubl. data; Wolfsberg, PAL gabbros and Permian of NCA).

their initial isotopic ratios (Fig. 10). For instance, a mean age of 257 ± 15 Ma for the emplacement of the magmatic protoliths of the gabbroic eclogite precursors in the Koralpe leads to the conclusion that this material was derived from a strongly depleted source at this time. Initial Sr and Nd isotopic compositions for the least altered mafic samples range from 0.7025 to 0.7029 and ε_{Nd} = +8 to +9, respectively (Thöni and Jagoutz, 1992; Miller and Thöni, 1997). The Wolfsberg metagranite (258 ± 11 Ma Rb–Sr whole rock isochron; Morauf, 1980), outcropping in the same area, shows an initial Sr isotopic ratio of 0.7046 ± 28 and positive ε Nd values of +0.3 to +1.6 (Thöni, unpubl. data). This could point to a deep-seated rift-zone, or more generally, a mantle origin of these melts. Other wide-spread magmatic rocks, like the pegmatites, however, show typical crustal signatures. From this geochronologic-geochemical evidence it has been argued that in the more south-easterly, Adria-related parts of the Austroalpine microplate extensional processes (probably combined with transtensional/strike-slip movements) governed the crustal evolution from Late Carboniferous / Early Permian time onwards, accompanied by upwelling of the asthenosphere, magma production, metamorphism and pegmatitic activity, under low-P/high-T conditions. For some other areas, even a high grade "Late Hercynian" (c. 270 Ma) metamorphism with partial anatexis was postulated (Stöckhert, 1985). Permian Sm–Nd ages from cm-sized metapelite garnet cores of the eastern AAB units prove the existence of a significant metamorphic imprint in the continental basement for the time c. 285–265 Ma (see Figs 4 and 6), which may, in the Saualpe for example, be tentatively interpreted in terms of a low-P/high-T event (Habler and Thöni, 1998; cf. Pilger and Weissenbach, 1970). A similar evolution has long been envisaged for parts of the Alpine crust further to the west (e.g. Dal Piaz, 1993). It is also speculated here that the extensive tholeiitic basaltic to andesitic dyke magmas (Ötztal, Silvretta, etc.), which are derived from subcontinental lithosperic mantle sources, as well as the basaltic (partly MORB-affinity) magmatism within the shelf-related, basal sequences of the NCA (Kirchner, 1980) share the same geodynamic background, although these magmas were probably emplaced in a less thinned, smoothly cooling continental basement further away from a nucleating rift zone and hot asthenospere, during and after Variscan orogenic collapse. Evidence for a weak, possibly Permo-Triassic thermal imprint in the western AAB has recently been put forward from vitrinite reflectance data (Ferreiro Mählmann, 1996).

Thus, it seems plausible to postulate such thermal pulses on a regional scale, immediately following the Variscan metamorphism. However, instead of inferring a "Late Variscan orogeny", this evolution may be interpreted as the onset of a new cycle, namely of Alpine divergence, i.e. of the Alpine cycle in a wider sense. In general, igneous Permo-Triassic rocks with clear MORB-affinity, emplaced beneath or within thinned continental crust (Miller et al., 1988; Miller and Thöni, 1997), is seen in connection with the evolution of the early Tethys mantle. However, this early magmatic activity is not directly related here, either in space or in time, with those processes that led to the opening of the Penninic-Ligurian Tethys. According to the stratigraphic and radiometric evidence, this latter oceanic domain was active essentially during the Jurassic, i.e. some 50–70 Ma after the main magmatic activity within the AAB units. It thus appears that two different oceanic domains (or, alternatively, three, if Valais is also considered) characterize the Permo-Mesozoic paleogeography in the Eastern Alps, although they may have been active contemporaneously for only a short time: (1) the Hallstatt-Meliata oceanic branch of the Tethys, bordering or "indenting" the Austroalpine units to the south-east (Channell et al., 1992; Haas et al., 1995; Channell and

KOZUR, 1997), and represented by the Hallstatt facies sediments of the NCA; (2) the South-Penninic ocean, as exposed in the Penninic windows of the Eastern Alps.

The close correlation of magmatic and metamorphic ages from the southeastern AAB (probable candidates for the immediate or neighbouring crystalline substratum of Hallstatt facies sediments) with the stratigraphic record from the Meliata-Hallstatt domain proper is a minor matter of debate. According to the available sedimentological-palaeontological information, oceanization in these areas is not older than Middle Anisian (Anisian = 242–234 Ma, following GRADSTEIN et al., 1995), whereas the range of magmatic and metamorphic ages from the basement (former passive continental margin), interpreted as being indicative for the early rifting stage, is essentially restricted to the Permian (see Fig. 6). This age "discrepancy" seems not to be real, but is interpreted as the result of an evolutionary trend between thermal mantle-crust processes and their sedimentological-geodynamic consequences in high crustal levels. Furthermore, the time gap between Hallstatt-Meliatic and Penninic spreading is not as sharp as supposed, since Triassic magmatic activity is proven for large parts of the Southern Alps (BORSI and FERRARA, 1967) and extending into the NCA (e.g., BECHSTÄDT et al., 1978).

During the Jurassic, extension in the western Tethys was superceded by a compressional stage. This rearrangement may be related to rotational and strike slip movements along the Adria-Austroalpine border (SCHMIDT et al., 1991; CHANNELL et al., 1992). The exact timing of this fundamental change in the kinematics of microplates (Austroalpine and Southern Alps as part of northern Apulia) is, at the moment, still highly uncertain. For the Western Carpathians, suturing of the Meliata oceanic domain is claimed already for Oxfordian-Tithonian time, on the basis of ^{40}Ar–^{39}Ar data on glaucophane (155.4 ± 0.6 Ma, DAL PIAZ et al., 1995; one date) and phengite (160–150 Ma, DALLMEYER et al., 1996; four data). A lowermost Cretaceous age for the peak of metamorphism was also postulated from the lower discordia intercept of zircon U–Pb data (multigrain) from the basement units of the eastern Greywacke zone near Leoben (NEUBAUER et al., 1987). A still older, Early-Middle Jurassic age is proposed as the possible time of eclogitisation in the Saualpe by HEEDE (1997). However, the interpretation of this number as "significant" geochronological date seems questionable, not only because of the complex composition of these generally very U-poor eclogite zircons, but also, because zircon is expected to record generally high-T conditions or/and intense fluid activity, rather than a pressure-dominated stage during metamorphism. Alltogether, there is weak, though not at all convincing geochronological evidence that subduction in this area commenced already during the Jurassic.

The timing of metamorphism, deformation and nappe imbrication within the former AAB cover rocks (NCA) is, again, somewhat controversial. On the one hand, the basal parts of this succession seem to have preserved an early metamorphic imprint (130–100 Ma; KRALIK et al., 1987; KIRCHNER, 1980), which may, however, be related to heat transfer via warm fluids, rather than being induced by tectonometamorphic processes during crustal thickening. Early Cretaceous ages (130–115 Ma; FRITZ, 1988) from the Graz Palaeozoic were interpreted as tracing the first stages of W-directed eo-Alpine nappe imbrication during plate convergence. Also, it was argued on the basis of > 100 Ma K–Ar ages on white mica, that thrusting of the Austroalpine complex onto the Penninic Tauern series is older than Late Cretaceous (STÖCKHERT, 1984). This would imply crustal shortening, active subduction and metamorphism in the basement before this time. Radiometric-geochemical and structural data from the western NCA, on the other hand, are difficult to reconcile with a model of Early Cretaceous nappe stacking and transport of the NCA nappe pile. Rather, these data give evidence that at 100 Ma (Latest Albian) the NCA were still situated in an extensional setting and that imbrication, stacking and deformation of the western/northern NCA nappes is younger (97–70 Ma) (EISBACHER et al., 1990; TROMMSDORFF et al., 1990). Similar conclusions may also be derived for AAB nappe internal thrusting (THÖNI, 1988; SCHMID and HAAS, 1989).

In the course of Late Mesozoic, Cretaceous convergence of Adria and the Austroalpine microcontinent, southeastern AAB units were subducted to depths of some 60 km, or even deeper (cf. ERTL and BRANDSTÄTTER, 1998). The majority of the available ages measured on metamorphic minerals from these southern, Alpine higher-grade areas is in the range of or younger than 100 Ma. From the highest grade parts, like the Saualpe (peak PT conditions 20 kbar / 685 °C), homogeneous element zonation is well preserved in 100–90 Ma old eclogite as well as pyropic metapelite garnet (THÖNI and MILLER, 1996; HABLER and THÖNI, 1998); diffusional retrograde resetting is restricted to the outermost c. 50 micron rim zones of the mm-sized grains. Hence the majority of garnet ages shown on figure 7 are interpreted as constraining the time of final peak PT conditions. In connection with similar or slightly younger Rb–Sr and $^{40}Ar–^{39}Ar$ ages on phengites, these data demonstrate that Cretaceous PT conditions have abruptly changed by Cenomanian-Turonian time, leading to isothermal decompression and rapid, tectonically driven exhumation of the HP assemblages in the upper Cretaceous (Fig. 11). In contrast, a much older (even Lower Jurassic, see Heede, 1997) age for the P-peak would, among other things, also be faced with the problem of preserving high-P assemblages (like the impressive type-locality eclogites) at shallow crustal levels over several tens of millions of years. A considerable portion of the continental crust seems to have been involved in this subduction and an "eo-Alpine high-P metamorphic belt" was postulated by Thöni and Jagoutz (1993), located within the southern AAB, but somewhat to the north of the present-day Periadriatic lineament, and stretching over some 350 km from the Koralpe in the east to the Texelgruppe (southern Ötztal basement) in the west. The close contemporaneity and, especially, kinematic interpretation for the exhumational evolution of this high-P belt is not yet clear, however.

For the Tauern window, there is vivid discussion as to the age of HP metamorphism (peak conditions for Alpine eclogites: 20 kbar / 550–630 °C; Kurz et al., 1998). It is to be expected that subduction processes during Alpine plate convergence propagated from the south-east to the north-west. Since early exhumation in the AAB high-P belt is dated at c. 90 ± 5 Ma (Figs 7, 8, 11), eclogite facies metamorphism in the Penninic Tauern window may be no older than Late Cretaceous. Late Cretaceous mica ages (see Hoke, 1990, for data compilation) from Austroalpine units overlying the Penninic Tauern series in the south may be interpreted as cooling ages in response to eo-Alpine continental collision, but some of the youngest ages (down to 65 Ma) could also reflect slight post-Cretaceous rejuvenation. At the western border of the greater Austroalpine thrust sheet Ar–Ar mica ages from structurally well-defined zones were interpreted to constrain suturing processes and diachronous deformation between the Austroalpine Err nappe and the Penninic Platta unit at 76–89 Ma (Handy et al., 1996). Zimmermann et al. (1994) and Dingeldey et al. (1997), on the other hand, published geochronological data which are in favour of a Paleogene, probably Eocene age of high-P metamorphism in the Tauern window and adjoining Lower Austroalpine units.

Since large-scale tectonic structures are crosscut in the Tauern window by the mineral isograds, it is clear that peak metamorphic conditions (maximum temperatures around 600 °C) in this area were attained essentially late- to post-kinematically, i.e., during exhumation. Minor defor-

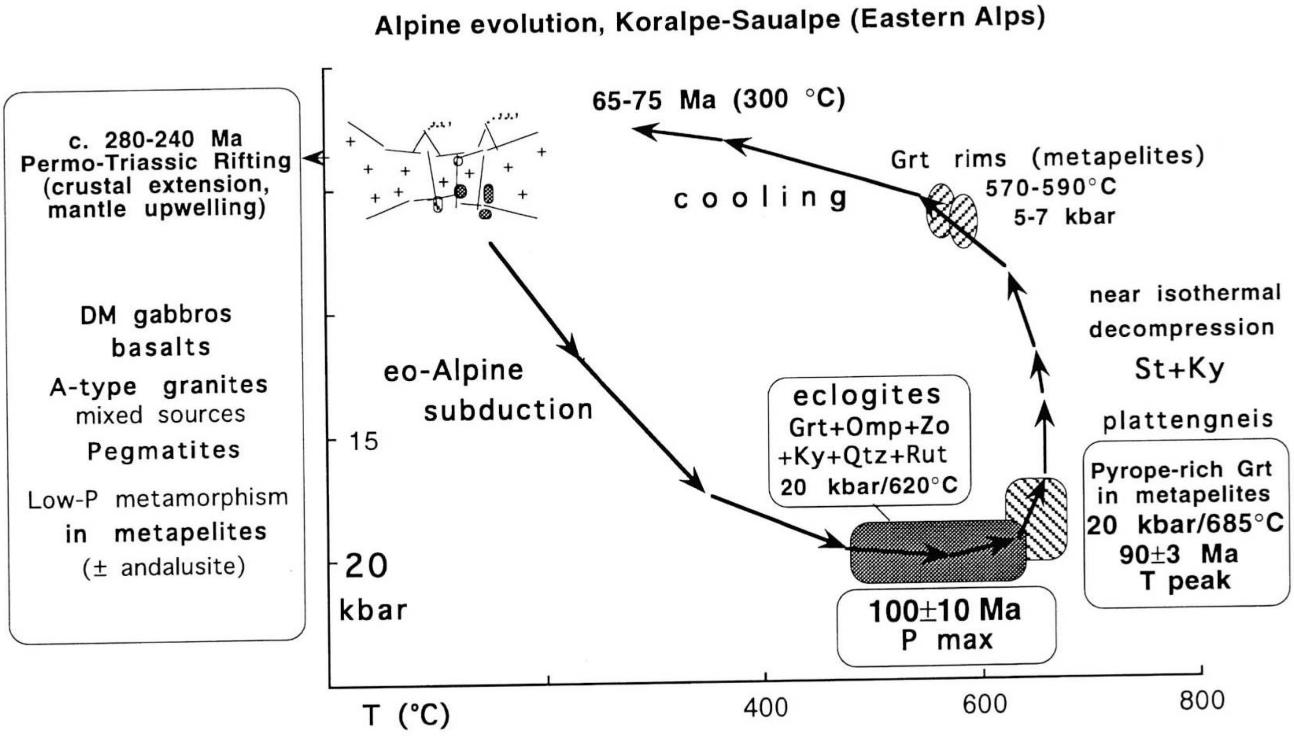

Fig. 11 PTt graph for deeply subducted south-eastern AAB units. Following the Permo-Triassic rifting stage, the exact timing of eo-Alpine subduction is still uncertain. It is clear, however, that high-P conditions prevailed up to c. 100 ± 10 Ma, followed by rapid exhumation during the Late Cretaceous.

mation, however, persisted locally into the cooling path. The thermal climax was reached earlier in higher tectonic levels, compared with deeper parts, but an overall time constraint for this last period of heating is possibly given by the 35 to 25 Ma time interval.

Due to continuing northward motion of Adria, compression and deformation was going on during the Tertiary within the AAB nappe edifice also. After Cretaceous nappe imbrication, transport and subsequent orogen-wide extension (e.g. FROITZHEIM et al., 1994, 1997), considerable deformation was accommodated along distinct faults. Some of them have been active since the Late Cretaceous, but others reached their main activity within well-defined time brackets, during the Eocene and Miocene (MÜLLER et al., 1997). Probably one late effect of Penninic ocean consumption is the post-collisional alkali-basaltic to shoshonitic dyke magmatism and plutonism around 30 Ma, which may have had its source at the base of a strongly thickened crust, due to final continental collision in the Eocene (VON BLANCKENBURG et al., 1998).

4. Conclusions

Available radiogenic isotope data allow the following conclusions to be drawn for the evolution of the Eastern Alps.

– The oldest inherited components (zircon cores) in the Austroalpine continental crust are Late to Middle Archean. The mean crustal residence time (Nd DM model ages) of the protolith material is 1.6 ± 0.1 Ga.

– Since the Late Proterozoic (c. 650 Ma) widespread magmatic activity is documented in both Austroalpine and Penninic realms. These magmatic suites may include igneous rocks from volcanic arcs, back arc settings as well as ocean floor and continental areas (at 650–600, 550–520 and 490–470 Ma), culminating in an intense S-type plutonism during the Early Palaeozoic ("Caledonian") orogenic cycle.

– Evidence for pre-Variscan metamorphism is scarce. The Variscan cycle is documented in the AAB by an early, c. 350 ± 10 Ma old high-P stage, followed by a sillimanite- to andalusite-grade metamorphism (c. 330–320 Ma) and, finally, regional cooling (< 310 Ma). Intense tonalitic-granodioritic plutonism characterizes the time span c. 335–310 Ma in the Penninic realm.

– Ages in the range of between 285 and 240 Ma, mainly from the southeasterly AAB units, signal crustal extension, subsequent block disruption, mantle upwelling and low-P metamorphism in the crust and are indicative for the onset of the Alpine cycle.

– In the Jurassic, extension in the southern AA units shifted into a compressional stage. Closure of the Meliata-Hallstatt oceanic branch of the Tethys was accomplished by subduction, crustal thickening, high-P metamorphism and final continent-continent collision in Mid-Cretaceous time. Eo-Alpine peak conditions reached 20 kbar/> 650 < 700 °C, some 100 ± 10 Ma ago. Fast exhumation is documented by near-isothermal decompression, and cooling, since c. 90 Ma, all over the Austroalpine sheet.

– Subduction of the Penninic was not initiated before Late Cretaceous times. Peak pressures were probably reached during the Eocene, while maximum temperatures were effective in different tectonic levels at different time, some 35–25 Ma ago.

– Late Oligocene plutonism and dyke magmatism documents enormous crustal thickening at the stage of continental collision and further northward movement of Adria, related with strike-slip movements and extrusion of AAB units along distinct faults up to the Early Miocene.

Acknowledgements

I thank F. Finger, G. Frasl and E. Kirchner (University of Salzburg) for providing sample powders (two data points on Fig. 1: F. Finger, 3 data points: G. Frasl; 6 data points from NCA samples on Fig. 8: E. Kirchner). The Ar measurements shown in figure. 9 are from J.A. Miller, University of Cambridge (England). I thank D. Gebauer and W. Hansmann (Zürich) for their critical review, which essentially improved the quality of the paper. H. Rice (Vienna) corrected the English. Most of the author`s isotopic results discussed or shown in the present review were determined over the years within various projects (FWF project nos. N25, S15, P5150, P6689E, S47/05 and /08, P9705). Funding of these projects by the Austrian Science Foundation (FWF) is gratefully acknowledged.

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Manuscript received March 26, 1998; revision accepted August 27, 1998.