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40Ar/39Ar AND Rb-Sr MINERAL AGE CONTROLS FOR THE PRE-ALPINE AND ALPINE TECTONIC EVOLUTION OF THE AUSTRO-ALPINE NAPPE COMPLEX, EASTERN ALPS

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Introduction

The Austro-Alpine Nappe Complex (AANC) represents a classical thick-skinned fold and thrust belt interpreted to have comprised the upper continental plate during the Tertiary collision of the European foreland/Penninic continental crust and Adriatic microplate. The AANC is composed of several regional internally imbricated thrust units which are structurally interlayered with Permo-Mesozoic sequences along northern margins (Fig. 1). Southwards, basement units from various thrust sheets are in mutual contact. Three major internally imbricated subcomplexes may be distinguished, within the AANC (Tollmann, 1959, 1987). Those include 1) the Lower Austro-Alpine Unit (LAA), 2) the Middle Austro-Alpine unit (MAA), and 3) the Upper Austro-Alpine unit (UAA). These units are characterized by a distinction in basement lithology, nature of protolith formation and/or degree of metamorphic overprint of basement units (Fig. 2). The MAA contains units which record an amphibolite facies overprint of Alpine/pre-Alpine age. The UAA is represented by weakly metamorphosed units and several thin units with amphibolite facies assemblages of pre-Alpine age (e.g., Kaintaleck Complex, Ackerl Complex). The LAA basement exposed along eastern margins ranges from units which display greenschist facies assemblages (Wechsel Gneiss, Wechsel Phyllite, both forming together with the Waldbach complex the Wechsel window basement) to predominantly amphibolite facies ("Grob gneiss"/Raabalpen Complex).

This contribution constitutes an overview of the timing of pre-Alpine and Alpine tectonic processes which affected the AANC east of the Penninic Tauern Window. The structure of this region is discussed in Frank (1987), Neubauer and Genser (1989), Ratschbacher (1986), Ratschbacher et al. (1987), Tollmann (1959, 1977, 1987). This have been evaluated by $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating. The main emphasis has been an evaluation of: (1) the presence of pre-Variscan tectonothermal events; (2) the sequence of thrusting within the Austro-Alpine thrust complex and, (3) the timing of post-metamorphic cooling of the Austro-Alpine complex.

Previous geochronological work in this area has been compiled by Frank et al. (1987) and Neubauer and Frisch (in press).

Analytical methods

Mineral concentrates for $^{40}Ar/^{39}Ar$ measurements were wrapped in aluminium-foil packets, encapsulated in sealed quartz vials, and irradiated for 40 hr in the central thimble position of the TRIGA Reactor at the U.S. Geological Survey, Denver. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 (Samson and Alexander, 1987). The samples were incrementally heated until fusion in a double-vacuum, resistance heated furnace. Temperatures were monitored with a direct-contact thermocouple and are controlled to 1°C between increments and are accurate to 5°C. Measured isotopic ratios were corrected for total blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using the factors reported by Dalrymple et al. (1981) for the TRIGA Reactor. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger and Jäger (1977) following the methods described in Dallmeyer and Keppie (1987).

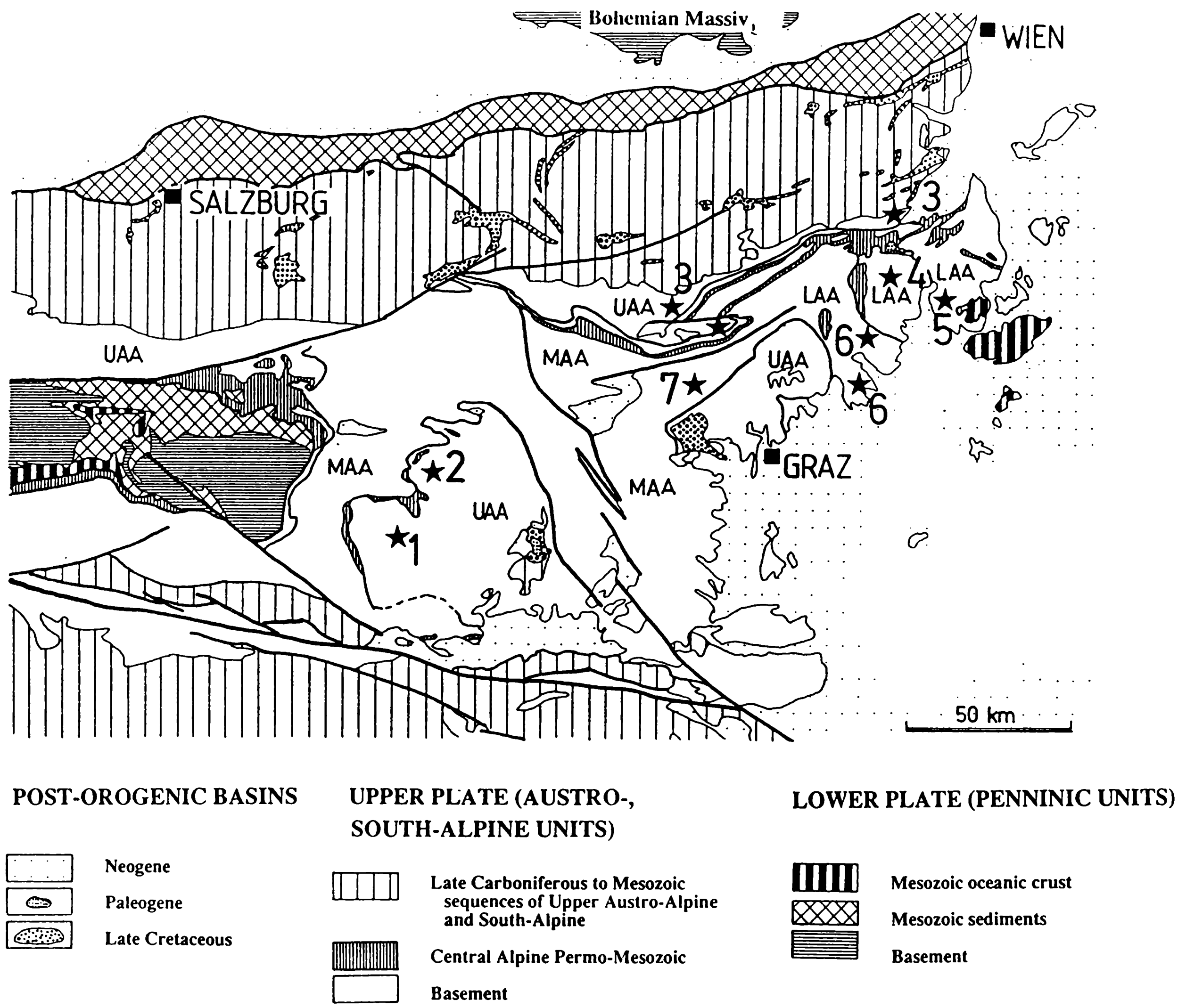

Fig. 1: Simplified tectonic map of the Eastern Alps with locations of $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating: 1 - Ordovician/Silurian sandstones of the Gurktal Thrust System; 2 - Ackerl Complex; 3 Kaintaleck Complex; 4 - Wechsel Complex incl. surrounding Raabalpen Complex; 5 - Sieggraben Unit; 6 - southern Raabalpen Complex; 7 - Gleinalm dome. LAA - Lower Austro-Alpine unit; MAA - Middle Austro-Alpine Unit; UAA - Upper Austro-Alpine Unit.

Two categories of uncertainties are encountered in $^{40}Ar/^{39}Ar$ incremental release dating. One group involves intralaboratory uncertainties related to measurement of the isotopic ratios used in the age equation. The other group considers interlaboratory uncertainties in the other parameters used in the age equation (monitor age, J-value determination, etc.), and are the same for each gas increment evolved from a particular sample. Therefore, to evaluate the significance of potential incremental age variations within a sample, only intralaboratory uncertainties should be considered. These are reported here, and have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are c. +/- 1.25 - 1.5% of the quoted age. Total-gas ages have been computed for each sample by appropriate weighting of the age and percent ^{39}Ar released within each temperature increment. A "plateau" is considered to be defined if the ages recorded by two or more contiguous gas fractions each representing > 4% of the total ^{39}Ar evolved (and together constituting > 50% of the total quantity of ^{39}Ar evolved) are mutually similar within a +/- 1% intralaboratory uncertainty. Analysis of the MMhb-1 monitor indicates that apparent K/Ca ratios may be calculated through the relationship 0.518 +/- 0.005 x $^{39}Ar/^{37}Ar$ corrected.

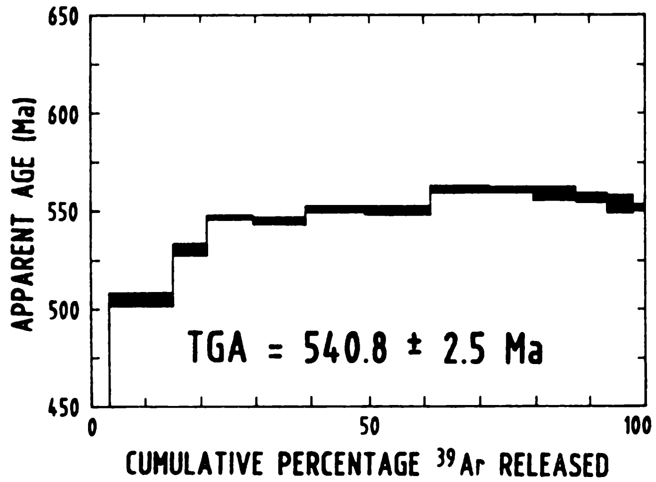

Fig. 2: $^{40}Ar/^{39}Ar$ release spectrum of detrital muscovites from a Late Ordovician/Silurian(?) sandstone of the Gurktal Thrust System. TGA - total gas age.

Plateau portions of the analyses have been plotted on $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation diagrams (Roddick et al., 1980, Radicati de Brozolo et al., 1981). Regression techniques followed the methods of York (1969). A mean square of the weighted deviates (MSWD) is the statistical parameter which has been used to evaluate isotopic correlations. Roddick (1978) suggests that an MSWD > c. 2.5 indicates scatter about a correlation line greater than that which can be explained only be experimental errors.

The Rb-Sr mineral dating was carried out at the Laboratory of Geochronology, Arsenal, Vienna. For analytical methods, see Thöni (1986).

Age of detrital micas in Early Paleozoic sandstones (UAA)

Detrital muscovite within Late Ordovician sandstones exposed in the Carnic Alps (South-Alpine Unit), yielded convincing evidence of Cadomian (ca. 620 Ma) cooling in the source region (Dallmeyer and Neubauer, in prep.). In continuation of this study, a muscovite concentrate from an Ordovician/Silurian sandstone of the the Gurktal Thrust System was examined. The $^{40}Ar/^{39}Ar$ analysis yielded an internally discordant age spectrum (Fig. 2). Intermediate and high-temperature increments recorded mutually similar aparent ages corresponding to a c. 560 Ma plateau. Systematically increasing ages were recorded at low experimental temperatures. These suggest that a slight loss of 40Ar occurred during a relatively low-grade thermal overprint in the late Paleozoic. We interpret the high temperature increments as the minimum age of post-metamorphic cooling after a late Cadomian tectonothermal event in the source region and the low temperature increments as combined effects of Variscan/Alpine metamorphic overprints. The Variscan/Alpine metamorphic overprints apparently did not exceed c. 375 - 400^{o} C.

Timing of pre-Alpine tectonothermal events in the eastern Greywacke Zone (UAA)

Mineral dating within the pre-Variscan Kaintaleck Complex was carried out to evaluate previous U-Pb zircon data which recorded tectonothermal events at ca. 520-500 Ma and ca. 390-360

Ma (for compilations, see, Neubauer and Frisch, in press). However, $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating on muscovites and amphiboles confirm a middle Paleozoic event in the Kaintaleck Complex (Fig. 3). For example, a highly discordant amphibole spectrum yielded a total gas age of ca. 547 Ma. Amphiboles of two further samples yielded more or less similar Ar release spectra but with quite younger ages. Both analyses suggest cooling after amphibolite facies metamorphism at or about 420 Ma. Therefore, the high age of the 547 Ma amphibole mentioned above is caused by a high component of extraneous ^{40}Ar.

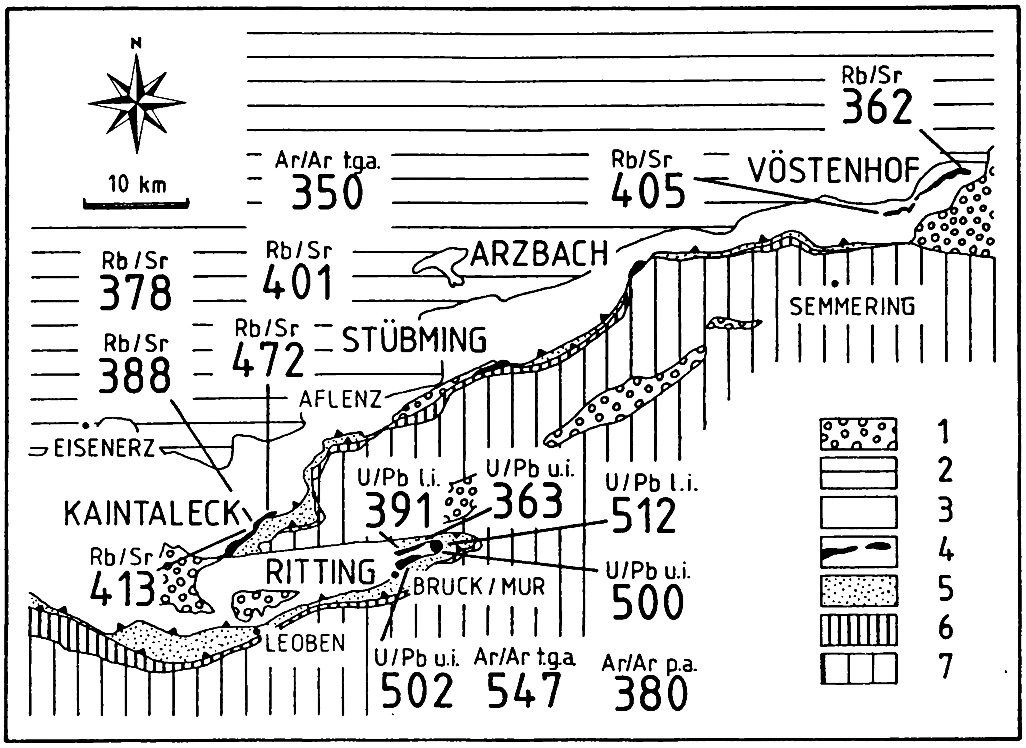

Fig. 3: Mineral ages [Ma] of the Kaintaleck Complex. Legend: 1 - Neogene basins, 2 - Mesozoic cover of the Upper Austro-Alpine Unit, 3 - Noric Nappe, 4 - Kaintaleck Complex, 5 - Silbersberg and Veitsch Nappe, 6 - Mesozoic cover of the Middle Austro-Alpine unit, 7 - Middle Austro-Alpine basement. Rb/Sr: two-point isochron age; Ar/Ar: p.a. - plateau age, t.g.a. - total gas age; U/Pb: u.i. - upper intercept, l.i. - lower intercept.

Muscovite from a foliated micaschist yielded a 472 +/-2 Ma Rb-Sr age, which probably reflects a "Cadomian Sr memory". All other muscovites from micaschists yielded Rb-Sr whole-rock mineral ages between 413 +/-3 Ma and 401 +/-3 Ma. $^{40}Ar/^{39}Ar$ analysis from the same samples displays an internally discordant age pattern, ranging from c. 375 Ma in high temperature portions to c. 290 Ma low-temperature portions of the experiment. A total gas age of 350 +/-2 Ma is similar to the Rb-Sr age. Muscovites of pegmatites within these crystalline slices yielded Rb-Sr two point isochron ages of 388 +/-4 Ma and 378 +/-4 Ma. That suggests intrusion of the pegmatites postdated penetrative ductile deformation and metamorphism. The significance of a muscovite Rb-Sr age from a highly deformed aplitic gneiss (362 +/-13 Ma) is uncertain.

These data argue for a peak of amphibolite-facies metamorphism in the Ritting and the Prieselbauer Subunits reached prior to c. 410 Ma (the time when the closure temperature of 500-550°C for Rb-Sr in phengitic white micas which was reached). Peak metamorphic conditions were followed by slow cooling to ca. 250-350°C (Ar-closure temperature for muscovites at c. 380 Ma. This was followed by intrusion of pegmatites and aplitic veins. The amphibolite-facies metamorphism was preceeded by a high-pressure event with formation of the eclogites in Ritting Subunit. The age of this metamorphic event has not been constrained.

The data indicate a possible paleogeographic linkage of protoliths Carboniferous clastic sequences of the Veitsch Nappe with portions of the Kaintaleck Complex. This is indicated by the age of detrital white micas which were deposited in phyllitic sequences of the Veitsch Nappe during the Carboniferous.

Timing of tectonothermal events in the Wechsel Window and surrounding units of the Raabalps (LAA)

The eastern part of the LAA is characterized by two contrasting tectonostratigraphic subunits. The Wechsel Unit forms the footwall and the Raabalpen Unit comprised the hangingwall. Both consist of Variscan basement and Permo-Mesozoic cover rocks (Tollmann, 1977). They are separated by an Alpine thrust fault (Mesozoic slices occur within this fault). Because of the lower greenschist facies metamorphism recorded in all cover rocks (quartzites and marbles), the metamorphism of the basement rocks in both units has also been considered to be of Alpine age. However, new Rb/Sr and $^{40}Ar/^{39}Ar$ mineral age data led to the following conclusions (Fig. 4):

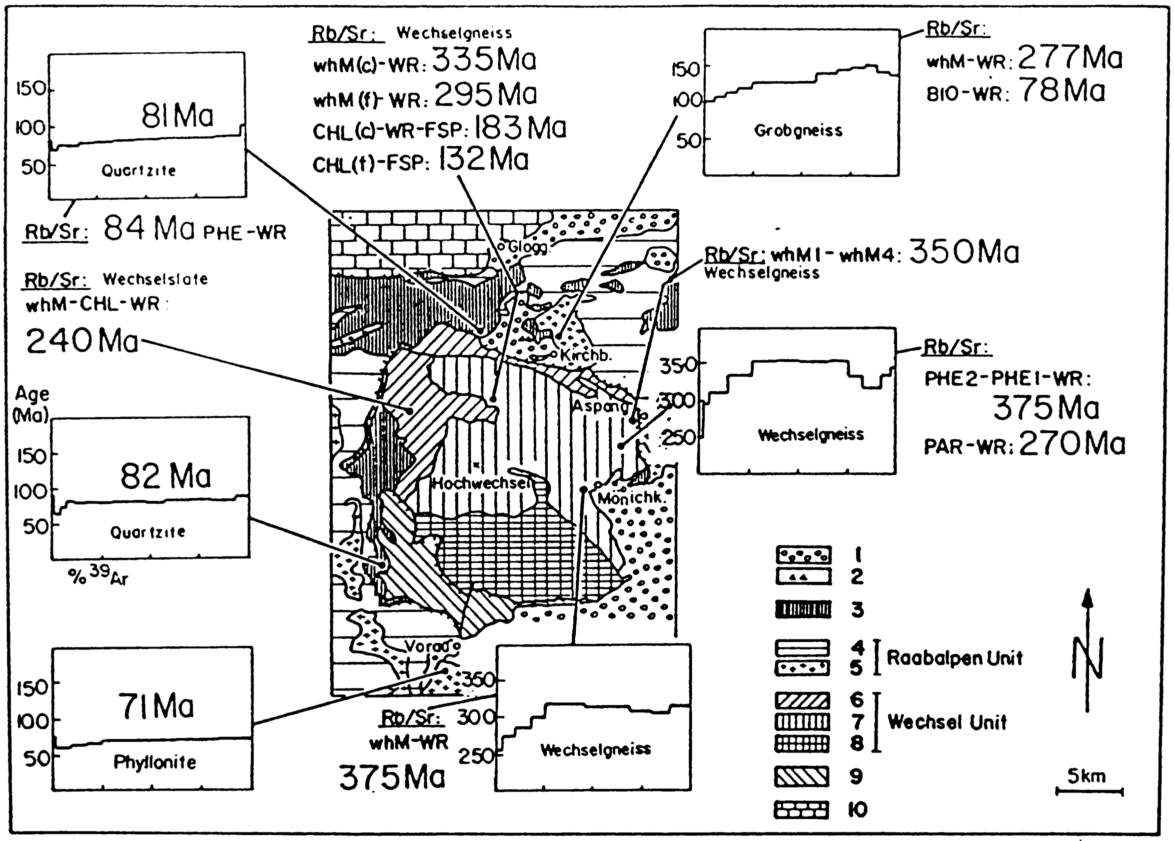

Fig. 4: Sketch map of the Wechsel Window and the surrounding Raabalpen Unit with recent Rb-Sr and $^{40}Ar/^{39}Ar$ mineral ages. Legend: 1 - Neogene deposit; 2 - Eocene limestone; 3 - Permo-Mesozoic cover (both units); 4 - phyllitic micaschist; 5 - Grobgneiss; 6 - Wechsel Phyllite; 7 - Monotonous Wechsel Gneiss; 8 - Variegated Wechsel Gneiss; 9 - Waldbach Unit; 10 - Northern Calcareous Alps. whM - white Mica; PHE - phengite; PAR - paragonite; BIO - biotite; CHL - chlorite; FSP - feldspar; WR - whole rock; 1,2,4 - different magnetic fractions; f - fine-grained; c - coarse-grained.

1) Phengitic white mica (Si content 3.5 (core) and 3.25 (rim)) indicate an initial high pressure metamorphism at c. 370 - 380 Ma (Late Devonian). This is represented by the highest Rb/Sr ages, recorded within the Wechsel Unit.

2) A large scatter of Rb/Sr (same Sr initial ratios of 0,71) and $^{40}Ar/^{39}Ar$ ages is interpreted to reflect very slow cooling rates (closing temperatures reached at different places at different times).

3) A late "Variscan" (270-240 Ma, Upper Permian) metamorphism can be inferred from: 1) Rb/Sr ages of paragonitic white mica (Wechsel gneisses); 2) Rb/Sr mineral isochron (white mica - chlorite - whole rock of the Wechsel Phyllites); 3) c. 250 Ma $^{40}Ar/^{39}Ar$ ages recorded by low temperature increments of discordant age spectra.

4) The age of ductile, top-to WNW shearing recorded both in basement and cover rocks remains unknown. Despite similar kinematics, an Alpine age appears unlikely because of the undisturbed Variscan mineral ages recorded in the basement.

5) Alpine metamorphic conditions in the Raabalpen Unit must have been slightly higher than in the Wechsel Unit because: 1) Alpine Rb/Sr ages recorded in biotite; 2) more strongly rejuvenated $^{40}Ar/^{39}Ar$ white mica system; 3) growth of small garnets within instable Ca-rich plagioclase.

7) Early Alpine metamorphism of the cover rocks is recorded in similar Rb/Sr and 40Ar/39Ar ages of c. 80 Ma, which are interpreted to date formation of new-grown phengitic white mica (Si content approximately 3.3).

Timing of metamorphism in the Ackerl Gneiss Complex (UAA)

The Ackerl Gneiss is part of a UAA amphibolite facies basement nappe in the northwestern Gurktal Thrust Complex (UAA; Fig. 1; Neubauer, 1980). $^{40}Ar/^{39}Ar$ release spectra of two muscovite concentrates yield corresponding plateaus of ca. 310 Ma with minor Alpine loss of radiogenic argon (Fig. 5). The data prove Late Carboniferous cooling of the Ackerl Gneiss Complex and Early Alpine emplacement of this basement nappe as one of highest nappes within the AANC.

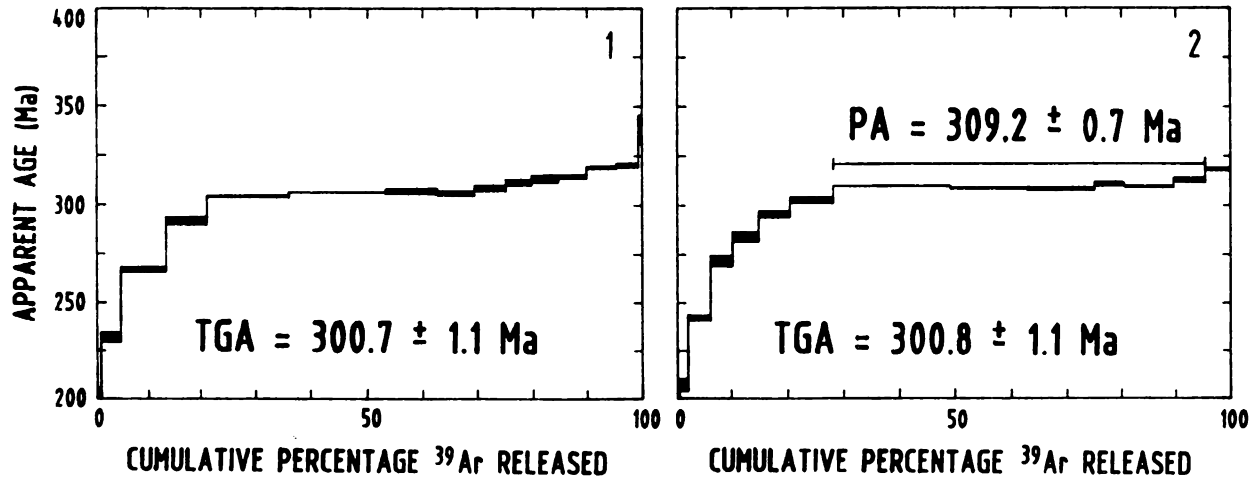

Fig. 5: $^{40}Ar/^{39}Ar$ release spectra of two white mica concentrates of the Ackerl Gneiss Complex. ICA - isotope correlation age; PA - plateau age; TGA - total gas age.

Timing of Early Alpine metamorphism and thrusting sequence in the AANC

The AANC is a large-scale internally imbricated thick-skinned nappe stack comprised of both thick basement and thin cover sequences (Fig. 1). Three major nappe complexes are distinguished from paleogeographic south to north: Upper Austro-Alpine (UAA), Middle Austro-Alpine (MAA), Lower Austro-Alpine (LAA). As already mentioned above, although these individual nappe complexes include distinct basement units which are covered by similar "Central Alpine" Permo-Triassic terrestrial and shelf sequences, these units record contrasting Alpine tectonothermal evolution.

Previous models have explained intra-Austro-Alpine nappe imbrication in terms of a Middle-Cretaceous collision between a Middle-Penninic microcontinent and the Apulian microplate (with its northern extension, the Austro-Alpine unit). Of special interest are, therefore, our new results from the Sieggraben Structural Unit. The Sieggraben Structural Unit is a tectonic klippe of the MAA exposed along eastern margins of the Alps (Fig. 1, location 5; Tollmann, 1978). It is a tectonic melange which includes eclogite-bearing metamorphic units containing both ophiolite-like fragments (retrogressed N-MORB type eclogites and serpentinites) and supracrustal, probably pre-Alpine continental rocks. Inclusions of hornblende and epidote in eclogite-facies garnets suggest that an initial epidote amphibolite facies assemblage dehydrated to eclogite. P-T conditions maintained during eclogite formation were c. 670-750° C and 14-16 Kb (based on garnet-clinopyroxene and jadeite-bearing assemblages). Retrogression of eclogite included: 1) replacement of eclogitic omphacite by sodic augite; 2) development of sodic plagioclase symplectite; and, 3) formation of epidote-hornblende bearing assemblages. The symplectite formed at c. 500-600° C and c. 6-9 Kb.

$^{40}Ar/^{39}Ar$ analyses of two concentrates of hornblende within retrograde assemblages yield similar internally-discordant age spectra (Fig. 6). Most intermediate-temperature increments record similar apparent ages. Isotope correlation of these data yielded plateau isotope correlation ages of 136.1 +/- 0.5 Ma and 108.2 +/- 0.3 Ma. These date the last cooling through c. 500° C.

Alternative models to explain similar late Jurassic - Cretaceous mineral ages which are recorded throughout the Austro-Alpine Thrust Complex include: 1) The Sieggraben Unit represents a basement nappe which was buried and remetamorphosed during Cretaceous A-subduction and associated imbrication within the Austro-Alpine Nappe Complex; and, 2) The Sieggraben Unit initiated within a Permo-Mesozoic ophiolitic suture zone during Mesozoic plate collision. The record of Cretaceous ages and high-pressure assemblages argue for development of the Sieggraben Unit within a Jurassic-Cretaceous subduction zone which likely entrained significant portions of Austro-Alpine crust.

New $^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages (white mica, biotite and amphibole) together with previously reported geochronological results from other AANC units (Frank et al., 1987; Fritz, 1988) range between c. 140 to 70 Ma (Figs. 3, 4, 6, 7, 8, 9). Systematic regional variatios in mineral ages combined with characteristics of Alpine metamorphic zonation display the following trends:

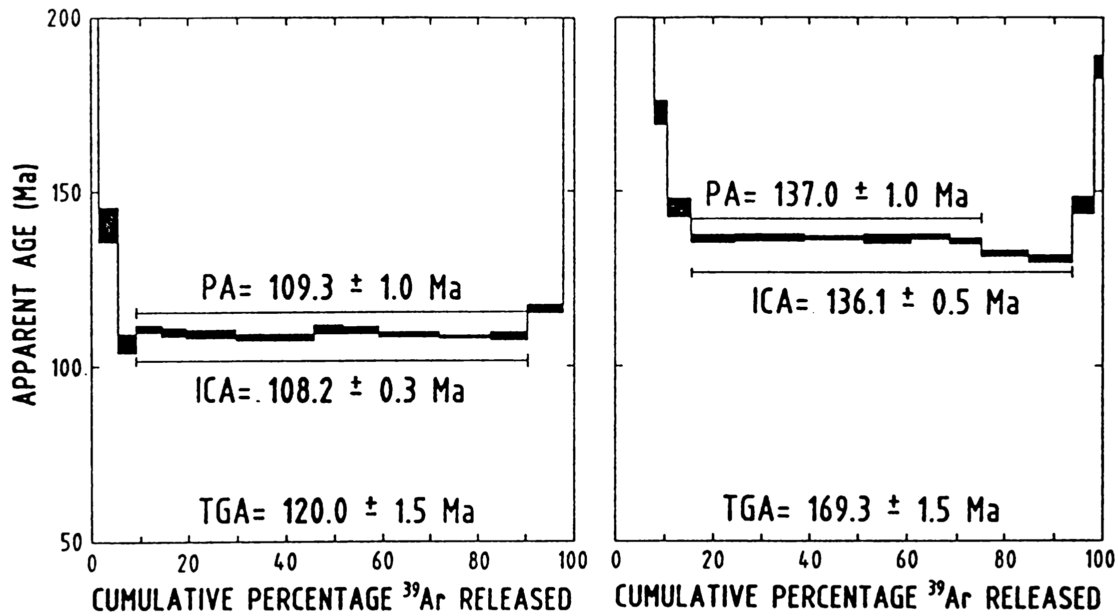

Fig. 6: $^{40}Ar/^{39}Ar$ amphibole age spectra of two retrogressed eclogites from the Sieggraben unit (Zöberndorf quarry; Schäffern klippe). ICA - isotope correlation age; PA - plateau age; TGA - total gas age.

(1) The extent of Alpine metamorphic overprint increases from greenschist metamorphic facies (north) to amphibolite facies conditions (south) in both LAA (Fig. 7) and MAA units. Correspondingly, confining thrust surfaces climb NW-ward from basement units to cover sequences. These relationships may reflect thrust propagation by splays of a deep-crustal, intra-continental master thrust.

(2) Mineral ages generally young from hangingwall to footwall nappe units (UAA: 140 - 125 Ma; MAA: 140 - 80 Ma; LAA: 125 - 70 Ma). This pattern likely reflects footwall propagation of the master fault and associated piggy-back transport of hangingwall structural units.

(3) Both, the basal MAA thrust and an important internal thrust within the LAA (between the Wechsel Unit in the footwall and the Raabalpen unit in the hangingwall) must represent an out-of-sequence thrusts, because they transported deep-crustal Alpine metamorphic sequences over units which were not penetratively affected by Alpine tectonothermal activity.

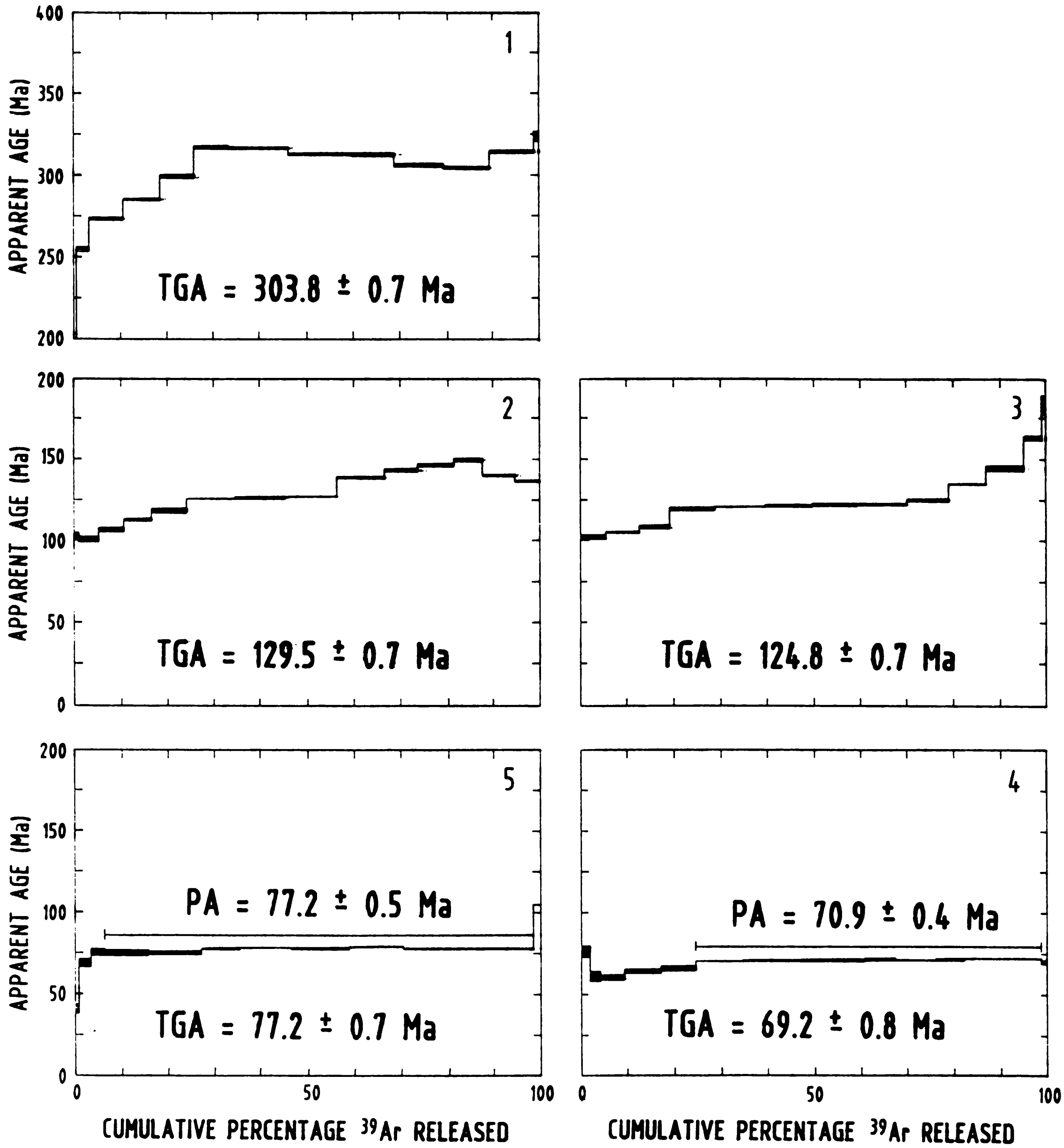

Fig.7: $^{40}Ar/^{39}Ar$ release spectra of the Raabalpen Unit (LAA). ICA - isotope correlation age; PA - plateau age; TGA - total gas age.

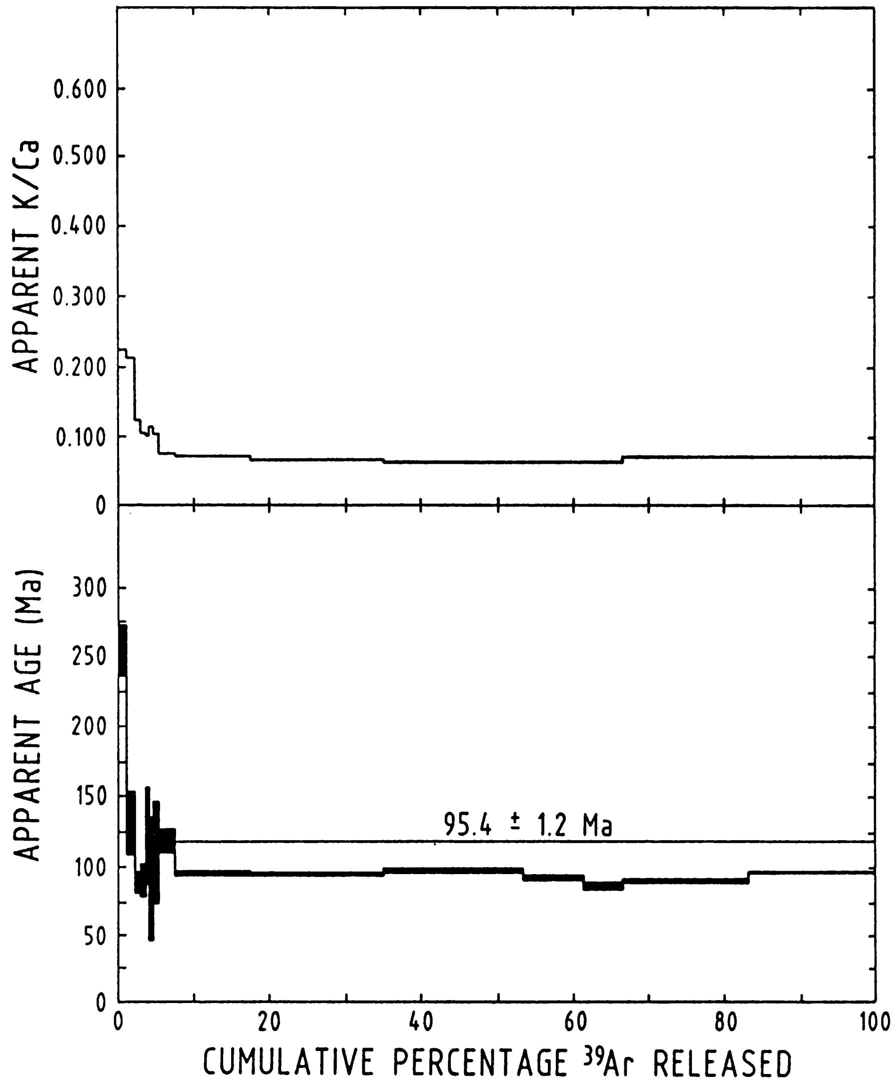

Fig. 8: $^{40}Ar/^{39}Ar$ release spectrum of a hornblende from the Humpelgraben quarry, Gleinalm dome.

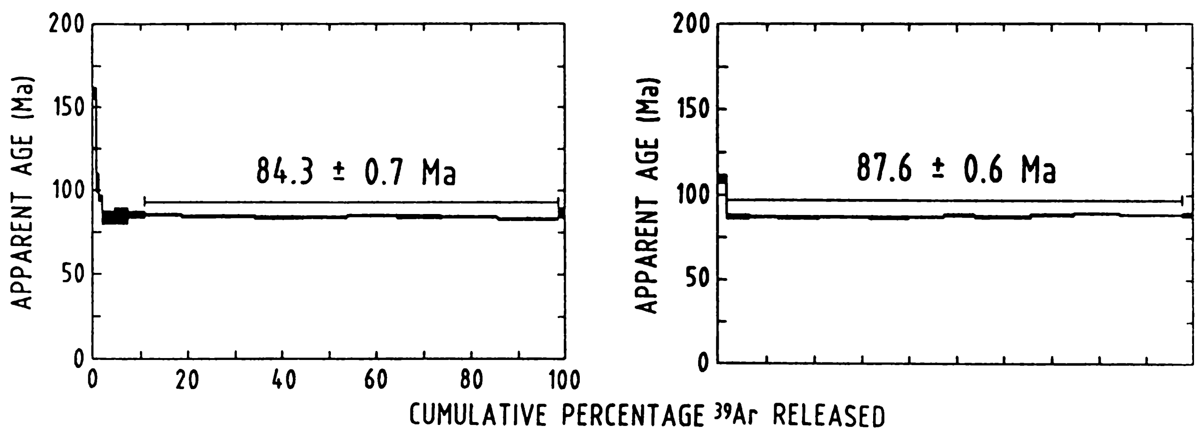

Fig. 9: $^{40}Ar/^{39}Ar$ release spectra of two muscovites (1 - Humpelgraben quarry; 2 - Neuhof valley), Gleinalm dome.

All these data suggest that the Austro-Alpine unit records Alpine metamorphism and deformation typical for a lower continental plate position during continent-continent collision. This is compatible with accepted paleogeographic restorations which indicate that a Triassic/Jurassic basin (probably associated with oceanic crust) developed SE of the Alpine continental fragment (e.g., Decker et al., 1987). Additionally, a zone of probable crustal thinning may occur between LAA and MAA units. Major Alpine thrust surfaces may correspond to pre-Alpine faults, which initially separated contrasting basement tectonic units and which were variably reactivated as Alpine thrust faults.

Cretaceous cooling of the Gleinalm metamorphic dome (MAA)

The metamorphic Gleinalm dome, part of the Middle Austro-Alpine Nappe Complex of the Eastern Alps, was exhumed during the Late Cretaceous in an overall sinistral wrench corridor (Fig. 10). Confining ductile shear zones form a system of low angle faults which is bounded by steep sinistral tear faults forming a large relais with the metamorphic dome in the center (Neubauer and Genser, 1988). Fabrics within all ductile shear zones suggest development during a decreasing temperature regime (from lower amphibolite/upper greenschist facies conditions with crystal plastic fabrics of quartz to cool temperatures below 300^{o}C with exclusively cataclastic fabrics without crystal annealing; Neubauer, 1988). A cooling path based on $^{40}Ar/^{39}Ar$ ages of amphibole (Fig. 11), muscovite (Fig. 12) and fission track ages of sphene and zircon together with Rb-Sr mineral ages from Frank et al. (1976) indicate cooling through c. 500^{o}C at 94 Ma to below c. 225^{o}C at 65 Ma (Fig. 11).

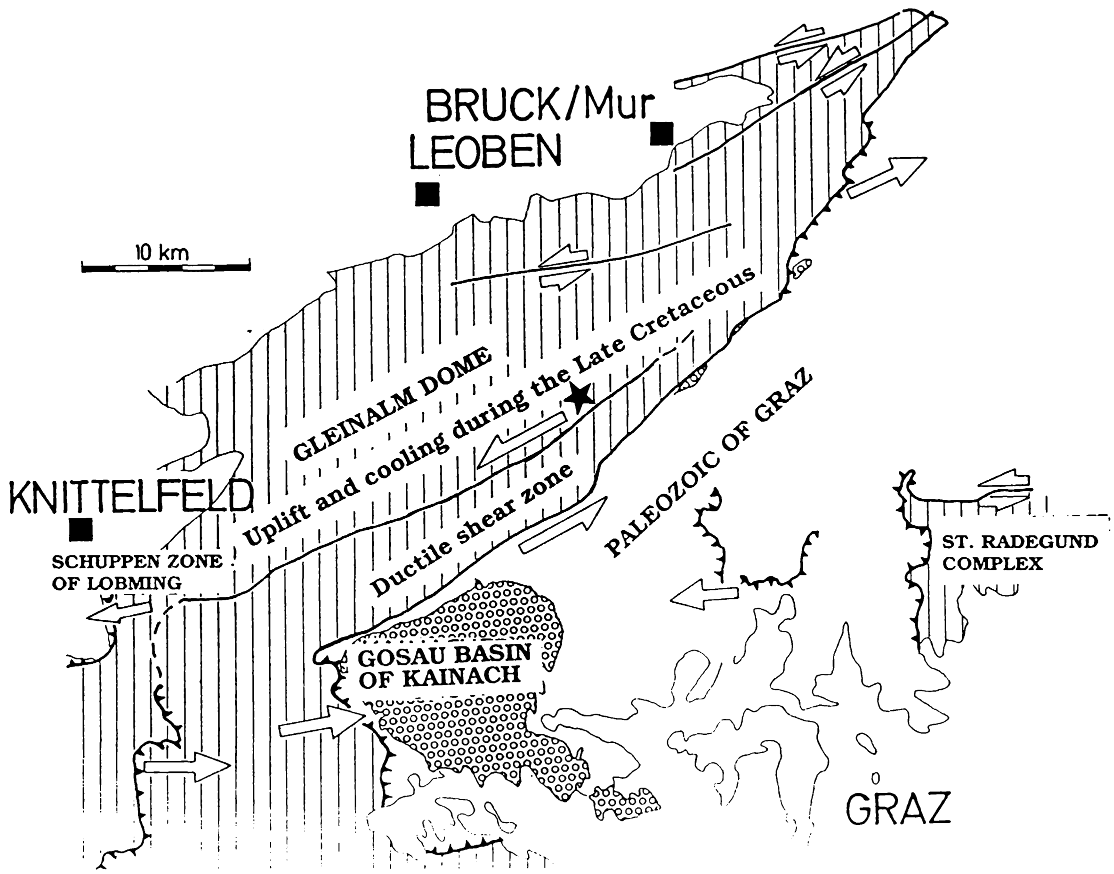

Fig. 10: General structure of the Gleinalm metamorphic dome and adjacent areas including the Late Cretaceous basin of Kainach. Asterisk marks location of samples which are used for construction of the cooling path of Fig. 11.

Subsidence of the adjacent Late Cretaceous Kainach basin (the Gosau basin within the same tectonic frame) was synchronous with cooling and exhumation of the Gleinalm dome. Internal depositional patterns display sharp subsidence at the time of cooling with internal synsedimentary block rotation.

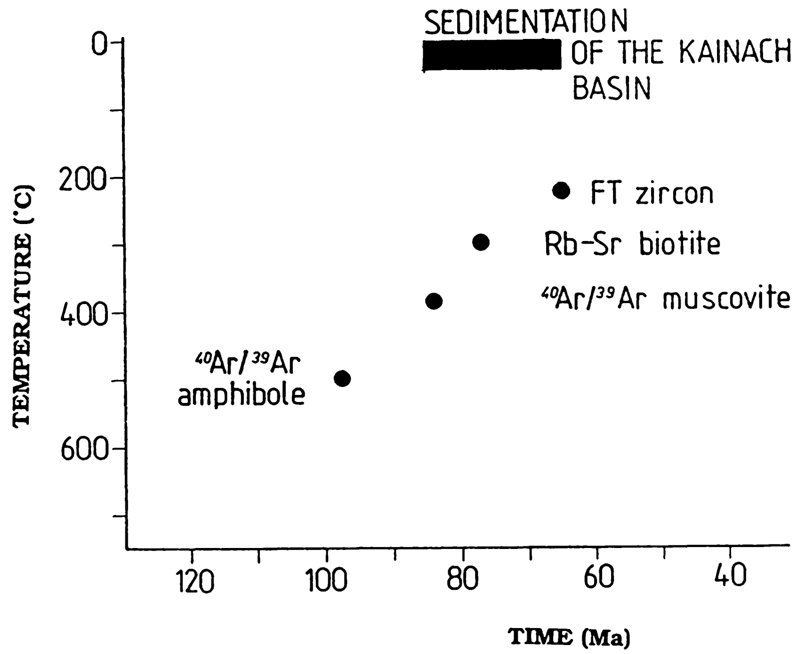

Fig. 11: Cooling path of the Core complex of the Gleinalm dome. All data are from one locality (Humpelgraben quarry).

Discussion

$^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages suggest that several distinct tectonothermal events affected the Austro-Alpine Nappe Complex. $^{40}Ar/^{39}Ar$ ages of detrital muscovite from the Carnic Alps and the Gurktal Thrust System emphasize the significance of Late Precambrian (Cadomian) metamorphic and/or plutonic sequences in the source regions of Early Paleozoic shelf deposits (part of the Noric terrane: Frisch and Neubauer, 1989). However hints of significant differences in precise ages (early and late Cadomian) may reflect distinct Cadomian basement structural units. Neubauer (1985) interpreted the Kaintaleck Complex as a basement to Ordovician to Early Carboniferous shelf sequences of the Noric terrane. U-Pb zircon analyses from several rocks of the Kaintaleck Complex indicated two distinct complexes with two age groups (520 - 500 Ma, and 400 - 360 Ma) which were interpreted as two distinct metamorphic complexes. Rb-Sr white mica, hornblende and muscovite $^{40}Ar/^{39}Ar$ ages range from 470 to 360. These suggest a tectonothermal evolution for major portions of the Kaintaleck Complex which, thus, cannot constitute a primary basement to the Noric composite terrane. Lithologies of the Kaintaleck Complex are part of a contrasting terrane ("Pannonian terrane" of Frisch and Neubauer, 1989) which is defined by a record of Silurian/Devonian metamorphism. The new data from the Wechsel Gneiss Complex (intra-Devonian ages) confirm correlation of this tectonostratigraphic unit with the "Pannonian" terrane.

The "classical" timing of the Variscan orogeny (Late Variscan orogeny) with c. 310 Ma is confirmed by the muscovite ages of the Ackerl Gneiss Complex. This unit might have been part of a Variscan lower plate which collided during Carboniferous with other Austro-Alpine basement complexes.

Permian ages (ca. 260 - 240 Ma) are recorded in the Wechsel and Raabalpen units and might have been related to post-Variscan extension leading to formation of the Tethyan shelf (Late Permian - Triassic). In this sense, the Wechsel data may record low temperature activity along a ductile shear zone (low angle normal fault) which separates Wechsel gneisses from Wechsel phyllites. Permian volcanic, and also plutonic activity, could have resulted in higher geothermal gradients.

Alpine tectonothermal activity recorded within the Austro-Alpine Nappe Complex reflects a long-lasting compression history more characteristic of a lower continental plate structural position than that of the upper plate suggested by previous geodynamic interpretations. Evidence for Alpine (pre-Late Cretaceous eclogite metamorphism with eclogites with pressures raging from 10 - 18 Kb (for data compilation, see Dallmeyer et al., in prep.).

The distribution of mineral data support footwall propagation of thrusts from early thrusting (ca. 140 - 110 Ma) within the UAA, and later overriding the LAA by the MAA thrust sheets between ca. 110 and 90 Ma which is followed by a period of extension in both MAA and LAA units (ca. 85 - 65 Ma).

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