Eclogae geol. Helv. 89/1: 203–227 (1996)

0012-9402/96/010203-25 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole-rock data

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Key words: $^{40}Ar/^{39}Ar$ technique, basement, nappe stacking, extension, Paleozoic, Cretaceous

ABSTRACT

$^{40}Ar/^{39}Ar$ dating within the internal Eastern Alps, Western Carpathians, Southern Carpathians, and Apuseni Mountains has been carried out in order to constrain and compare (1) ages of tectonothermal overprint within basement units; (2) the extent of Alpine metamorphic overprint on Permian to Mesozoic cover sequences and (3) the sequence of Alpine tectonothermal events. Stratigraphic controls suggest that all these sections were affected by Cretaceous ("early Alpine") orogenic events during Alpine evolution.

Pre-Alpine tectonothermal events range from Early Cadomian to Late Variscan within the area considered. $^{40}Ar/^{39}Ar$ ages of detrital muscovite of Ordovician-Silurian sandstones within the Eastern Alps suggest a linkage to Cadomian sources (640-580 Ma). Comparison of geochronological data from pre-Alpine Austroalpine basement complexes within the Eastern Alps, the Western Carpathians and the Apuseni Mountains indicates that these represent units which have been affected by contrasting and/or diachronous tectonometamorphic events. As indicated by new mineral age data, their tectonothermal evolution ranges from Early (e.g., c. 420-380 Ma) to Late Variscan (330-300 Ma). By contrast, preliminary amphibole and muscovite data from various basement units within Southern Carpathians argue for uniform Late Variscan cooling after medium grade metamorphism. It appears that the Eastern Alps, Western Carpathians and Apuseni Mts. represent a composite of basement units with variables ages of accretion during early to late Paleozoic orogenic events along northern margins of Gondwana. The uniform Late Variscan cooling ages within Southern Carpathian basement units are interpreted to represent cooling within rift shoulders during ongoing extension and break-up within the future Tethys realm. This interpretation is confirmed by the presence of distinct mylonite zones within the Southern Carpathians and Eastern Alps where white mica ages suggest Early Permian tectonothermal activity with cooling and extension.

Based on stratigraphic and $^{40}Ar/^{39}Ar$ mineral age control on mylonites and penetratively ductilely deformed cover and basement rocks we distinguish three major Alpine tectonic events: (1) blueschist facies metamorphism in the West Carpathian Meliata unit associated with subduction of oceanic crust during the Late Jurassic ($^{40}Ar/^{39}Ar$ phengite ages: 150-160 Ma); (2) varying tectonothermal overprint during continent-continent collision during the Middle and early Late Cretaceous ("pre-Gosau" deformation event) between c. 120 Ma and c. 86 Ma. The age of deformation decreases from hangingwall to footwall units in all investigated sections. This

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event apparently includes an early short-lived eclogite facies metamorphism (only in the Alps) associated with A-subduction of continental crust (with amphibole cooling ages indicating subsequent exhumation and cooling between c. 136 and 108 Ma); (3) Late Cretaceous ("intra-Gosaouian") cooling and associated activity of detachment faulting in higher tectonic levels and contemporaneous low-temperature tectonic stacking in deeper structural levels between c. 86 Ma and 65 Ma. This feature is interpreted to represent extension in an overall contractional setting. Furthermore, there is no apparent thermal overprint within the Austroalpine nappe stack in connection with the piggy-back emplacement of the entire Cretaceous nappe complex onto the stable European foreland during Tertiary continent-continent collision.

ZUSAMMENFASSUNG

$^{40}Ar/^{39}Ar$-Datierungen wurden in den internen Ostalpen am Alpenostrand, den internen Westkarpaten, Südkarpaten und im Apuseni-Gebirge durchgeführt, um folgende Merkmale zu vergleichen: 1. das Alter der tektonischen und thermischen Überprägung in den Grundgebirgseinheiten; 2. das Ausmaß der alpidischen metamorphen Überprägung in permomesozoischen Deckgebirgseinheiten und 3. die Sequenz alpidischer duktiler Deformationsereignisse. Wie bereits vorher bekannt war, wurden alle diese fünf Gebirgsgruppen wesentlich durch kretazische tektonische Ereignisse geprägt.

Nachweisbare voralpidische tektonothermale Ereignisse reichen von frühcadomischer bis spätvariszischer Aktivität. Detritische Hellglimmer in ordovizischen und silurischen Sandsteinen der Ostalpen zeigen eine Verknüpfung zu cadomischen Liefergebieten (640-580 Ma). Die Grundgebirgseinheiten der Ostalpen, Westkarpaten und des Apuseni-Gebirges zeigen eine weite Altersvariation der prägenden penetrativen tektonischen Ereignisse, die von einer cadomischen (ca. 500 Ma) über eine frühvariszische (ca. 420-380 Ma) bis hin zu einer spätvariszischen (ca. 330-300 Ma) Entwicklung reicht. Im Gegensatz dazu zeigen die bisher untersuchten Grundgebirgseinheiten der Südkarpaten uniforme spätvariszische Abkühlalter im Anschluß einer amphibolitfaziellen Metamorphose. Damit scheinen die untersuchten Grundgebirgseinheiten insgesamt das Resultat einer langdauernden Zusammenführung von verschiedenen Krustenblöcken am Nordrand von Gondwana darzustellen. Die einheitlichen spätvariszischen Abkühlalter der Südkarpaten werden als das Resultat der Abkühlung von variszischen Krustenblöcken durch beginnende Extension und Zerbrechen von kontinentalen Krustenblöcken im Gebiet der zukünftigen Tethys interpretiert. Dies wurde auch durch den Nachweis spätvariszischer Mylonite (ca. 286 Ma) innerhalb der Südkarpaten bestätigt.

Innerhalb der alpidischen Entwicklung lassen sich folgende größere Entwicklungsschritte unterscheiden: 1. subduktionsbezogene Blauschiefermetamorphose der ozeanischen Meliata-Einheit der Westkarpaten während des späten Jura ($^{40}Ar/^{39}Ar$-Phengitalter zwischen ca. 160 und 150 Ma); 2. darauffolgende Subduktion von kontinentaler Kruste im Zuge einer angenommenen Kontinent-Kontinentkollision während der mittleren und frühen Spätkreide (ca. 120-86 Ma) mit Liegendpropagation von Überschiebungen, die in allen Profilen nachzuweisen ist. Dieses Ereignis schließt anscheinend auch die Eklogitmetamorphose kontinentaler ostalpiner Einheiten ein, deren folgende Abkühlung durch Amphibolalter zwischen 136-108 Ma nachgewiesen wurde; 3. intragosauische (späte Spätkreide) Abkühlung ostalpiner Einheiten in den Ostalpen und Westkarpaten, assoziiert mit großräumigen Abschiebungen in hohen Krustenniveaus mit Überschiebungen in tieferen Krustenniveaus (ca. 86-65 Ma). Dieses dritte Ereignis wird als Resultat einer lateralen Dehnung in einem generellen Kontraktionsregime interpretiert. Der gesamte kretazische Deckenstapel der internen Alpen und Karpaten erlebte während der tertiären «piggy back»-Platznahme über europäische Einheiten anscheinend keinerlei nachweisbare penetrative Überprägung.

Introduction

The Alpine-Carpathian orogen originated during collision of Europe with continental tectonic elements derived from Africa. These were initially separated by oceanic elements including the Penninic and at least part of the Tethyian tracts. Stratigraphic constraints and previously published geochronologic data suggest that initial phases of oceanic subduction occurred during the Cretaceous (e.g. "Early" Alpine tectonothermal events: Frank et al. 1976, 1983, 1987; Krist et al. 1992; Dimitrescu 1988; Kräutner et al. 1988; Cambel & Kral 1989). As a result, nappe assemblage and associated imbrication of internal units occurred within the Alpine-Carpathian orogen. However, the exact timing

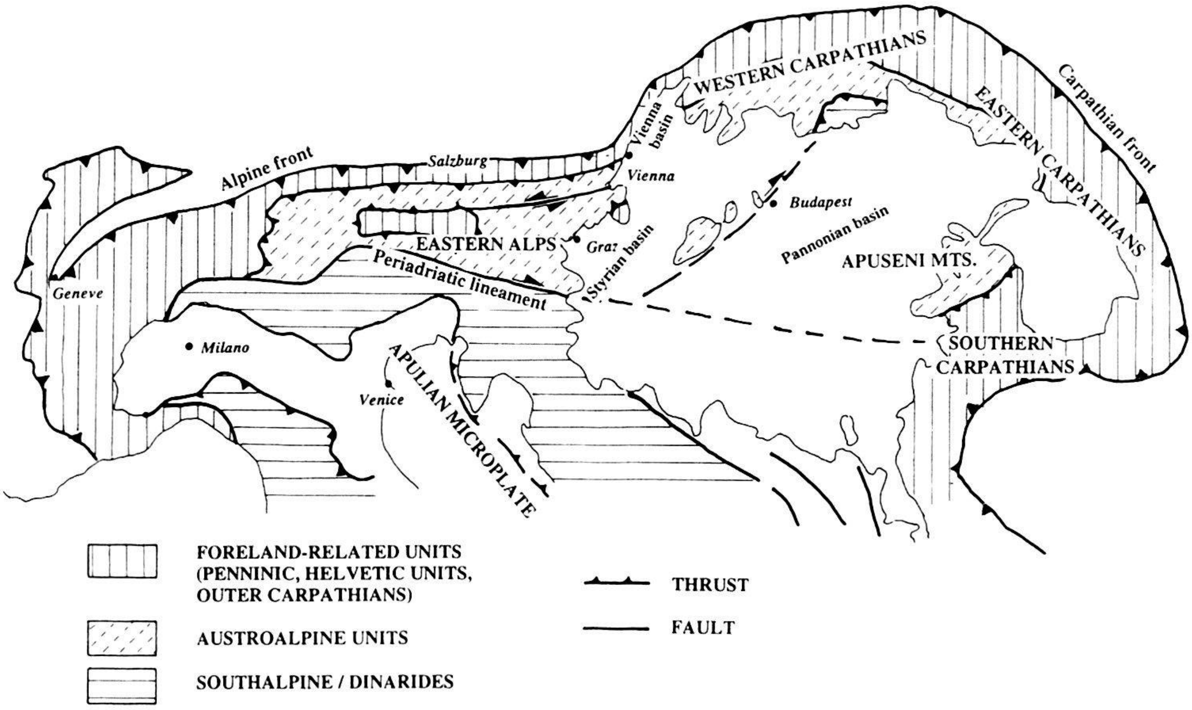

Fig. 1. Generalized map of the main tectonic elements comprising the Alps and Carpathian orogen.

of thrusting and the sequence of internal deformation from hangingwall to footwall has generally not been clearly resolved. Final collision of Europe and the Africa-derived continental elements occured in the Paleogene (Late Alpine orogenesis: e.g. Burchfiel 1980; Tollmann 1987; Trümpy 1988; Sandulescu 1984; Froitzheim et al. 1994; in press). Final collision resulted in emplacement of previously assembled nappe complexes onto external tectonic elements of the Alpine-Carpathian orogen. Therefore, the Paleogene collisional suture separates internal tectonic units which were affected by both Cretaceous and Paleogene penetrative Alpine deformation from external tectonic units which experienced only Late Alpine events. Resolution of the chronology of Alpine events and distinction from pre-Alpine evolution has been difficult within internal structural units which include basement units.

For detailed considerations of the timing of Alpine nappe assembly, the presence of Late Cretaceous sedimentary basins (so-called Gosau basins) in uppermost structural levels represents an important time marker. These Gosau basins are a common geologic feature of the area considered between Eastern Alps and Southern Carpathians (e.g. Burchfiel 1976; Sandulescu 1984; Tollmann 1977). These basins overstep Alpine nappes and yield, therefore, an upper bracket for the age of nappe assemly in high structural levels. The onset of sedimentation within these basins varies from c. early Santonian (c. 86 Ma following calibrations of Gradstein et al. 1994) to Campanian within internal Alps and Carpathians.

An extensive collaborative structural and $^{40}Ar/^{39}Ar$ geochronologic study has recently been completed within segments of the Eastern Alps and the Carpathians (Fig. 1). Results from several of the individual study areas have been published (Dallmeyer & Neubauer 1994; Neubauer et al. 1995), most have been presented in abstract form and/or in field guides, respectively (Antonitsch et al. 1994; Dallmeyer et al. 1992a, b; 1993; 1994a-f; Handler et al. 1992a, b, 1993a-c, 1994a-c, 1995; Müller et al. 1992). All of the data are currently in various stages of publication and complete analytical details will be available in the near future. (These manuscripts can be received from authors on request). The present contribution provides a general comparison of results from all the study areas and thus provides an important overview to: 1) document the tectonothermal evolution and establish correlations between pre-Alpine basement elements exposed within different Alpine structural levels; 2) resolve the timing, conditions and extent of Early Alpine (Cretaceous) metamorphism on both pre-Alpine basement and Permian-Mesozoic cover sequences; 3) evaluate regional trends in the diachronism of Early Alpine thrusting and nappe assembly; and, 4) determine the Late Alpine tectonothermal overprint on Cenozoic upper plate units throughout the Alpine-Carpathian orogen. The basis for the present contribution is comprised of an extensive data base reprented by $^{40}Ar/^{39}Ar$ incremental-heating ages determined for whole-rock phyllite/phyllonite and multigrain muscovite and hornblende concentrates prepared from samples collected within the Eastern Alps, the Western, Eastern and Southern Carpathians and the Apuseni Mountains.

In the present contribution reference will be made only to those analyses which have yielded unambiguous $^{40}Ar/^{39}Ar$ plateau ages and which are not complexed by potential contrasting interpretations of internally discordant spectra (e.g. mixed grain populations, incomplete rejuvenation of intracrystalline argon systems, etc.).

The general regional geologic setting of the individual study areas is described in the appropriate sections. $^{40}Ar/^{39}Ar$ plateau ages are shown on included geologic sketch maps (Fig. 2, 4, 6, 8) and are also relatively located on generalized tectonostratigraphic sections (Fig. 3, 5, 7, 9).

Methods

Different sample sets were collected from basement structural elements in order to resolve the record of the pre-Alpine tectonothermal evolution. $^{40}Ar/^{39}Ar$ ages were determined for multigrain mineral concentrates prepared from samples collected from medium- to high-grade pre-Alpine metamorphic basement within exposures which show no evidence of a penetrative medium- or high-grade metamorphic overprint during Alpine events. These mineral ages are interpreted to date cooling through temperatures appropriate for intracrystalline retention of argon following individual phases of the pre-Alpine tectonothermal evolution. In addition, concentrates of detrital muscovite were prepared from samples collected within very low- and low-grade metamorphic metasedimentary clastic sequences of the pre-Alpine basement. The resultant $^{40}Ar/^{39}Ar$ plateau ages are interpreted to date post-metamorphic and/or post-magmatic cooling within respective source areas prior to erosion and deposition within pre-Alpine basins.

Resolution of the Alpine tectonothermal record has been attempted through several techniques. In regions where temperatures of Alpine metamorphism exceeded those appropriate for intracrystalline argon retention, $^{40}Ar/^{39}Ar$ mineral plateau ages are interpreted to date post-Alpine cooling regardless of whatever pre-Alpine history is recorded. Within higher tectonostratigraphic levels of the Alpine-Carpathian orogen Alpine meta-

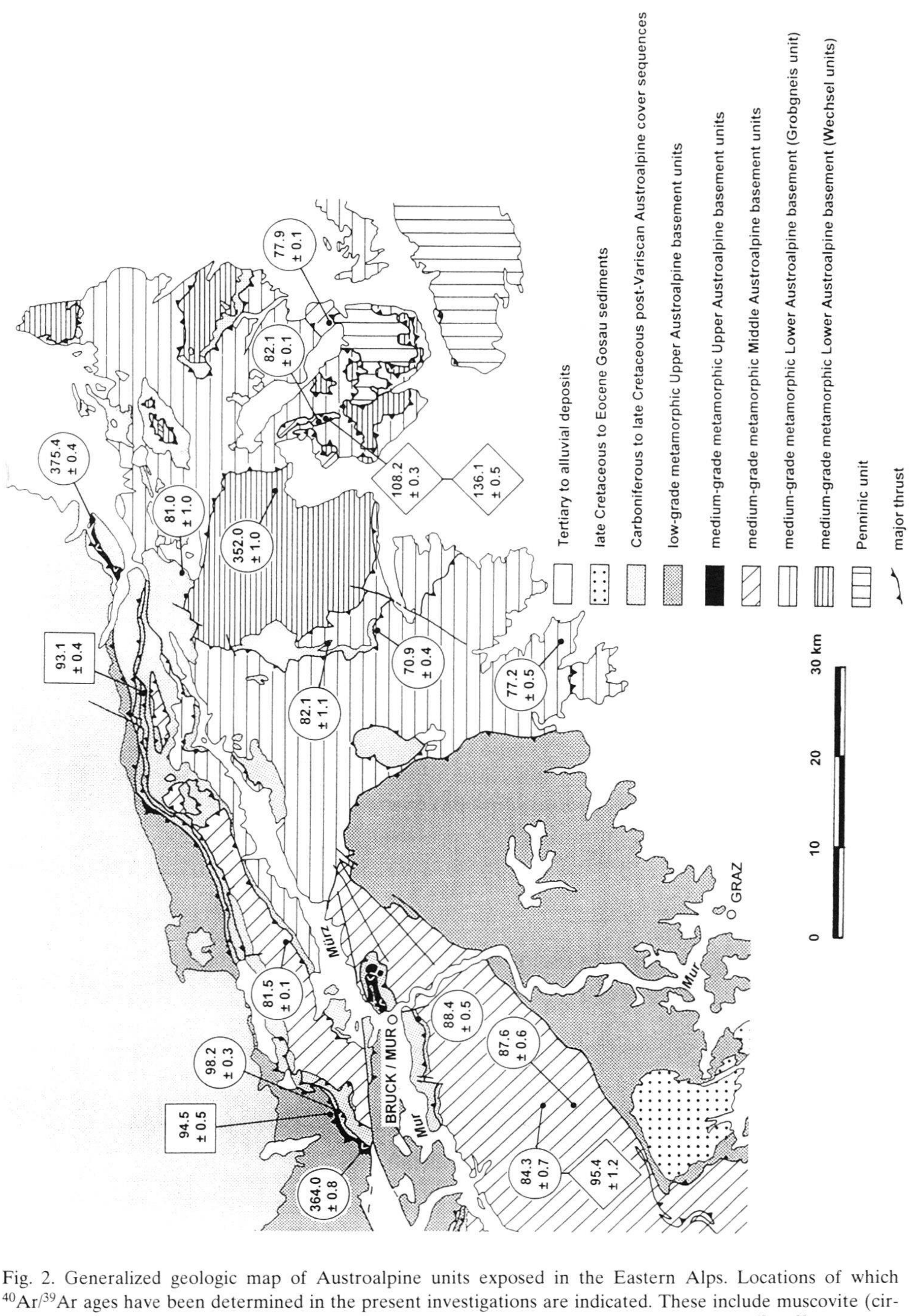

Fig. 2. Generalized geologic map of Austroalpine units exposed in the Eastern Alps. Locations of which $^{40}Ar/^{39}Ar$ ages have been determined in the present investigations are indicated. These include muscovite (circle), whole rock phyllite or phyllonite (square) and/or amphibole (diamond) concentrates. $^{40}Ar/^{39}Ar$ plateau ages are listed with two-sigma, intralaboratory uncertainties.

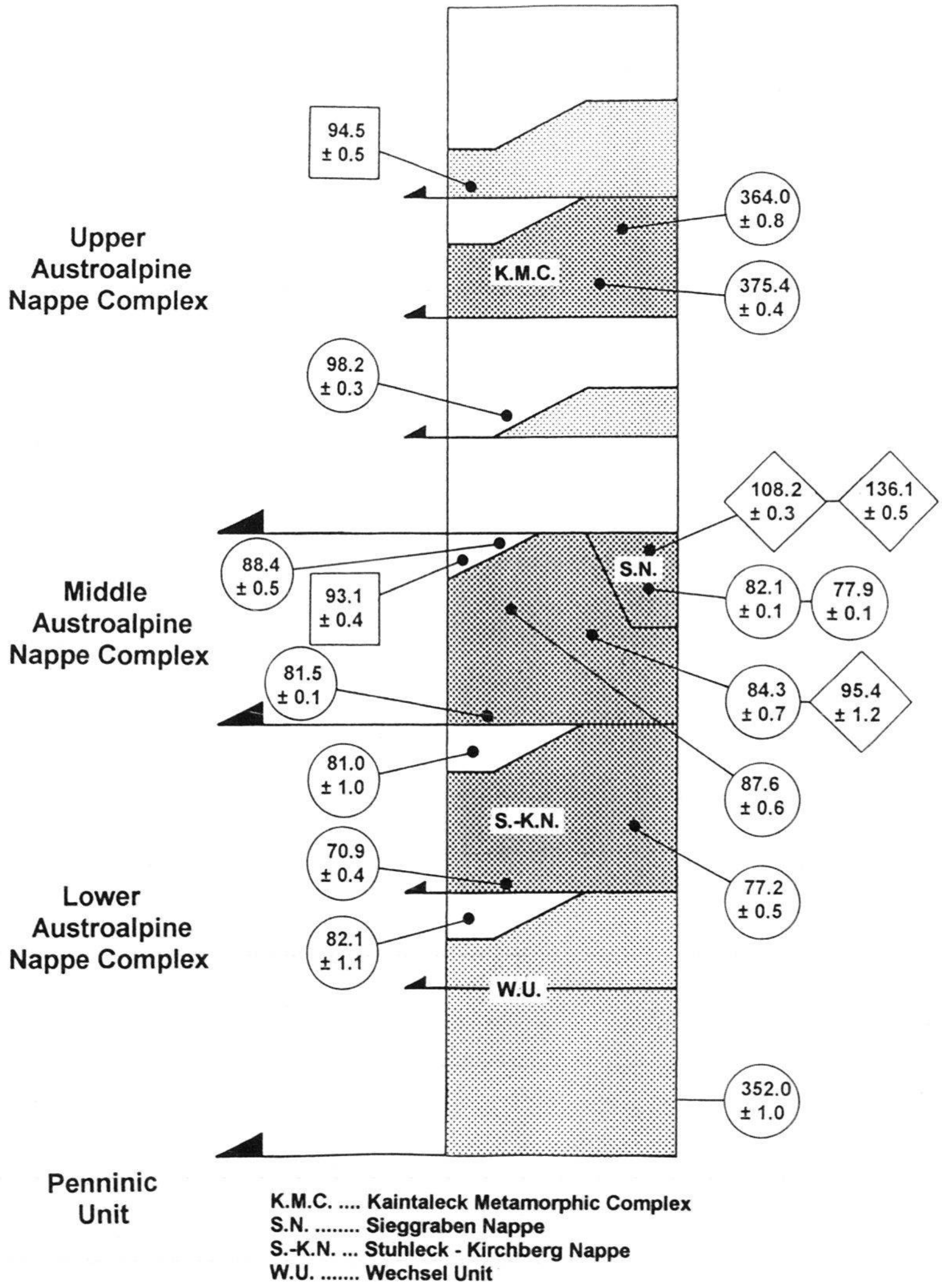

Fig. 3 Generalized tectonostratigraphy of Austroalpine units exposed in the Eastern Alps: white – Late Paleozoic-Mesozoic cover sequence; dark stipple – basement units recording pre-Alpine and/or Alpine amphibolite facies metamorphic mineral assemblages; stipple – basement units recording pre-Alpine greenschist facies metamorphic peak assemblages. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

morphic temperatures were generally relatively low and typically did not exceed those required for intracrystalline argon retention. In these settings fine- and very fine-grained muscovite was separated from penetratively deformed rocks. The $^{40}Ar/^{39}Ar$ plateau ages recorded are interpreted to closely date the time of synkinematic mineral growth associated with ductile deformation under greenschist facies metamorphic conditions. In some settings the synkinematic grain size was too small to allow mechanical separation. In these circumstances whole-rock samples of mica-rich phyllite or phyllonite (derived from metasedimentary or metafelsic volcanic protoliths) were prepared for analysis.

The $^{40}Ar/^{39}Ar$ results will be discussed in the context of the time-scale calibrations of Harland et al. (1989: Paleozoic) and Gradstein et al. (1994: Mesozoic).

Eastern Alps

Introduction

The Austroalpine nappe complex exposed in the Eastern Alps comprises an imbricated series of basement units which are separated by variably metamorphosed Permian-Mesozoic cover sequences along northern sectors. Units of the Austroalpine nappe complex exposed east of the Tauern Window (Fig. 2) have generally been described in terms of three contrasting, internally imbricated tectonostratigraphic elements, including (from hangingwall to footwall), the Upper, Middle and Lower Austroalpine Nappes (UA, MA and LA: e.g. Tollmann 1977, 1987; for alternative interpretations see Frank 1987). The grade of Alpine metamorphism recorded within the various structural units of the Austroalpine nappe complex systematically increases from north (very low- to low-grade) to south (amphibolite and local eclogite facies). Rb-Sr and K-Ar mineral ages previously reported for units of the MA exposed east of the Tauern Window were summarized by Frank et al. (1976, 1983, 1987; Neubauer & Frisch 1993). The present $^{40}Ar/^{39}Ar$ investigation focused on the various structural units of the Austroalpine nappe complex exposed within eastern sectors of the Eastern Alps (Fig. 2, 3).

Pre-Alpine history

A $^{40}Ar/^{39}Ar$ plateau age of c. 607 Ma was determined for a concentrate of detrital muscovite prepared from Ordovician-Silurian sandstones of the UA (Handler et al. 1994a). This documents a Cadomian source region in the Gondawanan hinterland. Late Proterozoic $^{40}Ar/^{39}Ar$ plateau ages have been previously reported for detrital muscovite from comparable sequences exposed in the Gurktal Nappe Complex (c. 540 Ma: Antonitsch et al. 1994) and in the Southalpine Carnic Alps (c. 640 Ma: Dallmeyer & Neubauer, 1994).

The age and extent of pre-Alpine tectonothermal activity is variable within the different basement structural units which comprise the Austroalpine nappe complex. Coarse-grained muscovite from discordant felsic pegmatite and aplitic gneiss of the Kaintaleck Nappe (UA) (Neubauer et al. 1994) record $^{40}Ar/^{39}Ar$ plateau ages of 364 Ma and 375 Ma (Handler et al. 1992a, b, 1993c). These ages suggest that basement of the Kaintaleck Nappe was affected by "Early" Variscan orogenesis (c. 400-380 Ma). By contrast, muscovite from other UA basement structural units (Ackerl Nappe) yielded $^{40}Ar/^{39}Ar$ plateau ages of c. 309 Ma which record cooling following Late Variscan ductile nappe stacking and associated tectonothermal activity (Neubauer & Dallmeyer, 1994). Muscovite concentrates prepared from basement lithologies within MA structural units generally record internally discordant $^{40}Ar/^{39}Ar$ apparent age spectra in which apparent ages systematically increase throughout experimental heating. Most gas fractions evolved at intermediate and high experimental temperatures record similar intrasample ages of c. 330-300 Ma (Handler et al. 1994b). These have been interpreted to date cooling through appropriate argon closure temperatures following Late Variscan orogenesis. The contrasting Variscan tectonothermal evolution of Austroalpine basement complexes is also recorded by constrasting $^{40}Ar/^{39}Ar$ apparent plateau ages of detrital white micas separated from post-Variscan cover sequences of the UA (Handler et al. 1994a). Muscovite from basement structural elements of the LA (Stuhleck-Kirchberg nappe) yield $^{40}Ar/^{39}Ar$ plateau ages of c. 320 Ma and date post Variscan cooling (Müller et al. 1992). Phengitic white mica from another LA structural units (Wechsel nappe) yielded $^{40}Ar/^{39}Ar$ plateau ages of c. 350 Ma which were interpreted to date cooling following an Early Variscan high-pressure metamorphism (Dallmeyer et al. 1992; Müller et al. 1992). Considered together, the general lack of rejuvenation of intracrystalline argon systems within most structural units of the Austroalpine nappe complex exposed along northern sectors of the Eastern Alps suggests that Alpine metamorphism within Upper and Lower Austroalpine units did not exceed c. 350 °C (Dallmeyer et al. 1992a, b; Handler et al., 1992b, 1993a; Müller et al. 1992; Neubauer & Dallmeyer, 1994). The $^{40}Ar/^{39}Ar$ plateau ages together with lithologic characteristics (e.g. Frisch & Neubauer, 1989) suggest a markedly constrasting pre-Alpine tectonothermal evolution for the various structural units of the basement which comprises the present-day Austroalpine nappe complex. It is likely that initial Variscan structural boundaries were at least locally reactivated during Alpine thrusting at relatively shallow crustal levels.

Alpine history

Results are discussed from hangingwall to footwall tectonic units within the Austroalpine nappe complex. Muscovite concentrates and whole-rock phyllite samples from penetratively deformed, progressively metamorphosed Permian-Lower Triassic cover sequences and from phyllonites and mylonites developed along ductile shear zones within basement sequences of the Austroalpine nappe complex record $^{40}Ar/^{39}Ar$ plateau ages which range between c. 98 Ma and 71 Ma (Dallmeyer et al. 1992a, b; Handler et al. 1993a, b, c, 1994c, 1995; Müller et al. 1992; Neubauer et al. 1995). Along the northern margin of the Austroalpine nappe complex muscovite concentrates record systematically decreasing $^{40}Ar/^{39}Ar$ plateau ages when traced from highest to lowest tectonostratographic levels. The ages decrease from c. 98 Ma within Permian cover of the UA (Silbersberg nappe) to c. 88 Ma in Permian cover of the MA, to c. 82 Ma within an Alpine mylonite developed in pre-Alpine basement exposed within lower structural levels of the MA. $^{40}Ar/^{39}Ar$ plateau ages defined in analyses of muscovite-rich whole-rock phyllite show a similar trend, and decrease from c. 95 Ma in Ordovician phyllite of the UA (Noric Nappe) to c. 93 Ma in penetatively cleaved Permian felsic metatuff of the MA. Within southernmost exposures of the MA hornblende records a plateau age of c. 95 Ma (Neubauer et al. 1995).

Variably retrogressed eclogite assemblages occur within the Sieggraben nappe (MA) exposed in klippen along the eastern margin of the Eastern Alps. $^{40}Ar/^{39}Ar$ plateau and isotope correlation ages of amphibole concentrates prepared from retrogressive assemblages range between c. 136 Ma and 108 Ma, and have been interpreted to date cooling following an early Middle Cretaceous high pressure metamorphism (Dallmeyer et al. 1992b). Muscovite from proximal garnet micaschist and orthogneiss record plateau ages

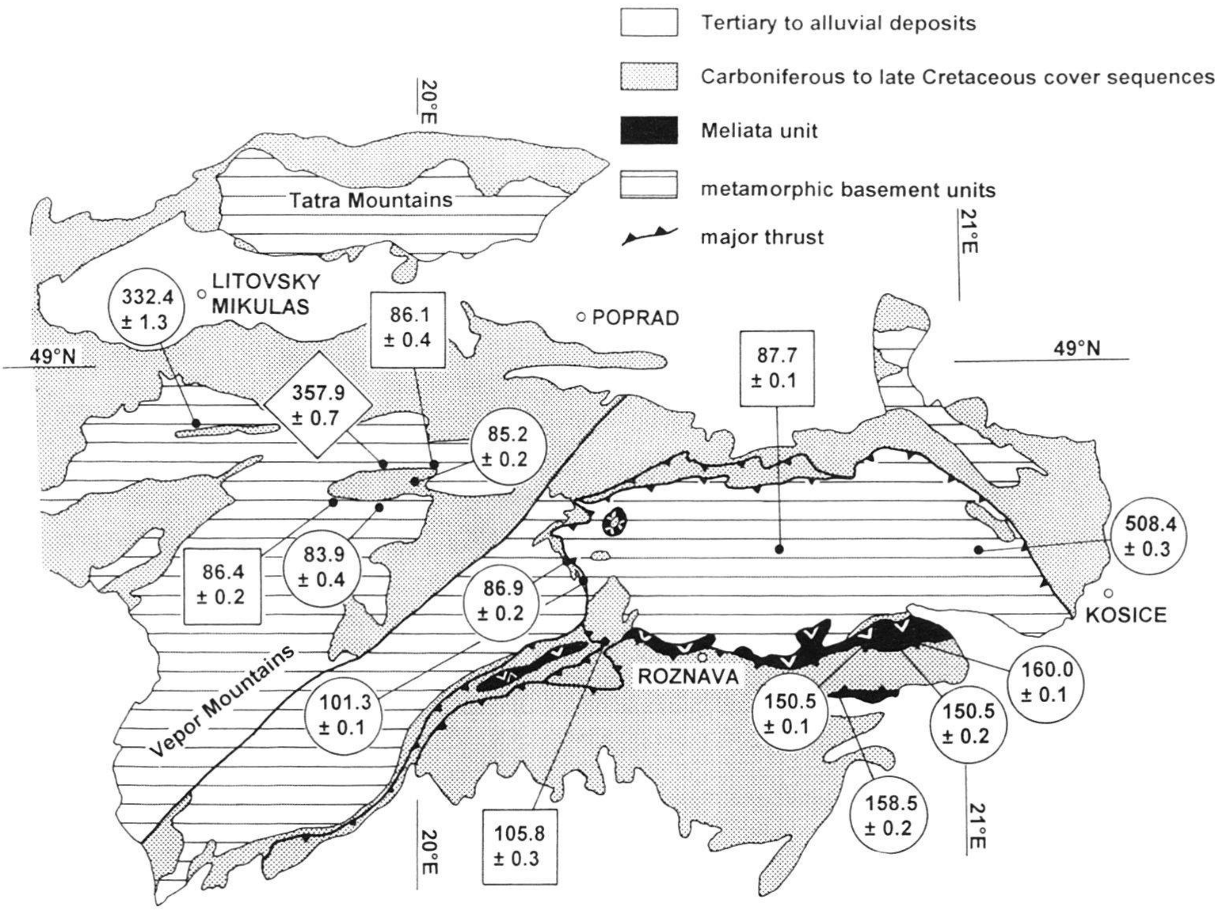

Fig. 4. Generalized geologic map comprising the internal Western Carpathians orogen. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

of 82 Ma and 78 Ma. These are similar to those recorded by muscovite in other exposures of the MA. Eclogite assemblages have also been described at the same general structural level in more western exposures of the MA (e.g. Frank 1987). Thöni and Jagoutz (1992, 1993) reported Cretaceous Sm/Nd ages for crystallization of the high pressure mineral assemblages.

Within structural units of the LA muscovite records $^{40}Ar/^{39}Ar$ plateau ages of c. 81 Ma to c. 71 Ma. Ages between c. 78 Ma and c. 71 Ma are recorded by muscovite concentrates prepared from mylonites along ductile shear zones locally developed in pre-Alpine basement of the LA (Stuhleck-Kirchberg Nappe). These have been interpreted to closely date the synkinematic growth of white mica during Alpine thrusting (Dallmeyer et al. 1992b). By contrast, muscovite from penetratively cleaved, progressively metamorphosed rocks of the Wechsel nappe records a slightly older age of c. 80 Ma. The inverse metamorphism zonation reflected along the tectonic contact between the Stuhleck-Kirchberg and structurally underlying Wechsel nappe is interpreted to be a result of an out-of-sequence thrust propagation with associated loading of deeper tectonic units onto structural elements which originated within relatively shallow crustal levels.

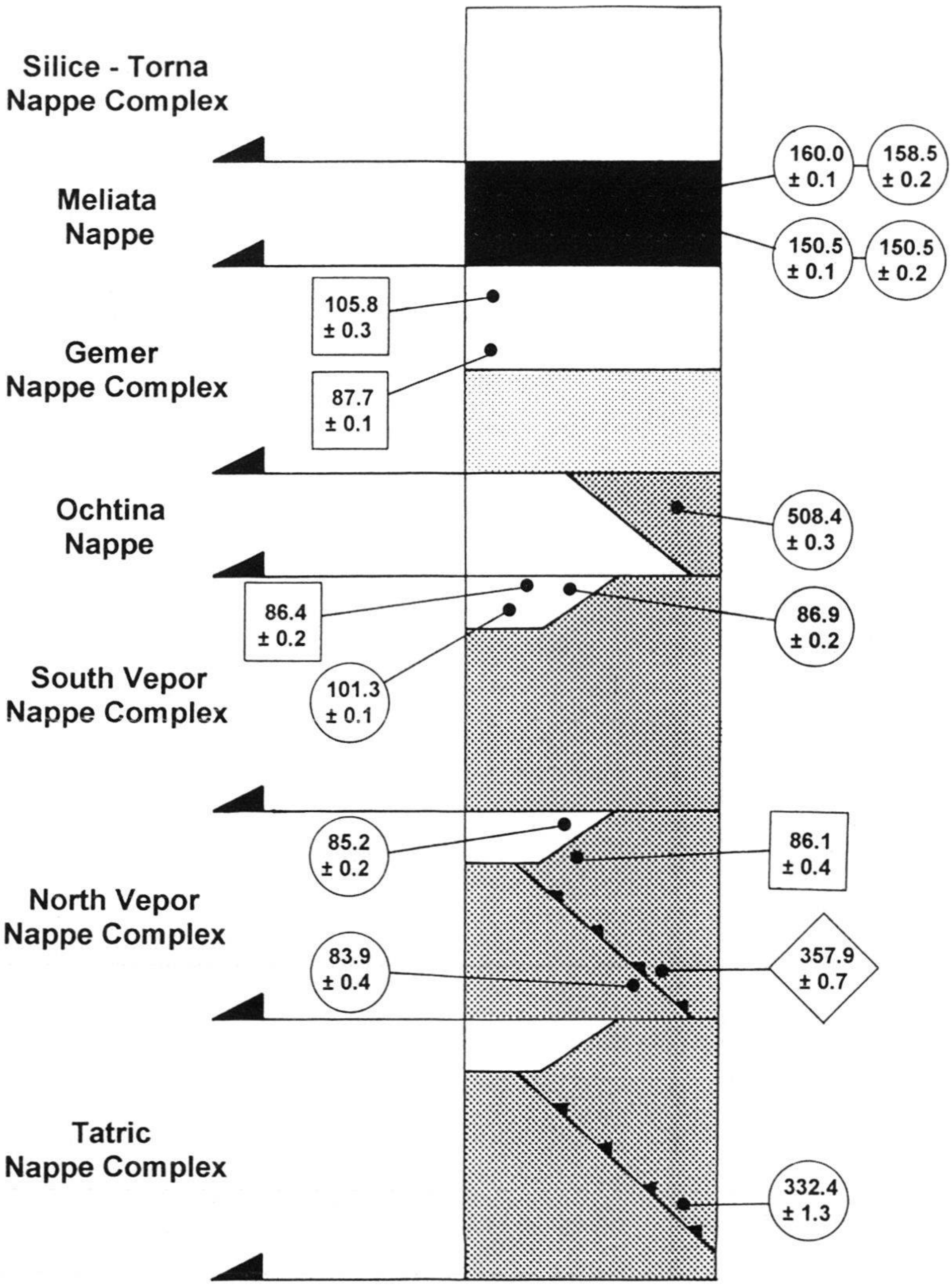

Fig. 5. Generalized tectonostratigraphy of the internal Western Carpathian orogen: black – Mesozoic oceanic sequences. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

Summary

In combination the new $^{40}Ar/^{39}Ar$ mineral and whole-rock age data from the Austroalpine nappe complex document a pre-Late Cretaceous eclogite facies metamorphism and an early Late Cretaceous ductile deformation associated with initial phases of Alpine nappe assembly. In general Alpine $^{40}Ar/^{39}Ar$ ages young tectonostratigraphically downward. This is consistent with regional stratigraphic relationships which indicate a pre-Santonian date (> 86 Ma: Gradstein et al. 1994) for Alpine nappe assembly and associated ductile deformation. Evidence includes the discordant overstep of clastic sequences deposited within "Gosau" basins. These sequences clearly postdate thrust imbrication within the Upper Austroalpine nappe complex within central Eastern Alps (e.g. Fritz 1988). Isotopic systems which record "intra-Gosauian" mineral ages (c. 86-65 Ma) within non-mylonitic basement exposed within the MA are interpreted to date exhumation and cooling following nappe assembly (Ratschbacher et al. 1989; Neubauer et al. 1995). By contrast intra-Gosauian mineral ages recorded within mylonites developed in basement of the LA are interpreted to date thrusting associated with initial nappe assembly in deeper crustal levels. This appears to have been contemporaneous with the extension recorded in more southern and relatively higher tectonostratigraphic levels (Dallmeyer et al. 1992a, b; Müller et al. 1992; Handler et al. 1995; Neubauer et al. 1995).

No Late Alpine overprint has been detected within LA units although these are in close tectonic contact with underlying Penninic units (Fig. 2) that are characterized by Late Alpine tectonothermal activity (Frank et al. 1987).

Western Carpathians

Introduction

The Western Carpathian orogen is largely represented by several internally imbricated nappe complexes comprised of pre-Alpine basement and variably metamorphosed (very low- to low-grade) Permian-Mesozoic cover sequences (e.g. Krist et al. 1992). These nappe complexes structurally overlie buried Penninic units and therefore occupy a tectonic level similar to that of the Austroalpine nappe complex. Traced tectonostratigraphically downward the major nappe complexes discussed here include (Fig. 4, 5): 1) Silice-Torna nappes (exclusively Mesozoic cover sequences); 2) the Meliata unit (Triassic oceanic sequences imbricated with high-pressure metasedimentary units); 3) Gemer nappes (low- to medium-grade metamorphic basement and cover); 4) northern and southern Vepor nappes (low-to medium-grade metamorphic basement and cover); and 5-6) supra-Tatric and Tatric nappes (predominantly basement and subordinate cover). Previously reported geochronological results have documented cooling following penetrative Variscan metamorphism and ductile deformation within the various basement structural units and a generally low-grade Alpine (Cretaceous) metamorphic overprint (Cambel & Kral 1989; Janak 1994; Krist et al. 1992; Dallmeyer et al. 1993; Maluski et al. 1993).

Pre-Alpine history

New $^{40}Ar/^{39}Ar$ results from the Western Carpathians suggest a more complex tectonothermal evolution as suggested in previous studies. A Cadomian record is reflected in a c. 508 Ma plateau age recorded by synkinematic muscovite in the tectonostratigraphically higher levels of basement represented by the Gemer nappe complex (Smolnik formation). Synkinematic hornblende and muscovite within the Veporic nappe complex record post-Variscan cooling ages of c. 358 Ma and c. 330-312 Ma respectively. Synkinematic muscovite from a retrogressed mylonite associated with a regional scale fault records a

c. 330 Ma plateau age. Muscovite concentrates prepared from non-mylonitic basement elements within the Tatric nappe complex are generally characterized by internally discordant $^{40}Ar/^{39}Ar$ spectra in which apparent ages systematically increase throughout incremental heating experiments to define high-temperature ages of c. 330-325 Ma.

Several muscovite concentrates from the Tatric nappe complex record well-defined plateau ages of c. 330-325 Ma. However, most concentrates are characterized by internally discordant $^{40}Ar/^{39}Ar$ spectra in which apparent ages systematically increase throughout the incremental heating analyses to define high-temperature ages of c. 325-300 Ma. Spectra discordance is interpreted to reflect variable Alpine rejuvenation of intracrystalline argon systems.

Alpine history

Phengitic white micas within the Meliata unit record well-defined plateau ages which range between 160 Ma and 150 Ma (Maluski et al. 1993; Dallmeyer et al. 1994c; own unpubl. data). These have been interpreted to date crystallization during maintenance of high-pressure conditions. Markedly younger Alpine ages are recorded within cover sequences in lower structural units. These include $^{40}Ar/^{39}Ar$ plateau ages of muscovite and whole-rock phyllite which range from c. 106 Ma to 82 Ma. Older ages are generally preserved within cover associated within higher tectonostratigraphic levels (Gemer nappe complex). Muscovite within mylonitic rocks associated with ductile, low-angle normal faults (e.g. Pohorela Line, Veporic nappe complex) records plateau ages of c. 90-84 Ma.

Summary

The new $^{40}Ar/^{39}Ar$ results in combination with previously reported geochronology suggests that at least two different basement terranes occur within the different nappe complexes which comprise the Western Carpathian orogen (Dallmeyer et al. 1993; 1994b, c). These record a contrasting pre-Alpine history which includes both Cadomian and Variscan tectonothermal events. A major Variscan suture is likely to have separated these terranes (e.g. Krist et al. 1992).

Ages recorded by synkinematic muscovite associated with development of mylonites along low-angle normal faults are interpreted to record subsidence of Late Cretaceous (Gosau) sedimentary basins by extension within intermediate crustal levels (Putis 1994). A history comparable with the Eastern Alps is suggested. Apparent ages older than c. 86 Ma are interpreted to date initial phases of "pre-Gosauian" nappe assembly. Older ages are at least locally recorded within mylonites developed along faults which separate major Alpine tectonic elements. Ages younger than c. 86 Ma are generally synchronous with deposition within Gosau basins which locally developed on Vepor units. The younger ages are interpreted to date uplift and associated activation of ductile normal faults which record a generally top-to-the-E or -ESE translation of hangingwall units (own unpubl. data).

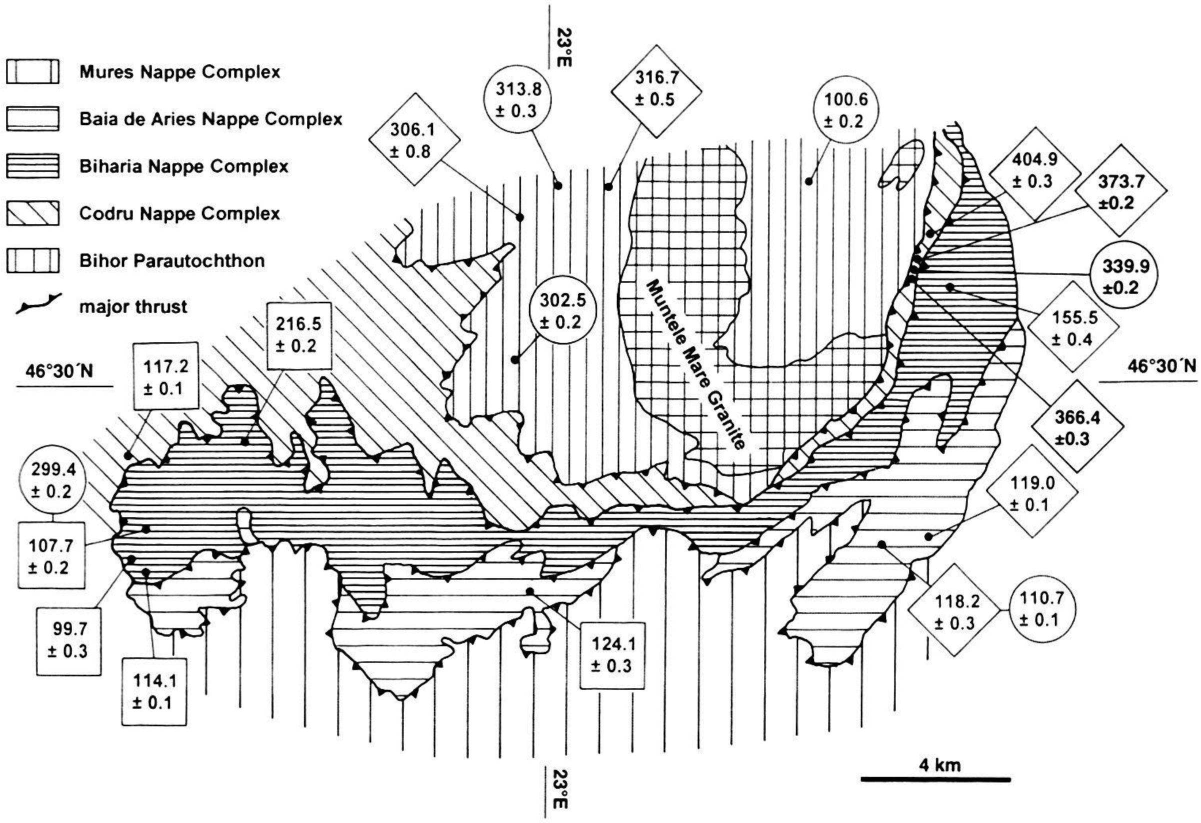

Fig. 6. Generalized geologic map of the tectonic units exposed in the Apuseni Mountains. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

Apuseni Mountains

Introduction

Previous workers have considered metamorphic basement rocks exposed in the Apuseni Mountains to have evolved in three distinct tectonothermal cycles, with the highest grade metamorphic sequences being considered as being the oldest units (see reviews in Burchfiel 1976; Sandulescu 1984; Dimitrescu 1988). Previous models have considered the amphibolite facies metamorphic units (e.g. Somes, Codru, Baia de Aries and Madrigesti series) to have evolved during a Middle Proterozoic tectonothermal event. Epidote-amphibolite facies metamorphic units (e.g. Biharia, Arada and/or Bistra series) were considered to reflect an Upper Proterozoic or Early Palaozoic (Caledonian) orogenic event. Relatively low-grade, greenschist facies metamorphic sequences (Paiuseni, Arieseni, Muncelu, Belioara, Vidolm and Trascau series) have traditionally been considered to have evolved during Late Paleozoic (Variscan) orogeny. The location of boundaries between the contrasting metamorphic sequences has been argued, and there have been conflicting interpretations of the tectonic character of unit boundaries and the age and origin of protoliths. The effects of Alpine orogenesis have generally been considered only in terms of rigid thrust sheets with relatively insignificant internal ductile strains (Burchfiel 1976; Dimitrescu 1988; Sandulescu 1984 and references cited therein).

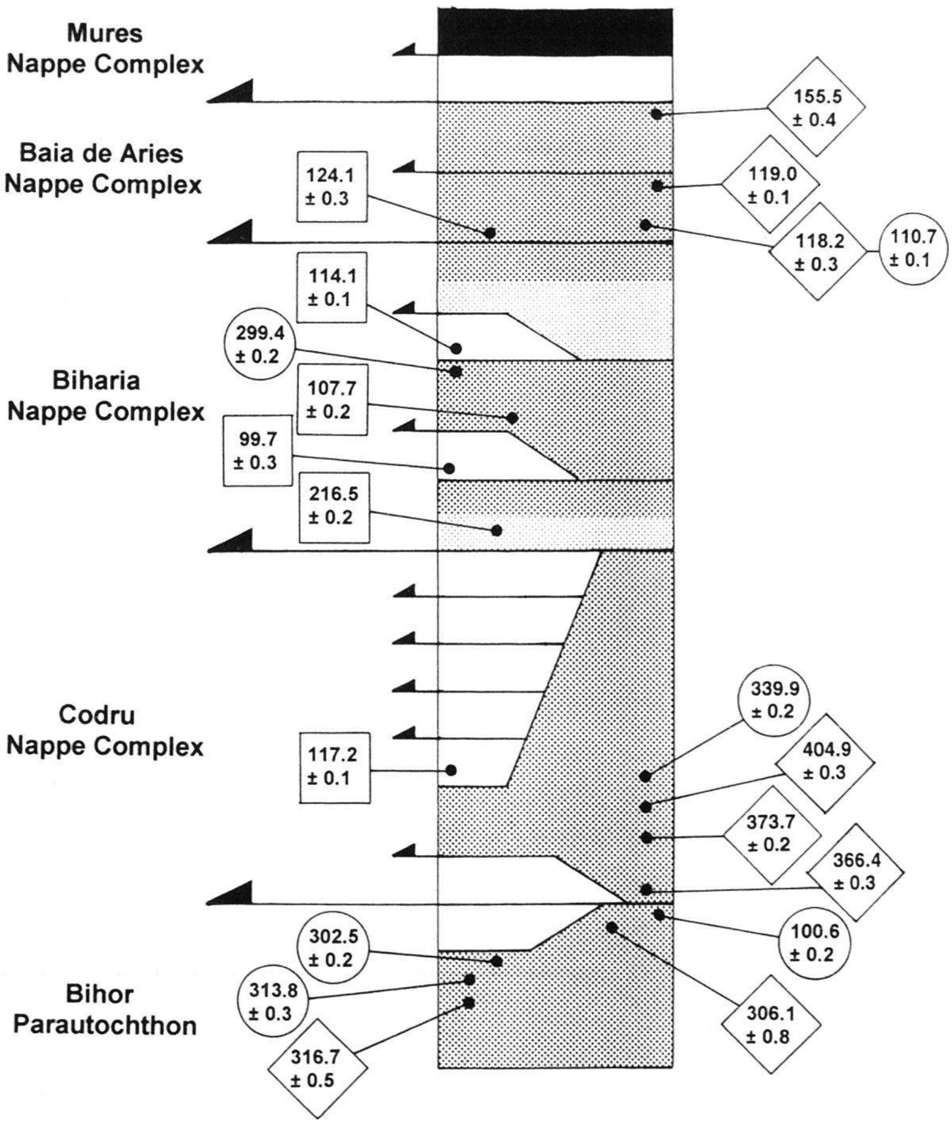

Fig. 7. Generalized tectonostratigraphy of the Apuseni Mountains: black – Mesozoic oceanic sequence. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

Recent detailed mapping by Pana (unpubl.) has enabled recognition of a regionally correlative succession of tectonic units involving four distinct, internally imbricated nappe complexes. Traced tectonostratigraphically downward these include (Fig. 6, 7): 1) the Mesozoic Mures ophiolite nappe; 2) the Baia de Aries nappe complex which consists of medium grade metamorphic assemblages which include plagiogneiss, micaschist, amphibolite, variably dolomitic marble, granite, pegmatite and quartzite; (polydeformational fabrics indicate a complex tectonothermal evolution); 3) the Biharia nappe complex which is represented by several structurally imbricated nappes composed of variably metamorphosed Permian-Mesozoic cover sequences in depositional and/or tectonic contact with metamorphic basement (largely comprised of magmatic arc elements which include variably metamorphosed gabbrodiorite and mafic to felsic subvolcanic units which are host to numerous granitic stocks and rhyolite dikes); 4) the Codru nappe complex composed of structurally interlayered Permian-Mesozoic cover and basement elements characterized by gabbro-diorite, dolerite, microdiorite and amphibolite (all cross-cut by granite and granodiorite); and, 5) the Bihor autochthon. The Bihor autochthon is represented by plagiogneiss, amphibolite, micaschist and variably deformed granite. This lithologic association underwent a medium-grade polyphase metamorphism and concomitant deformation prior to intrustion of the megacrystic Muntele Mare granite. We suggest that initial post-metamorphic uplift of the Bihor gneissic terrane from mid-crustal levels is recorded by sillimanite-bearing mylonitic gneisses that developed along low-angle shear zones (Pana & Erdmer 1994). The ductile, low-angle fabrics are everywhere overprinted by more steeply dipping fabrics formed during maintenance of greenschist grade metamorphic conditions. The ductile to brittle fabrics have been interpreted to represent a late, low-grade metamorphic detachment zone developed during extensional exhumation of the Bihor gneissic terrane. Lithotype associations exposed within the low-grade metamorphic detachment correspond tho what has traditionally been termed the Arada series (previously interpreted to represent a Late Proterozoic volcanic-sedimentary association which experienced Caledonian metamorphism: Dimitrescu 1988). Eastern sectors of the Bihor gneissic terrane record an increasingly significant, relatively low-temperature retrogression and mylonitization.

Pre-Alpine history

Results are discussed here from footwall to hangingwall tectonic units. Concentrates of hornblende and muscovite prepared from representative samples of high-grade metamorphic lithothypes exposed in north and northwestern sectors of the Bihor autochthon (Somes series) record mutually similar well-defined. $^{40}Ar/^{39}Ar$ plateau ages which range between c. 317 Ma and 306 Ma. These are interpreted to date relatively rapid cooling following penetrative Late Variscan orogenesis. No record of any earlier tectonothermal activity is preserved. The suggested rapid cooling is consistent with a rapid uplift effected by tectonic exhumation along low-angle extensional faults. A muscovite concentrate prepared from mylonitic quartzite collected within the proposed low-grade metamorphic detachment zone (Arada series) records a c. 303 Ma plateau age which is interpreted to closely date extensional exhumation of the Bihor gneissic terrane. Hornblende concentrates from amphibolites comprising part of the basement within structural units of the Codru nappe record plateau ages of c. 373-365 Ma. Muscovite within proximal felsic gneisses yield slightly younger $^{40}Ar/^{39}Ar$ plateau ages of c. 340-335 Ma. Together the Codru data are interpreted to date cooling through contrasting argon retention temperatures following phases of Early Variscan orogenesis.

A concentrate of detrital muscovite prepared from a metaconglomerate within the Biharia Nappe Complex displays a well-defined c. 300 Ma plateau age reflecting a Variscan metamorphic or plutonic source.

Alpine history

Concentrates of hornblende and muscovite prepared from samples collected in southern sectors of the Bihor Autochthon are generally characterized by internally discordant

$^{40}Ar/^{39}Ar$ age spectra in which apparent ages generally increase throughout low-temperature portions of the analyses. Most samples record intermediate- and high-temperature plateaus defining ages of c. 320-300 Ma. These discordant spectra suggest minor Alpine rejuvenation of initial Variscan isotopic systems. Muscovite separated from mylonitic gneisses associated with discrete ductile shear zones developed in eastern sectors of the Bihor autochthon yield ages of 101 Ma. A whole-rock phyllonite sample collected within a sinistral ductile shear zone developed in the Baia de Aries nappe complex yields an intermediate- and high-temperature plateau age of c. 217 Ma. This may record local thermal and/or structural rejuvenation during the Triassic extension documented in the Apuseni region by Pana & Erdmer (1994).

Whole-rock samples of phyllonite collected within northwest-vergent ductile shear zones developed in the Biharia nappe complex yield well-defined intermediate- and high-temperature plateau ages which range between c. 117 Ma to 100 Ma. These are interpreted to closely date "mid"-Cretaceous phases of Alpine nappe assembly. Hornblende and muscovite concentrates prepared from amphiolite and mylontic granite collected within the Baia de Aries nappe complex (Muncel Nappe) yield similar well-defined plateau ages which range between c. 119 Ma and 111 Ma. These record the effects of a penetrative Alpine deformation which was associated with metamorphic temperatures in excess of c. 500 °C.

Summary

The new $^{40}Ar/^{39}Ar$ ages suggest that contrasting basement units are exposed within the Apuseni mountains (Dallmeyer et al. 1994d, f). Basement exposed within Codru structural elements appears to have been affected by Early Variscan orogenic events whereas that within the extensive Bihor autochthon records Late Variscan orogenic activity. The data suggest that the intensity of Alpine overprint increases from northwest to east and southeast across the Bihor autochthon. Complete rejuvenation is locally recorded in easternmost ductile shear zones. A similar spatial trend is apparent in the Baie de Aries nappe complex where middle amphibolite facies Alpine metamorphism is clearly recorded in eastern exposures. The timing of the Alpine tectonothermal overprint appears to have been generally similar throughout the Apuseni mountains with most hornblende, muscovite and whole-rock phyllonite ages ranging between c. 118 and 110 Ma. Post-Alpine cooling therefore must have occurred prior to the overlying, discordant deposition of Late Cretaceous sequences (Santonian to Maastrichtian) within Gosau basins exposed in the Transsylvanian Depression.

Southern Carpathians

Introduction

The South Carpathian orogen exposes an extensive sequence of allochthonous basement units which comprise a series of nappe complexes that are structurally interleaved with variably metamorphosed, predominantly Jurassic cover sequences (e.g. Sandulescu 1984; Kräutner et al. 1988; Berza & Iancu 1994). Traced tectonostratigraphically downward these include (Fig. 8, 9): 1) the Supra-Getic nappe complex composed largely of high-

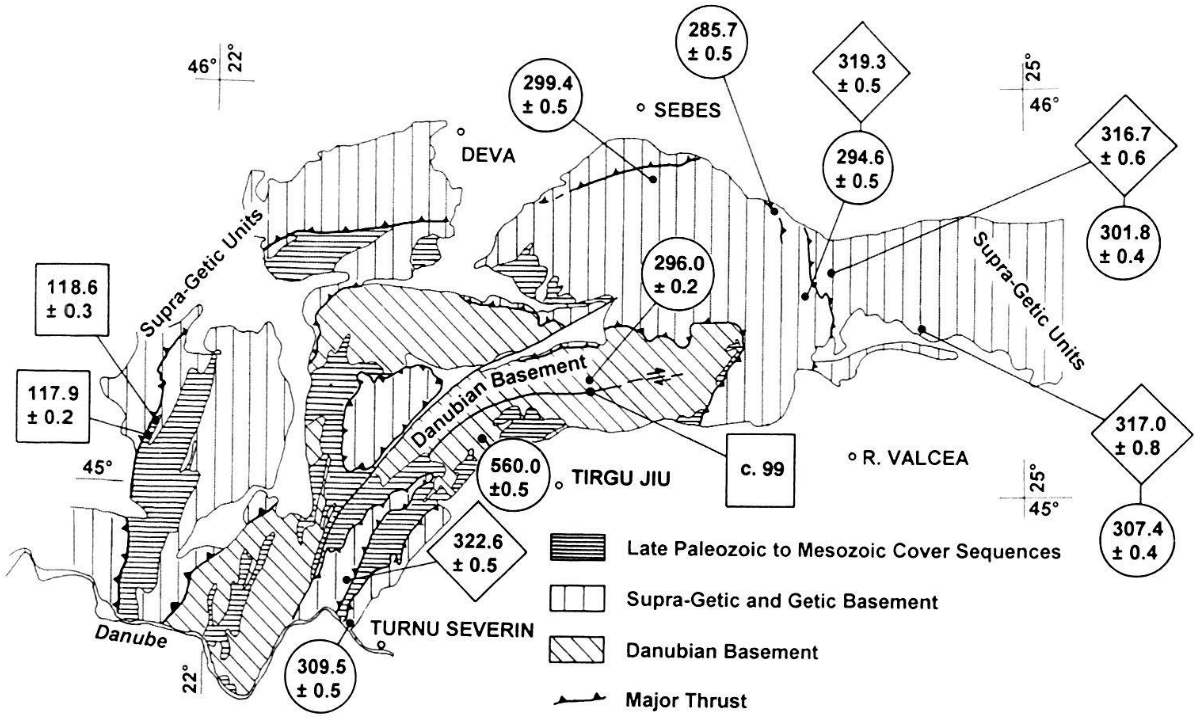

Fig. 8. Generalized geologic map of tectonic units comprising the Southern Carpathian orogen: black – Mesozoic oceanic sequences. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

grade metamorphic rocks; 2) the Getic nappe complex also composed of high-grade metamorphic units (including local exposures of variably retrogressed eclogite assemblages); 3) the Severin nappe which is represented by contrasting Jurassic-Cretaceous oceanic sequences including fragmented ophiolite and marine turbidites; and, 4) the Danubian nappe complexes which appear to consist of two distinct complexes (upper and lower) composed largely of high-grade metamorphic rocks. The intensity of Alpine tectonothermal activity recorded in the Southern Carpathians is generally low and only locally exceeds middle greenschist facies metamorphic conditions. Complex pre-Alpine relationships have been resolved (e.g. Grünenfelder et al. 1983; Sandulescu 1984; Ratschbacher et al. 1993; Berza et al. 1994). The high-grade metamorphism and associated ductile deformation recorded in the various basement elements have generally been regarded as Middle Proterozoic in age (e.g. Sandulescu 1984; Kräutner et al. 1988, and references cited therein).

Pre-Alpine history

An extensive sample suite has been dated from representative, non-retrogressed basement lithologic elements of the Southern Carpathians. A muscovite concentrate was prepared from a high-grade metamorphic gneiss comprising part of the lower Danubian nappe complex (Lainici-Paius Group). It recorded a c. 560 Ma $^{40}Ar/^{39}Ar$ plateau age suggesting that at least a local record of Precambrian orogeny is preserved. However, all

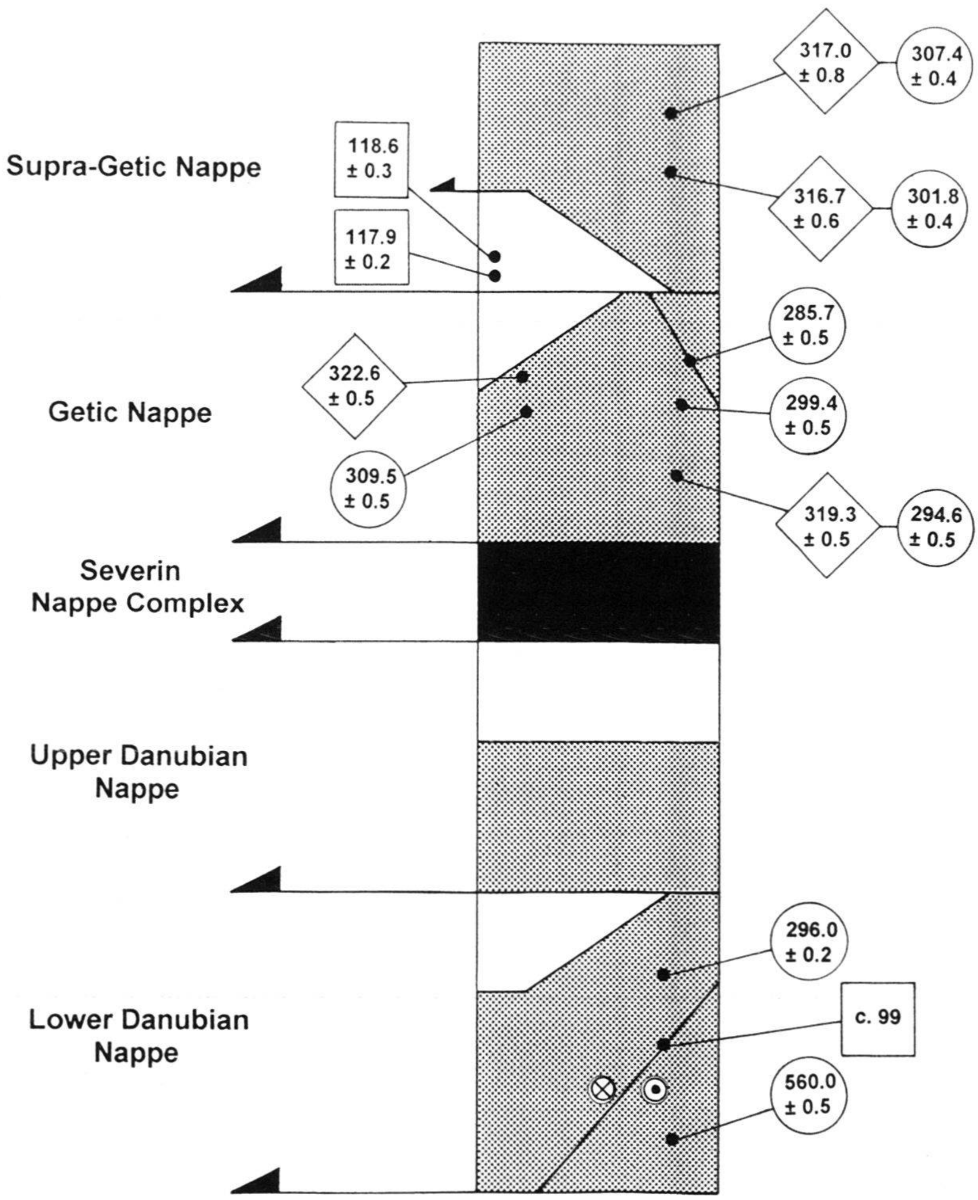

Fig. 9. Generalized tectonostratigraphy of the Southern Carpathian orogen. $^{40}Ar/^{39}Ar$ plateau ages indicated as in Figure 2.

other concentrates prepared from high-grade metamorphic samples yield markedly younger (Variscan) ages. For example, hornblende from amphibolite in the Upper Danubian nappe complex records a c. 288 Ma plateau age. Muscovite from the same structural level yields a c. 296 Ma plateau age. Hornblende and muscovite from eastern sectors of the Getic nappe complex yield plateau ages of c. 319-299 Ma. Hornblende and muscovite within southwestern exposures of the Getic nappe complex yield ages of c. 323-310 Ma.

Muscovite within a mylonite developed along a ductile shear zone, which is interpreted to tectonically separate the Supra-Getic and Getic nappe complexes, recorded a 286 Ma plateau age. This is interpreted to closely date this tectonic phase of nappe assembly.

Concentrates of hornblende and muscovite from Supragetic structural elements exposed in the Fagaras Mountains yielded plateau ages which range between 317 Ma and 302 Ma.

Alpine history

A sample of phyllonite was collected within a ductile shear zone developed along an intra-Danubian thrust interpreted to reflect a pre-Alpine (Variscan) tectonic contact (e.g. Berza et al. 1994). A whole-rock of the sample yielded a well-defined 99 Ma plateau age, suggesting at least local Alpine reactivation. Two samples of Late Carboniferous phyllite were collected along the thrust contact between the Supra-Getic and Getic nappes close to the western margin of the South Carpathian orogen. These yielded similar, well-defined whole-rock plateau ages of 119-118 Ma. These ages are interpreted to date penetrative deformation within high tectonic levels of the South Carpathian orogen.

Summary

The new $^{40}Ar/^{39}Ar$ data from the South Carpathian orogen suggest that all basement elements experienced a penetrative and relatively high-grade Late Variscan tectonothermal overprint of generally similar age (Dallmeyer et al. 1994e). In addition, Late Carboniferous sedimentary sequences unconformably overlie westernmost exposures of Getic and Danubian structural units (Nastaneasu 1987). These suggest that large-scale crustal extension resulted in exhumation and associated Late Carboniferous cooling of basement elements following Variscan orogenesis. The effects of any older activity appear to be only locally preserved in intracrystalline argon systems. The new data suggest that some of the major tectonic boundaries (e.g. supra-Getic/Getic in easternmost sectors of the South Carpathian orogen) are at least in part also of Variscan age. However, the data also suggest that at least locally penetrative Alpine reactivation occurred with resultant resetting of argon systems between 120 and 100 Ma.

Regional Tectonic Significance

The new $^{40}Ar/^{39}Ar$ ages determined within the various representative study areas have regional significance for resolution and understanding of the pre-Alpine and Alpine tectonothermal evolution within the Alpine-Carpathian orogen.

Nearly unmetamorphic Early Paleozoic sequences occur in high structural levels in Eastern Alps and Western Carpathians. Detrital white mica from low-grade, Ordovician-Silurian clastic basement sequences exposed in the Eastern Alps suggest linkages with Cadomian sources. This is also recorded in metamorphic units of comparable structural position within the Western Carpathians.

The higher-grade metamorphic pre-Alpine basement exposed within the Austroalpine nappe complex (Eastern Alps) and sectors of the Western Carpathians and Apuseni Mountains are represented by locally contrasting structural units. The $^{40}Ar/^{39}Ar$ ages indicate that the various basement units have been at least locally affected by Cadomian and Early Variscan tectonothermal activity. Following most recent tectonic reconstructions, the Eastern Alps, Western Carpathians and Apuseni Mountains appear to represent a collage of contrasting basement units which were tectonically juxtaposed during

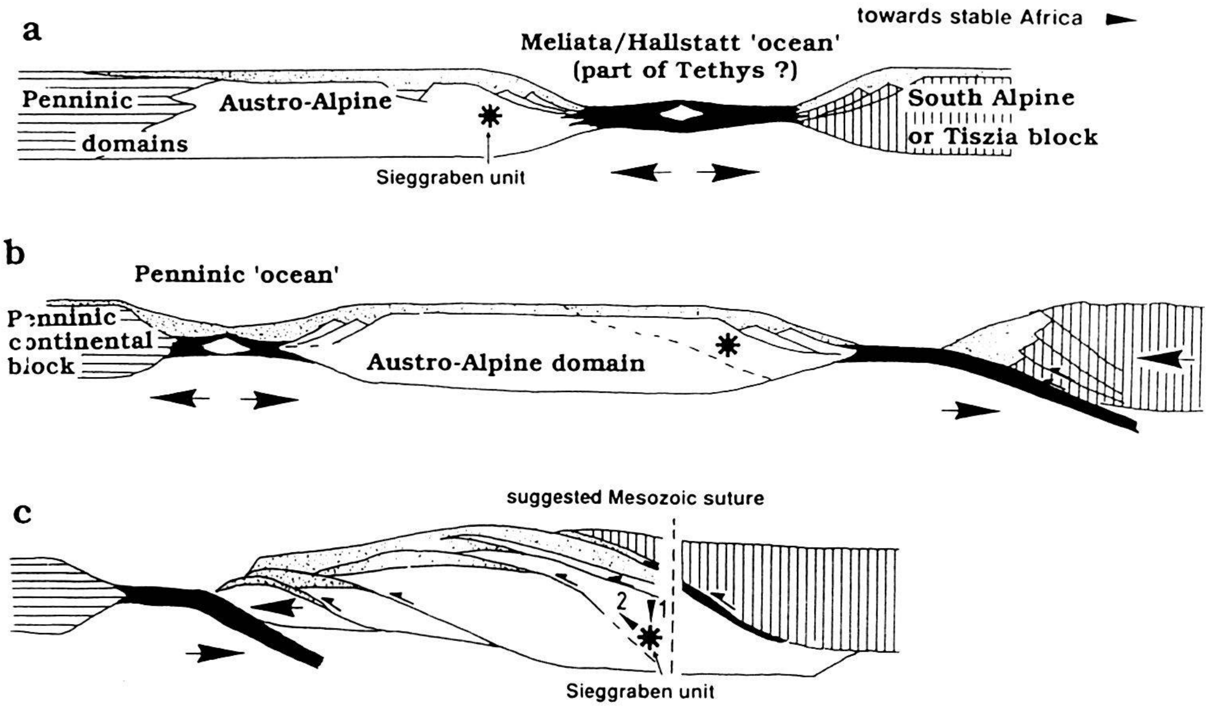

Fig. 10. Mesozoic tectonic evolution of the Western Carpathian orogen and the Eastern Alps. This included: 1) Formation of the Meliata-Hallstatt oceanic realm to the SE of the future Austroalpine realm; 2) Late Jurassic subduction of elements of the Meliata ocean; 3) Cretaceous A-type subduction with resultant eclogite metamorphism. The eclogite-bearing Sieggraben unit (Fig. 2) is located with a star. Modified from Neubauer (1994).

Variscan orogenic activity along northern margins of Gondwana (e.g. Neubauer & von Raumer 1993; von Raumer & Neubauer 1993, and references) Intervening pre-Alpine tectonic contacts appear to have been at least locally reactivated during Early Alpine tectonic events between c. 120 and 70 Ma. These basement units are presently exposed within relatively high tectonostratigraphic levels within their respective nappe complexes.

The majority of basement exposed in the Alpine-Carpathian orogen appears to be represented by high-grade metamorphic sequences which experienced at least middle amphibolite facies metamorphism and concomitant penetrative deformation in the Late Variscan. Units affected by Early Variscan orogenesis occur in high and deepest present-day structural levels (e.g. Kaintaleck and Wechsel Complexes, Eastern Alps). By contrast, intracrystalline argon systems within most basement units exposed in the Southern Carpathians only record Late Variscan tectonothermal activity. The relatively uniform post-Late Variscan, Late Carboniferous to Early Permian mineral cooling ages likely reflect regional scale uplift that appears to have been associated with cooling along rift shoulders developed during initial extension related to the formation of Tethys (as represented by the presence of Late Carboniferous to Permian marine sedimentary and volcanic sequences that overstep Variscan metamorphic crust). This interpretation is supported by the Early Permian ages recorded by synkinematically grown muscovite within mylonites which are associated with ductile shear zones in the Eastern Alps (LA) and Southern Carpathians. These zones appear to have been related to dextral, likely transtensional shearing of Europe relative to Gondwana (e.g. Arthaud & Matte 1977; Brand-

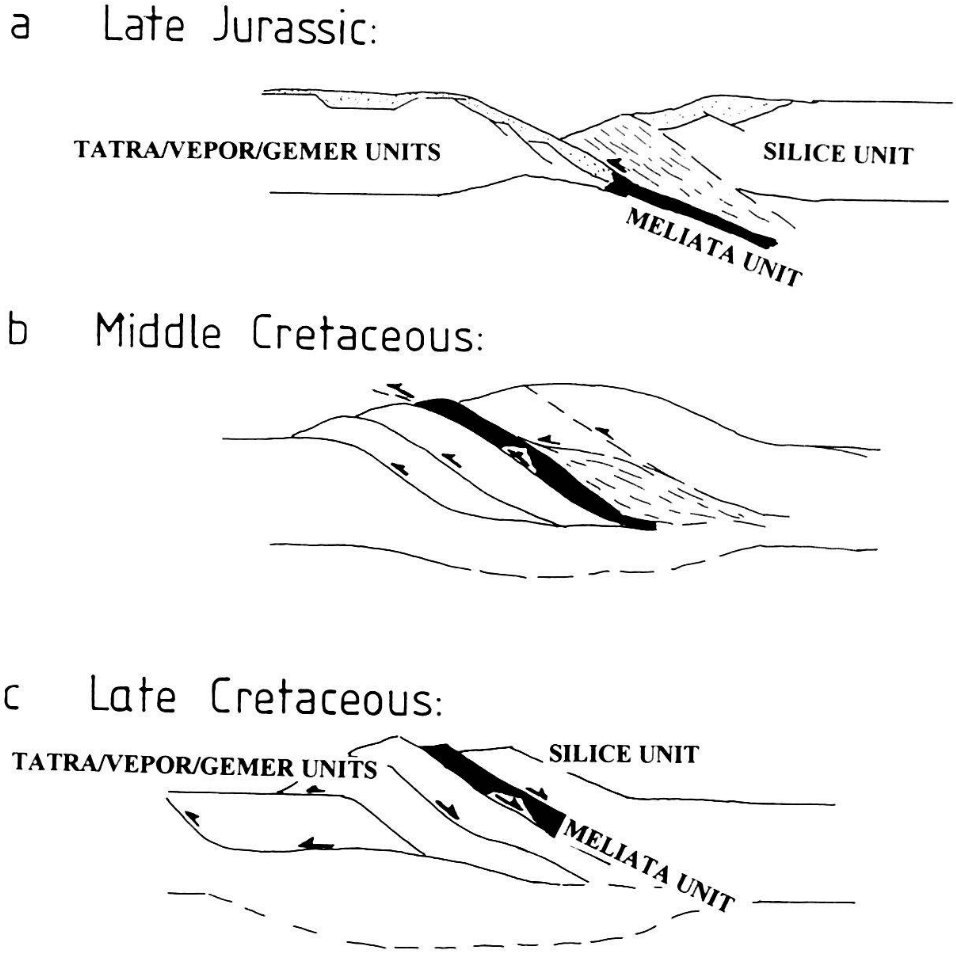

Fig. 11. Mesozoic tectonic evolution of Western Carpathian orogen. This included: 1) Late Jurassic subduction of the Meliata unit and resultant blueschist facies metamorphism; 2) Middle Cretaceous loading of the Meliata nappe complex onto the Gemer, Vepor and Tatra nappe complexes; and 3) Late Cretaceous extension accomodated along SE-directed low angle normal faults that operated contemporaneously to contraction in depth. This extension occurred in a regional stress field similar to that which led to the development of Late Cretaceous Gosau sedimentary basins and exhumation of metamorphic core complexes exposed in the Eastern Alps.

mayr et al. 1995), and to the exhumation of Variscan metamorphic crust during ongoing Alpine extension associated with the break-up of the southern European margin. Further distinct tectonothermal pulses related to the break-up of pre-Alpine crust occured in the Triassic (Apuseni Mountains) and at the Triassic-Jurassic boundary (c. 200 Ma, Southern Carpathians).

Consistent regional variations in the degree of metamorphism recorded in structurally imbricated Permian-Mesozoic cover sequences suggest that the degree of Alpine overprint varies both along strike and tectonostratigraphically downward within the representative sectors of the Alpine-Carpathian chain examined in this study. Three major phases of Early Alpine tectonothermal activity may be resolved by consideration of: 1) stratigraphic superposition of Late Cretaceous sedimentary sequences deposited in Gosau basins; 2) $^{40}Ar/^{39}Ar$ mineral ages within basement mylonites and generally low-grade metamorphic cover sequences; and, 3) the P-T characteristics of metamorphism. These include: 1) a Late Jurassic phase of blueschist metamorphism in the Western Carpathians; 2) an Early to early Late Cretaceous phase of nappe assembly; and 3) a phase of Late Cretaceous (< c. 86-65 Ma) contraction and nappe stacking in deep structural levels that is associated with extension in high structural levels and formation of Gosau sedimentary basins.

This sequence of tectonic events support models (Fig. 10, 11) that are significantly different from previous interpretations. A major difference is the presence of the Meliata-Hallstatt oceanic realm that opened during Middle Triassic (Fig. 10a; e.g. Kozur 1992). An early blueschist facies metamorphic event recorded in the Meliata unit of the Western Carpathians. Associated phengites yield c. 160-150 Ma ages and are interpreted to date Jurassic subduction of oceanic crust (Fig. 10b, 11a). Various tectonothermal overprints developed during the Early to early-Late Cretaceous (c. 125-86 Ma) continental collision ("pre-Gosau" deformational events). The local age of this deformation appears to decrease tectonostratigraphically downward in all areas examined. This activity apparently initiated with eclogite metamorphism (only recorded in the Eastern Alps) during a brief episode of A-subduction of continental crust. This activity was associated with development of a significant superincumbent load of continental crust and suggest a lower-plate setting (Fig. 10c). $^{40}Ar/^{39}Ar$ muscovite plateau ages recorded in the Eastern Carpathians suggest an age for ductile thrusting similar to that recorded in the Eastern Alps. The age of metamorphism and associated Alpine ductile deformation appears to have been markedly older in the Apuseni Mountains (c. 115-110 Ma). A similar relatively old Alpine age (c. 118 Ma) is recorded along a tectonic contact in the Southern Carpathians (thrust between the Supra-Getic and Getic nappe complexes). Considered in a regional context, the $^{40}Ar/^{39}Ar$ ages suggest that Cretaceous Alpine thrusting may have been diachronous along the Alpine-Carpathian orogen. Detailed resolution of this timing is difficult as a result of subsequent Late Alpine (Cenozoic) faulting which has dispersed previously juxtaposed Early Alpine structural elements.

Santonian to Maastrichtian ("intra-Gosauian") cooling, formation of metamorphic core complexes (e.g. Gleinalm dome in the Eastern Alps) and associated detachment faulting at higher crustal levels appears to have been contemporaneous with ductile thrusting and associated growth of synkinematic muscovite within deeper crustal levels at c. 86-65 Ma (Fig. 11b). This relationship has been interpreted to have developed as a result of local, high-level extension in an overall regional contractional tectonic setting (Neubauer et al. 1995). Detachment faulting was intimately associated with formation of Gosau sedimentary basins whose remnants spread all over the internal Alps and Southern Carpathians.

Post-Early Alpine (Cretaceous) cooling below closure temperatures for intracrystalline retention of argon in hornblende (c. 500 °C) occurred prior to c. 90 Ma throughout all sectors of the internal Alpine-Carpathian orogen. This indicates that the Cretaceus metamorphism was essentially independent from Late Alpine (Cenozoic) collisional events and resultant piggy-back upper plate thrusting (internal Alps and Carpathians) onto the European foreland (Fig. 10c). Results of the present study provide no record of any thermal activity within tectonic units considered that was associated with the Tertiary, piggy-back emplacement of the previously-assembled Early Alpine nappe complexes on the European foreland.

Acknowledgements

This work results from collaboration with many colleagues from various countries. They helped to collect samples in the field and provided useful discussion. These include: Marian Janak, Rudi Mock and Peter Reichwalder (Bratislava), Victor Mocanu and Marian Seclaman (Bucharest), Sigfried Hermann (Graz). Research was supported by a grant (EAR-93 16042) of the Tectonics Program of the U.S. National Research Foundation to R.D.D. and by grants (P7405, P8652) of the Austrian Research Foundation to F.N.

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Manuscript received April 28, 1995
Revision accepted November 5, 1995