Regional tectonothermal events in Gemericum and adjacent units (Western Carpathians, Slovakia): Contribution by the $^{40}Ar/^{39}Ar$ dating

R. D. DALLMEYER[1], ZOLTÁN NÉMETH[2] and MARIÁN PUTIŠ[3]

[1]Dept. of Geology, University of Georgia, Athens, GA 30602, U.S.A.
[2]Geological Survey of Slovak Republic, Jesenského 8, SK-040 01 Košice, Slovakia
[3]Dept. of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, SK-842 15 Bratislava, Slovakia

Abstract. The presented $^{40}Ar/^{39}Ar$ data, documenting the main Variscan and Alpine tectonothermal phases of two principal tectonic units of Western Carpathians - Veporicum and Gemericum, have revealed the age of Variscan collision between Gemericum and Veporicum-type basements as late as Westphalian (314.1 Ma; pre-Stephanian), however an earlier onset of the postcollisional Alpine unroofing (105.8 Ma).

The Upper Carboniferous age of detrital muscovite (314.1 Ma) from the sandstone of the Stephanian cover of the Variscan crystalline basement of future Alpine tectonic units Gemericum and Veporicum favours the new interpretation of Variscan convergent movements and collision (**VD** phase) of continental blocks with Gemeric and Veporic-type basements between Westphalian and Stephanian. The thickening of the continental crust, accompanied magmatic processes and extension led to opening of the Meliata oceanic basin south of the Veporic-Gemeric basement block at the beginning of Mesozoic. The dating of the high-pressure metamorphics as well as accompanying detrital sediments of exhumed melange from Meliata basin (the Bôrka nappe), being obducted on Gemericum, favours the Cimmerian age of exhumation processes (157.6 and 166.5 Ma) in Meliata(-Hallstatt) domain. The prograding of this process into the Lower Cretaceous north-vergent overthrusting and imbrication (**AD$_1$** phase) has been proved by existing geological and structural data. Despite, these compressional events of AD$_1$ phase occurred at relatively low temperatures and were not recorded by the K-Ar isotopic system.

The Upper Cretaceous cooling ages from the Veporic basement (85.5 Ma) and cover (105.8-82.7 Ma) indicate the post-collisional (post-overthrusting) regional unroofing, being well demonstrated in meso- and microscales (**AD$_2$** phase).

The pervasive north-vergent compression resulted in the origin of a conjugate system of regional transpressional shear zones trending NW-SE and NE-SW in AD$_3$ phase. The shearing of **AD$_3$** phase was a very low temperature event and remained without any geochronological evidence.

Key words: $^{40}Ar/^{39}Ar$ ages, tectonothermal events, Veporicum, Gemericum, Meliaticum, Silicicum, Western Carpathians

Introduction

The $^{40}Ar/^{39}Ar$ geochronological investigation in the region of Western Carpathians (Fig. 1A) has accelerated at the beginning of the 1990s (Maluski et al., 1993; Dallmeyer et al., 1993, 1996; Kováčik et al., 1996). The implementation of radiometric ages into geodynamic interpretations allowed the precise timing of particular tectonometamorphic phases of multiphase Variscan and Alpine evolution. This paper completes the existing geochronological data and contributes to recently developing concept of the Westphalian (pre-Stephanian) south-vergent collision of already amalgamated Tatro-Veporic basement block with the Gemeric basement in the more internal position (deformation phase **VD**, Fig. 4; Németh, 2002). Further data, documenting the pre-Alpine evolution, were registered by our samples only sporadically. Such samples were taken from the blocks preserved among anastomosing Alpine shear zones and by this way being protected from Alpine shearing.

During the Alpine (Cretaceous) orogeny of northern polarity three tectonic units Tatricum, Veporicum and Gemericum formed the zonal arrangement, being north-vergently overthrusted each other during the **AD$_1$** phase (Fig. 1A). Presented data are dealing with two Alpine tectonic units - Veporicum and Gemericum and their contact zone. The studied region as the triggering zone of Alpine collision, has almost exclusively preserved the Alpine ages of **AD$_2$** phase, being a product of Alpine post-collisional thermal overprint and unroofing.

Intending to siplify the correlation of obtained data with the tectonometamorphic evolution of Eastern Alps we briefly summarize the double regional division of Western Carpathians and, in extension, the corresponding zones in Eastern Alps:

The first division of the Western Carpathians into Outer, Central and Inner Western Carpathians (Mahel', 1986; Kozur and Mock, 1996, 1997) includes into the Outer Western Carpathians the sequences north of the Pieniny Klippen Belt (Fig. 1). The Central Western Carpathians encompass Tatricum, Veporicum and Gemericum, whereas the Inner Western Carpathians include rock sequences south of Gemericum (Meliaticum, Turnaicum and Silicicum). When linking the Western Carpathians

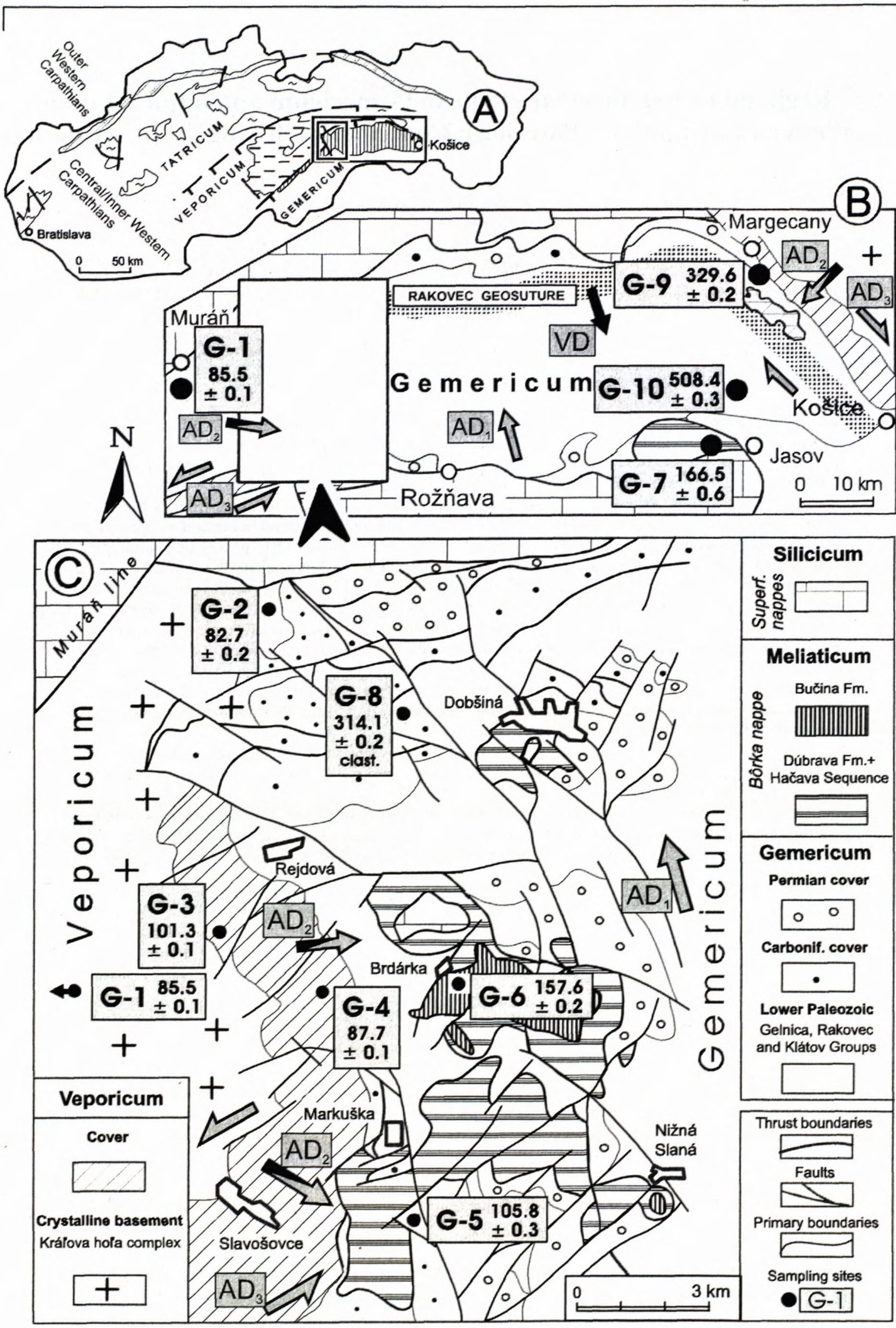

Fig. 1. Position of studied area, geological situation and sampling sites in the scale of whole Western Carpathians (A), Gemericum (B) and the western contact zone of Alpine tectonic units Gemericum and Veporicum (C). Modified after Németh (2002) and Madarás et al. (1995). The recent setting was formed by the deformation phases: Variscan VD (south-vergent obduction) and Alpine AD_1 (north-vergent overthrusting), AD_2 (post-collisional unroofing) and AD_3 (sinistral and dextral shearing in conjugate systems).

with Eastern Alps, the Tatricum, Veporicum and Gemericum of the Central Western Carpathians correspond to the Lower, Middle and Upper Austroalpine units.

According to second simplified division of Western Carpathians to Outer and Inner Western Carpathians (Biely, 1989, 1996), the Outer Western Carpathians include all units north of the Pieniny Klippen Belt, and the Inner Western Carpathians all units south of the Pieniny Klippen Belt.

Brief outline of geological setting and evolution of studied area

Attempting the best geochronological characterization of geological evolution of investigated region, the sampling was carefully focussed on lithologies and mylonitic zones from the contact zone of tectonic units Veporicum and Gemericum as well as the Bôrka nappe outliers of Meliaticum (Fig. 1).

Veporicum

The crystalline basement of investigated southern zones of Veporicum is built up by the Lower Paleozoic to Lower Carboniferous complexes of granitoids, migmatites and gneisses (cf. Bezák, Kováčik, Hraško, Siman and Madarás in Bezák et al., 1999). It is supposed that the protolith of metamorphites was represented by the lithology corresponding with the recently outcropping Lower Paleozoic sequences of Gemericum from the time of primary rifting of the pre-Variscan basement (Grecula, 1994; Németh, 2002). The Lower Paleozoic volcanosedimentary sequences of Veporicum and Gemericum are supposed to have been sedimented on the opposing sides of diverging basin and the provenances of sediments as well as magmatic and volcanic processes in Lower Paleozoic were corresponding. The possible presence of fragments of older Precambrian rocks among Lower Paleozoic metamorphic sequences of both Veporicum and Gemericum is still a matter of debate. The cover of Veporicum consists of Stephanian cyclic sandstone-claystone beds and the Permian coarse detrital arkose sediments (Vozárová and Vozár, 1982).

Gemericum

The Lower Paleozoic volcanosedimentary sequences of Gemericum are a product of rifting primarily on continental crust. There prevail the flyschoid lithology, products of bimodal volcanism, green schists ("green phyllites") and in the upper part of the lithological column the thick horizon of volcanic extrusive and effusive products is developed. The black schists ("black phyllites") with lydites and carbonates are located in lithostratigraphic column either in one horizon at the base of Lower Paleozoic sequences (Grecula, 1982; Németh, 2002), or according to another interpretation they are distributed through the whole Lower Paleozoic succession in several horizons (Snopko in Bajaník et al., 1983; Ivanička et al., 1989).

The Lower Paleozoic sequences of Gemericum can be generally divided into three rock groups, the products of divergent evolutionary phases of the basin (Németh, 2002; Fig. 4). The first rock group covers the volcanosedimentary sequences of the primary riftogenesis on continental crust (Gelnica Group), second the beginning of formation of oceanic crust (Klátov Group; cf. Hovorka et al., 1984; semimetapelite = pelite + carbonate + organic matter + tholeiitic basalt sensu Radvanec, 1992) and third – the Rakovec Group - the volcanosedimentary sequences of distal parts of the sedimentary basin between the Klátov and Gelnica Groups during more advanced stages of divergence (Németh, 2005; cf. Ivan, 1997). The convergence terminated with the south vergent collision during VD phase and the local obduction of the rocks of Rakovec and Klátov Groups on marginal rocks of Gelnica Group was confirmed (Németh, 2002; Fig. 4; Hovorka et al., 1984, defined the Klátov nappe). This setting is superfically expressed by the Rakovec geosuture including the rocks of the Rakovec and Klátov Groups plus exhumed Westphalian rocks. Field evidences show that the post-collision molasse in the suture zone started with the Stephanian Hámor Formation (Fig. 4). The Upper Carboniferous and Permian sedimentation continued in remnant basins (sensu Grecula, 1994) with locally differing sedimentary facies as the reflection of differing source of clastic material along the Rakovec geosuture. The comprehensive characterization of Gemeric cover sequences was published by Vozárová and Vozár (1988).

Because the collision - the Veporic and Gemeric type basements formed the first consolided terrane already at the end of Variscan orogeny (Grecula, 1994; Németh, 2002).

The Variscan collisional thickening of continental crust was reflected in the tectonothermal effects from the Upper Carboniferous and the extension dominated on both sides of Gemericum. Along the Rakovec suture zone a new Permian-Triassic elongated basin originated, though the strongest extension occurred in the south of Gemericum and followed to formation of Meliata oceanic domain in Mesozoic. The sedimentation of conglomeratic facies in this extended basin was followed by the psammitic and pelitic facies with transition to Triassic carbonates with intercalations of extrusive and effusive products of basalt volcanism, and, later by the Jurassic black shales (cf. Mello, ed., 1997, pp. 60-61 ibid). The platform carbonates of Silicicum were deposited south of the main spreading centres of Meliaticum and the position of the Tatric-Veporic-Gemeric block (Dallmeyer et al., 1996). As the possible driving force of this Upper Paleozoic-Triassic evolution in the southern part of the Western Carpathians the northward displacement of the lithosphere over the source of convectional heat (mantle plume) was suggested (Németh, 2002).

Meliaticum

The Mesozoic development on southern slopes of Gemericum includes the complete Wilson cycle from the opening of Meliata oceanic basin as a part of the Meliata-Hallstatt one in Triassic towards the subduction and collision in Upper Jurassic-Lower Cretaceous. The

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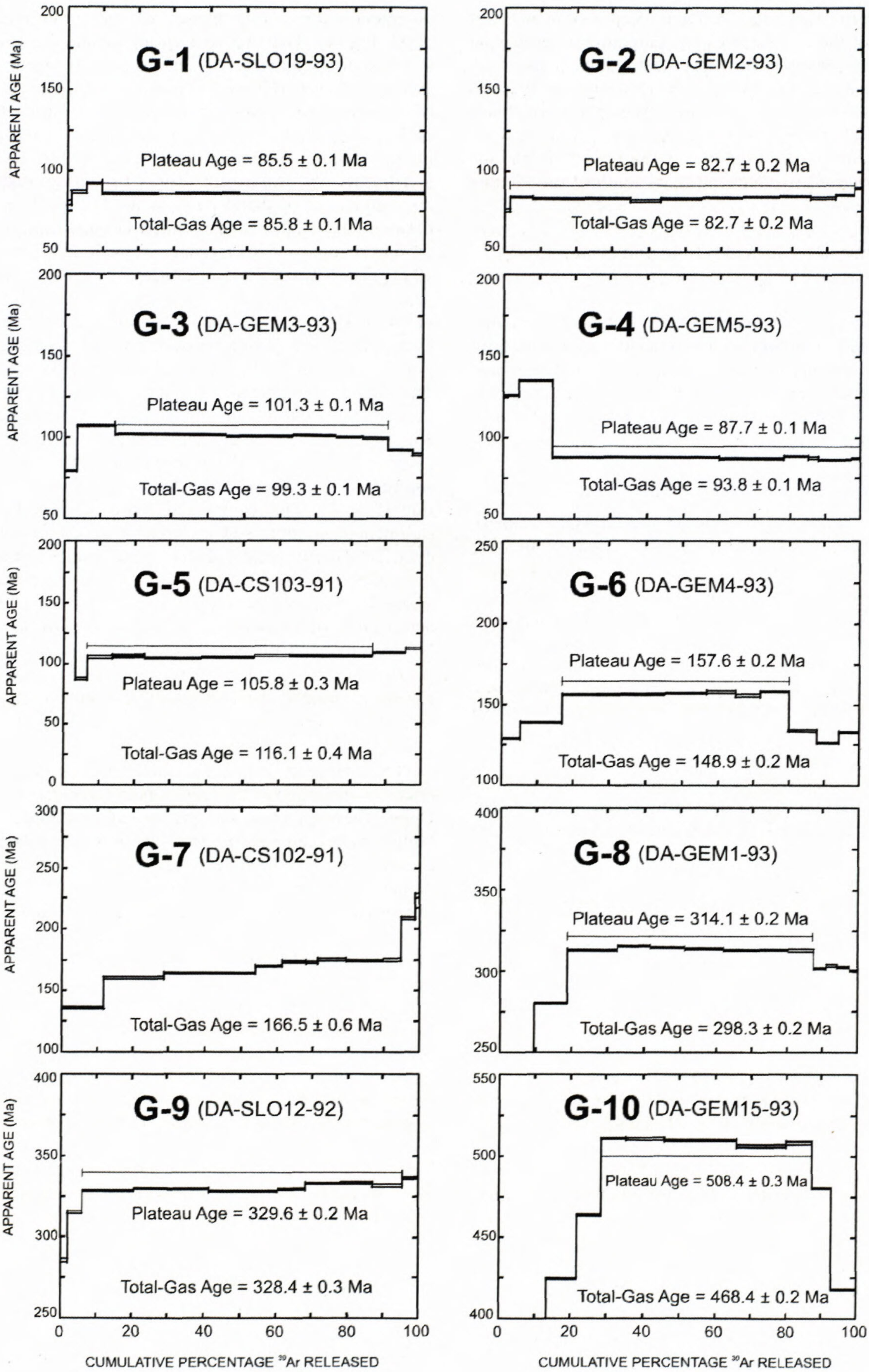

Fig. 2. Obtained $^{40}Ar/^{39}Ar$ age spectra. Horizontal lines express the cumulative percentage of ^{39}Ar released, the vertical line – apparent ages in Ma.

suture after the Meliata part of this basin is interpreted to be located in the so-called Rožňava discontinuity zone south of Gemericum (Németh, 2003; cf. Pawliszynova, 1978 in Grecula et al., 1995).

The Meliaticum (Kozur and Mock, 1973) is represented by the relics of former oceanic crust with the presence of pelagic sediments (radiolarites, black shales) with complexes of ophiolite suite (ultrabasics). The north-vergent obduction of this melange including a part of cover complexes of southern Gemericum is well documented in the Bôrka nappe (Mello et al., 1998). The beginning of forming of the Meliata basin by continental rifting along southern slopes of Gemericum is well demonstrable by the facial bounds of the sediments from the cover of Southern Gemericum and those being exhumed in the Bôrka nappe (e.g. the oligomict conglomerates of the Rožňava Formation of Gočaltovo Group of autochthonous Southern Gemeric cover correspond with the protolith of oligomict metaconglomerates of the Bučina Formation from the Bôrka nappe; cf. reconstruction in Fig. 4 of Németh, 1996). The internal setting of the Bôrka nappe outliers includes preferably the marginal detrital and carbonatic sequences of the southern slope of Gemericum from the time of Permo-Triassic riftogenesis (Németh, 1994, 1996).

Recent interpretations sensu Mello et al. (1997) understand the Meliaticum as individual tectonic unit, comparable with Gemericum and Veporicum.

Analytical methods

The methodology of the $^{40}Ar/^{39}Ar$ dating consisted from preparing of optically pure (>99 %) muscovite concentrates which were wrapped in aluminium foil packets, encapsulated in sealed quartz vials and irradiated in the TRIGA Reactor at the U.S. Geological Survey in Denver. Variations in the flux of neutrons along the length of the irradiation assembly were monitored by the mineral standards, including Mmhb-1 (cf. Sampson and Alexander, 1987). Samples then were incrementally heated until fusion in a double-vacuum resistance-heated furnace. Measured isotopic ratios were corrected for total system blanks and the effects of mass discrimination. Inferring isotopes produced during irradiation were corrected by factors reported by Dalrymple et al. (1981). The 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).

The 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 age was defined if the ages recorded by two or more continuous gas fractions with similar apparent K/Ca ratios represented >4 % of the total ^{39}Ar evolved and together constituted >50 % of the total quantity of ^{39}Ar evolved.

The muscovite concentrates display variably discordant $^{40}Ar/^{39}Ar$ age spectra. The K/Ca ratios suggest that the evolution of gas during measuring was from compositionally uniform populations of intracrystalline sites. Because the K/Ca ratios displayed no significant or systematic intrasample variations we have not displayed them with the muscovite age spectra in Fig. 2.

Obtained data and their regional significance

Intending the best geochronological dating of the particular evolution phases of the studied region we have collected 10 field samples taken from the representative lithotypes of principal complexes in Gemericum, Veporicum and the Bôrka nappe (Figs. 1 and 4). Obtained geochronological data (Fig. 2) can be generally clustered into four groups:

The oldest age 508.4 ± 0.3 Ma is from the detrital muscovites from the Lower Paleozoic schistose flyschoid sandstone G-10 (DA-GEM15-93) in the south-eastern part of Gemericum (termination of the Zábava valley 8 km to NNW of Jasov village). The preservation of Cambrian detrital muscovites in these sandstones indicates that the overheating during Variscan and Alpine orogeny was not sufficient enough to reset the isotopic system.

The second group, clustering the Variscan ages, is represented by the muscovite from the mylonitic schist G-9 (DA-SLO12-92) directly from the overthrust zone of Gemericum on Veporicum 1 km to SW of Margecany village. This sample with the Variscan plateau age 329.9 ± 0.2 Ma indirectly confirms the location of Alpine brittle and brittle-ductile overthrusting and normal faulting to discrete zones among which the rock blocks with former Variscan tectonometamorphic ages were preserved.

Into the category of Variscan ages belongs also that from the detrital muscovite in Stephanian sandstone of Hámor Fm. from post-collisional (post-VD) molasse of the sample G-8 (DA-GEM1-93). The plateau age 314.1 ± 0.2 Ma indicates that the Variscan exhumation/collision processes in the innermost zones of Variscan orogeny were still active in Westphalian. Samle was taken from the outcrop 4 km to W of Dobšiná town.

Third category of ages - the Jurassic cooling ages - documents the exhumation of marginal sequences of the Southern Gemeric slope of Meliata basin from subduction zone during the advanced phase of convergence. First sample, the mylonitic schist G-7 (DA-CS102-91) was taken directly from the type locality of the Bôrka nappe in Southern Gemericum (Teplica valley 1.8 km to W of Jasov village) from the rock sequence containing also bodies of glaucophanites. The total gas age 166.5 ± 0.6 Ma belongs into the cluster of the Bôrka nappe (Meliata) exhumation ages, being observed also by the earlier authors referred in introductory chapter.

Our study firstly dated the metaconglomerate from the Bôrka nappe outlier 1 km to SE of the Brdárka village, distant 12 km from the suture zone located south of Gemericum. The muscovite of this metaconglomerate G-6 (DA-GEM4-93) gave the plateau age 157.6 ± 0.2 Ma, which indicates the later frozing of isotopic system in comparison with the main exhumation ages of the Bôrka nappe being clustered around 166 Ma.

Fourth large group of ages represents the Alpine ages related to post-collisional cooling in Veporicum and in the Alpine contact zone of Veporicum with overthrusted

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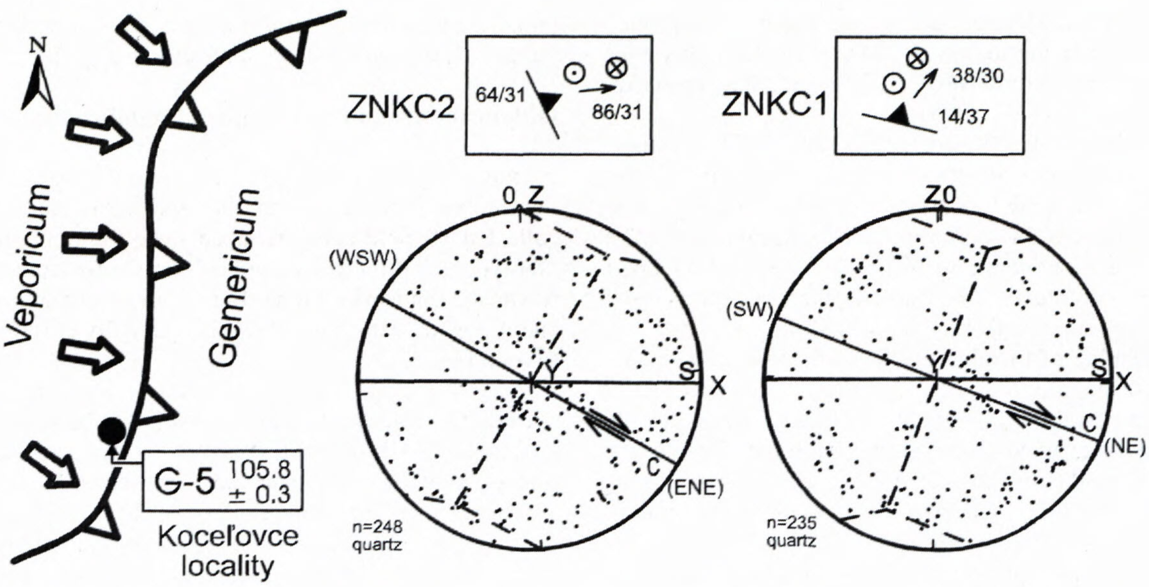

Fig. 3. Microstructural study of metaquartzite from the Koceľovce locality (G-5) with plateau age 105.8 ± 0.3 Ma expresses relatively weak top-to-the-ENE and NE normal faulting produced by unroofing. The sample from the Hámor Fm., representing the Stephanian cover of Rakovec geosuture was during the AD_1 phase sandwiched beneath overthrusted Gemeric nappe.

Gemericum. Uplift of the crystalline core caused the gradual unroofing generally to the south which is well documented by the cooling ages. The unroofing kinematics was documented by the structural investigation of numerous authors in mesoscale (Hók et al., 1993; Madarás et al., 1995), as well as microscale (Putiš, 1991, 1994; Putiš et al., 1999). The kinematics of AD_2 unroofing was registered not only by the soft lithology of Veporic cover sequences where the main kinematic activity occurred, but also by the underlying crystalline basement. This is confirmed by the muscovite of mylonitic "Muráň orthogneiss" from Veporicum G-1 (DA-SLO19-93), being sampled from the fresh road exposure at railway crossing 0.6 km to south of Muráň village and demonstrating the very flat plateau of the age 85.5 ± 0.1 Ma.

The corresponding unroofing plateau ages were given also by the muscovites from siliciclastic mylonitic schists of Veporic cover: G-2 (DA-GEM2-93) - 82.7 ± 0.2 Ma, Danková 8 km WNW of Dobšiná town and the sample G-4 (DA-GEM5-93) - plateau age 87.7 ± 0.1 Ma, Hanková village 3 km to NNW of Markuška village.

The earliest closure of isotopic system during the AD_2 phase occurred along the normal faults in the uppermost crustal levels. This is confirmed by the whole-rock age 105.8 ± 0.3 Ma of the white mica of metaquartzite of sample G-5 (DA-CS103-91) from the open pit 1 km to NW of Koceľovce, near the road Štítnik - Roštár – Hanková 2.5 km to SSE of Markuška. This sample of Hámor Formation represents the Stephanian cover of collided Veporic-Gemeric terrane. Because it was unclear whether this age is related with the termination of the overthrusting during AD_1 phase or the onset of unroofing during AD_2 phase, besides the mesoscopic structures, the crystallographic preferred orientation of synkinematic dynamically recrystallized quartz grains in metaquartzite was measured using the U-stage. The results from the oriented samples ZNKC1 and ZNKC2 from the same part of outcrop where the geochronological sample G-5 (DA-CS103-91) was taken proved that this age documents, though not very distinctly, the AD_2 unroofing kinematics and not the earlier AD_1 overthrusting (Fig. 3). This normal faulting was found also by the asymmetric structures in the mesoscopic scale (secondary foliation 64/31°, stretching lineation 86/31°, and 14/37° vs. 38/30°; Fig. 3).

Another important point is, as revealed also by the recent field mapping, that a part of Stephanian cover Hámor Formation (sample G-5 - DA-CS103-91; Fig. 4) was sandwiched during the AD_1 overthrusting beneath the Gemeric nappe, but a part with the sample G-8 (DA-GEM1-93) was passively displaced with the Alpine Gemeric nappe.

Similar older Variscan cooling age was demonstrated also by the sample G-3 (DA-GEM3-93) of muscovite from the siliciclastic mylonitic schist of the Veporic cover 2.5 km to SSW of Rejdová. The plateau age 101.3 ± 0.1 Ma indicates (together with the age 105.8 ± 0.3 Ma of the sample G-5) that the first records of Cretaceous unroofing can be allocated to earlier time period in comparison with the accelerated unroofing of the Upper Cretaceous age where the most data are clustered (around 86 Ma).

Similar results were obtained by the earlier dating of Veporic crystalline basement rocks by Kováčik et al. (1996): The first cluster of data from the newly formed amphiboles in the range 115-105 Ma presumably indicated the onset of Alpine thermal metamorphism (metamorphic core complex). The concentration of ages between 88-84 Ma (second cluster of data by l.c.) indicated the accelerated uplift. This was documented also by the strongly recrystallized micaschist with the nearly concordant cooling age of newly formed amphibole and muscovite (87.4 and 87.2 Ma), which supports the strong uplift in a short time period.

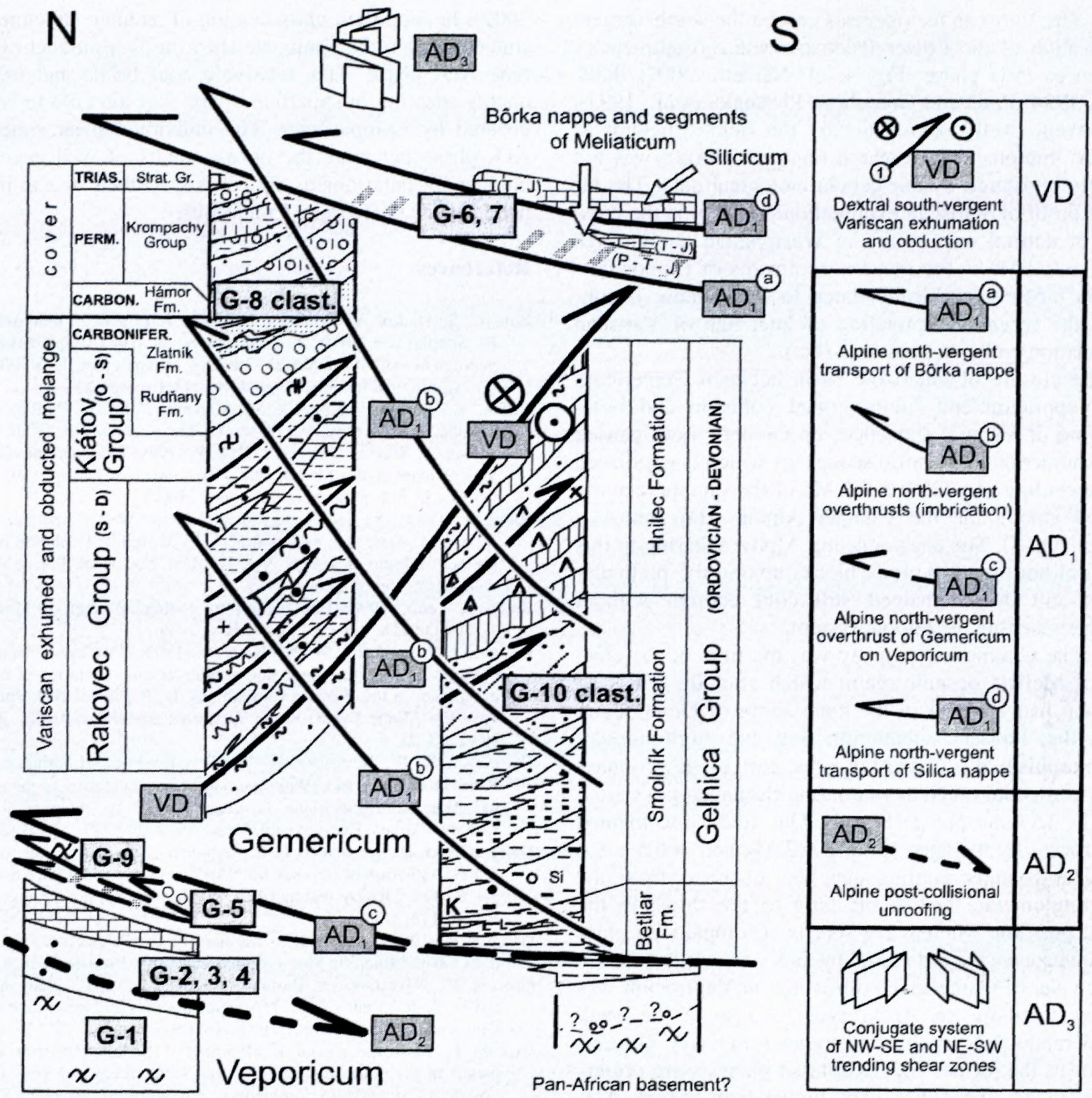

Fig. 4. Position of studied samples in lithotectonic scheme (modified after Németh et al., 2000). The succession of deformation events is depicted in the right side of the picture. The slice of Hámor Fm. was sandwiched beneath the AD_1 north-vergent Gemeric nappe (G-5), but prevailing part remained in parautochthonous position (G-8).

Conclusion

Obtained data documented the Variscan, Cimmerian as well as in details the Alpine tectonothermal events. The sampling sites were located along the tectonic contact zone of Veporicum with Gemericum and reference data were obtained also sidewards. The attention was put on the trasport of the Bôrka nappe close to the suture zone of Meliaticum as well as in its displaced frontal parts. Obtained ages, together with the older ones (not stated in exact values but taken into consideration - e.g. Maluski et al., 1993; Dallmeyer et al., 1993, 1996; Kováčik et al., 1996) allowed to reconstruct the succession of events in Gemericum and adjacent tectonic units (southern parts of Veporicum and the Bôrka nappe of Meliaticum).

New data in the studied region indicate, that the overthrusting during AD_1 and shearing during AD_3 were relatively "cold", so the obtained spectra demonstrate the warmer extensional events of AD_2. Because of cold compressional events neither Alpine AD_1 imbrication of Veporic-Gemeric region nor AD_3 shearing were registered by our samples. From the viewpoint of geological evolution the obtained data can be divided into several genetic groups reflecting four main tectonothermal events of the region.

1. The oldest cooling age 508.4 ± 0.3 Ma from detrital white mica obtained from Lower Paleozoic sedimentary sequence in the south of Gelnica Group indicates that these rocks in the southern parts of Gemericum were not sufficiently overheated neither during the Variscan nor Alpine orogeny to reset the isotopic system of old detrital white micas.

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2. The Variscan tectogenesis caused the south-vergent imbrication of the Lower Paleozoic volcanosedimentary sequences (VD phase; Fig. 4; cf. Németh, 2002; Putiš, 1992, 1994; Putiš and Grecula in Plašienka et al., 1997). This event, well documented by the field structural as well as microtectonic research (Németh, 2002), was not directly registered by our geochronological data. The indirect proof of Variscan exhumation/collision is the presence of detrital mica with the Westphalian cooling age 314.1 ± 0.2 Ma in the molasse sediments of Hámor Formation biostratigraphically dated to Stephanian. It confirms the recent interpretation of later age of Variscan exhumation/collision processes (l.c.).

The closure of Paleozoic basin between Gemericum and Veporicum and south-vergent collision and overthrusting of Veporic sequences on Gemeric ones caused the exhumation of Veporic sequences which is confirmed by the cooling age 329.9 ± 0.2 Ma of the sample recently located among the the younger Alpine AD_1 and AD_2 shears (Fig. 4). The anastomosing Alpine shearing in this zone did not affect the rock blocks among the particular shears and they remained still cold enough without younger resetting of isotopic system.

3. The Cimmerian orogeny was the time of the clossure of Meliata oceanic realm which after the Variscan collision had evolved in the zone south of Gemericum. After the Jurassic subduction and the high-pressure metamorphism the obduction of a part of accretionary prism northward on Gemericum (the Bôrka nappe) started the AD_1 tectonic phase (Fig. 4). Our study documented this process by the ages 157.6 ± 0.2 Ma and 166.5 ± 0.6 Ma. The younger cooling age was obtained from the metaconglomerate bed at the base of the thrust in the frontal position, whereas the schists accompanying glaucophanites gave the older cooling age.

The age of Gemeric overthrusting on Veporicum was not registered by the Ar/Ar ages because of the weak synkinematic recrystallization related to AD_1 process. Moreover, the former AD_1 overthrust planes were preferable used by the subsequent higher-temperature AD_2 normal faulting during unroofing.

4. The main kinematic activity of unroofing of the phase AD_2 was registered along the tectonic contact zone of Veporicum with Gemericum (Figs. 1C and 4). The sense of shearing during AD_2 phase was demonstrated by numerous works of structural geology and microtectonics (Hók et al., 1993; Putiš et al., 1999; Németh, 2002 a.o.) (Figs. 1, 3 and 4) and with cooling ages clustered in interval 87.7-82.7 Ma. The unroofing was accommodated also by the basement sequences (mylonitic "Muráň orthogneiss" at Muráň village) with cooling age 85.5 ± 0.1 Ma. New microtectonic study (Fig. 3) revealed that the AD_2 unroofing in the uppermost soft quartzitic horizons started earlier (105.8 ± 0.3 Ma), which confirms the earlier results by Kováčik et al. (1996).

The zonal arrangement of lithological as well as tectonic units withing the Western Carpathians (Fig. 1A), incl. courses of mountain ranges, has a distinct arc bending. This bending is interpreted as the product of offsets in conjugate system of shear zones of NE-SW (sinistral) and NW-SE (dextral) trends (Grecula et al., 1990; Németh, 2002). In simplified classification of tectonic structures of studied region, the conjugate shearing is a product of Alpine AD_3 phase. This relatively cold brittle and brittle-ductile shearing in superficial parts was too cold to be registered by isotopic ages. The individual shear zones of AD_3 phase penetrate the normal faults of well geochronologically determined AD_2 phase, so their age is interpreted as the post-Upper Cretaceous.

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