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ORIGINAL PAPER

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Alpine metamorphic evolution and cooling history of the Veporic basement in northern Hungary: new petrological and geochronological constraints

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Abstract Petrological and geochronological investigations were carried out on metamorphic rocks of the Veporic unit (Inner Western Carpathians) in northern Hungary. K/Ar and Ar/Ar data on micas and amphibole show only Alpine ages (mostly in the range of 87–95 Ma) in this basement unit. Thermobarometric calculations yield lower amphibolite facies peak conditions (ca. 550±300 °C and 9±1 kbar) for the Eoalpine metamorphic event. Complex evolution of gneissic rocks is reflected by the presence of discontinuously zoned garnets, the cores of which may represent relics of a pre-Alpine (presumably Variscan) thermal event. Zircon fission track (FT) data in the narrow range of 75–77.5 Ma indicate that this portion of the Veporic unit was emplaced to shallow crustal levels already during the Senonian time. The relative minor difference between zircon FT and K/Ar or Ar/Ar ages suggests very rapid cooling during the Late Cretaceous, most probably related to the extensional unroofing of the Veporic core complex. The obtained cooling ages do not support previous models of Tertiary uplift and exhumation of the Veporic unit along the Hurbanovo-Diósjenő Line.

Keywords Alpine metamorphism · Geothermobarometry · Geochronology · Veporic unit · Carpathians

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Introduction

Recently, numerous detailed geochronological and petrological works (Thöni and Jagoutz 1993; Török 1998; Plašienka et al. 1999) have proven the widespread and pronounced presence of Alpine metamorphism within the ALCAPA region (internal Eastern Alps–Carpathians-Pannonian Basin; Neubauer 1992). This is in contradiction to ideas from the past decades (see Balogh and Körössy 1974; Jantsky et al. 1988), emphasizing its very subordinate extent and intensity in comparison to earlier metamorphic events (Variscan, Caledonian, Cadomian, etc.).

In this contribution we consider the Alpine metamorphic evolution and cooling history of the Veporic unit (Fig. 1), which is one of the most important tectonic elements of the Inner Western Carpathians (IWC). Earlier works considered the crystalline rocks of this unit – exposed only in boreholes in northern Hungary – as a Variscan (or even older) medium-grade metamorphic sequence which underwent only "weak (sub)greenschist facies retrogression" during the Alpine orogeny (Ravasz-Baranyai and Viczián 1976; Fülöp 1990). Our new petrological and geochronological investigations allow us to constrain the P–T–t conditions of the Alpine tectonometamorphic evolution in the Veporic unit. These results unambiguously prove the presence of Eoalpine medium-grade

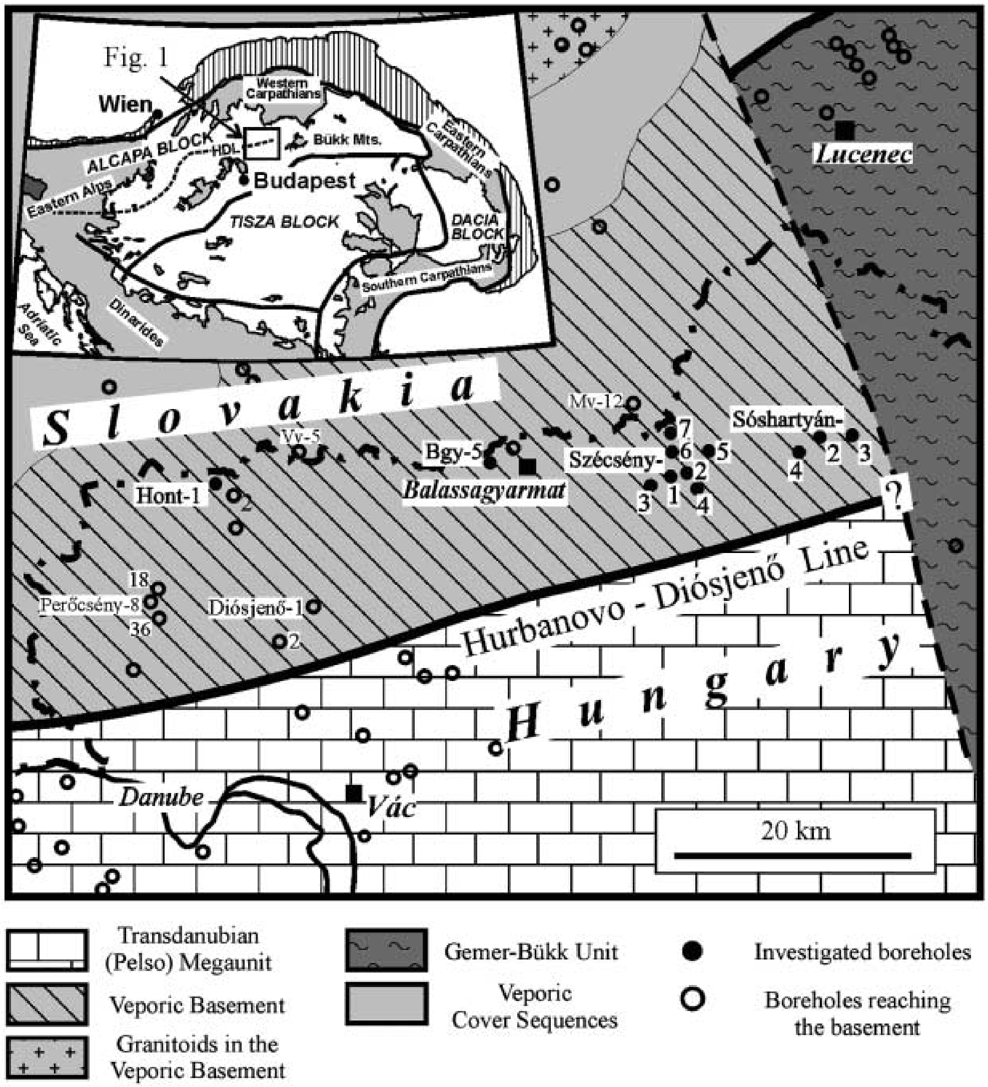


Fig. 1 Structural overview map of N Hungary and S Slovakia in the southern part of the Veporic unit. *Inset* shows the location of the study area in the Carpathian orogeny. (Slightly modified after Fülöp 1990)

metamorphism and enable the reconstruction of the cooling path in this unit.

Methods

Chemical analyses of minerals were carried out with a JEOL JXCA-733 electron microprobe in the Laboratory for Geochemical Research, Hungarian Academy of Sciences, Budapest. The measuring conditions were: 15 kV acceleration voltage; 40 nA sample current; electron beam with a diameter of 5–10 μm and 5 s counting time. Matrix effects were corrected using the ZAF method. The following standards were used for quantitative analysis: orthoclase (K, Al, Si), synthetic glass (Fe, Mg, Ca), spessartine (Mn), rutile (Ti) and albite (Na).

K/Ar measurements were performed in the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen. The interlaboratory standards Asia 1/65, HD-B1, LP-6 and GL-0 as well as atmospheric Ar were used for controlling and calibration of analyses. Details of the instruments, the applied methods and results of calibration have been described by Odin et al. (1982) and Balogh (1985) K/Ar ages were calculated using the constants proposed by Steiger and Jäger (1977).

For Ar/Ar dating samples were irradiated in the 229/3 position (out of the centre of the core) of the nuclear reactor of the Central Institute of Physics, Budapest, along with interlaboratory standard biotite LP-6. Particulars of the experimental method used in this work are described by Balogh and Simonits (1998).

For fission track dating, neutron irradiations were made at the RISØ reactor (Denmark). The FT ages were determined by the zeta method (Hurford and Green 1983) using zircon from the Fish Canyon Tuff, Buluk Member Tuff and Tardree Rhyolite. Reference ages of 27.8±0.2 Ma for the Fish Canyon Tuff, 16.2±0.6 Ma for Buluk Member Tuff and 58.7±1.1 Ma for Tardree Rhyolite have been adopted, following Hurford and Green (1983), Green (1985), Hurford and Hammerschmidt (1985) and Hurford and Watkins (1987). Mineral abbreviations are according to Kretz (1983).

Geological setting

The Veporic unit is a major thick-skinned, generally S-dipping tectonic domain in the IWC which was formed during Cretaceous crustal stacking related to the collision of the main IWC zones (Tomek 1993; Plašienka et al. 1999). It consists of pre-Alpine basement complexes and Permomesozoic cover sequences.

Basement rocks were intersected by hydrocarbon-prospecting boreholes in the late 1960s and early 1970s below the Tertiary sedimentary cover in northern Hungary, and were correlated under the name "Ipoly Crystalline Schist Series" or "Ipoly Complex" with the crystalline rocks of the neighbouring Veporic unit in southern Slovakia (Ravasz-Baranyai and Viczián 1976; Ivancsics and Kisházi 1982). Petrographic, X-ray diffraction and some scarce K/Ar investigations were carried out by Ravasz-Baranyai and Viczián (1976), Ivancsics and Kisházi (1982) and Balogh (1984), but no other detailed petrological and geochronological data have been available since that time. The Alpine K/Ar ages on micas (between 96 and 116 Ma) were interpreted by Lelkes-Felvári et al. (1996) as either largely rejuvenated Variscan ages (caused e.g. by the widespread Tertiary magmatism in this region) or possible Alpine cooling ages. Therefore, one of the main goals of this study was to gain new detailed mineralogical-petrological and geochronological data from these boreholes, in order to reconstruct the metamorphic evolution of this sequence.

The studied boreholes are located very close to the Hurbanovo-Diósjenő Line (HDL) which is a first-order tectonic boundary in this region (Fig. 1). It dips very steeply to the south and separates the Alpine metamorphic and deformed IWC units from the non-metamorphic Transdanubian (or Pelso) unit (Fülöp et al. 1987) which has also undergone major Alpine deformation. The kinematic evolution of this prominent tectonic line is rather poorly constrained, since it is covered by a thick pile of Tertiary sediments. Tari et al. (1993) have argued for its thick-skinned back-thrust activity during the Oligocene. Balla (1989) has proposed dextral slip motion of probably pre-Oligocene age with an approx. offset of 85 km. Based on the geometric relationship between the Early Tertiary stress field orientation determined in the adjacent Gerecse Mts. (Pelso unit) and the orientation of the HDL, Bada et al. (1996) have assumed Late Eocene reverse-dextral strike-slip activity. In the light of our new geochronological data we will later discuss the idea of Tari et al. (1993) in detail.

Petrography and microfabrics

Based on the large dataset deriving from the boreholes of the study area (see Fig. 1), samples can be divided into two main lithological groups. Some of the most important sections investigated in this work are shown in Fig. 2.

Gneiss-micaschist group

This group consists of garnet-bearing gneisses, associated (occasionally graphitic) micaschists and subordinate quartzites. These lithologies represent the predominant mass of the basement both in the investigated boreholes (Szécsény-1,-2,-3,-4,-5,-6,-7, Sóshartyán-3, Hont-1) and in others in the surroundings (e.g. Hont-2, Balassagyarmat-1,-5, Diósjenő-1,-2, etc., see also Figs. 1 and 2).

Medium-grained *gneisses* show weakly developed foliation defined by elongated micas alternating with plagioclase and/or quartz-rich layers. Strongly cracked, hypidiomorphic to idiomorphic garnet of 0.2–1.0 mm is present only in small modal content (<5 vol%). Sporadically small quartz inclusions (0.01–0.1 mm) can be observed in garnets. Plagioclase is present in high modal content (ca. 40–50 vol%) forming larger

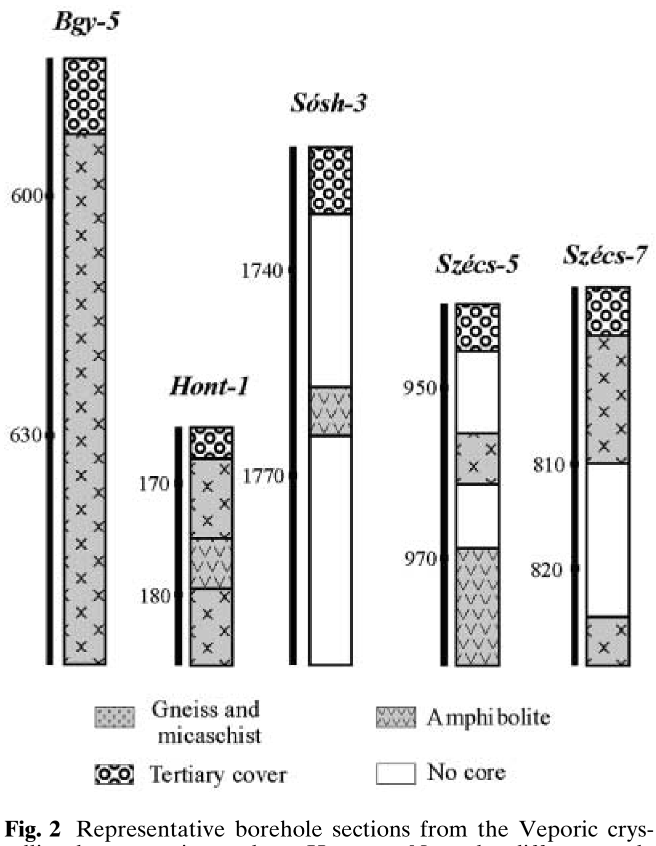


Fig. 2 Representative borehole sections from the Veporic crystalline basement in northern Hungary. Note the different scale at the different wells. Depth is given in meters from the surface

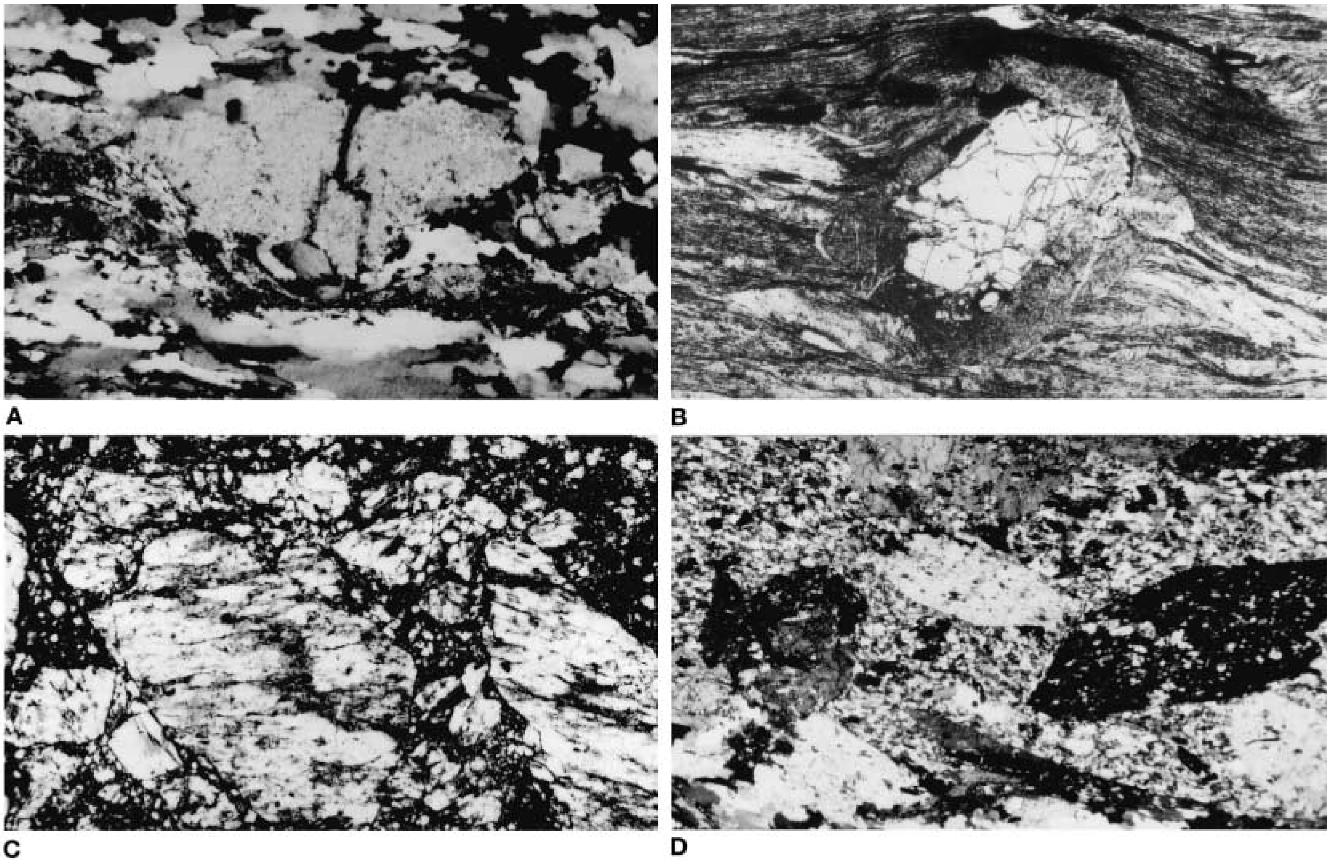


Fig. 3 Microfabrics from the two lithological group: **A** Quartz microfabrics from the gneissic lithologies (borehole Szécsény-7). Note the dynamically recrystallized, strongly elongated quartz grains with sutured grain boundaries wrapping around a larger, cracked feldspar porphyroclast (in the middle). Long edge: ca. 1.5 mm. **B** Well-foliated, graphitic micaschist with a mantled garnet porphyroclast. Outer rim is replaced by very fine-grained sericite and chlorite (borehole Szécsény-1). **C** Late cataclastic deformation of a garnet-bearing mica-quartzite. Note the angular fragments of different size in the fine-grained, blackish matrix (borehole Szécsény-4). **D** Large, idiomorphic amphibole crystals in a fine-grained plagioclase, quartz, epidote, (clino)zoisite matrix (borehole Sóshartyán-3). Long edge of **B, C** and **D** is ca. 4 mm

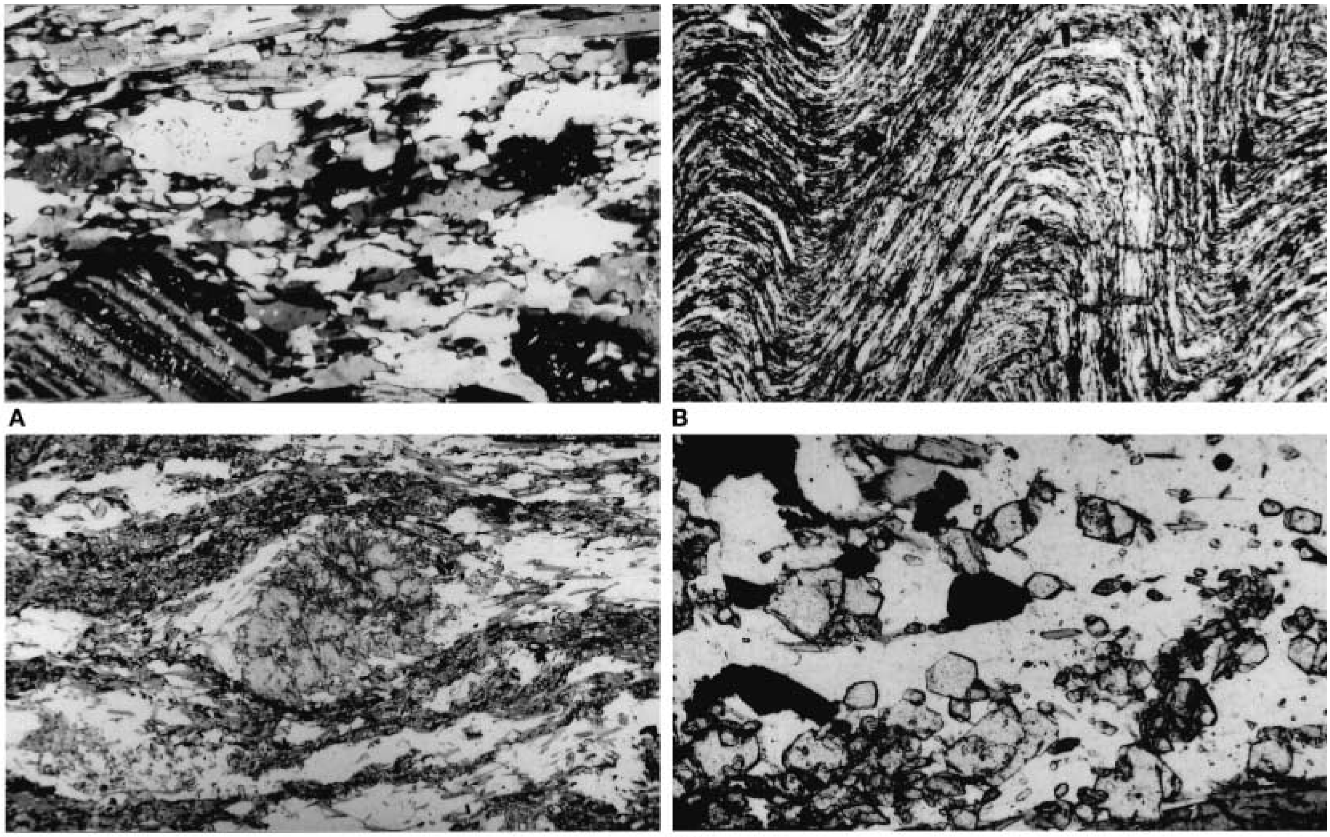
(0.4–2.5 mm), often cracked, (hyp)idiomorphic, tabular crystals with polysynthetic twinning. Deformation twins with characteristic tapering edges also occur frequently. Their sericitic alteration is rather widespread. Quartz occurs in thin layers or lenses in which it forms mostly small, elongated, dynamically recrystallized grains with lobate-serrate grain boundaries (Fig. 3A). Well-developed lattice preferred orientation indicates intense ductile shearing. Undulose extinction and deformation lamellae are frequent in larger, dynamically not recrystallized, older quartz grains. Among micas, 0.5–2 mm biotite is present in large quantities forming frequently deformed flakes with brownish-red pleochroism aligned parallel to the foliation, and is partly chloritized, recording retrogression. Chloritization is also frequent along fissures between garnet fragments. White mica occurs in small quantities only (<5 vol%). Accessories are rutile, tourmaline, zircon, apatite and opaque minerals.

Well-developed foliation in *micaschists* is defined by an alternation of phyllosilicate-rich (white mica, chlorite, biotite) and "ribbon-quartz" lenses or layers. The penetrative foliation is strongly folded resulting in the formation of crenulation cleavage. Ductile deformation is overprinted by strong cataclasis in many cases (Fig. 3C).

Large (up to 3–4 mm), pre-tectonic, hypidiomorphic, cracked garnets containing quartz and subordinate clinozoisite inclusions are wrapped around by the foliation. Biotite occurring in small quantities is strongly altered to chlorite in the samples studied. In graphitic micaschists, sericite-chlorite aggregates frequently replace garnets (Fig. 3B), indicating retrogression. Fine-grained layers are composed of white mica (generally smaller than 0.1 mm), quartz, chlorite and subordinately albite. Calcite is also present subordinately, occasionally forming idiomorphic grains in the matrix. Accessories are titanite and opaque minerals.

Amphibolite group

This group was originally described as "greenschists" (Ivancsics and Kisházi 1982). It comprises mainly



A B C D

Fig. 4 Microfabrics from the amphibolite group: **A** Dynamically recrystallized plagioclase grains with sutured grain boundaries from a garnet-bearing, mylonitic amphibolite (borehole Szécsény-2). Long edge: ca. 1 mm. **B** Strongly crenulated, fine-grained amphibolite (borehole Szécsény-4). **C** δ-Type porphyroclast after garnet (?) with asymmetric pressure shadow. Garnet is fully replaced by epidote-clinozoisite-chlorite aggregate (borehole Sóshartyán-3). Long edge of **B** and **C** is ca. 4 mm. **D** Small, idiomorphic garnet grains and epidote in the pressure shadow of a larger, wrapped garnet porphyroclast (borehole Szécsény-2). Long edge: ca. 1 mm

amphibolites (sometimes garnet-bearing), amphibole-epidote-chlorite-biotite schists and epidote-chlorite schists. These rocks form relatively thin layers or lenses (generally less than 5 m) in the "gneiss-micaschist" series (see Fig. 2).

Amphibolites show different microfabrics, mineral assemblage and intensity of retrograde alteration, occasionally even in one borehole. Medium-grained, weakly deformed, relatively fresh amphibolites containing large (up to 15 mm), idiomorphic amphiboles are characteristic in borehole Sóshartyán-3 (Fig. 3D). Pale brown-green, blue-green pleochroic amphiboles contain numerous inclusions of quartz, plagioclase, epidote, clinozoisite and opaque minerals. Weak optical zonation can be observed in some amphiboles. The matrix is built up of medium- to fine-grained plagioclase, quartz, epidote, clinozoisite, chlorite, white mica, carbonate and opaque minerals. Fine-grained, well-foliated varieties are present in boreholes Szécsény-4,-5, in which small-scaled folding is also very characteristic (Fig. 4B).

Mylonitic types, which show well-developed stretching lineation on the macroscopic scale, occur mainly in borehole Szécsény-2 and subordinately in Sóshartyán-3. Garnet forms either larger, pre-tectonic grains (2–3 mm) often with asymmetric pressure shadows (s-clasts), or small (0.2–0.5 mm), idiomorphic crystals in the strain shadows of larger ones (Fig. 4D). The larger garnet grains are wrapped around by amphibole, epidote, clinozoisite and micas, and sometimes totally replaced by alteration products (epidote, clinozoisite, chlorite, see Fig. 4C). Elongate lenses and/or thin layers of dynamically recrystallized plagioclase (mostly albite) is frequently observed in this rock type (Fig. 4A). Unfortunately, although numerous, well-developed shear sense indicators (e.g. shear bands) are present (occasionally in the micaschist and gneiss samples, as well), the sense of shear cannot be determined with respect to the present geographical coordinates, since the cores were not oriented.

It is noteworthy that there is an important difference in the microfabrics between the two main lithological groups: in the gneisses quartz shows crystal-plastic deformation with well-developed lattice preferred orientation, whereas feldspar displays essentially brittle, cataclastic behaviour, suggesting a temperature range of ca. 300–450 °C during deformation.

On the contrary, in the amphibolites, feldspar is often dynamically recrystallized, which indicates deformation temperatures over ca. 450 °C (Tullis and Yund 1985). This feature may represent the remnants of an earlier, higher-temperature shearing event in this group. Ductile fabrics are overprinted in both groups by (semi-)brittle structures, generally in the form of steep faults and fractures that are frequently accompanied by well-developed cataclasites (Fig. 3C).

Mineral chemistry

Representative mineral analyses from the two main lithological groups are given in Table 1. Cation numbers are calculated for 12 oxygens for garnet, 22 for biotite and muscovite, 23 for amphibole and 8 for plagioclase.

In the *gneisses* (Fig. 5A), discontinuously zoned garnets have almandine- and pyrope-rich cores, (X_{Alm}: 0.73–0.77, X_{Prp}: 0.15–0.19, X_{Grs}: 0.03–0.04, X_{Sps}: 0.04–0.05), whereas rims are heavily enriched in grossular component (X_{Alm}: 0.65–0.67, X_{Prp}: 0.09–0.1, X_{Grs}: 0.17–0.22, X_{Sps}: 0.02–0.05). Plagioclase composition is mostly oligoclase (X_{An}: 0.18–0.3), sometimes even andesine (X_{An} up to 0.33). White mica composition corresponds to muscovite with a Si content of 3.1–3.2 p.f.u. We have not found paragonite in the investigated samples, although it was previously reported by Ivancsics and Kisházi (1982) from the

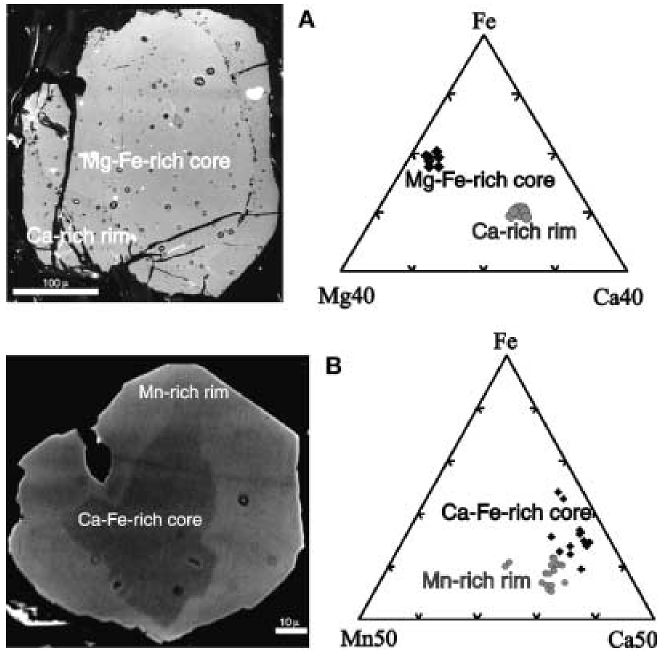


Fig. 5 Garnet compositions from the two lithological groups. **A** BSE image of zoned garnet from a gneiss, borehole Szécsény-7. **B** BSE image of zoned garnet from a garnet bearing amphibolite, borehole Szécsény-2. *Triangles* show the chemical composition of the cores (*black diamonds*) and rims (*shaded circles*) in both cases

Table 1 Representative mineral analyses from the two lithological groups, used for geothermobarometry

Amphibolite group								Gneiss-micaschist group								
Borehole Szécsény-2						Sóshartyán-3		Szécsény-7					Szécsény-4			
Mineral	Grt core	Grt core	Grt rim	Am	Pl	Am	Pl	Grt core	Grt rim	Bt	Ms	Pl	Grt core	Grt rim	Ms	Pl
SiO_2	36.88	37.12	37.21	43.18	63.80	43.32	62.15	37.56	37.20	36.31	46.33	61.98	37.45	36.75	47.82	62.59
TiO_2	0.02	0.05	0.11	0.36	0.00	0.49	0.12	0.00	0.00	1.85	0.60	0.01	0.02	0.22	0.32	0.02
Al_2O_3	21.27	20.08	21.41	15.33	22.53	14.78	24.62	22.28	21.63	19.12	36.49	25.51	21.83	20.96	34.14	24.96
FeO	28.25	28.63	25.49	17.24	0.16	19.05	0.00	33.19	30.73	18.47	1.01	0.00	27.80	33.23	2.06	0.07
MnO	1.75	1.14	5.85	0.20	0.00	0.65	0.10	2.16	0.85	0.11	0.00	0.00	5.94	1.32	0.04	0.00
MgO	2.12	2.00	1.43	8.85	0.00	9.70	0.00	4.45	2.55	10.92	0.67	0.00	1.10	1.51	1.58	0.00
CaO	9.55	10.22	9.37	10.75	3.91	9.03	4.84	1.08	6.59	0.00	0.01	5.05	6.45	6.17	0.00	4.98
Na_2O	0.01	0.00	0.00	1.84	9.24	2.02	8.56	0.04	0.01	0.18	0.62	8.34	0.01	0.06	0.62	7.18
K_2O	0.00	0.01	0.00	0.41	0.13	0.28	0.07	0.00	0.00	8.81	8.67	0.07	0.00	0.00	9.39	0.11
Total	99.85	99.25	100.87	98.16	99.77	99.32	100.46	100.76	99.56	95.77	94.40	100.96	100.60	100.22	95.97	99.91
Si	2.959	2.996	2.959	6.286	2.823	6.118	2.737	2.967	2.977	5.441	6.138	2.715	2.989	2.965	6.293	2.755
Ti	0.007	0.003	0.007	0.039	0.000	0.052	0.004	0.000	0.000	0.208	0.060	0.000	0.001	0.013	0.032	0.001
Al	2.007	1.910	2.007	2.630	1.175	2.460	1.278	2.074	2.040	3.377	5.698	1.317	2.053	1.993	5.295	1.295
Fe	1.695	1.933	1.695	2.099	0.006	2.250	0.000	2.192	2.057	2.315	0.112	0.000	1.855	2.242	0.227	0.002
Mn	0.394	0.078	0.394	0.025	0.000	0.078	0.004	0.145	0.058	0.014	0.000	0.000	0.401	0.090	0.004	0.000
Mg	0.169	0.241	0.169	1.920	0.000	2.042	0.000	0.524	0.304	2.439	0.132	0.000	0.131	0.182	0.310	0.000
Ca	0.798	0.884	0.798	1.677	0.185	1.366	0.228	0.091	0.565	0.000	0.001	0.237	0.552	0.533	0.000	0.235
Na	0.000	0.000	0.000	0.519	0.793	0.553	0.731	0.006	0.002	0.052	0.159	0.708	0.002	0.009	0.158	0.613
K	0.000	0.001	0.000	0.076	0.007	0.050	0.004	0.000	0.000	1.684	1.465	0.004	0.000	0.000	1.576	0.006
Alm/An	60.31	59.92	54.60	–	18.81	–	23.71	74.27	68.94	–	–	24.97	63.13	73.16	–	27.51
Prp/Ab	8.43	8.02	5.65	–	80.45	–	75.89	17.75	10.20	–	–	74.62	4.45	6.05	–	71.78
Sps/Or	3.95	2.60	13.13	–	0.74	–	0.41	4.90	1.93	–	–	0.41	13.66	3.01	–	0.72
Grs	25.25	24.77	24.93	–	–	–	–	3.09	18.94	–	–	–	18.76	15.72	–	–

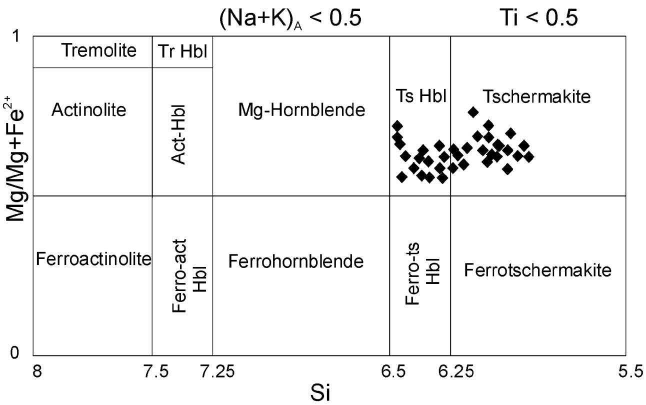


Fig. 6 Chemical composition of amphiboles from the amphibolite group according to the nomenclature of Leake (1978)

well Diósjenő–2. Biotite shows rather homogeneous composition, with minor variations in FeO, MgO and TiO_2 components (lower than 1.5 wt%).

Discontinuous zoning of garnets was not observed in the *micaschists*. They are characterized by a grossular-rich composition (X_{Alm}: 0.63–0.73, X_{Prp}: 0.04–0.06, X_{Grs}: 0.15–0.21, X_{Sps}: 0.03–0.15) that is very similar to the rim composition of the garnets from the gneisses. Continuously increasing X_{Alm}, Mg/(Mg+Fe) ratio and decreasing X_{Sps} from the core towards the rims (Table 1) suggest prograde metamorphic conditions during the crystallization of garnets. Plagioclase composition corresponds to oligoclase (X_{An}: 0.16–0.27). Si content of muscovite is about 3.15–3.2 p.f.u.

In the *amphibolites*, garnet cores are dominated by almandine with a considerable amount of grossular (X_{Alm}: 0.57–0.65, X_{Prp}: 0.07–0.1, X_{Grs}: 0.2–0.3, X_{Sps}: 0.02–0.05). The most distinctive feature of the rim is the high spessartine content (X_{Sps}>0.1, in some cases up to 0.2), whereas that of almandine and pyrope is somewhat lower. The grossular content does not show any significant change (Fig. 5B). However, this zoned character does not appear in all cases: both small, idiomorphic garnets with “rim-composition” and larger grains with “core-composition” are present.

Amphiboles have uniform tschermakitic composition according to the nomenclature of Leake et al. (1997), and show tschermakitic hornblende to pure tschermakitic compositions (Fig. 6) using the system of Leake (1978). The tschermakitic hornblende compositions (6.25<Si<6.5) are characteristic predominantly for the strongly sheared samples, whereas relatively undeformed samples have nearly pure tschermakitic (Si<6.25) composition. The optically observed weak zoning was detected by the microprobe measurements in some cases as well: the rims are generally somewhat richer in Al_2O_3 and CaO, and depleted in FeO and Na_2O components relative to the core regions. However, this chemical variation within individual amphibole grains is usually smaller than 2 wt% in the above mentioned components, and therefore does not cause a radical change in their classification. Plagioclase displays variable An content (X_{An}: 0 to 0.26) in this lithological group.

Geothermobarometry

In the case of the gneisses, we applied garnet-biotite thermometry (Ferry and Spear 1978, with the garnet mixing model of Berman 1990; Hodges and Spear 1982) and the garnet-phengite thermometry of Green and Hellman (1982). For pressure calculations we used the garnet-plagioclase-biotite-muscovite barometry of Hodges and Crowley (1985). Garnet-phengite thermometry and garnet-plagioclase-muscovite-quartz barometry (Hodges and Crowley 1985) were applied to the micaschists.

In the amphibolites, thermobarometric methods of Plyusnina (1982) and Holland and Blundy (1994) were applied for co-existing amphibole-plagioclase pairs. The thermometer of Graham and Powell (1984) and the barometer of Kohn and Spear (1990) were used for the low-Mn garnet-amphibole-plagioclase-quartz assemblage. Application of the garnet-amphibole thermometry of Graham and Powell (1984) for Mn-rich garnet resulted in low temperatures (<450°C) since their chemistry is out of the proposed composition range.

Thermobarometric calculations (Fig. 7) from the gneisses yielded temperatures up to 580 °C and pressures to 10 kbar (on average: 560±20 °C and 9± 1 kbar), using the garnet (Ca-rich rim)-biotite and the garnet-plagioclase-biotite-muscovite assemblages. From the micaschists we obtained 510–540 °C and 6.5–8 kbar using the garnet rim and adjacent muscovite-plagioclase-quartz paragenesis.

Considering the more basic plagioclase compositions (oligoclase) in the garnet-free amphibolites, an approximate range of ca. 500–530 °C and 7–8 kbar can be estimated for metamorphic conditions using the method of Plyusnina (1982). Amphibole-plagioclase thermometry of Holland and Blundy (1994) resulted in temperatures of 500–565 °C at 7–8 kbar (on average: 530±30 °C). For garnet amphibolites, results of 540±40 °C and 9±1 kbar were obtained using the thermometer of Graham and Powell (1984) and the barometer of Kohn and Spear (1990).

Geochronology

K/Ar measurements for this study were performed on biotite and amphibole separates. Ar/Ar investigations were carried out on muscovite separates from boreholes Hont-1 and Sóshartyán-3 (Fig. 8A, B). New K/Ar and Ar/Ar measurements resulted in more precise data than previous ones, which were mostly confirmed, in some cases somewhat corrected. All

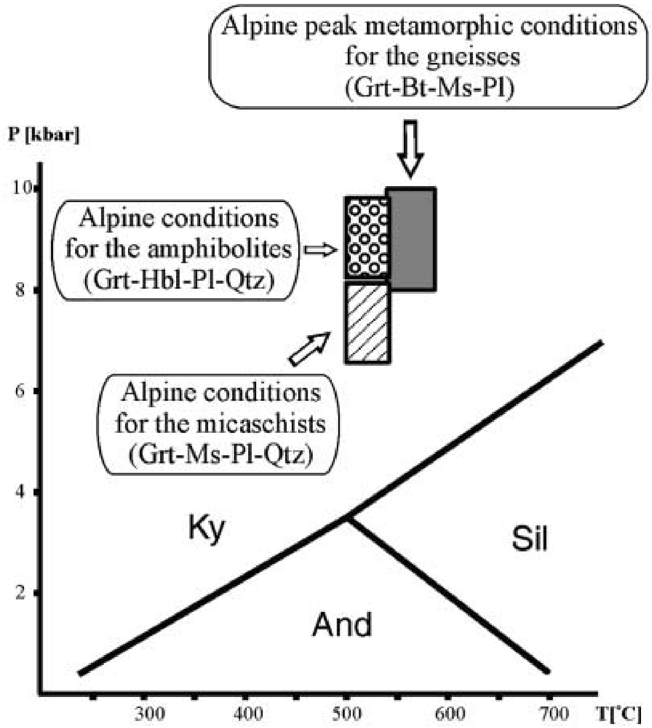


Fig. 7 Results of thermobarometric calculations obtained by the different methods for the Eoalpine metamorphic conditions. *Shaded box* represents calculated data (with error) for the gneisses, *striped box* for the micaschists and *stippled box* for amphibolite group. Al_2SiO_5 triple point is taken from Holdaway (1971)

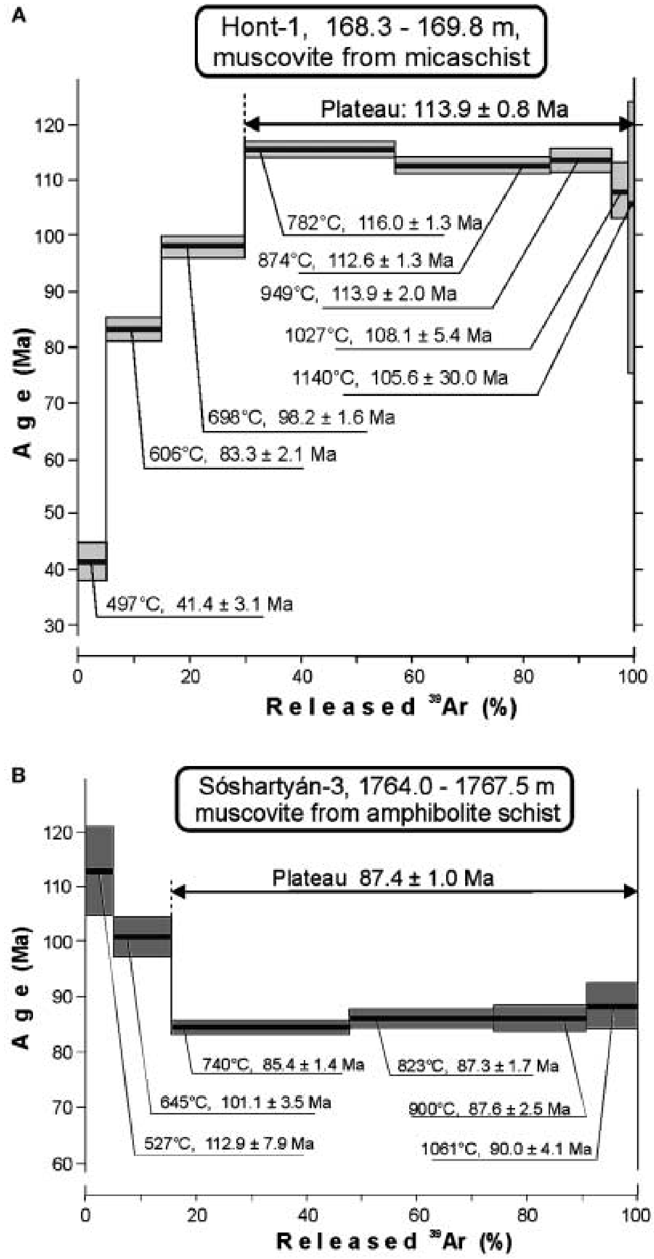


Fig. 8 $^{40}Ar/^{39}Ar$ age spectra measured on the white mica concentrates from boreholes **A** Hont-1 and **B** Sóshartyán-3

available geochronological data from the Veporic basement rocks in northern Hungary are listed in Table 2.

In the case of borehole Hont-1, a K/Ar age of 114±6 Ma was reported on muscovite from a micaschist sample (Balogh 1984; Lelkes-Felvári et al. 1996). On the same white mica separate, an Ar/Ar plateau age of 113.9±0.8 Ma was obtained in the 782–1140 °C temperature range where 70% of the ^{39}Ar was released (Fig. 8A). The youngest age (41.4±3.1 Ma) was measured at the lowest temperature step (at 497 °C). This rejuvenation might have been caused either by Eocene-Oligocene tectonism or the Miocene volcanism of the Börzsöny Mts.

From borehole Szécsény-7, a biotite K/Ar age of 96±7 Ma was published earlier (Lelkes-Felvári et al. 1996). This is somewhat corrected here by a new K/Ar age of 88.2±3.3 Ma on a fresher biotite separate from this borehole.

In well Sóshartyán-3, a K/Ar age of 108±5 Ma was measured earlier on muscovite (Lelkes-Felvári et al. 1996). The Ar/Ar step-heating spectrum on the same mineral separate defines a plateau age of 87.4±1.0 Ma in the 740–1061 °C temperature range where 84% of the ^{39}Ar was released (Fig. 8B). Older ages were obtained at lower temperature steps (112.9±7.9 Ma at 527 °C). This phenomenon is caused by incorporation of excess argon during the closure of muscovite. A new K/Ar age on amphibole of 93.5±5.6 Ma from the same rock agrees very well with the muscovite plateau age and shows that excess argon appeared only after the closure of amphibole. Excess argon was transported probably by hydrothermal fluids.

Zircon fission track (FT) data from the wells Szécsény-6; -7 and Sóshartyán-3 resulted in a narrow age cluster in the range of 75–77.5 Ma (for details see also Table 2). These ages are very close to the obtained K/Ar and Ar/Ar ages reflecting the same, rather fast cooling event.

Table 2 Summary of available geochronological data from the Veporic unit in northern Hungary

Locality	Lithology	Dating method	Dated mineral	Age (Ma±σ)	Reference
Borehole Hont-1, 168.3–169.8 m	Micaschist	K/Ar[a]	Muscovite	116±6	Balogh (1984)
Borehole Hont-1, 168.3–169.8 m	Micaschist	Ar/Ar	Muscovite (plateau age)	113.9±0.8	This work
Borehole Szécsény-7, 801.5–809.0 m	Gneiss	K/Ar[a]	Biotite	97±7	Lelkes et al. (1996)
Borehole Szécsény-7, 796–801.5 m	Gneiss	K/Ar[a]	Biotite	88.2±3.3	This work
Borehole Sóshartyán-3, 1764.0–1767.5 m	Amphibolite	K/Ar[a]	Muscovite	110±5	Lelkes et al. (1996)
Borehole Sóshartyán-3, 1764.0–1767.5 m	Amphibolite	Ar/Ar	Muscovite (plateau age)	87.4±1.0	This work
Borehole Sóshartyán-3, 1764.0–1767.5 m	Amphibolite	K/Ar[a]	Amphibole	93.5±5.6	This work
Borehole Sóshartyán-3, 1730–1735 m	Micaschist	FT[b]	Zircon	75.1±3.6[c]	This work
Borehole Szécsény-7, 796–801.5 m	Gneiss	FT[b]	Zircon	74.8±3.9	This work
Borehole Szécsény-6, 796–801.5 m	Gneiss	FT[b]	Zircon	77.5±3.5	This work

[a] Detailed analytical data are available on request from the third author
[b] Detailed analytical data are available on request from the fourth author
[c] Mean age, calculated from Veporic micaschist cobbles found in the directly overlying Miocene sediments

Discussion

Considering the new geochronological results, the calculated peak metamorphic conditions (550±30 °C and 9±1 kbar, lower amphibolite facies) are clearly assigned to the Eoalpine metamorphic event. The pressure values obtained suggest burial of these rocks to a depth of ca. 25–30 km during the mid-Cretaceous nappe stacking. The estimated values are very close to those reported by Janák et al. (1999) and Plašienka et al. (1999) for peak Alpine metamorphic conditions (temperature up to 600 °C and pressure about 10–12 kbar) of the Veporic unit and considerably higher than the proposed values (350–500 °C, 2.5–4 kbar) of Kováčik et al. (1996). The calculated P–T data from both lithological groups are in good agreement. The somewhat lower values from the micaschists are most probably caused by their retrogression. In micaschists, retrograde alteration resulted in the formation of fine-grained sericite-chlorite aggregates around garnet (Fig. 3B) and replacement of biotite by chlorite. In the case of amphibolites, Mn-poor garnet, tschermakitic amphibole, and basic plagioclase (with X_{An} up to 0.25) obviously reflect the peak conditions of Alpine medium-grade metamorphism. Euhedral epidote, clinozoisite, chlorite, and quartz inclusions in garnet and amphibole or idiomorphic-hypidiomorphic grains in the matrix were probably part of the prograde assemblage. Formation of epidote-clinozoisite-chlorite pseudomorphs after garnet (?), albite and Mn-rich garnet (both rim of large grains and small, individual, idiomorphic ones) was due to later retrogression. The relatively uniform composition of amphiboles may indicate that their chemistry was only weakly affected by retrograde processes, if at all.

The discontinuous character of the garnet zoning indicates a complex evolution of these rocks (Fig 5A, B). In the gneisses, garnet cores probably represent relics of a previous metamorphic event (Variscan?), whereas the chemically different rims were formed during the Alpine metamorphism. Similar zoned garnets were reported by Árkai et al. (1975), Vrána (1980), and Kováčik et al. (1997) from the medium-grade metapelites and gneisses of the southern Veporic crystalline complexes. In the case of amphibolites this compositional separation is not so obvious, although BSE images would suggest contrasting compositions (Fig. 5B). A possible explanation could be that enrichment of Mn in the rims is the result of late retrograde effects. This would mean that relatively Mn-poor cores of amphibolite garnets do not rep-

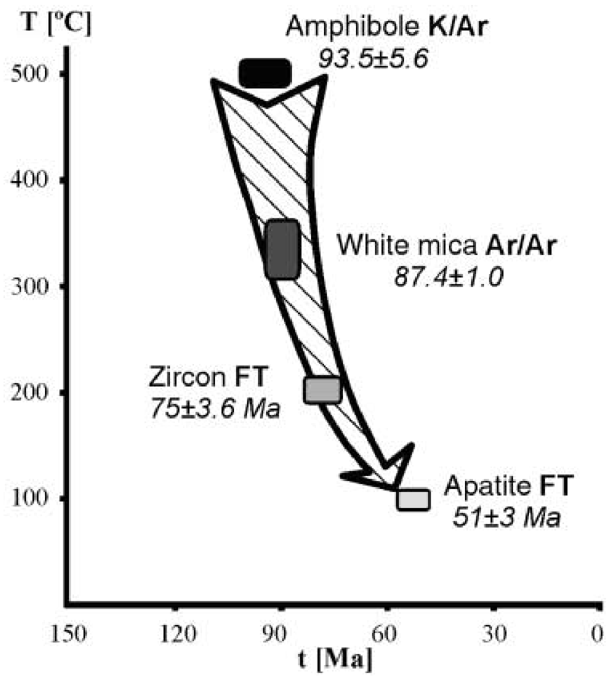


Fig. 9 Representative temperature–time (T–t) path for the Veporic crystalline basement in northern Hungary based on the geochronological results from borehole Sóshartyán-3

resent pre-Alpine relics (as in the gneisses), but may have been formed during the prograde stage of Alpine metamorphism.

New geochronological data obtained by the K/Ar, Ar/Ar and FT methods on white mica, biotite, amphibole and zircon record exclusively Eoalpine ages. We have not found any pre-Alpine age in the investigated minerals. Based on these new results – in contrast to Balogh and Körössy (1974), Ravasz-Baranyai and Viczián (1976) and Fülöp (1990) – we argue for an Alpine age of the medium-grade metamorphic event that must have reached at least 500 °C, as also indicated by the K/Ar age (93.5±5.6 Ma) of tschermakitic amphibole from borehole Sóshartyán-3 (Figs. 8 and 9). K/Ar and Ar/Ar data on micas are interpreted as cooling ages dating the final stage of the Eoalpine metamorphic event. They are in the range of 88–95 Ma in the Szécsény-Sóshartyán area, and about 113–116 Ma in the more westerly Hont area. The older K/Ar ages from the Hont-1 borehole may indicate somewhat earlier uplift and exhumation in that area. However, this explanation requires further data from the borehole and its surroundings. The new ages presented from the boreholes are in good agreement with the published data from numerous surface outcrops of the Veporic basement in Slovakia (Maluski et al. 1993; Dallmeyer et al. 1996; Kováčik et al. 1997).

The relative minor difference between FT and K/Ar respectively Ar/Ar ages suggests a very rapid cooling event representing the last phase of the Eoalpine tectonothermal evolution (Fig. 9). This fast cooling during Late Cretaceous is most probably related to the extensional unroofing of the Veporic core complex (Plašienka 1993; Plašienka et al. 1999). A very similar tectonometamorphic evolution is reported for the cooling and exhumation of many Middle-Austroalpine basement complexes in the Eastern Alps, where Late Cretaceous tectonic denudation of these units is associated with top-to-the-E(SE) movement of upper nappe complexes during orogen-parallel extension (Ratschbacher et al. 1990; Froitzheim et al. 1994, 1997; Neubauer et al. 1995; Handy 1996; Koroknai et al. 1999).

Zircon FT ages indicate that this portion of the Veporic unit was exhumed to shallow crustal levels (above the ca. 250 °C isotherm) during the Senonian time, and did not suffer any significant thermal overprint during the Tertiary. The Early Paleogene apatite FT ages measured in the same region (Dunkl 1993) are rather close to the new zircon FT data, and also point to rapid cooling and minor subsequent denudation. This result does not support the previous idea of Tari et al. (1993) concerning the HDL. They proposed that the HDL was a major, thick-skinned backthrust of Oligocene age along which important uplift and exhumation of deeply buried basement units (Veporic) occurred in the Oligocene. According to their assumption, this backthrust event was a consequence of the change in subduction type at the outer, Magura Flysch basin. Until the Late Eocene, there was a B-type subduction (normal oceanic crust of the flysch trench). Afterwards, the European crust was entering the subduction zone (A-type subduction), causing strong compression even at the rear of the Carpathian orogeny. Compression was manifested by tectonic reactivation of earlier structures as deep-seated backthrusts, i.e. the HDL. If the Veporic crystalline basement was exhumed only during Oligocene time, zircon and apatite FT ages would be younger than the Late Cretaceous and Early Paleogene ages found in this study. Consequently, our new zircon FT data clearly show that this crystalline basement was already largely exhumed during the Late Cretaceous, as also proved by the apatite FT data (Dunkl 1993).

Conclusions

1. The investigated rocks of the Veporic crystalline basement in northern Hungary were metamorphosed during the Eoalpine phase of the Alpine orogeny. Geochronological results from micas and amphiboles yielded exclusively Alpine ages, suggesting a temperature of at least 500 °C for the metamorphism.
2. Peak conditions of this Barrow type metamorphic event can be estimated at about 550±30 °C and 9±1 kbar (lower amphibolite facies) on the basis of geothermobarometric calculations. The polymetamorphic character of the gneisses is indicated by the presence of discontinuously zoned garnets, the cores of which represent the only relic of a pre-Alpine (most probably Variscan) event.
3. Geochronological data indicate rapid cooling during Late Cretaceous time, representing the last stage of the Eoalpine tectonothermal evolution. This fast cooling is most probably related to the extensional unroofing of the Veporic core complex reported by Plašienka (1993) and Plašienka et al. (1999).
4. The tectonometamorphic evolution of the Veporic unit recorded by the geochronological and petrological data is very similar to that of many Middle-Austroalpine basement complexes in the Eastern Alps, arguing for a common geodynamic setting during the Cretaceous orogeny.
5. Zircon FT data show that the investigated rocks did not suffer any significant thermal overprint (>250 °C) during the Tertiary. This result does not support the assumption of Tari et al. (1993) that the HDL is a major thick-skinned back thrust of Oligocene age along which important Tertiary uplift and exhumation of Veporic basement rocks occurred.

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References

Árkai P, Nagy G, Pantó Gy (1975) Types of composition zoning in the garnets of polymetamorphic rocks and their genetic significance. Acta Geol Acad Sci Hung 19 (1–2):17–42

Bada G, Fodor L, Székely B, Tímár G (1996) Tertiary brittle faulting and stress field evolution in the Gerecse Mountains, northern Hungary. Tectonophys 255:269–289

Balla Z (1989) Reevaluation of the Diósjenő dislocation zone (in Hungarian). Annu Rep Eötvös Loránd Geophys Inst Hung 1987:45–57

Balogh K (1984) Introduction of the K/Ar method in Hungary and the results of its application (in Hungarian). Sci Theses

Balogh K (1985) K/Ar dating of Neogene volcanic activity in Hungary: Experimental technique, experiences and methods of chronologic studies. Research Report, ATOMKI, Debrecen

Balogh K, Simonits A (1998) Improvements in experimental techniques of Conventional K/Ar and Ar/Ar Geochronological methods. Rapid Commun Mass Spectrom 12:1769–1770

Balogh K, Körössy L (1974) Hungarian Mid-Mountains and adjacent areas. In: Mahel M (ed) Tectonics of the Carpathian Balkan regions. Geol Inst of Dionýz Štúr, Bratislava, pp 391–403

Berman RG (1990) Mixing properties of Ca-Mg-Fe-Mn garnets. Am Mineral 75:328–344

Dallmeyer RD, Neubauer F, Handler R, Fritz H, Müller W, Pana D, Putiš M (1996) Tectonothermal evolution within the internal Alps and Carpathians: Evidence from ^{40}Ar-^{39}Ar mineral and whole-rock data. Eclogea Geol Helv 89:203–227

Dunkl I. (1993) Thermochronological investigation of bore cores. Research Report, Laboratory for Geochemical Research, Budapest

Ferry JM, Spear FS (1978) Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. Contrib Mineral Petrol 66:113–117

Froitzheim N, Schmid SM, Conti P (1994) Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogea Geol Helv 87:559–612

Froitzheim N, Conti P, van Daalen M (1997) Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Austria, Italy) and its significance for the tectonics of the Eastern Alps. Tectonophysics 280:267–293

Fülöp J (1990) Geology of Hungary, Paleozoic I (in Hungarian). Hung Geol Inst, Budapest, pp 1–325

Fülöp J, Brezsnyánszky K, Haas J (1987) The new map of basin basement of Hungary. Acta Geol Hung 30 (1–2):3–10

Graham CM, Powell R (1984) A garnet-hornblende geothermometer: calibration, testing and application to the Pelona Schists, southern California. J Metamorphol Geol 2:13–34

Green PF (1985) Comparison of zeta calibration baselines for fission-track dating of apatite, zircon and sphene. Chem Geol 58:1–22

Green TH, Hellman PL (1982) Fe-Mg partitioning between coexisting garnet and phengite at high pressure, and comments on a garnet-phengite geothermometer. Lithos 15:253–266

Handy MR (1996) The transition from passive to active margin tectonics: a case study from the zone of Samedan (eastern Switzerland). Geol Rundsch 85:832–851

Hodges KV, Crowley PD (1985) Error estimation and empirical geothermobarometry for pelitic systems. Am Mineral 70:702–709

Hodges KV, Spear FS (1982) Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. Am Mineral 67:1118–1134

Holdaway TJB (1971) Stability of andalusite and the aluminium silicate phase diagram. Am J Sci 271:97–131

Holland T, Blundy J (1994) Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. Contrib Mineral Petrol 116:433–447

Hurford AJ, Green PF (1983) The zeta age calibration of fission-track dating. Chem Geol (Isotope Geosci Sect) 41:285–312

Hurford AJ, Hammerschmidt K (1985) ^{40}Ar/^{39}Ar and K/Ar dating of the Bishop an Fish Canyon Tuffs: calibration ages for fission track dating standards. Chem Geol (Isotope Geosci Sect) 58:23–32

Hurford AJ, Watkins RT (1987) Fission-track age of the tuffs of the Buluk Member, Bakate Formation, northern Kenya: a suitable fission-track age standard. Chem Geol 66:209–216

Ivancsics J, Kisházi P (1982) Investigation of borehole samples from the Veporic and Zemplenic crystalline basement (in Hungarian). Research Report, Hung Geol Inst, Budapest

Janák M, Plašienka D, Lupták B, Frey M (1999) Alpine metamorphism in the central western Carpathians: relationships to Cretaceous continental collision. J Conf Abstr (EUG) 4/1:74

Jantsky B, Balázs E, Cserepes-Meszéna B (1988) Precambrian in the basement of the Pannonian Basin. In: Zoubek V, Cogné J, Kozhoukharov D, Kräutner HG (eds) Precambrian in younger fold belts. Wiley, Chichester, pp 687–711

Kohn MJ, Spear FS (1990) Two new geobarometers for garnet amphibolites, with applications to southeastern Vermont. Am Mineral 75:89–96

Koroknai B, Neubauer F, Genser J, Topa D (1999) Metamorphic and tectonic evolution of the Austroalpine units at the western margin of the Gurktal Nappe complex, Eastern Alps. Schweiz Mineral Petrogr Mitt 79:277–295

Kováčik M, Král' J, Maluski H. (1996) Metamorphic rocks in the Southern Veporicum basement: their Alpine metamorphism and thermochronologic evolution (in Slovakian). Miner Slovaca 28:185–202

Kováčik M, Král' J, Maluski H (1997) Alpine reactivation of the southern Veporicum basement: metamorphism, ^{40}Ar/^{39}Ar dating, geodynamic model and correlation aspects with the eastern Alps. In: Grecula P, Hovorka D, Putis M (eds) Geological evolution of the western Carpathians. Mineral Slov Monogr, Bratislava, pp 163–174

Kretz R (1983) Symbols for rock forming minerals. Am Mineral 68:277–279

Leake BE (1978) Nomenclature of amphiboles. Mineral Mag 42:533–563

Leake BE, Woolley AR, Arps CES, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG, Linthout K, Laird J, Mandarino J, Maresch WV, Nickel EH, Rock NSM, Schumacher JC, Smith DC, Stephenson NCN, Ungaretti L, Whittaker EJW, Youzhi G (1997) Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral names. Mineral Mag 61:295–321

Lelkes-Felvári G, Árkai P, Sassi FP, Balogh K (1996) Main features of the regional metamorphic events in Hungary: a review. Geol Carp 47 (4):257–270

Maluski H, Rajlich P, Matte P (1993) ^{40}Ar-^{39}Ar dating of the Inner Carpathian Variscan basement and Alpine mylonitic overprinting. Tectonophysics 233:313–337

Neubauer F (1992) ALCAPA. Geological evolution of the internal Eastern Alps and Carpathians and of the Pannonian Basin. The eastern central Alps of Austria. ALCAPA Field Guide, Graz

Neubauer F, Dallmeyer RD, Dunkl I, Schirnik D (1995) Late Cretaceous exhumation of the metamorphic Gleinalm dome, eastern Alps: Kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics 242:79–98

Odin GS, Adams CJ, Armstrong LR, Bagdasaryan GP, Baksi KA, Balogh K, Barnes IL, Boelrijk NAIM, Bonadonna FP, Bonhomme MG, Cassignol C, Chanin L, Gillot PY, Gledhill A, Govindaraju K, Harakal R, Harre W, Hebeda EH, Hunziker JC, Ingamells CO, Kawashita K, Kiss E, Kreutzer H, Long LE, McDougall I, McDowell F, Mehnert H, Montigny R, Pasteels P, Radicati F, Rex DC, Rundle CC, Savelli C, Sonet J, Welin E, Zimmermann JL (1982) Interlaboratory standards for dating purposes. In: Odin GS (ed) Numerical dating in stratigraphy. Wiley, Chichester, pp 123–149

Plašienka D (1993) Structural pattern and partitioning of deformation in the Veporic Foederata cover unit (central western Carpathians). In: Rakús M, Vozár J (eds) Geodynamic model and deep structure of the western Carpathians. Konferencie, Sympóziá, Semináre, Geol Inst of Dionýz Štúr, Bratislava, pp 269–277

Plašienka D, Janák M, Lupták B, Milovský R, Frey M (1999) Kinematics and metamorphism of a Cretaceous core complex: the Veporic Unit of the western Carpathians. Phys Chem Earth 24:651–658

Plyusnina LP (1982) Geothermometry and geobarometry of plagioclase-hornblende bearing assemblages. Contrib Mineral Petrol 80:140–146

Ratschbacher L, Schmid SM, Frisch W, Neubauer F (1990) Reply on the Comment of S.R. Wallis to "Extension in compressional orogenic belts: the eastern Alps." Geology 18:675–676

Ravasz-Baranyai L, Viczián I (1976) Mineralogical-petrographical investigation of crystalline basement rocks uncovered by borehole Hont-1, N-Hungary. (in Hungarian) Annu Rep Hung Geol Inst 1974:61–72

Steiger RH, Jäger E (1977) Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth Planet Sci Lett 12:359–362

Tari G, Báldi T, Báldi-Beke M (1993) Paleogene retroarc flexural basin beneath the Neogen Pannonian Basin: a geodynamic model. Tectonophysics 226:433–455

Thöni M, Jagoutz E (1993) Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the eastern Alps: bearing on Alpine orogenesis. Schweiz Mineral Petrogr Mitt 73:177–189

Tomek C (1993) Deep crustal structure beneath the central and inner Western Carpathians. Tectonophysics 226:417–431

Török K (1998) Magmatic and high pressure metamorphic development of orthogneisses in the Sopron area, Eastern Alps (W-Hungary). Neues Jahrb Miner Abh 173 (1):63–91

Tullis J, Yund RA (1985) Dynamic recrystallization of feldspar: a mechanism for ductile shear zone formation. Geology 13:238–241

Vrána S (1980) Newly-formed Alpine garnets in metagranitoids of the Veporides in relation to the structure of the central zone of the western Carpathians. Časopis Mineral Geol 25:41–54