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Exhumation and cooling rates of the Variscan basement metamorphic complex inferred from petrological data (Malé Karpaty Mts.)

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Abstract. Orogenic block transport and tectonic structuring occurred in Variscan era and later during Alpine movements which destroyed and displaced the polymetamorphic Tatric crystalline basement into new structural positions. Uplift stages were not unified within the studied crystalline basement units. Data confirm slower cooling during exhumation, probably controlled by erosion, for some samples, but for the others, the tectonically controlled rapid uplift trajectories.

The calculated petrological cooling rates and exhumation data thus verify different uplift conditions of individual tectonic blocks during final stages of the Variscan orogen events. The data obtained form the further arguments for the Tatricum crystalline basement disturbance and its allochthonity in the Malé Karpaty Mts.

Key words: Cooling rates, exhumation, geothermobarometry, crystal size distribution, tectonics.

The pre-Alpine basement of the Western Carpathians is represented mainly by medium to high-grade paragneisses, orthogneisses, amphibolites and other metamorphic rock complexes which were later intruded by granitoidic rocks of Variscan age. The spatial relationship and metamorphic zonality exists in some areas only as a rudimentary remnants. In other places the complete metamorphic zonality was preserved.

Complex structures of the mountains reflect their complicated development, which started hundreds of kilometers southwards, and the remnants of Variscan mountains were overridden by Paleo-Alpine nappe piles. Their structures were modified by back-thrusts and transpressional tectonics (Plašienka et al., 1991).

The sedimentary overburden was metamorphosed before granitoid rocks intruded and periplutonic processes became dominant in the area. The metamorphic process took place during the Variscan era. The biotite pairs Rb/Sr isochron gives age of 344 ± 3 m. y. (Cambel et al., 1990b). This age determination is considered to be the age of Bratislava granitoid massif intrusion.

Earlier tectonic concepts (Cambel, 1954) were not in favour of any Alpidic orogenic activity in the crystalline basement complexes, and only Alpidic fault retrograde processes development were considered. However, recent petrological research indicates complex tectonic and structural development of this core mountain mass (Dyda, 1980, 1994; Cambel et al., 1981; Korikovskij et al., 1984; Miklóš, 1987). This requires the assumption of several superimposed nappe units consisting of pre-Alpine crystalline basement with its Mesozoic cover (Putiš, 1991; Plašienka et al., 1991).

The present petrologic study is focused on petrological heating and cooling rate of basement paragneisses. This is based on garnet chemical zonality evaluation, garnet nucleation and growth and metapelitic rocks uplift trajectories. The aim is to describe some distinctive details of metamorphic features that bring some new aspects of metamorphic development of this important geological area.

Calculated approximative P-T trajectories, in the range of 570–650 °C and 3.5–6.1 Kbar, express the first order tectonic motion and represent specific uplift conditions of the particular tectonic blocks (Fig. 1). Some of the samples express uplift trajectories determined dominantly by decompression during cooling while the others may present more isothermal, probably rapid decompression during tectonicaly driven uplift period. The thermodynamic data are in accordance with index mineral appearances and mineral equilibrium domains. The occurrence of retrograde mineral domains, the microscopic appearance of garnets and their crystal size distribution all confirm the individuality of these basement tectonic blocks.

The compositional zoning of studied garnets at the biotite-garnet couple interface was the primary data source for petrological cooling rate approximation. Geothermobarometric determination of the culmination P-T conditions was considered as the attained mineral equilibrium, when compositional Fe-Mg distribution is uniform within mineral assemblage. As the post-culmination metamorphic cooling starts, the chemical affinity of the exchange reaction changes with temperature and diffusion drives the mobile components at the grain interface boundaries. The diffusion proceeds till the closure temperature froze-in the compositional profile in garnet. The chemical profiles obtained were averaged and normalized (Fig. 2). The further elaboration of the profiles with Lasaga´s (1983) diffusion equations thus provide the methodical tool for cooling rate estimation of studied basement

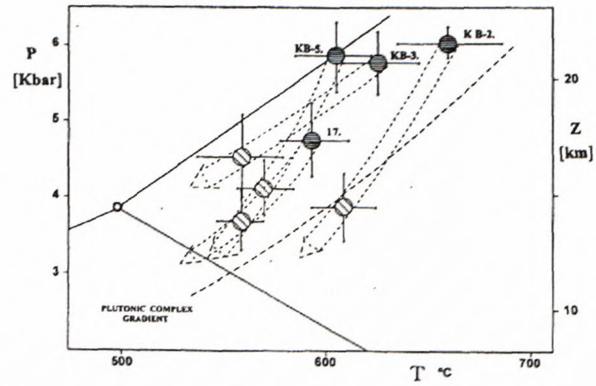


Fig. 1. Metamorphic culmination and closing retrograde P-T characteristics of of Malé Karpaty Mts. paragneisses metamorphic recrystallization, calculated from Grt-Bt-Ms-Plg-Sil-Qtz mineral equilibria. Temperature data were obtained on the basis of Grt-Bt calibrated equilibria (Ferry & Spear, 1978; Thompson, 1976; Newton & Haselton, 1981; Ganguly & Saxena, 1984; Hodges & Crowley, 1985). Pressure was calculated from calibrated equilibria Grt-Plg-Sil-Qtz (Ghent, 1976; Powell & Holland, 1988; Newton & Haselton, 1981) and equilibria including Grt-Bt-Ms-Plg-Qtz (Hoisch, 1990).

Tab. 1. Cooling rates of paragneisses from Malé Karpaty Mts. Tatric basement.

Sample	**17.**	**KB-2.**	**KB-3.**	**KB-5.**
T [°C]	592±17	657± 25	623± 21	601±19
P [Kbar]	4.66± 0.45	5.90± 0.05	5.70± 0.41	5.82± 0.41
r [mm]	0.604	0.366	0.384	0.359

Diffusion coefficient [cm^2/s] *

D_T(Ch&G)	$9.99*10^{-21}$	$1.48*10^{-19}$	$3.87*10^{-20}$	$1.55*10^{-20}$
D_T(F)	$1.00*10^{-20}$	$2.84*10^{-19}$	$5.24*10^{-20}$	$1.64*10^{-20}$
D_T(E)	$2.30*10^{-19}$	$2.04*10^{-18}$	$6.78*10^{-19}$	$3.18*10^{-19}$
D_T(L)	$5.49*10^{-20}$	$9.48*10^{-19}$	$2.55*10^{-19}$	$8.35*10^{-20}$

Cooling rate [°C/Ma]

S (Ch&G)**	4.07	1.86	2.66	0.22
S (F)	4.01	3.56	3.61	0.24
S (E)	94.03	25.62	46.71	4.69
S (L)	22.39	11.89	15.48	1.23

**calculated for metamorphic culmination P-T conditions using pre-exponential factor D_0 and activation energy for diffusion Δ E* according to **Ch&G – Chakraborty & Ganguly (1992), F – Freer (1981), E – Elphic et al., (1985), L – Lasaga (1977)*

metamorphic complexes (Tab. 1). However, a lot of garnet profiles have to be studied to obtain consistent petrological rate parameters and for accurate cooling rate determinations more data on diffusion are needed.

Crystal size distribution (CSD) of a garnet population determines garnet nucleation and growth rates, garnet producing reaction overstepping and average residence time of a garnet population. These data provide a numerical comparison of metamorphic recrystallization conditions based on a detailed textural study of the metamorphic rock sample.

Nucleation rate depends significantly on the type of metamorphic regime. High nucleation rates occur during contact metamorphic conditions whereas high-grade regional metamorphism is represented by slow rate of nucleation. Thus the calculated garnet nucleation rates 2.9 * $10^{-8}/cm^3/s$ to 1.0 * $10^{-7}/cm^3/s$ indicate the regional metamorphic regime for analysed paragneissic rock samples.

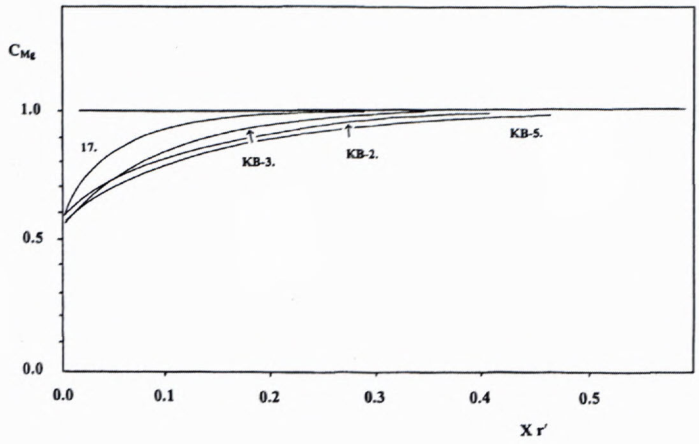
The strict numerical relationship among related reaction parameters ΔT and $\Delta S_{reaction}$ limits the calculated garnet growth residence times (Fig. 3). The comparison of garnet residence growth time estimates shows schematically that characteristic time estimates based on CSD of garnets match well with metamorphic reaction conditions of ΔT = 0.15 °C and $\Delta S_{reaction}$ = 25 cal/mol/deg. The reaction temperature overstep of ca. 0.15 °C is consistent with the regional thermal event and the modelled heating rate trends obtained (4^* 10^{-5} °C / year) are in good agreement with the thermal regional metamorphic regime.

The regional recrystallization products are usually subjected to prolonged cooling after thermal culmination and CSD histograms are mostly significantly modified. This process is represented by the change of shape of the crystal size histograms as small unstable garnet crystals dissolve and the material is precipitated on larger crystals. The annealing mass transfer is temperature and time dependent textural modification process where the large crystals retain the original crystal size frequency distribution. The numerical values of the garnet mass fraction transferred in particular studied samples are significantly different. The calculated annealing estimates indicate that in rock samples approximately 0.10–0.53 garnet mass fraction was transferred during the annealing process that lasted after the peak metamorphic conditions were completed (Fig. 4).

Some retrograde garnet diffusion rims are narrow and with the morphological appearance of idioblastic garnets clearly testify at least a rapid cooling during uplift period. This numerical estimate may be a good cooling rate indicator. Thus, the apparently quenched mineral assemblage of a particular tectonic block differs from other periplutonic assemblages which exhibit significantly higher garnet mass transfer estimates. Such numerical values testify more about the regional metamorphic environment than the contact recrystallization conditions. The extent of garnet mass transfer during the post-peak annealing indicates the prolonged cooling from the peak temperatures, reflecting presumably, the regional metamorphic thermal histories of the rock samples which now have the periplutonic tectonic position (Fig. 5).

In the absence of precise geochronological data the reliable geothermobarometrical metamorphic trajectory determination offer, in first numerical approximation, a useful basis for petrological subduction and exhumation estimates. The calculated temperature, depth and heating rate data (410^{-5} °C/year) may thus provide corresponding average burial rate value 1–2 km/Ma for the studied basement paragneisses. Accepting similar numerical

Fig. 2. Normalized Mg (C_{Mg}) concentrations as a function of normalized distance (Xr´) from Bt-Grt edge in garnets from Malé Karpaty Mts. Tatric basement paragneisses used as a tool for cooling rate calculations.



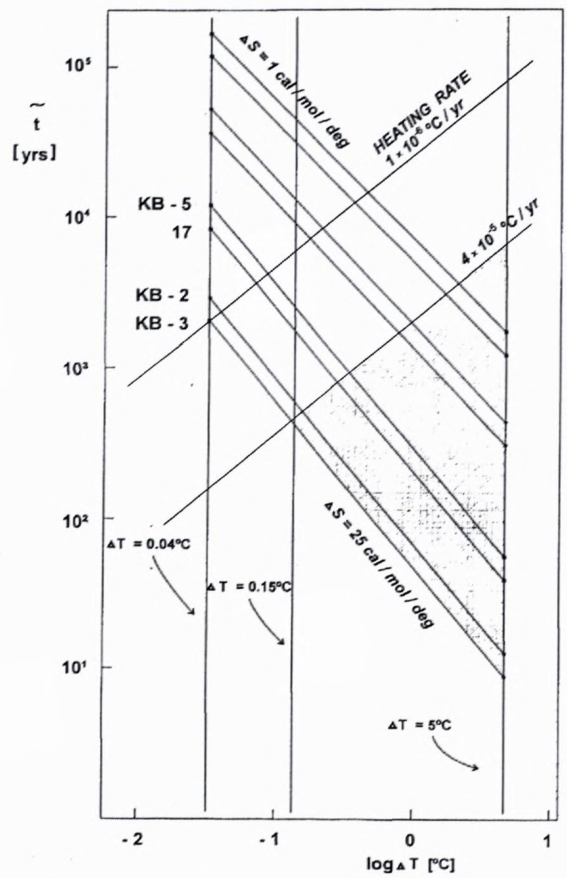


Fig. 3. Garnet growth residence time estimates calculated for the garnet populations in paragneissic samples. The calculation is based on the relation among equilibrium temperature (T_{equil}), equilibrium temperature overstep (ΔT), dehydration reaction entropy ($\Delta S_{reaction}$) and garnet crystal size distribution characteristics (CSD).

approach, the cooling rate data obtained on the basis of diffusional zonality development in garnets may asses the approximated exhumation rate 0.2–3.8 km/Ma for tatric basement rocks (Fig. 6).

These petrological observations clearly indicate that the studied rocks did not stay the same period of time under metamorphic culmination conditions which woud

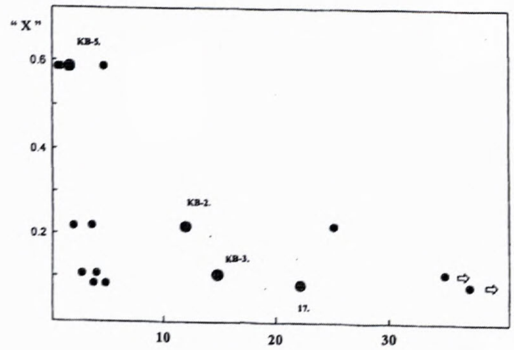


Fig. 4. The relation between calculated cooling rate (S, °C/Ma) of Malé Karpaty Mts. basement paragneisses and the extent of the garnet mass transfer („X“) in these mineral assemblages expresses the mutual connection between these characteristics, when rapid cooling enables only limited mass transfer.

probably cause the similar diffusion zonality and close postculmination cooling rate estimates. The data obtained form the first numerical comparison basis for petrological heating and cooling rates evaluation in the Western Carpathian region.

However, for other metamorphic terranes higher burial and cooling rates are reported. From Spanish Betics, minimum cooling rates of 200 °C/Ma and uplift rates of 2–5 km/Ma have been given (Zeck et al., 1989). But for the same geological area Monié et al., (1994) report cooling rates of 100–350 °C/Ma and exhumation rate of 3 km/Ma. Zeck et al. (1992) further suggest for Betics Cordilereas cooling rates of 150–350 °C/Ma and corresponding exhumation rates of 5-10 km/Ma. For Tauern Window the exhumation rate varied with metamorphic evaluation from >5 km/Ma to <1 km/Ma (Cliff et al., 1985). Exhumation and cooling rate of Dora Maira UHP terrane are 22 km/Ma and ~ 90 °C/Ma respectively (Gebauer et al., 1997).

The crystalline basement experienced two dominant distinct progressive metamorphic events. The earlier, before Variscan granitoid magma intrusions, is regionally presented by medium to high pressure and medium to high

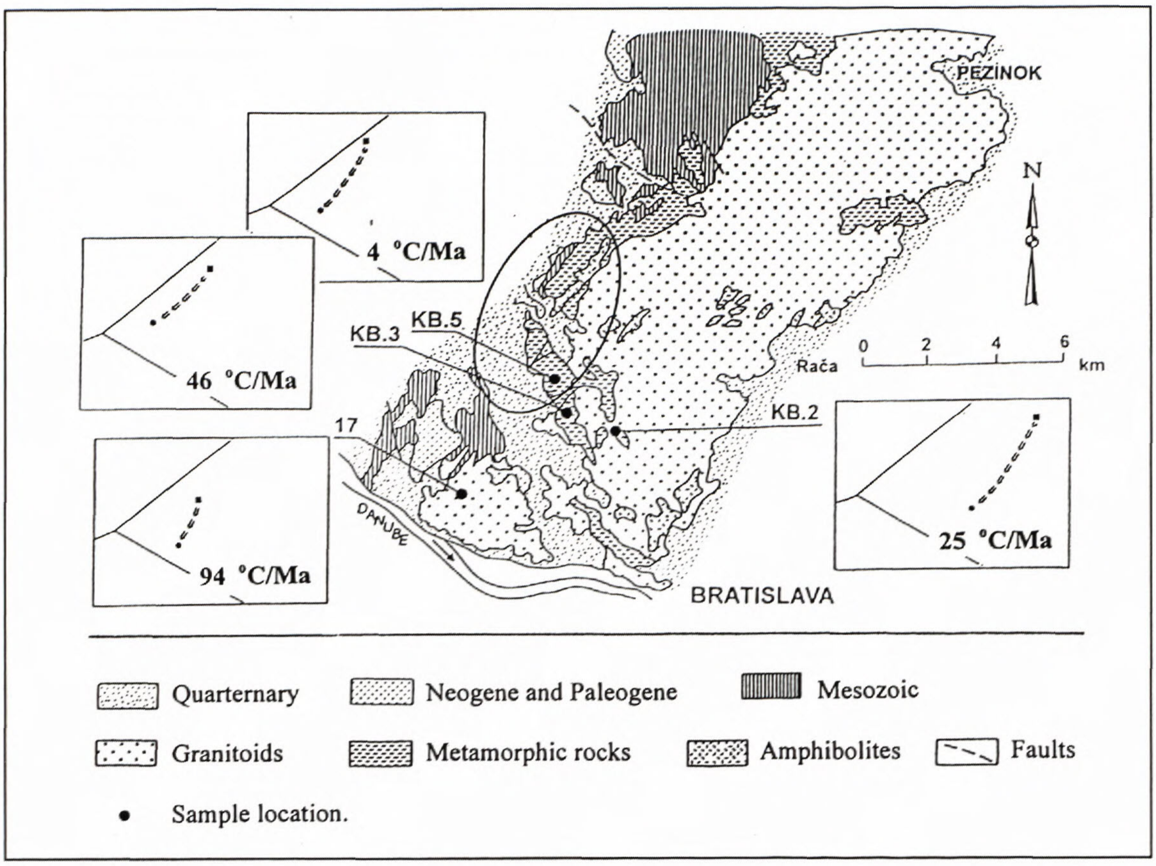


Fig. 5. The Malé Karpaty Mts. Tatric basement paragneisses present differences in the calculated petrological cooling rates S [°C/Ma]. These differences are confirmed by P-T data and post-culmination mass transfer. They manifest the individuality of post-culmination development and tectonic fragmentation of the tatric basement. The diffusional parameters D_o, E^* have the crucial importance in cooling rates determination. Thus for comparison purposes the S values of Elphic et al. (1985) are shown.

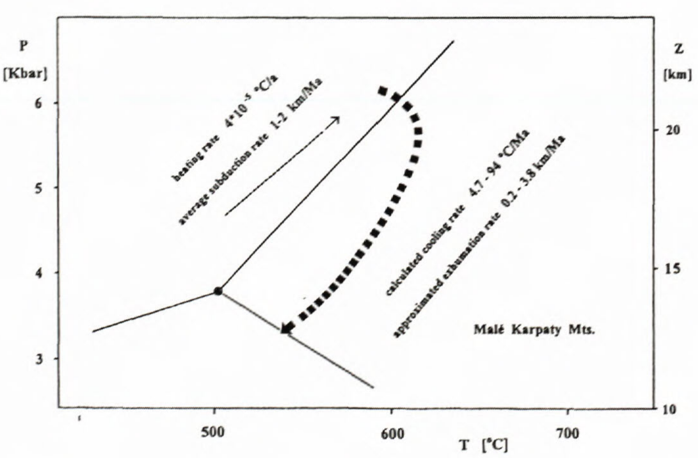


Fig. 6. Approximative time characteristics for Malé Karpaty Mts. Tatric basement metamorphic trajectories inferred from petrological data. Average heating rate of the regional metamorphic complex ($4*10^{-5}$ °C/a) was determined on the basis of garnet crystal size distribution and consistent muscovite dehydration time. In linear approximation, after anchimetamorphic zone crossing (c. 150–200 °C) time of 11 Ma is needed for metamorphic complex to reach thermal culmination ~ 600 °C in depth of ~ 24 km. In this numerical approximation, average burial rate ~ 1–2 km may be considered. Cooling rates calculated on the basis of diffusional zoning in garnets and Elphic et al. (1985) experimental data are in range of 4.7–94 °C/Ma. The exhumation rate of the Tatric basement complex is then consequently c. 0.2–3.8 km/Ma.

temperature mineral assemblages, which passed the kyanite stability field, as the unreacted rare kyanite rests are present in some samples (Dyda, 1999b). The later metamorphic event is connected with tectonothermal evolution of granitoidic intrusions producing zonal peri-plutonic recrystallization processes at depth. The peak progressive conditions were different for samples with different geological positions.

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