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# METAMORPHIC CONDITIONS OF THE VEPORIC UNIT IN THE WESTERN CARPATHIANS

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**Abstract:** Metamorphic mineral assemblages, mineral chemistry and geothermometric methods have been used to investigate probable conditions of the principal metamorphic stages that affected Veporic rocks. The oldest (Cadomian?) metamorphism took place in amphibolite-facies conditions, most probably at temperatures ranging from 600 to 650 °C. Hercynian metamorphism corresponds to the almandine zone of the greenschist facies at temperatures attaining 450–530 °C and pressures of 400–500 MPa. Synkinematic stage of Alpine metamorphism did not exceed the chlorite zone, with temperatures amounting to 360–430 °C and pressure of some 400 MPa. Superposed postkinematic (thermal-dome type) metamorphism locally reached higher temperatures.

**Key words:** Western Carpathians, Veporicum, metamorphic stages, geothermo-barometry.

## Introduction

Geological structure of the Alpine-formed Veporic tectonic unit in the Western Carpathians comprises Mesozoic, Upper Paleozoic and earlier crystalline complexes. The crystalline in turn consists of several metamorphic as well as granitoid complexes, and underwent a prolonged complex development. Its Hercynian structure, composed of Lower Paleozoic and older (probably Cadomian) rocks as well as Hercynian granites, was destructed during Alpine disturbances and its individual parts were incorporated into new, Alpine tectonic units. That is why the Hercynian structure of the Veporicum is difficult to reconstruct. In this stage we can only separately analyse the individual complexes, from the structural, lithologic and metamorphic points of view.

So far views on the division and tectonic structure of the crystalline and Veporicum were based on the assumption that it results from the main Alpine tectonic events. First, it was horizontally divided into zones of different lithology (Zoubek 1957) and later vertically into two principal tectonically superimposed complexes of granitoid and metamorphic rocks which are irregularly distributed throught the Veporicum (Klinec 1966). Latest interpretations again favour essentially scaled structure of several principal tectonic units (Mahef 1986). Our latest researches and detailed mapping have confirmed vertical division into three main age and structural storeys reworked into complicated structures during the Alpine orogeny. We have obtained structural and geochronological data indicating presence of pre-Hercynian elements in the structure of the territory, but mainly data on significant Hercynian tectonics (Bezák 1988). The long and complex tectonic development of the Veporicum is reflected also in its complicated metamorphic development. In this article we attempt to summarize the latest results of researches focused on conditions in which individual metamorphic stages took place. The metamorphic conditions have been studied by means of metamorphic mineral assemblages in the individual complexes, changes in mineral chemistry and by geothermometric methods (graphite and garnet-biotite thermometres have been employed; results and calibrations are given in Bezák 1989).

## Analysis of metamorphic conditions in individual development stages

From the structural-tectonic point of view, the lowest storey in the geological structure of the Veporicum is represented by the highest-metamorphosed and granitized complex composed mainly of banded migmatites, biotite hornfels-gneisses and hybrid granitoids. The gneisses contain a simple mineral assemblage: quartz-plagioclase-biotite along with frequent garnet and rare amphibole. Chemistry employed to evaluate the original lithology suggests sedimentary (graywackes) as well as mixed trend (admixture of volcanic material) of these rocks. The whole complex was intruded by Hercynian granitoids of several types in at least two stages. In this respect, formation of porphyroblastic K-feldspars is noteworthy.

Position of the complex, preserved structural elements other than Alpine, occurrences of tectonic breccias of gneisses cemented by Hercynian granitoids and some new geochronological data suggest that they are the oldest preserved elements in the Veporicum (presumably Precambrian in age). Conditions of the first (Cadomian ?) metamorphism of these rocks cannot be reliably resolved for the time being because of later superposed Hercynian and Alpine metamorphic events as well as Hercynian intrusive activity. Difference in metamorphic grade relative to the Early Paleozoic complexes, however, is evident, their contact being tectonic. Higher--grade metamorphism (amphibolite facies) is suggested by fairly pyrope-rich (some 16 %) and homogeneous garnets in paragneisses as well as by higher basicity of their plagioclases (up to $An_{33}$) and signs of migmatization. The first values indicated by graphite thermometre, which gives the highest temperature to which the rock concerned was subject, range from 600 to 620 °C. Garnet-biotite thermometre suggests higher temperatures (up to 730 °C, Bezák 1989). Signs of the Hercynian synkinematic metamorphism were largely obliterated by later recrystallization at increased heat flow related to granitoid intrusions. The postkinematic Hercynian stage is reflected mainly by the formation of biotite II. and K-feldspar porphyroblasts (question of the genesis of the latter remains so far unresolved, mainly whether it underwent only metamorphic recrystallization and/or how much potassium was introduced). The Alpine metamorphism clearly gave rise to diaphthoresis, mainly in tectonic zones.

Early Paleozoic rocks make up two principal complexes whose mutual contact is tectonic. They do not significantly differ from one another in age nor in metamorphic grade, the only important difference being their original lithology. The complex of garnet mica schists was originally represented by claystones without volcanic admixture, whereas the complex of albitized biotite gneisses was made up of graywackes locally with volcanoclastic material.

The principal mineral assemblages (garnet + biotite + muscovite + chlorite + quartz + plagioclase in metasediments and amphibole + plagioclase in metabasic rocks) indicate that the rocks were metamorphosed to the higher-temperature part (of the garnet zone) of the greenschist facies (lower--grade metamorphism, fairly close to medium-grade one according to Winkler 1979). Mineral assemblages are a much more significant petrogenetic indicator than the occurrence of a single index mineral, because they eliminate the effects of variable composition (Thompson 1957). The above-mentioned assemblages occur at temperatures ranging from 450 to 540 °C (between the formation of biotite and destruction of the assemblage chlorite + muscovite accompanied by the formation of staurolite and cordierite). The beginning of the garnet zone is not known exactly, because reaction according to which garnet is first formed has not yet been determined (it substantially depends also on the composition of garnet). According to Turner (1968) this reaction takes place alongside the formation of amphibole in place of actinolite in mafic rocks (because of its complexity, reaction actinolite + clinozoisite + chlorite + quartz = amphibole has a certain interval of P-T conditions but takes place at temperatures of some 500 °C, with the role of pressure being insignificant). The upper boundary of the garnet zone (transition to medium-grade metamorphism) is indicated by the formation of the assemblage plagioclase $An_{17-20}$ (in place of albite) + amphibole in metamorphosed mafic rocks but mainly by the first formation of staurolite or cordierite in metapelites. The formation of staurolite has been experimentally studied e.g. by Hoschek (1969): reaction chlorite + muscovite = staurolite + biotite + quartz + $H_2O$ has equilibrium conditions at 540 °C ± 15 °C and 400 MPa as well as at 565 °C ± 15 °C and 700 MPa.

Several samples of the Early Paleozoic complexes investigated by graphite thermometre indicate temperatures ranging from 495 to 530 °C, whereas garnet-biotite thermometre suggests 470–535 °C, the results of both methods being very similar (Bezák 1989). These results are also supported by chemistry of garnets (almandine component amounts to 60–80 % and histogram of Ti distribution in amphiboles (corresponds to conditions of the greenschist facies). Changes in plagioclase basicity cannot be studied because they are obliterated by advanced albitization. Only locally there occur relics of older plagioclases whose basicity amounts to $An_{15-20}$. Pressure is indicated mainly by conditions in which, at the above-mentioned temperatures, almandine occurs and staurolite is formed for the first time (over 400 MPa). In the diagram showing $Al^{VI}/Si$ ratio in amphiboles, those of the Early Paleozoic complexes lie on the boundary separating high- and low-pressure metamorphism (approx. 400–500 MPa). Summarizing geothermometric and experimental data on some metamorphic reactions expressed in a petrogenetic grid (Fig. 1), we may conclude that the main stage of the Hercynian metamorphism took place at 450–530 °C and 400–500 MPa.

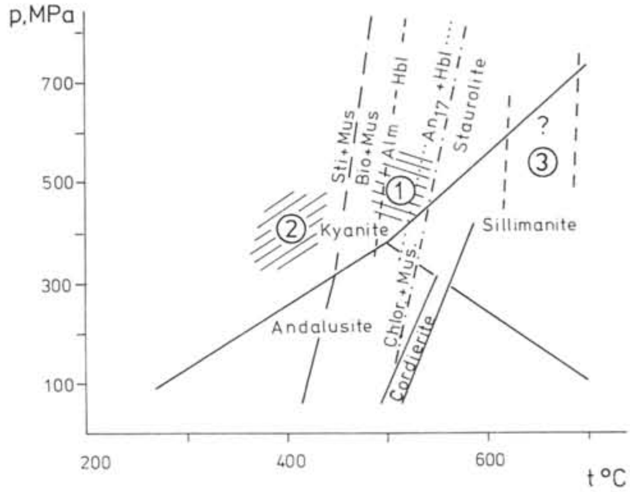


**Fig. 1.** Petrogenetic grid showing fields of P-T conditions during principal Hercynian (field 1) and Alpine (field 2) metamorphic stages. Field 3 – probable conditions of the oldest metamorphism. Experimental lines of P-T conditions in which metamorphic minerals were formed are given after various authors (mainly Winkler 1979; Turner 1968).

Character of the Alpine metamorphism can be best studied in Late Paleozoic and Mesozoic complexes. Mineral assemblages suggest that the intensity of the synkinematic stage did not exceed conditions of the chlorite zone, i.e. lower-temperature part of the greenschist facies. The upper limit of P-T conditions in this stage is determined by the formation of biotite. Biotite was most probably formed according to the reaction stilpnomelan + muscovite = biotite + chlorite + $H_2O$, and P-T conditions of this reaction have been experimentally determined at 400–700 MPa and 430–460 °C. Results obtained by graphite thermometre suggest temperatures ranging from 365 to 435 °C.

Postkinematic stage of the Alpine metamorphism is characterized by crystallization of transversal biotite, chlorite, chloritoid and kyanite. The minerals are irregularly distributed in space and probably owe their origin to local postkinematic ascensions of thermal front (small thermal domes locally associated with probably Alpine granitoid intrusions). Garnet-biotite thermometre indicates their crystallization temperature of 405–445 °C. Pressure conditions of the Alpine metamorphism are determined mainly by the presence of kyanite (Vrána 1964) and experimentally demonstrated conditions of biotite formation. We may conclude that the main (synkinematic) stage of the Alpine metamorphism most probably took place at temperatures of 360–430 °C and pressure of some 400 MPa (Fig. 1). The Alpine postkinematic stage was irregularly distributed (thermal-dome type) and was characterized by higher temperature conditions (formation of biotite, kyanite, and garnet).

## Discussion

The studied area underwent a complex polymetamorphic development which can be divided into several stages. In addition to the oldest (Cadomian?) metamorphism in the granitized complex, these include two stages of the Hercynian metamorphism – dynamic (probably reaching the highest intensity in the Upper Devonian–Lower Carboniferous) and static (related to Late Hercynian granitization) as well as two stages of the Alpine metamorphism – similarly dynamic and static ones (K-Ar dating – Burchart et al. (1987) and fission-track method – Kráľ (1982) indicate that both stages took place in the Upper Cretaceous). Each successive metamorphic stage (except for static ones) mostly resulted in progressive metamorphism of younger complexes and diaphthoresis of older ones or in isofacial recrystallization.

In this article we have attempted, on the basis of geothermometric data (Bezák 1989) and metamorphic mineral assemblages, to determine metamorphic conditions in all metamorphic stages. Other works dealing with metamorphic conditions of the principal Alpine metamorphic stage in the Veporicum include that by Vrána (1980) who, on the basis of Paleo-Alpine mineral assemblages, has determined metamorphic conditions at 450–500 °C and 500 MPa as well as work by Hurai (1983) who has studied fluid inclusions in vein quartz and distinguished two types of quartz, the first of them having been formed at 487 ± 67 °C and 275 ± 70 MPa and the second at 372 ± 43 °C and 115 ± 11 MPa. Korikovsky et al. (1986) have investigated samples collected on the southern periphery of the Veporicum by garnet-biotite thermometre as well as petrogenetic grid and determined conditions of regional metamorphism at 400–450 °C and 400–450 MPa and those of contact metamorphism at 450–490 °C and 100–150 MPa which is in agreement with data obtained in this area by J. Kamenický (1977) – 505 to 525 °C and Krištín and Vozárová (1986) – 448 to 523 °C. Assignation of the metamorphic conditions to either Alpine or Hercynian stage is controversial in some cases but on the whole these data do not contradict ours.

Metamorphic development is closely related to tectonic one, as has been demonstrated in a number of cases in different regions throughout the world. Geological development of the studied area resembles the complicated development of metamorphic complexes in continental-collision zones and in intracratonic orogens (Haxel et al. 1984; Dalmayrac et al. 1980; Dal Piaz et al. 1972; Badham 1982 etc.). Heat supply and formation of thermal domes are interpreted in different ways, either as separate ascensions from the mantle or as a result of piling up nappes. The formation of relative thermal and metamorphic anomalies may be also affected by the basement ("basement effect") as defined by Fonteille and Guitard (1964).

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