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VARISCAN UPLIFT OF THE CRYSTALLINE BASEMENT, TATRA MTS., CENTRAL WESTERN CARPATHIANS: EVIDENCE FROM $^{40}Ar/^{39}Ar$ LASER PROBE DATING OF BIOTITE AND P-T-t PATHS

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Abstract: The Variscan uplift between about 300 - 330 Ma has been documented for the crystalline basement in the Tatra Mts., Central Western Carpathians, on the basis of $^{40}Ar/^{39}Ar$ laser probe dating of biotite and reconstruction of P-T-t paths. The uplift history of two superimposed tectonic units - lower and upper, forming a Variscan nappe pile with inverted metamorphic zonation has been investigated.
The upper structural unit composed of migmatized ortho- and paragneisses, amphibolites, calc-silicates and granitoids reveals two distinct stages of metamorphism, differing in pressure conditions. An earlier, high-pressure event M1 reached the temperature of about 700 - 800 °C at a pressure of 10 -14 kbar, in the kyanite stability field, attaining conditions near the transition between amphibolite - granulite and eclogite facies. It is attributed to subduction (underthrusting) prior to Variscan uplift and exhumation. Subsequent low to intermediate pressure metamorphism M2 in the upper unit reached equilibria in the sillimanite stability field, at a temperature of about 650 - 750 °C and a pressure of 4 - 6 kbar. It is interpreted as a consequence of recrystallization during decompression and uplift, closely associated with the emplacement of granitoid pluton penetrating the upper unit.
The lower unit, composed of mica schists, shows metamorphic zonation where mineral assemblages in metapelites and P-T conditions record increasing metamorphic grade from 570 °C to 640 °C at a pressure of 6 - 7 kbars. Metamorphic zonation in the lower unit is inferred to be a consequence of Variscan overthrusting and emplacement of the upper unit, being locally disturbed by Alpine tectonics.
The reconstruction of metamorphic P-T-t paths yields generally "clockwise" trajectories, characteristic for metamorphism due to crustal thickening. Late-Variscan uplift due to extension is proposed for the exhumation of the entire nappe pile, recorded by the blocking temperature for argon diffusion in the biotites. The $^{40}Ar/^{39}Ar$ data also suggest that Alpine tectono-thermal overprint was generally low, not exceeding the temperature of 300 - 350 °C.

Key words: Variscan uplift, Western Carpathians, Tatra Mts., inverted metamorphism, P-T-t paths, $^{40}Ar/^{39}Ar$ dating.

Introduction

Tectonic inversion of metamorphic zones is a common phenomenon in collisional orogenic belts where hot rocks are thrust over cooler rocks due to large-scale, mid-crustal thrusting followed by rapid extensional uplift. Tectonic extension associated with exhumation is typically accompanied by emplacement of plutons into shallower crustal levels. As a consequence, low-pressure metamorphism largely overprints an earlier, higher-pressure metamorphic event, the time interval of which is commonly not well constrained (e.g. England & Thompson 1984; Hollister 1993). In recent years, such phenomena have also been observed in the Variscan basement of the Western Carpathians (e.g. Krist et al. 1992; Putiš 1992; Bezák 1994), mainly in the Tatra Mts. (Kahan 1969; Janák et al. 1988; Janák 1992a,b; Janák et al. 1993; Fritz et al. 1992). The aim of this paper is to summarize structural, mineralogical-petrological and isotopic data, in order to elucidate the uplift history in the Tatra Mts. New $^{40}Ar/^{39}Ar$ laser probe data from biotites are presented, documenting the Variscan uplift of the pre-Mesozoic crystalline basement.

Geological setting

The Tatra Mts. represent the so-called core mountains in the Tatric Unit of the Western Carpathians (Andrusov 1968; Mahel' 1986). An overview of geological investigations has been presented in Andrusov (1968), Mahel' (1986) and Nemčok et al. (1993). Isotopic dating by Rb/Sr method (Burchart 1968) brought the first evidence of Variscan age of granitoid magmatism and metamorphism. The whole-rock Rb/Sr isochron from metamorphites (Burchart 1968) also indicates an early-Variscan, or Caledonian tectonothermal event of about 400 - 420 Ma, not sufficiently proved yet. The crystalline basement in the Tatra Mts. is composed of pre-Mesozoic metamorphic rocks and granitoids. Metamorphic rocks are abundant in the western part of Tatra (the Western Tatra Mts.), whereas in the eastern part (the High Tatra Mts.) they form only xenoliths in granitoids (Fig. 1). Two structural units of the basement have been distinguished (Janák 1992) - lower and upper unit, differing in lithology and metamorphism (Figs. 1 - 3).

The lower unit is composed of an approximately 1000 m thick complex of mica schists in the Western Tatra Mts. (Figs. 1 - 3)

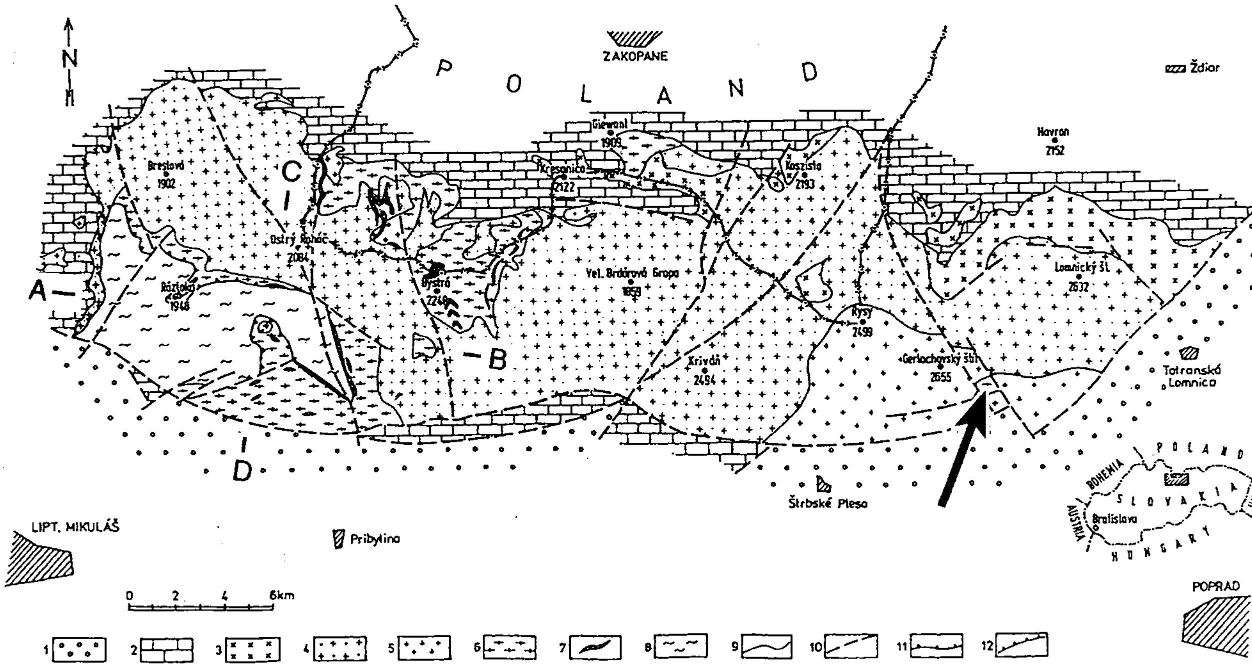

Fig. 1. Generalized geological map of the Tatra Mts. (Janák et al. 1993). Location of analysed sample for $^{40}Ar/^{39}Ar$ dating is marked by arrow. Crossections A-B and C-D are shown in the Fig. 2. Explanations: **1** - Paleogene, **2** - Mesozoic, **3**, **4**, **5** - granitoids, **6** - migmatites, **7** - amphibolites, **8** - mica schists, **9** - lithological boundaries, **10** - faults, **11** - Variscan thrusts, **12** - Alpine thrusts.

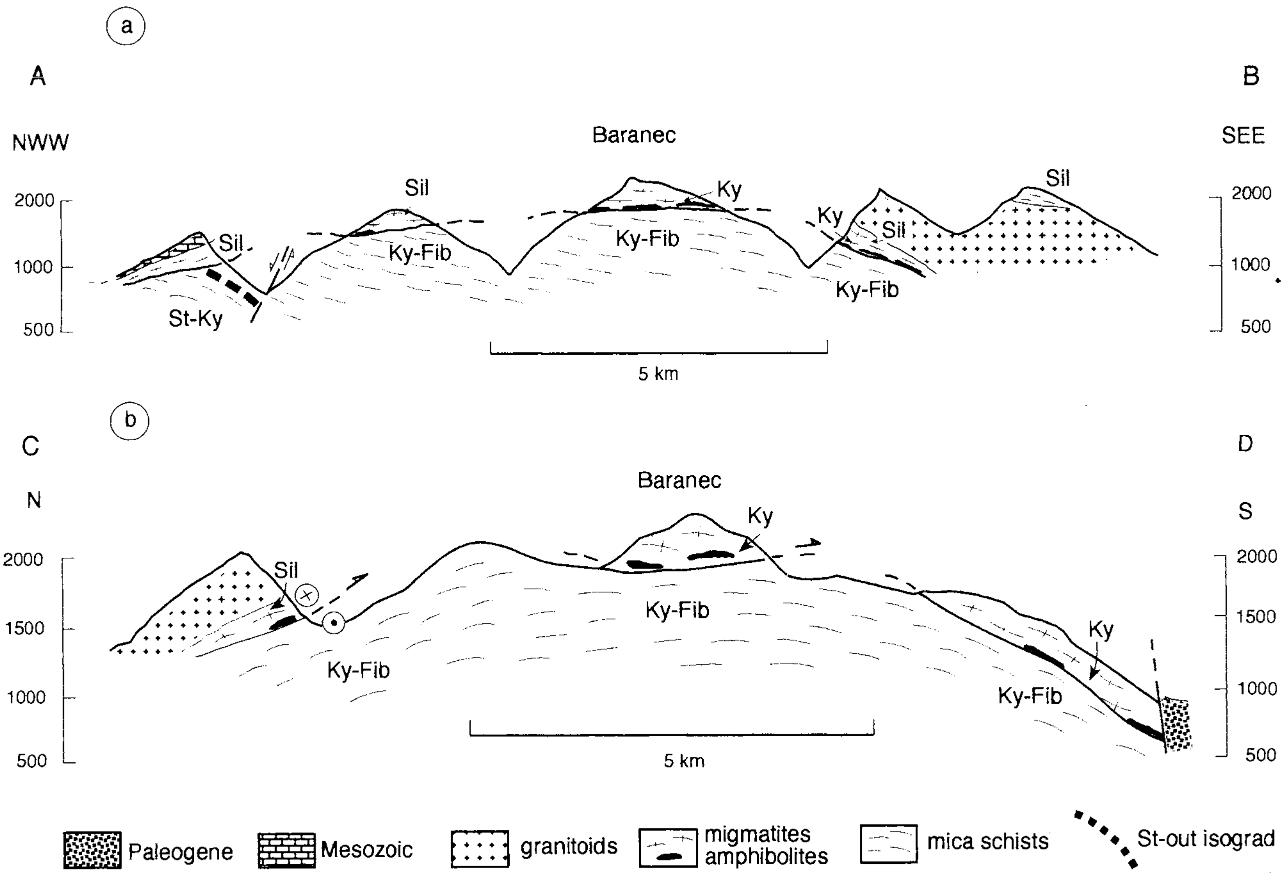

Fig. 2. Schematic cross-sections of the Western Tatra Mts. in the WNW - ESE (**a**) and NW - SE (**b**) direction. Present position of metamorphic zones and index minerals: staurolite (**St**), kyanite (**Ky**), fibrolite (**Fib**) and sillimanite (**Sil**) is shown relative to major Variscan thrust fault between lower unit (mica schists) and upper unit (amphibolites, migmatites and granitoids).

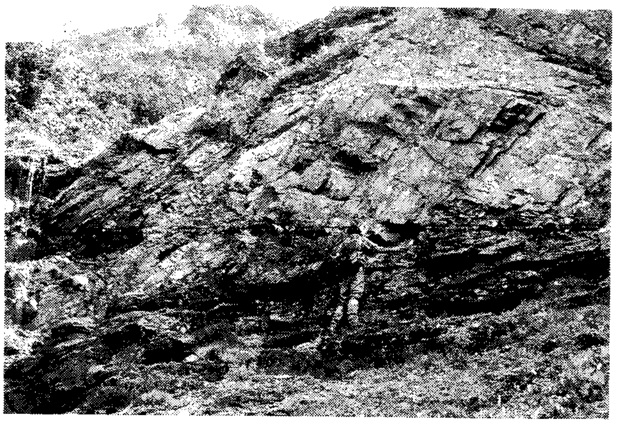

Fig. 3. Tectonic contact between upper and lower tectonic unit, Western Tatra Mts., profile from Jamnická Valley to Ostredky. Banded amphibolites at the base of the upper unit are discordant relative to the mylonitic thrust plane of mica schists.

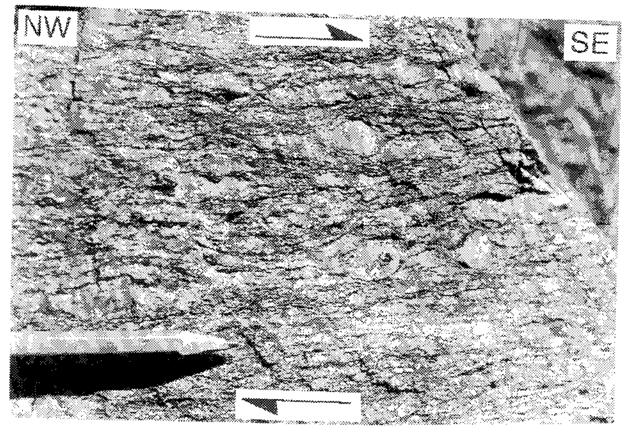

Fig. 4. Asymmetric tails of K-feldspars in the mylonitic orthogneiss, indicating ductile deformation D1 with top to the S-E sense of thrusting of the upper unit. The Western Tatra Mts., Žiarska Valley.

which probably represent the original flysch lithology of metasediments. Kyanite, staurolite, fibrolitic sillimanite and almandine garnet are characteristic Al-rich minerals in metapelites, while quartz and plagioclase are more abundant in psammitic layers. Ductile deformation, subparallel to metamorphic foliation is characteristic, with boudins and lenses of more competent, quartz-rich material.

The upper unit is formed by paragneisses, orthogneisses and amphibolites showing migmatization and rare calc-silicates. It is intruded by granitoid pluton, showing transitional contacts with surrounding migmatites. Structurally upwards, from the base to the top of the overthrust unit, distinct lithologies can be observed.

The base of the unit (Fig. 3) is composed of banded amphibolites, containing lenses and boudins of massive, garnet- and clinopyroxene-bearing amphibolites (Leptyno-Amphibolite Complex according to Hovorka et al. 1992). The alternation of mafic and felsic bands is observable on a mm to dm scale, the texture is indicative of high-temperature ductile deformation. The mafic layers are amphibolitic, consisting of amphibole and minor plagioclase, the composition of felsic layers is tonalitic to trondhjemitic, dominated by plagioclase and quartz, with minor garnet and amphibole. In some places, quartz-feldspathic material segregates into veins and pods, filling fractures, shears and boudin necks, being the product of partial melting of amphibolite (Janák et al. 1993). Felsic orthogneisses occur together with sporadic kyanite-bearing paragneisses. They show deformation under ductile conditions, with asymmetric tails of feldspars (Fig. 4), indicating S - E vergent sense of shearing during emplacement of the upper unit. On the basis of composition and texture, orthogneisses may represent former granitoids deformed during Variscan thrusting, however the age of the igneous protolith is unknown. Structurally higher, less deformed granitoids are abundant, forming the pluton. The composition is mostly granodioritic, comprising several types, described by Gorek (1959), Burchart (1970), Nemčok et al. (1993) and Kohút & Janák (1994 this volume). The structural position of granitoids is suggestive of sheet-like intrusion (Gorek 1959; Kohút & Janák 1994 this volume), emplaced solely within the upper unit. The granitoid pluton is surrounded by sillimanite-bearing migmatites, coarse- to medium-grained quartz - feldspatic (tonalitic) gneisses, fine- to medium-grained amphibolites and rare calc - silicates. Calc-silicate rocks appear mostly in the High Tatra (Pawlica 1918; Gorek 1969), with mineral assemblages of garnet, epidote, clinopyroxene, amphibole, K-feldspar, biotite and prehnite (Janák 1993) indicating a mixed volcano-sedimentary source material for the calc-silicates.

In the Western Tatra Mts., the upper and lower tectonic units of the crystalline basement form a nappe, where the foot wall and hanging wall are separated by a low-angle thrust fault (Figs. 1 - 3), inferred to be Variscan. This is supported by the lack of Mesozoic rocks in the contact between both tectonic units, as well as by the distinct P-T conditions and kinematics of Variscan vs. Alpine deformation (Kahan 1969; Fritz et al. 1992). Fritz et al. (1992) distinguished two stages of Variscan deformation (D1) and (D2), both in ductile conditions, differing slightly in kinematics. Deformation (D1) with predominant top to the S - E sense of shearing (Fig. 4) has been interpreted as the consequence of Variscan thrusting and emplacement of the upper unit in mid-crustal P-T conditions (Fritz et al. 1992; Janák 1992b). Deformation (D2) is manifested by extensional shearing with generally E - W, dextral sense of deformation, largely overprinting earlier compressional deformation (minor folds in metamorphites) and has affected also granitoids (Kohút & Janák 1994 this volume). Deformation (D2) is interpreted to be a result of extension, following thrusting, during Variscan uplift and exhumation from mid- to upper-crustal levels. Alpine deformation is manifested by lower P-T conditions (mostly brittle), and different kinematics with generally top to the N - W sense of shearing (D3). It is also recorded by magnetic fabric (Hrouda & Kahan 1991). Deformation (D3) is most probably the consequence of Late Cretaceous transpression and nappe displacement during Alpine collision, also documented in the Mesozoic sequences (e.g. Nemčok et al. 1993). Later refolding with a km-scaled open fold system with SSE-plunging fold axes bent the earlier penetrative foliation (Fritz et al. 1992), and the last major deformation is attributed to normal faulting and unroofing during neo-Alpine extension. The entire crystalline basement seems to be allochthonous, detached and transported during Alpine tectonics, as indicated by deep seismic profile (Tomek 1993; Bezák 1994).

Inverted metamorphic zonation

Metamorphic zonation in the Western Tatra Mts. shows inverted character with respect to major Variscan thrust (Fig. 2), the higher grade migmatites lie tectonically on the lower grade mica schists. Mineral assemblages and metamorphic zones in both units have been described in detail by Janák et al. (1988) and Janák (1992a).

Lower unit

The metamorphic evolution of the lower structural unit is recorded by the appearance of staurolite, kyanite and fibrolitic sillimanite in metapelites (Fig. 2). A prograde increase of metamorphic conditions towards the thrust contact between both tectonic units is indicated by the breakdown of staurolite beneath the thrust contact with the upper unit. Staurolite is abundant only in the westernmost part of the lower unit, where it appears in textural equilibrium with kyanite. At present, the staurolite-kyanite zone is exposed in the lowermost structural level, where the staurolite-out isograd dips below mica schists containing kyanite and fibrolitic sillimanite. Obviously, the present course of the staurolite-out isograd seems to be constrained mainly by the Alpine normal fault in the N - S direction (Figs. 1 and 2), juxtaposing Mesozoic sequences against crystalline basement. Extensive brittle deformation and condensed metamorphic zones in this area complicate the reconstruction of Variscan metamorphic zonation. In the central and eastern part of the area, staurolite relics appear only sporadically beneath the thrust contact, whereas kyanite and fibrolitic sillimanite are abundant, diagnostic of the kyanite-sillimanite (fibrolite) zone (Fig. 2). As inferred from metamorphic textures, fibrolitic sillimanite is a phase relatively younger than staurolite and kyanite, growing syn- to post-kinematically with respect to penetrative deformation, which affected staurolite and kyanite. Hence, the breakdown of staurolite and kyanite seems to be controlled by thrusting of the upper-hotter unit, and the original course of the staurolite-out isograd was probably sub-parallel to Variscan thrust plane. A later retrograde overprint is demonstrated by the formation of chloritoid, chlorite, margarite and secondary muscovite in extensional microfractures and pseudomorphs after staurolite, kyanite and fibrolitic sillimanite (Janák et al. 1988), post-dating peak metamorphic conditions of metamorphism in the lower-parautochthonous unit.

Upper unit

The metamorphic evolution of the upper structural unit seems to be more complex, being the consequence of two distinct metamorphic events M1 and M2, distinguished mainly by pressure conditions. Mineral assemblages indicating higher-pressure metamorphism M1 are preserved only sporadically, being mostly overprinted by lower-pressure recrystallization M2. The high-pressure event is best recorded at the base of the upper unit, in both metapelites and metabasites of the kyanite zone (Fig. 2), according to the presence of kyanite in metapelites. Structurally higher, in the vicinity of the granitoid pluton, high-pressure assemblages are generally lacking and prismatic sillimanite is a diagnostic mineral of metapelites in the sillimanite zone surrounding the pluton (Fig. 2).

High pressure conditions of metamorphism M1 in metapelites are indicated by the presence of kyanite, garnet, rutile and biotite assemblage, in some places also K-feldspar has been observed (Janák 1992a). Sporadic fibrolitic sillimanite in the matrix, showing post-kinematic growth relative to the penetrative deformation affecting kyanite indicates the transition from kyanite to the sillimanite stability field. Later retrogression and the origin of chloritoid, muscovite, margarite and chlorite is located in late extensional fractures of kyanite, similar to the situation in the lower unit. In metabasites, condensed as boudins and lenses in banded amphibolites, high-pressure metamorphism M1 is recorded by the presence of garnet, rutile, clinopyroxene and pargasitic amphibole. Clinopyroxene forms symplectites with plagioclase in the matrix, and it is diopsidic in composition (Janák 1992a). Due to the lack of omphacite, the evidence of the eclogitic stage is ambiguous. However, high-pressure amphibolite to garnet-granulite transition conditions are indicated by the garnet, diopsidic clinopyroxene, plagioclase and quartz assemblage. Kelyphitic, coronal and symplectitic textures, where garnet, clinopyroxene, rutile and pargasitic amphibole are replaced by cummingtonite, actinolite, ilmenite, sphene, epidote and chlorite, indicate pressure decrease due to decompression.

Structurally higher levels are dominated by medium- to low-temperature assemblages, generally lacking high-pressure relicts. In metapelites, the coexistence of prismatic sillimanite with K-feldspar, almandine garnet and biotite is characteristic. Garnets show poikiloblastic texture, with inclusions of sillimanite, biotite, ilmenite and quartz in the core, indicating the growth at the pressure conditions of sillimanite stability. Compositional zoning is well preserved, being modified by diffusion only in the outermost rim (Janák et al. 1988, 1993). This is suggestive of rapid cooling from high temperature conditions, preventing the homogenization due to diffusion (e.g. Spear 1991). Garnet growth in the stability field of sillimanite is interpreted as the consequence of metamorphic recrystallization M2 in medium- to low-pressure conditions, associated with heating from the granitoid pluton. Metabasites generally lack coronal textures as well as high-pressure phases, sporadic garnet is present in assemblage with hornblende and plagioclase.

Pressure - temperature conditions

The mineral composition and thermobarometric calculations of P-T conditions of metamorphism have been presented in detail by Janák et al. (1988) and Janák (1992a), some additional data are taken from Janák & O'Brien (in prep). The temperatures experienced by metapelites were estimated on the basis of the garnet-biotite Fe-Mg exchange geothermometer (Ferry & Spear 1978; Hodges & Spear 1982; Perchuk & Lavrentieva 1983; Ganguly & Saxena 1984). Pressure conditions were calculated on the basis of a net-transfer reaction between plagioclase, garnet, quartz and Al_2SiO_5 polymorphs - kyanite and sillimanite (Ghent et al. 1979; Newton & Haselton 1981; Koziol & Newton 1988; Powell & Holland 1988). In metabasites, temperatures were calculated according to the garnet-amphibole (Graham & Powell 1984) and garnet- clinopyroxene (Ellis & Green 1979; Powell & Holland 1988; Pattison & Newton 1989) geothermometer. Pressures were estimated using the assemblages containing garnet, amphibole, clinopyroxene, plagioclase and quartz, using the geobarometers of Kohn & Spear (1989; 1990), Newton & Perkins (1982) and Powel & Holland (1988). The estimation of peak metamorphic conditions took into consideration textural criteria for equilibrium as well as compositional zoning in coexisting phases, especially in the garnet. A summary of P-T conditions with mean values and standard deviation is given in Tab. 1. Fig. 5 shows the fields of P-T conditions in metamorphic zones within the lower and upper tectonic unit.

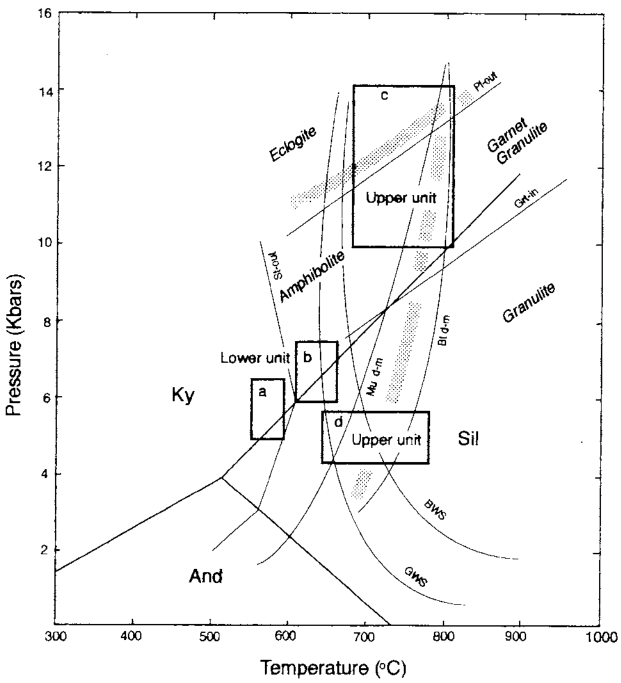

Fig. 5. Pressure-temperature diagram showing conditions of metamorphism in different metamorphic zones : **a** - staurolite-kyanite, **b** - kyanite-sillimanite(fibrolite), **c** - kyanite, **d** - sillimanite within lower and upper tectonic units. Boxes show P-T conditions calculated by geothermometry and geobarometry. Alumosilicate triple point is according to Holdaway (1971), metamorphic facies boundaries are from Fyfe et al. (1978). Staurolite decomposition (St-out) in the presence of alumosilicate, almandine and quartz is calculated from Geocalc (Berman 1988). References to the reaction curves indicated are as follows: Garnet-in (Grt- in) and Plagioclase-out (Pl-out) for quartz tholeiite metabasite composition (Green & Ringwood 1967); GWS - Granite wet solidus, BWS - basalt wet solidus, Muscovite dehydration-melting (Mu d-m) and Biotite dehydration- melting (Bt d-m) reactions (Thompson 1990 and primary references therein).

Lower unit

The P-T conditions in the lower unit (Fig. 4) show a temperature of 550 - 590 °C at a pressure of 5 - 7 kbar within the staurolite-kyanite zone (box **a** in Fig. 5). In the kyanite- sillimanite (fibrolite) zone, where staurolite is not stable, thermobarometry yields the temperature of 610 - 660 °C at a pressure of 6 - 7.5 kbar (box **b** in Fig. 5). The calculated temperatures and pressures in the lower unit record an increase in P-T conditions, suggesting heat input from the overriding hotter slab.

Table 1: Pressure - temperature conditions calculated by geothermometry and geobarometry.

Tectonic unit	Metamorphic zone	P(kbar)±s.d	T(°C)±s.d.
Lower unit	staurolite-kyanite	5.7±0.9	571±17
Lower unit	kyanite-fibrolite	6.7±0.8	638±20
Upper unit	kyanite	12.0±2.2	754±68
Upper unit	sillimanite	5.0±0.6	706±68

Upper unit

The pressures and temperatures at the base of the overthrust unit within the kyanite zone yield a temperature of 690 - 820 °C and pressure of 10 - 14 kbar (box **c** in Fig. 5), in the stability field of kyanite. The calculated P-T conditions of metamorphism M1 have attained high-pressure amphibolite facies, transitional to granulite and eclogite facies according to Fyfe et al. (1978), Fig. 5. High temperature is consistent with the observation of melt in both metapelites and metabasites. Inferred melting conditions are shown in Fig. 5. The absence of omphacite, together with the calculated P-T conditions suggests peak metamorphic equilibria in high-pressure amphibolite to granulite facies conditions, rather than in the eclogite field during metamorphism M1.

The P-T conditions near the contact with granitoids, in the sillimanite zone, yield the temperature of 640 - 770 °C at a pressure of 4 - 6 kbar, exceeding initial melting conditions (Fig. 5, box **d**), which is supported by the migmatitic texture. The calculated pressure as well as the observed mineraly assemblages are consistent with P-T conditions in the sillimanite stability.

$^{40}Ar/^{39}Ar$ laser probe biotite dating

In order to estimate the age of uplift of the upper structural unit, the biotites from migmatitic gneisses within the sillimanite zone of the upper unit were investigated, using the $^{40}Ar/^{39}Ar$ laser probe.

Analytical procedure

A polished thick section containing biotite was cut from migmatitic gneiss (Fig. 6), representing the sillimanite zone xenolith within the granitoid pluton, collected in the Velická Valley in the High Tatra Mts. (Fig. 1). Biotite appears in the matrix as well as in the form of inclusions inside the garnet. Based on textural criteria, biotite was in equilibrium with garnet, plagioclase, sillimanite and quartz during metamorphism M2, associated with

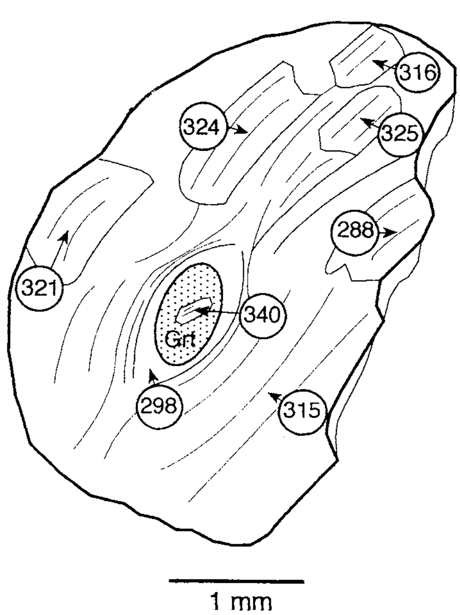

Fig. 6. $^{39}Ar/^{40}Ar$ laser spot analyses of biotite from migmatitic garnet-sillimanite gneiss, High Tatra Mts., showing total fusion ages in Ma for individual spots within the rock slab.

granitoid intrusion. The fabric shows dextral, E - W deformation, attributed to Variscan extensional deformation D2.

Laser "spot" dating using a narrowly -focused laser beam has been performed at Princeton University, similar to the method described by Phillips & Onstott (1988) and Lee et al. (1990). The sample was wrapped in an aluminum foil packet and stacked into an aluminum irradiation can with flux monitors irradiated by fast neutrons in McMaster University nuclear reactor in Hamilton, together with the amphibole Mmhb-1 standard (Sampson & Alexander 1987). After irradiation, the sample was degassed, J - values were calculated and argon was analyzed by mass spectrometer. Laser beam was focused on single grains of biotite, creating single or multiple "pits" on the order of 50 to 100 microns in diameter (Fig. 6). Hence, the total gas ages have been obtained during extraction of argon, measured in 7 cycles, corrected for the blank. Ages have been calculated using constants of Steiger & Jäger (1977), with corrections for atmospheric contamination; neutron-induced interference from K and Ca; the radioactive decay of ^{36}Cl, ^{37}Ar , ^{39}Ar, and Cl.

Results

The total gas ages with 2σ errors are presented in Tab. 2. The integrated age 316 ± 16 Ma represents the mean value with standard deviation. The highest age of 340.82 Ma has been obtained from the biotite inclusion in the garnet. However, as demonstrated by the ratio of ^{37}Ar(Ca)/^{39}Ar(K), excess ^{40}Ar related to degassing of Ca from the garnet is indicated. The argon data were also plotted on the ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotope correlation diagram (Fig. 7) which allows the calculation of an intercept date and an ^{40}Ar/^{36}Ar initial ratio from the best-fit line using the method of York (1969). As shown on Fig. 7, the straight line shows the inverse abscissa intercept age of 312 ± 23 Ma, which is compatible with integrated age of individual spots. This diagram also reveals that the sample was not significantly influenced by excess Ar , or atmospheric contamination; the ^{36}Ar/^{40}Ar ratio is less than the ratio in the present day atmosphere. Hence, the cluster of data points near the ^{39}Ar/^{40}Ar axis indicates that the age was mostly controlled by the ratio of radiogenic argon, as well as argon produced by irradiation. The range of age data obtained from individual grains of biotite is most probably controlled by diffusion of Ar within biotite crystals of different size and the amount of gas extracted by laser pits. However, the biotites obviously record the closure temperature of about 300 °C during the late Variscan uplift. They were not significantly rejuvenated by any younger thermal overprint, exceeding the blocking temperature of diffusion.

The step-heating procedure from muscovite and biotite concentrates has been presented by Maluski et al. (1993) from granitoids, and Dallmeyer (personal comm.) from ortho- and paragneisses. Both studies yield late-Variscan (330 - 300 Ma) cooling ages at high temperature steps, and only low temperature Alpine rejuvenation, in accordance with laser method.

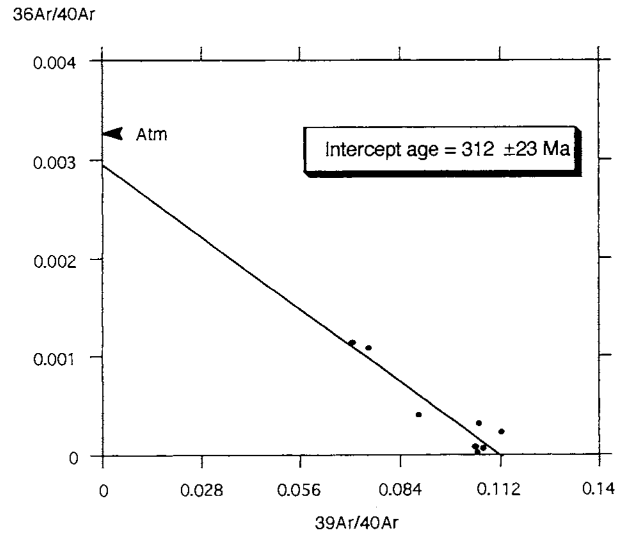

Fig. 7. ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotope correlation diagram for biotites from migmatitic garnet-sillimanite gneiss, High Tatra Mts. Atmospheric present day ratio is shown by arrow. Individual points are laser spot analyses.

Discussion

P-T-t paths and geodynamic interpretation

The estimation of metamorphic P-T-t paths of the studied region is problematic, mainly due to uncertainties in time constraints. At present, there is still not enough geochronological data to constrain the time of high-pressure metamorphism M1, indicated to be early-Variscan, or Caledonian, of about 420 - 400 Ma (Burchart 1968). Also, the age of thrusting and time-dependent P-T evolution in the parautochthonous unit remains uncertain with respect to heating from an overriding hot slab. As it has been pointed out by thermal modelling (e.g. England & Thompson 1984; Peacock 1989), preservation of inverted metamorphic conditions requires substantial heat input conducted from the hanging wall, as well as a very rapid uplift to prevent thermal relaxation of geotherms. Granitoid melt, tectonically transported into the mid-crustal levels during thrusting, may be an effective source of heat for inverted metamorphism (Hollister 1993). Taking into consideration the large amount of granitoids penetrating the upper structural unit, granitoid melt

Table 2: ^{40}Ar/^{39}Ar laser spot dating of biotite.

Spot No.	^{39}Ar/^{40}Ar (x100)	^{36}Ar/^{40}Ar (x1000)	^{37}Ar/(Ca) / ^{39}Ar(K)	^{38}Ar/(Cl) / ^{39}Ar(K)	Age (Ma)	$\pm 2\sigma$
1	7.072	1.1230	0.001	0.002	325.34	1.96
2	7.500	1.0610	0.002	0.015	316.06	1.16
3	10.530	0.0660	0.001	0.015	321.23	1.43
4	11.280	0.2206	0.001	0.022	288.47	1.20
5	8.926	0.3863	0.120	0.023	340.82	7.36
6	10.620	0.3005	0.001	0.014	297.83	1.01
7	10.600	0.0036	0.060	0.021	324.92	4.69
8	10.770	0.0506	0.001	0.002	315.93	2.03

J = 0.021±0.00022

may be a viable energy source to increase metamorphic conditions. Therefore, the time of granitoid intrusion within the hanging wall might be coeval with respect to heating and inverted metamorphic gradient in the foot wall. On the basis of isotopic data, the time of uplift through blocking temperature of 300 - 350 °C is recorded by cooling ages of 330 - 300 Ma from biotite (this study) as well as muscovite (Maluski et al. 1993; Dallmeyer pers.comm.). The minimal age of granitoid intrusion was probably 330 Ma, about 20 - 30 mil. years older than obtained by the Rb/Sr method (Burchart 1968). Nevertheless, available isotopic data clearly document that the intrusion of granitoids, as well as the uplift of the upper unit was Variscan, most probably during extensional collapse of the Variscan orogen (e.g. Dewey 1988).

The proposed model of P-T-t evolution is demonstrated on Fig. 8, showing generally clockwise paths, characteristic for collisional thickening followed by uplift (e.g. England & Thompson 1984; Harley 1989; Thompson 1990; Brown 1993).

Metamorphic conditions in the lower structural unit reveal an increase of temperature and also of pressure, as suggested by the prograde path from (a) to (b) in Fig. 8. This can be attributed to overthrusting by a hotter slab, the peak of metamorphism was probably attained in the sillimanite stability field, due to the thermal relaxation of geotherm after thickening, controlled by subsequent uplift. Later retrogression and exhumation are demonstrated by path to (c). Since no high-pressure relics are preserved within the lower unit, metamorphic evolution was probably mono-cyclic, controlled by the depth of underthrusting of sediments, heated by overriding hotter thrust sheet.

The upper unit shows exhumation from conditions of high-pressure metamorphism (d), exceeding the depths of the dynamically stable continental crust (Fig. 8). The age of the high-pressure event is poorly known, but probably about 400 Ma, as indicated by the Rb/Sr whole-rock isochron (Burchart 1968). The high-pressure event is inferred to precede the thrusting and uplift of the upper unit. This is supported by mineral textures documenting that high-pressure minerals are deformed and replaced by lower-pressure ones during nearly isothermal decompression. The development of coronal textures in metabasites and the transformation of kyanite to sillimanite in metapelites is characteristic. Hence, the generally clockwise P-T-t path manifesting the passage from kyanite to sillimanite stability field is proposed in Fig. 8. Substantial recrystallization within the stability field of sillimanite at mid-crustal levels (e) is recorded near the granitoid pluton, indicating heat advection from granitoid magma. A rapid phase of extensional uplift and cooling can be expected in order to exhume and preserve an inverted metamorphic zonation. Path (e) to (f) in the Fig. 8, demonstrates the late-Variscan uplift, recorded by Ar/Ar mineral cooling ages discussed above.

Taking into consideration geochronological data, the time span of about 70 - 80 mil. years between metamorphic events M1 and M2 is indicated, however, the uplift of high-pressure rocks was probably multi-stage, similar to the model proposed by O'Brien (1993) for Variscan high-pressure eclogites and granulites. The actual P-T-t paths might be more kinky than the ones presented in Fig. 8.

The overall conclusions are that pre-Alpine basement in the Tatra Mts. experienced a polyphase tectonometamorphic evolution during Paleozoic time, terminated by a late-Variscan (330 - 300 Ma) uplift, similar to the other areas of the European Variscides (e.g. Matte 1986).

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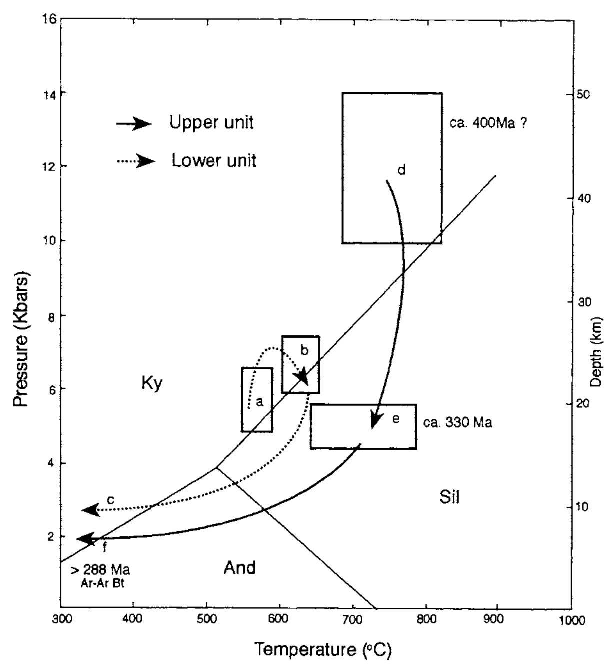

Fig. 8. Schematic P-T-t paths for metamorphic evolution of the lower and upper tectonic units in the Tatra Mts. Boxes show P-T conditions calculated by geothermometry and geobarometry. Individual points **a**, **b**, **c**, **d**, **e**, and **f** are discussed in the text.

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