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Origin and exhumation of mylonites in the Lúčanská Malá Fatra Mts., (the Western Carpathians)

JOZEF HÓK[1], PAVOL SIMAN[1], WOLFGANG FRANK[2], JÁN KRÁĽ[1], JÚLIA KOTULOVÁ[3] and MILOŠ RAKÚS[1]

[1]Štátny geologický ústav Dionýza Štúra, Mlynská dolina 1, 817 04 Bratislava, Slovensko
[2] Geozentrum , Universität Wien, Althanstrasse 14, 1040 Wien, Österreich
[3] Geologický ústav SAV, Severná 5, 974 01 Banská Bystrica, Slovensko
corresponding authors : hok@gssr.sk, kral@gssr.sk, kotulova@gu.bb.sanet.sk

Abstract. The Valča Formation, formerly interpreted as metamorphosed Devonian sediments is herein redefined as mylonite to ultramylonite in the Valča and Trebostovo valleys of the Lúčanská Malá Fatra Mts., (Central Western Carpathians). The mylonites and ultramylonites were derived from the surrounding granitic rocks under pure shear strain ductile deformation. $^{40}Ar/^{39}Ar$ dating of ultramylonite sericite yielded an age of 72 ± 3 Ma and of muscovite from the granitic rocks an age of 345 ± 2 Ma. Two different phases of exhumation and uplift of the ultramylonites are inferred. A Middle Miocene to Pliocene exhumation and a Pliocene to Recent uplift. The calculated rate of exhumation is about 0.5 mm/yr and for the uplift phase is about 1.0 to 1.4 mm/yr.

Key Words: Central Western Carpathians, Lúčanská Malá Fatra, mylonites, $^{40}Ar/^{39}Ar$ dating, exhumation, uplift

Introduction

The Lúčanská Malá Fatra Mts. (sensu Vass et al., 1988) is southwestern part of the Malá Fatra Mts. The basic geological information about the area is summarized in the geological maps by Andrusov and Kuthan (1943, 1946). The modern researches of this area are represented mainly by geological maps and research works by Rakús et al., (1988, 1989) and Gorek (1990).

At the end of the Valčianská dolina valley, at the end of the Trebostovská dolina valley and at its mouth SE ward of the Končiar site (1163 m) in the area of SE part of the crystalline complex of the Lúčanská Malá Fatra Mts. Pulec in Gorek (1990) described group of beds named Valča Formation. We did not succeeded in an identification of the mentioned beds, thus it is not shown in the simplified geological map (Fig. 1). According to the original understanding the beds consist of metasediments, metaclastics with intercalations of black shales that are classified into tufaceous shales metamorphosed in green schist facie. The composition of the rocks of the Valča Formation consists of quartz, orthoclase, feldspar, micas, chlorite, accessory zircon and newly generated rutile. At the end of the Valčianska dolina valley a poor sulfide ore mineralization was fond in black shales (Pulec l.c.). Based on findings of the palynomorphs, the whole formation was classified as Early Paleozoic - Devonian (Planderová et al., 1990). The Valča Formation comes to the surface in the middle of highly metamorphic rocks and granitoid of hybrid character, middle grain-size biotite granodiorite, tonalite with xenoliths of garnet - biotite paragneisses and biotite paragneisses with impurities of graphite. The immediate contact of the Valča Formation with crystalline complex is formed by mylonites (Gorek and Hók, 1992), - metamorphic rocks in which the original rock can by still macroscopically identified. It is difficult to identify the transition from the mylonites to the Valča Formation. The maximal thickness of the Valča Formation including the mylonite zone is about 100 m.

Methods of investigation

The field investigation was focused on study the transition zones among the granodiorite, mylonite and Valča Formation. The sampling was done along profiles in the Valčianská dolina and Trebostovská dolina valleys, as well as in relatively undeformed zones of granodiorite massive of Lúčanská Malá Fatra Mts. The methodology itself included field geological-structural research, documentation of macrostructure elements and textural changes of the rocks. Within the frame of the structural research, we have focused on collection of basic structural elements in the crystalline complex and Mesozoic formations. An interpretation of thin sections followed. The chemical composition and changes of grain size of individual minerals as reaction to deformation processes were verified by use of macroscopic and EDS-microanalyses of electron microanalyzer JEOL JXA 733 SUPERPROBE a KEVEX Delta, with the following parameters: acceleration voltage 15 kV, measuring current 1.2 nA, Taylor synthetic and natural standards were used.

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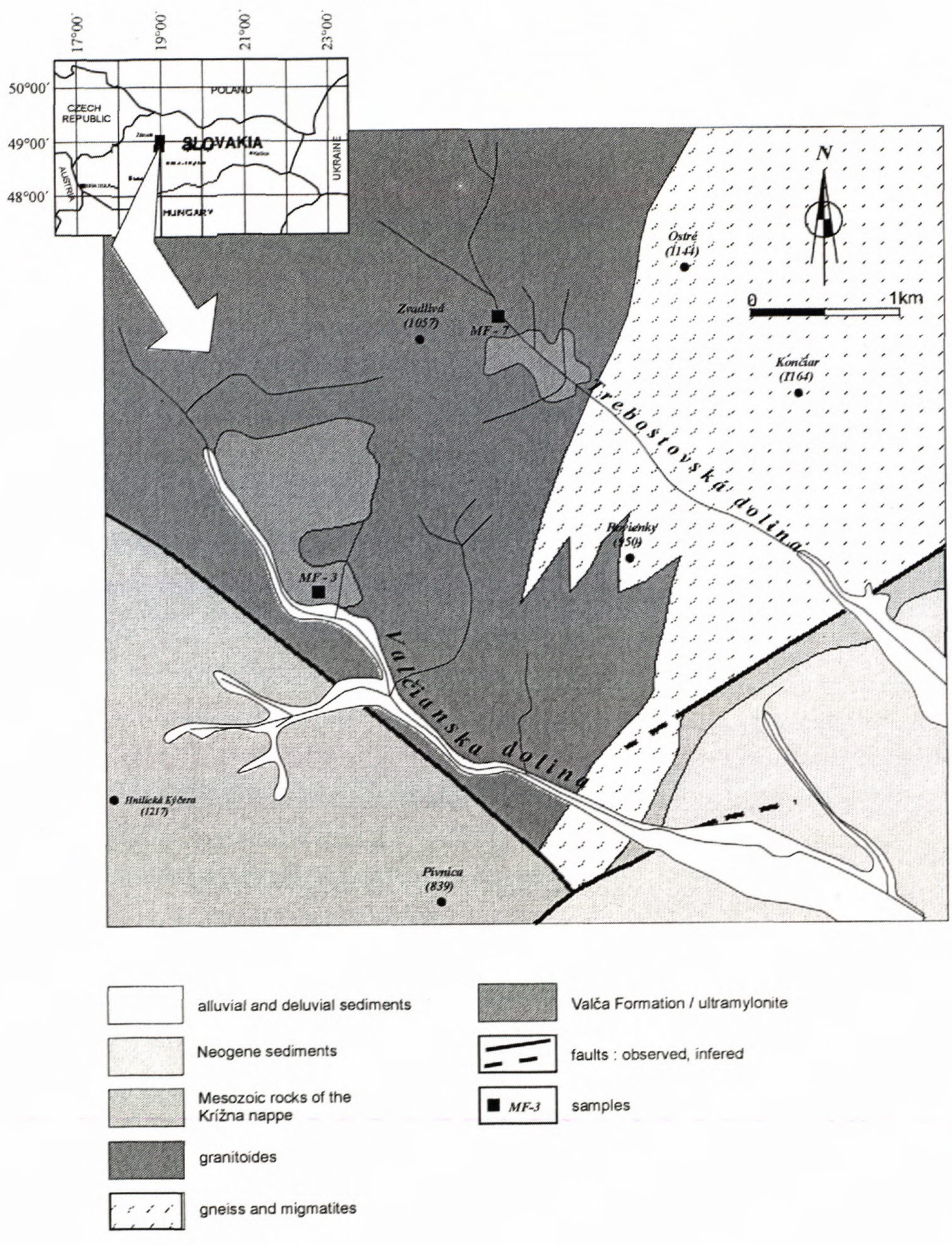


Fig.1 Schematic geological map of the investigated area (modified after Rakús et al.,1989).

After separation of muscovite and sericite from the collected rocks by standard methods (final manual purification under binocular, methanol and bi-distillated water in ultrasonic cleaner), the samples were analyzed in the laboratory GEOZENTRUM, Vienna. Charges with weight 10.4 mg were sealed into quartz tubes and irradiated in ASTRA reactor with dose of fast neutrons (about 10^{17} neutrons.cm^{-2}) together with internal standard WAP that was used to determine J parameter for six samples in the closest position. A degassing of the sample started at temperature 615 - 620 °C, the analysis was over at temperatures 1220 - 1350°C (total fussion), what enabled, with respect to amount of obtained ^{40}Ar and ^{39}Ar, making 6 - 10 analyses of Ar isotope composition. The Ar isotope composition (after its two steps of purification) was measured by mass spectrometer VG 5400 in six cycles. A standard program by fy VG was used for a statistical treatment of the measured isotope composition; the calculations of apparent ages were made with use of interpolated values of relevant isotope ratios, together with accepted age constants (Steiger and Jäger, 1977). More details about this $^{40}Ar/^{39}Ar$ dating technique can be found, for example, in McDougal and Harrison (1988).

The polished sections were made of the collected rock samples that contained graphite impurities, the light reflectivity of organic matter was determined under standard conditions: microscope Leitz Orthoplan with microphotometer MPV-compact, oil immersion, standard glass prism (R = 1.24 %), photometric field 2.5 x 2.5 microns, lenses 50x, light wave length 545 nm. The maximal (Rmax) and minimal (Rmin) reflectivity of organic matter particles were measured. The obtained values were basis for determination of degree of incarbonization and for calculation of the temperature of the origin.

RESULTS

Macroscopic and Macrostructural Description of the Rocks of the Valča Formation

Clearly developed sub-zonal foliation is typical sign of the Valča Formation. The least effected rocks represent undeformed or slightly deformed granodiorites to tonalites with hybrid character (Fig. 2). The mylonite granodiorite are middle to coarse-grained rocks in which development of metamorphic foliation is possible to observe (Fig. 3). Their shade is grayish, gray-black; the alignment is enhanced by biotite, chlorite, muscovite and deformed eyes of plagioclases, less orthoclase. With increasing deformation (Fig. 4) the rocks get greenish - light green shade caused by dispersed sericite and chlorite. Ultramylonite rocks are very fine-grained, massive, silicified, sometimes with till now preserved plagioclase eyes, else they are detailly folded fine-grained variety with altering 0.5 - 1 mm thick white and greenish strips (Fig. 5). Occasionally we can find layers of dark black fine-grained shales strongly limonitized with content of sulfide minerals: pyrite, chalcopyrite and pyrrhotine.

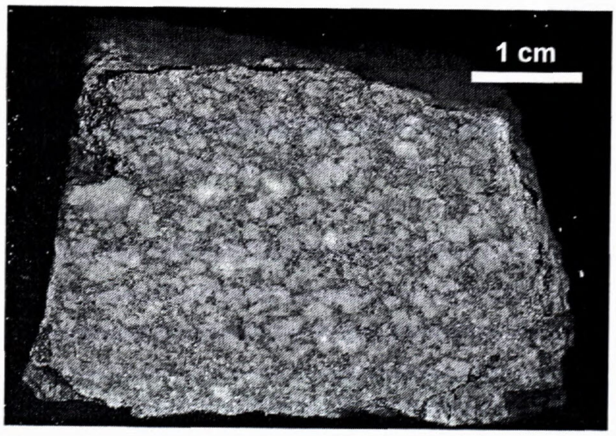


Fig. 2 Photograph of an undeformed granitoid rock. The Valčianska dolina locality.

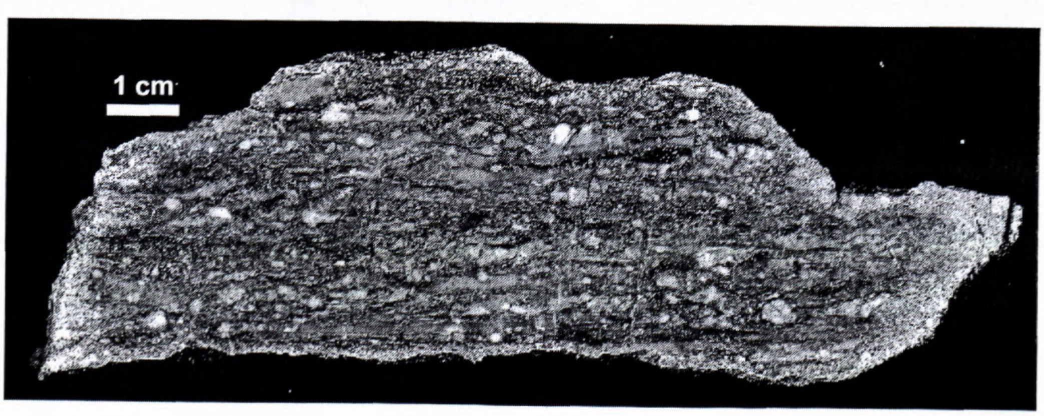
The Microscopic Research of the Rocks of the Valča Formation

The study of deformation structures in cross sections XZ and YZ planes, development and chemical composition of the minerals confirm macroscopic parameters. Gradual rock mylonitization can be observed - plastic deformation or brittle cataclase. We have divided the samples on the basis of degree of mylonitization into several groups.

The first group includes granodiorite mylonites with preserved mineral composition. They are composed of quartz, plagioclase, phyllosilicates - chlorite, muscovite (phengite, sericite), rarely chloritizated biotite is preserved, and tiny grains of desintegrated accessory minerals - apatite, titanite, rutile, Fe and Ti oxides, zircon, monazite, epidote - allanite. The basic mass is composed of cataclased strongly undulose quartz frequently stripped. The plastic deformation is related to reduction of grain size, local generation of sub-grains and displacement on grain margins. We characterize the microstructure by development of two foliation plains into fine S - C structure (Lister and Snoke, 1984) with inclination about 30°, in zones with higher intensity of deformation stress the degree of surface opening decreases to 15° and less. The detail of the microstructure is shown on the Fig. 6. The foliation planes are defined mainly by chlorite, rarely by chloritized biotite. The dependence of degree of chloritization (decreasing of content of K in the structure) upon degree of deformation is clearly observable. Further they are defined by muscovite of phengite composition, tiny newly developed grains of albite composition from disintegrated plagioclase, rutile, titanite, cataclased apatite and zircon. Some muscovites by their increased content of Ti, Fe and Mg indicate also possible origin by bauertization of biotite.

The second rock group includes mylonites with very fine-grained texture and tiny eyes of deformed minerals (Fig. 7). They have relatively similar composition as the first group, i.e. quartz, plagioclase - albite, phyllosilicates - muscovite prevails (phengite), chlorite, and grains of disintegrated accessory minerals - apatite, epidote, (including content of REE), titanite, rutile, Fe and Ti oxides, zircon. The microstructure is formed by undulosed strongly crushed and partly recrystallized quartz

Fg. 3 Photograph of the ductile deformed granitoid with mylonitic structure. Note the development of mylonitic foliation and stretching lineation. The Valčianska dolina locality.



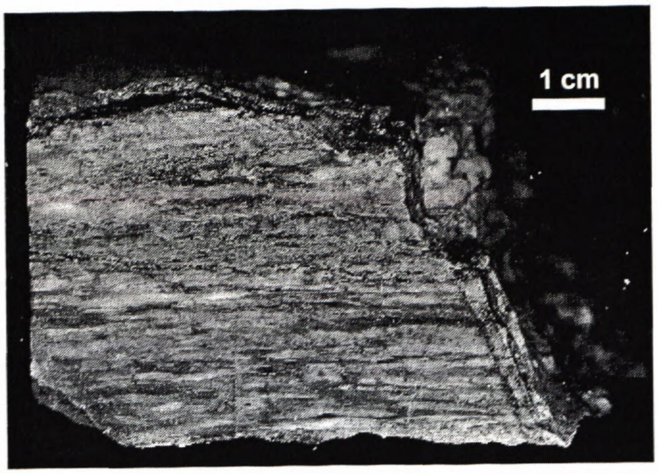


Fig. 4 Photograph of mylonitic structure with light ribbons of quartz and feldspar and dark ribbons of sericite - chlorite mixture. The Valčianska dolina locality.

Fig.5 Photograph of a fine - grained ultramylonitic rock with a well developed foliation and kink folds. The Valčianska dolina locality.

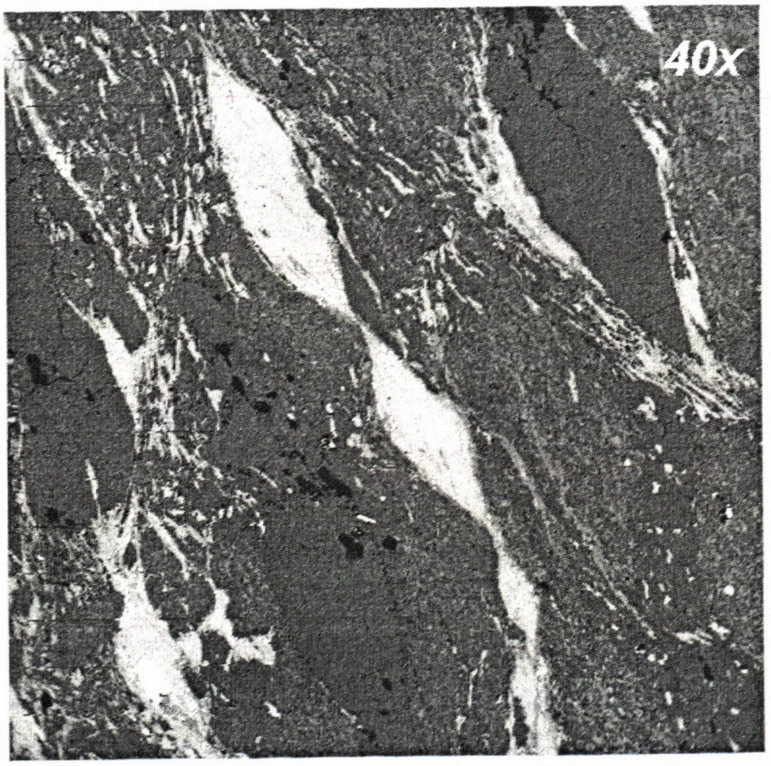


Fig. 6 Photomicrograph of a mylonitic texture. Mylonite, the Valčianska dolina locality. M = 40x

and plagioclase grains up to 1 mm, in fine-grained matrix composed of quartz and phyllosilicates. The foliation plane is formed by altering strips of very fine-grained plastically recrystallized quartz and phyllosilicates, mainly muscovite with phengitic composition. S-C composition is suppressed, S and C foliation plates with growing deformation blend. Similar phenomenon is described by Vernon et al. (1983). In the given deformation field the quartz behaves plastically and plagioclase more brittle, what results in creation of tiny eyes in the quartz matrix. We assume that this phenomenon is caused by a relatively high speed of the deformation. In pressure shadows of the eyes of some of the samples, we observe signs of creation of probably newly developed biotite. Chlorite together with epidote form as if phantom crystals after garnets.

The third investigated rock group is composed of ultra fine-grained, gray to gray-green fine-stripped rocks, ultramylonites (Figs. 5 and 8). The stripping is caused by very strong deformational elongation of the quartz and plagioclase that is changed to epidote, albite and phyllosilicate, although we can observe more ductile behavior of plagioclase than quartz in this rock. Fine-grained titanite and fine-flaked chlorite are abundant, they cause light greenish shade of the rocks. The muscovite is only accessory, however, in fine-grained matrix we can find also disintegrated epidote with a content of REE. The reduction of grain size of the rock basic mass - matrix is extreme and their size reaches range 0.005 - 0.030 mm (Fig. 8). The so-called equilibrium state is reached at this values in the quartz and the grains are not destroyed any more, although the degree of the deformation can be increased yet (c.f. Vernon et al., 1983).

Several conclusions can be draw from our results. In rock microstructures of the so-called Valča Formation we can find clearly provable phenomena of mylonitization: cataclastic structures of tectonic breccia when relatively angular porphyroclasts of plastically deformed quartz or feldspars in fine-grained matrix are preserved; asymmetric structures as S - C structure, fine intraformational folding; rotation of plastically deformed porphyroclasts and metacrystals; plastic deformation of phyllosilicates (originally biotite) along basal planes into shape of so-called mica "fish"; and finally the dynamic recrystallization of quartzite (crystal - plasticity) connected with generation, rotation of sub-grains and border migration in flatten the quartzite strips.

We tried to evaluated thermal - pressure conditions of the deformation with help of structural - petrography criteria. The existence of chlorite as alteration product of biotite

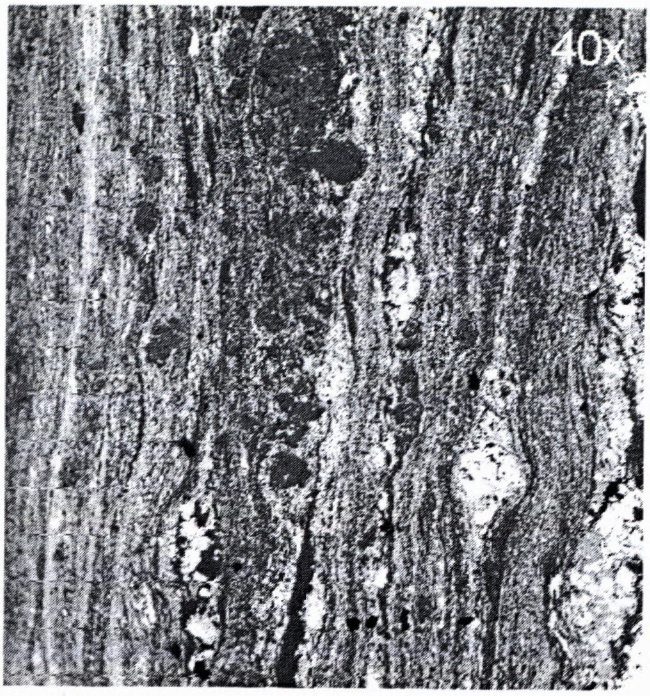


Fig. 7 Photomicrograph of elongate quartz grains and feldspar aggregates. Mylonite, the Valčianska dolina locality. M = 40x.

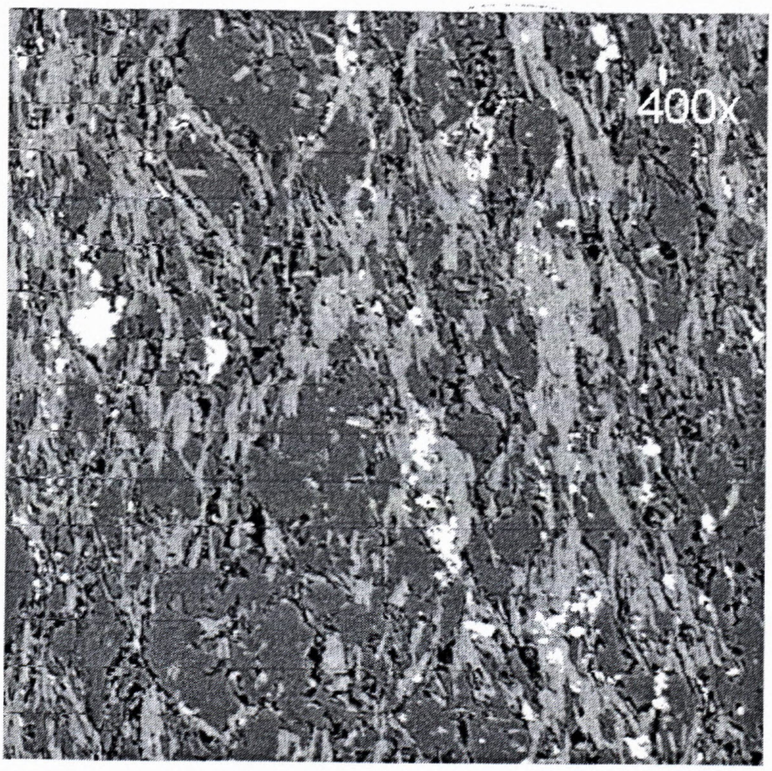


Fig. 8 Microphotograph fine-grained texture. Ultramylonite, the Valčianska dolina locality. M = 400x

biotite and plagioclase and signs of generation of new biotite in pressure shadows indicates reactions under conditions of middle and higher range of green shale facies to lower range of amphibolite facies. Eggleton and Banfield (1985 in Shelley, 1993) suppose the temperature for chloritization reaction 340°C. On the other hand, the crystal - plastic deformation of quartz in some of the samples indicates temperatures with maximum 450°C (Schulmann, oral consultation 1998). This is apparent mainly in generation of long flattened quartz strips with unstable moving margins, what indicates hither temperature solidus deformation, similar as in mylonited ortoschists of the crystalline complex of the Nízke Tatry Mts. (Madarás et al., 1999). According to changes of the rocks, we assume that the first deformation phase was cataclase under brittle conditions, followed by plastic deformation lasting until stage of the ultramylonitization. A release and intrusion of sufficient amount of reaction fluids is needed for such process. These can be obtained under sufficient temperature - pressure conditions by disintegration and transition of minerals containing water in their crystal lattices. The intruding fluids attack surrounding waterless minerals, mainly plagioclases, which change to albite, phyllosilicate and minerals of epidote - zionist group, reactionaly soften, and deform in the oriented pressure. Ultrafine-grained fine-stripped rocks without any macroscopic signs of eye structure can be created by described mechanism from coarse-grained and ocellar structure of granitoid rocks. Only during detail microscopic investigation, we can still observe as rounded relicts of original minerals, quartz and feldspars.

The Results of the Structural Research

The structural research was focused on collection and evaluation of basic structural elements. Foliation, mineral lineation and B - axis of folds in the case of the crystalline complex rocks and so-called Valča Formation. The directions of dips of the bedding and fold axis were measured on the Mesozoic rock successions. The results of the structural research are summarized in diagrams (Fig. 9).

The direction of bedding in the Mesozoic rocks is relatively uniform and it has NE - SW orientation (Fig. 9a). Fold axes with NE - SW direction have similar directional features (Fig. 9d). Rocks of the crystalline complex show considerable dispersion of foliation and fold axes directions, from N - S direction to NE - SW direction (Fig. 9b). This dispersion is caused by Alpine type directional reorientation of originally N - S to NNE - SSW oriented Hercynian structural elements to new NE - SW direction. The reorientation of the structures of crystalline complex is well documented also by lower degree of metamorphic changes of structures oriented in NE - SW direction. The signs of the Hercynian tectonics are most significant on the eastern margin of the area in crystalline schist of the Lúčanský complex (Gorek, 1990). The planes of the original foliation of the gneisses are fixed by granitization, what we considere as result of metamorphism of the

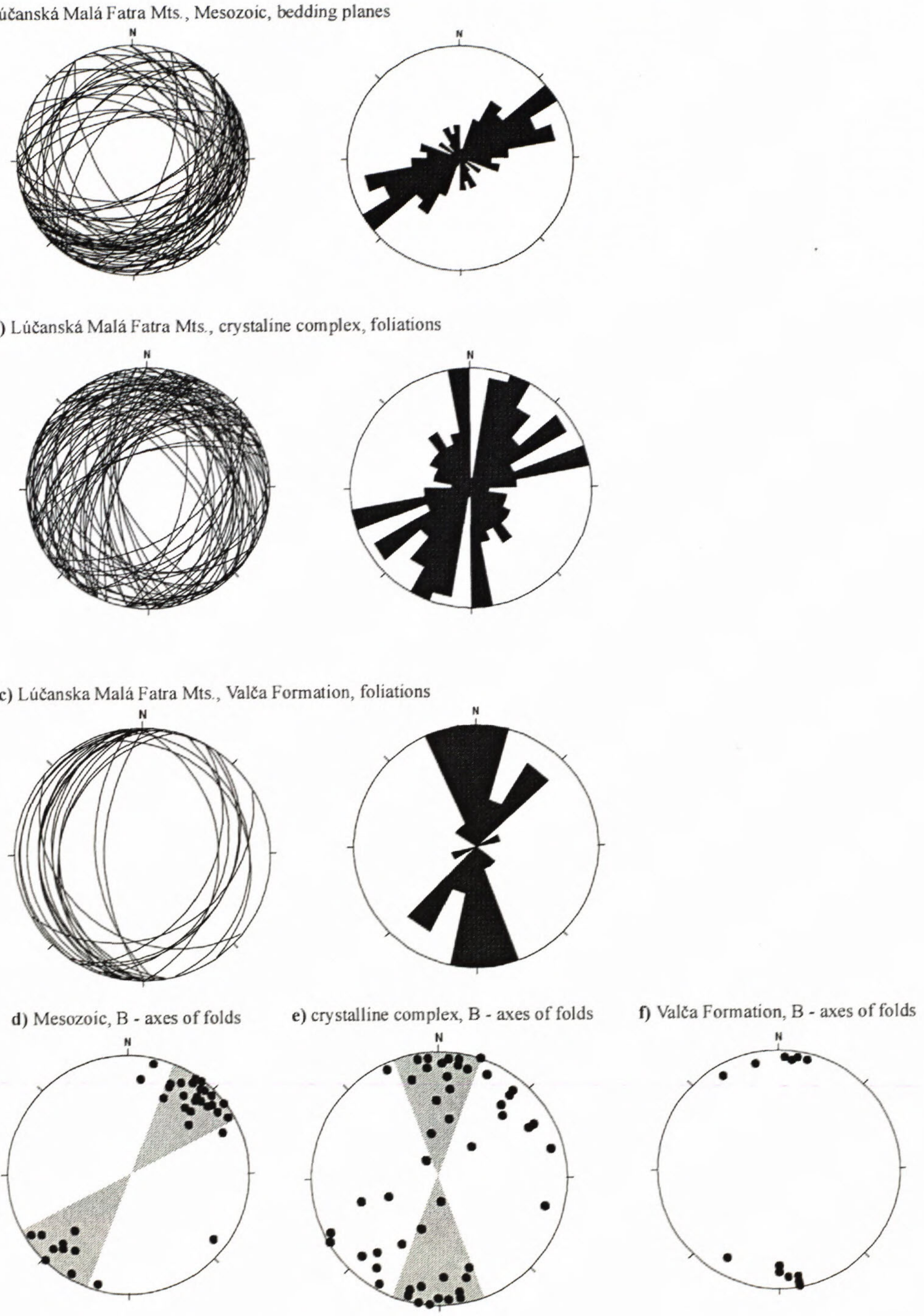


Fig. 9 Tectonic diagrams of the basic structural elements from the investigated area. (Lambert projection, lower hemisphere).

whole complex under conditions of the amphibole facies. The temperature - pressure conditions of metamorphism of the Lúčanský complex reached 700 - 750°C and pressure 8 - 10 Kbar (Janák and Lupták, 1997). The Lúčanský complex was folded to isoclinal and open folds with N - S to NNE - SSW direction. The generation of the folds was joined with compression that was generally oriented in E - W direction, and it could pass to transpresion (Gorek, 1990), what could be indicated also by part of the folds with steeply dipping fold axes (Fig. 9e). In the Alpine orogenetic cycle the planes of the original foliation that represent primary inhomogeneity were again tectonically used, however in lower metamorphic conditions of green schists facies, what resulted in recrystallization of originally higher temperature mineral associations.

Directional characteristics of rocks of the so-called Valča Formation are similar to rocks of the Lúčanský complex, although it is necessary to mention that the statistical data set is not sufficient enough (Fig. 9c, f). Basing on this, we assume that they were created by deformation of the crystalline complex rocks during the Alpine orogenetic cycle. Despite the fact that we have identified numerous asymmetric structures, we have not succeeded in clear determination of the direction of the tectonic transportation. We assume that pure shear without more significant directional component of displacement (simple shear) was significant, mainly during the final stages of deformation of rocks from which the Valča Formation was formed.

$^{40}Ar/^{39}Ar$ Data

The basic analytical data from the measured samples are shown in tables 1 and 2. The apparent age spectra of both samples are significantly different. The muscovite sample MF-7 from a granodiorite (Fig. 10) yielded smooth spectrum of apparent ages in volume of 84% of the total amount of ^{39}Ar released, from 337 Ma to 353 Ma. The plateau age from the four last steps is 345 ± 3 Ma. This age corresponds to rock cooling at temperature about 350°C (Purdy and Jäger, 1976). The characteristic shape of the spectrum in low and middle temperature part can be considered as result of Early Jurassic temperature event that caused partial release of ^{40}Ar of the sample. Although the Early Jurassic age is indicated only by a very low volume of released ^{39}Ar, it can have its real geological importance because spectrum of apparent ages of various minerals starts with these values also in other regions of the crystalline complexes of the Western Carpathians Mts. (Maluski et al., 1993, Kráľ et al., 1997).

Tab. 1. $^{40}Ar/^{39}Ar$ analytical data, sample MF - 7, muscovite, the Trebostovská dolina valley.

Step	T (°C)	% ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	Age (Ma) ± 2 SD
1	615	0.9	91.3	21.25 ± 4.0	173.2 ± 6.7
2	645	1.6	94.4	25.19 ± 2.2	203.7 ± 4.3
3	690	1.2	95.4	29.29 ± 2.5	234.9 ± 5.6
4	735	2.2	95.0	32.09 ± 1.5	255.8 ± 3.6
5	770	3.3	95.6	36.97 ± 0.9	291.9 ± 2.4
6	830	7.1	97.5	40.70 ± 0.7	319.0 ± 1.9
7	865	12.7	98.8	43.21 ± 0.3	336.9 ± 1.0
8	925	21.2	99.4	43.52 ± 0.4	339.2 ± 1.4
9	1065	22.0	99.3	44.28 ± 0.2	344.6 ± 0.7
10	1220	27.7	99.5	45.43 ± 0.2	352.8 ± 0.6

J = 0.004530 ± 0.4 % total gas age: 334.0 ± 2.6 Ma
84 % plateau age: 344.8 ± 2.2 Ma

Tab. 2. $^{40}Ar/^{39}Ar$ analytical data, sample MF - 3, sericite, the Valčianska dolina valley.

Step	T (°C)	% ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	Age (Ma) ± 2 SD
1	620	4.6	60.0	8.48 ± 13.1	71.1 ± 9.1
2	690	6.6	75.1	8.89 ± 10.5	74.5 ± 7.7
3	790	11.8	89.9	8.85 ± 4.2	74.1 ± 3.0
4	920	50.2	96.9	8.44 ± 0.8	70.8 ± 0.5
5	1050	18.7	93.5	9.03 ± 2.2	75.6 ± 1.6
6	1350	8.1	87.3	34.10 ± 4.1	270.8 ± 10.5

J = 0.004530 0.4% total gas age: 88.5 ± 3.5 Ma
92 % plateau age: 72.4 ± 2.7 Ma

The sample of sericite separated from the mylonite (MF-3, the Valčianska dolina valley) has totally different spectrum. The dispersion of the apparent ages is minimal in the first five temperature steps (71 - 76 Ma). The plateau age for volume 92 % of released ^{39}Ar is 72 ± 3 Ma (Fig. 11). We interpret this age as age of generation of the sericite. We reckon the apparent age 271 Ma in the last step (1350 °C) as relative age that indicates either the old cores of the separated sericite or the presence of individual tiny chips of muscovite grains (non-removed by separation) originating from the original granodiorite.

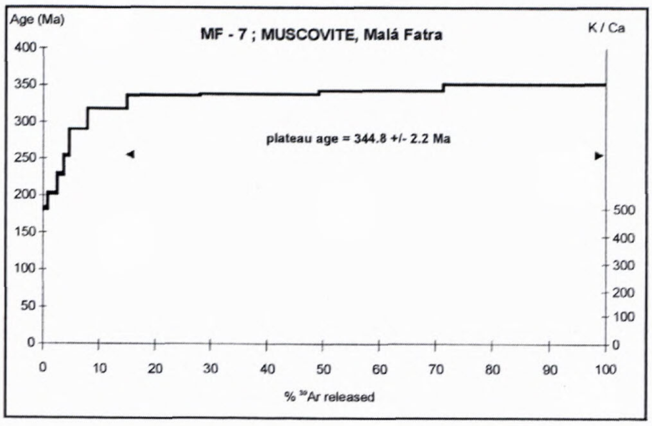


Fig. 10 $^{40}Ar/^{39}Ar$ apparent age spectrum (sample MF - 3; ultramylonite, the Valčianska dolina locality)

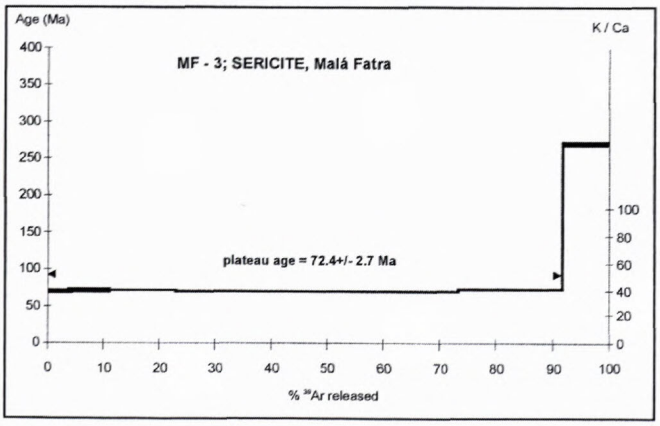


Fig. 11 $^{40}Ar/^{39}Ar$ apparent age spectrum (sample MF - 7, granitic rock, the Trebostovská dolina locality)

Results of Reflectance of Graphite Matter

In the studied samples there is graphite matter consisting mostly of 10 to 20 microns particles ordered in to the direction of rock foliation. The graphite matter has flake like form, it does not have preserved relict structures of the plant origin. The maximal values of reflectance are in range from Rmax = 3.6 - 4.6 % to Rmin = 2.0 - 3.0 %. It is apparent from the results that it is meta-anthracite graphite matter. We attempted with help of software Easy%Ro (Sweeney and Burnham, 1990) to calculate the temperature under which the meta-anthracite was generated. The minimal temperatures were determined to 260°C and the maximal to 360°C. Similar conditions (260 - 290°C) are reported also by Diessel et al. (1978) obtained from Tertiary shales in New Caledonia.

Discussion

The age of the granodiorite intrusion from the Malá Fatra Mts. was determined on the basis of U/Pb dating of zircon to 353 + 11/-5 Ma (quarry Dubná skala, Shcherbak et al., 1990). The attempt for Rb/Sr dating of granodiorite rocks from this area demonstrated very small Rb/Sr dispersion of the analyzed samples, however which can by statistically localized on reference isochrone from granodiorite rocks of the Veľká Fatra Mts. (361 ± 10 Ma, Bagdasaryan et al., 1992). Similar as U/Pb dating of the Malá Fatra granodiorite, this age is within of the analytical errors identical with U/Pb ages of a zircon from the granodiorite rocks of geographically closest crystalline cores (the Veľká Fatra Mts. 359 Ma; Kohút et al., 1999, the Strážovské vrchy Mts. 356 ± 9 Ma; Kráľ et al., 1997). Fission - track dating of apatite from granodiorite rocks of the Malá and Veľká Fatra Mts. are identical within of analytical errors (23 - 25 Ma), what was interpreted as age of Neogene uplifts of the core mountains (Kráľ, 1977).

Based on newly obtained experimental experiences, we assume that the so-called Valča Formation is product of the Alpine mylonitization of granitoid rocks. The mylonitization took place on boundary of Cretaceous and Paleogene (72 ± 3 Ma). At this time the granitoids were cooled down to temperatures lower than 300°C, as we have proved by dating of the sample MF - 7. We assume that the temperature conditions of the mylonitization were in the range 300°C - 350°C (Fig. 12).

The problematic is presence of the Devonian palynomorphs that were described in the rocks of the Valča Formation (Planderová et al., 1990). In the previous studies (Gorek, 1990; Gorek and Hók, 1992) a hydrothermal - metasomatic rock alteration related to sulphidization and probable income of organic, carbonic substance is assumed. The presence of water in the given tectonic environment is common and furthermore it can considerably modify the way of physical and metamorphic reactions (for example Sibson, 1977). The mentioned assumption can explain the presence of black shales with sulphidic mineralization within the Valča Formation. If we assume similar way also the contribution of the palynomorphs than it is questionable weather we can derive them only from surrounding rocks that, however, represent high metamorphic complex with temperatures of Hercynian metamorphism acceding 700°C (Janák and Lupták, 1997). The temperature conditions of the Hercynian metamorphism exclude preservation of the palynomorphs. However, the determined thermal transition of the graphite organic matter would not exclude preservation of the palynomorphs during their transport by hydrotherms (c.f. Planderová, 1991). It is apparent that the palynomorphs can be hydrodynamicaly carried to greater distances. In groundwaters in the environment of crystalline complexes of the Western Carpathians there were found beside Devonian also Early and Middle Miocene association of sporomorphs, which presence is hard to explain from stand point of known geology (Rapant et al., 1986). The palynomorphs could be redeponed into mylonites, however, their source has remained unknown.

On the basis of assumed temperature of the origin of the mylonites, their $^{40}Ar/^{39}Ar$ dating, assumed thickness of sedimentary formations and the average geothermal gradient we have made an attempt to reconstruct exhumation (uplift) of the ultramylonites. The exhumation according to England and Molnar (1990) is defined as transportation of rocks with respect to the Earth's surface (contact of rocks with air or water). The rate of the exhumation is identical with the rate of the erosion. The uplift of rocks is movement of rocks or a part of the Earth's surface (uplift of the Earth surface) with respect to reference level (geoid, sea level). The mean of the rock transportation acts against the Earth's gravitation during the uplift (England and Molnar, l.c.). At given definitions there is a relationship:

Uplift of the Earth surface = rock uplift - exhumation

If we consider geothermal gradient accepted for the Western Carpathians area about 35°C/km (30°C/km - 40°C/km e.g. Kováč et al., 1994. Hurai et al., 1991; Franko et al., 1995) and the temperature of mylonite generation 350°C than the rock transition took place at depth about 10 000 m. On the basis of sedimentation record of rocks from the Rajecká kotlina basin, however mainly of the Turčianska kotlina basin, we have tried to make reconstruction of the rate of exhumation / uplift of rocks of the Valča Formation. We assume that the mylonitization of crystalline complex rocks is a product of the tectonic extension between Cretaceous and Paleogene, which preceded development of the deposition basins and deposition of the Paleogene clastics. In the area of the Rajecká and Turčianska kotlina basins the sediments of the Paleogene were folded in the Early Miocene and the whole area of the Lúčanská Malá Fatra Mts. was in compressional tectonic regime (Hók et al., 1998). The first probative Neogene sediments in the Turčianska kotlina basin derived from Lúčanská part of the Malá Fatra Mts. deposited in the Middle Miocene, their material was derived predominantly from rocks of the Choč nappe and secondary from the Paleogene sediments (Abramová and Slovany Formations, sensu Hók et al., 1998). The thickness of the Paleogene sediments of the mentioned area does not exceed 1 500 m and the thickness of Choč nappe does not exceed 1 000m. The pebbles matter derived from the Krížna nappe and crystalline complex was uncovered in the sediments of the upper most Miocene to Pliocene (Bystrička Formation l.c.). The samples used for FT dating of apatite determined the age when the crystalline complex was cooled down to temperature 120 - 100°C, what with respect to accepted geothermal gradient indicates depth no more than 4 000 m and stratigraphic age Early Miocene (Eger). However, the samples for FT dating were taken from crystalline complexes at places where there is no verification of altitude of the erosive cut off of the crystalline complexes with respect to the Mesozoic cover. In sediments of Pliocene there are material derived from crystalline complexes, which totally domi-

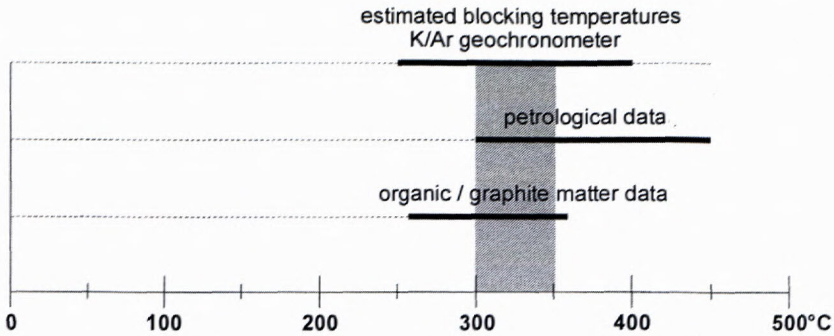


Fig. 12 Temperature of formation of the ultramylonite (shaded area) derived according to different methods (see text for details).

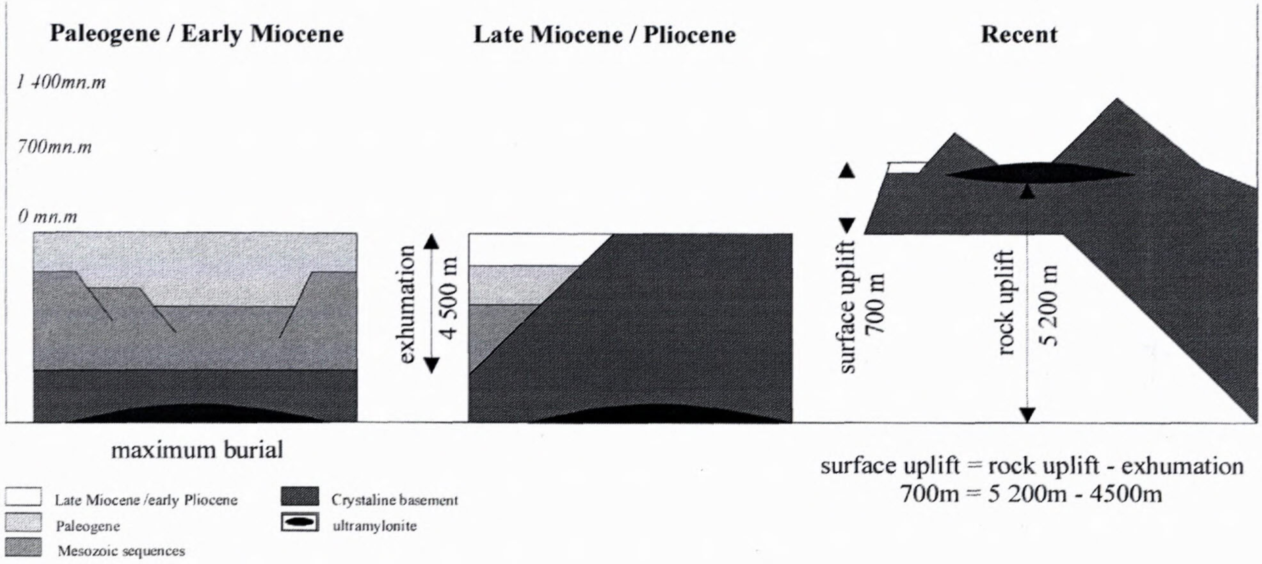


Fig. 13 Model of the exhumation and uplift rates of the Valča Formation (not to scale).

nates in the Quaternary sediments. We assume that crystalline complex of the Lúčanská Malá Fatra Mts. was uncovered in the Upper Miocene - Pliocene time. On the basis of duplex structure of Krížna nappe in the area of the Lúčanská Malá Fatra Mts. we assume its thickness to about 1 500 m. The thickness of the cover sequence does not exceeds about 500 m. However, it is necessary to mention that the cover sequence is not developed in the majority of the area of the Lúčanská Malá Fatra Mts. According to our assumption, the thickness of the sedimentation sequence of the crystalline complexes overburden did not reach 4 500 m. The estimated thickness of the Mesozoic sequence is about 3 000 m. We assume that the maximal burial depth of the mylonites (about 11 500 m) is on the border of Paleogene and Neogene, when in overburden of the Mesozoic sequences there were Paleogene rocks (Fig. 13). The crystalline complex was exhumated at the end of Miocene, what means that since Middle Miocene (The Latest Badenian, about 14 Ma), when the first clastics deposited in the Turčianska kotlina basin, to Pliocene (about 5 Ma) about 4 500 m of deposited overburden was eroded. The average rate of the exhumation is about 0.5 mm/year, which makes 4 500 m per 9 Ma.

The denudation relicts of Pliocene sediments remained in the northeastern part of the Lúčanská Malá Fatra Mts. at altitude 700 - 750 m a.s.l. At the same altitude, there are ultramylonite at the Valčianská dolina and Trebostovská dolina valleys. After the exhumation of the sedimentary sequences the uplift of the rocks of the Valča Formation represented the value about 7 000 m per 5 millions years i.e. about 1.4 mm/year.

If we consider the relationship that was defined by England and Molnar (1990) the value of the exhumation is 4 500 m, the uplift of he Earth's surface is 700 m and the rock uplift is 5 200 m. However, in the given case we do not consider any rate of erosion. From the point of view of above defined relationship the burial depth of the rocks of the Valča Formation would reach 10 000 m. The value of the uplift would reach in the given case about 1.00 mm/year. In both cases, in the calculations there is uncertainty of the main variables. In the first case, it is a value of the geothermal gradient. In the second case, it is the rate of the erosion since Pliocene to Recent. For example, we would consider the value of geothermal gradient 40°C/km, the difference of the uplift intensity estimated by various ways would be minimal. However, in any of the cases of the estimations we can conclude that since the end of the Miocene the rate of the uplift is greater than the rate of exhumation. This assumption could be indirectly confirmed also by positive values of the recent vertical movement tendencies of the Earth's crust in the area (c.f. for example Vanko, 1988; Joó et al., 1992). At the same time, we can accept assumption that the transition of the granitoid rocks to ultramylonites took place approximately at depth 10 000 m.

Conclusions

The rocks at the Valčianska dolina valley and Trebostovska dolina valley, which were defined as the metasediments of the Valča Formation of Devonian age (Pulec in Gorek at al., 1988) are mylonites to ultramylonites derived from crystalline rocks of the Lúčanská Malá Fatra Mts. For this reason, we do not consider as appropriate to use the name Valča Formation. The age of their origin was determined to 72 ± 3 Ma by $^{40}Ar/^{39}Ar$ dating of the ultramylonites. The mylonites and ultramylonites were formed at temperature 300° - 350°C in estimated depth 10 000 m. We assume that they were re-exposed and uplifted in two phases. The exhumation took place since Middle Miocene to Pliocene and rate of exhuation is about 0.5 mm/year. Uplift took place since Pliocene to Recent and its rate is about 1.0 to 1.4 mm/year.

Translated: Dr. Juraj Janočko

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