SLOVAK GEOLOGICAL MAGAZINE

VOLUME 11 NO 2-3 ISSN 1335-096X

Geological Survey of Slovak Republic, Bratislava
Dionýz Štúr Publishers

2-3/2005

ISSN 1335-096X

SLOVAK GEOLOGICAL MAGAZINE

Periodical journal of Geological Survey of Slovak Republic is a quarterly presenting the results of investigation and researches in a wide range of topics:

- **regional geology and geological maps**
- **lithology and stratigraphy**
- **petrology and mineralogy**
- **paleontology**
- **geochemistry and isotope geology**
- **geophysics and deep structure**
- **geology of deposits and metallogeny**
- **tectonics and structural geology**
- **hydrogeology and geothermal energy**
- **environmental geochemistry**
- **engineering geology and geotechnology**
- **geological factors of the environment**
- **petroarcheology**

The journal is focused on problems of the Alpine-Carpathian region.

Managing Editor: Gabriela Šipošová

Address of the publishers: Geological Survey of Slovak Republic, Mlynská dolina 1, 817 04 Bratislava, Slovakia

Printed at: ALFAPRINT Martin

Price of single issue: USD12

Annual subscription rate: USD 48 (4 issues) The price include the postage

Website at http: // www.geolo

SLOVAK GEOLOGICAL MAGAZINE

VOLUME 11 NO 2-3

ISSN 1335-096X

Geological Survey of Slovak Republic, Bratislava
Dionýz Štúr Publishers

2-3/2005

New approaches in investigation of pre-Mesozoic units of Western Carpathians

Foreword

The contributions in presented extended issue of the Slovak Geological Magazine are focussed on solving of selected topics in Lower and Upper Paleozoic units of the Western Carpathians. The articles preferably represent the specialized, in part methodologically oriented studies. More of such aim to open the new approaches in the interpretation of tectonic questions, as well as those related to mineral deposit formation. It is satisfactory, that the principal laboratory methods, applied in contributions – the REE and trace elements analyses and EMPA dating of monazite - are recently directly in use in the Geological Survey of Slovak Republic (State Geological Institute of Dionýz Štúr).

Practically all contributions deal with the until untreated data of rock geochemistry (e.g. subvolcanic basalts of the Hronicum; metasediments of the Malé Karpaty Mts.; ore bearing (meta)sedimentary rocks in Tatricum and Veporicum) as well as geochronology ($^{40}Ar/^{39}Ar$ data from the area of Gemericum; EMPA monazite dating of the crystalline basement). The new trends in facial analysis were applied in sedimentological investigation (Permian of Hronicum; Gelnica Group); whereas the special microstructural works indicate the perspective possibilities of further study (paleopiezometry applied in Gemericum; apatite cathodoluminescence structure in granitoids).

In addition to the workers of the Geological Survey, this issue benefits also from the articles submitted by the colleagues from the Faculty of Natural Sciences, Comenius University (Bratislava), the Geological Institute of Slovak Academy of Sciences, workers of foreign institutions, and in smaller scale also the private persons. The contributions were reviewed by A. Vozárová, F. Marko, Ľ. Hraško, P. Konečný, J. Kráľ and M. Kováčik. For English translations of majority of texts we are grateful to Z. Németh.

Data obtained by the new method get their importance only by discussion based on the generally accepted geological knowledge. Consistent knowledge of regional geological problematics allows responsible interpretation of the new data, avoiding the popular sentence of sceptics - "what is good does not need to be new and what is new does not need to be good", occurring also in the geological branch.

However, it has to be admitted, that lately some research techniques obtained the untrustworthy reputation (e.g. some geochronological approaches or applying the palinological age determinations in investigation of crystalline basement, the quality of analyses of trace elements, etc.). The problems arose not directly from the principle of factual methodologies, but mostly from the bad selection or routine pre-processing of sample material. The overestimation or even unsuitable uses of particular procedures in complex geological conditions are also not rare. On the other side, the application or testing of modern approaches using the real geological material can contribute to the further development of the methodologies by themselves.

The presented contributions represent a part of results of the research phase "Tectogenesis of Paleozoic basins" solved in the period 2000-2004 in the frame of the project "Tectogenesis of sedimentary basins in Western Carpathians" (No. 0801840303/130), funded by the Department of Geology and Natural Sources of Ministry of Environment of Slovak Republic. The investigation projects of this kind necessarily continually actualize some questions, which fits the principal requirement of scientific-investigation collaboration in the common European platform. These intentions can be fulfilled not only by enthusiasm of research workers, but also owing to the understanding and adequate support of the competent governmental structures.

Martin Kováčik
editor

Slovak Geol. Mag., 11, 2 – 3 (2005), 77 – 90

Geochemical properties of selected Paleozoic formations – bearers of stratiform mineralization in Veporicum and Tatricum

MIROSLAV SLAVKAY

Röntgenova 20, 851 01 Bratislava

Abstract. The investigation of selected formations in metallogenetic zones of Veporicum and Tatricum in the mountain ranges Slovenské rudohorie, Nízke Tatry, Malé Karpaty and Považský Inovec, was focussed on appraisal of their possible elevated metal content according to the suggestion of the project IGCP 254 definition "the black schists and metalliferous black schists" (sensu Huyck, 1991). The element contents in investigated rocks (complete chemical analysis of 16 major elements and 47 microelements) were normalized according to USGS standard SDO-1, according to the Geochemical atlas of Finland as well as the clark contents. The content of C_{org}, the bitumen type, origin and source of hydrocarbons, conditions of sedimentation, carbonification metamorphism, migration, etc. are presented. Besides known deposits and mineralizations in investigated formations, according to normalized values for standards and clarks and further criteria we indicated their possible metal content and perspective.

Key words: geochemistry, metalliferous black schists, organic matter, mineralization

Introduction

Presented work is focussed on metallogenetic zones of Veporicum and Tatricum (according to Ilavský and Sattran, 1980). It reviews the occurrences of ore and non-ore sedimentary mineralizations in particular formations, the influence of epigenetic mineralization processes connected with magmatic, volcanic and tectonic activity influencing the evolution of sedimentation as well as the later processes.

The main formations geochemical characteristics and information about anomalously increased contents compared to standards and clarks in the Earth crust are based on complete chemical analyses (16 main and 28–47 microelements).

The C_{org} content, its composition, the bitumen type, origin and source of hydrocarbons, sedimentation conditions, carbonification metamorphism, migration etc. are stated in studied formations. The metalliferous potential of uranium-bearing and copper-bearing formations was detected. Next there was investigated the ratio of K_2O/Na_2O, showing the degree of sediments maturity as well as the tuffitic admixture indicating the possible volcanosedimentary mineralization.

The evaluation of metalliferous capacity of sedimentary formations was done according to the suggestion of definition "black schists and metalliferous black schists" (sensu to Huyck, 1991) in the frame of the project IGCP 254. The metalliferous sediments have contents of C_{org} > 0.5 % (some samples did not reach this value) at twice or multiple enrichment by any of metals in comparison with standard (according to Vine & Tourtelot, 1970), for Be, Co, Mo and U already at the same level of enrichment. We used the well defined USGS standard SDO-1 (Devonian metalliferous black schists of Appalachian basin), based on analyses results from 32 laboratories (including the laboratory of Geological Survey of Slovak Republic - ŠGÚDŠ). For normalization of some next elements the values by Belinda Arbogast and Joel Leventhal (letter from 29. 1. 1989, later published in Kane et al., 1990) and from Geochemical atlas of Finland (6. schists and crystalline schists FNB). The clark value of particular elements is from the Geochemical atlas of Slovak Republic - rocks (Marsina et al., 1995) and from work by Sláma et al. (1999), where it was used for characteristic of geochemical types of the file of various rocks and contrast sources.

The substantial part of samples was analysed in following laboratories: Geological Survey, national enterprise, Spišská Nová Ves and Turèianske Teplice, Geological Survey of Slovak Republic, Bratislava, UNIGEO, state enterprise, Ostrava, laboratories Brno, GEL Spišská Nová Ves, EL Ecological laboratories Ltd. Spišská Nová Ves, GÚ PriF UK Bratislava, GÚ SAV Bratislava, ÚÚG Brno, laboratories Stráž pod Ralskem and Èernošice. The samples of organic matter were analysed by Geological-chemical department, Moravské naftové doly Comp. Hodonín. [The following analytical methods were used: Atomic emission spectrometry with inductively coupled plasma (AES-ICP); Automatic mercury analyser (Hg-AAS); Flame atomic absorption spectrometry (F AAS); Gravimetric analyses (VA, GA); Ion selective electrode (ISE); Flameless atomic absorption spectrometry (AAS-ETA); Optical emission spectrometry (OES); Radiometric gamaspectrometry (RAD); Pyrolysis (PYR); Neutron activation analysis (INAA)]. The majority of used analyses was performed in Ecological laboratories Ltd. in Spišská Nová Ves.

Slovak Geol. Mag., 11, 2 – 3 (2005),77 – 90

Because of limited extent of this contribution we do not treat the results of the study of mutual relation of steady and weakly reacting elements (La, Th, Sc, Hf, Co, Rb, Ta, Yb), being demonstrated in diagrams and graphs (according to Pearce et al., 1984; Taylor and Mc Lennan, 1985). The study of mutual relations aimed to reveal the source of volcanic and granitic clastic material in investigated sediments. The comprehensive results are accessible in the final report (Slavkay, 2003). This report from the Slovenské rudohorie Mts. characterizes paralelly with Veporicum also some Paleozoic to Triassic rocks and their metamorphic equivalents in next neighbouring tectonic units (Hronicum, Meliaticum, Turnaicum and Silicicum). The characteristic rock analyses in table form with corresponding recomputations and figures we display only from Veporicum of Slovenské rudohorie Mts. (besides main elements). From further areas they are stated preferably in works by Molák et al. (1993), Slavkay (2003) and further works cited in further text.

Veporicum

Slovenské rudohorie Mts.

Proterozoic? – Lower Paleozoic

From metamorphic rocks (protolith: prevailingly pelitic-psammitic sediments) the samples rich in carbon matter were investigated (the sample numbers are indicated in brackets). Two samples attacked by hydrothermal processes (Nos. 8 and 48) were taken. Further samples from macroscopically non-attacked rocks were used for finding of differences.

- Metaquartzite forming intercalations in chlorite-sericite schists of Sinec Complex from locality Hnúšťa-Mútnik (8) approximately 1.2 km to NE from the enterprise Talcum, near road to Polom.
- Schist with carbon matter from the Ostrá micaschist complex (9). Outcrop at forest road 1.2 km to NE from Talcum enterprise, app. 300 m to north from the road to Polom.
- Muscovite and graphite metaquartzites from the Ostrá micaschist complex (24). Outcrop 0.8 km to WNW from the Krížna poľana altitude point (1018 m), near forest hut.
- Black schist to phyllite (39). Sample from mining space of Cerberus occurrence (Mútnik, Balantky).
- Dark-grey schist from the Ostrá micaschist complex (40). Outcrop above forest road 350 m northward from the Cerberus occurrence (Mútnik, Balantky).
- Schist from paragneisses from Filier (48) altered by hydrothermal processes, bearing the fine-scattered pyrite-chalcopyrite sulphidic mineralization. Outcrop 750 m to NW of Filier, at junction of two small streams in altitude point 485 m.
- Quartzy paragneiss with graphite (60). Open pit in Kozlovo local part, 1.6 km to NW from the railway stop Rohozná,
- Graphitic gneiss from the micaschist of the Ostrá complex, trench RMT-1 at village Muránska Dlhá Lúka.

The normalizing of samples (8 and 48) altered by hydrothermal solutions using standards SDO-1 + FNB shows the multiple increase of element content: Co - 2.65; Cr - 2.16; V - 3.46 and 3.06; Ag - 59.63; As - 4.24; Cu - 7.32 and 33.19; Se - 38.33; Ni - 6.8. The differences between both rocks are in the content of Co, Cr, Ag, As, Se and Ni, which confirms diversity of their mineralization types (Tab. 1). The contents of Co and Ni above standard are caused by the presence of pentlandite in the Cerberus deposit. The vanadium is one of elements enriching the surrounding of supplying channels of hydrothermal solutions. The differences are visible also in behaviour of REE (Fig. 2). The increase of HREE contents in altered rocks can be explained by oxidation of mineralized zone, when the disintegration of sulphides has increased the acidity of environment where the LREE are unstable, easily transferred to solution and flushed away. At the same time the rocks were enriched by HREE, being stable in this environment. Besides above stated rocks, further ones of higher multiplication (24, 63) do not indicate any mineralization. According to 1/3 standard these are Co, B, Be, Hg, Pb and U. The manifold increase of As can be possibly assigned to original sedimentary mineralization.

The maturity of fine-grained sediments with C_{org} 1.74–3.76 % is demonstrated by the high K_2O/Na_2O ratio, besides the rocks with very low content of C_{org} (0.03 and 0.01) where samples 48 and 60 manifest the low ratio (1.60 and 0.8). All remaining rocks have higher content of C_{org} (1.74–3.76 %), but regarding the standard SDO-1 + FNB its part do not overreach 0.30. The evaluation of organic substance from samples 8 and 9 was presented by Slavkay and Širáňová (1993; in Molák et al., 1993). The content C_{org} in sample 8 is 2.9 %, in sample 9 it is 3.76 %, the average content is 3.38 %. In the carbon balance the same content was found in the case of C_{bit} (0.5 %), C_{hum} (0.7 %) and C_{resid} (98.8 %), which shows the substantial presence of metamorphosed component of organic substance - kerogene. When comparing with the standard SDO-1 + FNB the $C_{org.}$ ratio is low (0.28x and 0.37x). According to the component analysis (Tab. 3) the presence of oil, pitch and asphaltenic component is unbalanced. According to IR spectrometry and the ratio of absorption strips 1460/1735 cm^{-1} in samples, the absorbance of carbonyl strip prevails, so samples can be arranged among the remanent ones. According to the ratio of absorption strips 720/1610 cm^{-1} the bitumens have distinct preponderance of aliphatic component above aromatic, the bitumens are therefore of remnant sapropel type. According to distribution of hydrocarbons GC samples analyses (Fig. 1), the maxima C_{22}, C_{23} show the organic substance of marine provenance. According to the low bitumen content and not-fulfilling the condition $n\text{-}C_{15}>n\text{-}C_{17}>n\text{-}C_{19}$ the bitumens are not migrated. The ratio pristan/phytan > 1 expresses the oxidizing conditions during sedimentation.

Between Muránska Dlhá Lúka and Klenovec villages three main micaschist types with the intercalations of quartzite and schist with organic matter are spread (samples 9, 24, 40, 63): 1. garnet-chloritoid, 2. garnet-chlorite

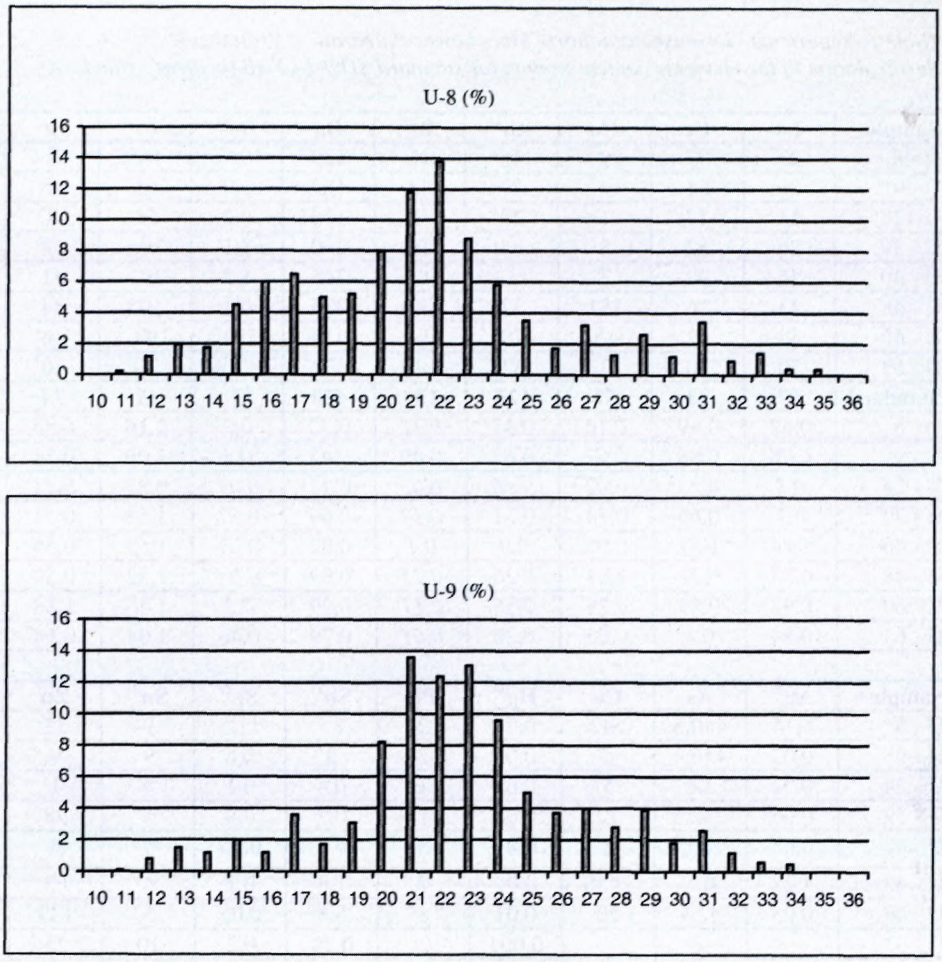


Fig. 1. Abundance of n-alkanes in sample U-8 and U-9 in %.

and 3. garnet-biotite micaschist with plagioclase. The quartz and muscovite are present in the same amount, in the third type quartz is prevailing and plagioclase is more often. The pseudomorphoses of chloritoid with sericite, porphyroblasts of staurolite and garnet, accessoric ilmenite, clinozoisite, zircon, apatite, tourmaline, magnetite, pyrrhotite and pyrite were found in these samples. They show the high content of Al_2O_3 (19.8–30.43 %), low SiO_2 (43.84–60.84 %), K_2O prevails above Na_2O in the ratio 2:1. In the majority of samples beneath the level of 1/3 of clark (Tab. 1a) remained Co, Sr, Zr, Cu, Hg, Pb, Zn, moderately increased are Ce, Y, Li, Sn and Ni (1.2–2.91x), triple to fivefold clark content is overreached by As, Sb and Se, but both elements in several samples reach even anomalous contents (6.38–1243.3 multiple).

The succession of muscovite-chlorite schists with metabasites, metacarbonates, graphite quartzites, metaconglomerates, metaarkoses and chlorite-sericite schists is variegated (Slavkay, 1996, in Sláma et al., 1999). The C_{org} content (1.19 %) represents 66.25-fold of clark, oxides are close to clark values, only MgO and MnO are lower and Fe_2O_3, CaO and Na_2O are scarce. The SiO_2 content varies from 58.34 to 83.36 %, Al_2O_3 from 5.92 to 20.61 % and ratio K_2O/Na_2O is very variable and highly in favour to K_2O. The higher than triple to quintuple of clark was registered in Sr, V, As, Cu, Sb, Se, Ni and U. The sample 8 is mineralized, but in sample 39 no ore minerals were found. The scarce elements (< 1/3 multiple of clark) are Ba, Be, Sr, Zr, Hg, Pb and Zn.

Mineralization

We suppose, that during sedimentation of former rocks of pre-Hercynian age in oxidic environment of the basin also leptochlorite and hematite ores with organic matter have sedimented. During regional metamorphism (later possibly also contact metamorphism, Gubač,1957) they were replaced to magnetite ore of the deposit Kokava nad Rimavicou, Hrabina and organic matter was changed to graphite. The deposit is formed by several lenses in the zone of migmatitized micaschist paragneisses in hybridic granitoids. As a protolith of ores Radvanec (2000) supposes the well sorted pelitic-psammitic sediments with content of organic substance and Fe carbonatic beds, bodies and veins, being metamorphosed at the boundary of lower crust in the field of normal geothermic gradient 25 °C/km. According to Kováčik (2000) the assemblage of magnetite-grunerite-garnet-biotite-quartz originated probable at temperature 600 °C in medium-pressure conditions. The presence of magnetite influences the high content of iron and more pelitic petrographic character (higher content of Al_2O_3, K_2O), with higher content of Fe^{3+} (differing from quartz-grunerite types). The deposit represents the formation of metamorphic Fe ore of pre-Hercynian to Hercynian phase (Slavkay and Petro, 1993).

Table 1. Veporicum, Slovenské rudohorie Mts., Lower Paleozoic, ? Proterozoic
Recalculation of the elements content in ppm for standard SDO-1+FNB (content : standard)

Sample	La	Ce	Co	Rb[1]	B[2]	Ba	Be[2]	Cr	Sr	V	Y	Zr	Li[2]
U - 8	23	37	9	46	16	139	0,9	145	26	554	32	57	0
U - 9	29	51	4	79	64	187	0,9	71	25	169	10	45	0
U - 24	11	17	1	20	4	176	0,2	58	8	575	10	28	2
U - 39	26	52	8	64	16	290	1,1	106	38	260	17	84	35
U - 40	46	98	3	113	13	345	1,7	102	41	146	49	101	22
U - 48	13	16	151	32	32	373	0,1	102	44	489	50	101	28
U - 60	34	62	15	70	14	416	0,9	97	139	147	28	193	42
U - 63	20	30	3	32	9	332	1,38	70	10	383	22,7	25	4
Standard	**37**	**75**	**57**	**125**	**130**	**420**	**3**	**67**	**74**	**160**	**36**	**120**	**60**
U - 8	0,62	0,49	*0,16*	0,37	*0,12*	0,33	*0,3*	**2,16**	0,35	**3,46**	0,89	0,48	0
U - 9	0,78	0,68	*0,07*	0,63	0,49	0,45	*0,3*	1,06	0,34	1,06	*0,28*	0,38	0
U - 24	*0,3*	*0,23*	*0,02*	*0,16*	*0,03*	0,42	*0,07*	0,87	*0,11*	**3,59**	*0,28*	*0,23*	*0,03*
U - 39	0,7	0,69	*0,14*	0,51	*0,12*	0,69	0,37	1,58	0,51	1,63	0,47	0,7	0,58
U - 40	1,24	1,31	0,05	0,9	*0,1*	0,82	0,57	1,52	0,55	0,91	1,36	0,84	0,37
U - 48	0,35	*0,21*	**2,65**	*0,26*	*0,25*	0,89	*0,03*	1,52	0,59	**3,06**	1,39	0,84	0,47
U - 60	0,92	0,83	*0,26*	0,56	*0,11*	0,99	*0,3*	1,45	1,88	0,92	0,78	1,61	0,7
U - 63	0,54	0,4	*0,05*	*0,26*	*0,07*	0,79	0,46	1,04	0,14	**2,39**	0,63	*0,21*	*0,07*

Sample	Ag[2]	As	Cu	Hg[1]	Pb	Sb[1]	Se[2]	Sn[2]	Zn	Ga	Ni	U	Th
U - 8	0,14	440,5	542	0,01	2	7,1	11,5	9	12	9	85	7,4	4
U - 9	0,02	446,4	5	0,01	2	5	0,6	9	9	12	18	2,4	3
U - 24	0,02	1,6	5	0,01	1	0,4	0,1	4	1	4	24	1	2
U - 39	0,06	232,6	72	0,02	1	0,7	0,4	5	28	15	79	3	6
U - 40	0,08	1865	8	0,01	3	6,2	0,05	5	6	23	47	5	11
U - 48	4,77	0,5	2456	0,01	7	1,8	0,1	4	63	11	871	13	10
U - 60	0,05	32,4	20	0,01	8	5,8	0,05	5	133	19	62	0,5	6
U - 63	-	7	7	0,001	2	0,13	0,2	10	25	5	57	2	2
Standard	**0,08**	**104**	**74**	**0,15**	**32**	**4**	**0,3**	**5**	**76**	**20**	**128**	**56**	**10**
U - 8	1,75	**4,24**	**7,32**	*0,07*	*0,06*	1,78	**38,33**	1,8	*0,16*	0,45	0,66	*0,13*	0,4
U - 9	*0,25*	**4,29**	*0,07*	*0,07*	*0,06*	1,25	**2**	1,8	*0,12*	0,6	*0,14*	*0,04*	*0,3*
U - 24	*0,25*	*0,02*	*0,07*	*0,07*	*0,03*	*0,10*	0,33	0,8	*0,01*	*0,2*	*0,19*	*0,02*	*0,2*
U - 39	0,75	**2,24**	0,97	*0,13*	*0,03*	*0,18*	1,33	1	0,37	0,75	0,62	*0,05*	0,6
U - 40	1	**17,93**	*0,11*	*0,07*	*0,09*	1,55	*0,17*	1	*0,08*	1,15	0,37	*0,09*	1,1
U - 48	**59,63**	*0,01*	**33,19**	*0,07*	*0,22*	*0,45*	0,33	0,8	0,83	0,55	**6,8**	*0,23*	1
U - 60	0,63	*0,31*	*0,27*	*0,07*	*0,25*	1,45	*0,17*	1	1,75	0,95	0,48	*0,01*	0,6
U - 63	-	*0,07*	*0,09*	*0,007*	*0,06*	*0,03*	0,67	**2**	0,33	*0,25*	0,45	*0,04*	*0,2*

0.XX < 1/3 of standard; X.XX > double of the standard value; [1] – according to Belinda Arbogast, 29. 1. 1989; [2] according to Geochemical atlas of Finland, column 6. schists

The pyrite-chalcopyrite ore of occurrence Revúca, Dolinský potok, has volcanosedimentary origin with regional metamorphic overprint in Lower Paleozoic. The mineralization is located at the contact of garnet micaschists of Ostrá complex with hybridic granitoids and migmatites. The minerals pyrite, marcasite, tetrahedrite and ankerite are related to younger remobilization. In occurrence Ratkovské Bystré, Filier in surrounding rocks with graphite the mineralization (quartz, pyrite, pyrrhotite, chalcopyrite) is developed in gneiss at the contact of migmatite with granite. Formerly it originated in anoxic environment of pre-Hercynian to Hercynian phase and belongs to formation of metamorphic pyrite ore (Slavkay and Petro, 1993).

The graphite in the occurrence Muránska Dlhá Lúka, Krížna Poľana forms larger concentrations with crystalline flakes disseminated in metaquartzite (about 3.5 % C_{org}) and in intercalations of metabasite in garnet micaschists of the Ostrá complex. The graphite is of excellent quality and very well flotative (Očenáš,1992). The graphite mineralization was found also in deposit Kokava nad Rimavicou, Zahrabina in the zone of biotite-albite paragneiss with quartzite bodies in hybridic granitoid with transitions to migmatite (Petro in Petro et al., 1998). The graphite originated by overheating of rocks rich in organic matter with following, most probable Hercynian regional metamorphic overprint (Radvanec, 2000; Kováčik, 2000). The gneisses with high graphite crystallinity occur in assemblage with high-iron gneisses (Pulec, 1989), which documents metamorphic conditions of amphibolite facies. Crystalline graphite is present also in occurrence Brezno, Kozlovo, in hybridic granitoid. The occurrences are enlisted to metamorphic deposits as products of regional (Hercynian resp. even pre-Hercynian) meta-

Table 1a. Veporicum, Slovenské rudohorie Mts., Lower Paleozoic, ? Proterozoic
Recalculation of the elements content in ppm for clark content in the Earth crust (content : clark)

Sample	La	Ce	Co	Rb	B	Ba	Be	Cr	Sr	V	Y	Zr	Li
U - 8	23	37	9	46	16	139	0,9	145	26	554	32	57	0
U - 9	29	51	4	79	64	187	0,9	71	25	169	10	45	0
U - 24	11	17	1	20	4	176	0,2	58	8	575	10	28	2
U - 39	26	52	8	64	16	290	1,1	106	38	260	17	84	35
U - 40	46	98	3	113	13	345	1,7	102	41	146	49	101	22
U - 48	13	16	151	32	32	373	0,1	102	44	489	50	101	28
U - 60	34	62	15	70	14	416	0,9	97	139	147	28	193	42
U - 63	20	30	3	32	9	332	1,38	70	10	383	22,7	25	4
Clark	**30**	**64**	**10**	**112**	**15**	**550**	**3**	**35**	**350**	**60**	**22**	**190**	**20**
U - 8	0,77	0,58	0,9	0,41	1,07	*0,25*	*0,3*	**4,14**	0,7	**9,23**	1,46	*0,3*	0
U - 9	0,97	0,8	0,4	0,71	1,27	0,34	*0,3*	2,03	0,7	2,82	0,46	*0,24*	0
U - 24	0,37	*0,27*	*0,1*	*0,18*	*0,27*	*0,32*	*0,07*	1,66	*0,02*	**9,58**	0,46	*0,15*	*0,1*
U - 39	0,87	0,81	0,8	0,57	1,07	0,53	0,37	**3,03**	*0,11*	**4,33**	0,77	0,44	1,75
U - 40	1,53	1,53	*0,3*	1,01	0,87	0,63	0,57	2,91	*0,12*	2,43	2.23	0,53	1.1
U - 48	0,43	*0,25*	**15,1**	*0,29*	2,13	0,68	*0,03*	2,91	*0,13*	**8,15**	2,27	0,53	1,4
U - 60	1,13	0,97	1,5	0,63	0,93	0,76	*0,3*	2,77	0,4	2,45	1,27	1,02	2,1
U - 63	0,67	0,47	*0,3*	*0,29*	0,6	0,6	0,46	2	*0,03*	**6,38**	1,03	*0,13*	*0,2*

Sample	Ag	As	Cu	Hg	Pb	Sb	Se	Sn	Zn	Ga	Ni	U	Th
U - 8	0,14	440,5	542	0,01	2	7,1	11,5	9	12	9	85	7,4	4
U - 9	0,02	446,4	5	0,01	2	5	0,6	9	9	12	18	2,4	3
U - 24	0,02	1,6	5	0,01	1	0,4	0,1	4	1	4	24	1	2
U - 39	0,06	232,6	72	0,02	1	0,7	0,4	5	28	15	79	3	6
U - 40	0,08	1865	8	0,01	3	6,2	0,05	5	6	23	47	5	11
U - 48	4,77	0,5	2456	0,01	7	1,8	0,1	4	63	11	871	13	10
U - 60	0,05	32,4	20	0,01	8	5,8	0,05	5	133	19	62	0,5	6
U - 63	-	7	7	0,001	2	0,13	0,2	10	25	5	57	2	2
Clark	**0,05**	**1,5**	**25**	**0,09**	**20**	**0,2**	**0,05**	**5,5**	**71**	**17**	**20**	**2,3**	**8,1**
U - 8	2,8	**293,67**	**21,68**	*0,11*	*0,1*	**35,5**	**230**	1,64	*0,17*	0,53	**4,25**	**3,22**	0,49
U - 9	0,4	**297,6**	*0,2*	*0,11*	*0,1*	**25**	**12**	1,64	*0,13*	0,71	0,9	1,04	0,37
U - 24	0,4	1,07	*0,2*	*0,11*	*0,05*	2	2	0,73	*0,01*	*0,24*	1,2	0,44	*0,25*
U - 39	1,2	**155,07**	2,88	*0,22*	*0,05*	**3,5**	**8**	0,91	0,39	0,88	**3,95**	1,3	0,74
U - 40	1,6	**1243,3**	*0,32*	*0,11*	*0,15*	**31**	1	0,91	*0,09*	1,35	2,35	2,17	1,36
U - 48	**95,4**	0,33	**98,24**	*0,11*	0,35	**9**	2	0,73	0,89	0,65	**43,55**	**5,65**	1,23
U - 60	1	**21,6**	0,8	*0,11*	0,4	**29**	1	0,91	1,87	1,12	**3,1**	*0,22*	0,74
U - 63	-	**4,67**	*0,28*	*0,01*	*0,1*	0,65	**4**	1,82	0,35	*0,29*	2,85	0,87	*0,25*

0.XX content beneath 1/3 of clark value; **X.XX** – content above triple of clark value; **X.XX** – content above quintuple of clark value.

morphism of rocks richer in organic matter, originating formerly in highly anoxic, Lower Paleozoic (? Proterozoic) environment.

The results of investigation and survey of carbonatic bodies in sedimentary rocks were summed up by Abonyi and Abonyiová (1980) and others. The limestones were suitable environment for later circulation of solutions and origin of magnesite and talc. The talc mineralization in deposit Hnúšťa, Mútnik (Kužvart, 1955; Lisý, 1971; Vitásek, 1988, 1990; Németh et al., 2004) bounds to intergranular spaces, joints and margins of magnesite bodies of quartzy type in biotite-garnet micaschist of the Ostrá complex and muscovite-chlorite schist with metabasics of the Sinec complex. The main minerals are accompanied with dolomite, minerals of illite group, Mg and Mg, Fe chlorites. The sulphidic mineralization originated during younger mineralization processes (Trdlička, 1961). In veins of brown-red dolomite penetrating the magnesite-talc body the sulphidic mineralization with disseminated uraninite was found (Varček, 1977), which explains also the multiple increase of the value of clark uranium content (Tab. 1a). Similar mineralization is developed in neighbouring occurrence Hnúšťa, Polom though with much weaker talc mineralization. Next deposits are Kokava baňa, Borovana, Sinec and Hnúšťa-Samobane (Suchár, 1974). In all these deposits the talc bodies are developed in the zone of sericite-chlorite schist with carbonate intercalations, being located at the contact with the biotite paragneiss of Klenovec complex (Slavkay and Lenárt, 1974). The talc in occurrence Muránska Dlhá Lúka forms the reaction rim of the serpentinite body in garnet micaschist of the Ostrá complex, which was caused by the metamorphic-recrystallization processes and hydrothermal activity.

Talc originated probable by reacting of hydrothermal solutions with limestone in Middle to Upper Cretaceous.

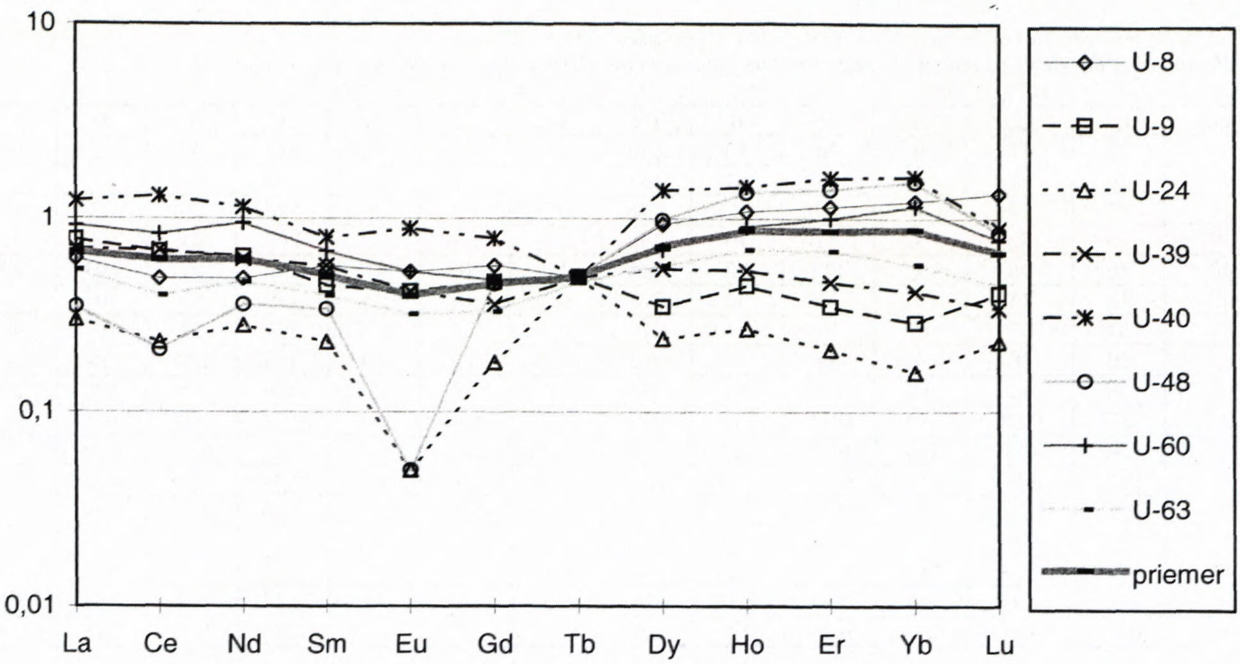


Fig. 2. Normalized REE values according to standard SDO-1. Slovenské rudohorie Mts., Veporicum, Lower Paleozoic - ? Proterozoic.

In the first phase there originated dolomite and magnesite, and in the second phase talc and next accompanying minerals from the solutions rich in SiO_2, at the expense of a part of magnesite. The process is associated with the Alpine metallogenetic phase and mineralization into magnesite-talc association of siderite formation (Slavkay in Slavkay et al., 2004).

The asbestos occurs in bodies of serpentinized ultrabasics in biotite paragneiss of the Klenovec complex. In the occurrence Uhorské the smaller bodies of antigoritic serpentinite are developed at the margin with carbonate-talc rim and fibroidal actinolite, less often chrysotile asbestos, similarly as in the deposit Muránska Dlhá Lúka (Hovorka, 1985). From the central part of the body the antigorite, actinolite and chlorite zone are developed, being a product of metasomatism of utrabasic rock with surrounding rocks and fluids. This territory is perspective for similar raw-material types (Slavkay et al., 1997).

Nízke Tatry Mts.
Jánov grúň Formation (Devonian – Lower Carboniferous)

The formation is built with metasandstone, metagreywacke, metarhyodacite, metadacite and their volcaniclastics, less often are the products of basic volcanism altered to green schist and phyllite with admixture of organic matter (C <0.13 %), ilmenite and tourmaline. The protolith of these rocks would be the clayey sediments with hydromicas. The metasandstone with the higher amount of quartz contains muscovite - phengite, biotite, chlorite, paragonite, K-feldspar, albite, carbonate, ilmenite and tourmaline. Rocks were metamorphosed in the middle part of the greenschist facies during Hercynian orogeny (Miko and Pulec in Molák et al., 1993; the cited work contains the complete rock analyses of stated samples and their description).

The Al_2O_3 content in phyllite varies in the range 20.67–23.12 %. The Fe and MnO contents are higher. The As, Ba and Ni have moderately increased contents comparing the clark composition. The metasandstone has increased SiO_2 and lowered TiO_2, Al_2O_3, MgO and K_2O. The fine-grained compact metapelite (ČB-22b) with black tourmaline has less SiO_2, more Al_2O_3 and K_2O (abundant sericite) and significantly higher content Ba, Ce, Cs, F, Hg, La, Rb, Sn, Sr, Y and more elements of REE. Miko and Pulec, l. c., attribute this composition to influence of granite porpfyries during intrusion into the rocks of this formation.

The organic matter with increased C_{org} and lower C_{bit} from the samples ČB-1 (phyllite), ČB-10 (metasandstone) from the lower part and ČB-22b (black metapelite) from the upper part of the formation was reviewed by Širáňová (in Molák et al., 1993). According to component analysis they represent the light hydrocarbons with oil component average in 87.7 %. According to IR spectrometry and the ratio of absorption strips 1460/1735 cm^{-1}, samples ČB-1 and ČB-10 belong to remnant type (with prevailing absorbance of carbonyle strip). In sample ČB-22b the intensity of strips is comparable (comparable content of aliphatic and aromatic groups). Based on ratio of absorption strips 720/1610 cm^{-1} of samples ČB-1 and ČB-10 they represent the sapropel-humus type and sample ČB-22b (aliphatic component < aromatic component) represents the humus type of remnant bitumens. The distribution of hydrocarbons (GC analysis) in sample ČB-1 (max. C_{22}, C_{25}) shows mixed source of hydrocarbons of marine and terrigenous origins; in sample ČB-10 (max. C_{22}) the marine source of the hydrocarbons origin and in sample ČB-22b (max. C_{31}) the terrigenous source of hydrocarbons. According to distribution of n-alkanes they do not represent the migrated hydrocarbons. The values pristan/phytan < 1 show reduction conditions.

Mineralization

It is supposed, that in sedimentary space and in oxidic environment the syngenetic iron ore originated in stratiform position with surrounding Paleozoic rocks. This ore was during Hercynian regional metamorphism replaced to magnetite iron ore in irregular comformable ore bodies, located in Bacúch - Biela skala locality in garnet-muscovite-biotite paragneiss, in localities Bacúch - Javorinka and Babiná in the strip of sericite-chlorite phyllites (Devonian – Lower Carboniferous). The ore contains also quartz, hematite, pyrite, pyrrhotite, chalcopyrite and sphalerite.

Further product of regional metamorphism is represented by pyrrhotite ore in deposit Heľpa. Originally it consisted from vulcanosedimentary pyrite mineralization (Precambrian?-Paleozoic) deposited in reduction environment of the basin. The ore bodies (pyrrhotite, pyrite, less ilmenite, chalcopyrite, sphalerite, calcite), conformable with schistosity, are present in paragneiss with intercalations of schist, phyllite, amphibolite, metarhyolite (away of the Jánov grúň Formation). Similar occurrences from the economic viewpoint are not interesting.

The more important anomalies in Veporic part of the Nízke Tatry Mts. were formed by younger mineralization processes preferably by ores of siderite formation. This group includes for example the occurrence Beňuš, Leňušská dolina valley (Fe-Cu ore) with quartz, ankerite, calcite, pyrite, pyrrhotite and chalcopyrite mineralization, disseminated in large area in Beňuš paragneisses. The quartz-siderite vein with chalcopyrite and pyrite in occurrence Jánov grúň - Adamov is developed in chlorite-sericite phyllite and in occurrence Sokolia dolina valley (Fe-Cu-Pb) the mineralization penetrates Mesozoic rocks (compare Slavkay et al., 1988; Slavkay, et al., 1994, Grecula et al., 1996).

Slovenské rudohorie Mts.

Slatviná Formation *(Upper Carboniferous)*

The complete analyses of characteristic samples of sedimentary rocks of psammitic-pelitic character (Tabs. 2 and 2a) are from various localities of the Slovenské rudohorie Mts. of following macroscopically moderately different types:

- Black schist (31) intercalation in fine-grained sandstone from the outcrop in the right slope of the road above railway station Slavošovce in direction to Čierna Lehota.
- Dark-grey sandy schist (32) in fine- to medium-grained sandstone from outcrop behind the waste dump of Slavošovce paper-factory, approximately 400 m west of gipsy settlement.
- Dark-grey strongly micaceous sandy schist (37) from outcrop in the forest road cut app. 1.5 km to NNE of village Rimavská Baňa, Klingové local part.
- Dark-grey brownish micaceous phyllite (38) from the outcrop in the road cut behind the public transport stop Hnúšťa - Likier,
- Dark-grey phyllitic schist in sandstone (41) from the outcrop at gamekeeper's house Podlaz (Mokra Lúka) app. 250 m to W from the road from under the mine dump Lubeník.
- Dark-grey graphitic phyllite sericitized and disintegrated (44) from the forest road cut (behind the stream) app. 1 km to N of Turčok. Sample (45) is from the forest road cut app. 0.9 km to N of Turčok.
- Dark-grey graphitic phyllite (43) from the left slope of Uhliarska dolina valley app. 1 km to N of Turčok.
- Graphitic phyllite (54) from the cut of the left bank of the Blh stream app. 300 m to SE from Ratkovská Zdychava.
- Graphitic phyllite (55) from the cut of the road from Vyšná Burda to Krokava, abrupt turn of the road, 2.3 km to SSE from Krokava.

Relative large variability of the K_2O/Na_2O contents ratios (in two samples 0.36 and 0.65; in three samples 2.25–8.05, in five samples 1.03–1.67) indicates the tuffitic admixture. Oxides after normalization to standard SDO-1 + FNB (Tab. 2) prevailingly fluctuate around its value. The double overreaching of its value was registered by MgO, MnO and Na_2O and deep beneath 1/3 are the contents of C_{org} (0.01–0.92 %). Co, B, As, Hg, Pb, Sb, Se and U have lower values than its 1/3, other elements vary tightly around the standard value. More than double values of Ag, Pb and Zn in sample 43 can be attributed to influence of hydrothermal processes, causing mineralization of the occurrences Turčok, Lipová dolina valley and Mokrá Lúka, Trešková. The REE in rocks, normalized according to SDO-1, do not show large variability and do not reach the standard values (Fig. 3). The schists of the Slatviná Fm. as a whole do not show metalliferous characteristics, so there is not expected the syngenetic sedimentary mineralization.

Vozárová (in Molák et al., 1993) supposes about this formation, that it represents the sequence of alluvial fans of small delta into the shallow water sedimentary basin. In calm poorly oxidized parts near continent the clay, organic matter and plant detritus were deposited in shallow water anoxic environment. The rocks have suffered the Alpine regional metamorphism in the greenschist facies.

Our geochemical study included also metasandstone, metaschist and phyllite (originally greywacke, sandstone, claystone), alternating in small cycles in the frame of two cycles of higher order (Vozárová and Vozár, 1988). The average modal composition from 6 analyses (in %): quartz 56; feldspars 4.5; biotite 7.5; muscovite 16.5; chlorite 10; epidote-zoisite 3; garnet 0.5, hydrothermal minerals 2. At the contact with granite the ratios of garnet, biotite and locally cordierite are increasing. Phyllites with intercalations of black schists are formed with following regional metamorphic minerals: quartz, muscovite, chlorite ± albite + graphite. They contain the grains of ilmenite, leucoxene, needles of tourmaline and rutile (Vozárová in Slavkay et al., 1995). In the places of contact metamorphism they have character of hornfels.

Oxides in clastic sediments have contents close to clark values, CaO is scarce. The ratio of average contents

Slovak Geol. Mag., 11, 2 – 3 (2005),77 – 90

Table 2. Veporicum, Slovenské rudohorie Mts., Slatviná Formation, Upper Carboniferous
Recalculation of the elements content in ppm for standard SDO-1+FNB (content : standard)

Sample	La	Ce	Co	Rb[1)]	B[2)]	Ba	Be[2)]	Cr	Sr	V	Y	Zr	Li[2)]
U - 31	27	48	5	107	495	439	3.2	85	40	97	27	211	36
U - 32	19	38	15	51	22	447	1,1	94	161	121	17	179	34
U - 37	18	35	19	121	57	560	1,9	99	73	140	16	152	54
U - 38	28	54	16	62	23	419	1,2	102	148	147	26	138	41
U - 41	17	37	21	113	35	837	1,8	75	71	107	19	177	38
U - 43	32	60	10	93	42	831	1,5	105	70	144	26	162	41
U - 44	29	57	21	96	40	479	1,8	112	67	141	30	156	40
U - 45	30	61	15	98	62	513	1,3	106	62	147	28	171	42
U - 54	33	70	14	89	37	721	1,3	99	83	132	33	233	47
U - 55	20	37	8	64	20	538	1,4	96	76	135	21	147	38
Stadard	**37**	**75**	**57**	**125**	**130**	**420**	**3**	**67**	**74**	**160**	**36**	**120**	**60**
U - 31	0,73	0.64	*0.09*	0,86	**3,81**	1,05	1,1	1,27	0,54	0,61	0,75	1,76	0,6
U - 32	0,51	0,51	*0,26*	0,41	*0,17*	1,06	0,4	1,4	**2,18**	0,76	0,47	1,49	0,57
U - 37	0,49	0,47	0,33	0,97	0,44	1,33	0,6	1,48	0,99	0,88	0,44	1,27	0,9
U - 38	0,76	0,72	*0,28*	0,5	*0,18*	1	0,4	1,52	**2**	0,92	0,72	1,15	0,68
U - 41	0,46	0,49	0,37	0,9	*0,27*	1,99	0,6	1,12	0,96	0,67	0,53	1,48	0,63
U - 43	0,86	0,8	*0,18*	0,74	*0,32*	1,98	0,5	1,57	0,95	0,9	0,72	1,35	0,68
U - 44	0,78	0,76	0,37	0,77	*0,31*	1,14	0,6	1,67	0,91	0,88	0,83	1,3	0,67
U - 45	0,81	0,81	*0,26*	0,78	0,48	1,22	0,4	1,58	0,84	0,92	0,78	1,43	0,7
U - 54	0,89	0,93	*0,25*	0,71	*0,28*	1,72	0,4	1,48	1,12	0,83	0,92	1,94	0,78
U - 55	0,54	0,49	*0,14*	0,51	*0,15*	1,28	0,5	1,43	1,03	0,84	0,58	1,23	0,63

Sample	Ag[2)]	As	Cu	Hg[1)]	Pb	Sb[1)]	Se[2)]	Sn[2)]	Zn	Ga	Ni	U	Th
U - 31	0,08	14,5	17	0,03	3	1,7	0,05	4	22	22	233	12	10
U - 32	0,02	29,3	59	0,03	2	0,7	0,05	4	106	18	40	5	3
U - 37	0,08	1,1	58	0,01	1	0,4	0,05	6	97	22	55	1	4
U - 38	0,08	11,7	36	0,01	4	0,5	0,05	5	127	21	53	1	3
U - 41	0,15	1,7	89	0,01	6	0,8	0,05	7	73	20	52	2	3
U - 43	0,19	2,2	43	0,14	515	0,3	0,05	5	251	20	24	1	4
U - 44	0,05	56,3	41	0,01	1	0,3	0,05	4	37	19	78	0,5	4
U - 45	0,2	27,4	55	0,01	4	0,4	0,40	5	83	21	34	2	4
U - 54	0,02	34	56	0,01	4	0,6	0,05	4	64	20	38	2	6
U - 55	0,02	24,4	46	0,01	5	0,5	0,05	5	82	19	30	1	3
Standard	**0,08**	**104**	**74**	**0,15**	**32**	**4**	**0,3**	**5**	**76**	**20**	**128**	**56**	**10**
U - 31	1	*0,1*	*0,23*	*0,2*	*0,09*	0,4	*0,17*	0,8	*0,29*	1,1	1,82	*0,21*	1
U - 32	*0,25*	*0,3*	0,8	*0,2*	*0,06*	*0,18*	*0,17*	0,8	1,39	0,9	*0,31*	*0,09*	*0,3*
U - 37	1	*0,01*	0,78	*0,07*	*0,03*	*0,1*	*0,17*	1,2	1,28	1,1	0,43	*0,02*	0,4
U - 38	1	*0,1*	0,49	*0,07*	*0,13*	*0,13*	*0,17*	1	1,67	1,05	0,41	*0,02*	*0,3*
U - 41	1,88	*0,02*	1,20	*0,07*	*0,19*	*0,2*	*0,17*	1,4	0,96	1	0,41	*0,04*	*0,3*
U - 43	**2,38**	*0,02*	0,58	0,93	**16,09**	*0,08*	*0,17*	1	**3,3**	1	*0,19*	*0,02*	0,4
U - 44	0,63	0,5	0,55	*0,07*	*0,03*	*0,08*	*0,17*	0,8	0,49	0,95	0,61	*0,01*	0,4
U - 45	**2,5**	*0,3*	0,74	*0,07*	*0,13*	*0,1*	1,33	1	1,09	1,05	*0,27*	*0,04*	O,4
U - 54	*0,25*	*0,3*	0,76	*0,07*	*0,13*	*0,15*	*0,17*	0,8	0.84	1	*0,3*	*0,04*	0,6
U - 55	*0,25*	*0,2*	0,62	*0,07*	*0,16*	*0,13*	*0,17*	1	1,08	0,95	*0,23*	*0,02*	*0,3*

0.XX < 1/3 of standard; **X.XX** > double and multiple of the standard value; [1)] – according to Belinda Arbogast, 29. 1. 1989; [2)] according to Geochemical atlas of Finland, column 6. schists

$K_2O:Na_2O$ varies from 1:3 through 1:1 up to 4:1. From the trace elements (Tab. 2a) in majority of samples As (7.8–37.53) more than five times overreaches the clark content, in some samples three to five-times this content is overreached by B, Cr, Ag, Cu, Sb, Se and Ni, scarce elements are Sr and Hg of less than 1/3 of clarks. All other elements vary between 1/3 and double clark values. The increase of Ag, Pb and Zn values in sample 43 shows the influence of hydrothermal processes. The higher value of B, As, Sb, Ni and U in the sample 31 is interesting and relates the schist intercalation in sandstone, tectonically wedged in granitic rocks, in area with occurrences of Fe and polymetallic mineralization in the range of influence of Rochovce granite.

Mineralization

The rocks of Slatviná Formation contain low elements concentrations, which do not overreach the double values of SDO-1+FNB standard and triple value of clarks. The higher contents of As, Sb and Zn are caused by ingress of epigenetic solutions bringing these elements and forming

Table 2a. Veporicum, Slovenské rudohorie Mts., Slatviná Formation, Upper Carboniferous
Recalculation of the elements content in ppm for clark content in the Earth crust (content : clark)

Sample	La	Ce	Co	Rb	B	Ba	Be	Cr	Sr	V	Y	Zr	Li
U - 31	27	48	5	107	495	439	3.2	85	40	97	27	211	36
U - 32	19	38	15	51	22	447	1,1	94	161	121	17	179	34
U - 37	18	35	19	121	57	560	1,9	99	73	140	16	152	54
U - 38	28	54	16	62	23	419	1,2	102	148	147	26	138	41
U - 41	17	37	21	113	35	837	1,8	75	71	107	19	177	38
U - 43	32	60	10	93	42	831	1,5	105	70	144	26	162	41
U - 44	29	57	21	96	40	479	1,8	112	67	141	30	156	40
U - 45	30	61	15	98	62	513	1,3	106	62	147	28	171	42
U - 54	33	70	14	89	37	721	1,3	99	83	132	33	233	47
U - 55	20	37	8	64	20	538	1,4	96	76	135	21	147	38
Clark	**30**	**64**	**10**	**112**	**15**	**550**	**3**	**35**	**350**	**60**	**22**	**190**	**20**
U - 31	0,9	0,75	0,5	0,96	**33**	0,8	1,07	2,43	*0,11*	1,62	1,23	1,11	1,8
U - 32	0,63	0,59	1,5	0,46	1,47	0,81	0,37	2,69	0,46	2,02	0,77	0,94	1,7
U - 37	0,6	0,55	1,9	1,08	**3,8**	1,02	0,63	2,83	*0,21*	2,33	0,73	0,8	2,7
U - 38	0,93	0,84	1,6	0,55	1,53	0,76	0,4	2,91	0,42	2,45	1,18	0,73	2,05
U - 41	0,57	0,58	2,1	1,01	2,33	1,52	0,6	2,14	*0,20*	1,78	0,86	0,93	1,9
U - 43	1,07	0,94	1	0,83	2,8	1,51	0,5	**3**	*0,20*	2,40	1,18	0,85	2,05
U - 44	0,97	0,89	2,1	0,86	2,67	0,87	0,6	**3,2**	*0,19*	2,35	1,36	0,82	2
U - 45	1	0,95	1,5	0,88	**4,13**	0,93	0,43	**3,03**	*0,18*	2,45	1,27	0,9	2,1
U - 54	1,1	1,09	1,4	0,79	2,47	1,31	0,43	2,83	*0,24*	2,2	1,5	1,23	2,35
U - 55	0,67	0,58	0,8	0,57	1,33	0,98	0,47	2,74	*0,22*	2,25	0,95	0,77	1,9

Sample	Ag	As	Cu	Hg	Pb	Sb	Se	Sn	Zn	Ga	Ni	U	Th
U - 31	0,08	14,5	17	0,03	3	1,7	0,05	4	22	22	233	12	10
U - 32	0,02	29,3	59	0,03	2	0,7	0,05	4	106	18	40	5	3
U - 37	0,08	1,1	58	0,01	1	0,4	0,05	6	97	22	55	1	4
U - 38	0,08	11,7	36	0,01	4	0,5	0,05	5	127	21	53	1	3
U - 41	0,15	1,7	89	0,01	6	0,8	0,05	7	73	20	52	2	3
U - 43	0,19	2,2	43	0,14	515	0,3	0,05	5	251	20	24	1	4
U - 44	0,05	56,3	41	0,01	1	0,3	0,05	4	37	19	78	0,5	4
U - 45	0,2	27,4	55	0,01	4	0,4	0,40	5	83	21	34	2	4
U - 54	0,02	34	56	0,01	4	0,6	0,05	4	64	20	38	2	6
U - 55	0,02	24,4	46	0,01	5	0,5	0,05	5	82	19	30	1	3
Clark	**0,05**	**1,5**	**25**	**0,09**	**20**	**0,2**	**0,05**	**5,5**	**71**	**17**	**20**	**2,3**	**8,1**
U - 31	1,6	**9,67**	0,68	0,33	*0,15*	**8,5**	1	0,73	0,31	1,29	**11,65**	**5,22**	1,23
U - 32	0,4	**19,53**	2,36	0,33	*0,1*	**3,5**	1	0,73	1,49	1,06	2	2,17	0,37
U - 37	1,6	0,73	2,32	*0,11*	*0,05*	2	1	1,09	1,37	1,29	2,75	0,43	0,49
U - 38	1,6	**7,80**	1,44	*0,11*	*0,2*	2,5	1	0,91	1,79	1,24	2,65	0,43	0,37
U - 41	**3**	1,13	**3,56**	*0,11*	*0,3*	**4**	1	1,27	1,03	1,18	2,60	0,87	0,37
U - 43	**3,8**	1,47	1,72	1,56	**25,75**	1,5	1	0,91	**3,54**	1,18	1,20	0,43	0,49
U - 44	1	**37,53**	1,64	*0,11*	*0,05*	1,5	1	0,73	0,52	1,12	**3,9**	*0,22*	0,49
U - 45	**4**	**18,27**	2,2	*0,11*	*0,2*	2	**8**	0,91	1,17	1,24	1,7	0,87	0,49
U - 54	0,4	**22,67**	2,24	*0,11*	*0,2*	**3**	1	0,73	0,9	1,18	1,9	0,87	0,74
U - 55	0,4	**16,27**	1,84	*0,11*	*0,25*	2,5	1	0,91	1,15	1,12	1,5	0,43	0,37

0.XX content beneath 1/3 of clark value; **X.XX** – content above triple of clark value; **X.XX** – content above quintuple of clark value.

also bigger accumulations, e.g. Fe and Cu ore occurrence Cinobaňa - Jarčanisko (quartz, siderite, pyrite, tetrahedrite, accessoric jamesonite); occurrence of Sb and Au ore Ozdín-Cerina (antimonite, pyrrhotite, pyrite, arsenopyrite, gold, less tetrahedrite, chalcopyrite, magnetite, galenite, sphalerite, accessoric berthierite, jamesonite, ullmannite a o.); occurrence of Sb ore Chyžné - Kubej (quartz, berthierite, antimonite, less carbonates, pyrite, arsenopyrite, pyrrhotite, sphalerite, marcasite, chalcopyrite, secondary antimonite ochres and limonite). The isotopic composition of sulphur from pyrrhotite is close to meteoric standard $\delta\ ^{34}S$ = -1.3 ‰, it was enriched with isotope ^{32}S (Kantor and Ďurkovičová, 1977), which confirms its hydrothermal origin; occurrence of Cu ore Kopráš-Slnná (chalcopyrite, pyrrhotite, pyrite, arsenopyrite, marcasite, sphalerite, actinolite, secondary covellite, limonite and malachite. In Slatviná Formation we do not suppose the possibility of finding the larger bodies of syngenetic sedimentary ore, but they are suitable environment for bigger accumulation of epigenetic ore (compare Slavkay et al., 1995, 1997, 2004).

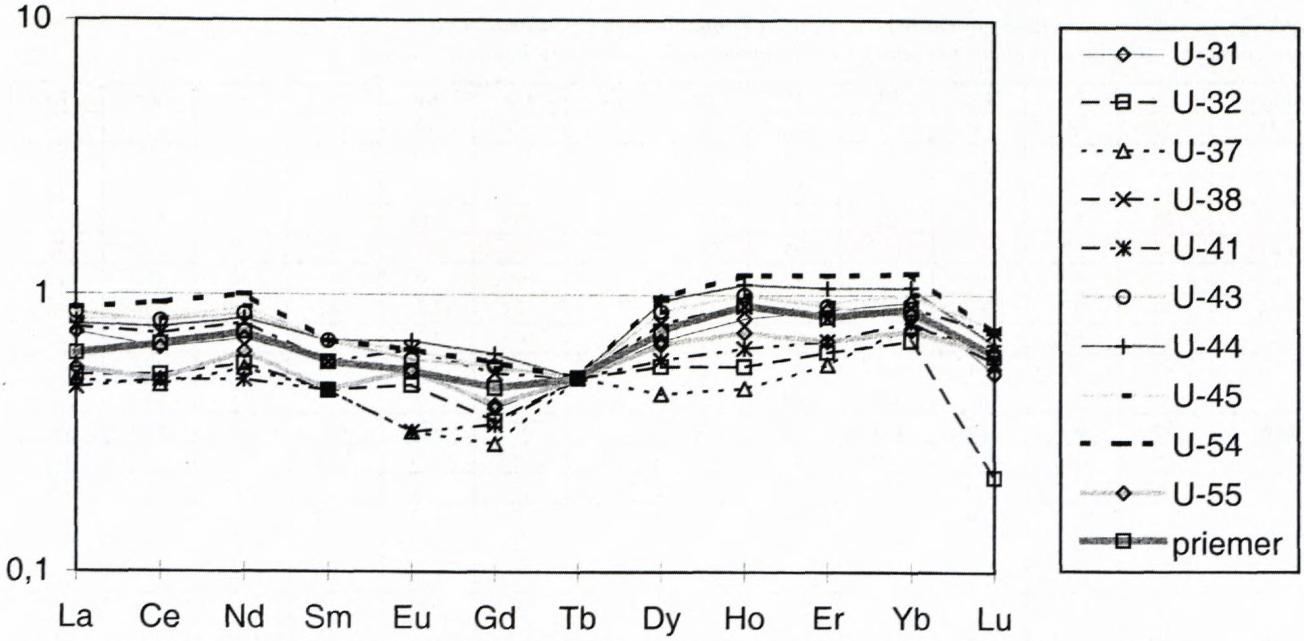


Fig. 3. Normalized REE values according to standard SDO-1. Veporicum, Slatviná Formation, Carboniferous.

Table 3. Results of organic matter analyses

Sample	rock	Lokalita	C_{org}	C_{resid}	C_{bit}
U - 8	graphitic metaquartzite	Mútnik	2,90	98,8	0,5
U - 9	graphitic metaquartzite	Mútnik	3,76	98,8	0,5

C_{hum}	C_{anorg}	karb	koef. bit.10^{-3}	bit.ppm	oil	pitch
0,7	0,19	1,6	15	273,7	40,4	9,6
0,7	0,19	1,4	19	338,2	12,7	8,2

asphaltenes	A1460-1735	A720-1610	CP1	prist-fyt	prist-C17	fyt-NC18
50	0,48	4,0	1,15	1,54	0,97	1,24
79,1	0,63	6,0	1,22	1,19	0,80	1,42

Tatricum

Nízke Tatry Mts.

Proterozoic? – Lower Paleozoic

On the southern slopes of the Nízke Tatry Mts. the volcanosedimentary complex is developed with southern (Medzibrod to Suchá dolina valley) strip of graphitic schists as well as the northern one (Husárka and Mlynárova dolina valley) along the contact of nebulites and ophthalmites (Vybíral and Molák, 1989). In the boundary zone of nebulites with ophthalmites the disseminated sulphidic mineralization is developed and in the contact zone of nebulites with granitoids of Prašivá type the occurrence of Sb ore Husárka (Slavkay, 1971). The graphite from nebulites has a high degree of crystallinity. The isotopic ratio $\delta\ ^{13}C$ (PDB) = −24.10 ‰ shows its organic origin (Molák in Molák et al., 1993).

The bed of graphitic schists with Sb (Au) mineralization between Vážna and Suchá dolina valley has a character of micaschists to phyllites. Chlorite-sericite phyllites with intercalations of dark schists are supposed to be a product of regressive alteration of migmatites. The low grade metasediments with volcanites in these phyllites are interpreted as tectonically wedged (Michálek, 1988). The zone is supposed as metalliferous horizon with ore bodies formed by antimonite, quartz, Fe-dolomite, barite and arsenopyrite, rarely tetrahedrite, jamesonite, berthierite, chalcopyrite, marcasite, gold and gold tellurides.

The rocks have low content of organic matter. The normalized values are towards standard SDO-1 + FNB enriched by SiO_2, Al_2O_3, Na_2O, Au, Sn, W, Zr and distinctly by Sb. They are moderately depleted by Ag, Co, Cu, Nb, Ni and distinctly low is Mo. The mineralized samples are strongly enriched by Zn and Pb, and moderately by Ag. The organic matter was recrystallized for semigraphite to graphite. The graphite is of organic origin and probable is derived from Precambrian source, because the high ratio of light carbon isotope, typical for Precambrian organic matter, was lowered by metamorphism to recent level $\delta\ ^{13}C$ around −30 ‰.

On the southern slopes of Ráztocká hoľa (Suchá dolina valley, Bukovská dolina valley, Pod Matúšovou a. o.), were found the low-grade metamorphic dark schists with Lower Paleozoic spores (Molák et al., 1989). They are in the vicinity, or continuation of W-Au mineralization Jasenie, Kyslá. The standard SDO-1+ FNB is double overreached by As, Au, Bi, W, to this standard converge the Ag content, highly anomalous is Sb (50-x). Following correlations of elements were found: Ag with Pb, V and W; Au with As; W with Pb and B; Cu with Ni; Sn with Sm and negative correlation W with Bi. The depleted Ni, Co and Cr show the low ratio of basic to ultrabasic component in former rocks and probable they had the recycled crustal origin. About crustal origin of these rocks prove also increased contents of La and Rb. Molák (in Molák et al., 1993) the increase of Au, Sb, W and Bi contents assigns to shear and shear-deformation zones and fluids with epigenetic mineralization. As protolith he supposes the schists and arkoses with admixture of acid, rarely basic volcaniclastics. The hydrothermal origin is indicated by increased contents of $\delta\ ^{13}C$.

The micaschists of Klinisko type (Lower Paleozoic, Čorná and Kamenický, 1976) are locally metamorphosed to chlorite-sericite to quartzy schists with subgraphite and crystalline graphite. The average schist (Koljonen, 1992) shows comparing to standard the relative increased contents of Bi, Hf, Sb.

The rocks from geothermal drill FGL-1 (in the depth interval 1800–2108.5 m) - the phyllites of Pavčina Lehota type are compared by Biely (in Biely et al., 1988) with the micaschist of Klinisko type a supposed to be pre-Upper Carboniferous. They contain metaantracite, semigraphite and graphite. The protolith of these rocks was represented with pelites, resp. sandstone with low content of organic matter. The samples after normalization to SDO-1 + FNB show moderate increase of contents SiO_2, MgO, Ba, La, W, Zr and multiple increase of Na_2O, Ag and Sb. In contact with Mesozoic sequences the Hg content is 36-fold overreaching the standard (1.09 ppm) and the ratio U x K/Th = 2.1 is also very high, which indicates the Alpine hydrothermal alteration and the possibility of mineralization in underlier of the Mesozoic cover.

Malé Karpaty Mts.

Sedimentary rocks of the Malé Karpaty Mts. in volcanosedimentary series of Pezinok-Pernek crystalline basement and in Harmónia Formation contain the disseminated sulphidic minerals and organic matter. According to Khun (in Molák et al., 1993) with increasing degree of metamorphism in black schists the contents of SiO_2 and Al_2O_3 are increasing and according to ratio Al_2O_3/Na_2O they have varying degree of maturity. In productive zones of Pezinok-Pernek crystalline and Harmónia formation the Cu, Ni, Au, As and Sb contents are increased, and especially V (6000 ppm = 37.5x SDO-1), but B neither 50 ppm (0.38x SDO-1), which is characteristic for Malé Karpaty Mts. The Au contents up to 1.45 ppm (725x SDO-1) represent very promising concentration for economic prognoses. Khun (l. c.) states, that the concentration of Au is indirectly influenced by organic matter, because underlies the course of the forming sulphides in reduction conditions and such produce the suitable environment. The Th/U ratio is characteristic for identification of black schists of Harmónia Formation (differing from Pezinok-Pernek crystalline) and similarly also the V/Cr ratio (in productive zones the value 4.35; in Harmónia Formation 3.65). The increased contents of uranium in black schists (so-called productive zones according to Cambel, 1959) reach up to 48 ppm.

According to the stable ratio La/Ce the calmer sedimentary conditions of Harmónia Formation are assumed, contrasting with the sedimentation of schists of productive zones, being influenced by basic volcanism. The content C_{org} is higher in fine-grained varieties (2.8 %) as it was in the case of medium-grained (1.1 %) and it represents the highly kerogened organic matter poor in bitumens. The sedimentation occurred in coastal marine zone and organic matter originated from marine fauna, flora and from plant detritus brought from the continent.

There were geochemically studied the graphitic schists with intercalations of quartzstone of Pezinok-Pernek Formation (Lower Paleozoic ?) being outcropped in the open pit left at the road Pezinok – Baba (Pulec & Širáňová, in Molák et al., 1993). Regarding the standard SDO-1 they have increased contents Pb, Zn, Cu, V, Sn, Ni and lowered contents of Mo and Co. The standard is highly overreached by V (1.75x–6.79x), in average 5.24x (838.25 ppm). The Malé Karpaty black schists, as a part of Harmónia Formation and the Pezinok-Pernek crystalline basement, are supposed as metalliferous. Their elements V, Cu, Ba, Sr, Au, As, Sb, Ag and Zn overreach and elements Ni and Cr are close to values of SDO-1 standard.

Mineralization

The syngenetic deposits are represented with the pyrite deposit Pezinok - Karolína and Ferdinand. The ore bodies are developed in actinolite and black schists together with amphibolites and amphibolitic schists in biotite gneisses and migmatites (Lower Paleozoic). Pyrite originated partly as a product of organisms decomposition, but its essential part originated from post-magmatic exhalations of basic volcanism (Silurian – Devonian?). The mineralization underwent the regional Hercynian metamorphism and contact metamorphism by granite (Polák, 1986). The deposit Jablonové - Turecký vrch (Rudolf) with pyrite mineralization is developed in beds of quartz-graphite schists at the contact with actinolite schists as well as in these schists (Lower Paleozoic). It is supposed that the deposit represents the sedimentary exhalative-volcanogenic type with Hercynian and Alpine metamorphic overprint (Rak a Polák, 1983). The same is demonstrated by the pyrite-pyrrhotite deposit Augustín in actinolite schists above graphite schists and amphibolites (Lower Paleozoic) and its continuation - Sb-pyrite mineralization of deposit Pernek - mining district Pavol štôlne developed in actinolite schists. Here belongs also the pyrite deposit Pezinok-Čertov kopec and deposit Pezinok-Rybníček with pyrite and Sb mineralization.

The stratiform hydrothermal Sb vein-stockwork deposit Pezinok-Kolársky vrch (Hercynian type) in mylonitic gneisses, graphitic, actinolitic, sericite-clayey schists, amphibolites and granitoids could originate by mobilization by metamorphic solutions before or during granitoid intrusions. There was found the important role of biogene sulphur and Alpine migration of sulphides (Polák, 1986; Chovan et al., 1994; Slavkay et al., 1994). In deposit of Sb-Au-As ore Pezinok-Vinohrady the mineralization is developed in gneisses, amphibolites and black schists in so-called black fault with parallel gold vein (see Molák et al., 1995; Molák and Slavkay, 1995).

Považský Inovec

Kálnica Group, Permian

The Permian rocks were divided by Novotný and Mihál (in Štimmel et al., 1984) into four formations of Kálnica Group: Chalmov, Klenkov vrch, Selec and Krivosúd Fms. The variegated clastic rocks consist from polymict conglomerate, quartzy-, greywacke- and arkose sandstone, variegated schists, acid volcaniclastics, rhyolites and their ignimbrites with U mineralization, silicites and quartzites. The schists and sandstone beds are bearing the intercalations of carbonate, gypsum and anhydrite.

The uranium mineralization was investigated by Rojkovič (1980a, 1980b). It is formed by uraninite, less Ti oxides, in oxidation zone torbernite and numerous accompanying minerals: arsenopyrite, bornite, digenite, dolomite, galenite, goethite, hematite, chalcopyrite, ilmenite, covellite, quartz, magnetite, molybdenite, pyrite, rutile, sphalerite, tennantite and tetrahedrite. The sediments have very low content of C_{org}. The positive U correlations with Pb, Cu, Mo and S were found. The contents of trace elements (which form also the ore bodies) vary in the range U = 5–5000 ppm; Mo = 10–2010 ppm; Cu = 20– 890 ppm; V = 30–2000 ppm, at the same time the highest contents are in the ashy tuff. The content of Th in mineralized rocks is about 6 ppm. The distinct difference of coefficient of radioactive balance in bed with rhyolite tuff (0.87) regarding to bed in conglomerate (1.00) proves the distinct migration of U and Ra in the first bed (Rojkovič and Novotný, 1993). The age of stratiform mineralization is 270 ± 30 Ma and Alpine remobilized richest mineralization (geochronology by U-Pb method was performed on 82 samples) showed the youngest age with maxima in Middle Cretaceous 100 ± 30 Ma (Štimmel et al., l. c.). Rojkovič and Novotný (l. c.) state the origin of oldest pour ore from U deliberated during devitrification and diagenesis of acid tuff and tuffite after its coagulation in horizons with reduction environment (pyrite) and suitable adsorbents (Ti oxides and clay minerals).

Conclusion

Veporicum

The Paleozoic (to Proterozoic?) rocks of Veporicum with higher content of $C_{org.}$ are bearing the conformable bodies of magnetite and pyrite-pyrrhotite ore as a product of regional metamorphism of former sedimentary ore. The iron ore originated during sedimentation in a part of the basin with oxidation conditions, the pyrite ore in parts with reducing environment. The distribution of hydrocarbons testifies their source of marine origin and in formation of Jánov grúň in Veporicum of the Nízke Tatry Mts. also of mixed origin. There is possible to suppose also the presence of further ore bodies of similar mineralization. Comparing with the standard SDO-1 + FNB, despite some anomalous contents, the investigated rocks can be supposed only as weakly metalliferous and not metalliferous and these ore types in this area are economically non-perspective. The former bodies of carbonates, ultrabasics and organic matter, changed to magnesite, talc and graphite by later metamorphic and hydrothermal processes, we suppose from the economic viewpoint as perspective for exploration of further deposits.

The Carboniferous rocks of the Slatviná Formation contain low contents of C_{org}. The values above double of SDO-1+FNB standard of the elements Ag, Pb and Zn in the sample 43 are caused by the influence of hydrothermal processes. The increased clark contents of As and in sporadic samples also of some next elements can be caused by tuffitic admixture, which is indicated by the high variability of K_2O : Na_2O ratios. The formation is not metalliferous and no more important accumulations of syngenetic sedimentary mineralization can be expected.

Tatricum

The Paleozoic to Proterozoic? volcanosedimentary complex of Tatricum in the Nízke Tatry Mts. with beds of graphite schists shows the low content of organic matter comparing the standard metalliferous schists. The distinct enrichment of graphite beds by Sb, as well as increased content of As, Au, W and Bi would indicate the increased metal contents, but with uncertainty whether it is its primary accumulation and Sb was remobilized into younger Alpine structures, or whether Sb was brought by hydrothermal solutions into the suitable environment.

For Pezinok-Pernek crystalline basement and Harmónia Formation of the Malé Karpaty Mts. the increased contents of Cu, Ni, Au, As, Ba, Sb, Zn and V are characteristic, locally also U and contain the highly kerogenized organic matter poor to bitumens. According to until obtained results and the presence of exploited and explored bodies of pyrite, pyrite-pyrrhotite and pyrite-antimonite ores, we suppose this so-called productive zone as metalliferous and perspective formation.

The productive formation in the Považský Inovec Mts. is represented by Permian sediments of the Kálnica Group with very low content of C_{org}, but high contents of U, Mo, Cu and V, bearing the known and explored stratiform uranium mineralization.

References

Abonyi, A. & Abonyiová, M., 1980: Magnesite deposits in Slovakia. (In Slovak). *Monograph, Mineralia Slov., Alfa Bratislava, 125.*

Bezák, V., Hurai, V. & Kráľ, J., 1996: A fluid inclusion analysis contribution to the study of tectono-metamorphic evolution of the Veporicum crystalline complex. *Slovak Geol. Mag., (Bratislava), 3–4, 185–187.*

Biely, A. (red), Beňuška, P., Bujnovský, A., Halouzka, R., Klinec, A., Lukáčik, E., Maglay, J., Miko, O., Molák, B., Pulec, M., Putiš, M. Vozár, J. & Vozárová, A., 1988: Explanation to Geological map of the Nízke Tatry Mts. 1:50 000. *Manuscript, archív GÚDŠ, Bratislava, 342 (In Slovak).*

Cambel, B., 1959: Hydrothermal deposits of the Malé Karpaty Mts., mineralogy and geochemistry of their ores. *Acta geologica et geographica Universitatis Comeniane, Bratislava, 3, 338 (In Slovak).*

Černyšev, J., Cambel, B. & Kodîra, M., 1984: Lead isotopes in galenas of the West Carpathians. *Geol. zbor. SAV 35, 307–328.*

Čorná, O. & Kamenický, J., 1976: Ein Beitrag zur Stratigraphie des Kristalinikums der West Karpaten auf Grund der Palinologie. *Geol. zbor. SAV, Geologica Carpathica, 27, 1, Bratislava, 117–132.*

Grecula, P., Chovan, M., Rojkovič, I. & Slavkay, M., 1996: The Variscan metallogeny of Western Carpathians. *In: Variscan metallogeny in the Alpine orogenic belt (Eds. P. Grecula and Z. Németh), 1996. Mineralia Slov. - Monograph, 191–238.*

Gubač, J., 1957: Paragenesis of skarn deposit near Kokava nad Rimavicou. *Geol. práce, Zprávy, Bratislava, 11, 89–99, (In Slovak).*

Hovorka, D., 1985: Ultramafic rocks of the Western Carpathians, Czechoslovakia. *GÚDŠ, Bratislava, 258.*

Huyck, H. L. O., 1991: Proposed definitions of "black shale" and "metalliferous black shale" for IGCP Project 254. *In: Pašava J. & Sobotka, M. (eds.), 1991: Newsletter 3. Geol. survey, Prague, 56.*

Chovan, M., Háber, M., Jeleň, S. & Rojkovič, I., 1994: Ore textures in the Western Carpathians. *SAP Bratislava, 219.*

Ilavský, J. & Sattran, V., 1980: Explanation to metalogenetic map of the Czechoslovakia 1 : 500 000. *ÚÚG Praha, 48. (In Slovak).*

Kane, J. S., Agrobast, B. & Leventhal, J., 1990: Characterization of Devonian Ohio Shale SDO-1 as a USGS Geochemical Reference Sample. *Geostandards Newsletter. Vol. 14, 1, 169–196.*

Kantor, J., 1975: Sulphur izotopes at Pb-Zn deposits in Mesozoic carbonates of the Western Carpathians. *Manuscript, GÚDŠ Bratislava, 181. (In Slovak).*

Kantor, J. & Ďurkovičová, J., 1977: Sulphur isotopes in barite deposits of the Western Carpathians. *Stadial final report from 1977, Manuscript, GÚDŠ Bratislava, 220. (In Slovak).*

Koljonen, T. (ed.), 1992: The geochemical Atlas of Finland, part 2. Till. *Geol. survey of Finland, Espoo.*

Kováčik, M., 2000: Petrogenesis of metamorphosed ironstones near Kokava nad Rimavicou (Veporicum, Western Carpathians). *Slovak Geol. Mag., 6, 367–376.*

Kužvart, M., 1955: Geology and petrography of talc deposits and their surroundings near Hnúšťa, Slovakia. *Sbor. Ústøední ústav geologický, Odd. geol., 22, Praha, 145–195. (In Slovak).*

Lisý, E., 1971: Deposits of talc, Slovakia. *Mineralia Slov., 3, 12–13, 343–348, (In Slovak).*

Michálek J., 1988: Nízke Tatry Mts., Sb-Au ores. *Final report. Manuscript, Geofond Bratislava. (In Slovak).*

Molák, B. & HvožĎara, P., 1986: Introductory study of deposits and occurrences in the region of the contact zone of Veporicum and Gemericum between villages Slavošovce and Poltár. *Stadial report. Manuscript, GÚDŠ Bratislava, 217.*

Molák, B., Kantor, J. & Blaha, M., 1989: Biotite – a possible indicator of formation conditions and age of scheelite - gold-bearing mineralization in the region Kyslá near Jasenie (Nízke Tatry Mts.). *In: Scheelite mineralization in Czechoslovakia, proceedings, Banská Bystrica – Donovaly, 11–13 October 1989, 62–69. (In Slovak).*

Molák, B., Began, G., Bujnovský, A., Ďurkovič, T., Elečko, M., Gargulák, M., Grecula, P., Hok, J., Khun, M., Knésl, J., Miko, O., Polák, M., Pulec, M., Radvanec, M., Rojkovič, I., Siráňová, Z., Slavkay, M., Snopko, L., Snopková, P., Širáňová, V., Turan, J., Turanová, L. & Vozárová, A., 1993: Mineral raw material potential of carbonaceous formations. *Manuscript, GÚDŠ Bratislava, 577. (In Slovak).*

Molák, B., Slavkay, M., Plašienka, D. & Gargulák, M., 1995: Regional map of the deposits and prognoses of mineral raw materials, Malé Karpaty Mts., 1 : 100 000. *Manuscript, GÚDŠ Bratislava, 50. (In Slovak).*

Molák, B. & Slavkay, M., 1995: Passports of the deposits and occurrences of mineral raw materials, Malé and Čachtické Karpaty Mts. *Manuscript, GÚDŠ Bratislava, 110. (In Slovak).*

Németh, Z., Prochaska, W., Radvanec, M., Kováčik, M., Madarás, J., Kodîra, P. & Hraško, Ľ., 2004: Magnesite and talc origin in the sequence of geodynamic events in Veporicum, Inner Western Carpathians, Slovakia. *Acta Petrologica Sinica, 20, 4, 837-854.*

Očenáš,D., 1992: Slovakia, graphite. *Study of exploration, Manuscript, ŠGÚDŠ-Geofond, 44. (In Slovak).*

Pearce, J. A., Haris, N. B. W. & Tindle, A. G., 1984: Trace element discrimination diagrams for tectonic interpretations of granitic rocks. *J. Petrol., 25, 956 – 983.*

Petro, M., Radvanec, M., Kováčik, M., Mudráková, M., Bezák, V., Očenáš, D., Tréger, M., Mihalík, F., Komoň, J., Filo, M. & Lukaj, M., 1998: Kokava nad Rimavicou, graphite. *Manuscript, GSSR Bratislava, 152. (In Slovak).*

Polák, S., 1986: Pezinok - Sb. *Final report, exploration, state to 1.1.1986. Manuscript, Geofond Bratislava, 222. (In Slovak).*

Pulec, M., 1989: Occurrence of crystalline graphite in paragneisses, granitoids, pegmatites and aplites of the crystalline complex of the West Carpathians. *Mineralia Slov., 21, 1, 53–58. (In Slovak).*

Quinby-Hunt, M. S., Wilde, P., Berry, W. B. N. & Orth, C. J., 1989: The redox-related facies of black shales. *Annual Meeting of the Geological Society of America, Denver, October, 1988, 20, 193*

Quinby-Hunt, M. S. & Wilde, P., 1991: The provenance of low-calcic black shales. *Mineral. Deposita, 26, 113–121.*

Radvanec, M., 2000: Metapelite, amphibole shists and origin of magnetite-graphite mineralizzation in Veporicum near Kokava nad Rimavicou. *Mineralia Slov., 32, 1,1–16. (In Slovak).*

Rak, D. & Polák, S., 1983: Malé Karpaty Mts., Sb. *Final report, exploration, state to 31. 5. 1983. Manuscript, Geofond Bratislava, 3012. (In Slovak).*

Rojkovič, I., 1980a: Geochemical characteristics of mineralized Permian rocks of Považský Inovec Mts. *Geol. Zbor. Geol. carpath., 31, 125–137.*

Rojkovič, I., 1980b: Mineralogical characterization of uranium mineralization in the Permian of the Považský Inovec Mts. *In: Permian of the West Carpathians. Bratislava, GÚDŠ, 137–146.*

Sláma, M. et al., 1999: Set of regional map of geological factors of the enviroment Jelšava – Lubeník – Hnúšťa region, scale 1 : 50 000. *Manuscript, Geokonzult, a. s., Košice. (In Slovak).*

Slovak Geol. Mag., 11, 2 – 3 (2005), 77 – 90

Slavkay, M., 1971: Some antimony deposits in the Nízke Tatry Mts. related to geological structures. *Mineralia Slov., 3, 9, Bratislava, 5–222. (In Slovak).*

Slavkay, M., 1996: Map of geochemic types of rocks, 1 : 50 000, region Jelšava – Lubeník – Hnúšťa. *Manuscript, Hydeko KV, In: M. Sláma et al., 1999, 832. (In Slovak).*

Slavkay, M., 2003: Characteristic of selected sedimentary complexes – bearers of sedimentary mineralization in Paleozoic rocks of Veporic and Tatric units. *Manuscript, ŠGÚDŠ Bratislava, 402. (In Slovak.)*

Slavkay, M. & Lenárt, J., 1974: Prospecting criteria and indication of talc deposits in the environs of Hnúšťa. *Mineralia Slov., 6, 1, 17–222 (In Slovak).*

Slavkay, M., Pecho, J., Gubač,J., Pulec, M., Badár, J., Biely, A., Čillík, I. & Ďuďa, R., 1988: Regional map of the deposits and prognosses of mineral raw materials, Nízke Tatry Mts. *Stadial report, manuscript, Geofond, Bratislava, 3522. (In Slovak).*

Slavkay, M. & Petro, M., 1993: Metallogenesis and ore formations of the Veporicum. *Mineralia Slov., 25, 313–317. (In Slovak).*

Slavkay, M., Gargulák, M., Chovan, M., Grecula, P. & Rojkovič, I., 1994: Variscan mineralization in the Alpine terranes of Western Carpathians. *Proceedings from the International Conference Variscan metallogeny in the Alpine orogenic belt, Stará Lesná, 117–126.*

Slavkay, M., Vozárová, A., Bezák, V., Hraško, Ľ. & Kováčik, M. 1995: Regional map of the deposits and prognoses of mineral raw materials, Slovenské rudohorie Mts., West. *Manuscript, GSSR Bratislava, 241. (In Slovak).*

Slavkay, M., Beňka, J. & Gargulák, M., 1995: Description of deposits and occurrences of mineral raw materials, Slovenské rudohorie Mts. West. *Manuscript, GÚDŠ Bratislava, 177 (In Slovak).*

Slavkay, M., Vozárová, A., Hraško, Ľ., Kováčik, M., Bezák, V., Koďira, P. & Tréger, M., 1997: Complex evaluation of the prognoses of mineral raw materials in contact zone of the Veporicum and Gemericum. *Manuscript, ŠGÚDŠ Bratislava, 186. (In Slovak).*

Slavkay, M., Beňka, J.†, Bezák, V., Gargulák, M., Hraško, Ľ., Kováčik, M., Petro, M., Vozárová, A., Hruškovič, S.†, Knésl, J., Knéslová, A., Kusein, M., Maťová, V. & Tulis, J., 2004: Mineral deposits of the Slovak Ore Mountains, volume 2. *Štátny geologický ústav Dionýza Štúra, Monograph, Bratislava, 286.*

Suchár, A., 1974: Results of the prospecting for talc in the environs of Kokava nad Rimavicou. *Mineralia Slovaca, 6, 1, 1–16. (In Slovak).*

Štimmel, I. et al., 1984: Geological exploration works in the Považský Inovec region. *Záverečná správa (1965–1983). Manuscript, Geofond Bratislava, 236. (In Slovak).*

Taylor, S. R. & McLennan, S. M., 1985: The continental crust: Its composition and evolution. *Blackweld, Oxford.*

Trdlička, Z., 1961: Mineralogical and geochemical reserch of talc and polymetallic ore mineralization in magnesite deposits in Slovakia. *Geol. práce, Zprávy 24, Bratislava, 5–69. (In Slovak).*

Varček, C., 1977: Some rare types of mineralization in the Spišsko-gemerské rudohorie Mts. *In: Proceedings from the conference Mineral deposit forming processes in the Western Carpathians devoted to 25th anniversary of foundation of Department of ore deposits of Faculty of Natural Sciences of Commenius University, Bratislava, 93–99. (In Slovak).*

Vine, J. & Tourtelot, E., 1970: Geochemistry of black shale deposits: A summary report. *Econ. Geol., 65, 253–272.*

Vitásek, A., 1988: Mútnik, Final report and calculation of reserves from detail exploration. *Manuscript, GP Spišská Nová Ves. (In Slovak).*

Vitásek, A., 1990: Prognostic sources of raw material in Slovak Republic: Talc. Final report. *Manuscript, ŠGÚDŠ-Geofond Bratislava.*

Vozárová, A. & Vozár, J., 1988: Late Paleozoic in West Carpathians. *GÚDŠ Bratislava, 314.*

Vybíral, V. & Molák, B., 1989: An IP geophysical anomaly in the area of the W–Au mineralization at Biela Voda (Low Tatra Mts.). Správy o výskumoch DSGI Bratislava, 181–184.

Wood, D. A., 1980: The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the Britisch Tertiary volcanic province. *Earth Planet. Sci. Letts. 50, 11–30.*

Electron microprobe dating of monazite in basement metamorphites from the Kohút zone of Veporicum and case correlation aspects (Western Carphatians)

MARTIN KOVÁČIK, PATRIK KONEČNÝ, VIERA KOLLÁROVÁ, IVAN HOLICKÝ, PAVOL SIMAN

Geological Survey of Slovak Republic, Mlynská dolina 1, 831 02 Bratislava, Slovakia
(kovacik@gssr.sk)

Abstract. Systematic microprobe monazite geochronological data from particular metamorphic rocks are presented, in which the five to six age groups can be generally distinguished. The Cretaceous, Permian and Carboniferous age groups underline also by the another ways proved tectonic phases. Multivalued Devonian-Silurian and rarely Precambrian ages brought new impulses into discussion about the "old" history of crystalline basement. The investigated monazites are often bearing signs of polygene development caused partly by allochemical origin.

The monazites enclosed in garnets or cores of polygene monazite grains indicate older ages, while the monazites from the groundmass commonly register also Carboniferous and younger ages. The group of Silurian-Devonian ages can be explained in terms of the Early-Hercynian metamorphism or as the reflection of (Late)-Caledonian tectonothermal activity. Effects of the Carboniferous granitization represent the predominat monazite-forming process in the crystalline basement. The monazite from the comparative metasandstone of Harmónia Group from Malé Karpaty Mts (321 ± 13 Ma) was developed by metamorphism in chlorite and/or biotite zone. In micaschists from the basement of the Ipeľská kotlina Basin there were found, besides Hercynian monazites with local Alpine margins, sporadically also grains with the oldest age records (ca 2 Ga, 1 Ga and 500-600 Ma).

Replacement of old monazite by the Alpine newly formed phases can be observed in numerous places of the Kohút zone. The lowermost reproducible monazite ages 87-88 Ma correspond to culminating values of $^{40}Ar/^{39}Ar$ dating of muscovite and amphibole in metapelites. Differentiated petrographic manifestations of Cretaceous recrystallization result also in irregular distribution of Alpine records in monazites.

Key words: monazite, EMPA dating, metamorphic rocks, Alpine, Hercynian, Pre-Cambrian, Western Carpathians.

Introduction

Because of the absence of paleontological or reliable geochronological data, the stratigraphic affiliation of the Western Carpathian crystalline basement is resolved only to limited extent. The absence of microfossils is a consequence of metamorphic overprint, generally ranging from the middle greenschist facies up to upper amphibolite facies. Probably the primary environment with sedimentation of clastic sandy-clayey source material, pelagic sediments rich in organic graphite and volcanic products, did not represent suitable environment for development of biogene horizons, too. The only basement rock-unit of relatively reliable stratigraphic assessment in the Tatro-Veporic domain is the Harmónia Group in the Malé Karpaty Mts., yielding the Devonian – Silurian age (for details see section *G*).

Implying various geological analogues in the case of the crystalline schists from other areas - the Lower Paleozoic age is interpreted in majority of cases (e.g. Zoubek, 1936; Andrusov, 1958). In the 1960s the concept of the Pre-Cambrian age of higher-metamorphosed crystalline rocks was represented using the structural-tectonic analysis (Máška and Zoubek in Buday et al., 1961). This concept was later regionally extended (e.g. Kamenický in Maheľ et al., 1967; Kamenický and Kamenický, 1983). The attempts to prove the Pre-Cambrian rocks failed, though in the recent level of knowledge the ideas about possible relics of the Pre-Cambrian crust cannot be unambiguously refused. On the contrary, the youngest possible age of metamorphites of crystalline basement is entirely reliably delimited by the age of orogenic granitoid intrusions with more-or-less uniform opinion about their Carboniferous (Lower Carboniferous) age (Vitális, 1908; Richarz, 1908; Zoubek, 1932 a.o.). These assumptions were in the era of modern geochronological investigation confirmed by the isotopic analyses (review in Cambel et al., 1990).

In the 1970s-1980s numerous palynological determinations were done in lower metamorphosed crystalline sequences (Čorná, 1968; Čorná and Kamenický, 1976; Klinec et al., 1975 a.o.), in majority of cases confirming the Lower Paleozoic age. Additional data later brought some doubts about the reliability of these determinations

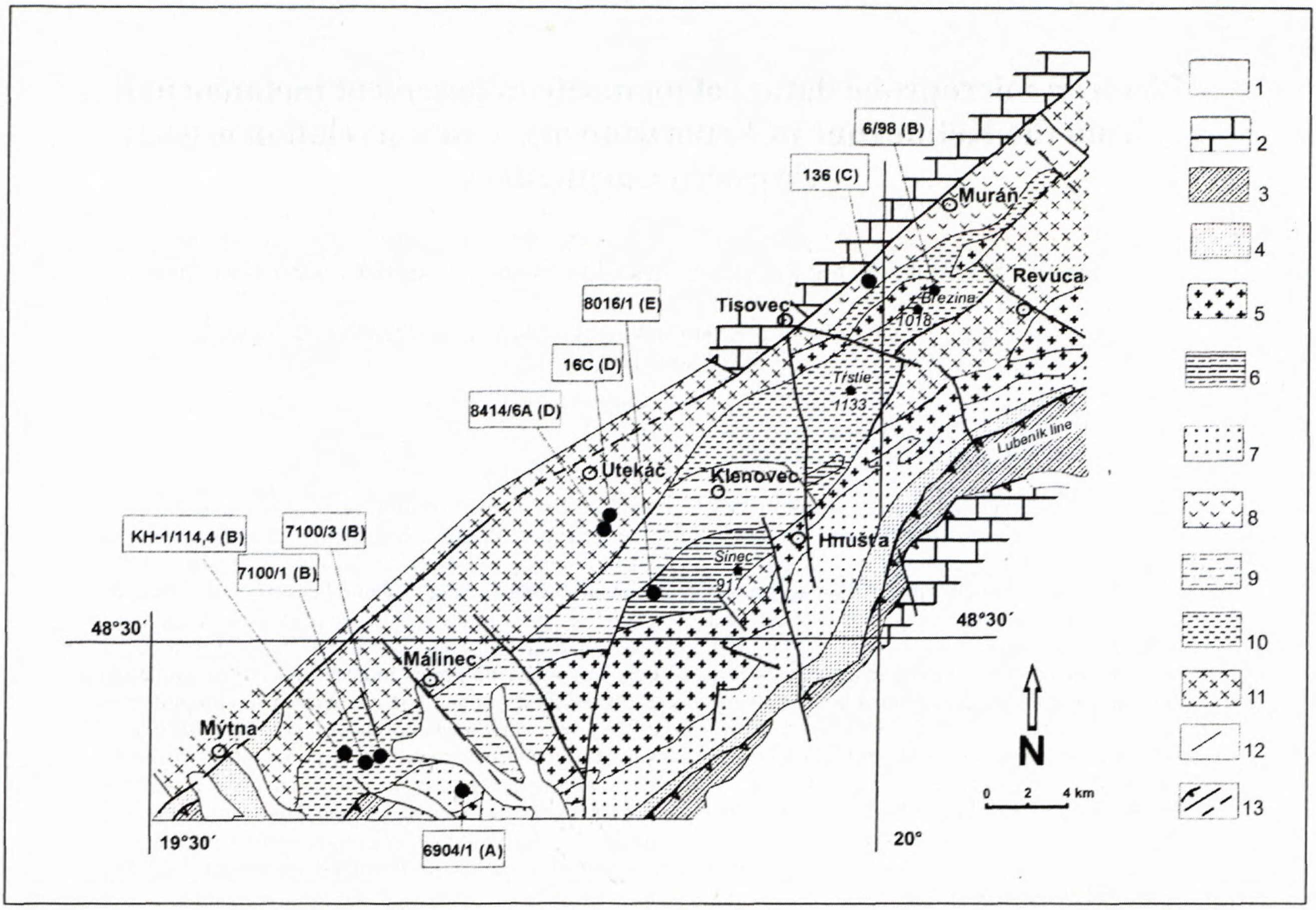


Fig. 1. General geological scheme of the Kohút zone (based mainly on Biely et al. 1996, Kuthan et al. 1963 and own adaptations) with location of analysed samples (for more detailed location and the rock characteristics see sections A, B, C, D, E, F and G in the text). Legend: 1 – Quartenary and Terciary volcanic and sedimentary rocks; 2 – Mesozoic of the Silicicum nappe; 3 – Ochtiná Group ("Gemericum Carboniferous"); Veporicum: 4 – Permian-Triassic cover, 5 – granitoid intrusions (Carboniferous), 6 – uncertain Paleozoic rock-unit or strongly Alpine diaphtorized basement rocks, 7 – phyllite zone, 8 - "Muráň" orthogneisses, 9 – biotite paragneisses, 10 – garnet micaschists, 11 – gneisses, migmatites and "hybridic granitoids"; 12 – geological boundaries; 13 – thrust, faults and supposed faults.

because of the finding of mixed populations of spores (as an example see section A), when the older ones were usualy interpreted as redeposited. In numerous cases there occurred the principal doubts about the plausibility of palynological age determinations in the crystalline schists.

The rare age determinations obtained from the detrital zircons in gneisses fall into the wide range of ages (mostly to Pre-Cambrian) and do not inform about the real time of sedimentation. The different is a question about the geochronological dating of pre-Carboniferous magmatic rocks where it is obvious, that are younger, or maximum syngenetic with sedimentary processes. Trondhjemite from amphibolite complex of Northern Veporicum yielded the age 514 (± 24) Ma by U/Pb method on zircons and its genesis is related with the Early Paleozoic extensional process (Putiš et al., 2001). The so-called Muráň orthogneisses (Fig. 1) were recently dated by two independent geochronological laboratories to approximately 500 Ma (Gaab et al., 2003; Kotov et al., unpublished). The determination of the monazite age using electron microprobe yielded the age 474 (± 14) Ma from the orthogneiss body in Northern Veporicum (Janák et al., 2002).

The age affiliation and geodynamic background of metamorphic processes preceding the main phase of Carboniferous granitization was since long ago a matter of discussion. More knowledge into this problematics was brought also by the recent $^{40}Ar/^{39}Ar$ geochronological dating (Maluski et al., 1993; Král' et al., 1996 a.o.). The chronology of the Alpine (Cretaceous) processes was studied in metamorphosed crystalline basement of the Kohút zone using the $^{40}Ar/^{39}Ar$ spectra of the newly formed micas and amphibole (Kováčik et al., 1996). The Permian age of localized leucocrate granite bodies in the Northern Veporicum and Gemericum (Putiš et al., 2000; Kovach et al., 1986) is supposed also in the Kohút zone (Hraško et al., 2002), which do not exclude certain thermal processes also in this time period.

Strategy in rocks selection and monazite analyses

The age parameters were, besides one exception (section C), investigated in the of metamorphic rocks of clastic origin with various grade metamorphism, frequently they underwent also the polymetamorphic overprint.

From the viewpoint of analysed rock types the majority of samples was taken from the Kohút zone of the Southern Veporicum (Fig. 1), partly including the Ipeľ Basin, and for some reference purposes there was chosen the sample from Tatricum of the Malé Karpaty Mts. The selection of metamorphites was firstly oriented on phyllitic members, because it was supposed that in low-grade metamorphic rocks the relics of clastic monazite could be preserved. We had an intention to restrict the analysing of higher-metamorphic rocks for the possible origin of monazite in the higher temperature conditions (e.g. Pyle and Spear, 2003; Kohn and Malloy, 2004) as well as because the possible material-thermal influence of granite magmatism. However, the opposite situation occurred – from the majority of sample analyses there resulted that monazite was formed in the lower metamorphic conditions and/or as a superimposed Alpine phase. This was the reason of extension of the monazite age determinations with the next investigation also of the higher-grade metamorphites, aiming to obtain the complex characteristic of polymetamorphic processes.

Monazite dating by electron microprobe

Monazite commonly occurs in a wide variety of intermediate to acid igneous and metamorphic rocks. On condition that the Pb content in newly formed monazite is negligible, the age depends on radiogenic Pb produced by radiogenic decay of Th and U. In the dependence of Th and U initial concentration and age, the concentration of Pb may reach the levels measurable with the electron microprobe. The method of monazite dating was in detail presented by Suzuki and Adachi (1991, 1994, 1998), Suzuki et al. (1994), Montel et al. (1996), Fialin et al. (1999) and Scherer et al. (2000).

Analyses of monazites were performed with the electron microprobe Cameca SX-100 at Department of electron microanalysis, State Geological Institute of Dionýz Štúr, Bratislava. Mostly synthetic and some nature standards were used for calibration of elements: Al-Al_2O_3, Si-wollastonite, P-apatite, Pb-PbS, U-UO_2, Th-ThO_2, REE-(REE)PO_4. The counting times were adjusted according to demand to achieve sufficient number of counts and acceptable statistical errors. Involvement of all elements present in monazite reduces the error caused by the ZAF correction matrix.

The age determination is directly dependent on quality of microprobe (WD) analyses. Crucial point of monazite dating is the very precise measurement of Pb, because of the major effect on the resulting age. In a common monazite with Th content > 2 %, U > 0.1 % and age higher then 100 Ma, the Pb content reaches concentrations from one hundreds up to one tenths percent. These concentrations are slightly above the detection limit of the microprobe. Obtaining of reliable ages requires measuring Pb at least 10-20 times more precisely as is the current detection limit. Other factors influencing the precision of Pb measurement and hence the monazite dating are: electron beam stability, detector noise, detector type, determination of background positions, choice of suitable place for microanalysis, quality of coating, surface devastation.

It is not possible to estimate the monazite age with one microprobe analysis, because of the high uncertainty in Pb measurement. To get around this problem we have to measure statistically suitable number of points and then calculate the resulting age, as was proposed by Montel (1996). The resulting age is calculated as weighted average, were the weight is the error caused by uncertainty in measurement of Pb, Th and U. The monazite formed during one event, magmatic or metamorphic, should at age histogram display a normal (Gaussian) distribution of point ages and the geochron at Th* vs. Pb should run nearly through the zero coordinate. More detailed information on monazite dating method can be found in Konečný et al. (2004).

Results of Th-U-Pb monazite dating and their interpretation

This chapter describes the particular crystalline basement rock types, containing analysed monazites. In introduction to each topic we define the problematics for which clarifying the monazite dating was done. The description of the age data in particular samples is illustrated by the BSE-images of phase relations in monazite, as well as statistic data, and in favourable cases the isochron diagram was constructed. At the end of description of analysed monazites in designated rock type we state the interpretation possibilities. The investigation of Kohút Zone (Fig. 1) was divided according to type of solved problematics on these topics (A-E):

A) Attempts to find the minimum age of phyllite zone.

B) Determination of the age relations of monazites in micaschist zone.

C) Analyse of monazite in the Muráň orthogneisses.

D) The age of monazites in the high-temperature garnet gneisses.

E) The study of monazite in the rocks with Alpine overprint.

F) Monazites in crystalline schists in the basement of the Ipeľská kotlina Basin.

G) Case correlation of studied rocks with metasandstones of the Malé Karpaty basement.

A) The crystalline of Kohút zone is rimmed at SE margin by so-called ***phyllite zone*** (Šuf, 1937), consisting dominantly from the sericite phyllites, metasandstones and layers of black schists. Nemčok (1953) considered the Lower Paleozoic age of phyllites, which were locally affected by the contact metamorphism by the Pre-Alpine granites. Klinec (1966) similarly supposes the Lower Paleozoic age of the rock sequence and designates it as the Hladomorná dolina Group. Later this series was ascribed the mixed - Lower as well as Upper Paleozoic age (Planderová and Vozárová, 1978; Klinec and Planderová, 1981). On the another side, this lower metamorphosed zone was understood as the Upper Carboniferous unit and designated as Slatviná Formation, being together with overlying Permian rocks incorporated into the so-called Revúca Group (Vozárová and Vozár, 1982). The regional metamorphism and thermal reworking by granites in this interpretation are understood as Alpine.

Sample *6904/1*. Location: Mountain range near the altitude point Hlonča (380.1 m), ca 5 km to ENE of Cinobaňa village
Chlorite-muscovite phyllite-micaschist with garnet

Though the monazite in this sample is rare, it forms relatively large (ca 0.05 mm) and generally homogenous grains. Because the monazite in this rock sequence is generally missing, it is very probable, that originated as a consequence of thermal overprint by surrounding granite. The age determinations are spread between 289 (± 32) Ma and 393 (± 38) Ma. The histogram (Fig. 2) displays two distinct maxima located around the value 310 Ma and 360 Ma. Indirectly there can be concluded, providing the absence of monazite grains from pre-metamorphic period, that monazite crystals reflect their new growths throughout the whole indicated age diapason. The considerable age scattering in this case either documents the lower accuracy of analytical determinations or complicated growth relations during polygenetic Hercynian orogenesis. The measured values assessing the weighted mean of ca 333.7 ± 17.8 Ma indicate the pre-Upper Carboniferous age of this rock.

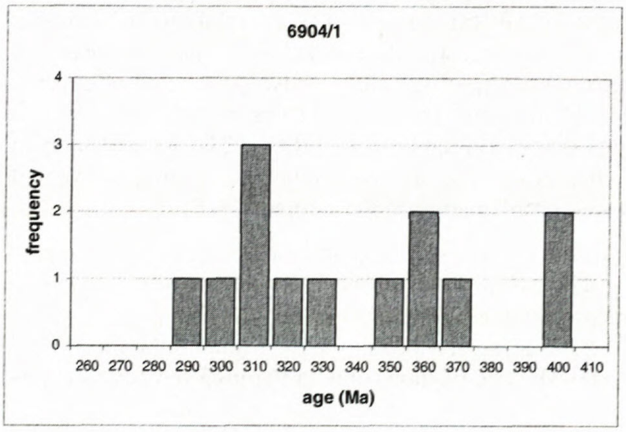


Fig. 2. Histogram documenting the pre-Alpine age of the rock of uncertain stratigraphic assessment and indicating the bimodal Hercynian age distribution.

B) Belt of ***garnet micaschists*** (Zoubek, 1932), Hron Complex (Klinec, 1966), micaschists of the Brezina type (Klinec and Vrána in Mahel' et al., 1967) or Ostrá Complex (Bezák, 1982) represent the largest areal of micaschistose rock-type in the Western Carpathian crystalline basement. This rock complex includes besides the micaschists and the extended domains of two-mica paragneisses also the bodies of amphibolites, metaquartzites, graphitic schists, etc.

The micaschists manifest strong tectonic deformation and recrystallization. From the viewpoint of the Pre-Alpine mineral assemblages, the prevailing rock type is represented by the garnet-chlorite micaschists, garnet-chloritoid micaschists (with relics of staurolite, eventually kyanite) and garnet-two-mica types with plagioclase, which can be classified as paragneisses.

Sample *7100/1*. Locality: Area of altitude point Staré Turíce (550 m), 2.5 km to north of Cinobaňa
Garnet-staurolite-muscovite micaschist. Retograde metamorphism most probable of Alpine age is reflected by nearly total disintegration of staurolite to sericite and chloritoid.

Monazite appears in thin micaceous layers, being later reactivated in planes of diaphtoritic foliation ("phyllonitization"). Except one zonal monazite (not introduced due to the large standard deviation), others are practically without the Alpine growth zones. Preliminary results show, that the so far tested rocks of micaschist belt from the south-western edge of Veporicum contain certain amount of monazite, differing from the more sterile micaschist-gneiss rocks in more northward located parts of the Kohút zone. The age determinations are widely scattered (Fig. 3). If we do not take into account the ages beneath 310 Ma, the ages are clustered into two maxima: 320-345 Ma and around 360-390 Ma. Taking into account further age records from the Kohút Zone metamorphites the best comparable values are mainly those, having the lowermost analytical error (343 ± 23 and 361 ± 25 Ma). The age distribution is in many aspects related with the following samples.

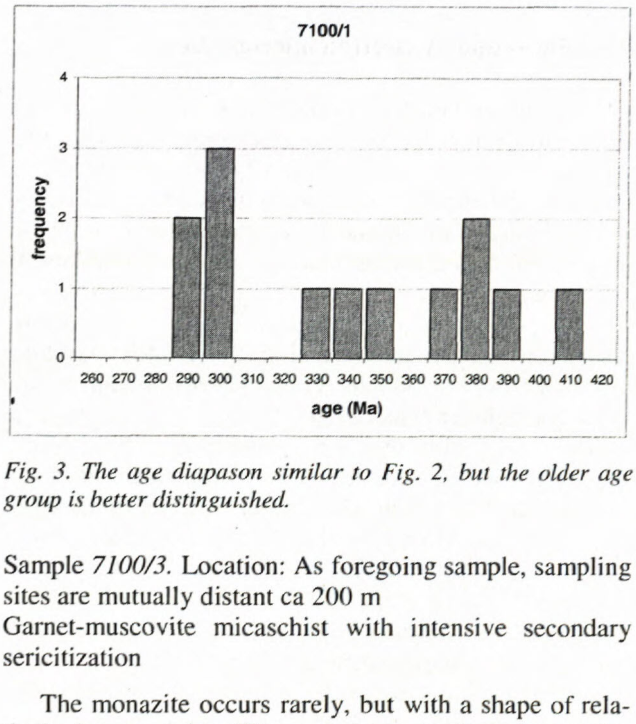


Fig. 3. The age diapason similar to Fig. 2, but the older age group is better distinguished.

Sample *7100/3*. Location: As foregoing sample, sampling sites are mutually distant ca 200 m
Garnet-muscovite micaschist with intensive secondary sericitization

The monazite occurs rarely, but with a shape of relatively larger grains. The age determinations have relatively lower analytical accuracy, ages are clustered into two groups (Tab. 1), being expressed by weighted means 387.5 (± 31) and 329 (± 29) Ma. The older and younger metamorphic episodes are detectable, possibly representing the Hercynian regional dynamometamorphism and of Carboniferous granitization.

Sample *KH-1/114.4*. Location: Borehole in the mouth of side valley to the Banský potok valley, 3 km to NW of Cinobaňa
Chlorite-muscovite phyllite with plagioclase. Rock metamorphosed max. up to the middle greenschist facies.

Monazites are usually tiny and corroded, often forming intricate phases. Great number of Alpine records (Table 2) we valuate as a product of transformations of older

Table 1. Summary of analyses of monazite grains (g 3 to g 8) with calculation of age and error according to Montel et al. (1996). Th, U, Pb and Y represents measured raw concentrations in wt. %.

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
7100/3 g3 an1	4,6993	0,5781	0,1243	0,3349	380	30
7100/3 g3 an2	3,4351	0,5273	0,106	0,2821	406	38
7100/3 g4 an1	3,738	0,5101	0,1097	0,4628	395	36
7100/3 g4 an2	4,0004	0,5698	0,1002	0,415	330	33
7100/3 g5 an1	3,5959	0,5406	0,0877	0,1281	322	37
7100/3 g5 an2	3,2163	0,5583	0,0964	0,1539	380	38
7100/3 g5 an3	3,6391	0,5394	0,0912	0,1624	332	36
7100/3 g6 an1	3,398	0,5661	0,0842	0,1428	313	38
7100/3 g6 an2	3,9717	0,5897	0,1114	0,1436	383	33
7100/3 g7 an1	3,6091	0,681	0,1	0,1453	343	34
7100/3 g8 an1	3,6437	0,5449	0,0906	0,1378	330	36

Table 2. Age determination and Y content divide clearly the Alpine and Hercynian phases of monazites from phyllitic rock in micaschist zone

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
KH-1 114,4 g1	4,4274	0,4472	0,0673	1,5604	259	32,8
KH-1 114.4 g2	2,7731	0,4721	0,0711	1,6605	373	44,5
KH-1 114.4 g3	3,0313	0,4373	0,0643	1,6929	326	43,6
KH-1 114.4 g4	6,0752	0,1185	0,0268	0,9555	94	29,1
KH-1 114.4 g7	5,8930	0,0351	0,0242	0,1818	91	31,2
KH-1 114.4 g9	4,0050	0,5200	0,0962	1,9261	381	33,8
KH-1 114.4 g9	3,8251	0,5552	0,0810	1,9948	325	34,7
KH-1 114.4 g9	2,9079	0,4221	0,0589	1,7820	311	44,5
KH-1 114.4 g10	2,7001	0,0998	0,0116	0,5573	87	60,9
KH-1 114.4 g10	4,8231	0,1516	0,0205	0,7573	87	35,2

Table 3. Hercynian age records in monazite-poor garnet micaschist in the zone of intense Alpine overprint

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
6/98 g1 an1	3,7123	0,2451	0,0683	0,5900	347	27,2
6/98 g1 an2	3,3825	0,2572	0,0759	0,6671	412	28,6
6/98 g2 an1	3,7495	0,3831	0,0646	1,1706	297	24,4
6/98 g3 an1	5,9052	0,4195	0,1127	0,9988	355	16,9

monazite grains during Cretaceous events. The newly formed phases, showing the age beneath 100 Ma, demonstrate the multiple lower contents of Y and U. Some grains (grains No. 2, 3 and 9) registered two Hercynian events, which proves the similar pre-Alpine genesis of this low-metamorphosed sample as it was in the case of previous rock. The phase relations in disintegrated monazite grain indicate, that "Permian" age (259 Ma) more probably reflects an incomplete Alpine reequilibration than real age value.

Sample *6/98*. Location: Mountain ridge 1.5 km to WNW of Brezina (altitude point 1017.9 m), NW of Revúca.

Garnet-muscovite micaschist. The garnet porphyroblasts commonly reach 1-2 cm in size. The metamorphism in the middle part of amphibolite facies is also documented by the regionally rare staurolite, kyanite and fibrolitic sillimanite.

Sporadic monazite occurs in the form of tiny grains identified in garnet. Small number of data (Tab. 3) admonishes to precaution because the marginal phase of the particular grain gives the age 410 (± 28.6) Ma whereas the central part 346 (± 27.2) Ma. The more reliable information is given by another homogenous grain with the age determination 354 (± 17) Ma. It could indicate the metamorphism connected with the thermal influence of hybridic granitoids (similarly as rocks described in section *D*). The information about the lower age (296 ± 24.4 Ma) was obtained from corroded, metamict grain, so the mixed age can be deduced.

*C) **"Muráň" orthogneisses*** – distinguished as migmatitic orthogneisses, representing pre- to synkinematic intrusions of "granites of older period in micaschist series" in the Kohút crystalline basement (Zoubek, 1932). In Western Carpathian basement untraditional lithological sequence is characteristic also with the occurrence of amphibolitic bodies and positions of the muscovite-biotite and garnet-biotite gneisses. According to Hovorka et al. (1987) the "complex of Muráň gneisses" consists from the middle-grade metamorphic products of acid and basic volcanism with variable admixture of sedimentary material.

The prevailing lithological type consists of the light to pinkish middle- to coarse-grained rocks, composing preferably of quartz, plagioclase and K-feldspar, which sometime occur in porphyric development. In scarcely present micas the (Fe-)biotite usually prevails above muscovite; in accessory amount there is present the tiny garnet, allanite, apatite and zircon. In complicated question of origin the orthogneisses are envisaged as the granite porphyries (Kováčik, 2002). Their Hercynian metamorphism reached the low- to middle-grade amphibolite facies and the highly-ductile fold-shearing structures with the signs of partial anatexis were locally developed.

Sample *136.* Location: Mountain ridge 700 m to SW from the Dielik saddle (altitude point 585 m) near the road between Tisovec and Muráň village.

The light-coloured orthogneiss with dominating quartz and albite. K-feldspar occurs only enclosed in the albite porphyroblasts and in interstitions. Monazite in not typical mineral for the "Muráň" orthogneisses, so in thin-section the disseminated monazite grains were not observed. The only one grain having 0.15 mm in diameter has occurred in association with magnetite (Fig. 4).

From this quasi-homogenous crystal we obtained 12 analyses with weighted mean 328 (± 15) Ma, being documented by isochron diagram, too (Fig. 5). This monazite probably crystallized during the culminating Hercynian metamorphism, which is most probably related to the intrusions of Carboniferous granitoids in the wider surrounding.

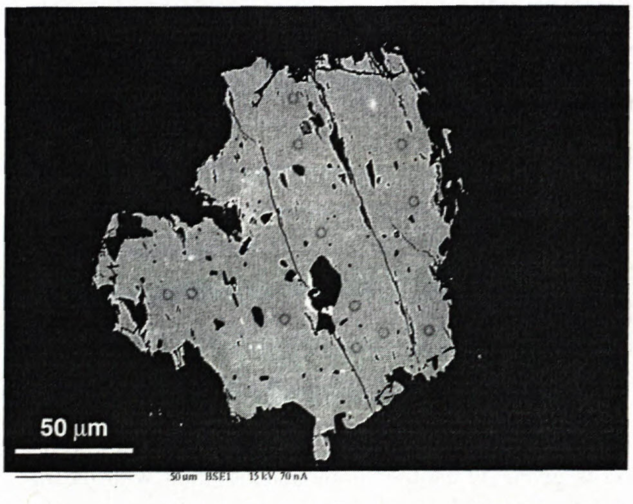


Fig. 4. The rare large monazite grain from the "Muráň orthogneiss" was analysed in more details (dark circles on BSE image represent the traces after the electron beam)

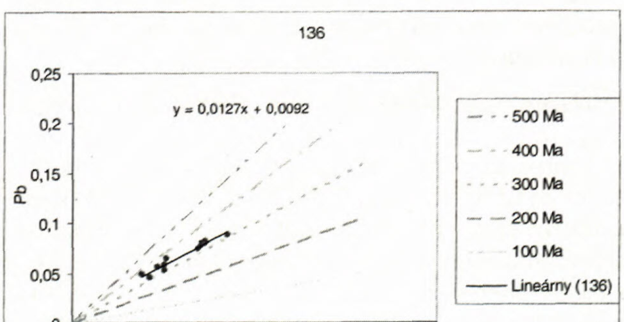


Fig. 5. The large extent of Th and Pb concentration in monazite of previous figure allowed constructing the isochron diagram close to the value of weighted mean 328 (± 15) Ma.

D) The high-temperature ***garnet-biotite gneisses*** occur in the higher horizons of the pre-Alpine setting in the vicinity of acid granite intrusions. Marginal parts of intrusions pass either into the zone of hybridic granites-granodiorites and/or hybridic migmatites to biotite gneisses, being diversified by the distinct garnet porphyroblasts. The age of the major mass of hybridic granitoids is considered about 350 Ma (Bibikova et al., 1988). In the area of magnetite mineralization at Kokava nad Rimavicou the leucocrate pegmatitoid melt enclosed the gneisses remnants (sample 16C), which are bearing 1–2 cm large garnet porphyroblasts. The magnetite mineralization alone is tied to the iron-rich biotite-garnet schists (sample 8413/6A).

Sample *16C.* Location: Northern tributary of the Kokavka river in the Zahrabina area, 2.5 km to NW from the village Kokava nad Rimavicou.

Garnet-two-mica gneiss, partly diaphtorized. The garnet porphyroblasts indicate two pre-Alpine growth zones (Kováčik, 2004) – older cores indicate the slightly higher temperatures of origin (ca 650-700°C) as the younger rims (ca 600-650°C). A quartz lamina is bearing a thin apatite intercalation, where the monazite is also present. The relatively large monazite grains were analysed also in lepidogranoblastic matrix and as inclusions in garnet.

Numerous monazite grains indicate more-or-less Alpine reequilibrated newly formed rims (Fig. 6), in BSE images showing the lightest phases. For increment zones the lower Y concentrations in comparison with the older cores is characteristic. These young rims register the wide (Jurassic-Cretaceous) age range, probable reflecting spectrum of mixed ages. (The reliability of younger data is limited by the systematically low Pb content.) The sample contains also grains with the exclusive Alpine ages, though the age range (e.g. 71–189 Ma, Tab. 4, grain 4) indicates, that these grains are bearing the replaced pre-Alpine monazites, and hardly the new Alpine nucleation. Contratry to this, Fig. 7 (grain 10) probable illustrate a rare case of newly-formed Alpine monazite, which in its central part shows the uniform age corresponding to Albian-Aptian (107-113 Ma). The distribution of Alpine phases is shown on Fig. 8 A and B. In the vicinity of grains with the Alpine record also allanite was found and their genetic relations may be supposed. From the viewpoint of mechanism of origin of Alpine monazite, there apparently impresses the fact, that the incremental zones are not formed in monazites enclosed into garnet. It documents, that the unambiguously pre-Alpine garnet was not penetrated with compounds forming new monazite.

The monazites locally included in garnets (Fig. 9) are hypidiomorphic and compositionally more homogenous. They usually give higher, Silurian-Devonian ages (Tab. 4

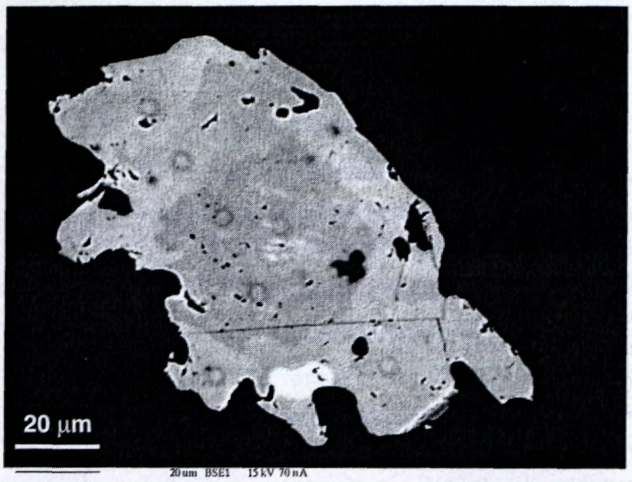


Fig. 6. BSE image of phases in inhomogeneous monazite illustrates four incremental zones - from the dark core with the age around 400 Ma to light margins of the Cretaceous age (grain 6 in Tab. 4).

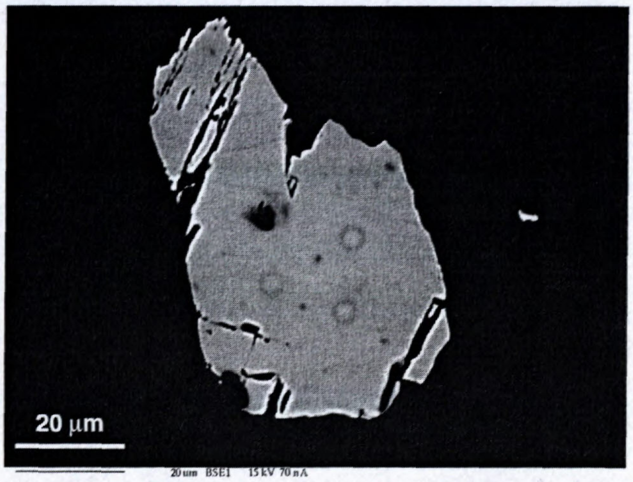


Fig. 7. Rare grain with exclusively Middle Cretaceous ages, probably indicating new Alpine nucleation.

grains 1, 7, 9 and 13). For illustration of compositional inhomogeneity in some groundmass monazites an example (Fig. 6 - grain 6 in Tab.4) with three observable phases can be stated: from the dark-grey central part obtained ages 384 (± 65), 443 (± 53) and 390 (± 23) Ma are the most significant because the highest content of measured elements. The transitional light-grey zone between the dark core and light rim indicates the age 321 (± 17) Ma. The light margin represents the Alpine rim (Fig. 6). Corresponding situation is observable on ca 0.07 mm large monazite (grain 8), where the dark centre states the age 409 (± 25) Ma and the light-grey rim 359 (± 27.7) Ma, but also 415 (± 26.2) Ma. After this "pre-Alpine" rim there follows again the light Alpine zone. In these grains the sequence of incremental crystallization zones is obvious, though the absolute chronology of older phases is not in each case clear.

In incrementing of particular zones the matter income plays the considerable role (because the content of radioactive elements also increased), during which the allochemical compounds are mixed with components of for-

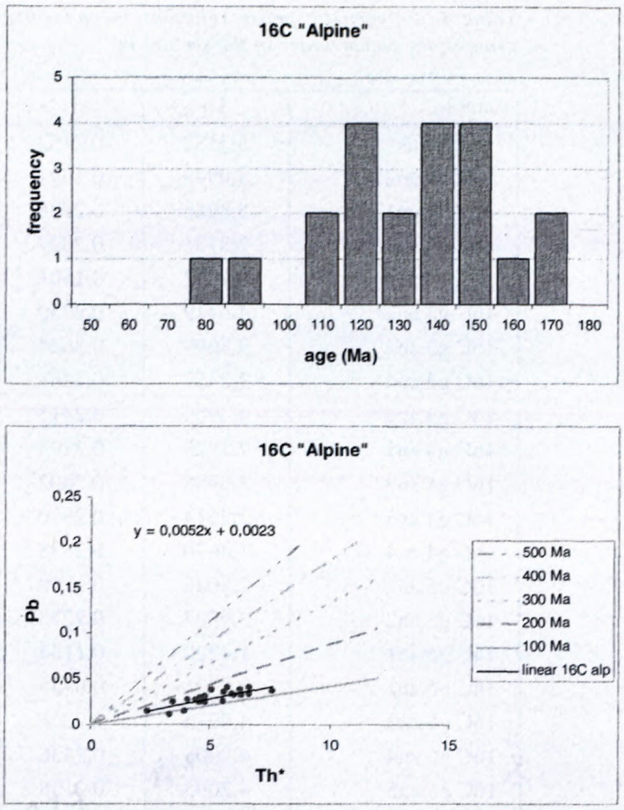


Fig. 8. Assembled data with Alpine age spectrum (see tab. 4) vizualized by means of histogram (A) and isochron diagram (B)

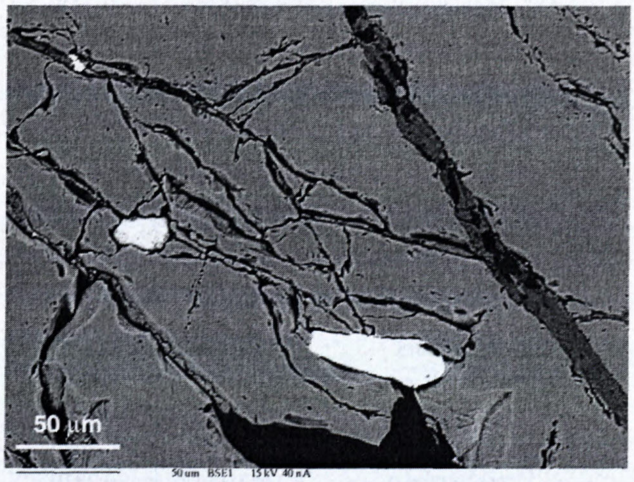


Fig. 9. Monazites included in garnet porphyroblasts recording the oldest ages within the varied age groups in high temperature gneisses

mer monazites and thus causing the mixed ages. It is evident, that older age records in cores of polygenetic grains or in monazites closed in garnet yielding the weighted mean 397 ± 18 Ma (summary "old" in Figs. 10 A, B) in one side and Carboniferous ages in the second side (ca 320–360 Ma, e.g. grains 3 and 12 as well as the "transition" zones in different grains, Tab. 4), record two pre-Alpine events. The garnet origin can be interpreted by multiple ways - either it is a product of older metamorphic period (early-Hercynian?, late-Caledonian?) or it registers

Table 4. Polygenetic phase relations in monazites from hight temperature gneiss project into several age groups (see commentary in the section D)

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
16C g1 an1	5,5182	0,2152	0,1112	0,1328	384	19,7
16C g1 an2	5,0949	0,1991	0,1079	0,0929	406	21,6
16C g2 an1	5,8986	0,2735	0,0448	0,0109	138	17,6
16C g2 an2	2,8731	0,2027	0,0292	0,0170	163	33,3
16C g3 an1	0,7792	0,1501	0,0329	0,5415	344	92,3
16C g3 an2	4,6419	0,2950	0,0926	0,2269	345	22,0
16C g3 an3	3,8699	0,3624	0,0856	0,6271	318	23,9
16C g3 an4	2,2351	0,1461	0,0446	0,4178	279	44,5
16C g3 an5	4,3905	0,2415	0,0422	0,0261	168	22,7
16C g4 an1	2,1978	0,2293	0,0302	0,1156	189	39,6
16C g4 an2	3,3988	0,2402	0,0331	0,1225	148	28,1
16C g4 an3	3,2514	0,2370	0,0203	0,0964	84	29,4
16C g4 an4	1,4670	0,2878	0,0296	0,6208	138	49,9
16C g5 an1	2,8046	0,1760	0,0160	0,0885	71	35,3
16C g5 an2	3,9327	0,2273	0,0296	0,0462	122	25,3
16C g6 an1	1,4220	0,1144	0,0438	0,5278	384	65,2
16C g6 an2	1,9721	0,0755	0,0552	0,4370	443	53,4
16C g6 an3	4,4926	0,2238	0,1049	0,6402	390	23,0
16C g6 an4	4,9008	0,2436	0,0311	0,0528	106	20,9
16C g6 an5	4,2093	0,2158	0,0298	0,0495	117	24,1
16C g6 an6	6,3541	0,2701	0,1127	0,3980	321	17,3
16C g6 an7	3,8908	0,1951	0,0318	0,0526	137	26,3
16C g7 an1	0,9180	0,0674	0,0389	0,4938	518	102,2
16C g7 an2	3,3179	0,1590	0,0719	0,2866	373	31,4
16C g8 an1	4,1516	0,2248	0,1064	0,8075	409	24,4
16C g8 an2	4,9561	0,2955	0,0849	0,3902	285	20,6
16C g8 an 2a	4,6519	0,3775	0,1018	0,3236	359	27,7
16C g8 an3	5,1201	0,2356	0,0449	0,0375	157	20,2
16C g8 an3a	5,2088	0,2450	0,1182	0,2676	415	26,3
16C g8 an4	4,0367	0,2589	0,0362	0,0799	145	24,4
16C z8 an5	5,5367	0,2680	0,0426	0,0282	137	18,5
16C g8 an6	4,9394	0,3105	0,0755	0,2961	255	20,6
16C g9 an1	0,7217	0,0417	0,0275	0,4358	414	135,9
16C g9 an2	1,7134	0,0983	0,0463	0,3293	407	57,2
16C g9 an3	1,2548	0,0245	0,0364	0,4700	407	87,7
16C g10 an1	6,8927	0,2646	0,0404	0,0142	107	15,5
16C g10 an2	5,6402	0,2565	0,0359	0,0189	113	18,4
16C g10 an3	5,9284	0,2672	0,0374	0,0212	112	17,7
16C g11 an1	5,0447	0,2810	0,1042	0,1462	374	20,6
16C g11 an2	5,0579	0,2036	0,0394	0,0053	142	20,9
16C g11 an3	4,0280	0,2048	0,0339	0,0380	143	25,3
16C g12 an1	0,8121	0,0482	0,0273	0,5101	330	121,4
16C g12 an2	0,7195	0,0108	0,0232	0,4882	312	156,3
16C g12 an3	5,0521	0,2696	0,1012	0,1647	363	20,6
16C g12 an4	5,3897	0,2369	0,0359	0,0160	118	19,5
16C g12 an5	5,2864	0,2466	0,0368	0,0000	124	19,7
16C g13 an1	0,9787	0,0337	0,0356	0,3645	521	106,4
16C g13 an2	0,6287	0,0385	0,0319	0,4239	606	152,8
16C g13 an3	1,9289	0,0525	0,0566	0,4896	473	56,3
16C g14 an1	1,5845	0,0603	0,0435	0,3461	425	66,1

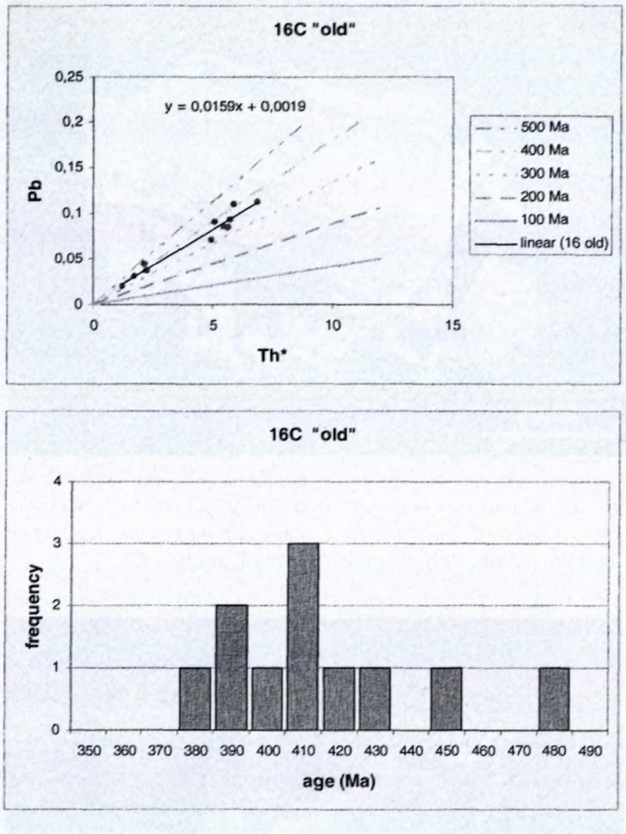


Fig. 10. Age records illustrating the oldest events prior to dominant Hercynian granitization processes are assorted among the pre-Alpine data; histogram of chosen values (*A*) for izochron diagram (*B*) showing about 400 Ma.

iron mineral assemblage is underlined also by the annite composition of biotite and the presence of amphibole - grunerite. For given parageneses, understood as a metamorphic product of primary ferrolites (Korikovskij et al., 1989; Kováčik, 2000), the apatite is symptomatic, graphite occurs frequently and allanite and quartz in variing abundance.

The monazite occurs rarely in the very fine individuals (max. dimensions ca 15 x 5 μm). The analysis of three grains enclosed in garnet, despite scarcity of data, offered the relatively uniform age composition (Tab. 5, Fig. 11) with weighted mean 368 (± 11) Ma. The diffu-

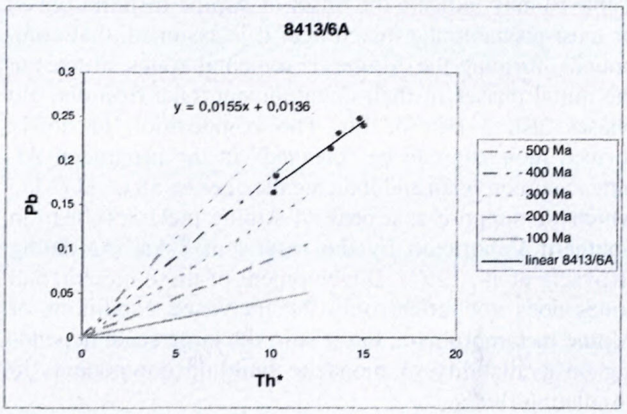


Fig. 11 Isochron diagram from monazites in magnetite-bearing metamorphic schists (weighted mean 368 ± 11 Ma).

Table 5. Monazites of metamorphosed iron-rich source material show besides the Hercynian ages of older group also uncommon high Th and low Y content

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
8413/6A an1	12,2755	0,2873	0,2126	0,0434	360	13,1
8413/6A an2	12,7442	0,2757	0,2306	0,0456	378	12,2
8413/6A an3	14,1053	0,2654	0,2384	0,0585	357	11,7
8413/6A an4	13,7593	0,2971	0,2470	0,0741	375	11,7
8413/6A an5	9,5830	0,2237	0,1820	0,0751	395	15,5
8413/6A an5	9,6229	0,1779	0,1626	0,0676	357	15,9

longer crystallization history culminating in the evolution of Carboniferous granitization (second age group). To opened questions of wider geological sence there can be counted in what extent the influences of Carboniferous granitoid magmatism rejuvenated older, often "transitional", age records in monazite cores and what means several ages in the range 255-285 Ma. Parallel with the interpretation of mixed age, these data would be connected also with the material-thermal influence of so-called Klenovec granite with supposed Permian age (Hraško et al., 2002).

Sample *8413/6A*. Location: Abandoned mining works in the vicinity of previous sample location

Biotite-garnet schist with magnetite. Rock is a bearer of magnetite mineralization containing of ca 2/3 of almandine garnet in the rock modal composition. The high-

sion material inhomogeneity, being observed in scanning images of two grains, has no direct influence on the age record. The given analyses, in comparison with further investigated samples, are conspicuous by the high Th content and lower order content of Y. These composition peculiarities depict more-or-less isochemical monazite genesis connected with unconventional protolith. The age records probably represent the Hercynian regional metamorphism - expressed mainly by the garnet development, in the time period before the crystallization of the main mass of the Southern Veporicum granitoids.

E) The investigation was focussed on ***kyanite-Mg-chlorite schist*** ("kyanite leucophyllite"), originating in the course of Mg-replacement from supposed crystalline basement in the vicinity of talc-magnesite deposits (location and next data in Kováčik, 1996). The whole-rock geochemical study indicated the mobility of nearly all elements, including the supply of LREE and P, so the growth of newly-formed monazite was expected. The temperature of formation of the Alpine mineral assemblage composed from Mg-chlorite, quartz, muscovite, kyanite, tourmaline and apatite is estimated on 350-430 °C.

Sample *8016/1.* The monazite analyses indicate two age groups – Carboniferous and Cretaceous (Tab. 6). The compositional zonality (Figs. 12 and 13) does not express precisely the age of monazite formation, because the age decrease was not confirmed in each case in the direction from the centre to margin of the crystals. The value 134 (± 14) Ma in the marginal dark phase (Fig. 13, grain 4, in Table 6) may indicate the onset of Alpine metamorphism or most probable the mixed age. It is assumed, that compounds, forming the Alpine incremental zones, at least at the initial phases of their development, take from the old phases also a part of Pb. The composition of newly formed monazite can be "cleaned" in the prograded Alpine metamorphism and indicate the ages ca 88 (± 11) Ma, which we suppose as a peak of Alpine metamorphism in Southern Veporicum by the results of $^{40}Ar/^{39}Ar$ dating (Kováčik et al., 1997). Development of these incremental zones does not reflect only the increased conditions of Alpine metamorphism, but it is in the large scale depending on availability of monazite building components in circulating fluids.

In this rock there is remarkable homogenous group of ages ranging between values 327 (± 11) to 353 (± 12) Ma (both marginal values were measured in crystal in Fig. 12, Tab. 6 - grain 1), being close to age of Sinec granite (ca 350 Ma, Bibikova et al., 1988). Moreover, the zonal variability of internal parts of monazite grains is more typical for magmatic than metamorphic origin. These data and the absence of older ages (see other clauses) support the assumption, that this lithotype hardly belongs to low-grade schists with eventual Carboniferous age, but more probable represents the metasomatically reworked phyllonites with the important portion of granitoid material.

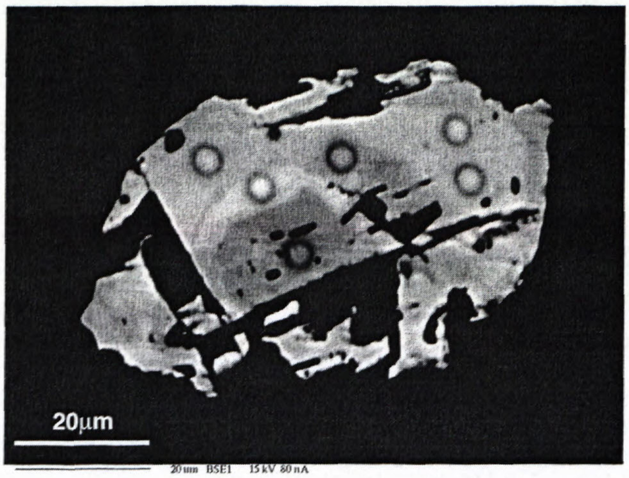


Fig. 12. Complex composition zonality generally proves the Lower Carboniferous age and argue for magmatic genesis of monazite (completely diaphtorized rock, section E).

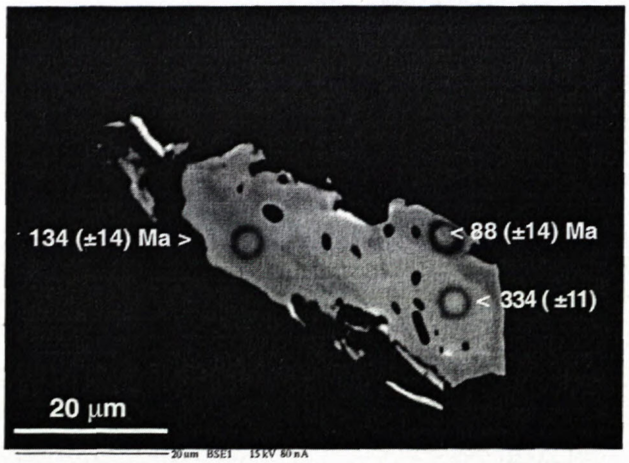


Fig. 13. Dark newly formed rims sometimes reaching up to the Late Cretaceous age, but the cores are preserving Hercynian records (sample 8016/1).

Table 6. Age records in zonal monazites with detailed phase description from kyanite – Mg-chlorite schist (for illustration see figs. 12 and 13)

sample	Th	U	Pb	Y	Age (Ma)	±error (Ma)
8016/1 g1 an1 light phase1	9,4813	0,4021	0,1780	0,7090	335	11,3
8016/1 g1 an2 light phase2	9,4955	0,4240	0,1752	0,6730	327	11,3
8016/1 g1 an3 light phase3	8,4612	0,3562	0,1701	0,8026	353	12,2
8016/1 g1 an4 darker phase	3,4229	0,0440	0,0508	0,2302	234	31,4
8016/1 g1 an5 lightest phase	11,9993	0,5070	0,2278	0,7246	347	8,9
8016/1 g1 an6 darkest phase	1,9808	0,0719	0,0528	0,8618	320	49,7
8016/1 g2 an7 dark centre	2,5521	0,3043	0,0754	1,0917	329	31,9
8016/1 g2 an8 light rim	8,6593	0,2958	0,1649	0,7302	343	12,2
8016/1 g3 an9 dark rim	5,1722	1,0393	0,0528	0,7473	88	13,2
8016/1 g3 an10 lighter phase	8,4681	0,9899	0,0708	0,7961	98	9,7
8016/1 g3 an11 light phase	9,8001	0,3699	0,1826	0,7192	337	10,8
8016/1 g4 an12 dark rim	5,3638	0,7624	0,0641	0,6057	134	14,3
8016/1 g4 an13 light phase	9,9773	0,4339	0,1866	0,7231	334	10,8
8016/1 g4 an14 darker phase	6,3131	1,0740	0,0588	0,8576	88	11,6

F) Monazites in *crystalline schists in the basement of the Ipeľská kotlina Basin.* Regarding the geographic configuration and corresponding processes of diaphtoresis this area can be supposed as a continuation of the belt of metamorphites of the Kohút zone. The crystalline basement, frequently found in drills, outcrops from under the Neogene formations only in territorially limited islands to NE of Šahy (ca 50 km to SW from the left corner of location scheme on Fig. 1).

Sample *21.* Location: Left slope cut of the Olvársky potok stream on northern margin of the outcropped crystalline basement
Muscovite-quartz schist.

In the thin-section the monazite occurs in two basic grain categories – either as very fine practically non-measurable grains, as well as ca 0.1 mm large, but less homogenous types. Recrystallization with the development of new crystal planes is proved in large monazites by the newly formed rims of Cretaceous age (Fig. 14 - grain 2 in Tab.7). The age data of the principal phases of large crystals in general division are concentrated in the range 343-386 Ma (Tab.7), which reliably reflects the Hercynian metamorphic history of the rock. The older ages can indicate the age of regional metamorphism and younger ages the influence of Lower Carboniferous granitization (granitoids on the surface), similarly as was discussed in the section *D*.

Sample *27 E.* Location: Right hillside of the Berinčénsky potok stream ca in the middle part of outcropped underlier. Muscovite metaquartzite.

The monazites form tiny isometric clusters in the frame of muscovite domains (Fig. 15). They are often present in the interface of muscovite leaves and their occurrence is accompanied with alterations – in the monazite surrounding the tiny muscovite and biotite were usually formed. Correspondingly the monazite clusters indicate genesis on the expence of Th–REE minerals, provisional analyses found huttonite (Tab. 8, analysis 7) and xenotime (tiny isometric grains in the centre beneath the luminous monazite in Fig. 15). The age data between 296 and 360 Ma (including the huttonite providing the age 333 ± 7 Ma) are in agreement with fair amount of values being registered in investigated metamorphic rocks.

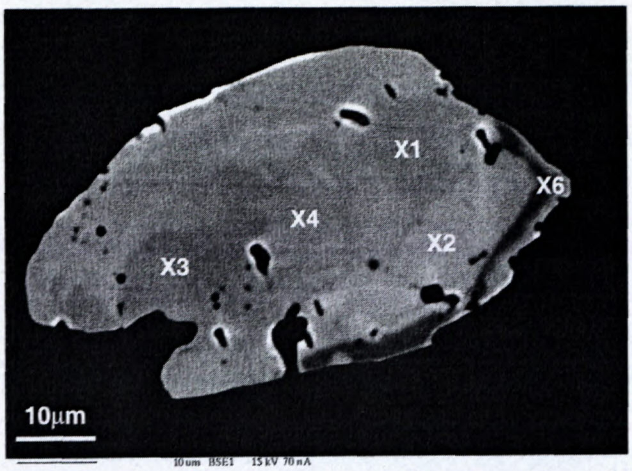


Fig. 14. The main mass of the crystal is formed with the compositionally inhomogenous monazite phases having Hercynian ages. Dark rim represents the Alpine incremental zone (crosses with numbers refer to analyses listed in Tab. 7 grain 2).

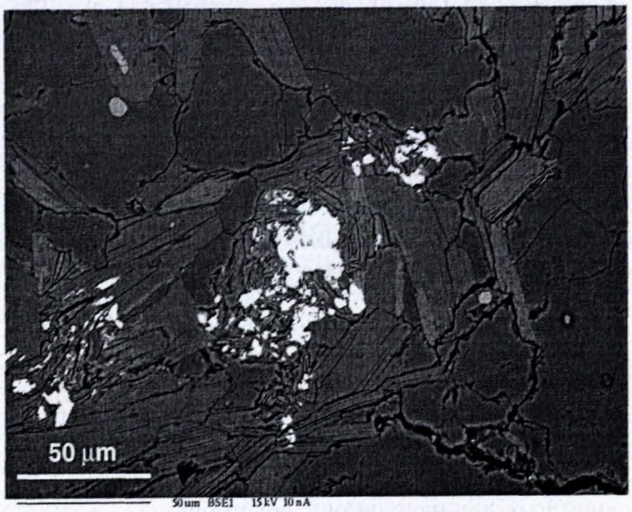


Fig. 15. Monazite is mainly localized in muscovite aggregates. The large lightening grain in the centre is monazite, the fine phases below represent xenotime (sample 27E).

Despite the insufficient number of analyses and systematically observed disintegration structures the preliminarily measured Precambrian ages (Tab. 8) cannot be unambiguously rejected. The age records could preserve

Table 7. Monazites in micaschist from basement of the Ipeľská kotlina Basin show bimodal age character comparable with the major part of metamorphites the Kohut Zone

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
21-4 g2-an1	4,5997	0,0588	0,0939	0,6716	386	33,8
21-4 g2-an2	6,0520	0,0983	0,1138	0,7175	360	26,3
21-4 g2-an3	4,5756	0,0849	0,0872	0,6933	349	32,3
21-4 g2-an4	5,5202	0,1438	0,1055	0,8951	343	27,2
21-4 g2-an6	4,3746	0,0524	0,0339	0,4860	120	34,5
21-4 g3 an1	6,3570	0,1033	0,1131	0,6527	343	24,4
21-4 g3 an2	3,9842	0,0737	0,0322	0,5975	112	37,3
21-4 g3 an3	6,6832	0,1095	0,1341	0,8291	386	23,4

Slovak Geol. Mag., 11, 2 – 3 (2005), 91 – 105

Table 8. Variegated spectrum of pre-Alpine ages, from which apparently huttonite (analysis 7) the most reliably expresses the influence of Hercynian granitization. Notable are the data indicating Proterozoic ages (see section F).

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
27E g1 an1	0,9443	0,0256	0,0696	0,3008	1179	99,8
27E g1 an2	0,7566	0,0107	0,0966	0,3092	2224	123,8
27E g2 an4	7,1094	0,1528	0,1168	0,5632	296	15,5
27E g2 an5	7,8429	0,1271	0,1302	0,5237	311	1[illegible],5
27E g3 an6	3,3866	0,1146	0,1154	0,5518	586	30,0
27E g4 an7	16,3372	0,1960	0,2672	0,6278	333	7,0
27E g5 an8	2,4968	0,0971	0,2989	1,3680	2074	41,3
27E g6 an9	1,9292	0,2017	0,0565	0,3572	360	40,3

also because this area is not conspicuously reprinted by Hercynian granitization, as well as Alpine metamorphism here not so dominant as in the NE parts of the Kohút zone. We do not exclude, that the ages 1.18 Ga and two higher 2 Ga age values can be compared with the upper intercept of zircon U/Pb geochronology from the crystalline basement in the Western Carpathians (e.g. Michalko et al., 1998; Poller et al., 1999, 2001; Putiš et al., 2001, 2003).

G) The sample, tentatively taken from the Harmónia Series in the Malé Karpaty Mts., belongs to the zone of ***sericite-chlorite phyllites with biotite*** (Cambel in Mahel' and Cambel, 1972), having been locally thermaly affected by the Modra granitoid massif. The age of the Modra granodiorite from available data (Cambel et al., 1990) was generalized on 320 Ma (U/Pb in zircon) and 327 (± 18) Ma (whole-rock Rb/Sr). The cross-section of tentaculites from low-metamorphosed crinoidal limestones demonstrated the Devonian age (Horný and Chlupáč in Buday et al., 1961), or even the Silurian age (Chlupáč in Andrusov, 1958). The monazite dating aimed to reveal the clastic monazites from the schistose metasandstones and/or to document the forming of the monazite in low-metamorphic conditions.

Sample *Mak-30A.* Location: Modra–Harmónia area, at the construction cut by the road, ca 300 m to SE from the valley dam.
Quartz phyllite with mineral assemblage quartz-albite-chlorite-muscovite-(Fe)-biotite.

The monazites are of differing dimensions, reaching maximum 20 μm. They are present together with the further accessory minerals (zircon, apatite) mainly in the muscovite environment (Fig. 16), sometimes in chlorite. Locally there is observable in monazite vicinity REE-epidote. Their genetic relations are very probable. The mutual relation of given phases can be preliminarily described by the reaction: allanite + P = monazite + REE-epidote. The monazite is compositionally homogenous, inspite of different composition of particular grains (see Tab. 9). The most reliable five age values range between 306 (± 15) and 330 (± 15.5) Ma. It roughly corresponds to the age of the Modra massif and accordingly with the synchroneous metamorphic crystallization of phyllosilicates in given phyllite. Different ages were obtained from monazites with low concentration of Th and Pb. With some restriction there can be stated the ages 353 (± 38) and 380 (± 34) Ma, which may record the traces after pre-granite regional metamorphism. The Fig. 17 demonstrates the isochron line close to weighted mean 321 (± 13) Ma. The Upper Permian age (grain 4 in Tab. 9; not involved into diagram in Fig. 17) is derived from monazite closed in chlorite mixture, which would indicate also the real time of hydrothermal processes. Even not regarding the particular age interpretations, from above stated it comes out that monazite was formed (or reequilibrated) in metamorphic conditions of chlorite, maximum biotite zone.

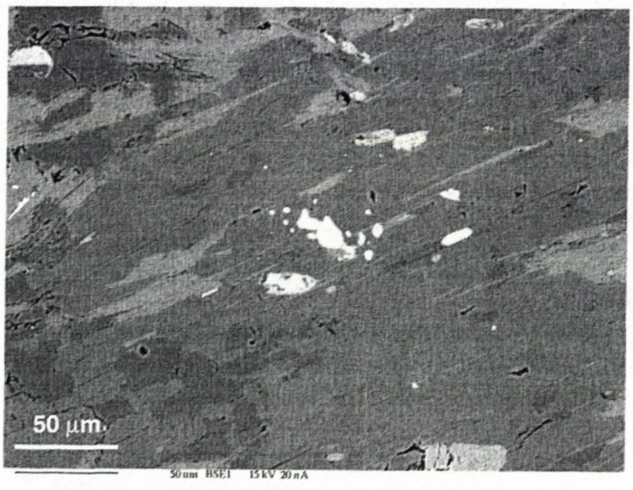


Fig. 16. Accessoric minerals – ilmenite, rutile, zircon and monazite (two tiny luminous grains in the centre) enclosed in transversal muscovite (refers to grain 1 in Tab. 9).

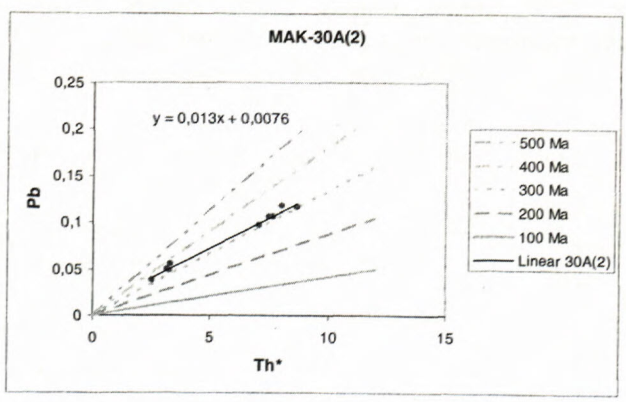


Fig. 17. Isochrone diagram and weighted mean 321 (±13) Ma indicate age relationship to the intrusion of Modra granodiorite (section G).

Table 9. Representative analysis of monazites (see Fig. 17) are presented for comparison purposes from phyllite of Harmónia Group (Malé Karpaty Mts.)

sample	Th	U	Pb	Y	age (Ma)	± error (Ma)
30A(2) g1 an1	0,9265	0,4980	0,0375	0,9422	337	46,4
30A(2) g2 an1	1,4339	0,5349	0,0494	1,0971	354	38,0
30A(2) g4 an1	1,4205	0,2820	0,0260	1,2872	253	51,1
30A(2) g5 an1	1,1159	0,6672	0,0487	1,1063	338	36,1
30A(2) g6 an1	5,6168	0,5659	0,1059	1,6843	320	16,9
30A(2) g7 an1	1,9708	0,6072	0,0439	1,2940	254	30,5
30A(2) g8 an1	5,1140	0,9000	0,1177	1,3907	331	15,5
30A(2) g10 an1	5,1728	0,7690	0,1060	1,2255	312	16,4

Discussion and conclusion

The determination of Th, U, Pb and Y in monazite has contributed to deeper understanding of polyphase processes in selected areas of the crystalline basement. The systematic microprobe monazite geochronological date from various metamorphic rocks are presented, in which the five to six age groups can be generally distinguished - the Cretaceous, Permian and Carboniferous age groups confirm also by the geological and geochronological ways proved tectonic phases. Multivalued Devonian-Silurian and rarely Precambrian ages brought new impulses into discussion about the veiled "old" history of crystalline basement.

The presence of monazite in pre-granitization (pre-Carboniferous) provenience is mainly influenced by the type of source material of given rock assemblage. The monazite grains are often very fine and non-measurable, or contain too low Th and Pb contents for reliable age interpretations. The investigated monazites are often bearing the signs of polygene development with demonstrations of composition zonality (Figs. 6 and 12, a.o.) caused mainly by allochemical origin. In some cases we infer the monazite genesis from allanite replacement by solutions enriched by phosphorus during the origin of monazite and REE-epidote to epidote. In comparison with further rocks, the monazites from magnetite-garnet schist (Tab. 5) have anomalous chemical composition (Th content ca 12 and Y 0.05 wt. %), which reflects their forming from the specific iron-rich protolith.

Despite the lithological and metamorphic relationship of some rock complexes, there were found notable differences in distribution of monazite. For example, in metasandstones of phyllite zone, in some domains of micaschist-gneiss zone or Muráň orthogneisses (Fig.1) the monazite practically does not occur, rarely it appears only in the form of large homogenous crystals (Fig. 4). Their age is close to the age of Lower Carboniferous granitoids (ca 350 Ma, Bibikova et al., 1988), obviously playing an important role during the origin of these monazites. The age of sporadic monazites (Fig. 2) from the phyllite zone indicates, that the age of deposition of source material was older than adjacent granites. There exist domains, where the age characteristic of this cartographically uniformly vizualized zone (Šuf, 1937; Klinec, 1966; Vozárová and Vozár, 1982) is not unambiguous and the problematics of differing of older phyllites from post-orogenic Upper Carboniferous is still actual.

The monazites enclosed in the garnets or cores of polygene monazite grains indicate higher ages (for example in the section *D* averaged to 397 ± 18 Ma), while the monazites from the groundmass commonly register also Carboniferous and younger ages. In the case of these ages we can suppose the influence of Carboniferous granitization as principal, though polyphase, plutonism terminating the Hercynian orogenesis of crystalline basement. It is difficult to express to which extent this process rejuvenated the older age records of monazites, which are conventionally ranged to the time of Hercynian regional metamorphism or Early-Hercynian metamorphism, if need be. Despite great number of monazite analyses, as well as the available isotopic dating, it seems, that the factual chronological interpretation of metamorphism from the time before the main Hercynian granitization is fairly uncertain. The group of Silurian-Devonian ages can be explained not only in terms of the Early-Hercynian metamorphism, but also as the reflection of (Late)-Caledonian tectonothermal activity.

It is obvious, that processes of Alpine metamorphism did not erase the older age records in Southern Veporicum, which are comparable with the available data from Tatric areas. The Alpine metamorphism did not exceed the conditions of Hercynian periplutonic metamorphism, from which we analogically derive, that Carboniferous granitization was more or less able to rejuvenate eventual older age records. Another reason, why in monazites prevail the ages close to Hercynian granitoid magmatism, stem from input of monazite forming components. It is probable, that fluids released from cooling granitoids represent the prevailing way of monazite growth in suitable dimensions and composition (sufficiency of Th, U and Pb) for the age analysis. However, this can then create a distorted opinion on the excessive role of granites in metamorphic reworking of the basement rocks.

The records about Permian age are often derived from corroded, metamict grains, and therefore we judge them in terms of mixed ages, which do not necessarily reflect the particular geological event. On the other hand, some "transitional" ages in the Upper Carboniferous-Permian period can not be definitively rejected due to thermal and material effects of potential bodies of Permian granites/granite porphyries.

Replacing of old monazite by the Alpine newly formed phases can be observed in numerous places of the

Kohút zone. There is observable also gradual reequilibration with transitional ages, being similar to $^{40}Ar/^{39}Ar$ spectra of mixed ages of micas and amphibole (e.g. Maluski et al., 1993; Kráľ et al., 1996). Development of these incremental zones, with prevailing age records between 87–120 Ma, reflects not only the Alpine metamorphic conditions, but in large extent it relates to availability of building components in circulating fluids. The Alpine incremental zones do not form in monazites enclosed in pre-Alpine garnet porphyroblasts, which were not penetrated by these compounds. In rare cases there appear the fine crystals as a product of supposed Alpine monazite nucleation (Fig. 7). The lowermost reproducable monazite ages reach 87-88 Ma, which correspond with culminating values of $^{40}Ar/^{39}Ar$ dating of muscovite and amphibole in metapelites (Kováčik et al., 1997).

The monazite development from the metasandstone of Harmónia Group (321 ± 13 Ma) was conditioned by metamorphism max. in biotite zone of contact metamorphism by Modra granodiorite. Several works advert to low-temperature genesis of monazite – for example the formation of newly formed monazite in veins of Alpine type (Stalder, 1986) or development of secondary monazite at the expense of older crystals (Townsend et al., 2000). Thus, example from the above metasandstone together with the Alpine phases in the Kohút zone documents the monazite development in conditions, which did not exceed the middle parts of greenschist facies. The differentiated petrographic manifestations of Alpine recrystallization (Kováčik et al., 1996) result also from irregular distribution of Alpine monazites – e.g. in SW part of Kohút zone the samples mutually distant several 100 m have mostly Cretaceous ages or are without the Alpine record (e.g. in the section *B* see sample KH-1/14.4 vs. 7100/3) or in the area of the most intense Alpine metamorphic overprint there are preserved samples without Alpine monazites (Tab. 3, Fig. 5 etc.) .

In micaschists from the underlier of the Ipeľská kotlina Basin there were found, besides Hercynian monazites with local Alpine margins, sporadically also grains with the oldest age records (ca 2 Ga, 1 Ga and 500-600 Ma, Tab. 8). In the frame of the Western Carpathians the published ages of clastic zircons as well as upper intercepts the U/Pb discordia yield similar values (Michalko et al. 1988, Poller et al. 2001, Putiš et al. 2003). So, these maiden pre-Cambrian monazite records should be not deprecated.

Submitted monazite study in metamorphic rocks opened several additional questions, namely geochronological (pre-Hercynian and older "mixed" ages), mineralogical (assemblage with xenotime, allanite, epidote, etc.) and geochemical (e.g. indications of chronologic and chemical relations) problems, to which the further systematic analyses probable will shed more light.

References

Andrusov, D. 1958: Geologie der Tschechoslowakischen Karpaten I. (In Slovak with German and Russian summary) SAV Bratislava, 304.

Bezák,V. 1982: Komplexy metamorfitov a granitoidov v kohútskom pásme veporíd. Geol. Práce, Spr. 78, 65-70.

Bibikova, E.V., Cambel, B., Korikovsky, S.P., Broska, I., Gracheva, T.V., Makarov, V.A., Arakeliants, M.M. 1988: U- Pb and K-Ar isotopic dating of Sinec (Rimavica) granites (Kohút zone of Veporides). Geol. Zbor. Geol. Carpath., Bratislava, 39, 2, 147-157.

Biely, A., Bezák, V., Elečko, M., Kaličiak, M., Konečný, V., Lexa, J., Nemčok, J., Potfaj, M., Rakús, M., Vass, D., Vozár, J. a Vozárová, A. 1996: Geological map of Slovak republic 1:500.000. Slovak Geol. Survey, Bratislava.

Buday, T., Kodym, O., Maheľ, M., Máška, M., Matějka, A., Svoboda, J. & Zoubek, V. 1960: Tectonic development of Czechoslovakia. Praha, ČSAV, 350 p.

Cambel, B., Kráľ, J. & Burchart, J. 1990: Isotopic geochronology of the Western Carpathian crystalline complex. (in Slovak with English summary.) Veda, Bratislava, 1-183.

Čorná , O., 1968: Sur la trouvaille de restes d´organisme dans les roches graphitique du cristallin des Petites Carpathes. Geol. Zbor. Geol. carpath., 19, 303-309.

Čorná, O. & Kamenický, L. 1976: Ein Beitrag zur Stratigraphie des Kristallinikum der Westkarpaten auf Grund der Palynologie. Geol. Zbor. Geol. carpath. 27, 1, Bratislava, 117-132.

Fialin, M. Rémy, H., Richard, C. & Wagner, Ch. 1999: Trace element analysis with electron microprobe: New data and perspectives. American Mineralogist, 84,70-77.

Gaab, A., Poller, U., Todt., W. & Janák., M., 2003: Geochemical and isotopic characteristics of the Murán Gneiss Complex, Veporic Unit (Slovakia). Journ. Czech Geol. Soc., 48/1-2, 52.

Hovorka, D., Dávidová, Š., Fejdi, P., Gregorová, Z., Határ, J., Kátlovský, V., Pramuka, S. & Spišiak, J. 1987: The Muráň Gneisses of the Kohút Crystalline Complex. Acta Geol. Geogr. Univ. Comen., Bratislava, 42, 5-101.

Hraško, Ľ., Broska, I. &. Finger,F. 2002: Permian granitic magmatism and disintegration of the Lower Paleozoic Basement in the SW Veporicum near Klenovec (Western Carpathians). Geol. Carpathica, 53, 185-187

Janák, M., Finger, F., Plašienka, D., Petrík, I., Humer, B., Méres, Š. & Lupták, B. 2002: Variscan High p-T recrystallization of Ordovician granitoids in the Veporic Unit: New petrological and geochronological data. Geolines 13, 66-67.

Kamenický, J. a Kamenický, L. 1983: Prekambrium Západných Karpát. Minerália Slov., 15, 289-302.

Klinec, A. 1966: Zum Bau und Bildung des Veporiden-Kristallin. (In Slovak with German summary.) Sbor. Geol. Vied, Západné Karpaty, 6, 7-28.

Klinec, A., Planderová, E. 1981: Otázka stratigrafickej jednoty série Hladomornej doliny. Geol. práce, Správy, Bratislava, 75, 13-18.

Klinec, A., Planderová, E. a Miko, O. 1975: Staropaleozoický vek hronského komplexu veporíd. Geol. práce, Správy, 63, 95-104.

Kohn, M.J. & Malloy, M.A. 2004: Formation of monazite via prograde metamorphic reactions among common silicates: Implications for age determinations. Geoch. et Cosmochim. Acta, Vol. 68, No. 1, 101-133.

Konečný, P., Siman, P., Holický, I., Janák, M. & Kollárová, V. 2004: Method of monazite dating by means of the electron microprobe. Mineralia Slovaca, 36, 225-235 (in Slovak with English abstract).

Korikovskij, S.P., Dupej, J. & Boronichin, V.A. 1989: High Fe metasediments from Kokava nad Rimavicou (Veporicum, Central Slovakia). (In Slovak, Engl. summary.) Min. slovaca, 21, 251-258.

Kováčik, M. 1996: Kyanite - Mg-chlorite schist and its petrogenetic significance (Sinec massif, Southern Veporic Unit, Central Western Carpathians). Geol. Zb. Geol. Carpath, 47, 245-255.

Kováčik, M. 2000: Petrogenesis of Metamorphosed Ironstones near the Kokava nad Rimavicou (Veporicum, Western Carpathians). Slovak Geol. Mag.,6, 367-376

Kováčik, M., 2002: Contribution to „Muráň" orthogneisses in the Southern Veporicum basement rocks (Inner Western Carpathians, Slovakia). Geol. carpath.,53, Spec. Issue, 168-170.

Kováčik, M. 2004: Pre-Alpine history of metamorphosed psammitic rocks in the central part of Kohút Zone (Southern Veporicum). (In Slovak with English abstract.) Geol. Práce, Správy 109, 83-92.

Kováčik, M. 2004: K predalpínskej histórii metamorfovaných psamitických hornín v centrálnej časti kohútskeho pásma (južné veporikum). (In slovak in English resume.) Geol. Práce, Správy 109, 83-92.

Kováčik, M., Kráľ, J. & Maluski, H. 1996: Metamorhic rocks in the Southern Veporicum basement: their Alpine metamorphism and thermochronologic evolution. (In Slovak with English resume.) Mineralia Slov., 28, 185-202.

Kováčik, M., Kráľ ,J. a Maluski, H. 1997: Alpine reactivation of the southern Veporicum basement: metamorphism, $^{40}Ar/^{39}Ar$ dating, geodynamic model and correlation aspects with the Eastern Alps. In Grecula, P., Hovorka, D. a Putiš, M. (eds.): Geological evolution of the Western Carpathians. Mineralia Slovaca-Monograph, 163-174.

Kovach, A., Svingor, E. & Grecula, P. 1986: Rb/Sr isotopic ages of granitoide rocks from the Spiš-Gemer metalliferous Mts., West Carpathians, Eastern Slovakia. Mineralia Slov., 18, 1–14.

Kráľ, J., Frank, W. a Bezák, V. 1996: Hornblende $^{40}Ar/^{39}Ar$ spectra from the hornblende-bearing rocks of the Veporic Unit. (In Slovak with English abstract.) Mineralia Slovaca, 28, 501-513

Kuthan, M., Biely, A., Čechovič, V., Fusán, O., Hovorka, D. 1963: Geological map of ČSSR 1 : 200 000, M-34-XXXII Zvolen. (In Slovak.) Geofond-Bratislava

Maheľ, M., Cambel, B. 1972: Geologische Karte der Kleinen Karpaten. Masstab 1 : 50 000. Verlag GÚDŠ, Bratislava

Maheľ, M., Kamenický, J., Fusán, O., Matějka, A. 1967: Regionální geologie ČSSR. Díl II, Západní Karpaty 1. Vyd. ČSAV, Praha, 407 s.

Maluski, H., Rajlich, P., Matte, P. 1993: $^{39}Ar/^{40}Ar$ dating of the Inner Carpathians Variscan basement and Alpine mylonitic overprinting. Tectonophysics, 223, 313-337.

Michalko, J., Bezák, V., Kráľ, J., Huhma, H., Mäntäri, I., Vaasjoki, M., Broska, I., Hraško, Ľ. & Határ, J. 1998: U/Pb zircon data from the Veporic granitoids (West Carpathians). Krystallinikum, (Brno), 24, 91-104.

Miko, O., Planderová, E. a Vozárová, A. 1985: Vymedzenie mladopaleozoických metasedimentov v kryštaliniku krakľovského pásma veporíd (Horehronské podolie). Geol. práce, Správy, 82, 77-88.

Montel, J. M., Foret, S., Veschambre, M., Nicollet, Ch. & Provost, A. 1996: Electron microprobe dating of monazite. Chemical Geology, 131, 37-53.

Nemčok, A. 1953: Geologická stavba oblasti medzi Rimavskou Baňou a Sirkom. Geol. zbor. SAV, Bratislava, 4, 3-4, 589-622.

Planderová, E. a Vozárová, A. 1978: Vrchný karbón v južnej časti veporíd. Geol práce, Spr., 70, 129 - 141.

Poller, U., Todt, W., Janák, M. & Kohút, M. 1999: The geodynamic evolution of the Tatra Mountains constrained by new U-Pb single data on orthogneisses, migmatites and granitoids. Geol. Carpath. (Bratislava), 50, special issue, 129-131.

Poller, U., Todt, W., Kohút M., Janák, M. 2001: Nd, Sr, Pb isotope study of the Western Carpathians: implications for Paleozoic evolution. Schweiz. Min. Petr. Mitt.,81, 159-174.

Putiš, M., Kotov, A.B., Uher, P., Salnikova, E.B. & Korikovskij, S. 2000: Triassic Age of the Hrončok Pre-Orogenic A-Type Granite Related to Continental Rifting: a New Result of U-Pb Isotope Dating. Geol. Carpathica,51, 59-66.

Putiš,M.,Kotov,A.B.,Korikovskij,S.P.,Salnikova,E.B.,Yakovlevova,S.Z. ,Berezhnaya,N.G., Kovach,V.P. a Plotkina,J.V. 2001: U-Pb zircon ages of dioritic and trondhjemitic rocks from a layered amphibolitic complex crosscut by granite vein (Veporic basement, W. Carpathians). Geol. carpathica,52, 49-60.

Putiš, M., Kotov, A.B., Petrík, I., Korikovsky, S.P., Madarás, J., Salnikova, E.B., Yakovleva, S.Z., Berezhnaya, N.G., Plotkina, Y.V., Kovach, V.P., Lupták, B. & Majdán, M. 2003: Early - vs. lateorogenic granitoids: structural, age and petrological relationships in the Variscan basement (Nízke Tatry and Malá Fatra Mountains, Slovakia). *Geol. Carpath.* 54, 3, 163-174.

Pyle, J. M., Spear, F. S. 2003: Four generations of accessory-phase growths in low-pressure migmatites from SW New Hampshire. Am. Mineral., 88, 338-351.

Richarz, P. 1908: Der südliche Teil der Kleinen Karpathen und die Hainburger Berge. Eine petrographisch-geologische Untersuchung. Ver. k.k. Geologischen Reichsanstalt, 58, 1-48.

Scherer, M., Engi, M., Gnos, E., Jakob, V. & Liechti, A. 2000: Monazite analysis; from sample preparation to microprobe age dating and REE quantification. Schweiz. Mineral. Petrogr. Mitt. 80, 93-105.

Stalder, H.A. 1986: Die geschuetzte Mineralkluft Grimsel. Schweiz. Miner. Petr. Mitt., 66, 502-505.

Suzuki, K, & Adachi, M. 1991: The chemical Th-U-total Pb isochron ages of zircon and monazite from the Gray Granite of the Hida Terrane, Japan. Journal of Earth Sciences, Nagoya University, 38, 11-37.

Suzuki, K. & Adachi, M. 1994: Middle Precambrian detritalmonazite and zircon from Hida gneiss on Oki-Dogo Island, Japan: their origin and implications for correlation of basement gneiss of Southwest Japan and Korea. Tectonophysics, 235, 277-292.

Suzuki, K. & Adachi, M. 1998: Denudation history of the high T/P Ryoky metamorphic belt, southwest Japan: constraints from CHIME monazite ages of gneisses and granitoids. Journal of Metamorphic Geology, 16, 23-37.

Suzuki, K., Adachi, M. & Kajizuka, I. 1994: Electron microprobe observations of Pb diffusion in metamorphosed detrital monazites. Earth and Planetary Science Letters, 128, 391-405.

Šuf, J. 1937: Survey of economic mineral repositories with respect to geological setting in the surroundings of Hnúšťa in Slovakia. (In Czech.) Bánský svět, 2-4, Praha.

Townsend, K.J., Miller, C.F., D´Andrea, J.L., Ayers, J.C., Harrison, T. & Coath, C.D. 2000: Low temperature replaceent of monazite in the Ireteba Granite, southern Nevada; geochronological implications. Chem. Geol., 172, 95-112.

Vitális, S. 1908: Beiträge zur Geologie des Gebietes zwischen Rima- und Baloghbach. Jahresberichte d.k. Ung.Geol.Anstalt.

Vozárová, A. a Vozár, J. 1982: New lithostratigraphical division of the basal part of the cover of Southern Veporicum. (In Slovak with English resume.) Geol. Práce, Spr., 78, GÚDŠ, Bratislava, 169-194

Zoubek,V. 1932: Compte rendu préliminaire des levers géologiques sur la feuille Velká Revúca (4564). (In Czech with French summary.) Věstník SGÚ,VII, Praha.

Zoubek, V. 1936: Bemerkungen ueber das Kristallin der Westkarpathen. (In Czech with German summary.) Věstník St. geol. Úst. Čs. Republ, 12, 1-2, 207-239.

Major, trace element and REE geochemistry of metamorphosed sedimentary rocks from the Malé Karpaty Mts. (Western Carpathians, Slovak Republic): Implications for sedimentary and metamorphic processes

ŠTEFAN MÉRES

Comenius University Bratislava, Faculty of Natural Sciences, Department of Geochemistry, Mlynská dolina G, 842 15, Bratislava, Slovak Republic, meres@fns.uniba.sk

Abstract. In Lower Paleozoic crystalline basement of the Malé Karpaty Mts., two geochemical groups of metamorphosed sedimentary rocks were observed: (1) the Active Continental Margin Environment Sedimentary Rocks (ACMESR) and (2) the Deep Ocean Basin Ridge Environment Sedimentary Rocks (DOBRESR). The chemical composition of ACMESR (variable composition, values of the ratio Th/U > 1, values Th/Sc 0.3-0.8, values $La_N/Yb_N > 5$ and values Eu/Eu* 0.6-0.9) indicates components derived from the Young Differentiated Arc (YDA) provenance type. The same geochemical parameters of various types of metamorphosed sedimentary rocks (metapelites, metapsammites, black schists, gneisses, contact metamorphosed rocks) of this group indicate: the same protolith (greywackes, lithic arenites ± organic matter), the same parental rocks (tonalite-granodiorite alternatively dacite-rhyodacite), the same source area (active continental margin) and the same sedimentary environment (continental slope). The chemical composition of DOBRESR indicates the components being derived from the Young Undifferentiated Arc (YUA) provenance type (variable composition, ratio Th/U < 1, ratio Th/Sc < 0.25, ratio $La_N/Yb_N < 6$ and values Eu/Eu* ~1). The protolith of metamorphosed sedimentary rocks of this group consisted of pelagic shales + organic matter, protolith of metacherts formed by deep marine siliceous sedimentary rocks + organic matter, protolith of actinolite schists and chlorite-actinolite schists represented by halmyrolytic altered hyaloclastites, and basalts of N-MORB type + organic matter. The sedimentary environment of the protolith of these metamorphosed sedimentary rocks was the ocean floor. Sedimentation was accompanied by rift volcanism producing basalts of N-MORB type and hydrothermal activity forming the stratiform hydrothermal sulphidic bodies in sediments.

Key words: metamorphosed sedimentary rocks, geochemistry, protolith, paleoweathering, sedimentary environment, geotectonic setting

Introduction

Metamorphosed sedimentary rocks of the Malé Karpaty Mts. are, for the purposes of geochemical paleoreconstruction, most suitable from all metamorphosed rocks of the pre-Alpine crystalline basement of the Western Carpathians. Detailed geological mapping (Mahel' and Cambel, 1972) shows changes in chemical composition of metamorphosed sedimentary rocks in relation to their geological position. Known sedimentological properties allow observing and verifying the variability of chemical composition of metamorphosed sedimentary rocks in relations to distribution of chemical elements in the process of sedimentogenesis. The mobility/immobility of chemical elements in metamorphosed sedimentary rocks can be investigated from the viewpoint of the influence of regional and contact metamorphism. In this work the chemical composition of metamorphosed sedimentary rocks was subjected to geochemical analysis aiming to verify the behaviour trends of oxides of the main elements, trace elements and lanthanoids (REE): (a) as a result of pre-metamorphic sedimentary processes, (b) from the viewpoint of various intensity and type of metamorphism, (c) regarding the geological position and lithostratigraphic division.

Geological setting

The Malé Karpaty Mts. (MK) represent a part of the Tatra-Fatra Belt of the Central Western Carpathians (Plašienka et al., 1997). The crystalline basement of MK build-up the metabasites (amphibolites, actinolite schists), metamorphosed sedimentary rocks (phyllites, gneisses, black schists, hornfelses, and calc-silicates) as well as the Bratislava and Modra granitoid massifs (Koutek and Zoubek, 1936; Cambel 1954, 1962). In comparison with further Tatric cores the crystalline basement of MK can be characterized by several peculiarities: (1) The presence of higher (gneisses) and lower (phyllites) grade metamorphic rocks, (2) in metamorphosed sedimentary rocks relict sedimentary structures are preserved, (3) relatively large spread of the black schists, (4) clear intrusive relation of granitoids with their mantle/core, and (5) extended manifestations of the contact and periplutonic metamorphism (Cambel, 1962; Korikovsky et al., 1984). The Silurian-Carboniferous age of the complex of magmatic and sedimentary rocks of the MK crystalline basement was determined by paleontological investigation (Andrusov, 1959; Cambel and Čorná, 1974; Planderová and Pahr, 1983; Cambel and Planderová, 1985). In the Lower Carboniferous period the complex was intruded by Bratislava and Modra granitoid massifs.

Slovak Geol. Mag., 11, 2 – 3 (2005), 107 – 122

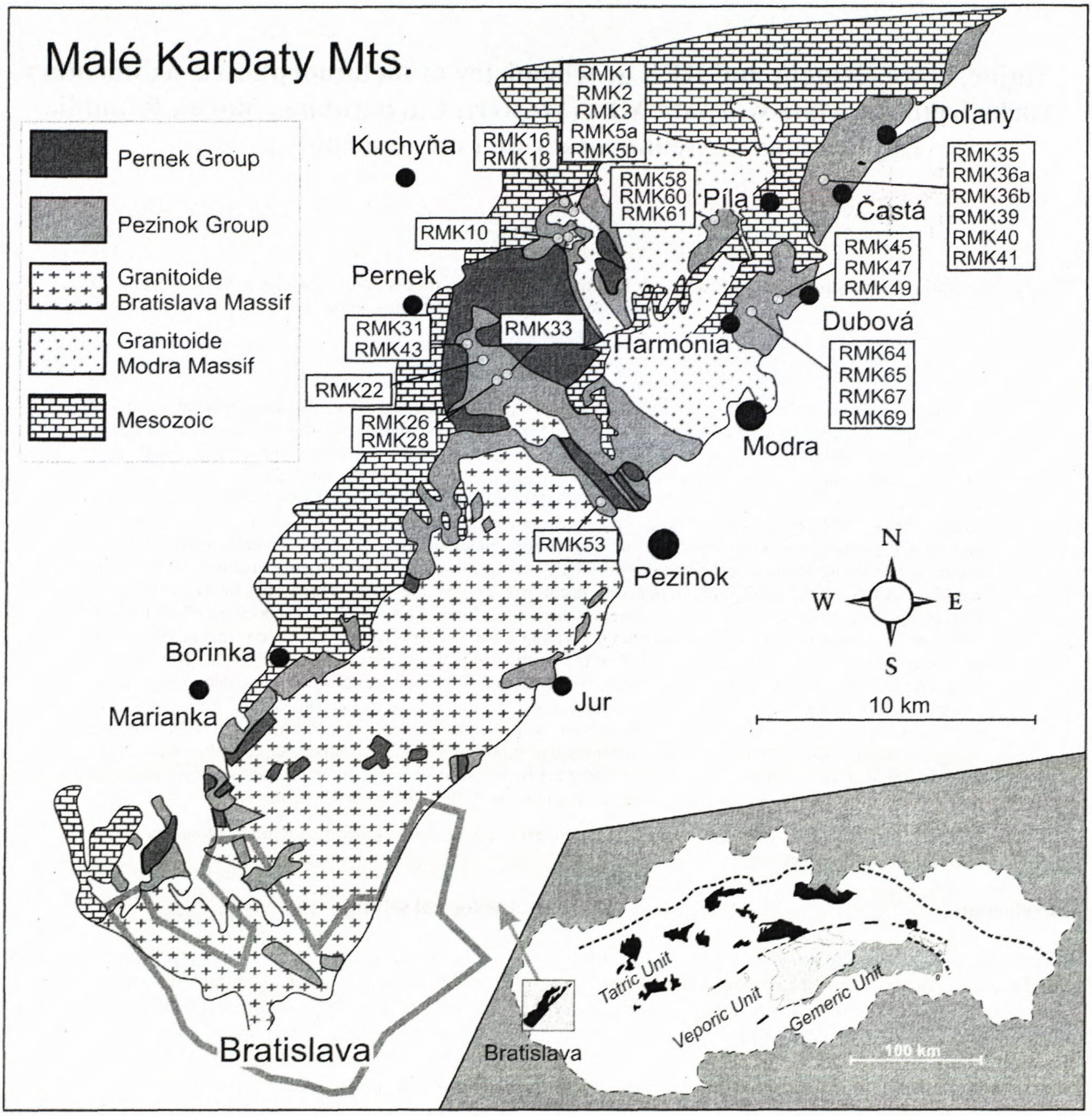


Fig. 1. Schematic geological map of the Malé Karpaty Mts. with location of the studied samples (Table 1 - this work, Table 2 taken from Ivan et al., 2001).

Two principally different opinions exist about the pre-metamorphic development of the crystalline basement of the MK.

(1) The first opinion interprets the crystalline basement as one pre-metamorphic volcanosedimentary lithostratigraphic unit. The variability in metamorphosed sedimentary rock compositions is explained as a result of pre-metamorphic gradual changes of sedimentary conditions in time and space (Cambel, 1954; Hovorka, 1985 in Grecula and Hovorka, 1987; Putiš, 1992).

Cambel (1954) distinguished two regional units: ***Pezinok-Pernek crystalline basement*** and ***Harmónia Series***. Pelitic-psammitic metamorphosed sedimentary rocks, locally containing organic matter, metabasalts, metavolcaniclastics and metagabbros, were in the Pezinok-Pernek crystalline basement (Cambel, 1954). Sulphidic mineralization concentrated mainly in black schists of so-called productive zones (= uppermost part of the Pezinok-Pernek crystalline basement) was proposed by Cambel (1959) as syngenetic with the basalt volcanism in Pezinok-Pernek crystalline basement. The Harmónia Series differs with more frequent alternating of psammitic and pelitic compounds and also contains limestones of organogenic origin with sporadic mafic volcaniclastics (Cambel, 1954).

Hovorka (1985, in Grecula and Hovorka, 1987) defined three formations: (1) ***Pernek Fm.***, formed prevailingly with metabasites, (2) ***Pezinok Fm.***, containing mainly clastic sediments including black schists with intercalations of mafic volcanites and volcaniclastics, the "productive zones" were affiliated also with this formation, and (3) ***Harmónia Fm.*** (identically with Harmónia Series according to Cambel, 1954).

Plašienka and Putiš (1987) divided all metamorphosed igneous rocks and metamorphosed sedimentary rocks of the MK crystalline basement into two Paleoalpine tectonic units: the ***Bratislava nappe*** and ***Orešany nappe***. The complex of metamorphosed igneous rocks and metamorphosed sedimentary rocks of the MK crystalline basement was divided more precisely by Putiš (1992).

2) The second opinion proposes two pre-metamorphic lithostratigraphic groups, originating principally in differing sedimentary and geotectonic environment: ***Pernek Group*** and ***Pezinok Group*** (Fig. 1, Ivan et al., 2001; Méres and Ivan, 2003; Ivan and Méres, 2003).

The complex of metabasites and metamorphosed sedimentary rocks of MK crystalline basement, together with granitoid massifs, was originally regarded as autochthonous (Cambel, 1962). This opinion was later exchanged by the concept of nappe setting (Plašienka and Putiš, 1987; Plašienka et al., 1991; Putiš, 1992; Ivan and Méres, 2003).

Petrography

Metamorphosed sedimentary rocks from the Malé Karpaty Mts. were, in this work, divided into several groups by petrographic characteristics and geological position (in the sense of Cambel, 1954). ***The first group*** is formed by the metamorphosed sedimentary rocks tied to Bratislava granitoid massif and metamorphosed sedimentary rocks in **Pezinok-Pernek crystalline basement** as well as **Harmónia Series**: *phyllites (**MPEL & MPSA** = metapelites and metapsammites), gneisses* (**G**), *contact metamorphosed rocks (**CMR** = hornfelses, spotted phyllites and spotted gneisses), and black schists (**BS1**).* ***The second group*** is formed by metamorphosed sedimentary rocks outcropping in so-called ***productive zones*** (according to Cambel, 1959): *black schists (**BS2**).*

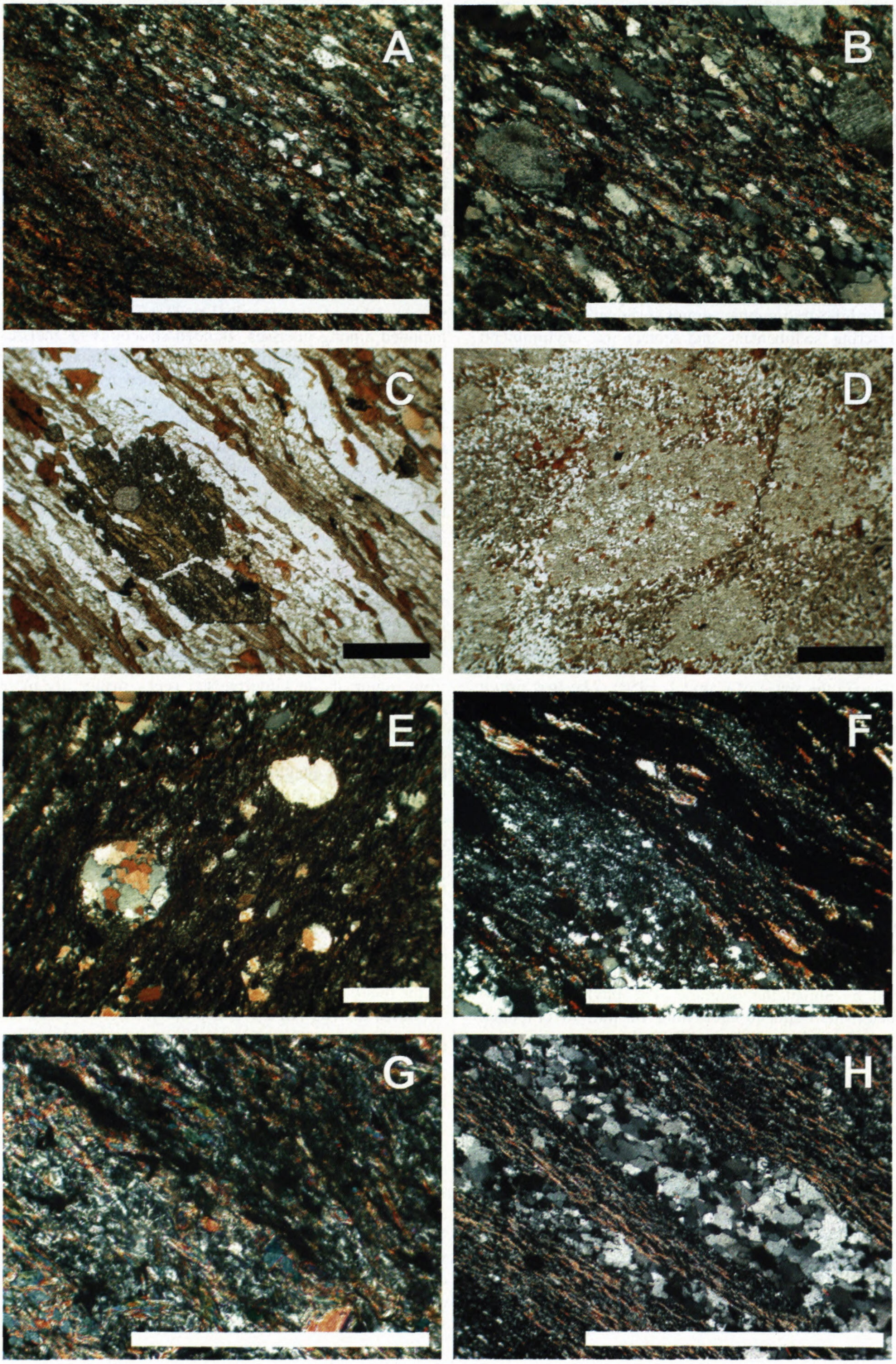
Phyllites (MPEL&MPSA). Greenschist facies pelitic-psammitic sediments were originally included among phyllites. The boundary between phyllites and gneisses is formed by almandine isograde. The phyllites manifest characteristic frequent alternating of mm to cm thick intercalations of metapelites (MPEL) and metapsammites (MPSA). The metamorphic grain-size of phyllites often evidently copies the former sedimentogenous grain-size (Fig. 2A, B, D, E, F). MPEL according to grain-size scale (Wentworth, 1922) range from silt (siltstone, clay, mud) to very fine-grained sand (grain-size less than 0.0625 mm). MPEL are fine-schistose and often have the darker colour as MPSA caused by the higher content of chlorite, biotite and frequently organic pigment (Fig. 2A). In MPEL the millimetre lamina with prevalence of quartz-plagioclase frequently alternate with lamina having prevalence of sericite ± organic pigment. Because the granularity of MPSA usually varies between 0.2-0.5 mm, they correspond to medium- to coarse-grained sandstones. The lighter colour of MPSA is caused by the prevalence of quartz and plagioclase in their composition. MPSA have often the augen (eye-shaped) structure - individual augens are formed by plagioclase and quartz, having character of former clasts and usually they are present in fine-grained matrix (Fig. 2B). Sporadically the polymineral clasts are also present consisting of plagioclase (with indications of former zonal setting) and quartz. Metapelitic and metapsammitic structures are the most common in phyllites. The characteristic minerals of phyllites are represented by chlorite, sericite, quartz, plagioclase and biotite. Zircon, apatite, tourmaline and ore minerals are the dominant accessories.

Gneisses (G). Former pelitic-psammitic sediments metamorphosed to amphibolite facies were originally included among gneisses. Banded structures in gneisses are scarcer than in phyllites. The finer-grained matrix (granularity below 0.0625 mm), formed by quartz, plagioclase and muscovite, alternates with coarser-grained matrix (0.2-0.5 mm) of the same composition. Lepidogranoblastic, granoblastic, porphyroblastic and fibroblastic structures are the most common in gneisses. The characteristic minerals of gneisses are represented by biotite, muscovite, garnet, staurolite, sillimanite, plagioclase and quartz (Fig. 2C) with accessory minerals of zircon, apatite, tourmaline and ore-minerals.

***The contact metamorphosed rocks (CMR** = hornfelses, spotty phyllites and spotty gneisses)* often have well preserved relics of former sedimentary structures and metamorphic minerals of regionally metamorphosed metapelites (more often) and metapsammites. They differ from regionally metamorphosed rocks mainly by more massive texture and typical spotted structure (Fig. 2D). The main minerals of hornfelses include biotite, muscovite, cordierite, andalusite, plagioclase and quartz. Biotite, muscovite, plagioclase and quartz usually form the fine-grained matrix of hornfelses. Porphyroblasts of cordierite and andalusite (dimensions up to 1 cm) poikilitically enclose minerals of fine-grained matrix.

Black schists (BS1) are petrographically similar to the finest-grained phyllitic fraction (MPEL) outcropping in the Pezinok-Pernek crystalline basement and in the Harmónia Series. BS1 differ from MPEL only by the darker colour caused by the content of organic pigment (up to 5 % C_{org} according to Cambel and Khun, 1983) and by the relatively higher content of sulphides (Fig. 2E).

Black schists (BS2). Black schists of the so-called productive zones Cambel (1959) are included in this group. The BS2 are represented by the very fine-grained (less than 0.06 mm) rocks usually demonstrating detail lamination. They can be divided into three subgroups: (1) very fine-grained black schists (BS2a) characteristic with very thin lamination without more distinct presence of basic material ± sulphides. In the scale of thin section the 0.0X mm thick lamina with dominant quartz and lamina with prevalence of sericite containing disseminated organic pigment are alternating (Fig. 2H), (2) very fine-grained metacherts (BS2b) dominated by quartz and also containing organic pigment ± amphibole ± sericite ± sulphides, and (3) very fine-grained black schists with the presence of altered mafic rocks (BS2c),


A
B
C
D
E
F
G
H

having a very fine-grained matrix composed mainly of sericite, quartz, organic pigment, amphibole, epidote, sulphides ± carbonate.

Geochemistry

Chemical analyses for the geochemical study of the Malé Karpaty metamorphosed sedimentary rocks in our study were used from several sources (Cambel and Khun 1983, Cambel et al. 1990, Ivan et al. 2001 and our original chemical analyses - see Table 1).

Major element geochemistry. The initial geochemical approach to study the nature of the source area and the tectonic setting of the depositional basin was attempted using discrimination plots based on major elements composition of the Malé Karpaty Mts. (MK) metamorphosed sedimentary rocks. SiO_2 (64 wt.%) and Al_2O_3 (15 wt.%) contents divide the phyllites of the MK into two groups – metapelites and metapsammites (Fig. 3). From the distribution of samples in the plot, it is obvious that the protolith suffered neither intensive weathering nor sorting. One of the main factors of variability in composition of

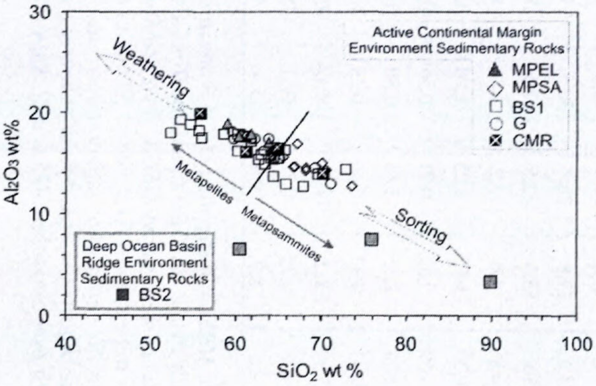


Fig. 3. Plots of Al_2O_3 vs. SiO_2 for the Early Paleozoic metamorphosed sedimentary rocks from the Malé Karpaty Mts. ACMESR = the Active Continental Margin Environment Sedimentary Rocks: MPEL = metapelites, MPSA = metapsammites, G = gneisses, CMR = contact metamorphosed rocks, BS1 = black schists from the Pezinok-Pernek crystalline complex and from the Harmonia Series (after Cambel l.c.). DOBRESR = the Deep Ocean Basin Ridge Environment Sedimentary Rocks: BS2 = black schists from "productive zones". (Analyses in Table 1.)

of observed oxides is the granularity of studied samples. The majority of fine-grained samples (MPEL and BS1) have higher contents of Al_2O_3 and the coarser-grained samples (MPSA) have the higher contents of SiO_2. The higher contents of Al_2O_3 are a result of the relatively higher content of clayey minerals in finer-grained protolith of MPEL and BS1. The samples BS1 occur in the whole range of values of these oxides and together with the samples MPEL & MPSA, G and CMR they form **the first geochemical group**. The presence of organic matter also in MPEL as well as in MPSA indicates the quick transport and burial of the protolith of metamorphosed sedimentary rocks from one source area. We suppose that samples with the position in the immediate surrounding of the boundary dividing MPEL and MPSA have a composition close to composition of the parental rocks. **The second geochemical group** is formed by black schists outcropping in so-called productive zones (BS2) having distinctly different contents of SiO_2 and Al_2O_3. It indicates another protolith and another the source area than in the case of the first group.

The metamorphosed sedimentary rocks of the first geochemical group form in geochemical classification plot for sediments (Herron, 1988) the relatively homogenous field with position corresponding to greywackes and shales (Fig. 4). MPSA have the higher values log SiO_2/Al_2O_3 as MPEL and black schists (BS1) at comparable values log Fe_2O_3/K_2O. The gneisses (G) have in this geochemical classification plot essentially the same position as phyllites and CMR. The metamorphosed sedimentary rocks of second geochemical group (BS2) had evidently different protolith.

In geochemical classification plot for sediments (Garrels and McKenzie, 1971) the metamorphosed sedimentary rocks of the first geochemical group demonstrate the position in the compositional fields of lithic arenites and greywackes (Fig. 5). The parameter (Na+Ca)//Na+Ca+ K) well divides the MPSA and MPEL and is relatively higher in MPSA. The gneisses have in this plot the same position as phyllites. The black schists (BS1) and contact metamorphosed rocks (CMR) demonstrated comparable parameters with MPEL. The metamorphosed sedimentary rocks of the second geochemical group (BS2) manifest

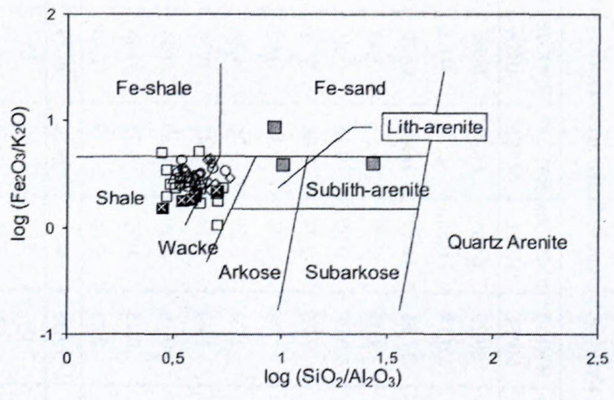


Fig. 4. The major element chemical classification plot of the terrigenous clastic rock types (after Herron, 1988) for metamorphosed sedimentary rocks from the Malé Karpaty Mts. Explanations in Fig. 3

Fig. 2. The Early Paleozoic metamorphosed sedimentary rocks of the Malé Karpaty Mts. - the Pezinok Group: 2A = metapelite (sample RMK-36a), 2B = metapsammite (sample RMK-36b), 2C = gneiss (sample RMK 33), 2D = spotted metapelite (sample RMK 64), 2E = black schist (BS1) from Pezinok Group (sample RMK-17). The Pernek Group: 2F = metachert (BS2b) sample RMK-13, 2G = actinolite schist (BS2c) sample RMK 03-23, 2H = black schist (BS2a) sample RMK 04-23. Scale in all figures is 1 mm.

Table 1. Representative chemical analyses of metamorphosed sedimentary rocks of the Malé Karpaty Mts.

	RMK-13 chert	RMK-5b MPEL	RMK-16 MPEL	RMK-22 MPEL	RMK-36a MPEL	RMK-49 MPEL	RMK-18 MPSA	RMK-5a MPSA	RMK-36b MPSA	RMK-40 MPSA	RMK-52 MPSA	RMK-2 G	RMK-26 G	RMK-31 G	RMK-43 G	RMK-58 G	RMK-60 G	RMK-67 CMR	RMK-69 CMR
SiO_2	89,78	59,00	61,79	60,29	63,85	64,47	70,06	67,21	73,63	70,45	68,16	69,15	64,64	61,83	60,79	65,13	63,26	55,70	61,07
TiO_2	0,22	0,89	0,88	0,78	0,68	0,78	0,63	0,82	0,45	0,62	0,68	0,64	0,84	0,75	0,70	0,85	0,77	0,95	0,72
Al_2O_3	3,35	18,98	17,86	17,61	16,97	16,43	15,00	16,95	12,70	14,31	14,51	14,48	16,29	17,41	17,87	15,42	16,16	19,98	16,24
Fe_2O_3tot	0,47	6,21	6,73	8,07	6,39	5,57	3,43	5,00	3,99	4,27	4,33	5,15	6,30	7,09	7,20	5,79	6,00	6,39	6,95
MnO	0,02	0,07	0,04	0,08	0,05	0,15	0,03	0,06	0,04	0,05	0,06	0,07	0,08	0,11	0,12	0,13	0,09	0,07	0,11
MgO	0,49	2,85	2,34	3,26	2,24	2,00	1,74	1,83	1,47	1,62	2,32	2,13	2,42	2,86	2,83	2,23	2,28	3,08	2,51
CaO	0,62	2,11	0,79	1,76	0,39	1,36	0,92	1,61	0,43	1,25	0,78	2,88	1,29	1,37	1,77	2,17	2,77	0,95	1,54
Na_2O	0,29	5,43	3,27	2,20	3,35	3,76	4,86	3,90	3,33	3,57	3,65	2,78	2,72	2,67	2,99	4,10	3,58	5,34	2,70
K_2O	0,12	2,15	2,58	2,69	2,24	2,47	0,78	1,72	1,38	1,68	1,93	1,43	2,81	2,11	2,93	1,80	2,28	4,19	3,71
P_2O_5	0,03	0,17	0,14	0,16	0,20	0,19	0,08	0,15	0,14	0,13	0,13	0,14	0,18	0,20	0,19	0,18	0,18	0,19	0,27
H_2O	0,73	0,70	0,95	0,45	0,72	0,55	0,46	0,40	0,42	0,62	0,71	0,42	0,53	0,30	0,71	0,69	0,54	0,39	0,96
LOI	4,80	1,41	2,93	2,23	2,68	1,79	1,30	0,93	1,87	1,69	2,09	1,12	1,59	2,66	1,96	1,77	1,55	1,44	2,62
Total	100,92	99,97	100,30	99,58	99,76	99,52	99,29	100,58	99,85	100,26	99,35	100,39	99,69	99,36	100,06	100,26	99,46	98,67	99,40
Sc	7	17	20	19	18	16	13	13	12	14	15	13	17	19	20	15	17	20	16
Hf	2,0	5,5	4,7	3,2	5,3	5,0	5,8	6,2	5,3	5,5	5,2	6,3	5,1	4,9	4,9	5,9	5,1	5,1	4,7
Ta	0,35	0,81	0,64	0,70	0,78	0,74	0,55	0,62	0,60	0,60	0,62	0,53	0,69	0,79	0,82	0,68	0,83	0,94	0,97
Th	2,5	9,7	7,6	7,7	8,3	9,0	8,3	7,0	7,4	7,4	9,0	7,4	7,5	8,9	8,0	10,1	8,7	11,2	10,0
La	3,7	28	21,5	28,2	28	28,2	28,7	23,2	27,8	28,7	30,5	25,6	29,2	27	26,5	25,6	27,9	39	33,5
Ce	7,3	67	49,5	62	64	68	64	56	63,5	62,5	67,5	57	67,5	62	62,5	63	67,5	97,5	79
Sm	1,1	6,4	4,2	5	5,6	6,2	4,3	4,8	4,9	5,2	4,9	4,1	5,5	5,8	5,4	5,7	6	6,3	5,8
Eu	0,29	1,70	1,05	1,30	1,20	1,35	1,15	1,20	1,15	1,25	1,20	1,05	1,35	1,30	1,35	1,30	1,35	1,30	1,30
Tb	0,22	0,93	0,60	0,65	0,76	0,89	0,56	0,69	0,63	0,71	0,56	0,55	0,77	0,85	0,82	0,77	0,85	0,93	0,71
Yb	1,30	2,50	2,10	1,95	2,55	2,80	1,70	2,05	2,15	2,15	1,80	1,80	2,45	2,50	3,00	2,90	2,90	3,30	2,50
Lu	0,28	0,56	0,48	0,39	0,49	0,54	0,32	0,43	0,37	0,46	0,38	0,32	0,49	0,55	0,53	0,48	0,50	0,54	0,52
REE_{tot}	14,19	107,09	79,43	99,49	102,6	107,98	100,73	88,37	100,5	100,97	106,84	90,42	107,26	100	100,1	99,75	107	148,87	123,33
Eu/Eu*	0,75	0,82	0,78	0,83	0,68	0,68	0,85	0,78	0,75	0,76	0,81	0,81	0,77	0,69	0,77	0,72	0,70	0,64	0,73
La_N/Yb_N	1,9	7,6	6,9	9,8	7,4	8,0	11,4	7,6	8,7	9,0	11,4	9,6	8,0	7,3	6,0	6,0	6,5	8,0	9,0

Explanations: major oxides in wt.%, trace elements in ppm, LOI = loss on ignition, MPEL = metapelite, MPSA = metapsammite, G = gneiss, CMR = contact metamorphosed rocks.
All major elements were determined by XRF method, H_2O and LOI gravimetrically by the UNIGEO Company, Brno, Czech Republic. The analyses of the other elements were performed by the INAA using the slightly modified method by Kotas and Bouda (1983) in laboratories of the company MEGA, Stráž pod Ralskem, Czech Republic.
***Location of the samples in Table 1:** RMK-2 - gneiss, Kuchyňa village, northern slope of the Výrvať valley, 500 m a.s.l., outcrop in a road cutting. RMK-5a - metapsammite, Kuchyňa village, northern slope of the Výrvať valley, 500 m a.s.l., outcrop in a road cutting. RMK-5b - metapelite, adjacent layer near the position of sample RMK-5a. RMK-13 - metachert, Kuchyňa village, Modranský potok valley, 0.5 km south from Kuchynský revír, RMK-16 - metapelite, Kuchyňa village, Výrvať valley, east from Ostrý hill, east from the altitude 418, 410 m a.s.l. RMK-18 - metapsammite (the same location as sample RMK-16), RMK-22 - metapelite, 150 m west from Šingráben, 475 m a.s.l. RMK-26 - gneiss, road Pernek-Baba, 300 m south-east from Mäsiarsky ostrovec,*

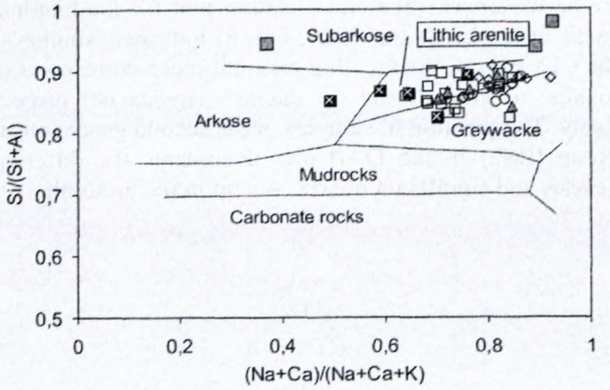


Fig. 5. The major element chemical classification plot of the sedimentary rocks (after Garrels & McKenzie, 1971, range value in molecular proportions). Explanations in Fig. 3.

the large dispersion of values (Na+Ca)//Na+Ca+K) and higher values of Si/(Si+Al), which indicates the higher quartz content in the protolith.

Paleoweathering conditions. The range of chemical changes caused by the weathering in source area or during transport of sediments into the sedimentary basin is expressed by the paleoweathering index (CIA=100* [Al_2O_3/(Al_2O_3+CaO*+Na_2O+K_2O)] all in molecular proportions and CaO* represents the CaO in silicate fraction only; Nesbitt and Young, 1982; Fedo et al., 1995). The low CIA values (50–60) indicate the absence or poor chemical weathering in the source area. For medium phase of weathering the values CIA 70–75 are characteristic, the higher CIA values demonstrate the intensive chemical weathering (Nesbitt and Young, 1982; Fedo et al., 1995). The low CIA values of metamorphosed sedimentary rocks of the first geochemical group indicate the absence (or near absence) of chemical weathering in the source area (Fig. 6). The higher CIA values in MPEL relative to MPSA can be explained by the relatively higher clay ratio in finer-grained protolith resulting from depositional sorting. From the intersection point of the trend formed by samples of this group with the line between Plg and K-feldspar it can be supposed that composition of rocks in the source area was similar to tonalite/dacite. The corrected values of CIA (pre-metasomatic) have ranged from 55-70 and from calculated values they more distinctly differ only by insignificant

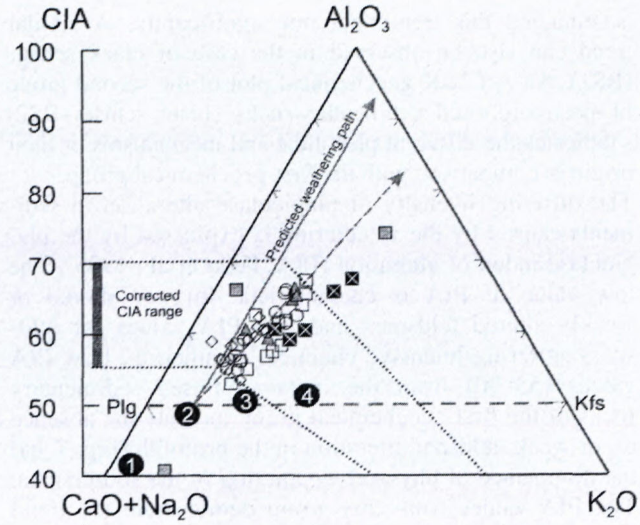


Fig. 6. A–CN–K ternary plot for the metamorphosed sedimentary rocks from the Malé Karpaty Mts. Pre-metasomatized CIA values can range from ~50 for fresh primary igneous rocks to a maximum of 100 for the most weathered rocks (Fedo et al., 1995). Average data of gabbro (1), tonalite (2), granodiorite (3) and granite (4) taken from Le Maitre (1976). Dash line = trend of the weathering of the protolith. Explanations in Fig. 3.

number of samples (mainly in the case of CMR). The MPSA lies close to supposed weathering trend and their computed and corrected CIA values are nearly identical. It indicates the minimum influence of MPSA by K-metasomatism. This fact confirms the assumption that chemical composition of MPSA closely corresponds with the composition of parental rocks. Gneisses (G) have a range of CIA values, as well as a range of corrected CIA values, similar to phyllites. This indicates the influence of metamorphism and metasomatism on distribution of discussed chemical elements is insignificant. The position of MPEL in the A-CN-K ternary plot farthest from the supposed weathering trend towards K_2O can be caused by relatively higher content of clays in the fine-grained protolith, or it can be a result of K-metasomatism. CMR have the CIA range values similar to MPEL. CMR have corresponding granularity like MPEL, so we suppose, that higher K_2O contents in MPEL and in CMR are caused mainly by relatively higher presence of clays in fine-grained protolith. It is possible that K-metasomatism has

over the road curve. RMK-31 - gneiss, Pernek village, east slope of the Klokočina, outcrop. RMK-36a metapelite, Častovská valley, 300 m south-east from Dolina house, 410 m a.s.l. RMK-36b - metapsammite, adjacent layer near position of the sample RMK-36a. RMK-40 - metapsammite, Častovská valley, 300 m south-east from two quarries, 335 m a.s.l. RMK-43 - gneiss, near Pernek village, east slope of the Klokočina. RMK-49 - metapelite, Dubová, east of the Fúgelka. RMK-52 - metapsammite, south-west from Pezinok village, Šalátová, 390 m a.s.l. RMK-58 - gneiss, Píla village, Kobylská valley, Papiernička, 300 m to north. RMK-60 - gneiss, Píla village, Kobylská valley, Papiernička, 300 m to north, contact with granite. RMK-67 - spotted metapelite, Harmónia village, Dolinkovský hill, valley on the south-west slope. RMK-69 spotted metapelite (same location as the sample RMK-67).

***Sources of the other chemical analyses.** The group "MPSA" samples RMK: 41, 45, 47, 53, 61 are from the work by Ivan et al. (2001), Table 2. The group "G" samples RMK: 1, 3, 10, 28, 33 are from the work by Ivan et al. (2001), Table 2. The group "CMR" included the samples RMK: 39, 64, 65 from the work by Ivan et al. (2001), Table 2. The group "BS1" had enlisted the samples from the work by Cambel et al. (1990; 31/63-JV, KV-43/368, KV-43/20, KV-43/10, 176-B, 179A, 181A, 182B, 187A) and samples from the work by Cambel and Khun (1983; 13A, 19A, 26A, 11-C, KV-43/423, 175A, 177B, 178A, 183B, 184A, 21/63-JV, 185A). The group "BS2" included the samples from the work by Cambel and Khun (1983): the subgroup BS1a = samples 41A, 47B, 53B, 54A, 60A, 61A, 62A, 70B, 145A, 164A, 165B, 166A, 170A, 171A, 173A, 174A, samples BS1b = samples 57A, 172A.*

Slovak Geol. Mag., 11, 2 – 3 (2005), 107 – 122

accentuated this trend, but not significantly. A similar trend can also be observed in the case of black schists (BS1). An A-CN-K geochemical plot of the second group of metamorphosed sedimentary rocks - black schists (BS2) - indicates the different protoliths and mechanisms of their origin in comparison with the first geochemical group.
The differing intensity of plagioclase alteration in sediments caused by the weathering is expressed by the plagioclase index of alteration (PIA, Fedo et al., 1995). The low value of PIA is characteristic for non-altered or weakly altered feldspars and high PIA values for feldspars suffering intensive chemical weathering. Low PIA values (55–70) from the metamorphosed sedimentary rocks of the first geochemical group indicate the absence of, or weak, feldspar alteration in the protolith (Fig. 7 and the dominance of physical weathering in the source area. The PIA values from this group demonstrate the trend from labradorite to albite. This trend is distinct mainly in samples MPSA, having the lowest values of CIA as well as PIA values. This trend can theoretically reflect also the magmatic fractionation of feldspars in former plutonic/volcanic (?) parental rocks. The position of MPEL is, in comparison with MPSA, closer to the Al_2O_3-K_2O peak. It is a result of relatively more intensive alteration of plagioclases and confirms the assumption about the relatively higher clay content in MPEL protolith. The PIA values of the metamorphosed sedimentary rocks of the second geochemical group indicate different genesis of the protolith.

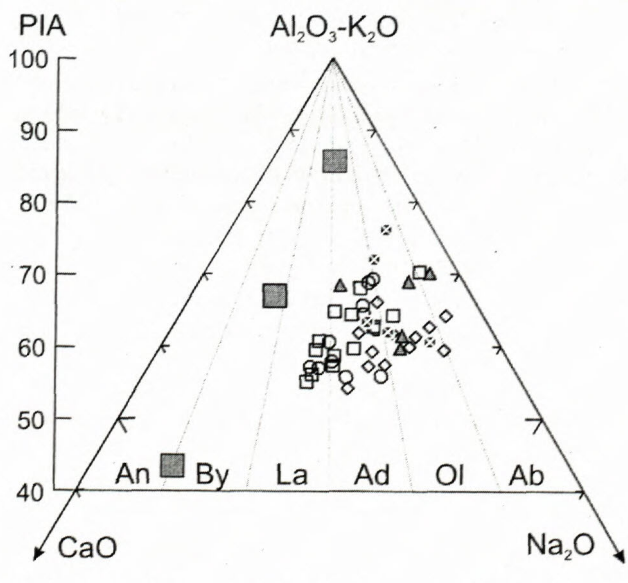


Fig. 7. (A–K)–C–N ternary plot for the studied rocks. Compositions: Ab = albite, Ol = oligoclase, Ad = andesine, La = labradorite, By = bytownite, An = anorthite (Fedo et al., 1995). Explanations in Fig. 3.

The indices about the siliciclastic protolith, which could correspond in composition with the parent rocks mainly in the case of the first geochemical group of metamorphosed sedimentary rocks of the MK, led us to testing of chemical composition in classification schemes for plutonic and volcanic rocks. The position of metamorphosed sedimentary rocks of the first geochemical group in the mesonormative classification plot for the plutonic rocks QAP (LeMaitre, 1989, Fig. 8) indicates, similar to the CIA values, the fact that parental rocks correspond to tonalite to granodiorite (or dacite - rhyodacite) respectively. The position of samples of the second geochemical group (BS2) in the QAP plot documents the different genesis and significant quartz content in the protolith.

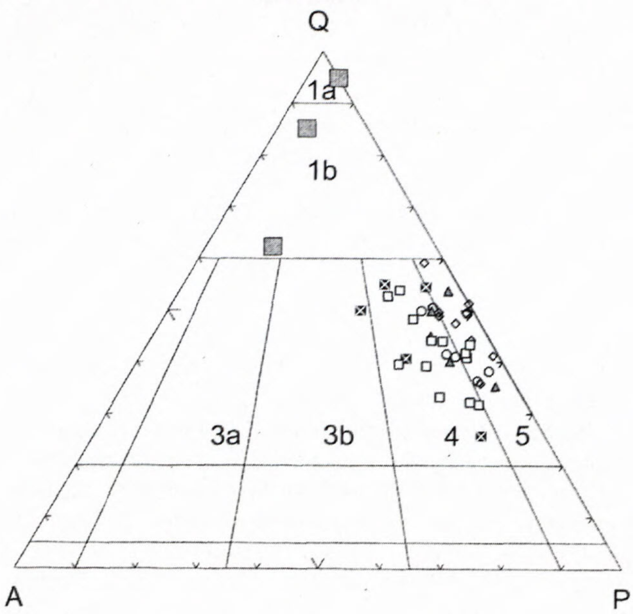


Fig. 8. The metamorphosed sedimentary rocks from the Malé Karpaty Mts. in the QAP mesonormative classification plot for plutonic rocks (LeMaitre, 1989): 1a - quartzolite, 1b - quartz-rich granitoids, 3a - syeno-granite, 3b - monzo-granite, 4 - granodiorite, 5 - tonalite. Explanations in Fig. 3.

Trace element geochemistry. The High Field Strength Elements (HFSE) and certain trace elements have proved to be very useful for provenance and tectonic setting discrimination (Bhatia and Crook, 1986; Cullers, 1995). Particularly, Th, Zr, Sc, Ti, La, Ce, Nd, Hf, Nb, and Y are the most suited for provenance and tectonic setting determinations because of their relatively low mobility during sedimentary processes and their low residence time in sea water (Taylor and McLennan, 1985).

Variable contents of Th and U in metamorphosed sedimentary rocks of the Malé Karpaty Mts. indicate variable oxidation-reduction conditions during their sedimentation (Cambel et al., 1981; Cambel and Khun, 1983, 1985). Relatively high values of the ratio Th/U (>1) at higher contents of Th (>5 ppm) and lower contents of U (>5 ppm) in metamorphosed sedimentary rocks of the first geochemical group indicate oxidizing conditions during sedimentation. The similar Th/U ratio and Th range of the values also indicates a common source area and the same parental rocks. It is also confirmed by the similar range of Th/U ratios in metamorphosed sedimentary rocks of this group and in metabasalts of E-MORB type from the Malé Karpaty Mts. (Ivan et al., 2001).

Low contents of Th (<5 ppm) and high contents of U (5-60 ppm) in metamorphosed sedimentary rocks of the second geochemical group indicate reducing conditions present during sedimentation. The similar range of Th/U ratios in metamorphosed sedimentary rocks of the second geochemical group and metabasalts of N-MORB type indicates the synchronous basic volcanism during sedimentation of the protolith of metamorphosed sedimentary rocks of this group.

The La/Sc ratio in very fine-grained siliciclastic sediments correspond well with the average La/Sc ratio in the source area of sedimentary rocks (Cullers 1995). The metamorphosed sedimentary rocks of the first geochemical group have a positive correlation of La/Sc and Th/Sc, higher values La/Sc (> 1) and Th/Sc (> 0.25) compared to metamorphosed sedimentary rocks of the second geochemical group and have a relatively tight span of range of the values of Th and La/Sc ratio (1-3, Fig. 9). Such values are close to the average value of sediments from the continental island arc (La/Sc = 1.8; Bhatia and Crook, 1986). The range of values of La/Sc and Th/Sc ratios in metamorphosed sedimentary rocks of the first geochemical groups indicates the prevalence of intermediate island arc sources (La/Sc around 1; Th/Sc <0.5) and have trend to acid island arc sources (expressed with arrow, La/Sc ~ 6; Th/Sc ~ 2). The metamorphosed sedimentary rocks of second geochemical group have prevailingly lower values of the ratio La/Sc (<1). Such values are similar to sediments from oceanic island arcs (Bhatia and Crook, 1986). In the case when the La/Sc ratio in metamorphosed sedimentary rocks of the second group is higher, this group is discriminated from the first by lower Th/Sc ratio. The range of the ratios La/Sc vs. Th/Sc in metamorphosed sedimentary rocks of the second group indicates the substantial influence of a mafic source in the chemical composition of protolith. It is documented by the range of the La/Sc ratio and Th/Sc ratio in subgroups BS2a and BS2c which are very similar to these values in metabasalt of N-MORB type (Ivan et al., 2001). The ratios Th/Sc, being lower in all studied samples of metamorphosed sedimentary rocks of MK as in the upper continental crust (UCC= Th/Sc >1, Taylor and McLennan, 1985), indicate that protolith was produced from an immature source area.

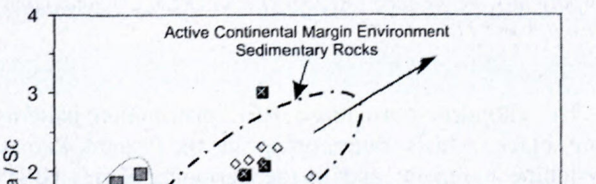


Fig. 9. The metamorphosed sedimentary rocks from the Malé Karpaty Mts. in the plot La/Sc vs. Th/Sc. Explanations in Fig. 3.

First and second geochemical group of MK metamorphosed sedimentary rocks is very well discriminated by values of ratios La/Yb vs. La/Ce (Fig. 10). The higher value La/Yb (8-30) in metamorphosed sedimentary rocks of the first group indicates the higher measure of crustal fractionation of the parental rocks in the source area. At the same time, the lower value of La/Yb (<8) in metamorphosed sedimentary rocks of the second group indicates a less differentiated protolith. The range of the La/Ce values in metamorphosed sedimentary rocks of the second group indicates the measure of Ce depletion in the protolith as a result of interaction by sea water, hydrothermal fluids and basalts of N-MORB type, and their hyaloclastites on the ocean bottom.

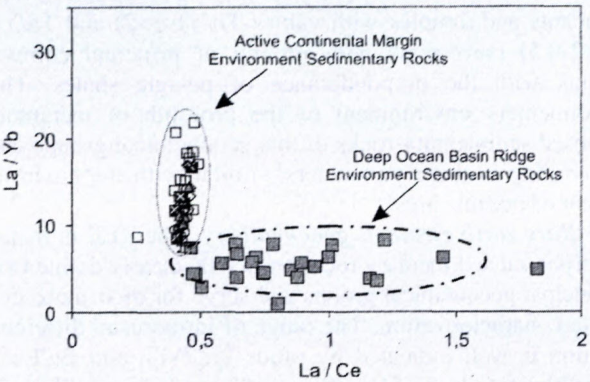


Fig. 10. The metamorphosed sedimentary rocks from the Malé Karpaty Mts. in the plot La/Yb vs. La/Ce. Explanations in Fig. 3.

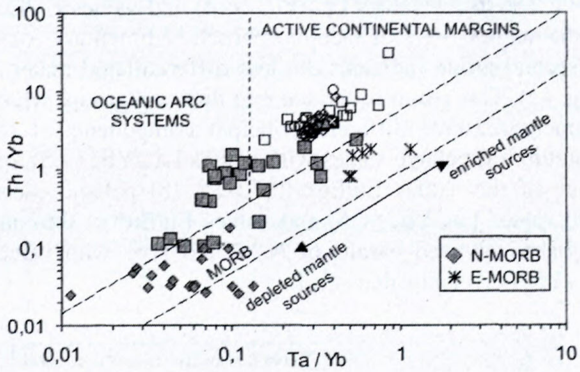


Fig. 11. The metamorphosed sedimentary rocks from the Malé Karpaty Mts. in the plot Th/Yb vs. Ta/Yb. Fields after Cluzel et al. (2001). N-MORB = metabasalts of N-MORB type from Pernek Group, E-MORB = metabasalts of E-MORB type from Pezinok Group (chemical composition of the metabasalts from Ivan et al., 2001). Further explanations in Fig. 3.

The higher values Th/Yb (> 3.5) and Ta/Yb (> 0.2) in plot in Fig. 11 indicate the more felsic parental rocks of the first group of metamorphosed sedimentary rocks including the black schists (BS1). Similar range of Th/Yb values and range of Ta/Yb values are characteristic for rocks, originating in environment of active continental margins. The similarity of this range of values in metamorphosed sedimentary rocks of this group with the range of values in metabasalts of E-MORB type from Pezinok Group (Ivan et al., 2001) shows a common environment of sedimentation. The metamorphosed sedimentary rocks of second geochemical group have lower values of the ratio Th/Yb (< 2) and majority also the

Slovak Geol. Mag., 11, 2 – 3 (2005), 107 – 122

lower values of the ratio Ta/Yb (< 0.2). Part of samples of this group has distinct affinity to values of Th/Yb and Th/Yb typical for metabasalts of N-MORB type. The metamorphosed sedimentary rocks of the second group form in this plot three subgroups, indicating besides the organic matter next three next basic components of the protolith: a) pelagic shales, b) pelagic cherts and c) altered mafic rocks. Samples with values Th/Yb (< 0.3) and Ta/Yb (< 0.1) correspond with altered mafic rocks and pelagic cherts, samples with values Th/Yb (0.3-2) and Ta/Yb (0.3-0.5) correspond with mixing of all three components and samples with values Th/Yb (>2) and Ta/Yb (0.2-0.5) correspond with mixing of principal components with the preponderance of pelagic shales. The sedimentary environment of the protolith of metamorphosed sedimentary rocks of this geochemical group was, according to these parameters, similar with the environment of oceanic arcs.

Rare earth elements geochemistry. The REE in metamorphosed sedimentary rocks from MK clearly define two principal geochemical groups and serve for their more detailed characterization. The range of intracrustal differentiation is well indicated by ratios La_N/Yb_N and Eu/Eu*. The higher values of La_N/Yb_N (> 5) and values Eu/Eu* in the range of the values 0.6-0.9 indicate, that protolith of metamorphosed sedimentary rocks of the first geochemical group represented the more differentiated crustal material. The lower values La_N/Yb_N (< 6) and values Eu/Eu* in the range 0.5-1.1 of metamorphosed sedimentary rocks of second group indicates the less differentiated material (Fig. 12). This group is divided into three subgroups which characterize three different principal components of the protolith: (a) pelagic shales with values La_N/Yb_N (~ 5) and range of the values Eu/Eu* (0.7-0.8), (b) pelagic cherts with values La_N/Yb_N (< 5) and values Eu/Eu* (~ 0,6) and (c) halmyrolytized basalts of N-MORB type with values La_N/Yb_N (< 4) and values Eu/Eu* (~ 1).

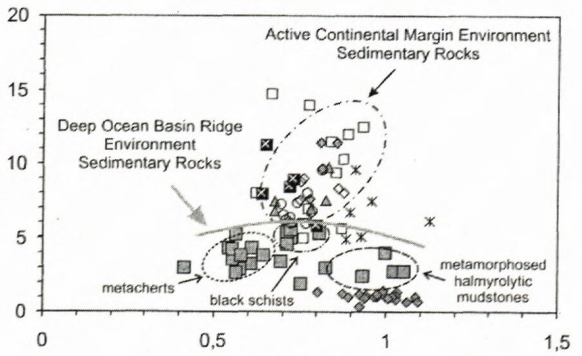


Fig. 12. The metamorphosed sedimentary rocks from the Malé Karpaty Mts. in the plot La_N/Yb_N vs. Eu/Eu. Explanations in Figs. 3 and 11.*

The metamorphosed halmyrolytized basalts (BS2c) have the range of values Eu/Eu* similar with the range of value in metabasalts of N-MORB type (~1). The value Eu/Eu* is in the subgroup of metacherts (BS2b) probably influenced by chemical composition of the sea water. In the subgroup (BS2a) the range of the value Eu/Eu* is influenced mainly by the prevalence of pelagic shales in the protolith (Fig. 12). The presence of chemogenous alternatively organogenous SiO_2 in the protolith of subgroup BS2b also confirms relatively small dispersion of range of values La_N/Yb_N and range of values Eu/Eu*. The generally low values La_N/Yb_N in all samples BS2 can be interpreted as a result of the same environment of protolith sedimentation of metamorphosed sedimentary rocks of this group - the ocean floor.

Also higher values LREE/HREE (ratio > 20) and higher values REE_{tot} (> 80 ppm) in metamorphosed sedimentary rocks of the first group (Fig. 13) indicate a source area with more differentiated parental rocks. It is also confirmed by the affinity of their chemical composition to the composition of metabasalts of E-MORB type. Metamorphosed sedimentary rocks of the second group have low values of both these parameters, which are similar with these values in basalts of N-MORB type. The low values LREE/HREE and REE_{tot} confirm the important ratio of less differentiated material in composition of the protolith of metamorphosed sedimentary rocks of the second group. In the frame of subgroups (a, b, c) the lowest values of LREE/HREE and REE_{tot} are in majority of samples with the prevalence of basic material (BS2c).

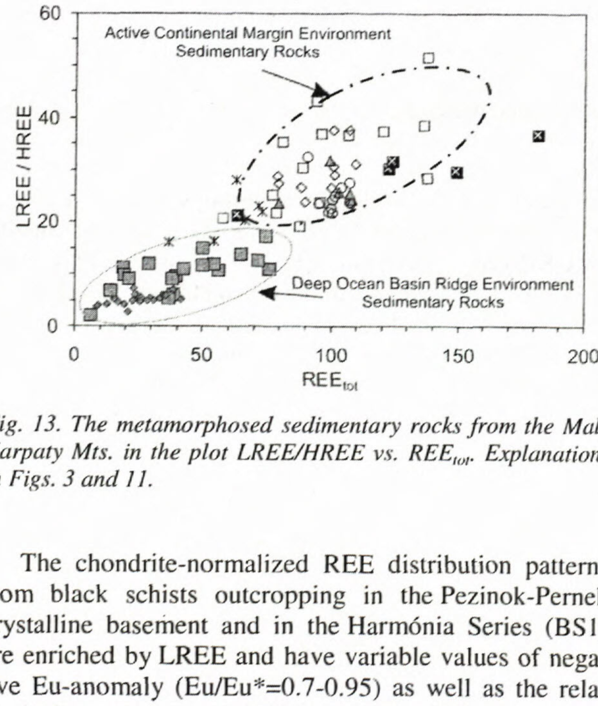


Fig. 13. The metamorphosed sedimentary rocks from the Malé Karpaty Mts. in the plot LREE/HREE vs. REE_{tot}. Explanations in Figs. 3 and 11.

The chondrite-normalized REE distribution patterns from black schists outcropping in the Pezinok-Pernek crystalline basement and in the Harmónia Series (BS1) are enriched by LREE and have variable values of negative Eu-anomaly (Eu/Eu*=0.7-0.95) as well as the relatively lower contents of REE in comparison with PAAS (Fig. 15). Similar REE characteristics (Eu/Eu*, LREE/HREE, ΣREE) in black schists (BS1) with further metamorphosed sedimentary rocks of first geochemical group (MPEL, MPSA, G and CMR, Fig. 14) indicate the differentiated intermediate to acid rocks in common source area.

The chondrite-normalized REE distribution patterns from black schists of the second geochemical group (BS2) distinctly differ from the REE patterns from the black schists of the first group (Fig. 15). The chondrite-normalized REE patterns from BS2a have the distinct negative Ce-anomaly, negative or none Eu-anomaly (Eu/Eu*=0.55-1.05) and have relatively lower content of LREE and higher content of HREE in comparison with BS1.

The PAAS-normalized REE patterns from the samples BS2 (a, b, c) have typical negative Ce-anomaly, positive Eu-anomaly and are depleted by LREE and moderately enriched by HREE. These REE characteristics are known from abyssal marine sediments (Toyoda et al., 1990; Sholkovitz and Schneider, 1991; Holser, 1997; Kato et al., 2002).

The chondrite-normalized REE patterns from metacherts (BS2b, Fig. 15) show characteristic negative Ce-anomaly, negative or none Eu-anomaly and are only

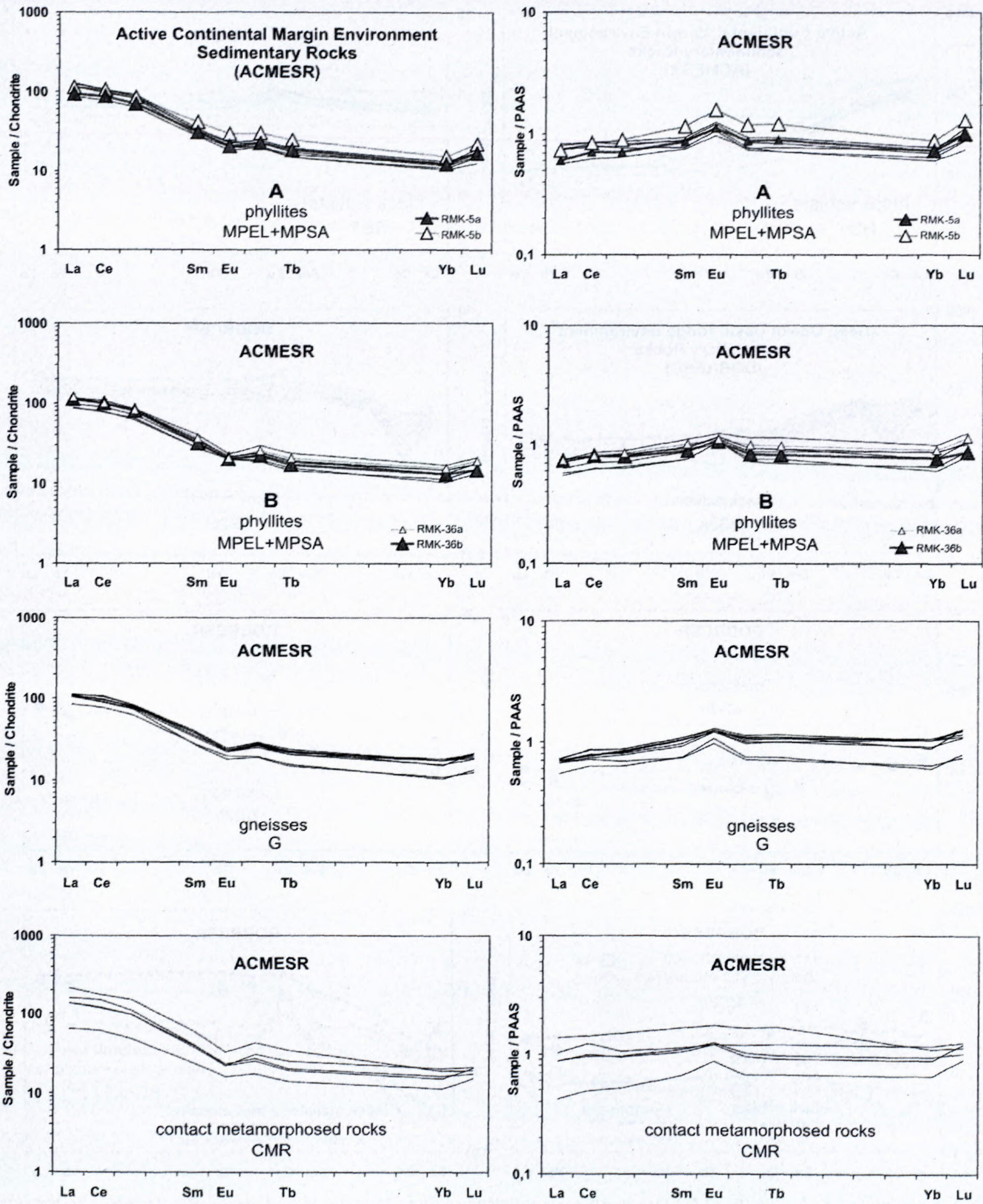


Fig. 14. The normalized REE patterns of the metamorphosed sedimentary rocks from Pezinok Group (after Ivan et al., 2001, in following Figs. too). On the left - the chondrite-normalized REE patterns (Evensen et al., 1988). On the right - the PAAS normalized REE patterns (Taylor & McLennan, 1985).

moderately enriched by LREE. The PAAS-normalized REE patterns from metacherts have a negative Ce-anomaly and show the depletion of LREE in metacherts. In the sample with lower ΣREE the depletion is more distinct and the positive Eu-anomaly (RMK13, 172A) is distinct as in the case of higher ΣREE (RMK 57A). The lowermost ΣREE was found in the case of sample with highest SiO_2 content (RMK13 ~ 90 wt.% SiO_2). Such REE characteristics resemble these characteristics in sea water (Elderfield, 1988; White, 1998) and indicate the presence of chemogenous quartz, which can represent the residual components in halmyrolytically altered volcanic glass (halmyrolytic mudstone). In modern seafloor environments, hydrothermal, hydrogenous, halmyrolytic, and

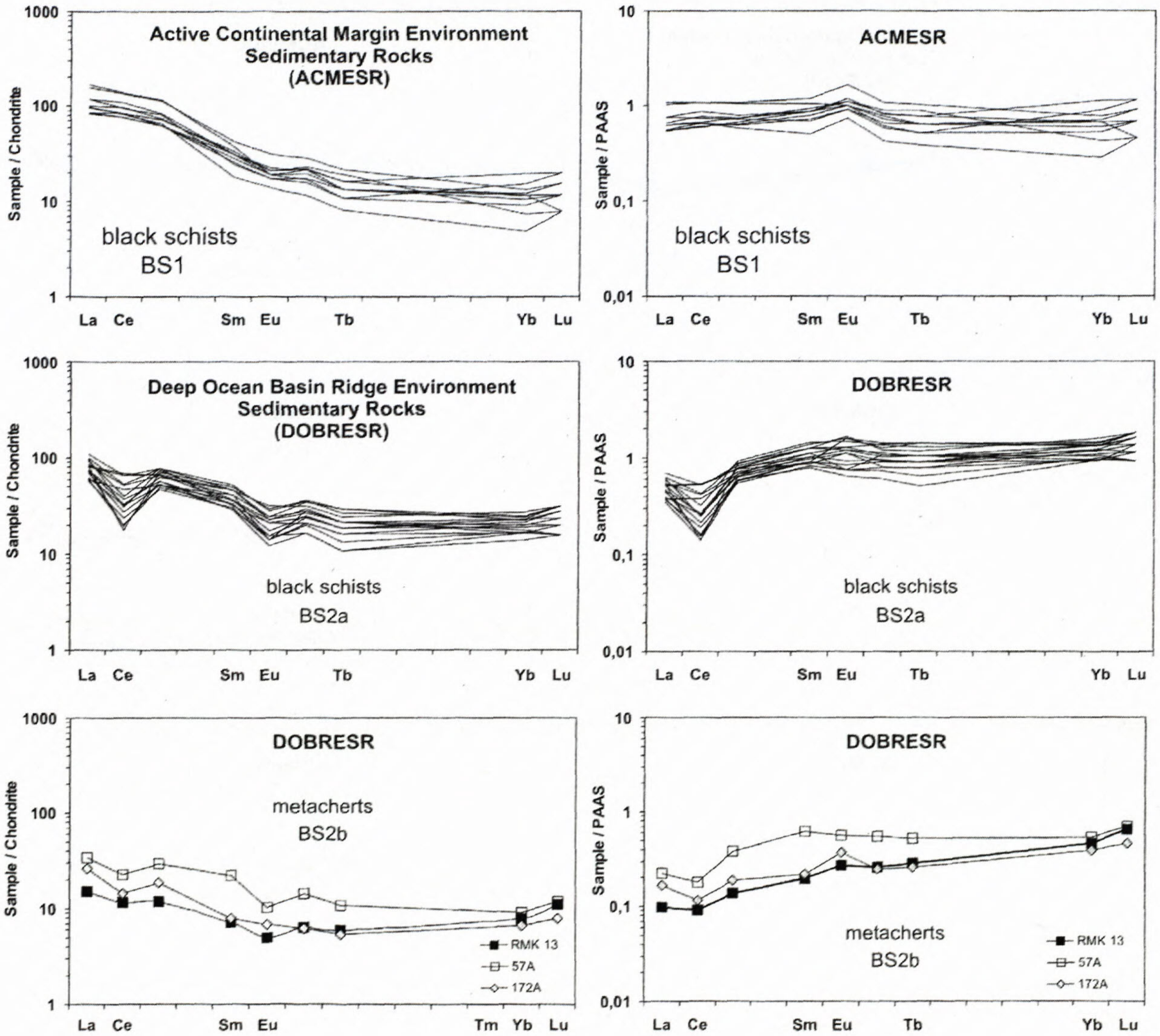


Fig. 15. The normalized REE patterns of the metamorphosed sedimentary rocks from the Malé Karpaty Mts. On the left - the chondrite-normalized REE patterns (Evensen et al., 1988). On the right - the average post-Archean Australian Shale normalized REE patterns (PAAS, Taylor & McLennan, 1985). Pezinok Group: BS1 = black schists, Pernek Group: BS2a = black schists, BS2b = metachert, BS2c = metamorphosed halmyrolytically altered basalts (49A, 52B), typical black schists from Pernek Group (167A and 168A), metabasalts N-MORB types (VMK 1 and VMK 7).

diagenetic processes contribute to the formation of seafloor sediments (Sivell, 2002). Similar REE characteristics are also known from radiolarites (Murray, 1994), which would also be present in the quartz compound of the metacherts protolith.

In plots designated BS2c (Fig. 15) the normalized REE patterns from typical samples of pelagic shales (BS2a) are compared with halmyrolytic mudstone (BS2c) from the second geochemical group of metamorphosed sedimentary rocks of MK with patterns of normalized REE from metabasites of N-MORB type from the Pernek Group (Ivan et al., 2001). Sample 52B (= actinolite schist with sulphides and C_{org} = 1.26 %) represents the former altered basalt hyaloclastite. Sample 49A (= amphibolite with sulphides, C_{org} and carbonates) represents the former altered basalt. Samples 167A and 168A (= black schists from the productive zones) represent the typical pelagic clay (analyses from the work by Cambel and Khun, 1983; Cambel et al., 1985). Sample VMK 1 represents metabasalt of N-MORB type with the highest ΣREE and sample VMK 7 represents metagabbro of N-MORB type with the lowest ΣREE (analyses from the work by Ivan et al., 2001).

Chondrite-normalized REE patterns and PAAS-normalized REE patterns from selected samples BS2c have the position in the range of normalized REE patterns from the metabasites of N-MORB type (between VMK 1 and VMK 7) and will copy the principal characteristics of metabasites (Fig. 15). Chondrite-normalized REE patterns of sample 49A are moderately enriched by LREE, which is caused by the higher content of clay admixture in protolith. The normalized REE patterns of samples BS2c have a typical negative Ce anomaly at both normalizations. The negative Ce anomaly is typical for basalts disintegrated by sea water and hydrothermal solutions in the rift systems (Sivell, 2002). The PAAS-normalized REE patterns from samples BS2c have a positive Eu anomaly; they are depleted by LREE and enriched by HREE. Samples representing the subgroup BS2c are from a geochemical viewpoint similar to halmyrolytically altered hyaloclastites and halmyrolytically altered basalts of N-MORB type (Sivell, 2002). The total variability of REE contents in metamorphosed sedimentary rocks in the second geochemical group is evidently caused by various quantitative content of principal components in protolith of this group of metamorphosed sedimentary rocks: (a) pelagic shales, (b) pelagic chemogenous/organogenous cherts, (c) halmyrolytic muds derived from N-MORB type basites and (d) organic matter.

Chondrite-normalized REE patterns and PAAS-normalized REE patterns from phyllites (MPEL&MPSA), gneisses (G) and from contact metamorphosed rocks (CMR) from various lithostratigraphic units of the Malé Karpaty Mts. (sensu Cambel l.c.) are depicted in Fig. 14. Plot (A) shows phyllites (MPEL&MPSA) connected with the Bratislava massif and the Pezinok-Pernek crystalline basement and plot (B) shows phyllites (MPEL&MPSA) outcropping in the Harmónia Series. The plots of both A and B phyllites depict also pairing of samples from neighbouring beds with differing grain-sizes. In the case of phyllites (A) these are the samples RMK5a (=metapsammite) and RMK5b (=metapelite), in the case of phyllites (B) these are samples RMK36a (=metapelite) and RMK36b (=metapsammite). The small differences in patterns of normalized REE between MPEL and MPSA indicate in both cases the mineralogically and chemically non-mature less sorted protolith, differing mainly by the grain-size (greywackes, lithic arenites). The finer-grained protolith from coarser-grained one differed besides the grain-size only by the relative higher content of clay minerals. In the REE contents it was demonstrated by the relatively higher ΣREE in MPEL, which is typical for the fine-grained fractions (Taylor and McLennan, 1985). The normalization for PAAS (lower ΣREE, positive Eu/Eu*) confirms about the important presence of plagioclases in protolith.

The chondrite-normalized REE patterns from phyllites (A) and from phyllites (B) have the same characteristics: They are enriched by LREE, have negative Eu-anomaly and form relatively tight spectrum of patterns. The PAAS-normalized REE patterns from phyllites (A) and gneisses (B) show also the same characteristics: lower ΣREE as PAAS, positive Eu-anomaly as well as they form relatively tight spectrum of patterns. The normalized REE patterns from the contact metamorphosed schists (CMR) have similar characteristics as phyllites and gneisses, though they form wider spectrum of patterns (Fig. 14).

The same REE characteristics in phyllites and gneisses tied to Bratislava massif and the Pezinok-Pernek crystalline basement (A) and phyllites and gneisses outcropping in the Harmónia Series (B) and in CMR confirm the same source area and protolith in both cases. The higher ΣREE in the case of CMR can be in the context of further until found geochemical characteristics explained as a result of the higher ratio of clays in finer-grained fractions of the protolith and lower ΣREE can be explained by the higher presence of quartz in the protolith of CMR.

Tectonic setting

HFS elements and some trace elements in sedimentary rocks effectively discriminate various types of tectonic settings of sedimentary basins (Bhatia and Crook, 1986). The first geochemical group of metamorphosed sedimentary rocks of MK has a range of La, Th and Sc values characteristic for continental island arcs (Fig. 16). The range of values for La, Th and Sc from the second geochemical group are similar to rocks from oceanic island arcs and they indicate the oceanic sedimentary environment (Fig. 17).

Metamorphic effect

During geochemical analysis we also observed the distribution of all studied chemical elements from the viewpoint of influence of regional and contact metamorphism. The immobility of these chemical elements is confirmed by their comparable contents (range of values, ratios, trends) in differently metamorphosed metamorphosed sedimentary rocks of the first geochemical group:

Slovak Geol. Mag., 11, 2 – 3 (2005), 107 – 122

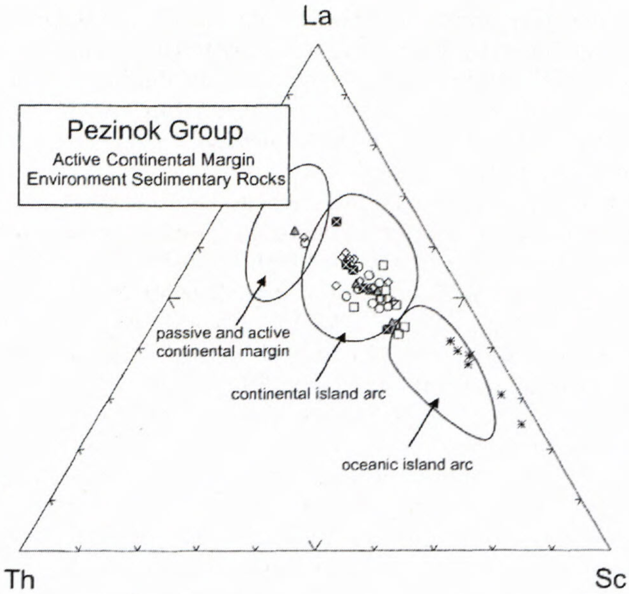


Fig. 16. Plot of the metamorphosed sedimentary rocks of the Pezinok Group in the tectonic discrimination plot La–Sc–Th for discrimination of the tectonic setting of sandstones (after Bhatia and Crook, 1986). Explanations in Figs. 3 and 11.

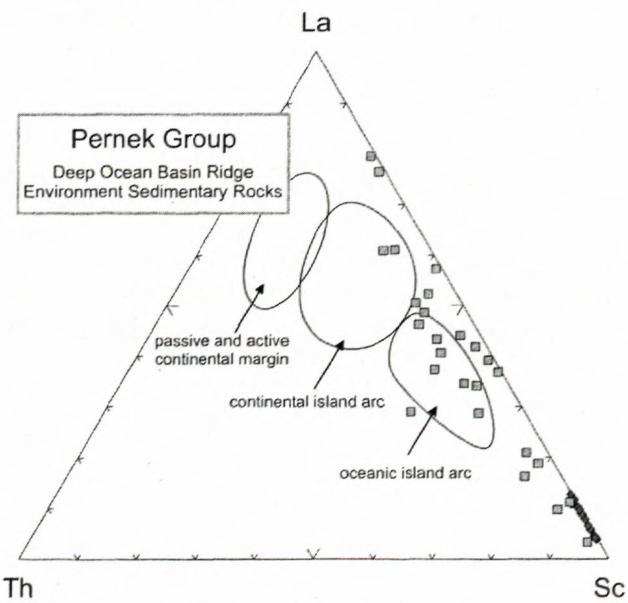


Fig. 17. Plot of the metamorphosed sedimentary rocks of the Pernek Group in the tectonic discrimination plot La–Sc–Th for discrimination of the tectonic setting of sandstones (after Bhatia and Crook, 1986). Explanations in Figs. 3 and 11.

in phyllites, gneisses and contact metamorphosed rocks. In all plots the differently metamorphosed rocks have always position in the whole range of values. It shows on it, that these geochemical parameters express the pre-metamorphic distribution. As an exception there would be CMR with relatively high K_2O content, which could be expressed also by biotitization, which is typical for CMR. The most probable reason of high K_2O contents in CMR is probable the higher ratio of clays in fine-grained protolith. In favour of such interpretation is also the petrographic character of these samples: they represent in all cases the very fine-grained rocks (Fig. 2D).

Synthesis and conclusions

The paleoreconstruction of pre-metamorphic development of metamorphosed sedimentary rocks is complex due to great petrographic and geochemical variability. Among the most important of variables are the composition of parental rocks, type and intensity of weathering in the source area, transport, sorting, environment of sedimentation, and mobility/immobility of chemical elements during diagenesis and metamorphism. The complex chemical analyses of metamorphosed sedimentary rocks (main oxides, trace elements and REE) provided objective qualification and quantification of these processes. For the paleoreconstruction of metamorphosed sedimentary rocks from the Malé Karpaty Mts., we used only those geochemical characteristics which were not significantly affected by element mobility during regional or contact metamorphism. The petrographic characteristics of metamorphosed sedimentary rocks of MK indicate the variability in protolith composition in individual lithological members. Only the petrographic characteristic of the metamorphosed sedimentary rocks generally, without more detail geochemical analysis, does not serve precise identification about variable origin of theese rocks. It is very well confirmed by the black schists (BS1 and BS2) from the Malé Karpaty Mts. Their differing protolith and origin was investigate only by detail geochemical study.

In the Early Paleozoic crystalline basement of the Malé Karpaty Mts. the geochemical study of metabasites and part of metamorphosed sedimentary rocks allows the definition of two pre-metamorphic lithostratigraphic groups: Pezinok and Pernek Groups (Ivan et al., 2001). In this work, we divided these metamorphosed sedimentary rocks by petrographic study, geological position and geochemical study, and also into two principal geochemical groups. The metamorphosed sedimentary rocks of the first geochemical group are a part of the Pezinok Group and metamorphosed sedimentary rocks of the second geochemical group are a part of the Pernek Group (in the sense of Ivan et al., 2001). These geochemical groups differ by the source area, protolith and the sedimentary environment.

Metamorphosed sedimentary rocks of the Pezinok Group protolith evidently came from the same source area. This protolith represented the Active Continental Margin Environment Sedimentary Rocks (ACMESR). The weak chemical weathering of the source area (low range of CIA and PIA values), accelerated transport (geochemical and mineralogical non-mature weakly sorted protolith) and rapid burial (the presence of organic matter) show that protolith of ACMESR was similar to greywackes and lithic arenites ± organic matter. The geochemistry of parent rocks in the source area resembled tonalite-granodiorite (or dacite–rhyodacite) respectively. The geochemical composition ACMESR is variable, values of ratio Th/U (>1), negative Eu anomaly (0.5-0.9), ratio Th/Sc (0.3-0.8), values La_N/Yb_N (> 5) and values Eu/Eu^+ (0.6-0.9) La_N/Yb_N indicate the components derived from the Young Differentiated Arc provenance type (YDA, McLennan et al., 1993; Girty et al., 1996). The YDA province included the young (derived from the mantle) volcanic and plutonic rocks from the island and continental arcs, which underwent significant intracrustal differentiation (they have negative Eu anomalies). The geochemical classification of the type of tectonic position of the sedimentary basin (Bhatia and Crook, 1986) indicates the sedimentary basin in a continental island arc (Fig. 16). The sedimentation took place on the continental slope of the active continental margin locally accompanied with synchronous mafic volcanism producing the basalts of E-MORB type (Ivan et al., 2001).

The protolith of metamorphosed sedimentary rocks of Pernek Group rocks represent the Deep Ocean Basin Ridge Environment Sedimentary Rocks (DOBRESR). From a petrographic viewpoint, the DOBRESR are very fine-grained schists with fine laminations and variegated quantitative proportion of quartz, sericite, amphibole and organic matter ± chlorite ± epidote ± sulphides ± carbonate. The petrographic variability of DOBRESR is also reflected in geochemical variability. The geochemistry indicates that DOBRESR represent the metamorphosed, originally pelagic sediments, outcropping together with the stratiform hydrothermal sulphidic bodies. The protolith of black schists (BS2a) was represented by pelagic shales with organic matter, while the protolith of metacherts (BS2b) was represented by pelagic siliceous deposits with organic matter. The quartz in chemogenous sediments BS2b can be of hydrothermal, hydrogenous or biogenous origin. In metacherts, all of these quartz sources were present by some proportion. Protolith of actinolite schists and chlorite-actinolite schists with admixture of organic matter (BS2c) was formed by basalts with halmyrolytic alteration and their hyaloclastites ± organic matter. The sedimentary environment of DOBRESR was the ocean floor and sedimentation was accompanied with rift volcanism producing basalts of N-MORB type (Ivan et al., 2001). The geochemical characteristic of a part of DOBRESR (BS2c - halmyrolytic mudstone) are: variable composition, low ratio Th/U (<1), value of Eu anomaly (around 1) and ratio Th/Sc (<0.25), La_N/Yb_N (<6) and values Eu/Eu^*(~1) indicate components derived from the Young Undifferentiated Arc provenance type (YUA, McLennan et al., 1993; Girty et al., 1996). YUA was represented by the young effused arc material (volcanic or plutonic), which has not undergone significant intracrustal differentiation (i.e., it has not undergone the plagioclase fractionation and therefore it has no Eu-anomalies). The values La, Th and Sc from halmyrolytic mudstone (BS2c) resemble rocks from oceanic island arcs (Fig. 17) with typical extremely low La and Th contents, and high Sc content. The general contents of La, Th and Sc in DOBRESR document the common oceanic sedimentary environment with mixing of four principal compounds of protolith: pelagic shales, pelagic cherts, halmyrolytically altered basalts/hyaloclastites and organic matter.

Acknowledgements

Author is grateful to RNDr. Martin Kováčik CSc. (Geological Survey of Slovak Republic, Bratislava) and Harmen Keyser (Vancouver, Canada) for constructive reviews which significantly improved the manuscript. This work was supported by the Science and Technology Assistance Agency under the contract No. APVT-20-020002 and APVT-20-016104, Project VEGA 1/2025/05 and Project "Tectonogenesis of Paleozoic Basins" funded by Ministry of Environment of the Slovak Republic.

References

Andrusov, D., 1959: Geology of the Czechoslovak Carpathians. II. Veda, Bratislava, 1-375 (In Slovak).

Bhatia, M. R. & Crook, K. A. W., 1986: Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins. Contr. Miner. Petrol., 92, 181-193.

Cambel, B. & Čorná, O., 1974: Stratigraphy of the crystalline basement of the Malé Karpaty Mts. in the light of the palynological investigations. Geol. Zbor. Geol. carpath., 25, 2, 231-241. (In Russian).

Cambel, B. & Khun, M., 1983: Geochemical characteristics of black shales from ore-bearing complex of the Malé Karpaty Mts. Geol. Zbor. Geol. carpath., 34, 3, 359-382.

Cambel, B. & Khun, M., 1985: Rare earth elements in metamorphosed black shales of the Malé Karpaty Mts. Geol. Zbor. Geol. carpath., 35, 1, 3-16.

Cambel, B. & Planderová, E., 1985: Biostratigraphic evaluation of metasediments in the Malé Karpaty Mts. region. Geol. Zbor. Geol. carpath., 36, 6, 683-701.

Cambel, B., 1954: Problems of the geology and petrography of the north-east part of the Malé Karpaty Mts. crystalline basement. Geol. Práce, 36, 3-74. (In Slovak).

Cambel, B., 1959: Hydrotermal deposits in the Malé Karpaty Mts.: Ore mineralogy and geochemistry. Acta geol. Univ. Com., Geologica, 3, 3-348. (In Slovak.)

Cambel, B., 1962: Pre-Mesozoic complexes of the Malé Karpaty Mts. In: Explanations to the geological map of Czechoslovakia 1 : 200 000, sheet Wien - Bratislava. Geofond Publ., 28-73.

Cambel, B., Kátlovský, V. & Khun, M., 1981: Geochemistry of the uranium, thorium, carbon and others elements in the black shales of the crystalline schists of the Malé Karpaty Mts. Mineralia Slov., 13, 5, 423-441. (In Slovak).

Cambel, B., Miklóš, J., Khun, M. & Veselský, J., 1990: Geochemistry and petrology of the clayey-quartzy metamorphic rocks of the Malé Karpaty Mts. crystalline schists. Geol. Inst. SAV, Bratislava, 1-267 (In Slovak with English summary.)

Cambel, B., Šimánek, V. & Khun, M., 1985: Study of organic matter in black schists of the Malé Karpaty Mts. crystalline complexes. Geol. Zbor. Geol. carpath., 35, 1, 37-50.

Cluzel, D., Aitchison, J.C. & Picard, Ch., 2001: Tectonic accretion and underplating of mafic terranes in the Late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific): Geodynamic implications. Tectonophysics, 340, 23– 59.

Cullers, R. L., 1995: The controls on the major- and trace-element evolution of shales, siltstones, and sandstones of Ordovician to Tertiary age in the Wet Mountains region, Colorado, USA. Chem. Geol. 123, 107– 131.

Elderfield, H., 1988: The oceanic chemistry of the rare-earth elements. Philos. Trans. R. Soc. London A, 325, 105–126.

Evensen, N. M., Hamilton, P. J. & O'Nions, R. K., 1978: Rare earth abundances in chondritic meteorites. Geochim. Cosmochim. Acta, 42, 1199-1212.

Fedo, C. M., Nesbitt, H. W. & Young, G. M., 1995: Unravelling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. Geology, 23, 921–924.

Garrels, R. M. & McKenzie, F. T., 1971: Evolution of sedimentary rocks. Norton, New York, 1-397.

Girty, G. H., Ridge, D. L., Knaack, C., Johnson, D. & Al-Riyami, R. K., 1996: Provenance and depositional setting of Paleozoic chert and argillite, Sierra Nevada, California. J. Sedim. Res. 66, 107–118.

Grecula, P. & Hovorka, D., 1987: Early Paleozoic volcanism of the Western Carpathians. In: Pre-Variscan and Variscan events in the Alpine-Mediterranean mountain belts. H. W. Flügel, F. P. Sassi & P. Grecula eds. Bratislava, Alfa Publ., 251-270.

Herron, M. M., 1988: Chemical classification of terrigenous sands and shales from core or log data. J. Sed. Petrology, 58, 5, 820-829.

Holser, W. T., 1997: Evaluation of the application of rare-earth elements to paleoceanography. Paleogeography, Paleoclimatology, Paleoecology 132, 309–324.

Ivan, P. & Méres, Š., 2003: Pre-Visean nappe structure in the Malé Karpaty Mts. crystalline basement: Evidence from the geochemical study of metamorphosed basic magmatic and sedimentary rocks. Journal of the Czech Geological Society, 48/1-2, 67-68.

Ivan, P., Méres, Š., Putiš, M. & Kohút, M., 2001: Early Paleozoic metabasalts and metasedimentary rocks from the Malé Karpaty Mts. (Western Carpathians): Evidence for rift basin and ancient oceanic crust. Geologica Carpathica, 52, 2, 67-78.

Kato, Y., Nakao, K. & Isozaki, Y., 2002: Geochemistry of Late Permian to Early Triassic pelagic cherts from southwest Japan: Implications for an oceanic redox change. Chemical Geology, 182, 15–34.

Khun, M., 1985a: Geochemical differentiation of black schists of the Harmónia Group from the crystalline basement in the Malé Karpaty Mts. Geol. Zbor. Geol. carpath., 35, 1, 17-27.

Khun, M., 1985b: Boron in black schists of the Malé Karpaty Mts. crystalline complexes. Geol. Zbor. Geol. carpath., 35, 1, 29-36.

Korikovsky, S. P., Cambel, B., Miklóš, J. & Janák, M. 1984: Metamorphism of the crystalline basement of the Malé Karpaty Mts.: Stages, zonality and relation to granitoid rocks. Geol. Zbor. Geol. carpath., 35, 4, 437-462 (In Russian).

Kotas, P. & Bouda, T., 1983: Gamaspectroscopic methods in the Central laboratories of C.S.U.P. Radioisotopy, 24, 5, 725-773. (In Czech).

Koutek, J. & Zoubek, V., 1936: Explanations to the geological map. Scale 1:75 000, Sheet Bratislava, Library SGÚ, Prague.

Le Maitre, R.W. (ed.), 1989: A classification of igneous rocks and glossary of terms. Blackwell, Oxford, 1-193.

Maheľ, M. & Cambel, B., 1972: Geological map of the Malé Karpaty Mts. Scale 1:50 000. D. Štúr Geol. Inst., Bratislava.

McLennan, S., Hemming, S., McDaniel, D. K. & Hanson, G. N., 1993: Geochemical approaches to sedimentation, provenance and tectonics. In: M. J. Johnsson & A. Basu Eds.: Processes controlling the composition of clastic sediments. Geol. Soc. America, Spec. Paper 285, 21-40.

Méres, Š. & Ivan P., 2003: Geochemistry of the metasedimentary rocks from the Malé Karpaty Mts. (Western Carpathians): Implications for protolith, provenance, sedimentary environment and tectonic setting. Geophysical Research, Abstracts, Vol. 5, 13475. Murray, R. W., 1994: Chemical criteria to identify the depositional environment of chert: General principles and applications, Sediment. Geol. 90, 213.

Nesbitt, H. W. & Young, G. M., 1982: Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature, 299, 715.

Planderová, E. & Pahr, A., 1983: Biostratigraphical evaluation of weakly metamorphosed sediments of Wechsel Series and their possible correlation with Harmónia Group in Malé Karpaty Mts. Mineralia Slov. 15, 385-436.

Plašienka, D. & Putiš, M., 1987: Geological structure of the Tatricum in the Malé Karpaty Mts. In: Structural development of the Carpathian-Balkan Orogenic Belt. Guide to excursions. Bratislava, D. Štúr Geol. Inst., 47-82.

Plašienka, D., Grecula, P., Putiš, M., Kováč, M. & Hovorka, D., 1997: Evolution and structure of the Western Capathians: An overview. In: P. Grecula, D. Hovorka & M. Putiš (eds.): Geological evolution of the Western Carpathians. Mineralia Slov., Monograph, 1-24.

Plašienka, D., Michalík, J., Kováč, M., Gross, P. & Putiš, M., 1991: Paleotectonic evolution of the Malé Karpaty Mts.: An overview. Geologica Carpathica, 42, 4, 195-208.

Putiš, M., 1992: Variscan and Alpine nappe structures of the West Carpathian crystalline basement. Geologica Carpathica, 43, 6, 369-380.

Sholkovitz, E. R. & Schneider, D. L., 1991: Cerium redox cycles and rare earth elements in the Sargasso Sea. Geochim. Cosmochim. Acta, 55, 2737–2743.

Sivell, W. J., 2002: Geochemistry and Nd-isotope systematics of chemical and terrigenous sediments from the Dun Mountain Ophiolite, New Zealand. Journal of Geology & Geophysics, 45, 427-451.

Taylor, S. R. & McLennan, S. M., 1985: The continental crust: Its composition and evolution. Blackwell, Oxford, 1-312.

Toyoda, K., Nakamura, Y. & Masuda, A., 1990: Rare earth elements of Pacific pelagic sediments. Geochim. Cosmochim. Acta, 54, 1093–1103.

Wentworth, C. R., 1922: A scale of grade and class terms for clastic sediments. Jour. Geology, 30, 377-392.

White, W. M., 1998: The ocean as a chemical cycle. Geochemistry. Ch 15, 645-701.

Apatite internal structure and estimation of initial fluorine concentration in the Western Carpathians granitoids

ALEXANDRE AUBIN[1*], IGOR BROSKA[1], MICHAL KUBIŠ[1] and JAROMÍR LEICHMANN[2]

[1]Geological Institute of the Slovak Academy of Science, Dúbravská cesta 9, 840 05 Bratislava, Slovak Republic, E-mail: geolbros@savba.sk
[2]Institute of Geology and Palaeontology, the Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic
*Current address: Department of Earth Sciences, Biological & Geological Building, The University of Western Ontario, London, Ontario, Canada N6A 5B7. E-mail: aaubin2@uwo.ca

Abstract. A study of primary apatite (white and dark pigmented) in Western Carpathians granitoids revealed three types of internal structure: oscillatory zoning, presence of old core (inheritance or two generation origin), and absence of internal structure. Secondary apatite is typically found in the specialized S-type granitoids, forming minute grains within plagioclase as a result of P leaching from the berlinite molecule in the alkali feldspars. The formation of tiny apatite veinlets and apatite-bearing veins in the host rocks is possible considering the high mobility of P. Apatite composition depends both on the geotectonic origin of the host rock and on granitoid evolution. Mn and Fe contents in apatite are indicators of the geotectonic setting of the granitoids; low Mn and Fe content being characteristic of I-type granitoids, as opposed S-type or A-type, which both show a higher Fe content. Apatite composition has been used for the estimation of primary F content in the felsic melts. Fluorine content is approximately 10 times lower in the volatile phases than in the melt. S-type and I-type granitoids show similar fluorine concentration in the liquidus (60-90 ppm). A significantly higher primary F content in the Western Carpathian granitoid melts was calculated in the specialized S-type granitoids (cca 300 ppm) and A-type granitoids (cca 1 000 ppm). This shows that apatite composition in granitoids can be used both for determining the geotectonic setting and the initial F content of the felsic melts.

Key words: apatite, black apatite, fluorine, S-type granites, I-type granites, A-type granites.

Introduction

Apatite is considered an abundant accessory mineral in the more basic granitoids of the Western Carpathians and less common in the assemblages with monazite (e.g. Hovorka & Hvožďara, 1965; Hovorka, 1968; Veselský & Gbelský, 1978; Chovan & Határ, 1978). The most important information derived from apatite in the Western Carpathians was from fission track dating of the various granitoid types, which determined uplift rates in the Tatric and Veporic units (Kráľ, 1977; Danišík et al., 2004). Apatite has also been used in establishing the compositional criteria for the distinction of the S-, I- and A-type granitoids (Broska et al., 2004). Carboniferous impurities in the apatite, such as graphite, carbides and hydrocarbons, recognized in some Tribeč and Malá Fatra Mts. granitoids were interpreted as the results of assimilation of black shales during granitoid emplacement in a reducing regime (Broska et al., 1992).

Despite the fact that apatite is one of the most common accessory phases in the granitoid rocks of the Western Carpathians (e.g. Hovorka & Hvožďara, 1965; Hvožďara & Határ, 1978), many questions remain concerning its structure and composition. The objectives of this study were to 1) determine the internal structure of apatite using cathodoluminescence techniques, 2) outline the significance of apatite composition with respect to the host rock, and 3) use apatite for modelling of the fluorine concentration in the initial silicic melts; the latter becoming more frequently used as a method derived from apatite analysis (e.g. Sallet, 2000; Mathez & Webster, 2005).

Sample location

Apatite grains were derived from various S-, I- and A-type granitoids from the Tatric, Veporic, and Gemeric units of the Western Carpathians (Fig. 1). The S-type granitoids are typically of Lower Carboniferous age, whereas I-type granitoids are of Upper Carboniferous age (Petrík et al., 1994; Petrík & Broska, 1994; Petrík & Kohút, 1997). The rift-related, A-type granitoids are Permian in age and are located in the Gemeric unit, along with the Permo-Triassic specialized S-type granitoids (Uher & Broska, 1996; Broska & Uher, 2001). In addition to the ZK set samples (Macek et al., 1982), granitoid specimens from the Tribeč, Žiar, Malá Fatra, Vysoké Tatry Mts., Hnilec a Dlhá dolina localities in Slovenské Rudohorie were chosen because of the large amount of apatite analyses available (Broska et al. 2004). The distribution of dusky apatite in the samples is presented in Table 1, in addition to abundances of monazite and allanite.

Methods

The granitoid samples were crushed and heavy minerals were extracted using a Wilfley table and bromoform

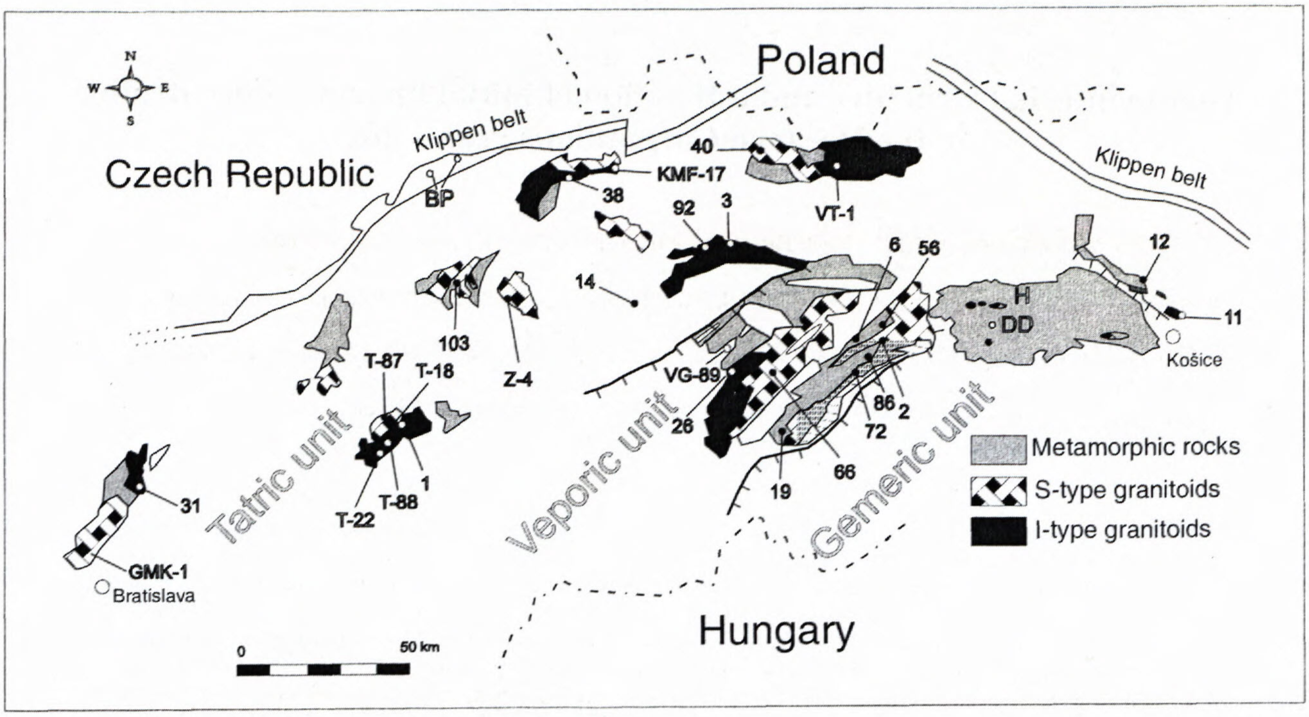


Figure 1. Location of the samples studied in this paper. The samples with only numbers are part of the ZK- series. The ZK- prefixes have been dropped for space reasons. Only the granitoids are shown. The locations of the samples are taken from Macek et al. (1982). The position of samples in the Gemeric unit: H – Hnilec granite; DD - Dlhá dolina valley with the hidden granites.

(S.G. 2.85). Minerals were then separated according to their magnetic properties using a Cook magnetic separator. The apatite grains were hand-picked using a binocular microscope, and were mounted in epoxy on thin sections. The thin sections were then polished to expose the middle of the apatite grains.

Cathodoluminiscence microscopy (CL) was conducted using a Simon Neuser HC/LM2 hot cathode CL microscope at Masaryk University in Brno (Czech Republic). Analytical conditions were at 14 kV accelerating voltage, and 10 mA/mm^2 current density. The films used for CL photography were Fujichrome MS 100/1000, exposed and developed at 800 ASA. The time of exposure varied from 20 to 100 seconds.

Microprobe analyses were done on 1) a JEOL JCXA-733 Superprobe (Geological Survey of Slovak Republic) using fluorapatite as a standard and 2) a Cameca SX50 electron microprobe at the National History Museum, London. During measurement, the operating conditions were 15kV, with a 25 nA beam current and a beam diameter of 1-5 μm. Care was taken in determining of F, and a PC1 (multi-layer crystal) was used to eliminate potential interference from the P 3^{rd}-order line.

Carbon analyses on sample T-87 were performed on a STROHLEIN C-MAT 5500 infrared organic carbon detection instrument (Geological Institute of the Slovak Academy of Sciences). The specimens were burned in an oxygen current with a gradual increase of temperature from 70 °C to 1000 °C. The bulk carbon content of the sample was measured, all inorganic carbon was removed by HCl, and the remaining carbon (organic) was measured and compared with the calibration standard.

Results

Apatite distribution

Early magmatic differentiates of I-type granitoid suites in the Western Carpathians are the most rich in apatite because they often contain several hundred g/t and locally more than 1000 g/t. The amount of apatite decreases in differentiated I-type granitoids, which is reflected by the decrease of P concentration in these rocks. Apatite often forms stubby, milky or yellow pigmented crystals which are usually located within biotite and in interstices between grains. S-type granitoid suites, which are relatively poor in apatite, contain crystals that are smaller. The concentration of black pigmented apatite (dusky apatite) is locally common in S-type granitoids but dusky apatite is also present in some I-type granitoids (Table 1).

Apatite composition

According to primary magmatic apatite composition, the essential known criteria for the recognition of the I-, S- and A-type granitoids is the concentration of Mn and Fe along with REE distribution. The Mn content of apatite in the Western Carpathians increases with the peraluminousity of granitoids and with decreasing fO_2. Thus, apatite from S-type granitoids has slightly higher Mn contents in comparison to apatite from the I-type granitoids. Apatite in the A-type granitoids is enriched in Fe and HREE similar to apatite from specialized tin-bearing S-type granitoids, which show an increase in Y and HREE content (Broska et al., 2004). General Mn and Fe distribution within the granitoid suites is shown in Fig. 2.

Table 1: Characteristics of the samples used in this paper in regard to their allanite, monazite and black apatite contents. The position of the samples is given in Figure 1. The ZK- series is represented here without the ZK- prefix.

Sample #	Granitoid type	Monazite (g/ton)	Allanite (g/ton)	% of black apatite in total apatite
KMF-17	S	30	0	85
T-18	S	200	15	80
T-22	I	0	90	0
T-36	I	0	140	0
T-87	S	60	0,5	99
VT-1	I	n.d.	n.d.	0
Z-4	S	n.d.	n.d.	15
ZK-1	I	1	470	Tr
ZK-2	S	6	0,5	3
ZK-3	S	16	5	Tr
ZK-6	I	0,5	30	2
ZK-9	I	0,5	38	1
ZK-11	S	33	48	6
ZK-12	I	0	958	50
ZK-14	S	19	0	1
ZK-19	S	33	0	3
ZK-26	S	0	0	Tr
ZK-31	I	0	12	80
ZK-38	I	0	348	10
ZK-40	S	42	3	50
ZK-56	S	1	0	2
ZK-66	I	n.d.	n.d.	Tr
ZK-72	S	12	0,5	40
ZK-86	I	6	292	2
ZK-92	S	18	7	Tr
ZK-103	S	4	0	2

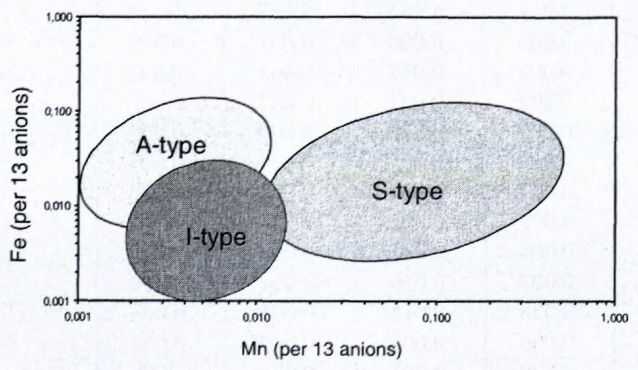


Figure 2: General scheme of Mn and Fe distribution in the granitoids of the Western Carpathians. (Generalized according to Broska et al. 2004).

In adition to minor femic and REE components, volatiles phases are also an important discriminative component of apatite. Although the concentrations of F and Cl are similar in all granitoid, there are slight differences in the distribution that help differentiate between the different types. Table 2 presents the results of microprobe analysis of characteristic apatite grains from all principal granitoid suites in the Western Carpathians. The mean concentration of fluorine is generally above 3 wt % and chlorine is often beyond the detection limit in the A-type granitoids, but is quite high in the I-type suites (Fig. 3). All analyzed apatites are fluorapatites (Fap). The highest concentration of fluorapatite and hydroxylapatite molecule is present in the specialized S-type granitoids (Fig. 3). The lower Cl concentration in apatite from the S-type granitoids in comparison to I-type granitoids was explained by Sha & Chappel (1999) as a selective loss of Cl in the sedimentary protolith, because of higher Cl solubility in aqueous solutions.

Internal structure

Apatite grains under the binocular (B), polarised (M), cathodoluminescence (CL), and back-scattered electron (BSE) microscopes contain three types of internal structures: oscillatory zoning, relict cores (or two generation origin), and absence of internal structure.

Oscillatory zoning (Fig. 4A): This pattern is observed mainly in I -, less in S -type samples, in white and dark pigmented apatite. It consists of small dark and light zones (in CL) that are repeated from the core to the rim of the grains. The thickness of the zones can vary from smaller than a micron to tens of microns. Typical grains are composed of a central zone (core), which is generally black. Oscillatory zoning was also observed on the polarised microscope in the dark pigmented apatite, but was invisible in the white apatite. The zones that are darker in CL appear brighter on BSE images.

Two types of mechanisms have been suggested for the origin of oscillatory zoning (Shore & Fowler, 1996): extrinsic mechanisms and intrinsic mechanisms. The extrinsic mechanisms refer to changes outside the grains (mixing of magma, changes in composition of volatile phases, etc.) whereas intrinsic mechanisms refer to changes that occur within the crystal during the crystallisation process (diffusion of elements, small scale convection currents, adsorption of minor and trace elements). It is believed that the internal structure of the studied apatite from the Western Carpathians is a result of crystal growth under certain conditions and that the rapidity of growth produced the oscillatory zoning.

The difference in colour contrast in CL zoning (Fig. 4B) is probably due to the variation of Mn and REE concentrations, elements which are known to be the main activators in apatite under CL (Murray & Oreskes, 1997). It is believed that the oscillatory zoning in apatite is caused by the variation of the concentration and/or nature of Mn and REEs during magma crystallization (intrinsic mechanism). Cherniak (2000) proved that REE zoning occurs in fluorapatite.

Old cores (Fig. 4C,D): In some samples, the presence of an old (inherited) core was visible under CL but not in BSE images. Both white and dark pigmented grains contain inherited cores, and they generally occur in S-type granitoids. The old cores are present as rounded inclu-

Slovak Geol. Mag., 11, 2 – 3 (2005), 123 – 131

Table 2: Representative analyses of apatites from the S- , I- , A- and spec. S- type granitoids. The concentration of the elements and oxides are in wt %. $X^{Ap}{}_{FAp}$ represents the mole fraction of fluorine in apatite, $X^{Ap}{}_{ClAp}$ represents the mole fraction of chlorine in apatite and $X^{Ap}{}_{HAp}$ represents the mole fraction of hydrogen in apatite. Sample GK-8 P represents primary apatite and GK-8 S is secondary one (minute grain in alkaline feldspar).

Sample	Z-4 S-type	GMK-1 S-type	T-88 I-type	ZK-38 I-type	VG-89 A-type	BP-20 A-type	GK-8 P sS-type	GK-8 S sS-type
SO_3	0.00	0.00	0.25	0.05	0.02	0.02	0.00	0.04
P_2O_5	42.18	41.96	41.80	43.14	39.60	39.78	41.72	42.00
SiO_2	0.22	0.06	0.16	0.04	0.35	0.40	0.05	0.05
CaO	54.13	54.20	55.76	54.93	52.29	53.18	52.65	56.07
La_2O_3	0.05	0.00	0.07	0.00	0.00	0.19	0.04	0.00
Ce_2O_3	0.16	0.08	0.11	0.10	0.18	0.53	0.11	0.11
Pr_2O_3	0.00	0.00	0.00	0.04	0.10	0.23	0.07	0.05
Nd_2O_3	0.00	0.00	0.03	0.06	0.26	0.38	0.00	0.00
Sm_2O_3	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.01
Gd_2O_3	0.00	0.00	0.00	0.00	0.06	0.13	0.03	0.00
Er_2O_3	0.00	0.00	0.00	0.03	0.15	0.06	n. a.	n. a.
Dy_2O_3	0.00	0.00	0.00	0.06	0.15	0.05	0.26	0.02
Yb_2O_3	0.00	0.00	0.00	0.00	0.08	0.00	0.05	0.00
Y_2O_3	0,10	0,11	0,12	0,26	0,60	0,32	0,02	0,07
PbO	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,07
ThO_2	0,06	0,04	0,05	0,01	0,02	0,04	0,01	0,00
UO_2	0,07	0,05	0,03	0,00	0,00	0,00	0,10	0,02
Al_2O_3	0,01	0,00	0,00	0,05	0,00	0,02	0,00	0,03
+FeO	0,20	0,33	0,12	0,04	0,70	0,96	0,59	0,09
MnO	0,19	0,30	0,10	0,02	0,59	0,12	3,04	0,27
MgO	0,02	0,00	0,00	0,01	0,00	0,01	0,00	0,00
Na_2O	0,13	0,12	0,08	0,05	0,13	0,06	0,05	0,07
SrO	0,06	0,06	0,08	0.12	0,00	0,00	0,04	0,21
F	2,53	3,10	2,50	2.22	3.49	2.80	3.72	3.41
Cl	0.04	0.00	0.05	0.02	0.02	0.00	0.12	0.02
OH	0.49	0.26	0.51	0.64	0.04	0.34	-0.01	0.15
total	101.20	100.67	101.82	101.88	99.38	99.79	102.67	102.76
O=F.Cl	1.07	1.30	1.06	0.94	1.47	1.18	1.59	1.44
TOTAL	100.13	99.36	100.76	100.94	97.91	98.61	101.08	101.32
S	0.000	0.000	0.020	0.004	0.002	0.002	0.000	0.003
P	3.045	3.025	2.992	3.073	2.941	2.945	2.978	2.977
Si	0.019	0.005	0.014	0.003	0.030	0.035	0.004	0.004
Ca	4.945	4.944	5.051	4.952	4.914	4.983	4.757	5.029
La	0.001	0.000	0.002	0.000	0.000	0.006	0.001	0.000
Ce	0.005	0.002	0.003	0.003	0.006	0.017	0.003	0.003
Pr	0.000	0.000	0.000	0.001	0.003	0.007	0.002	0.002
Nd	0.000	0.000	0.001	0.002	0.008	0.012	0.000	0.000
Sm	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000
Gd	0.000	0.000	0.000	0.000	0.002	0.004	0.001	0.000
Er	0.000	0.000	0.000	0.000	0.002	0.004	n. a.	n. a.
Dy	0.000	0.000	0.000	0.002	0.004	0.001	0.007	0.000
Yb	0.000	0.000	0.000	0.000	0.002	0.000	0.001	0.000
Y	0.005	0.005	0.005	0.012	0.028	0.015	0.001	0.003
Pb	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002
Th	0.001	0.001	0.001	0.000	0.000	0.001	0.000	0.000
U	0.001	0.001	0.001	0.000	0.000	0.000	0.002	0.000
Al	0.001	0.000	0.000	0.005	0.000	0.002	0.000	0.003
Fe	0.014	0.024	0.009	0.003	0.051	0.070	0.042	0.006
Mn	0.014	0.021	0.007	0.001	0.044	0.009	0.217	0.019
Mg	0.003	0.000	0.000	0.001	0.000	0.001	0.000	0.000
Na	0.021	0.020	0.014	0.008	0.021	0.011	0.008	0.011
Sr	0.003	0.003	0.004	0.006	0.000	0.000	0.002	0.010
XApFAp	0.68	0.83	0.67	0.59	0.97	0.78	0.99	0.90
XApClAp	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00
XApHAp	0.31	0.17	0.33	0.41	0.03	0.22	0.00	0.10

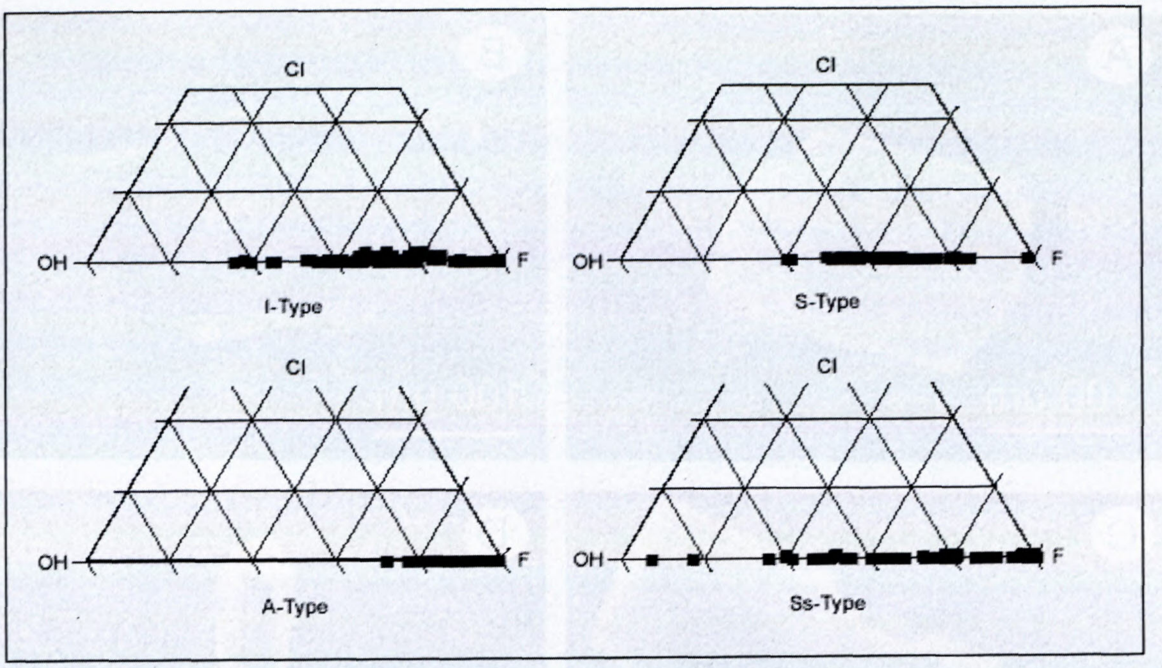


Figure 3: Ternary diagram of apatite composition in respect to granitoid types. F: fluorapatite; Cl: chlorapatite; OH: hydroxylapatite. The Cl axis is cut at 50%. The apatites from I-type granitoids tend to have a generally higher Cl component whereas the apatites from A-type granitoids are generally above 80% fluorapatite. Differences between the other granitoid types (S and Ss) are not as clear.

sions in the centres of the grains. They have no typical crystalline shape and are a different colour than the rest of the grain in CL (brighter and darker). The estimated volume occupied by the old cores varies from 15 vol. % to 40 vol. % of the grains.

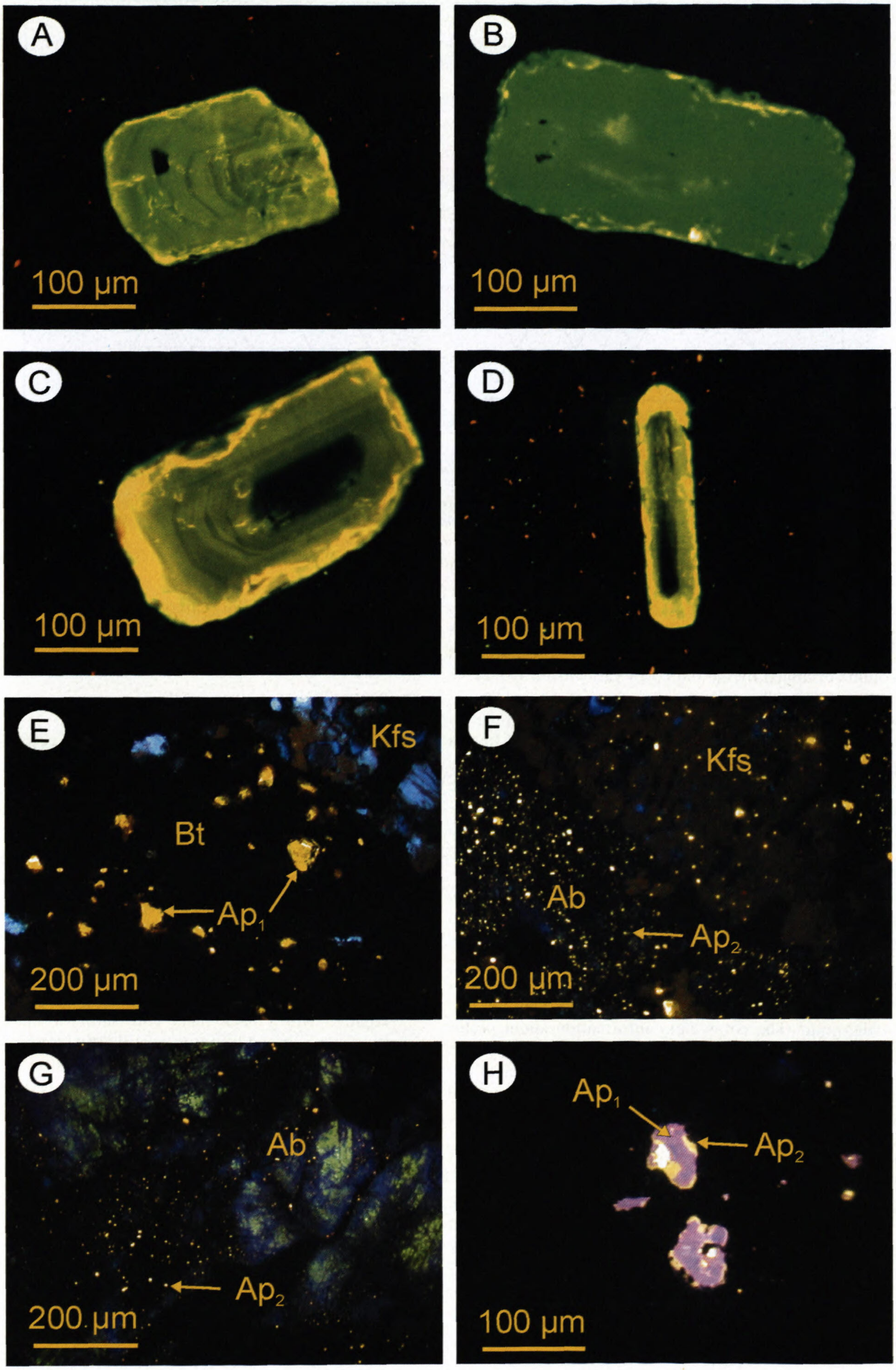
The presence of old cores is probably due to the incorporation of partly-dissolved apatite grains into a phosphorus-saturated melt. This phenomenon occurs with the arrival of newly melted material into the magma chamber. The new melt, which is already saturated in P prevents further dissolution of the apatite and allows for the old apatite grain to act as a nucleation site for the crystallisation of new material. Harrison & Watson (1984) also mentioned that the dissolution of apatite is very fast (e.g. hundreds of years for a 500 micron grain) for melts with an average water content of 3 %, so that the only way to keep this mineral from dissolving is to saturate the melt. Therefore, it is assumed that the core is derived from a different origin than the rest of the grain. The cores carry information about protoliths, and indicate the presence of recycled crustal material (see Kohút, 1998; Petrík, 2000). The presence of old cores also indicates a lower crystallization temperature for S-type granitoids in comparison to I-type granitoids in which older cores were not observed. The same inherited core and zoning phenomenon has been observed by other authors (Dempster et al., 2003) who also suggest a dissolution-crystallization system.

Absence of internal structure: Most of the studied grains (especially from I-type granitoids) have no internal structure. The images obtained from CL and BSE show uniform grains without any change in structure, which indicates rapid crystallization, probably in the early magmatic stage. Most of the studied grains contained inclusions (mainly zircon, with minor biotite and albite), which were observed in all three types of internal structures.

Dark pigmented apatite

Two different types of dark pigmented apatite were observed, 1) dark cores inside clear apatite grains (the dark portion constitutes 100 % of the grain in some cases, but is generally around 50 %) and 2) two coexisting cores (a black inner core and a dark outer core) (Fig. 4C,D). The two types of dark pigmented apatite were observed mainly in S-type granitoids, but some were also present in I-type granitoids. When studied under CL and BSE, almost all the dark pigmented apatite presented oscillatory zoning. Under cross polarised light, the dark pigmented apatite shows a strong pleochroism, similar to that of tourmaline.

Apatite with a black inner core shows a change of crystal shape in addition to oscillatory zoning. The black core appears to be of a different crystal system (monoclinic?) and the entire grain tends to evolve towards the hexagonal shape of the apatite during its growth. Some analyses were conducted to investigate this phenomenon (carbon detection, microprobe and X-rays) and the results pointed mostly to apatite, but with another unknown phase. Murray & Oreskes (1997) mentioned that differences in CL colours (zoning for instance) could also be due to crystallographic effects. This theory could be appropriate because the shape of some dark pigmented apatite cores appears to be monoclinic. Fleet et al. (2000) experimentally proved that the substitution of REE for Ca interferes with the crystalline


A
100 µm
B
100 µm
C
100 µm
D
100 µm
E
Kfs
Bt
Ap1
200 µm
F
Kfs
Ab
Ap2
200 µm
G
Ab
Ap2
200 µm
H
Ap1
Ap2
100 µm

system of apatite and that a transition from hexagonal system ($P6_3/m$) to monoclinic system ($P2_1/b$) is one of the results of this substitution.

Little or no carbon (below the detection level of the device) was found in the black pigmented apatite mentioned by Broska et al. (1992) and there were no measured foreign phases (unlike e.g. Gottesmann & Wirth, 1997). It is proposed that the variation in colour is more likely due to the presence of another mineral phase and/or to the presence of a different crystalline system (monoclinic) than the hexagonal system. The graphite extracted from the dusky apatite found by Broska et al. (1992) does not appear to be the principal factor of apatite coloration.

Secondary apatite

Secondary apatite is a leaching product of the berlinite molecule from the alkali feldspar (Fig. 4E,F,G,H). Berlinite, $AlPO_4$, is isostructural with quartz or the Si_2O_4 framework component of feldspars and is incorporated into feldspars by the coupled substitution of $Al^{3+} + P^{5+}$ for $2\ Si^{4+}$. This exchange is well-known as the berlinite substitution (London, 1992; 1998). Posmagmatic fluid activity releases P from feldspars or from the berlinite molecule along with Ca from the anorthite molecule, and secondary apatite can precipitate. Secondary apatite is represented by minute crystals usually within albite, but sometimes also within K-feldspar. The mass balance calculation shows that the significant amount of secondary apatite in the presented albite on Fig. 4 E,F was derived from albite with An concentration below An_{20}. Minute apatite is often close to stoichiometric composition (Broska et al., 2002). Locally, apatite also forms small veinlets as well as veins outside of the main granitoid body (Fig. 5).

Fluorine content

The apatites were used to determine the amount of fluorine in the melt using the following equations (Piccoli & Candela, 1994):

$$C_F^{aq} = \frac{X_{FAp}^{Ap}}{X_{HAp}^{Ap}} \cdot \frac{1.90\times10^7}{18} \cdot \frac{1}{10^{\left[0.18219+\frac{5301.1}{T}-\frac{0.00360\cdot(P-1)}{T}\right]}}$$

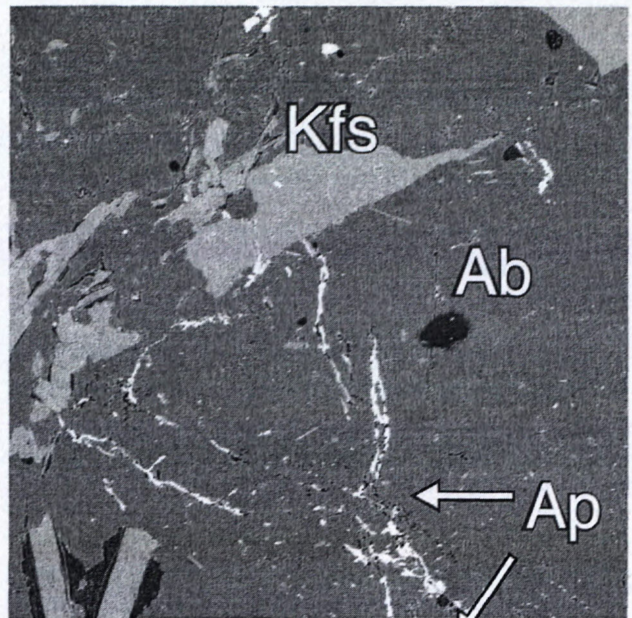


Figure 5. BSE of the apatite veinlets from the apogranite of the Dlhá dolina valley (borehole DD-20; 266 m depth). All white parts on the image represent the apatite exsolution and mobilization within alkali feldspar. (magnification 160x).

and

$$C_F^{l} = \frac{\frac{X_{FAp}^{Ap}}{X_{HAp}^{Ap}} \cdot \frac{1.90\times10^7}{18} \cdot \frac{1}{10^{\left[0.18219+\frac{5301.1}{T}-\frac{0.00360\cdot(P-1)}{T}\right]}}}{D_F^{aq/l}}$$

and

$$D_F^{aq/l} = -0.56 + 0.00093 \cdot T(°C)$$

where the terms used are:

X_i^{ϕ}	mole fraction of phase component i in phase ϕ
C_i^{l}	concentration of i in melt
C_i^{aq}	concentration of i in magmatic volatile phase
$D_i^{aq/l}$	partition coefficient of i between the magmatic volatile phase and melt
T	temperature in Kelvin, unless specified
P	pressure in bars

Figure 4: Cathodoluminescence images of primary and secondary apatite from Western Carpathian granitoids(apatite creates yelow luminiscence). A: white apatite grain from sample T-22 (I-type granitoid). Oscillatory zoning is present but no core is visible. B: white apatite grain from sample ZK-40 (S-type granitiod. Note the absence of internal structure. C: dark-pigmented apatite grain from sample ZK-66 (I-type granitoid). D: dark-pigmented apatite from sample T-87 (S-type granitoid). Note the very dark core and the oscillatory zoning. E: primary apatite grains (Ap_1) as inclusions in biotite (Bt). From sample GK-6, specialized S-type granitoid, Betliar area. F: secondary apatite grains (Ap_2) in albite (Ab). From sample GZ-1, specialized S-type granitoid, Hnilec area. G: secondary apatite grains (Ap_2) in albite (Ab). From sample GZ-1, specialized S-type granitoid, Hnilec area. H: Two generations of apatite in sample GZ-1 (specialized S-type granitoid, Hnilec area). The older generation shown in purple (violet Ap_1) and the younger generation is represented in yellow (Ap_2). The difference in apatite luminescence colour is due to the different compositions of the two generations: purple being generally activated by trace quantities of rare earth element ions (Ce^{3+}, Eu^{2+}, Sm^{3+}, Dy^{3+} and Nd^{3+}), whereas yellow is generally activated by Mn^{2+} (Marshall, 1988).

The temperature used for the calculation was the AST (apatite saturation temperature) (Harisson & Watson, 1984) as suggested by Piccoli & Candela (1994), although this is quite unrealistically high. All samples were calculated on the basis of a 300 MPa pressure.

The results, which are presented in Table 3, show a clear difference in fluorine concentrations (in the melt and in the volatile phase) among the different kinds of granitoid rocks (I-, S- and A-type). Fluorine content in the volatile phase is about 10 times lower than in the melt. The amount of fluorine in the S-type melt is similar to samples with I-type affinity except for the specialized S-type granitoids of the Gemeric unit in which a high primary amount of F exists (Kubiš and Broska, 2005). The A-type granitoid melts were more than 10 % richer in fluorine than the I-or S-type melts. The higher F content in the A-types and specialized S-types could be connected with known metallogenetic capacity of these granitoids.

Table 3 represents the results of all calculated values. The halogen equations (Piccoli & Candela, 1994) can also be used to calculate chlorine concentrations, but because most of the studied samples did not contain any chlorine (beyond the detection limit of the microprobe), only the fluorine amounts were calculated.

Table 3: Estimated fluorine content in the granitoid melt and volatile phases after the model of Piccoli & Candela (1994). The fluorine content is in ppm. X^{Ap}_{FAp} represents the mole fraction of fluorine in apatite, X^{Ap}_{HAp} represents the mole fraction of hydrogen in apatite, C^{aq}_{F} represents the concentration of fluorine in the volatile phase and C^{l}_{F} represents the concentration of fluorine in the melt. Results are statistically evaluated by the average of all the individual values obtained.

	I-type	S-type	A-type	spec.S-type
Number of analyses	34	25	20	28
X^{Ap}_{FAp}	0.64	0.63	0.86	0.67
X^{Ap}_{HAp}	0.35	0.36	0.14	0.33
C^{aq}_{F}	16	9	229	27
C^{l}_{F}	88	61	979	296

Concluding remarks

Apatite distribution and internal structure is different within I-, S- and A-type granitoids. This accessory mineral is abundant in the early magmatic granitoids of the I-type suites and often shows strong zonality because of its long-term crystallization, which occurred deeper than that of S- type granitoids. In contrast, absence of internal structure (uniform grains) is most common in S-type granitoids. Apatites from the Western Carpathians granitoids are present in two colours: milky or white with yellow tones (depending on the Fe content), and dark pigmented (dusky). The latter is more typical for S-type granitoids, but it can be present also in smaller amounts in the I-type granitoids. The compositional impurities in apatite are not as significant compared with structural peculiarities that need further detailed investigation. Old rounded cores due to inherited material from partial melting are more common in the S-type granitoids.

The composition of apatite grains can be used as a discrimination factor for the division of granitoids into geotectonic suites. Mn and Fe content are the most important discriminative factors. Low Mn content is typical in I–type granitoids, higher Mn and Fe contents are typical of apatites from the S-type granitoids, and the highest Fe content is characteristic of the A-type granitoids.

The amount of fluorine in the melt and in the volatile phase, as calculated from apatite compositions, suggests that S-type granitoids show similar fluorine concentrations in the melt and the volatile phase to I-type granitoids. The highest fluorine content was calculated in the specialized S-type and A-type granitoids, which are of metallogenic significance (e.g. tin-bearing granites in Hnilec area). However, calculations of fluorine contents carry many error factors and they should be taken as a preliminary estimation of initial fluorine content.

Acknowledgements

The authors are grateful to Julia Kotulová for the carbon investigation in apatite specimen from the Tribeč Mts., as well as to Ivan Dianiška and Pavol Malachovský for providing the samples DD-3 from Dlhá dolina valley borehole. The work was financed by VEGA Ga 4097.

References

Broska, I., Dikov, Y.P., Čelková, A. & Mokhov, A.V. 1992: Dusky apatite from the Variscan granitoids of the Western Carpathians. Geologica Carpathica, 43, 195-198.

Broska I., Uher P. 2001: Whole-rock chemistry and genetic typology of the West-Carpathian Variscan granites. Geol. Carpath. 52, 2, 79-90.

Broska I., Kubiš M., Williams C.T. & Konečný P. 2002: The composition of rock-forming and accessory minerals from the Gemeric granites (Hnilec area, Gemeric superunit, Western Carpathians). Bull Czech Geol. Survey, 7, 147-155.

Broska I., Williams C.T., Uher P., Konečný P. & Leichmann J., 2004: The geochemistry of phosphorus in different granite suites of the Western Carpathians, Slovakia: the role of apatite and P-bearing feldspar. Chemical geology. 205, 1-15.

Cherniak D.J., 2000: Rare earth element diffusion in apatite. Geochim. et cosmochim. acta 64, 3871-3885.

Chovan M. & Határ 1978: Akcesorické minerály niektorých typov hornín kryštalinika veporíd. Min. Slov. 10, 9, 24-32.

Danišík, M., Dunkl, I., Putiš M., Frisch W., Kráľ, M., 2004: Tertiary burial and exhumation history of basement highs along the NW margin of the Pannonian basin – an apatite fission track study. Austrian J. Earth Sci., 95/96, 60-70.

Dempster, T.J., Jolivet, M., Tubrett, M.N., & Braithwaite, C.J.R. 2003. Magmatic zoning in apatite: a monitor of porosity and permeability change in granites. Contributions to Mineralogy and Petrology, 145, 568-577.

Fleet, M.E., Liu, X. & Pan, Y. 2000: Rare-earth elements in chlorapatite [$Ca_{10}(PO_4)_6Cl_2$]: Uptake, site preference, and degradation of monoclinic structure. American Mineralogist, 85, 1437-1446.

Gottesmann, B. & Wirth, R. 1997: Pyrrhotite inclusions in dark pigmented apatite from granitic rocks. European Journal of Mineralogy, 9, 491-500.

Harrison, T.M. & Watson, E.B. 1984: The behaviour of apatite during crystal anatexis: Equilibrium and kinetic considerations. Geochimica et Cosmochimica Acta, 48, 1467-1477.

Hovorka D. & Hvožďara P. 1965: Accessory minerals Veporic granitoid rocks I. Acta geol. Geogr. Univ. Comen. Geol. 9, Bratislava, 145-179 (In Slovak).

Hovorka D., 1968: Akcesorické minerály niektorých typov granitoidov Malej Magury, Malej Fatry a Tribča. Acta geol. et geograph. Univ. Com. 13, 165-189.

Hvožďara P. & Határ J. 1978: Accessory mineral of some magmatic and metamorphic rocks of veporides. Acta geol. Geogr. Univ. Comen., Bratislava, 33, 113-128.

Kráľ J. 1977 : Fission track ages of apatites from some granitoid rocks in West Carpathians. Geol. Zbor. Geol. Carpath. Bratislava, 28, 2, 269-276.

Kohút, M. 1998: The geochemical and isotopic characteristic of the Hercynian granitoid rocks of the Western Carpathians-Slovakia; evidences for crustal recycling. Acta Universitatis Carolinae. Geologica, 42, 276.

Kubiš M. & Broska I. 2005: Role of Boron and fluorine in evolved granitic rock systems (on an example of the Hnilec area, Western Carpathians). Geol. Carpath. 53, 3, 193-204.

London, D., 1992. Phosphorus in S-type magmas: the P_2O_5 content of feldspars from peraluminious granites, pegmatites and rhyolites. Am. Mineral. 77, 126-145.

London, D., 1998. Phosphorus-rich peraluminious granites. Acta Univ. Carol. Geol. 42, 64-68.

Macek, J., Cambel, B., Kamenicky, L. & Petrík, I. 1982: Documentation and basic characteristics of granitoid rock samples of the West Carpathians. Geologica Carpathica, 33, 601-621.

Marshall, D.J. 1988: Cathodoluminescence of geologic materials. Boston, Unwin Hyman, 146 pp.

Mathez, E.A. & Webster, J.D. 2005. Partitioning behaviour of chlorine and fluorine in the system apatite-silicate melt-fluid. Geochimica et Cosmochimica Acta, 69, 1275-1286.

Murray, J. R. & Oreskes, N. 1997: Uses and limitations of cathodoluminescence in the study of apatite paragenesis. Economic Geology, 92, 368-376.

Petrík, I., Broska I., & Uher P., 1994: Evolution of the Western Carpathian granite magmatism: Age, source rock, geotectonic setting and relation to the Variscan structure. Geologica Carpathica, 45, 283-291.

Petrík, I. & Broska, I. 1994: Petrology of two granite types from the Tribeč Mountains, Western Carpathians: an example of allanite (+ magnetite) versus monazite dichotomy. Geological Journal, 29, 59-78.

Petrík, I. & Kohút, M. 1997 : The evolution of granitoid magmatism during the Hercynian Orogen in the Western Carpathians. In Grecula et al. (Eds). : Geological evolution of the Western Carpathians, Bratislava, 235-252.

Petrík, I. 2000: Multiple sources of the West-Carpathian Variscan granitoids : a review of Rb/Sr and Sm/Nd data. Geologica Carpathica, 51, 145-158.

Piccoli, P. & Candela, P. 1994: Apatite in felsic rocks: a model for the estimation of initial halogen concentrations in the Bishop Tuff (Long Valley) and Tuolumne Intrusive Suite (Sierra Nevada Batholith) magmas. American Journal of Science, 294, 92-135.

Sallet, R. 2000. Fluorine as a toll in the petrogenesis of quartz-bearing magmatic associations: applications of an improved F-OH biotite-apatite thermometer grid. Lithos, 50, 241-253.

Sha, L.-K. & Chappell, B.W. 1999: Apatite chemical composition, determined by electron microprobe and laser-ablation inductively coupled plasma mass spectrometry, as a probe into granite petrogenesis. Geochimica et Cosmochimica Acta, 63, 3861-3881.

Shore, M. & Fowler, A.D. 1996: Oscillatory zoning in minerals: a common phenomenon. Canadian Mineralogist, 34, 1111-1126.

Uher P. & Broska I., 1996: Post-orogenic Permian rocks in the Western Carpathian-Panonian area: Geochemistry, mineralogy and evolution. Geol. Carpath. 47, 311-321.

Veselský J & Gbelský J. 1978: The results of accessory minerals studies from granitoids and pegmatites of the Malé Karpaty Mts. Acta geol. et geograph. Univ. Comen. , Geol. 33 Bratislava, 91-111.

Slovak Geol. Mag., 11, 2 – 3 (2005), 133 – 142

Fluviolacustrine style sedimentation of the lower part of Malužiná Formation from the NE slopes of Nízke Tatry Mts.

MÁRIO OLŠAVSKÝ

Geological Survey of Slovak Republic, Banská Bystrica, Kynceľovská 10, 947 01, olsavsky@gssrbb.sk

Abstract. The middle stage basin-fill history of the Malužiná Fm., as a part of Ipoltica Group is described. Ten identified facies, building four facies associations (FA1 to FA4), were interpreted as the deposits of shallow sandy braided system, lacustrine system, gravelly braided - minor debris-flow braided system and sand-bed alluvial system with dominant sheet floods. Facies associations arranged a succession of two cogenetic second-order fluvial depositional sequences. The vertical profile of both sequences displays an overall fining-upwards trend related to the gradual decrease in topographic slope. Fluvial styles can be observed within each sequence, from initial higher to final lower energy systems. The change in fluvial style, combined with the widespread evidence of bioturbation, desiccation and evaporation, suggest an evolution towards a more semi-arid climate in the upper part of the sequence. The controlling mechanisms for this may be autocyclic as well as allocyclic processes, although the tectonic influence on sedimentation was probably significant.

Keywords: Permian, Hronicum Unit, Malužiná Fm, facies associations, fluviolacustrine style

Introduction

The paper deals with depositional environments in investigated lower part of Malužiná Formation (lowermost Permian to lower part of Upper Permian), situated in the northeastern part of the Nízke Tatry Mts. The results of sedimentological analysis are based on outcrop studies. Studied territory is located between villages Liptovská Teplička and Vernár, resp. south of villages Vikartovce, Kravany, Spišské Bystré and Hranovnica.

Studied continental volcanosedimentary sequence of the basal part of superficial nappe of Hronicum Unit represents the complete megasequence of several depositories of Upper Carboniferous to Lower Cretacious age. It belongs to Ipoltica Group (Vozárová & Vozár, 1981, 1988), developed gradually (Biely, 1965; Ďurovič, 1965; Drnzík, 1969; Novotný & Badár, 1971; Vozárová & Vozár, 1981, 1988) from the underlying Nižná Boca Formation of Stephanian B-C age (Sitár & Vozár, 1973). The stratigraphic overlier of the group is built by the Benkovský potok Formation (Biely in Andrusov & Samuel et al., 1984). The Lower Triassic age of this formation was determined by the fauna occurrence at Šuňava village (Roth, 1938). According to this relation and finding of microflora assemblage, the Malužiná Formation covers the age range of Lower-Upper Permian (Planderová in Vozárová & Vozár (edit.), 1979; Planderová & Vozárová, 1982). The important and determining constituent of the formation is the multiphase sedimentary volcanism of continental tholeiites, from geotectonic viewpoint ranked among the non-orogenic volcanism types and connected with the origin of continental rift (Vozár, 1977, 1997; Dostal et al., 2003).

The main petrographic types of sediments are represented with red arkose sandstone, greywacke sandstone,

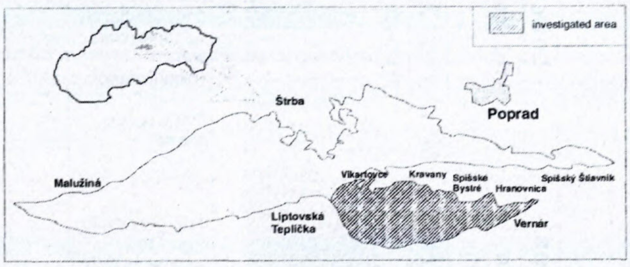


Fig. 1. Location map showing part of investigated area of Ipoltica Group, NE part of the Nízke Tatry Mts.

arkose, greywacke and conglomerate. The anhydrite-gypsum horizons and occurrences of redeposited gypsum were described from boreholes (Novotný & Tulis, 1998). The pyroclastic rocks as tuffs, tuffitic sandstones, tuffitic breccia are present in the vicinity or among particular effusive bodies.

The general assumption allows deriving the clastic detritus from its immediate underlier, rimming the margin of sedimentary basin, eventually from synsedimentary volcanic centres. The petrofacial analysis of clastics indicates the dual provenance: from rejuvenated continental basement and from truncated volcanic arc (Vozárová & Vozár, 1993).

Drnzík (1969) interpreted the sedimentary environment from the Lower Carboniferous as shallow marine (coastal-marine) with alternation of transgressive-regressive cycles with facies from deltaic to bay-lagunary. Drnzík (l.c.) used for the first time the term megacycle for cyclic setting of "melaphyre series"

The works by Novotný (1970, 1972), Novotný & Badár (1971) and Novotný & Jančok (1971) brought first more detail sedimentological knowledge about this forma-

Geological Survey of Slovak Republic, Dionýz Štúr Publisher, Bratislava 2005 ISSN 1335-096X

Slovak Geol. Mag., 11, 2 – 3 (2005), 133 – 142

tion, but allocated relatively complicated names for lithostratigraphic units. Authors suppose, that sedimentation in Lower Permian occurred by traction flows in near-shore zones of shelf sea with ingress of lagoon environment. In Upper Permian they suppose the shallowing of the basin and its diversification into subenvironments of lagoons to continental lakes with increasing salinity. Authors distinguished two Permian cycles. Third cycle was interrupted with intensive volcanism. In later summarizing work (Tulis & Novotný, 1998) authors allocated a new designation for earlier defined lithostratigraphic units (Fig. 2 b)).

Vozárová & Vozár (1981) defined Malužiná Fm. being composed from three upward fining megacycles (Fig. 2 a). Generally they determined the sedimentary environment as continental, deltaic-lagoonal, eventually complex of bottom lacustrine sediments with wedged deltaic sediments. In later work (Vozárová & Vozár, 1988) the interpretation of the sedimentary environment was as follows: Each megacycle is formed with fluvial channel deposits. In middle parts of megacycles the floodplain deposits tied with levee and temporary riverain pools sedimentary conditions have the main representation. The upper parts of megacy-

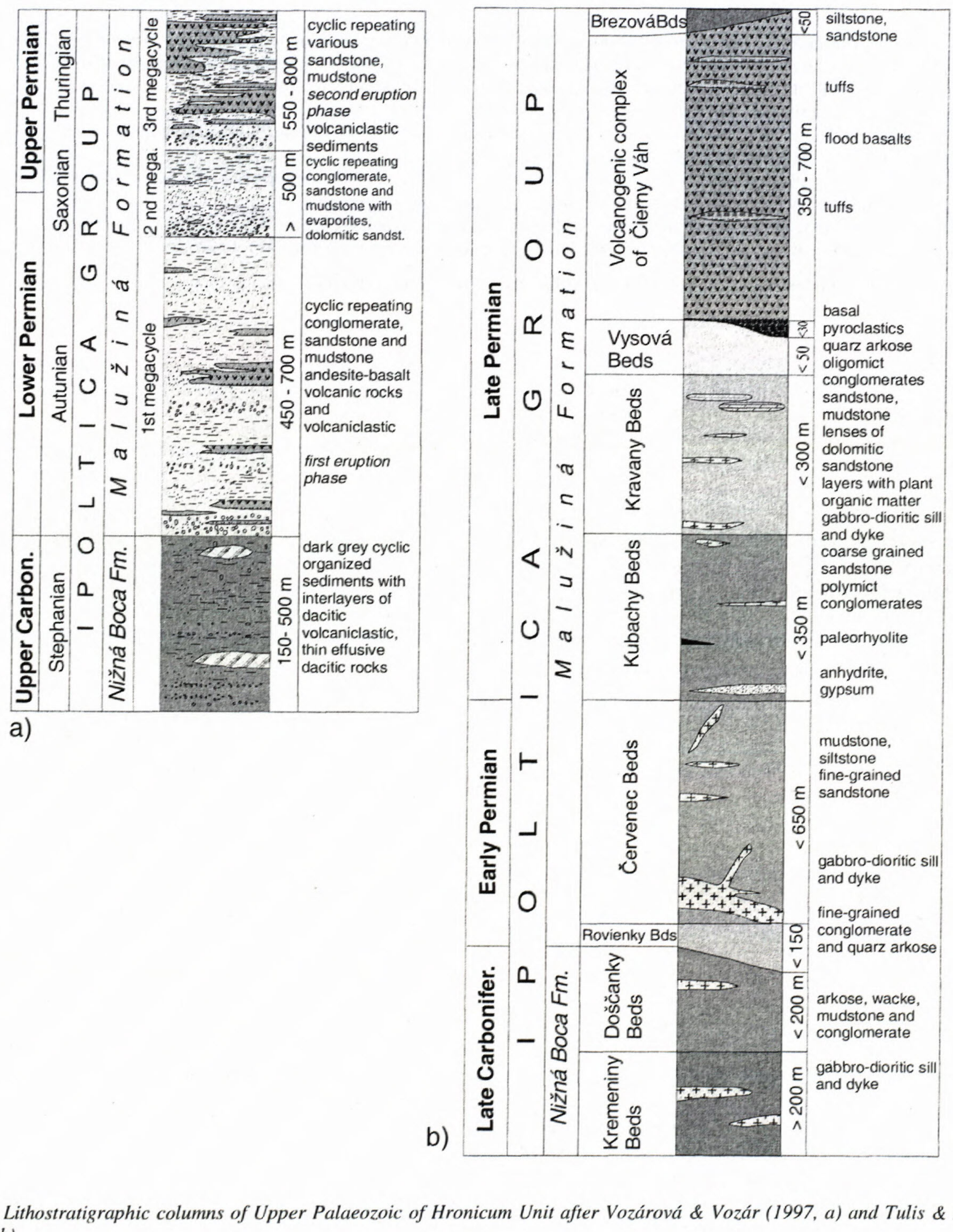


Fig. 2. Lithostratigraphic columns of Upper Palaeozoic of Hronicum Unit after Vozárová & Vozár (1997, a) and Tulis & Novotný (1998, b).

cles are characteristic with sediments deposited in alluvial lowland, where the constant riverain pools, eventually the extended lakes originated. The occurrence of evaporite association the authors connect with the distal facies of intracontinental sedimentary basin.

Lithofacies

The characteristic feature of Malužiná Fm. is the prevalence of repeatedly arranged cycles of fourth- and fifth-orders (parasequences and small cycles) into the third-order depositional sequences. Taking into account the lithological characteristics, primary sedimentary structures and geometry of sedimentary bodies, we distinguish ten lithofacial types. Lithofacies are a part of architectural elements, and their association defines the fluvial style of investigated sediments. The facies codes and terminology of architectural elements were compiled according to Miall (1985, 1996). The Malužiná Fm. is composed by massive bedded bodies 40-50 % *(Gm, Sm, Fm)*, horizontally laminated, eventually cross-bedded 30-40 % *(Gt, Gp, Sm, Sh, Sp, Fl)* and grade-bedded 10-20 % *(Gm, Gt, Gp, Sp, St)*.

Facies Fm (massive bedding)

Facies Fm are composed of brownred-purple siltstones, claystones, less often fine-grained sandstones. The sandstones can form intercalations of lensoidal shapes, or individual tabular bodies thick app. 1.5 m and long along strike to 10 m. The upper part is usually eroded by new cycle (sharp contact). The erosion intensity is proportional to clast dimensions of eroding overlying bed. This facies type can bear the pseudobed horizons of concretion bodies of mm to dm dimensions, most often there are developed the cavities after these concretions.

Facies Fl (horizontally laminated)

The fine lamination of lighter- and rich-purple thin beds as well as indistinct ripple bedding (Fig. 5a) are observable in this case. Bodies reach thickness of several metres, they can be divided by fine erosion boundaries. The bioturbation are very often, being reflected by chaotic small corridors with diameter from 0.5 to 1.5 cm, coursing perpendicularly, diagonally, or paralelly with bedding.

Facies Sm (massive bedding)

These sandstone bodies reach thickness 2-3 m. They can bear the internal gradations or marks of slight bedding. Sometimes they contain clasts of quartz pebbles and intraclasts of older sediments and volcanites.

Facies St (trough cross-bedding)

Trough cross-bedded sandy sediments are tightly associated with above stated facies of sandy fraction. Material at the base of such body with developed trough cross-bedding is usually more coarse-grained, with developed graded-bedding and often with erosion contact at underlying bed. The trough cross-bedding is developed through whole thickness of the bed, eventually it changes into planparallel, or cross-bedding in upper part. These bodies reach thickness 1-2 m and most often are composed from channel infillings thick 10 - 40 cm (Fig. 5c).

Facies Sp (planar cross-bedding)

The sandy sediments with planar cross-bedding outcrop together with facies Sm, St, Sh and Fm. The cross-bedding either represents the solitary bed (30 cm), or most commonly its basal part (thick to 50 cm) with transition to parallel lamination. It outcrops in small extent also in upper part (20 cm) of positive graded beds thick up to 2 m. The angle of cross-bedding reaches <15° (Fig. 5f). Sedimentary structures include planar cross-stratification with angular contacts and planar parallel to planar non-parallel discontinuous lamination.

Facies Sh (horizontal stratification)

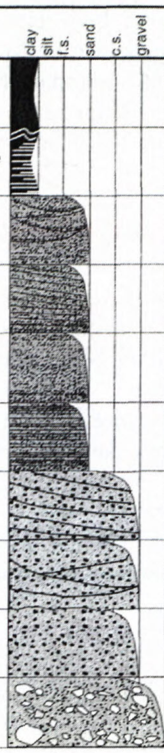
The current lamination in sandstones represents relatively frequent textural element of upper part of sedimentary bodies of lighter colours, well sorted quartz arkoses, alternating with finer red sandstones. It represents characteristic alternation of lighter and light-pink or red lamina (Fig. 5e)

Coarse-grained conglomeratic facies can be enlisted correspondingly according to the same marks among the massive *(lithofacies Gm)*, planar cross-bedded *(lithofacies Gp)* (Fig. 5g) and trough cross-bedded ones. The positive graded bedding is prevailing. Similarly, the distribution of coarse-grained conglomeratic facies is tied with sandy varieties. Principally they vary from sandy conglomerates to fine-grained conglomerates with the clasts dimensions most often beneath 1 cm. A special kind is represented with coarse-fragment unsorted sediments of red-brown colour with gravel matrix support having higher content of clayey matrix *(lithofacies Gms)*. These coarse-grained conglomeratic bodies with quartzy pebble material of dimensions 5-10 cm and more (max. 30 cm) are present only in this lithofacies (subaquaceous debris flow?). Very often there are the erosion contacts between beds, cutting older horizons, large intraclasts of fine-grained sediments and disproportion in clasts dimension (Fig. 5h).

Architectural elements

By enlarging the scale of observation, lithofacies are combined into architectural elements. In the Malužiná Fm. (in study area) there were identified mainly architectural elements as gravelly bars and bedforms, element **GB** and sandy bedforms, element **SB** comprising from lithofacies: Gm, Gp, Gt, Sm, Sh, Sp, St, filling of small chute channels (element **CH**), representing lithofacies Gt, St. Next there are floodplain deposits (element **FF**), or overbank fines (element **OF**), consisting from lithofacies Fm and Fl. Associations of architectural elements are then used to define the styles of the fluvial systems.

Slovak Geol. Mag., 11, 2 – 3 (2005), 133 – 142



facies		sedimentary structures and characteristic of deposits	interpretation	flow regime
Fm	mudstone, fine-grained sandstone, interbed ~ bed	massive bedding, bioturbation, mudcracks	sheet-flood deposit, floodplain	lower flow regime *low energy*
Fl Sr	very fine-laminated mudstone with sand interlaminae	horizontally laminated, loc. ripples, bioturbation	levee and floodplain deposits	lower planar bed condition
St	trough cross-stratified sandstone, loc. gravel	trough cross-bedding	channel fill deposits dunes	lower flow regime
Sp	planar cross-stratified sandstone, loc. gravel	planar cross-bedding (up to 10°)	transverse bars bottom accumulation	rythmic phase of transport
Sm	massive bedding sandstone	slightly graded	longitudinal bars	upper flow regime
Sh	planar horizontally-stratified sandstone	current lamination, planar stratification	large flat bars in active channels, loc. sheetflood	upper flow regime *higher flow velocities*
Gp	stratified gravel	planar cross-bedding	longitudinal bars	upper flow regime
Gt	stratified gravel	trough cross-bedding, erosive base	small chute channel	upper flow regime
Gm	massive or slightly stratified gravel	massive texture	longitudinal bars, sorted gravel, bottom sediments	upper flow regime
Gms	massive unsorted gravel with sand matrix supported	gradation, slight horizontal bedding, imbrication	subaqaceous debris flow	upper flow regime *high energy*

Tab. 1. Sedimentary facies recognized in the Malužiná Formation and their description and interpretation. Facies codes after Miall (1978).

FA	dominant lithofacies	minor lithofacies	architectural element	interpretation
FA4	Sm, Sh, Sp	St, Fm	SB: *sandy bedforms* FF: *overbank deposits (floodplains fines)*	sand-bed alluvial system ephemeral sheet-floods
FA3	Gms, Gm	Gp, Gt, Sp	CH: *channel fill* GB: *gravelly bars*	gravelly braided system/ debris-flow-dominated braided system
FA2	Sm, Sh, Sp	Fm, Fl, Sr	FF: *overbank deposits (floodplains fines)*	terminal alluvial plain ephemeral floods
FA1	Gm, Gp, Sm, Sh, Sp	Gt, Fm	SB: *sandy bedforms* CH: *channel fill* GB: *gravelly bars*	shalow sandy braided system on alluvial plain

Tab. 2. Facies associations recognized in the investigated area. Classification from Miall (1978, 1985, 1996).

Facies associations of the Malužiná Formation

Four facies associations have been recognized taking into account the lithology, assemblages of sedimentary structures, and sediment body architectures. These facies associations correspond to individual lithostratigraphic member after Novotný and Tulis (1998) and are summarized in Fig. 4. In investigated area south of Spišské Bystré and Kravany villages four facial association can be distinguished from the bottom upwards:

Facies association 1

The light coloured massive microconglomerates, coarse-grained sandstones (Gm, Sm, 40 %), coarse-grained subarkoses (Sp, Sh, 30 %), with graded-bedding (Gm, Gt, Sp, Sh, 20 %), cross- bedding (Gp, Sp, 5 %), locally with sandy conglomeratic bodies are prevailing. The typical arrangement: At the base the light-coloured microconglomerate with graded transition into sandy light-pink sandstone in upper part with low-angle cross-bedding, eventually the trough cross-bedding are present in the bed. The intercalations of red siltstones (Fm, 5%) thick from 1 to 20 cm are sporadically present in upper part of such graded bed. They are covered with erosive light-red microconglomerate fining upwards. The thickness of this cycle ranges from 50 cm to 3 m. The beds with internal positive gradations, as well as following geometrical and textural elements are present: wedging of the beds, channel load, trough cross-bedding and cross-bedding. Novotný (1972) describes in upper parts of beds the current ripples, rolled bedding, mainly in overlier of

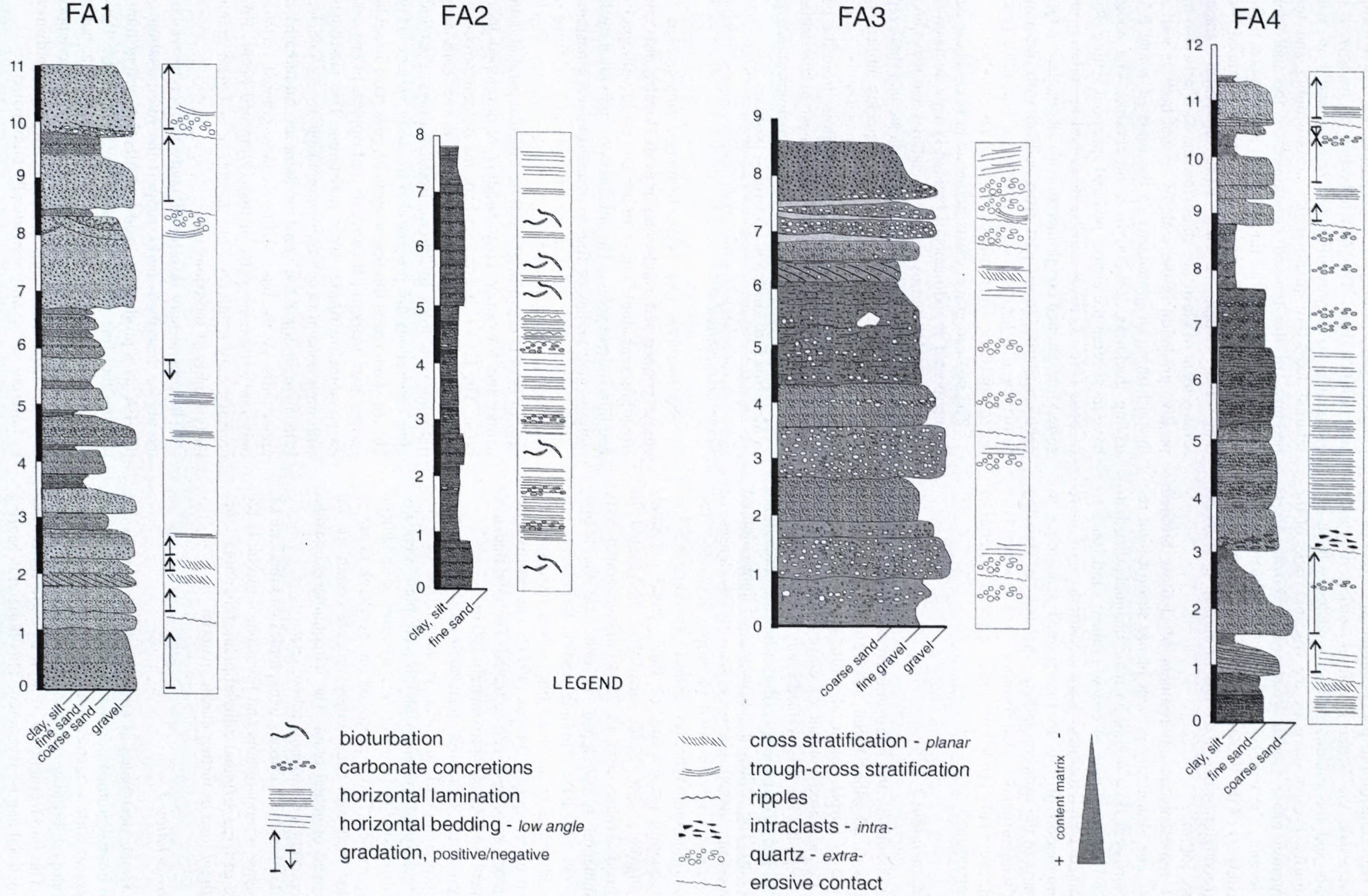


Fig. 3. Characteristic logs of the facial associations from Malužiná Fm. mapped in the study area. FA1 - Bystrá valley, Grúň. FA2 - Mokrá valley, Grúň. FA3 - Bystrá valley, Karabinovo mokré. FA4 - Bystrá valley, Palesák.

Slovak Geol. Mag., 11, 2 – 3 (2005), 133 – 142

ripples with transition to planar lamination. For this FA is characteristic the better structural sorting of clastic sediments and the middle-grained sandstones have the best maturity. Present there are the volcanic rocks of the first eruption phase (sensu Vozárová & Vozár, 1981; 1988), forming the vein bodies, as well as effusions (approximately 2) of the thickness 1–2 m. They are covered by microconglomerates. FA1 has in studied area thickness app. 150 m.

FA1 represents an environment of shallow braided systems. The abundantly present planar stratification reflects consistent flow regime in main channels distributing material prevailingly of coarse-grained sandstones to fine-grained conglomerates. Rare occurrences of more often alternation of silts to fine-grained sandstones in upper parts of the beds can indicate the states of flooding periods with suspended load forming levee deposits, later covered, eventually eroded by coarse-grained material of migrating channel.

Facies association 2

FA2 is built by the finest-grained sediments in comparison with all other facial associations. The typical brown-red to purple colour of sediments in this FA is caused by increased content of clayey matrix in sediments containing the fine-grained sandy fraction (Sm, Sh, Sp, 70 %) and having the sporadic carbonatic concretions (ca to 5 cm). The bodies of coarse-grained light-coloured sandstones are developed only scarcely as lenses of coarse-grained sandy material in purple siltstones. The thickness of individual bodies varies in the range 0.5-3 m. Most frequently present are the fine-grained red sandstones/siltstones with clastic mica, often bioturbated. In fine-grained varieties (Fm, Fl, 30 %) the horizontal, very fine lamination is developed. In one case the texture strongly resembled the climbing ripples. Relatively common muddy fractures and local fine slide deformations are described by Novotný & Jančok (1971). The positive gradation in bed association can be traced. The total thickness of sediments of FA2 is approximately 250 m.

All presented signatures, resp. their combination support interpretation of this FA as association of fine–graided lacustrine system with alluvial plain deposits, which correspond to facies of "playa" type, or ephemeral lakes. Sporadical floods produced the overbank facies as suspended load with exceedingly suitable conditions for development of actual biota. The ichnofauna is considered to represent the Scoyenia ichnofacies.

The laminated claystones with ripples and mudcracks, the presence of concretions and bioturbates resemble the presence of large terminal alluvial plain, remaining long-time without load of further clastic material.

Facies association 3

The facies, designated as Gms, is present only in this FA. The coarse-grained horizon of red-brown to red colour is typical with its textural non-maturity. Locally there are developed brighter horizons with relatively better sorting. The intraformational as well as extraformational pebble material can be registered. This horizon is bearing conglomerates with gravel supported, less often matrix supported texture. The bench bodies of massive conglomerates have prevailing thickness around 1 m, with internal marks of plan-parallel cross-bedding and thin bedding. In fine-grained conglomerates the individual beds of pebble material thick 4-6 cm and composed prevailingly of quartz are present. The positive graded bedding and trough bedding with sporadical graded arrangement of clasts are characteristic. Similarly also the positive gradation in the scale of several beds as well as upward-fining of granularity in the scale of whole FA3 having thickness 200-300 m is observable. The bodies have most often the coarse-bed and sphenoid setting. Part of beds (Fig. 3, FA3) can be described as follows: unsorted fine-grained conglomerate with 28 cm clast of Qtz, pebble material, lower part cross-bedded with transition to planparallel lamination, erosive basis – positive grading to sandstone, overlying bed is in erosive relation.

The bedload gravel clasts dominate in FA3. These can be interpreted as sediments of braided systems initiated by flood events. Numerous erosive boundaries and prevalence of channel arranged conglomerates indicate that these represent the system of relatively shallow quickly infilled and non-stable channels. Though the Gms facies we cannot directly characterize as typical debris flow, from the genetic viewpoint it is genetically very near to this facies. This FA is in hierarchy of deposition environment energy of Malužiná Fm. located in uppermost position.

Facies association 4

The massive, less often laminated fine-grained to coarse-grained red sandstones prevail, locally also siltstone horizons thick app. 1 m are preserved with graded bedding (microcycles). The thickness of individual cyclically bedded bodies of fine to coarse-grained sandstones varies in the range 0.5-2 m, prevailingly to 2 m. Some of these entities have platy bedding thick 7-10 cm. Thickness of FA4 is prevailingly 200 m. The planparallel lamination and low-angle cross-bedding is developed more often. The FA4 is bearing perhaps the biggest carbonatic concretions (up to 30 cm), but also the carbonate-dolomite beds thick to 20 cm. Bedded arrays of cavities after concretions are present also in sandy varieties (Fig. 5b). In some cases the upper parts of beds have irregular surface with marks of flood-casts and ripples. In one case the asymmetric ripples were registered. The sandstones with high content of silt-clay component are a characteristic member for FA4; some of them are bioturbated in upper parts. At the base of more coarse-grained varieties only rarely the clay galls of underlying bed occur. FA4 contains only relatively tight spectra of sediment granularity mainly of sandstone type.

The prevailingly developed sandy fraction as well as the above described marks support the interpretation of this FA as a product of sand-bed alluvial system transporting the fine-grained material with sporadic flood events on alluvial plain. It is similar like in FA2, but in this case the overbank sediments were earlier overlapped by new charges of clastic materials, which is confirmed by horizons being only sporadically bioturbated.

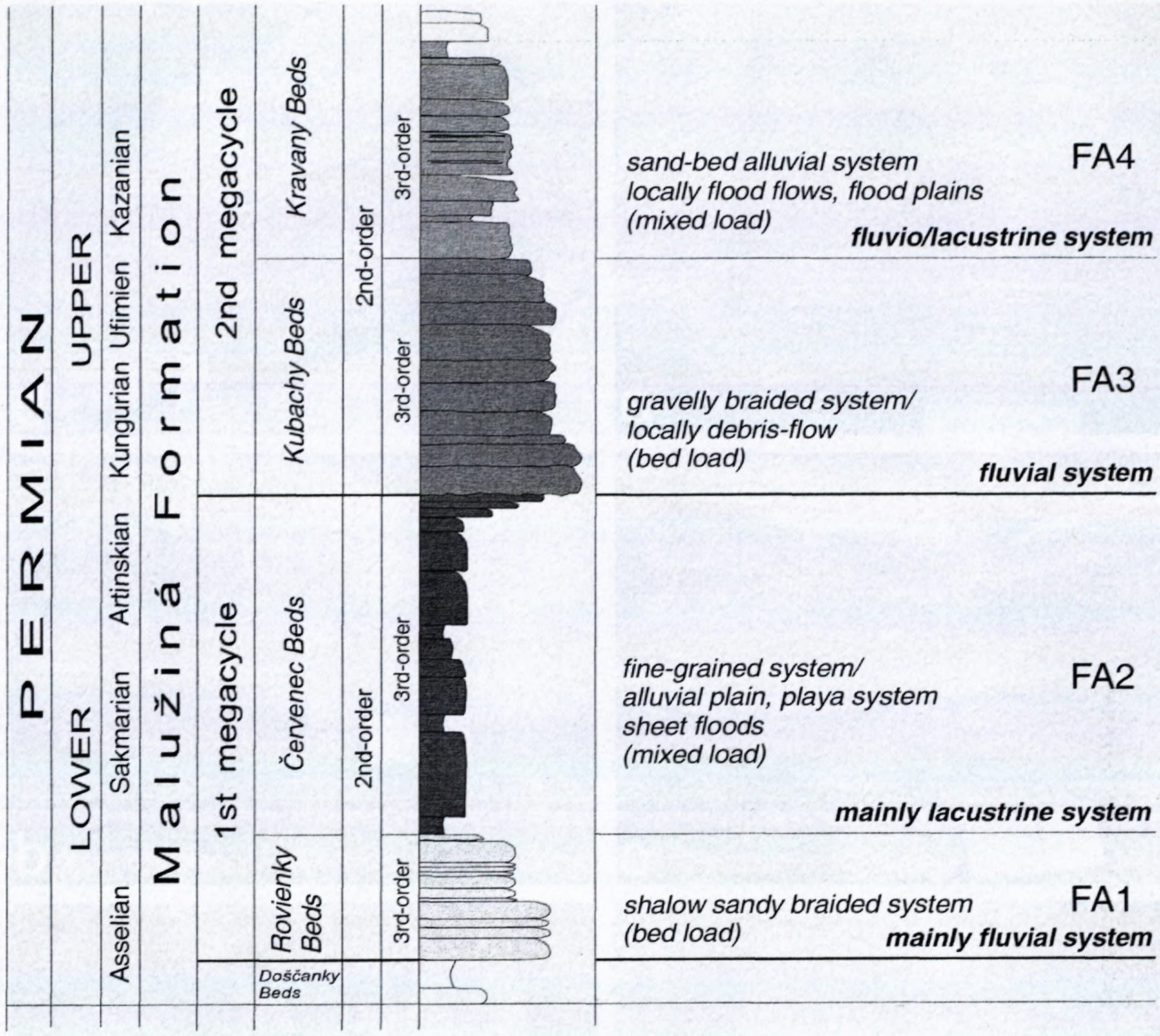
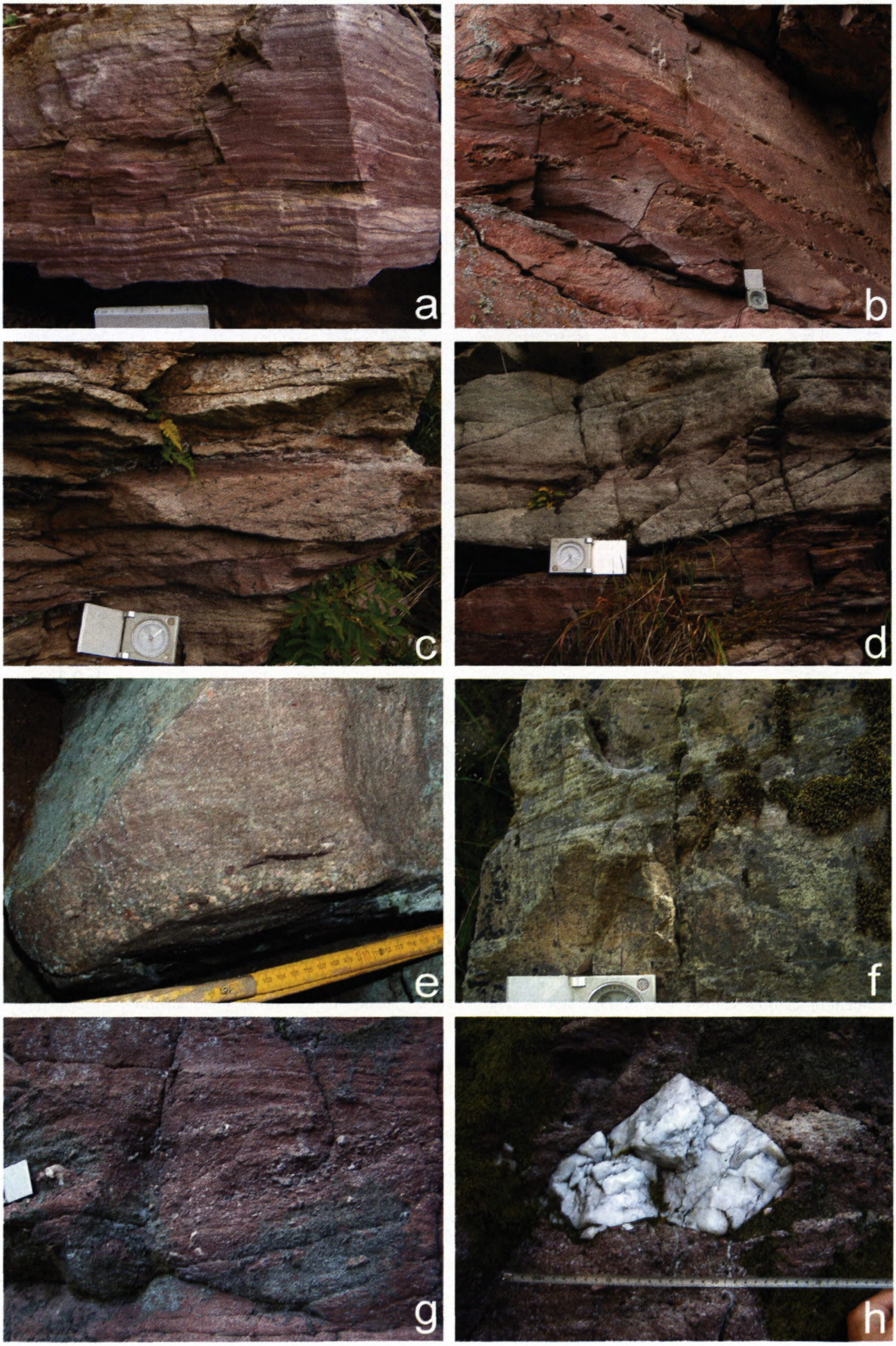


Fig. 4. Evolution of fluviolacustrine style of the Malužiná Fm. in studied area. The Doščanky Beds represent probable the stratigraphic boundary between Carboniferous and Permian. They are a constituent of lower sequence, resp. FA. FA4 belongs to lower part of Kravany Beds, their upper part with content of coalified flora and carbonatic clastic rocks, as well as upper part 2nd-order sequence (3rd megacycle) are not included here. Volcanic rocks are also missing in this scheme.

Discussion

The stratigraphy of facial associations reveals following four stages of sedimentary evolution of investigated part of Malužiná Fm.: (1) Deposition of FA1 occurred in environment of shallow sandy/gravel braided system. The positive graded beds with footwall sharp contact with amalgamation character (Fig. 5d) and through cross-bedded set (Fig. 5c) in FA1 (Rovienky Beds) bear the marks of fluvial deposition. The prevalence of sorted clastics - relatively matured subarkoses is evident. (2) The change of fluvial style is characterized with gradual but quick transition into sediments typical for overbank facies in floodplain area, being represented by FA2 (Červenec Beds). It builds the upper part of 1st megacycle. Its considerable thickness (250-650 m) reflects long-term monotonous development of stable sedimentary area. (3) Abrupt transport of coarse-grained and partially unsorted clastics into the basin indicates the tectonic activity and younging of source area. Such sediments present the basis of 2nd megacycle. Sedimentary environment was obviously more diversified and described FA3 (Kubachy Beds) represents only a part of sedimentary area with higher relief inclination and conditions for quick deposition with participation of flood events (Gms facies, subaqueaceous debris flow). The unsorted material prevails over the better sorted coarse-grained sediments. (4) Transition to overlying FA4 (lower part of Kravany Beds) is again gradual and connected with fining of positive graded cycles. The main presence of the sand, connected with the massive, locally planar structures and carbonate concretions, suggests that the main transport was generated by ephemeral sheet floods events (upper flow regime) in alluvial plain conditions.

Despite every effort, there is still not possible satisfactorily explain the character of deposition boundaries between individual FA. The answer would be obtained by analysis of sequence stratigraphy of Malužiná Fm.. accompanied with revision of results of drilling works, located near the boundaries. Although, principal there is


a
b
c
d
e
f
g
h

knowledge about boundary between Červenec Beds (FA2) and Kubachy Beds (FA3), being described as gradual with coarsening positive grading with transition to overlier (Novotný & Jančok, 1971).

The presented lower (monotonous) part of Kravany Beds is bearing the most probable the fluvial marks. Some authors (e. g. Novotný & Tulis, 1998) suppose, that later (upper part of Kravany Beds) there occurred the basin shallowing and gradual diversification to partial sedimentary areas of fluvial type with local transition to continental lakes with increasing salinity. According to Vozárová and Vozár (1988) the sediments are typical lacustrine ones being deposited in semiarid conditions. The change of sedimentary environment is characterized by change of colours to grey, greygreen and rarely to blackgrey and red. The intercalations bearing the flora fragments in the form of coalified plant detritus are often associated with fine-scale cross-bedding. The carbonate sedimentation represented by dolomite-calcite sandstones and sandy limestones in lensoidal bodies appears here for the first time.

The base of next third-order depositional sequence (3rd megacycle) is built with positive graded Vysová Beds (Fig. 2) prevailingly of light colours and locally with quartzstone beds. Quartzstones represent mineralogically the most mature sediment of Malužiná Fm. (Novotný & Tulis, l. c.).

Significant occurrences of evaporite association indicate the intensive evaporitization in environment of intermittently flooded parts of floodplain with character of continental sebkha or playas (Vozárová & Vozár, 1988). Gypsum in veins, presented as "redeposited", occurring in upper part of FA2 and probable also in lower part of FA3, indicates, that originally it could form cement, or thin beds which could be later resedimented. Also 30 m thick bed, being penetrated by borehole No. 310 (Novotný & Tulis 1998), formed by alternating evaporites (dolomite, anhydrite, gypsum), claystones to microconglomerates (Ďurovič, 1968, 1970), belongs into this stratigraphic horizon. Tightly above the bodies of coalified flora the bodies of carbonatic sandstones are developed. Next similar occurrences of "redeposited" gypsum are located similarly at the boundary between Kravany Beds and Vysová Beds (Novotný & Tulis l. c.).

The setting of Malužiná Fm. was influenced by three allocyclic controls: eustasy, tectonics and climate. From these the global change of sea level (eustasy) principally did not have any effect for development in lower part of Malužiná Fm. Succession of two third-order depositional sequences (FA1–FA4) can be correctly understood as reflection of tectonics in sedimentary area of the basin. The transition from higher energy fluvial regime (braided to meandering streams) towards the regime of calm sedimentary conditions reflects the shifting of facies from proximal to distal part.

Conclusions

Investigated lower part of the Malužiná Fm. consists from four third-order depositional sequences, corresponding to 1st and 2nd megacycle and being divided by sequence boundary of started deposition of coarseclastics. We have distinguished ten principal facies in sediments: massive and finely laminated mud with ripples (Fm, Fl, Sr), massive, trough cross and planar cross-stratified sandstone (Sm, St, Sp, Sh), massive and stratified gravel (Gm, Gp, Gt), unsorted gravel (Gms). Three basic kinds of architectural elements are defined in this study: mainly sandy bedforms (SB), channel (CH) and overbank fines (OF), which are built by four facies associations (FA1-FA4). Described FA mostprobable represent the stratigraphic boundary Lower Permian to lower part of Upper Permian (1st and 2nd megacycle sensu Vozárová & Vozár, 1988). They represent two genetically neighbouring sequences. First of them represent the sediments of shallow braided alluvial system with transition to large terminal alluvial plain. The second sequence characterizes the gravel braided system connected with erosion of underlier, quick sedimentation and repeated origin of floodplain sedimentary environment. Climatic conditions can be characterized as semiarid. Cyclicity of Malužiná Fm. has fluviolacustrine characteristics. The upward-fining cycles of 2nd order reflect the change in topographic gradient and fluvial sedimentation style. Stratigraphic architecture and cyclicity of 2nd order fluvial sequences was controlled by tectonics. The cycles of fourth and fifth order were influenced by fluvial regime in co-influencing climate.

Acknowledgements

This work originated as a part of the project of Ministry of Environment of Slovak Republic No. 130 *Tectogenesis of sedimentary basins.* It was also supported by the project No. 27 98 *Geological map of Slovak Republic in scale 1:200 000.* Author expresses his thanks to Prof. A. Vozárová for her review comments. The study was partly supported by Grant 1/1036/04 of VEGA.

Fig. 5. a) Laminated mudstone facies (Fl) showing finely-laminated mud with very fine sand interlaminae, (FA2). b) Calcretes horizonts in fine-grained red sandstone/mudstone facies (Fm), (FA4). c) Trough cross-bedding in the coarse sandstone facies (St), (FA1). d) Sharp contact between the underlying shale and overlying coarse graded bed, (FA1). e) Graded bed with intraclasts, upper part of the bed is horizontally laminated (Sh), (FA1). f) Planar cross-beds sandstone facies (Sp), (FA1). g) Trough cross-bedded (Gt) gravel, (FA3). h) Almost 30 cm clast of vein quartz in Gms facies (FA3).

Literature

Andrusov D. & Samuel O. et. al., 1984: Stratigraphic dictionary of Western Carpathians, vol. 1, *Geol. Úst. Dionýza Štúra, Bratislava, 125-126.*

Biely A., Beňuška P., Bezák V., Bujnovský A., Halouzka R., Ivanička J., Kohút M., Klinec A., Lukáčik E., Maglay J., Miko O., Pulec M., Putiš M. & Vozár J., 1992: Geological map of the Nízke Tatry Mts. 1:50 000. *Geol. Úst. Dionýza Štúra, Bratislava.*

Biely A., Bujnovský A., Vozárová A., Klinec A., Miko O., Halouzka R., Vozár J., Beňuška P., Bezák V., Hanzel V., Kubeš P., Liščák E., Lukáčik E., Maglay J., Molák B., Pulec M., Putiš M., Slavkay M., (Biely & Bezák edit.) 1997: Explanations to geological map of the Nízke Tatry Mts. 1 : 50 000. *Geol. Úst. Dionýza Štúra, Bratislava, 7-232.*

Dostal J., Vozár J., Keppie J. D., Hovorka D., 2003: Permian volcanism in the Central Western Carpathians (Slovakia): Basin-and-range type rifting in the southern Laurussian margin. *Int J Earth Sci (Geol Rundsch) 92, Springer-Verlag, 27-35.*

Drnzík E., 1969: Mineralization of copper-bearing sandstones in Permian of melaphyre series on south-eastern slopes of the Nízke Tatry Mts. *Mineralia Slov., 1, 1, Sp. N. Ves, Alfa, 7-38.*

Ďurovič V., 1965: Melaphyre series in surrounding of Liptovská Teplička and Spišské Bystré villages. *Acta geol. et geogr. Univ. Komenského, 13, Bratislava, 181-186.*

Ďurovič V., 1968: Petrography, lithology and sedimentology of melaphyre series on south-eastern slopes of the Nízke Tatry. *Manuscript-archive of Department of petrography of Faculty of natural sciences, Comenius Univ., Bratislava, 3-240.*

Ďurovič V., 1970: Geological-petrographic investigation of volcanogene-sedimentary (melaphyre) series on south-eastern slopes of the Nízke Tatry Mts. *Acta geol. geogr. Univ. Comen., Geol. No 19, Bratislava, 25-100.*

Miall A. D., 1978: Facies types and vertical profile models in braided river deposits: A summary. *Fluvial sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, 597-604.*

Miall A. D., 1985: Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. *Earth Sci. Rev.*, 22: 261-308.

Miall A. D., 1996. The geology of fluvial deposits: Sedimentary facies, basin analysis and petroleum geology. Berlin, Heidelberg, New York: Springer-Verlag, 582 p.

Novotný L., 1970: Sedimentology and paleocurrent analysis in Permian of the Choč Unit between villages Liptovská Teplička and Spišský Štiavnik. *Diploma thesis. Archive PRIFUK, Bratislava.*

Novotný L., 1972: Sedimentology and paleocurrent analysis in Permian of Choč Unit between villages Liptovská Teplička and Spišský Štiavnik. *Doctoral thesis. Geofond, 86 p.*

Novotný L. & Badár J., 1971: Stratigraphy, sedimentology and mineralization of Upper Paleozoic of the Choč Unit in south-eastern part of the Nízke Tatry Mts.. *Mineralia slov., 3, 9, Bratislava, 23-42.*

Novotný L. & Jančok J., 1971: Sedimentological investigation of Permian formations of the Choč Unit between villages Nižný Chmelienec and Liptovská Teplička. *Geofond, 64 p.*

Planderová E. & Vozárová A., 1982: Biostratigraphical correlation of the Last Paleozoic formations in the West Carpathians. *Newsletter No. 4, IGCP project 5 ed. F. P. Sassi, Univ. Padova, p. 67-71.*

Roth Z., 1938: Geological relations in Lučivná surroundings beneath the High Tatra Mts. *Rozpr. Čes. Akad. Věd a Um., 48, 13, Praha, 7-22.*

Sitár V. & Vozár J., 1973: Die ersten makrofloren – Funde in dem Karbon der Choč – Einheit in der Niederen Tatra (Westkarpaten). *Geol. Zbor. Geologica carpath., 24,2, SAV, Bratislava, 441-448.*

Tulis J. & Novotný L., 1998: Evaluation of geological works for U-ores in Upper Paleozoic of Hronicum Unit in northern part of the Nízke Tatry Mts. and Kozie chrbty Hills. *Geofond, 144 p.*

Vozár J., 1977: Magmatic rocks in the tholeiitic series of Permian of the Hronicum Unit in the West Carpathians. *Mineralia slov., 9, 4, Alfa, Bratislava, 241-258. (in Slovak).*

Vozár J., 1997: Rift-related volcanics in the Permian of the Western Carpathians. In: Grecula P., Hovorka D., Putis M. (eds): *Geological evolution of the Western Carpathians. Mineralia Slovaca, Monograph Geocomplex, Bratislava, Slovakia, 225-234.*

Vozárová A. & Vozár J. (eds.), 1979: Permian of the West Carpathians. *Guide-book for geol. excursion. Geol. Úst. Dionýza Štúra, Bratislava, 3-79.*

Vozárová A. & Vozár J., 1981: Lithostratigraphic characteristics of Upper Paleozoic of Hronicum Unit. *Mineralia slov., 13, 5, Bratislava, 385-403.*

Vozárová A. & Vozár J., 1988: Late Paleozoic in the West Carpathians. *Geol. Úst. Dionýza Štúra, Bratislava, 7-314.*

Vozárová A. & Vozár J., 1993: Pre-Alpine terranes in the West Carpathians: Variscan orogen collisional–postcollisional reconstruction.. *In: Rakús M. & Vozár J. (eds.): Geodynamic model and depth setting of Western Carpathians, Geol. Úst. Dionýza Štúra, Bratislava, 129-143. (in Slovak).*

Petrography and geochemistry of subvolcanic basalt bodies among the Upper Carboniferous sediments from the underlier of Muráň Mesozoic sequences (Slávča and Furmanec valleys, Western Carpathians)

RASTISLAV DEMKO and MÁRIO OLŠAVSKÝ

Geological Survey of Slovak Republic (ŠGÚDŠ), Kynceľovská 10, 97401 Banská Bystrica

Abstract: The dykes of basic rocks were found in several tectonic slices with the Upper Carboniferous clastic sediments in the underlier of the Muráň Mesozoic sequences, being located in the Slávča and Furmanec valleys north of the town Tisovec. The dykes consist of tholeiitic basalts with subophitic to intersertal texture. They are characteristic with the prior crystallization of plagioclase, which led to origin of plagioclase network, and subsequent crystallization of ilmenite and augite. The chemical composition of the rocks is influenced by the fractionation of penetrating melt through the plagioclase network, leading to high values of MgO, Ni, Cr and Al_2O_3. The basalts indicate partially the cumulate character.

The petrographic and chemical compositions correspond with the Permian dyke subvolcanic basalts from the Upper Carboniferous Nižná Boca Formation of Hronicum. Accordingly we assign the same petrogenetic conditions for the origin of basalts from Slávča, Furmanec as well as Hronicum. The same distribution of REE-HFSE as in the case of low-Ti flood basalts from the Paraná province (Brazil) and Noriľsk (Siberian traps) evokes the within-plate flood basalts environment for the origin of studied basalts.

Key words: *Permian volcanism, tholeiitic dykes, solidification, geochemistry*

Introduction

The Upper Carboniferous clastic sediments in the underlier of Muráň Mesozoic sequences are bearing already known occurrences of magmatic rocks, though without detail petrographic study. The bodies are compared with the potential Permian analogues of the vein bodies, being situated mainly in the Upper Carboniferous Nižná Boca Formation of the Ipoltica Group of Hronicum (Vozárová & Vozár, 1988). The enlistment of described occurrences to Hronicum mainly by their identical lithology was preferred already earlier (Zoubek, 1957; Biely, 1961, 1966). On the other side, their affinity to Gemericum was supposed by Kovařík et al. (1954), Klinec (1976) and Kamenický in Maheľ et al. (1967). In the last studies about the Carboniferous sequences in the underlier of Muráň Mesozoic in the Furmanec area (Vojtko, 2000; Plašienka & Soták, 2001) these isolated occurrences in the overlier of Veporicum and underlier of Silicicum nappes are understood by structural inventory as belonging to North-Gemeric.

The presented work gives the first detail petrographic description of rocks of subvolcanic bodies. This description, together with the geochemistry, analyses the genetic aspects concerning the solidification phase and paleotectonic regime of origin of parental magmas.

Geological setting

The lowermost element in the region with described localities (Fig. 1) is formed by the Hercynian crystalline basement – Veporicum, prevailingly composed from granitoids. The so-called Federáta sequence (Rozlozsnik, 1935) represents the cover of this basement and in its lower part it is formed mainly by the Permian-Triassic clastic sediments. The Permian sediments belong to Rimava Formation of the Revúca Group (Vozárová & Vozár, 1988). The preserved Triassic carbonate sedimentary succession according to Plašienka & Soták (2001) the best converges to so-called Tuhár Succession. The Carboniferous sediments from the Furmanec valley belong to two tectonic lenses. The upper clastic-carbonatic lens was correlated with the Lubeník Formation of the Ochtiná Group of Gemericum and its age was determined by biostratigraphy to Upper Visean (Plašienka & Soták, 2001). The lower slice is formed exclusively by the clastic sediments with basic volcanics designated as diorites. The listed authors (Plašienka & Soták, 2001) allocate both slices into the Furmanec partial unit, which is supposed to be a part of Gemericum. The clastic sediments of the Furmanec and Slávča valleys, composed of dark schists, greywackes, arkoses and locally conglomerates and accompanied with the bodies of basic volcanites, were mainly by lithological similarity supposed to be Upper Carboniferous (Stephanian) and correlated with the Nižná Boca Formation of Hronicum (Vozárová & Vozár, 1988). The relics of these Carboniferous sediments are tectonically superimposed by partial elements of Muráň nappe, composed of Mesozoic sequences of Silicicum (Lower Triassic-Lower Jurassic, Vojtko, 2000), but the author considers also the Turnaicum and Meliaticum.

Slovak Geol. Mag., 11, 2 – 3 (2005), 143 – 153

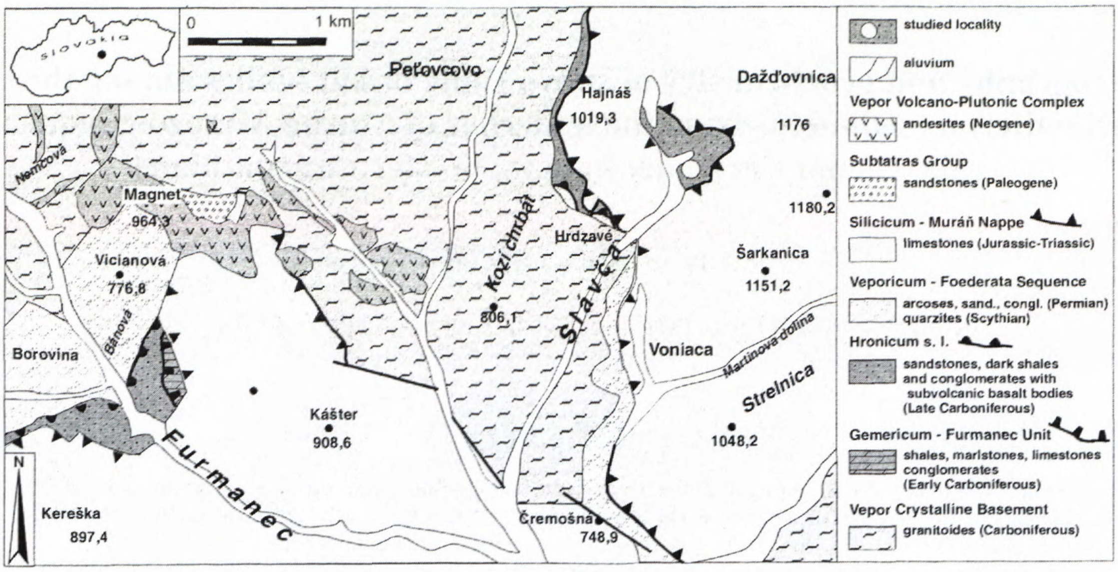


Fig. 1. Schematic geological map of the territory north of Tisovec describes the studied localities from the Furmanec and Slávča valleys. Compiled from the works by Klinec (1976), Vojtko (2000) and Plašienka & Soták (2001).

Analytical methods

The mineral phases were analysed by electron microprobe CAMECA SX-100 in Geological Survey of Slovak Republic (ŠGÚDŠ). Analytical conditions: accelerating voltage 15 kV, measured electric current 20 nA, the diameter of electron ray 5 μm. The selected analyses of clinopyroxene and amphibole are stated in Tables 1 and 2. The rock samples were manually purified from weathered parts and consequently analysed for essential silicates and selected trace elements in Geoanalytic laboratories of Geological Survey of Slovak Republic (ŠGÚDŠ) by the method of X-Ray Fluorescence spectrometry (XRF) and atomic emission spectrometry with inductively coupled plasma (AES-ICP). For the reasons of elimination of alteration (LOI) influence the analyses were recalculated for 100 % and water-free basis. The original analyses are stated in Tab. 3.

Petrography

The rocks demonstrate the subophitic, or intersertal texture. The primary mineral composition consists of plagioclase, ilmenite, clinopyroxene and accessoric apatite. They are characteristic with the developed plagioclase skeleton, which documents the early extensive plagioclase crystallization. The skeleton is formed with numerous plagioclase crystals, being interconnected due to the minimalization of surface energy of plagioclase in host parental melt (Philpotts et al., 1998; Philpotts & Dickson, 2000). The plagioclase skeleton (PS) has a morphology of three-dimensional network and determines the next crystallization development of generating rock (Demko & Olšavský, 2005). The PS dictates the morphology and permeability of cell spaces infilled with melt. Locally the deformations of PS were observed, being the result of pushing up the plagioclase crystals due to the outer mechanical impulse – the stroking of dyke walls, compaction of dyke material, local thermal or compositionally induced convection. In rock the zones characteristic with the frequent occurrence of the subophitic clinopyroxene (Fig. 2) were observed, contrary to the zones with sporadically present clinopyroxene. The crystallization did not reach the phase of holocrystalline rock. Part of PS cells contains chlorite, which we suppose to be the product of volcanic glass alteration together with the mineral assemblage K-feldspar, albite and Fe-Ti oxide. The skeletal development of plagioclase margins in intersertal parts (Fig. 3) we suppose as a sign of the fast crystallization due to undercooling, which preceded the final overall frozing and the volcanic glass origin. The early crystallization of plagioclase prior the clinopyroxene is typical for tholeiitic crystallization trend with increase of FeO in residual melt during fractionation (Grove & Baker, 1984; Grove & Kinzler, 1986). The rock parts with the high degree of crystallinity dominantly contain the mineral association plagioclase, ilmenite, clinopyroxene and altered volcanic glass. In the case of crystallization of parental tholeiitic melt in closed system the increasing percentage of fractional crystallization would lead to crystallization of pigeonite and quartz with local granophyre development (l.c). The presence of parts without pigeonite and quartz we suppose to be an effect of cumulate process (Cox et al., 1979), in which the percolating melt in composition varied in phase volume of plagioclase and augite. The modified augite-poor and with pigeonite + quartz enriched melt was continuously displaced to effusive rock or quartz granophyre, which in locality was not observed. The rocks are penetrated with plagioclase veins of the thickness up to 2 cm - plagioclase pegmatites. These particular phenomena were firstly described by Šťastný (1927), later Vozár (1971) and analysed in details by Philpotts et al. (1996). They are the segregates of the melt from deformed PS by the process of filter pressing as a reason of pressing of the side walls of dyke and reduction of its volume, or by mechanical

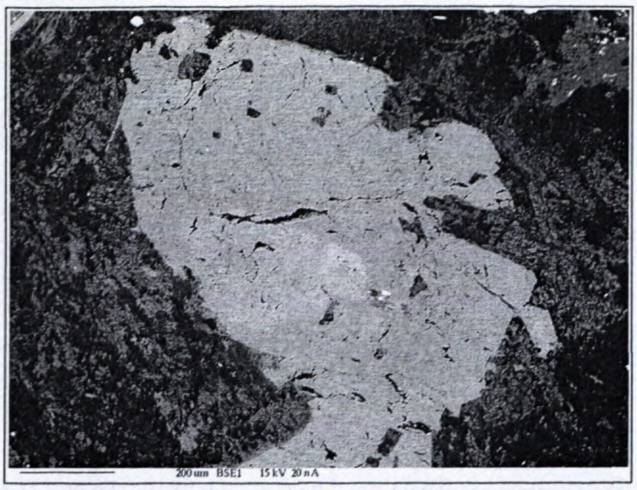


Fig. 2. Detail of subophitic cpx in plagioclase network. Plagioclases are strongly saussuritized. Clinopyroxene crystallized from the plagioclase surface towards the centre of PS cell. The light central part preserves the morphology of PS cell being dictated by the plagioclase configuration. BSE.

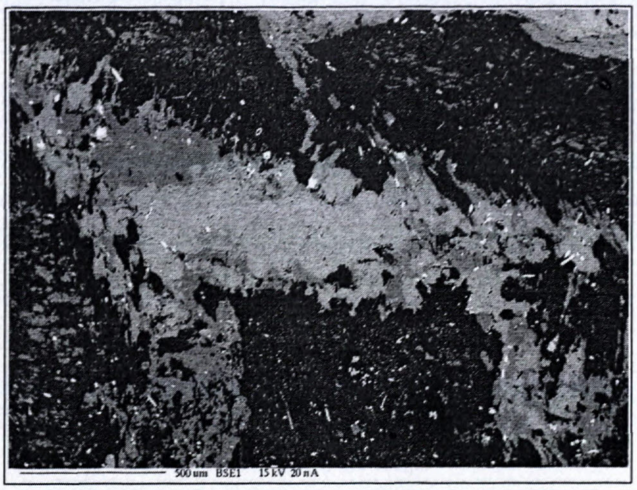


Fig. 3. Detail of relic thin channel in plagioclase network, being infilled with glass. The saussuritized plagioclase margins are bearing the traces of final undercooling with skeletal habit. Altered glass is transformed to mixture of chlorite, K-feldspar, albite and minute Fe-Ti oxide. BSE.

influence of a new melt injection into PS. The plagioclases in veins are of tabular morphology, variable dimensions, with locally observed phenomena of throttling of veinlet passage.

Chemical composition of clinopyroxenes and magmatic development of subvolcanic dykes

Clinopyroxenes (Tab. 1) are the only preserved minerals from the magmatic phase. According to classification by Morimoto et al. (1989) they are represented by augite to diopside. They can be divided into three groups: A) Cpx with composition **En**(49.3-40.6)**Fs**(15.2-6.1) **Wo**(46.7-40.9) **#Mg**(88.6-74.2). The monomineral clinopyroxene thermometer by Mercier (1976) demonstrates the temperatures in the range 1197-1039 °C. In the group the strong variations occur in the composition of Al_2O_3

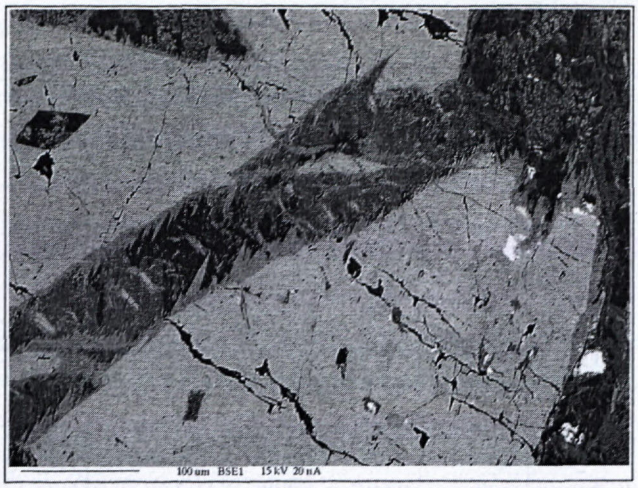


Fig. 4. Detail of obliquely cataclased clinopyroxene separated with antitaxial vein and with the development of directional metamorphic acicular actinolite. The picture documents the brittle deformation superimposed on phase of hydrothermal alteration (saussuritization of plagioclases). BSE.

(4-1.73 wt.%); TiO_2 (1.5-0.5 wt.%). Cpx associates with skeletal ilmenites, which mutual configuration in host cpx indicates the possible epitaxial relation. B) Cpx **En**(46.1-39.5)**Fs**(16.3-9.2)**Wo**(45.6-42.2) **#Mg**(83.3-71), temperatures 1196-1066 °C. The transitional group between the groups A) and C). The group C) with composition **En** (39.8-31.9)**Fs**(22.5-11.3)**Wo**(48.9-43.8) **#Mg**(77.9-58.6). The content of wollastonite component indicates their low-temperature origin (Mercier, 1976; Lindsley & Andersen, 1983). Differing from Cpx-A) the contents Al_2O_3 (0.55-0.24 wt.%), TiO_2 (0.2-0.06 wt.%) are low at variation MgO (14-10.9 wt.%), indicating the strong decrease of Al, Ti activities during the melt differentiation in PS (Fig. 5a, b). Cpx A, B, C occur in rock in tight spatial relation. They often form various composition zones of Cpx. The Cpx zonality types (core→rim) can be divided: A→B→C, A→C, but also A→C→B and C→A.

The absence of pigeonite and quartz in PS cells, the former presence of glass in PS cells and low Al_2O_3 content in cpx can be explained by the flotation of melt through the PS skeleton. The penetrating melt was continually filtered by plagioclase component, pushing its composition into the phase volume of augite. Augites start to crystallize on plagioclases surface with the gradual infilling of PS cells and origin of subophitic texture. In this case the PS operates as catalyzer of cpx nucleation. The process causes the lowering of the ratio of intersertal texture towards the subophitic texture. The lowering of PS permeability leads to origin of partially closed microreservoirs of basaltic melt. The combined zonality of cpx is a result of crystallization with the increasing system undercooling (the heat conduction into the surrounding sediments) and interaction of chemically heterogeneous melts in PS (Demko & Olšavský, 2005).

Alteration of subvolcanic dykes

Clinopyroxenes are the only preserved magmatic minerals. Plagioclases are saussuritized. The products of

Table 1: EPM analyses of clinopyroxenes, recalculated to 6 oxygens. Fe^{3+} is obtained by charge balance calculation procedure of Papike et al., (1974; in Lindsley & Andersen, 1983).

	Cpx23	Cpx24	Cpx 38	Cpx 39	Cpx 45	Cpx 3	Cpx 9	Cpx 10	Cpx 20	Cpx 27	Cpx31
SiO_2	50,50	50,05	51,36	52,25	51,61	52,94	51,74	51,86	52,09	49,67	52,00
Al_2O_3	3,39	3,95	2,99	2,33	3,08	1,05	2,27	2,40	1,83	3,56	1,59
TiO_2	1,31	1,45	0,96	0,83	0,94	0,36	0,90	0,92	0,85	1,54	0,77
FeO	5,14	4,82	6,10	6,38	6,12	5,65	5,31	4,44	6,52	5,40	8,43
Fe_2O_3	2,60	2,69	1,57	0,87	0,98	1,85	2,03	2,40	1,45	3,06	1,62
MnO	0,21	0,27	0,19	0,24	0,25	0,24	0,24	0,22	0,33	0,23	0,35
MgO	15,29	15,25	15,48	15,20	15,38	15,80	16,25	16,40	16,37	15,14	14,99
Cr_2O_3	0,29	0,37	0,19	0,20	0,25	0,06	0,36	0,31	0,25	0,26	0,02
CaO	21,36	21,33	21,21	21,91	21,39	21,79	21,19	21,65	20,32	20,95	20,51
Na_2O	0,34	0,33	0,25	0,30	0,30	0,39	0,25	0,31	0,22	0,33	0,27
K_2O	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	0,01	0,00
Total	100,43	100,50	100,30	100,51	100,29	100,13	100,55	100,93	100,23	100,15	100,55
Si	1,862	1,843	1,893	1,922	1,900	1,951	1,899	1,892	1,920	1,841	1,928
Al (IV)	0,138	0,157	0,107	0,078	0,100	0,046	0,098	0,103	0,079	0,155	0,069
Fe^{3+} (IV)	0,000	0,000	0,000	0,000	0,000	0,003	0,003	0,004	0,000	0,004	0,003
Al (VI)	0,009	0,015	0,023	0,023	0,034	0,000	0,000	0,000	0,000	0,000	0,000
Fe^{3+} (VI)	0,072	0,075	0,044	0,024	0,027	0,048	0,053	0,061	0,040	0,082	0,043
Ti	0,036	0,040	0,027	0,023	0,026	0,010	0,025	0,025	0,024	0,043	0,022
Cr	0,009	0,011	0,005	0,006	0,007	0,002	0,010	0,009	0,007	0,008	0,001
Mg	0,840	0,838	0,850	0,834	0,844	0,868	0,889	0,892	0,899	0,836	0,828
Fe^{2+}	0,159	0,148	0,188	0,196	0,188	0,174	0,163	0,135	0,201	0,167	0,261
Mn	0,007	0,008	0,006	0,008	0,008	0,007	0,008	0,007	0,010	0,007	0,011
Ca	0,844	0,842	0,838	0,864	0,844	0,860	0,834	0,847	0,803	0,832	0,815
Na	0,024	0,024	0,018	0,021	0,021	0,028	0,018	0,022	0,015	0,024	0,020
K	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,001	0,000
cationes	4	4	4	4	4	4	4	4	4	4	4
Charge+	12	12	12	12	12	11,99	11,99	11,99	11,99	11,99	11,99
#Mg	0,841	0,849	0,819	0,809	0,818	0,833	0,845	0,868	0,817	0,833	0,760

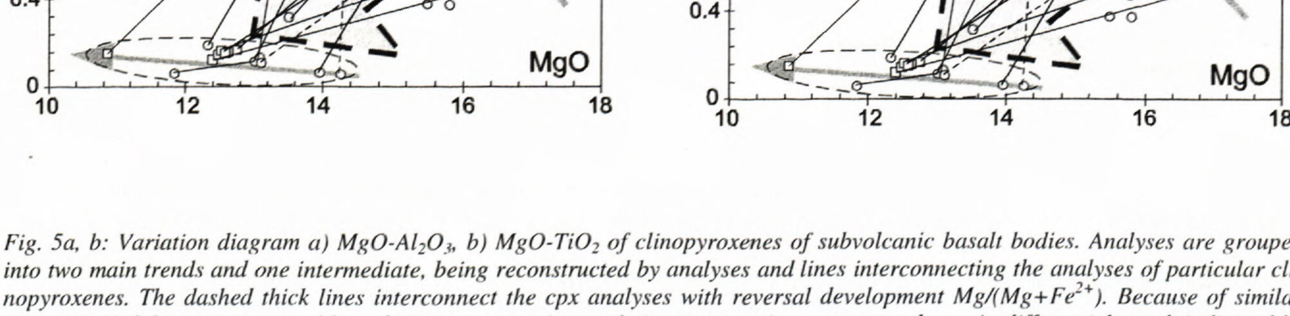


Fig. 5a, b: Variation diagram a) MgO-Al_2O_3, b) MgO-TiO_2 of clinopyroxenes of subvolcanic basalt bodies. Analyses are grouped into two main trends and one intermediate, being reconstructed by analyses and lines interconnecting the analyses of particular clinopyroxenes. The dashed thick lines interconnect the cpx analyses with reversal development $Mg/(Mg+Fe^{2+})$. Because of similar orientation of thin uninterrupted lines between two main trends (grey arrows), we suppose the main differential trend, indicated by the thick dashed arrow. The variation along two grey arrows is caused by interaction with chemically heterogeneous melt fractions, being a result of variable filtration effect of PS in zones with the variable permeability.

their alteration are dominantly the albite, prehnite and sericite. Ilmenite is altered. Phantoms after ilmenite are represented with pyrophanite, titanite, pyrrhotite, rutile and zircon. The volcanic glass is transformed to association chlorite, K-feldspar, albite and tiny Fe-Ti oxide (Fig. 3).

The unique feature of subvolcanic rocks at Slávča and Furmanec is the presence of actinolite, being specifically tied to the contact of relic clinopyroxene and chlorite (Fig. 4). It forms the tiny idio-hypidiomorphic individuals to aggregates of often orthorhombic habit. Analogical feature we have observed also in another occurrences of basalt rocks of Hronicum, namely in Lower Permian effusive basalt from Ipoltica valley and basalt lavas of the Čierny Váh valley. This phenomenon has probably validity for basalt rocks of the whole Hronicum. The rocks frequently contain also brown amphiboles, which, according to the approximation of minimum and maximum Fe^{3+} content in classification by Leak et al. (1997), represent the magnesiohornblende and magnesiohastingsite. They are a product of the high-temperature (probable synvolcanic) phase of hydrothermal alteration. They effectively consume the magmatic clinopyroxenes. Amphiboles form phantoms after subophitic clinopyroxenes, or reaction rims. In rock of Slávča locality their preferable concentration on the surrounding of plagioclase pegmatite was found. In strongly altered parts of rock the saussuritization reached the extreme extent. The phantoms after plagioclases are not present. The rocks are formed only by the angular clinopyroxenes with improper morphology, being inherited after the shape of PS cells. These clinopyroxenes are distributed in the plastic mixture formed by mineral association prehnite, albite and sericite.

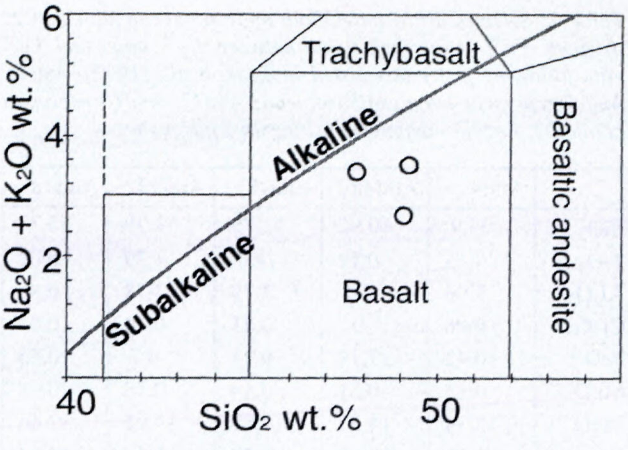


Fig. 6. Classification diagram for effusive rocks (sensu Le Maitre et al., 1989). The curve discriminating the alkaline and subalkaline rocks is according to Irvine & Baragar (1971). Analysed samples represent the subalkaline basalts.

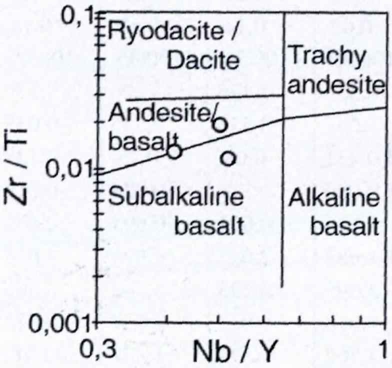


Fig. 7. Complementary classification diagram for altered and metamorphic rocks according to Winchester & Floyd (1977). Analysed samples belong to the subalkaline basalts to andesites.

Rock classification

Because the studied rocks represent the shallow-intrusive or subvolcanic equivalents of basaltic melt, they can be classified by TAS diagram (Le Maitre et al., 1989; Fig. 6). Analyses cluster into the basalt field beneath the discrimination curve defining the subalkaline rocks (sensu Irvine & Baragar, 1971). The superimposed hydrothermal alteration of rocks led to decomposition of primary plagioclase and ilmenite (sea the paragraph about the rock alteration). Because of this fact the redistribution of alkalis can be expected and consequently the subalkaline basalt character of rocks can be simulated. The complementary classification diagrams Nb/Y-Zr/TiO_2 and Zr/TiO_2-SiO_2 (Winchester & Floyd, 1977) designated for altered and metamorphic rocks confirm the basic subalkaline character of rock (Fig. 7).

The petrography and composition of clinopyroxenes demonstrate the partially cumulative character of rocks. The origin of plagioclase network and course of cumulative process distinctly affected the chemical composition of subvolcanic body. Analysed MgO varies in interval 9.09–11.26 wt.%, at #Mg/(Mg+Fe*) 70.55-67.8. The contents Ni 283-181 ppm and Cr 472-343 ppm reach values for primitive undifferentiated basalts Ni > 200 ppm and Cr > 400 ppm (Tatsumi & Eggins, 1995). The absence of olivine or its phantoms in plagioclase network demonstrates the relative advanced differentiation of parental basalt magma, away of normative olivine phase volume. The high MgO content is then the result of adcumulative effect of through flow fractionation of augite and closed basic glass (the product of its alteration is mainly the abundant chlorite above 20 wt.% MgO). The content of Al_2O_3 in interval 12.93–15.84 wt. % converges to values for highly aluminium basalts ($\geq$ 16 wt.%). The high Al_2O_3 content is a result of cumulative effect of plagioclase. The closed crystallization of melt would lead to crystallization of pigeonite and quartz (Grove & Baker, 1984; Grove & Kinzler, 1986), but they were not observed. This phenomenon can be explained by continuous removal of differentiated melt into associated effusion or by continuing part of unseen subvolcanic body. The rocks therefore do not represent clearly effusive members. The early crystallization of plagioclase (origin of plagioclase network) before the augite clinopyroxene proves the tholeiitic character of magmatic differentiation (Grove & Baker, 1984; Grove & Kinzler, 1986).

The applying of stated principles we suppose the studied rocks as a differentiation product of a tholeiitic basalt melt. Despite influencing the composition by cumulate process, the rocks have a character of subalkaline tholeiitic basalt.

Table 2: Selected EPM amphibole analyses recalculated to 22 oxygens. Fe^{3+} is average value between Fe^{3+} max. and Fe^{3+} min. following procedure listed in Leak et al., (1997). Amf4a, Amf-5 represent magnesiohornblend; Amf12, Amf18 represent actinolite, Amf4a – magnesiohastingsite / pargasite.

	Amf4	Amf4a	Amf-5	Amf12	Amf18
SiO_2	43,9	50,92	51,79	51,79	55,78
TiO_2	4,15	0,72	1,4	1,29	0,02
Al_2O_3	9,94	3,1	3,79	3,78	0,85
Cr_2O_3	0,08	0	0,21	0,14	0,01
FeO*	10,42	17,11	9,11	9,7	10,55
MnO	0,15	0,31	0,14	0,18	0,18
MgO	15,34	14,27	17,81	17,92	17,46
CaO	11,39	10,13	11,99	11,53	13,24
Na_2O	2,72	1,15	1,13	1,23	0,08
K_2O	0,65	0,28	0,36	0,4	0,02
H_2O	2,05	1,90	1,99	2,01	2,03
F	0,02	0,21	0,1	0,16	0,17
Cl	0,02	0,14	0,17	0,14	0,01
total	100,85	100,36	100,35	100,09	100,48
Si	6,339	7,476	7,38	7,379	7,899
Al	1,692	0,536	0,636	0,635	0,142
Ti	0,451	0,08	0,15	0,138	0,002
Cr	0,009		0,024	0,016	0,001
Fe^{3+}	0,175	0,074	0,091	0,079	0,006
Fe^{2+}	1,083	2,027	0,994	1,077	1,243
Mg	3,302	3,123	3,783	3,806	3,686
Mn	0,018	0,039	0,017	0,022	0,022
Ca	1,762	1,594	1,831	1,76	2,009
Na	0,762	0,327	0,312	0,34	0,022
K	0,12	0,052	0,065	0,073	0,004
total	15,713	15,329	15,283	15,324	15,036

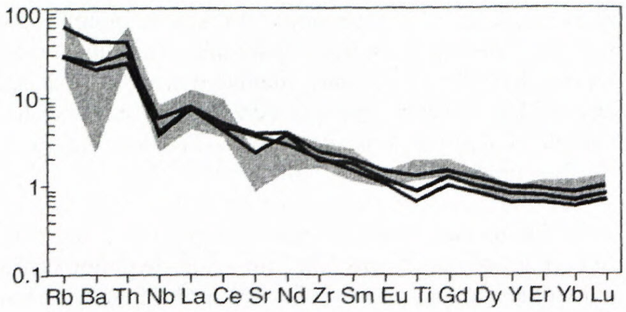


Fig. 8. NMORB normalized abundance patterns of elements of subvolcanic dykes from Slávča and Furmanec (curves) and analyses of genetically related Permian basalts and basaltic andesites of Hronicum, grey area. Taken from Dostál et al. (2003). NMORB normalized values are from Sun & McDonough (1989).

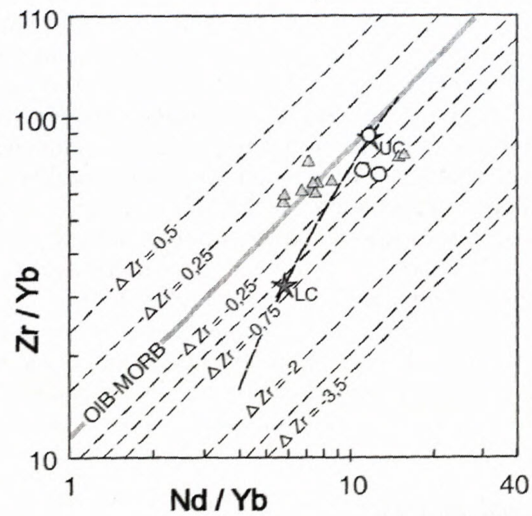


Fig. 9: Diagram Nd/Yb-Zr/Yb characterizing the development of Zr-anomaly. The values Δ Zr were taken by recalculation after Pearce et al. (1999). The negative values characterize the development of negative Zr anomaly, the positive values the development of positive anomaly. Grey OIB-MORB line is calibrated by average OIB-MORB values from Sun & McDonough (1989) and represents the rock members without development of Zr-anomaly. Triangle symbols represent the analyses of genetically related Permian basalts of Hronicum sensu Dostál et al. (2003). The asterisks represent the average values of lower (LC) and upper crust (UC; taken from Taylor & McLennan, 1985). The curve cutting the points of lower and upper continental crust represents the mixing between these end members.

Geochemistry of subvolcanic dykes

The basalt subvolcanic dykes in localities Slávča and Furmanec are characteristic with low SiO_2 47.82-49.33 wt.%, high MgO 12,18-9,69 wt.%, high Al_2O_3 16,89-13,99 wt.% and FeO* 9.06-7.63 wt.%. In the frame of basalt rocks it represents an extreme composition, being influenced by the cumulative process. The TiO_2 contents vary in interval 0,91-1,71 wt.% and P_2O_5 in interval 0,16-0,23 wt.%. The main bearer of Ti is a skeletal, partially corroded ilmenite, crystallizing as a second mineral after plagioclase. Phosphorus is tied on apatite, which distribution in rock is not unambiguously specific. The high LOI (3.84-3.06 wt.%) is a result of synvolcanic hydrothermal alteration modification. In comparison with the genetically related Permian basalts of Hronicum (Dostál et al., 2003) the subvolcanic dykes at Slávča and Furmanec have more primitive contents Cr 511-365 ppm, Ni 306-193 ppm, V 172-90 ppm and Sc 43-29 ppm.

The subvolcanic dykes are typical with enrichment by Rb, Ba, Th, with moderate development of Ba-anomaly, which is one of typical features of basalts from Hronicum (Fig. 8). The influence of plagioclase fractionation for Ba and Sr contents (the distinctive deficit of Permian basalts) in conditions of plagioclase network of subvolcanic dykes is clearly hypothetical. The more distinctive deficit of Ba and Sr in Permian basalts we connect with the more intensive hydrothermal alteration, which the studied rocks suffered. The subvolcanic basalts have at enrichment by LREE developed the negative HFSE-anomalies: Nb_N/La_N[1] 0.46-0.67 and Δ Zr in interval (–0.03-0.44)[2], (Fig. 9).

[1] PM normalized values after Sun & McDonough (1989)

[2] Values of Zr-anomaly are characterized using the method by Pearce et al. (1999).

Table 3: Whole rock analyses of subvolcanic basalts. Samples MP-01-2 and MP-01-3 belong to Slávča locality, and MP-s belongs to Furmanec locality. Detailed localisation is presented in schematic map, Fig 1.

	MP-01-2	MP-01-3	MP-s		MP-01-2	MP-01-3	MP-s		MP-01-2	MP-01-3	MP-s
SiO_2	50,26	49,22	50,64	Sc	29	41	28	La	19	20	20
TiO_2	0,889	1,640	1,171	V	86	165	116	Ce	37	39	35
Al_2O_3	16,14	14,46	13,31	Cr	349	432	486	Nd	21	29	29
Fe_2O_3	1,726	1,919	1,668	Co	37	34	43	Sm	4,1	5,6	5,0
FeO	5,74	6,21	7,12	Ni	184	191	291	Eu	1,12	1,55	1,28
MnO	0,117	0,148	0,139	Rb	35	17	17	Gd	3,7	5,6	4,8
MgO	9,26	9,38	11,59	Sr	335	358	220	Tb	0,7	1,0	0,8
CaO	7,74	9,43	6,62	Ba	269	155	132	Dy	3,8	5,6	4,7
Na_2O	2,41	2,85	2,09	Th	5	4	3	Ho	0,8	1,2	0,9
K_2O	1,15	0,61	0,6	Hf	3	3	4	Er	2,0	2,9	2,4
P_2O_5	0,15	0,22	0,19	Nb	9	14	10	Yb	1,8	2,6	2,2
LOI	3,68	3,06	3,84	Zr	160	181	150	Lu	0,33	0,47	0,38
H_2O -	0,41	0,37	0,45	Y	18	27	24				

The chondrite normalized REE patterns are characteristic with the extreme fractionation La_n/Sm_n 2.51-2.31 at relatively flat development of Tb_n/Yb_n 1.77-1.65 (Fig. 10). The La_n values reach 88,7-83,9 at content 21,02-19,88 ppm. Eu/Eu* varies in the range 0.88-0.8. The effusive rocks of this character do not occur in the environment of oceanic crust, NMORB-EMORB-OIB types.

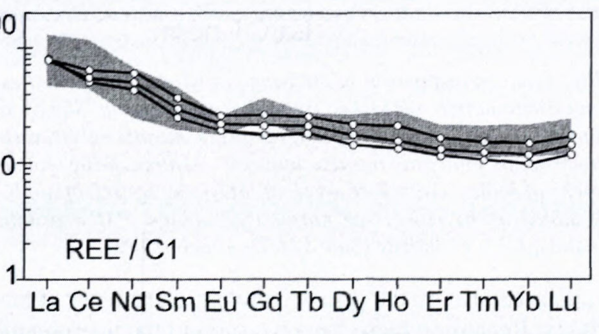


Fig. 10: Chondrite normalized REE patterns. The normalized values for Cl are taken from Sun & McDonough (1989). The grey field represents the comparing analyses of genetically related Permian basalts of Hronicum. Taken from Dostál et al. (2003).

The preservation of relatively constant course of normalized content Tb_n/Yb_n at fractionation La_n/Sm_n requires the presence of garnet and amphibole in magmatic source. The garnet alone has a tendency to fractionate La-REE-Yb as a whole without selective fractionation of MREE. The amphibole fractionates MREE and causes the concave depletion by MREE. The combination of garnet and amphibole allows the selective enrichment by LREE in level of La-Sm at flat development Gd/Yb, Tb/Yb, during which it need not be a single-shot event, but also the polystadial fractionation. This normalized REE course is characteristic for continental crust (Taylor & McLennan, 1985) and for some active continental margins, for example central and southern Andes or Kamchatka - the volcanoes Kluchevskoy, Achtang (Churikova et al., 2001).

The process of modification of mantle melts in the environment of thick continental crust is analysed by Hildreth & Moorbath (1988), presenting the MASH hypothesis based on the composition of volcanic rocks of Chilean active margin. The MASH represents the combined process of melting, assimilation, storage and homogenization. Process is directly in the field observed for example on gabbroid intrusion Fiambalá in NW Argentina (DeBari, 1994). The modification of mantle melts in continental crust is solved by the numerical model of RTF magmatic reservoir (analogical to process MASH) by Wooden et al. (1993) for the basalts of Siberian traps.

The function of MASH process is tectonically controlled. The enhancing extension expands the percentage of the adiabatic decompression melting of the mantle and consequently the bigger volume of the melt. The bigger amount of melt has thereafter the tendency to penetrate the continental crust with shortening of time of its remaining in the crustal magmatic reservoirs and lowering the possibility of current hybridization. The transport of the bigger amount of basic melt through the continental crust uses the dyke system which manifests the lower reaction surface and assimilation potential contrary to the transport of volume lower melt fractions, where the transport by porous flow occurs (one of the MASH requirements). Because of La/Sm fractionation at flat Tb/Yb of studied basalt subvolcanic rocks we suppose the function of MASH process, as a modification agent of primary basalt magmas, being produced by volume weak partial melting of subcontinental lithospheric mantle as a consequence of indistinct extension.

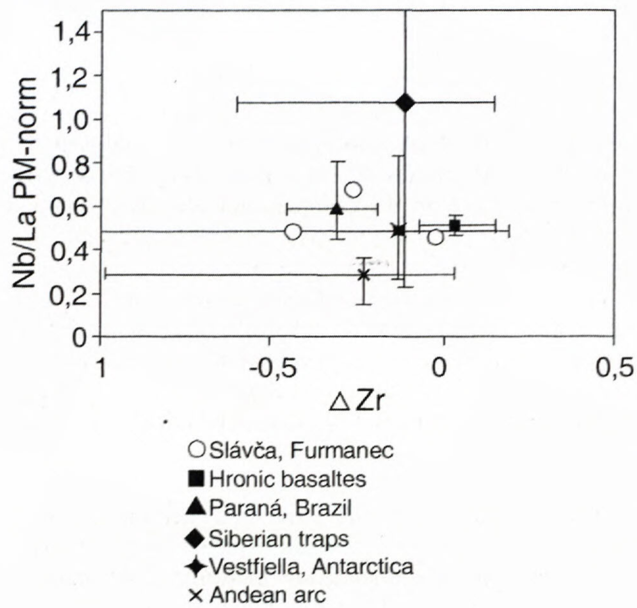
Geodynamic environment of origin of subvolcanic basalt dykes

For reconstruction of geodynamic environment of the basalt origin the principal factor is the relative distribution of REE-HFSE, indicating the strong resistance against the mobilization during hydrothermal alteration processes (e.g. Humphris, 1984; Rollinson, 1993).

Slovak Geol. Mag., 11, 2 – 3 (2005), 143 – 153

Tab. 4. Comparison of range of HFSE anomalies. The ratios Nb_n/La_n are normalized for the primitive mantle (according to Sun & McDonough, 1989). The numbers stated in table correspond in order to maximum, average and minimum value. The data about Permian basalts of Hronicum were taken from Dostál et al. (2003); Paraná - low titanium basalts (Peate & Hawkesworth, 1996); Siberian traps – Noril'sk (Wooden et al., 1993). Basalts of province Vestfiela, Antarctica (Luttinen & Furnes, 2000). The basic calk-alkaline volcanic rocks of Andes (source: web geochemical database GEOROCK). Zr anomaly is computed using the method by Pearce et al. (1999). The lower value ΔZr, the more intensive negative Zr anomaly, resp. deficiency against REE. The values REE are normalized to chondrite according to Sun & McDonough (1989).

	Nb_n/La_n	Δ Zr	La_n/Sm_n	Tb_n/Yb_n	La_n
Slávča, Furmanec	0,67 – 0,46	-0,03 až –0,44	2,5 – 2,3	1,8 – 1,7	88,7 – 83,9
Hronic basaltes	0,56 / 0,51 / 0,46	0,15 / 0,03 / -0,07	2,9 / 2,5 / 2,1	1,7 / 1,4 / 1,3	126,6 / 80,8 / 46,4
Paraná, Brazil	0,8 / 0,59 / 0,45	-0,17 / -0,31 / -0,42	2,8 / 2,1 / 1,3	1,6 / 1,4 / 1,3	135,9 / 76,8 / 34,6
Siberian traps	3,28 / 1,07 / 0,23	0,15 / -0,11 / -0,6	3,2 / 1,9 / 1,2	1,9 / 1,3 / 0,9	145,6 / 48,1 / 19,7
Vestfjella, Antarctica	0,83 / 0,49 / 0,26	0,19 / -0,13 / -1,49	2,71 / 1,55 / 0,83	2,16 / 1,84 / 1,67	86,2 / 45,82 / 15,15
Andean arc	0,36 / 0,29 / 0,15	0,03 / -0,23 / -0,99	3,1 / 2,2 / 1,4	2 / 1,4 / 1	92,8 / 58,3 / 25,3



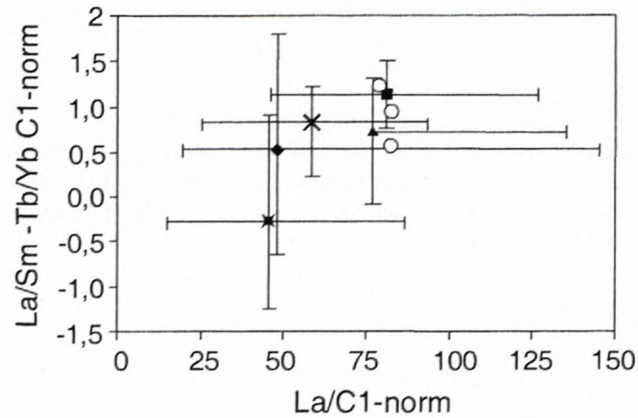


Fig. 11a, b. Comparison of the range of Nb and Zr anomalies a) and fractionation of LREE b) in basalt dykes at Slávča and Furmanec with genetically neighbouring basalts of Hronicum, inner-plate tholeiitic basalts and calk-alkaline basic volcanic rocks of Andes with 49-56 wt.% of SiO_2. The source of analyses is stated in the text. Used normalized values: PM = primitive mantle, C1 = chondrite (Sun &McDonough, 1989).

The basalts have developed negative HFSE anomalies, which is a typical feature of the volcanic rocks of convergent boundaries of lithospheric plates (e.g. Pearce & Peate, 1995). The negative HFSE anomalies are present also in the case of basalts of inner-plate provinces, though of lower intensity (Wooden et al., 1993; Molzahn et al., 1996; Peate & Hawkesworth, 1996; Luttinen & Furnes 2000). The next feature is represented by the selective fractionation LREE from HREE ($La_n/Sm_n >> 1$, $Tb_n/Yb_n \approx 1$). This phenomenon is present only in the case of volcanic rocks generated in the environment with evolved continental crust. As an example there serve the volcanic rocks of Andes and Kamchatka (volcanoes Kluchevskoy, Achtang; Churikova et al., 2001), being tied to convergent tectonic regime. In the case of inner plate volcanic provinces this specific distribution is observed in the case of some Siberian trap basalts – the Noril'sk province (Wooden et al., 1993) and at low-Ti basalts of Paraná province (Brazil). The comparison of distribution of HFSE anomalies and REE is summarized in Tab. 4 and graphically depicted in Fig. 11 a, b.

The comparison of REE-HFSE distribution (Tab. 4; Fig. 11a, b) confirms the affinity of dykes basalts from Slávča and Furmanec to inner-plate basalts. This fact is supported also by the primary tholeiitic character of basic dykes. Regarding these facts we support the interpretation of inner-plate geodynamic regime of the origin of basalts, being present in localities Slávča and Furmanec.

Discussion

The investigated rocks, owing their characteristic appearance also from further occurrences, were generally classified as diorites - veiny diorite porphyrites (Šťastný, 1927; Vozár, 1967), gabbrodiorite porphyrites (Vozár, 1976), or also as augite/quartz/gabbro porphyrites (Tulis & Novotný, 1998). The detail petrographic investigation from several localities of Western Carpathians has manifested, that these rocks represent the subvolcanic basalts without the presence of porphyric intratelluric mineral phases, which means the crystallization of all rock-forming minerals in situ inside the dyke. The found subophitic texture is characteristic for tholeiitic subvolcanic basalts with the specific development of crystallization (Philpotts et al., 1998; Philpotts & Dickson, 2000; Demko & Olšavský, 2005). The rocks manifest the transitional character between effusive basalts and gabbro cumulates. From effusive basalts they differ by continual removal of more differentiated pigeonite–quartz normative melt fraction, which was probable transferred to associated effusion, or unwatched part of subvolcanic body of granophyre composition (plagioclase + quartz) as we observed for example in the locality SE of Hranovnica (the Nízke Tatry Mts.). From the cumulate gabbro they differ by the presence of intersertal glass, being the result of rapid final undercooling in superficial conditions. The specific petrographic character and peculiar chemical composition of dykes, being identical with the Permian basalts in Hronicum (Dostál et al., 2003), requires to allocate the studied rocks to mentioned tectonic unit. In the locality Furmanec there is biostratigraphically dated only the upper tectonic slice with carbonatic development of Upper Visean age affiliated to Gemericum (Plašienka & Soták, 2001). The lower lens we understand as the Upper Carboniferous of Hronicum - the Nižná Boca Formation. As one of arguments against the competency to Hronicum there was stated the following fact: *"these magmatic rocks are mylonitized and recrystallized in greenschist facies, so they cannot be correlated with the Nižná Boca diorites"* (Plašienka & Soták 2001). We can agree with the metamorphism of studied rocks, but especially this metamorphism proves the identical character of rocks with analogical occurrences in Hronicum.

Based on following facts we can exactly state that petrogenetic and metamorphic development of subvolcanic rocks was identical as in Hronicum.

- The similar position of subvolcanic basalt bodies among clastics of Upper Carboniferous sediments with the same lithology
- Identical primary petrographic character as in the case of bodies from Hronicum: Dikula, Podbrezová, Nižná Boca, Vernár - Barbolica (the Nízke Tatry Mts.), Žiare (Tríbeč Mts.) as well as from locality Spálený vrch (the Čierna hora Mts., Faryad et al., 2005)
- Identical metamorphism of subvolcanic bodies (saussuritization of plagioclase, presence of prehnite, pumpellyite, actinolite), as well as basalt bodies from Hronicum (Ipoltica, Čierny Váh)
- Identical courses of normalized contents of trace elements (Figs. 8 and 10).

As the geodynamic environment of origin of Permian basalts of Hronicum Vozár (1997) determined the inner-continental rifts, Ivan et al. (2002) affiliated basalts of Hronicum with calk-alkaline series of the convergent boundaries of lithospheric plates, Dostál et al. (2003) associated the geodynamic regime with that of the inner-plate volcanic province Basin and Range (U.S.A.). Because of distinct similarity of chemical composition with tholeiitic basalts of Paraná volcanic province and Siberian traps we support the interpretation of their inner-plate origin. Tholeiitic and alkaline volcanisms are related on the range of adiabatic decompression melting being controlled by the degree of extension (McKenzie & O'Nions, 1991; Kinzler, 1997; Niu, 1997; Takahahshi et al., 1998). The lower degree of extension results in lower extent of mantle melting and specific geometry of melted space (O'Hara, 1985). It results also in the higher percentage of melt from the field of grt-lherzolite stability. As an example there is stated the NMORB/EMORB distribution in oceanic basalts, or distribution of tholeiitic and alkaline rift zones in Africa (Wilson, 1989). The products are the alkaline rocks. The high degree of extension leads to higher percentage of total melting and higher percentage of melt from the stability field of sp-lherzolite. The products of this melting are tholeiites.

The degree of extension of continental crust connected with the basalt volcanism had to fulfil the conditions of tholeiite generating and simultaneously the course of MASH process (La/Sm fractionation in flat development of Tb/Yb). It means that extension should be bigger than for the alkaline volcanism and at the same time the lower than for the ideal tholeiite volcanism. The increase of extension would lead to depletion by LREE with transition to $La_n/Yb_n \leq 1$ and to erasure of HFSE anomalies.

Conclusions

The subvolcanic bodies in Carboniferous sediments at Slávča and Furmanec represent the dykes of tholeiitic basalts. These subophitic to intersertal basalts are formed by the dominant network plagioclases, skeletal ilmenite, clinopyroxene of augite to diopside composition and glass. The rocks are penetrated with thin plagioclase pegmatites, being a product of segregation of melt from plagioclase network as a result of compaction. The rocks are altered. Alteration affected dominantly the plagioclase (saussuritization). The intersertal glass is altered to chlorite, Fe-Ti oxides, K-feldspar and albite. Clinopyroxene is locally consumed by brown amphibole, or tiny needles of metamorphic actinolite. The particular character of former mineralogy of dykes - plagioclase, ilmenite, clinopyroxene, complicated composition of relic clinopyroxene, absence of pigeonite with quartz, high content of MgO, Cr, Ni, demonstrate the role of flow cumulated process in dykes genesis. The character of distribution of trace elements corresponds with the same character and distribution in Permian subvolcanic and effusive basalts of Hronicum. The dykes were probable the feeding channels of these basalts (aphyric). Chemical composition of studied rocks is similar with the composition of some inner-plate basalts (Siberian traps, Paraná). Weakly developed negative Nb-, Zr- anomalies, the distinct fractionation of LREE and tholeiitic character correspond with inner-plate volcanism, being connected with the relatively low extension of continental crust. The stated localities in underlier of Muráň Mesozoic we suppose to be the analogues of Upper Carboniferous Nižná Boca Formation with the presence of the vein basalt bodies of the Permian age.

Acknowlwdgement

We are grateful to Dr. P. Konečný for the useful suggestions and for critically reading of the manuscript.

This work originated as a part of the project of Ministry of Environment of Slovak Republic No. 130 *Tectogenesis of sedimentary basins.* It was also supported by the project No. 27 98 *Geological map of Slovak Republic in scale 1 " 200 000.*

References

Biely, A., 1961: Remarks to geology of Mesozoic of root zones in Veporides. *Geol.* Práce, Zpr., 21, 109-125. (In Slovak.)

Biely, A., 1966: To the problem of boundary of Gemerides and the Choč nappe. Geol. Práce, Zpr., 40, 171-172. (In Slovak.)

Biely, A., Beňuška, P., Bezák, V., Bujnovský, A., Halouzka, R., Ivanička, J., Kohút, M., Klinec, A., Lukáčik, E., Maglay, J., Miko, O., Pulec, M., Putiš, M. & Vozár, J., 1992: Geological map of the Nízke Tatry Mts. 1:50 000. Geol. Úst. Dionýza Štúra, Bratislava. (In Slovak.)

Biely, A., Bujnovský, A., Vozárová, A., Klinec, A., Miko, O., Halouzka, R., Vozár, J., Beňuška, P., Bezák, V., Hanzel, V., Kubeš, P., Liščák, E., Lukáčik, E., Maglay, J., Molák, B., Pulec, M., Putiš, M., Slavkay, M., (Biely & Bezák edit.) 1997: Explanations to geologickej map of the Nízke Tatry Mts. 1 : 50 000. Geol. Úst. Dionýza Štúra, Bratislava, 7-232 (In Slovak).

Cox, K. G., Bell, J. D. & Pankhurst, R. J., 1979: The interpretation of igneous rocks. G. Allen & Unwin (publishers), London, 450.

DeBari, S. M., 1994: Petrogenesis of the Fiambalá gabbroic intrusion, North-western Argentina, a deep crustal syntectonic pluton in a continental magmatic arc. J. Petrol., 35, 679-715.

Demko, R. & Olšavský, M., 2005: Subophitic clinopyroxenes of basic subvolcanic bodies in the Upper Carboniferous sediments of Western Carpathians. Min. Slovaca, 37, abstrakt, 477. (In Slovak).

Demko, R. & Olšavský, M., 2005: Petrography and geochemistry of subvolcanic basalt bodies among the Upper Carboniferous sediments from the underlier of Muráň Mesozoic sequences (Slávča and Furmanec valleys, Western Carpathians), Slovac Geol. Mag., 11, 2-3, Bratislava, 143-153.

Dostál, J., Vozár, J., Keppie, J. D. & Hovorka, D., 2003: Permian volcanism in the Central Western Carpathians (Slovakia): Basin-and-range type rifting in the southern Laurussian margin. Geol. Rundsch., 92, 27-35.

Faryad, S. W., Ivan, P. & Jacko, S., 2005: Metamorphic petrology of metabasites from the Branisko and Čierna Hora Mountains (Western Carpathians, Slovakia), Geol. Carpathica, 56, 3-16.

Hildreth, W. & Moorbath, S., 1988: Crustal contributions to arc magmatism in the Andes of Central Chile. Contrib. Mineral. Petrol., 98, 455-489.

Humphris, S. E., 1984: The mobility of the rare earth elements in the crust. In: Rare earth element geochemistry. Henderson P. (ed.), British Museum, London, 317-340.

Irvine, T. N. & Baragar, W. R. A., 1971: A guide to the chemical classification of the common volcanic rocks. Can. J. Earth Sci., 8, 523-548.

Ivan, P., Demko, R., Rojkovič, I. & Vozár, J., 2002: Geochemistry and geodynamic setting of the Permian volcanism in the Western Carpathians: A review. Special issue of Geologica Carpathica (CD), 53, 1335-0552.

Georock, internet geochemical database, Max Planck Institute in Mainz, http://georock.mpch-mainz.gwdg.de

Grove, T. L. & Baker, M. B., 1984: Phase equilibrium controls on the tholeiitic versus calc-alkaline differentiation trends. J. Geophysic. Res., 89, 3253-3274.

Grove, T. L. & Kinzler, R. J., 1986: Petrogenesis of andesites. Ann. Rev. Earth Planet. Sci., 14, 417-454.

Churikova, T., Dorendorf, F. & Wörner, G., 2001: Sources and fluids in the mantle wedge below Kamchatka, evidence from across-arc geochemical variation, J. Petrol., 42, 1567-1593.

Kinzler, R. J., 1997: Melting of mantle peridotite at pressures approaching the spinel to garnet transition: Application to mid-ocean ridge basalt petrogenesis. J. Geophys. Research, 102, 853-874.

Klinec, A., 1976: Geological map of the Slovak Ore Mts. and the Nízke Tatry Mts. Geologický Ústav Dionýza Štúra. Bratislava. (In Slovak).

Kovařík, J., Kužvart, M., Pouba, Z., 1955: Report about geological mapping in surrounding of Tisovec and Muráň. *Zprávy o geol. výskumech v roku 1954. ÚÚG, Praha.* (In Czech).

Leake, B. E., Woolley, A. R., Arps, C. E. S., Birch, W. D., Gilbert, M. C., Grice, J. D., Hawthorne, F. C., Kato, A., Kisch, H. J., Krivovichev, V. G., Linthout, K., Laird, J., Mandarino, J., Maresch, W. V., Nickel, E. H., Rock, N. M. S., Schumacher, J. C., Smith, D. C., Stephenson, N. C. N., Ungaretti, L., Whittaker, E. J. W. & Youzhi, G., 1997: Nomenclature of amphiboles: Report of the Subcommittee on amphiboles of the International Mineralogical Association commission on new minerals and mineral names. Mineral. Mag., 61, 295-321.

Le Maitre, R. W., Bateman, P., Dudek, A., Keller, J., Lameyre, Le Bas, M. J., Sabine, P. A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R. & Zanettin, B., 1989: A classification of igneous rocks and glossary of terms. Blackwell, Oxford.

Le Bas, M. J. et al., 2000: IUGS Reclassification of the high-Mg and picritic volcanic rocks. J. Petrol., 41, 1467-1470.

Lindsley, D. H. & Andersen, D. J., 1983: A two-pyroxene thermometer. J. Geophys. Res., 88, A887-A906.

Luttinen, A. V. & Furnes, H., 2000: Flood basalts of Vestfjella: Jurassic magmatism across an Archaean-Proterozoic lithospheric boundary in dronning Maund Land, Antarctica. J. Petrol., 41, 1271-1304.

McKenzie, D. & O'Nions, R. K., 1991: Partial melt distributions from inversion of rare earth element concetrations. J. Petrol., 32, 1021-1091.

Mercier, J-C. C., 1976: Single-pyroxene geothermometry and geobarometry. Amer. Mineralogist, 61, 603-615.

Molzahn, M., Reisberg, L. & Wörner, G., 1996: Os, Sr, Nd, Pb, O isotope and trace element data from the Ferrar flood basalts, Antarctica: Evidence for an enriched subcontinental lithospheric source. Earth Planet. Sci. Lett., 144, 529-546.

Morimoto, N., 1989: Nomenclature of pyroxenes. Canadian Mineralogist, 27, 143-156.

Niu, Y., 1997: Mantle melting and melt extraction processes beneath ocean ridges: Evidence from abyssal peridotites. J. Petrol., 38, 1047-1074.

O'Hara, M. J., 1985: Importance of the "shape" of the melting regime during partial melting of the mantle. Nature, 314, 58-62.

Pearce, J. A., Kempton, P. D., Nowell, G. M. & Noble, S. R., 1999: Hf-Nd element and isotope perspective on the nature and provenance of mantle and subduction components in Western Pacific arc-basin systems. J. Petrol., 40, 1579-1611.

Pearce, J.A. & Peate, D.W., 1995: Tectonic implications of the composition of volcanic arc magmas. Annu. Rev. Earth Planet. Sci. 251-285.

Peate, D. W. & Hawkesworth, Ch. J., 1996: Lithospheric to asthenospheric transition in low-Ti flood basalts from southern Paraná, Brazil. Chem. Geol., 127, 1-24.

Philpotts, A. R., Carroll, M. & Hill, J. M., 1996: Crystal-mush compaction and the origin of pegmatitic segregation sheets in a thick flood-basalt flow in the Mesozoic Hartford basin, Connecticut. J. Petrol., 37, 811-836.

Philpotts, A. R., Shi, J. & Brustman, C., 1998: Role of plagioclase crystal chains in the differentiation of partly crystallized basaltic magma. Nature, 395, 343-346.

Philpotts, A. R. & Dickson, L. D., 2000: The formation of plagioclase chains during convective transfer in basaltic magma. Nature, 406, 59-61.

Plašienka, D. & Soták, J., 2001: Stratigraphic and tectonic position of Carboniferous sediments in the Furmanec valley (the Muráň plain). Min. Slov. 1/33, 29-44. (In Slovak.)

Rollinson, H. R., 1993: Using geochemical data: Evaluation, presentation, interpretation. Longman Scientific & Technical, 352.

Rozlosznik, P., 1935: Die geologischen Verhältnisse der Gegend von Dobsina. *Geologica hung., Ser. Geol. Palaeont., 5, 1-118.*

Šťastný, V., 1927: Study about so-called melaphyres in the Low Tatra Mts. in Slovakia. Rozpravy II. tr. ČA 36, č.29. (In Czech.)

Sun, S.-s. & McDonough, W. F., 1989: Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. From Saunders A. D. & Norry M. J. (eds): Magmatism in the ocean basins. Geological Society Special Publication No. 42, 313-345.

Takahahsi, E., Nakajima, K. & Wright, T. L, 1998: Origin of the Columbia River basalts: Melting model of a heterogeneous plume head. Earth Planet. Sci. Lett., 162, 63-80.

Tatsumi, Y. & Eggins, S., 1995: Subduction zone magmatism. Cambrige (Ma.), Blackwell Sci. Publ., 248.

Taylor, St. R., McLennan, S. M, 1985: The continental crust: Its composition and evolution. Blackwell Scientific Publications. Geoscience texts.

Tulis, J. & Novotný, L., 1998: Evaluation of geological works for U ore in the Upper Paleozoic of Hronicum in the northern part of the Nízke Tatry Mts. and Kozie chrbty. Geofond 144 s. (In Slovak).

Vojtko, R., 2000: Are there tectonic units derived from the Meliata-Hallstatt trough incorporated into the tectonic structure of the Tisovec karst? (Muráň karstic plateau, Slovakia). Slovak Geol. Mag., 4/2000, 335-346.

Vrána, S., 1966: Alpidische Methamorphose der Granitoide und der Foederata Serie im Mittelteil der Veporiden. Sbor. Geol. Vied, rad ZK 6, Bratislava

Vrána, S. & Vozár, J., 1969: Mineral assemblage of pumpellyite-prehnite-quartz facies in the Nízke Tatry Mts. Geol. Práce, Správy, 49, 91-99. (In Slovak).

Vozár J., 1967: Der permische Vulkanismus in der Choč-Decke (Westkarpaten). Geologické práce, Správy 42. Bratislava.

Vozár, J., 1971: Multiphase character of Permian volcanism of the Choč Unit in the Nízke Tatry Mts. Geol. Práce, Správy, 55, 131-137. (In Slovak).

Vozár J., 1976: Permian volcanites of the Choč Unit in the Tríbeč Mts. Záp. Karpaty, sér. Miner., petrol., geoch., lož., 1, Geol. Úst. Dionýza Štúra, Bratislava, 151-187. (In Slovak).

Vozárová, A. & Vozár, J., 1988: Late Paleozoic in the West Carpathians. Geol. Úst. Dionýza Štúra, Bratislava, 7-314.

Vozár, J., 1997: Rift-related volcanics in the Permian of the Western Carpathians. In: Grecula, P., Hovorka, D. & Putiš, M. (eds.): Geological evolution of the Western Carpathians. Min. Slovaca – Monograph., 225-235.

Wilson, M., 1989: Igneous petrogenesis. London, Unwin Hyman, 466 p.

Winchester, J. A. & Floyd, P. A., 1977: Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chem. Geol., 20, 325-343.

Wooden, J. L., Czamanske, G. K., Fedorenko, V. A., Arndt, N. T., Chauvel, C., Bouse, R. M., King, B. W., Knight, R. J. & Siems, D. F., 1993: Isotopic and trace-element constraints on mantle and crustal contributions to Siberian continental flood basalts, Noril'sk area, Siberia. Geoch. Cosmoch. Acta., 57, 3677-3704.

Zoubek, V., 1957: Report about geological investigation in the Vepor Mts. in surrounding of Tisovec town. Zpr. Geol. Výzk. V roku 1965, Praha, 201-203. (In Czech.)

Slovak Geol. Mag., 11, 2 – 3 (2005), 155 – 163

Regional tectonothermal events in Gemericum and adjacent units (Western Carpathians, Slovakia): Contribution by the $^{40}Ar/^{39}Ar$ dating

R. D. DALLMEYER[1], ZOLTÁN NÉMETH[2] and MARIÁN PUTIŠ[3]

[1]Dept. of Geology, University of Georgia, Athens, GA 30602, U.S.A.
[2]Geological Survey of Slovak Republic, Jesenského 8, SK-040 01 Košice, Slovakia
[3]Dept. of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, SK-842 15 Bratislava, Slovakia

Abstract. The presented $^{40}Ar/^{39}Ar$ data, documenting the main Variscan and Alpine tectonothermal phases of two principal tectonic units of Western Carpathians - Veporicum and Gemericum, have revealed the age of Variscan collision between Gemericum and Veporicum-type basements as late as Westphalian (314.1 Ma; pre-Stephanian), however an earlier onset of the postcollisional Alpine unroofing (105.8 Ma).

The Upper Carboniferous age of detrital muscovite (314.1 Ma) from the sandstone of the Stephanian cover of the Variscan crystalline basement of future Alpine tectonic units Gemericum and Veporicum favours the new interpretation of Variscan convergent movements and collision (**VD** phase) of continental blocks with Gemeric and Veporic-type basements between Westphalian and Stephanian. The thickening of the continental crust, accompanied magmatic processes and extension led to opening of the Meliata oceanic basin south of the Veporic-Gemeric basement block at the beginning of Mesozoic. The dating of the high-pressure metamorphics as well as accompanying detrital sediments of exhumed melange from Meliata basin (the Bôrka nappe), being obducted on Gemericum, favours the Cimmerian age of exhumation processes (157.6 and 166.5 Ma) in Meliata(-Hallstatt) domain. The prograding of this process into the Lower Cretaceous north-vergent overthrusting and imbrication (**AD_1** phase) has been proved by existing geological and structural data. Despite, these compressional events of AD_1 phase occurred at relatively low temperatures and were not recorded by the K-Ar isotopic system.

The Upper Cretaceous cooling ages from the Veporic basement (85.5 Ma) and cover (105.8-82.7 Ma) indicate the post-collisional (post-overthrusting) regional unroofing, being well demonstrated in meso- and microscales (**AD_2** phase).

The pervasive north-vergent compression resulted in the origin of a conjugate system of regional transpressional shear zones trending NW-SE and NE-SW in AD_3 phase. The shearing of **AD_3** phase was a very low temperature event and remained without any geochronological evidence.

Key words: $^{40}Ar/^{39}Ar$ ages, tectonothermal events, Veporicum, Gemericum, Meliaticum, Silicicum, Western Carpathians

Introduction

The $^{40}Ar/^{39}Ar$ geochronological investigation in the region of Western Carpathians (Fig. 1A) has accelerated at the beginning of the 1990s (Maluski et al., 1993; Dallmeyer et al., 1993, 1996; Kováčik et al., 1996). The implementation of radiometric ages into geodynamic interpretations allowed the precise timing of particular tectonometamorphic phases of multiphase Variscan and Alpine evolution. This paper completes the existing geochronological data and contributes to recently developing concept of the Westphalian (pre-Stephanian) south-vergent collision of already amalgamated Tatro-Veporic basement block with the Gemeric basement in the more internal position (deformation phase **VD**, Fig. 4; Németh, 2002). Further data, documenting the pre-Alpine evolution, were registered by our samples only sporadically. Such samples were taken from the blocks preserved among anastomosing Alpine shear zones and by this way being protected from Alpine shearing.

During the Alpine (Cretaceous) orogeny of northern polarity three tectonic units Tatricum, Veporicum and Gemericum formed the zonal arrangement, being north-vergently overthrusted each other during the **AD_1** phase (Fig. 1A). Presented data are dealing with two Alpine tectonic units - Veporicum and Gemericum and their contact zone. The studied region as the triggering zone of Alpine collision, has almost exclusively preserved the Alpine ages of **AD_2** phase, being a product of Alpine post-collisional thermal overprint and unroofing.

Intending to siplify the correlation of obtained data with the tectonometamorphic evolution of Eastern Alps we briefly summarize the double regional division of Western Carpathians and, in extension, the corresponding zones in Eastern Alps:

The first division of the Western Carpathians into Outer, Central and Inner Western Carpathians (Mahel', 1986; Kozur and Mock, 1996, 1997) includes into the Outer Western Carpathians the sequences north of the Pieniny Klippen Belt (Fig. 1). The Central Western Carpathians encompass Tatricum, Veporicum and Gemericum, whereas the Inner Western Carpathians include rock sequences south of Gemericum (Meliaticum, Turnaicum and Silicicum). When linking the Western Carpathians

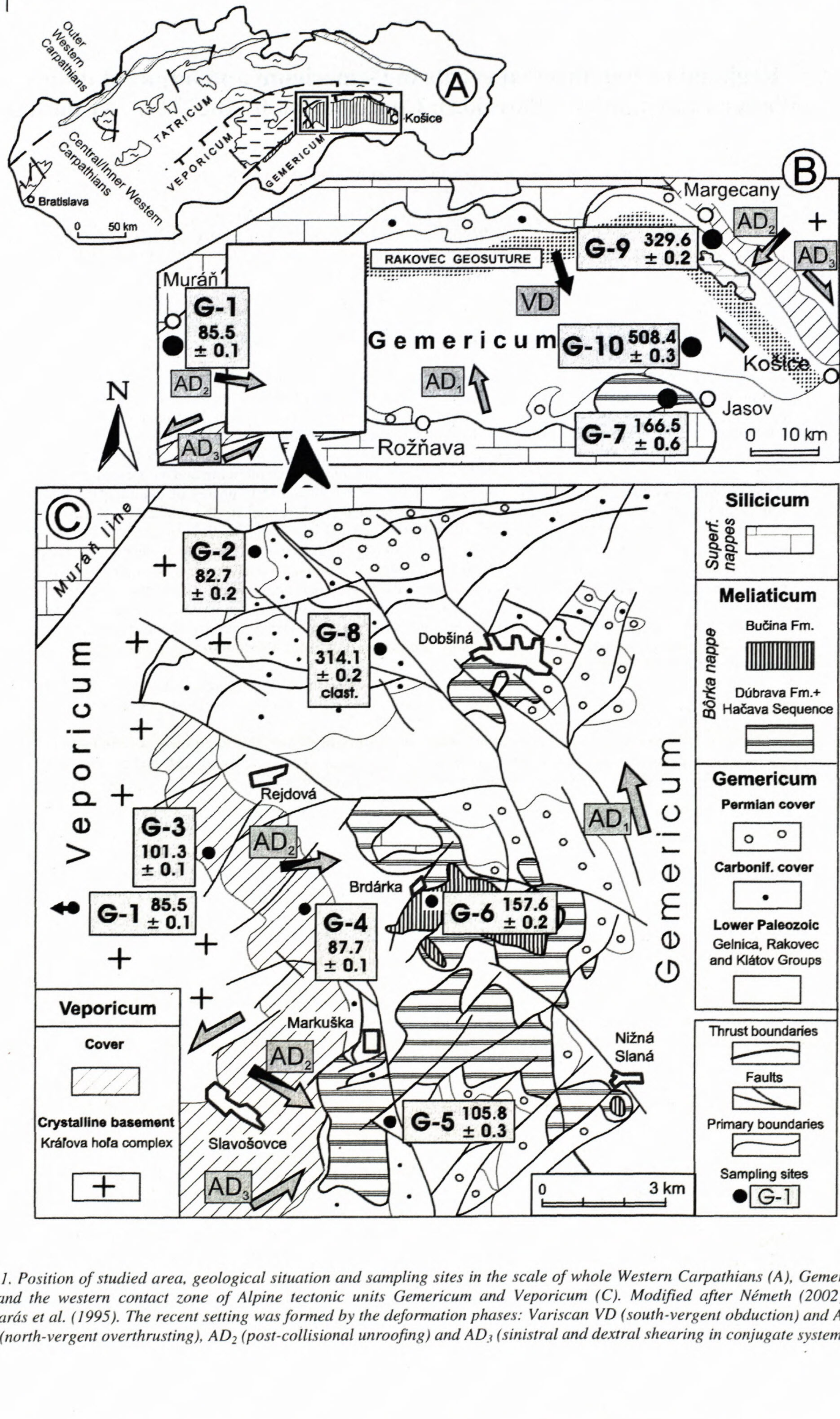


Fig. 1. Position of studied area, geological situation and sampling sites in the scale of whole Western Carpathians (A), Gemericum (B) and the western contact zone of Alpine tectonic units Gemericum and Veporicum (C). Modified after Németh (2002) and Madarás et al. (1995). The recent setting was formed by the deformation phases: Variscan VD (south-vergent obduction) and Alpine AD_1 (north-vergent overthrusting), AD_2 (post-collisional unroofing) and AD_3 (sinistral and dextral shearing in conjugate systems).

with Eastern Alps, the Tatricum, Veporicum and Gemericum of the Central Western Carpathians correspond to the Lower, Middle and Upper Austroalpine units.

According to second simplified division of Western Carpathians to Outer and Inner Western Carpathians (Biely, 1989, 1996), the Outer Western Carpathians include all units north of the Pieniny Klippen Belt, and the Inner Western Carpathians all units south of the Pieniny Klippen Belt.

Brief outline of geological setting and evolution of studied area

Attempting the best geochronological characterization of geological evolution of investigated region, the sampling was carefully focussed on lithologies and mylonitic zones from the contact zone of tectonic units Veporicum and Gemericum as well as the Bôrka nappe outliers of Meliaticum (Fig. 1).

Veporicum

The crystalline basement of investigated southern zones of Veporicum is built up by the Lower Paleozoic to Lower Carboniferous complexes of granitoids, migmatites and gneisses (cf. Bezák, Kováčik, Hraško, Siman and Madarás in Bezák et al., 1999). It is supposed that the protolith of metamorphites was represented by the lithology corresponding with the recently outcropping Lower Paleozoic sequences of Gemericum from the time of primary rifting of the pre-Variscan basement (Grecula, 1994; Németh, 2002). The Lower Paleozoic volcanosedimentary sequences of Veporicum and Gemericum are supposed to have been sedimented on the opposing sides of diverging basin and the provenances of sediments as well as magmatic and volcanic processes in Lower Paleozoic were corresponding. The possible presence of fragments of older Precambrian rocks among Lower Paleozoic metamorphic sequences of both Veporicum and Gemericum is still a matter of debate. The cover of Veporicum consists of Stephanian cyclic sandstone-claystone beds and the Permian coarse detrital arkose sediments (Vozárová and Vozár, 1982).

Gemericum

The Lower Paleozoic volcanosedimentary sequences of Gemericum are a product of rifting primarily on continental crust. There prevail the flyschoid lithology, products of bimodal volcanism, green schists ("green phyllites") and in the upper part of the lithological column the thick horizon of volcanic extrusive and effusive products is developed. The black schists ("black phyllites") with lydites and carbonates are located in lithostratigraphic column either in one horizon at the base of Lower Paleozoic sequences (Grecula, 1982; Németh, 2002), or according to another interpretation they are distributed through the whole Lower Paleozoic succession in several horizons (Snopko in Bajaník et al., 1983; Ivanička et al., 1989).

The Lower Paleozoic sequences of Gemericum can be generally divided into three rock groups, the products of divergent evolutionary phases of the basin (Németh, 2002; Fig. 4). The first rock group covers the volcanosedimentary sequences of the primary riftogenesis on continental crust (Gelnica Group), second the beginning of formation of oceanic crust (Klátov Group; cf. Hovorka et al., 1984; semimetapelite = pelite + carbonate + organic matter + tholeiitic basalt sensu Radvanec, 1992) and third – the Rakovec Group - the volcanosedimentary sequences of distal parts of the sedimentary basin between the Klátov and Gelnica Groups during more advanced stages of divergence (Németh, 2005; cf. Ivan, 1997). The convergence terminated with the south vergent collision during VD phase and the local obduction of the rocks of Rakovec and Klátov Groups on marginal rocks of Gelnica Group was confirmed (Németh, 2002; Fig. 4; Hovorka et al., 1984, defined the Klátov nappe). This setting is superfically expressed by the Rakovec geosuture including the rocks of the Rakovec and Klátov Groups plus exhumed Westphalian rocks. Field evidences show that the post-collision molasse in the suture zone started with the Stephanian Hámor Formation (Fig. 4). The Upper Carboniferous and Permian sedimentation continued in remnant basins (sensu Grecula, 1994) with locally differing sedimentary facies as the reflection of differing source of clastic material along the Rakovec geosuture. The comprehensive characterization of Gemeric cover sequences was published by Vozárová and Vozár (1988).

Because the collision - the Veporic and Gemeric type basements formed the first consolided terrane already at the end of Variscan orogeny (Grecula, 1994; Németh, 2002).

The Variscan collisional thickening of continental crust was reflected in the tectonothermal effects from the Upper Carboniferous and the extension dominated on both sides of Gemericum. Along the Rakovec suture zone a new Permian-Triassic elongated basin originated, though the strongest extension occurred in the south of Gemericum and followed to formation of Meliata oceanic domain in Mesozoic. The sedimentation of conglomeratic facies in this extended basin was followed by the psammitic and pelitic facies with transition to Triassic carbonates with intercalations of extrusive and effusive products of basalt volcanism, and, later by the Jurassic black shales (cf. Mello, ed., 1997, pp. 60-61 ibid). The platform carbonates of Silicicum were deposited south of the main spreading centres of Meliaticum and the position of the Tatric-Veporic-Gemeric block (Dallmeyer et al., 1996). As the possible driving force of this Upper Paleozoic-Triassic evolution in the southern part of the Western Carpathians the northward displacement of the lithosphere over the source of convectional heat (mantle plume) was suggested (Németh, 2002).

Meliaticum

The Mesozoic development on southern slopes of Gemericum includes the complete Wilson cycle from the opening of Meliata oceanic basin as a part of the Meliata-Hallstatt one in Triassic towards the subduction and collision in Upper Jurassic-Lower Cretaceous. The

Slovak Geol. Mag., 11, 2 – 3 (2005), 155 – 163

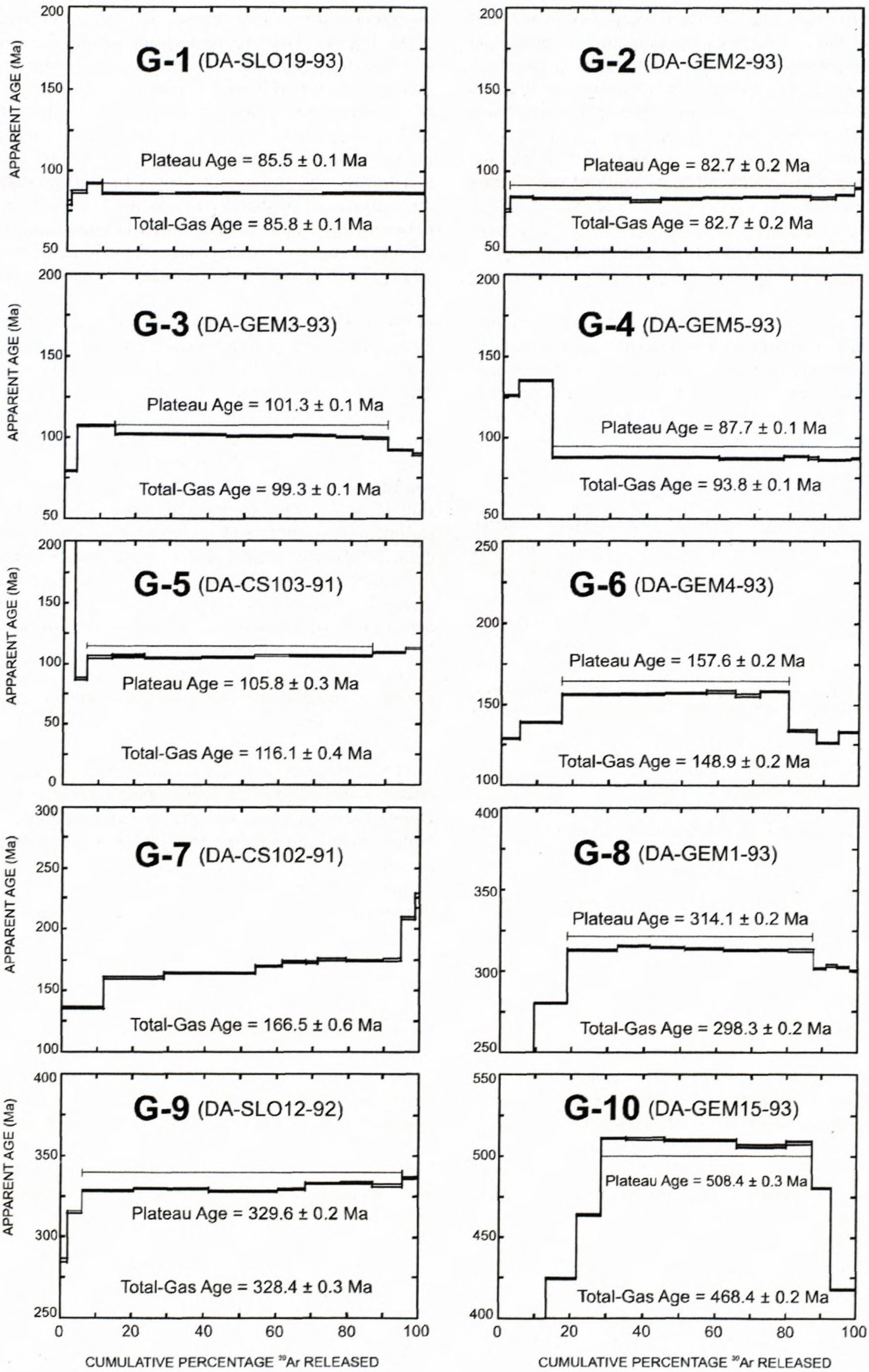


Fig. 2. Obtained $^{40}Ar/^{39}Ar$ age spectra. Horizontal lines express the cumulative percentage of ^{39}Ar released, the vertical line – apparent ages in Ma.

suture after the Meliata part of this basin is interpreted to be located in the so-called Rožňava discontinuity zone south of Gemericum (Németh, 2003; cf. Pawliszynova, 1978 in Grecula et al., 1995).

The Meliaticum (Kozur and Mock, 1973) is represented by the relics of former oceanic crust with the presence of pelagic sediments (radiolarites, black shales) with complexes of ophiolite suite (ultrabasics). The north-vergent obduction of this melange including a part of cover complexes of southern Gemericum is well documented in the Bôrka nappe (Mello et al., 1998). The beginning of forming of the Meliata basin by continental rifting along southern slopes of Gemericum is well demonstrable by the facial bounds of the sediments from the cover of Southern Gemericum and those being exhumed in the Bôrka nappe (e.g. the oligomict conglomerates of the Rožňava Formation of Gočaltovo Group of autochthonous Southern Gemeric cover correspond with the protolith of oligomict metaconglomerates of the Bučina Formation from the Bôrka nappe; cf. reconstruction in Fig. 4 of Németh, 1996). The internal setting of the Bôrka nappe outliers includes preferably the marginal detrital and carbonatic sequences of the southern slope of Gemericum from the time of Permo-Triassic riftogenesis (Németh, 1994, 1996).

Recent interpretations sensu Mello et al. (1997) understand the Meliaticum as individual tectonic unit, comparable with Gemericum and Veporicum.

Analytical methods

The methodology of the $^{40}Ar/^{39}Ar$ dating consisted from preparing of optically pure (>99 %) muscovite concentrates which were wrapped in aluminium foil packets, encapsulated in sealed quartz vials and irradiated in the TRIGA Reactor at the U.S. Geological Survey in Denver. Variations in the flux of neutrons along the length of the irradiation assembly were monitored by the mineral standards, including Mmhb-1 (cf. Sampson and Alexander, 1987). Samples then were incrementally heated until fusion in a double-vacuum resistance-heated furnace. Measured isotopic ratios were corrected for total system blanks and the effects of mass discrimination. Inferring isotopes produced during irradiation were corrected by factors reported by Dalrymple et al. (1981). The apparent $^{40}Ar/^{39}Ar$ ages were calculated from corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger and Jäger (1977).

The total-gas ages have been computed for each sample by appropriate weighting of the age and percent ^{39}Ar released within each temperature increment. A plateau age was defined if the ages recorded by two or more continuous gas fractions with similar apparent K/Ca ratios represented >4 % of the total ^{39}Ar evolved and together constituted >50 % of the total quantity of ^{39}Ar evolved.

The muscovite concentrates display variably discordant $^{40}Ar/^{39}Ar$ age spectra. The K/Ca ratios suggest that the evolution of gas during measuring was from compositionally uniform populations of intracrystalline sites. Because the K/Ca ratios displayed no significant or systematic intrasample variations we have not displayed them with the muscovite age spectra in Fig. 2.

Obtained data and their regional significance

Intending the best geochronological dating of the particular evolution phases of the studied region we have collected 10 field samples taken from the representative lithotypes of principal complexes in Gemericum, Veporicum and the Bôrka nappe (Figs. 1 and 4). Obtained geochronological data (Fig. 2) can be generally clustered into four groups:

The oldest age 508.4 ± 0.3 Ma is from the detrital muscovites from the Lower Paleozoic schistose flyschoid sandstone G-10 (DA-GEM15-93) in the south-eastern part of Gemericum (termination of the Zábava valley 8 km to NNW of Jasov village). The preservation of Cambrian detrital muscovites in these sandstones indicates that the overheating during Variscan and Alpine orogeny was not sufficient enough to reset the isotopic system.

The second group, clustering the Variscan ages, is represented by the muscovite from the mylonitic schist G-9 (DA-SLO12-92) directly from the overthrust zone of Gemericum on Veporicum 1 km to SW of Margecany village. This sample with the Variscan plateau age 329.9 ± 0.2 Ma indirectly confirms the location of Alpine brittle and brittle-ductile overthrusting and normal faulting to discrete zones among which the rock blocks with former Variscan tectonometamorphic ages were preserved.

Into the category of Variscan ages belongs also that from the detrital muscovite in Stephanian sandstone of Hámor Fm. from post-collisional (post-VD) molasse of the sample G-8 (DA-GEM1-93). The plateau age 314.1 ± 0.2 Ma indicates that the Variscan exhumation/collision processes in the innermost zones of Variscan orogeny were still active in Westphalian. Samle was taken from the outcrop 4 km to W of Dobšiná town.

Third category of ages - the Jurassic cooling ages - documents the exhumation of marginal sequences of the Southern Gemeric slope of Meliata basin from subduction zone during the advanced phase of convergence. First sample, the mylonitic schist G-7 (DA-CS102-91) was taken directly from the type locality of the Bôrka nappe in Southern Gemericum (Teplica valley 1.8 km to W of Jasov village) from the rock sequence containing also bodies of glaucophanites. The total gas age 166.5 ± 0.6 Ma belongs into the cluster of the Bôrka nappe (Meliata) exhumation ages, being observed also by the earlier authors referred in introductory chapter.

Our study firstly dated the metaconglomerate from the Bôrka nappe outlier 1 km to SE of the Brdárka village, distant 12 km from the suture zone located south of Gemericum. The muscovite of this metaconglomerate G-6 (DA-GEM4-93) gave the plateau age 157.6 ± 0.2 Ma, which indicates the later frozing of isotopic system in comparison with the main exhumation ages of the Bôrka nappe being clustered around 166 Ma.

Fourth large group of ages represents the Alpine ages related to post-collisional cooling in Veporicum and in the Alpine contact zone of Veporicum with overthrusted

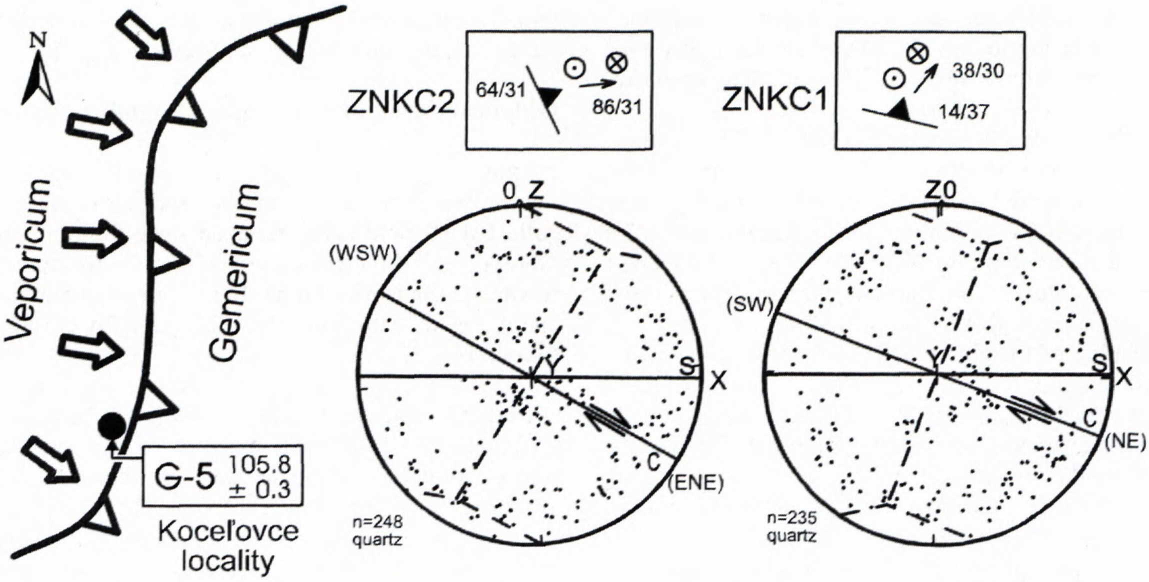


Fig. 3. Microstructural study of metaquartzite from the Koceľovce locality (G-5) with plateau age 105.8 ± 0.3 Ma expresses relatively weak top-to-the-ENE and NE normal faulting produced by unroofing. The sample from the Hámor Fm., representing the Stephanian cover of Rakovec geosuture was during the AD_1 phase sandwiched beneath overthrusted Gemeric nappe.

Gemericum. Uplift of the crystalline core caused the gradual unroofing generally to the south which is well documented by the cooling ages. The unroofing kinematics was documented by the structural investigation of numerous authors in mesoscale (Hók et al., 1993; Madarás et al., 1995), as well as microscale (Putiš, 1991, 1994; Putiš et al., 1999). The kinematics of AD_2 unroofing was registered not only by the soft lithology of Veporic cover sequences where the main kinematic activity occurred, but also by the underlying crystalline basement. This is confirmed by the muscovite of mylonitic "Muráň orthogneiss" from Veporicum G-1 (DA-SLO19-93), being sampled from the fresh road exposure at railway crossing 0.6 km to south of Muráň village and demonstrating the very flat plateau of the age 85.5 ± 0.1 Ma.

The corresponding unroofing plateau ages were given also by the muscovites from siliciclastic mylonitic schists of Veporic cover: G-2 (DA-GEM2-93) - 82.7 ± 0.2 Ma, Danková 8 km WNW of Dobšiná town and the sample G-4 (DA-GEM5-93) - plateau age 87.7 ± 0.1 Ma, Hanková village 3 km to NNW of Markuška village.

The earliest closure of isotopic system during the AD_2 phase occurred along the normal faults in the uppermost crustal levels. This is confirmed by the whole-rock age 105.8 ± 0.3 Ma of the white mica of metaquartzite of sample G-5 (DA-CS103-91) from the open pit 1 km to NW of Koceľovce, near the road Štítnik - Roštár – Hanková 2.5 km to SSE of Markuška. This sample of Hámor Formation represents the Stephanian cover of collided Veporic-Gemeric terrane. Because it was unclear whether this age is related with the termination of the overthrusting during AD_1 phase or the onset of unroofing during AD_2 phase, besides the mesoscopic structures, the crystallographic preferred orientation of synkinematic dynamically recrystallized quartz grains in metaquartzite was measured using the U-stage. The results from the oriented samples ZNKC1 and ZNKC2 from the same part of outcrop where the geochronological sample G-5 (DA-CS103-91) was taken proved that this age documents, though not very distinctly, the AD_2 unroofing kinematics and not the earlier AD_1 overthrusting (Fig. 3). This normal faulting was found also by the asymmetric structures in the mesoscopic scale (secondary foliation 64/31°, stretching lineation 86/31°, and 14/37° vs. 38/30°; Fig. 3).

Another important point is, as revealed also by the recent field mapping, that a part of Stephanian cover Hámor Formation (sample G-5 - DA-CS103-91; Fig. 4) was sandwiched during the AD_1 overthrusting beneath the Gemeric nappe, but a part with the sample G-8 (DA-GEM1-93) was passively displaced with the Alpine Gemeric nappe.

Similar older Variscan cooling age was demonstrated also by the sample G-3 (DA-GEM3-93) of muscovite from the siliciclastic mylonitic schist of the Veporic cover 2.5 km to SSW of Rejdová. The plateau age 101.3 ± 0.1 Ma indicates (together with the age 105.8 ± 0.3 Ma of the sample G-5) that the first records of Cretaceous unroofing can be allocated to earlier time period in comparison with the accelerated unroofing of the Upper Cretaceous age where the most data are clustered (around 86 Ma).

Similar results were obtained by the earlier dating of Veporic crystalline basement rocks by Kováčik et al. (1996): The first cluster of data from the newly formed amphiboles in the range 115-105 Ma presumably indicated the onset of Alpine thermal metamorphism (metamorphic core complex). The concentration of ages between 88-84 Ma (second cluster of data by l.c.) indicated the accelerated uplift. This was documented also by the strongly recrystallized micaschist with the nearly concordant cooling age of newly formed amphibole and muscovite (87.4 and 87.2 Ma), which supports the strong uplift in a short time period.

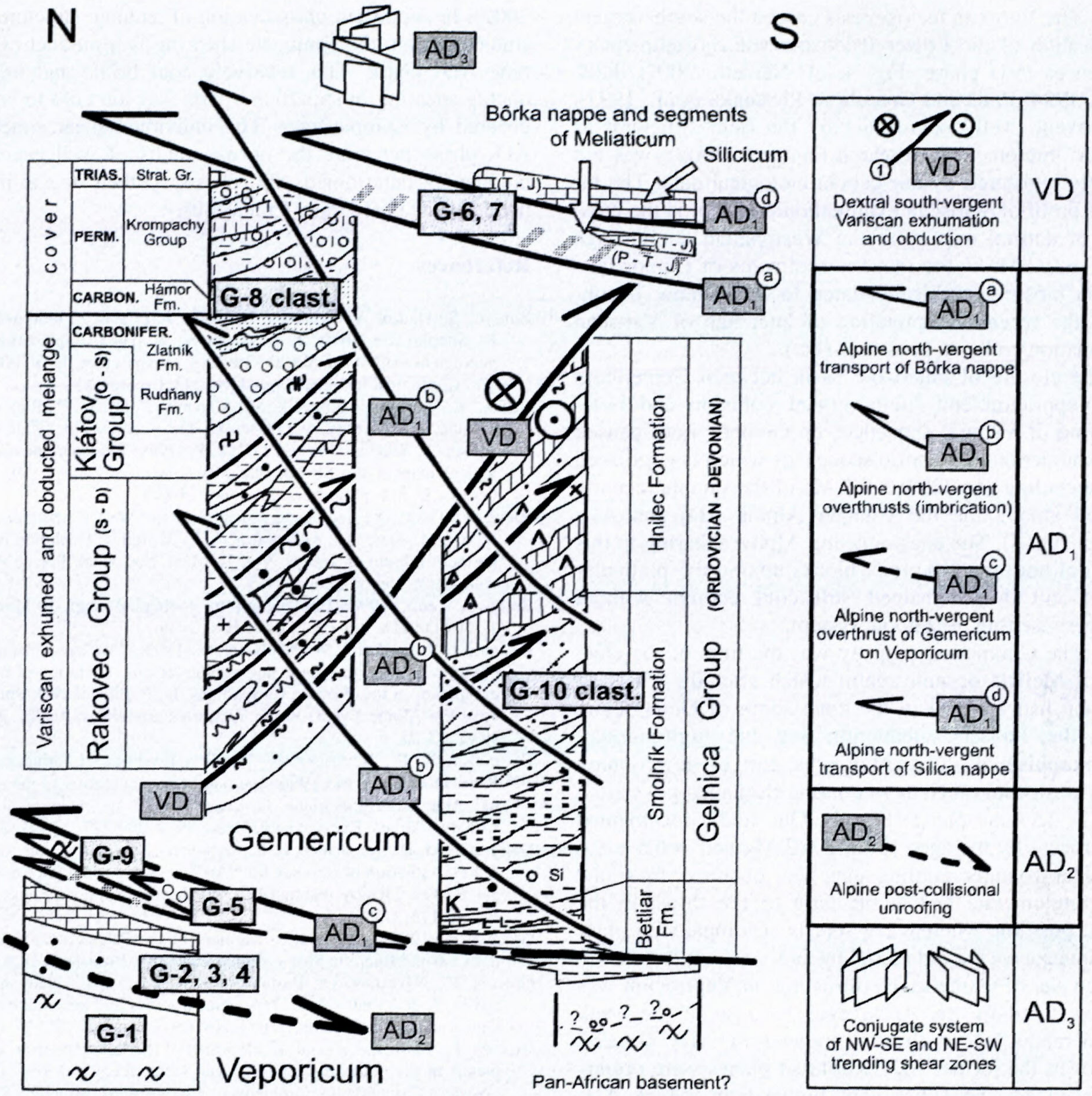


Fig. 4. Position of studied samples in lithotectonic scheme (modified after Németh et al., 2000). The succession of deformation events is depicted in the right side of the picture. The slice of Hámor Fm. was sandwiched beneath the AD_1 north-vergent Gemeric nappe (G-5), but prevailing part remained in parautochthonous position (G-8).

Conclusion

Obtained data documented the Variscan, Cimmerian as well as in details the Alpine tectonothermal events. The sampling sites were located along the tectonic contact zone of Veporicum with Gemericum and reference data were obtained also sidewards. The attention was put on the trasport of the Bôrka nappe close to the suture zone of Meliaticum as well as in its displaced frontal parts. Obtained ages, together with the older ones (not stated in exact values but taken into consideration - e.g. Maluski et al., 1993; Dallmeyer et al., 1993, 1996; Kováčik et al., 1996) allowed to reconstruct the succession of events in Gemericum and adjacent tectonic units (southern parts of Veporicum and the Bôrka nappe of Meliaticum).

New data in the studied region indicate, that the overthrusting during AD_1 and shearing during AD_3 were relatively "cold", so the obtained spectra demonstrate the warmer extensional events of AD_2. Because of cold compressional events neither Alpine AD_1 imbrication of Veporic-Gemeric region nor AD_3 shearing were registered by our samples. From the viewpoint of geological evolution the obtained data can be divided into several genetic groups reflecting four main tectonothermal events of the region.

1. The oldest cooling age 508.4 ± 0.3 Ma from detrital white mica obtained from Lower Paleozoic sedimentary sequence in the south of Gelnica Group indicates that these rocks in the southern parts of Gemericum were not sufficiently overheated neither during the Variscan nor Alpine orogeny to reset the isotopic system of old detrital white micas.

2. The Variscan tectogenesis caused the south-vergent imbrication of the Lower Paleozoic volcanosedimentary sequences (VD phase; Fig. 4; cf. Németh, 2002; Putiš, 1992, 1994; Putiš and Grecula in Plašienka et al., 1997). This event, well documented by the field structural as well as microtectonic research (Németh, 2002), was not directly registered by our geochronological data. The indirect proof of Variscan exhumation/collision is the presence of detrital mica with the Westphalian cooling age 314.1 ± 0.2 Ma in the molasse sediments of Hámor Formation biostratigraphically dated to Stephanian. It confirms the recent interpretation of later age of Variscan exhumation/collision processes (l.c.).

The closure of Paleozoic basin between Gemericum and Veporicum and south-vergent collision and overthrusting of Veporic sequences on Gemeric ones caused the exhumation of Veporic sequences which is confirmed by the cooling age 329.9 ± 0.2 Ma of the sample recently located among the the younger Alpine AD_1 and AD_2 shears (Fig. 4). The anastomosing Alpine shearing in this zone did not affect the rock blocks among the particular shears and they remained still cold enough without younger resetting of isotopic system.

3. The Cimmerian orogeny was the time of the clossure of Meliata oceanic realm which after the Variscan collision had evolved in the zone south of Gemericum. After the Jurassic subduction and the high-pressure metamorphism the obduction of a part of accretionary prism northward on Gemericum (the Bôrka nappe) started the AD_1 tectonic phase (Fig. 4). Our study documented this process by the ages 157.6 ± 0.2 Ma and 166.5 ± 0.6 Ma. The younger cooling age was obtained from the metaconglomerate bed at the base of the thrust in the frontal position, whereas the schists accompanying glaucophanites gave the older cooling age.

The age of Gemeric overthrusting on Veporicum was not registered by the Ar/Ar ages because of the weak synkinematic recrystallization related to AD_1 process. Moreover, the former AD_1 overthrust planes were preferable used by the subsequent higher-temperature AD_2 normal faulting during unroofing.

4. The main kinematic activity of unroofing of the phase AD_2 was registered along the tectonic contact zone of Veporicum with Gemericum (Figs. 1C and 4). The sense of shearing during AD_2 phase was demonstrated by numerous works of structural geology and microtectonics (Hók et al., 1993; Putiš et al., 1999; Németh, 2002 a.o.) (Figs. 1, 3 and 4) and with cooling ages clustered in interval 87.7-82.7 Ma. The unroofing was accommodated also by the basement sequences (mylonitic "Muráň orthogneiss" at Muráň village) with cooling age 85.5 ± 0.1 Ma. New microtectonic study (Fig. 3) revealed that the AD_2 unroofing in the uppermost soft quartzitic horizons started earlier (105.8 ± 0.3 Ma), which confirms the earlier results by Kováčik et al. (1996).

The zonal arrangement of lithological as well as tectonic units withing the Western Carpathians (Fig. 1A), incl. courses of mountain ranges, has a distinct arc bending. This bending is interpreted as the product of offsets in conjugate system of shear zones of NE-SW (sinistral) and NW-SE (dextral) trends (Grecula et al., 1990; Németh, 2002). In simplified classification of tectonic structures of studied region, the conjugate shearing is a product of Alpine AD_3 phase. This relatively cold brittle and brittle-ductile shearing in superficial parts was too cold to be registered by isotopic ages. The individual shear zones of AD_3 phase penetrate the normal faults of well geochronologically determined AD_2 phase, so their age is interpreted as the post-Upper Cretaceous.

References

Bajaník, Š., Hanzel, V., Ivanička, J., Mello, J., Pristaš, J., Reichwalder, P., Snopko, L., Vozár, J. & Vozárová, A., 1983: Explanations to geological map of the Slovak Ore Mts. - eastern part, 1 : 50 000. D. Štúr Geological Institute, Bratislava, 223. (In Slovak).

Bezák, V., Hraško, Ľ., Kováčik, M., Madarás, J., Siman, P., Pristaš, J., Dublan, L., Konečný, V., Plašienka, D., Vozárová, A., Kubeš, P., Švasta, J., Slavkay, M. and Liščák, P., 1999: Explanations to geological map of the Slovak Ore Mts. - western part, 1 : 50 000. GSSR - D. Štúr Publishers, Bratislava, 1-178.

Biely, A., 1989: The geological structure of the West Carpathians. In: Rakús, M., Dercourt, J. & Nairn, A. E. M. (eds.): Evolution of the northern margin of Tethys. Vol. II. Mém. Soc. Géol. France, Nouvelle Série, 154 (II), Paris, 51-57.

Biely, A. (ed.), 1996: Explanation to geological map of Slovakia 1 : 500,000. D. Štúr Publ., Bratislava, 1-76.

Dallmeyer, R. D., Putiš, M., Neubauer, F., 1993: $^{40}Ar/^{39}Ar$ mineral age controls for the Pre-Alpine and Alpine tectonic evolution of nappe complexes in the Western Carpathians. In: P. Pitoňák & J. Spišiak, eds.: Pre-Alpine Events in the Western Carpathians' Realm. Bratislava, 13-20.

Dallmeyer, R. D., Neubauer, F., Handler, R., Fritz, H., Müller, W., Pana, D. & Putiš, M., 1996: Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole-rock data. Eclogae geol. Helv., 89, 1, 203-227.

Dalrymple, G. B., Alexander, E. C., Lanphere, M. A. & Kraker, G. B., 1981: Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA reactor. U.S. Geological Survey Professional Paper 1176, 1-55.

Grecula, P., 1982: Gemericum - segment of the Paleotethyan riftogenous basin. Mineralia Slov., Monograph, Alfa, Bratislava, 1-263.

Grecula, P., Návesňák, D., Bartalský, B., Gazdačko, Ľ., Németh, Z., Ištván, J. & Vrbatovič, P., 1990: Shear zones and arc structure of Gemericum, the Western Carpathians. Mineralia Slov., 22, 97-107.

Grecula, P., 1994: Lithofacial development of the Late Paleozoic complexes in the boundary zone between Gemericum and Veporicum (Western Carpathians) - problems and suggestions. Mineralia Slov., 26, 411-426.

Grecula, P., Abonyi, A., Abonyiová, M., Antaš, J., Bartalský, B., Bartalský, J., Dianiška, I., Drnzík, E., Ďuďa, R., Gargulák, M., Gazdačko, Ľ., Hudáček, J., Kobulský, J., Loerinz, L., Macko, J., Návesňák, D., Németh, Z., Novotný, L., Radvanec, M., Rojkovič, I., Rozložník, L., Rozložník, O., Varček, C. & Zlocha, J., 1995: Mineral deposits of the Slovak Ore Mountains. Vol. 1. Geocomplex, Bratislava, 1-829.

Hók, J., Kováč, P. & Madarás, J., 1993: Extensional tectonics of the western part of the contact area between Veporicum and Gemericum (Western Carpathians). Mineralia Slov., 25, 172-176.

Hovorka, D., Ivan, P. & Spišiak, J., 1984: Nappe with amphibolite facies metamorphites in the Inner Western Carpathians – its position, origin and interpretation. Mineralia slov., 16, 73-86.

Ivan, P., 1997: Rakovec and Zlatník Formations: Two different relics of the pre-Alpine back-arc crust in the central Western Carpathians. In: P. Grecula, D. Hovorka & M. Putiš (eds.): Geological evolution of the Western Carpathians. Mineralia Slovaca – Monograph, Bratislava, 281-288.

Ivanička, J., Snopko, L., Snopková, P. & Vozárová, A., 1989: Gelnica Group: Lower unit of Spišsko-Gemeriské Rudohorie Mts. (West Carpathians) Early Paleozoic. Geologický Zborník, Geol. Carpathica, 40, 4, 283-501.

Kováčik, M., Kráľ, J. & Maluski, H., 1996: Metamorphic rocks in the Southern Veporicum basement: Their Alpine metamorphism and thermochronologic evolution. Mineralia Slov., 28, 185-202.

Kozur, H. & Mock, R., 1973: Zum Alter and zur tektonischen Stellung der Meliata-Serie des Slowakischen Karstes. Geol. Zbor. Geol. carpath., 24, 2, 365-374.

Kozur, H. & Mock, R., 1996: New paleogeographic and tectonic interpretations in the Slovakian Carpathians and their implications for correlations with the Eastern Alps. Part I: Central Western Carpathians. Mineralia Slov., 28, 151-174.

Kozur, H. & Mock, R., 1997: New paleogeographic and tectonic interpretations in the Slovakian Carpathians and their implications for correlations with the Eastern Alps. Part II: Inner Western Carpathians. Mineralia Slov., 29, 164-209.

Maheľ, M., 1986: Geological structure of Czechoslovak Carpathians. Part 1: Paleoalpine units. Veda, Bratislava, 1-503. (In Slovak.)

Maluski, H., Rajlich, P. & Matte, P., 1993: ^{40}Ar-^{39}Ar dating of the Inner Carpathians Variscan basement and Alpine mylonitic overprinting. Tectonophysics, 223, 313-337.

Mello, J.(ed.), Elečko, M., Pristaš, J., Reichwalder, P., Snopko, L., Vass, D., Vozárová, A., Gaál, Ľ., Hanzel, V., Hók, J., Kováč, P., Slavkay, M. & Steiner, A., 1997: Explanations to geological map of the Slovak Karst 1 : 50 000. Dionýz Štúr Publishers, Bratislava, 1-255. (In Slovak with English summary.)

Mello, J., Reichwalder, P. & Vozárová, A., 1998: Bôrka nappe: High-pressure relic from the subduction-accretion prism of the Meliata ocean (Inner Western Carpathians, Slovakia). Slovak Geol. Mag., 4, 261-273.

Németh, Z., 1994. Alpine tectonics in the Nižná Slaná Depression (contact zone between Gemericum and Veporicum, Western Carpathians). Mineralia Slov., 26, 399-410.

Németh, Z., Putiš, M. and Grecula, P., 2000: Tectonic evolution of Gemericum (the Western Carpathians) outlined by the results of petrotectonic research. Mineralia Slov., 32, 169-172.

Németh, Z., 2002: Variscan suture zone in Gemericum: Contribution to reconstruction of geodynamic evolution and metallogenetic events of Inner Western Carpathians. Slovak Geol. Mag., 8, 3-4, 247-257.

Németh, Z., 2003: Tectogenesis of Lower Paleozoic and Upper Paleozoic sedimentary basins in the Gemeric region in the frame of geodynamics of Inner Western Carpathians. Final report of the research project Tectogenesis of the sedimentary basins of Western Carpathians. Archives of State Geological Survey of Dionýz Štúr, Bratislava, 1-91.

Németh, Z., 2005: Geodynamic evolution of Gemericum and neighbouring Veporicum in the frame of two-phase divergence and convergence. Mineralia Slov., 37, 2002-2004.

Németh, Z., Radvanec, M., Hraško, Ľ. & Madarás, J., (in print): Ochtiná zone from the view of new results of geological mapping and petrological study in the contact zone of Veporicum and Gemericum. Mineralia Slov., 2, Geovestník, 15.

Pawliszynova, J., 1978: Magnetotelluric method. Report from geophysical research in the Poproč area. Manuscript – archives Geofond, Spišská Nová Ves, 1-189. (In Slovak).

Plašienka, D., Putiš, M., Kováč, M., Šefara, J. and Hrušecký, I., 1997: Zones of Alpidic subduction and crustal underthrusting in the Western Carpathians. In: Grecula, P., Hovorka, D. and Putiš, M. (eds.): Geological evolution of the Western Carpathians. Mineralia Slov. – Monograph, Geocomplex, Bratislava, 1-24i.

Putiš, M., 1991: Geology and petrotectonics of some shear zones in the West Carpathian crystalline complexes. Mineralia slovaca 23, 6, Newslet. 3, 459-473.

Putiš, M., 1992: Variscan and Alpidic nappe structures of the Western Carpathian crystalline basement. Geol. Carpath. 43, 6, 369-380.

Putiš, M., 1994: South Tatric-Veporic basement geology: Variscan nappe structures; Alpine thick-skinned and extensional tectonics in the Western Carpathians (Eastern Low Tatra Mts., Northwestern Slovak Ore Mts.). Mitt. Österr. Geol. Ges. 86, 83-99.

Putiš, M., Németh, Z., Unzog, W., Wallbrecher, E., 1999: The quartz and calcite X-ray texture goniometer patterns from the Western Carpathians Cretaceous ductile shear zones used as kinematic indicators. Geol. Carpathica 50, 165-169.

Radvanec, M., 1992: Zonality of low-pressure polyphase metamophism in open system for the fluid phase in the gneiss-amphibolite complex of Gemeric Unit. Mineralia Slov., 24, 175-196. (In Slovak.)

Sampson, S. D. & Alexander, E. C., Jr., 1987: Calibration of the interlaboratory $^{40}Ar/^{39}Ar$ dating standard, Mmhb-1. Chemical Geology, 66, 27-34.

Steiger, R. H. & Jäger, E., 1977: Subcommission of geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters, 36, 669-390.

Vozárová, A. & Vozár, J., 1982: New lithostratigraphic units in southern part of Veporicum. Geol. práce, Správy, 78, 169-194. (In Slovak.)

Vozárová, A. & Vozár, J., 1988: Late Paleozoic in West Carpathians. Veda, Geological Institute of Dionýz Štúr, Bratislava, 1-314.

Slovak Geol. Mag., 11, 2 – 3 (2005), 165 – 183

Deep-water sedimentary facies and depositional environments in the eastern part of the Lower Paleozoic Gelnica Group (Gemericum, Inner Western Carpathians)

MARTIN KOVÁČIK

Geological Survey of Slovak Republic, Jesenského 8, 040 01 Košice; kovacik@gssr-ke.sk

Abstract. Sedimentological investigation was focussed on psammitic horizon belonging to upward fining and thinning sequence, being a constituent part of sedimentary filling of Gelnica Group. The lithofacies of this horizon demonstrate their deep-water character. The coarse-grained sediments were transported to deposition place by concentrated density (gravity) flows, and the finer-grained lithofacies by turbidity flows. The finest pelitic lithofacies have the hemipelagic character. The lydites as an important lithofacies originated by pelagic deposition with contribution of siliceous solutions of submarine volcanic springs and low-density turbidity flows. Lydites together with alodapic carbonates and dark pelitic lithofacies represent a condensed horizon from the time of maximum height of sea level.

The psammitic horizon alone has a complex cyclic character. In its lower part (Tinesová dolina valley) the shallow distributary channels built by coarse-grained lithofacies are present. The channels are spatially connected with finer-grained lithofacies of levee and interchannel environments and together form the middle part of submarine fan. The upper, substatial part of psammitic horizon is formed by sediments of lobes and their margins (lobe fringes) of outer part of submarine fan (valleys Hutná dolina, Gelnická dolina and Zlatá dolina) with frequent compensation cycles.

Fining and thinning character of studied psammitic horizon, as well as whole sequence, to which it belongs, is a result of sea-level rising, attenuation of sedimentary material contribution into the basin and backstepping of deep-water sedimentary system towards continent.

Key words: deep-water facies, submarine depositional environments, Lower Paleozoic, Gelnica Group, Gemericum, Western Carpathians

Introduction

Metamorphosed and structurally complicated sedimentary successions seldom became an object of detail sedimentological investigation. Despite, in some cases the former composition, sedimentary structures and fabric are partially or fully preserved and it allows the sedimentological analysis.

Sedimentological investigation in the area of Lower Paleozoic sequences of Gemericum was done by several authors in the past. The sedimentological description and classification of deep-water depositional systems of this unit was presented by Snopko (1967) using terms by Vassojevič (1960). The thickness of lithofacies, uninterrupted sedimentary development, presence of lydites and alodapic carbonates, the relatively well developed Bouma intervals (Bouma, 1962) as well as the absence of large-scale cross-bedding were supposed to be the marks of deep-water sedimentation (Snopko and Ivanička, 1978). Later work by Vozárová and Ivanička (2000) determined seven principal lithofacies of Lower Paleozoic rocks of Gemericum using model defined by Mutti and Ricci-Lucchi (1972).

This work is aiming to present the lateral and vertical stratigraphic development of Lower Paleozoic Gelnica Group in its eastern part and to determine the lithofacies and sedimentary processes during their origin as well as to reconstruct the depositional environments of studied sedimentary system.

Methodology

The work integrates the data from two N-S trending profiles directed perpendicularly to course of lithological strips in eastern part of the Gelnica group of Gemericum (Fig. 1). First, western profile, was directed through Medzev town - Zlatá dolina valley - elevation points Zbojnícka skala and Kloptaň - Tinesova dolina valley - Hutná dolina valley and Helcmanovce village. Second, eastern profile, is coursing in the line Baňa Lucia settlement - Tri studne saddle - Gelnická dolina valley (respectively the Zimná voda valley) and Prakovce town.

The detail sedimentological investigation (Kováčik, 2004) was realized in 4 additional localities with numerous outcrops in the valleys Zlatá dolina, Tinesova dolina and Hutná dolina in western profile, and Gelnická dolina valley (resp. Zimná voda valley) in eastern profile (Figs. 1-3). Lithofacies were defined and interpreted using their thickness, geometry, sedimentary structures, fabric and petrography. The particular depositional environments

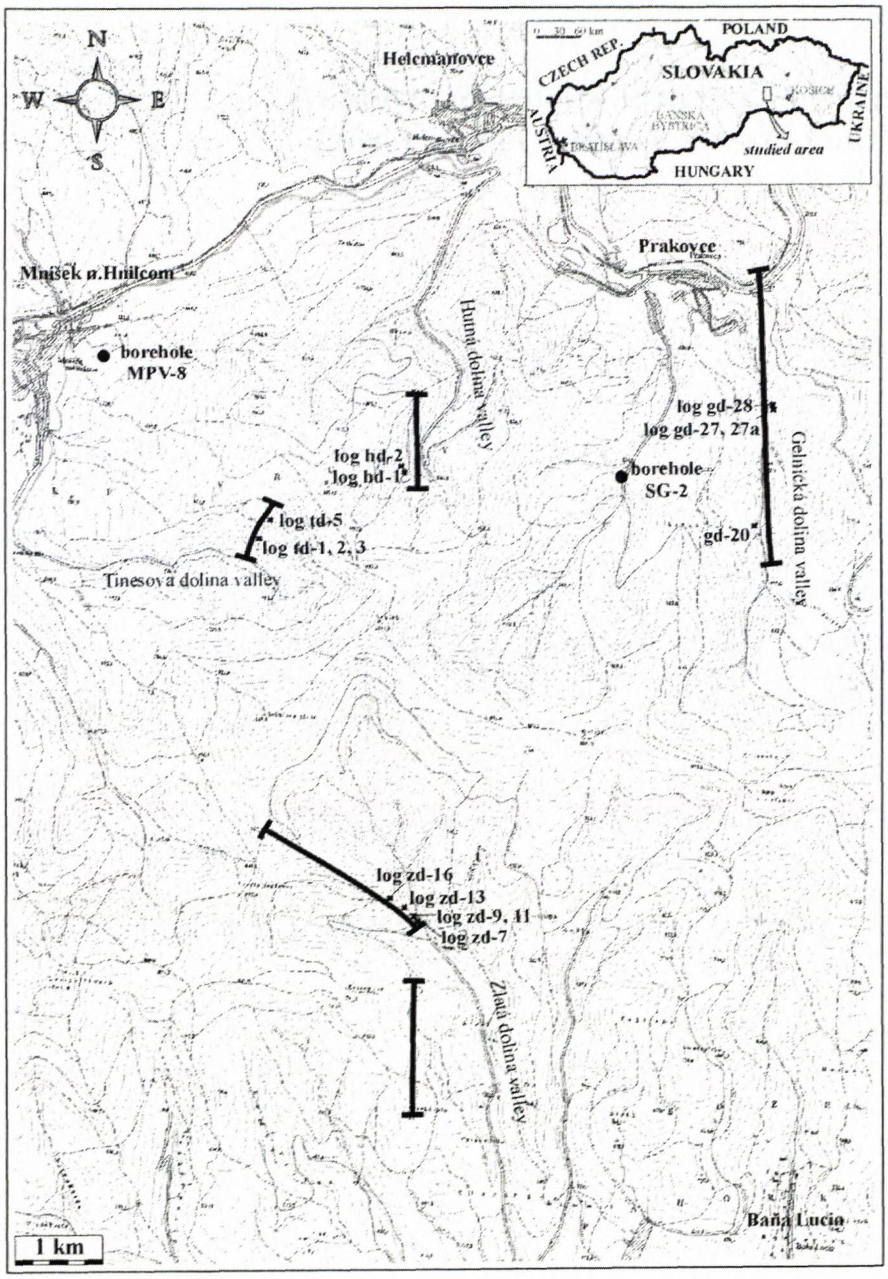


Fig. 1. Location of studied area, profiles, logs and drills

were distinguished by lithofacies and their characteristic associations, as well as vertical changes in bed thickness and grain size.

Sedimentological profiles (logs) from outcrops were supplemented by data from field mapping and geological maps (Kobulský et al., 2001) as well as older mining and drill works (e.g. Grecula et al., 1977; Kobulský et al., 1988) aiming to obtain the integrated profile through particular lithostratigraphic unit from its lowermost to uppermost parts.

Obtained data were elaborated in graphic form (logs from outcrops) and statistically (tables with principal statistic parameters, graphs of the trend of vertical changes of bed thickness from underlier to overlier – rhythmograms, where the thickness of the gravel-sand-silt fraction was plotted against the cumulative thickness of the total sediment, Fig. 10). Detail study of depositional conditions allowed to express lithostratigraphic conclusions and relative position of particular lithological units in vertical succession.

Geological setting and lithostratigraphy

The Lower Paleozoic Gelnica Group of Gemericum represents a volcano-sedimentary succession with regional metamorphic overprint in greenschists facies and deformation of at least in two orogenic cycles - Variscan and Alpine (e.g. Németh et al., 1997 and others). Paleozoic sedimentary successions were intruded by post-orogenic granite of Permian age (e.g. Kovách et al., 1986 and others).

Lithostratigraphic relations in Lower Paleozoic sequences of Gemericum were studied by numerous authors. Superposition of lithological units was and is evaluated by particular authors very differently, which causes also very differing lithostratigraphic division of this region (cf. Grecula, 1982; Ivanička et al., 1989b).

Ivanička et al. (1989b) supposes the Gelnica Group as a flysch formation 4500-8000 m thick with polygenetic and polycyclic development of mesorhythms. From its basal parts there were distinguished following formations: Vlachovo Formation (3 mesorhythms), Bystrý potok Formation (1 mesorhythm), Drnava Formation (2 mesorhythms). According to this interpretation the investigated area (Gelnica Group east of Smolnícky potok valley) has an anticline character with the Bystrý potok Fm. in its core and the northern as well as southern limb formed by Drnava Formation. The age of Bystrý potok Fm. was determined by microfossils as Upper Silurian. The Drnava Formation is Lower Devonian (Ivanička et al., 1989 a, b). The Vlachovo Fm., being present only in western part of Gelnica Group, is the oldest one. Its stratigraphic span was determined to Cambrium - Middle Silurian (Bajaník et al., 1984; Ivanička et al., 1989 b; Vozárová et al., 1998).

Recently in the eastern part of the Gelnica Group three sequences were distinguished (Seq 1, Seq 2, Seq 3, Kováčik, 2004, Figs. 2 and 3), but only the second one is completely preserved. Distinguished sequences are upward fining and thinning. Each sequence alone originated during one trangressive-regresive cycle (Vail et al., 1977; Haq, 1991). The sequence bases are built with volcanic horizon, upwards gradually passing to psammitic (sequence 2 – Seq 2, Figs. 2 and 3) or metapelitic horizons(sequence 1 – Seq 1). In the eastern part of Gelnica Group the sequence 1 is represented mainly by its upper lithological members belonging to the Bystrý potok Formation. They are built by dark-grey to black metapelites with small lenses of alodapic limestones and lydites, volcaniclastics are present less often. The substantial part of sequences 2 and 3 belongs to the Drnava Formation. The base of sequence 2 consists of acid metavolcaniclastics gradually passing to overlying psammitic horizon (so-called Kojšov metapsammites; Grecula, 1970), forming the

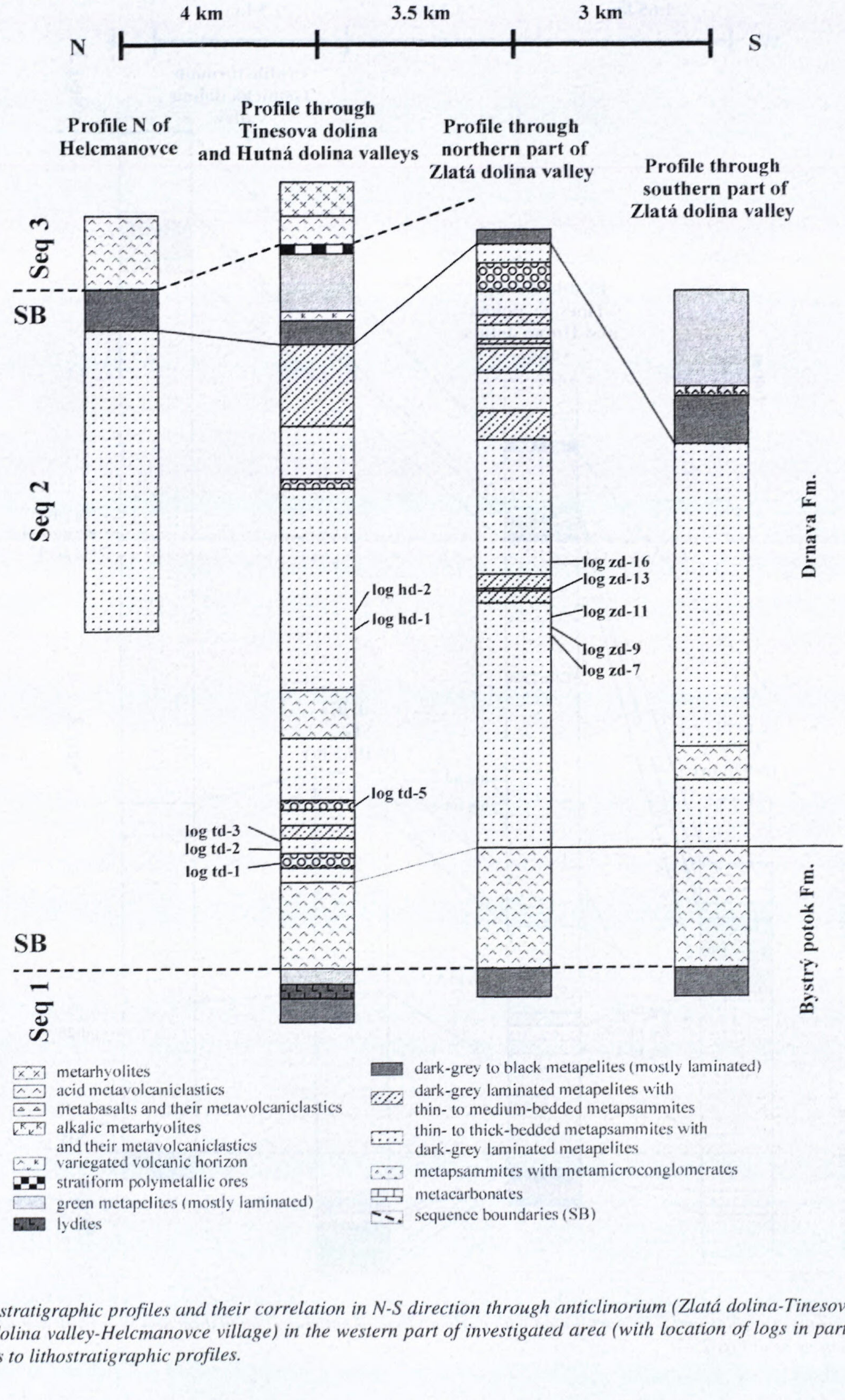


Fig. 2. Lithostratigraphic profiles and their correlation in N-S direction through anticlinorium (Zlatá dolina-Tinesova dolina valleys and Hutná dolina valley-Helcmanovce village) in the western part of investigated area (with location of logs in particular profiles). Explanations to lithostratigraphic profiles.

Slovak Geol. Mag., 11, 2 – 3 (2005), 165 – 183

prevailing part of basin-floor fan (Kováčik, 2003). This horizon gradually passes into dark, prevailingly laminated metapelites with lydite beds and sporadical metacarbonates (Smolník locality, e.g. Ilavský and Mrozek, 1960). This horizon has similar lithological content as upper part of the sequence 1 and represents the second phase of basin development with maximum value of sea level (Kováčik, 2004). Grecula (1982) assigned all Lower Paleozoic lydites and carbonates (from both sequences) of Gemericum into single Betliar Formation (Holec Beds), but our analysis did not confirm this opinion. In overlier of dark metapelites with lydites the horizon of green, pre-

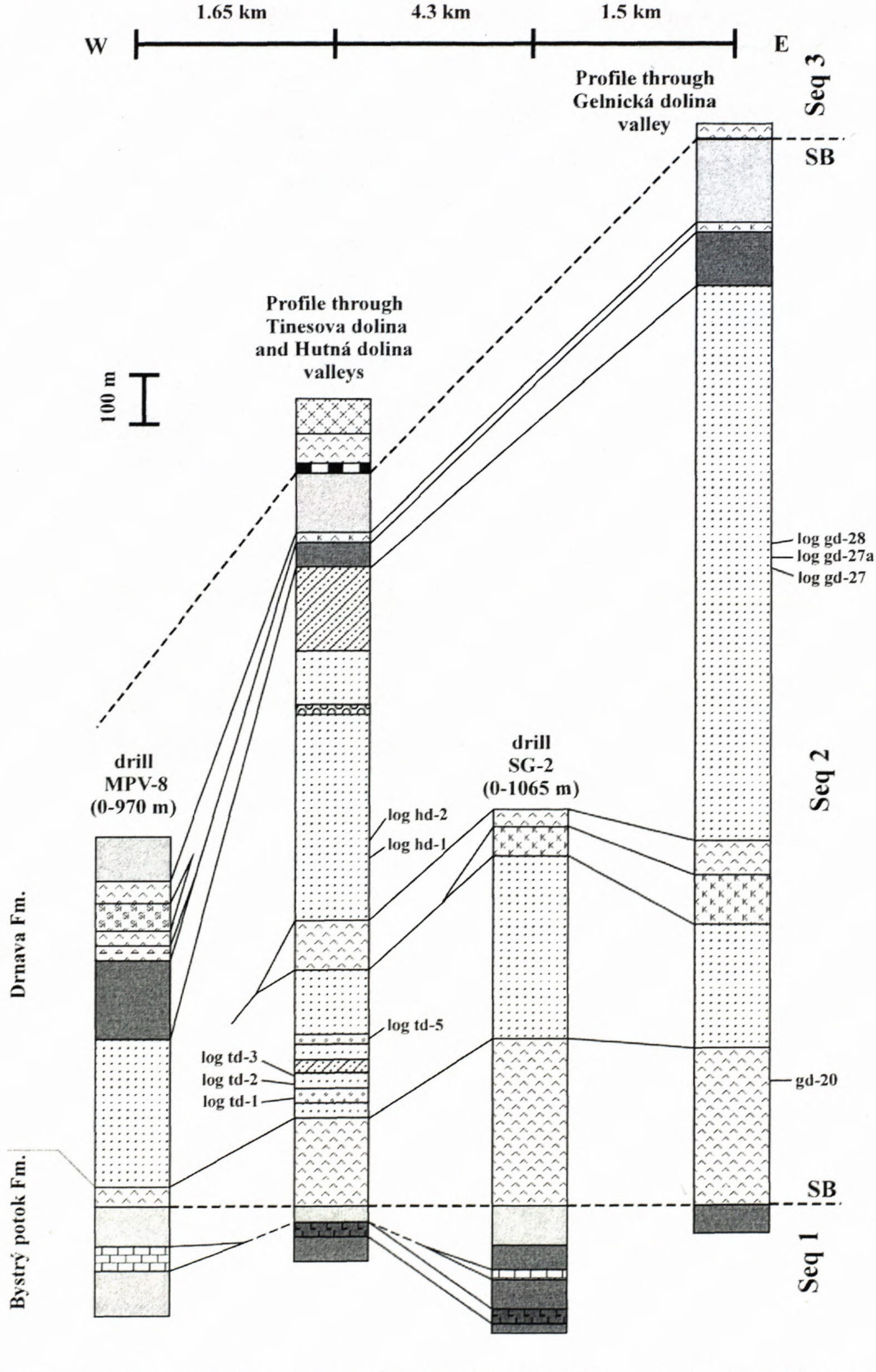


Fig. 3. Lithostratigraphic profiles and their correlation with northern limb of anticlinorium in direction W-E (with location of logs in profiles). Explanations as in Fig. 2.

vailingly laminated metapelites with small volcanite bodies in its lower part is developed (so-called lower variegated complex, Grecula, 1982). The horizon of green metapelites terminates the sequence 2 and in its overlier the main body of Gelnica Group volcanites is present. It is typically developed at Mníšek nad Hnilcom village and forms the base of sequence 3 (Figs. 2 and 3) and probably the highest part of lithostratigraphic succession of Gelnica Group.

Lithofacies – description and interpretation of depositional processes

The detail sedimentological analysis was focussed on metapsammite horizon (so-called Kojšov metapsammites, Grecula, 1970), forming the middle part of sequence 2 (Seq 2, Figs. 3 and 4). The lower part of the horizon is formed by metapsammites with pebbly psammite bodies, less of dark-grey laminated metapelites and volcaniclastics. In the upper part of horizon the metapelites gradually appear, and in the uppermost parts they prevail among further lithofacies. We have distinguished 11 lithofacies of siliciclastic sediments (Kováčik, 2004). Individual lithofacies are designated with codes with accompanied description and interpretation of depositional processes. Volcaniclastics and carbonates were not subjected to detail sedimentological investigation, but because they are the integral and important constituent of Gelnica Group, they will become a subject of the next evaluation.

Lithofacies Cs - stratified pebbly metapsammites

The lithofacies Cs was found in the Tinesova dolina valley (Fig. 5, log td-1, bed No. 66; Fig. 6, log td-5). Beds with stratified pebbly metapsammites are developed in medium to high thickness with typical parallel stratification (S_1 and S_2 interval, Lowe, 1982). Lithofacies Cs is characteristic with alternation of fine- and coarse-grained tabular layers in the frame of one bed (Fig. 4H). Finer-grained layers are formed with fine- to coarse-grained metapsammite, coarser-grained layers with very coarse-grained metapsammite to pebbly psammite. The thickness of individual layers varies between 5 to 25 cm. Their contacts are sharp or transitional, sometimes with inverse grading at the base of coarse-grained body. More coarse-grained intervals are matrix supported and the rafted clasts of dimensions 1-5 mm consist prevailingly from the fragments of quartz, quartzy rocks or dark metapelites. Quartzy-sericitic matrix has granularity 0.02-0.2 mm.

The lithofacies Cs correspond to lithofacies A2.5 according to Pickering et al. (1986) or lithofacies F4 according to Mutti (1992) and originates by deposition from concentrated density (gravity) flows. The particles in the flow are maintained by the grain-to-grain interactions making the dispersive pressure; the turbulence is suppressed (Mulder and Alexander, 2001). The individual coarser inverse graded units represent the traction carpets (sensu Dżułyński & Sanders, 1962; S_2 interval, sensu Lowe, 1982), originating from moving body of coarser-grained material in lower part of the flow.

Deposition of traction carpets can occur by continuous aggradation beneath a sustained steady or quasi-steady current, while the upper part of the current is supplying the sedimentary material (Lowe, 1982; Kneller & Branney, 1995). Traction carpets can reflect cyclically changing hydrodynamic conditions in unstable gravity flows (Hiscott, 1994) or changeable contribution and differing transport velocities of various granularity fractions in the current (Hand, 1997).

Lithofacies Cg - normally graded pebbly metapsammites

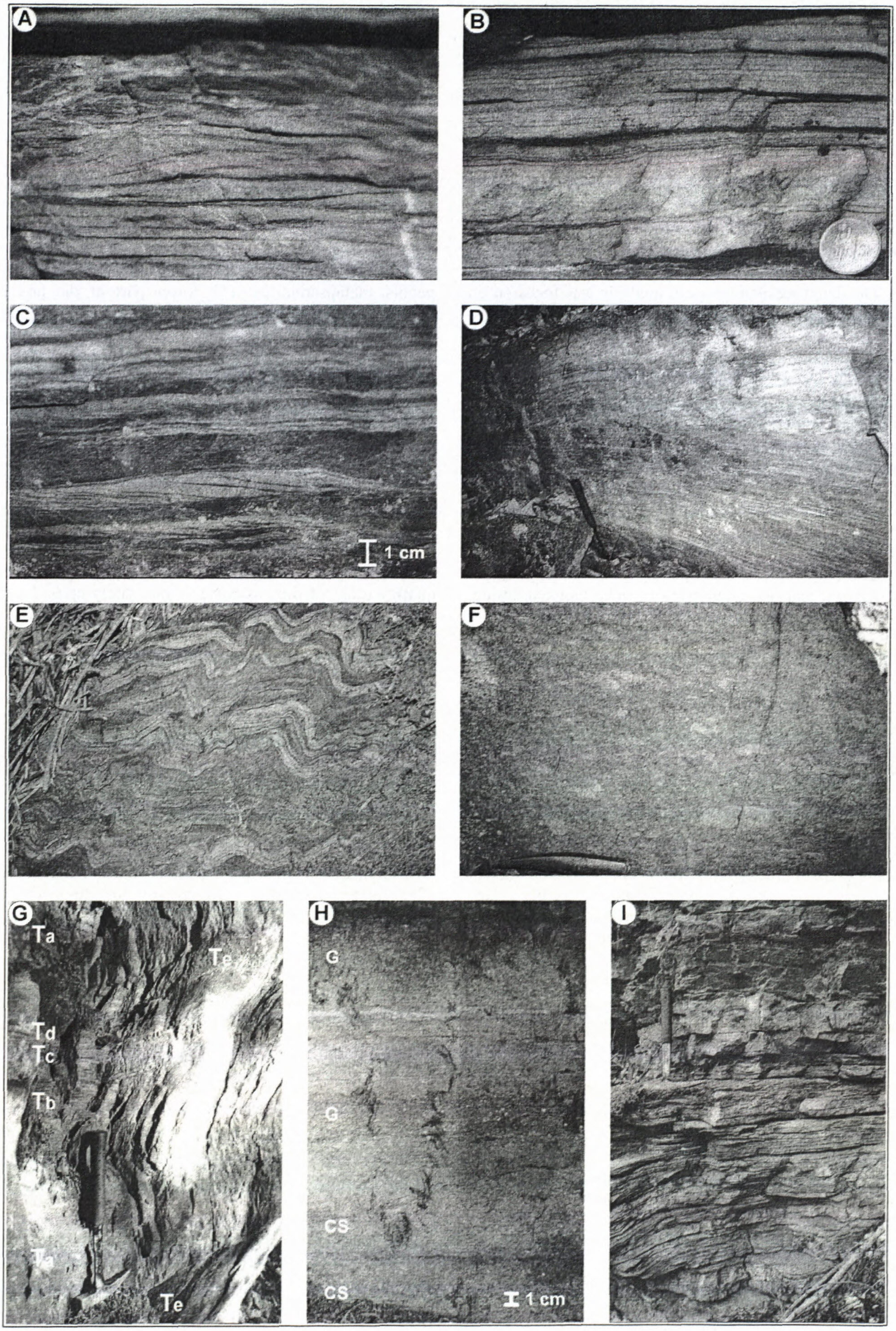
Lithofacies Cs is represented by normally graded pebbly metapsammites. The lower part of the bed is formed by massive pebbly psammite upward grading into the medium- to fine-grained metapsammite with preserved Bouma intervals (prevailingly T_a, T_b). Grading is manifested by gradual decrease of very coarse grains of psammite (1-2 mm) and granules (2-4 mm) in finer-grained matrix upwards (coarse-tail grading). Lithofacies Cg is developed together with lithofacies Cs in the Tinesova dolina valley (Fig. 5, log td-1; Fig. 6, log td-5). Beds thickness is usually more than 50 cm. Bases are sharp, flat, sometimes with preserved erosion structures. Similarly as at lithofacies Cs the pebbly psammites are matrix supported. Granularity has polymodal character. Very pourly sorted grains prevailingly of quartz or quartzy rocks of dimensions 1-4 mm, rarely up to 1 cm, are disseminated in fine-grained matrix. Matrix consists prevailingly from quartz (> 80 %), sericite, chlorite, sporadically there occur biotite, feldspar (prevalence of plagioclase), eventually carbonate. Lithofacies Cg originates by fast deposition from concentrated gravity flow in its lower part. In the upper less dense part it was formed from turbulent suspension, without more important traction transport of bed-load. Lithofacies Cs and Cg are typical mostly for channel sediments.

Lithofacies Pm - massive metapsammites

Lithofacies Pm (facies B1.1, sensu Pickering et al., 1986) is represented prevailingly by fine to medium-grained metapsammites with medium to very high thickness (e.g. Fig. 9, log gd-28). They are usually without sedimentary structures, with indications of undistinct gradation in the uppermost part of the beds. Lower as well as upper bedding planes are usually sharp, sometimes with preserved erosion structures at the base of the beds. Beds are usually amalmagated. Their former massive character, without any significant fabric, is often obscured by dense metamorphic schistosity. Granularity has polymodal character, though a part of finest fraction (0.01-0.05 mm) has a character of pseudomatrix. Its secondary enrichment in all lithofacies was found by post-sedimentary processes (diagenesis, metamorphism, deformation; Vozárová, 1993).

Lithofacies Pm originated probable by deposition of long-lasting quasi-steady concentrated density (Mulder & Alexander, 2001) or turbidity current (Kneller & Branney, 1995), in some cases from rapidly decelerating gravity flow (Lowe, 1982).

Slovak Geol. Mag., 11, 2 – 3 (2005), 165 – 183



Lithofacies Ps - cross-stratified metapsammites

Lithofacies Ps (lithofacies B2.2, sensu Pickering et al., 1986) represents cross-stratified metapsammites (Figs. 4D and 8, log hd-2, beds No. 65 to 74). They are fine to coarse-grained, bedding planes are moderately undulated or flat, sharply bordered, without grading. Beds are thick 15-70 cm, but their thickness can be laterally changed. Characteristic feature of internal setting of metapsammite is its planar or trough cross-lamination formed by migration of bedforms (e.g. dunes) or by reworking of deposited psammite by overriding concentrated density or turbidity flow, eventually by strong ocean bottom (contour) current (e.g. Pickering et al., 1986).

Sporadic climbing ripples indicate the high amount of sediment falling out from suspension in comparison to intensity of bed-load transport (Allen, 1982). At high angles of climbing the lamination has undulating character and originates as transitional form between horizontal lamination of upper flow regime and a ripple phase of lower flow regime.

Lithofacies Ph - thick- to very thick-bedded sand-mud couplets

The relatively well developed grading mainly in upper part of beds as well as sharp erosion bases are characteristic for this lithofacies. Beds are laterally unchangeable and can be correlable for distance of several hundreds to thousands metres. The monothonous alternation of psammitic and pelitic intervals in the frame of vertical succession is typical together with the relatively well preserved inner sedimentary structures of metapsammites being defined by Bouma (1962): T_a - massive (without structure) or graded fine to medium-grained metapsammite, T_b - horizontally laminated fine- to medium-grained metapsammite, T_c - obliquely laminated fine-grained metapsammite, locally bearing marks of convolution (strongly tectonically modified), T_d - very fine-grained metapsammite to metasiltstone with horizontal lamination (this interval is hardly recognizable in tectonized and weathered outcrops), T_e - dark grey to black metapelite, massive or with undistinct very fine lamination.

The Bouma sequence is a good base for hydrodynamic interpretation of deposition from turbidity flows, in which the upward component of fluid turbulence is a dominant supporting mechanism for particles carried by flow (e.g. Walker, 1965; Middleton & Hampton, 1976; Mulder & Alexander, 2001). The deposition of entire Bouma sequence progresses in three phases. First phase consists of a quick deposition of grains from suspension, during which the continuing friction of deposited grains by flow together with escaping water from intergranular spaces cause, that lowermost unit T_a is massive, eventually contains water escape structures. The second deposition phase is characteristic with traction of grains on ground, during which T_b originates in upper flow regime. Continuing decreasing of flow velocity causes the origin of ripples and their migration forms the ripple cross-bedding. In the case of strong addition of material the T_c has a character of climbing ripples. The last, third deposition phase is represented by intervals T_d and T_e originating by slow accummulation of finest suspended particles from the tail of the flow.

In the lithofacies Ph the T_a and T_b Bouma intervals are prevailing, quickly grading to T_c, T_d or T_e. These intervals are obscured by younger tectonic structures, which causes their difficult distinguishing. Together with lithofacies Pt and Fcl the lithofacies Ph forms the main part of deep-water deposition system of Gelnica Group in the middle part of sequence 2.

Lithofacies Pt – very thin to medium-bedded psammitic-pelitic beds

In comparison with lithofacies Ph they are thinner (1-10 cm), prevailingly fine-grained and with more distinctive gradation. They are formed with T_b, T_c, T_d and T_e Bouma intervals. They represent the more distal lithofacies and form a constituent part of less energetic environments (lobe fringes, levees, inter-channel sheets, basin plains), in minor amount they can occur also in other deep-water environments.

Lithofacies Fcl – dark-grey laminated metapelites

This lithofacies is formed by positive graded laminae of medium-grained metasiltstone to very fine-grained metapsammite having a character of ripple or regular laminae with cross- or horizontal internal lamination (T_0 interval, Stow & Shanmugam, 1980), or it is formed by regular laterally continuous or indistinct, very thin laminae of metasiltstone (T_3, T_4 interval, Stow & Shanmugam, 1980) alternating with lithofacies Fcm. Rarely the metasiltstone laminae are irregular and have a charac-

Fig. 4. Some lithofacies from documented logs. A) Lithofacies Pt, T_{bcde} turbidite thick 2.3 cm, log zd-13 (bed No. 14), Zlatá dolina valley. B) Lithofacies Pt, T_{bde} turbidite, log zd-16 (bed No. 3), Zlatá dolina valley (scale: coin with 2 cm diameter). C) Lithofacies Fcl, with preserved oblique ripple and horizontal lamination of metasiltstones, log td-3, beds Nos. 56-60, Tinesova dolina valley. D) Dark-grey laminated phyllites in lower part of outcrop - lithofacies Fcl, oblique laminated fine-grained metapsammites in overlier of phyllites - lithofacies Ps, log hd-2 (9.5-10.5 m), Hutná dolina valley. E) Disharmonically folded lamina and very thin beds of light-grey very fine-grained metapsammites and metasiltstones alternating with dark-grey metapelites, log gd-29a (0.5-0.8 m), Gelnická dolina valley. F) The base of bed of acid volcanoclastics – debris flows (lithofacies Vm), with preferred orientation of longer axes of clasts into the direction E-W, locality gd-20, Gelnická dolina valley. G) Completely preserved succession of Bouma intervals T_a – T_e, lithofacies Ph, log td-3 (bed No. 38), Tinesova dolina valley (scale: 30 cm hammer). H) Stratified microconglomerate (lithofacies Cs), in the scale of 1 bed the bodies of medium to coarse-grained psammites (CS) and pebbly psammite (G) are vertically alternating being deposited parallely to bed planes, log td-1 (Fig. 5, upper part of the bed No. 66), Tinesova dolina valley. I) Laminated thin to medium-thick fine-grained metapsammites (lithofacies Pt) with subsidiary intercalations of dark-grey laminated phyllites (lithofacies Fcl), lower part of the log zd-16, Zlatá dolina valley (scale: 30 cm hammer).

Log td-1

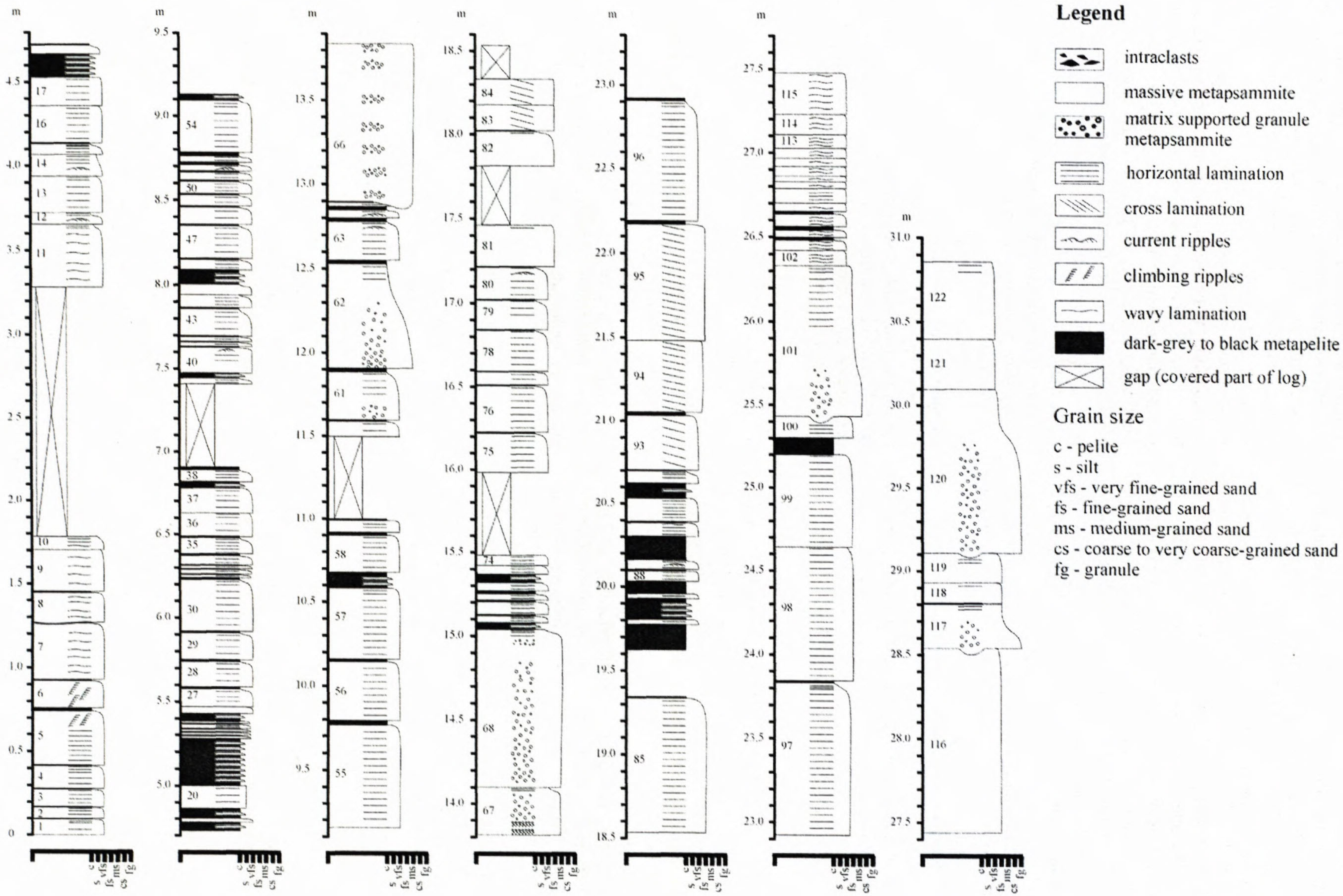


Fig. 5 Log td-1, Tinesova dolina valley. Explanations to logs.

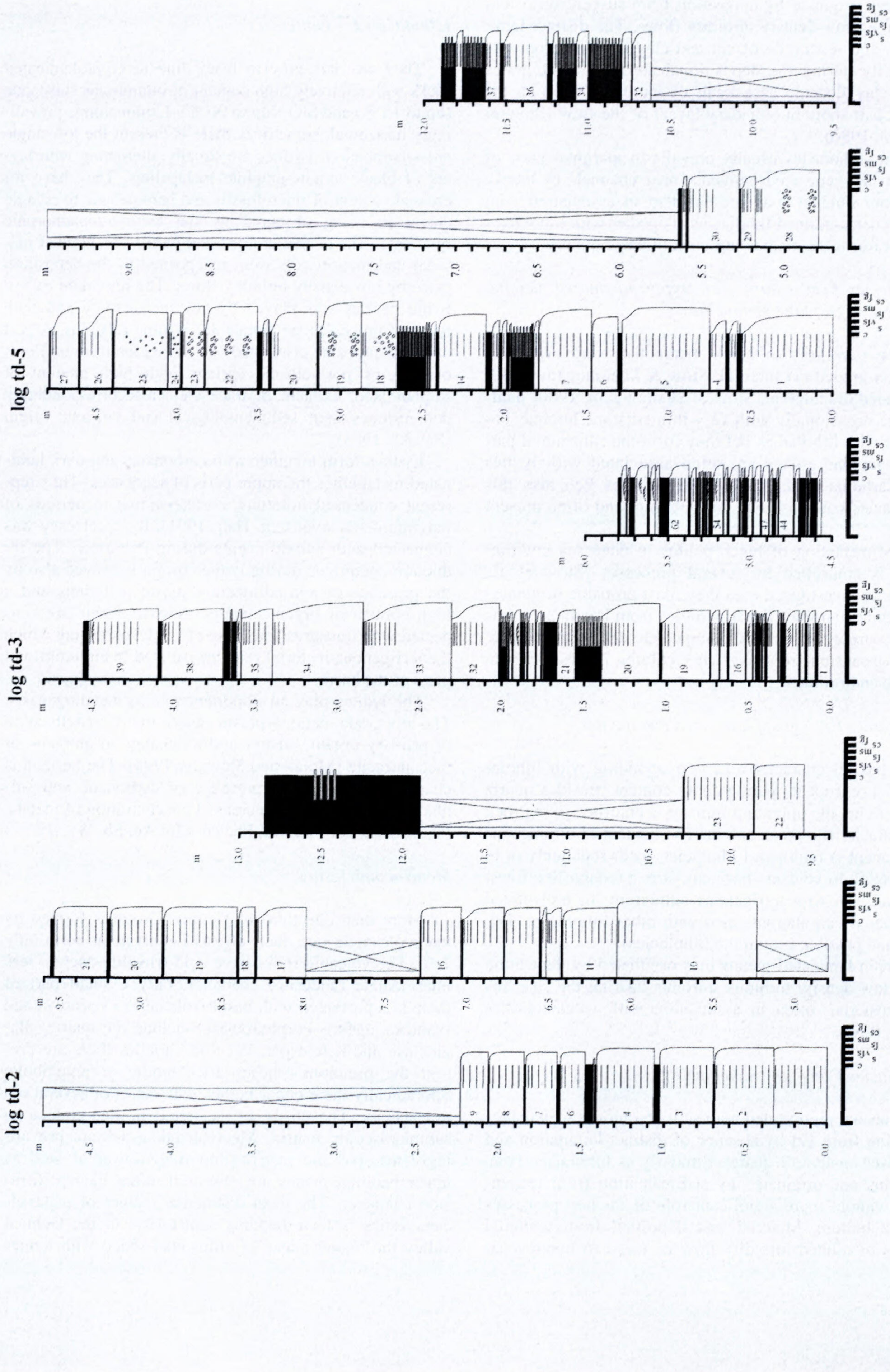


Fig. 6 Logs td-2, td-3 and td-5, Tinesova dolina valley. Explanations to logs are in Fig. 5.

Slovak Geol. Mag., 11, 2 – 3 (2005), 165 – 183

ter of thin lenses. They contain abundant bitumen fraction and synsedimentary pyrite, which proves the reduction, anoxic conditions during deposition and diagenesis.

They originate by deposition from suspension of decelerating low-density turbidity flows. The distinct lamination and separation of silt and clay laminae originates primarily during the depositional sorting of silt grains from clay floccule as a result of increased shear in the lower part (bottom boundary layer) of the flow (Stow & Bowen, 1980).

This lithofacies usually prevails in marginal parts of higher energetic environments (near channels or lobes), in minor amount it is present also in association with more coarse-grained lithofacies. Together with lithofacies Fcm it forms the main component of basin plain.

Lithofacies Fcm – dark-grey cryptic laminated metapelites, black graphitic metapelites

The dark-grey to black metapelite were originally the non-graded (T_7 interval, Stow & Shanmugam, 1980) or graded (T_6 interval, Stow & Shanmugam, 1980) mudstones, occasionally with very thin siltstone lamina. Together with lithofacies Fcl they form the substantial part of basin plain. They are often associated with lydites and carbonates. Similarly as lithofacies Fcl, also this lithofacies contains abundant graphite and often present pyrite.

Sedimentation of black pelites in deep sea environment is controlled by several processes (Stow et al., 2001). In investigated area they most probable originated by sedimentation of finest particles from low-density turbidity current or by slow hemipelagic deposition of passive suspension from overlying column of sea water in anoxic environment.

Lithofacies Fzl – green laminated metapelites

It has all characteristics corresponding with lithofacies Fcl, except its petrographic content. Besides quartz and sericite, the important mineral is chlorite, giving rock its characteristic green colour. The content of bitumenous component is minimal. Lithofacies occur separately or in connection to volcanic horizons. It is a redeposited finest volcanic ash with terrigenous admixture. In transitional horizons it can alternate also with other lithofacies (Fcl, Fcm and possible psammitic lithofacies).

Green laminated metapelites originated by deposition from low density turbidity currents bearing the fine tuffitic material, often in association with volcaniclastics debris flows.

Lithofacies Fzm – green metapelites

They are represented with sericite-chlorite metapelites differing from Fzl by absence of distinct lamination and by lower content of quartz. Similarly as lithofacies Fcm, also this one originated by sedimentation from suspension, without more significant role of traction processes on the bottom. Material was deposited from scattered clouds of diluted turbidity flow or meso to hypopycnal flows transporting volcanic ash from the continental margin. Lithofacies is in tight association with lithofacies Fzl and Vm.

Lithofacies L – lydites

They are dark-grey to black fine to cryptolaminated rocks with relatively high content of bituminous substance (up to 15 %) and SiO_2 (up to 90 %). Lamination is prevailingly horizontal, sometimes there is present the low-angle cross-lamination. Lydites are usually alternating with layers of black sericite-graphite metapelites. They have increased content of microfossils and hemipelagic to pelagic character, being obscured by the tectono-metamorphic processes. The coarse-grained and partly fine-grained material and microfossils were redeposited to the deposition place by low density turbidity flows. The important role in lydite genesis was played by volcanic activity and both types of processes are frequently in time relations. A part of quartz probable originated by coagulation from outflows of syn- or postvolcanic springs with high amount of sulphur acid. Content of trace elements correspondingly demonstrates their sedimentological and volcanic origin (Ilavský, 1985).

Lydites form together with carbonates and dark laminated metapelites the upper parts of sequences. They represent condensed horizons, corresponding to periods of maximum sea-level (e.g. Haq, 1991). Its occurrence was connected with anoxic events during Paleozoic. The reduction conditions during lydites origin is proved also by the presence of synsedimentary pyrite in lydites and a high content of organic matter. Anoxic events are connected with transgressions, rise of sea level, during which the terrigenous material remains isolated in circumlittoral parts of the basin.

The lydites play an important role in metallogenesis. The low grade metamorphism caused the recrystallization of primary organic matter and its change to antracite or metaantracite (Molák and Slavkay, 1994). The horizon is characteristic with the presence of carbonatic and sulphidic deposits having increased concentration of metals: Fe, Mn, Ti, V, P, Ni, Co, Pb, Zn, Mo, Ag, Sb, W.

Metavolcaniclastics

More than one third of Gelnica Group is formed by metavolcaniclastics, their effusive equivalents form only 1 %. The volcanic rocks have acid (rhyolite-dacite), less intermediate (andesite) character, only a small part of them is represented with basalt volcanites (Vozárová and Ivanička, 1996). Porphyroclasts include the quartz, plagioclase and K-feldspar, in basic varieties there are present the pseudomorphoses after biotite or amphibole. Sporadically there occur bodies with clasts of several cm dimensions. The clasts are scattered in fine-grained to submicroscopic matrix. Metavolcaniclastics are prevailingly massive and matrix-supported. Lower as well as upper bedding planes are obscured, often having diffusion character. The most distinctive feature of metavolcaniclastics is their bedding schistosity. In the Gelnica valley the bigger clasts of ellipsoidal shape with longer

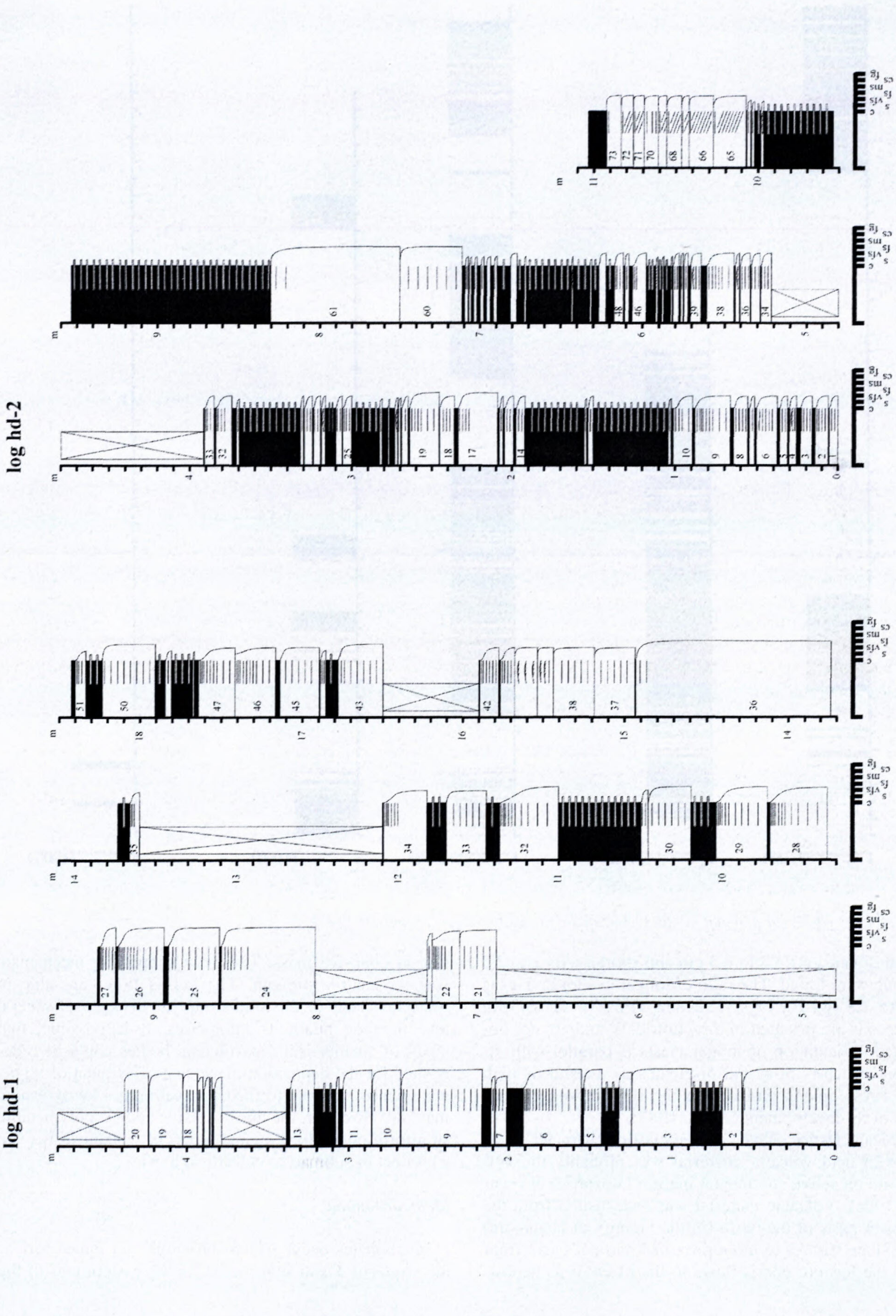


Fig. 7 Logs hd-1 and hd-2, Hutná dolina valley. Explanations to logs are in Fig. 5.

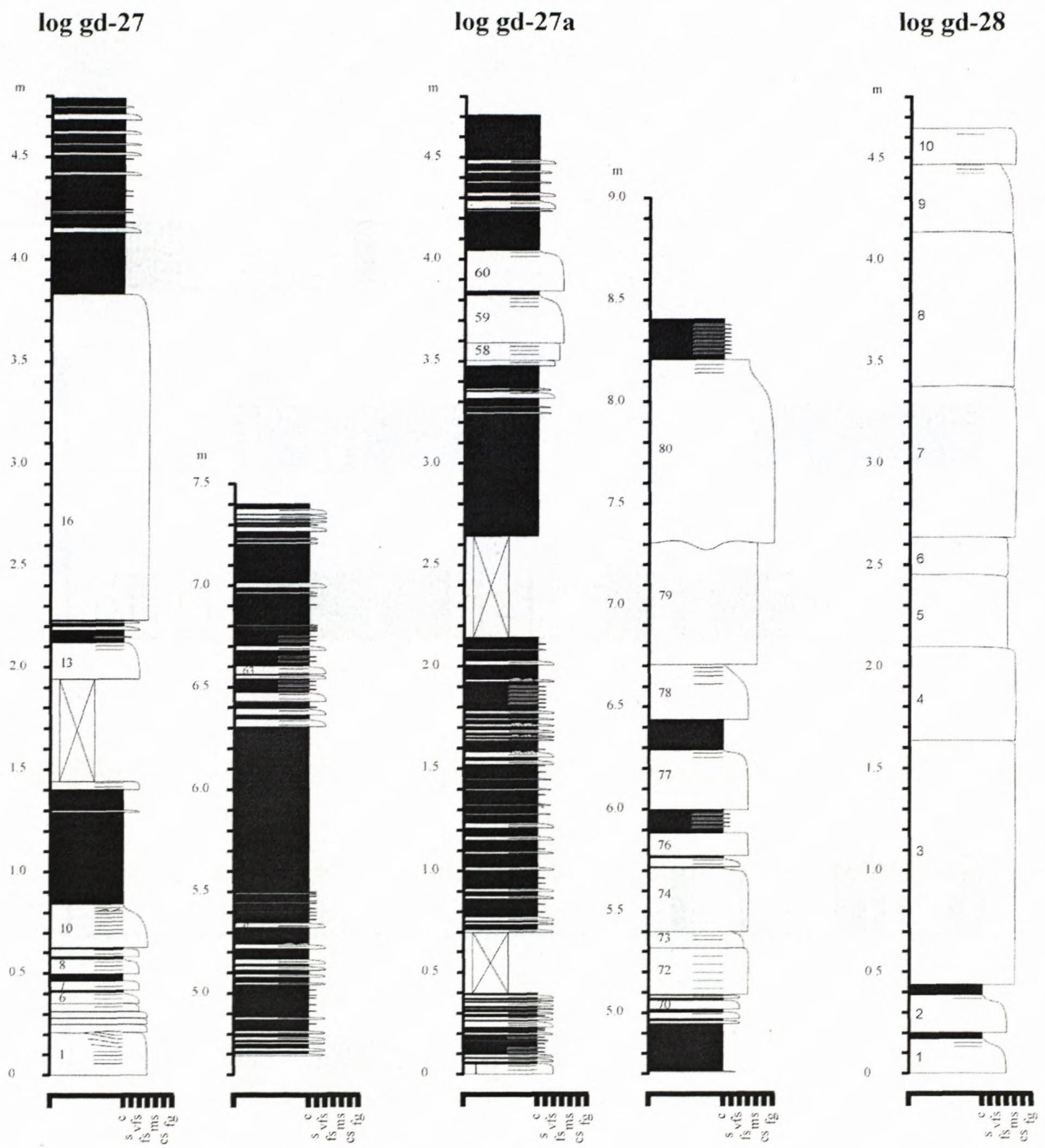


Fig. 8 Logs gd-27, gd-27a and gd-28, Gelnická dolina. Explanations to logs are in Fig. 5.

axis of dimensions 3.8 to 8.5 cm and shorter axis 1 to 2.5 cm long were found. The ratio of longer to shorter axes is 2.52 to 3.8 (gd-20, Figs. 1, 3 and 4F). The clasts with longer axis are oriented in direction E-W and are not imbricated. Orientation of longer clasts is parallel with direction of debris flow and originates as a result of high shear stress among particles in the flow during the last phase of its development (Allen, 1982).

Volcaniclastics have an epiclastic character. The source of acid volcanic material was probably the volcanic arc on active continental margin (Vozárová & Ivanička, 1996). Volcanic material was redeposited from the shallower parts of the basin (in the vicinity of island arc) to the slope base or to more proximal parts of basin-floor fan in the form of debris flows to the place of its deposition as cohesive mass. The main supporting mechanism was the matrix strength. The debris flows are able to transport clasts or olistoliths into the distance of several tens or even hundreds kilometres. It is possible, that a part of smaller isolated volcanic bodies could be redeposited for the deposition place as a constituent of vigorous debris flows formed prevailingly by volcanic material. However, the thick effusive bodies, polymetallic stratiform mineralization and a part of volcaniclastics are a product of submarine volcanism in situ.

Metacarbonates

Carbonates occur in two horizons - in upper part of the sequence 1 and sequence 2. In the eastern part of the

Gelnica Group directly in studied profiles this lithofacies superficially outcrops in the area of village Baňa Lucia, where the dark-grey fine-grained crystalline limestone was found together with lydites and black metapelites (Kováčik, 2004). They together form a condensed interval of the sequence 2 belonging to Lower Devonian Drnava Formation. Into this interval also carbonates from Smolník stratiform polymetallic deposit belong, being constrained on horizon of lava flow of paleodolerites to paleoandesites, chloritic metapelites and polymetallic ore with intercalations of graphitic and sericitic metapelites (Ilavský & Mrozek, 1960).

In eastern part of the Gelnica Group the carbonates are known from the surrounding of the Holec elevation point north of Smolnícka Huta, locally between Holec and Jedľovec elevation points and at Zlatá Idka village (Kobulský et al., 2001). They were penetrated by drills MPV-8 (Kobulský et al., 1988) and SG-2 (Grecula et al., 1977). This horizon is older (Upper Silurian, Bajaník et al. 1984) and allocated is in upper part of sequence 1.

The carbonates by their chemical composition correspond to limestone, dolomite, magnesite, ankerite and siderite. Their former composition (limestone, dolomite), sedimentary textures and structures are distinctly obscured by diagenetic-metamorphic and hydrothermal-metasomatic processes. Most often they are massive, crystalline or horizontally laminated, sporadically with cross-lamination. Carbonates in the eastern part of the Gelnica Group are alodapic (Vozárová & Ivanička, 1993). The sporadically preserved gradation and traction structures (Bouma intervals) indicate the resedimentation probable by turbidity currents.

In western part of the Gelnica Group the carbonatic bodies are more abundat. They are known from numerous places on the surface as well as from the drills in the surrounding of villages Vlachovo, Gočovo, Nižná Slaná, Dlhá dolina valley, Henclová village and another places. According to some authors they are of shallow-water origin (Grecula, 1982; Varga, 1970). It is proved neither sedimentological nor paleontological, though in distinctly laminated ankerite from Nižná Slaná Mišík found (in Turan & Turanová, 1993) the ostracode and stromatolite fragments, which can indicate the shallow water environment. These fossils were not more precisely systematically classified and there is also possible, that the fragments were resedimented.

Depositional environments

In recent studies of deep-water sedimentary systems the architectural element analysis is preferred (e.g. Clark & Pickering, 1996). It better indicates the spatial relations and variations in composition as well as geometry in individual depositional environments. The concept of "elements" in turbidite systems was established by Mutti & Normark (1987), correspondingly for recent as well as ancient settings.

The outcrop dimensions as well as complicated geological setting in our case do not allow the geometrical analysis of individual architectural elements and the direct observation of relations among them. This is the reason why we have determined individual elements by facies associations with characteristic vertical trend of change of bed thickness and granularity. We have applied the traditional vertical analysis on profiles. Asymmetric cycles in deep-water environments were supposed as one of key criteria for identification of individual subenvironments in submarine fan systems (e.g. Ricci-Lucchi, 1975), but statistic importance of these cycles was later disputed (Chen & Hiscott, 1999). Despite, we use in this study also the vertical variations of beds thickness visualized in rhythmograms (Fig. 10), because some vertical bed successions have evident asymmetric trend (e.g. rhythmogram of the log zd-13, Fig. 10) and the bed thickness is one of few values measured directly in the field. As a "bed" there is supposed the lower, coarse-grained (sandstone, sandstone-siltstone) part of deposit, originating from deposition of one density flow (e.g Lowe intervals S_1 to S_3, Bouma intervals T_a to T_d, besides the upper mudstone interval T_e).

Locality Tinesova dolina valley

Studied outcroups (logs td-1, td-2, td-3, td-5; Figs. 5 and 6) are located in termination of Tinesova dolina valley approximately 3 km to SE of the village Mníšek nad Hnilcom (Fig. 1). They are formed by prevailingly fine- to medium-grained metapsammites with intercalations of dark-grey laminated metapelites and pebbly metapsammites or coarse-grained metapsammites. They belong to lower part of the sequence 2 (Figs. 2 and 3). Metapsammites are relatively steeply dipping with inclination of bedding, resp. bedding schistosity to north in normal position. They are developed between two partial horizons of acid pyroclastics forming together the lower part of the sequence 2 in overlier of the sequence 1, which is demonstrated also by drill SG-2 (Fig. 3).

In this sedimentary succession the sandy horizons with prevalence of lithofacies Ph, Pm, Ps, Cg and Cs are alternating with horizons formed prevailingly by lithofacies Pt and Fcl (Figs. 5 and 6) being richer on pelitic (pre-metamorphic mud) component. Lithofacies Cg and Cs (Fig. 4H) represent together with volcaniclastics the coarsest-grained sediments of the Gelnica Group. They form elongated bodies of uncertain, probable lenslike shape with high length ratio (usually some tens m, maximum 200-300 m) in comparison with thickness (5-10 m). They are deposited correspondingly with surrounding finer-grained lithofacies, having frequent erosive contacts. They form probable the thalwegs of depositional distributary channels (Fig. 5 - log td-1: 11.6–15 m, 25.5 –31 m; Fig. 6 - log td-5: 2.6–5.2 m), in which the deposition from denser, concentrated gravity currents is prevailing (lithofacies Cg, Cs, Pm, Ph). The channel density flows are often stratified (for example the lithofacies Cs originated by their deposition), they are usually thick and towards both sides of the channel form wide overbank bodies. Bodies of coarse-grained facies associations are vertically stacked in sedimentary succession and probable originated by aggradation of sinuous submarine channels (Peakall et al., 2000). Thinning and fining of beds of channel fill indicate the gradual diminishing of currents,

Slovak Geol. Mag., 11, 2 – 3 (2005), 165 – 183

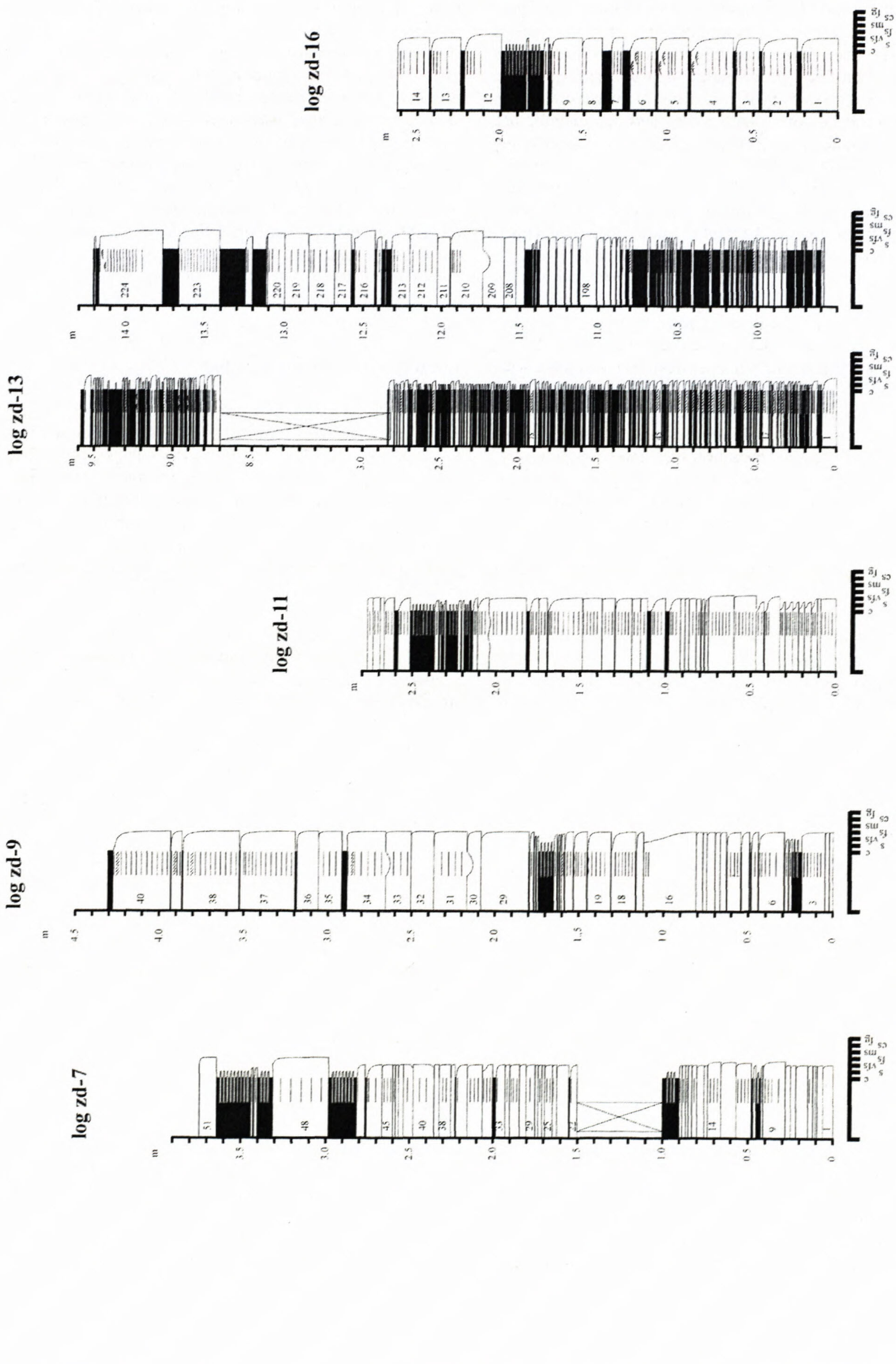


Fig. 9 Logs zd-7, zd-9, zd-11, zd-13 and zd-16, Zlatá dolina valley. Explanations to logs are in Fig. 5.

which backward infilled the channels. This trend is commonly supposed as typical for channel fills (Mutti & Ricci-Lucchi, 1972; Stow & Piper, 1984 and others). In some cases, when the lower part of channels is infilled with fine-grained thin beds from tails of flows and channels are consequently backward infilled with coarser beds, the channel infill has the upward thickening trend. This trend is usually observed in fine-grained sandstone deep-water systems, mainly in lower part of the slope, where the steeper gradient supports the bypass of the sediment into the basin (Gardner & Borer, 2000; M. Grecula et al., 2003). In the area of Tinesova dolina valley the fill & spill phases of the channels prevail as well as the high sand/mud ratio, which is typical rather for basin than for slope parts of deep-water depositional system. The phase of infilling of the channels originates due to base-level rise and lowering of the bottom gradient (Clark & Pickering, 1996).

The channel elements are in the space alternating with finer-grained and thinner levee facies (Fig. 6, log td-3). The shallow distributary channels caused, that density flows were not fully confined by the channel margins and so the coarse-grained lithofacies are present in levees and towards the inter-channel space they become finer-grained. The beds are laterally continual and have character of turbidites with well preserved Bouma intervals and positive grading. In the proximal parts of levees the cross- and wavy-laminated fine- to medium-grained metapsammites of the lithofacies Ps are often. Towards the distal parts the lithofacies Pt, Fcl and Fcm are gradually prevailing.

Distributary channels, levees and inter-channel sheets are a constituent of the middle part of submarine fan.

Localities Hutná dolina and Gelnická dolina valleys

Studied outcrops are located in the termination of Hutná dolina valley, approximately 1 km to east of the elevation point Hutná hoľa (1093.7 a.s.l.) and in Gelnická dolina valley south of Prakovce town (Fig. 1). They are formed prevailingly by fine to medium-grained metapsammites with bodies of dark-grey laminated metapelites. They are located in horizon belonging to middle part of the sequence 2 (Figs. 2 and 3). Metapsammites are, similarly as in the Tinesova dolina valley, in normal position and relatively steeply dipping to north. From the underlier they are gradually developed from basal volcaniclastics of the sequence 2 and towards overlier they are gradually exchanged by lithofacies of dark-grey laminated and crypto-laminated metapelites with intercalations of lydites. Contrary to lithofacies from the Tinesova dolina valley, their position in the bed succession is relatively higher (they are younger) and their lithofacies content is less variegated.

The bed succession (Fig. 7: logs hd-1 and hd-2; Fig. 8: logs gd-27, gd-27a and gd-28) has relatively monothonous lithofacies content with prevalence of metapsammites above metapelites. The metapsammites abundance ranges from 50 % up nearly to 100 % (Tab. 1). The conglomeratic lithofacies (Cs, Cg) are very rare (Figs. 2 and 3, upper part of the profile through Tinesova dolina and Hutná dolina valleys). The beds thickness is prevailingly several cm to 40 cm, maximum thickeness is 160 cm. The lithofacies Pt, Ph and Fcl are dominating, the lithofacies Pm and Ps are less often. Beds are parallel and have uniform thickness in lateral direction. The lower bed planes are sharp and flat, rarely with shallow erosion forms, while the upper bed planes are graded. Lithofacies have character prevailingly of T_{b-e} or T_{bde} turbidites, in thin-bedded turbidites the T_c interval is also present. Massive T_a interval is developed in lower parts of medium to thick-bedded lithofacies Ph and Pm. The upper cross lamination of metapsammites is in several cases dipping to NW (Fig. 4D and Fig. 7: log hd-2, beds 65 to 72), which indicates the direction of paleocurrent from SE to NW, corresponding with older data (Snopko, 1967; Snopko & Ivanička, 1979). Despite, cross-lamination and current ripples are commonly understood as a less reliable indicator of paleo-currents, therefore they must be controlled by measurements of sole marks on lower bed planes of turbidites. In some cases the difference towards the current direction determined by sole marks can be up to 90° (Kneller et al., 1991). The structures of lower bed planes are in metasediments of the Gelnica Group very poorly observable and their recognition can be subjective (some closures of mostly non-cylindrical folds of lower bed planes of metapsammites resemble the flute marks of parabolic shape) as a consequence of imperfect exposition of basal bed planes and tectonometamorphic overprint of former sedimentary facies, therefore the objective paleocurrent analysis in the studied region is impossible.

The vertical successions in Hutná dolina and Gelnická dolina valleys are characteristic with cyclic setting and changes of sand/mud ratios as well as the changes of beds thickness. Only small cycles (up to 5 m thick) are present, having simple or composite character with symmetric or asymmetric trends of the thickness changes of individual beds (Fig. 10: rhythmgram of the logs hd-2 and gd-27a). Often there are the thickening-upward compensation cycles (Mutti & Sonnino, 1981) originating as a consequence of progressive smoothing of subtle depositional relief produced during the upbuilding of individual lobe (Mutti & Normark, 1987). Their upward coarsening trend is usually connected with progradation of lobe and upward fining and thinning of beds indicate its regression. However, over the short time scales, most fans are built by aggradation, not progradation, so that lithofacies shift are controled mostly by channel avulsion and switching (Chen & Hiscott, 1999). In this case the vertical arrangement has no preferred trend reflecting irregular variations in the currents volume, particle concentrations and supplying paths of density flows. The marginal parts of lobes have larger abundance of fine-grained lithofacies Pt, Fcl and Fm and surround the proximal parts of lobes.

In the area of Gelnická dolina valley the several metres thick beds of massive amalgamated fine- to medium-grained metapsammites are sporadically present (Fig. 8: log gd-28, the lithofacies Pm and Ph predominate) forming the proximal parts of lobes, in which the sand/mud ratio is very high (> 90 %, Tab. 1). Erosion structures are in these facies more often. These lithofacies are from the

Table 1 Principal statistic parameters for logs in Hutná dolina and Gelnická dolina valleys.

LOG	No. of beds	Ratio of psammitic component (%)	Ratio of pelitic component (%)	Minimum bed thickness (cm)	Maximum bed thickness (cm)
hd-1	57	83.3	16.7	1	119.5
hd-2	73	52.4	47.6	1	80
gd-27	79	51.9	48.1	0.2	160
gd-27a	79	56.4	43.6	0.3	90
gd-28	10	98.3	1.7	17	120

side of underlier and overlier bordered by lithofacies of lobe fringes. The distinguishing of particular beds became complicated by amalgamation. The beds amalgamation originates due to erosion and soft-sediment deformation or as a result of internal friction in concentrated gravity flows.

In the Hutná dolina and Gelnická dolina valleys the lithofacies associations of lobe fringes are prevailing over the proximal part of lobes, which indicates the competence of psammitic horizon to outer part of submarine fan. Though the pebbly psammitic bodies in upper parts of horizon indicate the sporadic progradation of higher energetic environments of distributary channels of middle fan among the lithofacies of the outer fan.

The vertical arrangement of lobes in the Hutná dolina and Gelnická dolina valleys has a character of type 1 (sensu Pickering, 1981). This lobe type originates directly after middle part of submarine fan.

Locality Zlatá dolina valley

Studied outcrops (logs zd-7, zd-9, zd-11, zd-13, zd-16, Fig. 7) are located on NW-SE mountain ridge approximately 1 km to south-east of the altitude point Zbojnícka skala (1147 m n.m., Fig. 1). They are formed prevailingly by fine- to medium-grained metapsammites with intercalations of dark-grey laminated metapelites. They belong to medium part of the sequence 2 (Fig. 3). Metapsammites are relatively shallowly inclined to SW in normal position. The underlier of metapsammites is probable formed by metavolcaniclastics forming the lowermost part of the sequence 2. Towards the overlier the transition of metapsammites to dark-grey laminated metapelites with lydite intercalations in upper part of the horizon occurs in surrounding of the Jedľovec altitude point (Grecula, 1970). Lydites are connected with variegated volcanic horizon, where the stratiform pyrite deposit at Smolník town is developed (e.g. Ilavský & Mrozek, 1960).

Lithological and sedimentological character of bedding successions in the area of Zlatá dolina valley strongly resembles that in the Hutná dolina and Gelnická dolina valleys. The beds are typical tabular (when not accounting the deformation of beds by tectonic processes) with few erosion structures and well developed Bouma intervals (prevailingly T_b to T_e intervals) in metapsammites. Beds are thick up to 50 cm and abundance of psammitic component in the range of whole succession is 60 to 90 %. The lithophacies Pt (Fig. 4A, B, I) and Fcl are prevailing, less common are the lithofacies Fcm and Ph. Similarly like in the Hutná dolina and Gelnická dolina valleys, also for facies successions in Zlatá dolina valley the cyclicity is characteristic (Fig. 10). The several metres thick asymmetric cycles are present, often with thickening-upward trend (Fig. 10: rhythmograms of logs zd-9 and zd-13). Symmetric or upward thinning as well as irregular cycles (Fig. 10: rhythmgram of log zd-7) are less often present. Therefore the lithofacies development in the area of Zlatá dolina valley belongs to outher part of the fan similarly as it is in northern development of studied horizon.

Conclusion

Studied psammitic horizon belongs to middle part of thinning-upward sequence 2, thick approximately 1500 m, forming the constituent part of sedimentary content in the eastern part of the Gelnica Group. The base of sequence 2 is formed by metavolcaniclastics sharply deposited on fine-grained lithofacies (Pt, Fcl, Fcm, Fzl, Fzm, lydites and carbonates) of the basin plain of sequence 1. The volcaniclastics were redeposited prevailingly by debris flows from the area of volcanic arc on active continental margin into the deeper part of the basin (Vozárová, 1993), or by influence of increased volcanic and tectonic activivy the submarine volcanoes supplied the pyroclastic material directly to sedimentation area. Psammitic horizon forms the middle part of the sequence and gradually passes into the finer facies of basin plain, being formed by the same lithofacies as in the sequence 1. The lydites, black metapelites (lithofacies Fcl and Fcm) and sporadic carbonate bodies (Smolník) of the sequence 2 form a condensed horizon, representing the second period when the sea level in the area of Gelnica Group reached its maximum level. In the basin there prevailed the hemipelagic and pelagic sedimentation with sporadical inputs of fine-grained clastics by low density turbidity currents. The coarser-grained clastic material was that time prevailingly deposited in shallow-marine environments. The volcanic phase of polymodal volcanism and related origin of stratiform sulphidic deposits (e.g. the Smolník deposit) is important in this period. In its overlier the horizon of green, prevailingly laminated metapelites is developed and it terminates the sequence 2.

The psammitic horizon is formed by 11 lithofacies of deep-water character. Clastics were redeposited by density flows from shallower parts of the sea on the slope to bottom of the basin and deposited in the environment of submarine fan during subsidence, low state as well as first phases of rise of sea level. More coarse-grained lithofacies (Cs, Cg, Pm) were transported by concentrated density flows, where the grain-to-grain interactions had

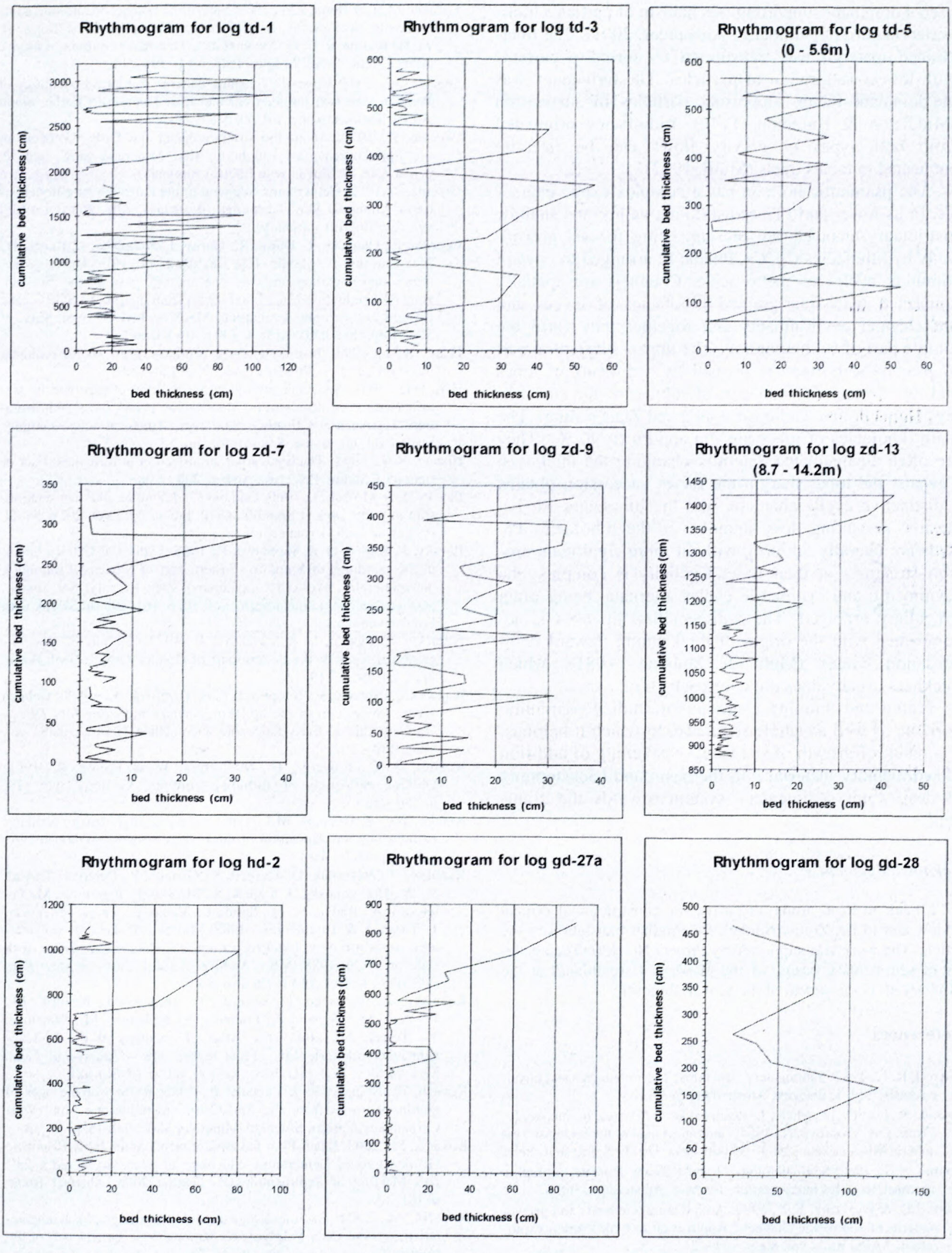


Fig. 10 Rhythmograms for logs td-1, td-3 and td-5 in Tinesova dolina valley, for logs zd-7, zd-9 and zd-13 in Zlatá dolina valley, for logs hd-2 in Hutná dolina valley and for logs gd-27a and gd-28 in Gelnická dolina valley.

been a dominant supporting mechanism of particles transported in current (Mulder & Alexander, 2001). The finer-grained material was transported by turbidity currents with low concentration of particles. The turbulency was the dominant factor supporting particles in suspension (Middleton & Hampton, 1976). Lithofacies originated from both types of gravity flows can be laterally connected in facies tracts (Mutti, 1992).

The psammitic horizon has a complex cyclic character. In its lower part (Tinesova dolina valley) the shallow distributary channels are present, being formed prevailingly by lithofacies Cg, Cs, Ph and Pt arranged to upward -thinning cycles of metre scale. Channels are spatially connected with finer-grained lithofacies of levees and interchannel environments and together they form the middle part of submarine fan. The upper, substantial part of psammitic horizon is formed by sediments of lobes and lobe fringes of outer part of submarine fan (the valleys Hutná dolina, Gelnická dolina and Zlatá dolina). The main lithofacies of lobes are Pm and Ph (> 90 %). They are often amalgamated, laterally changing the thickness. Towards the lobes margin the facies succession obtains a distinctive cyclic character and the lithofacies Pt, Fcl became prevailing, less abundant is the lithofacies Ph. Beds are laterally uniform, without more significant erosion structures at their base. Cyclicity is complex, the asymmetric and symmetric cycles alternate, being often irregullary arranged. The sedimentation in lobes is accompanied with the origin of thickenning upward compensation cycles (Mutti & Sonnino, 1981), which thickness usually does not overreach 10 m.

Fining and thinning character of studied psammitic horizon, as well as whole sequence, to which it belongs, is a result of growth of sea level, weakening of addition of sedimentary material into the basin and backstepping of deep-water sedimentary system towards the continent.

Acknowledgement

I thank to Prof. Anna Vozárová for constructional critical review and to Dr. Zoltán Németh for English translation of the article. The work was supported by Project No. 130 (Tectogenesis of sedimentary basins of the Western Carpathians) at the Ministry of environment of the Slovak Republic.

References

Allen, J. R. L., 1982: Sedimentary structures: Their character and physical basis. Vol. 1, Elsevier, Amsterdam, 593 p.

Bajaník, Š., Ivanička, J., Mello, J., Reichwalder, P., Pristaš, J., Snopko, L., Vozár, J. & Vozárová, A., 1984: Geological map of the Slovenské rudohorie Mts. - eastern part, 1 : 50 000. Geol. Úst. D. Štúra, Bratislava.

Bouma, A.H., 1962: Sedimentology of some flysch deposits: A graphic approach to facies interpretation. Elsevier, Amsterdam, 168 p.

Clark, J.D. & Pickering, K.T., 1996: Architectural elements and growth patterns of submarine channels: Application to hydrocarbon exploration. AAPG Bull., vol. 80, p. 194–221.

Chen, C. & Hiscott, R.N., 1999: Statistical analysis of turbidite cycles in submarine fan successions: Tests for short-term persistence. J. Sedim. Res., vol. 69, p. 486–504.

Dżułyński, S. & Sanders, J.E., 1962: Current marks on firm mud bottoms. Conn. Ac. Of Arts and Sciences, Transactions, vol. 42, p. 57 – 96.

Gardner, M.H. & Borer, J.M., 2000: Submarine channel architecture along a slope to basin profile, Brushy Canyon Formation, West Texas. In: A. H. Bouma & C. G. Stone (Eds.): Fine-rained turbidite systems. AAPG Mem. 72/SEPM Spec. Publ. 68, p. 195–214.

Grecula, M., 2003: Upward-thickening patterns and lateral continuity of Permian sand-rich turbidite channel fills, Laingsburg Karoo, South Africa. Sedimentology, vol. 50, p. 831–853.

Grecula, P., 1970: About the stratigraphy of the Early Paleozoic of the Spišsko-gemerské rudohorie Mts. Mineralia Slov., vol. 2, p. 191–216 (in Slovak with English summary).

Grecula, P., 1982: Gemericum: Segment of the Paleotethyan riftogenous basin. Mineralia Slov. - Monogr., Bratislava, Alfa, 263 p. (in Slovak with English summary).

Grecula, P., Dianiška, I., Ďuďa, R., Hurný, J., Kobulský, J., Kusák, B., Malachovský, P., Matula, I. & Rozložník, O., 1977: Geology, tectonics and metallogenesis of the eastern part of the Spišsko-gemerské rudohorie Mts.: Final report from the project SGR – east, Cu-ores and complex evaluation. MS – Archive of Geol. Surv. of Slov. Rep. (ŠGÚDŠ), Košice, 390 p. (in Slovak).

Hand, B.M., 1997: Inverse grading resulting from coarse-sediment transport lag. J. Sedim. Res., vol. 67, p. 124–129.

Haq, B.U., 1991: Sequence stratigraphy, sea-level change and its significance for the deep sea. In: MacDonald, D.I.M. (ed.): Sedimentation, Tectonics and Eustasy. Sea level changes at active margins. Spec. Publ. Int. Assoc. Sedimentol., no. 12, p. 3–39.

Hiscott, R.N., 1994: Traction-carpet stratification in turbidites: Fact or fiction? J. Sedim. Petr., vol. A64, p. 204 – 208.

Ilavský, J. & Mrozek, J., 1960: Gotland (?) dolomites and their relationship to pyrite ores at Smolník. Geol. Práce, Zpr., vol. 20, p. 51–56 (in Slovak with German summary).

Ilavský, J., Kupčo, G. & Snopková, P., 1985: Lydites of Gelnica Group in Surroundings of Smolník (Eastern part of Slovenské rudohorie ore mountains, Western Carpathians). Záp. Karpaty, Sér. miner., petrogr., geochém., metalogen., vol. 10, p. 161–198 (in Slovak with English summary).

Ivanička, J., Snopko, L. & Snopková, P., 1989a: Results of biostratigraphical study in the eastern part of Gelnica Group. Geol. Práce, Spr., vol. 89, p. 119–136.

Ivanička, J., Snopko, L., Snopková, P. & Vozárová, A., 1989b: Gelnica group: Lower unit of the Spišsko-gemerské rudohorie Mts. (Western Carpathians) Early Paleozoic. Geol. Zbor. Geol. carpath., vol. 40, p. 483 – 501.

Kneller, B. C., Edwards, D., McCaffrey, W. & Moore, R., 1991: Oblique reflection of turbidity currents. Geology, vol. 19, p. 250–252.

Kneller, B.C. & Branney, M.J., 1995: Sustained high-density turbidity currents and the deposition of thick massive beds. Sedimentology, vol. 42, p. 607 – 616.

Kobulský, J., Návesňak, D., Gerhart, S., Grecula, P., Derco, J., Faryad, S., W., Hodermarský, J., Lajčák, Š., Mrosko, J., Papšíková, M., Petercová, A., Radvanec, M., Sasák, L., Valko, P., Varga, M., Vozár, J., Turan, J. & Turanová, L., 1988: Mníšek – Prakovce: - polymetallic stratiform ores: Final report and calculation of reserves, with state on 30. 6. 1988. MS - Archive of Geol. Surv. of Slov. Rep. (ŠGÚDŠ), Košice, 165 p. (in Slovak).

Kobulský, J., Gazdačko, Ľ., Grecula, P., Hojnoš, M., Kandrík, M., Kováčik, M., Németh, Z., Pramuka, S., Radvanec, M., Szalaiová, V., Tréger, M., 2001: The Atlas of geomaps of the Spišsko-gemerské rudohorie Mts.: Final report. MS – Archive of Geol. Surv. of Slov. Rep. (ŠGÚDŠ), Košice, 605 p. (in Slovak).

Kovách, Á., Svingor, É. & Grecula, P., 1986: Rb/Sr isotopic ages of granitoide rocks from the Spiš-Gemer metalliferous Mts., West Carpathians, Eastern Slovakia. Mineralia Slov., vol. 18, p. 1 – 14.

Kováčik, M., 2003: Basin-floor fan environments of the Early Paleozoic Gelnica Group, Gemericum, Slovakia. in Vlahović, I. (ed.): 22nd IAS Meeting of Sedimentology - Opatija 2003, Abstract Book, p. 101.

Kováčik, M., 2004: Sedimentological and lithostratigraphical characteristics of the Early Paleozoic formations in the eastern part of the Gelnica Group, Gemericum. In: M. Kováčik, Sr. (Ed.): Tectogenesis of Paleozoic sedimentary basins of the Western Carpathians. MS - Archive of Geol. Surv. of Slov. Rep. (ŠGÚDŠ), Bratislava, 54 p. (in Slovak).

Lowe, D.R., 1982: Sediment gravity flows, II. Depositional models with special reference to the deposits of high-density turbidity currents. J. Sedim. Petr., vol. 52, p. 279–297.

Middleton, G. V. & Hampton, M. A., 1976: Subaquaeous sediment transport and deposition by sediment gravity flows. In: Stanley, D. J. & Swift, D. J. P., (Eds.): Marine sediment transport and environmental managment. New York, Wiley Intersci., p. 197–218.

Molák, B. & Slavkay, M., 1994: Role of black shales/schists in Variscan and Alpine metallogenetic processes in the West Carpathians. In: P. Grecula & Z. Németh (Eds.): Variscan metallogeny in the Alpine orogenic belt. Mineralia Slov. - Monogr., p. 307 – 313.

Mulder, T. & Alexander, J., 2001: The physical character of subaqueous sedimentary density flows and their deposits. Sedimentology, vol. 48, p. 269–299.

Mutti, E., 1977: Distinctive thin-bedded turbidite facies and related depositional environment in the Eocene Hecho Group (south-central Pyrenees). Sedimentology, vol. 24, p. 107–131.

Mutti, E., 1992: Turbidite sandstones. Agip Inst. Di Geol. Univ. Di Parma, Milano, 275 p.

Mutti, E. & Ricci Lucchi, F., 1972: Le torbiditi dell´ Appenino settentrionale: Introduzione all´ analisi di facies. Mem. Soc. Geol. Ital., vol. 11, p. 161–199.

Mutti, E. & Sonnino, M., 1981: Compensation cycles: A diagnostic feature of turbidite sandstone lobes. IAS 2nd Europe Reg. Mtg. Bologna, Abstracts, p. 120–123.

Mutti, E. & Normark, W. R., 1987: Comparing examples of modern and ancient turbidite systems: Problems and concepts. In: Legget, J. K. & Zuffa, G. G. (Eds.): Marine clastic sedimentology. London, Graham and Trotman, p. 1–38.

Németh, Z., Gazdačko, Ľ, Návesňák, D. & Kobulský, J., 1997: Polyphase tectonic evolution of the Gemericum (the Western Carpathians) outlined by review of structural and deformational data. In: P. Grecula, D. Hovorka & M. Putiš (Eds.): Geological evolution of Western Carpathians. Mineralia Slov. - Monogr., Bratislava, p. 215–224.

Pickering, K.T., 1981: Two types of outer fan lobe sequence, from the late Precambrian Kongsfjord Formation submarine fan, Finnmark, northern Norway. J. Sedim. Petr., vol. 51, p. 1277 – 1286.

Pickering, K. T., Stow, D. A. V., Watson, M. P. & Hiscott, R. A., 1986. Deep-water facies, processes and models: A review and classification scheme for modern and ancient sediments. Earth-Sci. Rev., vol. 23, p. 75–174.

Peakall, J., McCaffrey, B. & Kneller, B., 2000: A process model for evolution, morphology and architecture of sinuous submarine channels. J. Sedim. Res., vol. 70, p. 434–448.

Ricci-Lucchi, F. 1975: Depositional cycles in two turbidite formations of Northern Apennines (Italy). J. Sedim. Petr., vol. 45, p. 3–43.

Snopko, L., 1967: Lithological characteristics of the Gelnica Series. Sbor. geol. Vied, Západ. Karpaty, vol. 7, p. 103–152 (in Slovak with German summary).

Snopko, L. & Ivanička, J., 1978: Considerations on the paleography in the Early Paleozoic of the Spišsko-gemerské rudohorie Mts. In: J. Vozár, R. Marschalko, M. Mišík & J. Nemčok (Eds.): Paleogeographical evolution of the Western Carpathians. GÚDŠ, Bratislava, p. 269–279 (in Slovak with English summary).

Stow, D. A. V. & Bowen, A. J., 1980: A physical model for transport and sorting of fine- grained sediment by turbidity currents. Sedimentology, vol. 27, p. 31 – 46.

Stow, D. A. V. & Shanmugam, G., 1980: Sequence of structures in fine-grained turbidites: Comparison of recent deep-sea and ancient flysch sediments. Sedim. Geol., vol. 25, p. 23 – 42.

Stow, D. A. V. & Piper, D. J. W., 1984: Deep-water fine-grained sediments: Facies models. Spec. Publ. Geol. Soc. London 15, p. 611 – 646.

Stow, D.A.V., Huc, A.-Y. & Bertrand, P., 2001: Depositional processes of black shales in deep water. Mar. Petr. Geol., vol. 18, p. 491–498.

Turan, J. & Turanová, L., 1993: Carbonate mineralization of the Nižná Slaná deposit. Záp. Karpaty, Sér. miner., petrogr., geochém., metalogen., vol. 16, p. 147 – 167 (in Slovak).

Vail, P. R., Mitchum, R. M., Jr., Todd, R. G., Widmier, J. M., Thompson, S., Sangree, J. B., Bubb, J. N. & Hatlelid, W. G., 1977: Seismic stratigraphy and global change of sea level, parts 1-6. In: C. E. Payton (Ed.): Seismic stratigraphy: Applications to Hydrocarbon Research. AAPG Mem., vol. 26, p. 49-133.

Varga, I., 1970: Some regularities of the genesis and evolution of geological environment of metasomatic carbonate deposits in Spišsko-gemerské rudohorie Mts. Mineralia Slov., vol. 2, p. 85 – 92 (in Slovak with English summary).

Vozárová, A., 1993: Provenance of Gelnica Group metasandstones and relationship to paleotectonics of the basin of deposition. Záp. Karpaty, Sér. miner., petrogr., geochém., metalogen., vol. 16, p. 7–54 (in Slovak with English summary).

Vozárová, A. & Ivanička, J., 1993: Lithogeochemistry of Early Paleozoic metasediments in Southern Gemericum. Záp. Karpaty, Sér. miner., petrogr., geochém., metalogen., vol. 16, p. 119–146 (in Slovak with English summary).

Vozárová, A. & Ivanička, J., 1996: Geodynamic setting of Gelnica Group acid volcanism. Slov. Geol. Mag., vol. 2, no. 3–4, p. 245–250.

Vozárová, A. & Ivanička, J., 2000: Early Palaeozoic deep-sea turbidites of the Southern Gemeric Unit (Western Carpathians; Slovak Republic). Slov. Geol. Mag., vol. 6, no. 2–3, 273–274.

Vozárová, A., Soták, J. & Ivanička, J., 1998: A new microfauna from the Early Paleozoic formations of the Gemericum (foraminifera): Constrains for another fossils or subfossils. In: M. Rakús (Ed.): Geodynamic development of the Western Carpathians. GSSR, Bratislava, p. 63–74.

Walker, R. G., 1965: The origin and significance of the internal sedimentary structures of turbidites. Yorkshire Geol. Soc. Proc., vol. 35, p. 1–32.

Paleopiezometry: Tool for determination of differential stresses for principal ductile shear zones of Gemericum, Western Carpathians

ZOLTÁN NÉMETH

Geological Survey of Slovak Republic (ŠGÚDŠ), Jesenského 8, 040 01 Košice, Slovak Republic; nemeth@gssr-ke.sk

Abstract. In contribution the differential stresses during dynamic recrystallization of monomineralic rocks (quartzites, calcitic marbles) are numerically expressed using paleopiezometry.

Research took into account comparable protoliths from the main ductile shear zones in Gemeric region. The deformation gradients during Alpine collisional imbrication (AD_1; calcitic marbles of Lower Paleozoic Holec Beds of Gemeric Gelnica Group) and Bôrka nappe displacement (southern and northern occurrences; AD_1) as well as the post-collisional unroofing (AD_2) in the eastern contact zone of Gemericum with Veporicum are documented.

The research contributed to methodology of calcite paleopiezometry (methods of Twinning Incidence and Twin Density) using altogether six ways of differential stress calculation and compared it with quartz paleopiezometry. The case comparison of both methodologies (calcite and quartz paleopiezometry) was realized on neighbouring marble and quartzite mylonite beds in the Črmeľ valley, documenting the ductile low angle normal faulting (unroofing) in the eastern contact zone between Gemericum and Veporicum (Margecany zone; AD_2 phase).

Key words: paleopiezometry, ductile shear zones, imbrication, unroofing, Bôrka nappe, Gemericum, Veporicum.

Introduction

Previous study (Németh, 2001, 2002) has distinguished three ductile shear zones of principal importance in tectonic evolution in Gemeric region:

1. Shear zone between Lower Paleozoic Gelnica and Rakovec Groups (Variscan; linear course of E-W direction bended to NW-SE in its eastern segment; product of deformation phase VD; kinematics of south-vergent exhumation overthrusting of Rakovec Group melange on Gelnica Group; Figs. 1 and 3),

2. Bôrka nappe north-vergent displacement mylonitic horizons (Alpine; areally outcropping nappe outliers; deformation phase AD_1; exhumed melange of Meliata-Hallstatt basin marginal facies) and

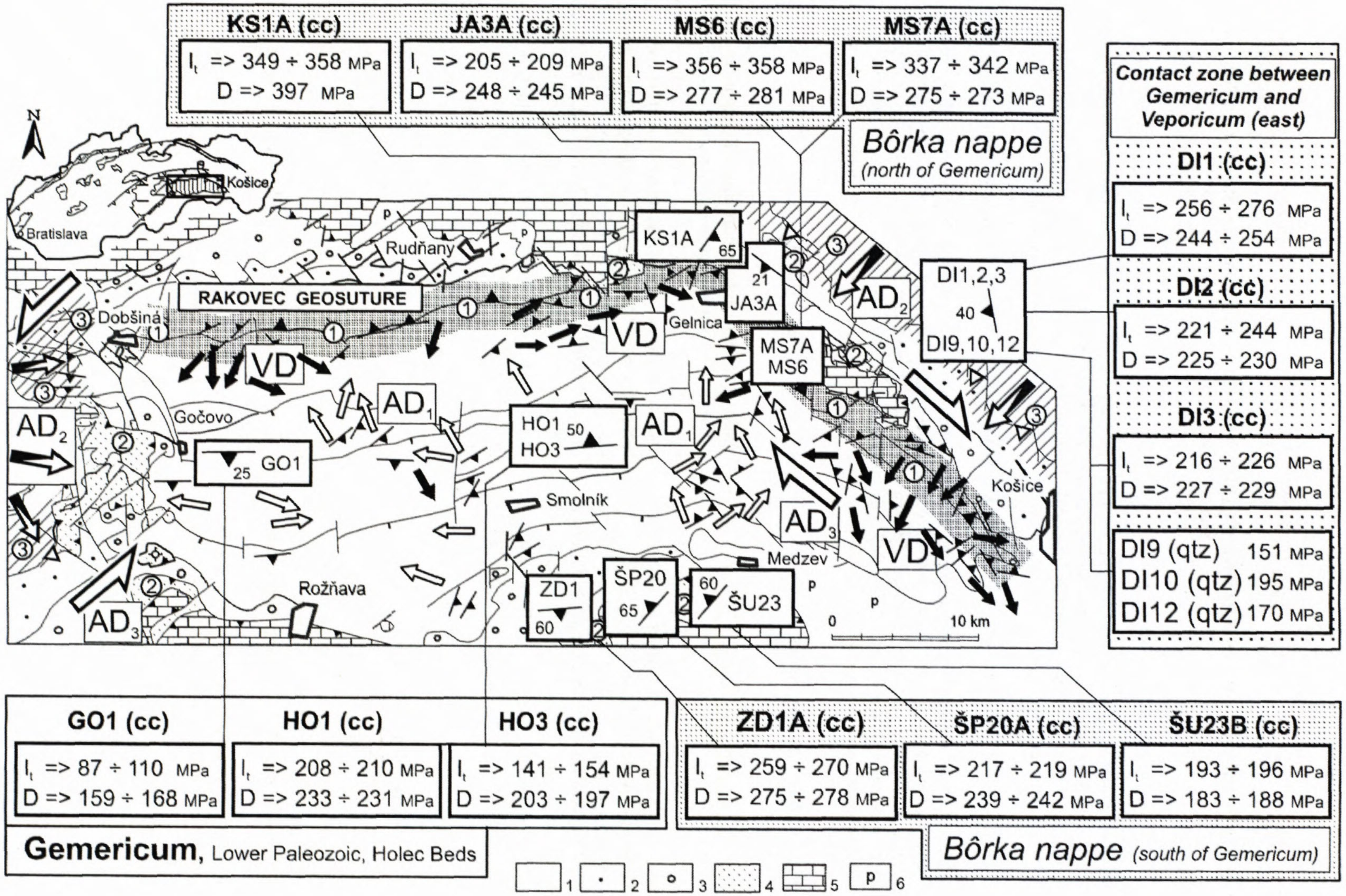
3. Shear zone between Gemericum and Veporicum (Alpine; linear bended course separating both megaunits corresponding with Lubeník-Margecany line; pervasive ductile deformation during AD_2 phase; Alpine post-collisional unroofing of SE- and SW-vergency in western resp. eastern part of the contact zone).

The main aim of the paleopiezometry application was the obtaining of the exact numeric data about the distribution of differential stresses in mylonites of comparable protoliths and thus to contribute to reconstruction of geodynamic evolution. The paleopiezometry is best calibrated for monomineralic calcitic and quartzy rocks (marbles, quartzites), so our attempt was to collect samples with evident ductile deformation from the most softened parts of the shear zones listed above.

The softest horizon, where the south-vergent ductile shear zone between Gelnica and Rakovec Groups has developed (exhumation kinematics; designation 1 in Fig. 1), consists of green and grey laminated flyschoid sandstones, green metapelites, acid and intermediate volcaniclastics and basalt pyroclastics. Because no suitable monomineralic tectonites were found directly in the shear zone, our research took into consideration the Lower Paleozoic calcitic marbles from Holec altitude point and from Gočovo village (Holec Beds, Betliar Formation, central part of Gemericum; Figs. 1 and 3). As discussed later, because of the position of this marble strip at the base of the north-vergent Alpine AD_1 overthrust (Fig. 3) we suppose that the preserved ductile deformation in studied marbles was more realistically caused by AD_1 overthrusting than by Variscan VD phase.

The evidences of two phase deformation of these marbles were not found. It confirms former interpretation (Németh, 2002), that during the south-vergent VD exhumation the lowermost horizons of Lower Paleozoic rock pile were protected against deformation by their position near the rigid crystalline basement, and the deformation was accommodated by the uppermost horizons of autochthonous Gelnica Group. As shown further in the text, the results of paleopiezometry brought new data for this assumption.

The calcite paleopiezometry applied on southern and northern occurrences of the Bôrka nappe (designed 2 in Fig. 1) aimed to contribute with new data to prolonged discussion about one or two branches of Meliata ocean, resp. autochthonous or allochthonous position of the Jaklovce Meliaticum. Studied samples were represented with the coarse-crystalline and multitwins calcitic marbles from Šugov valley, Špičiak hill and Zádiel valley



KS1A (cc)
I_t => 349 ÷ 358 MPa
D => 397 MPa
JA3A (cc)
I_t => 205 ÷ 209 MPa
D => 248 ÷ 245 MPa
MS6 (cc)
I_t => 356 ÷ 358 MPa
D => 277 ÷ 281 MPa
MS7A (cc)
I_t => 337 ÷ 342 MPa
D => 275 ÷ 273 MPa
Bôrka nappe
(north of Gemericum)
Contact zone between Gemericum and Veporicum (east)
DI1 (cc)
I_t => 256 ÷ 276 MPa
D => 244 ÷ 254 MPa
DI2 (cc)
I_t => 221 ÷ 244 MPa
D => 225 ÷ 230 MPa
DI3 (cc)
I_t => 216 ÷ 226 MPa
D => 227 ÷ 229 MPa
DI9 (qtz) 151 MPa
DI10 (qtz) 195 MPa
DI12 (qtz) 170 MPa
N
Košice
Bratislava
Rudňany
RAKOVEC GEOSUTURE
Dobšiná
Gelnica
VD
AD1
AD2
AD3
KS1A 65
21 JA3A
MS7A MS6
DI1,2,3
40
DI9,10,12
Gočovo
GO1 25
HO1 50
HO3
Smolník
Medzev
Rožňava
ZD1 60
ŠP20 65
60 ŠU23
0 10 km
GO1 (cc)
I_t => 87 ÷ 110 MPa
D => 159 ÷ 168 MPa
HO1 (cc)
I_t => 208 ÷ 210 MPa
D => 233 ÷ 231 MPa
HO3 (cc)
I_t => 141 ÷ 154 MPa
D => 203 ÷ 197 MPa
Gemericum, Lower Paleozoic, Holec Beds
ZD1A (cc)
I_t => 259 ÷ 270 MPa
D => 275 ÷ 278 MPa
ŠP20A (cc)
I_t => 217 ÷ 219 MPa
D => 239 ÷ 242 MPa
ŠU23B (cc)
I_t => 193 ÷ 196 MPa
D => 183 ÷ 188 MPa
Bôrka nappe (south of Gemericum)
1 2 3 4 5 6

(southern occurrences of the Bôrka nappe) as well as Kurtová and Murovaná skala hills and Jaklovce village (Jaklovce Meliaticum/?northern occurrences of the Bôrka nappe).In the ductile shear zone, representing the eastern contact zone between Gemericum and Veporicum (Margecany line; AD_2; designation 3 in Fig. 1), the case comparison of both methodologies (calcite and quartz paleopiezometry) was realized on neighbouring marbles and quartzites at Diana locality in the Črmeľ valley.

Methodology

The size of dynamically recrystallized grains in deformed rock relates on differential stress. This principle was used in paleopiezometers for estimation of paleostress (Mercier et al., 1977; Etheridge and Wilkie, 1981; Christie and Ord, 1980; Schmid et al., 1980; Michibayashi, 1993; Post and Tullis, 1999, Passchier and Trouw, 1996 and others). The paleopiezometry was best elaborated for monomineralic rocks with pervasive ductile deformation - calcitic marbles and quartzites.

Quartz paleopiezometry. This method takes into consideration only one parameter - the size of dynamically recrystallized grains. This is the reason of large diversities in calibrations of different authors (Koch, 1983; Twiss, 1977; Mercier et al., 1977) resulting to restriction of this methodology in practical use. This inappropriateness is demonstrated in Fig. 2, documenting the calibrations used for the earlier obtained results from the locality Košice – Diana (Németh and Putiš, 1999).

Calcite paleopiezometry. Because of the weakness of quartz paleopiezometry, the accent in our study has been given for calcite paleopiezometry, accounting the size of dynamically recrystallized calcite grains, but also the number and character of deformation twins. Moreover, there are known two independent ways how to determine the differential stresses in calcitic rocks with the possibility of mutual comparison of results of both methods. These methods are *Twinning Incidence* and *Twin Density* (Rowe and Rutter, 1990).

Twinning incidence. It, is defined as the percentage of grains of the distinguished size interval that demonstrate optically visible twins. We have measured in each sample 240 grains. The differential stress σ(MPa) was determined using below stated equation, where d represents the size of grains in μm (sensu l.c.). The standard error in this technique was stated by its authors to 31 MPa.

$$\sigma = 523 + 2.13\ I_t - 204 \log d\ [\text{MPa}]$$

Twin density, D, is defined as the number of twins regarding the grain diameter, measured perpendicularly to the twins. Input data are necessary to be correlated by the variation coefficient 0.25 (Ranalli, 1984). The standard error in this method is 43 MPa. The differential stress relates on twin density D by the following equation:

$$\sigma = -52.0 + 171.1 \log D\ [\text{MPa}]$$

The primary data were obtained from thin sections, measuring the grain size in μm and number of deformation twins in corresponding grain. To guarantee the maximum representativeness of data, measurements were done systematically on profiles through thin section taking into account each neighbouring grain. Extreme dimensions (extremely small or large grains) were excluded from following calculations, using the variation coefficient 0.25.

For numerical processing we developed the below described procedure, consisting from several steps:

1. Separation and batching of obtained data according to the grain size. This procedure is easier when working with relative values of the grain size, i.e. the number of segments on micrometric scale. Determination of the real grain size in μm was obtained by multiplication of segments number by the real dimension of segment in μm.

2. Finding of number of grains in individual size categories as well as the grains with twins. Values are used for calculation of twinning incidence It.

3. Determination of the number of twins in individual size categories and sums of all perpendicular diameters of grains related to twins. Obtained information was used for calculation of twin density D.

To be sure with the maximal correctness of obtained results the calculation has been realized by six ways. Four calculations were restricted with the variation coefficient below 0.25 (± 25 %; Ranalli, 1984). By this way we avoided the possible inaccuracy of results by extremely small and large grains being included into calculations.

Fig. 1. Location of studied samples and results of paleopiezometry in Gemeric region. Lithology: 1 – Lower Paleozoic rocks of Gemericum, 2 – Carboniferous rocks of Gemericum and in its contact with Veporicum, 3 – Permian rocks of Gemericum, 4 – Upper Paleozoic and Triassic rocks of Meliaticum (Bôrka nappe), 5 – Mesozoic rocks of Silicicum, 6 – Paleogene. Numbers in circles designate the principal ductile shear zones: 1 – s.z. between Gelnica and Rakovec Groups (Variscan obduction kinematics; thick dotted line), 2 – Bôrka nappe (exhumed and obducted Meliaticum), 3 – s.z. between Gemericum and Veporicum (Alpine overthrust and subsequent unroofing). Arrows indicate kinematics during Variscan obduction and collision VD (black arrows) and Alpine tectogenesis (AD_1 – white arrows; AD_2 – half filled arrows; AD_3 – half-arrows). Location of samples: Lower Paleozoic Holec Beds of Gemericum: GO1 – Gočovo village, unnamed hill 1.5 km to SSE of the village, HO1 and HO3 – Holec altitude point 6 km to NE of Smolník village. Outliers of Bôrka nappe in Southern Gemericum: ŠU23B – Šugov valley 4 km to SSW of Medzev town, ŠP20 – Špičák altitude point (808 m) 4 km to WSW of Medzev town, ZD1 – Zádiel valley 11 km SE of Smolník town. Outliers of Bôrka nappe in Northern Gemericum: KS1A – 1.5 km to NNW of Jaklovce village, JA3A – 1.2 km to NE of Jaklovce village, MS6 and MS7 – 1.5 km to NE of Kojšov village. Eastern contact zone between Gemericum and Veporicum: DI1, DI2, DI3, DI9, DI10, DI12 – Črmeľ valley, Diana hunter hut 3.5 km to NW of Kavečany village near Košice.

DI9 (qtz)

σ (MPA)		Koch (1983)	Twiss (1977)	Mercier et al. (1977)
aver. diam	——	151.3	75.9	38.0
max. diam	– –	89.1	57.5	29.5
min. diam	- - -	371.5	102.3	55.0

DI10 (qtz)

σ (MPA)		Koch (1983)	Twiss (1977)	Mercier et al. (1977)
aver. diam	——	195.0	83.2	42.7
max. diam	– –	120.2	64.6	32.4
min. diam	- - -	389.1	102.3	56.2

DI12 (qtz)

σ (MPA)		Koch (1983)	Twiss (1977)	Mercier et al. (1977)
aver. diam	——	169.8	83.2	43.7
max. diam	– –	104.7	64.6	31.6
min. diam	- - -	407.4	125.9	67.6

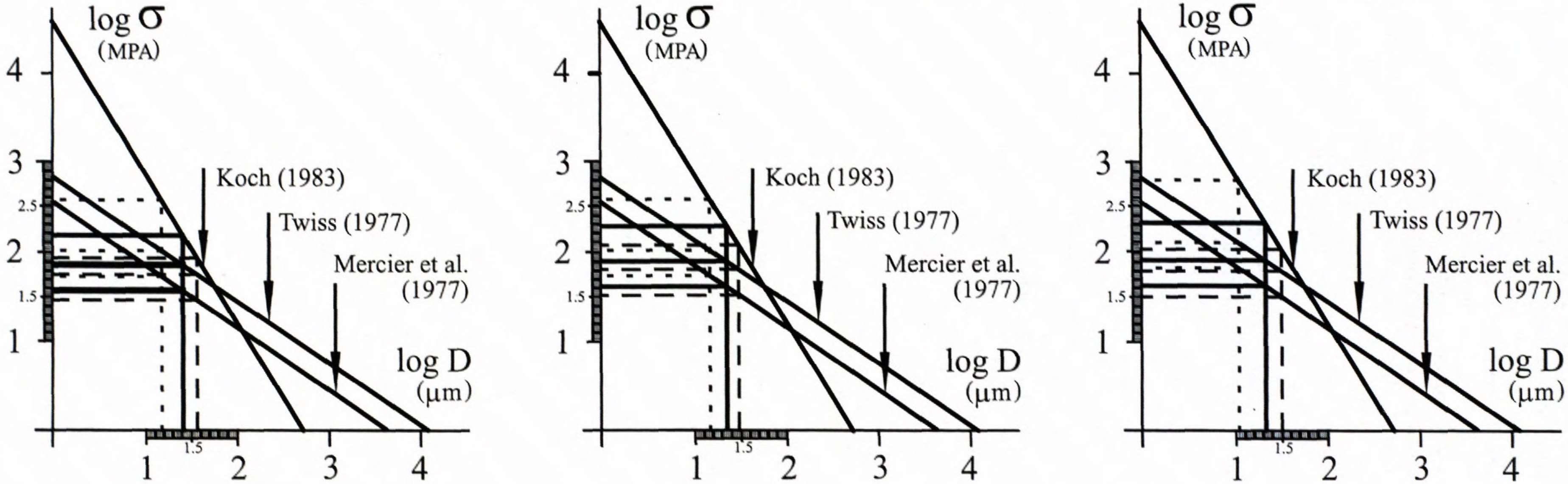


Fig. 2. Quartz paleopiezometry: Determination of differential stresses affecting during deformation AD_2 on Veporic cover quartzites (eastern contact zone of Gemericum and Veporicum) in the locality Košice-Diana. The quartzite bed (samples DI9, DI10, DI12) is in immediate vicinity of the bed of calcitic marbles (samples DI1, DI2 and DI3). Tables above graphs in figure display differing differential stresses obtained using calibrations by Koch (1983), Twiss (1977) and Mercier et al. (1977). Stresses were calculated in each calibration for minimal, maximal and average diameters of grains. The results were compared with results of calcite marbles paleopiezometry of samples DI1, DI2 and DI3, neighbouring to studied quartzites and suffering the comparable AD_2 overprint. Nearer to results of calcite paleopiezometry and geologically most significant are the results by Koch (1983) calibration when taking into account the average diameter of grains. These results indicate, that quartz bed represented either softer medium for stress accommodation and displacement than marble bed, or the marble bed accommodated majority of deformation being located closer to thrust plane.

Multiple determination of the differential stress by method of Twinning Incidence:

1. The differential stress has been calculated selectively for each grain size class. The total differential stress has been calculated by weighted mean. The variation coefficient was not implemented into calculations.

2. The calculation with the total twinning incidence (without selective calculation for each grain size). Calculation with the coefficient of variation.

3. Determination of differential stress by the arithmetic mean from the partial results for individual categories. Calculation with the coefficient of variation.

4. Determination of differential stress by the weighted mean from the partial results for individual categories. Calculation with the coefficient of variation.

Multiple determination of the differential stress by method of Twin Density:

1. Calculation with application of mathematically determined twins number with respect to grain sizes perpendicular to twins without separation of calculations for individual size classes. The coefficient of variation was not implemented into calculations.

2. The same way of calculation with implemented coefficient of variation.

In prevailing number of samples, the results of both methods (Twinning Incidence and Twin Density) were comparable. In several cases we have registered some differences in differential stresses. These will be discussed when commenting individual samples. The Twin Density method is considered to be more precise and obtained result (with implementation of the coefficient of variation by Ranalli, 1984) most realistic.

Obtained data

Lower Paleozoic calcitic marbles of Gelnica Group

To contribute for comprehensive characterization of the tectonic evolution of the Gemericum, we tried to obtain the deformation characteristics of comparable lithologies from individual shear zones. Because of the absence of suitable monomineralic lithology in ductile shear zone dividing Lower Paleozoic Rakovec and Gelnica Groups (VD phase of deformation), for characterization of the deformation gradient in Lower Paleozoic Gemeric sequences we studied carbonates from the deeper lithostratigraphic levels of the Gelnica Group (Lower Paleozoic Holec Beds of Betliar Formation; Fig. 3). The samples were taken directly from the Holec elevation point (804) in the centre of Gemericum (**HO1**, **HO3**) and ESE of the village Gočovo (**GO1**; Fig. 1).

Paleopiezometry of the less deformed calcitic marble found in the Gemeric region, **GO1** *(AS_2 = 180/25)*, demonstrated the lowest values of differential stress (87 ÷ 110 MPa by Twinning Incidence, T.i., and 159 ÷ 168 MPa by Twin Density, T.d.; compare data in Table 1). Calculated representative grain size is 253.90 μm. Differential stress caused migration of grain boundaries accompanied with origin of deformation twins in some grains.

The calcitic marble **HO1** *(AS_2 = 355/50)* consists of seriate interlobate calcite grains. Representative grain size is 202.90 μm. More intensive deformation of HO1 in comparison with HO3 is indicated also by higher values of differential stresses (208 ÷ 210 MPa contrary to 141 ÷ 154 MPa by T.i., and 233 ÷ 231 MPa contrary to 203 ÷ 197 MPa by T.d.) and results in origin of microshears.

Calcitic marble **HO3** *(AS_2 = 355/50)* represents type with distinctly elongated grains. The average grain-size is 350.80 μm. The trends to grain boundary area reduction in marble HO3 in comparison with HO1, are reflected also by the lower differential stresses. The comparison of data of samples **HO1** and **HO3** from different carbonatic lenses of Holec Beds suggests the role of the protolith character prior deformation (e.g. different granularity) as well as possibly slightly different deformation temperature of rocks recently outcropping in close vicinity.

Carbonates from the Bôrka nappe outliers in Southern and Northern Gemericum

Coarse-grained calcitic marbles represent several hundred metres thick bed in Dúbrava Fm. of Hačava Sequence (cf. Mello, ed., 1997). They form sceneric hills Jelení vrch (947) and Špičák (808) to WSW of the village Medzev. Carbonates often contain intercalations of basic pyroclastic material, after tectonization and boudinage being reshaped to σ and δ porphyroclasts (known excursion localities in termination of the Šugov valley). In microscale the thin calcitic intercalations are typical feature nearly for all lithotypes of Dúbrava Fm.

Coarse-grained marbles contain twins of several generations. Oldest generation of thick twins of low number (usually to 5) indicates higher temperature conditions of their origin. Inside big calcite grains (average dimensions 300-400 μm) are closed small quartz and albite grains. It indicates total recrystallization of carbonatic matter and resetting of original grain boundaries. With generation of twinning also the core-mantle structures in marbles are related. First system of twins is penetrated with younger system of very thin deformation twins of extremely high number (about 50 twins per grain are the common case). Successive decrease of temperature during generation of both systems is indicated by twinning character - first system has variegated twin thicknesses along their course and their bending is characteristic (temperature of origin of first system is above 200-250 °C). Younger system contain sharp, strait twins of razor-type (<200 °C). Anomalously high number of deformation twins of the second system indicates, that deformation has realized in the high state of plasticity with bulk distribution of differential stress in whole crystal lattice and activation of each suitable lattice plane. Described two twin systems are penetrated by brittle fractures being the result of final low T brittle deformation.

Paleopiezometry was applied on samples from the terminations of Šugov valley (**ŠU23B**; AS_2 = *340/60*), Zádiel valley (**ZD1A;** AS_2 = *175/60*) and from apical parts of the elevation point 808 m Špičák (**ŠP20**; AS_2 = *312/65*). The finding that described coarse-grained marbles do not ex-

Slovak Geol. Mag., 11, 2 – 3 (2005), 185 – 193

Table 1 Results of paleopiezometry of calcitic marbles obtained by six ways of calculation by methods of Twinning Incidence and Twin density (location of samples – see explanation to Fig. 1).

		TWINNING INCIDENCE					TWIN DENSITY		
	Representative grain-size	Calcul. without variation coeffic. / Calculat. with weight. mean	It for interval determined by variation coefficient	Calculation with variation coefficient: Calculat. with the whole It	Arith. mean of σ for size classes	Weight. mean of σ for size classes	D – number of lamellae per 1 mm of perpendicula diameter	Calculat. without variation coeffic.	Calculat. with variation coeffic.
	µm	σ(MPa)		σ(MPa)	σ(MPa)	σ(MPa)		σ(MPa)	σ(MPa)
Lower Paleozoic carbonates of Holec Beds – AD_1 phase									
GO1	253.90	109.95	26.04	87.91	87.17	88.65	17.18	159.30	**168.06**
HO1	202.90	209.99	73.19	208.20	209.86	208.95	46.17	232.80	**230.98**
HO3	350.80	154.45	64.49	141.16	154.85	144.89	30.93	203.00	**197.39**
Bôrka nappe (outliers in Southern Gemericum) – AD_1 phase									
ŠU23B	403.20	193.09	95.08	193.99	195.74	195.02	23.77	183.40	**187.56**
ŠP20A	330.00	217.44	90.14	201.23	192.40	219.46	50.35	239.20	**242.12**
ZD1A	174.00	270.13	90.43	258.55	266.37	259.37	81.10	274.60	**277.92**
Bôrka nappe (outliers in Northern Gemericum) – AD_1 phase									
KS1A	58.08	358.31	88.64	351.93	348.92	352.93	420.3	396.90	**396.66**
JA3A	165.10	205.46	64.38	207.71	211.33	208.57	56.96	248.40	**244.79**
MS6	50.73	358.43	85.71	357.70	356.33	358.46	84.17	277.40	**281.46**
MS7	56.09	342.28	82.35	341.63	337.23	342.28	81.63	275.10	**273.03**
Ductile shear zone between Gemericum and Veporicum - AD_2 phase									
DI1	54.95	276.46	41.38	256.18	253.32	256.96	53.72	244.00	**253.71**
DI2	85.02	243.70	43.28	221.57	221.08	222.39	41.77	225.30	**230.13**
DI3	95.19	215.77	49.52	224.85	221.31	226.08	42.81	227.20	**228.82**

hibit considerable high differential stresses was surprising (183-278 MPa in the whole range of results; Tab. 1, Fig. 1). It is probable due to the fact that deformed material was coarse-grained already prior this pervasive deformation (**ŠU23B** 403.20 µm, **ŠP20** 330.00 µm, **ZD1A** 174.00 µm) and the grain size represents the principal parameter in mathematical expression in both calibrations.

From the Bôrka nappe outliers in Northern Gemericum (deformation phase AD_1) our research took into account the marbles from the lower carbonatic horizon of the north-western slope of the Murovaná skala massif south-east of Gelnica town (samples **MS6** and **MS7**) and those of so-called Jaklovce Meliaticum (**JA3A**, ENE of Gelnica town; AS_2 = *216/21*). As proved by microtectonic studies (Németh, 2001), thin section parallel with the dip of foliation indicated in Jaklovce sample tectonic transport top-to-the-NE. The carbonates from the North Gemeric Bôrka nappe outliers of the representative grain size 50.73-58.08 µm (**KS1A,** AS_2 = *125/65*; **MS6** and **MS7**) and 165.10 µm (**JA3A**) gave the highest values of differential stresses yet obtained in Gemeric region: 245 ÷ 397 MPa (T.d., calculation with variation coefficient). The higher values in comparison with those in "typical localities" in Southern Gemericum we explain by frozing of the products of ductile deformation in frontal parts of the nappe without possibility of static recrystallization, reshaping of grains, growth of larger individuals and obscuring of former deformation twins from the state of dynamic recrystallization.

Carbonates and quartzites from the eastern contact zone between Gemericum and Veporicum

The calcite marbles behaviour during ductile shearing has been studied on sample locality Košice-Diana (**DI1**, **DI2**, **DI3**, AS_2 = *235/45*). Marbles showed dynamically recrystallized layers (medium to fine-grained) alternating with layers of flattened, elongated twinned grains

(Németh and Putiš, 1999). The textural patterns reflect both combined dislocation creep and mechanical e-twinning as the plastic deformation mechanisms. The representative grain size of marbles is 54.95 µm (**DI1**), 85.02 µm (**DI2**) and 95.19 µm (**DI3**). Differential stresses found from three marble samples by both methods are mutually comparable (cf. Tab. 1). As the most representative results are supposed those, reached by the Twin Density method calculated with variation coefficient **DI1** = 253.71 MPa, **DI2** = 230.16 MPa and **DI3** = 228.82 MPa.

The quartz paleopiezometry on quartzite samples **DI9**, **DI10** and **DI12** located in immediate vicinity of marble samples at Diana locality showed large diversity of results. Geologically the most meaningful results were obtained by calibration by Koch (1983): **DI9** = 151.3 MPa, **DI10** = 195.0 MPa and **DI12** = 169.8 MPa (Fig. 2). When comparing results from neighbouring calcite marbles and quartzites, the differential stresses in dynamically recrystallized quartzite horizon were lower. There is necessary to stress that the quartz paleopiezometry is based only on one parameter - the size of dynamically recrystallized grain. Therefore the results of calcite paleopiezometry calculating with more parameters (grain-size, number and orientation of deformation twins) can be supposed to be more credible. Despite weakness of quartz paleopiezometry, the tectonic reasons of lower differential stresses in quartzite bed than in marble bed are meaningfully explainable, as stated in the next chapter.

Discussion

Tectonization of Lower Paleozoic sequences

It is commonly known that polymineralic rocks are rheologically harder than monomineralic ones owing to their numerous phase boundaries and different internal free energies of minerals. Presented study, using known calibrations for monomineralic calcitic marbles and quartzites, states the differential stresses during tectogenesis in principal ductile shear zones in Gemeric region.

Because the absence of suitable monomineralic rocks directly in ductile shear zone between Gelnica and Rakovec Groups with kinematics of Variscan exhumation (Németh, 2002), our attempt to state differential stresses in Lower Paleozoic rock column was restricted to marble lenses from Holec Beds (Betliar Formation; Lower Paleozoic of Gelnica Group; cf. Fig. 2 in l.c.; Figs. 1 and 3).

More-or-less continual and homogenous horizon of black phyllites with organic matter (tectonization facilitated with fluid deliberation), located on lithologically and rheologically heterogeneous footwall (?variegated coarse-grained sediments, resp. ?Proterozoic basement), as well as hanging wall (variegated Lower Paleozoic sequences) satisfies conditions for preferred detachment plane. Strong rheological contrasts were effective after metamorphic compaction during Variscan orogeny. Moreover it is necessary to mention that this horizon, in difference to rocks of higher stratigraphic levels of Lower Paleozoic, very probable has not been deformed during south-vergent Variscan tectogenesis. Its primary "colmatage" position on significantly more rigid crystalline basement (with depressions infilled with coarser detritus) in comparison with "softer" plastic and relatively thin sedimentary and volcanic Paleozoic rocks in overlier, preserved this horizon in low differential stresses (compare results of paleopiezometry of sample GO1 and other Lower Paleozoic calcitic marbles in Table 1, Fig. 1). It is therefore very probable, that this rheologically distinct and tabular horizon of black phyllites of Betliar Fm., bearing interbeds of carbonates and lydites in its upper part, has been preserved against deformation till Cretaceous when it served as the main detachment horizon during Alpine overthrusting of Gemericum on Veporicum as well as internal imbrication in Gemericum (Fig. 3). The relative low differential stresses found in calcite lenses (**GO1**, **HO1** and **HO3;** compare Table 1, Fig. 1) are in accordance with the fact that the north-vergent overthrusting was accommodated by their host black phyllites. Based on results of regional meso- and microstructural analysis and overprinting relations (Németh, 2002) we correlate the deformation and recrystallization of carbonatic lenses of Holec Beds with Alpine AD_1 thrusting in Lower Cretaceous. The Alpine north-vergent reverse faulting – imbrication of Lower Paleozoic Gemeric sequences (marked with white arrows in Fig. 1 and AD_1b in Fig. 3) caused not only the superficial presence of thin strips of black phyllites of Betliar Fm. (with marbles and lydites of Holec Beds), but also several times repeated stratigraphy (Betliar Fm., Smolník Fm. and Hnilec Fm.) in generally E-W trending strips in central and southern parts of Gemericum.

Bôrka nappe - southern vs. northern occurrences

The north-vergent Bôrka nappe transport and emplacement were formerly characterized with LPO data of various kinds of tectonites (Németh, 2001). From this viewpoint the interesting result was brought by proof of NE-vergent sense of displacement in oriented marble sample from so-called Jaklovce Meliaticum (l.c.).

As paleopiezometry has showed us, the Bôrka nappe newly distinguished northern occurrences (**KS1A**, **JA3A**, **MS6**, **MS7**) demonstrate higher differential stresses than the Bôrka nappe marbles from the type localities in Southern Gemericum (**ŠU23B**, **ŠP20A**, **ZD1A**; Fig. 1). It can be explained by "frozing" of deformation in frontal parts of the nappe, while later exhumed parts had more time for recovery and ongoing static recrystallization. The complex evolution of Bôrka nappe marbles from Southern Gemericum is reflected in three generations of twins – the higher temperature usually bended twins of low number, being developed in large, totally recrystallized calcite grains (dimensions 300-400 µm), are overprinted by extremely numerous thin straight twins of razor type, and all these are penetrated by brittle low temperatures fractures.

Differential stresses during Alpine unroofing kinematics in the eastern part of contact zone between Veporicum and Gemericum

The superficial projection of the nappe emplacement of Gemericum on Veporicum in recent erosion cut is re-

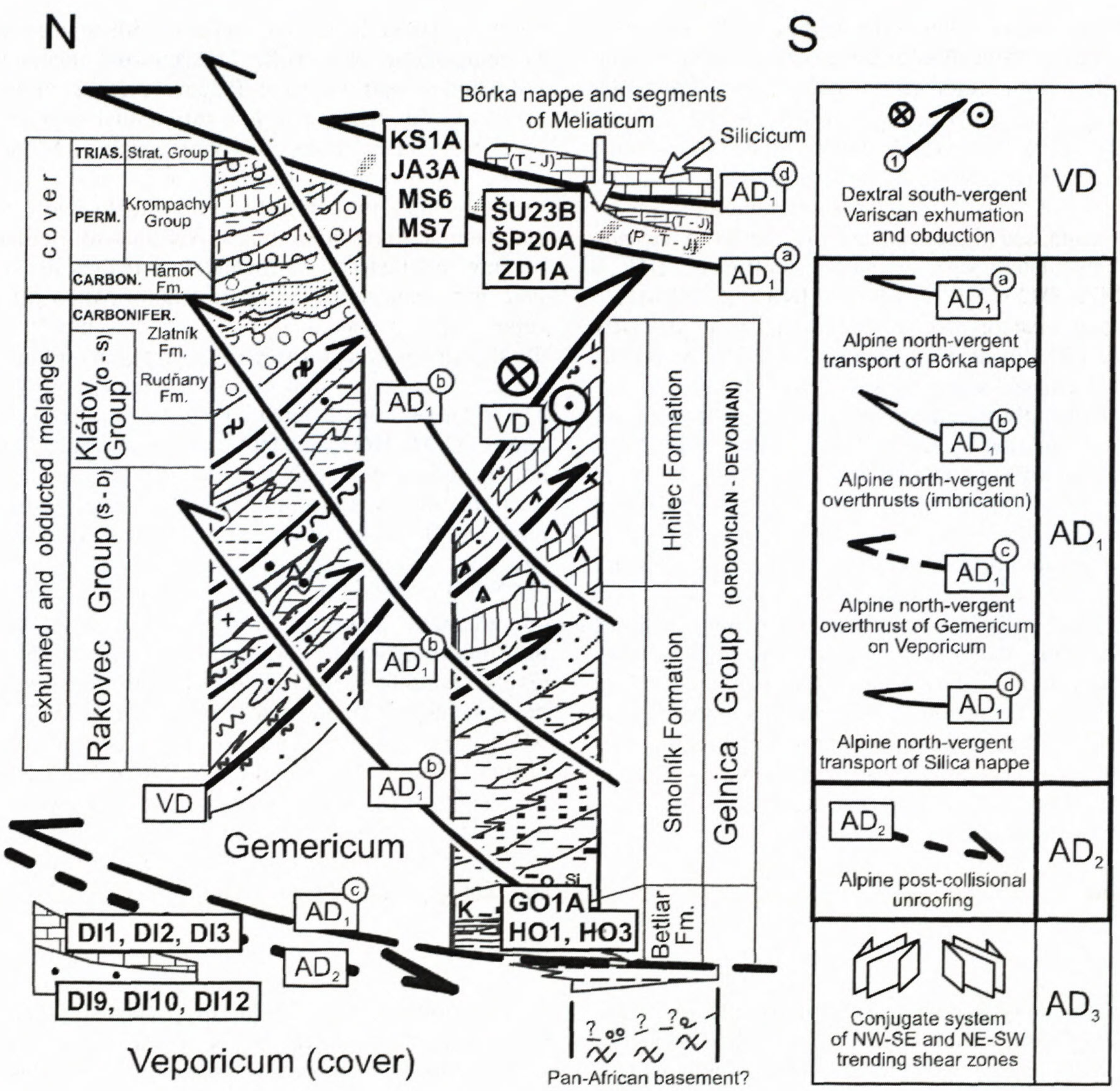


Fig. 3. Lithotectonic relations in Gemeric region (modified after Németh, 2001) and location of studied samples in lithotectonic horizons. Paleopiezometry documented differential stresses during dynamic recrystallization of selected samples during Alpine phases AD_1 and AD_2. For lithostratigraphic affiliation of studied samples, positioned in lithotectonic columns, see text and location of samples in explanation to Fig. 1.

presented with Lubeník-Margecany line. In the eastern – Margecany part of the zone, the mesostructural and microstructural evidences of the Gemeric nappe overthrust on Veporicum were given by numerous work (e.g. Jacko, 1978; Gazdačko, 1994; Jacko et al., 1996, 1997a,b).

The Alpine post-collisional unroofing, known formerly only in the western part of the contact zone (Upper Cretaceous tectonometamorphic ages; Maluski et al., 1993; Kováčik and Maluski, 1995; Dallmeyer et al., 1996), was revealed also in its eastern Margecany zone (Németh, 2001 and following works). The microtectonic research of deformation gradient in Margecany zone (l.c.) showed an important role of Triassic quartzites and carbonatic marbles of Veporic cover as the most softened horizons during Alpine ductile SW-vergent low angle normal faulting. The recent picture of apparently opposite kinematics of unroofing in the western and eastern part of the Lubeník-Margecany line was the product of shifting and rotation of rock blocks owing to displacement on conjugate system of shear zones of NW-SE and NE-SW directions with brittle-ductile to brittle shearing (AD_3; white half-arrows in Fig. 1; cf. Grecula et al., 1990; Gazdačko, 1994; Németh et al., 1997).

In attempt to document this process, the differential stresses from calcitic marbles (DI1, DI2 and DI3, Figs. 1 and 3, Tab. 1) as well as quartzites (DI9, DI10 and DI12) were determined and mathematically expressed. The presence of two monomineralic horizons contacting each other allowed us to test various calibrations of calcite and quartz paleopiezometry. From the large diversity of results for quartz paleopiezometry, the geologically most meaningful ones were obtained by calibration by Koch (1983) when inputting the average diameter of grains (Fig. 2). The differential stresses in dynamically recrystallized quartzite horizon were lower than in the case of marble horizons. This indicates, that (1) quartzite bed represented the softer medium than marble bed during the same tectonic process and smaller differential stresses were necessary for its kinematic activity, or (2) the marble bed was located closer to thrust plane (compare position of both beds in Fig. 3) and thus suffered higher differential stresses.

Conclusions

Research tested two methods of calcite paleopiezometry (Twinning Incidence and Twin Density, Rowe and Rutter, 1990) as well as quartzite paleopiezometry and obtained new data about the values of differential stresses accommodated by samples from principal ductile shear zones of Gemericum. Data are in agreement with recent interpretation of Alpine Lower Cretaceous overthrusting and imbrication during AD_1 phase, the Bôrka nappe transport through Gemericum and confirm and express the differential stresses during the post-collisional normal faulting AD_2 in the eastern contact zone between Gemericum and Veporicum.

When comparing both methods of calcite paleopiezometry – Twinning Incidence and Twin Density, the method of Twin Density with inputted variation coefficient 0.25 brought geologically best reliable and interpretable data. The Twin Density method takes into account not only number of grains with deformation twins, but the number of twins measured for the 1 mm distance perpendicularly to course of twins. This method is recommended for prior use in further tectonic research.

In the quartz paleopiezometry the calibration by Koch (1983), accounting the average diameter of grains, brought the results best converging to those of calcite paleopiezometry. When comparing results from neighbouring calcite marbles and quartzites, the differential stresses in dynamically recrystallized quartzite horizon were lower. This indicates, that quartzite bed represented either softer medium than marble bed during the same tectonic process, or marble bed was located closer to thrust plane.

New data contributed to geological and tectonic interpretation of geodynamic evolution of Inner Western Carpathians.

Acknowledgement

Author expresses his thanks to Professor Marián Putiš for guidance and fruitful discussions during author's Ph.D. studies in Comenius University, Bratislava, in 1998 – 2001.

References

Christie, J. M. & Ord, A., 1980: Flow stress from microstructures of mylonites: Example and current assessment. J. Geophys. Res., 85, 6253-6262.

Dallmeyer, R. D., Neubauer, F., Handler, R., Fritz, H., Müller, W., Pana D. & Putiš, M., 1996: Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole-rock data. Eclogae geol. Helv., 89/1, 203-227.

Etheridge, M. A. & Wilkie, J. C., 1981: An assessment of dynamically recrystallized grainsize as a paleopiezometer in quartz-bearing mylonite zones. Tectonophysics, 78, 475-508.

Gazdačko, Ľ., 1994: Polyphase deformational development in the eastern part of contact zone of Gemericum and Veporicum (Western Carpathians). Mineralia Slov., 26, 387 - 398. (In Slovak).

Grecula, P., Návesňák, D., Bartalský, B., Gazdačko, Ľ., Németh, Z., Ištván, J. & Vrbatovič, P., 1990: Shear zones and arc structure of Gemericum, the Western Carpatians. Mineralia slov., 22, 97-110.

Jacko, S., 1978: Lithological-structural characteristics of the central part of Čierna hora Mts. Západné Karpaty, sér. geológia, 3, 59-80. (In Slovak)

Jacko, S., Sasvári, T., Zacharov, M., Schmidt, R. and Vozár, J., 1996: Contrasting styles of Alpine deformations at the eastern part of the Veporicum and Gemericum units, Western Carpathians. Slovak Geol. Mag., 2, 151-164.

Jacko, S., Hók, J. & Madarás, J., 1997a: Pre- and syn-granitoid deformations of the Western Carpathian metamorphic complexes. In: P. Grecula, D. Hovorka & M. Putiš (Eds.). Geological evolution of the Western Carpathians. Mineralia Slovaca - Monograph, Bratislava, 359-370.

Jacko, S., Vozár, J. & Polák, M., 1997b: Tectonics. In: M. Polák: Explanations to geological map of Branisko and Čierna hora, 1 : 50 000. Dionýz Štúr Publishers, Bratislava, 124-148. (In Slovak)

Koch, P. S., 1983: Rheology and microstructures of experimentally deformed quartz aggregates. Ph.D. thesis, Univ. California, Los Angeles.

Kováčik, M. & Maluski, H., 1995: Alpine reactivaction of the Eastern Veporic basement metamorphites (Western Carpathians). Terra Nova, 7, Abstract suppl. 1, 45.

Maluski, H., Rajlich, P. a Matte, P., 1993: ^{40}Ar-^{39}Ar dating of the Inner Carpathians Variscan basement and Alpine mylonitic overprinting. Tectonophysics, 223, 313 - 337.

Mello, J. (ed.), 1997: Explanations to geological map of Slovak Karts, 1 : 50 000. Dionýz Štúr Publishers, Bratislava, 1-255. (In Slovak)

Mercier, J. C., Anderson, D. A. & Carter, N. L., 1977: Stress in the lithosphere: Inferences from steady-state flow of rocks. Pure Appl. Geophys., 115, 119-226.

Michibayashi, K., 1993: Syntectonic development of a strain-independent steady-state grain size during mylonitization. Tectonophysics, 222, 151-164.

Németh, Z., 2001: Petrotectonics of the ductile shear zones of Gemericum. Ph.D. thesis. Comenius Univ., Bratislava, 1-98.

Németh, Z., 2002: Variscan suture zone in Gemericum: Contribution to reconstruction of geodynamic evolution and metallogenetic events of Inner Western Carpathians. Slovak Geol. Mag., 8, 3-4, 247-257.

Németh, Z., Gazdačko, Ľ., Návesňák, D. & Kobulský, J., 1997: Polyphase tectonic evolution of Gemericum (Western Carpathians) outlined by review of structural and deformational data. In: P. Grecula, D. Hovorka a M. Putiš (red.): Geological evolution of Western Carpathians. Monografia Mineralia Slovaca.

Németh, Z. & Putiš, M., 1999: Microfabrics, kinematics and differential stresses at the eastern contact zone of Gemericum with Veporicum (the Košice-Diana locality, Western Carpathians). Acta Mont. Slov., 4, 195-216.

Passchier, C. W & Trouw, R. A. J., 1996: Microtectonics. Springer, 1-289.

Post, A. & Tullis, J., 1999: A recrystallized grain size piezometer for experimentally deformed feldspar aggregates. Tectonophysics, 303, 159-173.

Ranalli, G., 1984: Grain size distribution and flow stress in tectonites. J. Struct. Geol., 6, 443-447.

Rowe, K. J. & Rutter, E. H., 1990: Paleostress estimation using calcite twinning: Experimental calibration and application to nature. J. Struct. Geol., 12, 1-17.

Schmid, S. M., Paterson, M. S. & Boland, J. N., 1980: High temperature flow and dynamic recrystallization in Carrara marble. Tectonophysics, 65, 245-280.

Twiss, R. J., 1977: Theory and applicability of a recrystallized grain size piezometer. Pure Appl. Geophys., 115, 227-244.

Instructions for authors

Slovak Geological Magazine – periodical of the Geological Survey of Slovak Republic is quarterly presenting the results of investigation and researches in wide range of topics: regional geology and geological maps, lithology and stratigraphy, petrology and mineralogy, paleontology, geochemistry and isotope geology, geophysics and deep structure, geology of deposits and metallogeny, tectonics and structural geology, hydrogeology and geothermal energy, environmental geochemistry, engineering geology and geotechnology, geological factors of the environment, petroarcheology.

The journal is focused on problems of the Alpine-Carpathian-Balkan region

General instructions

The Editorial Board of the Geological Survey of Slovak Republic – Dionýz Štúr Publishers accepts manuscripts in correct English. The papers that do not have sufficient accuracy in language level will be submitted back for language correction.

The manuscript should be addressed to the Chief Editor or the Managing Editor.

Contact address:

Geological Survey of Slovak Republic – Dionýz Štúr Publishers, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic

e-mail addresses: hok@gssr.sk
siposova@gssr.sk
http://www:geology.sk

The Editorial Board accepts or refuses a manuscript with regard to the reviewer's opinion. The author is informed of the refusal within 14 days from the decision of the Editorial Board. Accepted manuscript is prepared for publication in an appropriate issue of the Magazine. The author(s) and the publishers enter a contract establishing the rights and duties of both parties during editorial preparation and printing, until the time of publishing of the paper.

Text layout

The manuscript should be arranged as follows: TITLE OF THE PAPER, FULL NAME OF THE AUTHOR(S); NUMBER OF SUPPLEMENTS (in brackets below the title, e.g. 5 figs., 4 tabs.), ABSTRACT (max. 30 lines presenting principal results) – KEY WORDS – INTRODUCTION – TEXT – CONCLUSION – ACKNOWLEDGEMENTS – APPENDIX – REFERENCES – TABLE AND FIGURE CAPTIONS – TABLES – FIGURES. The editorial board recommends to show a localisation scheme at the beginning of the article.

The title should be as short as possible, but informative, compendious and concise. In a footnote on the first page, name of the author(s), as well as his (their) professional or private address.

The text of the paper should be logically divided. For the purpose of typography, the author may use a hierarchic division of chapters and sub-chapters, using numbers with their titles. The editorial board reserves the right to adjust the type according to generally accepted rules even if the author has not done this.

Names of cited authors in the text are written without first names or initials (e.g. Štúr, 1868), the names of co-authors are divided (e.g. Andrusov & Bystricky, 1973). The name(s) is followed by a comma before the publication year. If there are more authors, the first one, or the first two only are cited, adding et al. and publication year.

Mathematical and physical symbols of units, such as %, ‰, °C should be preceded by a space, e.g. 60 %, 105 °C etc. Abbreviations of the units such as second, litre etc. should be written with a gap. Only SI units are accepted. Points of the compass may be substituted by the abbreviations E, W, NW, SSE etc. Brackets (parentheses) are to be indicated as should be printed, i.e. square brackets, parentheses or compound. Dashes should be typed as double hyphens.

If a manuscript is typed, 2 copies are required, including figures. The author should mark those parts of a text that should be printed in different type with a vertical line on the left side of the manuscript. Paragraphs are marked with 1 tab space from the left margin, or by a typographic symbol. Words to be emphasized, physical symbols and Greek letters to be set in other type (e.g. *italics*) should be marked. Greek letters have to be written in the margin in full (e.g. *sigma*). Hyphens should be carefully distinguished from dashes.

Tables and figures

Tables will be accepted in a size of up to A4, numbered in the same way as in a text.

Tables should be typed on separate sheets of the same size as text, with normal type. The author is asked to mark in the text where the table should be inserted. Short explanations attached to a table should be included on the same sheet. If the text is longer, it should be typed on a separate sheet.

Figures should be presented in black-and-white, in exceptional cases also in colour which must be paid approx. 100 EUR per 1 side A 4. Figures are to be presented by the author simultaneously with the text of the paper, in two copies, or on a diskette + one hard copy. Graphs, sketches, profiles and maps must be always drawn separately. High-quality copies are accepted as well. Captions should be typed outside the figure. The graphic supplements should be numbered on the reverse side, along with the orientation of the figures. Large-size supplements are accepted only exceptionally. Photographs intended for publishing should be sharp, contrast, on shiny paper. High quality colour photographs will only be accepted depending on the judgement of the technical editors.

If a picture is delivered in a digital form, the following formats will be accepted: *.cdr, *.dxf, *.bmp, *.tiff, *.wpg, *.fga., *.jpg *.gif, *.pcx. Other formats are to be consulted with the editors.

References

Should be listed in alphabetical and chronological order **according to annotation in the text** and consist of all references cited.

Standard form is as follows: 1. Family name and initials of author(s), 2. Publication year, 3. Title of paper, 4. Editor(s), 5. Title of proceedings, 6. Publishers or Publishing house and place of publishing, 7. Unpublished report – manuscript should be denoted MS. Unpublished paper can appear as personal communications only. 8. Page range

Quotations of papers published in non-Latin alphabet or in languages other than English, French, Italian, Spain or German ought to be translated into English with an indication of the original language in parentheses, e.g.: (in Slovak).

Example:

Andrusov, D., Bystrický, J. & Fusán, O., 1973: *Outline of the Structure of the West Carpathians*. Guide-book for geol. exc. of X[th] Congr. CBGA. Bratislava: Geol. Úst. D. Štúra, 44 p.

Beránek, B., Leško, B. & Mayerová, M., 1979: Interpretation of seismic measurements along the trans-Carpathian profile K III. In: Babuška, V. & Plančár, J. (Eds.): *Geodynamic investigations in Czecho-Slovakia*. Bratislava: VEDA, p. 201-205.

Lucido, O., 1993: A new theory of the Earth's continental crust: The colloidal origin. *Geol. Carpathica*, vol. 44, no. 2, p. 67-74.

Pitoňák, P. & Spišiak, J., 1989: Mineralogy, petrology and geochemistry of the main rock types of the crystalline complex of the Nízke Tatry Mts. MS – Archiv GS SR, Bratislava, 232 p. (in Slovak).

Proofs

The translator as well as the author(s) are obliged to correct the errors which are due to typing and technical arrangements. The first proofs are sent to author(s) as well as to the translator. The second proof is provided only to the editorial office. It will be sent to authors upon request.

The proofs must be marked clearly and intelligibly, to avoid further errors and doubts. Common typographic symbols are to be used, the list and meaning of which will be provided by the editorial office. Each used symbol must also appear on the margin of the text, if possible on the same line where the error occurred. The deadlines and conditions for proof-reading shall be stated in the contract.

Final remarks

These instructions are obligatory to all authors. Exceptions may be permitted by the Editorial Board or the managing editor. Manuscripts not complying with these instructions shall be returned to the authors.

1. Editorial Board reserves the right to publish preferentially invited manuscript and to assemble thematic volumes,
2. Sessions of Editorial Board – four times a year and closing dates for individual volumes will be on every 31[th] day of March, June, September and December.
3. To refer to one Magazine please use the following abbreviations: *Slovak Geol. Mag.*, vol. xx, no. xx. Bratislava: D. Štúr. Publ. ISSN 1335-096X.

Indexed/Abstracted in: Chemical Abstracts, Ulrich´s International Periodical