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LOW-TEMPERATURE METASEDIMENTS FROM THE NÍZKE TATRY MTS. (WESTERN CARPATHIANS)

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Abstract: This paper describes the petrological and mineralogical features of the quartz-muscovite metasandstones (QMM), a lithology found in the form of tectonic slices in an augen-gneissic environment N and W of Jasenie, Nízke Tatry Mts., Western Carpathians. These rocks have an exemplary psammitic texture, and are composed of detritic phases, represented by oval quartz grains, large muscovite flakes and sparse individual grains of albite and metamorphic phases consisting mainly of quartz and microcrystalline aggregate of muscovite-phengitic mica. Small amounts of tiny, metamorphic, newly formed albite and needle-like tourmaline are accompanied by scattered scales of chlorite and crystals of magnetite. Neither the QMM nor the associated siderite-ankerite metasandstones and phyllites (SAMP) contain biotite indicating that their metamorphic degree did not reach the biotite subzone. The total content of alkalies in the metamorphic muscovite-phengites is fairly high (>0.86 per formula unit), thus, they should be illite-free and their estimated degree of metamorphism should correspond to the epizone. This estimate is also supported by the incomplete compositional and grain size equalization between clastogenic and metamorphic white potash micas at their contacts. In contrast, the metamorphic white micas are considerably enriched in the phengite molecule. The X-ray and selected area electron diffraction (SAD) analyses made to visualize and to measure the crystallinity of individual carbonaceous matter (CM) particles revealed that most samples are composed of a mixture of anthracitic and graphitic carbon. While the anthracite is an indicator of very low metamorphism, the graphite first forms under greenschist facies conditions. A search for non-graphitizing carbons, such as shungite, skeleton crystals, or fullerenes, which form under medium or high-grade metamorphism, has been unsuccessful. Thus, all the ill-ordered carbons in the samples developed under low-grade metamorphism. This conclusion supports the authors' earlier view that the rocks under study are metasediments and not diaphthorites.

Key words: metasediments, low-grade metamorphism, mineralogy of mica, crystallinity of carbon, correlations.

Introduction

The objective of this paper is to describe mineralogical and petrological features of quartz-muscovite metasandstones (QMM) that occur as tectonic slices in the augen-gneissic environment N and W of Jasenie village, Nízke Tatry Mts., (Tatric Superunit). It is a follow-up of our previous petrographic study (Korikovsky & Molák 1995) of the siderite-ankerite metasandstones and phyllites (SAMP), with which the QMM form a common metasedimentary suite and share tectono-metamorphic development. Both rock types were discovered in the eighties, during the course of geological mapping carried out as part of an exploratory programme to investigate local Au-W mineralization. As an update to the methods and criteria to distinguish the sedimentary features from the diaphthoritic we have undertaken a study of two important, albeit quantitatively differing constituents of the QMM — white micas and carbonaceous matter (CM), the former using a microprobe and the latter using transmission electron microscopy (TEM), selected area electron diffraction (SAD), X-ray diffraction, differential thermic and thermo-gravimetric (DTA and TGA) analyses.

Since the QMM are generally more susceptible to weathering than their augen-gneissic host, they are very poorly exposed. This is why the best samples for this study were collected from the diamond drill cores and/or from the tunnels driven during the above mentioned exploratory campaign. The location of the QMM occurrences and samples is shown on Fig. 1.

Geological setting of the low-grade metamorphic rocks

Klinec (in Pulec et al. 1983) described occurrences of low-grade metamorphosed rocks in the augen-gneissic environment in the area N of Jasenie village (Fig.1). He and his adherents claimed that these rocks, emplaced as tectonic slices, not only have an appearance but also a mineral composition similar to that of their host — augen-gneissic mylonites, so, the two rocks can easily be confused. Other geologists, represented by Miko (in Miko & Lukáčik 1983), refused the presence of low-grade rocks and described them simply as mylonites of local medium- to high-grade rocks.

To solve the dispute Vozárová (1983) made a detailed petrological study of the problematic rocks and found, among the mylonites, fine-grained conglomerates, gravelites, greywackes and sericitic phyllites which she assigned to a Late Paleozoic–Lower Triassic metasedimentary assemblage.

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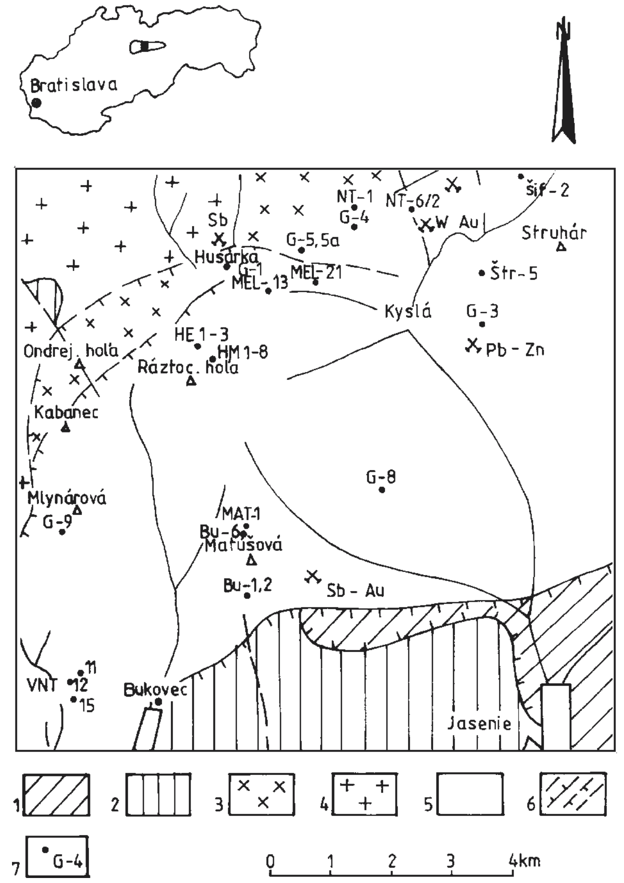

Fig. 1. Schematic geological map of the central-western part of the Nízke Tatry Mts. (after A. Biely, O. Miko, I. Lehotský, E. Lukáčik, A. Klinec, B. Molák, J. Michálek et al. with sample locations). Inset shows location of the Nízke Tatry Mts. and the area under study. *Legend:* 1 — Mesozoic nappes; 2 — Mesozoic cover; 3 — nebulitic migmatite; 4 — granitoids; 5 — crystalline schists; 6 — tectonic lines; 7 — QMM sample locations. Crossed hammers: mines (abandoned) with the main metals mined.

Furthermore, Planderová (1983) identified sporomorphs indicating Stephanian C to Early Permian age in the dark phyllitic rocks of this assemblage, thus, the sedimentary and low-grade metamorphic origin of these rocks seemed to be justified.

Further search for low-grade rocks resulted in a finding of other metasedimentary looking rocks wedged in the tectonic zones (Molák et al. 1986), in which Planderová (1986) identified Early Paleozoic microfossils.

The above findings did not help solve the dispute, because the "tectonists" denied sedimentary structures, low-grade prograde metamorphism of rock-forming minerals, as well as the authenticity of sporomorphs in the problematic rocks.

Analytical methods

The Camscan microprobe analyzer installed at the Department of Petrology, Moscow University, was used to assay the chemical composition of the rock-forming minerals. The whole rock chemical analyses were made in the laboratory of Dionýz Štúr Institute of Geology and in the laboratories of the Geological Survey in Brno, or in Spišská Nová Ves. The interlayer distances (d(002)-parameters) in CM powder preparates were measured on a Philips 1050 with a goniometer 1050 operating with the crystal reflected Ni-filtered, CuKα-radiation, installed at the Geological Institute of the Slovak Academy of Sciences and on an URD-6. The ZDS program, version 5.17 was applied to process the data. A few samples were analysed using the STOE powder diffraction system, stationed at the Institute of Inorganic Chemistry, Slovak Academy of Sciences in Bratislava. Because the contents of CM in the QMM were usually too low to apply the X-ray powder diffraction method (some 0.1 wt. %, or even less) we used the JEOL JEM-200CX and JEM-100 transmission electron microscopes, the former installed at the Centre for Physiological Research and the latter at the Institute of Materials and Mechanics of Machines, Slovak Academy of Sciences in Bratislava, in order to visualize single CM particles and to measure their d-parameters by means of selected area diffraction. The SAD pattern of a standard (gold) has been recorded immediately after each exposure of CM particle to avoid any degree of freedom (such as the effects of electricity fluctuations, focal distance deviations, etc.) in the subsequent calculation. In a few cases the standard was mounted onto the preparate to record both *hkl* bands simultaneously. The SAD patterns exposed on glass slides proved to be most suitable for measuring the diffraction ring diameters on a micrometric gauge with an accuracy of 1/100 mm. Construction of a regression line computed from the *hkl* values of the standard was followed by an iteration procedure to exactly calculate the interlayer distances d(002). The EDAX systems attached to both TEMs were also used, firstly to assist indirectly in selecting carbon particles (carbon, with its atomic number 6 gives no response) and secondly to indicate and study inclusions in the carbon particles.

Petrographic features and mineral composition

An important petrological feature preserved in several QMM samples is their exemplary psammitic texture accounted for by the arrangement of clastogenic or detritic and meta-

Table 1: Mineral content of the quartz-mica carbonate-free metasandstones.

	Metamorphic minerals						**Detritic minerals**		
SAMPLE	Qtz	Ser	Chl	Ab	Tour	Ore	Qtz	Ms	Ab
HE-3	+	+	±	±	-	±	+	+	-
MEL-13	+	+	-	-	-	+	+	+	-
G-4	+	+	+	-	-	±	+	+	-
G-5A	+	+	-	-	-	-	+	+	-
BU-6	+	+	+	-	-	±	+	+	-
HM-8	+	+	-	±	-	±	+	+	±
ŠTR-5	+	+	+	-	±	±	+	+	-
ŠIF-2	+	+	±	±	-	±	+	-	-
BU-2	+	+	-	-	±	±	+	±	-

Minerals: + major; ± minor; - absent

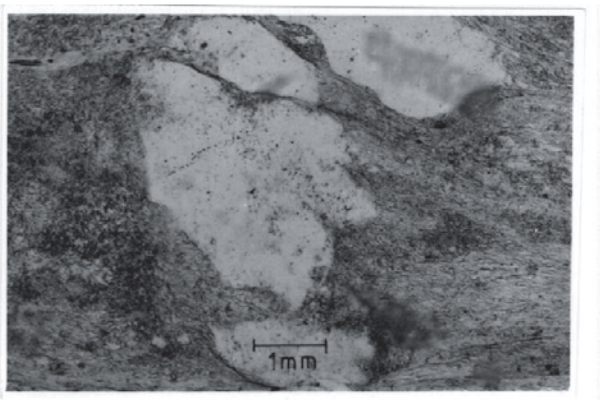

Fig. 2. Clastogenic quartz in quartz–sericite mesostasis. Sample HE-1. //nicols.

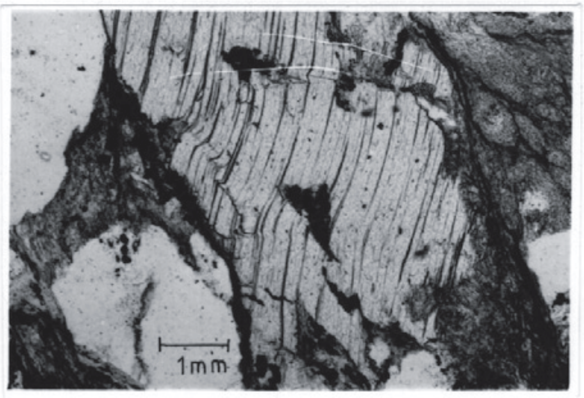

Fig. 3. Clastogenic muscovite in sample HE-3. //nicols.

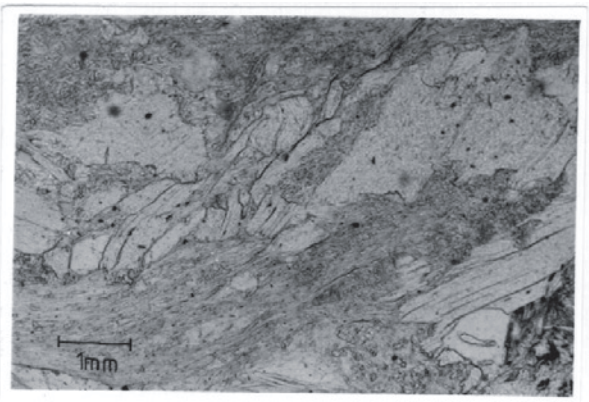

Fig. 4. Clastogenic muscovite in quartz–sericite mesostasis. Sample HE-3. //nicols.

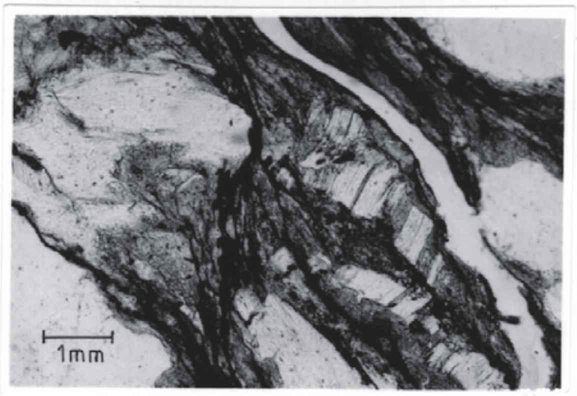

Fig. 5. Destruction and resorption of clastogenic muscovite in quartz–sericite mesostasis. Sample HE-2. //nicols.

morphic minerals (Table 1). The detritic phases comprise oval quartz grains, large muscovite flakes and rare individual grains of albite. In contrast, quartz and sericite (metamorphic microcrystalline aggregate of muscovite-phengitic mica) are predominant constituents of the metamorphic fraction. Small amounts of tiny, metamorphic, newly-formed albite, chlorite as scattered scales, dispersed crystals of magnetite and small needles of newly-formed tourmaline were also encountered in some samples.

The absence in the clastic fraction of albite and, moreover, of potash feldspar, indicate a monomict rather than a polymict origin of these minerals and suggests a prolonged sedimentary process, accompanied by considerable mass transport of clastic material.

Clastogenic minerals

Most quartz grains are well rounded and measure 2–3 mm across. Their rounding demonstrates that the origin of their host rock is sedimentary. As a subject of tectono-metamorphic processes, quartz was fractured and the voids in it were filled with sericite or with secondary, newly formed quartz. The blastomylonitization brought about an elongation, or dismembering of rounded quartz grains and caused secondary extinction under crossed polars.

Muscovite forms large flakes, locally affected by plastic deformation (Fig. 3), oriented either at random or perpendicular to the rock schistosity (defined by the arrangement of metamorphic sericites, see Fig. 4). As a result of metamorphic processes local desintegration of clastogenic muscovites took place and included a partial substitution by sericite-quartzite aggregate (Fig. 5). The following features characterize the composition of clastic muscovite (Tables 2 and 3): **1)** increased content of TiO_2 (as much as 1.48 %), **2)** high total content of (Na+K) (exceeding 0.9 per formula unit) and **3)** moderate admixture of Na and (Mg+Fe). All these features make this muscovite akin to granitic muscovites (Speer 1984). Elevated CaO contents in samples Mel-13 and Šif-2 are probably due to some contamination. We have no explanation for the much higher than general content of Na_2O in the sample G-4.

Metamorphic minerals

Fine-grained sericite makes up as much as 70 % of the metamorphic fraction and is a major constituent of the matrix. Its composition is characterized by a relatively high content of (Na+K) in the interlayer positions (0.86–0.95 per formula unit) and by variable abundances of Mg and Fe. Therefore, it can be classified as muscovite-phengite, a min-

Table 2: Representative microprobe analyses of the metamorphic, fine-grained sericites from quartz-mica metasandstones.

Sample	HE-3		MEL-13	G-4		G-5A		BU-6		HM-8	ŠTR-5		ŠIF-2		BU-2	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	48.68	48.34	48.40	47.45	48.63	48.62	48.41	49.34	49.18	48.87	49.63	50.08	49.69	49.61	49.17	49.17
TiO_2	0.28	0.25	0.21	0.13	0.25	0.05	0.17	0.32	0.39	0.16	0.46	0.35	0.55	0.50	0.47	0.43
Al_2O_3	32.95	33.17	31.90	37.69	35.91	34.56	34.47	29.30	28.25	29.39	29.56	28.63	25.13	24.98	30.22	30.39
FeO	1.76	1.67	2.51	0.13	0.59	0.74	0.80	3.23	4.50	5.22	3.04	3.36	6.12	5.90	2.82	2.97
MnO	-	-	0.02	-	-	0.11	0.03	-	-	-	-	0.05	-	0.02	0.07	-
MgO	1.17	0.96	1.48	0.04	0.51	0.98	0.88	2.58	2.62	1.88	2.35	2.32	3.36	3.30	1.63	1.64
CaO	0.03	0.13	-	0.02	-	0.02	0.05	0.01	-	0.04	0.01	0.10	0.19	0.06	0.13	0.15
Na_2O	0.07	0.26	0.31	1.51	1.22	0.14	0.13	-	-	0.04	0.13	0.20	0.08	0.13	0.05	0.04
K_2O	10.55	10.54	10.08	8.73	8.56	10.30	10.35	10.82	10.78	9.97	10.27	10.48	10.58	10.68	10.54	10.87
Total	95.49	95.29	94.89	95.70	95.67	95.52	95.29	95.60	95.72	95.57	95.45	95.57	95.70	95.18	95.10	95.66
Si	3.22	3.21	3.23	3.09	3.16	3.20	3.19	3.30	3.31	3.29	3.31	3.35	3.38	3.39	3.29	3.28
AlIV	0.78	0.79	0.77	0.91	0.84	0.80	0.81	0.70	0.69	0.71	0.69	0.65	0.62	0.61	0.71	0.72
AlVI	1.79	1.81	1.74	1.98	1.92	1.88	1.87	1.61	1.55	1.62	1.63	1.61	1.39	1.40	1.67	1.67
Ti	0.01	0.01	0.01	0.01	0.01	-	0.01	0.02	0.02	0.01	0.02	0.02	0.03	0.03	0.02	0.02
Fe	0.10	0.09	0.14	0.01	0.03	0.04	0.04	0.18	0.25	0.29	0.17	0.19	0.35	0.34	0.16	0.17
Mn	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-
Mg	0.12	0.10	0.15	-	0.05	0.10	0.09	0.26	0.26	0.19	0.23	0.23	0.34	0.34	0.16	0.16
Ca	-	0.01	-	-	-	-	-	-	-	-	-	0.01	0.01	-	0.01	0.01
Na	0.10	0.09	0.04	0.19	0.15	0.02	0.02	-	-	-	0.02	0.03	0.01	0.02	0.01	-
K	0.89	0.90	0.86	0.73	0.71	0.86	0.87	0.92	0.92	0.86	0.87	0.89	0.92	0.93	0.90	0.93

Table 3: Representative microprobe analyses of the detritic, coarse-grained muscovites from quartz-mica metasandstones.

Sample	HE-3		Mel-13		G-5A		BU-6	HM-8	Štr-5	Bu-2
	1	2	3	4	5	6	7	8	9	10
SiO_2	46.84	47.05	47.19	47.41	46.86	46.95	46.74	47.06	47.06	48.00
TiO_2	0.83	1.48	1.12	1.71	1.20	1.09	0.89	1.36	0.63	0.87
Al_2O_3	34.66	34.88	35.27	33.15	35.08	35.13	35.82	34.81	35.55	33.65
FeO	1.33	1.35	1.22	1.42	1.26	1.43	0.99	1.32	1.50	1.80
MnO	0.02	-	0.06	-	-	0.06	-	0.07	-	0.02
MgO	0.63	0.47	0.57	0.94	0.42	0.46	0.47	0.49	0.30	1.02
CaO	0.02	-	0.04	0.06	-	-	-	-	0.02	-
Na_2O	0.44	0.29	0.43	0.26	0.78	0.66	0.28	0.45	0.72	0.47
K_2O	10.38	10.58	10.26	10.47	10.16	10.29	10.77	10.33	10.38	10.00
Total	95.15	96.10	96.16	95.42	95.76	96.07	95.96	95.89	96.16	95.83
Si	3.12	3.10	3.10	3.15	3.10	3.10	3.08	3.11	3.10	3.17
AlIV	0.88	0.90	0.90	0.85	0.90	0.90	0.92	0.89	0.90	0.83
AlVI	1.84	1.81	1.83	1.75	1.83	1.83	1.86	1.82	1.86	1.79
Ti	0.04	0.07	0.06	0.09	0.06	0.05	0.04	0.07	0.03	0.04
Fe	0.07	0.07	0.07	0.08	0.07	0.08	0.05	0.07	0.08	0.10
Mn	-	-	-	-	-	-	-	-	-	-
Mg	0.06	0.05	0.06	0.09	0.04	0.04	0.05	0.05	0.03	0.10
Ca	-	-	-	-	-	-	-	-	-	-
Na	0.06	0.04	0.06	0.03	0.10	0.08	0.04	0.06	0.09	0.06
K	0.88	0.89	0.86	0.89	0.86	0.87	0.91	0.87	0.87	0.84

Table 4: Microprobe analyses of chlorite and albite from the quartz-mica metasandstone.

	Chl	Ab	
SAMPLE	G-4	BU-6	HM-8
	1	2	3
SiO_2	26.36	68.32	68.38
TiO_2	0.06	-	-
Al_2O_3	24.76	19.34	19.54
FeO	22.69	-	-
MnO	0.16	-	-
MgO	13.09	-	-
CaO	-	0.07	0.05
Na_2O	-	12.11	11.80
K_2O	0.29	0.04	0.07
Total	87.40	99.88	99.84
X_{Fe},%	49.3		
	An	0.3	0.2
	Ab	99.5	99.4
	Or	0.2	0.4

eral typically forming under epizonal metamorphic conditions, or under conditions of the chlorite zone of the greenschist facies. Low contents of TiO_2 indicate that the crystallization took place at low temperatures.

Albite contains less than 1 % of the anorthite molecule (Table 4) and forms minute, often euhedral, glassy grains set in a sericitic aggregate matrix.

Chlorite is disseminated in the form of small scales, locally intergrown with sericite. It belongs to the alumina-rich amesite-daphnite variety (Table 4).

Of the opaque minerals, magnetite representing as much as 4–5 % of the rock, predominates.

Tourmaline occurs in some samples as small needle-shaped prisms, indicative of its metamorphic origin.

Recrystallization parameters

Since neither the QMM nor the SAMP contain biotite, the metamorphism of this complex most likely did not reach the biotite subzone. In addition, the content of total alkalies in the metamorphic muscovite-phengite is fairly high (10.86 per formula unit, higher than in typical illites), so our estimated degree of metamorphism should correspond to the epizone (>300 °C, Hunziker et al. 1986). This estimate can also be supported by other significant criteria, such as incomplete compositional equalization (or retention of original composition) between clastogenic and metamorphic white potash micas at their immediate contacts (Figs. 6–7). Regardless of the fact that this feature was not systematically used to infer anchimetamorphic and low-grade conditions, its applicability was justified in the previous studies of Tatric anchimetamorphosed complexes (Korikovsky et al. 1989, 1992; Korikovsky & Molák 1995; Plašienka et al. 1993) and also seems to be justified in this study. Figures 6 and 7 exemplify the compositional difference between clastogenic and metamorphic micas, typical for all samples. While the former retain a composition of high-temperature micas, with high relic content of Ti and low content of (Mg+Fe) and Na, the latter have a composition of a low temperature mica, with considerably lower abundance of Ti, lower total content of alkalies, higher contents of (Mg+Fe) and occassionally of Na. Inasmuch as the metamorphism under conditions of the upper part of greenschist facies would ultimately result in a compositional and grain size equalization, only the very low, or low, in this case epizonal conditions could allow for a coexistence of both, equilibrated (metamorphic) and not recrystallized and consequently nonequilibrated (clastogenic) micas of the same group. In other words, had the metamorphic temperatures been higher than medium-grade greenschist facies, the composition of both mica types would become wholy or nearly identical (Frey 1987; Hunziker et al. 1986). A similar conclusion can be drawn to the associating SAMP. In contrast, the metamorphic white micas in the QMM are considerably enriched in the phengite molecule. The metamorphic phengite in sample Šif-2 (Table 2) contains 6.12 wt. % FeO, 3.36 wt. % MgO and 3.38 to 3.39 per formula unit Si^{4+}.

Study of carbon

The crystallographic features of carbonaceous matter (CM) from different metamorphic rocks of the Nízke Tatry Mts., including QMM, have been described in our earlier papers (Molák et al. 1986, 1989). Since then, however, our X-ray powder diffraction facility has been upgraded to handle smaller samples and to evaluate data using up-to-date software. Therefore, we undertook a further study to test the previous results and eventually, to strengthen their validity. We also applied the TEM and SAD (Figs. 8–13) to visualize individual CM particles and to measure their interlayer spacings.

Although, for most QMM samples we have both, the microprobe and the CM study results, for some no latter data is available because the amounts of CM in them are too small for analysis. Therefore, we present a few results from other QMM samples and add data and diagrams for the reference graphites from the medium- to high-grade rocks that crop out in this area, and also for an anthracite from a low-grade black shale from Smolník (Gemeric Superunit) and for a graphite from the high-grade graphitic gneiss from Český Krumlov (Bohemian Massif). Their list is attached to the caption to Figs. 14, 15 and 16.

Table 5: Crystallinity of carbon and graphite in QMM samples.

SAMPLE	d(002) (Å)	TYPE
HE-1	3.3676	G
	d_1= 3.3287, d_2= 3.3846	MA
HE-2	3.3699	G
	d_1= 3.3946, d_2= 3.4038	MA
	3.3830	MA
	3.4043(*)	A
G-5	3.3635	G
	3.3658	G
	d_1= 3.3542, d_2= 3.4226	A
MEL-13	3.3717	
MEL-21	3.3713	SG
	3.3903	MA
	3.4499	SA
BU-1	3.3890	MA

Explanation: SA — semianthracite, A — anthracite, MA — metaanthracite, SG — semigraphite, G — graphite; d_1,d_2 — short and long diameters in elliptic *hkl* rings, * — measured with internal standard.

TEM and SAD

As shown in Table 5, the crystallinity of carbon in QMM samples (HE-1, HE-2, G-5, MEL-13, MEL-21 and BU-1) ranges between semianthracite and graphite.

The elliptical diffractograms obtained from some A and MA samples were previously thought to indicate lattice deformations. However, more recent research into the problem has shown that they can more reasonably be explained as diagonal transmissions of electron beams through tubular or curly features, which typically occur in the particles of subgraphitic carbon (Figs.10 and 12). In such cases, the d-parameters can be calculated, although with somewhat reduced accuracy, from the longer diameters of the elliptical rings.

Because the carbons in the samples under study are either anthracite–graphite mixtures, or homogeneous graphite, their host rock must have been subject to either an anchimetamorphic–greenschist facies metamorphism in the former, or to an amphibolite facies in the latter case. Thus, the anthracite can either be resedimented carbonaceous detritus from the very low metamorphosed rocks or, more likely, it is an authentic organic material. In any case, had the superimposed metamorphism exceeded the epizonal conditions, it would achieve a much higher degree of crystallinity. Although, the graphites first form under epizonal conditions, their abundance and crystalline perfection grows from the biotite zone through the amphibolite to granulite facies metamorphism, which was, obviously, not achieved in our samples. Therefore, much of this graphite must have been introduced in the QMM through resedimentation processes from the desintegrated higher grade rocks. This conclusion supports our concept of metasedimentary development of the rocks under study.

X-ray, STOE, DT and TG analyses

To further check our earlier reported X-ray and DTA results (Molák et al. 1986, 1989; Molák 1990), some additional samples were X-rayed and DT/TG analysed. As shown, the new results either comply with, or only slightly deviate (Figs. 14, 15 and 16) from the former ones. Thus, the conclusion that the host rocks have a sedimentary origin, and that they were metamorphosed at low-grade, seems justified.

As can be observed on Figs. 14, 15 and 16, the samples cluster in, or occupy two fields, a low-metamorphic one and a medium- to high-metamorphic one. The carbonaceous matter from QMM samples falls, together with the reference sample from Smolník (Gemeric Superunit), into the former, while the reference graphites from the Tatric Superunit and from the Bohemian Massif fall into the latter field. An interesting feature, common for the carbons from QMM and from the Ge-

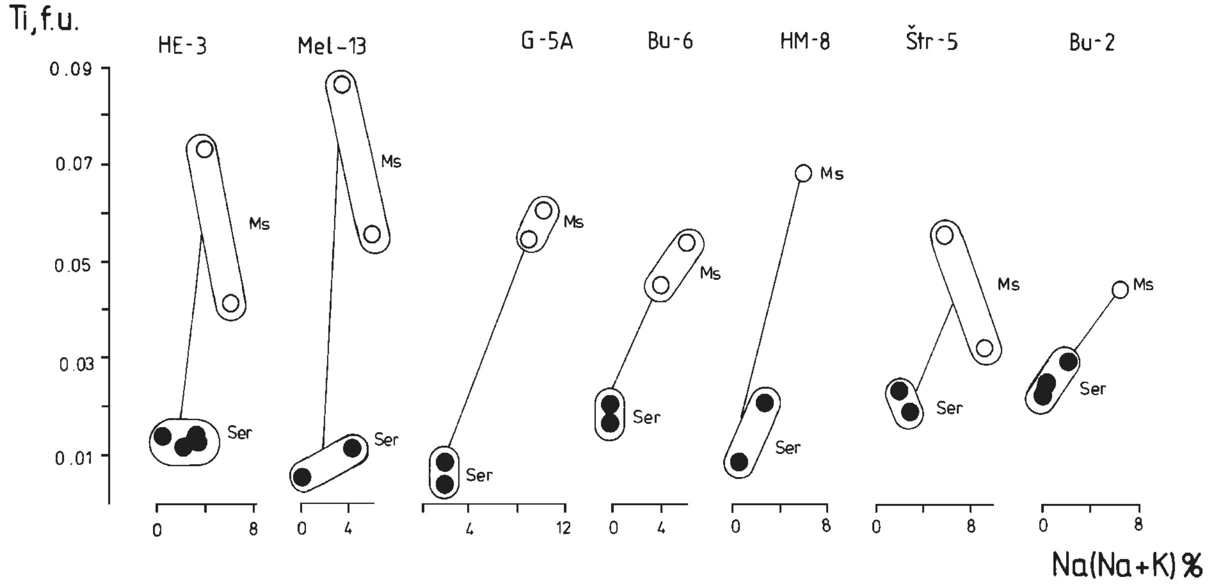

Fig. 6. Compositional difference between clastogenic (o) and metamorphic (•) micas: Ti vs. Na/(Na+K).

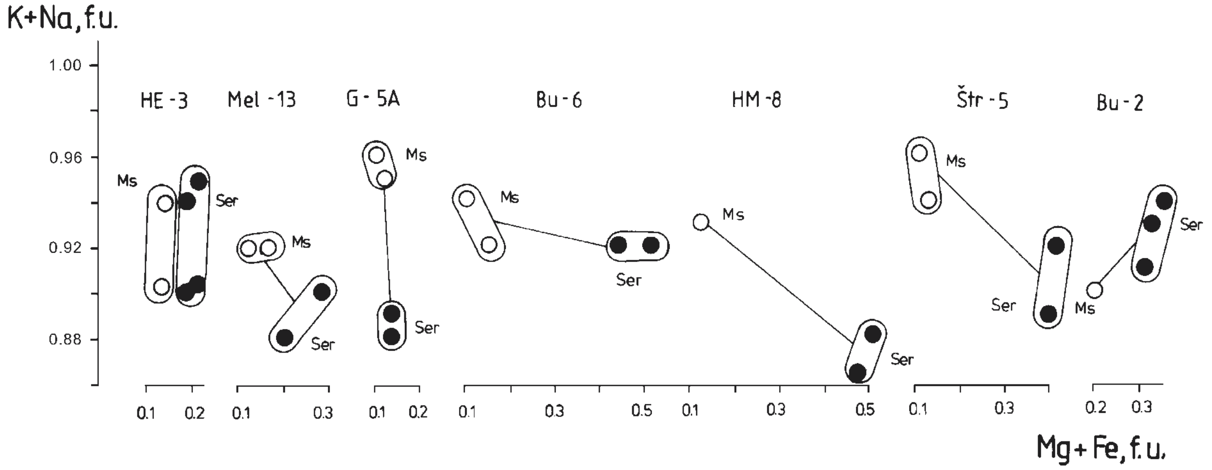

Fig. 7. Compositional difference between clastogenic and metamorphic micas: K+Na vs. Mg+Fe.

meric Superunit is shown on the STOE diffractograms (Fig.17). The dilated 002 peaks are in all these cases composed of four maxima indicating mixtures of four, crystallographically nearly identical varieties of carbon. In addition, our earlier carbon isotope study (Molák & Buchardt 1996) has shown that these carbons have a similar enrichment in the heavy isotope. Although this structural and isotopic likeness of carbons in the QMM and in the Gemeric black shale suggests a similar origin and metamorphic history, this suggestion cannot be accepted without reservations until more information is available to reasonably explain these features.

A review of imperfectly crystalline carbon from medium- to high-grade environments

In medium and high metamorphic environments, sparse varieties of imperfectly crystalline, hard or non-graphitizing carbon occur, such as shungite (Khavari-Khorasani & Murchison 1979), graphite skeleton crystals (Weis 1980) and fullerenes (Buseck et al. 1992), which are likely to preserve their low crystallinity even after being exposed to subsequent low metamorphism. Therefore, we made a survey of whether such substances occur in our samples, which would cast some doubts on our concept of QMM's low metamorphism.

Soft carbons, such as anthracites and anthraxolites, start to graphitize under biotite zone conditions. In contrast, shungite described from a Precambrian sedimentary sequence at Shunga, Karelia, (Inostrancev 1886), was subjected to a high degree of organic metamorphism due to the injection of diabase melt into the sedimentary-organic horizon, a principal agent responsible for the considerable degree of molecular-structural ordering. During the course of thermal metamorphism, the original OM formed a resistent and strongly cross-linked structure due to low H content and high O content, or both, which prevented graphitization.

Fig. 8. A graphite particle in sample G-3 (TEM), 7500×.

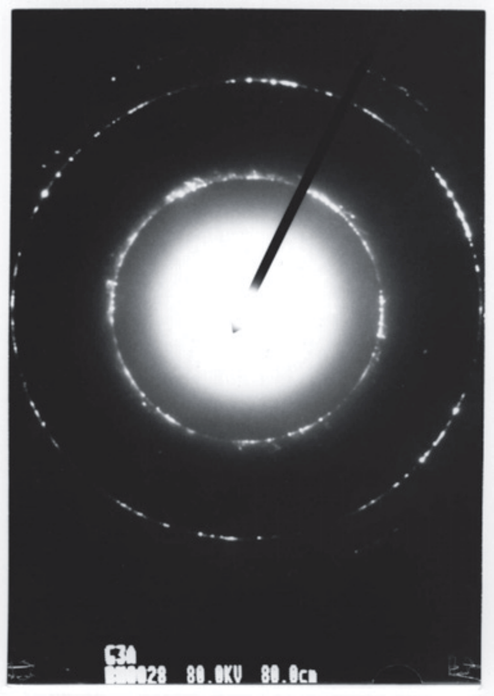

Fig. 9. SAD pattern of graphite particle, sample G-3.

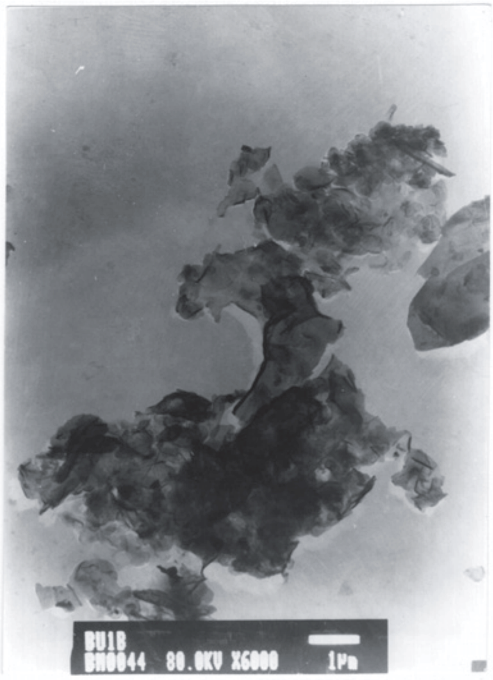

Fig. 10. A meta-anthracitic particle, sample BU-1 (TEM), 6000×.

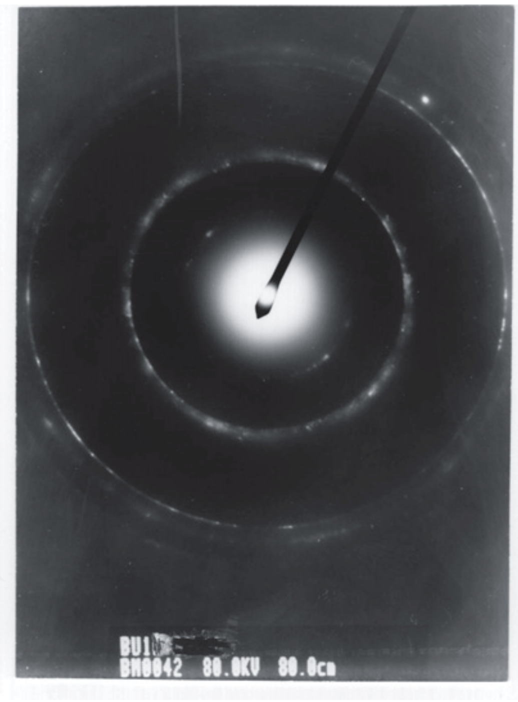

Fig. 11. SAD pattern of meta-anthracitic particle, sample BU-1.

On heating up to 2900 °C, the structure of shungite remained an ill-ordered, granular and fine mosaic, with a high content of mineral matter, typical of a substance with inferior coking properties (Khavari-Khorasani & Murchison 1979).

The fullerenes (C_{60} and C_{70}), known to occur in interstellar space and as an artificial form, have been found quite recently within the fracture filling films in shungite (Buseck et al. 1992).

The skeleton graphite crystals were found to be associated with the ordinary flaky graphite in Precambrian graphitic marbles from New York and Montana (Weis 1980). As a product of granulite facies metamorphism, this marble con-

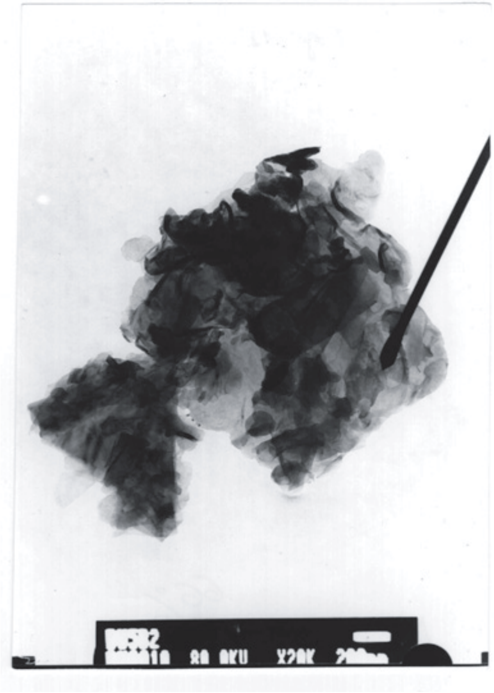

Fig. 12. A meta-anthracite particle, sample BU-6 (TEM), 20,000×.

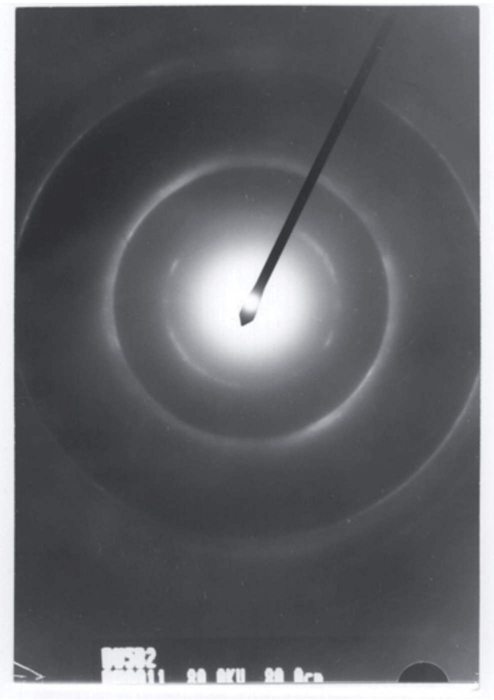

Fig. 13. SAD pattern of meta-anthracite particle, sample BU-6.

tains less than 5 % of skeleton crystals of the total graphite with a lower degree of crystallinity.

A crosscheck of our results with the above data shows that none of the above mentioned non-graphitizing carbons occurred in our samples. Firstly, neither of the attributes indicative of shungite (granular or mosaic structure, substantial amounts of mineral matter) were observed. Although, Francŭ (in Molák et al. 1986) reported some massive vitrinitic carbon particles with R_{max} = 4.5 and R_{min} = 3.4 %, associated with the photometrically non-measurable microcrystalline graphite particles, these cannot be attributed to shungite variety, because the mineral inclusions are too scarce and much smaller than in shungite. Secondly, the absence of shungite automatically eliminates the presence of fullerenes in our samples, and thirdly, the skeleton crystals cannot be expected to occur in our samples because marbles are not present in the area of the QMM outcrop, and neither is a marbled rocks admixture, like that in the associated SAMP.

The above observations allow us to draw the conclusion that the non-graphitized CM in the samples under study has been subjected to low-grade metamorphism and never had anything to do with medium- or high-grade metamorphism, as postulated by some petrologists.

Age of QMM

Another question to answer is the age of the QMM. The palynomorphs found by Planderová (1986) in this suite indicate an Early Paleozoic age, but their authenticity cannot be taken for granted because Rapant et al. (1986) found a mixture of palynomorphs originating from various lithologies and stratigraphic horizons in the spring waters in surrounding areas. This suggests that the palynomorphs can be washed out from the rocks by circulating waters and subsequently dissipated in tectonically affected rocks, such as the QMM. However, the relatively small stratigraphic range of microfossils in the QMM somewhat contradicts this postulate.

Although, the degree of metamorphism inferred for this suite would probably be too low to destroy microfossils in the QMM, it cannot be used as a proof of their autochthonity.

Recent zircon dating of volcanic rocks from the Jánov Grúň Formation, considered on the basis of geological data as a Lower Paleozoic suite, and as a possible analogue of the QMM, gave Late Paleozoic age (Kotov et al. 1996). White micas and zircon in the QMM should also be submitted to radiometrical dating in order to shed more light upon their age.

Conclusion

Emplaced in the augen-gneissic environment N and W of Jasenie, Nízke Tatry Mts., the quartz-muscovite metasandstones are composed of detritic and metamorphic phases and have an exemplary psammitic texture. While the former phases comprise oval quartz grains, large muscovite flakes and sparse individual grains of albite, the latter consist mainly of quartz and microcrystalline aggregate of muscovite-phengitic mica. Rounding of clastogenic quartz clearly demonstrates that its host rock has a sedimentary origin. Due to blastomylonitization the quartz grains are elongated or dismembered. Clastogenic muscovite forms large flakes, locally affected by plastic deformation, oriented either at

SAMPLE	d 002	FWHM
G-1	3.355	0.22
G-3	3.353	0.3
MAT-1	3.359	0.33
VNT-12 (38.5 m)	3.351	0.24
VNT-15 (114 m)	3.358	0.27
MEL-21	3.396	0.53

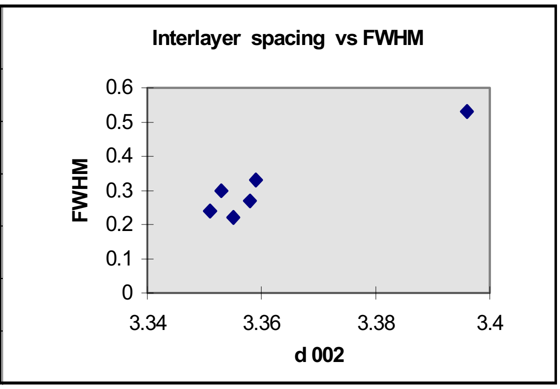

Fig. 14. Relation of d(002) vs. FWHM of CM.

SAMPLE	DTA	d 002
G-1	790	3.356
G-3	725	3.360
G-4	595	3.410
G-8	625	3.400
G-9	635	3.400
HE-1	645	3.410
HE-2	660	3.400
HM-1	605	3.400
HM-5	585	3.400
S-1	550	3.440
ČK-MV	885	3.356

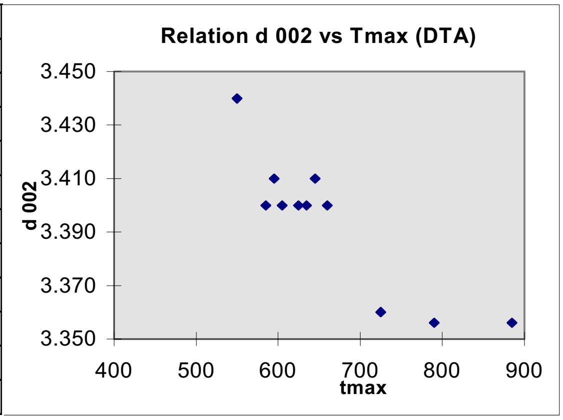

Fig. 15. Relation of d(002) vs. DTA Tmax of CM.

SAMPLE	TGA	d 002
G-1	706	3.356
G-3	627	3.360
MAT-1	819	3.359
MEL-21	669	3.390
NT-1	895	3.350
NT-6/2	850	3.360
VNT-11 (51,5m)	773	3.357
VNT-12 (38,5 m)	726	3.354
VNT-15 (114 m)	769	3.358
ČK-MV	849	3.356

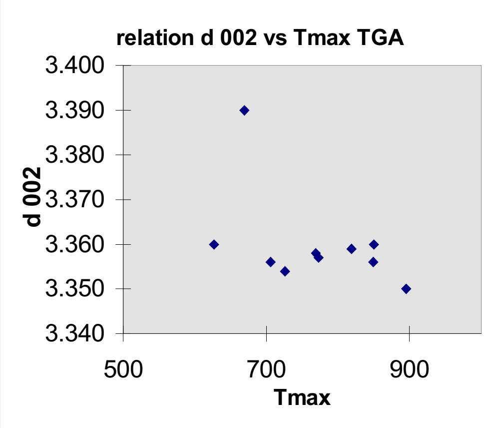

Fig. 16. Relation of d(002) vs. TGA Tmax of CM. **Carbons and graphites in Figs. 14, 15 and 16:** QMM samples: G-4, G-8, G-9, HE-1, HE-2, HM-1 and HM-5; reference samples: G-1, G-3, MAT-1, VNT-11, 12 and 15 series, and NT are graphites from bimicaceous paragneisses, commonly turned into phyllonites and from migmatites, from the area N and W of Jasenie, (see Fig. 1). Sample S-1 is an anthracite from black shale, Smolník mine (Fe-Cu), Gemeric Superunit and ČK-MV is a graphite from the graphite deposit Městský Vrch near Český Krumlov, Bohemian Massif.

random or perpendicular to the rock schistosity. As a result of metamorphism the muscovite is locally desintegrated or partially substituted by sericite-quartzite aggregate. Its composition differs from that of the metamorphic muscovite by having increased contents of TiO_2, total (Na+K) and by a moderate admixture of (Mg+Fe) which make it akin to granitic muscovite. Small amounts of tiny, metamorphic, newly formed albite and chlorite in the form of scattered scales, dispersed crystals of magnetite and small needles of newly formed tourmaline, also occur.

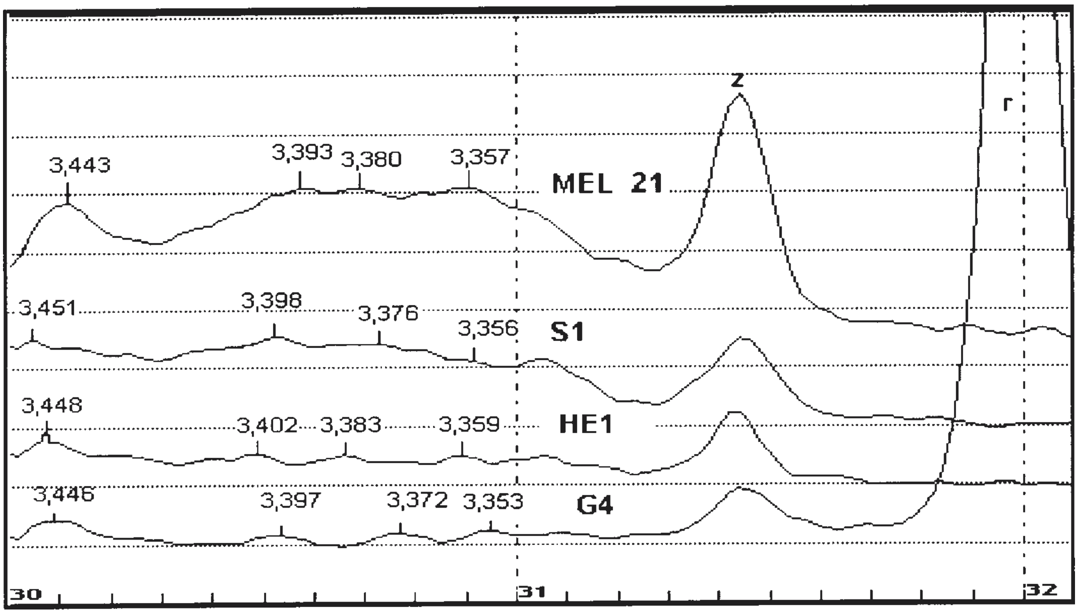

Fig. 17. STOE diffractograms for samples MEL-21, HE-1 and G-4 (QMM) and for S-1 (Smolník, Gemeric Superunit). **z** — zircon, **r** — rutile.

Fine-grained, metamorphic muscovite is a major constituent of the matrix. It has a relatively high content of (Na+K) in the interlayer positions and variable abundances of Mg and Fe, so, it can be classified as a muscovite-phengite. Low contents of TiO_2 indicate low crystallization temperatures.

Neither the QMM nor the associated SAMP contain biotite, indicating that their metamorphism most likely did not reach the biotite subzone. The total content of alkalies in the metamorphic muscovite-phengites is fairly high (>0.86 per formula unit), thus, they ought to be illite-free and their estimated degree of metamorphism should correspond to epizone. This estimate is compatible with the incomplete compositional and grain size equalization between the clastogenic and metamorphic white potash micas at their contacts. In contrast, the metamorphic white micas are considerably enriched with phengite molecules.

To test our earlier carbon crystallinity results, we made additional X-ray analyses and also applied the SAD to visualize and to measure the crystallinity of individual CM particles. This study revealed that the samples are composed of a mixture of anthracitic and graphitic carbons, the former being a result of anchimetamorphic or greenschist facies metamorphism, and the latter formed during the amphibolite facies metamorphism. The anthracite is either a resedimented carbonaceous detritus from rocks with a very low level of metamorphism or, more likely, it is an authentic organic material. In contrast, well crystallized graphite, which first forms under biotite zone conditions and which grows both, in abundancy and crystalline perfection with increasing metamorphic grade, must have been introduced in the QMM from the higher grade rocks via resedimentation processes. This conclusion supports our earlier view that the rocks under study are low-grade metasediments and not diaphthorites of medium- to high-grade rocks.

A survey has been made to find out whether the samples under study contain a variety of non-graphitizing carbon, which would undermine our concept of low metamorphism of the QMM. However, neither shungite, nor skeleton crystals, nor fullerenes were identified in the CM indicating that the ill-ordered carbons developed under the low-grade metamorphism, and were not subjected to medium- or high-grade metamorphism. Therefore, the QMM, together with the associating SAMP, can be assigned to a single metasedimentary suite.

The age of QMM remains a matter of dispute. Although, the degree of their metamorphism would be too low to destroy Early Paleozoic microfossils, the authenticity of these microfossils is still uncertain, because they could easily have been washed out from an unknown lithology by circulating waters and dissipated later in tectonically affected rocks, such as the QMM. The only suspect is a relatively narrow stratigraphic range of microfossils compared to that reported by Rapant et al. (1986). Surprisingly, the recent zircon dating of volcanic rocks from a possible analogue of QMM — the Jánov Grúň Formation — gave a Late Paleozoic, and not an Early Paleozoic age, as indicated by the geological data. The white-mica and zircon present in the QMM should be dated to help shed more light upon their age.

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