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Provenance of the Malužiná Formation sandstones (Western Carpathians, Slovakia): constraints from standard petrography, cathodoluminescence imaging, and mineral chemistry of feldspars

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Petrographic, cathodoluminescence, and phase chemistry studies of detrital grains were carried out on sandstones from the Permian Malužiná Formation in the Malé Karpaty Mts. (Hronic Unit, Western Carpathians, Slovakia) to determine their provenance and tectonic setting during the Permian. The results of the present study suggest derivation of the Malužiná Formation sandstones from multiple source areas. Major source lithologies were acid (felsic) plutonic rocks and low- to high-grade metamorphic rocks (probably metamorphosed igneous rocks and metasedimentary rocks), but notable amounts of detritus were also derived from felsic and mafic volcanic rocks. There was only a minor contribution from sedimentary rocks. Detritus was stripped rapidly from broken, high-relief source areas before weathering processes could destroy unstable framework constituents, as documented by the relatively high content of unstable rock fragments and the high feldspar content in the sandstones investigated. The provenance characteristics indicate that deposition of the sandstones of the Malužiná Formation occurred in a rifted continental margin environment supplied from an uplifted area on a thick continental crust composed of rocks of older fold belts.

Key words: Western Carpathians, sandstone petrography, cathodoluminescence, mineral chemistry, provenance.

INTRODUCTION

Most research on provenance of siliciclastic sedimentary rocks has focused on sandstones (e.g., Skilbeck and Cawood, 1994; Wanas and Abdel-Maguid, 2006; Ghosh et al., 2012). Much of this research has been concerned with attempts to interpret source-rock lithology from detrital mineral assemblages (e.g., Chappell, 1968; Laird, 1972; MacKinnon, 1983). Petrographic analysis of quartz, feldspars, micas, heavy minerals and rock fragments forms the basis for most such studies (e.g., Jafarzadeh and Hosseini-Barzi, 2008; Dey et al., 2009; Najafzadeh et al., 2010). However, some investigators utilize also supplementary techniques, such as cathodoluminescence microscopy and geochemical studies of major and trace elements in detrital minerals (e.g., Triebold et al., 2007; Malila et al., 2008; Asiedu et al., 2009).

Cathodoluminescence (CL) microscopy is a particularly useful tool for studying sedimentary rocks because this technique provides information about the provenance of mineral grains that constitute sedimentary rocks (Götze and Zimmerle, 2000; Boggs et al., 2002; Götte and Richter, 2006; Boggs, 2009). Specifically, the CL characteristics, such as colour and fabric, of mainly quartz grains have been used to link them to their source rocks. The applications of CL techniques to interpretation of provenance are splendidly reviewed in Boggs and Krinsley (2006).

Both the mineralogy and chemistry of feldspars may have provenance significance. For instance, microcline tends to be derived from felsic igneous or metamorphic rocks, while calcic plagioclase from basic igneous or metamorphic rocks. Also, the chemical composition of feldspars is known to be a function of the source rocks (e.g., Helmold, 1985; Boggs, 2009).

In this study, provenance analysis of the Permian sandstones of the Malužiná Formation in the Malé Karpaty Mts. (Hronic Unit, Western Carpathians, Slovakia) has been carried out using petrographic microscopy, the cathodoluminescence technique, and the phase chemistry of detrital feldspar grains. The study of rocks from the Hronic Unit is extremely important for the geodynamic reconstruction of the Western Carpathian Variscan Orogen. Furthermore, the basal siliciclastic deposits of the Hronicum may provide information on the original basement of this unit and cast light on the continental rifting process responsible for the formation of these sediments. The results obtained in the present study contribute significantly to a better understanding of the lithology of the parent rocks of the Malužiná Formation sandstones in the source area.

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GEOLOGICAL OVERVIEW

Samples of sandstones representing the Permian Malužiná Formation in the Malé Karpaty Mts. were analysed. The geological characteristics and evolution of this formation are described in detail by Vozárová and Vozár (1981, 1988), Vozárová and Túnyi (2003) and Vozárová et al. (2009), and are summarized below.

The Permian Malužiná Formation together with the Pennsylvanian Nižná Boca Formation are lower-order lithostratigraphic units of the Ipoltica Group which represents the Late Paleozoic volcano-sedimentary successions in the basal part of nappes of the Hronic Unit (Vozárová and Vozár, 1981, 1988). The Late Paleozoic of the Hronic Unit is variably preserved and occurs as reduced tectonic fragments in the basal part of the multi-nappe structure in various regions of the Western Carpathians (Fig. 1).

The Malužiná Formation has a gradual transition from the underlying Nižná Boca Formation. The Malužiná Formation is of Cisuralian to the Lopingian age (Autunian–Saxonian–Thuringian) (e.g., Planderová and Vozárová, 1982; Vozárová et al., 2005). Lithologically, it consists of a thick succession of redbeds (alternating polymict conglomerates, sandstones, siltstones, and shales) and sporadic chemogenic sediment interbeds (caliches and evaporites) of variable thickness. One of the basic lithological characters of the Malužiná Formation is the internal cyclic structure of the sedimentary sequences which are arranged in three regional megacycles one above the other. A further important phenomenon is the polyphase synsedimentary andesitic-basaltic volcanism represented by rift-related continental tholeiites (Vozár, 1997; Dostal et al., 2003). The maximum thickness of the Malužiná Formation is 2,200–2,400 m (Vozárová and Vozár, 1988). Volcanic and sedimentary rocks in the Malužiná Formation are generally very low-grade metamorphosed. The alteration is characterized by the pumpellyite-prehnite-quartz mineral association (Vrána and Vozár, 1969; Šucha and Eberl, 1992). Lithofacial analyses of the Malužiná Formation sequences, the character of volcanism and the structural arrangement of strata in the entire megasequence suggest an intracontinental, rift-related type of original depositional basin (Vozárová and Vozár, 1988). Further, these authors supposed that the depositional environment was continental and was characterized by deltaic-lacustrine and alluvial sub-environments, including microenvironments controlled by arid to semiarid climate.

The Permian sedimentary basin of the Malužiná Formation belonged to a large geodynamic zone connected with the internal part of the Variscan orogenic domain, in which rift-related and strike-slip continental post-orogenic basins were formed during the Pennsylvanian-Permian interval (Vozárová et al., 2009). As a consequence of post-Variscan extensional tectonics, the Malužiná rift system originated on a high-grade crystalline core complex penetrated by large masses of syn- and late-orogenic igneous rocks, as is characteristic for the Variscan terranes of the Central Western Carpathians (e.g., Biely et al., 1996; Vozárová et al., 2009).

In the Malé Karpaty Mts., the Ipoltica Group represents the basal part of the lower (Šturec) nappe of the Hronicum. The Ipoltica Group occupies the area to the SW of Smolenice and

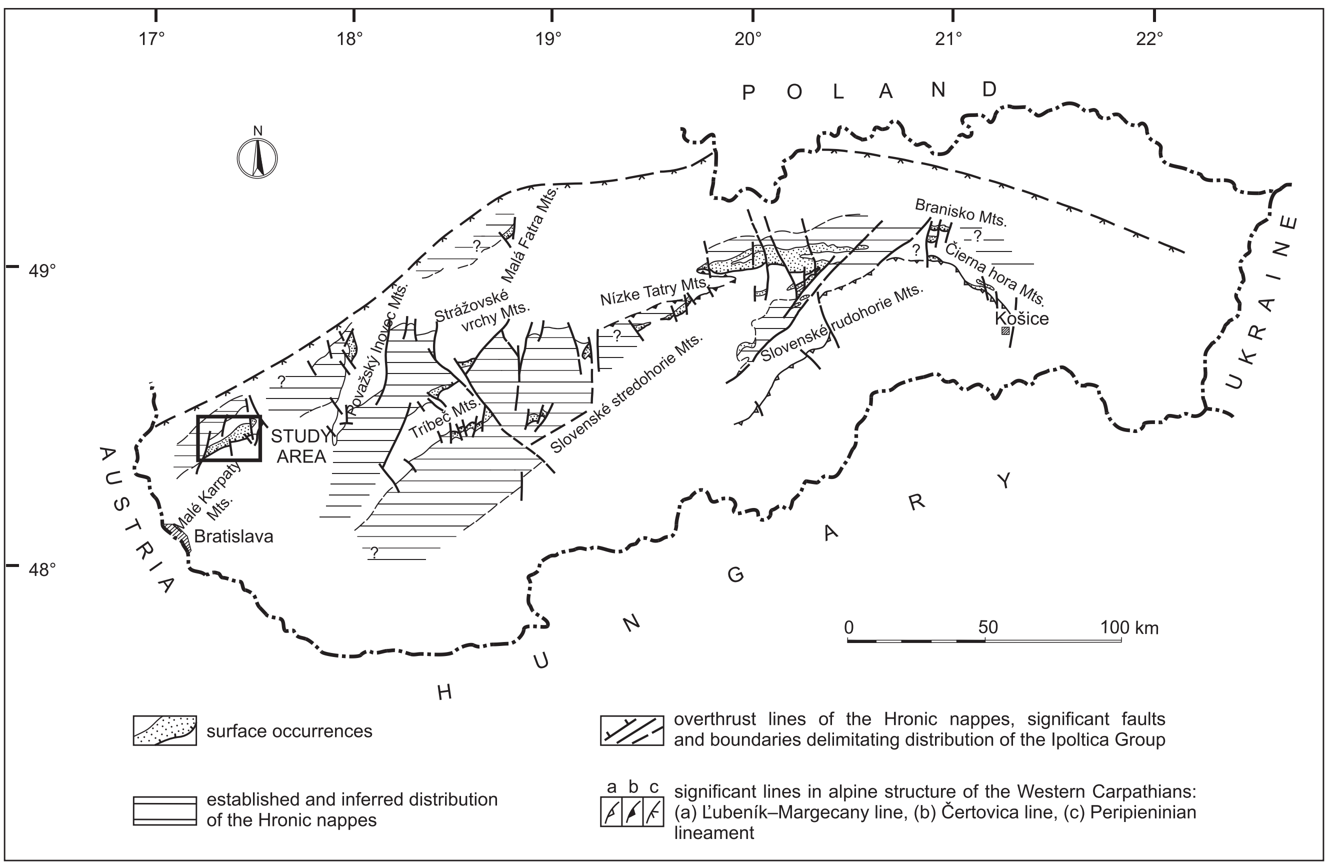


Fig. 1. Distribution of the Ipoltica Group in the Western Carpathians (after Vozárová and Vozár, 1988)

Rectangle marks the study area, for details see Figure 2

Lošonec in a belt 1.5–2.5 km wide, NE–SW-oriented, and extends to the western margin of the mountain range to the S of Sološnica (Fig. 2). The Mesozoic of the Krížna Nappe is the tectonic basement of the Ipoltica Group across the whole area. The basal part of the Ipoltica Group (the Nižná Boca Formation) is markedly reduced. Intense tectonic reduction also affected the preservation of individual parts of the Malužiná Formation.

SAMPLING AND METHODS

Fieldwork was carried out on the Malužiná Formation in the northern part of the Malé Karpaty Mts. during November, 2009 and July, 2010. Twenty-five representative sandstone samples were collected from several main section profiles between the villages of Sološnica and Smolenice as well as from selected localities between these villages, according to the geological situation. The whole regional occurrence of the lithostratigraphic unit studied, including its lower and upper parts, was covered during sampling (Fig. 2).

Thin sections were prepared from the samples collected. A detailed petrographic study of these thin sections was performed with a *LEICA DM 2500 P* polarizing microscope at the Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University in Bratislava. Modal analysis (framework mineral composition) was conducted on the thin sections by counting 500 points on each slide, using the Gazzi-Dickinson point-counting method as described by Ingersoll et al. (1984). Compositional dependence on grain size is minimalized by this point-counting method which, in fact, enables comparison of sandstones having different grain sizes.

Conventional heavy mineral analysis was realized on ten medium-grained sandstone samples which were disaggregated, sieved, cleaned and dried. Heavy minerals were separated from the 0.063–0.250 mm fraction with the gravity separation method using bromoform having a measured specific gravity of 2.8. In order to estimate mineral proportions, 350 opaque and non-opaque grains were point-counted in each heavy mineral mount.

Cathodoluminescence measurements were performed on extremely smooth, highly polished, and carbon-coated thin sections to prevent charging under electron bombardment. Cathodoluminescence was carried out using a “hot cathode” *Simon-Neuser HC2-LM* CL microscope (Department of Geological Sciences, Faculty of Science, Masaryk University, Brno), which enables light, polarized-light, and cathodoluminescence

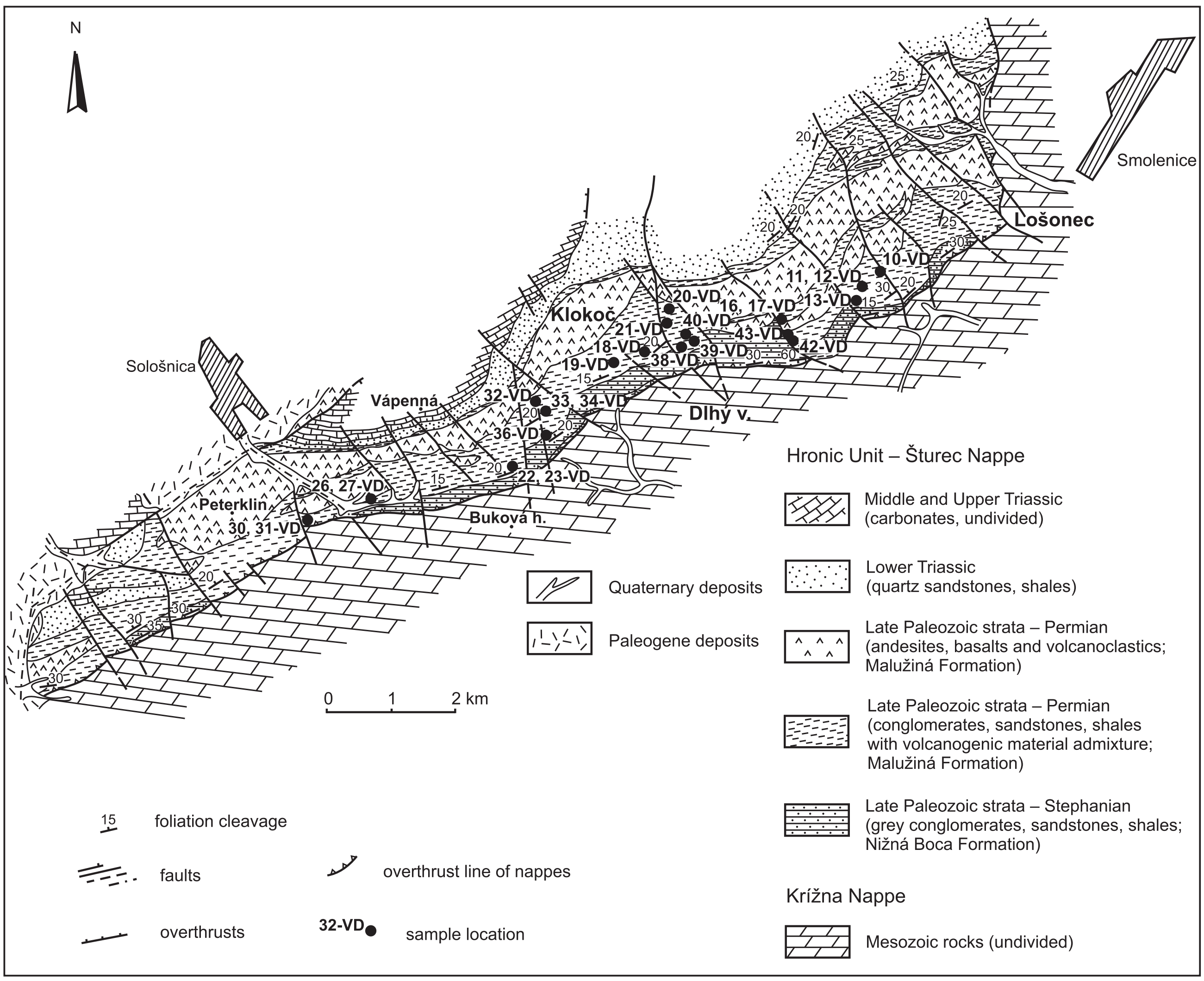
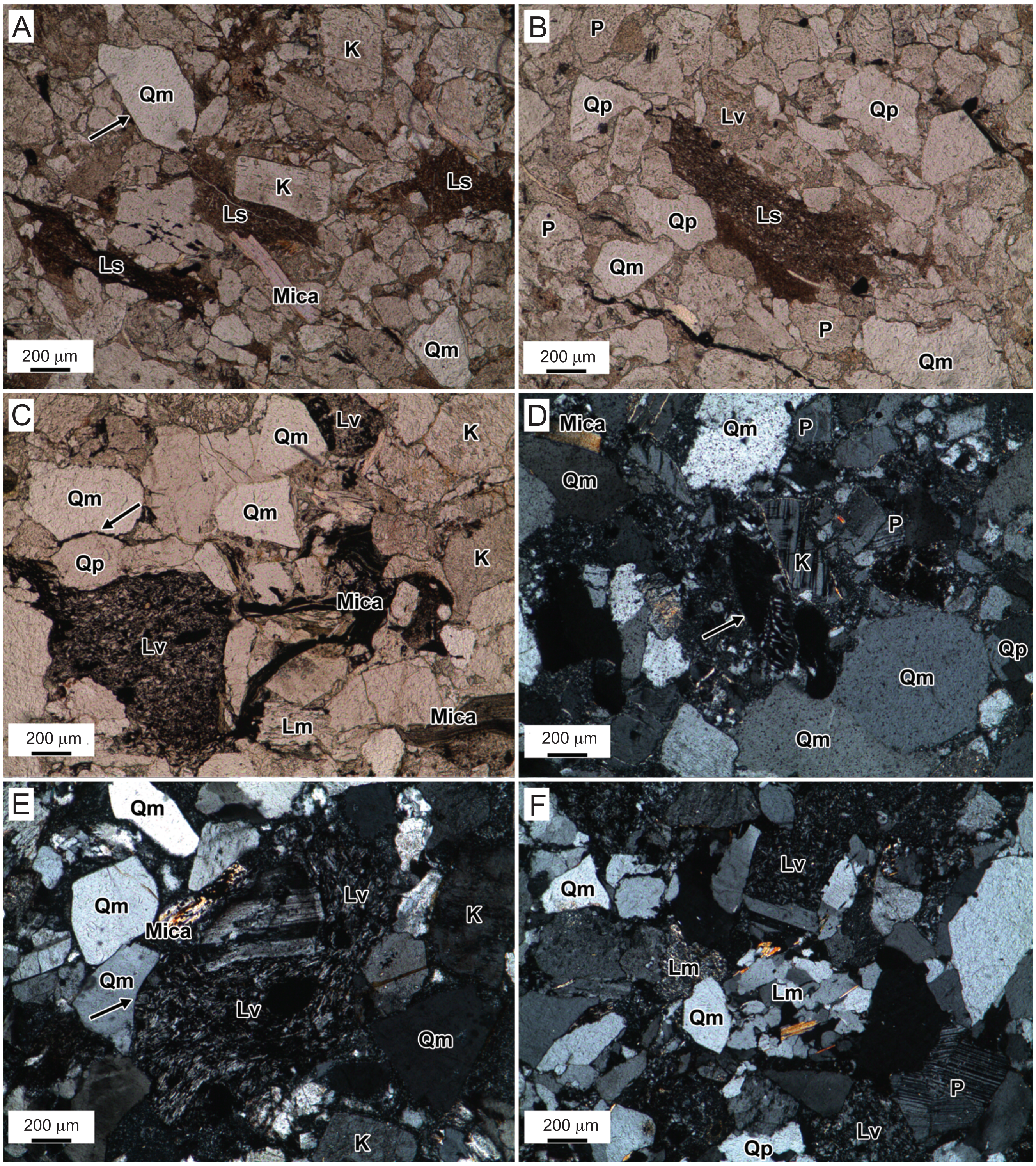


Fig. 2. Simplified geological map of the Late Paleozoic rocks of the Hronic Unit in the Malé Karpaty Mts. (after Vozárová and Vozár, 1988) showing sampling sites (19)

microscopy without sample readjustment. The electron gun was operated at 14 kV with a current density of 10–40 μA mm^{-2} in a vacuum (10^{-6} bars). The luminescence images were taken with an *Olympus C-5060* digital camera. Longer exposure times were set, ca. 8 s for short-lived CL and more than 15 s for CL passing to stable CL. Emission spectra were not gathered and thus CL colours were established visually. The shift of CL colours was not analysed.

The chemical composition of detrital feldspars in the Malužiná Formation sandstones was obtained by a *CAMECA SX-100* electron microprobe housed in the laboratories of the State Geological Institute of Dionýz Štúr in Bratislava. The operating conditions were as follows: accelerating voltage (15 kV); beam current (20 nA); and electron-beam diameter (5–10 μm). Analyses of individual elements in feldspars were carried out using the following standards: albite (Na Kα), wollastonite (Si, Ca Kα), orthoclase (K Kα), Al_2O_3 (Al Kα), barite (Ba Lα), $SrTiO_3$ (Sr Lα), forsterite (Mg Kα), and fayalite (Fe Kα). Calculation of the feldspar structural formula was based on 8 oxygen atoms.



OBSERVATIONS AND RESULTS

SANDSTONE PETROGRAPHY

The sedimentary structure of the Malužiná Formation sandstones is mostly massive and horizontal current-laminated, occasionally cross-bedded. The sandstones are typically medium to coarse grained and moderately well to poorly sorted. The framework grains are typically subangular to angular, while subrounded grains are much less common (Fig. 3). Grain contacts are tangential, straight and rarely also concavo-convex (Fig. 3C, E, thin arrows). The sandstones are texturally and mineralogically immature, and have undergone very little or no metamorphism (see also Vrána and Vozár, 1969; Šucha and Eberl, 1992).

The proportion of the quartz (including microcrystalline chert) ranges from 40.2 to 75.4% of the detritus (Table 1). Monocrystalline quartz (~40.4%) is more abundant than the polycrystalline variety (~17.0%). A few of the monocrystalline quartz grains are of volcanic origin as they typically show euhedral shapes, non-undulatory extinction, embayments, and inclusion-free clear transparency (Fig. 3A, thin arrow). Such volcanic quartz is present in all samples analysed. Monocrystalline quartz crystals, showing tectonic fabric, mostly contain mineral inclusions of white mica. Polycrystalline quartz grains are composed mainly of non-oriented crystallites, commonly three or more crystals per grain, with straight to undulose extinction and straight grain boundaries (Fig. 3D, F). Some polycrystalline quartz grains display sutured internal boundaries between composite crystals, indicating a probable early stage in the development of metamorphic polycrystalline quartz.

Euhedral to subhedral feldspar grains constitute between 15.2 and 43.2% of the total framework grains of the sandstones (Table 1). Both potassium feldspar (~13.4%) and plagioclase (~11.1%) are present mostly in almost equal amounts. Microcline and microperthite were observed in a few samples. Microcline grains have well-developed grid twinning, with the two sets of twin lamellae approximately at right angles to each other. The lamellae are commonly tapered (Fig. 3D). Many plagioclase grains are characterized by distinctive albite twinning, with twin lamellae that are straight and parallel (Fig. 3D, F). The feldspars in the sandstones studied range from fresh, unaltered grains to those showing some degrees of alteration to sericite or kaolinite.

Lithic fragments make up on average 14.0% of the total framework constituents. As concerns particular kinds of rock fragments, volcanic rock fragments constitute on average 6.8%, metamorphic fragments 3.8%, and sedimentary ones 3.4% of the total framework grains of the sandstones (Table 1). Two broad categories of lithic volcanic clasts were identified: felsic volcanic and mafic volcanic clasts. The felsic volcanic clasts are more abundant and are characterized by a microcrystalline mosaic of individual quartz crystals with relict feldspar. Vitric varieties also occur and have a groundmass consisting mainly of altered and devitrified glass. Mafic volcanic fragments mostly show a microlitic texture with laths of plagioclase in an altered aphanitic groundmass (Fig. 3E, F). Metamorphic rock fragments include grains of schist, sericite- and quartzose phyllite, paragneiss, and metaquartzite (Fig. 3F). Sedimentary rock fragments are generally poorly represented in the sandstones. They involve fine-grained sandstone, mudstone, and chert fragments (Fig. 3A, B). Microcrystalline chert grains were distinguished from microcrystalline felsic volcanic rock fragments by a lack of marked internal relief between individual crystals, a lack of feldspar microphenocrysts and sometimes by the presence of criss-crossing veinlets.

Mica constitutes on average 1.5% of the total framework grains (Table 1). White mica is the most dominant phyllosilicate mineral in all sandstones analysed and occurs mainly as short plates (Fig. 3A, D). Biotite is generally rare and is usually baueritized, i.e., bleached (Fig. 3C, E).

Heavy minerals in the sandstones studied are present in concentrations of less than 1%. After the enrichment procedure, the heavy-mineral assemblage in the Malužiná Formation sandstones includes in order of decreasing percentage (Table 2): biotite (~29.55%), magnetite, ilmenite and hematite (~27.58%), titanite (~13.86%), tourmaline (~10.21%), garnet (~8.68%), apatite (~5.78%), zircon (~3.93%), and rutile (~0.39%). Only the morphology of zircon grains is treated below because features of all other heavy minerals were destroyed during disaggregation of the sandstone samples. Further, zircon morphology may be related to the source-rock characteristics of the sandstones. The detrital zircon grains from the Malužiná Formation sandstones are mostly colourless and range from 0.08 to 0.25 mm in length. Observed zircon grains

Fig. 3. Photomicrographs of selected sandstone samples from the Malužiná Formation

A – general view showing sub-rounded to subangular quartz grains (Qm) and minor K-feldspar grains (K); note the lithic grains of sedimentary origin – laminated and silty shale (Ls); thin arrow shows the monocrystalline quartz grain of volcanic origin; grains are coated with hematite, giving red/brown rims (plane-polarized light); **B** – general view showing mono- (Qm) and polycrystalline (Qp) quartz as well as plagioclase (P) grains; notice also the mudrock fragment showing lamination (Ls) and the lithic grain of volcanic origin (Lv); there is a red hematite coating around grains (plane-polarized light); **C** – typical immature sandstone of the Malužiná Formation; note the common presence of many angular quartz (Qm, Qp), feldspar (K) and lithic (Lv, Lm) grains; large biotite micas (brown) show effects of compaction; hematite replaces biotite along some cleavage planes (black); see also the concavo-convex grain to grain contact (thin arrow); hematite coatings around sand grains are apparent (plane-polarized light); **D** – thin arrow marks a grain of albite with granophyric intergrowth (myrmekite) of quartz; quartz intergrowths are white to light grey and have a wormy-tubular morphology; also present are many quartz (Qm, Qp) and feldspar (K, P) grains; note the microcline grain (K, centre of photograph) with well-developed grid twinning (cross-polarized light); **E** – in the centre of the field of view, there is a large volcanic rock fragment of fine-grained basic rock (Lv); it consists of plagioclase microphenocrysts set in a groundmass of feldspar crystals and opaques; both the quartz (Qm) and the K-feldspar (K) grains surround this rock fragment; thin arrow denotes the concavo-convex grain to grain contact (cross-polarized light); **F** – litharenite of the Malužiná Formation with metamorphic (Lm) and volcanic (Lv) rock fragments; quartz (Qm, Qp) and plagioclase (P) grains are also present; note the metamorphic rock fragment of muscovite-bearing quartz-rich rock in the centre of the photograph; the mica flakes show a preferential alignment resulting in a schistose texture; a volcanic rock fragment (in the centre, near the top) consists of plagioclase laths set in an altered groundmass; several multiple-twinned plagioclase crystals are also visible (lower right of photograph) (cross-polarized light); for explanation of abbreviations see also Table 1

Table 1

Modal compositions of Permian sandstones from the Malužiná Formation

Sample no	Qm [%]	Qp [%]	P [%]	K [%]	Lm [%]	Lv [%]	Ls [%]	Mica [%]	Matrix [%]
10-VD	53.2	8.6	16.8	17.4	3	0.2	0.4	0	0.4
11-VD	47.2	16.8	12.4	13.8	1	0.6	4.2	0	4
12-VD	29.8	13.6	13.4	17.2	3.2	16.2	5	0.6	1
13-VD	32.6	13.4	12.6	11.4	4	20.4	5.2	0	0.4
16-VD	51.8	9	9.6	12.2	1.2	3.4	4	4.6	4.2
17-VD	43.4	12.6	12.6	10.6	2.6	7	4.8	0.8	5.6
18-VD	48.2	26	7.8	8.4	2	0.8	4.6	2	0.2
19-VD	55.4	16.8	10	13.8	0	0	1	1	2
20-VD	42.4	12.8	24.4	18.8	0	0	0	0	1.6
21-VD	40.6	23.4	15.6	15.4	2.6	0.2	1	0	1.2
22-VD	18	24	9	9.8	16.4	9.2	10.6	2.2	0.8
23-VD	24.6	19.8	10.2	11.4	12.2	7.8	5.8	7.8	0.4
26-VD	49.4	17.2	6.6	10.2	2.2	4.4	7.4	2	0.6
27-VD	64.2	11.2	8.2	11	0.8	1.2	0.4	2.2	0.8
30-VD	31.2	17.6	13	12.4	1.8	15	6.6	1	1.4
31-VD	24.6	15.6	14.2	11.6	4.6	17.4	8.6	1.8	1.6
32-VD	36.6	25.8	10	16.8	1.6	3.8	3.4	0.6	1.4
33-VD	59.6	12	3.2	19	2.4	0.2	1.4	0	2.2
34-VD	48.4	13	4.8	26	4.8	0	0.4	0.6	2
36-VD	35.6	16.6	6	9.2	7	2.2	3.4	9.6	10.4
38-VD	25.4	19	12.6	12.6	5.8	18	2.6	0	4
39-VD	35.6	15.4	10.8	6.2	5.2	16.6	3.6	0	6.6
40-VD	22.6	28.6	8.4	10	6	15	0.4	0	9
42-VD	31.6	29.4	8.6	12	4.2	10	0.4	0	3.8
43-VD	57	7	17.8	17.2	1	0	0	0	0
Minimum	18	7	3.2	6.2	0	0	0	0	0
Maximum	64.2	29.4	24.4	26	16.4	20.4	10.6	9.6	10.4
Mean	40.4	17.0	11.1	13.4	3.8	6.8	3.4	1.5	2.6
St. Dev.	12.8	6.2	4.5	4.3	3.7	7.2	2.9	2.5	2.8

Although a few heavy minerals were observed in the thin sections during the petrographic investigation, data on their volumetric proportions are not included in this Table because no heavy mineral grains were recorded during point-counting; Qm – monocrystalline quartz grains, Qp – polycrystalline quartz grains, P – plagioclase feldspar grains, K – potassium feldspar grains, Lm – metamorphic lithic grains, Lv – volcanic-hypabyssal lithic grains, Ls – sedimentary lithic grains

have the following morphologies: euhedral with slightly rounded ends, rounded to well-rounded, and anhedral. The euhedral zircon grains typically display prismatic forms among which grains with bipyramidal habits occur very rarely.

The sandstones are characterized by a very low proportion of matrix (Table 1). The mean matrix content of the sandstone samples analysed from the Malužiná Formation is 2.6%. The sandstone matrix is generally composed of fine-grained quartz (grain size <0.03 mm), clay minerals, iron oxide minerals, chlorite, highly altered unstable grains (secondary matrix), and material too fine to be identified. Pseudomatrices described by Dickinson (1970) as representing deformation and compression of lithic fragments also occur.

According to the classification of Pettijohn et al. (1972), the Malužiná Formation sandstones are represented by arkoses, subarkoses, and litharenites (Fig. 4). These sandstone types are scattered throughout the regional occurrence of the Malužiná Formation in the Malé Karpaty Mts. without any clear concentration in a specific region.

CATHODOLUMINESCENCE CHARACTERISTICS

The CL study of the Malužiná Formation sandstones reveals brown, dark blue, bright blue, violet, red, and green luminescing quartz grains (Fig. 5). Most of the quartz particles show brown, dark brown or brownish-violet CL colours, described as typical of low-grade metamorphic quartz (Richter et al., 2003). Zinkernagel (1978) reported that brown luminescence is characteristic of quartz in metamorphosed igneous rocks, metasedimentary rocks, some contact metamorphic rocks, and regionally metamorphosed rocks. A part of the quartz grains show dark blue, blue, and violet CL colours (Fig. 5), which are typical of volcanic, plutonic, and high-grade metamorphic quartz (e.g., Zinkernagel, 1978; Götze and Zimmerle, 2000). Several quartz grains display red luminescence (Fig. 5A, B, H), which indicates that these grains are of volcanic origin. A few quartz grains show a typical green CL colour (Fig. 5D) that is suggestive of hydrothermal and pegmatitic origin.

Four characteristic CL features of detrital quartz observed in the Malužiná Formation sandstones are healed fractures

Table 2

Relative abundance of opaque and non-opaque heavy minerals in the 63–250 μm fraction of Permian sandstones from the Malužiná Formation, expressed as frequency [%]

Sample no	Ap	Bt	Grt	Hem, Ilm, Mag	Rt	Ttn	Tur	Zrn
10-VD	3.65	17.52	15.33	4.38	0.00	26.28	24.82	8.03
12-VD	2.46	3.17	15.85	67.25	0.00	5.28	3.17	2.82
13-VD	8.84	3.31	26.52	45.86	0.00	5.52	8.29	1.66
17-VD	25.00	7.03	13.67	34.77	0.00	5.47	7.03	7.03
19-VD	3.89	33.85	6.61	3.89	2.72	37.74	7.78	3.50
21-VD	9.64	25.30	1.20	0.00	1.20	19.28	33.73	9.64
22-VD	1.41	84.86	1.06	7.39	0.00	2.11	2.11	1.06
23-VD	1.23	90.80	0.92	3.07	0.00	1.53	1.84	0.61
26-VD	1.36	11.56	2.72	53.06	0.00	23.47	6.46	1.36
31-VD	0.36	18.12	2.90	56.16	0.00	11.96	6.88	3.62
Minimum	0.36	3.17	0.92	0.00	0.00	1.53	1.84	0.61
Maximum	25.00	90.80	26.52	67.25	2.72	37.74	33.73	9.64
Mean	5.78	29.55	8.68	27.58	0.39	13.86	10.21	3.93
St. Dev.	7.46	32.21	8.73	26.45	0.90	12.26	10.52	3.19

Ap – apatite, Bt – biotite, Grt – garnet, Hem – hematite, Ilm – ilmenite, Mag – magnetite, Rt – rutile, Ttn – titanite, Tur – tourmaline, Zrn – zircon

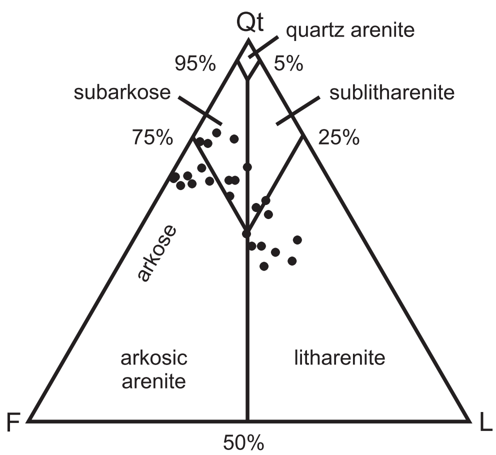


Fig. 4. Classification of the Malužiná Formation sandstones according to Pettijohn et al. (1972)

Points within the triangle represent relative proportions of Qt (total quartzose grains), F (total feldspar grains), and L (total unstable lithic fragments) end members

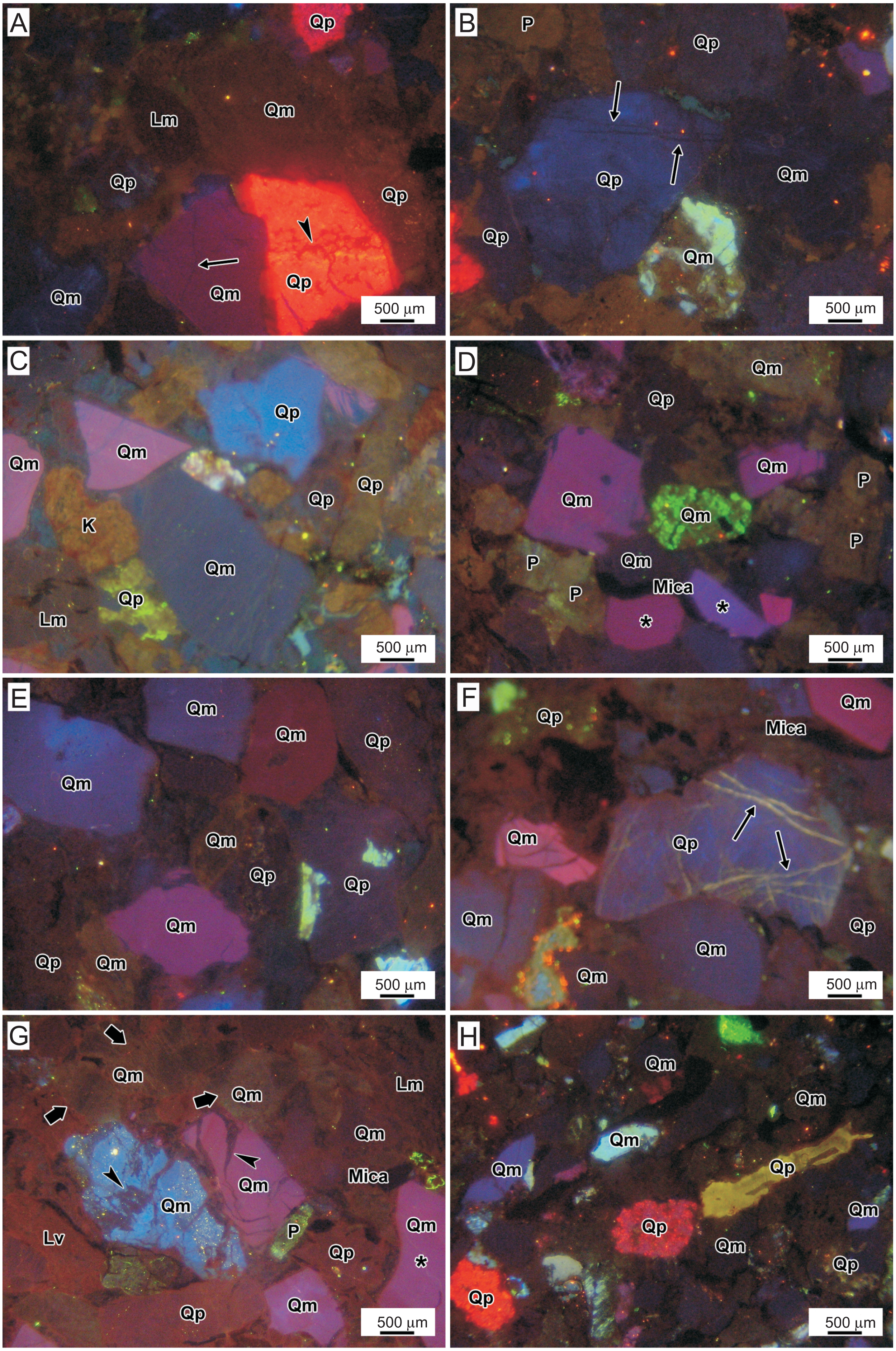
(Fig. 5A, B, F), low-intensity dark-CL streaks and patches (Fig. 5A, G), mottled-texture (Fig. 5G), and homogeneous (non-differential) CL (Fig. 5D, G). The healed fractures appear as thin (<5–>20 μm wide), distinct, black lines (CL weak or absent) (Fig. 5A, B, F). The fracture-healing material is SiO_2. The observed fractures probably originated during the transition of beta quartz to alpha quartz, which takes place during cooling below the inversion temperature of about 570 to 600°C. The beta-alpha transition is associated with large distortional strains, which can cause extensive cracking of the quartz grains (e.g., Heaney, 1994; Müller et al., 2000). Healed fractures are particularly common in plutonic quartz, are present in some metamorphic quartz, and are uncommon in volcanic quartz (Boggs and Krinsley, 2006).

The presence of irregularly shaped, CL-dark patches and streaks (~10 to >100 μm), informally dubbed "spiders", in detrital quartz in the Malužiná Formation sandstones most likely indicates plutonic origin (Fig. 5A, G). Müller (2000) suggested that the origin of "spiders" is related to decrepitation (breakage) of fluid inclusions induced by differences between fluid pressure and lithostatic pressure during uplift. An alternative explanation for the origin of "spiders" involves late-stage invasion of quartz grains by external fluids (Boggs and Krinsley, 2006). The mottled texture observed, which is very common in metamorphic quartz (and is present in some plutonic and volcanic quartz), indicates irregular distribution of activator ions or defect structures within the grains (Fig. 5G). The brighter CL areas contain more activator ions or defect structures than do the darker areas. The mottled texture may be caused by incomplete recrystallization or annealing accompanying metamorphism or it may be the result of deformation during metamorphism (Boggs and Krinsley, 2006; Boggs, 2009). Several quartz grains display nearly uniform CL intensity (CL appears essentially homogeneous) (Fig. 5D, G). Homogeneous bright-CL grains apparently form by recrystallization at high temperatures (Boggs, 2009). A homogeneous texture is very common in metamorphic quartz (Boggs and Krinsley, 2006).

MINERAL CHEMISTRY OF FELDSPARS

Electron microprobe analyses carried out on fresh feldspar crystals with little or no replacement textures show an abundance of perthitic orthoclase or microcline and a compositional range of albite-oligoclase, with most being oligoclase (Fig. 6). Alkali feldspars present in the sandstones from the Malužiná Formation have compositions in the range of $Ab_{10.2}An_{0.3}Or_{89.5}$ to $Ab_{3.4}An_{0.1}Or_{96.5}$. The composition of plagioclase feldspars in the Malužiná Formation sandstones varies from $Ab_{73.1}An_{25.4}Or_{1.5}$ to $Ab_{99.6}An_{0.3}Or_{0.1}$. Representative analyses are shown in Table 3.

The use of feldspars in provenance analysis is greatly hampered by the process of albitization during diagenesis (see also


A
Qp
Lm
Qm
Qp
Qp
Qm
Qm
Qp
500 µm
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P
Qp
Qp
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Qm
500 µm
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Qm
Qm
Qm
Qm
Qp
Qp
Qm
Qm
Qp
Qp
500 µm

Table 3

Representative analyses of detrital feldspar grains from the Malužiná Formation sandstones

Sample no	17-VD	24-VD	19-VD	24-VD	24-VD	31-VD	19-VD	22-VD	12-VD	12-VD	12-VD	23-VD
Analysis no	7	5	2	4	6	3	4	7	15	1	4	9
SiO_2	64.13	64.11	64.25	63.81	61.69	63.80	64.60	65.82	66.79	68.08	68.00	68.75
Al_2O_3	18.47	18.51	18.20	18.50	23.71	22.40	21.45	21.86	21.00	19.71	19.61	19.43
CaO	0.06	0.04	0.02	0.01	5.35	3.70	3.01	2.39	1.04	0.62	0.26	0.06
Na_2O	1.14	0.75	0.56	0.37	8.50	9.56	10.02	10.34	10.69	11.15	11.65	11.99
K_2O	15.11	15.40	15.92	15.89	0.26	0.22	0.16	0.08	0.44	0.03	0.05	0.02
FeO	0.02	0.03	0.01	0.00	0.07	0.03	0.03	0.01	0.02	0.04	0.10	0.14
Total	98.93	98.84	98.96	98.59	99.57	99.71	99.26	100.50	99.98	99.63	99.66	100.39
Formula on the basis of 8 oxygen atoms												
Si	2.979	2.988	2.997	2.985	2.748	2.823	2.865	2.879	2.931	2.995	2.979	2.986
Al	1.011	1.017	1.000	1.020	1.245	1.168	1.121	1.127	1.086	1.022	1.013	0.995
Ca	0.003	0.002	0.001	0.000	0.255	0.175	0.143	0.112	0.049	0.029	0.012	0.003
Na	0.102	0.067	0.051	0.034	0.734	0.820	0.861	0.877	0.910	0.951	0.989	1.010
K	0.896	0.916	0.947	0.948	0.015	0.013	0.009	0.004	0.024	0.001	0.003	0.001
Fe^{2+}	0.001	0.001	0.000	0.000	0.003	0.001	0.001	0.000	0.001	0.002	0.003	0.005
Total	4.991	4.991	4.997	4.987	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
End-member compositions [%]												
Ab	10.2	6.8	5.1	3.4	73.1	81.4	85.0	88.3	92.5	96.9	98.5	99.6
An	0.3	0.2	0.1	0.1	25.4	17.4	14.1	11.3	5.0	3.0	1.2	0.3
Or	89.5	93.0	94.8	96.5	1.5	1.2	0.9	0.4	2.5	0.1	0.3	0.1

Fe^{2+}/Fe^{3+} charge balance

Asiedu et al., 2000, 2009). Albitization of feldspar grains during sediment burial has been observed at depths greater than 2,500 m (Dutta and Wheat, 1993). The Malužiná Formation sandstones have undergone some degree of low-grade metamorphism (Vrána and Vozár, 1969; Šucha and Eberl, 1992) which may favor alteration of calcic plagioclase to albite. To minimize the effect of albitization, only detrital feldspars with no replacement textures were analysed. The detrital feldspars show bimodal distribution (Fig. 6), even in a single thin section. Dutta and Wheat (1993) have suggested that such compositional bimodality may indicate that the feldspar composition is primary.

DISCUSSION

SANDSTONE PETROGRAPHY

The proportions of framework grains of the Malužiná Formation sandstones suggest derivation from several distinct lithologies that may be connected with one or more source areas. The high proportion of strained monocrystalline quartz and the sodic compositions of plagioclase feldspars in the Malužiná Formation sandstones suggest that substantial amounts of detritus were derived from terranes built of felsic plutonic rocks. On the other hand, contribution of detritus from a metamorphic terrane is indicated by the occurrence of strained polycrystalline quartz with sutured contacts between subgrains, by the presence of quartz with a tectonic fabric, and by fragments of quartz-mica schist, phyllite, slate, and less commonly gneiss. Some of the strained quartz may, however, be due to post-depositional deformation processes as the sandstones have undergone some degree of metamorphism (Vrána and Vozár, 1969; Šucha and Eberl, 1992). Volcanic rock fragments with felsitic and microlitic textures suggest derivation from felsic and mafic volcanic terranes, respectively. The small amount of chert and sedimentary lithic fragments suggest a minor contribution from sedimentary rocks.

Heavy-mineral petrographic data of the Malužiná Formation sandstones provide very similar information on provenance to

Fig. 5A–H – cathodoluminescence photomicrographs of representative sandstones from the Malužiná Formation

A–D – brown quartz grains are dominant in the sandstones studied; however, some quartz grains display dark blue, bright blue, violet, red or green CL colours; thin arrows (A, B) show healed fractures, arrowhead (A) denotes dark-CL streaks and patches, and asterisks (D) mark nearly homogeneous CL across the entire grains; **E–H** – there is a dominance of brown quartz grains in the studied sandstones; a few quartz grains are dark blue, bright blue, dark violet, bright violet, red or green; thin arrows (F) show healed fractures, arrowheads (G) mark dark-CL streaks and patches, thick arrows (G) denote mottled CL texture, and asterisk (G) denotes nearly uniform CL intensity across the entire grain; for explanation of provenance significance of the observed CL colours and internal fabrics, see Observations and Results; for other explanations see Table 1

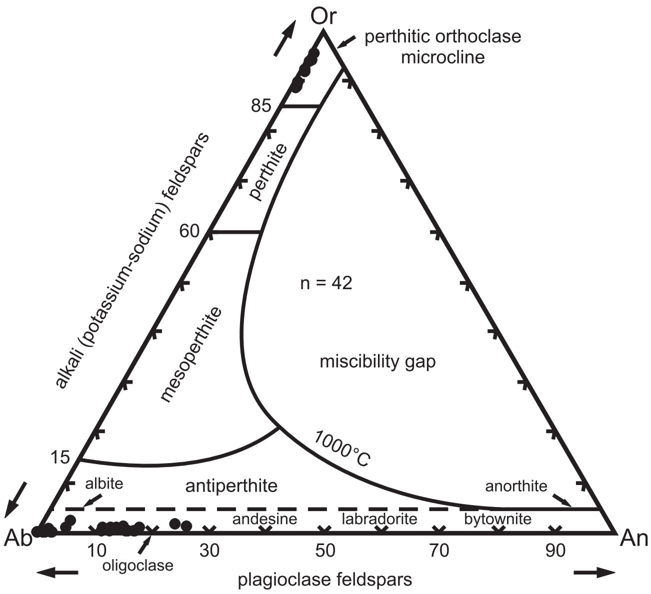

Fig. 6. Ternary diagram showing the composition of the detrital feldspar grains from the sandstones of the Malužiná Formation

Compositional fields are from Pichler and Schmitt-Riegraf (1993)

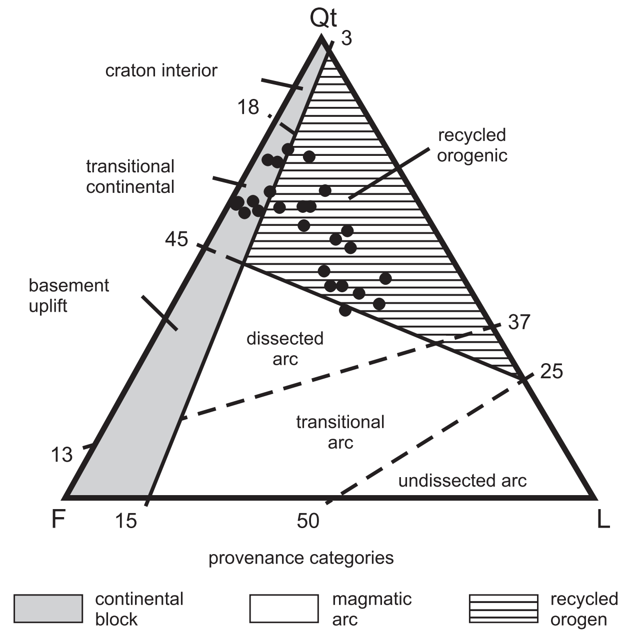

Fig. 7. Ternary plot of detrital components of the sandstones of the Malužiná Formation on the tectonic provenance discrimination diagram of Dickinson (1985)

The solid and dashed lines mark the major fields of provenance in terms of tectonic setting; solid circles represent the samples studied; Qt – total quartz, F – total feldspar, L – total rock fragments

that from the bulk petrographic analysis. The heavy-mineral suite of the sandstones studied suggests a derivation mainly from acid igneous and metamorphic rocks, accompanied by reworked sedimentary rocks. Specifically, a source of acid igneous rocks is indicated by the common association of apatite, biotite, rutile, titanite, tourmaline, and zircon. Further, an association of garnet and titanite suggests metamorphic source rocks, while an assemblage of iron ores, rutile, tourmaline, and zircon (rounded grains) hints at reworked sedimentary source rocks (Feo-Codecido, 1956). This is also corroborated by the morphology of zircon grains from the Malužiná Formation sandstones. The euhedral prismatic zircons, which very likely have a first-cycle origin, may be derived from felsic plutonic rocks, whereas the rounded zircons are from sedimentary or metasedimentary rocks (Blatt et al., 1980).

The generally immature nature of the Malužiná Formation sandstones (i.e., higher contents of lithic fragments and rarity of rounded quartz grains) suggests short-distance transport of detritus. Therefore, the source areas were probably located quite close to the site of deposition. The relatively high content of unstable rock fragments and the high feldspar content in the sandstones investigated are suggestive of their derivation from source areas with broken high relief (Boggs, 2009). Inasmuch as the weathering processes did not manage to destroy unstable clasts and other framework grains, it is assumed that the detritus of the Malužiná Formation sandstones was stripped rapidly from the elevated areas.

In the QtFL ternary diagram of Dickinson (1985), the majority of the Malužiná Formation sandstones plot within the recycled orogenic field and some samples lie within the transitional continental subfield (Fig. 7). Since most of the samples studied are placed in the area which is typical of sandstones having collision orogen tectonic provenance, it can be assumed that the Malužiná Formation sandstones were derived mainly from metasedimentary, plutonic basement and volcanic source rocks. This assumption about petrographic types of rocks building the orogen is also consistent with the present petrographic data. In addition, the transitional continental provenance of some Malužiná Formation sandstones hints at their derivation from positive features along marginal offsets at transform segments or at other structural discontinuities breaking the trend of a rifted continental margin. Based on this and on previous findings (Dostal et al., 2003; Vozárová et al., 2009), it can be concluded that the deposition of the Malužiná Formation sandstones took place in a rifted continental margin environment supplied from a collision orogen on a thick continental crust composed of rocks of older fold belts. Also, the heterolithic nature of the Malužiná Formation sandstones (i.e., metamorphic rock fragments, felsic and mafic volcanic rock fragments, and sedimentary rock fragments) suggests an active margin tectonic environment such as rift-related and strike-slip basins, which is compatible with previous studies (e.g., Vozárová et al., 2009). Miall (1990) has indicated that strike-slip basins show complex compositions because of the juxtaposition of source terranes of various kinds.

CATHODOLUMINESCENCE CHARACTERISTICS

The CL characteristics of quartz grains of the Malužiná Formation sandstones suggest derivation from multiple source areas or lithologies. Major source lithologies are plutonic rocks and low- to high-grade metamorphic rocks, but notable amounts of detritus were also derived from volcanic rocks. A contribution from plutonic rocks is documented by blue to violet CL colours of, and the healed fractures and “spiders” in, the quartz grains. An addition from low- to high-grade metamorphic rocks is shown by a brown CL colour and by the mottled and homogeneous texture of the quartz grains. Finally, derivation from volcanic rocks is evident from a red CL colour in quartz. A compositional mixture of several different detrital sources is also indicated by the results of petrographic examination of the Malužiná Formation sandstones. The co-occurrences of several provenance types in the sandstones studied, along with their textural and mineralogical immaturity, indicate the close proximity of the source areas. Taking into consideration the inferred close proximity of the source areas to the depositional site (see also Dostal et al., 2003; Vozárová et al., 2009), I envisage that a rifted continental margin presumably supplied the detritus to the sedimentary basin where the Malužiná Formation formed.

MINERAL CHEMISTRY OF FELDSPARS

Trevena and Nash (1979, 1981) have provided probably the most comprehensive studies on detrital feldspar composition and have shown that the chemistry of detrital feldspars is useful in provenance analysis. The positions of points in the discrimination diagram of Trevena and Nash (1981) suggest that the feldspars in the Malužiná Formation sandstones are of plutonic and/or metamorphic origin (Fig. 8). This feature may, therefore, indicate that most of the detritus of the Malužiná Formation sandstones was directly derived from plutonic igneous and metamorphic rocks. Evidence for this interpretation is also supported by the results of the present petrographic and cathodoluminescence study.

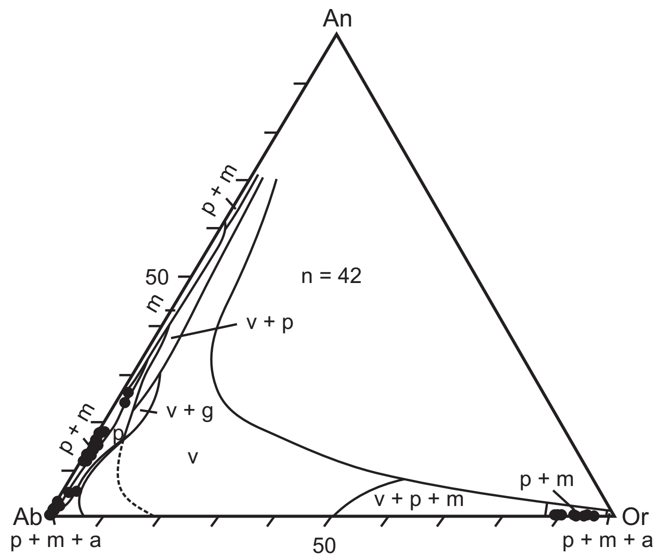

Fig. 8. Ternary diagram showing the composition and provenance of the detrital feldspar grains from the sandstones of the Malužiná Formation

Compositional ranges of eight provenance groups of feldspars are from Trevena and Nash (1981); a – authigenic, g – granophyre, m – metamorphic, p – plutonic, v – volcanic

CONCLUSIONS

The provenance of the Malužiná Formation sandstones has been assessed using an integrated petrographical, cathodoluminescence, and phase chemistry approach of derived detrital grains. This has revealed that the sandstones of the Permian Malužiná Formation are mineralogically immature and heterolithic in nature, and that their major sources were acid (felsic) plutonic rocks and low- to high-grade metamorphic rocks, but notable amounts of detritus were also derived from felsic and mafic volcanic rocks. There was only a minor contribution from sedimentary rocks.

The generally immature nature of the Malužiná Formation sandstones suggests short-distance transport of detritus. The source areas were probably located quite close to the site of deposition. The relatively high content of unstable rock fragments and the high feldspar content suggest that the Malužiná Formation sandstones were derived from source areas with broken high relief. Inasmuch as the weathering processes did not manage to destroy unstable framework constituents, the detritus of the Malužiná Formation sandstones was stripped rapidly from the elevated areas.

The Malužiná Formation sandstones have transitional continental to recycled orogen provenance. The deposition of the Malužiná Formation sandstones took place in a rifted continental margin environment supplied from an uplifted area on a thick continental crust composed of rocks of older fold belts. The heterolithic nature of the Malužiná Formation sandstones suggests their accumulation in rift-related and strike-slip continental basins.

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