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Provenance analysis of the Permo-Carboniferous fluvial sandstones of the southern part of the Boskovice Basin and the Zöbing Area (Czech Republic, Austria): implications for paleogeographical reconstructions of the post-Variscan collapse basins

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Abstract: The provenance analyses of Permo-Carboniferous fluvial sandstones of the southern part of the Boskovice Basin and the Zöbing area are based on a wide spectrum of analytical techniques (petrography, heavy mineral assemblages, chemistry of garnet, rutile and spinel, zircon study, major and trace elements). The studied sandstones are poorly sorted and reveal a relatively immature composition implying short distance transport, rapid deposition, a high-relief source area, mainly physical weathering and the minor role of chemical weathering. Different source areas for the Boskovice Basin and the Zöbing area were proved. The Zöbing material was predominantly derived from crystalline units, mainly formed by metamorphic complexes, although the portions of magmatic and volcanic material were significant. The source area is supposed to be located in the Moldanubian Unit. The Boskovice Basin deposits, on the other hand, seem to be mainly derived from metamorphic complexes, corresponding especially to the Moravian Unit, with a relatively wider spectrum of metamorphites, together with the derivation of the detritus from pre-existing sedimentary rocks (especially from Moravo-Silesian Paleozoic deposits/Drahany Culm unit). The transport direction in the basin was more complex, both from the west and east. These results did not confirm the possibility of communication between the Boskovice Basin and the Zöbing area during the Late Paleozoic. The existence of "colinear" marginally offset half grabens with predominant transversal sources is here hypothesized. The general heavy mineral evolution in time does not indicate the successive exhumation of a simple structured orogen but may be interpreted as differences in the extent of the source areas.

Key words: Permo-Carboniferous, terrestrial deposits, provenance, axial vs transverse sources.

Introduction

Studies of the provenance of clastic sediments in sedimentary basins are important in paleogeographical and tectonic reconstructions. The composition of clastic sediment is controlled by a broad range of parameters starting with the composition of source rocks, processes such as weathering, abrasion, hydrodynamic sorting, mixing during transportation, diagenetic processes, etc. (Johnson 1993; Cox & Lowe 1995; Eynatten 2004). Integrated (modal analysis of sandstones, heavy mineral and bulk chemical analyses) methods of provenance study of the sedimentary infill of collapse-type grabens are used for constraining tectonic uplift and unroofing episodes in orogenic belts (Adhikari & Wagreich 2011), evaluating the transport distance, climate and weathering effects and relief (Pettijohn et al. 1987).

Additionally, in order to use provenance analysis in the paleogeographical reconstruction of ancient continental basins, one should understand the facies architecture and the distribution of depositional environments in the basin. An axial river or rivers are in general most important for redistribution of the sedimentary material in a continental half graben. Rivers are often situated in the topographically lowest part of a basin, which again is situated above the zone of the maximum subsidence near the footwall block. The distribution of facies and transport direction in continental, extensional basins are largely controlled by the tilt of the basin floor (Bridge & Leeder 1979; Alexander et al. 1994; Mackey & Bridge 1995; Mack & Leeder 1999; Gawthorpe & Leeder 2000; Peakal et al. 2000; Gawthorpe et al. 2003). This situation may be modified by variables in differential erosion of the rock types in the source areas, headward growth of drainages, fault segregation, or vertical or lateral fault propagation (Leeder & Jackson 1993; Mack & Stout 2005).

The continental Permo-Carboniferous basins of the Bohemian Massif record a long history of post-Variscan extensional collapse from the Westphalian up to the Early Triassic (Kalvoda et al. 2008; Martínek et al. 2009). The erosional remnants of these deposits provide speculations regarding the original paleogeographic extent of the basins. The purpose of this study is to use chemical and petrographical approaches for: i) confirming or denying supposed communication during the deposition of the currently isolated Permo-Carboniferous deposits of the Boskovice Basin (Moravia, Czech

Republic) and the Zöbing Upper Paleozoic (Lower Austria, Austria), ii) an improved determination of the source areas and its evolution, and, iii) identification of the paleogeographical, climatic and tectonic events responsible for the material supply.

Regional geological setting

The Boskovice Basin

The elongated asymmetrical Boskovice Basin (BB) is striking in a SSW-NNE direction, filled with Permo-Carboniferous deposits. The current width of the basin is only 5 to 12 km and the length approximately 90 km (Fig. 1). The BB is situated along an important SSW-NNE trending dextral strike slip structure, separating the principal geological units of the Bohemian Massif namely the Moldanubian Unit, the Moravian Unit, the Letovice and Zábřeh Crystalline Complexes to the west and the Brno Massif and Moravo-Silesian Paleozoic deposits (Culm facies) to the east (Čepek 1946; Jaroš 1961). The BB can be classified as an extensional basin (half graben) with several stages of development. The entire thickness of the sedimentary infill is estimated at 5700 m; the maximum present-day thickness of the sediment fill in the BB, however, is assumed to be less than 3000 m

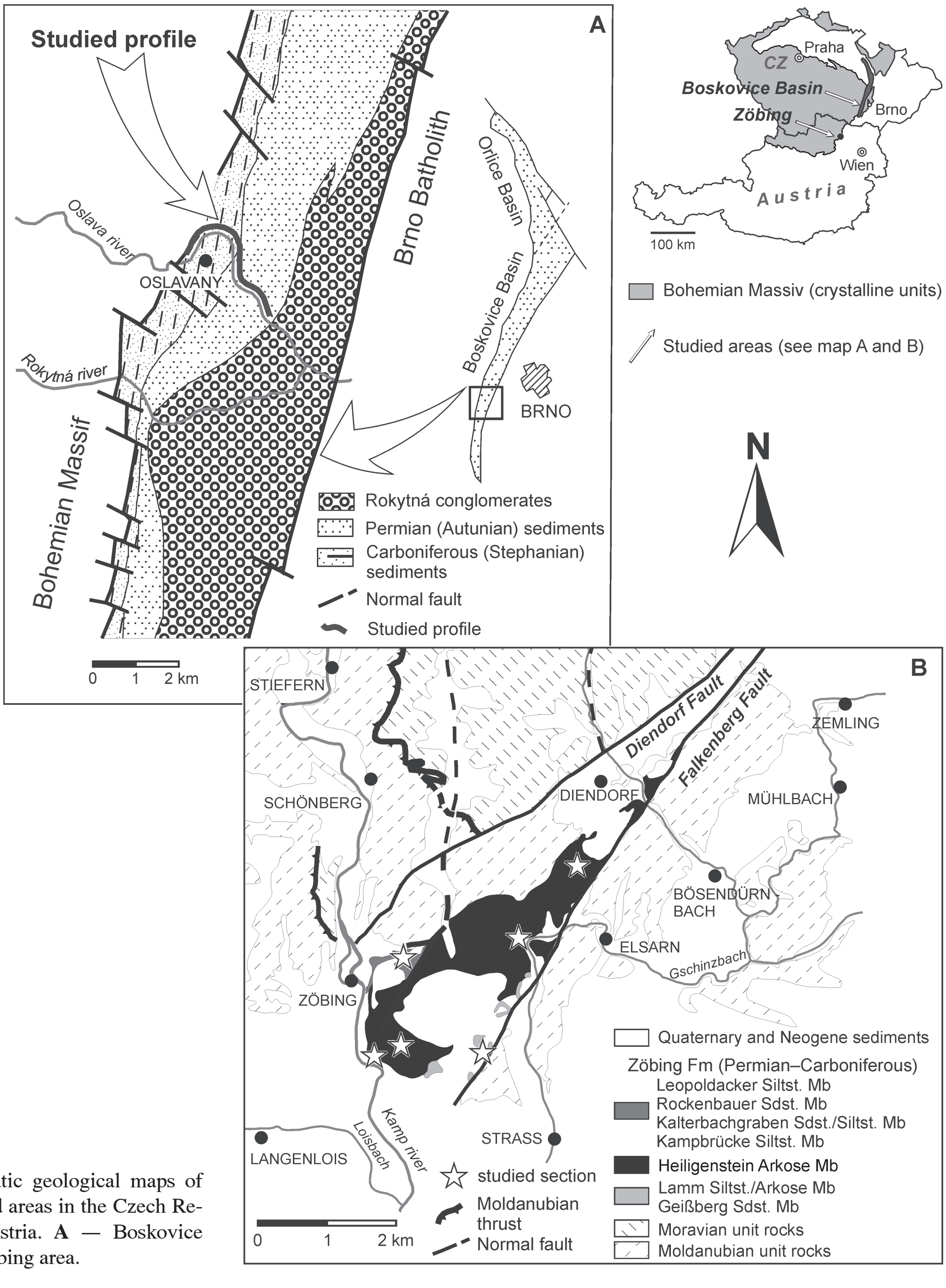

Fig. 1. Schematic geological maps of the investigated areas in the Czech Republic and Austria. **A** — Boskovice Basin, **B** — Zöbing area.

(Šimůnek & Martínek 2008). The tectonic (NW-SE extension, dextral strike-slip reactivation along the NW oriented fault) and the climatic processes (a general but not gradual trend from the tropical humid paleoclimate in the Carboniferous, through humid to semi-arid conditions with several climatic fluctuations in the Permian) were the principal leading factors of the filling of the BB (Mikuláš & Martínek 2006; Šimůnek & Martínek 2008). The BB basin was also transversally segmented by NW-SE trending faults/elevations into "subbasins". The northern Letovice subbasin (Lower Autunian — Middle Autunian) is younger than the southern Rosice-Oslavany subbasin (Stephanian C — Lower Autunian) according to Havlena (1964) or Jaroš & Malý (in Pešek et al. 2001). The opening of the Rosice-Oslavany subbasin to the south and a relation to the Early Paleozoic deposits in the surroundings of Zöbing in Lower Austria is widely assumed (Jaroš & Mísař 1967).

A strongly asymmetric distribution of the sedimentary facies and the continental depositional environments is typical for the BB (Fig. 2). Breccias and conglomerates initiated the deposition in the entire basin. In the eastern part the coarse-grained deposition continued throughout the entire basin succession with the facially monotonous *Rokytná conglomerates* comprising pebbles from easterly located geological units (wackes, arkoses, shales, limestones, conglomerates, rarely magmatic or metamorphic rocks). The lowest lithostratigraphic unit on the western limb of the basin is the so called *Basal Red-Brown Formation* (Stephanian C) with the *Balinka conglomerates* at its base. Pebbles from generally westerly situated crystalline units (mica schists, gneisses, quartzites, marbles, amphibolites, granulites, serpentine, magmatic rocks, etc.) are most common in these conglomerates. The Basal Red-Brown Formation is a product of alluvial and fluvial deposition (Jaroš & Malý 2001). The succession grades upwards into the *Rosice-Oslavany Formation* (Stephanian C — lower Autunian/Asselian) with a coal seam complex (Šimůnek & Martínek 2008; Štramberk et al. 2008). The Rosice-Oslavany Formation is subdivided into the *Lower Grey Member*, *Middle Red-Brown Member* and *Upper Grey Member*. The sedimentary infill is represented by an alternation of shales, sandy shales, siltstones, fine- to coarse sandstones and rarely also of thin conglomerate layers. Three coal seams were identified within the Lower Grey Member. Mastalerz & Nehyba (1992) described the deposits of an anastomosing fluvial system with abundant avulsion in the Lower Grey Member. Episodic overfill of the channels and overbank deposition (channel belts, crevasses) were typical processes. Both episodic (one phase) and multi-storey channel fill were recognized along with collapses of the channel banks. A bituminous shale horizon was described within the Upper Grey Member with an abundant flora and fauna content. This horizon belongs to the *Acanthodes gracilis* Biozone (Štamberk et al. 2008). Mastalerz & Nehyba (1997) recognized that the lacustrine sequence within the Upper Grey Member is composed of a transgressive, open-lake and regressive segment. Evidence of frequent lake level fluctuations, subaerial exposure and small-scale shallowing-up motifs was recognized. The following *Padochov Formation* (Autunian/Asselian) represents a complex of brown arkosic sandstones, arkoses and conglomerates (Jaroš 1961; Malý 1993; Pešek et al. 2001; Šimůnek & Martínek 2008). Extensive fluvial channels with variations in sediment and fluvial discharge and sediment load are assumed.

The next two upper formations namely the *Veverská Bítýška Formation* (Autunian/Asselian) and the *Letovice Formation* (Early Sakmarian–Late Sakmarian) are only developed in the middle and northern part of the BB. They are represented by cyclic fluvial and fluvio-lacustrine deposits with several fossiliferous horizons (Pešek et al. 2001; Zajíc 2002; Zajíc & Štramberk 2004; Šimůnek & Martínek 2008).

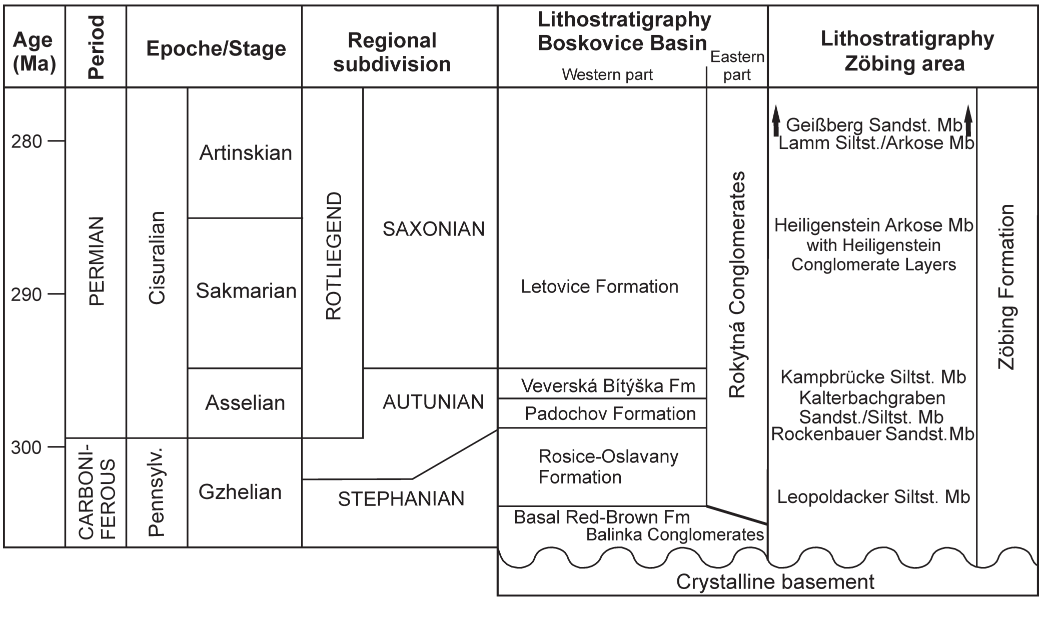

Fig. 2. Lithostratigraphic correlation of the Upper Carboniferous–Permian sediments in the Boskovice Basin (modified after Šimůnek & Martínek 2008) and the Zöbing area (Vasícek 1991a).

Zöbing area

In the surroundings of Zöbing a more than 1000 m thick succession of Upper Carboniferous to Permian sediments occur in a wedge-shaped distribution about 6.5 km long and maximally 2.3 km broad. They mainly crop out at the Heiligenstein east to southeast of Zöbing and reach as far as Diendorf and Olbersdorf in the northeast (Fig. 1). These deposits of the Zöbing Paleozoic (ZP) have been well known since the 19th century (cf. Holger 1842; Partsch 1843, 1844; Cžjžek 1849, 1853; Ettingshausen 1852; Stur 1870; Suess 1912; Waldmann 1922; Vohryzka 1958; Schermann 1971). The last detailed mapping was done by Vasícek (1974, 1975), who also defined the Zöbing Formation and divided it in several members (Vasícek 1991a; cf. Vasícek 1977, 1983, 1991b; Vasícek & Steininger 1996). From the Zöbing Formation remains of plants were described by Berger (1951), Vasícek (1977, 1991a,b, 1983) and Vasícek & Steininger (1996) (cf. Tenchov 1980; Cichocki et al. 1991). Bachmayer & Vasícek (1967) described remains of insects, Flügel (1960) non-marine molluscs and Schindler & Hampe (1996) remains of fish. However, until now no detailed sedimentological study was done.

The sediments of the Zöbing Formation are tectonically tilted together with the crystalline basement (mainly granulite and ultrabasits) and preserved in a tectonic half graben between the Diendorf fault in the northwest and the Falkenberg fault in the southeast (Waldmann 1922; cf. Fuchs et al. 1984, Fig. 1). Today in the surroundings of the Permo-Carboniferous sediments, crystalline rocks of the Moldanubian Unit (granulite, Gföhl gneiss, mica schists, amphibolite) occur. North of the ZP granites, Biteš gneiss and mica-schists of the Moravian unit are also located close to the Paleozoic sediments.

In the succession of the Zöbing Formation a trisection of the sediments can be observed (Fig. 2). Above the crystalline basement the Zöbing Formation starts in the southwest with a succession about 300 m thick of alternating silt- and sandstones, which can be divided into four members.

The lowermost *Leopoldacker Siltstone Member* mainly consist of dark grey, fine-grained, laminated silt- and sandstones with small coal seams and a high amount of organic remains. In coaly shales and coal-streaks close to the base a well preserved flora with Late Carboniferous ferns and horsetails occurs (Vasícek 1983, 1991a,b; Vasícek & Steininger 1996). Siltstones contain freshwater bivalves (Flügel 1960) and in dark grey carbonate nodules (coal balls) freshwater gastropods, ostracods and small fish teeth and fish scales (Schindler & Hampe 1996) were found.

The above following ochre-brown, thin-bedded and slightly calcareous silt- to sandstones of the *Rockenbauer Sandstone Member* pass over into varve-like carbonaceous shales ("Brandschiefer"). The sediments often contain resedimented clay- and sandstone-pebbles and remains of conifers (Vasícek 1983, 1991a,b; Vasícek & Steininger 1996). Besides ostracods, teeth and coprolites of fish and a fragment of an insect wing were found in this member (Schindler & Hampe 1996).

In the *Kalterbachgraben Sandstone/Siltstone Member* above, an alternation of massive layers of arkoses and sandstones with dark grey, laminated silt- to sandstones can be observed (Vasícek 1983, 1991a,b; Vasícek & Steininger 1996). In this alternation dark, laminated limestones, reddish siltstones, a coal seam, and a thin layer of rhyolitic tuff (Schindler & Hampe 1996) are intercalated. Fossils were only found in a single limestone bed, from where Schindler & Hampe (1996) described many ostracods and few fish teeth.

The topmost member of the basal succession is the *Kampbrücke Siltstone Member*, which mainly consists of layered siltstones alternating in longer intervals with arkoses and sandstones and two fossil-bearing horizons. In the lower fossiliferous horizon a rich flora with ferns and horsetails (Vasícek 1974, 1977, 1983) occurs, whereas the higher horizon contains remains of conifers, freshwater bivalves and insect wings (Bachmayer & Vasícek 1967; Vasícek 1991b).

The second, about 700 m thick middle part of the Zöbing Formation is the *Heiligenstein Arkose Member*, which consists of an alternation of banks of arkoses, sandstones and conglomerates. The grain size of this member increases towards the top, where the *Heiligenstein Conglomerate Layers* comprise mainly granulite, additionally also quartz, quartzite, granitic gneisses, amphibolites, marble, Gföhl gneiss and clasts of rhyolite (Waldmann 1922; Vohryzka 1958; Schermann 1971; Vasícek 1977, 1991b). Boulders in these conglomerates reach sizes up to 1 m in diameter.

Above the Heiligenstein Arkose Member the third, about 400 m thick upper part of the Zöbing Formation starts with the *Lamm Siltstone/Arkose Member*. It shows an alternation of reddish-brown siltstones, sandstones and arkoses. In finer parts of the succession intercalations of dark grey silicified limestones can be observed (Vasícek 1983, 1991a,b; Vasícek & Steininger 1996). From pelitic sediments Vasícek (1991b) describes imprints of raindrops. In the uppermost part of the Zöbing Formation the *Geißberg Sandstone Member* occurs. It is a varied series of red and grey claystones in alternation with arkoses and sandstones (Vasícek 1983, 1991a,b; Vasícek & Steininger 1996). No biostratigraphic data are available until now from the Lamm Siltstone/Arkose Member and the Geißberg Sandstone Member.

The sediments of the Leopoldacker Siltstone Member at the base of the Zöbing Formation are dated by the seed fern *Alethopteris zeilleri* and similar forms to the Late Carboniferous (Stephanian) (Vasícek 1977, 1983, 1991a; Vasícek & Steininger 1996). In the above following Rockenbauer Sandstone Member and Kampbrücke Siltstone Member callipterids like the seed fern *Autunia conferta*, the conifer *Ernestiodendron filiciformis* and fructifications of horsetails (*Calamostachys dumasii*) already point to an Early Permian (Autunian) age (Schindler & Hampe 1996; Vasícek & Steininger 1996). Volcanoclasts from rhyolite in the Heiligenstein Arkose Member are correlated with the volcanism in the Middle Permian "Saalic orogenic phase" (Vasícek 1977, 1983, 1991a,b; Vasícek & Steininger 1996).

For the basal, fine-grained part of the Zöbing Formation Schindler & Hampe (1996) assume that the depositional environment was shallow eutrophic lakes with a vegetation-rich riparian zone or stagnating oxbow lakes close to a fluvial environment. With the beginning of the Kalterbachgraben Sandstone/Siltstone Member a clear climatic and environmental turn looms. The arkoses and conglomerates of the Kalterbachgraben Sandstone/Siltstone Member and the

Heiligenstein Arkose Member are interpreted as periodic flash-flood deposits in arid alluvial environments of the Permian (Vasícek 1991a,b).

Methods

The presented results are based on the study of the profile along the Oslava River between Oslavany and Ivančice, where deposits of the Basal Red-Brown Formation, Rosice-Oslavany Formation, Padochov Formation, and Rokytná conglomerates (the Rosice-Oslavany subbasin of the BB) were investigated. In the broader surroundings of Zöbing Upper Paleozoic deposits are accessible in several small outcrops. The studied outcrops belong to the Rockenbauer Sandstone Member, Kalterbachgraben Sandstone/Siltstone Member, Heiligenstein Arkose Member, and Lamm Siltstone/Arkose Member (Vasícek 1991a; cf. Fig. 1).

All the outcrops and sections were logged, the depositional environment and its evolution was evaluated (Nehyba et al. in prep.). Samples for provenance analyses were only selected from sandstone bedforms (dunes) of fluvial channels. Ten samples were selected from the BB and thirteen from the ZP. The framework grains were point counted in thin sections according to the standard method (Dickinson & Suczek 1979; Zuffa 1980, 1985; Dickinson 1985; Ingersoll 1990). The entire rock geochemistry was evaluated in the ACME laboratories Vancouver, Canada (10 analyses of the BB, 15 analyses of the ZP).

Heavy minerals were quantified by counting method under the polarizing microscope in the grain-size fraction 0.063–0.125 mm (8 samples from the BB, 13 samples from the ZP). The opaque minerals were not considered in the calculation. Detailed studies of the zircon characteristics were carried out on samples with enhanced occurrence of this mineral. The outer morphology, colour, presence of older cores, inclusions and zoning were evaluated in the entire zircon spectra (291 zircons from the BB and 223 from the ZP). Only the euhedral or subhedral zircons were considered in the study of typology (29 grains from the BB and 43 grains form the ZP) and elongation (89 grains from the BB and 81 grains from the ZP). The electron microprobe analysis of garnet, rutile and spinel were evaluated with a CAMECA SX electron microprobe analyser (Faculty of Science, Masaryk University, Brno, Czech Republic). Data from 276 analysed garnet grains for the ZP and from 133 for the BB, as well as from 100 analysed rutiles for the ZP and from 67 for the BB were available. The analyses of 22 spinels for the BB and 10 for the ZP were obtained.

Results

Petrography

Sandstones from both the BB and the ZP are in general coarse- to medium-grained, often texturally immature, poorly sorted with a certain admixture of granules. The sandy grains are often angular and sub-angular, whereas small pebbles are usually rounded. The amount of the matrix is limited (Fig. 3) and is mostly of the coating type. Sericite, chlorite and clastic micas were recognized in the matrix. Cement, which often intensively colours the matrix, is formed by carbonates and amorphous Fe oxi-hydroxides. The studied samples occupy the wacke field to a predominant extent; some of them being arkoses, whereas subwackes are rare (Petránek 1963; Kukal 1986) (Fig. 3).

The sandstones from the ZP contain a significant amount of both monomineral and aggregate quartz. The anhedral quartz grains suggest an origin from granitoids. Cataclasis of the quartz grains resembles a source from muscovitic quartzites or mica schists. In all probability coarse subhedral feldspar grains with microperthites and plagioclases originated from cataclased granitoids. The clasts of fine grained acidic plutonites, fine-grained gneisses, granulites, and feldspar phenocrysts were determined regularly, whereas quartzites were rare. The partly reworked clasts of glasses or volcanites with micropoikilitic structures represent the acidic volcanic source. The source of micas (both biotite and muscovite) is probably mainly connected with mylonites or cataclasites, rarely with granitoids. Garnet, cordierite, rutile, tourmaline and zircon were identified as accessory minerals.

A broader spectrum of detrital grains was recognized within sandstones of the BB. Monomineral and aggregate quartz dominates and originate from granitoids, cataclasites and mylonites. The content of feldspar is generally lower than in the ZP, but relatively coarse grains of plagioclases are common. Their source is connected with granodiorites or diorites. Argillizated acidic volcanic glasses, felsites or grains with fluidal structures represent the most common volcanic derivates. Grains of quartzites, fine-grained slates or even mica schists are more common in the BB than in the ZP. Grains of silty shales originate in all probability from the Lower Carboniferous "Culmian" rocks. The content of micas (both biotite and

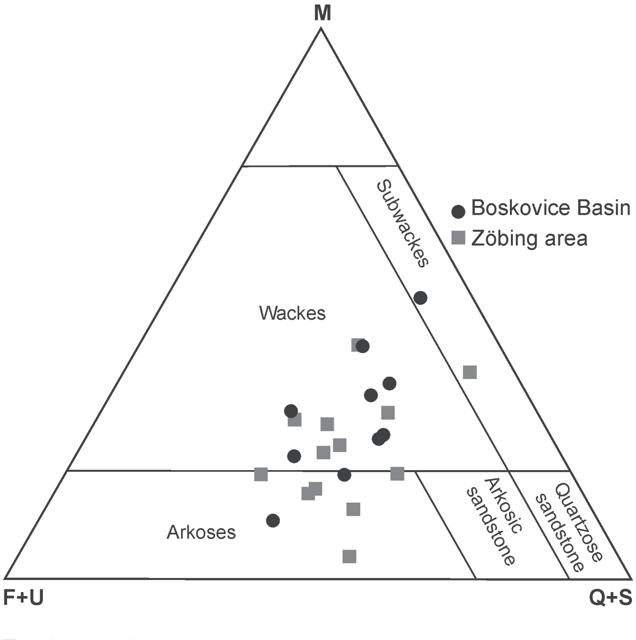

Fig. 3. Classification ternary diagram (according to Petránek 1963; Kukal 1986) of the studied sandstones. **M** = matrix (%), **F** = plagioclase + K-feldspar (%), **U** = unstable rock fragments (%), **Q** = quartz (%), **S** = stable rock fragments (%).

muscovite) varies to a great extent and is generally lower in the BB than in the ZP. The presence of carbonate cement is more frequent. Garnet, tourmaline, rutile and zircon form the most common accessory minerals. The remnants of clasts of organic material were regularly observed.

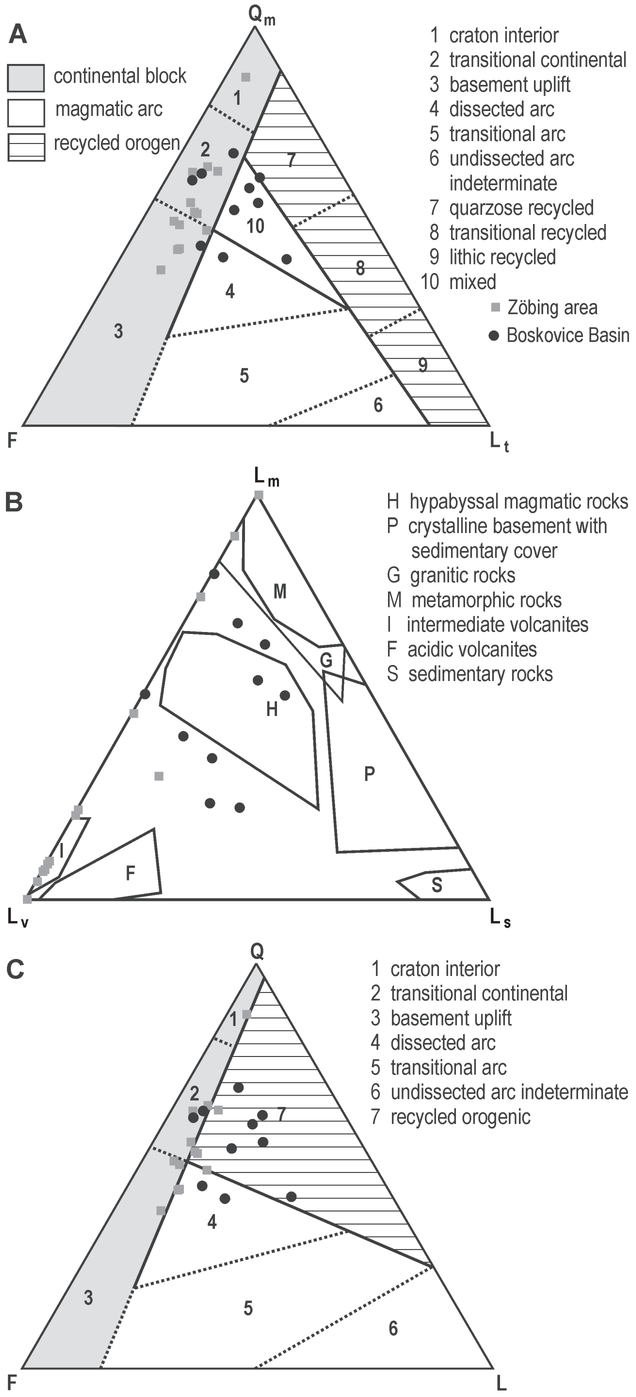

Fig. 4. Discrimination ternary diagrams (according to Dickinson 1985, 1990; Ingersoll 1990) of the studied sandstones. (**Q** = $Q_m + Q_p$, **Q_m** — monocrystalline quartz, **Q_p** — polycrystalline quartz; **F** = plagioclase + K-feldspar; **L** = $L_v + L_s + L_m$, **L_v** — volcanic lithic fragments, **L_s** — sedimentary lithic fragments, **L_m** — metamorphic lithic fragments; **L_t** = L + Q_p).

Table 1: Framework mineral data of studied sandstones (BB — Boskovice Basin, ZP — Zöbing area).

Sample	Q_m	F	L_t	L_m	L_v	L_s	Q_t	L
BB 1	55.7	22.1	22.2	68.1	19.7	12.2	55.7	22.2
BB 2	62.7	32.7	4.6	23.7	48.3	28	62.7	4.6
BB 3	42.1	36.8	21.1	50.3	18.8	30.9	42.1	21.1
BB 4	60	21.3	18.7	70.3	29.7	31.4	60	18.7
BB 5	78.4	9.3	12.3	36.3	6.7	57	78.4	12.3
BB 6	63.8	29.9	6.3	51.1	48.9	0	63.8	6.3
BB 7	68.8	20.4	10.8	80.7	19.3	0	68.8	10.8
BB 9	62.1	18.3	19.6	22.4	42.6	35	62.1	19.6
BB 10	68.8	20.4	10.8	80.7	19.3	0	68.8	10.8
BB 11	62.1	18.3	19.6	22.4	42.6	35	62.1	19.6
ZP 1	87.3	8.9	3.8	87.8	12.2	0	87.3	3.8
ZP 2	63.6	32.3	4.1	46	54	0	63.6	4.1
ZP 3	65	28.3	6.7	30.5	56.3	13.2	65	6.7
ZP 4	56	36.3	7.7	8.8	91.2	0	56	7.7
ZP 5	39	51.2	9.8	22.1	77.9	0	39	9.8
ZP 6	51.2	42.5	6.3	6.9	93.1	0	51.2	6.3
ZP 7	50.4	41.5	8.1	20.8	79.2	0	50.4	8.1
ZP 8	63.8	26.7	9.5	9.5	90.5	0	63.8	9.5
ZP 9	49.9	36.5	14.6	74.9	25.1	0	48.9	14.6
ZP 10	44.3	44.6	11.1	89.8	10.2	0	44.3	11.1
ZP 11	53.1	36.5	9.4	4.3	95.7	0	53.1	9.4
ZP 12	44.1	45.1	10.8	0	100	0	44.1	10.8
ZP 13	53.1	36.3	10.4	7.5	92.5	0	53.1	10.4

On the Q_m–F–L_t (Fig. 4A) discrimination diagram, the majority of the samples from the ZP occupy the continental block field, whereas the samples from the BB reveal a mixture of the granitoid detritus with remnants of acidic volcanism and metamorphosed sediment origin. Differences in the provenance of the ZP and the BB are supported by the position of the samples in the diagram L_m–L_v–L_s, (Fig. 4B, Ingersoll 1990) and Q–F–L (Fig. 4C, Dickinson 1985, 1990). Framework mineral data are presented in Table 1. The sandstones of the ZP plot in the field of the basement uplift of the stable craton, on the other hand the BB sandstones plot in the recycled orogen and the dissected volcanic arc fields (Fig. 4C). The mixing of material from the crystalline basement (metamorphic and plutonic rocks) with volcanogenic and recycled sedimentary rocks typifies the BB.

Heavy mineral studies

The heavy mineral ratios apatite:tourmaline (ATi), garnet:zircon (GZi), TiO_2-group:zircon (RZi) and the ZTR (zircon+tourmaline+rutile) index have been used (cf. Morton & Halsworth 1994). The ZTR index is widely accepted as a criterion for the mineralogical "maturity" of heavy mineral assemblages (Hubert 1962; Morton & Hallsworth 1994). Garnet, zircon, and rutile represent the most common heavy minerals in the studied deposits, being relatively stable in diagenesis and having a wide compositional range, so as to be further evaluated in detail along with spinel.

Heavy mineral assemblages and mineral ratios

The heavy mineral assemblages differ significantly between various lithostratigraphic units of the BB and the ZP but also between individual beds of the single units. Garnet (46.2 %)

and zircon (22.1 %) predominate in the transparent heavy mineral spectra of the Basal Red-Brown Formation of the BB. Further minerals (monazite, kyanite, rutile, tourmaline, staurolite, apatite, zoisite, amphibole, and spinel) represent only a small percentage. The ATi-ratio is 20.8, the GZi-ratio 67.6, the RZi-ratio 14.7 and the ZTR index 29.7. A high content of kyanite (62.4 %) and epidote (28.9 %) together with an accessory occurrence of rutile, zircon, staurolite, tourmaline and spinel were determined in certain heavy mineral spectra of the Rosice-Oslavany Formation. There the RZi-ratio is 80.6 and the ZTR index 9.0. In further samples from this formation zircon (78.9 %) strongly predominates with a subordinate occurrence of apatite, rutile, tourmaline, kyanite, and spinel. Here the ATi-ratio is 24.4, the RZi-ratio 92.9 and the ZTR index 94.7. Zircon (22.3–41 %), garnet (12.5–25.6 %), apatite (17.4–24.5 %) and kyanite (11.8–16.7 %) predominate in the heavy mineral spectra of the Padochov Formation. Rutile, tourmaline, staurolite, epidote, monazite, titanite, spinel, and andalusite were also recognized and usually have a few percent. The ATi-ratio is 82.9–95.0, the GZi-ratio 11.1–53.4, the RZi-ratio 5.3–17.5, and the ZTR index 28.9–53.3. In sandstone beds within the Rokytná conglomerates zircon (30.8–35.8 %), garnet (15.6–54.6 %) and apatite (15.6 %) dominate. Significantly less common were rutile, zoisite, amphibole, kyanite, epidote, monazite, staurolite, andalusite, titanite, and spinel. The ATi-ratio is 100, the GZi-ratio 30.4–64, the RZi-ratio 9.9–18.8, and the ZTR index 32.4–44.1.

In the Rockenbauer Sandstone Member of the ZP rutile (72.1 %) and zircon (14.7 %) dominate. Additional heavy minerals (apatite, titanite, zoisite, epidote, monazite, garnet, staurolite, tourmaline, and andalusite) form several percent at a maximum. The ATi-ratio is 33.3, the GZi-ratio 19.7, the RZi-ratio 84.0, and the ZTR index 87.8. Two heavy mineral assemblages were determined within the Kalterbachgraben Sandstone/Siltstone Member. An association with predominance of garnet (69–81.6 %), rutile (10.9–15.2 %) and zircon (5.5–16.1 %) and occurrences of kyanite, apatite, titanite, and monazite prevail in the majority of the samples. The ATi-ratio is 100, the GZi-ratio 81.1–96.9, the RZi-ratio 40.4–84.1, and the ZTR index 15.8–27.0. Zircon (39 %), rutile (16.9 %) and garnet (16.9 %) predominate in the second association of this member with the occurrences of apatite, andalusite, tourmaline, epidote, kyanite, and amphibole. The ATi-ratio is 79.7, the GZi-ratio 30.2, the RZi-ratio 47.2, and the ZTR index 75.1. Two associations were also determined in the samples from the Heiligenstein Arkose Member. The first one is characterized by a predominance of garnet (78.6–85.0 %), with occurrence of rutile, apatite, zircon, staurolite, monazite, zoisite, and kyanite. The ATi-ratio is 100, the GZi-ratio 97.8–98.9, the RZi-ratio 70.6–83.0, and the ZTR index 3.2–8.8. The second one is typified by a predominance of garnet (30.7–63.3 %), rutile (11.2–19.8 %), and also apatite (6.6–22.2 %) and zircon (6.6–33.2 %), and occurrences of staurolite, monazite, zoisite, tourmaline, epidote, andalusite and kyanite. The ATi-ratio is 83.5–100, the GZi-ratio 52.0–88.5, the RZi-ratio 33.0–69.3, and the ZTR index 19.2–46.8. Garnet (84.9 %) predominates in the heavy minerals of the Lamm Siltstone/Arkose Member. Additional heavy minerals (apatite, rutile, kyanite, and zircon) consist of only several percent. The ATi-ratio is 100, the GZi-ratio 99.0, the RZi-ratio 82.0, and the ZTR index 5.0.

The amount of heavy mineral analyses is insufficient thus we can only speculate about the general evolution of the heavy mineral assemblages. The situation seems to be less complicated in the ZP. Basal deposits (Rockenbauer Sandstone Member, Kalterbachgraben Sandstone/Siltstone Member) are typified by a strong predominance of rutile and zircon, show low ATi and GZi-ratios, a high RZi-ratio and ZTR index. The middle part of the succession (Heiligenstein Arkose Member) is typically characterized by the presence of garnet, but also of rutile, zircon and apatite. The ATi is 100, the GZi-ratio 81.1–96.9, the RZi-ratio 40.4–84.1, and the ZTR index 15.8–27.0. The ATi and GZi-ratios are higher and the RZi-ratio and ZTR index lower than in the basal parts of the succession. Garnet strongly predominates in the upper part of the succession (Lamm Siltstone/Arkose Member). The ATi, GZi and RZi-ratios are the highest in the succession and the ZTR index is particularly low.

In the BB the basal deposits are characterized by a strong predominance of garnet and zircon, low ATi and RZi-ratios, a high GZi-ratio and a medium ZTR index. For the middle part of the succession (Rosice-Oslavany Formation) the presence of varied heavy mineral spectra in different samples with an important presence of kyanite, epidote in some samples and a strong predominance of zircon are typical. The ATi-ratio is low, the RZi-ratio is high and the ZTR index varies significantly. Zircon, garnet, apatite and also kyanite dominate in the upper parts of the succession (Padochov Formation and Rokytná conglomerates). The heavy mineral assemblages differ particularly in terms of the relative content of garnet and kyanite. The ATi ratio is high; GZi and Rzi ratios and ZTR index vary.

Rutile

The concentration of the main diagnostic elements (Fe, Nb, Cr, and Zr) varies significantly in the studied samples. Data from the ZP have revealed that the concentration of Nb varies between 182 and 7340 ppm (average 2082 ppm), the concentrations of Cr vary between 4 and 4050 ppm (average 1011 ppm), of Zr between 170 and 8410 ppm (average 3183 ppm), and the value of logCr/Nb is mostly negative (87.5 %). The data from the BB reveal that the concentration of Nb varies between 129 and 8538 ppm (average 1565 ppm),

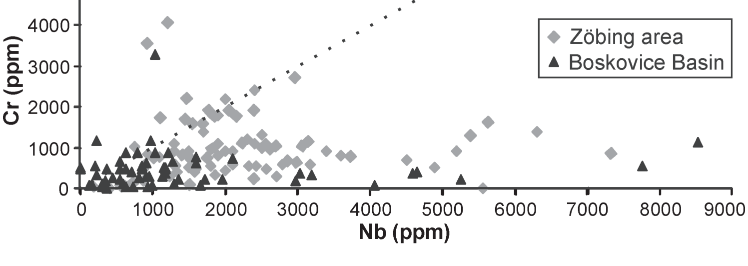

Fig. 5. Discrimination plot Cr vs. Nb of investigated rutiles.

Table 2: Garnet types of the studied deposits of the Boskovice Basin (BB) and Zöbing area (ZP) (ALM — almandine, GRS — grossular, PRP — pyrope, SPS — spessartine, AND — andradite).

Garnet type	ZP	BB
ALM$_{(82–90)}$	2.2 %	5.3 %
ALM$_{(49–83)}$–PRP$_{(11–48)}$	93.5 %	50.4 %
ALM$_{(69)}$–PRP$_{(18)}$–SPS$_{(12)}$	–	0.8 %
ALM$_{(62–64)}$–PRP$_{(18–25)}$–GRS$_{(10–15)}$	1.9 %	2.3 %
ALM$_{(58)}$–GRS$_{(22)}$–SPS$_{(16)}$	–	0.8 %
ALM$_{(60–67)}$–GRS$_{(19–34)}$	0.7 %	16.7 %
ALM$_{(63–68)}$–GRS$_{(12–20)}$–PRP$_{(10–16)}$	–	11.3 %
ALM$_{(50–83)}$–SPS$_{(14–42)}$	1.4 %	4.5 %
ALM$_{(71–72)}$–SPS$_{(13–15)}$–PRP$_{(10–11)}$	–	2.3 %
ALM$_{(42–56)}$–SPS$_{(21–27)}$–GRS$_{(15–21)}$–PRP$_{(13–15)}$	–	1.6 %
GRS$_{(66–89)}$–AND$_{(11–31)}$	0.4 %	1.5 %
GRS$_{(74)}$–PRP$_{(13)}$–AND$_{(12)}$	–	0.8 %
GRS$_{(50)}$–ALM$_{(41)}$	–	0.8 %
PRP$_{(40)}$–AND$_{(36)}$–ALM$_{(20)}$	–	0.8 %

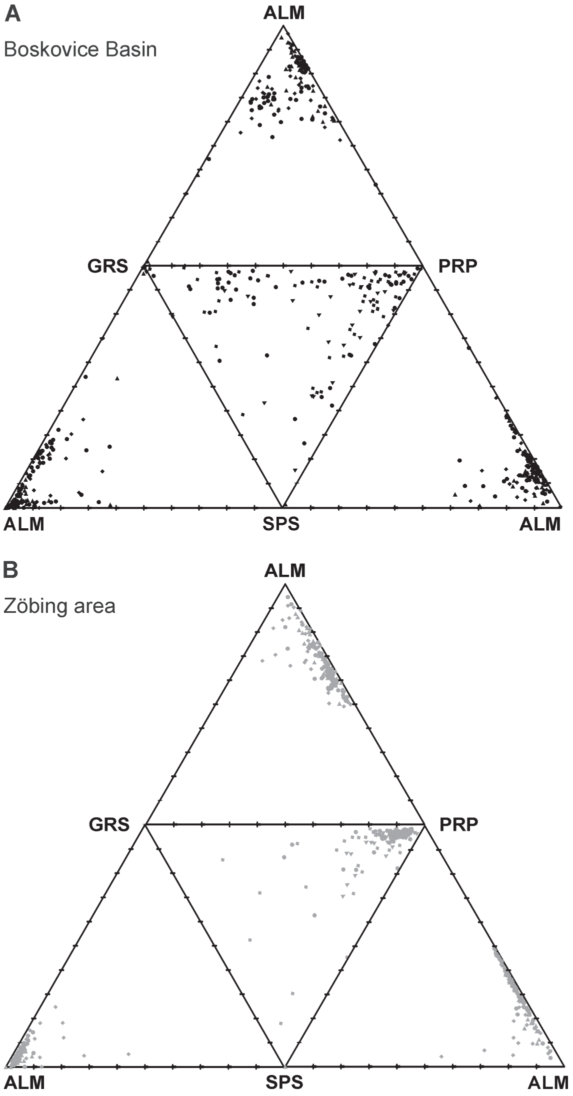

Fig. 6. Ternary diagram of the chemistry of detrital garnets (Morton 1985). **A** — analysis from Boskovice Basin, **B** — analysis from Zöbing area (ALM — almandine, GRS — grossular, PRP — pyrope, SPS — spessartine).

of Cr between 3 and 5080 ppm (average 510 ppm), of Zr between 15 and 8330 ppm (average 1291 ppm), and the value of logCr/Nb is also mostly negative (85.1 %). The discriminate plot Cr vs. Nb is presented in Fig. 5. Rutiles from the BB reveal higher variations in the concentrations of diagnostic elements than rutiles from the ZP.

The Zr-in-rutile thermometry was applied for metapelitic zircons only (for a stable rutile-quartz-zircon assemblage cf. Zack et al. 2004a,b; Meinhold et al. 2008). The results indicate that 94.7 % of metapelitic rutiles from the ZP belong to granulite metamorphic facies and 5.3 % to the amphibolite/eclogite facies. In the BB the metapelitic rutiles of granulite metamorphic facies form 53.6 %, the rutiles of the amphibolite/eclogite facies 32.1 % and 14.3 % belong to the greenschist/blueschist facies.

Garnet

The results of the analyses of detrital garnet chemistry are presented in the Table 2 and Fig. 6A,B. The garnet composition is different for the ZP and the BB. The garnet composition of all lithostratigraphic members of the ZP (Fig. 6B) was surprisingly monotonous. Almandine absolutely predominates as pyrope-almandines make 93.5 % of the spectra. Almandines form 2.2 %, grossular-pyrope-almandines 1.4 %, spessartine-almandines form 1.4 %, grossular-almandines form 0.7 %, while pyrope-andradite-almandine and grossular were exceptional. The spectra of garnets are much wider in the BB (Fig. 6A), where 14 types of garnet were determined. Pyrope-almandines predominate forming 50.4 %, grossular-almandines form 16.7 % and pyrope-grossular-almandines were determined in 11.3 % of the studied grains.

Zircon

In the BB subrounded and rounded zircons in all studied samples amounted to 49.8 %, whereas the subhedral ones formed 45.7 % and the euhedral zircons constituted 4.4 %. In the ZP subrounded and rounded zircons in all studied samples amounted to 47.9 % whereas, subhedral ones made 42.7 % and euhedral zircons constituted 9.4 %. Certain differences in the shape of zircons were recognized between deposits of various members of the ZP. The highest occurrence of euhedral zircons was observed in the Heiligenstein Arkose Member.

Zircons with a pale colour shade predominate in the BB with 66.6 %. The colourless zircons constitute 23.6 % of the spectra. Zircons with a brown colour form 5.8 %, opaque ones 3.4 %, and pink zircons are very rare (0.7 %). Zircons with a pale colour shade also predominate in the ZP forming

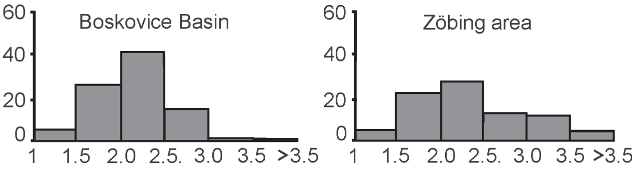

Fig. 7. Histograms of zircon elongation.

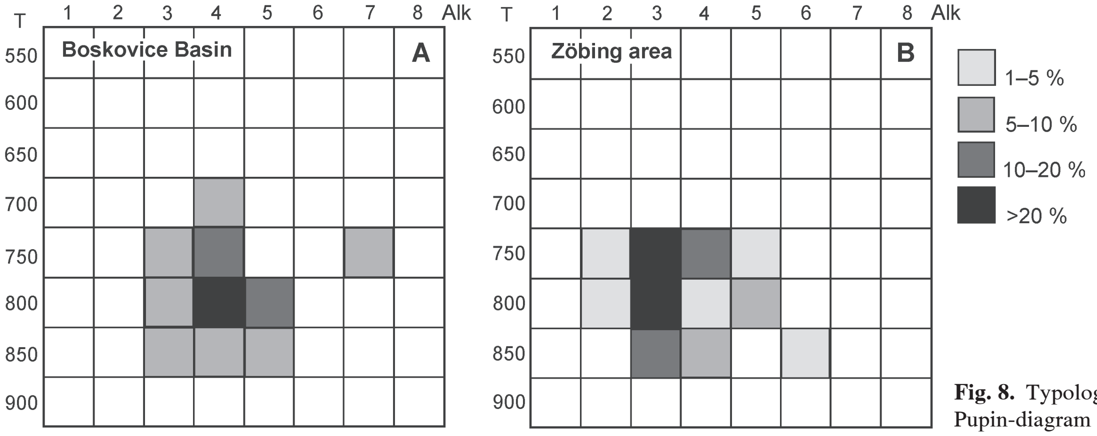

Fig. 8. Typology of zircons in the Pupin-diagram (Pupin 1980).

48.4 % while colourless zircons constitute 42.2 % of the spectra. Zircons with a brown colour form 7.6 %, opaque ones 0.4 % and pink zircons 1.3 %.

The proportion of zoned zircons in the BB samples is 19.8 % while older cores occur in zircons to an amount of 14.7 %. These zircon characteristics are significantly less common in the ZP where zoned zircons form maximally 9.7 % and zircons with older cores 4.7 %. All the studied zircons show inclusions.

The average value of the elongation (the relationship between the length and width of the crystals) for the BB samples was 2.18 and for the ZP 2.33. The histograms of elongation are presented in Fig. 7. Zircons with elongation above 2.0 predominate with 65.2 % in the BB and 69.7 in the ZP. Zircons with an elongation of more than 3 are supposed to reflect a magmatic/volcanic origin (Zimmerle 1979) and/or only limited transport. The presence of such zircons is very limited in the BB with 5.6 %, whereas it is significantly higher in the ZP with 19.1 %.

The parental magmas of the studied zircons had a hybrid character (close to the anatectic origin) in accordance with the position of the "typology mean point" (Pupin 1980, 1985). The predominance of the typological subtypes S18 of Pupin (1980) can be observed in the BB and of S17 and S12 in the ZP (Fig. 8A,B).

Spinel

The microprobe study reveals a strong predominance (86.4 % in the BB and 70 % in the ZP) of spinels with a high content of Cr (>2500 ppm). These spinels can be classified as chromian ones which are a typical mineral for peridotites and basalts (Pober & Faupl 1988) reflecting a source from mafic/ultramafic rocks. Plotting TiO_2 against Al_2O_3 (Fig. 9) for spinels points to a volcanic source, which also suggests the relatively high TiO_2 concentrations (Kamenetsky et al. 2001; Zimmermann & Spalletti 2009).

Major element geochemistry

The major element composition is presented in Table 3. In the studied samples the positive inter-relationship between Al_2O_3 and TiO_2 is well developed (Fig. 10A). The trends in Al_2O_3 and TiO_2 contents are not consistent and indicate either different provenance or weathering and depositional history for the deposits of the ZP and the BB (Young & Nesbitt 1998; Passchier & Whitehead 2006). The studied deposits reveal relatively low Al_2O_3 and TiO_2 values, characteristic for granulites and granitoids (Passchier & Whitehead 2006). Significant enrichment in Al with respect to average crystalline rocks (due to weathering) was not determined (Passchier & Whitehead 2006). Several samples from the ZP and the BB are relatively enriched in Al_2O_3 (more than 12 %) probably caused by the matrix rich in kaolinite. The Ti : Al ratio for the studied samples varies between 0.02 to 0.06 (average 0.04) for the BB and 0.01–0.07 (average 0.03) for the ZP. Relatively low TiO_2 and Al_2O_3 concentrations can be partly explained by grain-size effect (Young & Nesbit 1998; Paschier 2004). In contrast to Al and Ti, which occur mainly in phyllosilicates concentrated in a finer mud fraction, Zr-bearing minerals generally concentrate in the fine sand fraction. A plot of TiO_2/Zr–Zr/Al_2O_3 (Fig. 10B) illustrates, that the data follow completely different patterns and point to a different provenance for the BB and the ZP samples (Passchier & Whitehead 2006).

The value of the ratio K_2O/Na_2O (Roser & Korsch 1986) for the studied sediments from the BB varies between 0.48 and 2.07 (average 1.28) and for the ZP between 0.32 and 3.3 (average 1.23). Such relatively low values reflect a derivation from the mainly primary sources and a highly varied

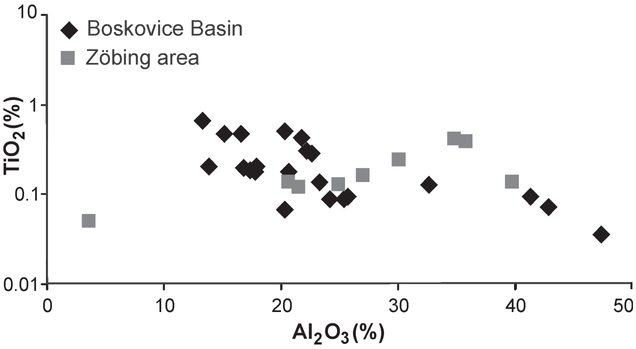

Fig. 9. Discrimination plot of TiO_2 vs. Al_2O_3 for investigated spinels.

Table 3: The major element composition (%) of the studied samples (BB — Boskovice Basin, ZP — Zöbing area).

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	LOI
BB 1	73.93	10.46	2.1	0.86	3.55	3.02	1.45	0.24	0.09	0.1	0.013	4.1
BB 2	72.26	12.5	3.97	0.85	0.43	2.32	3.25	0.69	0.14	0.09	0.031	3.2
BB 3	78.82	11.21	0.52	0.15	0.29	2.39	4.94	0.16	0.13	0.01	0.007	1.2
BB 4	67.02	9.76	1.85	1.85	4.88	2.08	2.49	0.24	0.07	0.1	0.034	7.5
BB 5	75.36	10.97	1.72	0.97	1.64	2.93	3.27	0.24	0.11	0.03	0.012	2.6
BB 6	62.47	13.9	4.61	3.05	2.87	2.97	3.29	0.63	0.19	0.05	0.017	5.7
BB 7	65.7	13	4.6	1.88	3.12	2.21	2.62	0.63	0.14	0.08	0.01	5.8
BB 8	30.41	9.5	3.22	2.84	25.3	1.19	2.26	0.43	0.16	0.18	0.013	24.3
BB 9	62.13	11.11	3.99	1.35	7.51	2.19	2.46	0.51	0.1	0.1	0.009	8.4
BB 10	71.99	9.95	2.6	1.06	4.14	1.99	2.45	0.36	0.09	0.07	0.007	5.2
ZP 1	78.72	10.75	1.45	0.52	0.27	2.41	3.83	0.2	0.11	0.01	0.006	1.6
ZP 2	75.1	11.66	2.92	1.19	0.35	2.49	3.33	0.32	0.13	0.07	0.018	2.3
ZP 3	75.9	11.14	2.2	1.14	1.09	2.94	3.11	0.29	0.22	0.03	0.009	1.8
ZP 4	67.38	14.1	4.07	2.56	1.15	2.04	2.96	0.52	0.15	0.04	0.011	4.9
ZP 5	76.44	11.86	1.53	0.78	0.22	2.88	4.34	0.18	0.12	0.03	0.014	1.4
ZP 6	69.45	13.58	3.49	1.99	0.59	3.86	3.01	0.4	0.17	0.05	0.012	3.3
ZP 7	79.76	9.04	3.29	0.77	0.41	0.53	1.75	0.56	0.13	0.06	0.033	3.6
ZP 8	77.64	9.53	4.15	1.39	0.33	2.52	0.81	0.55	0.1	0.02	0.033	2.8
ZP 9	75.21	12.23	2.11	0.84	0.35	2.68	4.22	0.28	0.15	0.03	0.011	1.8
ZP 10	73.8	12.44	2.92	1.25	0.34	2.36	3.77	0.34	0.15	0.11	0.01	2.4
ZP 11	79.31	10.18	1.33	0.35	0.11	2.15	3.66	0.24	0.07	0.01	0.006	2.5
ZP 12	78.63	9.18	1.54	0.32	1.68	2.7	1.79	0.12	0.09	0.18	0.004	3.7
ZP 13	75.35	10.91	3.84	1.53	0.53	2.56	1.06	0.37	0.19	0.02	0.043	3.5
ZP 14	74.62	11	4.16	1.66	0.53	2.45	1.11	0.35	0.18	0.02	0.041	3.8
ZP 15	73.87	11.62	3.85	1.67	0.49	2.19	1.44	0.4	0.16	0.04	0.036	4.2

role of recycled sedimentary sources (McLennan et al. 1993; Bock et al. 1998). Higher ratios (above 1) can reflect a derivation from the recycled sedimentary sources with an extended weathering history (Roser & Korsch 1986). Similarly, the K_2O/Al_2O_3 ratio can be used to estimate the degree of recycling (Cox & Lowe 1995; Passchier 2004). Its value is between 0.14 and 0.44 for the BB and between 0.09 and 0.37 for the ZP. The relatively low ratios could indicate a source from quartz-rich rocks and significant variations of the ratio point to a variation in the content of recycled sediments. Typically, samples from the basal depositional units of both occurrences (i.e. Rockenbauer Sandstone Member and Basal Red-Brown Formation) reveal the lowest value of recycling. However, because of the relatively easy affection of the alkali elements during weathering and diagenesis, the use of alkali elements could be problematic.

The studied samples are sedimentary rocks from heterogeneous source rocks and have undergone sorting during transportation in fluvial channels. The weathering indices could reflect variations in parent rock composition rather than the degree of weathering (Borghes & Huh 2007). The chemical index of alteration is commonly used (CIA index — Nesbitt & Young 1982), although due to the highly varying carbonate content and absence of CO_2 data, a precise correction for the carbonate CaO was difficult. After correcting for P_2O_5 (apatite), the value of CaO is consequently accepted, if the mole fraction of $CaO \leq Na_2O$. However, if $CaO \geq Na_2O$, it was assumed, that the moles of $CaO = Na_2O$ (McLennan et al. 1993). The CIA index ranges between 58 and 81 (average 63.4) for the BB and between 61 and 77 (average 67.4) for the ZP. The CIA index of sediments is, in general, about 50 in the case of first cycle sediments predominantly derived from physically weathered igneous rocks, and tends to increase as chemical weathering intensifies (Nesbitt & Young 1982). The variations in the CIA index reflect differences in the proportion of the content of weathered/recycled material. The effect of chemical weathering depends on (1) intensity (controlled primarily by the climate and vegetation) and (2) weathering time. The second effect includes a complex set of factors, of which the physiography is particularly important (Johnsson 1993; Le Pera et al. 2001). Higher CIA values may indicate more intense chemical weathering in more humid conditions or weathering in a sub-humid condition, whereas lower CIA values can be attributed to an influx of less weathered detritus under semi-arid conditions.

The studied sediments were plotted on the Al_2O_3–$(CaO+Na_2O)$–K_2O diagram (Fig. 10C), (called A-CN-K in the following text). The trends in A-CN-K are not consistent for the ZP and the BB. The samples from the BB are arranged almost parallel to the A-CN axis and follow a trend of increasing Al_2O_3 (and slightly also K_2O) with decreasing $CaO+Na_2O$. The elongated distribution reflects the varied role of the weathering trend/clay minerals and can be associated with grain size variations (Corcoran 2005). The samples from the ZP are more concentrated in the upper part of the diagram near the feldspar join. Such a distribution indicates a prevailing physical weathering and the low role of chemical weathering. The compositional variations between the BB and the ZP reveal that the source rocks should be different. Some deviations from the "ideal weathering trend" towards an illite composition and similarly a subhorizontal distribution of the samples can possibly be interpreted as a result of an increase in K during diagenesis (Fedo et al. 1995; Bock et al. 1998; Ohta 2008). Alternatively, these patterns may indicate the mixing of a moderately weathered source with an unweathered one (McLennan et al. 1993).

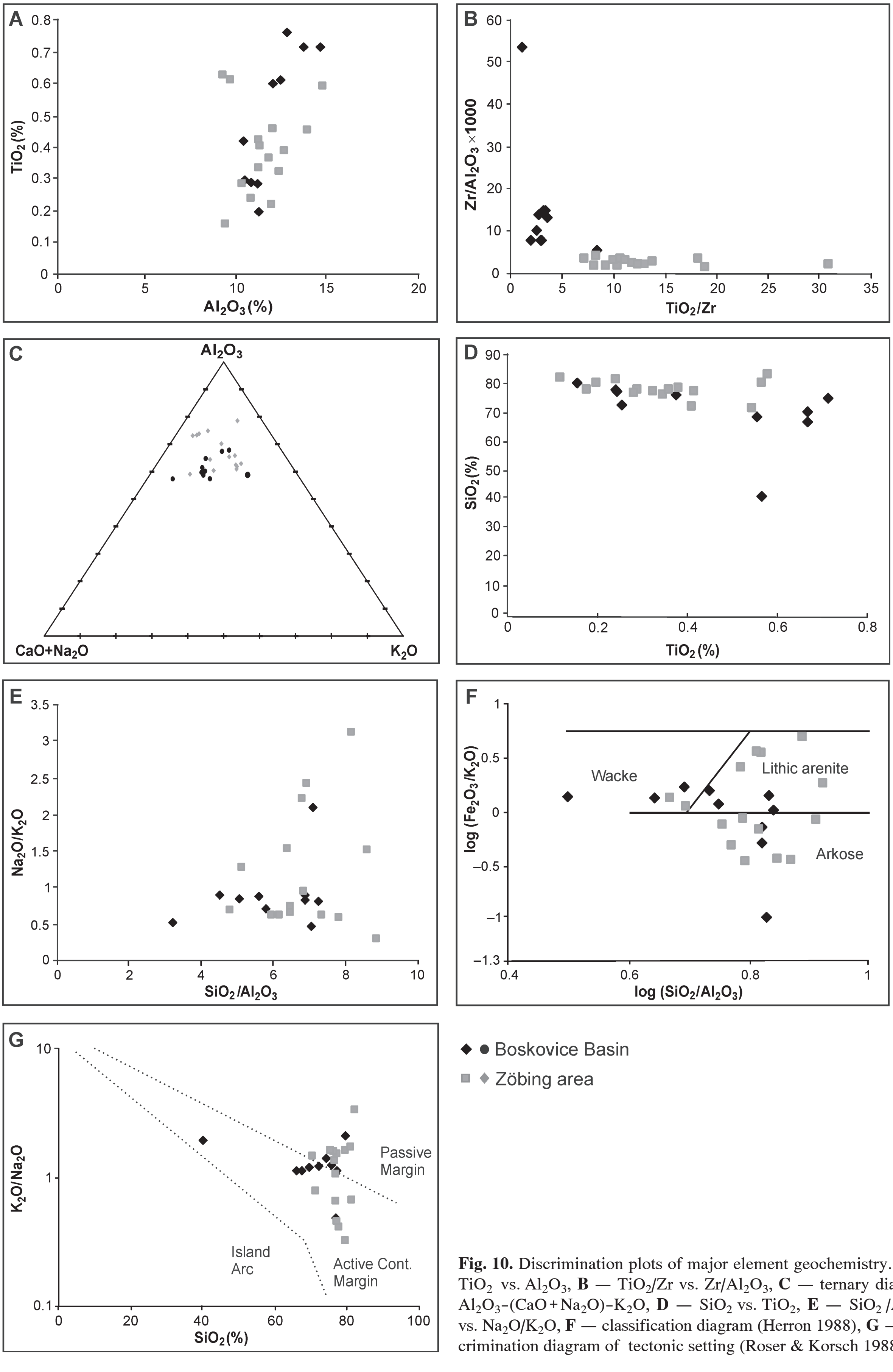

Fig. 10. Discrimination plots of major element geochemistry. **A** — TiO_2 vs. Al_2O_3, **B** — TiO_2/Zr vs. Zr/Al_2O_3, **C** — ternary diagram Al_2O_3–($CaO+Na_2O$)–K_2O, **D** — SiO_2 vs. TiO_2, **E** — SiO_2/Al_2O_3 vs. Na_2O/K_2O, **F** — classification diagram (Herron 1988), **G** — discrimination diagram of tectonic setting (Roser & Korsch 1988).

With no extra input of detritus the sediment recycling results in a negative correlation of SiO_2 and TiO_2 (Gu et al. 2002). Such a trend can be generally followed for the samples both from the ZP and the BB. Whereas in the ideal case (Cox & Lowe 1995; Corcoran 2005) the overlying sequence/formation should contain more quartz (i.e. SiO_2), less feldspar and clays (lower content of TiO_2, Al_2O_3 and MgO) in the studied cases the distribution is more complex (Fig. 10d). This can be connected with several factors: a) variations in fluvial discharge when a higher energy fluvial environment inhibited the removal of finer-grained feldspar, clay and heavy minerals richer in TiO_2 relatively to SiO_2; or b) by a renewed uplift and erosion of the source area during the depositional history. Erosion of the high relief profile would have resulted in the deposition of the stronger weathered portion first (Youngston et al. 1998).

Ohta (2008) has demonstrated that the SiO_2/Al_2O_3 and Na_2O/K_2O ratios are highly susceptible to the effect of hydraulic sorting and grain-size fractionation. On the SiO_2/Al_2O_3–Na_2O/K_2O diagram (Fig. 10E) two compositional trends can be observed, in which the geochemical variability induced by hydraulic sorting is expressed by the range and extent of these trends. The majority of samples (especially from the BB) are arranged horizontally and derived from the quartz-rich recycled sedimentary provenance. Certain samples (from the Kalterbachgraben Sandstone/Siltstone Member of the ZP and the Basal Red-Brown Formation of the BB) are arranged obliquely and reveal an increased content of the material derived from the crystalline/igneous provenances.

According to the diagram of Herron (1988), which utilizes the major oxides, the studied sandstones (Fig. 10F) can be classified as lithic arenites or arkoses, only a few of them as wackes. In terms of tectonic setting (Fig. 10G), the studied samples plot in the majority in the active continental margin field, while a number of them are in the passive margin (Roser & Korsch 1988). Such an interpretation of the tectonic settings can be affected by the mobility of K and Na, particularly during the weathering of feldspar.

Trace element geochemistry

The trace element composition is presented in Table 4. In order to determine the tectonic setting associated with the deposits, the samples were plotted on a Th-Zr/10-Sc and La-Th-Sc ternary diagram (Bhatia & Crook 1986; Fig. 11A,B). The different positions of the samples from the BB and the ZP are visible. Whereas samples from the BB lie out of the discrimination fields the samples from the ZP can be found in the continental volcanic arc field (McLennan et al. 1993; Bahlburg 1998). The Th/Sc ratios of the studied formations of the BB vary between 0.82 and 5.6 (average 1.78) and for the ZP between 0.61 and 2.63 (average 1.52).

The Zr/Sc ratio of the studied formations of the BB varies between 6.23 and 76.34 (average 23.24) and for the ZP between 10.00 and 39.95 (average 24.31). The samples show the Th/Sc and Zr/Sc values (Fig. 11C) along the trend from the mantle to the upper continental crust composition (McLennan et al. 1993), the predominant provenance from the upper continental crust, a relatively low and highly varied role of the reworking and significant compositional heterogeneity in the source areas. The highest values of the factors were recognized in the BB in the sample from the Rosice-Oslavany Formation close to the coal seams whereas in the ZP they come from the Kalterbachgraben Sandstone/Siltstone Member. Variations in the role of tectonics (slope, areal

Table 4: The trace element composition (ppm) of the studied samples (BB — Boskovice basin, ZP — Zöbing area).

Sample	**Ni**	**Th**	**Sc**	**La**	**Rb**	**Nb**	**Zr**	**V**	**Ba**	**Be**	**Co**
BB 1	24	6.1	6	13.9	60	4.8	85.3	39	144	1	6.2
BB 2	74.2	50.8	9	81.8	113.9	18.1	687.1	50	485	2	13.8
BB 3	8.8	9.5	3	12.5	154.7	5.1	86.8	14	944	2	2.4
BB 4	67.4	6.5	9	21.2	93.2	4.9	107.5	56	287	1	10.7
BB 5	40.5	9.4	5	17.6	106.5	4.7	88.3	30	541	1	4.5
BB 6	80.7	13.9	11	27.8	152	12.2	192.9	65	475	2	13.3
BB 7	30.4	12.4	12	26.2	106.4	10.2	201.8	76	500	3	10.9
BB 8	64.2	8.2	10	28.6	124.7	9.2	68.3	53	244	2	12.6
BB 9	26.7	9.8	10	32.1	101.5	9.1	179.2	64	405	2	7.4
BB 10	19.8	7.9	6	20.4	90.2	6.5	145.2	42	412	1	5.2
ZP 1	18.6	8	4	20.3	131.5	4.6	112.7	19	708	1	3.3
ZP 2	45.4	17.5	8	20.2	113.4	8.1	154.4	36	676	1	7.7
ZP 3	34.8	7.8	6	21.8	108.6	6.2	132.8	30	635	0.5	5.1
ZP 4	28.8	14.5	9	31.9	134.8	11	202.7	53	370	2	8.8
ZP 5	34.3	5.6	4	14.6	120	3.5	110.5	13	994	0.5	4.3
ZP 6	74.1	12.9	8	24.1	98.9	9.6	138.6	44	533	2	9.4
ZP 7	117.8	7.3	7	18.9	61.2	10.6	288.4	41	134	0.5	10.8
ZP 8	103.2	5.7	8	16.2	28.5	10.3	177.6	38	192	0.5	12.3
ZP 9	30.2	7.5	5	21.3	136.4	6.1	88.4	35	957	1	4.4
ZP 10	42.5	13.5	6	30.3	144	8.4	239.7	38	741	2	6.2
ZP 11	12.7	10.5	4	19.6	134.2	5.6	128.4	25	465	0.5	2.9
ZP 12	14.9	4.9	2	10.4	62	3.8	76.6	15	277	0.5	2.4
ZP 13	105.6	5.5	9	19.5	44.9	8.1	119	55	155	1	10.3
ZP 14	114.2	5.3	9	17	46.8	7.4	126.2	56	167	1	11.3
ZP 15	112.7	6.9	10	19.4	61	9.1	100	60	177	0.5	17.4

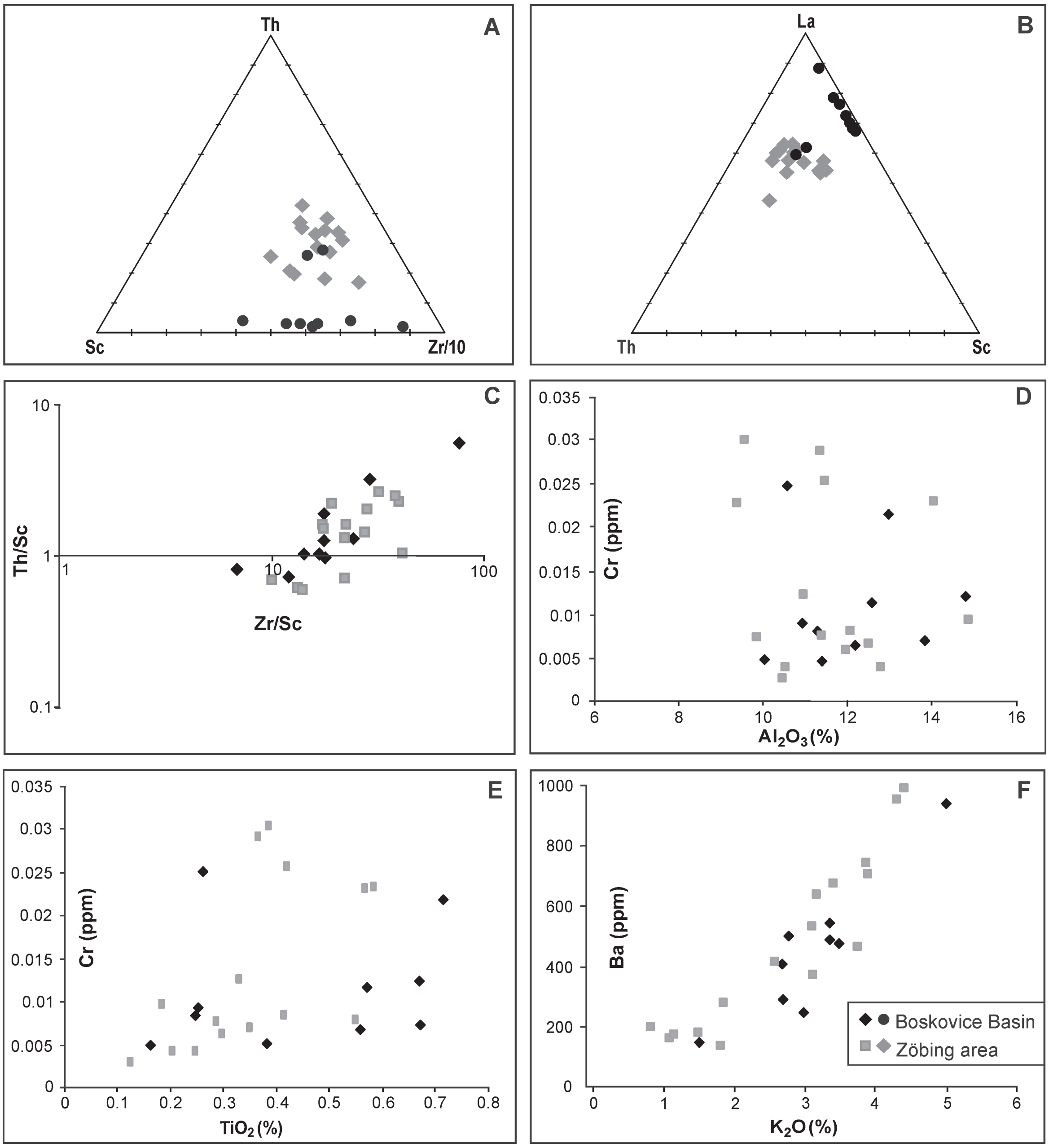

Fig. 11. Discrimination plots of trace element geochemistry. **A** — Th-Zr/10-Sc ternary diagram, **B** — La–Th–Sc ternary diagram, **C** — Th/Sc vs. Zr/Sc, **D** — Cr vs. Al_2O_3, **E** — Cr vs. TiO_2, **F** — Ba vs. K_2O.

extent, etc.) during the evolution of the basin are assumed to be responsible for the variations in the value of these factors.

The Cr values of the studied formations of the BB vary from 47.8 to 232.6 ppm and for the ZP from 41 to 280.5 ppm. The elevated content of the Cr (Cr above 150 ppm) was determined in the BB in samples from the Rosice-Oslavany Formation close to the coal seams whereas in the ZP it was from the Kalterbachgraben Sandstone/Siltstone Member and the Rockenbauer Sandstone Member. Samples from the upper parts of the stratigraphic successions in both basins reveal a generally lower content of Cr. An input from the mafic sources would also result in an enrichment of Ni and V. The abundances of Ni of the studied formations of the BB vary from 19.8 to 80.7 ppm and for the ZP from 18.6 to 117.8 ppm. The V values of the studied formations of the BB vary from 14 to 76 ppm and for the ZP from 15 to 60 ppm. Elevated abundances of Ni (i.e. Ni over 100 ppm) and the highest abundances of V were determined for samples from the Kalterbachgraben Sandstone/Siltstone Member and Rockenbauer Sandstone Member. The Cr/Ni ratio for the BB is 1.44–3.45 and for the ZP 1.1–3.23. The elevated Cr and Ni abundances with low Cr/Ni ratios (between 1.3–1.5) were suggested as having been indicative of mafic/ultramafic rocks in the source area (Bock et al. 1998; Sensarma et al. 2008). Low Cr/Ni ratios were recognized only in two samples from the Padochov Formation and in one sample from the Heiligenstein Arkose Member. These results and also the high Y/Ni ratios (above 11.8 for the BB and 18.7 for the ZP) point to the limited significance of a mafic and ultramafic contribution to these deposits (McLennan et al. 1993).

A poor correlation and different trends exist between Al_2O_3 and TiO_2 with Cr (Fig. 11D,E), signifying differences in their provenance. The different position of samples of the BB from the Rosice-Oslavany Formation and of the ZP from the Kalterbachgraben Sandstone/Siltstone Member and Rockenbauer Sandstone Member is remarkable.

The immobile Ba shows a particularly strong positive correlation with K_2O in both of the sample suites (Fig. 11F). The differences in the provenance of the two catchments, determined above, are discernible in the K_2O-Ba distribution. Variations in fluvial discharge (fluvial channel vs. crevasse channel) are responsible for an increase in the contribution of K-feldspar ± biotite increase in both the Ba and K contents in the different samples from the same formation or member (Padochov Formation and Kalterbachgraben Sandstone/Siltstone Member).

The Zr/Th ratio is another measure of the degree of recycling. Its values vary from 8.3 to 18.4 for the BB, which is close to the upper crustal average of 17.76. The Zr/Th ratio for the ZP varies from 12.2 to 39.5. Such an enriched value (above the UCC) results from the low values of both Th and Zr (in comparison with the BB) especially from the lower Th concentrations. Th is commonly abundant in heavy minerals like monazite, zircon, titanite, the minerals of the epidote group and clay minerals. The results point to different provenance and the lower role of recycling in the ZP since the concentrations of the heavy minerals during recycling would accordingly lead to an increase in Zr and Th abundances in the respective deposits (Zimmermann & Bahlburg 2003).

Discussion

Clear differences in the composition of the detrital material of the fluvial sandstones of the BB and the ZP were identified in all the employed analytical techniques (petrography, heavy mineral studies, geochemistry of both major and trace elements) and indicate different source areas. Therefore the assumed communication between the BB and the ZP during the Late Paleozoic (Jaroš & Mísař 1967) is unlikely. The traditional model of a single narrow half graben occupied by an axial drainage with transport to the south (Malý 1993) is also questionable. The existence of "colinear" marginally offset half grabens with predominant transversal sources can be assumed.

Improved determination of the source areas and their evolution was the second target of the study. The predominance of quartz as well as certain amounts of plagioclase and alkali feldspar reflects the derivation of detritus from the pre-existing sedimentary rocks (especially in the BB) and granitic rocks exposed in the source area (particularly in the ZP). Polycrystalline quartz grains are an additional indicator of the metamorphic source. The preservation and transport of feldspar, particularly of less stable plagioclase, are indicators of limited chemical weathering conditions (Einsele 1992). All the geochemical indicators would indicate the derivation from mainly primary sources (particularly in the case of the ZP) and the highly varied role of recycled sedimentary sources (particularly in the case of the BB). The most significant differences in the source areas are predominantly in the sedimentary rocks, volcanics and recycling.

The significant presence of garnet and the occurrence of staurolite mainly indicate mica schist complexes as sources. The monotonous spectra of the garnet composition indicate a first cycle detritus and the predominant garnet provenance from metamorphic rocks such as gneisses, (amphibole + biotite) schists and granulites in the ZP. The wide spectrum of garnet composition in the BB indicates either a more complex source area (gneisses, amphibole+biotite schists, granulites, calc-silicate rocks or marbles, eclogites) or reflects the redeposition of an older sedimentary cover close to the basin. A comparison with data from greywackes of the Drahany Culm Unit (Otava et al. 2000; Čopjaková 2007) reveals important similarities (a wide spectrum of garnet composition, extremely similar garnet types). The erosion and redeposition of the older Culm deposits is also documented by the occurrences of Culm pebbles within the conglomerates of the BB.

ZTR minerals are common in acidic to intermediate magmatic rocks as well as in mature siliciclastic sediments and certain metamorphic rocks (Eynatten & Gaupp 1999). Moreover, high ZTR values commonly characterize relatively old sandstones, because extensive diagenetic dissolution reduces the mode of less stable minerals (Garzanti & Andó 2007). The predominant provenance of rutile from metapelitic rocks (mica schists, paragneisses, felsitic granulites) both in the ZP (62.5 %) and the BB (50.8 %) is evident. Approximately 38.8 % of the rutiles from the BB originate from metamafic rocks (eclogites, mafic granulites) whereas only 14.1 % of such provenance was recognized in the ZP. Approximately 21 % of the studied rutile from the ZP in all probability originated from magmatic rocks (pegmatites?), but only about 6 % are of such provenance in the BB. Approximately 2.4 % or 4.4 % of the rutile could not be discriminated in relation to the source rocks.

The spectra of zircons of the BB show a higher content of rounded and subrounded zircons, a lower value of elongation, a lower content of "highly" elongated zircons, a higher content of zoned zircons, zircons with older cores and opaque zircons than in the ZP. All this would indicate the increased role of recycled detritus and metamorphic rocks in the provenance of the BB and the increased role of magmatic and volcanic rocks in the source area of the ZP. The parental magma of magmatic zircons for the ZP had a slightly higher alkaline content (Al_2O_3 vs. Na_2O+K_2O) than for the BB (differences in the composition of granitoids were also confirmed by petrography). Direct identification of the source of the zircons lacks sufficient data from the possible provenance rocks. Niedermayr (1967) has documented the elongation of zircons for the Gföhl gneiss between 1.8 and 2.3 and for the granulites of St. Leonhard between 1.5 and 1.7. Hoppe (1966) has revealed the elongation in the granulites of St. Leonhard of about 2.

Apatite may be derived from biotite-rich rocks but is a common accessory mineral in almost all igneous and a number of metamorphic rocks (Adhikari & Wagreich 2011). Epidote was derived from the low-grade metamorphic series. Kyanite indicates the presence of high-pressure metamorphic rocks. The presence of andalusite also reveals the provenance from a higher-T metamorphic facies. Spinels indicate the existence of basic/ultrabasic rocks in the source area.

Whereas Moravian and adjacent Moravo-Silesian Paleozoic deposits (Culm facies) represent the predominant source area for the studied part of the BB, the Moldanubian Unit was the predominant source area for the ZP. This implies for the BB a complex transport direction both from the west and east. In the Zöbing area the main part of the Moldanubian Unit is west of the ZP but today it is also bordering it in the east. But the Moldanubian rocks east of the ZP are displaced by the Diendorf fault system and it is very doubtful, if this was already the case in the Late Paleozoic. Therefore a transport direction for the ZP cannot be clearly determined.

The amount of analyses is limited thus we can only speculate as to the general evolution in the source area. A local source from weathered crystalline rocks can be assumed for the basal successions both in the BB and the ZP. A wider provenance, less weathered detritus, the predominance of mica schist complexes and the minor role of reworking and floodplain modifications can be assumed for additional parts of the succession in the ZP. A wider provenance, variations in the input of the first cycles of detritus from the wide spectra of metamorphic rocks and the recycled detritus (older sedimentary rocks) as well as floodplain modifications can be assumed for the additional parts of the succession of the BB, in all probability with the rising importance of the source from the older (Culm) deposits upwards. The provenance evolution over time does not indicate the successive exhumation of a simple structured (lower- to higher grade metamorphic source) orogen but may be interpreted as differences in expansion in the source areas. The source areas seem to be largely stable during the depositional history, reflecting the tectonic history and the resulting depositional phases.

Identification of the paleogeographical, climatic and tectonic events responsible for the material supply was the last and most complicated target of the study. Sedimentological studies, identification of the depositional environment, its evolution, along with the identification of the ruling factors of deposition (i.e. tectonics and climatic processes) should be compared with changes in petrography and geochemistry in order to fulfil such a target.

The studied sandstones are poorly sorted and reveal a relatively immature composition implying a short transport distance and rapid deposition. The high content of micas can be interpreted in a similar manner, as the detrital muscovite rarely survives multiple depositional cycles. The higher proportion of unstable lithic components and the moderately high feldspar content indicate a high-relief source area. The prevailing physical weathering and the low role of chemical weathering can be confirmed by geochemistry. Wide fluctuations of mineral percentages and indices indicate local sources such as an adjacent alluvial fan, which is in accordance with the interpreted depositional environments. These types of fluctuations are regarded as typical for post-orogenic sedimentary basin fills such as the extensional collapse grabens. They can also reflect the hydraulic conditions during deposition (Morton 1985).

The role of climatic variations in the formation of a heavy mineral suite is probable. The significantly lower contents of apatite were determined in the Stephanian deposits whereas Autunian deposits are characterized by a higher content. Wide variations in the ATi ratios suggest that the ratio are likely to be, at least in part, a function of weathering during alluvial storage (dissolved by contact with acidic waters) (Morton & Hallsworth 1999; Hallsworth & Chisholm 2008; Adhikari & Wagreich 2011). A possible burial of deposits below 3.5 km calls into question the validity of the GZi, ATi and MZi indices.

Conclusions

The erosional remnants of the continental Permo-Carboniferous deposits of the Boskovice Basin in Moravia and the Zöbing Upper Paleozoic in Lower Austria have recorded the paleogeographic, tectonic and climatic post-Variscan history of the Bohemian Massif. A wide spectrum of methods of provenance analyses of the fluvial sandstones (petrography, heavy mineral assemblages, chemistry of garnet, rutile and spinel, zircon study, major and trace elements) were used to confirm or deny the generally supposed and published communication of these at present isolated Permo-Carboniferous deposits and for better determination of the source areas and their evolution.

The results would indicate different source areas for the studied rocks of both basins. The detritus of the Upper Paleozoic deposits in the Zöbing area was predominantly derived from primary sources formed by crystalline rocks. The role of metamorphites (particularly metapelitic rocks — mica schists, paragneisses, felsitic granulites) was predominant along with the importance of the presence of magmatic and volcanic rocks. The source area is predominantly located in the Moldanubian Unit.

The source from the primary crystalline units (magmatic and metamorphic rocks) with a relatively wider range of metamorphites, along with the derivation of the detritus from preexisting sedimentary rocks (in particular Moravo-Silesian Paleozoic deposits) has been demonstrated for the analysed part of Boskovice Basin. The metapelitic rocks (mica schists, paragneisses, felsitic granulites) predominate in addition to the importance of the metamafics (eclogites, mafic granulites). The Moravian Unit and the adjacent Drahany Culm unit represent the predominant source areas while the transport direction was complex (both from the west and east).

The general provenance evolution over time may be interpreted as differences in expansion in the source areas. The basal successions both in the Boskovice Basin and the Zöbing area are typified by material from the local/adjacent sources whereas the wider provenance and variations in the role of the primary and recycled detritus are assumed for the further parts of the successions.

The assumed communication between the southern part of the Boskovice Basin and the Zöbing area during the Late Paleozoic and the existence of a single narrow half graben occupied by axial drainage (with transport from north to south, cf. Jaroš & Mísař 1967) is improbable. An existence of "colinear" marginally offset half grabens with predominated transversal sources can be assumed. The examined fluvial sandstones reveal short transport distance, rapid deposition, high-relief source area, and prevailed physical weathering and a minor role of chemical weathering. Wide fluctuations of the mineral percentages and indices indicate local sources such as an adjacent alluvial fan, which is in accordance with the interpreted depositional environments. The type of fluctuations is regarded as typical for post-orogenic sedimentary basin fills such as those found in extensional collapse grabens.

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