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Depositional environment and provenance of the Gresten Formation (Middle Jurassic) on the southeastern slopes of the Bohemian Massif (Czech Republic, subsurface data)

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Abstract

The deposits of the Gresten Formation (Middle Jurassic) obtained from deep wells in the territory of southern Moravia (Czech Republic) have been newly examined with the aim to better describe their provenance and depositional environment.

Deposition within a relatively broad flood plain with fluvial/distributive channels, crevasse channels, crevasses splays and coal-swaps have been recognised in the majority of well cores. Open marine deposits are less common. The heavy mineral association is quite stable, with significant dominance of garnet and commonly also with high content of zircon. The mineralogical spectra of garnet types are broad with strong dominance of almandines. The rutiles were mostly derived from metapelites and additionally also from metamafic rocks and pegmatites. The results point to mixed sources from both intensively weathered crystalline rocks of the eastern margin of the Bohemian Massif (primary source) and the older sedimentary rocks - especially from the Moravo-Silesian Paleozoic deposits (recycled source).

1. Introduction

With the exception of a few smaller exposures near Brno, the autochthonous Jurassic deposits in the territory of southern Moravia and northeastern Austria (i.e. southeastern slopes of the Bohemian Massif) are deeply buried below the Neogene Alpine-Carpathian Foredeep and the Carpathian thrustbelt units. Numerous wells indicate that these Jurassic strata are confined to a zone of the Carpathian foreland between Brno and the Danube Valley (Golonka and Picha, 2006).

The Jurassic deposition started in the area under study by terrestrial and deltaic deposits (Middle Jurassic, Middle Bajocian-Middle Bathonian) more traditionally known as the Gresten Formation, but also formerly designated as the Divaky Formation (Brix et al., 1977; Eliáš, 1981; Adámek, 1986, 2002; Eliáš and Wessely, 1990; Řehánek et al., 1996). Despite stratigraphical and paleogeographical importance of the Gresten Formation, these deposits attracted only little detailed geological attention so far especially in the area of the Czech Republic.

The aim of the proposed paper is to provide information about the deposits of the Gresten Formation with focus on description of their depositional environment and source area. A special attention was paid to the use of the heavy minerals in the provenance analyses. A simplified map of the studied area is presented in Fig. 1.

2. Geological setting

The autochtohonous Jurassic sequence along the southeastern slopes of the Bohemian Massif begins with clastic deposits mostly known as the Gresten Formation (Dogger, Middle Bajocian-Middle Bathonian in age) (Řehánek et al., 1996; Brix et al., 1977). Hauer (1853) published the original work naming the Gresten beds („Grestener Schichten") from the Gresten (Klippen) Zone in Austria. For simplification the abbreviation GF will be used herein for the Gresten Formation. The basement of the GF is mostly formed by Paleozoic deposits (Cambrian-Carboniferous) (Kalvoda et al., 2008; Vavrdová et al., 2003; Nehyba et al., 2001; Wojewoda et al., 2015) in the Nesvačilka paleovalley and Nikolcice-Kurdejov ridge areas, and by the crystalline basement of the Brno Massif in the area west of this ridge.

Lithologically variable sandstones and clays of the GF are mostly interpreted as terrestrial deposits or as a product of combined deltaic and marine deposition along the flanks of the Bohemian Massif affected by extension, and slowly flooded by the Tethys sea (Adámek, 2002, 2005). The traditional interpretation is presuming that the deposition of the GF was influenced by varied subsidence of individual fault blocks during the formation of Jurassic SW-NE trending syn-rift fault system (Jiříček, 1990; Stráník et al., 1993; Adámek, 2002, 2005; Brix et al., 1977).

However, according to the new 3D seismic interpretation in the territory of the Czech Republic, there is no direct evidence for any significant rifting activity during the Jurassic; a fact which is also supported by the limited thicknesses of the GF in the area. The thickness of the GF reaches here mostly only tens of meters. The maximal thickness of the GF is about 200 m in the Hostěrádky 3 well and about 140 m in the area of the Uhřice gas storage field (see Fig. 1 for positions of the wells). The only exception might be the 465 m thickness of GF suggested in the well Klobouky 2 by Řehánek et al. (1996); nevertheless, this well provides an unclear stratigraphy, not fully logged due to technical complications, and with an Upper

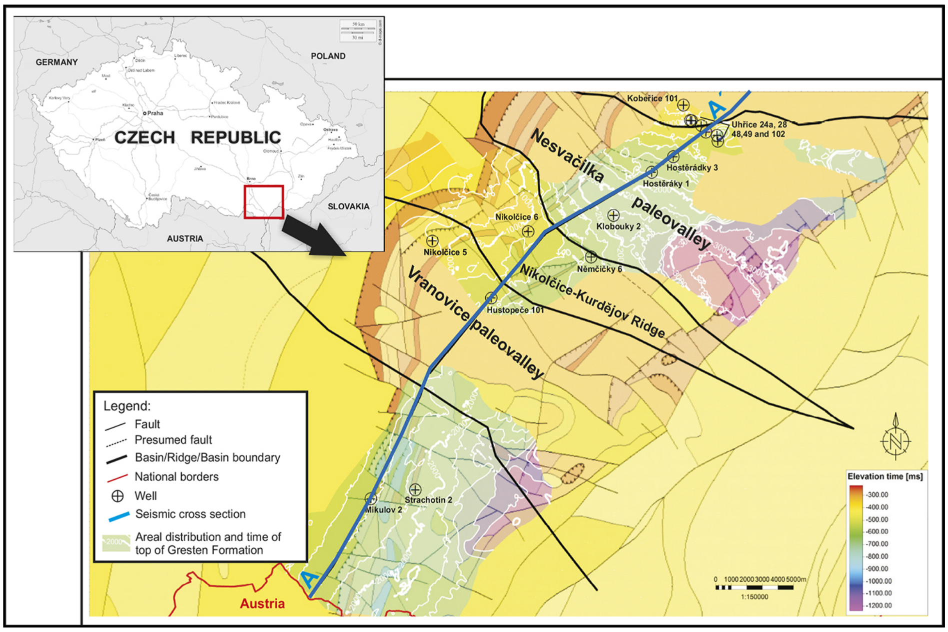


Figure 1

1998). The thickness of the GF deposits is reaching here more than 1700 m and clearly depends on the position within the fault block system (Adámek, 1995). The GF deposits in the Austrian territory are subdivided into four members due to an alternation of sandy and pelitic deposits: Untere Quarzarenitserie (sandy), Untere Tonsteinserie (pelitic), Obere Quarzarenitserie (sandy) and Obere Tonsteinserie (pelitic). The basal member contains intercalations of coaly shales and coals (Brix et al., 1977; Eliáš and Wessely, 1990). This succession is interpreted as a transgressive one; then „Untere Quarzarenitserie“ represents fluvial deposits, „Untere Tonsteinserie“ prodeltaic deposits and „Obere Quarzarenitserie“ deltaic deposits (Sachsenhofer et al., 2006).

In the Callovian, the terrestrial and deltaic synrift sedimentation of the GF was followed by a further marine incursion and gradual development of the predominantly carbonate depositional environment along the passive continental margin. These dolomitic sandstones are known as the Nikolčice Member in Moravia and the Höflein beds in Austria (Golonka and Picha, 2006). The opening of the half-graben of the Nesvačilka paleovalley in the area under study during the Upper Cretaceous to the Eocene was followed by significant erosion of the pre-Cenozoic sedimentary cover of the Bohemian Massif. As a result both the original areal distribution and thickness of Mesozoic and Paleozoic deposits have been highly reduced. Finally, the area underwent massive peneplenization and sub-

Jurassic fauna described from the two cores within the presumed GF interval. The interpreted seismic cross section (Fig. 2) documents the general lateral thickness uniformity of GF in the SW-NE direction and also reflects the Upper Cretaceous to Paleogene age of the major NW-SE faults which dissects the area under study. The recent dataset is therefore implying a different geological setting than the former assumption of Middle Jurassic rifting predominantly confined to the NW-SE trending Dyje-Thaya Depression marked by the deposition of GF (Golonka and Picha, 2006).

A different situation was recognised in the territory of Lower Austria, where the GF is presumed to fill tilted Variscan graben structures. The Paleozic rift faults were still active here during the Jurassic period, and the synsedimentary tectonics within the discrete fault blocks influenced the distribution of lithofacies by their palaeographic position (highs or lows) (Wagner,

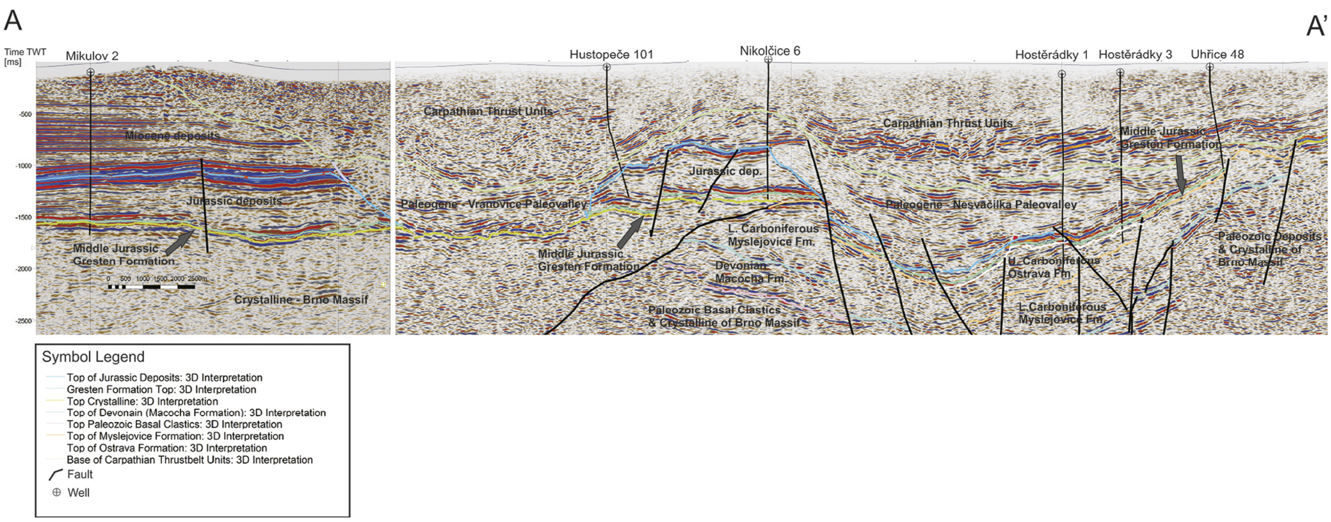


Figure 2

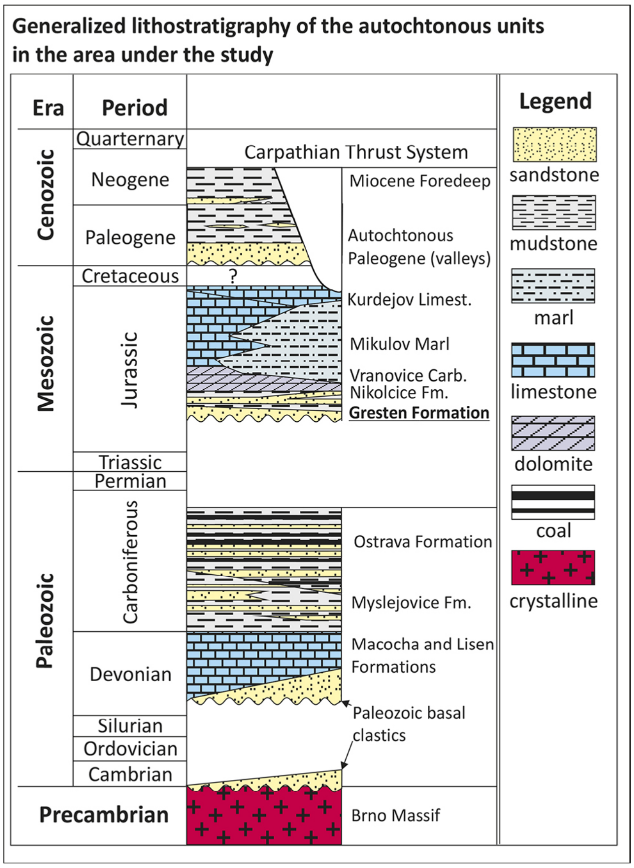


Figure 3

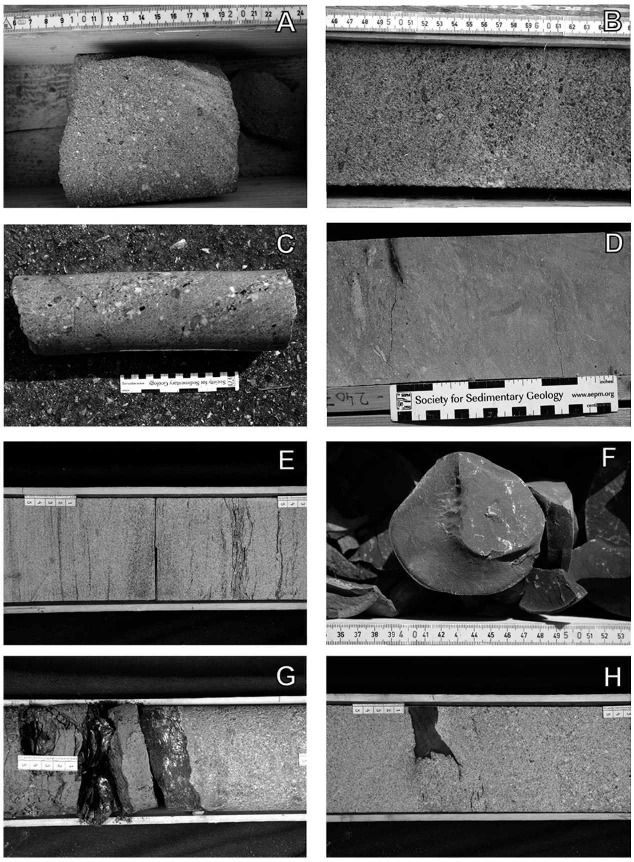


Figure 4

sequent deposition connected to the Carpathian Foredeep (Miocene peripheral foreland basin) formation and evolution, which was followed by the overthrusting of the Western Carpathian Thrust Front (Nehyba and Šikula, 2007). A simplified regional stratigraphic scheme is presented in Fig. 3.

3. Methods of study

Facies analysis is based on the sedimentological study of borehole cores, following Tucker (2004) and Walker and James (1992). Cores from petroleum industry wells Dambořice 3, Hostěrádky 1, Hostěrádky 3, Hustopeče 101, Klobouky 2, Kobeřice 101, Mikulov 2, Němčičky 6, Nikolčice 5, Nikolčice 6, Strachotín 2, Uhřice 24a, Uhřice 28, Uhřice 46, Uhřice 48, Uhřice 49, Uhřice 51 and Uhřice 102 were available for the study. The quality and thickness of the cores varies highly. The largest "continuous" thickness of the cores was almost 50 m, however it mostly reaches only a few meters. Altogether, more than 212 m of cores were logged. Further information was provided by evaluation of the available wire-line logs ("standard" wire-line techniques i.e. spontaneous potential (SP), resistivity (Rag 2, 12) and gamma-ray (gamma-API) (Rider, 1986).

Grain size analysis was provided on 26 unlithified samples by sieve method only. Interpretations of results of pebble analyses (28 samples) of conglomerates and thin section study of sandstones (11 samples) are based on the classical approaches (Dickinson and Suczek, 1979; Dickinson, 1985; Ingersoll, 1990; Zuffa, 1980, 1985). Assemblages of heavy minerals (133 analyses) were evaluated in the grain-size fraction 0.063-0.125 mm. Garnet, zircon, and rutile represent the common heavy minerals in the studied deposits, being relatively stable during diagenesis and having a wide compositional range, so as to be further evaluated in detail. Zircon studies (outer morphology, colour, presence of older cores, inclusions and zoning, typology, elongation) were provided on 112 grains. Electron microprobe analysis of garnet (59 grains) and rutile (20 grains) were evaluated with a CAMECA SX electron microprobe analyser (Faculty of Science, Masaryk University, Brno, Czech Republic).

4. Results

4.1. Facies analyses

Fifteen lithofacies were distinguished according to grain size and sedimentary structures. The description of lithofacies is presented in Table 1. Examples of identified lithofacies are demonstrated in Figure 4. Coarse-grained and sandstone lithofacies strongly prevail in the studied cores over the fine grained and organic rich lithofacies.

The lithofacies have been combined, based on their spatial grouping within the cores into four facies associations (FA), which are also representing the depositional environment. These FA are: FA1) channel deposits, FA2) open marine deposits, FA3) overbank deposits (floodplain), and FA4) deposits of coal-swamp. The FA1 and FA 3 were subdivided into sub-associations in detail. The distribution of both lithofacies and fa-

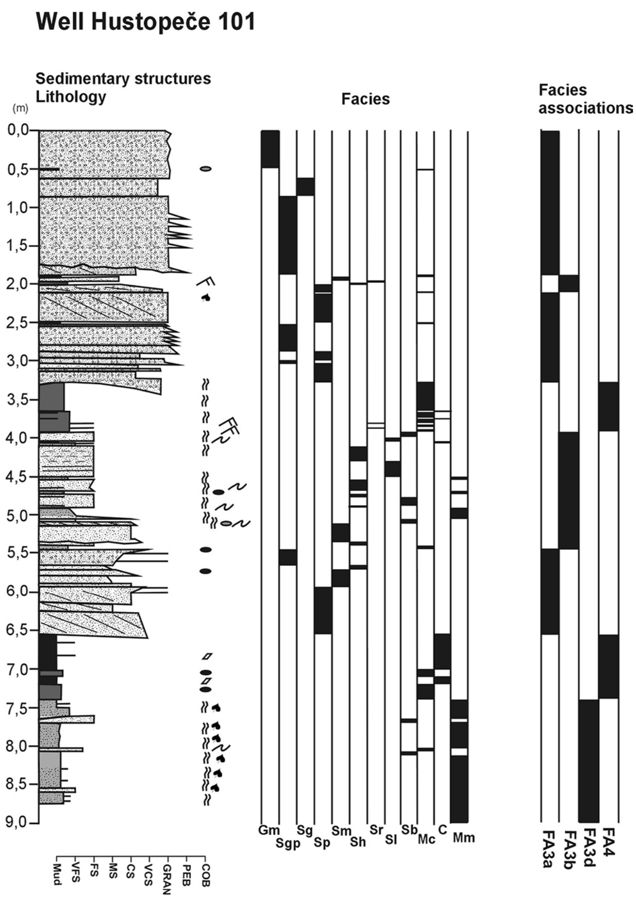
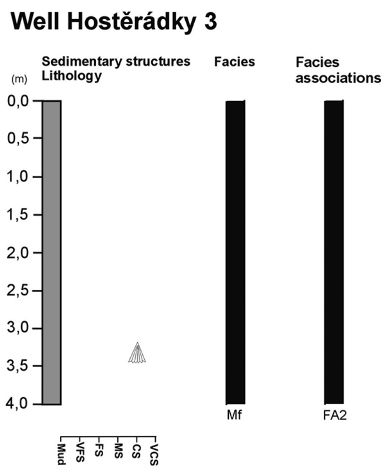


Figure 5 A



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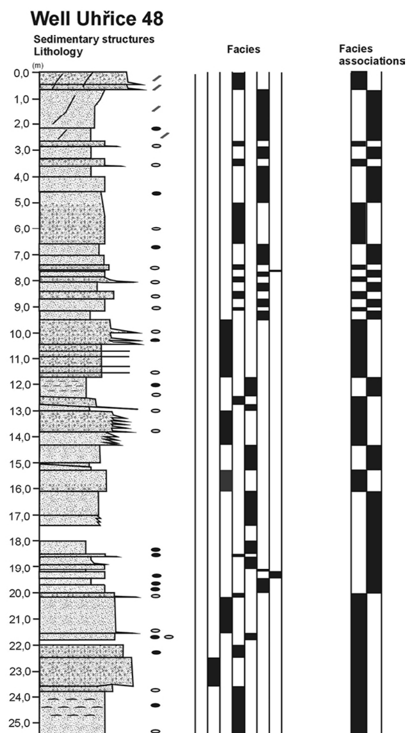

Figure 5 C

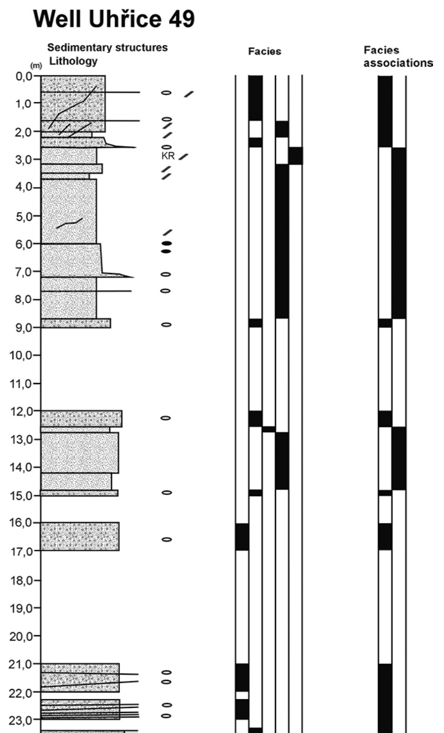

Figure 5 D

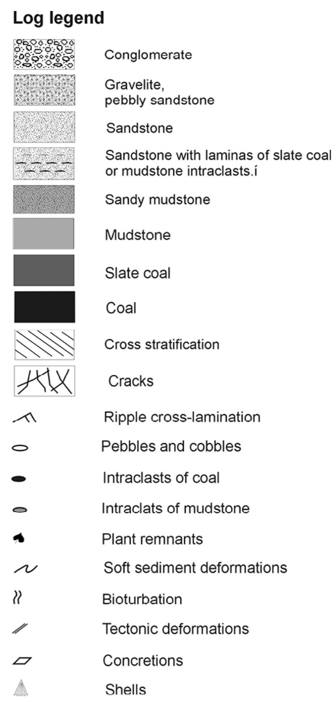

Fig. 5E

cies associations differ significantly in the studied cores/wells, which is marked in the lithostratigraphic logs (Fig. 5 a-f).

4.1.1 Facies association 1

FA1 represents the dominant association forming 80% of the studied cores. FA1 is formed by conglomeratic and sandstone lithofacies which are in oil and gas exploration informally called „monotonous" Gresten sandstones. FA1 can be subdivided into two subassociations. Subassociation FA1a, formed by coarse-grained lithofacies Gm, Gp, Sgp and Sg (see Tab. 1 for lithofacies types), is connected with lower parts of FA1. An erosive base with relatively common fragments of coalified plant stems and intraclasts of coal is typical. The upper part of FA1 represents subassociation FA1b, which is formed by sandy lithofacies (mostly Sp, Sm and Spt, significantly less common are Sl, Sr and Sd). Occurrences of fine-grained lithofacies are exceptional. General fining upward trends can be observed in FA1 and also in FA1a and FA1b. The thickness of FA1 units range from 2 m to 6 m and the succession of amalgamated FA1 units can reach thickness of about 50 m. Reduction of thicknesses of individual units of FA1, together with reduction of the thickness and occurrence of coarse-grained lithofacies, and a more common occurrence of lithofacies Sr, Sl and Sh were determined from base to top in such successions. The FA1 is characterized by an irregularly blocky or bell shape character with a fining-upward trend on gamma-ray and SP well logs.

Interpretation: Monotonous, coarse grained succession of lithofacies with a common fining upward trend, absence of fine grained deposits and erosive planar base, all point to deposition within a broad channel belt, where branching and migrating channels are separated by mid-channel bars and dunes. Lithofacies Gm and Sg represent deposits of the channel base or cores of the bars, cross-stratified lithofacies Gp and Sgp are explained by dune/bar accretion. Preservation of lithofacies Gp or Sgp in superposition of lithofacies Gm or Sg can be interpreted as preservation of substantial part of the dune/bar. Although the channel margins were not identified, we suppose that the channels were cut within the floodplain formed dominantly by deposits of FA3. Evidence of channel abandonment by channel avulsion was exceptional.

Variations in the presence of angular and rounded clasts, different intensities of material sourced directly from the crystalline basement and mudstone intraclasts from the adjacent floodplain, all reflect different role of material recycling and redeposition and also significant variations in fluvial discharge. Occurrences of coal intraclasts point to flat overbank areas with numerous small depressions, where condition suitable for accumulation of organic matter existed. Absence of wood fragments reveals a greater distance from densely vegetated areas.

Amalgamation of the sandy infill of fluvial channels is usually connected with variations in the rate of rise or fall of erosional base level (Shanley and McCabe, 1994) and low rate of aggradation. Coarse-grained facies are commonly connected with braided or low sinuosity fluvial style (Cant and Walker, 1978; Rust and Gibling, 1990), however Shanley and McCabe (1994) show that they can be also connected with higher-sinuosity channel belts. Dominance of lithofacies Sgp, Sg and Sp and their relative low thickness could be connected with a rather shallow system of branching channels within the flat floodplain (Rust and Gibling, 1990). However, the occurrence of mudstones with marine fauna (core from well Hostěrádky 1/ core not available for the study) directly above deposits of FA1, could point to existence of FA1 in nearshore environment. In such a case FA1 channels may be (partly?) interpreted as distributary channels within the coarse-grained delta plain. Sea-level oscillations for the deposition of GF have to be taken into consideration.

Different orders/thickness of FU trends can be observed within the FA1. Allen (1965) interpreted the complete fining upward succession as a product of migration and filling of the fluvial channel terminated by its abandonment. However, in dynamic fluvial systems the preservation of the complete fining upward cycle is limited due to the important role of erosion and channel migration (Bridge, 2003). Preservation of relatively thick deposits of fluvial channels is morphologically determined by the position within topographically lowermost parts of the relief. FA1a could represent the sedimentary infill of the deepest parts of channels and basal portions of the fluvial bars, whereas FA1b the upper parts of the channels or mid-channel bars. Preservation of the complete FA1 (with both FA1a and FA1b) could be connected with low to slightly rising aggradation (Miall, 1996).

The general fining upward trend with upward reduction of the thickness of FA1 and different role of coarse-grained and sandstone lithofacies upward the succession can be explained by retrogradation of distributive system (transition from proximal to distal parts) and relative prevalence of accommodation space over the sediment input. Tens of m thick FU trends probably reflect regional processes leading to avulsion of the channel belts or even change in the fluvial style (McLaurin and Steel, 2007).

Several meter thick fining upward trends can be connected with autocyclic processes such as continuous filling of the smaller channels and avulsion in the direction of local paleoslope. Prevalence of coarser grained facies is typical for such a situation (Miall, 1996; Bridge, 2003).

The lithofacies Sp (10 do 25 cm) signalises (according to Bridge, 2003) that the depths of the channels could be between 1.8 and 7.5 m and their width about 250 m. Such proportions are similar to estimations of McLaurin and Steel (2007).

4.1.2 Facies association 2

FA2 is represented by monotonous, several m thick beds of lithofacies Mf and Mm (see Tab. 1 for lithofacies types). FA2 represents 6.9% of the studied cores and is characterized by an irregularly blocky character of the gamma-ray and SP well logs.

Interpretation: The FA2 is interpreted as a product of quiet deposition mostly from suspension in a greater distance from the coarser grained input. Bioturbation points to lower depositional rate suitable for the bottom colonisation. Dark colour reveals an increased content of organic matter. A significantly thick succession of FA2 (over 2 m) without sandy interbeds points to open marine conditions. Marine deposition is moreover supported by the presence of marine fauna (P. Hudec, person. comm. 2011). The FA2 was recognised along the base of the GF in the well Hostěrádky 1 and was probably covered by thicker sandstone beds as indicated by the blocky pattern of the wireline log. Such a situation could point to the progradation of the sandstones into the basin (deltaic environment?). However, such an interpretation is not supported by facies analyses of the cores.

4.1.3 Facies association 3

FA3 comprises lithofacies Gm, Sg, Sgp, Sp, Sr, Sl, Sb, Sm, Mm, Mc and C (see Tab. 1 for lithofacies types), with dominance of sandstone lithofacies. FA3 represents 11% of the studied cores and is characterized by an irregularly blocky character of the gamma-ray and SP well logs with a slight fining-upward trend in the uppermost parts of the logs. Several subassociations of FA3 have been recognised.

Facies subassociation FA3a is formed predominantly by medium to coarse grained sandstones of lithofacies Sgp, Sp and Sm with subordinate occurrences of lithofacies Gm and Sb. Thin (up to 10 cm thick) interbeds of lithofacies Mc or Sh and Sb are less common. Sharp erosive base of FA3a is characteristic. Deposits of FA3a are commonly terminated by facies Mc. The units of FA3a are usually about 1 m thick commonly with a finning upward trend. Deposits of FA4 or FA3b were recognised below FA3a and deposits of FA3b above it.

Facies subassociation FA3b is formed by alternation of beds of fine to fine grained sandstones of lithofacies Sb, Sl, Sh and Sr with thin interbeds of fine-grained lithofacies Mm and Mc. Contacts of lithofacies are both sharp and transitional, erosional ones were less common. The thickness of units of FA3b is usually about 1 m. The occurrence of synsedimentary deformations and bioturbation is relatively common. Deposits of FA3a were recognised below FA3b and deposits of FA4 above them.

Facies subassociation FA3c is formed by monotonous several m thick sandstone beds with dominance of lithofacies Sb and less common max. 10 cm thick interbeds of lithofacies Gm, Sg, Sl, Sm and only exceptionally C. Bases of lithofacies are commonly erosive. The occurrences of loading structures and intraclasts of coal or coaly mudstone are common. Intraclasts orientation is mostly parallel to stratification. Evidence of trace fossils (Planolites, Arenicolites, Monocraterion, Skolithos?) is relatively common.

Facies subassociation FA3d is formed dominantly by massive or fine laminated deposits of lithofacies Mm or Mf with thin interbeds or interlaminae of lithofacies Sb or Sl. Common loading structures are formed along the base of sandstone interbeds. Coalified plant stems are relatively abundant.

Interpretation: Rapid and frequent alternation of lithofacies is typical, reflecting rapid and dramatic changes of conditions of transport and deposition. Deposits from traction currents here multiply alternate with suspension deposits. Quiet conditions are reflected especially by lithofacies C and Mc. Frequent changes in depositional conditions are indirectly confirmed also by the low diversity of the ichnofabric, occurrence of Skolithos ichnofacies and varied intensity of bioturbation. The FA3 is in general interpreted as overbank deposits. A rather broad flat floodplain with numerous relatively small depressions is supposed, where conditions suitable for accumulation of organic matter (see FA4). The floodplain was cut by crevasse channels with crevasse splays (facies subassociations FA3a-c) and by active fluvial channels (FA1).

The FA3a represents proximal crevasse deposits and confined flows by banks. Rapid deposition and flash flood character is connected with facies Gm and Sm. Interbeds of fine grained lithofacies points to a complex history of deposition and several stages of filling. Upper fine-grained part of FA3a can reflect channel abandonment. This process can continue into almost complete filling of the small depression (lithofacies Mc in the upper most part of FA1a). Lateral transition of FA3a into FA3b, FA1 or FA4 is supposed. The FA3b represents medial crevasse deposits and crevasse splays within the flood plain. Lithofacies succession reflects alteration of deposition from suspension and from rapid unconfined sheet flows (flat tops and bases). Alternations of Fa3b and FA3a could reflect a long lasting existence of crevasse channels.

The FA3c is interpreted as terminal parts of the crevasse channel or deposits of crevasse splay prograding into the floodplain. Flat and sharp bases and relatively low thicknesses of sandstone lithofacies and the occurrence of trace fossils point to episodic (flash flood) deposition of poorly confined or unconfined beds. Deposits of FA3c are typically much more bioturbated than associated deposits of FA3b or even FA3a. Absence of rootlet beds could point to prevalent deposition below the body of water. The subsequent time periods were long enough to allow animal colonization, but not enough to plant colonization (Buatois and Mangano, 2011). Increased intensity of biogenic structures is observed in substrates where oxic conditions likely prevailed and sedimentation rate was low. The thickness of FA3c (i.e. about 1m) could reflect the maximum depth of depression in the floodplain, if the water level was stable (Coleman and Prior, 1980; Tye and Coleman, 1989). Common loading structures indicate high water content in the deposits. FA3d represents distal "interfluve" floodplain deposits beyond the direct influence of crevasses. The major role was played by deposition from suspension, which was interrupted (periodically?) by sudden input of relatively coarser material during floods. Preservation of organic material generally reflects oxygen deficiency during deposition and rapid burying.

Deposits of FA3 were commonly eroded and the abundance of intraclasts within the deposits of FA1 (deposits of channels) is reflecting this situation.

4.1.4 Facies association 4

FA4 is formed predominantly by lithofacies C and Mc with only rare occurrence of Sh (see Tab. 1 for lithofacies types). The maximally observed thickness of FA4 was 3 m. FA4 occured rarely, forming only 2.1% of the studied cores. However, the original broader extend of FA4 could be inferred from common occurrences of deformed intraclasts (several cm large) of bituminous coal or coaly mudstones within coarse-grained lithofacies. FA4 was mostly determined above or below the FA3, and less commonly associated with FA1.

Interpretation: Deposits of FA4 are interpreted as autochtonous deposits of a coal swamps, which originated in a semi-permanent depressions with stagnant water within the floodplain with reduced drainage. Thicker coal rich deposits generally point to a highly reduced input of clastic material, a stable rate of accommodation space formation and rising water table. Lithofacies C is often formed in the uppermost parts of the small scale FU succession. If avulsion terminates formation of the peat then deposits of floodplain or even of fluvial channel can be recognised above FA4.

Characteristic condition for peat formation in fluvial/deltaic depositional system is reduced water discharge and clastic delivery. Fairly thick and extended coal beds are typically connected with „low-sinuosity rivers“ (Martini and Johnson, 1987; Rust and Gibling, 1990; Diessel, 1992; Nemec, 1992; Fielding et al., 1993). Conditions of reduced input of clastic material typical for deposition of bituminous coal are on the other hand relatively rare in conditions of alluvial outwash plain. Peat deposits within the active floodplain represent rather episodic event with limited lateral extent and thickness. Peat is accumulated rapidly after channel abandonment, when the area is in higher position and protected from clastic input. Aggrading of the channels led to the final penetration of the fluvial deposits into the coal swamp and termination of the peat accumulation (Nemec, 1992).

We can speculate about deposition and preservation of FA4 along the margins of the coarse grained distributive system or about the role of a rise of the erosional base (retrograding pattern/transgressive systems tract?). Further possibilities for such peat depositions are connected with allogennic processes such as tectonics and sea-level changes. Haszeldine and Anderton (1980) proposed periodic tectonic rise in the source area, which led to spreading of channels of braided rivers across the flat protected coastal plain. Titheridge (1993) describes syn-depositional fault activity and deposition of such deposits within individual blocks of half-grabens. According to Nemec (1992) coal deposition in the environments of the braided rivers and coastal plains is connected with relatively high water level, when the floodplain is flooded, which could be related to sea-level changes. Conjunction of coal beds and braided river channels is often explained by the fluvial deposits related to the lowstand systems tract, whereas condition of the transgressive and highstand systems tract are more suitable for production of peat (coal) beds (Shanley et al., 1992; Yoshida et al., 1996; Greb and Chesnut, 1996; Hampson et al., 1997).

Sachsenhofer et al. (2006) put the origin of the coal of the Lower Quarzarenite Member of the GF into a flood basin with transitions to a delta-plain environment. Coal originated in frequently flooded mires and evolved within an oxygenated and acidic environment.

5. Provenance analyses

Results of the provenance analyses are based on a combination of pebble petrography, study of thin section and analyses of heavy minerals.

5.1 Pebble analyses

The largest recognized cobble was about 10 cm in diameter, however medium to coarse pebbles absolute predominate, with grain size in range 1 to 2 cm in diameter.

Conglomerates can be partly (39.3%) classified as monomict/quartzose ones, where the content of quartz pebbles is higher than 90%. Quartz pebbles dominate in the absolute majority of the studied samples and their content mostly varied between 51 to 96% (80.4% in average). In one exceptional sample the content of quartz pebbles was only 33.3%. Pebbles of quartz were mostly well to very well rounded, whereas sub-angular ones were less common. Quartzes are mostly milky, whitish or light gray in color.

About 40% of conglomerates can be classified as oligomict with predominant presence of quartz clasts and higher occurrence of cherts and orthoquartzites. The content of cherts varies between 0 to 14.9% (average 5.9%) and the one of orthoquartzites between 0 to 22% (average 5.0%). Several color varieties of cherts were observed. Radiolarite pebbles were very exceptional. Pebbles of these rocks are commonly less rounded and smaller (up to 1 cm in diameter) than the quartz ones. Both monomict/quartzose and oligomict conglomerates are mineralogically mature.

Part of analyzed conglomerates (20.7%) was polymict, with the content of unstable rock pebbles higher than 10%. Rock pebbles are generally both less rounded and smaller than quartz ones. The diameter of rock pebbles only rarely exceeds 1cm. Occurrence of very coarse pebble (5 cm in diameter) of granulite was exceptional. Pebbles of metamorphic rocks are the most common between the rock pebbles and their content reach 10 - 20%. Phyllites often dominate among the unstable rock pebbbles. Pebbles of gneisses (biotitic paragneisses, orthogneisses), mica schists, graphitic quartzites and granulites are less common. The presence of pebbles of magmatic rocks was recognized only in a few samples. These granites, pegmatites, aplites and quartz porphyres mostly represent only several percent, exceptionaly reach slightly over 10% of the pebble spectra. All these magmatic rocks are quartz-rich, i.e. relatively stable ones, showing only slight weathering.

Pebbles of sedimentary rocks (claystones, quartzose sandstones, glauconitic sandstones, dolomites, coal) are not very common. They were also identified only in some samples forming here few percent of the pebble spectra. Occasionally coal fragments reach 10 cm in diameter. They were commonly plastically deformed, which point to their intrabasinal origin.

Interpretation: Pebble analyses points to a source from intensely weathered crystalline and also to a partial role of redeposited/recycled material. Occurrences of large pebbles and cobbles and variations in grains size point to significant and fluctuating fluvial discharge. Cannibalisation within the depositional basin is reflected especially by coal fragments and mudstone pebbles. High variation in both abundance and content of these fragile intraclasts, similarly as variation in the maturity of the clasts could reflect significant differences in depositional environments and erosive bases. The source of silicites could be with high probability located into the Moravo-Silesian Paleozoic deposits especially in the Hády-Říčka limestones (Devonian to Lower Carboniferous) of the Líšeň Formation (Přichystal, 2009) located generally NW from the area under study.

5.2 Petrography of sandstones

Sandstones are mostly medium to coarse grained, with varying occurrence of scattered granules (mostly quartz). The values of skewness (Sk) range between 0.11- 1.14 (average 0.7), negative skewness absolute predominate (88.9%). Value of sorting So varies significantly, being between 1.3 and 2.5 (average 1.7).

The sandstones contain prevalent amount of quartz, which is both mono- and polycrystalline. Cataclasis of grains is common. The content of spar grains varies and is mostly about 20%. Feldspars (mostly orthoclase to microcline) often dominate over plagioclases (mostly albite-oligoclase). The content of rock fragments reaches usually only few percents. Grains of quartz porphyre/porphyrite, aplite, pegmatite, chert, orthoquartzes and granitic rocks are the most common ones. Grains of mudstone and coal fragments are less common. Micas are rare, but in some samples both muscovite and biotite were present. The matrix is mostly formed by a mixture of clay and silt, however carbonates (dolomite) often replace detrital grains. Occurrence of SiO_2 cement is less common.

Sandstones were predominantly classified as arkosic sandstones (69%), less common were arkoses (11.25%), quartz arenites (11.25%), wackes (5.25%) and subwackes (3.25%). The results point to high variation in mineralogical maturity of the sandstones. On the Qm-F-Lt (Fig. 6) discrimination diagram (Dickinson, 1985; Ingersoll, 1990), the samples clearly reflect a continental block source.

Interpretation: Significant predominance of quartz, with some content of feldspars and plagioclases points to source from acidic crystalline rocks and/or recycling from older sedimentary rocks. Occurrence of polycrystalline quartz indicates source from metamorphic rocks. Low content of feldspar (especially plagioclases) can indicate stronger role of chemical weathering in the source area (Einsele, 1992). Sorting of sandstones differs similarly as their mineralogical maturity, which indicate variations in the role of primary and recycled material. Absence or low presence of micas (especially muscovite) would point to longer transport and recycling (Reynolds et al., 2009). Some limited source from volcanic rocks can be in some samples indicated by presence of biotite and fragments of volcanic rocks. Both low content of lithic fragments and relatively low content of spars point to less dramatic relief in the source area, deep weathering and redeposition.

5.3 Heavy mineral studies

Heavy mineral studies are commonly used for evaluation of the provenance, condition of weathering, transport, deposition and also diagenesis. Study of heavy mineral association was combined with the ZTR index (zircon+tourmaline+rutile), which provides a reflection of the mineralogical „maturity" (Hubert, 1962; Morton and Hallsworth, 1994) especially in the case of supposed similar source.

Garnets dominate in the absolute majority (98.4%) of samples. The content of garnet commonly represents over 70% of the heavy mineral spectra, and varies between 25.4 and 97.1%. Zircon dominates in the rest of samples (1.6%) and its content generally varies between 1.5% and 68.4%. Rutile (0-13.2%), anatase (0-8.7%), tourmaline (0-9.8%), apatite (0-18.6%) and titanite (0-2.2%) represent further commonly identified heavy

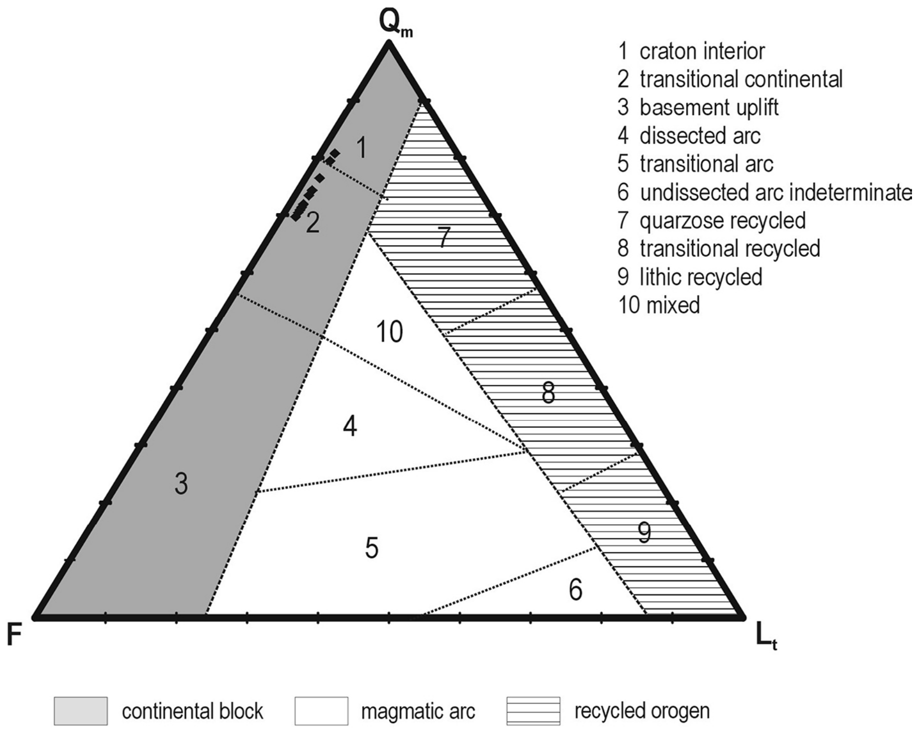

Figure 6

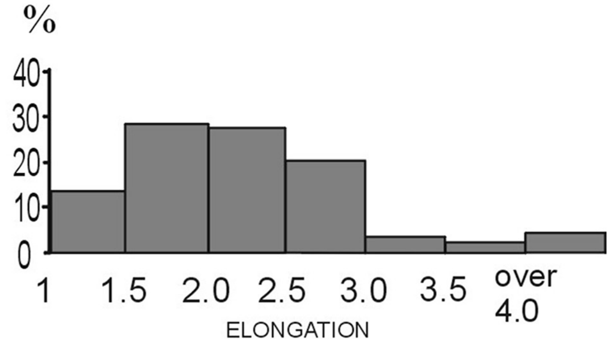

Figure 7

minerals. The presence of pyroxene, amphibole, epidote and staurolite was less common and chromite was exceptional. The heavy mineral assemblages are mostly (78.8%) described as garnet-zircon ones, less commonly (18.0%) as garnet one and exceptionally as zircon-garnet, zircon-garnet-rutile, garnet-apatite or garnet-zircon-apatite ones. The value of the ZTR ranges between 2 and 68.4 (average 20.1).

Interpretation: Dominant presence of garnet confirms an important role of metamorphic complexes (crystalline schists) in the source area. Zircon, tourmaline and rutile are common in acidic to intermediate magmatic rocks and in certain metamorphic rocks (von Eynatten and Gaupp, 1999). Higher values of the ZTR index are typical for mature clastic deposits. Dominant source of rutile is commonly placed into medium to highly metamorphosed metapelites or metamafites (Force, 1980), or pegmatites (Zack et al., 2004 a,b). Apatite is a typical accessory mineral of the majority of magmatic and metamorphic rocks. Titanite points to acid plutonites or crystalline schists. Rare occurrences of epidote point to low-grade metamorphic rocks and exceptional chromite to basic-ultrabasic magmatic rocks. Rare staurolite is connected with crystalline schists.

The fairly stable heavy mineral assemblage, significant differences in the ZTR index value, low and varied content of the low-stable heavy minerals (apatite, pyroxene, amphibole,..), all point to a relatively intense weathering in the source area, formed by both crystalline schists and magmatic rocks (a mature continental crust). The primary source underwent (partially?) repeated recycling before it was finally deposited as part of the GF. Samples with high ZTR index reflect significant role of secondary source (recycling) whereas samples with low ZTR index point to input of „fresh" material from primary sources. Higher ZTR index could be connected with deeply buried sandstones and diagenetic solution of less stable minerals (Garzanti and Andó, 2007), however the significant presence of garnets and in some cases also apatites does not support this assumption. Similarly dissolution of the garnets due to a deep burial was not determined (Morton, 1984).

Faupl (1975) studied the Grestener Schichten of the Grestener Klippen-unit in both Upper and Lower Austria. The dominant heavy mineral assemblages consist of garnet, apatite and zircon, which is similar to the studied units.

5.4 Zircon

Studies of zircon are commonly focused on the source rock, role of recycling, relative age, conditions of parental magma formation, etc. (Poldervaart, 1950, Zimmerle, 1979, Mader, 1980, Pupin, 1980, 1985, Winter, 1981, Finger and Haunschmid, 1988; Lihou and Mange-Rajetzky, 1996).

The euhedral zircons represent 9.2%, subhedral zircons form 42.9% and rounded to subrounded ones 47.9% of the zircon spectra. Very similar results of zircon outer shape were obtained for the terrestrial Permo-Carboniferous deposits of the Boskovice Basin (Nehyba et al., 2012).

Colourless zircons forming 45.5% dominate over zircons with pale color (40.9%), brown ones (11.8%) or pink zircons (1.8%).

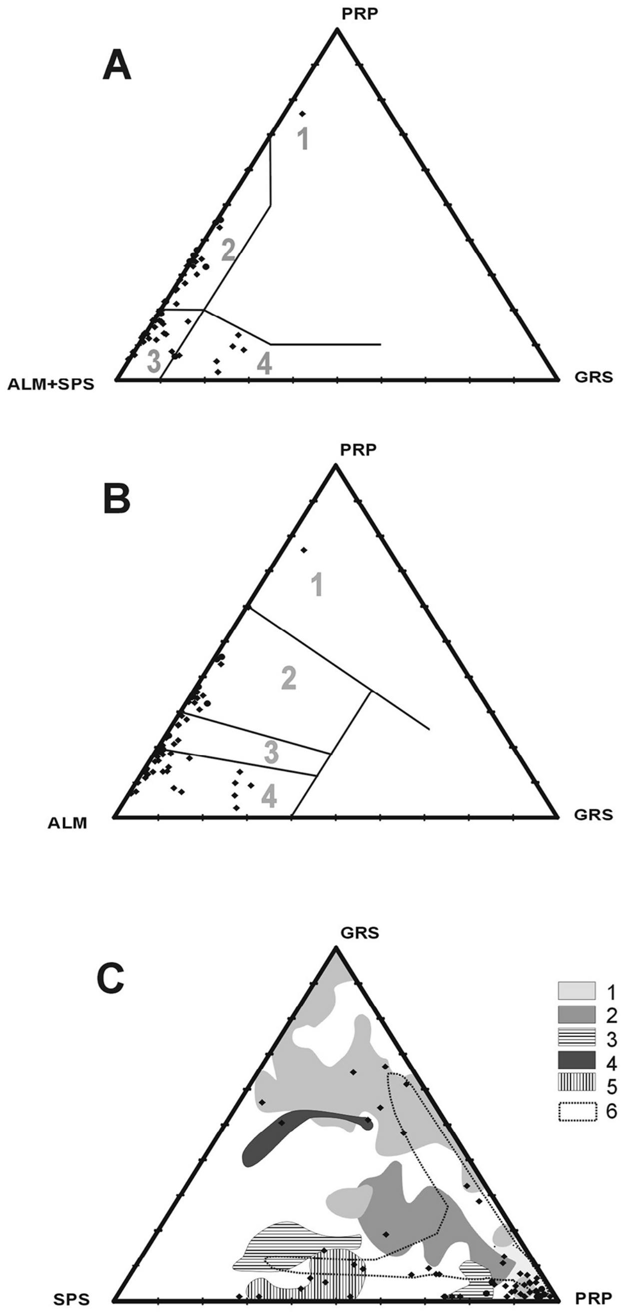

Figure 8

The proportion of zoned zircons is relative high (19.5%), whereas zircons with older cores are relatively rare (6.3%). Inclusions were found in 88.4% of the studied grains.

The average value of elongation of zircons (the relationship between the length and width of crystals) is 2.3 and the distribution of elongation is presented on Fig. 7. Zircons with elongation above 2.0 are more common (58 %) than zircons with elongation below 2.0 (42%). Zircons with an elongation of more than 3 represent 10.2%. Such zircons are supposed to reflect a volcanic origin and/or limited transport (Zimmerle, 1979). The maximum elongation was 5.6, however broken prismas of columnar crystals of zircon were relatively common. Zircon intergrowths were common similarly as numerous crystal fractures.

Study of zircon typology points to a hybrid character of paternal magma (Pupin, 1980, 1985). The most common were the typological subtypes S24 (28.1%), S22 (15.6%), S 12 (12.5%) and S14 (12.5%). Further subtypes i.e. S13, S18, S17, S19, S21 and S23 were less common (less than 6%).

5.5 Garnet

The chemistry of detrital garnet is widely used for the more detailed determination of source rocks (Morton, 1984).

Table 2 shows the relative abundance of the garnet types in the studied samples. The results of the analyses reveal strong dominance of almandines. Pyrop-almandines (ALM 52-84%, PRP 10-44%, GRS 0-5%, SPS 1-9%, AND 1-3%) strongly predominate (67.8%) in the garnet type spectra. About 18.7% of these pyrope-almandines reveal high (more than 30%) content of pyrope.

Several ternary discrimination diagrams were utilized to obtain more detailed information on the primary source of garnet (Fig.8). The diagram PRP-ALM+SPS-GRS (Mange and Morton 2007) on Fig.8a reflects the most important role (48.1%) of garnets from intermediate to felsic igneous rocks, less common (36.5%) are garnets from high-grade granulite facies metasediments or garnets from amphibolite-facies metasedimentary rocks (13.5%). Exceptional (1.9%) are garnets from ultramafic rocks (pyroxenites, peridoties). Diagram PRP-ALM-GRS (Aubrecht et al. 2009) on Fig. 8b indicates the dominant (72.9%) primary source of garnets derived from amphibolite-facies rocks (mostly amphibolites or granulites and gneisses). Less common (25%) are garnets derived from eclogite- and granulite facies rocks or garnets from high-pressure rocks (2.1%).

The diagram GRS-SPS-PRP (Fig. 8c) allows a comparison with possible source rocks along the eastern margin of the Bohemian Massif (Otava et al., 2000; Čopjaková et al., 2002; 2005; Čopjaková, 2007; Buriánek et al., 2012). A few garnets from the GF can be compared to the Moravian Zone of the Bohemian Massif or to the Svratka Crystalline Complex of the Bohemian Massif. The lateral distribution of the results is noticeable in the both PRP-GRS and PRP-SPS lines. Generally similar distribution in such lines was recognised also for the younger part of Moravian-Silesian Paleozoic (Culmian) deposits (Otava et al., 2000).

Dominance of the almandine garnets points to a primary source from gneisses and mica schists. Almandine-pyrops and almandine-pyrop-uvarovites represent relatively exotic type of garnet, which may have been derived from metamorphosed ultrabasic rocks. Wide spectra of garnet types recognised in studied GF, despite the limited amount of analyses, indirectly point to redeposition and recycling of material from older deposits. Data can be compared with the results from the Boskovice Basin (Nehyba et al., 2012) and the Moravian-Silesian Paleozoic deposits ("the Drahany Culmian") (Otava, 1998; Otava et al., 2000; Čopjaková et al., 2002; 2005; Čopjaková, 2007). The most commonly identified garnet types i.e. pyrop-almandines and also pyrop-grossular-almandines, spessartin-grossular-almandines and grossular-almandines, with strong dominance of pyrop-almandines (close to 80%), are typical for the younger parts of the Moravian-Silesian Paleozoic (the Myslejovice Formation) (Otava et al., 2000; Čopjaková et al., 2002).

Data can be also compared with the results from the Jurassic deposits of the Western Carpathians (Aubrecht and Méres, 2000; Aubrecht et al., 2009; Méres et al. 2012). Although the high-pyrope garnets are known to be abundant in Mesozoic sediments of the Outer Western Carpathians, the distribution of the garnet types and comparison of discriminating diagrams reveal only little similarity to the data from the GF.

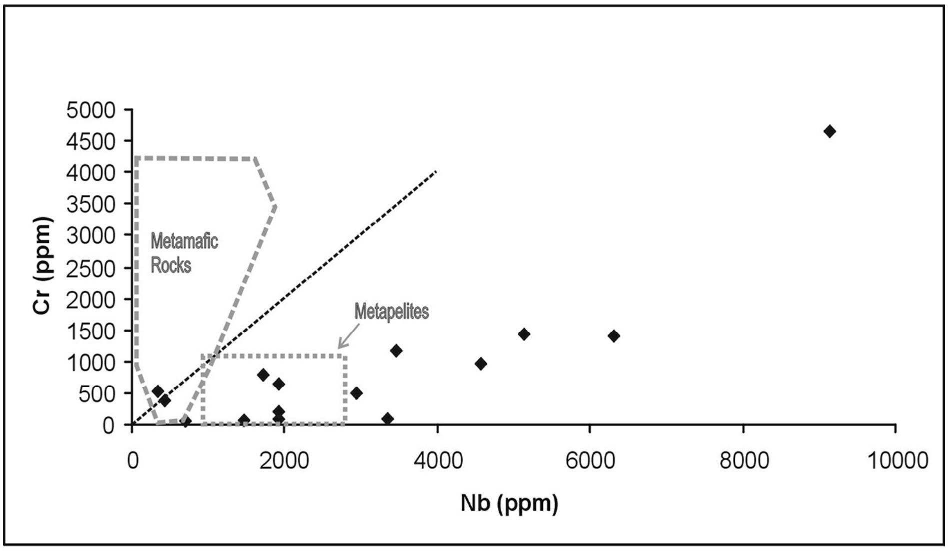

Figure 9

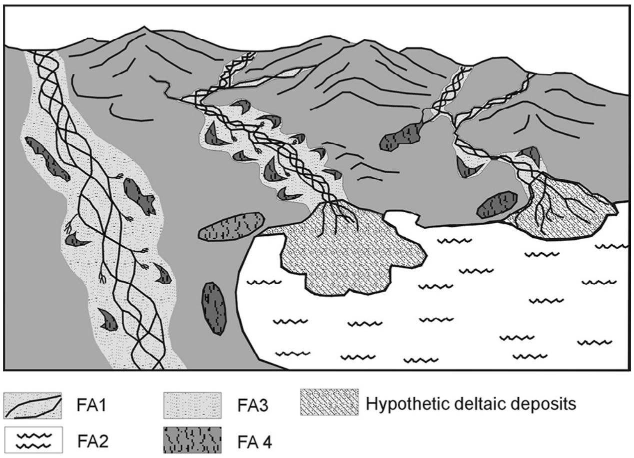

Figure 10A

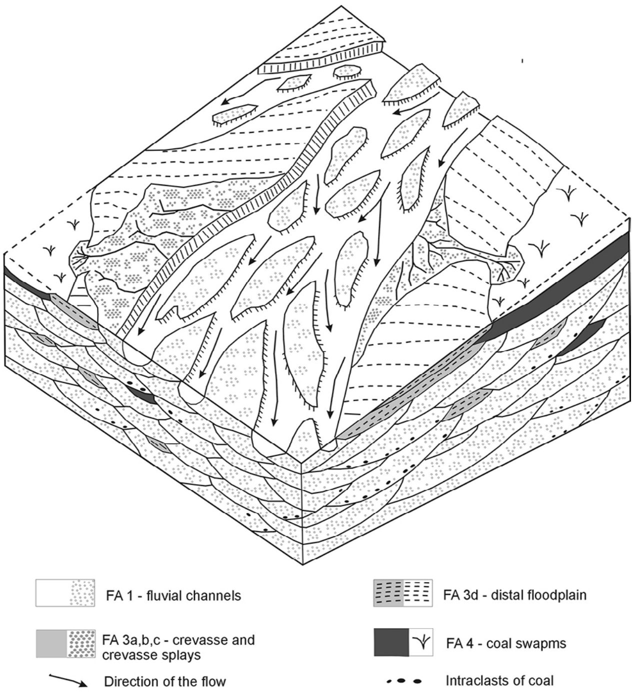

Figure 10B

5.5 Rutile

Rutile represents one of the most stable heavy mineral and is often used for provenance analyses (Force, 1980, Zack et al., 2004a, b; Triebold et al., 2007).

The concentrations of the main diagnostic elements (Fe, Nb, Cr and Zr) significantly vary in the studied samples. The concentrations of Nb ranges between 330 and 9130 ppm (average 2646 ppm), the concentrations of Cr varies between 20 and 4660 ppm (average 887 ppm), the concentrations of Zr ranges between 60 and 3820 ppm (average 1880 ppm) and absolute majority (80%) of logCr/Nb values was negative. The discrimination plot Cr vs. Nb is presented in Fig. 9. The dominant (70%) origin of rutile was from metapelites (mica-schists, paragneisses, felsitic granulites) and additional (15%) one from metamafic rocks (eclogites, basic granulites) and also (15%) from pegmatites according to the grouping by Zack et al. (2004a,b) or Triebold et al. (2005).

The Zr-in-rutile thermometry was applied on metapelitic rutiles only (see Zack et al., 2004 a, b; Meinhold et al., 2008). The results indicate that the majority of the metapelitic rutiles originates from granulite metamorphic facies or possibly to amphibole/eclogite facies. Source from such highly metamorphosed crystalline indirectly points to advanced stage of erosion of the source area.

6. Discussion

Results of the facies analyses allow us to propose a depositional model for the studied deposits of the GF. Studied cores indicate a relatively wide outwash plain where deposition from fluvial/distributive channels dominated. Crevasse channels and floods are responsible for the sediment delivery into the adjacent floodplain. The coal-swamps represent the most restricted subenvironment of the plain. These terrestrial deposits continue into the adjacent shallow marine environment. Modified models of Casshyap and Tewar (1984) or Tibert and Gibling (1999) can be used as depositional model for the studied GF. Hypothetical reconstruction of the general depositional system of the studied GF is presented in Figure 10a, whereas a more detailed model of the most common terestrial FA1, 3 and 4 is proposed in Figure 10b.

Several variations of the log shapes of the GF deposits have been recognised within the area under study. Generally blocky shape of wireline log with a slight FU trend and relatively constant thickness of the GF (74 to 80 m) have been recognised in the rather limited, but well data rich northeastern part of the area. Deposits of FA1 dominate in the well cores. The situation is interpreted as a result of channel belt deposition, where highly mobile channels with sandstone infill dominate and floodplain deposits are highly restricted. Stable thickness points to tabular shape of the beds.

Complicated and irregular shape of the well logs was recognised for the deposits of the GF in the majority of the remaining wells. The thickness of the GF here varies and the deposits of FA1, FA2, FA3 and FA4 have all been identified within the cores. Two subtypes of the log shapes can be recognised in detail. The first subtype is characteristized by an irregular shape with a general tendency to irregularly funnel (coarsening upward) shape of the logs for the lower part of the GF. Upper parts of the GF show generally blocky character of the logs with low values of gamma-API and SP, which is interpreted as sandstone and conglomerate deposits. Such patterns of the logs are showing a generally progradational trend, where the tabular beds of sandstone intervene into the area with fine grained deposition. The second subtype also reveals an irregular shape of the logs in the lower parts of the GF, however with a general tendency to form "bell" (fining upward) shape of the curve. The upper part of the GF has a monotonous character of the logs with higher values of gamma-API and SP, which is explained by monotonous mudstone deposition. Such patterns are explained as representing generally retrograding trends.

The general lateral thickness stability of GF in all directions, together with fairly stable depositional environments, does not support the synsedimentary control model by distinct Middle Jurassic SW-NE trending fault activity known from the area of Austria (Sauer et al., 1992; Zimmer and Wessely, 1996) in the area under study. If such activity continued into the area of the Czech Republic, then the resulted horst and graben structures are probably deeply buried below the thrusts of the Western Carpathian Flysch Zone out of the reach of the available geological data known from the boreholes and seismic acquisitions.

The source area was located in the geological units of the eastern margins of the Bohemian Massif. The source rocks are supposed to be located in both the crystalline units (the Moldanubicum and the Moravian Zone) and the Moravo-Silesian Paleozoic deposits. Similarly, Faupl (1975) located the source area of the Austrian Gresten Formation into the so-called Vindelician-Bohemian land and mentioned some connections to the Moravian zone of the eastern Bohemian Massif.

7. Conclusions

Sedimentological study of the clastic deposits of the Gresten Formation (Middle Jurassic) was conducted on the deep subsurface cores from 18 wells in Moravia. Altogether, 15 lithofacies and 4 lithofacies associations have been identified. Depositional environments of overbank deposits/floodplain, basinal/open marine deposits, channel (fluvial and/or distributive channels) deposits and deposits of coal-swamp have been interpreted. The overbank/floodplain deposits were further subdivided into deposits of proximal and medial crevasse channels, crevasse splays and distal floodplain deposits. The channel deposits have been subdivided into the infill of the lowermost parts of the channels and deposits of the mid-channel bars. The relatively broad outwash plain with a dominance of deposition from fluvial/distributive channels is considered a dominant sedimentary environment of the studied deposits of the Gresten Formation. Crevasse channels and floods are responsible for the clastic delivery into the floodplain. Coal-swamps represent the most restricted depositional environment. Association of these terrestrial deposits with basinal deposits is explained by transition into the marine environment.

Conglomerates can be mostly classified as mature monomict/quartzose or oligomict ones, with predominant presence of quartz pebbles. Some part of analysed conglomerates (20.7%) was polymict, with the content of unstable rock pebbles higher than 10%. Sandstones of the Gresten Formation have been mostly classified as arkosic sandstones, less common were arkoses and quartz arenites, whereas wackes and subwackes were rare. The heavy mineral association is quite stable, with significant dominance of garnet and common important role of zircon. The content of stable heavy minerals (zircon+tourmaline+rutile) highly varies. The chemistry of detrial garnet reveals strong dominance of almandine and relatively broad spectra of the garnet types. The rutiles were mostly derived from metapelites and additionally also from metamafic rocks and pegmatites. These results point to sources from intensively weathered crystalline together with important role of recycling from the older sedimentary rocks (a mature continental crust). The source of the recycled material might be located in the Moravo-Silesian Paleozoic deposits (Hády-Říčka limestones of the Líšeň Formation, the Myslejovice Formation) located generally NW from the area under study. The crystalline units of the eastern margin of the Bohemian Massif are representing the primary source. Varied content of coal and mudstone intraclasts points to canibalisation of the older basin infill and repeated changes of the erosive base level.

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