GEOLOGICA CARPATHICA, 52, 4, BRATISLAVA, AUGUST 2001
195–203

DEPOSITIONAL ENVIRONMENT OF THE "OLD RED" SEDIMENTS IN THE BRNO AREA (SOUTH-EASTERN PART OF THE RHENOHERCYNIAN ZONE, BOHEMIAN MASSIF)

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(Manuscript received January 18, 200l; accepted in revised form June 13, 2001)

Abstract: Lower Devonian monomict-quartzose coarse-grained clastics near Brno (on the Červený kopec Hill) are interpreted as the deposits of an alluvial fan built up mainly by catastrophic sheetfloods. The main sources were probably granites and gneisses, other components were derived from rhyolites, older siliciclastic sediments and low-grade metamorphic rocks. Abundant presence of muscovite reflects some role of an exotic source area. Rapid uplift, erosion dominated by mechanical weathering and multiple redeposition are supposed within the drainage basin. The flat alluvial fan was only slightly reworked and eroded during subsequent non-catastrophic overland flows (secondary processes). A relatively mature stage of the evolution of the alluvial fan and drainage basin was accepted. A continental extensional basin represents the most probably depositional setting of the studied deposits.

Key words: Early Paleozoic, monomict-quartzose clastics, conglomerates, sheetfloods.

Introduction and geological setting

The thick, siliciclastic unit that typically mantles the Neoproterozoic crystalline rocks of Brunovistulicum (eastern margin of the Bohemian Massif) has been described as the "Devonian Basal Clastics" or Moravian "Old Red" in the Czech geological literature. They were the subjects of numerous studies (Dudek 1960; Dvořák 1993, 1998; Dvořák & Skoček 1997; Batík & Skoček 1980; Jaroš & Mísař 1976; etc.). These sediments were assigned to the Devonian on the basis of their similarity to Devonian rocks in the European neighbourhood. However, the Devonian age of these clastics is proved by paleontological findings (Chlupáč 1989; Havlíček & Mergl 1990; Hladil 1985) or suggested by carbonate-clastic interfingering in the Moravian Karst facies only for their uppermost part (Chlupáč 1988; Galle et al. 1988; Hladil 1988, 1994). An assumption of Cambrian age existed for some very thick clastic sequences in SE Moravia (Roth 1981). Recent studies of acritarchs in the boreholes Měnín-1, Němčičky-3 and Němčičky-6 indicated an Early Cambrian age (Jachowicz & Přichystal 1997; Fatka & Vavrdová 1998).

Basal Paleozoic Clastics (BPC), which seems to be the more precise designation of the bulk of the rocks under consideration, occur mainly in the subsurface. The greatest part is hidden below the Outer Carpathian units. The BPC have a highly variable thickness (50 m up to >1500 m), with several post-Carboniferous erosion windows where the entire Paleozoic sequence is entirely removed (Adámek et al. 1980). The tectonic environment influenced the thickness of the BPC as well (Skoček 1980; Leichmann et al. 1999).

BPC rocks also differ in the composition and lithology. They are commonly highly mature with a strong prevalence of quartz and stable minerals. Quartz sandstones and conglomerates are fairly abundant (Štelcl 1969). A generally decreasing amount of quartz clasts stratigraphically upward was formerly accepted in the Czech geological literature. The BPC were subdivided into three types, mainly on the basis of petrographic studies. These types are: (1) polymict clastics with a lower content of quartz,

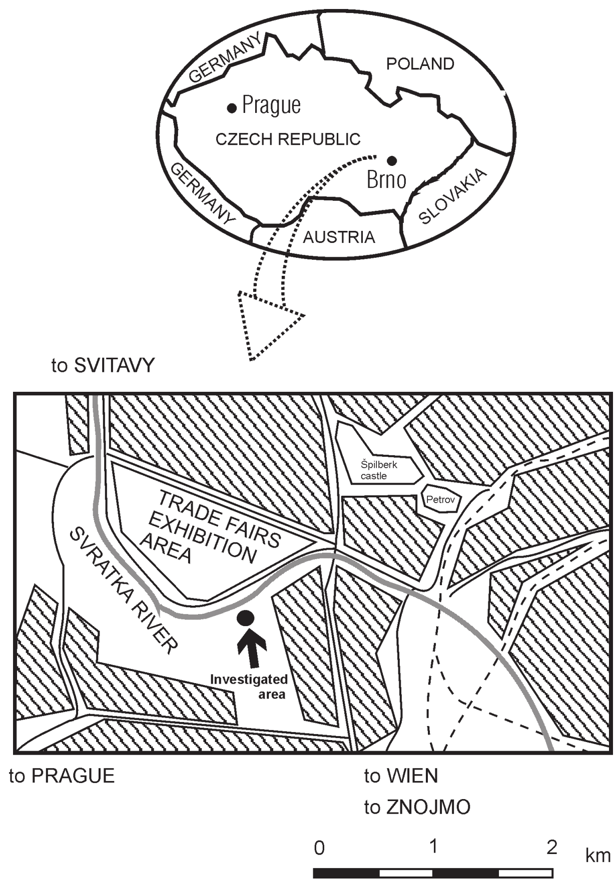


Fig. 1. Location map of the Červený kopec Hill in Brno.

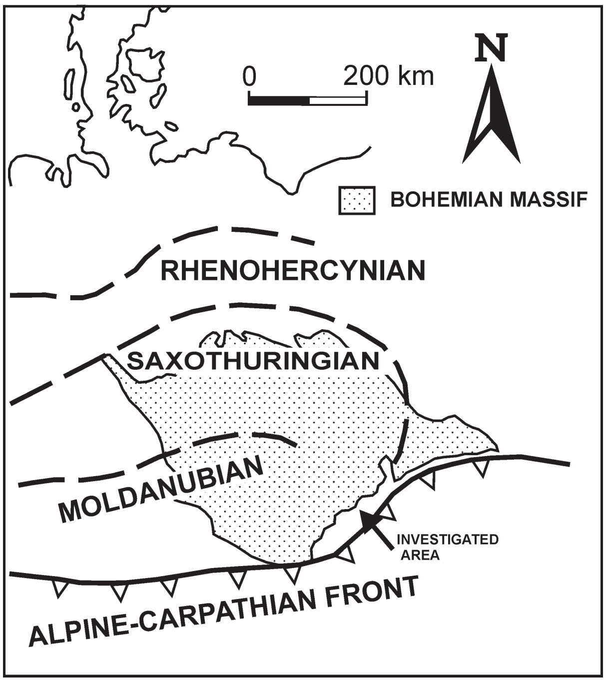


Fig. 2. Variscan zones of the Bohemian Massif and position of investigated area.

(2) monomict-quartzose clastics, and (3) arcose and quartzose sandstones and mudstones (Skoček 1980). The BPC are usually green or red coloured. The abundance of quartz clasts corresponds to ultrastable composition of the heavy mineral association. Argillaceous or clayey beds are relatively rare. Pokorný (1948) and Přichystal (1993) described coarse-grained, intermediate volcanic tuff layers within the BPC.

The presence of the BPC reflects the evolution of the Brunovistulian Panafrican Terrane. The presence of Lower Cambrian continental and marine siliciclastic sediments may indicate extension related to the fragmentation of the Gondwana Panafrican margin. After the early Paleozoic accretion, the Brunovistulian Terrane formed a Baltica promontory, which was involved in an oblique convergence with the Armorican group of terranes during the Devonian and Carboniferous. In the first stage of convergence, a slab pull contributed to the widespread aegotype rifting on the Brunovistulian passive margin and led to the formation of half-graben subbasins where Devonian Basal Clastics (DBC) were deposited (Kalvoda 1995). These red continental rocks have been compared to the Old Red facies of the British Isles. However, in contrast to the typical British Old Red facies, they do not represent a Caledonian molasse.

According to present knowledge, it is assumed that the BPC originated in a mainly fluvial and lacustrine depositional environment with occasional alternation with nearshore marine sedimentation at the top of the sequence. Opinions about an origin as residues, aeolian silts and sands or coastal sabkha have been presented by Zádrapa & Skoček (1983) and by Dvořák & Skoček (1997).

All these findings proved that besides the rough similarity of the BPC, great differences in stratigraphy, depositional environments, source areas, tectonic and basinal settings, etc. must be taken into account in the process of geological evaluation of these rocks.

The presented paper is focused on the nicely exposed profile of the BPC (monomict-quartzose clastics) on the Červený kopec Hill in the southern part of the city of Brno. In the locality studied here, the BPC is supposed to represent the first member of the "Moravian Karst Development" (Zukalová & Chlupáč 1982) which is characterized by the predominance of shallow-water platform carbonates at the top. The BPC can be studied both in the river Svratka bench cut and in quarries on the hill. The basement is not exposed. The area is situated in a N-S elongated depression that extends between Červený kopec Hill in the south and the Babí lom Hill in the north (Fig. 1). The position of the Moravia in the context of Paleozoic terrains geology is presented in Fig. 2, and geological development of this area during the Devonian is described in Fig. 3.

The aim of the present study is to describe depositional processes and environments and to contribute to the recognition of source areas.

Sedimentary facies and facies distribution

Five lithofacies (A–E) have been recognized within the logged profile (Fig. 4) on the basis of textures, sedimentary structures and geometry of bedding surfaces. The width of the studied profile was limited (max. 10 m) and enabled the study only in one direction.

Facies A

The most common facies (about 86 %) consists of rhythmic conglomerate and sandstone planar couplets (Fig. 5A and 5B). Almost planar beds of pebbly conglomerate (cobbles are very rare) are rhythmically interstratified with planar beds of parallel laminated pebbly sandstone. This rhythmic stacking of relatively coarse and fine beds is a most characteristic feature of facies A. The thickness of each couplet ranges between 8 cm and 30 cm.

Both conglomerate and sandstone beds are poorly sorted. The conglomerates play a relatively more important role in the couplets. They are clast-supported or show open-work fabric. Pebbles and small cobbles are mainly subrounded to rounded, although angular clasts have also been noted. Quartz pebbles dominate, chert pebbles occur rarely. The maximum length (A-axis) of clasts is 12 cm, but it averages 3–4 cm. Crude, preferred orientation of elongated pebbles, dominantly perpendicular to, but also parallel to the supposed transport direction can be traced. Vertically aligned clasts were observed close to the base of a bed. Sandstones are medium to very coarse grained, and contain scattered pebbles up to 3 cm in size. Locally crude planar bedding with aligned coarser elongated clasts can be found.

The bedding planes are mainly sharp, flat or erosive. Low-relief scouring was observed on the base of beds. The beds are laterally persistent on the scale of outcrop. In places they display broad convex-down shape (very broad and flat channels?). These beds have almost continuous sheet-like geometry.

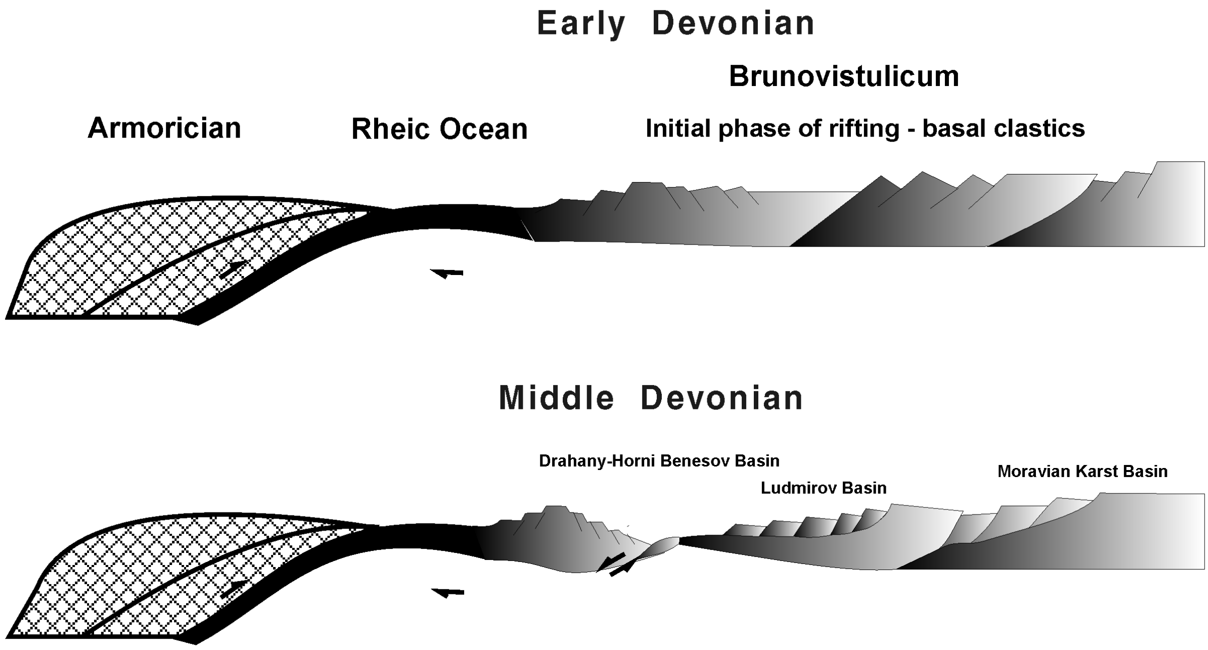


Fig. 3. Geological development of Moravia during the Lower Paleozoic.

Facies B

Laterally limited wedges of gravely sandstone with cross or planar stratification belong to this facies (Fig. 6). The sandstone is medium to coarse-grained and micaceous. Scattered pebbles and angular clasts up to 0.7 cm in diameter are more abundant towards the top of the beds. Cross-bedding is slightly sigmoidal. Facies B is interfingering and interstratified with facies A. Beds of facies B are laterally discontinuous and erosively cut by overlaying facies A. Facies B represents only 3.8 % of the logged profile and occurs only in the upper part of the studied profile.

The orientation of the cross-beds is oblique to dip of bedding planes and for that reason upfan-dipping (backsets) can be supposed. The angle of cross bedding reaches 20°. Bed thickness ranges from 10 to 30 cm, and cross-bedding is best developed in the thickest beds.

Facies C

Facies C consists of beds of clast-supported conglomerates, occasionally clast- to matrix-supported, ungraded, massive to crudely parallel bedded. Vertically aligned clasts are present. Bed thickness ranges from 20 to 40 cm. The largest clasts are 6 cm in diameter, dominantly about 3 cm. Facies C occurs only interstratified with facies A and represents 3.4 % of the studied profile.

Facies D

This facies is formed by medium to coarse-grained, granular or pebbly sandstone with coarser clasts concentrated near the base of the bed (gravel lag?) and parallel bedding with scattered coarser grains in the upper part (Fig. 7). Normal grading can be observed due to fining upwards of sandstone grains and lower presence of pebbles towards the top. The conglomerates are poorly sorted, with the maximum grain-size about 1 cm, occasionally up to 3 cm. Both angular and subrounded clasts have been observed. The content of angular, coarser clasts seems to be higher than in facies A. Bed thickness ranges from 8 cm to 30 cm. Facies D represents 7.1 % of the studied profile and has been documented mainly near the base of the studied profile.

Erosive soles with broad convex-down shapes are typical. The repeated occurrence of low-relief scours (up to 10 cm depth and max. 50 cm width) has been observed along the base of some coarser beds. Pebble preferred orientation is rare. The beds of facies D cut each other erosively and are finally erosively cut by conglomerates of facies A.

Facies E

Facies E is formed by red mudstone or very fine sandstone, massive or parallel laminated. Sandstone is micaceous. Facies E is extremely rare (0.5 % of the studied profile) and occurs as interbeds within facies D. The beds are only 2 to 7 cm thick. They occur either as small erosional relics or as thin layer traceable for the distance of only 3 m. Both lower and upper bedding planes are irregular. Tops are erosive, locally with broad scourings. Small loading structures are rarely observed (Fig. 7).

Depositional processes and sedimentary environment

The interfingering of facies A and B points to their common origin. They are the products of sediment-charged, upper-flow-regime sheetfloods of high capacity and competence that expanded across the almost flat surface of a fan or its active

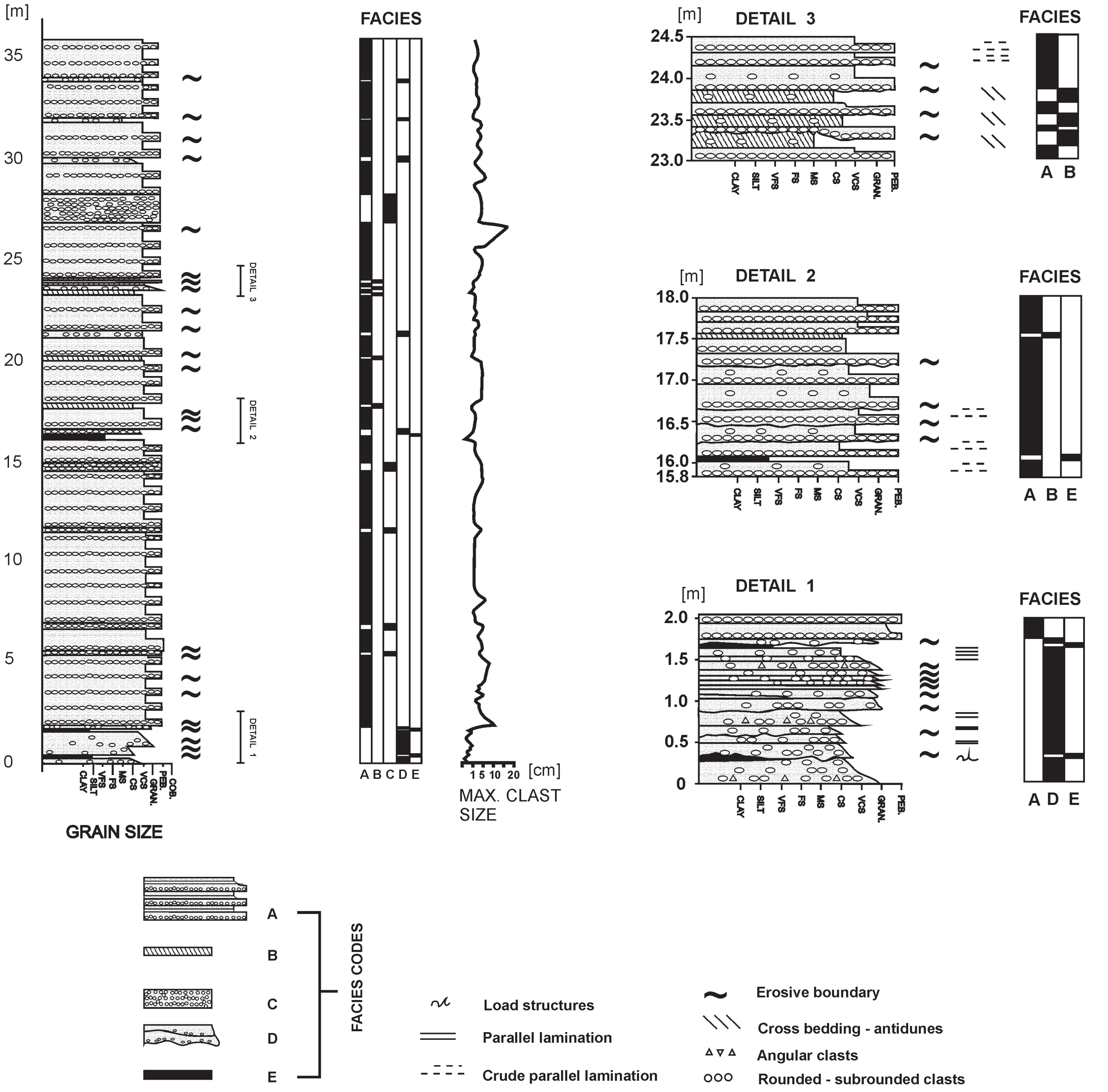


Fig. 4. Lithological log through "Devonian Basal Clastics" on the Červený kopec Hill and facies distribution.

lobes. Hence, depositional environment is interpreted as an alluvial fan mostly formed by catastrophic sheetfloods typified by supercritical condition. Sheetfloods are instigated by the rapid drainage of high volumes of water from the catchment after heavy rainfall, rapid snowmelt or released stored water (Blair 1999). Facies A and B are interpreted as having originated as upper-flow-regime antidune bedforms deposited on the fan surface beneath evolving standing wave trains of high-discharge sheetfloods (cf. Blair 1999; Blair & McPherson 1994). Waves are autocyclically developed and destroyed many times during a single flood and numerous sheetflood couplets may have been deposited during one flash-flood event.

Facies B is typical for sedimentation during the growth phase of a standing wave cycle, whereas facies A is the product of a violent style of standing wave destruction. Details about the origin of upper-flow-regime sheetfloods facies and standing waves are described by Blair (1999). A sharp, rather than gradational contact between conglomerate and sandstone implies that coarse member deposition occurs in a rapid pulse, followed by a more sustained phase of finer-grained fall-out of the intermittent suspended load. The alternation of coarser and finer material is caused by changing hydraulic conditions related to flow expansion and decreasing slope, as well as to intrinsic variations in depth and velocity typical of supercritical flow.

The strong predominance of facies A over the facies B in the studied fan indicates that the standing waves most commonly underwent destruction by violent breakage and washout. The

Fig. 5A, B. Rhythmic conglomerate and sandstone couplets.

Fig. 6. Gravelly sandstone with well developed cross stratification.

Fig. 7. Erosional relic of red mudstone (facies E) within the medium to coarse-grained granular to pebbly sandstone (facies D).

relatively low preservation of facies B and the thickness of single beds also reflect relatively shallow flows. Preservation of cross-bedded antidune sets is most likely in the proximal fan, where flow depth is greatest. The spatial distribution of facies B supports the idea of a mainly distal part of the fan (or its lobe) and its prograding.

The interpretation of facies C is difficult, because of uncertainty regarding the shape of beds and their orientation on the fan (ribs, clusters?). A close relationship to the facies A reflects a secondary reworking of the host sheetflood deposits. The surface of the fan was reworked and partly eroded away during subsequent non-catastrophic overland flows. These flows are usually not strong enough to remove coarser gravel, and tend to produce coarse clast lags by winnowing fine-grained material. The very minor role of these deposits within the studied profile suggests that such secondary processes only slightly remoulded the shape of the fan. This is consistent with rapid deposition on the fan and sufficient accommodation space (tectonic subsidence?).

The deposits of facies D are interpreted as the products of waning traction currents initially with high competence (Nemec & Steel 1984). This suggests deposition within "distal parts" of alluvial fan (or its temporarily inactive lobe). Facies D has been produced either by overland flows (secondary processes), or more probably by stream currents originated from waning catastrophic flows (primary processes). The erosional cuts of facies D beds itself and erosional contact with overlaying facies A can represent important "bounding surface" reflecting progradation of the fan (tectonic or climatic cycles?). This interpretation can be supported by the close relationship of facies D and E (see Fig. 4).

Facies E represents suspended load deposition in quiet conditions. It forms only erosional relics. Their presence provides evidence of probably shallow and small depressions on the fan surface. These depressions occurred in the more distal part of the fan (or its inactive lobes) and were filled mainly during overland flows (secondary processes). The minimal role of these deposits in the studied section supports the opinion about mud deficiency in the depositional system, which is primarily connected with processes in the source area. It also supports the minor role of secondary processes and relatively rapid deposition (aggradation of the fan).

The sandstones (facies B) were studied in detail to add some information about the source rocks. Quartz, plagioclase, K-feldspar, biotite, muscovite, and pebbles of ryolites, pegmatites, slates and clasts of sandstones and siltstones formed the main components. The cathodoluminescence (CL) study of selected polished thin-section have provided some additional information important for interpretation. Quartz and plagioclase as the dominant minerals were subjected to the CL study (Fig. 8).

Six types of quartz were distinguished in the samples (Fig. 8). The first type exhibits bright red luminescence with clear zoning. This feature is typical for high-temperature quartz derived from volcanic rocks, such as rhyolites. Some grains exhibit bright blue luminiscence with indistinct zoning. This population was probably derived from acid plutonic rocks such as granites. The majority of quartz displays dark blue luminescence. These grains were probably derived either from granites or high-grade gneisses. The quartz grains without CL or with dull purple-brown CL point to low-temperature source rocks, for example, older sediments or low-grade metasediments. Quartz grains with medium blue rims formed the 6-th type of quartz. Because the rims are developed over all previously mentioned quartz types, they must be of diagenetic origin.

Several types of plagioclase grains were also identified in the rock (Fig. 8). The most common type exhibits bright blue or yellow-blue CL. Some grains are normally zoned with the yellow CL in the centre and blue CL at the rim. Other grains with purple-magenta CL are strongly altered in the core. Both types were probably derived from plutonic rocks. Some grains exhibit only dull purple-blue CL, or are without CL due to alteration.

Discussion

Alluvial fans constructed principally by water flows have been documented in both arid and humid weather conditions (Nemec & Postma 1993; Blair & McPherson 1994), although fans dominated by water-laid deposits are sometimes interpreted as originating in humid conditions and fans dominated by debris-flow deposits as originating in arid conditions. Numerous factors can potentially affect fan sedimentation including climate, tectonic conditions, catchment area and relief, vegetation type and density, fan area, density of fans in their catchment, relief and drainage density, bedrock types in the catchment area (Blair 1999).

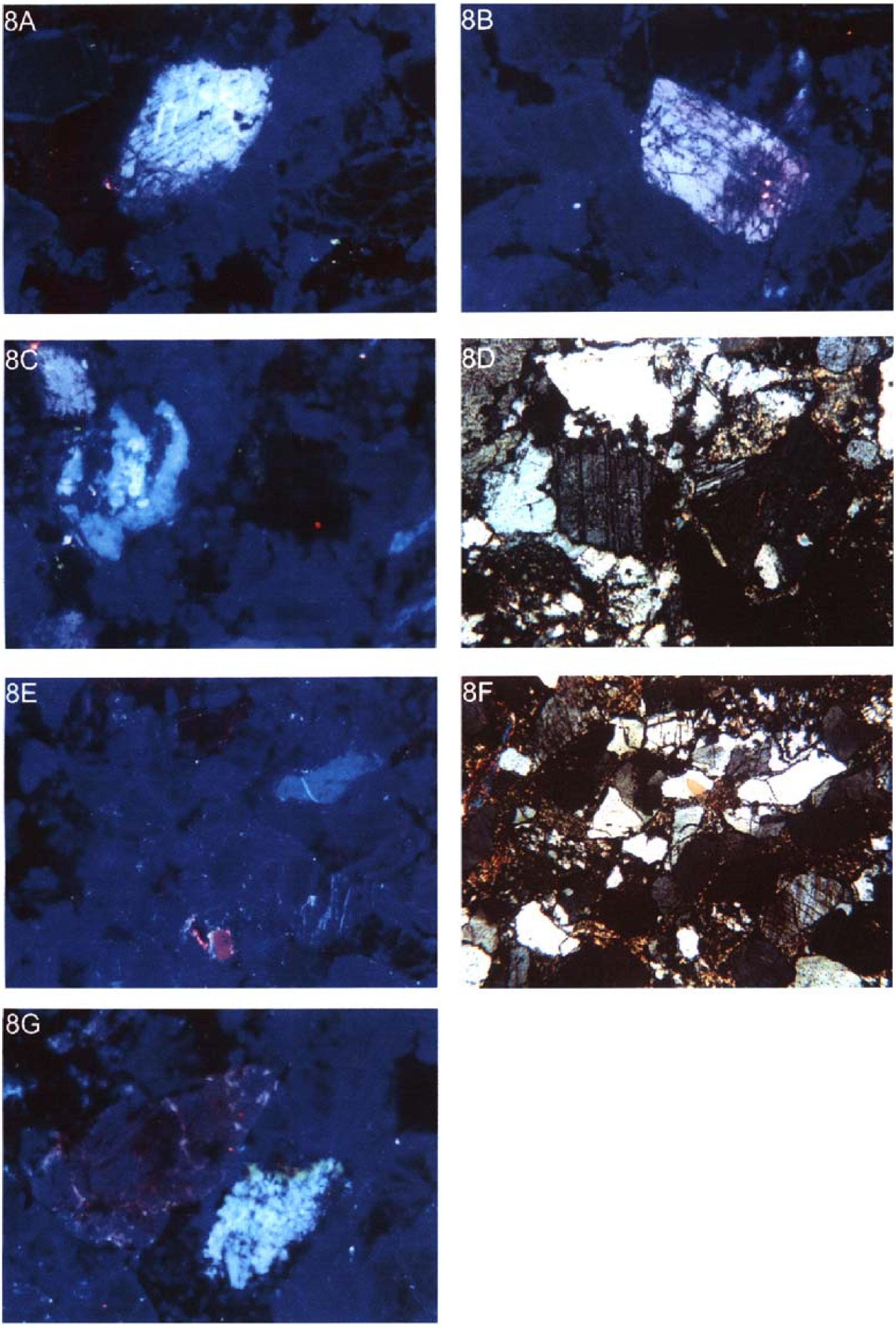
The slope materials are transported to the fan as fluid gravity flows (i.e. water flows), in which sediment is moved by the force of water. In the studied case, the primary fan processes were represented by fluid gravity flows generated by destabilization of colluvial slopes in the drainage basin (sheetfloods and incised-channel floods). Fluid gravity flows result from flashy concentration of runoff from snowmelt or rainfall over colluvial slopes in drainage-basins, leading to sediment-laden and catastrophic discharge downslope. Debris flows fail to be generated in this situation, because of the low concentration of clay in colluvium, insufficient sediment concentration, or a slow rate of sediment entrainment by the flow. Colluvium can be transported within these flows as bed load, or suspended load, and the sediment content may range from low to hyperconcentrated (Blair & McPherson 1994).

A casual relationship exists between the primary sedimentary processes active on alluvial fans and in drainage basins (Blair & McPherson 1994; Nemec & Postma 1993). In the studied case, a relatively mature stage of the evolution of the alluvial fan and the drainage basin can be presumed. The abundant presence of subrounded and rounded quartz pebbles reflects multiple redeposition within the drainage basin before the final deposition on the alluvial fan depositional lobe. The absolute dominance of sheetflood deposits can be connected to a relatively low fan slope angle. The relative absence of boulders and predominance of pebbles, together with abundance of coarse sand, can be explained by relative scarcity of coarse gravel in the source area. The absence of incised channel facies can be explained by the distal position of the studied deposits with respect to the fan apex.

Though both debris-flow and sheetflood deposits can be present on the same fan, most modern alluvial fans are dominated by one of these. This is because lithological and weathering conditions in the drainage basin usually promote one of these processes to the near exclusion of the other (Blair & McPherson 1994). The domination of sheetfloods over debris-flows occurs on fans where: (1) the drainage-basin bedrock weathers to produce clay-deficient sediment, or (2) the size, storage capacity, and roughness of the catchment of the feeder channel and channel gradient commonly incite deposition of debris flows before they reach the fan site. The very low presence of mud material in the studied section is remarkable. It can be explained by the deficiency of clay material within the weathered source rock and by the further transport of such material on the fan slopes (climatic control?). Clay-deficient colluvial sediments are commonly generated in drainage basins underlain either by quartzose deposits or acid crystalline bedrock under arid conditions of weathering. The petrological study indicates that the source area of the BPC was heterogeneous. Granites and possibly gneisses were the dominant sources. Other components were derived from rhyolites, older siliciclastic sediments and low-grade metamorphic rocks. Only granites and small rhyolite bodies are exposed in the broader vicinity of the studied section in the present-day erosion level. However, muscovite is not a typical mineral for the granites in the basement nearby. Some clasts, at least, must therefore be interpreted as exotic with respect to the recently known geological situation.

An important role can also be played by rapid uplift and erosion under minimal chemical, but intense mechanical weathering. In the studied case, the occurrence of such conditions is supported by the presence of rounded quartz pebbles together with angular clasts, mostly from granitic source rocks, relatively fresh feldspars without traces of kaolinite weathering features, fresh biotite, etc.

Fig. 8. Thin-section photomicrographs of BPC on Červený kopec Hill. **A** — Fresh and non-zoned plagioclase with bright blue luminescence. LP (length of the photograph) is 1.2 mm, **B** — Plagioclase grain with magenta CL and altered core without CL. The bright orange grains in the altered zone are carbonates. LP is 1.2 mm, **C** — Zoned plagioclase with very bright core (originally yellow CL), bright blue rim and a zone with dull blue CL in-between. Plagioclase without CL could be found on the left side of the photograph. LP is 1.2 mm, **D** — The same area as in C, but with crossed polars, **E** — The three main quartz types in CL image. The most common grains exhibit dull blue luminiscence. Grains with bright blue or bright red CL are not so abundant. Note that some grains are rimmed by authigenic quartz with medium blue CL. LP is 3.2 mm, **F** — The same area as in E, but with crossed polars, **G** — Plagioclase with dull purple CL as a consequence of alteration (left-right corner) and common plagioclase fragment with bright blue luminescence (right down). LP is 1.2 mm.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A down-fan change from debris flows to fluid flows is supposed in some large fans (Ammorosi 1996; Leeder 1999; Wells & Harvey 1987; Yoshida 1994). Facies sequences are in that case dominated by stream channels deposits on various scales. Such channels are probably absent in the studied case.

The depositional settings of the studied deposits can most probably be associated with high-angle normal or strike-slip faults within a continental extensional basin (cf. Busby & Ingersoll 1995). The question of drainage catchment area, fan slope and area is difficult to discuss because of insufficient data.

Previous discussion is based mainly on comparison with modern or Pleistocene fans. Some differences in sedimentary processes and environments may be expected between modern alluvial fans and the studied Lower Paleozoic ones, formed before the appearance of abundant metazoans and land plants (MacNaughton et al. 1997). Similar sedimentary structures and facies associations have been observed in conglomerates of Middle Devonian Pointagare Group (Old Red Sandstone sequences of Western Ireland) which are interpreted as alluvial fan deposits (Richmond 1998).

Conclusions

Lower Devonian monomict-quartzose coarse-grained clastics from Červený Kopec Hill near Brno are interpreted as the deposits of an alluvial fan mainly formed by catastrophic sheetfloods.

The mode of transport of the material was controlled both by the source area (chemistry of source rocks, weathering condition, extent of the drainage basin) and the alluvial fan itself (shape, angle of the slope, rapid deposition and formation of accommodation space, etc.).

The provenance of the deposits was heterogeneous and geologically varied. The main source was probably granites and gneisses, other components were derived from rhyolites, older siliciclastic sediments and low-grade metamorphic rocks. The important presence of muscovite reflects some role of an exotic source area with respect to the recently known geological situation. The abundant presence of subrounded and rounded quartz pebbles reflects multiple redeposition within the drainage basin before the final deposition in the alluvial fan depositional lobe. The deficiency of clay material within the weathered source rock, rapid uplift and erosion under intense mechanical weathering together with the relatively low fan slope angle were the most important factors for absolute dominance of sediment transport by fluid gravity flows (sheetfloods). These flows were relatively shallow.

Mainly the distal part of the fan (or its lobe) can be observed in the studied profile. Five different lithofacies have been recognized in the logged profile on the basis of different grainsize, sedimentary structures and shape of bedding-plains. The absolutely dominant facies was formed by almost planar beds of pebbly conglomerate rhythmically interstratified with planar beds of parallel laminated pebbly granular sandstone. These couplets formed more than 80 % of the profile.

The surface of the fan was reworked and partly eroded during subsequent non-catastrophic overland flows. These secondary processes played a minor role and slightly remoulded the surface of the fan. A relatively complicated stage of the evolution of the alluvial fan and drainage basin can be accepted. The limited length and width of the profile and post-depositional tectonic did not allow us to reconstruct the shape and orientation of the whole alluvial fan. Continental extensional basin stage represents the most probably depositional settings for the studied deposits which is in accord with the interpretation of the Devonian basal clastics as a record of the initial rifting phase of the Brunovistulian foreland (Kalvoda 1995).

Acknowledgment: The study was supported by the Research Project CEZ J07/98-1431000004.

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