N. Jb. Geol. Paläont. Abh.
2009, vol. 252/3, p. 269–288, Stuttgart, June 2009, published online 2009

Silicified wood from the Czech part of the Intra Sudetic Basin (Late Pennsylvanian, Bohemian Massif, Czech Republic): systematics, silicification and palaeoenvironment

Václav Mencl, Petra Matysová and **Jakub Sakala,** Prague

With 13 figures and 2 tables

Mencl, V., Matysová, P. & Sakala, J. (2009): Silicified wood from the Czech part of the Intra Sudetic Basin (Late Pennsylvanian, Bohemian Massif, Czech Republic): systematics, silicification and palaeoenvironment. – N. Jb. Geol. Paläont. Abh., **252**: 269–288; Stuttgart.

Abstract: Silicified trunks, colloquially called "*araukarity*", are plentiful plant fossils of the Late Pennsylvanian in the Czech part of the Intra Sudetic Basin (ISB) in NE Bohemia. They are predominantly embedded in Žaltman Arkoses, a unit of fluvial sediments deposited during Barruelian, Late Carboniferous. This unit is a part of the Odolov Formation with the richest outcrops in the area of "Jestřebí hory" (Hawk Mts.). Since Goeppert (1857) firstly described these fossils as species *Araucarites brandlingii* and *A. schrollianus*, interpreting both as conifer woods close to the Araucariaceae, they have later never been re-examined or studied as a whole by any modern analytical methods. As the original material of Goeppert was unavailable to our study, we re-evaluated the previous taxonomical assignments on the basis of newly collected material and supplemented a detailed description of their mineral matter (petrography, mineralogy). Following the modern classification, *A. brandlingii* (= *Dadoxylon brandlingii*) describes the wood of cordaites, and *Araucarites schrollianus* (= *Dadoxylon saxonicum* syn. *Dadoxylon schrollianum*) is a name of conifer wood, but our systematical study proves only the presence of cordaites. The pycnoxylic stems were silicified in alluvia without apparent influence of volcanic material. Data from sedimentary structures were used for reconstructions of palaeostreams. The weathering of feldspars is presumed as a source of silicification amplified by the oscillation of water table under seasonally arid periods within Late Pennsylvanian/Early Permian long climate cycles. This mode of permineralization is responsible for frequently poor preservation and high recrystallization of these fossils. Their mineral mass consists of pure highly crystalline quartz without other SiO_2 phases. Cathodoluminescence (CL) microscopy and spectroscopy revealed a polyphase process of silicification including influence of thermal fluids which healed cracks in previously silicified mass. It is possible that all these facts responsible for poor preservation of anatomical features of *Dadoxylon* wood type have precluded its more detailed taxonomical study for more than one century.

Key words: silicified wood, *Dadoxylon*, α-quartz, petrography, cathodoluminescence, imaging, Late Pennsylvanian, Intra Sudetic Basin, arkoses, fluvial sediments.

1. Introduction

1.1. Historical insight

In the area of Jestřebí hory (Hawk Mountains, Czech part of the Intra Sudetic Basin – ISB), silicified trunks colloquially called "*araukarity*" (in *Czech*) have been known for a long time. The first scientific description was done by Heinrich Robert Goeppert, a famous palaeontologist from the University of Wroclaw. He once received several samples from Benedikt Schroll,

DOI: 10.1127/0077-7749/2009/0252-0269 0077-7749/09/0252-0269 $ 5.00

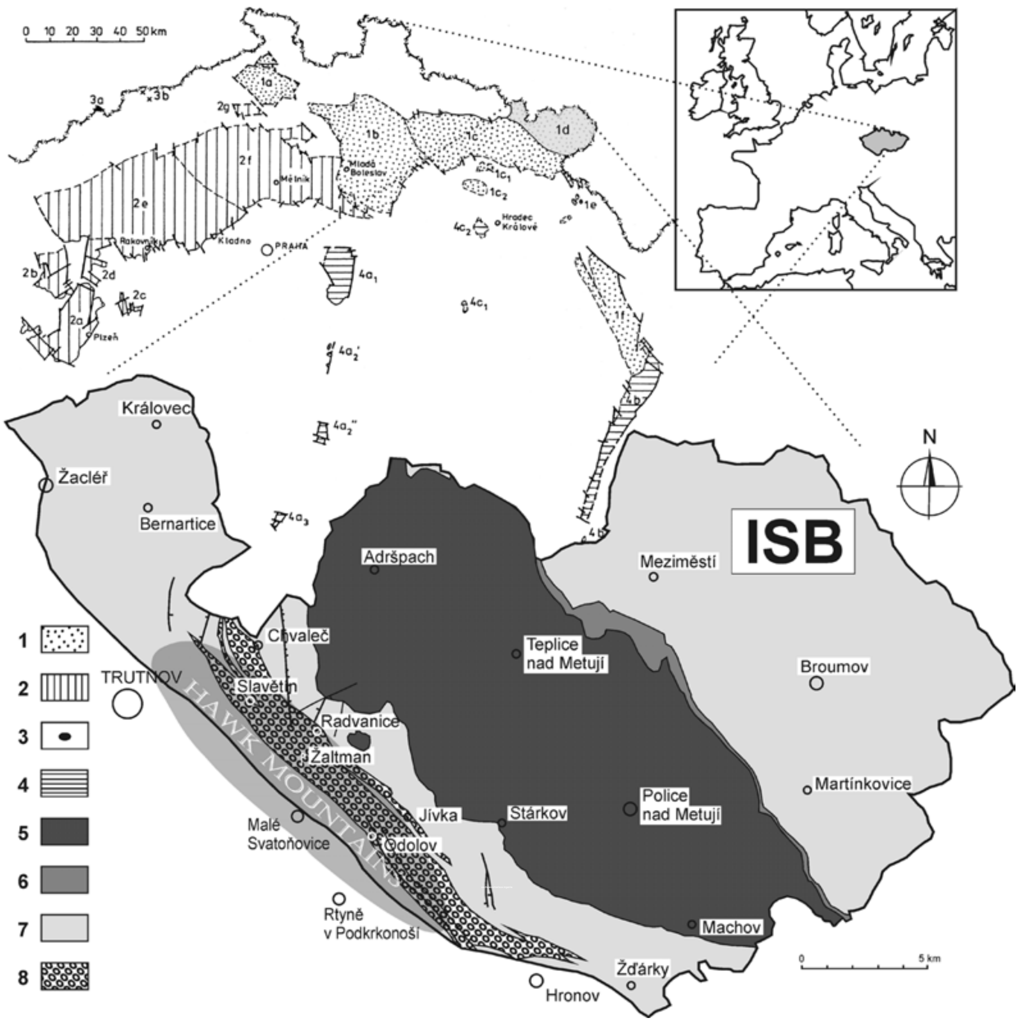

Fig. 1. 1-4: Permo-Carboniferous basins of the Czech Republic with the position of the Intra Sudetic Basin (1 – Lugic Basins with '1d' as the Czech part of the Intra Sudetic Basin; 2 – Central and Western Bohemian basins, 3 – Upper Palaeozoic of the Krušné Mts., 4 – furrows). 5-8: Simplified geological map of the Czech part of the Intra Sudetic Basin with a highlighted area of the Hawk mountains (5 – Upper Cretaceous, 6 – Triassic, 7 – Permo-Carboniferous, 8 – Žaltman Arkoses (Odolov Fm.), some tectonic faults or grabens marked) modified after Report (1994) and Pešek et al. (2001).

a local mine and factory owner living in the area of Hawk Mts., and accepted his invitation. Schroll as an amateur geologist and collector possessed several pieces of local silicified fragments and recognized xylem structures within them. Goeppert came to the Hawk Mts. for the first time in 1856. He explored the whole region and specified that silicified woods occurred in the area of about 30 x 7.5 kilometres (Goeppert 1858). The biggest amount of trunks was found on the Slavětín hill and in a neighbourhood of Brendy village. He named this place "Radvanice fossil forest" (*Versteinerter Wald bei Radowenz*) and considered it to be of a world uniqueness. In the area of the Hawk Mts., he estimated the total mass of woods to almost 1700 tonnes. The length of stems reached about 6 m in some cases and average thickness varied between 40 and 50 cm. Some stems were circular in cross-section but most of them were oval because of compression. On the surface of all stems there were obvious striae but bark was not preserved or only very exceptionally (Goeppert 1858). On some logs, knots with fragments of branches with a maximum length of 45 cm were discovered. The largest trunks had cavities up to 7 cm in diameter and reportedly also growth

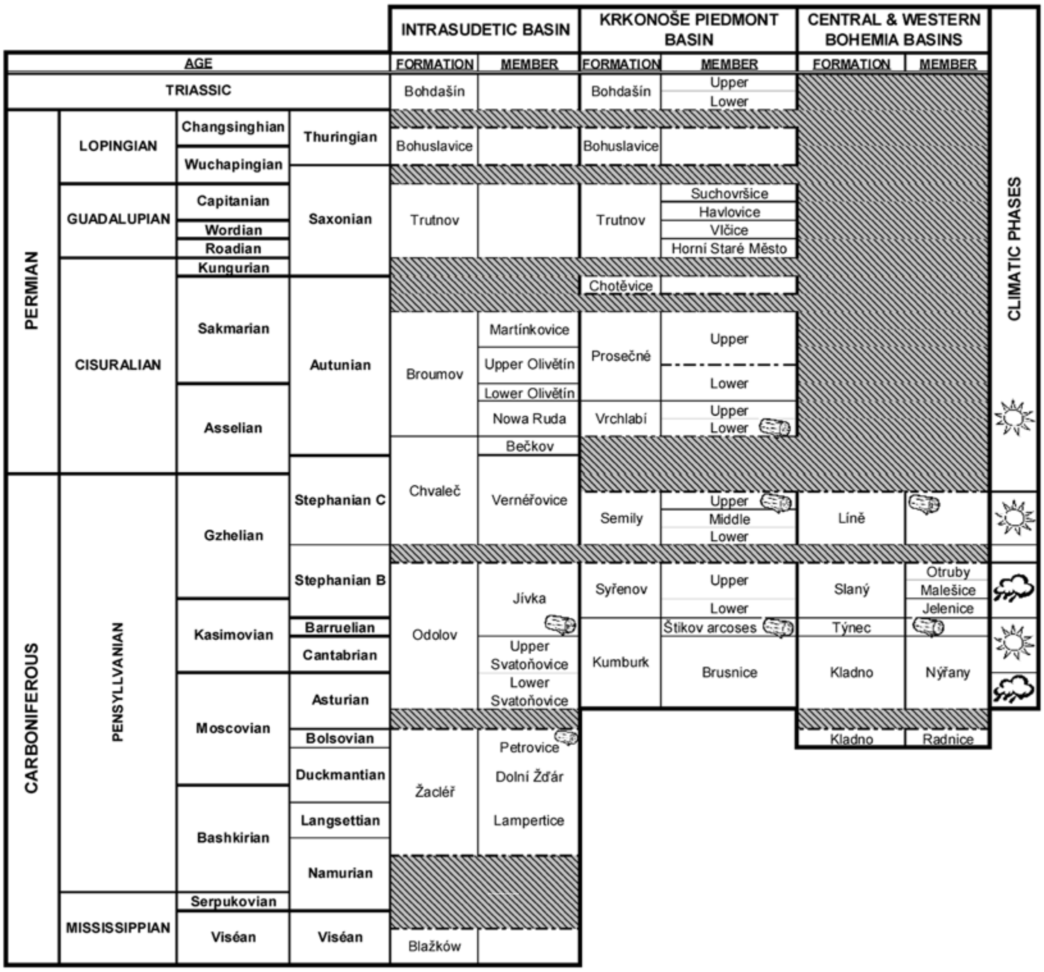

Fig. 2. Stratigraphy of the Intra Sudetic Basin in comparison with the Krkonoše-Piedmont and Central and Western Bohemian basins; positions of the fossil wood (small log) and supported climatic phases marked, compiled after Skoček (1970), Tásler et al. (1979), Pešek et al. (2001), Roscher & Schneider (2005), and Opluštil & Cleal (2007). Notes to pictures: cloud – humid or seasonally humid climate, sun – seasonally dry to seasonally arid climate.

rings, 2.5 to 8 cm wide. Goeppert (1857, 1858) considered light-grey chalcedony and chert as the main components forming the permineralized stems. After a microscopic study based on the similarity to the wood of modern *Araucaria*, Goeppert (1857, 1858) classified these silicified woods to two following species: the previously described *Araucarites brandlingii* (Lindl. & Hutt.) Goepp., and his newly erected *Araucarites schrollianus* Goepp. (Goeppert 1857). He interpreted both species as belonging to a group of conifers (type *Araucarites*). Furthermore, he described the fossiliferous rock Žaltman Arkoses (*Sandsteinfelsen*) as the Upper Carboniferous part of a black coal bearing unit (*Steinkohlenformation*). Goeppert's works raised attention of a lot of scientists and amateur collectors. An unwanted consequence was that most of deposits had been spoiled or destroyed during following years. The locality followed the unlucky fate of once famous silicified *Dadoxylon* wood formed in very similar facies in the Kyffhäuser Massif in Germany (Rössler 2002).

Although many authors (e.g., Stur 1877; Makowsky 1878; Katzer 1892; Petrascheck 1924; Purkyně 1927; Březinová 1970) wrote about this area and its silicified wood in general, nobody has studied both wood anatomy and systematics in detail since Goeppert.

1.2. Current research

In this contribution, we focused on newly discovered silicified trunks, still very common in the studied area (Mencl 2007). Silicified trunks are found almost in all large Late Palaeozoic basins in the Czech Republic shown in Fig. 1 (Pešek 1968; Holub et al. 1975; Tásler et al. 1979; Report 1994; Pešek et al. 2001). They are mostly embedded in very similar sedimentary sandstones or arkosic units (Skoček 1970; Tásler et al. 1979; Pešek et al. 2001; Matysová 2006; Mencl 2007; Opluštil & Cleal 2007 and references therein; Fig. 2) that correspond to drier intervals from the Stephanian to the Early Permian mentioned by Opluštil & Cleal (2007). Contrary to other Permocarboniferous basins in the world with variable types of fossil wood/plants (e.g., Falcon-Lang & Scott 2000; Falcon-Lang & Bashforth 2005; Rössler 2006; Uhl 2006; Wagner & Mayoral 2007), only one type of wood (*Dadoxylon*) is considered to be present in the Czech part of the Intra Sudetic Basin. Fossils are very recrystallized, probably preserved without any direct influence of volcanism, and fit to Barruelian sedimentary units (Fig. 2).

The systematical study of the newly collected material presents only one aspect of our work; we paid attention to geological setting and orientations of trunks in fluvial deposits (Valín 1960; Liu & Gastaldo 1992; Bridge 2003; Gastaldo & Degges 2007), furthermore to mineralogical, petrographical and instrumental analyses in the sense of the work done by Matysová (2006) and Matysová et al. (2008). Microscopic studies as well as geochemical analyses were undertaken on polished thin slides or sections. For petrograhic description of SiO_2 the international classification was used (Flörke et al. 1991). For textures of SiO_2 crystals in permineralized plants we used terminology published by Weibel (1996) and references therein. Cathodoluminescence microscopy and spectroscopy (CL) proved very useful in qualitative and quantitative analysis of mineral matter creating the fossil trunks (Götze & Rössler 2000; Götze & Zimmerle 2000; Götze et al. 2001; Matysová et al. 2008) or just various mineral grains (e.g., Götte & Richter 2006). All new gathered data served as a clue for upgraded framing such fossils into basinal history and palaeoenvironment.

2. Geological setting

The Czech part of the Intra Sudetic basin is situated in the NE part of the Czech Republic (Fig. 1). Its stratigraphical range of deposits is the widest among all Czech Late Palaeozoic basins. The sedimentation was continuous (except for several hiatuses) from the Mississippian to the Middle Triassic (Pešek et al. 2001; Opluštil & Cleal 2007). The maximum thickness of deposits is about 3500 m (Chlupáč et al. 2002). The whole set is divided into 8 formations with a well established correlation to European stratigraphical units (after Tásler et al. 1979; Tásler et al.

Table 1. List of selected representative permineralized samples of *Dadoxylon* sp. from the Hawk Mts. (Intra Sudetic Basin). Cathodoluminescence measurements (CL) of chosen samples marked by *i* (imaging) and *s* (spectroscopy). Abbreviations: VS (*in Czech*) means Intra Sudetic Basin, *OdFm* – Odolov Formation (Žaltman Arkoses), *s.a.d.* – secondary alluvial deposits, * – without stratigraphic assignment, *qtz* – quartz (SiO_2), *K-fld* – K-feldspars.

Sample	Description of deposit	Stratigraphy	Mineralogy	CL
VS1	fragment from a memorial – unknown origin	*	qtz	*i*
VS2	fragment from a bigger trunk – on a road	*s.a.d.*	qtz	*i*
VS3	outcrop – Žaltman	*OdFm*	qtz	*i*
VS4	weathered on surface	*s.a.d.*	qtz	*i*
VS6	freely in a stream	*s.a.d.*	qtz	*i, s*
VS7	on a track in wood	*s.a.d.*	qtz	*i, s*
VS10	weathered material – marshland	*s.a.d.*	qtz	
VS11	artificial assemblage	*	qtz	
VS12	surface of a field	*s.a.d.*	qtz	
VS13	artificial assemblage	*	qtz	
VS14	artificial assemblage	*	qtz	
VS21	in a stream	*s.a.d.*	qtz + K-fld	*i*
VS34	in a stream	*s.a.d.*	qtz	
VS35	in a stream	*s.a.d.*	qtz	

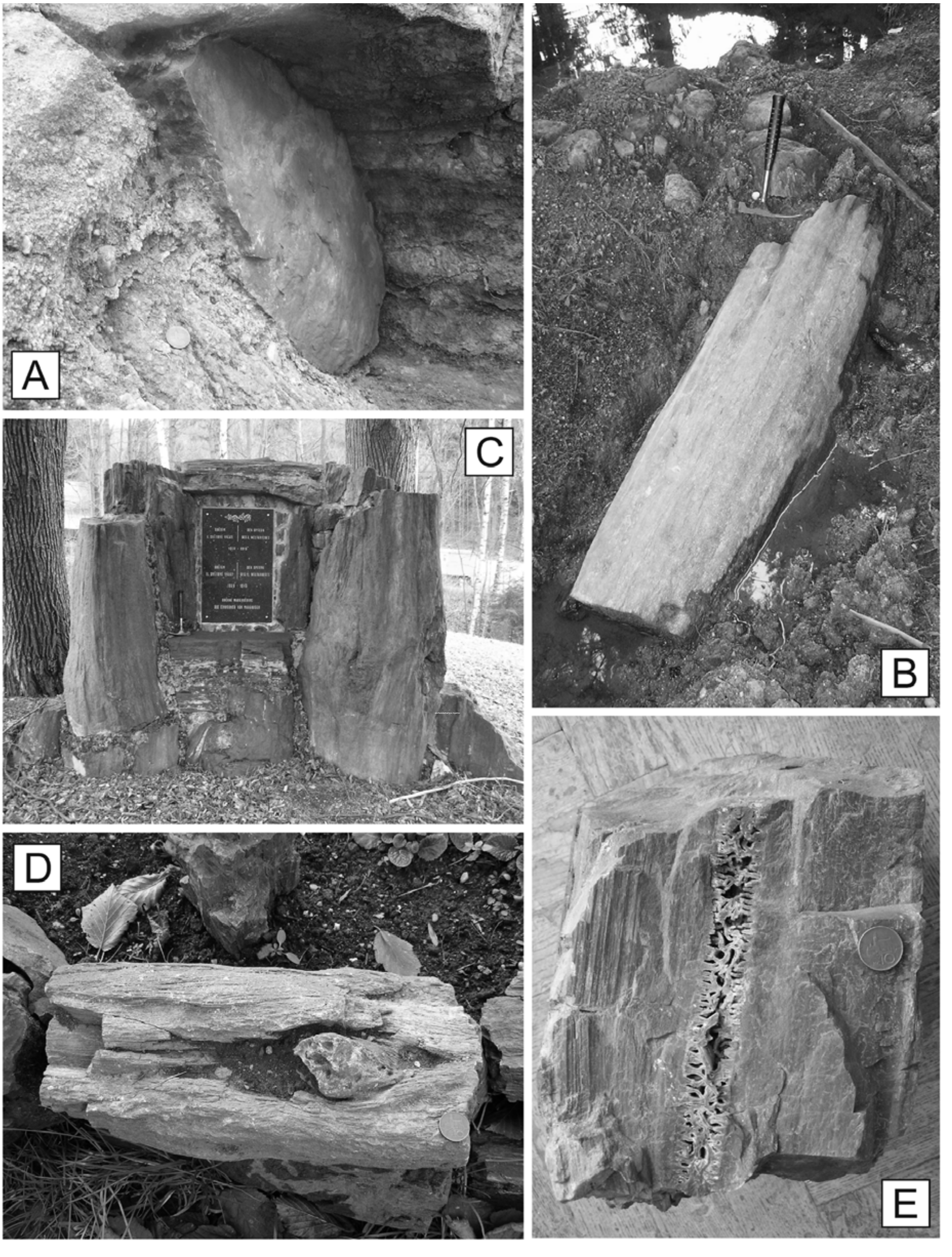

Fig. 3. *Dadoxylon* sp. (macroscopic photos). **A** – Silicified trunk in allochthonous position, Hronov locality. **B** – Silicified trunk secondary embedded in Quaternary deposits, U Studánky locality. **C** – Silicified wood in monument, Markoušovice. **D** – Fragment of silicified stem with a branch remain. **E** – Silicified trunk with a central pith of *Artisia*-type.

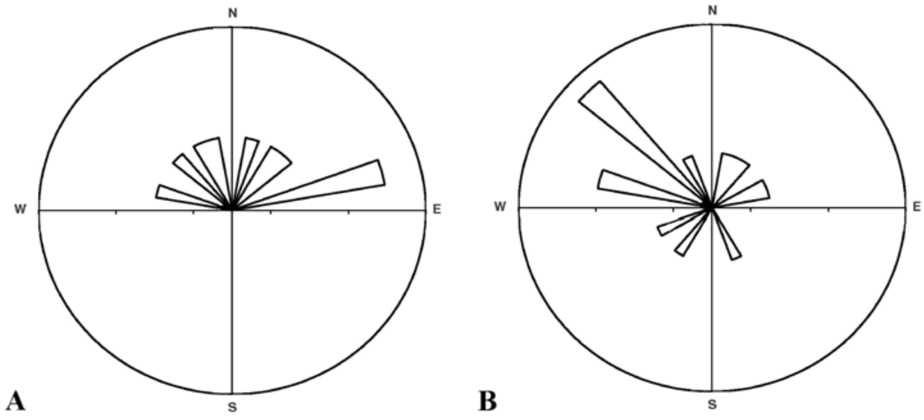

Fig. 4. Palaeoflow directions (A) and directions of the longest axes of stems (B).

in Pešek et al. 2001; Fig. 2). The axis of the basin is oriented in NE–SW direction congruently with the centre lines of the other Late Carboniferous limnic basins of the Bohemian Massif. The Intra Sudetic Basin joins on the SW edge the Krkonoše Piedmont Basin, from which it is separated only by the Hronov-Poříčí Fault. The basin is interlaced by numerous tectonic faults of a variable extent (Fig. 1).

Except for the very oldest part, the filling of the basin is purely continental. Sediments have mostly a fluvial or proluvial character, in some levels with finer deposits of temporary lakes or swamps. Volcanic material is present in several units. Silicified wood can either be found directly embedded in the arkosic sediments of Barruelian age (Jívka Member of Odolov Formation), which are called Žaltman Arkoses (Fig. 2), or spread in neighbouring fields, meadows or forests in the form of fragments or trunks. Their best outcrops are in the area of the Hawk Mts. where the Žaltman Arcoses rise up to the surface. These strata are mainly composed of more or less coarse arkosic conglomerates and sandstones, deposited by river streams (Valín 1956, 1960) and they lack any compressions of leaves or reproductive organs.

3. Materials and methods

In the area of the Hawk Mts. we collected several hundreds of samples of silicified stems, and the databases of photos and information for palaeoecological reconstructions have been improved considerably (Table 1; Mencl 2007) Results gained from samples belonging to the National Museum in Prague (Matysová 2006) were also considered. For the trunks embedded in the original sediment, a standard geological compass was used to measure their azimuth and inclination and the surrounding stream structures (bedforms) in order to reconstruct the direction of palaeostreams, and the reaction of the wood during its sedimentation. The values were corrected using the software STEREONETT 2.02 and the results were subsequently plotted in the geological map with the help of the programme ArcGIS 9 (application ArcMAP 9.2). Several tens of the best preserved samples were selected to make thin sections and study them with microscopic and other instrumental techniques. Each chosen sample of silicified wood was cut in 3 directions: transverse, tangential and radial. Systematic parameters were finally processed by Anova programme.

For microscopic observations of standard (polished) thin sections in transmitted light (PPL) and polarized light (XPL) optical microscopes Olympus BX-51 and Olympus BX-60 were used. Microscope Leica with fluorescence regime in UV spectral scale was used for observations of transverse polished sections in reflected light. Cathodoluminescence imaging was performed with a "hot cathode" CL microscope Simon-Neuser HC2-LM (Masaryk University, Brno, Czech Republic), which enables both light microscopy and cathodoluminescence microscopy without sample readjustment. The electron gun was operated at 14 keV with a current density 10-40 $\mu A \cdot mm^{-2}$ in vacuum (10^{-6} bars). The luminescence images were taken by a digital camera Olympus C-5060. CL spectral measurements were carried out on a "hot cathode" CL microscope HC1-LM (TU Bergakademie Freiberg, Germany) under the same experimental conditions as to imaging in MU Brno. EG&G digital triple-grating spectrograph with CCD detector, which was attached to the CL microscope by a silica fibre guide, served to gain CL spectra. Thin sections were carbon coated before CL measurements to prevent build-up of electrical charge. Spectra were firstly processed by Microsoft Office Excel 2003 and subsequently evaluated in OriginPro 7.5 (OriginLab, USA). Spectral deconvolution to Gaussian components & examination of 2nd derivatives of smoothed spectra was used to find maxima of luminescence

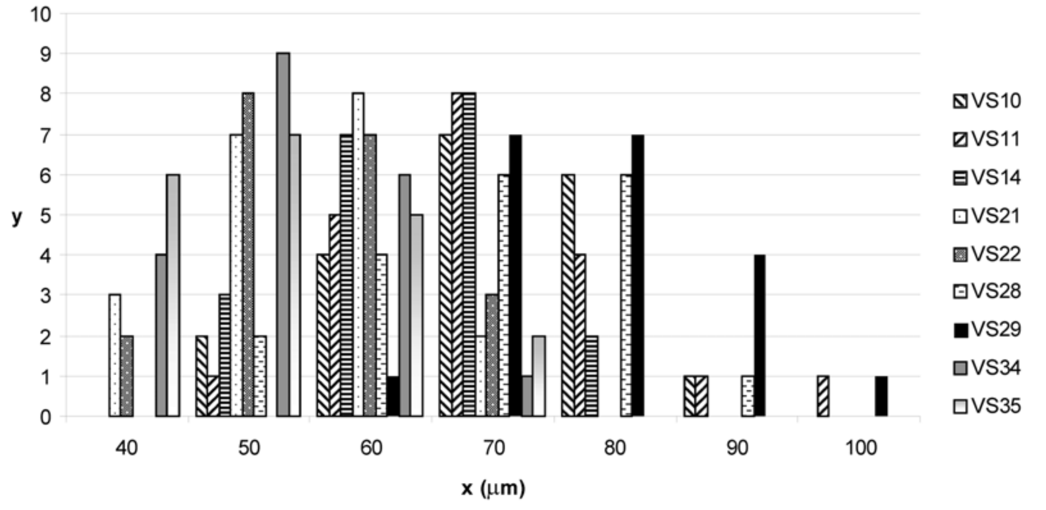

Fig. 5. Radial tracheid diameter in transverse section; x – diameter (µm), y – number of tracheids.

bands. Selected one-sided planar remains from cutting of samples were measured by X-ray diffraction (XRD) to identify mineral matrix of the permineralized samples using Siemens D5005 diffractometer. Diffractograms were processed using PANalytical HighScore search/match programme.

4. Results

4.1. Sedimentology

Three main types of occurrences of the fossil trunks have been recognized in the field: sedimented horizontally as allochthonous material and embedded in fluvial sediments (Fig. 3A); in secondary alluvia without any relation to the original sediment (Fig. 3B), and artificially removed in relation to human activities (monuments, communal town decorations; Fig. 3C). Valín (1956, 1960) described 17 outcrops of the first category, which can be directly used to measure the orientation of the trunks. Unfortunately, most of them are destroyed nowadays. Nevertheless, we have discovered several other useful outcrops. Finally, we selected 8 localities with 14 stems em-

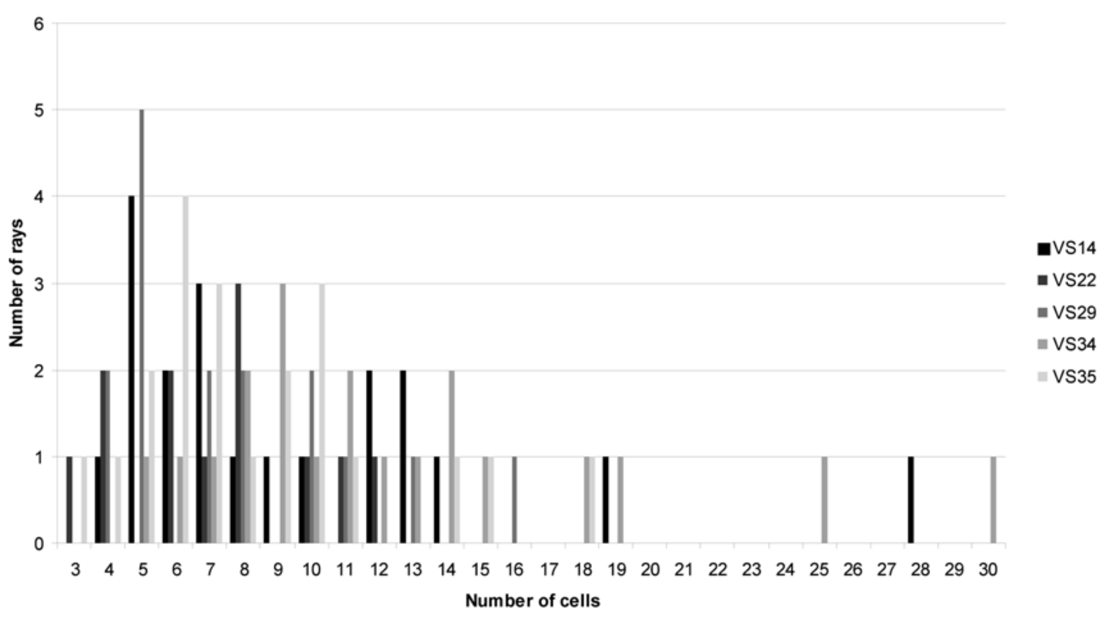

Fig. 6. Histogram of height of rays in tangential longitudinal section.

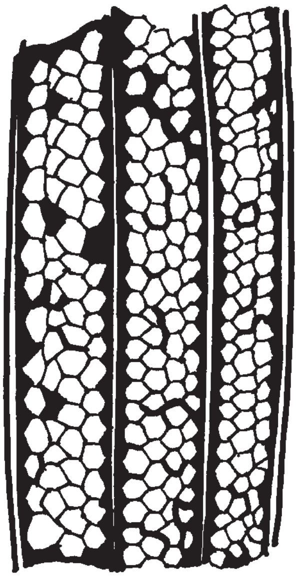

Fig. 7. Sketch of bordered pits in a radial wall of tracheids in the specimen VS12 – cordaite type.

bedded in sedimentary strata. The orientation of the trunks themselves was studied as well as the sedimentary structures in their neighbourhood to recognize the direction of palaeostreams.

The fossil logs are mostly oriented in NW or WNW directions. Fossil trunks are relatively short, preserved without bark or branches, often damaged or split into pieces that are surely due to the transport in torrential rivers together with gravel and sand. The logs are shorter than axes of bedforms, which are in our case utmost about 10 m that, in accordance with the observations by Bridge (2003), means that the logs laid almost perpendicularly to the palaeostream (Fig. 4). Moreover, the logs are embedded on the bottom of sandy channels with very coarse residual gravel that indicate their transport during extreme floods. The river behaviour can be interpreted as an intermediate type between braided and meandering (Martínek, pers. comm.).

4.2. Palaeobotany

Gymnosperms
Dadoxylon Endlicher
Dadoxylon sp.

Specimens: VS10, VS11, VS12, VS13, VS14, VS21, VS22, VS28, VS29, VS34, VS35.

Description: Transverse section (Figs. 5, 8A, B) – Growth rings indistinct. Tracheids thin-walled, round or oval in cross-section or irregular in shape when compressed, placed in deformed radial lines. Radial diameter 40-100 µm (mean 63 µm, n = 180). Axial parenchyma absent.

Tangential longitudinal section (Figs. 6, 8C, D) – Tracheid pits not observed. Rays mostly uniseriate (74 %), partly biseriate (25 %) or triseriate (1%) and generally medium (9) in height sensu IAWA Committee (2004) with total extent of 3-30 cells. Ray cells round to oval in section. The density of rays varies between 3 to 9 (mean 5) rays per tangential mm.

Radial longitudinal section (Figs. 7, 8E, F) – Tracheid pitting in radial walls (preserved only in 6 samples VS10, VS12, VS13, VS21, VS34, VS35) 2-3(-4) seriate and alternate (araucarioid). Pits bordered, hexagonal, crowded, covering all width of a tracheid wall. Pit diameter 10-12 (-20) µm. Cross-field pitting not observed.

All here described specimens are characterized only by the structure of the secondary xylem, the features of primary xylem as well as pith are lacking. The wood is homoxylous pycnoxylic without axial parenchyma and resin canals, traumatic or normal. Its age (Late Pennsylvanian, Barruelian) and the overall “araucarioid” character (alternate multiseriate tracheid pitting in radial walls with uniseriate rays and no parenchyma) allow its safe attribution to the morphogenus *Dadoxylon* Endlicher. However, a more accurate attribution on a specific level remains problematic because the stems are strongly recrystallized by highly crystalline quartz (see 4.3.1. below). Some of the features cannot be detected (cross-field pitting), some of them only rarely and in a bad state, e.g. pits in radial tracheid walls are visible only rarely thanks to pigmentation that highlights their outlines. Therefore, we prefer to leave our woods in open nomenclature, designate them as *Dadoxylon* sp. We used this generic name following Vogellehner’s (1964) concept as the only correct name for an araucarioid type of secondary xylem where neither primary xylem nor pith is present. Nomenclatural discussions, e.g., priority of *Pinites* Lindley & Hutton over *Dadoxylon* Endlicher (see Bamford & Philippe 2001), are beyond the scope of this paper.

The fossil record of this case exists only in forms of decorticated trunks or thicker branches; bark, small branches and other co-occurring plants remains (leaves, reproductive organs etc.) that could facilitate the systematic attribution of the fossil wood are absent. The only exception is represented by two extraordinary specimens that we had an opportunity to study during our field-work. They possessed other unique macroscopic features: the first one (Fig. 3D) has one solitary rest of a branch preserved without any

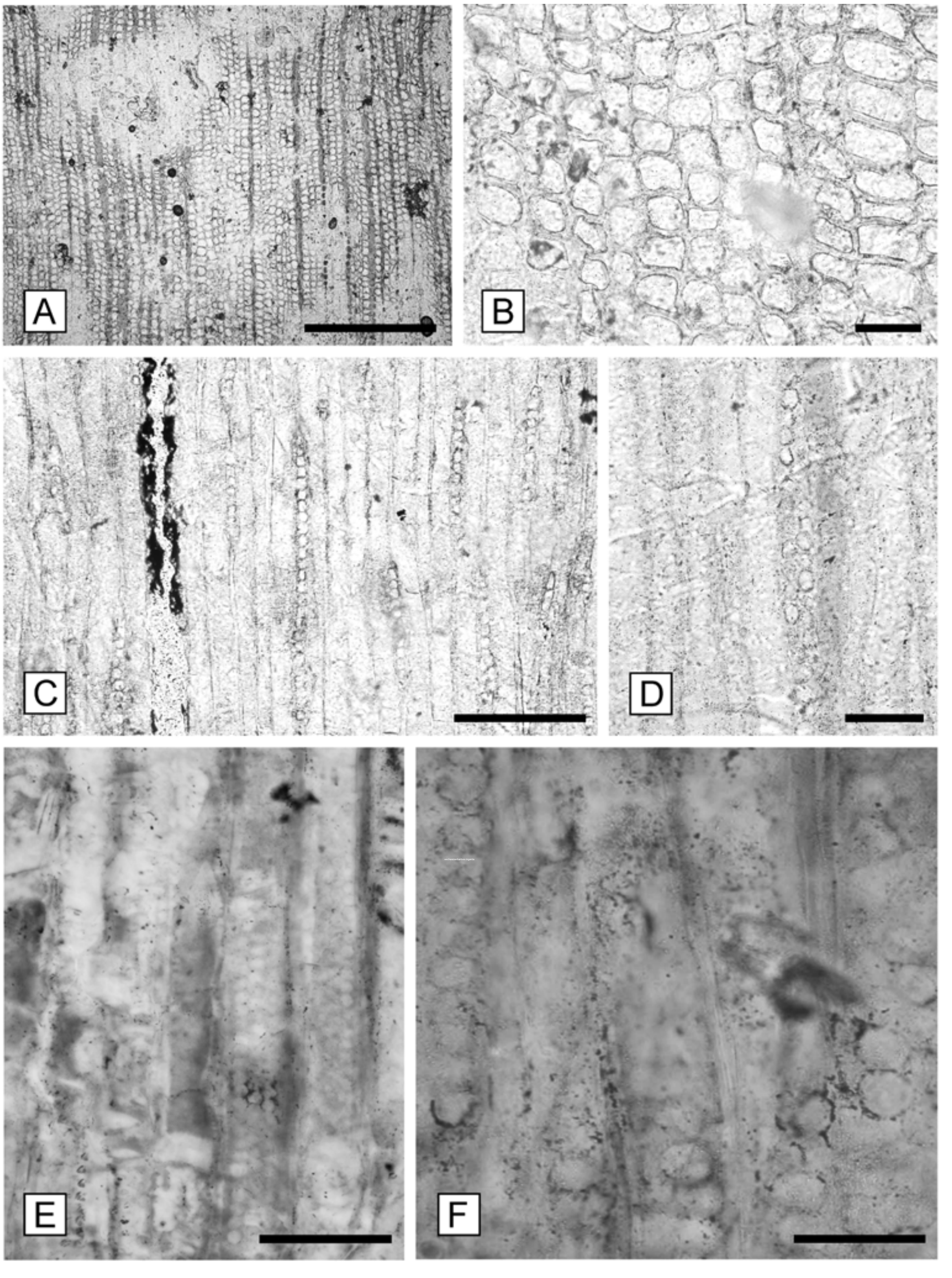

Fig. 8. *Dadoxylon* sp. (microscopic photos). **A –** Transverse section, VS12, scale bar 1 cm. **B –** Transverse section, thin-walled tracheids, VS14, scale bar 50 µm. **C** – Tangential longitudinal section, uniseriate rays, VS14, scale bar 100 µm. **D –** Tangential longitudinal section, biseriate ray, VS12, scale bar 50 µm. **E** – Radial longitudinal section, alternate (araucarioid) pitting, VS12, scale bar 100 µm. **F** – Radial longitudinal section, araucarioid pitting, VS35, scale bar 25 µm.

indication of the branch in the close proximity, the second one (Fig. 3E) shows the pith of *Artisia*-type. Both these features are considered to belong to cordaitaleans (e.g., Noll et al. 2005).

4.3. Geochemistry

4.3.1. Mineralogy and petrography

All samples from ISB (Table 1) are mainly permineralized by pure α-quartz (α-SiO_2) of a high crystal-

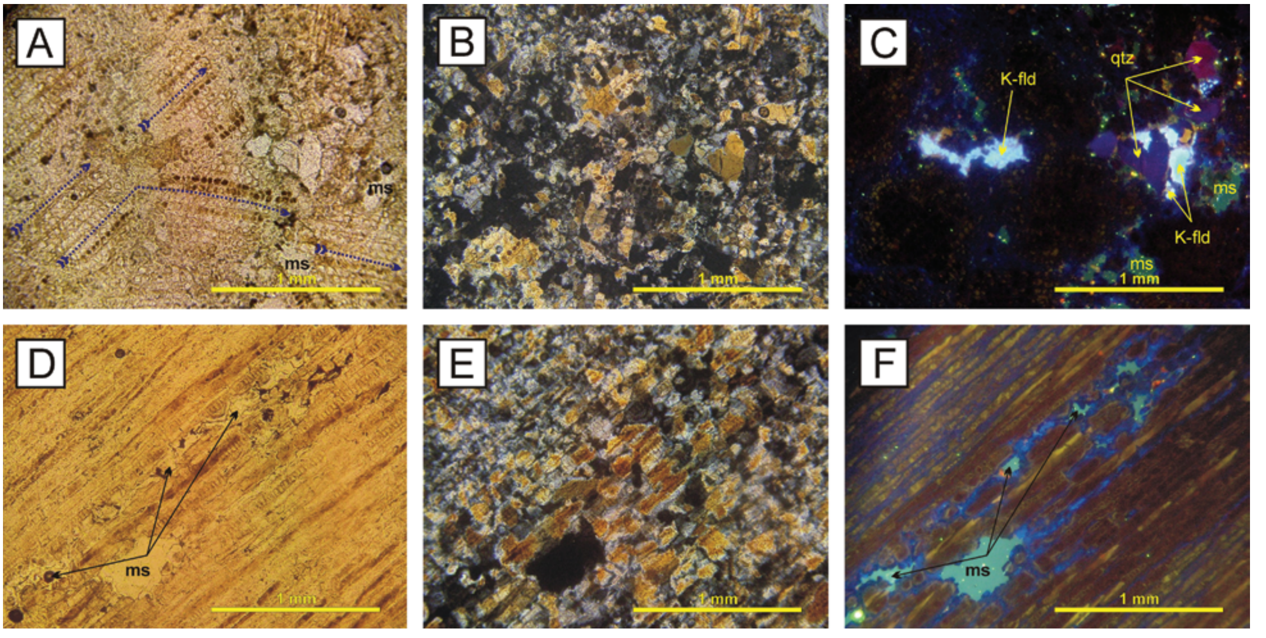

Fig. 9. Demonstration of particular mineralogy of *Dadoxylon* sp. From left: Normal light (PPL), polarized light (XPL) and cathodoluminescence (CL) pictures of sample VS21. **A-C –** Transverse section, **D-F** – tangential (longitudinal) section. Dotted line in A indicates strong fragmentation of secondary xylem, surrounded by allochthonous sedimentary grains (viz C). Short-lived blue CL in C and F as a secondary overprint of silicification. E shows preferred orientation of qtz grains respecting anatomy of tracheids. Yellow CL in F is attributed to hydrothermal quartz. Abbreviations: *K-flds* – K-feldspars (stable bright blue CL), *qtz* – allochthonous crystals of quartz, also of volcanic origin (violet CL), *ms* – visible microscope slide. Further explanation in the text.

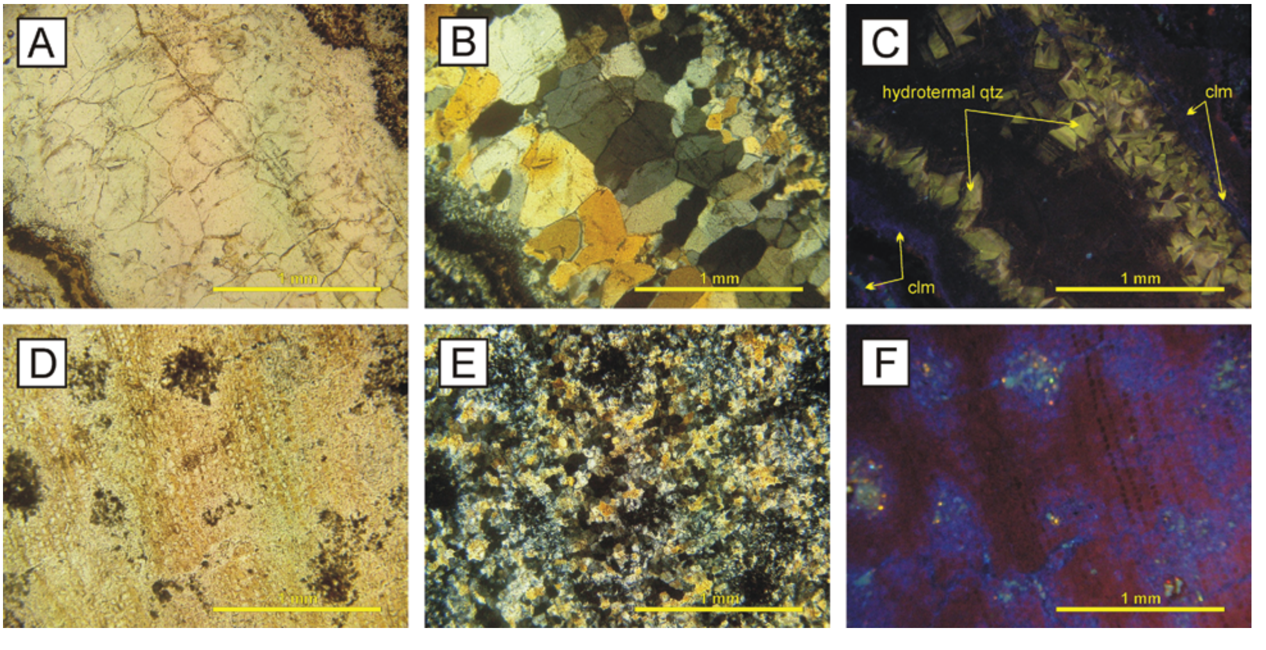

Fig. 10 (Legend see p. 279)

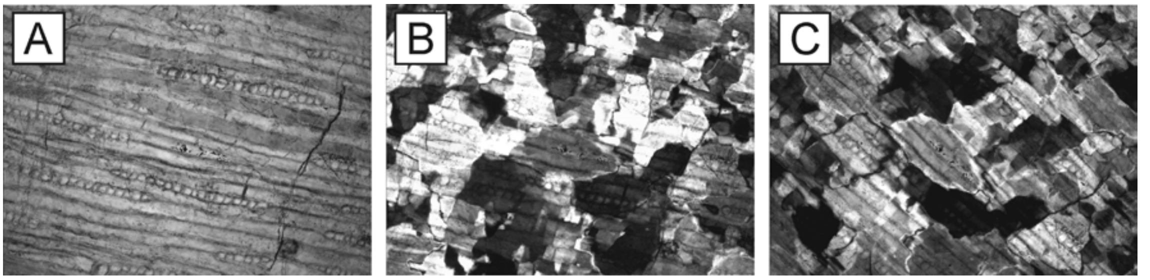

Fig. 11. Illustration of particular petrography in tangential longitudinal section (VS21): A (PPL), B (XPL), C (XPL shift 30º). Megaquartz grains are arranged in domains that respect the former anatomy of tracheids (secondary xylem) in the longitudinal direction.

linity as was proven by XRD in bulk samples and petrography microscope in a microscopic scale. Furthermore, fragments of wood are often "contaminated" by allochthonous sediment, such as polymict quartz grains, K-feldspars, or clay minerals, mainly kaolinite, as was analytically proved by XRD or visualized by CL (Fig. 9A-C). The absolute majority of the samples are highly recrystallized. Although the rough anatomical features are more or less visible, tiny anatomical details such as pits or cross fields are mostly unreadable (see 4.2 above). Wood is very often unevenly pigmented by Fe_xO_y, and sometimes this pigmentation helps to highlight/preserve particular tiny anatomical details, such as tracheids and pits. Obviously, the residual coalified organic matter is almost or completely missing. In petrographical terms used to classify SiO_2 polymorphs (Flörke et al. 1991) and quartz textures in silicified plants (e.g., Weibel 1996; Matysová 2006; Matysová et al. 2008, and references therein), the best preserved parts of secondary xylem were mostly permineralized by microcrystalline quartz ("microquartz", 5-20 µm in diameter) mainly being arranged in polyblastic textures. On the other hand, the presence of macrocrystalline quartz ("megaquartz", 20-2000 µm across) is by far more frequent in our samples, particularly in hyperblastic textures not respecting former anatomical arrangement of plant tissues. These types of silica crystals vary in both size and shape through the whole collection of thin sections. It is interesting that XPL pictures of transverse and longitudinal cuts are very different. An apparently chaotic arrangement of SiO_2 crystals in recrystallized transversal cuts (Figs. 9B, 10E) looks in longitudinal sections as megaquartz crystals elongated along the tracheids (Figs. 9E, 11A-C). These samples were often heterogeneous, broken by abundant fissures of a various size, passing across the secondary xylem, and frequently the "fragmentation" of the former plant tissue produced a misoriented mosaic of preserved wood in a purely inorganic non-templated secondary silica mass (Fig. 9A). The cracks were often filled by large idiomorphic megaquartz crystals, agate-like structures of microquartz, or palisades of fibrous quartz (Fig. 10B). Different silica arrangements in cracks etc. mark later steps of permineralization, probably thanks to tectonic movements that caused mechanical breakage of plant fossils (see part 2).

Due to high SiO_2 crystallinity, coarseness, large recrystallized parts and frequent fissures, silicified samples of *Dadoxylon* type from ISB are often heterogeneous, incompact, and frequently mechanically disintegrated. Therefore, their thin section processing was not easy, and on some of them a microscope slide is obvious through (Fig. 9D-F).

4.3.2. Cathodoluminescence

CL microscopy was used on 7 samples marked in Table 1. CL imaging revealed conspicuous heterogeneity of siliceous mass that seemed to be uniform at

Fig. 10. Demonstration of particular mineralogy of *Dadoxylon* sp. on transverse sections. From left: Normal light (PPL), polarized light (XPL) and cathodoluminescence (CL) pictures of samples VS6 (A, B, C) and VS7 (D, E, F). **A-C** – Secondary fissure inside the wood sample fulfilled by well-zoned hydrothermal quartz, bordered by reduction line consisted of clay minerals and Fe_xO_y; **D-F** – conspicuous geochemical patterns in wood structure. Complicated mechanism of silicification proved by different CL shades (F) of uniform siliceous mass (D, E). Abbreviations: *qtz* – quartz, *clm* – clay minerals (stable blue CL). Further explanation in text.

Table 2. Results of spectral CL measurements and their assignment. For spectra see Figs. 12-13.

Shade CL	Cathodoluminescence maximum [nm]		Assignment
	VS6	VS7	
short-lived blue (initial)	451	447	450 nm
stable blue (initial)	–	438	
yellow (initial)	585	–	580 nm
(after 60/120/180 sec)	(637/641/643)		
stable red	649	640	620-650 nm

first sight in transmitted light (PPL, XPL). Silicification proceeded in several distinct environments under a varying temperature and chemical composition, and the silicification resulted in silica mass in wood that is rich in microscopic impurities, substitution of Si, and abundant defects in the crystal lattice. Some of so called intrinsic or extrinsic defects are CL activators.

Prevailing CL shades in the silicified fossils from ISB are: stable red – typical for primary siliceous mass, les commonly stable blue; and short-lived blue CL – typical for secondary overprints, which passes into stable red CL after longer exposition (see also Matysová et al. 2008). Some of these shades alternate through thin sections, sometimes are not anticipated, sometimes reflect domains of recrystallization, where already the appearance of SiO_2 in PPL seemed to be different (Fig. 10D-F).

CL spectroscopy was performed on two representative thin sections, VS6 and VS7. It served to a detailed spectral study of prevailing CL shades that are not megascopic. It was supposed that every CL shade corresponds to a particular CL activator in the crystal lattice. Acquired CL spectra show several CL emission bands (Figs. 12-13; Table 2). Time dependent short-lived blue CL around 450 nm in α-quartz (see Figs. 12A, 13A; Table 2) is supposed to be typical in quartz crystallized from hydrothermal solutions (Götze 2000; Götze et al. 2001a, b; Witke et al. 2004; Boggs & Krinsley 2006). The typical change from initial blue to final brown CL colours (Fig. 12A) is caused by the rapid decrease of the CL emission bands just below 400 nm and about 450 nm and the associated increase of the red emission band at about 650 nm.

Transient yellow CL unexpectedly appeared in samples VS1, VS6 and VS21. It was detected for the first time in Czech samples of silicified wood. In VS6 (Fig. 12B; Table 2) it was observed particularly in large fissures healed by idiomorphic quartz grains (Fig. 10C) whereas in VS1 or VS21 the yellow CL appeared in patches of silica mass with wood structures (see Fig. 9F). During the measurement transient yellow CL passed to stable red CL with the same emission maximum as in the case of short-lived blue CL (Table 2).

CL also very well displayed some allochthonous sedimentary grains, such as clay minerals (blue CL along fissure healed by hydrothermal quartz in Fig. 10C), grains of K-feldspars (bright blue CL of angular grains) or detritus quartz grains (plutonic? qtz – darker blue CL, qtz of supposed volcanic origin – violet-reddish CL). CL intensity of these admixtures was so high that it overshadowed CL of wood (Fig. 9C).

5. Discussion

5.1. Taxonomical assignment, taphonomy and their importance

The wood of *Dadoxylon*-type generally represents both cordaites and conifers and their distinction based only on the anatomy of secondary xylem is not easy. Doubinger & Marguerier (1975: 40) distinguished three groups (*Dadoxylon* of type I-III) in which the first group belongs to cordaites and the second one to primitive conifers of *Walchia*-type. Distinctive features are outlines of tracheids in cross-section, presence of growth rings, tracheid pitting in radial walls, cross-field pitting and height of rays. Most recently, the wood of *Dadoxylon*-type was reviewed in detail by Noll et al. (2005). Authors specified the following features, which help to distinguish the wood of cordaites from that of conifers: arrangement and outlines of bordered pits in radial tracheid walls of secondary xylem, a shape of the transition between the primary xylem and the pith, external and internal disposition of the pith, leaf traces and branching. It is obvious that Noll et al. (2005) contrary to Doubinger & Marguerier (1975) used not only the secondary xylem but also other parts of fossilized stems that, however, are rarely present.

In spite of rather bad preservation of our specimens, we could definitely use the character which is common to both classifications: pitting in radial tracheid walls. The bordered pits observed in PPL in radial sections of several specimens have a typical hexagonal outline and they alternate in 2-4 rows, covering almost the entire width of the radial tracheid wall (Figs. 7, 8E, F). Moreover, Anova programme on radial tracheid diameter and height of rays (Figs. 5, 6) showed results with insignificant deviation that means that samples of wood are very similar to each other. Consequently we interpret these woods as belonging to cordaites. Another evidences confirm our observations; the piece of the stem possessing the solitary knot, which has no indication of a branch in the close proximity meaning the absence of pseudo-verticillate branching (Fig. 3D), and the typically fragmented pith of *Artisia*-type (Fig. 3E). Both such findings further indicate a cordaitalean affinity (Noll & Wilde 2002; Noll et al. 2005), even if we could not analyse secondary xylem of these two samples due to their insufficient preservation. Unfortunately, the co-occurring plant remains as leaves or reproductive structures that could facilitate the systematic attribution of the fossil wood are absent in the whole Jívka Member. Summarizing this part we can say that our new observations of petrified stems cannot confirm the presence of conifers contrary to Goeppert's (1857, 1858) observations, which point to both groups in the Radvanice fossil forest – cordaites and conifers; Goeppert's *Araucarites brandlingii* (Lindley & Hutton) Goeppert, known today as *Dadoxylon brandlingi* (Lindley & Hutton) Frentzen, corresponds to the wood of cordaites and his *Araucarites schrollianus* Goeppert = *Dadoxylon schrollianum* (Goeppert) Frentzen is the wood of conifers. Moreover, we never found growth rings in our samples as Goeppert (1857, 1858) described (compare 1.1. vs. 4.2.); we only observed the so called "false" growth rings (IAWA Committee 2004: 16) or ring-like structures that appear in secondary xylem for instance due to diagenetic mechanical compaction (Noll & Wilde 2002; Noll et al. 2005; Matysová et al. 2008).

The poor preservation of plant tissues and fragmentary preservation of silicified decorticated stems represent a typical problem met in analyses of Late Palaeozoic *Dadoxylon* wood type, and, maybe, the general reason of unsatisfactory taxonomical assignment of silicified stems found in alluvial facies. The differentiation between cordaites and conifers is, however, of great importance with respect to a global environmental change around Carboniferous/Permian boundary. While cordaites had flourished in equatorial Pangean uplands during the Westphalian (e.g. Falcon-Lang & Scott 2000; Falcon-Lang & Bashforth 2005), the Permian upland flora consisted mostly of conifers (Noll & Wilde 2002; Diéguez & López-Gómez 2005; Uhl 2006), e.g. of *Walchia*-type (Wagner & Mayoral 2007). A similar pattern was recorded by the preserved specimens of *Dadoxylon*-type of wood. Doubinger & Marguerier (1975: 42) traced the stratigraphical significance of the fossil record of their "*Dadoxylon de type I-III*" from the Euramerican province, starting with *Dadoxylon* of type I (cordaites), the most frequently found type in Namurian, Westphalian and Stephanian times while *Dadoxylon* of type II (conifers) started in the Stephanian with a maximum during the Stephanian/Early Permian, and *Dadoxylon* of type III (probable conifers) occurred mostly in the Late Permian. A systematic occurrence in favour of cordaites in the case of the Žaltman Arkoses (Barruelian or Stephanian A) where conifer stems were not yet confirmed can not be excluded. In this respect, an exact re-assignment of the silicified wood of *Dadoxylon*-type of Westphalian D/Stephanian age from the Central and Western Bohemia Late Palaeozoic basins (Skoček 1960; Pešek 1968) will be of particular interest in the future. Another possible explanation of a virtual lack of conifers in our fossil wood record can be in taphonomy. DiMichele et al. (2001) in their extensive review of floral development in Late Carboniferous/Early Permian flora as supposed that during the Bolsovian-Westphalian D (Middle Pennsylvanian) conifers persisted in seasonally dry climate periods in uplands, which influenced the possibility being preserved in fossil record. In river systems, alluvial deposits gave more chance to preserve plants, which grew closer to the river. Such a way of fossilization could have preferred the cordaites from riparian or transitional (piedmont) environments, rather than more distant and 'xerophilous' conifers from uplands (mountain areas).

Due to size and shape of pebbles in fossiliferous layers we consider that transport of wood could process in the distance of utmost 100 km (Martínek, pers. comm.). This rather long transport probably resulted in highly selected preservation of hard pycnoxylic wood only thanks to high resistance of stems:

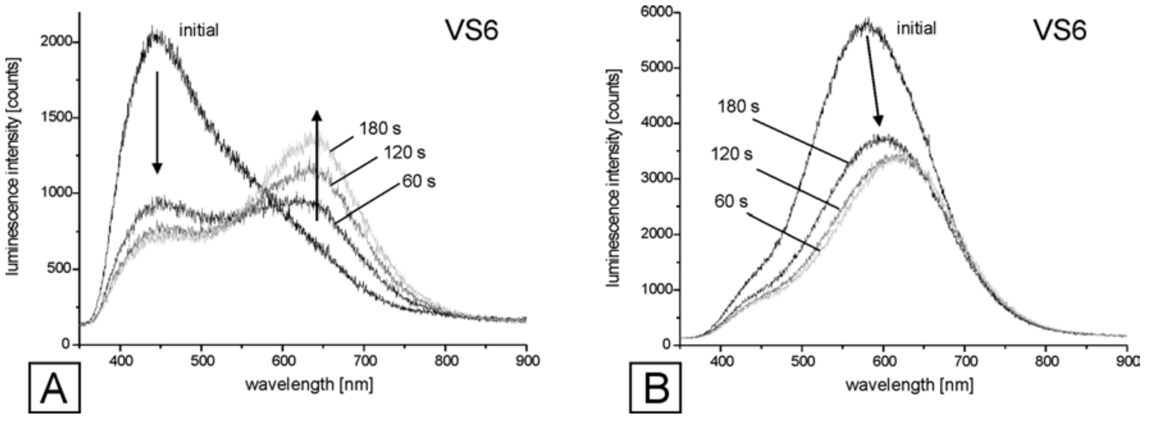

Fig. 12. Time dependent spectra (VS6) of short-lived blue CL (A) passing into stable red CL, and short-lived yellow CL (B). Numerical CL spectral data in Table 2.

other remnants of plants or charcoals were not maintained, they should have been damaged during the rapid transport in high energetic water stream systems among coarse gravels and rock fractions. Most fossil logs are oriented perpendicularly to the palaeostream direction (Fig. 4). These logs must have been deposited after their damage and breakage into pieces smaller than approximately 10 m. The dominant palaeostream directions were hence from the SW to the NE, which corresponds with older observations on other localities in the same basin (Valín 1956, 1960; Pešek et al. 2001). Thanks to the compactness of the *Dadoxylon* kind of wood, no pebbles, cobbles or boulders could be found enclosed in our samples and therefore we could not for example do provenance analysis as was done by Liu & Gastaldo (1992), or Gastaldo & Degges (2007).

5.2. Cathodoluminescence, petrography, and silicification

The aim of petrographic and cathodoluminescence analyses was to understand the actual silicification pathway of petrified trunks because this multiphase and complicated process has still remained puzzling (viz 5.3. below). We proved high crystallinity of the SiO_2 in the stems by XRD, pure α-quartz can be an inevitable consequence of aging the metastable forms (see Moxon 2002). Sometimes quartz was accompanied by minor allochthonous admixtures, also visualized by CL (Fig. 9C). No other phases of SiO_2, such as opal-A, opal-CT, or moganite (e.g. Březinová et al. 1994; Witke et al. 2004), were found. Similar conclusions were reached by Matysová et al. (2008).

CL imaging and CL spectroscopy revealed more generations of SiO_2 by contrasting structures of reddish and blue shades, and occasionally yellow shades of CL (viz 4.3.2.). The preserved plant tissues (the 1st generation of quartz) have usually a dark red (620-650 nm) or stable blue CL (Figs. 10F, 12A, 13B; Table 2). The second or further generations, showing transient blue (~450 nm) and yellow CL (~580 nm; see Fig. 12B), are mainly present in cracks and fissures in the silica mass. Interestingly, in specimens from Krkonoše Piedmont Basin the short-lived blue CL was less common than in ISB, and yellow was absent (Matysová et al. 2008). These short-lived blue CL and especially yellow CL shades point most probably to hydrothermal SiO_2 (Götze 2000; Götze et al. 2001a, b; Boggs & Krinsley 2006). Götze et al. (1999) detected the yellow CL emission predominantly in agates and hydrothermal vein quartz with high contents of oxygen vacancies (E' centres) and Si-substituting elements, and also in Permian silicified wood from Chemnitz, Germany (Götze et al. 2001a, b; Witke et al. 2004). It could be explained by increased temperatures due to burial or tectonic dislocations in the basin that caused first mechanical ruptures and fragmentation and then healing the cracks by the second generation of quartz (Fig. 10C).

CL can help to distinguish alluvial and volcanic environment of silicification, because the latter produced more plentiful mineral phases with more intense luminescence, which is obvious in comparison of our current and already published results (Matysová et al. 2008), and with results published by

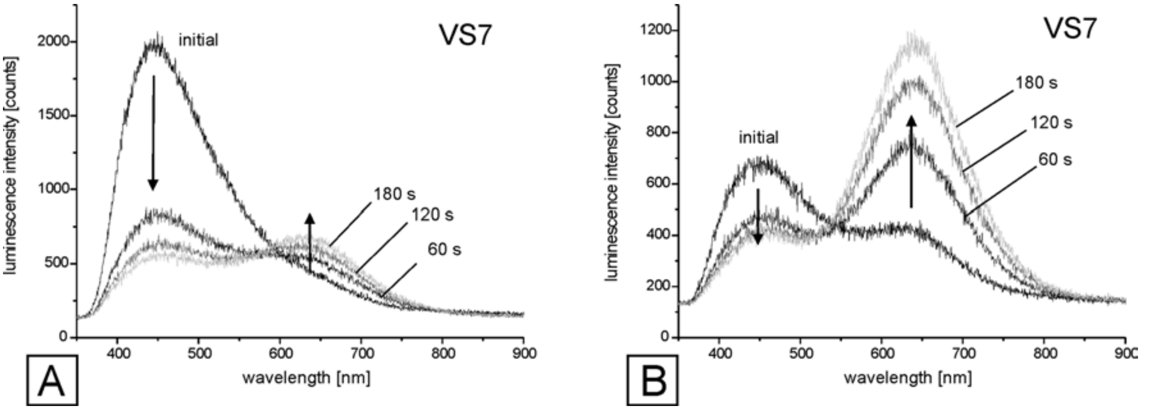

Fig. 13. CL spectra of sample VS7. Stable blue CL (A), short-lived blue CL passing into stable red much faster than stable blue (B). Numerical CL spectral data in Table 2.

Götze & Rössler (2000), Götze et al. (2001 b), and Witke et al. (2004). Besides, fossil plants from volcanic strata are in most cases much better preserved including tiny anatomical details than those from alluvia. Even if the mechanism of the silicification process was studied a lot in the past (e.g., Landmesser 1994, 1995; Weibel 1996; Landmesser 1999), we still cannot say whether quartz crystals in wood were formed straight from solution of H_4SiO_4 or through various hydrated SiO_2 phases (Opal-A, Opal-CT, moganite etc.) because those were not detected in our samples.

CL and XPL revealed that silicification must have proceeded through tracheids because the specific distinct CL patterns/generations of SiO_2 (Fig. 9F, 10F) reflect the only permeable route how silicic species could pass through the wood with partly silicified cellular walls. They passed via tracheids, and the pits, which joined them, also took part in the transport. Furthermore, XPL pictures domains of equally oriented crystals (Fig. 11) which also support this hypothesis.

CL and PPL can also visualize parts in wood with different preservation of organic matter: so called bleaching due to locally increased organic matter consumption by fungi (e.g., Diéguez & López-Gómez 2005) under simultaneous action of repeating changes of water table produced alterations of oxidative and reductive conditions. The resulting different physico-chemical conditions likely caused different quartz structural defects and hence different shades of CL.

Because the *Dadoxylon* type of wood has quite uniform and simple structure (Noll et al. 2005, Schweingruber et al. 2006) it might have influenced the specific way of arrangement of quartz crystals within the stem. Abundance of hyperblastic "megaquartz" so typical of secondary overprint (Fig. 9E, 10B) is followed by tiny "microquartz", which appears in very well preserved tracheids as subordinated to former uniform anatomy of secondary xylem. It can also be seen in common recrystallized parts. Such petrographical patterns, very often reflecting a high level of recrystallization, are very similar to those published by Skoček (1970), Weibel (1996), and Matysová et al. (2008).

Material from ISB is mostly pigmented by ferrous oxides that are dispersed through the stems irregularly and thanks to that, some of tiny anatomical details were preserved/visible (pits, tracheids). Weathering of arkoses is supposed to be the source of Fe_xO_y, the important pigment. The presence of Fe oxides (instead of sulfides) clearly indicates the resulting oxidation conditions during the final stage of wood silicification.

5.3. Silicification process and paleoenvironmental interpretation

Already in 1970, Skoček discussed a possible palaeoenvironmental aspect of the formation of silicified wood (Skoček 1970). In the Central and Western Bohemian basins he noticed its presence in the boundaries between the formations and attributed it to periods of unstable humidity conditions, namely aridization of climate (Skoček, pers. comm.). Certainly, at least seasonal humidity was required to the growth of large trees. On the other hand, seasonally arid climate prevented stems from fast rot and total decay of organic matter and simultaneously provided ground water supplying silicic acid. Fluctuating water table was supposed as a prerequisite to wood silicification in alluvial formations also by Weibel (1996), Parrish & Falcon-Lang (2007) and Wagner & Mayoral (2007). Climate instability during Pennsylvanian and earliest Permian times was attributed to instability (glacials/interglacials) of the South Gondwana ice sheet (Scheffler et al. 2006). These South Gondwanian deglacial cycles were correlated to global climatic cycles in equatorial Pangaea (Izart et al. 2003; Roscher & Schneider 2005; Schneider et al. 2006). On shorter time scales, Milankovitch-like climate cycles were also acting during extensive Gondwanian glaciation.

Before any palaeoenvironmental interpretation of the occurrences of silicified wood in basinal sediments can be provided, it is necessary to distinguish two main modes of silicification. The first one, silicification after a volcanic material fall out (tephra burial) – Chemnitz, Germany (Rössler 2006), or silicification obviously closely influenced by volcanism – Balka, Czech Republic (Pešek et al. 2001) – mirrors the palaeoenvironment by almost completely preserved plant morphotaxa, often preserved in an excellent way. Such silicified assemblages can represent a nearly complete fossilized biome, usually including numerous hygrophilous elements as if the simultaneous presence of lakes was essential for silicification (Wagner & Mayoral 2007). In the second mode, there is riparian or upland vegetation preserved in river alluvia, usually containing chemically unweathered minerals, such as feldspars and dark minerals. Among others, subsequent weathering of these minerals in seasonally arid environment is supposed to produce silicic acid to successive permineralization (Skoček 1970; Matysová 2006; Matysová et al. 2008). Such deposits were studied in this work, and similar deposits were also found in the stratigraphic equivalent positions in other Czech basins (Fig. 2) and in the Early Autunian Nová Paka Sandstone of the Vrchlabí Formation (Pešek et al. 2001; Matysová 2006; Matysová et al. 2008) and other localities as Kyffhäuser in Germany (Rössler 2002). Furthermore, allochthonous trunks from alluvia possess complicated taphonomy because they surely underwent transport to various extent during which they were often damaged to a certain degree (decortication, fragmentation etc.).

The alluvial occurrence of redeposited trees producing araucarites in the Czech Massif was reported in three to four stratigraphic levels (Fig. 2), that can be correlated with four intraglacial/glacial cycles recorded in S Gondwana (Scheffler et al. 2006). Silicified wood from the Petrovice Member (Bolsovian) was mentioned only in one reference (Tásler et al. 1979). The other three stratigraphic levels with silicified wood are confirmed by more references, museum collections and by our own fieldwork. The absence of regular growth rings in *Dadoxylon* wood of the Barruelian age is worth mentioning. Between the second silicified-wood-bearing strata in the Barruelian (reported in this work) and the third one (Stephanian C) there was a mid-Stephanian B humidity period (Pešek et al. 2001; Opluštil & Cleal 2007). During that humid period a large lake was formed across all basins in the Bohemian Massif with a very rich flora in its watershed and chiefly kaolinite-quartz siliciclastic sediment – components indicating very intense chemical weathering (Holub et al. 1975; Lojka et al., submitted). This climate alteration clearly proves a palaeoenvironmental significance of *Dadoxylon* type of wood preserved in alluvia of unstable rivers as indicators of seasonally arid climate supposed for Barruelian. Unfortunately, any detailed palaeoenvironmental analysis has not yet been undertaken in the studied area. Concerning the presence of growth rings, Brison et al. (2001) concluded that even in Mesozoic it could also be taxonomically controlled. The authors instigate not to make conclusions from anatomical features alone because it might be in some cases false and misleading; in other words they claim that some taxa cannot make any growth rings even if they grew in highly seasonal climates. Therefore, the lack of clear indications of growth rings in the Upper Carboniferous *Dadoxylon* wood could not necessarily mean a lack of seasonality. The similar explanation was also given by Falcon-Lang & Scott (2000). Their work deals with cordaites found as permineralizations or charcoals in the Westphalian of Nova Scotia, Canada and England. Their studied material also lacked regular growth rings even if trees were supposed to grow in seasonal climates (proved by calcrete fragments in channel units etc.); it follows that cordaites had to possess wood with a low sensitivity to climatic seasonality. Moreover, we either agree with the fact that cordaite logs being found in fluvial sandstone units and such trees might grow in so called streamside niches where local environmental anomalies could sometimes exist as irregular drought periods, which might be recorded on anatomical level as “false” growth rings.

6. Conclusions

Silicified wood is still very common in the Late Pennsylvanian of the Hawk Mts. (Intra Sudetic Basin, Czech Republic), although many localities were destroyed or damaged. Trunks or their remains can be attributed systematically, they indicate seasonally arid climate because crystal lattice of quartz reflects specific environmental conditions, and should be considered by geologists and palaeontologists as an important stratigraphic indicator. The trunks are purely allochthonous, embedded in fluvial arkosic sediments, preserved in their original position of sedimentation, in outcrops mostly weathered, decorticated. Nowadays, it is not very easy to find such stems; we discovered only 14 pieces. In addition to these stems there is a big amount of stems or fragments dispersed in the landscape or even pieces stored in gardens, monuments, museums etc. From several hundred stems we selected several tens of well preserved specimens to make thin sections for systematic assignment, but tissue structures suitable for correct determination were found only on seven specimens.

Even if absolute majority of stems are very poorly preserved due to recrystallization of α-quartz, our detailed study proved that there is only one type of homoxylic wood in the study area – *Dadoxylon* sp. On several specimens we found microscopical bordered pits in radial tracheid walls typical of cordaites. Furthermore, one trunk presents the *Artisia*-like pith, the other has branching rather typical of cordaites. Other suitable features were not preserved. All stems are without bark, roots, small branches or any other parts or plant organs that might be found in the same stratigraphic level.

The allochthonous logs were embedded in fluvial deposits crosswise or perpendicularly to the river streams and in coarse-grained parts of the deposits. Therefore, the stems were transported and embedded only during increased level of rivers or during extreme floods. A quite long and high-powered transport damaged and split the stems, other parts of plant bodies or less resistant plants were destroyed. The river system into which the logs were deposited can be interpreted as an intermediate type between braided and meandering.

Detailed petrographical analysis revealed variable permineralization in the former plant tissue, particularly thanks to strong recrystallizations (almost no organic remains left). Cathodoluminescence microscopy and spectroscopy exposed a multiphase process of silicification and distinct defects in the structure of silica crystal lattice. Hydrothermal quartz in veins proved an important influence of higher temperatures after burial or difficult genesis of wood due to tectonic activity in the Intra Sudetic Basin. Those processes as well as complicated taphonomy of the wood were not favourable to wood preservation thanks to which the wood is difficult to assign to particular species. Finally, the specific silicification of the wood in alluvial formation was possible thanks to a fluctuating water table caused by a seasonally arid climate. This generally agrees with a dry climate phase supposed for this time span (Barruelian).

Acknowledgements

We are thankful to V. Prouza, K. Martínek, and V. Skoček (Czech Geological Survey, Prague) for help in field works, V. Gryc (Mendel University of Agriculture and Forestry in Brno) for special microscopy hours and statistical data proceeding, R. Rössler (Museum für Naturkunde, Chemnitz) for palaeobotanic professional advise, J. Pešek and S. Opluštil (Charles University, Prague) for fruitful discussions on palaeoenvironment. We would like to acknowledge particularly J. Leichmann (Masaryk University, Brno) and J. Götze (TU Bergakademie Freiberg) for cathodoluminescence microscopy and spectral analysis, respectively. T. Grygar (Institute of Inorganic Chemistry, ASCR, Řež) deserves our thanks for the evaluation of the data from analytical methods (CL spectra and XRD processing) and for the help with the manuscript finishing. Our last thanks belong to both referees, H. Falcon-Lang and R. Rössler whose critical comments helped to improve the manuscript. The present research was possible thanks to the financial support of the following grants: KJB301110704, IAA300460510, and MSM0021620855.

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Manuscript received: July 3rd, 2008.
Revised version accepted by the Stuttgart editor: October 20th, 2008.

Addresses of the authors:

VÁCLAV MENCL, Institute of Geology and Palaeontology, Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic & Municipal Museum Nová Paka, Treasury of Gem stones, F. F. Procházky 70, 509 01 Nová Paka, Czech Republic;
e-mail: vaclavmencl@seznam.cz

PETRA MATYSOVÁ (corresponding author), Institute of Geology and Palaeontology, Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic & Department of Geochemistry, Institute of Rock Structure and Mechanics, ASCR, v.v.i., V Holěsovičkách 41, 182 09 Prague 8, Czech Republic;
e-mail: pmatysova@email.cz

JAKUB SAKALA, Institute of Geology and Palaeontology, Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic;
e-mail: rade@natur.cuni.cz