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DOI: 10.2478/fbgp-2022-0006

CONSTRUCTION OF THE METRO LINE D IN PRAHA-PANKRÁC: AN INTRODUCTORY REPORT ABOUT A UNIQUE OPPORTUNITY FOR STUDY OF THE UPPER ORDOVICIAN FOSSIL ASSEMBLAGES AND SEDIMENTS IN THE PRAGUE BASIN (CZECH REPUBLIC)

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Abstract: *The construction of the new metro line D in Praha-Pankrác provides a unique opportunity to study different aspects such as lithology, stratigraphy and fossil assemblages from the Upper Ordovician and Silurian of the Prague Basin. Results from the sections in tunnels mined so far allowed detailed information about the succession of fossil assemblages, facies variability and actual thicknesses of the upper part of the Bohdalec Formation, the Králův Dvůr and Kosov formations in this part of Prague Basin. The stratigraphic position of Michle Facies in the Bohdalec Formation was also indicated.*

Key words: Upper Ordovician, Bohdalec Formation, Králův Dvůr Formation, Kosov Formation, fossil assemblages, lithology, Michle Facies

INTRODUCTION

A construction of fourth metro (subway) line has been planned in Prague for three decades. The current network of the Prague metro with the total operational length of 65.2 km has three lines labelled A, B and C, mostly operating in tunnels tens of metres below the surface and connecting 61 stations. A course for the new metro line D has been delimited in the Master Plan for the city of Prague since the 1990s that connects a southern suburb and the downtown. Since 2010 the building companies that won the public tender have started preparational stages for the construction of new stations. At the same time, the companies started detailed geotechnical explorations such as borehole drillings, dynamic penetration tests, and sampling and laboratory analyses of rock samples.

The tunnels and stations of the metro line D are constructed through mechanical digging. Thus, the construction has provided a unique opportunity to acquire palaeontological, sedimentological and geochemical datasets from several hundred metres long, continuous and unweathered sections penetrating throughout the Upper Ordovician and Silurian rocks. These units are only rarely accessible on the territory of Prague that is densely built-up and if exposed the surface outcrops have been weathered in some degrees.

RESEARCH OBJECT, GEOLOGICAL SETTINGS, AND TECHNOLOGICAL ASPECTS

The first constructed segment of the metro line D will connect the Depo Písnice and Náměstí Míru. It will be 10.6 km long and comprise 10 stations (Figure 1). The construction of this line segment is divided into two stages: first is from Pankrác to

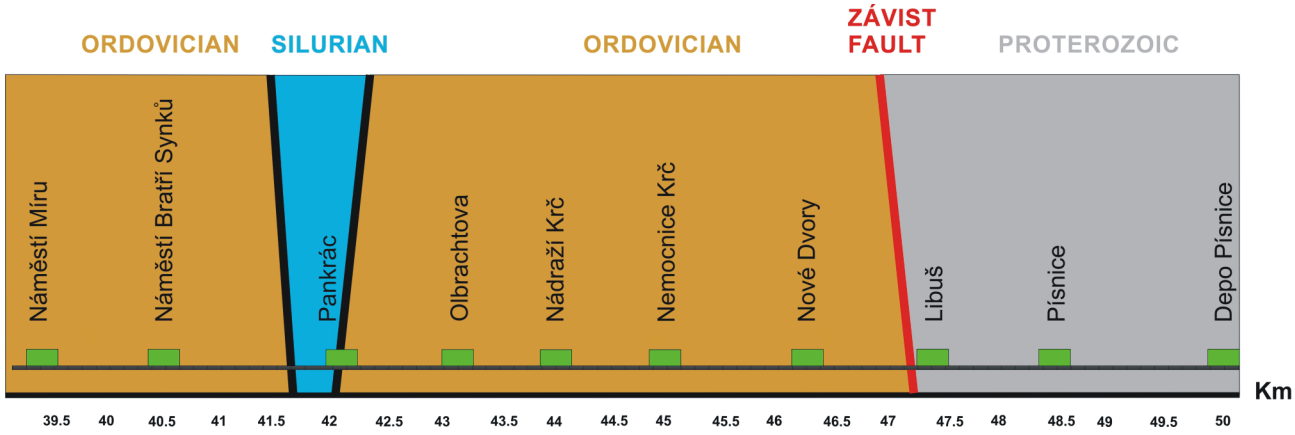


Figure 1. *Schematic longitudinal section along the metro line D with simplified geological section. Modified after Kubát (2019).*

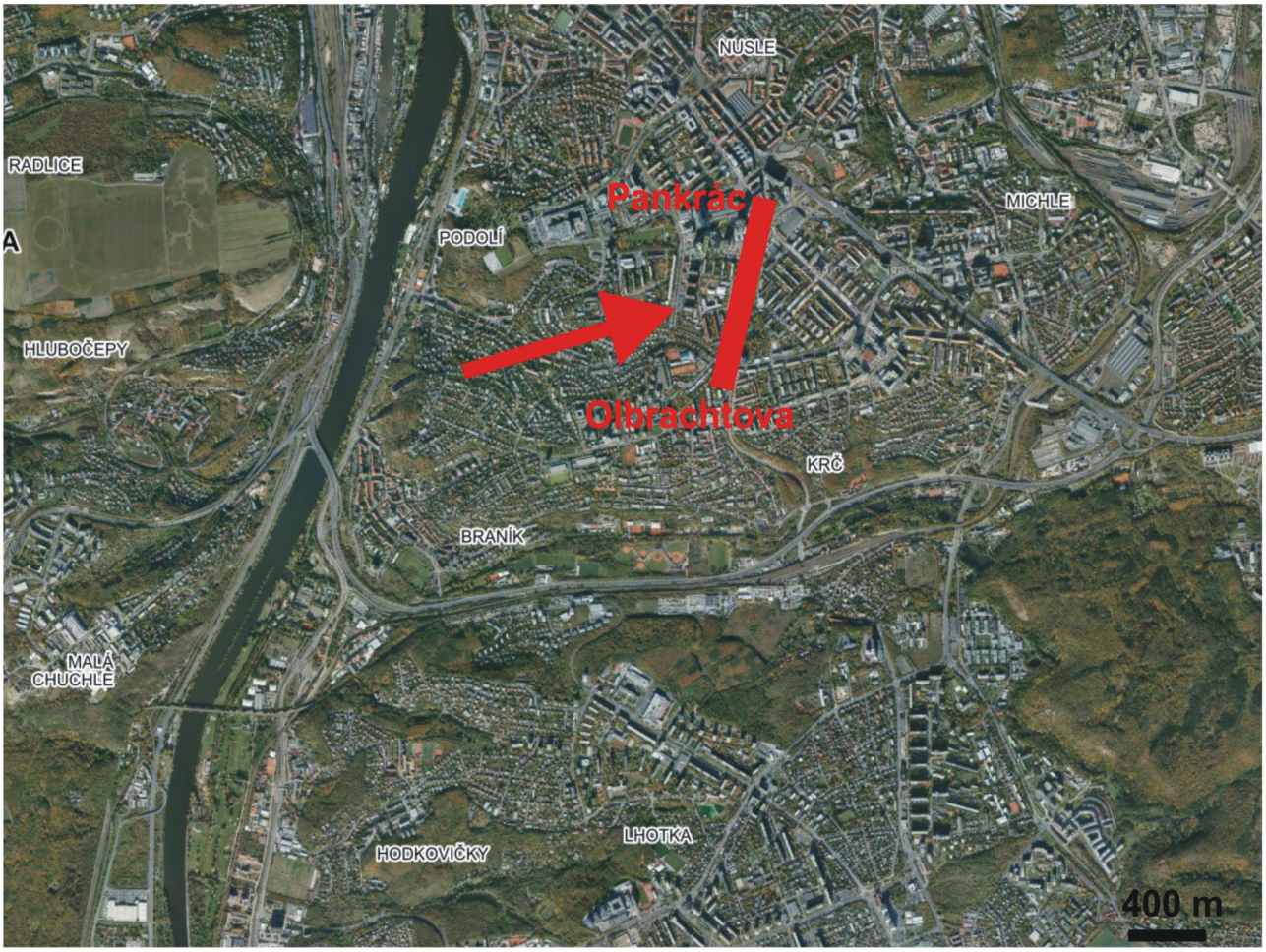


Figure 2. *Orthophotomap of the southern central part of Prague (www.mapy.cz) with the marked location of the studied tunnels between Pankrác and Olbrachtova stations.*



Plate I. 1 – The Olbrachtova tunnel showing the profile in the point where a double-track tunnel splits into two single-track tunnels. The Michle Facies of the Bohdalec Formation is exposed in the temporary face behind the excavator. 2 – Dumps of the mined material at Praha-Pankrác near VO-OL, the main source of the studied rocks. 3 – The Kosov Formation exposed in the tunnel face near the Pankrác station; the section illustrates thin bedded sandstones alternated with siltstones and shales. 4 – A temporary face of the Pankrác tunnel with dark shales of the Bohdalec Formation. 5 – The bedding plane of the Bohdalec Formation showing characteristic bivalve accumulation in the Michle Facies. 6 – The bedding plane of the Bohdalec Formation showing typical accumulation of disarticulated trilobites, disintegrated bivalve valves, crinoids and bryozoans in the dark shale.

Depo Písnice stations, second covers the connection of Pankrác and Náměstí Míru stations in the opposite direction from Pankrác. The first stage started in the summer of 2019 with a detailed geological exploration and subsequently, excavations of shafts and mining of tunnels. It was expected that the first subsegment between Pankrác and Olbrachtova stations (Figure 2) would be constructed in 7.5 years. At the beginning of 2023, one of the tunnels between those stations is still under

construction. It also includes various accompanying constructions such as excavation of ventilation shafts, connecting tunnels, the Olbrachtova station itself and the pedestrian tunnels connecting C and D lines at Pankrác. Conventional mining methods (Plate I, fig. 1) have been used for all excavations and mining, with grouting from temporary faces used to strengthen the walls of the tunnels and subsequent digging with excavators. For next subsegment, from Olbrachtova to Nové Dvory stations, the same technology is planned but from Nové Dvory to Depo Písnice use of a tunnel boring machine (TBM), that completely crushes the rock to small pieces and immediately covers the walls, is proposed. Consequently, the different mining methods used will provide different possibilities for study, and thus influence the geological and palaeontological knowledge of the segments of the D line of Prague metro. In addition, the entire line will go under the surface but with exception of the Nádraží Krč station.

Volumes of the rocks excavated from the stations and available for study will be different. The Pankrác is designed as a spacious, one-vault, transfer station. In contrast, Olbrachtova station will have one of the smallest passenger turnovers on the line, so it will be a space-saving two-vault station (Krása & Martínek 2019).

The tunnels of the D line cross various stratigraphical units and lithologies. The oldest rocks will be excavated in the southern part of the line between Depo Písnice and Nové Dvory stations (Figure 1). This area is formed by slightly metamorphosed, fine-grained shales, siltstones and greywackes of the Štěchovice Group belonging to the uppermost Neoproterozoic – lowermost Cambrian of the Teplá-Barrandian unit (Hajná *et al.* 2010, 2017). Between the Libuš and Nové Dvory stations, the route crosses the Závist Fault, along which the Neoproterozoic succession was thrusted over the Ordovician sediments. The Ordovician section started from the Šárka Formation (Darriwilian) on its tectonic base and ranges up to the Kosov Formation (Hirnantian). The youngest rocks belonging to the lower and upper Silurian (ranging from upper Llandovery to Přídolí) occur near the Pankrác station in the axis of the fill of the Prague Basin deformed to the syncline structure (Vacek & Žák 2017).

The authors of this contribution have made a rescue research in the subsegment between Pankrác and Olbrachtova stations from the beginning. As the geological exploration, intensive excavation, and mining took place in several locations at the same time frequency of research activities and site visits were limited. Therefore, our palaeontological and stratigraphical research focused mainly on the Ordovician units of Bohdalec, Králův Dvůr and Kosov formations. The former is very rich in fossils throughout the section and was the main object of our research. The Králův Dvůr Formation was studied less intensively because of its much sparser fossil content. The Kosov Formation was sampled only occasionally. Petrographic features and sedimentary structures have only been studied in the Bohdalec Formation so far.

Our research was focused on various sources of material and data from several sites. We studied drill cores from vertical boreholes and horizontal boreholes drilled from tunnel faces. The largest amount of the studied sediments, however, come from a temporary dump of excavated material, stored there before its transport to landfill, near Krčský hřbitov, where is situated a technical shaft VO-OL (Plate I, fig. 2). The tunnels have been mined into two directions from it: toward the Pankrác (we label it as Pankrác tunnel) and Olbrachtova (Olbrachtova tunnel) stations. The former tunnel has been mined in the Bohdalec, Králův Dvůr, Kosov (all Ordovician), Litohlavy and Motol formations (both Silurian). The longest continual section which we have documented was over 320 m long (as of December 2022) in the Pankrác tunnel. The rock material excavated from the tunnel was studied at the temporary dump. We had also available a drill core from the horizontal, 90 m long borehole drilled before mining the tunnels in volcanites and graptolite shales of Llandoverian and early Wenlockian age. In the Olbrachtova tunnel mined in opposite direction towards the older sediments of Bohdalec Formations we have investigated 280 m (December 2022) of shales and sandstones. In total almost 700 m of sections in the tunnels were measured.

Bohdalec Formation

The Bohdalec Formation (middle Katian) was defined by Bouček (1928) with the type locality at the northern slope of Bohdalec Hill in Prague (Figure 3). There are not many sections of this



Figure 3. *Sketch map of Prague with localities of the Michle Facies.*

formation exposed today, research over the last decades was made mainly in temporary exposures of construction sites (Röhlich & Chlupáč 1952, Röhlich 1957, Budil & Kraft 2003, Röhlich *et al.* 2008, 2009, 2014, David & Novotný 2017, Bruthansová 2019).

Havlíček (1998) supposed that the Prague Basin was intensively affected by synsedimentary tectonics during the Sandbian and Katian. It resulted to the uplift of two parallel elevations divided from each other by a narrow, maximum 2 km wide, central depression. He also supposed that another narrow elevation zone developed along the Prague Fault. In his model these tectonic movements also influenced the thickness of the Bohdalec Formation ranging from 20 m up to 550 m in the central depression. The sedimentation of black-grey silty shales is characteristic of the Bohdalec Formation but its base is indicated by the Karlík Iron Ore Horizon that is locally replaced by shales with oolitic and carbonate admixture (Havlíček 1998). The silty shales often contain disseminated pyrite, which indicates a poorly oxygenated environment (Havlíček 1998). Although typical and prevailing these dark silty shales are not only the facies forming the Bohdalec Formation. Röhlich (2006) summarized knowledge about several typical stratigraphic levels typified by lithology or fossil content. Lower part of the formation is composed of grey and grey-black shales with typical trilobite *Declivolithus alfredi* (Želízko, 1906). These shales are overlain in the area between Praha-Řeporyje and Praha-Běchovice (Figure 3) by the *Polyteichus* Facies (Bouček 1928) differentiated by lithology and fossil composition. It is typified by a coarser sedimentation of sandstones and greywackes alternated with silty shales often with carbonate admixture. They contain a distictive fauna composed mainly of bryozoans, crinoids and large brachiopods (Bouček 1928, Röhlich 2006 and others). As the index bryozoan *Polyteichus novaki* (Perner, 1900) seems to be abundant only in a part of this informal unit and occurs sporadically in its main portion, Röhlich (2006) suggested to replace the name '*Polyteichus* Facies' by a descriptive term 'silty-sandy facies' or informal designation as the 'Michle Facies' with '*Polyteichus Horizon*' inside. The stratigraphic position of the Michle Facies within the Bohdalec Formation has been discussed in the past. Some authors placed it in the lower part of the formation (Havlíček 1982). However, it seems more likely that it occurs in the upper part of the formation (Röhlich 2006). Above the Michle Facies dark grey silty shales, similar to those below the Michle Facies, form the top of the formation and contain characteristic fossil assemblage with trilobite *Onnia superba* (Bancroft, 1929); see David & Novotný (2017). The exact thicknesses of the Michle Facies and the overlying shales are unknown even though thin layer of silty limestone and calcareous shale, probably belonging to the Michle Facies, was recorded about 12 m below the base of the ovelying Králův Dvůr Formation at the Reiserova cihelna Praha-Řeporyje (Röhlich 2006, fig. 3). Havlíček (1982) supposed that the erosion of the underlying Zahořany Formation in two elevation zones inside the basin, south of Praha-Michle (Figure 3) and along the Prague Fault, was a source of clastic material of the Michle Facies. He also assumed a total thickness of the formation reaching up to 500 m in the area south of Praha-Bohdalec (Figure 3). Havlíček's (1982) main argument for this interpretation was the absence of the *Polyteichus* (= Michle) Facies along the margins of the Prague Basin. Röhlich (2006) explained the Michle Facies as a response of a local shallowing that is documented in this area also from the Llandovery (Štorch 1986).

Králův Dvůr Formation

The slope above the former cement factory at Králův Dvůr is the type locality for the Králův Dvůr Formation (Katian) established by Lipold & Krejčí (1860). Thickness of the formation reaches 50–60 m (Havlíček 1984). On the territory of Prague, there is only one complete section of this formation exposed in Velká Chuchle (Chlupáč 1951a). Another complete section was described from Karlík situated 20 km south-west of Prague (Chlupáč 1951b). The most fossiliferous upper part of the formation was studied in several localities such as Liteň, Zadní Třebáň (Chlupáč 1953) and Levín (Vaněk & Vokáč 1997). Comprehensive information about the sections of the Králův Dvůr Formation was summarized by Štorch & Mergl (1989).

The section of siliceous grey and greyish-green siltstone is clearly different from sediments of the Bohdalec Formation. Podolí Ore Horizon, with sideritic siltstones and ooids, is found at the base of the Králův Dvůr Formation (Röhlich 1957). Low diversity fossil assemblages representing faunas that inhabited relatively deep-water environments are typical for this unit although some stratigraphical levels and localities in the Prague Basin yielded richer fossil content. In the upper part of Králův Dvůr Formation, a monotonous assemblage reflecting the global cooling with predominating trilobite *Mucronaspis grandis* (Barrande, 1852) and significantly reduced or missing sessile benthos was found in the green silty shales. Havlíček & Vaněk (1966) established three horizons in the Králův Dvůr Formation based on successive occurrences of trinucleoid trilobites (from low to high): *Nankinolithus granulatus* (Wahlenberg, 1818), *Tretaspis seticornis seticornis* (Hisinger, 1840), *Marekolithus kosoviensis* (Marek, 1952). The former two species, however, occur only locally and their occurrences are rather controlled by palaeoecological responses to the environmental conditions (David & Novotný 2017). The graptolite biostratigraphy and ranges of graptoloids has recently been revised by Kraft *et al.* (2015). However, graptolites are generally infrequent, only locally abundant and often completely absent at localities of the Králův Dvůr Formation (David & Novotný 2017).

Kosov Formation

Sedimentation of the Kosov Formation reflects global climatic changes and the world-wide glaciation that caused a prominent sea level drop. The base of the formation is marked by a thin layer of diamictite sharply overlying shales of the Králův Dvůr Formation. This glaciomarine sediment is overlain by 1–4 m thick silty to sandy shales, and subsequently a thicker layer of diamictite with dropstones (Brenchley & Štorch 1989, Havlíček 1998). The Kosov Formation is barren across almost the entire section but ichnofossils are very common and diversified throughout the formation. Body fossils occur sporadically in two levels in its upper part, as documented in some localities such as Běchovice and Pankrác. The lower association typified by the bivalve *Modiolopsis* was recorded in sandstones. Strongly bioturbated mudstones from the uppermost part of the formation yielded brachiopod dominated *Hirnantia* fauna together with the index graptolite *Normalograptus persculptus* (Elles & Wood, 1907) (see Štorch 1990).

Kříž (1984) recorded a basalt sill intrusion between the top of the Ordovician and the base of the Silurian. The younger basalt volcanites intruded also to the Bohdalec Formation as documented by Havlíček (1988) in Řeporyje.

BOHDALEC FORMATION BETWEEN OLBRACHTOVA AND PANKRÁC STATIONS

In the text below, the distances in tunnels are related to the main shaft VO-OL in Na Strži Street, located 150 m north of the Krčský Hřbitov. From this shaft, tunnels were mined to opposite directions: northward to the constructed Pankrác (Pankrác tunnel) and southward to the Olbrachtova stations (Olbrachtova tunnel). The shaft is of a circular outline, 36.6 m deep and 21 m in diameter. To indicate directions from the shaft the measurements in the tunnel towards Olbrachtova are negative values and towards Pankrác station are positive values. Zero in each tunnel is set to its opening to the shaft; it means that both starting points are 21 m apart from each other (*i.e.* ~10 m of the actual thickness).

During our research (in this study until December 2022), we have gradually studied excavated

rocks from –270 m (Olbrachtova tunnel) to +320 m (Pankrác tunnel). The study was extended by a 90 m long horizontal borehole drilled from the tunnel face throughout the succession that will be mined during the construction of the Pankrác station (Figure 2) in the future. During the tunnel mining, geologists from companies documented the faces in metre distances and measured strikes and dips of bedding planes. These data were used for calculation of the actual thicknesses of the studied units.

The succession in both tunnels has a general stratigraphical orientation from the lowermost layers in Olbrachtova station and the uppermost part in the Pankrác station (Figure 2). This succession is tectonised and apparently not complete, and repetition of some parts cannot be excluded.

The actual thickness of the part of the Bohdalec Formation excavated thus far is slightly less than 140 m. In the Olbrachtova tunnel, entirely mined in the Bohdalec Formation almost parallel with bedding planes, the actual thickness is only 51 m. The actual thickness in the shaft with its diameter of 21 m was calculated to represent ~10 m. Part of the Pankrác tunnel mined in the Bohdalec Formation (0 m to +115 m) recorded 76 m of the actual thickness.

The studied section represents the upper portion of the Bohdalec Formation formed by the Michle Facies (Röhlich 2006, known also as *Polyteichus* Facies, Bouček 1928, see above) in its lower part as indicated by fossil assemblages and lithology typified by alternation of calcareous siltstone to sandstone layers, few to tens centimetres in thickness, and thin shaly interbeds. The Michle Facies was confined to the section in the Olbrachtova tunnel. It is overlain by dark shales and silty shales (Plate I, fig. 4) forming the remaining part of the formation, recorded over a short distance in the Olbrachtova tunnel and the entire Pankrác tunnel.

In general, the shales are often tectonically affected and deformed as they are more ductile and represent one of the most deformable materials in the Prague Basin. This played an important role during folding of its lithologically variable Ordovician to Middle Devonian fill. Thus, common faulting and occasional small flat folds are frequent in the tunnel sections.

It was inferred that more than 85% of the studied section of the Bohdalec Formation comprises monotonous grey to black silty shales (Plate I, fig. 4). The remaining 15% is composed of sandstone beds from 0.1 to 1 m thick (mostly a few decimetres thick). They extend at least tens of metres laterally but probably much more (estimated from the documentation of tunnel faces). Sandstone beds are sandwiched between the shales as interbeds of thicknesses ranging from a few decimetres to a maximum of about 1.5 m. Packages of 3 to 7 sandstone beds in shale commonly occur in monotonous shales.

Shales are dominantly formed by parallelly aligned phyllosilicates (muscovite, illite, chlorite, kaolinite) with silt admixture composed mainly of quartz but also a few percent of plagioclase and K-spar (data based on element mapping on SEM and XRD). A few percent is commonly represented by dolomite (Kocourek 2020). Micropyrite as well as framboidal pyrite are also common. The sandstones have considerable carbonate admixture.

The horizontal lamination is most common in shales. In sandstones, ripples (both straight ripples and linguoid ripples), planar bedding and flute casts are frequently observed. At the transition between sandstones and silty shales flaser and wavy bedding occurs. Soft sediment deformation structures such as flame structures are very common at sandstone/shale transition.

It is worth noting features of the occurrence pattern of trinucleoid species *Onnia superba* (Bancroft, 1929), which is one of the most abundant trilobites of the Bohdalec Formation. It is quite common in the shaly facies and occurs in large quantities in some layers and on some bedding planes. The specimens are mainly disarticulated in these mass occurrences but complete specimens, holaspid and also meraspid stages, can be rarely found in the accumulations and more often dispersed in the layers (*cf.* Bruthansová 2019). This species is supposed to be confined to specific life conditions because it is nearly absent in the shallow-water Michle Facies. In contrast, trilobites such as the very abundant *Phacopidina quadrata* (Hawle & Corda, 1847), and *Eudolatites angelini* (Barrande, 1852) have been found throughout the entire section, including the Michle Facies (Plate I, fig. 6). Both species were often found as complete individuals but they were also frequently found disarticulated together with *Onnia* in the dense fossil accumulations. The complete specimens of *Phacopidina* were usually enrolled indicating that they do not represent exuviae.

Among other trilobite species found in the low diversity fossil assemblages of silty shales were *Selenopeltis vultuosa* (Přibyl et Vaněk, 1966), *Chlustinia keyserlingi* (Barrande, 1846), *Flexicalymene pragensis* (Vaněk et Vokáč, 1997), and *Calymenella media* (Barrande, 1852) found mostly disarticulated, only rarely as complete specimens. Cephala and pygidia of *Nobiliasaphus kumatox* (Šnajdr, 1982), *Sokhretia solitaria* (Barrande, 1846), *Chattiaspis oinopion* (Vaněk et Vokáč, 1997), and *Dalmanitina asta* Šnajdr, 1982 were less frequent. Dark shales also yielded other invertebrate fauna such as minute gastropods, bivalves, cephalopods, hyoliths, disarticulated machaeridians, conulariids, and rarely orthid and lingulid brachiopods (including frequent large valves in the uppermost part of the formation near the Podolí Iron Ore Horizon) and graptolites. Fossils occurred as external and internal molds and were completely pyritized at some layers.

Almost all bedding planes and layers display bioturbation, namely *Chondrites* isp. In some cases, minute pyritized tunnels penetrated distinct beds. Nodules of variable shapes and/or sizes were frequently recorded in sediments, usually formed around a shell or trace fossil.

Fossil abundance strongly alternates between almost barren layers with occasional occurrences of disarticulated fossils to large accumulations covering large bedding planes and fossiliferous beds (Plate I, fig. 6). Scattered parts of trilobites, and disarticulated bivalves commonly found in linear accumulations are typical for the latter mode of occurrence. We have recorded several stratigraphic levels (a few metres in the actual thickness) in the Pankrác tunnel with distinctly enriched fossil assemblages, notably with echinoderms, cnidarians, planktic graptolites and sessile dendroid graptolites. Accumulations of columnals or articulated stem parts of crinoids (only a single calyx with arms, partially washed away was found) indicate solid substrate suitable for their attachment, maybe indicating shallowing. Other echinoderms such as *Aristocystites* sp. and *Aristocystites metroi* Parsley et Prokop in Parsley, 1990 are present only in some beds and were apparently a minor component of the community found in silty shales. Cephalopod shells are often found scattered in the shales of the Bohdalec Formations. Large accumulations of straight shells, sometimes oriented parallel to one another by currents, were collected in some levels. Due to their preservation the cephalopods are mostly unidentifiable. Cnidarians represented by conulariid skeletons have been occasionally discovered throughout the section. Specimens of *Sphenothallus* sp. represented by different morphotypes were found only in some layers and commonly in large accumulations. It is worth noting that their basal discs (holdfasts) attached to cephalopod shells occur in layers where their thecae absent. Cephalopod shells also often hosted encrusting bryozoans or colonies of *Conchicolites meskai* Prantl, 1948 in some layers. An occurrence of abundant dendroid graptolites is peculiar and had no analogy in the Bohdalec Formation. They belong to two genera (*Callograptus* and *Desmograptus*) and both produced quite large colonies that were often found complete. In several cases specimens of *Desmograptus* were attached to some fossil remain, probably columnals of the crinoid stems. Graptoloids (planktic graptolites) occur with a very variable abundance. They are sparse or missing on some stratigraphic levels while very common on others. Although their taxonomy is in need of revision it is obvious that their diversity is very low and monospecific or two-species associations completely prevail.

The Michle Facies in the studied section is typified by some beds being almost barren, only with trace fossils, and others with rather poor fossil assemblages and ichnoassemblages with remarkable *Jamesonichnites* isp. typical for of coarser-grained layers. Abundant valves of bivalves form large accumulations covering bedding planes of some layers (Plate I, fig. 5). Large shells of *Rafinesquina pseudoloricata* (Barrande, 1848), trilobites *Phacopidina quadrata* (Hawle et Corda, 1847), *Flexicalymene pragensis* (Vaněk et Vokáč, 1997), *Chlustinia keyserlingi* (Barrande, 1846), *Eudolatites angelini* (Barrande, 1852) and *Calymenella media* (Barrande, 1852) are characteristic of this facies. Sometimes, trilobites are found as complete outstretched or enrolled specimens. The latter case is typical for *P. quadrata*. Although the Michle Facies is typified by occurrences of diverse bryozoans, encrusting or ramose colonies were confined to several beds in the section. Graptolite colonies and conulariid walls are rare.

The Pankrác tunnel cuts the uppermost layers of the Bohdalec Formation. The base of the overlying Králův Dvůr Formation is mostly character-

ized by the presence of the Podolí Iron Ore Horizon (Röhlich 1957). However, we have observed minute ooids dispersed in dark silty shales in the beds 39 m below the base of the Králův Dvůr Formation. The density of the ooids gradually increased. First, scattered ooids occur among fossils and higher in the section they form narrow linear accumulations on bedding planes. The presence of ooids indicates, among other things, a shallowing of the environment. This presumption is supported also by the common presence of dendroid graptolites that require a hard substrate for their attachment, and which are absent in the rest of the Bohdalec Formation. Dendroid graptolites were recorded in the 28 m-thick interval (actual thickness) in the Pankrác tunnel (between +71 and +105 m). Large lingulid shells are also characteristic for the shales with ooids. It is worth noting that the ooids do not occur continually up to the base of the Králův Dvůr Formation where they could be expected to become abruptly denser forming the iron ore horizon but instead they suddenly disappear 19 m higher. They reappear 4 metres below the limit of the Bohdalec and Králův Dvůr formations. Although an oscillation of sea level cannot be excluded a tectonic dislocation seems to be more probable as a cause of this occurrence pattern. An appearance of the aseptate graptolite *Anticostia* cf. *teres* (Perner, 1895) is a stratigraphical marker of the top of the Bohdalec Formation.

KRÁLŮV DVŮR AND KOSOV FORMATIONS IN THE METRO TUNNEL

The Králův Dvůr Formation was excavated in the Pankrác tunnel between +115 and +215 metres with the actual thickness of 84 metres. The Podolí Iron Ore Horizon is developed on the base of the formation. This distinct unit is formed in the studied section by calcareous shales containing abundant ooids, large nodules (30–40 cm in diameter) and dispersed pyrite. Typical facies forming the main part of the formation are silty grey or greenish shales alternating in some layers with harder siltstones containing carbonate admixture. The shale frequently also contains scattered pyrite crystals or pyritized fossils/ichnofossils. In contrast with the Bohdalec Formation, shelly fossils are generally rare throughout the section but they are abundant in some layers. At least three stratigraphic levels with slightly different faunal assemblages can be differentiated in the section (Martin David, personal communication). In the above mentioned fossil-rich levels disarticulated trilobite exoskeletons (and rarely complete specimens of some species) of *Flexicalymene declinata* (Hawle et Corda, 1847), *Amphitryon radians* (Barrande, 1846), *Phillipsinella parabola* (Barrande, 1846), *Zetillaenus wahlenbergianus* (Barrande, 1852), *Octillaenus hisingeri* (Barrande, 1846), *Stenopareia hospes* (Barrande, 1872), *Zdicella zeidleri* (Barrande, 1872), *Alceste latissima* Hawle et Corda, 1847, *Carmon mutilus* (Barrande, 1852), *Actinopeltis carolialexandri* Hawle et Corda, 1847, *A. insocialis* (Barrande, 1852), *Birmanites* sp., *Brongniartella platynota* (Dalman, 1828), *Microparia speciosa* Hawle et Corda, 1847, *Dionide speciosa* (Hawle et Corda, 1847), *Onnia ultima* (Barrande, 1852), *Dindymene* sp., *Selenopeltis vultuosa* Přibyl et Vaněk, 1966, *Duftonia morrisiana* (Barrande, 1852), *Kloucekia ruderalis* (Hawle et Corda, 1847), *Mucronaspis grandis* (Barrande, 1852), and *Mucronaspis* sp. were found. Incomplete or deformed shells of large bellerophontids, conulariid walls, small orthids, minute bivalves, hyolithids, disarticulated echinoderm thecae, tiny crinoid stems and rare graptolites were also found. Ichnofossils are common throughout the section. The findings of small faecal pellets *Tomaculum problematicum* Groom, 1902 forming narrow chain-like accumulations are typical for this formation.

An approximately 15 cm thick layer of green-grey-blue coloured and bioturbated pelocarbonate with frequent nodules was observed in the uppermost part of the Králův Dvůr Formation. Cephalopod shells, disarticulated exoskeletons of the trilobites *Mucronaspis* sp. and *Flexicalymene* sp., and echinoderm thecae of *Echinosphaerites* sp., *Heliocrinites* sp. are common in these sediments.

The basal diamictite of the Kosov Formation was recorded at +215 metres of the Pankrác tunnel. This formation is characterized by alternation of siltstones, sandstones, conglomerates and shales in the studied section (Plate I, fig. 3). The actual thickness of this unit inferred from the section in the tunnel is 69 m with the exceptions in the lower part and at the top. A tectonic interruption in its the lower part is demonstrated by a small tectonic block of the Bohdalec Formation

(about 3 m thick) with characteristic fossil content that was emplaced there. The upper limit of the formation is marked by a basalt sill intrusion. It separated dark grey shales in the top of the Kosov Formation from the green siltstones of the Litohlavy Formation (Llandovery, Silurian).

The Kosov Formation is barren of shelly fossils in most of its thickness, as typical, only various types of ichnofossils can be found. The only fossiliferous sandstone beds were detected in the upper part. One bed contained a monospecific bivalve association composed of mostly disarticulated, but rarely also articulated, shells. Sparse graptolites *Metabolograptus persculptus* (Elles et Wood, 1907), sometimes preserved in relief, were found in another sandstones of exactly unknown stratigraphical position. Among the lithological features, claystone pebbles (supposed clay galls) of various sizes were recorded in the light-yellow sandstone layers.

Based on graptolites, Silurian sedimentation has started in the *Monoclimacis griestoniensis* Biozone, *i.e.* in the middle of the Litohlavy Formation just above the basalt sill. The basal Silurian Želkovice Formation is absent, just as in the entire Pankrác area of the central segment of the Prague Basin (Petr Štorch, personal communication). Calcareous shales with predominant graptolites up to the *Oktavites spiralis* Biozone belonging to the lowermost part of the Motol Formation occur in the continuation of the section in the Pankrác tunnel.

SUMMARY/CONCLUSIONS

In the Pankrác and Olbrachtova tunnels, the actual thicknesses of the Bohdalec, Králův Dvůr and Kosov formations are 135 m, 85 m, and 70 m respectively. Due to tectonic deformation, that affected especially the shales, the actual thicknesses, calculated from strike and dip of layers measured in tunnels, should be taken with caution. The two latter formations are present in their entire thickness in the studied sections in tunnels, only the upper part of the Bohdalec Formation was encountered. This formation was observed in two different lithotypes, as grey-black silty shales with relatively abundant fauna and the Michle Facies with actual thickness of about 40 m. It is comprised of calcareous sandstones, greywackes and siltstones alternating with silty shales. According to our investigations this facies occurs in the upper part of the Bohdalec Formation with upper limit less than 90 m below the base of the Králův Dvůr Formation. Thus, it confirms the observations by Bouček (1928) and Röhlich (2006). Faunal assemblages of the Bohdalec Formation are similar to those documented by Röhlich *et al.* (2014) at Praha-Brumlovka but with a difference of the lower diversity of echinoderms at Praha-Pankrác. Construction of the metro line D and mining of the tunnels in Praha-Pankrác is still in progress. A penetration to the older sediments of the lower part of the Bohdalec Formation and next to the underlying units of Zahořany, Vinice, Letná, Libeň, Dobrotivá and Šárka formations is expected.

ACKNOWLEDGEMENTS

The authors appreciate the helpful support of the employees of the following companies: SG Geotechnika, GeoTec, Hochtief, Strabag and Subterra. They allowed us regular visits to dumps of the mined material and to the tunnel faces, and possibilities to sample boreholes. Namely, we would like to thank (in alphabetical order) Petr Černatovič, Ondřej Jaroš, Roman Kocourek, Radek Kozubík, Nikolaj Kukušhkin, Filip Lednický, Vitalij Mic, Jiří Tlamsa, Pavel Tůma, Jan Zemánek. Private collectors Martin David, Marcela Dvořáková, Radek Labuťa, Jaroslav Šmíd and Ondřej Zicha kindly provided their material for the study. We are also grateful to Martin David for his information about the Králův Dvůr Formation from the material deposited in the landfill in Praha-Letňany, and Petr Černatovič (construction manager) for information about the Kosov Formation. We thank reviewers Michal Mergl (University of West Bohemia) and Lukáš Laibl (Institute of Geology of the Czech Academy of Sciences) for their constructive comments, and Stephen Pates for his kind improvement of English. This work was financially supported by Ministry of Culture of the Czech Republic through the DKRVO 2019–2023/2.IV.e, National Museum, 00023272 (to J.B.), by West Bohemian Museum in Plzeň through projects nos UUP 2018/1 and IGP 2021/01 (to P.K.), and by Charles University, Prague, through the project Cooperatio GEOL (to P.K.). This paper is a contribution to IGCP Project 735, Rocks and the Rise of Ordovician Life: Filling Knowledge Gaps in the Early Palaeozoic Biodiversification.

REFERENCES

Bancroft, B. B. 1929. Some new species of *Cryptolithus* (s.l.) from the Upper Ordovician. *Memoirs Proceedings Manchester Literary and Philosophical Society 73*, 67–98.

Barrande, J. 1846. *Notice préliminaire sur le système silurien et les trilobites de Bohême*. I–VI, 97 pp. Hirschfeld, Leipzig.

Barrande, J. 1848. Über die Brachiopoden der silurischen Schisten von Böhmen. *Naturwissenschaftliche Abhandlungen 2*, 155–256.

Barrande, J. 1852. *Système Silurien du centre de la Bohême: 1ère Partie, Crustacés: Trilobites*. 935 pp. Prague, Paris.

Barrande, J. 1872. *Système Silurien du centre de la Bohême. Vol. I, Suppl. I*. 647 pp. Prague, Paris.

Bouček, B. 1928. O vrstvách zahořanských – dε českého ordoviku. *Rozpravy České Akademie Věd Umění, Tř. II 37*, 33, 1–60.

Brenchley, P. J. & Štorch, P. 1989. Environmental changes in the Hirnantian (upper Ordovician) of the Prague Basin, Czechoslovakia. *Geological Journal 24*, 165–181.

Bruthansová, J. 2019. Předběžná zpráva o studiu ontogeneze a tafonomie trilobita *Onnia superba* (Bancroft, 1929) z českého ordoviku (katian, bohdalecké souvrství). *Geoscience Research Reports 52(2)*, 125–128.

Budil, P. & Kraft, P. 2003. Nová fauna z bohdaleckého souvrství v Praze-Vysočanech. *Zprávy o geologických výzkumech v roce 2002 36*, 119–122.

Chlupáč, I. 1951a. Profil královdvorskými břidlicemi (Ashgillian) u Velké Chuchle. *Věstník Královské české společnosti nauk. Třída mathematicko-přírodovědecká*, 1950, 1–10.

Chlupáč, I. 1951b. Stratigrafické poměry královdvorských břidlic u Karlíka a Zadní Třebáně. *Věstník Ústředního ústavu geologického 26(4)*, 194–212.

Chlupáč, I. 1953. Poznámky ke stratigrafii královdvorských břidlic v okolí Litně. *Časopis Národního muzea, oddíl přírodovědný 122(1)*, 28–33.

Dalman, J. W. 1828. Uppställning och Beskriftning af de i Sverige funne Terebratuliter. *Kunglige Svenska Vetenskapsakkademiens Handlingar 1827*, 85–155.

David, M. & Novotný, F. 2017. Příležitostné naleziště zkamenělin svrchního ordoviku (katianu) severně od Prahy – Dolních Počernic. *Zprávy o geologických výzkumech v roce 2017 50*, 33–37.

Elles, G. L. & Wood, E. M. R. 1907. A monograph of British graptolites. Part 6. *Monograph of the Palaeontological Society 61, 297*, 217–272.

Groom, T. 1902. The sequence of the Cambrian and associated beds of the Malvern Hills. *Quarterly Journal of the Geological Society of London 58*, 89–149.

Hajná, J., Žák, J., & Dörr, W. 2017. Time scales and mechanisms of growth of active margins of Gondwana: a model based on detrital zircon ages from the Neoproterozoic to Cambrian Blovice accretionary complex, Bohemian Massif. *Gondwana Research 42*, 63–83.

Hajná, J., Žák, J., Kachlík, V. & Chadima, M. 2010. Subduction-driven shortening and differential exhumation in a Cadomian accretionary wedge: the Teplá–Barrandian unit, Bohemian Massif. *Precambrian Research 176(1–4)*, 27–45.

Havlíček, V. 1982. Ordovician in Bohemia: development of the Prague Basin and its benthic communities. *Sborník geologických věd, Geologie 37*, 103–136.

Havlíček, V. 1984. *Ordovik*. Vysvětlivky k základní geologické mapě ČSSR 1: 25 000, Praha-sever. Ústřední Ústav geologický, 1–144. Praha.

Havlíček, V. 1988. *Ordovik*. Vysvětlivky k základní geologické mapě ČSSR 1: 25 000, Praha-jih. Ústřední Ústav geologický, 1–144. Praha.

Havlíček, V. 1998. Prague Basin. 39–41. In Chlupáč, I., Havlíček, V., Kříž, J., Kukal, Z. & Štorch, P. (eds) *Palaeozoic of the Barrandian (Cambrian to Devonian)*. Czech Geological Survey, Prague.

Havlíček, V. & Vaněk J. 1966. The biostratigraphy of the Ordovician of Bohemia. *Sborník geologických věd, Paleontologie 8*, 7–69.

Hawle, A. & Corda, I. 1847. *Prodrom einer Monographie der böhmischen Trilobiten*, 176 pp. Praha.

Hisinger, W. 1840. *Lethaea Svecica seu Petrificata Sveciae, iconibus et characteribus illustrata*. Suppl. Secundum, 6 pp., Holmiae.

Kocourek, R. 2020. *Metro I.D-DIGP-HTF. Petrografické rozbory*. MS, Geofond (GF P176559), 1–34.

Kraft, P., Štorch, P. & Mitchell, C.E. 2015. Graptolites of the Králův Dvůr Formation (mid Katian to earliest Hirnantian, Czech Republic. *Bulletin of Geosciences 90(1)*, 195–225.

Krása, D. & Martínek, L. 2019. Trasa D – Kdy se začne stavět čtvrtá linka pražského metra? *Tunel 2*, 4–12.

Kříž, J. 1984. *Silur*. Vysvětlivky k základní geologické mapě ČSSR 1: 25 000, Praha-sever. Ústřední Ústav geologický, 1–144. Praha.

Kubát, A. 2019. Geotechnický průzkum pro trasu metra „D" v úseku Náměstí Míru – Depo Písnice. *Tunel 2*, 13–27.

Lipold, M. V. & Krejčí, J. 1860. Ein Beitrag vorgelegt an der Sitzung am 24. April 1860. *Verhandlungen der Kaiserlich-Königlichen Geologischen Reichsanstalt 11*, 88–91.

Marek, L. 1952. Contribution to the stratigraphy and fauna of the uppermost part of the Králův Dvůr Shales (Ashgillian). *Sborník Ústředního Ústavu geologického 19*, 429–455.

Parsley R. L. 1990. *Aristocystites*, a recumbent diploporid (Echinodermata) from the Middle and Late Ordovician of Bohemia, ČSSR. *Journal of Paleontology 64(2)*, 278–293.

Perner, J. 1895. *Études sur les graptolithes de Bohême. II*^{ieme} *Partie: Monographie des Graptolites de l'Étage D*. 31 pp. Leipzig, Prague.

Perner, J. 1900. Miscellanea silurica Bohemiae. Příspěvek k poznání českého siluru, díl I. *Česká akademie císař Františka Josefa pro vědy, slovesnost a umění v Praze*, 1–16.

Prantl, F. 1948. The genus *Conchicolites* Nicholson, 1872 (Serpulimorpha) in the Ordovician of Bohemia. *Věstník Královské české společnosti nauk, Třída matematicko-přírodovědecká 9*, 1–7.

Přibyl, A. & Vaněk, J. 1966. Neue Trilobiten des böhmischen Ordoviziums. *Věstník Ústředního ústavu geologického 40(4)*, 277–282.

Röhlich, P. 1957. Stratigrafie a vývoj bohdaleckých vrstev středočeského ordoviku. *Sborník Ústředního Ústavu geologického, oddíl geologický 23(2)*, 373–439.

Röhlich, P. 2006. O takzvané polyteichové facii v bohdaleckém souvrství (ordovik, střední Čechy). *Zprávy o geologických výzkumech v roce 2005*, 40–42.

Röhlich, P., Budil, P. & Steinová, M. 2008. Fauna bohdaleckého souvrství z dočasného odkryvu v Praze 4. *Zprávy o geologických výzkumech v roce 2007*, 132–133.

Röhlich, P. & Chlupáč, I. 1952. Svrchní ordovik v býv. Reiserově cihelně u Řeporyj. *Sborník Ústředního ústavu geologického, oddíl geologický 19*, 1–36.

Röhlich, P., David, M., Budil, P. & Polechová, M. 2014. Naleziště zkamenělin v bohdaleckém souvrství (ordovik, stupeň katian) na dočasném odkryvu v Praze-Michli. *Zprávy o geologických výzkumech v roce 2013*, 89–93.

Röhlich, P., David, M., Budil, P. & Steinová, M. 2009. Fauna bohdaleckého souvrství (ordovik, stupeň katian) z dočasného odkryvu v Praze-Michli. *Zprávy o geologických výzkumech v roce 2008*, 109–111.

Šnajdr, M. 1982. New trilobites from the Bohdalec Formation (Berounian) in the Barrandien *Věstník Ústředního ústavu geologického 57(4)*, 227–230.

Štorch, P. 1986. Ordovician-Silurian boundary in the Prague Basin (Barrandian area, Bohemia). *Sborník geologických věd, Geologie 41*, 69–103.

Štorch, P. 1990. Upper Ordovician – lower Silurian sequences of the Bohemian Massif, Central Europe. *Geological Magazine 127(3)*, 225–239.

Štorch, P. & Mergl, M. 1989. Královdvor/Kosov Boundary and the late Ordovician environmental changes in the Prague Basin (Barrandian area, Bohemia). *Sborník geologických věd, Geologie 44*, 117–153.

Vacek, F. & Žák, J. 2019. A lifetime of the Variscan orogenic plateau from uplift to collapse as recorded by the Prague Basin, Bohemian Massif. *Geological Magazine 156(3)*, 485–509.

Vaněk, J. & Vokáč, V. 1997. Trilobites of the Bohdalec Formation (Upper Berounian, Ordovician, Prague Basin): Czech Republic. *Palaeontologia Bohemiae 3*, 20–50.

Wahlenberg, G. 1818. Petrificata telluris Svecanae. *Nova Acta. Royal Society of Science, Uppsala 8*, 1–116.

Želízko, J. V. 1906. Geologicko-paleontologické poměry nejbližšího okolí Rožmitálu. *Rozpravy České akademie císaře Františka Josefa pro vědy, slovesnost a umění, Třída II 15*, 1–27.