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Carbonate microfacies and depositional environments of the Silurian–Devonian boundary strata in the Barrandian area (Czech Republic)

FRANTIŠEK VACEK

Institute of Geology and Paleontology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Prague, Czech Republic; f.vacek@seznam.cz

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Abstract: The sedimentary record of the Silurian-Devonian (Pridoli–Lochkovian) boundary interval was assessed using eight sections, which essentially represent two different environments and facies types. The local predominance of bioclastic packstones to grainstones indicates the presence of relatively shallow marine environments, between the upper carbonate slope and lower subtidal. The thickest limestone beds show locally wave ripple-bedding structures, erosional surfaces, and hardgrounds with accumulated angular lithoclasts; these features may have been markers of deposition above the storm wave base level. Slightly beneath these environments, the irregular rhythmites of the upper slope contain erosional channels, which are also frequently associated with hardgrounds. Here, the debris-flow material fills braided-channel systems and contains various clasts from the slope. Rhythmites deposited in relatively deeper water are dominated by platy limestones: bioclastic and peloidal wackestones, mudstones. They represent typical lower fan calciturbidites interbedded with basin-floor mudstones and shales. Very thin-bedded distal calciturbidites occur here frequently. Normal-graded calciturbidite beds with horizontal lamination and current-ripple bedding have large proportions of Tc and Td units of the Bouma sequence, the indication of lower flow-regime deposition. Calcareous shale interbeds represent background hemipelagic sediments (Tep-Tet). Occurrences of several meters thick layers composed of coarse-grained proximal calciturbidites with submarine mass-flow conglomerates are typical of the lowermost part of the Lochkov Formation (Lochkovian). These deposits were accumulated near the carbonate shelfbreak and on adjacent parts of the slope.

Key words: Silurian, Devonian, Barrandian area, carbonate microfacies, calciturbidites.

Introduction

The Barrandian area (particularly the Prague Synform, central Bohemia) has been known as a classical region for the study of Silurian and Devonian sequences. The Global Boundary Stratotype Section and Point (GSSP) of the Silurian-Devonian (Pridoli–Lochkovian) boundary with auxiliary reference sections were established here (sections at Klonk near Suchomasty and Karlštejn; McLaren 1977). The detailed biostratigraphic, chemostratigraphic, magnetostratigraphic and sedimentological studies were concentrated primarily on these type sections (e.g. Chlupáč & Kukal 1977; Davies & MacQueen 1977; Paris et al. 1981; Kříž et al. 1986; Jeppson 1988, 1989; Hladil 1991, 1992; Hladil & Beroušek 1992; Hladíková et al. 1997; Crick et al. 2001; Mann et al. 2001; Frýda et al. 2002; Brocke et al. 2002, 2006; Buggisch & Mann 2004), whereas a number of other sections have been investigated to a lesser extent. The present study has been, therefore, focused on different sections in different parts of the Prague Synform (Fig. 1) to assess the basic facies variability of sediments and their approximate proportions (Figs. 2 and 3). From the stratigraphical viewpoint, these eight outcrops were already described in previous papers (e.g. Chlupáč et al. 1972), but both the sedimentological characteristics and their depositional context were sporadically reported (Čáp et al. 2003) or unnoticed in the past.

Some preliminary results of microfacies and sedimentological studies in this stratigraphic level were published in a paper by Čáp et al. (2003). Nevertheless, only three sections have been described (Požáry Quarry near Praha-Řeporyje, Praha-Podolí, and Praha-Radotín — near the Cement Plant). This paper contributed to more detailed biostratigraphy (as cited in the following text). Standard microfacies (SMF) sensu Wilson (1975) and Flügel (1982) have been used for description of carbonate rocks. Depositional settings have been vaguely interpreted according to association of SMF types and idealized succession of facies belts.

In the presented paper these three sections have been sampled in more detail for microfacies study and a new sedimentological interpretation and model are introduced.

Geographical and geological setting

The Prague Synform, principally an eo-Variscan deformation structure, is situated in the central part of the Barrandian area between the cities of Prague and Beroun (Fig. 1). Long stripes of folded limestone units dissected

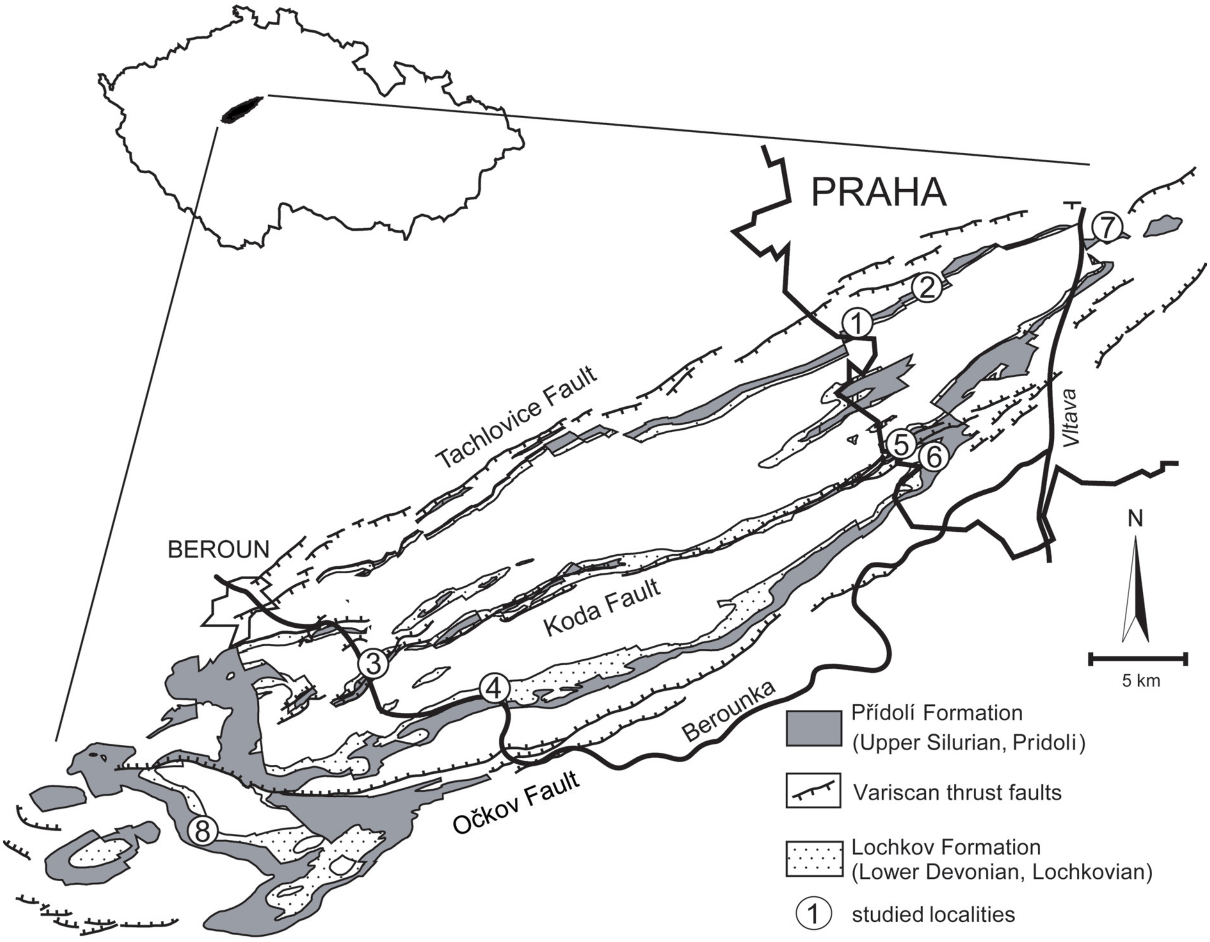

Fig. 1. Position of studied localities in the Barrandian area: **1** — Požáry Quarry near Praha-Řeporyje, **2** — Opatřilka Quarry near Praha-Holyně, **3** — Srbsko, **4** — Karlštejn, **5** — Radotín Valley — U topolů, **6** — Radotín Valley — near the Cement Plant, **7** — Praha-Podolí, **8** — Klonk near Suchomasty. The geological sketch map of the Prague Synform benefits partly (not completely) from the working materials provided by R. Melichar and J. Hladil.

by brook valleys give good access to the Silurian-Devonian (S-D) sequences. Eight S-D sections were selected to exemplify the diversity of carbonate slope facies deposited both in shallower and in deeper environments (Fig. 1).

The S-D boundary is principally situated close to the boundary of the Požáry (~Pridoli) and Lochkov Formations (Fm). The boundaries of these two lithostratigraphic units are slightly diachronous over the region, however. The explanation of the extent and details of the diachroneity is directly related to particular aims of this study.

Two different facies developments may be distinguished. The shallower of these two contrastive deposition types, in the Lochkov Fm (~Lochkovian), is the Kotýs Limestone facies (Chlupáč et al. 1972). It occurs mainly along the NW flank of the Prague Synform (e.g. in areas between villages of Praha-Nová Ves and Tetín near Beroun). Bioclastic, mostly crinoidal limestones predominate (studied sections at the sites of Srbsko, in the Opatřilka Quarry near Praha-Holyně, and Požáry Quarry near Praha-Řeporyje; Fig. 1).

The second facies, the Radotín Limestone (Lochkov Fm, Lochkovian), is distributed mainly along the SE flank of the area. It corresponds to relatively deeper-water depositional conditions. Blackish-grey coloured wackestones to packstones alternate with calcareous shale interbeds as the rhythmites. They are often marked by the presence of disseminated, laminated or nodular cherts. The successional structure of rhythmites was locally disturbed by the deposition of several meters thick accumulations of crinoidal and cephalopod limestone beds located just beneath and above the S-D boundary, but principally in the lowermost part of the Lochkov Fm. They belong to the *Scyphocrinites* Horizon (Bouček 1936). In its typical form, it is related mainly to stratigraphically condensed but coarse-grained bioclastic sediments (e.g. sections at Karlštejn, Praha-Radotín, and Praha-Podolí; Fig. 1).

The relatively pure carbonate facies contains a rich benthic fauna, including crinoids, brachiopods and trilobites. According to the occurrences of macropaleontological index species, the uppermost Silurian was characterized by short-term increase in abundance and rapid cessation of the trilobite *Tetinia minuta*. The first appearance of the index trilobite *Warburgella rugulosa rugosa* indicates the base of the Devonian, and concur-

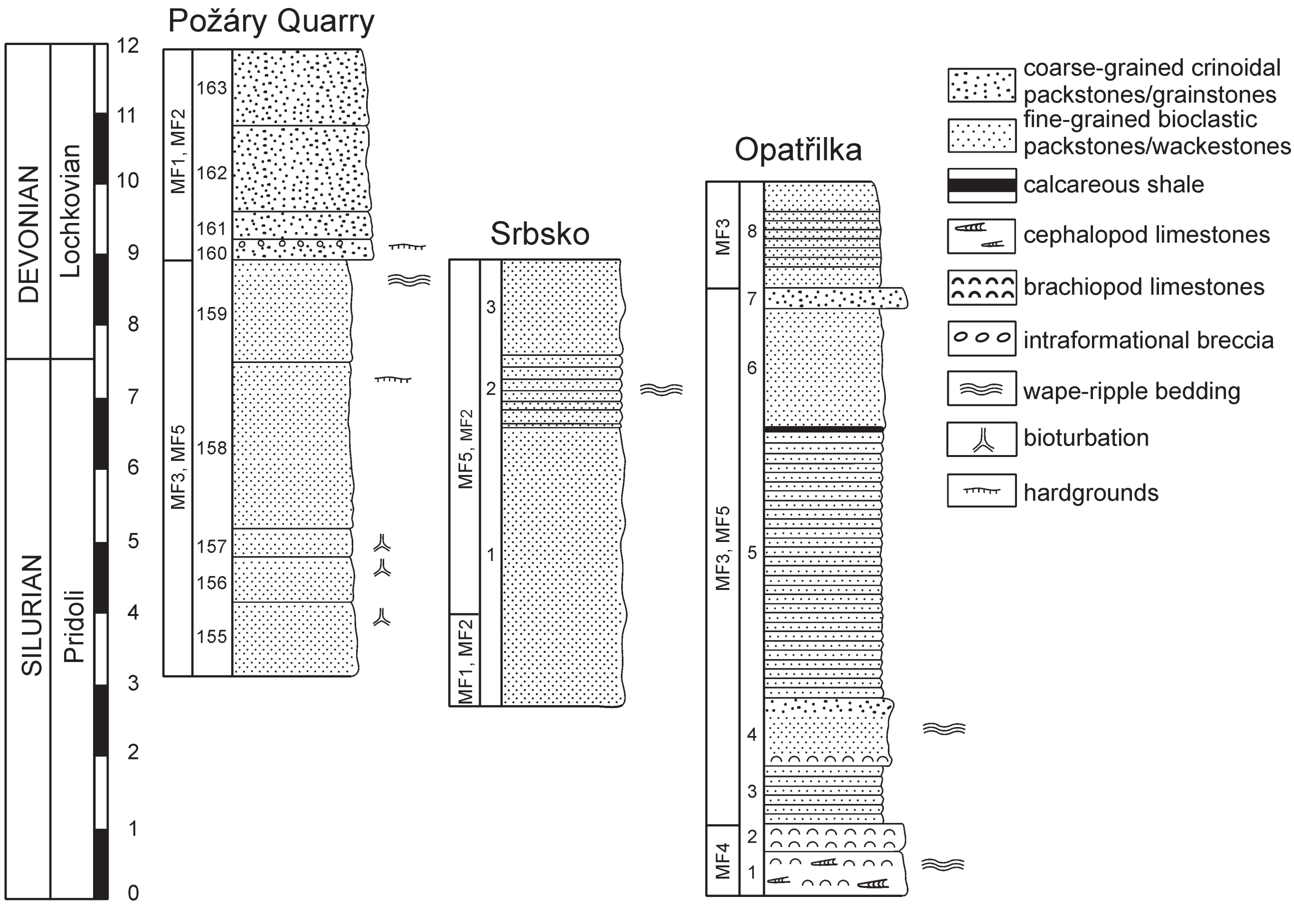

Fig. 2. Lithological logs of the sections with predominance of bioclastic limestones. The Silurian-Devonian boundary is marked by the first occurrence of index trilobite *Warburgella rugulosa rugosa*. The left columns show distribution of microfacies: **MF1** — crinoidal grainstones, **MF2** — crinoidal packstones, **MF3** — homogeneous packstones with sponge spicules, **MF4** — cephalopod wackestones with peloids, **MF5** — peloidal wackestones/packstones. Dominating microfacies are indicated by title letters, microfacies designated by small letters are present subordinately. For a detailed description of microfacies see the text.

rently the base of the Lochkovian Stage (Chlupáč et al. 1972). The increased proportion of pelagic material in deeper-water facies also corresponds to common occurrence of pelagic fauna, such as graptolites, cephalopods and ostracods. The uppermost Silurian beds belong to graptolite Zone *Monograptus transgrediens*, and the base of the Devonian is marked by the first appearance of the index graptolite *Monograptus uniformis*. In general, graptolites and trilobites have very practical, although approximate, use in the local S-D biostratigraphy, because the occurrences of chitinozoans and conodonts of high-resolution potentials are also dependent to various degrees on the facies, recycling of sediments and diagenetic conditions. The onset of the index chitinozoa *Angochitina chlupaci* indicates the base of the Lochkovian, while *Urnochitina urna* and *Linochitina klonkensis* terminate at the S-D boundary (Paris et al. 1981; Brocke et al. 2002). Recent studies of conodonts show problematic establishment of biozonation in the uppermost Pridoli and the lowermost Lochkovian, which causes problems when the conodont-based boundary is correlated with the S-D GSSP (e.g. Carls et al. 2007).

Methods

Although the prevailing part of the selected stratigraphic sections have been published in classical papers where the intervals of beds ("beds") were arbitrarily numbered, a general re-numbering of these "beds" was implemented. Nevertheless, the new numbers were introduced to prevent the confusion where photographic documentation of the original state was insufficient as original numbers are rarely preserved (e.g. in the old Požáry Quarry or Praha-Podolí). Therefore, new numbers were introduced for visible limestone beds (some of them can consist of more beds with obscure contacts; 1, 2, 3 etc.) and for shale interbeds (1/2, 2/3 etc.) in the S-D sections.

The study of sedimentary structures and microfacies was based on the method of visible facies contrast. Therefore, samples for microfacies analysis were collected selectively in order to represent all the main lithological types and sedimentary structures. More than seventy thin-sections were studied. Dunham's (1962) classification is used for description of macro- and microfacies.

The orientation of conical cephalopod shells was measured in several S-D sections to find the directions of paleocurrents. For interpretation, it was generally agreed that conical shells oriented their apices facing mostly the current, also following the data related to depositional environments of limestones in the Barrandian area (e.g. Petránek & Komárková 1953; Turek 1983; Hladil 1992 or Ferretti & Kříž 1995).

Sections

***Požáry Quarry near Praha-Řeporyje** (Fig. 1.1)*

The old abandoned quarry is located approximately 1 km to the east of Řeporyje village. The S-D boundary strata are in the eastern face of the quarry close to the southern end of the tunnel. The biostratigraphically determined boundary lies within the sequence of bioclastic, mostly crinoidal grainstones to packstones at the base of bed 159 (Fig. 2, according to Čáp et al. 2003), where the first Lochkovian index conodont *Icriodus hesperius* was found in the lowermost part (Carls et al. 2007). The first *Warburgella rugulosa rugosa* appears in bed 162. The thickness of individual and visually discernible beds on the quarry face ranges from 0.4 to 2.5 meters. Wave-ripple bedding was found in beds 159, 161, and 162. Eroded hardground covered by angular lithoclasts occurs in the upper part of bed 160. Crinoidal debris with brachiopods and trilobites are the main components. Remains of terrestrial plant *Cooksonia* sp. were reported from the upper part of bed 158 (Čáp et al. 2003). The interval of beds 155–157 holds possible (diagenetically altered) bioturbations visible both on bedding planes and in vertical sections (Fig. 4F).

***Opatřilka Quarry near Praha-Holyně** (Fig. 1.2)*

The boundary beds are exposed in abandoned quarries on the left bank of the Dalejský Brook, in the distance of about 300 m NNE of Praha–Holyně railway station.

The lower part of the section consists of thick-bedded crinoidal, brachiopod, cephalopod packstones/grainstones (the interval of beds 1–4; Fig. 2). The overlying part is characterized by thin-bedded fine-grained bioclastic limestones (packstones). The upper part (beds 6–8) is composed of thick-bedded, medium- to coarse-grained crinoidal limestones. The S-D boundary is indicated by the first occurrence of *Warburgella rugulosa rugosa*, which enters the section at ca. 1 m above the base of bed 6 (first reported by Chlupáč et al. 1972).

***Srbsko** (Fig. 1.3)*

The S-D boundary beds crop out in the rock-wall Na bříči on the right bank of the Berounka River north of Srbsko village. The relevant part of the sequence is composed of thick-bedded poorly-stratified crinoidal grainstones to packstones (Fig. 2) containing common benthic fauna (brachiopods, crinoids, and trilobites). The S-D boundary was indicated in the upper part of bed 3 by the first occurrence of *Warburgella rugulosa rugosa* (Chlupáč et al. 1972).

***Karlštejn** (Fig. 1.4)*

The Budňany Rock section (Budňanská skála) near Karlštejn village serves as the auxiliary stratotype of the S-D boundary. The boundary is marked and labelled within the rock face, at an exposed bedding plane on the left side of the exposure. Its position corresponds to the first appearance of *Monograptus uniformis* in the thin shale interbed 19/20 (cf. Chlupáč et al. 1972). The first *Angochitina chlupaci* occurs in bed 20 (first by Paris et al. 1981), nevertheless Brocke et al. (2002) reported only moderately preserved specimens not allowing detailed biozonation and correlation. The more continuous section on the right side of the exposure was selected for the study. The upper part of the Požáry Fm (Upper Silurian, Přídolí Series) is developed as alternation of dark mudstones to wackestones with calcareous shale interbeds (Fig. 3). The thicknesses of limestone beds range from 0.05 to 0.25 m, and the thicknesses of shale interbeds vary from 0.05 to 0.3 m. The overlying, more than 4 m-thick accumulations of crinoidal and cephalopod packstones/grainstones (beds 14–23), with horizons of intraformational conglomerates (bed 16) belong to the lower part of the Lochkov Fm. Amalgamation of coarse-grained crinoidal packstone beds is common in the upper part of this horizon (beds 20–23).

The following sequence consists of laminated wackestone to packstone beds and calcareous shale interbeds (beds 24 to 43, Radotín Limestone facies). Limestone beds show normal grading, parallel horizontal lamination, and current ripple-bedding.

The orientation of shells of orthocone nautiloids was measured in several beds. The preferred directions of shell apices were as follows: bed 7 — S to SW, minor to NE to E (40 shells have been measured); bed 11 — S to SW, minor to N (34 shells have been measured); and bed 19 — SW, minor to E (43 shells have been measured). It is in accordance with Kříž (1998), who reported apparent current-driven orientation of cephalopod shells in a SSW-NNE direction in beds 14–19 (or 40 and 41 sensu Chlupáč et al. 1972). The evident imbrication of carbonate lithoclasts in the bed 16, however, cannot be unequivocally interpreted due to unfavourable exposure and strong protection of this outcrop as a Natural Monument (only one section is available).

***Radotín Valley — U topolů** (Fig. 1.5)*

The boundary beds are exposed in an old railway trench on the left bank of the Mlýnský Brook to the NW of the Lochkov Cement Plant. The upper part of the Požáry Fm is mostly covered. It consists of dark platy limestones (mudstones to wackestones) alternating with calcareous shales (beds 1–10; Fig. 3). The thickness of

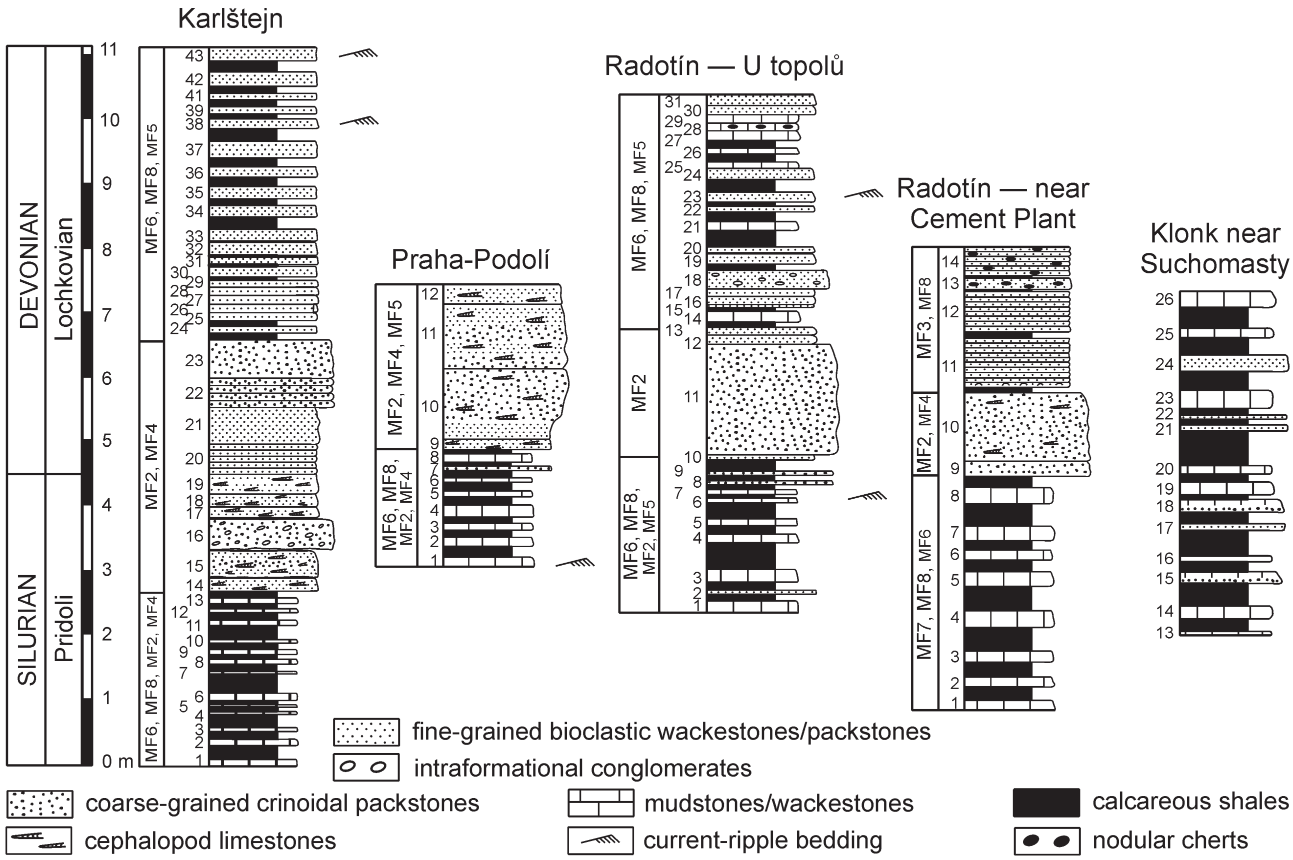

Fig. 3. Lithological logs of the sections with predominance of platy limestones with shale interbeds. The Silurian-Devonian boundary is indicated by the first occurrence of index graptolite *Monograptus uniformis*. The left columns show distribution of microfacies: **MF2** — crinoidal packstones, **MF3** — homogeneous packstones with sponge spicules, **MF4** — cephalopod wackestones with peloids, **MF5** — peloidal wackestones/packstones, **MF6** —laminated wackestones/packstones, **MF7** — homogeneous mudstones, **MF8** — calcareous shales with graptolites. Dominating microfacies are indicated by title letters, microfacies designated by small letters are present subordinately. For a detailed description of microfacies see the text.

limestone beds ranges from 0.05 to 0.2 m, shale interbeds reach from 0.05 to 0.4 m. The first occurrence of *Monograptus uniformis angustidens* in bed 9 fixes the S-D boundary (Chlupáč et al. 1972). Study of Chitinozoa indicates a considerable condensation of stratal thicknesses in the lower part of the section (Brocke et al. 2002). The overlying 1.8 m thick bank of crinoidal packstones to grainstones (bed 11) corresponds to the base of the Lochkov Fm. It is overlain by platy limestones (wackestones to packstones) and shale interbeds (beds 12–31) with a single bed of intraformational conglomerates (bed 18). Nodular cherts occur in bed 28.

Radotín Valley — near the Cement Plant *(Fig. 1.6)*

The section is situated in the road trench to the S of the Lochkov Cement Plant. The upper part of the Požáry Fm is covered (beds 1–8; Fig. 3). The thickness of individual beds ranges from 0.15 to 0.25 m, and the thickness of shale interbeds from 0.25 to 0.5 m. Limestone beds contain poorly represented pelagic fauna (cephalopods and ostracods). The lowest part of the Lochkov Fm consists of a 1.2 m thick bank of crinoidal and cephalopod packstones (bed 10) with abundant and more diversified fauna (e.g. crinoids *Scyphocrinites* with preserved large loboliths, cephalopods, and bivalves; for detailed description of bivalve communities see Kříž 1999). The first occurrence of *Monograptus uniformis* in bed 9 indicates the position of the S-D boundary (Čáp et al. 2003). The apices of nautiloid shells in bed 10 are oriented mainly to the NW with secondary N to NE maxima (55 specimens have been measured).

The overlying part of this stratal sequence developed as fine-grained platy limestones (packstones) with cherts and subordinate shale intercalations (beds 11–14; Fig. 3).

Praha-Podolí *(Fig. 1.7)*

The S-D boundary beds crop out in the northern face of the former quarry of the Podolí Cement Plant. The boundary is situated in shale interbed 6/7 according to the first occurrence of *Monograptus uniformis angustidens* (Chlupáč et al. 1972). The uppermost part of the Požáry Fm (Pridoli and the lowermost levels of the Lochkovian Stage) consists of platy wackestones with shale interbeds (beds 1–8; Fig. 3). The thicknesses of the lime-

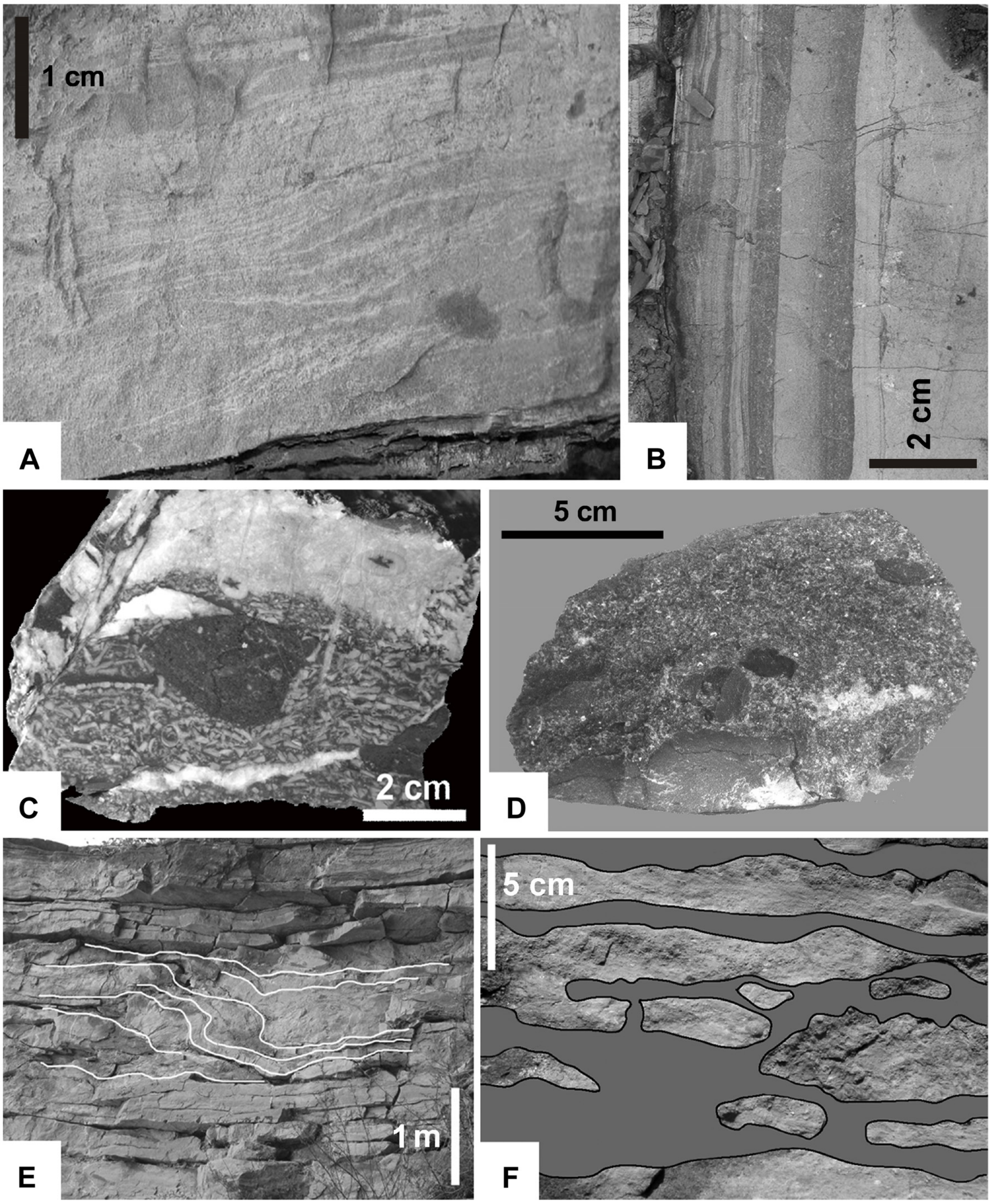

Fig. 4. Sedimentary structures of the Silurian-Devonian boundary strata, details of rock faces and slabs: **A** — Typical example of current ripple-bedding that usually marks the fills in systems of flat and braided channels on the carbonate slope. Praha-Radotín (U topolů), just above the documented boundary section (Devonian, Lochkovian). **B** — Normally graded bed with horizontal lamination, little erosion and fracturing the substrate and slight signs of current ripple-bedding; the position up is marked by the scale bar. Karlštejn, above the depicted section (Devonian, Lochkovian). **C** — An example of subangular to partly rounded limestone lithoclast floating in crinoidal debris, from the sample, which was taken close beneath the *Scyphocrinites* Horizon. Small parts of broken loboliths are present. Karlštejn, bed 16 (Silurian, Pridoli). **D** — Deeply dissected hardground was covered by poorly sorted packstones to grainstones which contain a mixture of "floating" angular and rounded lithoclasts. Rocks in the fissured, corroded and highly rugged hardground have stylolitic sutures, and the surface has thin rims of dark colour, locally with pyrite. Požáry Quarry near Praha-Řeporyje, the upper part of the bed 160 (Devonian, Lochkovian). **E** — An example of subaquaeous slump structure. Not all deformation structures observed in or around the S-D sections are of tectonic origin, although the section Praha-Radotín (U topolů) lies in the area with many bedding-parallel faults and strong folding of the rocks. Photographed above the selected S-D section (Devonian, Lochkovian). **F** — Completely altered parts in a thin-bedded, laminated and rippled succession of beds (dyed). Strong alteration of these parts, accompanied by brownish coloured dolomitization with sharp fronts enlarged and covered the primary bioturbation (and bioerosion?) structures. Požáry Quarry near Praha-Řeporyje, the upper part of bed 156 (Silurian, Pridoli).

stone beds range from 0.1 to 0.25 m and the thicknesses of the shale interbeds are slightly thinner (0.1 to 0.15 m). The lower part of the Lochkov Fm is developed as massive crinoidal and cephalopod packstones to grainstones (beds 9–12). The fauna of the platy limestone beds is represented by cephalopods, ostracods, and graptolites, while the massive bioclastic limestone beds contain crinoids, cephalopods, trilobites, etc.

Klonk near Suchomasty *(Fig. 1.8)*

This section was not included to the detailed study, but it is referred for comparison. The section at Klonk was approved as the GSSP of the S-D boundary at the session of the 24th International Geological Congress in Montreal in 1972 (McLaren 1977). The S-D boundary is marked by the first occurrence of *Monograptus uniformis* in the upper part of bed 20 (Chlupáč et al. 1972; Fig. 3), other index fossils such as trilobites, Chitinozoa, conodonts are used as auxiliary biostratigraphical indicators (see the summaries about the stratigraphy of this section — e.g. Chlupáč & Hladil 2000; Chlupáč & Vacek 2003). Surface exposure consists of rhythmical alternation of limestone and shale beds. The first sedimentological study of Klonk interpreted the limestone–shale rhythms as the result of cyclic changes in bioproductivity and carbonate accumulation in a mostly pelagic depositional environment (Chlupáč & Kukal 1977). Davies & MacQueen (1977) regarded the entire stratal sequence as distal calciturbidites, but their interpretation was based only on the observation of one sample taken from the boundary bed 20. According to the latter authors, this bed consists of a single turbidite layer with Tb and Tc units of the Bouma sequence.

Results published by Hladil (1991, 1992) show that an unequivocal turbidite interpretation is more complex and partly incorrect; particularly the lower part of this GSSP section is dominated by hemipelagic laminites, but divided into segments by some beds of calciturbidites or re-deposited, washed and drifted turbidite material. The dominant direction of currents was from the NE, but other directions from the NNE, SSE and SW were represented as well. The rate of sedimentation was estimated to be as high as ~20 meters per million years, and this rate almost certainly indicates a significant influx of turbidite and drifted sedimentary material.

In 1999, a full-cored 57 m deep borehole was drilled close to the surface outcrop. The core was compared with the GSSP section on the surface and analysed by a number of methods: e.g. magnetostratigraphy (Crick et al. 2001), chemostratigraphy (Herten 2000; Kranendonck 2000; Frýda et al. 2002; Buggisch & Mann 2004), biostratigraphy (Brocke et al. 2006).

Sedimentary and post-sedimentary structures

Parallel horizontal lamination is the most common structure in the platy limestones. It is characterized by the lack of bioturbation. Lamination can be recognized both in weathered surfaces and thin or polished sections. The thicknesses of laminae usually vary from 0.1 to 2 mm.

Current ripple-bedding appears both in the coarse- and fine-grained limestones (Fig. 4A). It is usually small-scale (1–1.5 cm in height, 3–5 cm in length, with a few examples of decimeter sizes), and the upper limits are erosional in some places.

Wave ripple-bedding is present in the Požáry Quarry section (namely in beds 159, 161, and 162; Fig. 2), and sporadically also in the Srbsko (bed 2) and Opatřilka sections (beds 1 and 4). The wave length is usually about 10 cm, the height does not exceed 3–4 cm (Fig. 5), although some of the observed structures can indicate larger ripple forms.

The normal grading occurs commonly in fine-grained, platy-shaped limestone beds with smooth bedding surfaces (Fig. 4B). The beds have erosional bases, and in many cases, the coarser-grained detritus deposited at the base is followed by fine-grained limestones with a gradual transition.

Two types of erosional surfaces can be described mainly within platy limestone beds. The first one corresponds to the bases of coarser-grained portions of calciturbidite sediment. The second one is identical with the sharp contacts of limestone beds with underlying hemipelagic shales. Diagenetically sharpened contacts between these differently compacted materials (e.g. Hladil 1991), or

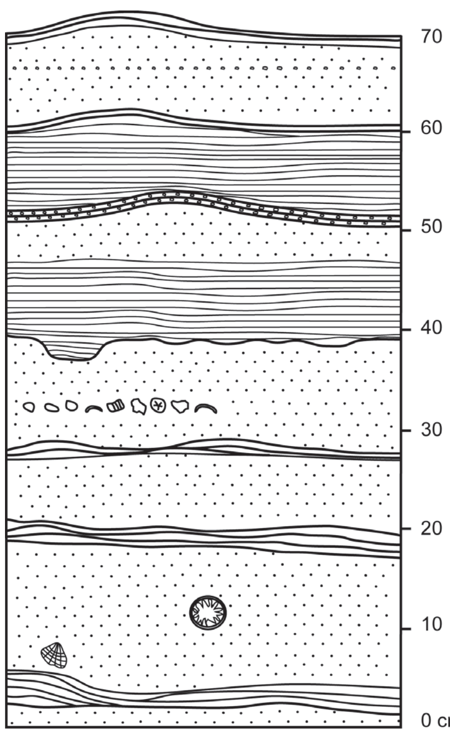

Fig. 5. Diagram of the upper part of bed 159 in the old Požáry Quarry section. The structure and succession of beds, including the wave ripple-bedding and eroded surfaces, are interpreted as the evidence of storm-influenced deposition.

smoothing due to small bedding-parallel shifts can also be observed.

Lithoclasts of centimeter to decimeter dimensions and intraformational conglomerates and/or breccias occur especially in the Karlštejn, Praha-Podolí, Praha-Radotín (U topolů), and Požáry Quarry sections. In the Karlštejn (bed 16) and Praha-Radotín (U topolů, bed 18) sections, a number of elongated and considerably rounded limestone clasts were also found "floating" in crinoidal debris material (Fig. 4C). Beds of matrix-supported carbonate conglomerates are massive without any visible grading. The lateral extent of such beds is not more than a few tens of meters, and then they are wedging or missing from the wall of the outcrop. Large lithoclasts are often imbricated. Many of them consist of dark grey coloured, fine-grained crinoidal wackestones to packstones. Clast sizes vary from 2 to 10 cm, in most cases. In relatively shallow-water deposits, lithoclasts are mainly angular, consisting of fine-grained, and strongly dolomitized limestones (Požáry Quarry, the upper part of bed 160; Fig. 4D).

Hardgrounds commonly occur in relatively shallow-water bioclastic deposits as can be exemplified by the old Požáry Quarry (in beds 158, 159, 160, and 162) or the Srbsko section. Hardgrounds are often marked by several millimeters thick limonitized laminas. Their lateral extent does not exceed several meters in the respective bed. They might have been originally developed as microbial pyrite crusts formed during periods of sedimentary starvation. Hardgrounds developed in exemplary forms occur in the old Požáry Quarry section in bed 160; they are covered by accumulations of angular lithoclasts, which show nearly identical lithologies if compared with the dissected bottom of this bed.

Subaqueous slumps (Fig. 4E) occur mainly above the measured and depicted part of the section in the Radotín Valley, U topolů site. They were formed on a sea-floor dipping in a low-angle due to sub-continuous soft-sediment downslope movements. The direction of transport is approximately from the NW to SE.

The bioturbations were very rare. Their absence seems to be typical for the platy limestones facies. In spite of this scarcity, the ichnogenus *Zoophycos* sp. was reported from the GSSP at Klonk near Suchomasty (Mikuláš & Vacek 2003). In the old Požáry Quarry, bioturbations were observed in the lower part of the S-D section (in the beds 155, 156, and 157). Their depth is usually several centimeters below the upper bedding plane. Burrow fills are mostly dolomitized. Therefore, primary structures are obscured: only the shapes or axes of bioturbations can be distinguished (Fig. 4F).

Microfacies

According to thin and polished sections, eight carbonate microfacies were distinguished, avoiding undue levels of detail. The microfacies were mainly characterized according to the content of skeletal (e.g. crinoids, cephalopods, sponge spicules) and non-skeletal grains (e.g. peloids), amounts of fine-grained sediment matrices and sedimentary structures. These microfacies signatures were used to verify the accuracy of the overall sedimentological evidence related to facies zones.

MF1: crinoidal grainstones and grainstone-to-rudstone are composed of slightly abraded or corroded crinoidal columnals, branchials, and other ossicles (~80 % of bioclasts), fragments of brachiopod and mollusc shells (~10 %), and trilobite carapaces (5–10 %; Fig. 6A). Other bioclasts were less important, although fragmented bryozoans, ostracods, and sponges are often involved in minor bioclastic components. They are locally abundant in some thin laminas or lenses within the sediment. Micritic to calcisiltitic fractions were commonly washed out. Syntaxial cements and dolomitization are common. The sizes of bioclasts range between 0.2 and 2 mm. Such materials were found mainly in poorly-stratified bodies with bed thickness of 25 to 35 cm. The typical examples of this microfacies occur in the old Požáry Quarry section (beds 160 and 162) and in the Srbsko section (e.g. the lower part of bed 1).

MF2: crinoidal packstones consist of angular crinoidal debris (~80 %), often with sutured grain contacts (Fig. 6B). Other bioclasts (e.g. ostracods and molluscs) represent a minor constituent (10–20 %). Micritized bioclasts are common. The diameter of grains varies between 0.5 and 5 mm. The microfacies is particularly related to poorly-stratified bodies with bed thicknesses up to 2.5 m. However, sediments of this microfacies were also found as thin intercalations in relatively finer-grained sediments. Such intercalations have commonly sharp erosional bases and they tend to fine upwards.

MF3: homogeneous packstones with sponge spicules (Fig. 6C) represent a fine-grained mixture of monoaxone sponge spicules (~30–40 %), ostracod shells (~30 %), and crinoidal detritus (~20 %). The diameter of bioclasts is between 0.1 and 0.5 mm. The microfacies forms several centimeters thick layers without marked stratification separated by thin shale intercalations.

MF4: cephalopod wackestones with peloids (Fig. 6D) contain large complete or fragmented cephalopod shells (~50 %) scattered in slightly recrystallized matrix with peloids. Other components are represented by crinoidal hash (~40 %) and fragments of ostracod shells (~10 %). Bioclasts are often micritized. Geopetal fillings are common. Preserved fragments of shells inside micritic pellets suggest that many of the peloids were formerly bioclasts transformed due to bacterially induced micritization. The populations of mixed, 0.1–0.6 mm peloids are present both in the matrix and inside the chambers of biomorphs, such as the orthocone cephalopod shells.

MF5: peloidal wackestones/packstones are characterized by a fine-grained mixture of crinoidal debris (40–50 %), molluscs (~30 %), together with ostracod shells (10–20 %), trilobite carapaces and peloids.

MF6: laminated wackestones/packstones (Fig. 6F) consist of alternation of detrital laminas with crinoidal detritus (~30 %), ostracod (~40 %) and mollusc (~20–

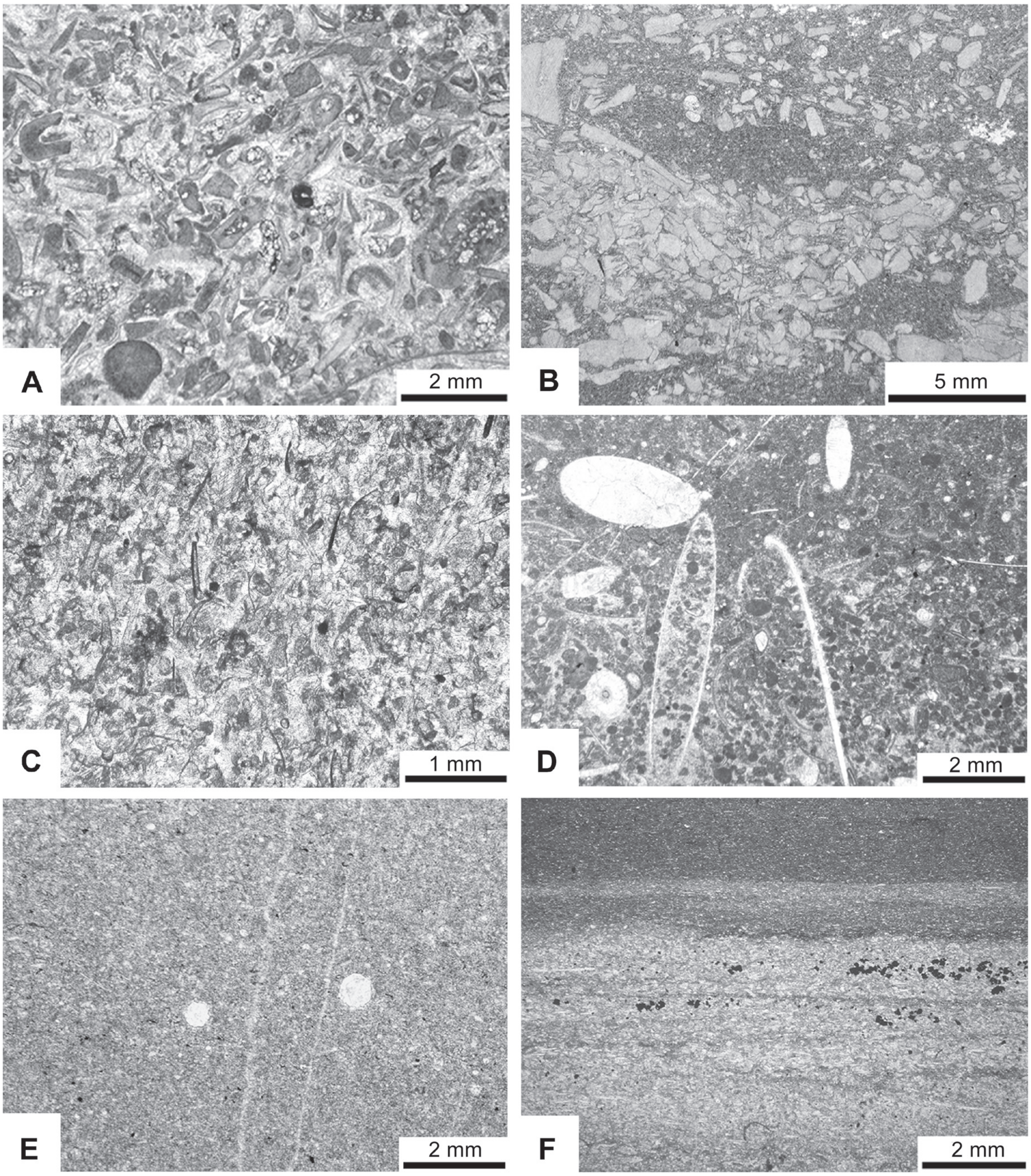

Fig. 6. Main microfacies types of the Silurian-Devonian boundary strata: **A** — Crinoidal grainstone. Crinoidal debris consists of abraded clasts, which were altered to various degrees and in different way. Parts of calcite cements were replaced by small dolomite crystals. Požáry Quarry near Praha-Řeporyje, bed 162 (Devonian, Lochkovian). **B** — Crinoidal packstone close to *Scyphocrinites* Horizon consists of patchy accumulations of unaltered ossicles, which frequently have dissolution contacts. Fine-grained material between accumulated (and partly also poorly disintegrated) ossicles contains small skeletal chips and fine-grained calcisiltitic material that is also dissolved. Praha-Podolí, bed 7 (Devonian, Lochkovian). **C** — Skeletal packstone/grainstone shows a parallel (and imbricated?) arrangement of platelet-shaped skeletal fragments and ostracod valves. This pattern is supported by common occurrence of sponge spicules. Praha-Radotín (near the Cement Plant), bed 14 (Devonian, Lochkovian). **D** — Cephalopod wackestone with peloids contains various assortments of mixed small grains. Calcisiltite particles are mixed with a variety of completely or partly micritized subangular and well-rounded particles of 0.1–0.3 mm in size. Karlštejn, bed 14 (Silurian, Pridoli). **E** — Relatively homogeneous mudstone formed from very fine-grained pelagic and hemipelagic particles. The moderately recrystallized rock contains numerous spherical objects filled by calcite crystals; they usually belong to mazuelloids (small) and prasinophycean algae (larger). Praha-Radotín (near the Cement Plant), bed 7 (Silurian, Pridoli). **F** — Slightly irregular and wedging horizontal lamination of calcisiltites and packstones (both considerably recrystallized and/or dissolved). This section shows the transition of laminated wackestone/packstone material into overlying calcareous graptolitic shale. Note chains of pyrite crystals in the lighter bands, which were originally composed of coarser calcisiltite material. Praha-Radotín (U topolů), bed 24 (Devonian, Lochkovian).

30 %) shells, mazuelloids (Muellerisphaerida), sponge spicules, and micritic laminas with thickness in millimetric scale. Dissolution seams expressed by accumulated insoluble residue are common. The microfacies forms beds several cm to 20 cm thick, commonly with erosional bases. It possesses horizontal lamination or ripple-bedding.

MF7: homogeneous mudstones (Fig. 6E) are characterized by slightly recystallized matrix with minor content of scattered fragments of cephalopod (~30 % of bioclasts) and ostracod (~50 %) shells, where the presence of Muellerisphaerida is typical. This microfacies forms approximately 20 cm thick beds without distinct stratification, some of them are really homogeneous, but others seem to contain poorly recognizable millimetric rhythms.

MF8: calcareous shale microfacies with graptolites (Fig. 6F) contain apparent horizontal lamination and common pelagic faunas (e.g. graptolites, ostracods).

Context and relationships of microfacies and facies

Grainstone-dominated sections

Sections with predominance of bioclastic limestones show a typical lack of laminated wackestones/packstones, homogeneous mudstones, and calcareous shales microfacies. The small-scale interfingering of these two major facies (bioclastic beds and rhythmites with shaly interbeds) seems to be quite rare, although the first can continue the second, and vice versa (Figs. 2 and 3).

The lower part of section in the Požáry Quarry (the uppermost part of the Požáry Fm, beds 155–159; Fig. 2) is mainly composed of fine-grained wackestones/packstones with peloids and sponge spicules. It is followed by coarser-grained crinoidal grainstones/packstones of the lower part of the Lochkov Fm (beds 160–163; Fig. 2).

The lower part of the Srbsko section (approximately 1.5 m above the base of bed 1) is characterized by coarser-grained crinoidal grainstones/packstones, but peloidal wackstones/packstones predominate in the main part of the section (the upper part of bed 1 up to bed 3; Fig. 2).

On the contrary, the lowest part of the Opatřilka section is formed by a bed of peloidal cephalopod wackestone (bed 1; Fig. 2), and the entire middle part of the section consists of thin bedded peloidal wackestones/packstones (interval of beds 3 and 5). The overlying massive beds 6–8 are characterized by the alternation of two microfacies assemblages: homogeneous, sponge-spicule packstones and peloidal wackestones/packstones.

Sections dominated by fine-grained limestones and shales

The number of other sections with alternation of fine-grained limestones and calcareous shales show similar vertical trends in change of microfacies types, but poorly-sorted and matrix-washed crinoidal grainstones do not occur in these deeper depositional settings.

The upper part of the Požáry Fm in Karlštejn is characterized by alternation of laminated wackestones/packstones with thin intercalations of crinoidal packstones and calcareous shales with graptolites (beds 1–13; Fig. 3). The *Scyphocrinites* Horizon with several beds of cephalopod limestones fills the entire interval of the uppermost Pridoli and lower Lochkovian, with predominace of crinoidal packstones and peloidal cephalopod wackestones microfacies (beds 14–23; Fig. 3). Laminated wackestones/packstones, peloidal wackestones/packstones, and calcareous shales prevail in the overlying beds (24–39).

The lower part of the Praha-Podolí section (the upper part of Požáry Fm, beds 1–8; Fig. 3) consists of laminated wackestones/packstones with thin intercalations of crinoidal packstones, and peloidal cephalopod wackestones alternating calcareous shales. Massive beds 9–12 with the alternation of crinoidal packstones, peloidal cephalopod wackestones, and peloidal wackstones/packstones already belong to the lower part of the Lochkov Fm.

The uppermost level of the Požáry Fm in the U topolů section is composed of laminated wackestones/packstones, peloidal wackstones/packstones, crinoidal packstones, and calcareous shales (beds 1–10; Fig. 3). The overlying massive accumulation of crinoidal packstones corresponds to the lowest part of the Lochkov Fm (bed 11). The above-lying rest of the formation is dominated by laminated wackestones/packstones and calcareous shales (beds 12–31).

The upper part of the Požáry Fm in the Praha-Radotín section is poorly exposed and the shale beds are intensively weathered. The limestones are mostly composed of homogeneous mudstones and laminated wackestones/packstones (beds 1–8; Fig. 3). Homogeneous mudstones were not found in other sections. The overlying *Scyphocrinites* Horizon (at the base of the Lochkov Fm, beds 9 and 10) consists of crinoidal packstones and cephalopod wackestones, and beds 11–14 are characterized by the presence of thin layers of homogeneous sponge-spicule packstones with thin shale intercalations.

Depositional model

The sedimentary system of the S-D boundary strata (Fig. 7) is characterized by lateral transition from coarse-grained bioclastic facies to platy limestones with shale interbeds (from the NW to the SE). Bioclastic packstones and grainstones of the Kotýs Limestone (sections in Praha-Řeporyje, Srbsko, partly Praha-Holyně) were deposited close to the source of organodetrital material in flat shallow-water areas and the upper parts of carbonate slope covered by crinoidal meadows. These deposits show reworking by storm action resulting in washing out of fine-grained matrix and erosion of cemented sea floor (angular limestone lithoclasts are present). This feature was documented in the Požáry Quarry section in the beds 159, 161, and 162 (Figs. 3 and 5). However, the

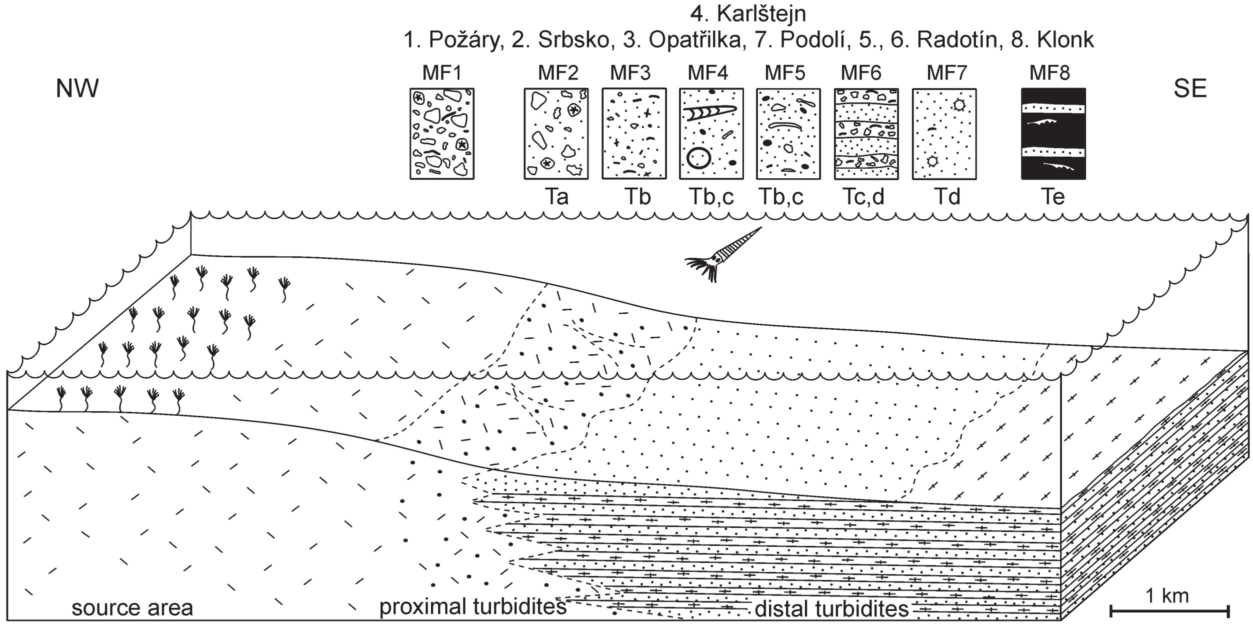

Fig. 7. Simplified depositional model of the Silurian–Devonian boundary strata in the Prague Synform near Prague. The diagram is basically not to scale, and the horizontal scale indicates mainly the rapid transitions between the areas covered by proximal and distal calciturbidites as suggested in this paper. The simplified diagram intentionally neglects the role of partial highs on the seafloor, because their original positions and the distances between them are not yet sufficiently based on the very detailed data covering all the parts of the Prague Synform. **MF1** — crinoidal grainstones, **MF2** — crinoidal packstones, **MF3** — homogeneous packstones with sponge spicules, **MF4** — cephalopod wackestones with peloids, **MF5** — peloidal wackestones/packstones, **MF6** — laminated wackestones/packstones, **MF7** — homogeneous mudstones, **MF8** — calcareous shales with graptolites. Microfacies types are interpreted as Ta–Te units of Bouma turbidite sequence. The position of studied sections in the model is marked in the upper part.

deposition was generally located below the fair weather base level, but still in a well-oxygenated environment with sea floor colonized by common benthic fauna. Carbonate tempestites were reported by Suchý (1991) from the Choteč Limestone (Middle Devonian, Eifelian). In spite of these indications, the occurrence of typical hummocky-cross stratification is problematic in both these places, and some of these sediments can be explained as braided channels on carbonate slope, at least.

The deeper-water Radotín Limestone facies contains all the characteristic sedimentary features of calciturbidites (erosional bases, normal grading with presence of individual units of the Bouma turbidite sequence; Bouma 1962); but later reworking by the traction bottom currents is quite possible in many cases. This effect may also be expected for some types of the cephalopod limestones beds where strong current-driven orientation of cephalopod shells is associated with irregular wash out of small sedimentary particles. This facies contains numerous distal turbidite beds with prevailing Tc–Td Bouma units, which alternate with background hemipelagic deposits (Te). Platy limestone beds show multiple turbidite events, in many cases. The transition between shallow-water and deeper-water environments is still characterized by a considerable amount of coarse-grained proximal calciturbidites (Ta and Tb units are common; e.g. the *Scyphocrinites* Horizon in Karlštejn, Praha-Podolí, and Praha-Radotín). Intraformational matrix-supported carbonate conglomerates with elongated and rounded lithoclasts can be classified as deposits from debris flows to dense turbidite flows, the infill of submarine channels. Debris flow beds pass upwards into amalgamated coarse-grained crinoidal turbidites, which typically lack graded parts (Karlštejn, bed 16). However, the complete Bouma sequence has not been observed in the studied turbidite beds. It is one of diagnostic features, which differentiate calciturbidites from siliciclastic turbidites (for summary see e.g. Tucker & Wright 1990; Flügel 2004). Possible diagenetic overprint destroying primary sedimentary structures must also be taken into account.

According to Ferretti & Kříž (1995) or Kříž (1998) the deposition of cephalopod limestones took place in relatively shallow-water well-oxygenated conditions with periodical influence of surface currents. However, the occurrences of undeformed completely preserved *Scyphocrinites* loboliths in the Karlštejn and Praha-Radotín sections (up to 20 cm in diameter) suggest relatively rapid deposition and durability of calm environments between the sedimentation events. Neither can the imbrication of limestone lithoclasts in size between 2 and 10 cm be explained by the activity of surface currents but by rapid transport and deposition in the upper flow-regime of gravitational currents.

The orientation of cephalopod shells, therefore, can also reflect the directions of gravity flows, not only the subsequent washing and re-sedimentation of this material. In this context, the dominant paleocurrent directions in the Karlštejn section are from the S and SW to N and

NE, but the other episodic currents were likely to be oriented from the NE to SW. In Praha-Radotín, the northerly currents predominated, with the NW to NE variations. The direction of synsedimentary to early post-sedimentary slump movements as indicated in the U topolů section is from the NW to SE, and this and similar data provide the additional evidence about local inclinations on paleoslopes. Paleocurrent interpretation is in accordance with Ferretti & Kříž (1995), who presumed the prevailing currents coming from SW to NE lasting for the whole Silurian (from late Wenlock to latest Pridoli). This direction seems to be widely spread along the northern Gondwana shelf (Prague Synform, Carnic Alps, Sardinia, Montagne Noire, Morocco).

Chlupáč (2000) suggested the idea of climatic-driven cyclicity expressed in bedding couplets (limestone bed and overlying shale bed). However, the results of concurrently developed magnetic susceptibility (MS) studies of these S-D sections (in progress, to be published soon) show that the cyclic patterns in the MS record do not respect the lithological characteristics of such successions of the beds in detail. The MS cycles often include several limestone beds and shale interbeds or other disproportions in comparison with the facies and microfacies. This can be preliminarily explained by the effect of several processes. First, the orbital driven and other climatic fluctuations influenced not only the terrigeneous inputs but also the erosion on the slopes. The medium-long erosional hiatuses (usually several tens of kyr) seem to be much more frequent in these beds than was previously assumed. Secondly, also the differential compaction must distort the possible, orbitally-driven lithological characteristics (cf. Westphal 2006). In addition, there are also a number of analysed S-D limestone beds, which have higher MS values than the interbeds. It is indicative of a large amount of detrital particles delivered to the basin with calciturbidites.

The presented model fits well the slope apron of Mullins & Cook (1986). It is characterized by gentle gradient, redeposited carbonate gravity-flows extend up to the adjacent shelf/slope break without an upper-slope bypass zone. In contrast to the submarine siliciclastic fan model, in which a fan is fed by a point source (submarine canyon), carbonate aprons are fed by many small channels dissecting the upper slope of a carbonate platform where they act rather as a line source. Any evidence of deeper channels or canyons was not found in the studied area as well as megabreccias indicating a steeper slope of the carbonate platform. Deposits of carbonate aprons form in general sheets of debris spreading across the slope area. Organized vertical sequences are not usually developed.

Due to the tectonic shortening from NNW to SSE, the distance of outcrops with different facies complexes do not exceed several kilometers. However, the nappe tectonics model presented by Melichar & Hladil (1999) or Melichar (2004) requires a serious shortening of the basins in a N–S direction. However, this model does not need to explain all structural features of the Prague Synform. In this context, particularly the facies research has a great potential to explain the original dimensions and distances in the basin.

Sea-level fluctuations

The broader S-D boundary interval in the Prague Synform is characterized by facies change, which is more pronounced in relatively deeper-water environments than in their shallower counterparts. The succession of rhythmites with fine-grained calcilutitic microfacies, mudstones and wackstones, was interrupted by deposition of a several meters thick accumulation of coarse-grained bioclastic limestones (crinoidal and cephalopod limestones, intraformational conglomerates, and breccias). Such facies changes indicating relative shallowing of sedimentary environments are also described from other regions of Europe (e.g. Carnic Alps; Schönlaub et al. 1994), and North America, e.g. central Nevada (Klapper & Murphy 1975; Matti & McKee 1977), Appalachian Basin (Denkler & Harris 1988).

The input of coarse-detrital material to a deeper-water environment is usually connected with increased erosion in the shallow parts of the shelf during lowstands. The short-term regression pulse in the uppermost Pridoli in the Prague Synform was documented in several papers (e.g. Kříž et al. 1986; Chlupáč & Kukal 1988; Kříž 1991). Hladíková et al. (1997) described gradual increase in $\delta^{13}C$ in Klonk and Karlštejn sections, which has been interpreted either as a result of increased organic productivity or relative sea-level drop. A positive excursion in $\delta^{13}C$ at/close to the S-D boundary is well documented in many regions of Europe (Buggisch & Mann 2004), North America (Saltzman 2002) and seems to reflect a global event. Saltzman (2002) explains this excursion as a result of enhanced carbonate weathering during exposure and erosion of older Silurian platform deposits in combination with enhanced nutrient delivery to the oceans and increase in organic carbon burial rates in organic-rich sediments.

Magnetostratigraphic data (Crick et al. 2001) also suggest a regression event during the latest Pridoli, which resulted in larger amount of detrital magnetic material delivered into the basin. This short regression was followed by gradual sea-level rise and recovery of hemipelagic deposition alternating with distal calciturbidites.

The maximum thickness of coarse-grained calciturbidites (and debris-flow fills) is known from the Karlštejn-Budňany Rock (4 m), while small thickness can be exemplified by outcrops at Praha-Radotín (1–2 m). In the vicinity of Suchomasty, the stratigraphically condensed succession of massive, coarse-grained beds is completely missing, having the analogues in relatively thin and separated beds with medium increased contents of disarticulated "floating crinoids". It is interesting, that sections with maximum accumulation of coarse-grained debris are usually located close to the Koda Fault (Fig. 1). The input of this material thus might have been triggered by emergence of unknown paleoheights (a significant eo-Variscan shortening at this fault), perhaps in combination with a growth-fault system as presumed by Kříž (1991).

Conclusions

The results of sedimentological and microfacies studies allow us to characterize the depositional system of the time interval at the Silurian-Devonian boundary. It was the margin of an open-sea carbonate shelf with adjacent carbonate slope environment (slope apron). The latter environments are predominantly expressed in the preserved part of the Prague Synform. If generalized, the deepening trend can be traced from the NW to SE. The relatively shalower carbonate facies (upper slope) with predominance of bioclastic limestones locally show reworking by storms, which indicates the conditions above the storm wave base. On the lower carbonate slope and its toe, rhythmically deposited distal calciturbidites prevail (often with the Bouma Tc and Td units). This quantitatively based observation is highly indicative of distal calciturbidite deposition. These turbidite beds alternate with interlayers of the "background" hemipelagic sediments (Te), which are preserved mostly in the form of highly compacted calcareous shales. The occurrences of channelized turbidite grainstones and rudstones with several layers of intraformational conglomerates are interpreted as debris flow deposits. The input of the coarse-grained detrital material of shallow-water origin is interpreted as the result of relative sea-level drop in the S-D boundary interval.

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