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SILURIAN OF THE PRAGUE BASIN, BOHEMIA**

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Cephalopod Limestone Biofacies in the Silurian of the Prague Basin, Bohemia

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We interpret biostratigraphy of Silurian cephalopod limestone biofacies of the Prague Basin, Bohemia. Two facies types are recognized. One is the result of a surface current and the other one is the effect of redeposition within the current itself in a shallower environment during storm events. Orientation of cephalopod shells in these two facies types is discussed in relation to the Prague Basin development and to phenomena like telescoping, trap-structures and geopetal structures.

Silurian cephalopod limestones of the northern Gondwana region show influence of equatorial surface currents which transported empty shells of cephalopods, larvae of bivalves and other fauna. These currents ventilated during low-stand events the elevated parts of the bottom and deposited there the cephalopod limestone levels. All the occurrences are accompanied by bivalve-dominated Cardiola Community Group.

"Life is sometimes strange. We started this project in August 1990 in Prague, where we shared our spare time with Hermann Jaeger who was also working there. Now, just at the end of this work, we have lost a friend."

To his memory this paper is dedicated."

INTRODUCTION

Recent studies of the Silurian in the Prague Basin (Kříž, 1991, 1992, in press, a), Sardinia (Ferretti, 1989; Kříž and Serpagli, 1993) and Montagne Noire (Kříž, in press, b) have shown that one of the most important tools for the correlation of the non-graptolite facies is the cephalopod limestone biofacies.

The facies was already known to Barrande (1846, 1852) from central Bohemia. His workers collected cephalopods representing one of the most attractive groups of fossils for the majority of collectors in those days from this facies. Bivalves, which form the dominant benthic community adapted to this biofacies, were collected only incidentally and described by Barrande much later than trilobites and cephalopods (1881).

We decided to analyze some aspects of sedimentology and biostratigraphy of the cephalopod limestone. Our work is based on field and laboratory research during years 1990–1992.

SILURIAN CEPHALOPOD LIMESTONE OCCURRENCES

Silurian cephalopod limestones developed all around the northern Gondwana basins at the same stratigraphic horizons, as shown by the analysis of bivalve-dominated communities and by the occurrence of conodonts, ostracods and rare graptolites. The most important region for the study of their stratigraphical position is the Prague Basin in Bohemia (Fig. 1), thanks to well exposed and tectonically undisturbed fossiliferous sections. The recent summary of the Prague Basin development in the Silurian (Kříž, 1991, 1992) shows

FIGURE 1—Locality map showing the position of the Prague area.

that cephalopod limestone levels are developed in upper Wenlock (*T. testis* Biozone), in lowermost Ludlow (*C. colonus* Biozone), in middle Ludlow (*M. fritschii linearis* Biozone; base of the Ludfordian), in uppermost Ludlow (*M. fragmentalis* Biozone), in lowermost Přídolí (*M. parultimus* Biozone) and in uppermost Přídolí.

Similar occurrences are in other north Gondwana basins (Kříž, 1979, in press; Kříž and Serpagli, 1993; in uppermost Wenlock, lowermost Ludlow and in middle Ludlow. In the Carnic Alps (the Alticola Kalke of Walliser, 1964; Jaeger, 1975) the cephalopod limestone biofacies is developed in the uppermost Ludlow.

This level is lacking in Sardinia and in Montagne Noire (Kříž and Serpagli, 1993; Kříž, in press, b) probably due to syndimentary tectonic development of the basins, where eustatic movements (regression) were compensated by contemporaneous subsidence. In the upper Přídolí the cephalopod limestone biofacies is also not developed in these regions for similar reasons.

CEPHALOPOD LIMESTONES OF THE PRAQUE BASIN

The Prague Basin (Barrandium) has always offered ideal and fascinating clues for Silurian facies pat-

terns and paleogeography reconstruction, thanks to its extensive outcrops and to the absence of a tectonic overprint (Fig. 2). Eustatic movements, syndimentary tectonics and volcanism were the main factors controlling facies development of the basin (Kříž, 1991, 1992). Cephalopod limestones were deposited just below wave base at a maximum depth of several tens of meters. They accumulated on paleo-highs adjacent to shale facies, but below the oxygenated higher energy environment where brachiopod-trilobite communities were living. Basing on septal strength speculations, Westermann (1985) had reached different conclu-

FIGURE 2—Sketch of the Prague Basin with distribution of Silurian rocks and main synsedimentary tectonics. Principal localities and most characteristic stratigraphical columns are here reported. Kosov Quarry: lower part of the section in western face of Kosov n. 780–782 (middle Ludlow); upper part of the section in eastern face n. 778 (Ludlow-Přídolí).

FIGURE 3—Sketch of main features of Braník Type cephalopod limestone: isoriorientation of cephalopods (A), well developed bivalve-dominated communities (B), geopetal structures of cephalopods (C) and telescoping (D).

sions, suggesting that the Silurian Prague Basin was several hundreds meters deep in places of cephalopod limestone sedimentation.

Our analysis deals mainly with five sections (Braník, Cephalopod Quarry, Marble Quarry, Pankrác Section and Kosov Quarry; Fig. 2) studied both directly in the field and with oriented thin sections. Samples were also collected from Jinonice, Mušlovka Quarry and Karlštejn. Two different facies types of cephalopod limestone are recognized.

Braník Type

This type (Figs. 3 and 4) has been found in the Braník, Cephalopod Quarry, Marble Quarry and Pankrác localities. This is the common cephalopod limestone type of the Prague Basin and it is therefore interpreted as the "normal" sedimentation facies.

The Braník Section was described by Kříž et al. (1986) and Kříž (1992). At the base of the sequence, shales are followed by a layer, only some decimeters thick, of dark micritic limestone with the bivalve-dominated *Cheiropteria glabra* Community (Kříž, in press, a). Bivalves *Cardiola pectinata*, *C. alata*, *Dualina* div. sp., *Spanila* sp. and the trilobite *Encrinurus beaumonti* also occur. The *Cheiropteria glabra* Community indicates high density of the dominant species and thus restricted living conditions for benthic organisms. The bed was deposited below wave base at limited oxygen content and little or no current activity.

This micritic bed is covered by a bank of cephalopod limestone with thickness, depending on time span of the layer, from 80 cm (upper Ludfordian—Braník) to a maximum of 380 cm (whole Ludfordian—Marble Quarry). Most common thickness in

other upper Ludfordian sections is 100 cm. In the Cephalopod Quarry, Braník and Pankrác sections the age of the cephalopod limestone is upper Ludlow and in Marble Quarry the cephalopod bank corresponds to the interval from the middle Ludlow (base of the Ludfordian) up to the upper Ludlow.

Cephalopods are abundant in the formation and keep a uniform SW-NE direction through the whole deposition time. Bivalve-dominated communities of the *Cardiola* Community Group (Kříž, in press, a), composed mostly of epibyssate forms, are well represented and show a great diversity. Abundant ostracods, crinoids, conodonts, rare brachiopods, bryozoans, gastropods, trilobites and graptolites are associated with most common cephalopods.

Microfacies analysis indicates episodic higher energy deposition of cephalopod wackestones to packstones inside a quieter micritic finer-grained sediment with small ostracods, juvenile bivalves, gastropods, crinoids, graptolites, cephalopods and muellerisphaerida. Small pelagic forms seem to be dominant in the finer-grained sediment. Dissolution effects occur at the lower contact of the wackestones-packstones with the fossiliferous mudstones.

Just above the cephalopod bed is sometimes developed a thin layer of micrite and biomicrite (Braník, Pankrác and Cephalopod Quarry) or locally the cephalopod limestone is directly covered by shales (Marble Quarry).

The cephalopod bank represents a significant change in sedimentation inside a generally low-energy environment dominated by shale or micritic limestone intercalations (Fig. 4). The unidirectional current evidenced by the SW-NE cephalopod orientation deposited episodically in the basin lots of cephalopod shells and other material carried in, probably as a response to energy decrease. At the bottom of the sea, other benthic forms adapted their morphology and feeding strategy to the shell material just deposited representing therefore a firm substrate. Typical and special bivalve-dominated com-

munities of the *Cardiola* Community Group, characteristic for the Silurian, were so originated (Kříž, in press, a). The same current was responsible for oxygen diffusion, survival and distribution of benthic forms in the basin. Oxygen rate was apparently limited, however, as no true brachiopod and trilobite dominated communities are present. Accumulations of juvenile bivalves and gastropods, found locally, document even periods with no oxygen which juvenile populations did not survive.

Biomicritic intercalations in the limestone represent minor periods of quiet sedimentation alternating with current deposition of high-energy episodes.

Kosov Type

This type was found only in the region of the Kosov Volcanic Centre in the Western Segment of the basin, west of the Tobolka fault. A first level of cephalopod limestone occurs in the *M. fritschi linearis* Biozone as evidence of the middle Ludlow regression (Kříž, 1991, 1992).

The cephalopod limestone overlies a platy bioclastic limestone dominated by shallow-water brachiopod-trilobite communities. Micritic layers with dominant pelagic organisms alternate with thin beds of coarse bioclasts through about 120 cm. Bioclastic layers are mainly composed of cephalopod shells, intraclasts and benthic organisms (trilobites, brachiopods, gastropods and rare bivalves; Fig. 5). Bivalves are very rare. Lack of mud indicates repeated winnowing; sharp erosional bases of beds are common, as well as remobilization of clasts from the lower micritic layers (Fig. 6). Dissolution and erosion took place on the bottom of these "bioclasts-dust" clouds. Many bioclasts and lithoclasts are bordered by iron-oxide crusts.

On the top bedding surface hundreds of exposed orthocones are one of the most picturesque and unforgettable views of the all Paleozoic life (Figs. 7 and 8). Big and small orthocones have an almost constant S-N direction. Longiconic orthocones, 20 to 35 cm long and mainly micheli-

FIGURE 4—Reconstruction of depositional history of Braník Type cephalopod limestone. A) Quiet micritic area of sedimentation of dark micritic limestones with bivalve-dominated *Cheilopteria glabra* Community. B) Cephalopod limestone episode with deposition of isoriented cephalopods, graptolites, bivalves and other associated forms. C) At the top of the bank, a micritic cover is locally developed or, in other localities, the limestone is directly covered by shales.

noceratids, have long body chambers always infilled by micritic sediment, contrasting with the coarse-grained embedding material. Micritic areas are locally present. Rare cyrtocoones are visible. Concentration of small shells in the "shadow" of those having greater dimensions are common. Moreover, small orthocoones up to 6 cm long are almost always lacking body chamber. Small shells have same direction as big ones but opposite apex orientation (pointing to the south). Small orthocoones are filled with coarse-grained sediment.

A thin micritic layer covers this cephalopod limestone and passes quite sharply to locally developed tuffs and then to a shallow water monospecific brachiopod community (*Atrypa linguata*) with a quiet rich benthic fauna of corals, trilobites, brachiopods, gastropods, bryozoans and crinoids. Moving to deeper water to the south of the Kosov Quarry, limestones pass quickly into laminated calcareous tuffaceous shales with abundant brachiopods, ostracods and trilobites and with limestone nodules.

Another cephalopod limestone level, with the same double cephalopod orientation, was deposited in the Kosov area during uppermost Ludlow (*M. fragmentalis* Biozone) just above a thick bedded massive bioclastic trilobite-brachiopod-crinoid grainstone to packstone of very shallow water (Fig. 9H) which contains a rich community of trilobites, relatively big articulated brachiopods, crinoids, beautifully preserved bryozoans, gastropods, graptolites and corals. Peloids are locally concentrated. *Stromatactis* like structures are visible in outcrop. No gradating or lamination have been observed in the field. In thin section, however, thin micritic intercalations have been found.

A quiet micritic environment of undisturbed sedimentation below wave base with small, thin-shelled

FIGURE 6—Sharp erosive base of a coarse bio-debris episode in the Kosov Type limestone. Clasts of the underlying micritic sediment are included in the upper coarse-grained limestone. Kosov Quarry, section n. 782.

FIGURE 7—General aspect of a slab of the Kosov Type cephalopod limestone. Current direction is from left to right. Kosov Quarry, section n. 782, Ludlow.

ostracods, small bivalves, crinoids, brachiopods, trilobites, gastropods and sponge spicules, was periodically reached by storms, depositing only some centimeters thick winnowed shell lags with sharp erosional bases.

These shell layers, composed primarily of granule-size fossil debris and shale clasts, are close one each other. This could suggest low sedimentation rate (as also indicated by oxide-crusts) and that they were a

FIGURE 5—Typical aspect of Kosov Type limestone in thin section. A) Cross-sectioned orthocoones in a bioclastic sediment. Bioclasts (ostracods, gastropods, small bivalves and unrecognizable fragments) are often coated by micritic envelopes. Kosov Quarry, uppermost Ludlow, $\times 4.5$. B) Shelter porosity and calcite-roofs are well expressed. Note bio-sediment gradation in the nautiloid body chamber. Kosov Quarry, uppermost Ludlow, $\times 4.5$.

normal trend in the area. High percentages of benthic forms (gastropods, brachiopods, trilobites) and articulation of many juvenile bivalves suggest a proximity to the source area. At the same time large cephalopods were accumulating in a micritic deeper environment below normal storm wave base, where normal current of the Braník Type cephalopod limestone was acting. Here most of these longiconic and rare cyrtconic cephalopods, swimming and living close to the bottom, descended to the sea floor after death of the organism. There, they were buried in micritic sediment and had their body chamber completely filled by the same sediment. A probable much more intense storm event at the end of the alternation reached deeper areas and involved also these larger cephalopods with micrite infilling. Sedimentation of this big last "cloud" of large cephalopods included also small ones and was followed by reorientation of both and winnowing of finer sediment by the same storm current. Micrite could remain only in sheltered areas (such as body chambers of big orthocones).

The deposition which occurred in the Kosov Area is one of the best examples of how intensive volcanic activity and accumulation of volcanoclastics can influence sedimentation and facies development in a basin. The Kosov Area represented an elevation responsible for development of typical rich shallow water benthic communities, often buried by volcanic products (mainly tuffs), and explosive bioclastic sedimentation.

Shell Preservation

Organisms of the Braník Type have different sizes; a slight sorting is locally evident. Cephalopods have circular cross-section so no intensive deformation took place. Telescoping (both of cephalopods and other shells) and geopetal structures are common.

A peculiar geopetal structure of some brachiopods, infilled by peloids in the lower part of the shell is in Fig. 9C. Equidimensional bioclasts, frequently coated by micrite, abundant pellets, ostracods and crinoid fragments are the main constituents of the matrix. The same admixture is present inside the shells; iron-oxides are common in small juvenile articulated bivalves and gastropods, giving rise to particular geopetal structures. Iron-oxides inside shells may have developed in two ways, or directly as infillings of circular microborings (?bacterial activity) with a concentric growth or as precipitation from the outside to the center of the shell. Shelter porosity beneath shell is then filled with bladed calcite cement. Coarser peloidal sediment and skeletal debris beneath large shells may grade upward to finer-sediment under sheltered voids. Normal gradation can be observed also in some samples, where big cephalopods are at the base while the upper part of the deposit consists of smaller shells. Intraclasts are also present. Carbonized fragments of algae (*Prototaxites*) which occur in the cephalopod limestones at the Wenlock-Ludlow boundary (Arethusina Gorge, *T. testis* Biozone and Jinonice, *C. colonus* Biozone) are remarkable. Dolomitization is sometimes so widespread to obliterate the original structure. Crinoidal fragments are frequently overgrown by calcite crystals in optical continuity (Fig. 9A). Bioturbation and its typical mottled appearance has been rarely observed. Sedimentation rate inferred for this limestone is very low.

The Kosov-Type limestone matrix is micritic. Micrite is sometimes recrystallized in a mosaic of pseudosparite, especially in sheltered areas. Sparite is present in some of the higher energy events as infilling of primary vugs and voids in the shells and within them. Lamination is sometimes visible in the matrix of the

biomicritic limestone; bioturbation also occurred there. Gradation is locally developed in high-energy events with finer material at the bottom. Both the limestones are comparatively rich in pyrite. Finely disseminated crystalline aggregates are more frequent than framboidal ones; pyrite is also found along bioclast rims. Contemporaneous presence of pyrite and benthic organisms indicates that reducing conditions were created after transport and shell deposition.

CEPHALOPOD ORIENTATIONS

The problem of cephalopod orientation has been directly observed in the field (e.g., Petránek and Komárková, 1953; Krinsley, 1960; Laufeld, 1974; Sundquist, 1982; Hewitt and Hurst, 1983; Skinner and Johnson, 1987) and the subject of laboratory experiments with different plastic models or empty shells (e.g., Reymont, 1958, 1968; Loubere, 1977; Gnoli et al., 1980). Orthoconic cephalopods are particularly useful fossils for directional and hydrodynamic analysis, as they have a predominant axis of symmetry. Possibility of extensive transport of actual empty, drifting cephalopod shells in oceanic waters has been extended to the past to imply that many or all fossil nautiloid accumulations represent deposition after some transport from the living habitat of the organism. In another interpretation, most Paleozoic nautiloid assemblages would represent true biological associations that were essentially in place, accumulating in the area occupied by the living animals (Flower, 1957). Moreover, in the Silurian in particular, the deposits in which we generally find nautiloids are more probably typical of shallow water rather than oceanic conditions (Holland, 1984).

It is important to realize how many unknown variables are present in the problem: i.e., weight of the organism, velocity of the current, presence or

FIGURE 8—Photographic details of Figure 7. A) Isoriented small cephalopods widespread among bigger conchs. B) A "trap-structure": smaller cephalopods share the same orientation of bigger cephalopods, as they could not assume the more stable position of apex facing current, being obstructed by the presence of the bigger ones. Scale bar = 10 cm.

absence of air in the shell, depth, water temperature, existence of cameral deposits and size and presence of body chamber. So, many of the results derived from experiments have to be considered as simple suggestions and not real rules. Nevertheless, Reymont's work (1958) still stands as one of the best examples dealing with the subject. He concluded that "positively buoyant orthocones lacking significant apical cameral deposits probably drifted in oblique, apex-up orientations; orientations varied from essentially horizontal "boat-like" drifting for phragmocones lacking living chambers to vertical for conchs with large living chambers. For intermediate conditions, conchs listed obliquely in the water with the apex protruding above the surface" (Baird, Brett and Frey, 1989). After deposition, it is generally accepted that elongate conical bodies will be orientated with their long axes in a uni-directional current with their apical end upstream (Kindle, 1938; Nagle, 1967; Laufeld, 1974).

We developed our study using different steps. First of all, we collected in the field as many indications and measurements as possible and then tested our conclusions with very simple laboratory experiments and with theoretical criteria. Two different situations, one for each type of cephalopod limestone just described, occur.

Braník Type

Almost all of the orthocones share the same SW-NE orientation and have apexes pointing mostly to SW. This is common both to small and big shells (even if smaller than those found in the Kosov Type limestone). Most cephalopods have long body

chambers infilled by the same coarse-grained sediment present between the shells. This would imply, according to generally accepted evidences, a

current moving from SW to NE. Nevertheless, we searched carefully in the field and in thin sections other direct current evidences to test a conclusion

FIGURE 10—Interpretation of cephalopod deposition and orientation in the Upper Wenlock calcareous shales of Kosov Quarry according to Turek (1983). Cephalopods were transported by the current with apex-up orientation. Once they came to rest on the bottom, they could entrap graptolite rhabdosomes in the characteristic graptolite "comets."

FIGURE 9—Typical photomicrographs of the Braník Type (A–D) and Kosov Type (E–H) cephalopod limestone. A) Calcite crystal overgrown in optical continuity on a crinoid fragment. A trilobite fragment is present in the upper part of the picture. Řeporyje, Požáry Section, *M. fritschi linearis* Biozone, Ludlow, $\times 60$. B) Transverse section of orthocones showing geopetal internal sediment. Jinonice, *C. colonus* Biozone, Ludlow, $\times 10$. C) Geopetal structures of brachiopods infilled by peloids in the lower part of the shell. Mušlovka Quarry, *M. fritschi linearis* Biozone, Ludlow, $\times 10$. D) Iron-oxides concentration along rims of a cephalopod shell. Jinonice, *C. colonus* Biozone, Ludlow, $\times 10$. E) Sponge spicules and gastropods in a micritic mudstone. Kosov Quarry, section n. 782, Ludlow, $\times 20$. F) Bioclasts covered by micritic sediment are typical constituents of the matrix of higher-energy events. Kosov Quarry, section n. 699, uppermost Ludlow, $\times 60$. G) Bioclasts as sediment infilling of a nautiloid. Kosov Quarry, section n. 699, uppermost Ludlow, $\times 10$. H) Packstone rich in corals, crinoids, bryozoans and trilobite fragments. Kosov Quarry, section n. 777, uppermost Ludlow, *M. fragmentalis* Biozone, $\times 10$.

mainly derived from artificial experiments. We found no real proofs, but only simple suggestions and subjects open to discussion.

The apex facing current direction is undoubtedly the more stable shell position, therefore the orthocones of the Braník Type limestone, even if eventually deposited in an opposite direction, had enough time to be reoriented.

The lowermost Ludlow cephalopod limestones, deposited on the southern slope of the Nová Ves Volcanic Centre volcanoclastic accumulation (Kříž, 1991, 1992), show the same cephalopod orientation seen in other outcrops, but they lack the tuffaceous admixture which would be there with a current from NE to SW.

Nautiloid specimens are frequently telescoped one into another. Telescoping is an important but puzzling point to understand. If one considers telescoping happened when the shells were already deposited on the bottom, it is then difficult to imagine an infilling of the shells perfectly one inside each other with a current moving in the opposite direction. A possible explanation is that telescoping occurred within the current before deposition (but again the direction of transport of the shells is supposed with apex against the current) or that a kind of turbulence could develop just behind the "host" shell immediately after deposition. Transversal sections of the specimens show how telescoping is not limited to the bottom of the shell, but it is much more frequent exactly inside them: that is telescoping happened when bigger outer shells were partly filled by sediment.

Shell infilling by sediment in geopetal structures is only partial, as expected by body chamber openings not in current direction: that is again with apices facing the current.

Kosov Type

A WSW–ENE current has been suggested by Turek (1983) in the deeper water upper Wenlockian shales (*T. testis* Biozone) in the Kosov Area. Apices of most cephalopods he studied were pointing in fact

FIGURE 11—Reconstruction of the history of deposition of the Kosov Type cephalopod limestone. A) Close to volcanic elevation, storms were active removing material and depositing shell-lags, while at bigger depths current-transported orthocones were normally accumulating. B) A probable larger event reached deeper waters and involved also large orthocones there accumulated. C, D) All the orthocones were then reoriented by the existing current. Big orthocones, with heavy body chamber filled with micritic sediment, were mostly shifted in apex up vertical position and then deposited aligned in the current direction. Only smaller orthocones (mostly without body chambers) were then reoriented in opposite direction to a most stable

FIGURE 12—Interpretation for the Silurian cephalopod limestone depositional environment in the Prague Basin. Close to volcanic centers, brachiopod-trilobite association developed in shallower and better ventilated waters (Kosov Type cephalopod limestone). At greater depths but still in regime of surface currents, typical current-oriented cephalopods and bivalve-dominated communities mostly living on empty cephalopod shells are present (Braník Type cephalopod limestone). Black shale deposition persisted in the deepest parts of the basin during the Silurian.

to WSW. Some shells, preserved inclined to the bedding plane or even vertical, entrapped graptolite rhabdosomes in the famous “comets” structures (Fig. 10) documenting a WSW–ENE current direction.

Both in the middle and uppermost Ludlow cephalopod limestones of Kosov Quarry a peculiar situation occurs: shells are predominantly parallel to the bedding plane and directed in a N–S direction, but with different orientation according to their size. Big longiconic orthocones up to 35 cm long, mainly michelino-

ceratids complete with the body chamber, have apices pointing to the north. Small orthocones, almost completely lacking the body chamber, have apices pointing in opposite direction to the south. Bigger shells have frequently body chambers filled with fine micritic sediment, which is also present in sheltered areas. The problem of different shell orientations according to size is not new, starting from Kay (1945) who distinguished two different perpendicular orientations of cephalopods in Upper Ordovician sediments, going on with

Schleiger (1968) who reported a similar situation with graptolites as a response to different energy of the current.

Prevalent Current Directions

A current moving from SW to NE is suggested for the Braník Type. But which is the current responsible of this orientation? We suggest that the answer lies in consideration of the entire Gondwana area, and not limiting the study to Bohemia (in contrast to the Kosov Type situation). The current we are playing with is not local, but it is a widely spread current moving along the northern Gondwana shelf (Bohemia, Carnic Alps, Sardinia, Morocco, Montaigne Noire) that

position on the bottom (by apex against current direction) by the same current losing energy or a later one. Big orthocones, filled by micritic sediment, were too heavy to be reoriented. A “trap structure” of small orthocones is indicated with “t.”

caused here the deposition of the densely-packed cephalopod limestones exactly at the same stratigraphic levels and that made possible that exactly the same benthic communities could develop exactly at the same time in so distant areas. Then, this current was probably a surface current ventilating the bottom, enabling the surviving of bivalve-dominated recurring communities of the *Cardiola* Community Group and of benthic cephalopods living in the basin and the larval dispersal (actual surface currents may reach the depth of 200 m). The current had a S-N direction in the Kosov Volcanic Centre region and changed its direction north of this region (Fig. 2) in front of volcanic accumulations in the Svätý Jan and Nová Ves Volcanic Centres, developed along the SW-NE synsedimentary growth fault (Kříž, 1991, 1992). Current direction then followed the direction of volcanic accumulations (SW-NE) and kept constant from late Wenlock to latest Pridoli at least, even if shifting laterally from NW to SE.

According to the study of the outcrops, the general consideration of the basin, microfacies analysis and the Kosov Volcanic Centre situation, we interpret the Kosov-Type cephalopod orientation as local response to the action of storm currents (Fig. 11), able to involve also bigger shells of deeper waters (as revealed clearly by different body chamber infilling in bigger orthocones). As body chamber infilling in distal portion of the shell would have notably increased weight, big orthocones were most probably shifted in apex-up position (Reyment, 1958) and deposited simply within the current aligned with its constant linear direction. Micrite could stand in sheltered areas as well as in the same body chambers. Smaller phragmocones were possibly deposited slightly later when the current was losing energy, and were reoriented or directly inside the water or more probably after deposition by the same current or a later one. Thanks to their light weight, they were more susceptible to reorientation in the stable position of apex toward the current. This is the main

evidence of a current moving from S to N. On the contrary, once resting on the bottom, big orthocones were too heavy to be pivoted in a new more stable position. This explains the different cephalopod orientations according to shell size observed in the field. Particles interfered with each other ("neighbouring effect"; Grahn, 1986). Some small shells share the same orientation of big ones; this is evidenced by "trap-structures" (Fig. 8B) of small orthocones deposited in the shadow of bigger ones, forced to keep an opposite direction as they could not find space to be reoriented.

CONCLUSIONS

The cephalopod limestone biofacies was apparently coupled with the Silurian equatorial current regime. Such a distribution was developed close to the Silurian equatorial region in northern Gondwana and in Tajmyr Basin (Zlobin, 1965; Kříž and Bogolepova, in press). This facies is considered to be dependent on the presence of a surface current which caused partial ventilation of deeper parts of the basins during low-stand events and was distributing bivalve, gastropod and other fauna larvae and empty cephalopod shells over the region. Cephalopod shells represented a firm substrate important for the development of epibyssate bivalve-dominated communities of the *Cardiola* Community Group (Kříž, in press a). A preferred orientation of cephalopod shells facilitates reconstruction of the paleocurrent directions.

The two occurrences of Braník Type and Kosov Type cephalopod limestone must be seen as different perspectives of the same view, as they simply represent two depositional cases occurring at different depths and hydrodynamic regime. The Kosov Type suggests shallower and better ventilated water, periodically swept by storm action. The Braník Type was deposited at greater depths, although it was still affected by surface currents. In deepest parts of the basin, sedimentation of black shales and anoxic conditions continued undisturbed in Wenlock and Ludlow time (Fig. 12).

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REFERENCES

- BAIRD, G.C., BRETT, C.E., and FREY, R.C., 1989, "Hitchhiking" epizoans on orthoconic cephalopods: Preliminary review of the evidence and its implications: *Senckenbergiana lethaea*, v. 69, p. 439-465.
- BARRANDE, J., 1846, Notice Préliminaire sur le Système Silurien et les Trilobites de Bohême, Leipzig, p. 1-97.
- BARRANDE, J., 1852, 1881, *Système Silurien du Centre de la Bohême*: vol. I, VI, Prague, Paris.
- FERRETTI, A., 1989, Microbiofacies and constituent analysis of Upper Silurian-Lowermost Devonian limestones from Southwestern Sardinia: *Bollettino della Società Paleontologica Italiana*, v. 28, p. 87-100.
- FLOWER, R.H., 1957, Nautiloids of the Palaeozoic: in H. LADD, ed., *Treatise of Marine Ecology and Paleoecology*: Geological Society of America, Memoir 67, p. 829-852.
- GNOLI, M., PAREA, G.C., RUSSO, F., and SERPAGLI, E., 1980, Paleoeological remarks on the "*Orthoceras* limestone" of southwestern Sardinia (middle-upper Silurian): *Memorie della Società Geologica Italiana*, v. 20, p. 405-423.
- GRAHN, Y., 1986, Orthocone nautiloid orientations in Arenig and Llanvirn limestones of Öland, Sweden: *Geologiska Föreningens i Stockholm Förhandlingar*, v. 104, p. 321-330.
- HEWITT, R.A., and HURST, J.M., 1983, Aspects of the ecology of actinocerid cephalopods: *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, v. 165, p. 362-377.
- HOLLAND, C.H., 1984, Form and function in Silurian cephalopoda: in BASSETT, M.G., and LAWSON, J.D., eds., *Autecology of Silurian Organisms: Special Paper in Palaeontology*, v. 32, p. 151-164.
- JAEGER, H., 1975, Die Graptolithenführung im Silur/Devon des Cellon-Profiles (Karische Alpen): *Carinthia II*, v. 165, p. 111-126.
- KAY, M., 1945, Paleogeographic and palinspatic maps: *Bulletin of the American*

- Association of Petroleum Geologist, v. 29, p. 426–450.
- KINDLE, E.M., 1938, A pteropod record of current direction: *Journal of Sedimentary Petrology*, v. 12, p. 515–516.
- KRINSLEY, D., 1960, Orientation of orthoceracone cephalopods at Lemont, Illinois: *Journal of Sedimentary Petrology*, v. 30, p. 321–323.
- KŘÍŽ, J., 1979, Silurian *Cardiolidae* (Bivalvia): *Sborník Geologických Věd, Palaeontology*, v. 22, p. 5–157.
- KŘÍŽ, J., 1991, The Silurian of the Prague Basin (Bohemia). Tectonic, eustatic and volcanic controls on facies and faunal development: *Special Paper in Palaeontology*, v. 44, p. 179–203.
- KŘÍŽ, J., 1992, Silurian field excursions: Prague Basin (Barrandian), Bohemia: *National Museum of Wales, Geological Series*, v. 13, p. 1–111.
- KŘÍŽ, J., in press (a), Bivalvia dominated communities of Bohemian type from the Silurian and Lower Devonian carbonate facies: in BOUCOT, A.J., and LAWSON, J.D., eds., *Final Report, Project Ecostratigraphy*: Cambridge University Press, Cambridge.
- KŘÍŽ, J., in press (b), Silurian Bivalvia of Bohemian type from Montagne Noire and the Massif Mouthomet, France: *Palaeontographica*.
- KŘÍŽ, J., and BOGOLEPOVA, O.K., in press, Bivalvia dominated *Cardiola signata* community in cephalopod limestone biofacies from Tajmyr (uppermost Gors-tian, Ludlow, Silurian, Russia): *Geobios*.
- KŘÍŽ, J., JAEGER, H., PARIS, F., and SCHÖNLAUB, H.P., 1986, Přídolí—The fourth subdivision of the Silurian: *Jahrbuch der Geologischen Bundesanstalt*, v. 129, p. 291–360.
- KŘÍŽ, J., and SERPAGLI, E., 1993, Upper Silurian and lowermost Devonian Bivalvia of Bohemian type from Southwestern Sardinia: *Bollettino della Società Paleontologica Italiana*, v. 32, p. 289–347.
- LAUFELD, S., 1974, Preferred orientation of orthoconic nautiloids in the Ludlovian Hemse Beds of Gotland: *Geologiska Föreningens i Stockholm Föreläsningar*, v. 96, p. 157–162.
- LOUBERE, P., 1977, Orientation of orthocones in the English Lake District based on field observations and experimental work in a flume: *Journal of Sedimentary Petrology*, v. 47, p. 419–427.
- NAGLE, J.S., 1967, Wave and current orientation of shells: *Journal of Sedimentary Petrology*, v. 37, p. 1124–1138.
- PETRÁNEK, J., and KOMÁRKOVÁ, E., 1953, Orientace schránek hlavonožců ve vápencích Barrandienu a její paleogeografický význam: *Sborník Ústředního Ústavu Geologického*, v. 20, p. 129–148.
- REYMENT, R.A., 1958, Some factors in the distribution of fossil cephalopods: *Stockholm Contributions in Geology*, v. 1, p. 97–179.
- REYMENT, R.A., 1968, Orthoconic nautiloids as indicators of shoreline surface currents: *Journal of Sedimentary Petrology*, v. 38, p. 1387–1389.
- SCHLEIGER, N.W., 1968, Orientation distribution patterns of graptolite rhabdosomes from Ordovician sediments in central Victoria, Australia: *Journal of Sedimentary Petrology*, v. 38, p. 462–472.
- SKINNER, D.F., and JOHNSON, M.E., 1987, Nautiloid debris oriented by long-shore currents along a late Ordovician-early Silurian rocky shore: *Lethaia*, v. 20, p. 157–164.
- SUNDQUIST, B., 1982, Wackestone petrography and bipolar orientation of cephalopods as indicators of littoral sedimentation in the Ludlovian of Gotland: *Geologiska Föreningens i Stockholm Föreläsningar*, v. 104, p. 81–90.
- TUREK, V., 1983, Hydrodynamic conditions and the benthic community of upper Wenlockian calcareous shales in the western part of the Barrandian (Kosov quarry): *Časopis pro mineralogii a geologii*, v. 28, p. 245–260.
- WALLISER, O.H., 1964, Conodonten des Silurs: *Abhandlungen des Hessischen Landesamtes für Bodenforschung*, v. 41, p. 1–106.
- WESTERMANN, G.E.G., 1985, Post-mortem descent with septal implosion in Silurian nautiloids: *Paläontologische Zeitschrift*, v. 59, p. 79–97.
- ZLOBIN, M.N., 1965, Eastern Taimyr: in *Stratigrafija SSSR, Silurijskaja sistema*, Izdat. Nedra, p. 364–370.

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