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Konzentrat-Lagerstätte-type carbonate concretions from the uppermost Bajocian (Middle Jurassic) of the Częstochowa area, South-Cental Poland

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Early-diagenetic calcitic concretions of latest Bajocian (*parkinsoni* Zone, *bomfordi* Subzone) age in the Polish Jura contain an extremely rich and well-preserved macrofauna. In addition to bivalves and brachiopods, there are numerous ammonites of the (sub)genera *Parkinsonia*, *Nannolytoceras*, *Lissoceras* (*Lissoceras*), *L.* (*Microlissoceras*), as well as rare representatives of *Vermisphinctes*, *Strigoceras* (*Strigoceras*) and *Phylloceras*. Carapaces of primitive prosopid crabs are found associated. Such a diverse and well-preserved fauna (previously unknown from Bajocian epicratonic deposits of the Polish Jura), is typical of Konzentrat-Lagerstätte-type deposits. The random distribution of the concretions in exposure and the small size of the fauna may suggest that all remains were concentrated by bottom-current action in small depressions on an uneven sea-floor. The presence of numerous small-sized ammonites may be regarded as reflecting post-spawning assemblages which suffered mass-mortality. Although cause of their death remains unclear, storm events are a possibility. Such depressions acted as natural "traps" as well as constituted a size-limiting factor for the accumulating fauna. The fact that all elements are well preserved indicates brief post-mortem transport and rapid burial, followed by early diagenesis that protected them from compaction. The absence of such fossil-rich concretions higher in the Middle Jurassic sequence clearly shows that our current assessment of biotic diversity may be an underestimate. The carbonate concretions contain a predominantly terrestrial type of organic matter (OM). Samples analysed are extremely immature, but early diagenetic transformations of OM occurred prior to concretion formation.

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INTRODUCTION

Carbonate concretions undoubtedly constitute a valuable source of palaeontological information. In the surrounding matrix, fossil faunas can often be relatively impoverished (El Albani *et al*., 2001); however, within carbonate concretions fossils are generally perfectly preserved. This holds true mainly for concretions which originated during early diagenesis processes (Brett and Baird, 1986), when all the biological remains underwent mineralization (e.g. calcitic or pyritic) prior to compaction, which safeguarded them from subsequent destruction.

Such carbonate concentrations are widely distributed in time and space. They are known from e.g. the Carboniferous of the United States (Baird, 1990) and Canada (Zodrow and Cleal, 1999), the Middle Jurassic of Germany (Geraghty and Westermann, 1994), the Upper Cretaceous (Turonian and Coniacian) of Morocco (El Albani *et al*., 2001), Sakhalin (Yazykova, 1994, 2002; Wilmsen and Yazykova, 2003), Japan (Maeda, 1987, 1991; Wani, 2003) and the United States (Walaszczyk *et al*., 2001; Ozanne and Harries, 2002) and the Paleogene of New Zealand (Middleton and Nelson, 1996). In Poland, carbonate concretions generally occur in Middle Jurassic (Bajocian and Bathonian), ore-bearing clays in the Kraków–Wieluń Upland, and are especially sought after because of their well-preserved ammonite fauna (e.g. Różycki, 1953; Majewski, 2000; Matyja and Wierzbowski, 2000), and one of the most influential palaeobiological papers on the sexual dimorphism of ammonites was based upon perfectly preserved material from the locality of Łuków (Makowski, 1962).

The main aim of this paper is to describe unusual latest Bajocian carbonate concretions from the Polish Jura: their fossil content, organic geochemistry and origin. Gas Chromatography-Mass Spectrometry (GC-MS) methods were used to define the source of organic matter occurring in the concretions, as well as to shed light on sedimentary conditions prevailing during OM deposition.

The main interest of these concretions lies in the fact that they occur at a single exposure only, where they do not form continuous levels, in contrast to siderite concretions in the area (Majewski, 2000; Matyja and Wierzbowski, 2000). Moreover, they yield the most diverse and best-preserved fauna in the whole Kraków–Częstochowa area.

LOCALITY AND GEOLOGICAL SETTING

The carbonate concretions under discussion come from Kawodrza Górna, *ca*. 11 km west of Częstochowa (Fig. 1A–C), from a sequence exposed at the "Sowa" working brick-pit. The section was logged on the southern quarry face (Fig. 1D); it comprises dark grey clays averaging *ca*. 8.5 m in thickness, in part bioturbated, with common detritus, fragments of wood, as well as gastropods (pleurotomariids), bivalves (frequent *Trigonia*), brachiopods (mainly rhynchonellids), fragmentary belemnite rostra, fragmentary and crushed ammonites and isolated shark teeth (Palaeospinacidae, Jürgen Kriwet, pers. comm.). In some places, rhynchonellid clumps and oyster (*Liostrea*) "reefs" occur. This monotonous clay sequence is interbedded with three grey and grey-brownish levels of massive siderite, and a single level of limonitic sphaerosiderite. The section forms part of the Częstochowa Ore-bearing Clay Formation (Kopik, 1998).

The lowermost siderite level (A) is 16 cm thick and contains rare rhynchonellids and bivalves (*Trigonia*, *Corbula*), as well as pieces of wood. Isolated ammonites, assigned to *Parkinsonia* (*Parkinsonia*) aff. *dorni* Arkell, also occur. The overlying siderite level (B) is 14 cm thick and also contains rare parkinsoniids. Locally, small rhynchonellid and bivalve (*Trigonia*, *Corbula*, *Liostrea*) patches may occur. The next level (C) comprises grey-brownish, weathered siderite 12 cm thick. Apart from small parkinsoniids assigned to the above species, it contains bivalves of the genus *Pholadomya*. The highest level (D) consists of 10 cm thick, limonitic and oval-shaped sphaerosiderites, yielding shell fragments.

Level A was formerly exposed at the nearby "Anioł" brick-pit (Matyja and Wierzbowski, 2000). This level, as well as levels B and C at the "Sowa" brick-pit, were assigned by Matyja and Wierzbowski (2000) to the uppermost Bajocian (*parkinsoni* Zone, *bomfordi* Subzone). Sphaerosiderite level D, on the other hand, was assigned by the same authors to the lowermost Bathonian (*zigzag* Zone, *convergens* Subzone). A similar age assignment was obtained by Poulsen (1998) based on dinoflagellate cysts. The most interesting part of the section, however, is the interval between levels A and B (Fig. 1D), since here, in certain places, occur fossil-rich carbonate concretions. Majewski (2000) only mentioned two, discontinous occurrences. Unfortunately, their exact position in the section has not yet been traced, consistent with the random distribution of these concretions.

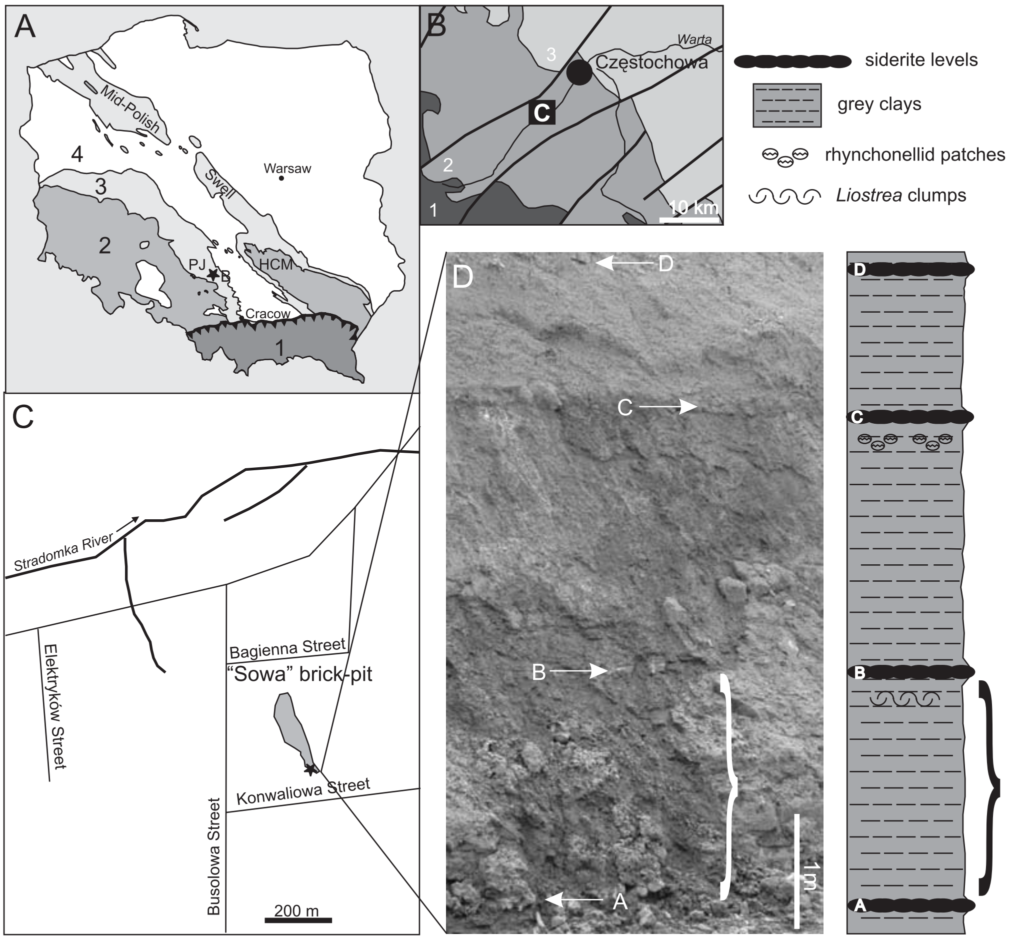

Fig. 1. A — simplified geological map of Poland without Cenozoic cover: the asterisk — area investigated, 1 — Carpathian Orogen, 2 — Pre-Jurassic rocks, 3 — Jurassic rocks, 4 — Cretaceous rocks, PJ — Polish Jura, HCM — Holy Cross Mts.; B — geological map of the study area: 1 — Lower Jurassic, 2 — Middle Jurassic, 3 — Upper Jurassic; C — localization sketch of "Sowa" brick-pit at Kawodrza Górna (adopted from Matyja and Wierzbowski, 2000), the asterisk — face investigated; D — the photograph of the section investigated with indicated siderite levels (A–D), with schematic section to better show their position, the brackets indicate the interval of fossil-rich carbonate concretions

It is worth noting that currently the lower half of the sequence, up to the level C, is covered due to a continuous exploitation of the clays. The uncovering of this level will take place not before *ca*. 2006.

MATERIAL AND METHODS

Several carbonate concretions have been broken and the ammonite fauna was separated as carefully as possible. Due to the very hard nature of these concretions, some ammonites were crushed, and only the most complete have been measured for statistical purposes. All retrieved ammonites (complete and large fragments) have been counted and calculated as percentages. The rest of the fauna, especially bivalves, were assigned to genus level. Thin-sections were prepared to described the general characteristics of the biofacies.

A sample from one carbonate concretion was subjected to geochemical analysis, including total organic carbon (TOC), Gas Chromatography-Mass Spectrommetry (GC-MS) and X-ray diffractometry (XRD). Surrounding clays from the same level as the concretions, as well as massive siderite levels A and B (Fig. 1D) were also sampled for comparative data. Level C was excluded from the analysis, because of its considerable degree of weathering.

1. The total organic carbon (TOC) content was determined using an automated *LECO CR-12* analyser by the method described by Marynowski *et al*. (2000).

2. Extraction and fractionation. The powdered to finer than 120 mesh samples were Soxhlet-extracted in pre-extracted thimbles with dichloromethane for 72 h. Extracts were further separated using preparative pre-washed TLC plates coated with silica gel (Merck, 20 × 20 × 0.25 cm). Prior to separation, the TLC plates were activated at 120°C for 1 h. The plates were loaded with the *n*-hexane soluble fraction and developed with *n*-hexane. Bands comprising aliphatic (R_f 0.4–1.0), aromatic (R_f 0.05–0.4) and polar (R_f 0.0–0.05) fractions were collected.

3. Gas Chromatography-Mass Spectrometry (GC-MS). GC-MS analysis was carried out with a *HP6890 II* gas chromatograph equipped with a fused silica capillary column (60 m × 0.25 mm i.d.) coated with 95% methyl/5% phenylsilicone phase (DB-5MS, 0.25 µm film thickness) and 50% methyl/50% phenylsilicone phase (DB-17MS, 0.25 µm film thickness). Helium was the carrier gas used. The GC oven was programmed from 35 to 300°C at a rate of 3°C min^{-1}. The gas chromatograph was coupled with a *HP 5973* mass selective detector (MSD). The MS was operated with an ion source temperature of 200°C, an ionisation energy of 70 eV, and a cycle time of 1 sec in the mass range 40–600 Daltons.

4. X-ray diffractometry (XRD). The samples were powdered and analysed with X-ray diffractometry (XRD) using a horizontal goniometer (*HZG-4B*), Cu-Ka radiation and Ni-filter.

THE LAGERSTÄTTE CONCEPT

The term "Lagerstätte" (plural Lagerstätten) is derived from the German mining tradition, referring to any rock or sediment body containing constituents of economic interest (Seilacher, 1990). Accordingly, a "Fossil-Lagerstätte" is any rock containing unusually well-preserved and (or) exceptionally abundant fossils (Briggs, 2001). Generally, two types of Lagerstätten-type deposits (Seilacher, 1990; Speyer and Brett, 1991; Briggs, 2001) can be distinguished:

1. Deposits yielding exceptionally well-preserved fossils (Konservat-Lagerstätten). In this case, organisms not only preserve their hard parts, but also the soft tissues, due to specific decay patterns of the organic matter, leading to authigenic mineralization caused by anaerobic bacterial activity (Sagemann *et al*., 1999; Allison, 2001). Here, the main interest lies in the individual quality of preservation. There are many examples of this type of preservation, ranging in age from the Precambrian to the Quaternary and in marine as well as terrestrial environments (for detailed reviews see Briggs and Crowther, 1990, 2001; Martin, 1999). Polish examples include well-preserved fauna (insects, xiphosurans, eurypterids) and flora from Upper Carboniferous sphaerosiderites (Filipiak and Krawczyński, 1996; Krawczyński *et al*., 1997).

2. Deposits of high fossil concentration (Konzentrat-Lagerstätten). This type not only concerns biological remains preserved in large quantities (coquinas, oyster beds, bone beds), but also with unaltered hard parts. This type of Lagerstätte, in contrast to the previous one, can also form over longer periods of time, causing such assemblages to be time-averaged (Kidwell and Bosence, 1991; Kidwell, 1998; Niedźwiedzki, 2002). Polish Konzentrat-Lagerstätten include the beautifully preserved Middle Jurassic ammonite faunas from Łuków (Makowski, 1952, 1962; Dzik, 1990), the Bathonian ammonite faunas from Faustianka, Wieluń Upland; and Late Triassic vertebrate remains from Krasiejów (Dzik *et al*., 2000; Dzik, 2001).

Rapid burial of biological remains means that soft parts are safeguarded from scavengers, and hard parts from chemical (oxidation, dissolution), physical (abrasion, fragmentation) and biological (bioerosion) agents (Brett and Baird, 1986; Brett, 1990). Therefore, both types of Lagerstätten, contrary to the "common" accumulation of biological remains, allow for precise quantitative and qualitative analyses of biocenotic assemblages over short timespans (Konzentrat-Lagerstätten), as well as for detailed palaeobiological studies of organisms which normally have low fossilization potential (Konservat-Lagerstätten).

TYPICAL FEATURES OF CALCITIC CONCRETIONS FROM KAWODRZA

The carbonate concretions from the uppermost Bajocian of Kawodrza are calcitic, as shown by XRD analysis. They are moderate in size (up to *ca*. 16 cm in diameter), oval or spherical in shape and dark grey in colour. In cross-section, they show two distinct zones: an inner, darker (almost black) zone, richest in fossil content, consists of pure calcite with organic matter, and an outer zone, grey in colour, *ca*. 2 cm thick, containing a scarce fauna, and consisting of calcite with significant amounts of quartz (Fig. 2A). Both zones contain very small amounts of siderite and pyrite. These concretions, apart from their rich fossil content, are highly indurated.

They contain representatives of many groups, such as gastropods, scaphopods (*Dentalium*), bivalves (*Trigonia*, *Alectryonia*, *Liostrea*, *Pleuromya*, *Palaeonucula*, *Corbula*, *Goniomya*, pectinids), rhynchonellid brachiopods, carapaces of prosopid crabs (Krobicki and Zatoń, in prep.) and, of special note, ammonites, most of which were documented for the first time from the Bajocian of epicratonic Poland (Zatoń and Marynowski, submitted). The ammonite fauna consists mainly (78%) of parkinsoniids (*Parkinsonia*). Second in abundance are lytoceratids (*Nannolytoceras* — 13%) and lissoceratids (*Lissoceras* (*Lissoceras*) and *L.* (*Microlissoceras*) — 7%). Isolated occurrences are known of phylloceratids (*Phylloceras*), leptosphinctids (*Vermisphinctes*) and strigoceratids [*Strigoceras* (*Strigoceras*)], which constitute only 2% of the whole ammonite assemblage. Parkinsoniids are considered to have mostly lived beyond the Mediterranean areas (mainly NW Europe). The other ammonite species, however, were most diverse in taxa and numbers in Tethyan areas (Galácz, 1980). In addition to faunal remains, each concretion contains numerous fragments of wood.

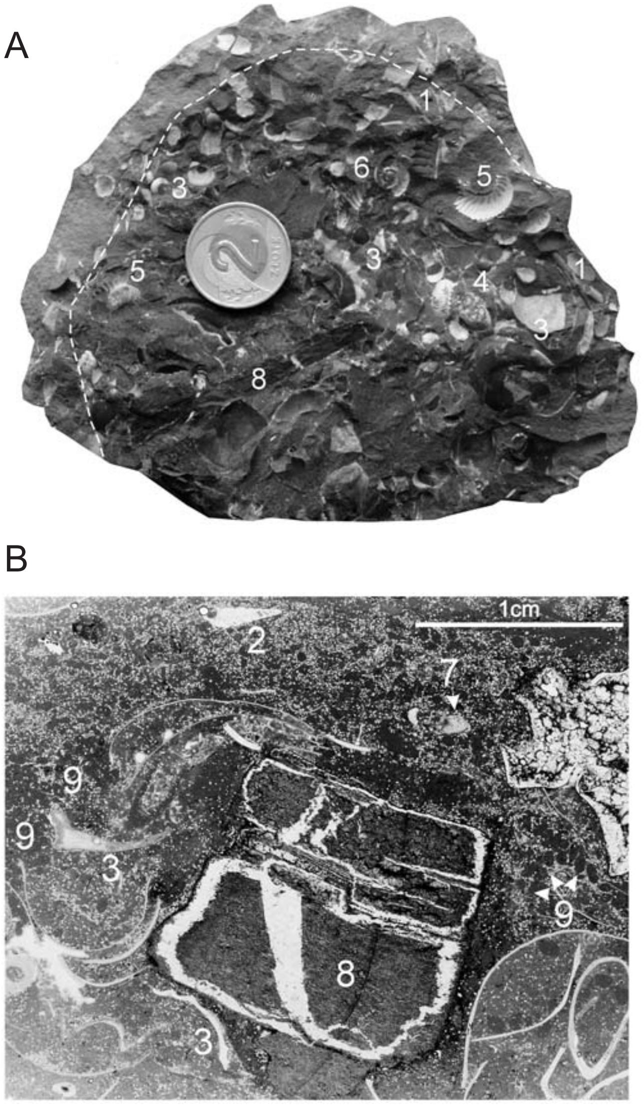

Fig. 2. A — broken carbonate concretion showing dense accumulation of fossils: the dashed line indicates the boundary between the outer and inner zone; B — thin-section showing a densely-packed shelly biomicrite microfacies

1 — scaphopods, 2 — gastropods, 3 — bivalves, 4 — belemnites, 5 — parkinsoniids, 6 — lissoceratids, 7 — echinoderm ossicle (?ophiuroid), 8 — wood fragments, 9 — burrows with fecal pellets

In thin section the concretions possess a micritic matrix with chaotically distributed bioclasts, especially bivalve shells, although tiny ammonites, gastropods, echinoderm ossicles (ophiuroids?) and nodosariid foraminifers occur. The matrix often bears traces of burrows with fecal pellets (Fig. 2B).

It is worth noting that prosopid crabs, generally rare in Middle Jurassic strata, have not been recorded from concretions before now (Müller *et al.*, 2000).

CHARACTERISTICS OF THE ORGANIC MATTER

In the recent years, investigations of organic matter in different types of concretion has been used in the context of concretion genesis (Kiriakoulakis *et al.*, 2000), determination of the source of the organic matter (Ogihara, 1999) and implications about thermal transformations of OM (Ogihara and Ishiwatari, 1998). For the first time, we demonstrate characteristics of organic matter extracted from carbonate concretions and the surrounding upper Bajocian clays from the "Sowa" brick-pit, in Kawodrza Górna near Częstochowa.

The total organic carbon (TOC) content of the concretions equals 0.42%, approximately half of the total carbon content of the surrounding clays (TOC = 0.77%).

Gas chromatography coupled with mass spectrometry (GC-MS) was performed in order to characterise biomarkers from the carbonate concretions.

***n*-alkanes and isoprenoids**. The distribution of *n*-alkanes is bimodal, with two maxima at n-C$_{17}$ and n-C$_{25}$. A prevalence of odd over even long chain *n*-alkanes occurred between n-C$_{23}$ and n-C$_{31}$ (Fig. 3A). CPI$_{(25–31)}$ values (Carbon Preference Index from n-C$_{25}$ to n-C$_{31}$)of 1.35 for carbonate concretions and 1.71 for surrounding clays were recorded. Pristane (Pr) to phytane (Ph) ratios (Pr/Ph) are above 1.08 for concretions and 1.24 for clays.

Diterpenoids, triterpenoids and steroids. The carbonates are characterised by a similar distribution of pentacyclic triterpenoids (hopanes and hopenes — *m/z* 191). Mass spectra and retention times of individual compounds identified high concentrations of 17β21β(H)-hopanes, hop-13(18)-enes of 29, 30 and 31 carbon atoms in the molecule in both concretions and clays (Fig. 3B). Quantitatively, the next important group of hopanoids are hop-17(21)-enes of 30 and 31 carbon atoms, and a minor amount of hop-17(21)-enes of 32 to 34 carbon atoms in the molecule. Among hopanes of $\alpha\beta$ configuration, C$_{30}$-17α21β(H)-hopane dominated. However, among homohopanes the major constituent is C$_{31}$-17α21β(H)-hopane (with a marked predominance of the less stable R epimere) (Fig. 3B). Diterpanes are represented by small concentrations of fichtelite.

Among steroids the $^{13(17)}$diasterenes (20R i 20S epimers) and $^{13(17)}$4β-methyldiasterenes (20R i 20S epimers) are dominant (Fig. 3C), and their concentrations are similar to those of the hopanoids. Moreover, by comparing the spectrum of an un-

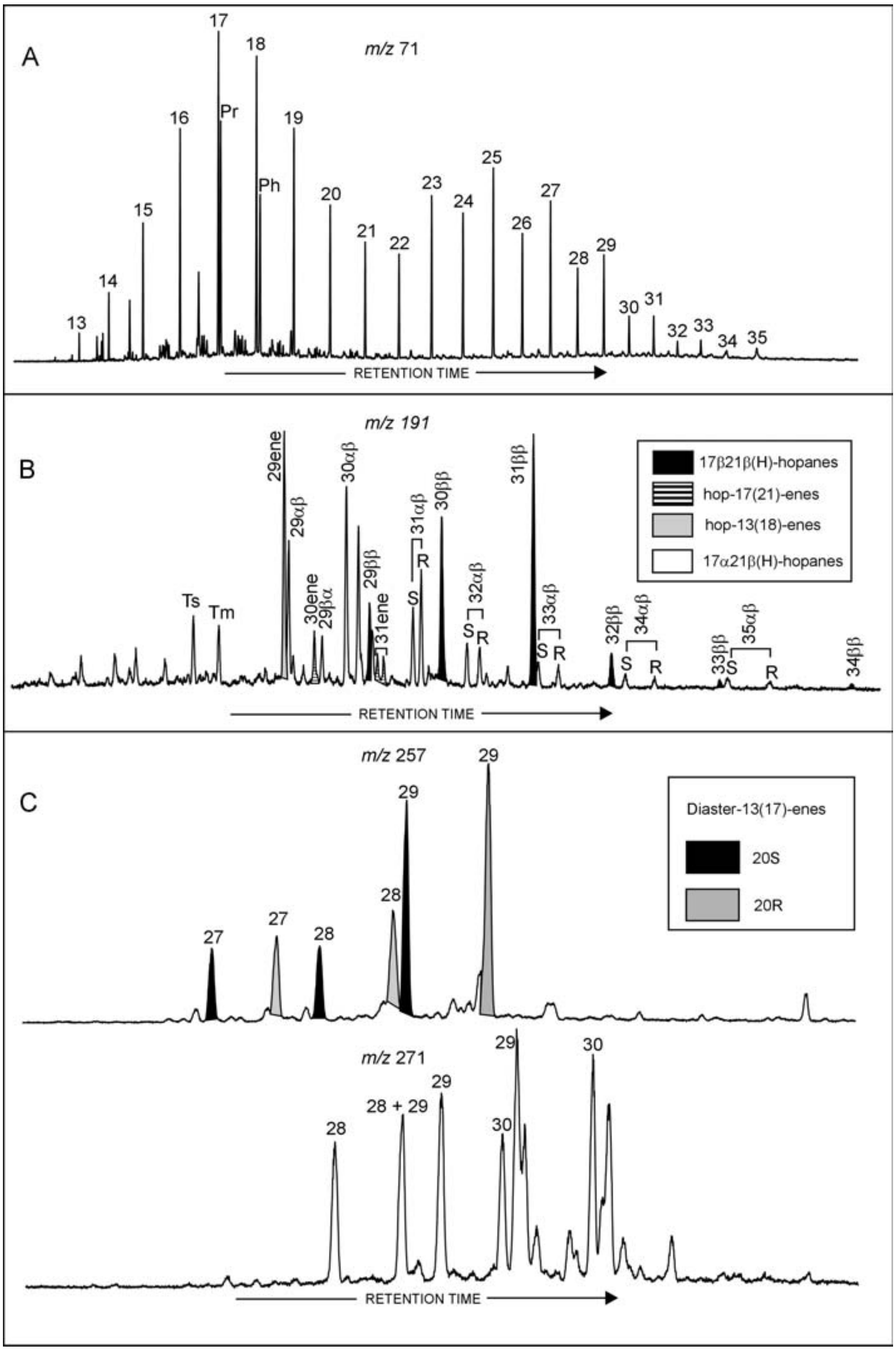

Fig. 3. Distribution of A — *n*-alkanes and isoprenoids (numbers indicate chain length of *n*-alkanes, Pr — pristane, Ph — phytane); chromatographic column: DB-5MS; B — pentacyclic triterpenoids; column: DB-5MS; C — diaster-13(17)-enes (*m/z* 257) and 4β-methyldiaster-13(17)-enes (m/z 271); column: DB-17MS from the Bajocian carbonate concretions

known compound with the spectrum published by Rushdie *et al*. (2003), we have identified diacholestadiene. Surprisingly, in the analysed samples we detected only trace concentrations of $\Delta^4 + \Delta^5$ sterenes in both clays and concretions. Steranes with 27, 28, 29 and 30 carbon atoms, as well as diasteranes are also present only as traces.

Polycyclic aromatic compounds. A similar distribution of polycyclic aromatic compounds was identified in both clays and carbonate concretions. Among polycyclic aromatic hydrocarbons, perylene is the dominant compound (Fig. 4). Methyl- (*m/z* 266) and dimethyl- (*m/z* 280) derivatives of perylene are also present in relatively high concentrations. Other important hydrocarbons in the aromatic fraction are: 5, 6, 7, 8-tetrahydrocadalene, cadalene, phenanthrene, methylphenanthrenes and dimethylphenanthrenes, fluoranthene, pyrene, dehydroabietane, simonellite, retene, as well as more condensed polycyclic aromatic hydrocarbons: benzo[*g*, *h*, *i*]fluoranthene, benzo[*a*]anthracene, chryzene + triphenylene, indeno(1, 2, 3-*c*, *d*)pyrene and benzo[*g*, *h*, *i*]perylene (Fig. 4). Also present are common constituents of sedimentary organic matter such as: methyl-, dimethyl-, trimethyl- and tetramethylnaphthalenes, methyl-, dimethyl- and trimethyldibenzothiophenes, biphenyls and dibenzofurans, as well as benzonaphthothiophenes and benzonaphthofurans. In both samples, benzohopanes and monoaromatic steroids were only detected in trace amounts.

SOURCE OF ORGANIC MATTER AND DEPOSITIONAL TO DIAGENETIC CONDITIONS

Values of $CPI_{(25–31)}$ were recorded as 1.35 in concretions and 1.71 in clays, and together with the fichtelite occurrence, prevalence of C_{29}-diasterenes and the occurrence of perylene, cadalene, dehydroabietane, simonellite and retene in the aromatic fraction, this suggests a strong predominance of terrestrial organic matter in both concretions and clays. Dehydroabietane, simonellite and retene are diagenetic products of abietic acid conversion (Otto and Simoneit, 2001). Other possible pathways of phyllocladane formation are degradation and aromatisation of pimarene- and phyllocladane-derivatives when catalysed by clay minerals (Alexander *et al*., 1987). On the other hand, 5, 6, 7, 8-tetrahydrocadalene and cadalene are derived from cadalene-type sesquiterpenoids, such as cadinenes and cadinols (Simoneit *et al*., 1986). Both groups of compounds are characteristic of conifers (Otto and Wilde, 2001). Tetracyclic diterpanes (including phyllocladane) were not found in the samples analysed, probably due to their complete early diagenetic aromatisation under acidic conditions, catalysed by clays and/or by microbial activity (see Bechtel *et al*., 2001). Another charac-

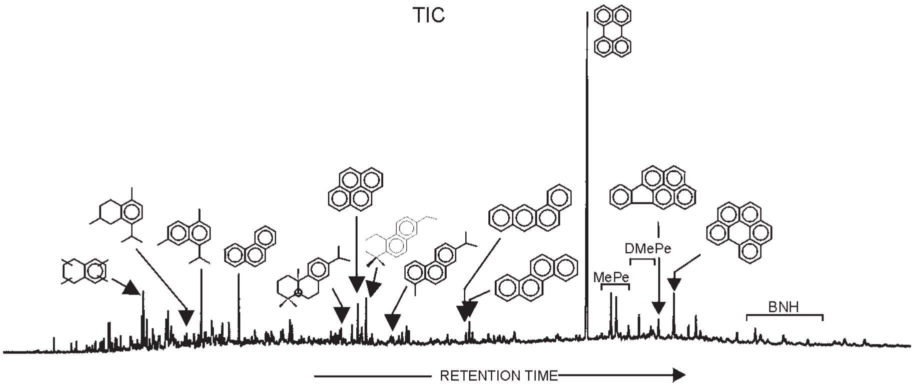

Fig. 4. Total ion chromatogram (TIC) of the aromatic fraction from the Bajocian Konzentrat-Lagerstätte-type carbonate concretions

Column: DB-5MS; MePe — methylperylenes, DmePe — dimethylperylenes, BNH — benzohopanes

teristic feature of the terrestrial organic matter in our samples is the prevalence of C_{29}-diasterenes over diasterenes with 27 and 28 carbon atoms in the molecule (see Brassell *et al*., 1985). Steroids with 29 carbon atoms in the molecule may be generated also by marine organisms (Peters and Moldowan, 1993), which may also be a problem for perylene. This major aromatic hydrocarbon in the samples (Fig. 4) is characteristic of terrestrial, immature organic matter (Jiang, 2000), and is also sometimes connected with marine organic matter (Silliman *et al*., 2000). The co-occurrence of all these groups of compounds unquestionably indicates a large contribution of terrestrial organic matter to the kerogen in the samples investigated.

Organic matter (OM) in the host deposits and carbonate concretions of the Middle Jurassic Częstochowa region is thermally immature. This is indicated by a large concentration of biomarkers with biological configurations, such as ββ-hopanes, hop-13(18)-enes and hop-17(21)-enes, diasterenes and sterenes. Additional organic compounds characteristic of the early stage of OM transformation are dehydroabietane and simonellite. These compounds are present only in highly immature organic matter and disappear with increasing maturation. Relatively immature organic matter from the Middle Jurassic of southeastern Poland was described recently by Kotarba *et al.* (2003). However, based on results presented by Kotarba *et al.* (2003), the maturity of organic matter from S–E Poland is characterised by a more advanced stage of thermal transformation than the organic matter from the Częstochowa region.

An interesting feature of the OM in the carbonate concretions is the overwhelming dominance of diasterenes over steranes and sterenes. It is well known from the literature that $\Delta^{13(17)}$diasterenes are the products of early diagenetic acid-catalysed backbone rearrangement (Rubinstein *et al*., 1975). However, $\Delta^{13(17)}$diasterenes are present in relatively large concentrations in the carbonate concretions (Fig. 3C) as well as in the clays. This group of compounds must have been formed by contact with clay minerals before formation of the carbonate concretions. Carbonate concretions then trapped the diagenetically transformed sedimentary organic matter, and subsequently, OM has not significantly changed. These processes may have followed the early stages of diagenesis, but certainly only at depths not exceeding a few tens of metres. Carbonates "diluted" the organic matter concentrated in the clays, which is reflected in the lower content of organic carbon in the concretions.

The formation of carbonate concretions (including siderite ones) required anoxic conditions (Coleman *et al.*, 1993). Such an environment may have existed after burial, ten or so metres beneath the sea-floor. However, evidence of anoxic conditions during organic matter sedimentation in the late Bajocian epicontinental sea has not been found. There is a relatively low amount of total organic carbon in the sedimentary rocks (TOC = 0.77%), low concentrations of homohopanes containg 33 to 35 carbon atoms in the molecule, relatively high Pr/Ph ratios, an absence of compounds characteristic of anoxia and water column stratification, such as isorenieratane and gammacerane, as well as a common benthic fauna. This points to rather well oxygenated conditions in the sedimentary basin with abundant transport of terrestrial material. The predominantly terrestrial organic matter in the upper Bajocian marine sediments may have resulted from the resistance of terrestrial material to bacterial reworking and oxidation (Prahl *et al*., 1997).

TAPHONOMY

STATE OF PRESERVATION

All fossils are calcitic and reveal well-preserved ornament. Although bivalves are often disarticulated and ammonites lack apertural features, the majority of fossils do not show any signs of crushing or deformation caused by compaction. The exception are fossils from the outer zone of the concretions, these were more clearly affected by the latter process, in being crushed, and ammonite septa are torn, displaced and pyritized (Fig. 5B). This mineralization also affected, though to a lesser extent, the outer portions of fossils. The ammonites, especially parkinsoniids, preserve shell across such delicate structures as spiny tubercules and projected ribs (Fig. 5A). The umbilici are intact and protoconchs (ammonitellas) often clearly visible. Although they lack apertural features, longitudinal cross-sections of their shells show practically complete body chambers of almost one (or slightly more) whorl. The organic constituents of their siphuncles are also well preserved (Fig. 5C).

The body chambers are filled with sediment lithologically identical to the concretion matrix. The septa in a majority of them, from the inner zone of concretions, are intact and the chambers are not filled with sediment, which could attest to reworking (Wani, 2001). Instead, they are filled with sparry calcite (Fig. 5C).

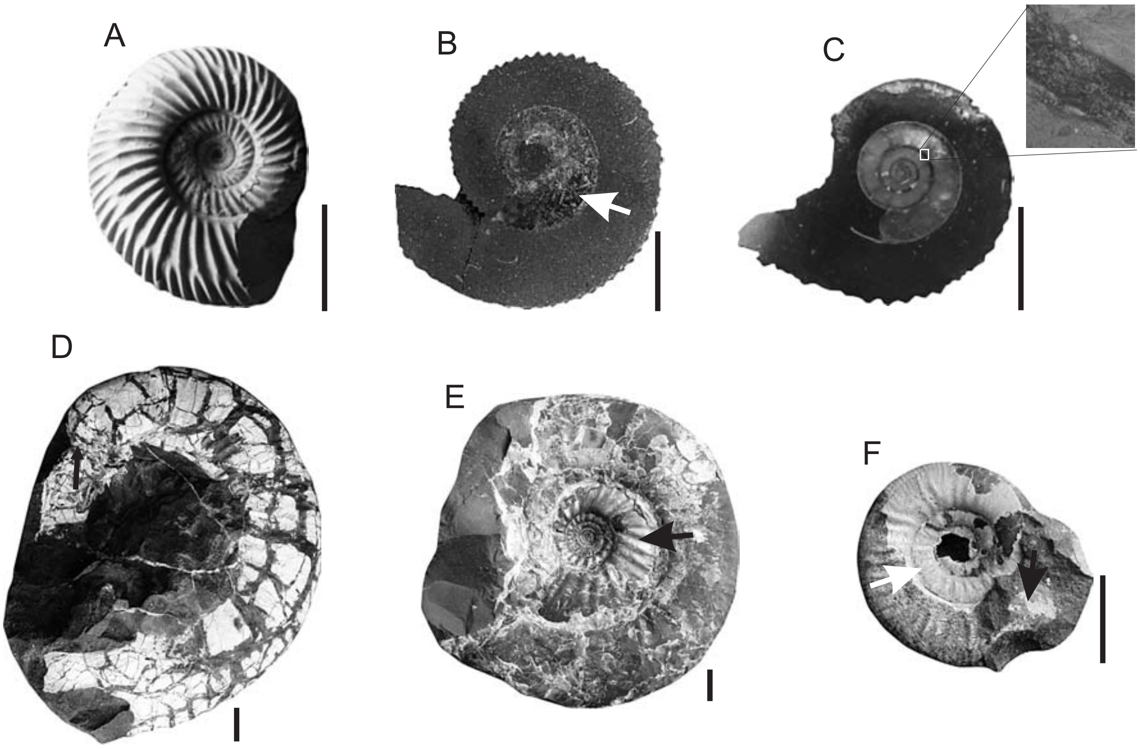

Fig. 5. Examples of preservation of ammonites from carbonate concretions

A — *Parkinsonia* sp. — the most numerous representative of ammonite fauna from the Bajocian concretions: the specimen is well-preserved without any signs of deformation; **B** — *Parkinsonia* sp. from the outer part of the concretion, the whole body chamber is sediment-filled, the septa, on the other hand, are crushed by compaction and pyritized (white arrow), the space in the phragmocone is filled with sparry calcite; **C** — *Parkinsonia* sp. from the inner part of the concretion, the body chamber, similar to the previous one, is sediment-filled, the phragmocone is completely intact, and the organic parts of the siphuncle are preserved; **D** — *Procerites* (*Siemiradzkia*) sp. from the middle Bathonian (*morrisi* Zone) of the Gnaszyn area, despite the preservation of whole body chamber, the phragmocone is completely crushed, this is the common preservation of Bathonian ammonites in that area, black arrow — the beginning of the body chamber; **E** — *Asphinctites* (*Asphinctites*) *tenuiplicatus* (macroconch) from the upper lower Bathonian (*tenuiplicatus* Zone) of Faustianka, black arrow — the shell showing multicolour iridescence; **F** — *Asphinctites* (*Polysphinctites*) *secundus* (microconch) from the upper lower Bathonian (*tenuiplicatus* Zone) of Gnaszyn area, unlike its counterparts from Faustianka, these specimens are mostly deformed with the umbilical parts often completely crushed (white arrow), note the presence of lappets (black arrow); scale bar at each specimen measures 1 cm

BIOSTRATINOMY

Considering the state of preservation, a time of exposition of the organic remains to a variety of chemical and physical processes on the sea-floor must have been short. Evidence for this is the complete absence of encrusting fauna and lack of borings. Such phenomena as the lack of ammonite apertures or dissarticulation of bivalves, can be ascribed to biostratinomic processes (Fernández-López and Fernández-Jalvo, 2002) that took place upon death of organisms.

It is interesting that most ammonites do not occur in other siderite levels or concretions. This means that the concretions are some kind of "taphonomic window", which allows us to estimate a real biodiversity. The quantitative condensation of well-preserved fauna, mainly ammonites, as well as the occurrence of crustaceans (normally rare and of low fossilization potential; see Müller *et al*., 2000), leads us to classify these as Konzentrat-Lagerstätte-type deposits (*sensu* Seilacher, 1990; Briggs, 2001).

In this case, bottom currents would have been the main agent of faunal accumulation. Although the fauna is randomly distributed and indications of palaeotransport direction (belemnite rostra, elongated wood fragments) are few and far between, this interpretation is supported by:

— the small size of fossils preserved in the concretions — the maximum diameter of ammonite shells is up to 4.5 cm (Fig. 6), which may indicate sorting;

— the lack of preserved ammonite apertures and disarticulation of part of the bivalve assemblage (many shells could have been disarticulated by burrowers);

— the nature of concretion occurrence — they do not form continuous levels in the section. Moreover, any palaeotransport indicators are bound to have been obliterated by later infaunal activity (e.g. Wani, 2001).

However, in their preliminary report, Merta and Drewniak (1998) characterised the basin as quiet with a very slow or even extremely slow rate of deposition. In their opinion, the sediments were distributed by near-bottom low-energy currents, probably as clouds of suspended matter. The origin of the clouds was connected with resuspension (storms) of the deposits within the shallower zones of the basin. These researchers also noted "only several of indistinct current structures similar to lenses with "ghost" of cross-bedding. Maybe these forms represent incomplete current ripple marks". Possible erosion

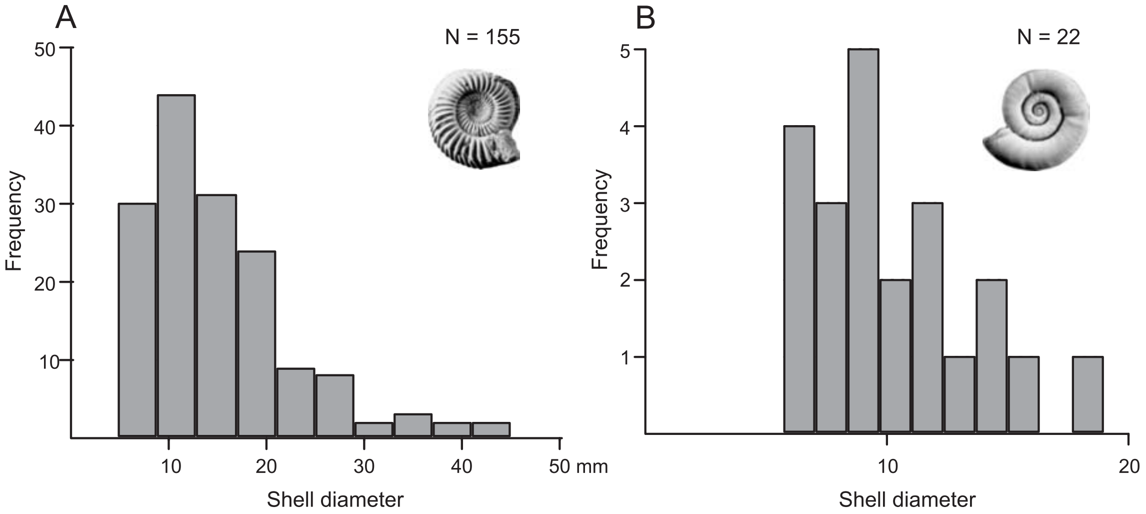

Fig. 6. Size-frequency histogram of A — *Parkinsonia* and B — *Nannolytoceras* shells — the most common ammonites in the concretions investigated; juvenile specimens dominate

surfaces were also noted. In the opinion of Merta and Drewniak (1998, p. 27), the rarity of such dynamic sedimentary structures in the entire Bajocian-Bathonian clay sequence in that area is, probably not primary. Nevertheless, these deposits still need further studies using more sophisticated methods of examination (Merta and Drewniak, 1998, p. 29).

These points may suggest the presence of small, randomly situated depressions on the epicratonic sea-floor, even though we do not have any physical evidence of their existence because we could not observe the concretions *in situ* (see above). Together with bottom currents, these pockets could have acted as “traps” concentrating only objects of a certain maximum size. This would explain why the fauna consists of small, juvenile ammonites. Moreover, crustaceans have a greater chance of being preserved on such uneven bottoms when their remains are washed into depressions and rapidly buried (Müller *et al*., 2000).

Depressions of this type may form by two different processes: physical, such as wave action or current-related eddies, or organic processes such as rays feeding on benthic fauna (Geraghty and Westermann, 1994). The latter process is documented by actualistic examples. Extant rays which feed on benthic organisms remove the sediment by jetting air through their gills to produce depressions of this type. This can be no more than a working hypothesis, since neither Geraghty and Westermann (1994) nor the authors have found any remains (e.g. teeth) of rays. Maeda (1987, 1991) also reported similar, nest-like accumulations of ammonites, bivalves and wood fragments from Upper Cretaceous concretions of Hokkaido, Japan. He explained them as a “traps” formed by large ammonites (e.g. *Mesopuzosia*), which caught smaller transported organisms. In the concretions studied here, large ammonites are practically absent, and, when at all present, they are preserved as fragments of whorls only.

Assemblages consisting of small ammonites have been reported from Italy (Sturani, 1971) and Hungary (Galácz, 1995). Fragments of larger ammonites had also been found occasionally. Although in both cases the assemblages consisted of fissure-filling material, the mechanisms of their accumulation could have been similar.

PALAEOBIOLOGICAL REMARKS

Although size-limiting depressions scattered on the sea-floor may have existed and influenced the faunal preservation, another aspect concerning the presence of small, juvenile ammonite populations (Fig. 6) in the area can be deduced. Juvenile shells are generally rare in “normal” rich assemblages (Westermann, 1996), so their large amount not only attests to a high-density population in the area, but also to factors that wiped them out. It is known (Westermann, 1996) that rising anoxia may have caused high mortality rates among pelagic juveniles but not among adults, which were mobile enough to escape. However, the assemblages from concretions consist of a diverse benthic fauna which does not indicate unfavourable anoxic conditions. Also, the strongly bioturbated sites around the carcasses clearly point to a well-oxygenated sediment-water interface, as well as the zone below. The same is concluded from organic geochemistry investigations. Therefore, it is possible that the juvenile ammonites are a post-spawned population that occupied shallow-water environments. It is well known (Sturani, 1971; Soja *et al*., 1996; Westermann, 1996) that recent coleoids, such as squids and cuttlefishes, undergo seasonal or monthly migrations and die in masses following reproductively intense spawning episodes. Recent inferences about ammonite behaviours based on the recognition of a shared phylogeny with coleoids (Engeser, 1996) suggest that large concentrations of ammonites in the fossil record reflect behavioral similarities with coleoids involving migrations, congregation and mass mortalities following group reproductive activities (Jacobs and Landman, 1993; see also Soja *et al*., 1996). Although such physiological and behavioral manners are different from those of the recent *Nautilus*, it is probable that they first evolved in Palaeozoic nautiloids (Soja *et al*., 1996).

In our case, a lot of small ammonites may be a remnant of such reproductive events. The presence of herbivorous gastropods (Dr. Andrzej Kaim, pers. comm.) may be indirect evidence of benthic algal meadows, which created attractive sites for spawning ammonites, as Sturani (1971; see also Westermann, 1996) hypothesised on the basis of his research in the Venetian Alps. Significant concentrations of juveniles may reflect the normally high rate of mortality among juveniles, which are particularly vulnerable during and after hatching in a restricted environment affected by salinity or temperature fluctuations and by storms (Soja *et al*., 1996). What exact cause affected the ammonites studied here is unclear, but their unusual abundance can be certainly related to sedimentary events. Taking into account the statement of Merta and Drewniak (1998) about the storm-driven resuspension in the shallower part of the basin, it is highly probable that all juveniles may have been swept and quickly buried by clouds of suspended sediment. Schumann (1988) also described small ammonites preserved in Upper Jurassic carbonate concretions from similar, fine-grained sediments. He interpreted this accumulation as caused by episodic powerful hurricanes completely destroying the nektonic and planktonic fauna. It cannot be excluded that the ammonite assemblages under study were affected by similar storm events.

This scenario is not in conflict the size-limiting role of the sea-floor depressions. Moreover, accumulation and rapid burial during such events in these "traps" saved the small, delicate shells rather quickly from being destroyed, thereby increasing the preservational potential of juveniles that are typically underrepresented in the fossil record (Soja *et al*., 1996). The adults, on the other hand, due to their greater sizes, have not been "caught" by the small depressions and so were not preserved. For evaluating and testing whether one or more such episodes are preserved, the exact positions of the concretions in the section studied needs be ascertained.

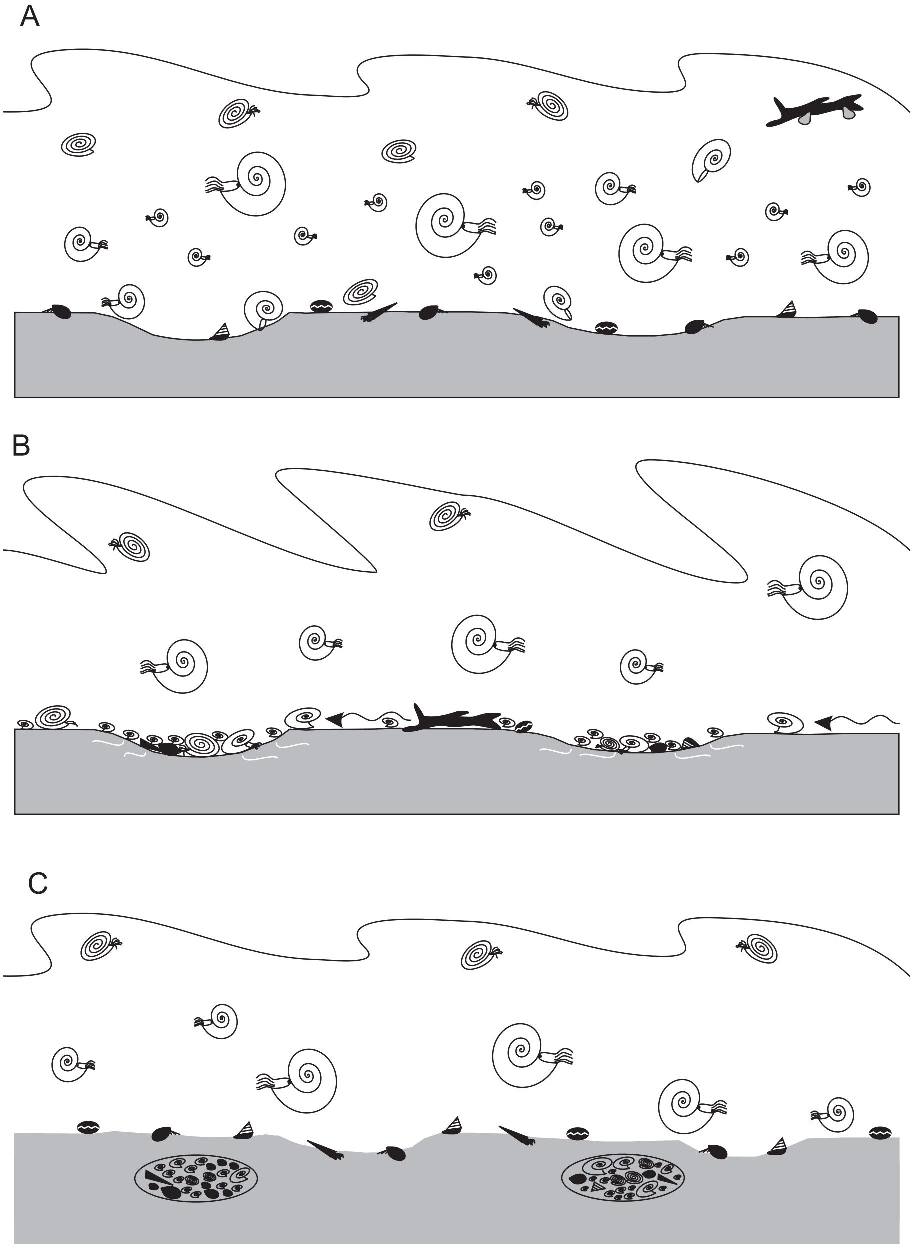

Fig. 7. Biostratinomic scenario describing accumulation of biological remains

A — living biocenosis and its simultaneously accumulating remains on the epicratonic sea-floor; **B** — bottom currents lead to their accumulation in small depressions, scattered on the sea-floor, small diameter of the depressions primarily promoted accumulation of the small-sized ammonites; **C** — after burial of biological remains, the formation of concretions started, in the meantime, such dense accumulation of organic matter in relatively small area attracted numerous bioturbators/scavengers

To summarize, the fossil-rich carbonate concretions from Kawodrza could have originated in the following way (Fig. 7):

— Remains of benthonic, nektonic and planktonic fauna living in the shallow epicratonic basin, along with floating plant remains, slowly accumulated on the basin floor. Ammonites could have probably drifted post-mortem over a short timespan (suggested by the lack of epibionts) in the water column, as is suggested by the complete lack of aptychi (Olóriz *et al*., 2002).

— Bottom currents, acting simultaneously, led to brief and short-distance transport and accumulation of remains in small depressions scattered on the sea-floor. All faunal elements underwent size-sorting and only small individuals accumulated, larger ones were caught in these traps only as fragments after longer transport. The preponderance of juvenile ammonites may point to mass-mortality event, and although the cause is yet unclear, a storm event is possible.

— Following the accumulation and rapid burial of this biota, the processes that were to lead to concretion formation started. In the meantime, the localized accumulations of organic matter attracted numerous bioturbators/scavengers. Furthermore, a portion of the organic matter underwent oxidation and bacterial reworking. As at least part of the benthic fauna was disarticulated by burrowing activity just after accumulation and burial, the concretion assemblages may be included in taphonomic grades A (high amount of articulated, non-degraded shells) and B (moderate amount of articulated, non-degraded shells) *sensu* Brandt (1989).

DIAGENESIS

It is well known (Brett and Baird, 1986; Allison, 1990; Sellés-Martínez, 1996; Martin, 1999), that the origin of fossil-rich carbonate concretions is associated with anaerobic decay of organic matter by sulphate-reducing bacteria (e.g. Coleman *et al*., 1993; Mortimer *et al*., 1997), just after burial. In this case, a large number of dead organisms became an ideal nucleation site for the processes leading to concretion origin. Carcasses were responsible for local pH fluctuations: elevated pH triggered carbonate precipitation (Middleton and Nelson, 1996; Sagemann *et al*., 1999); decreased pH, in contrast, favoured sulphate reduction causing precipitation of sulphides, such as pyrite (Trueman *et al*., 2003). Moreover, organisms burrowing around the biological remains stimulated the anaerobic decay of organic matter: the rate of sulphate reduction can be up to three to five times higher in bioturbated sediments than in the comparable but unbioturbated deposits (Orr *et al*., 2003). The precursors of concretions could be the microbial (bacterial-fungal) halo surrounding decaying organic matter within the sediment (Borkow and Babcock, 2003).

The concretions studied contain consistently more calcium carbonate than pyrite. Earlier laboratory experiments (Briggs and Kear, 1994; Sagemann *et al*., 1999) have shown that precipitation of calcium carbonate predominates in open conditions when diffusion prevails, such as in normal marine systems. A rapid drop of pH, on the other hand, stops carbonate precipitation, which enables the precipitation of other minerals such as calcium phosphate or pyrite. The rate at which these minerals precipitate just after accumulation and burial of remains can be high. Briggs and Kear (1994) observed that carbonates surrounded by organic matter can precipitate in 2 to 4 weeks and sulphides (Sagemann *et al*., 1999) just after 24 hours. Such a short timespan of mineralization strongly impacted on the state of preservation of the fossils within the concretions. The absence of any signs of deformation and the presence of the mineralization mentioned above attest to early-diagenetic processes (Brett and Baird, 1986; Allison, 1990; Allison *et al*., 1995; Majewski, 2000; El Albani *et al*., 2001) which started just after burial. An additional indicator of early diagenesis is the presence of organic remains of the siphuncle in the ammonites (Khiami and Murphy, 1988). Furthermore, on the basis of geochemical data we know that the origin of carbonate concretions must have taken place just after the early diagenetic transformations of organic matter.

Although virtually the entire area of the Polish Jura abounds in carbonate concretion levels containing fossils, the state of preservation encountered in the concretions described here is exceptional. Ammonites from other Bajocian and Bathonian concretion levels often have crushed phragmocones and collapsed umbilici. Generally, the umbilical region is wholly missing and the only structure surviving is the ultimate whorl, in particular the body chamber, filled with sediment and thus reinforced prior to compaction (Fig. 5D). This state of preservation is related to processes that acted upon these fossils in the later stages of diagenesis, when compaction affected the shells just after burial (see Majewski, 2000). There are concretions that do contain well-preserved fossils, for example those from the uppermost lower Bathonian (*tenuiplicatus* Zone; see Matyja and Wierzbowski, 2000) of Faustianka, near Wieluń. The ammonites preserved within these concretions are complete, uncrushed and preserve their multicoloured iridiscent shells (Fig. 5E). In strong contrast, however, is the ammonite fauna of the same zone from Gnaszyn near Częstochowa (see Matyja and Wierzbowski, 2000). Despite their completeness (often with aperture and lappets preserved), the same species, comprising the dimorphic pair *Asphinctites/Polysphinctites*, are so strongly affected by compaction that the umbilical regions collapse upon extraction from the rock (Fig. 5F). These examples clearly demonstrate that various concretions, of different ages but from the same area and *vice versa*, may show a quite different burial and diagenesis history.

CONCLUSIONS

The entire set of biological remains entombed in the Bajocian calcitic concretions accumulated and was buried in rather small, randomly distributed depressions on the sea-floor. Ammonites could have suffered from mass-mortality event(s) after their spawning. The number and size of fossils and their state of preservation, not showing any signs of abrasion or bioerosion, indicate that transport and residence time on the sea-floor was brief. During the initial stages of diagenesis, concretion formation began, as is indicated by the presence of early diagenetic mineral phases and by the preservation of the fossils. Neither are these fossils crushed or deformed. Except for the disarticulation of bivalve shells, which in part may be ascribed to the activity of bioturbators, and the lack of apertural features in ammonites, the entire faunal assemblage is very well preserved.

This type of preservation and the presence of faunal elements which have never been reported previously from the Bajocian of the Polish Jura (e.g. crustaceans) allow these concretions to be typified as a Konzentrat-Lagerstätte. Their origin is suggestive of an event concentration (*sensu* Kidwell, 1991). Such "taphonomic windows" furnish a valuable insight into the structure of biocoenoses of the shallow epicontinental seas in south-central Poland. In addition, they also demonstrate that our picture of Middle Jurassic biotic diversity in the study area might be underestimated, both qualitatively and quantitatively.

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