

Carboniferous plants preserved within sideritic nodules – a remarkable state of preservation providing a wealth of information

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ABSTRACT. Fossil plants preserved within sideritic nodules have been known from European and North American Carboniferous coal measures since the early 19th Century. However, only a few of them have been described thoroughly palaeobotanically, mainly in the 19th and early 20th centuries; thus their taxonomy often requires revision. Animal fossils preserved within sideritic nodules beside plant fossils became a base of the description of many rare new taxa of animals undiscovered in other modes of preservation. Published hitherto works about such preserved flora indicate that plants preserved within concretions represent rare taxa, not known in other modes of preservation. The dissimilarities in composition of floras preserved in ironstone concretions when compared to those from surrounding sediments likely results from the process of concretion formation which selectively influences the preservation of small, delicate plant organs. The most famous floras preserved within concretions come from Mazon Creek in the USA and Coseley in Great Britain. These localities were the source of many previously unknown taxa with important evolutionary significance. The new flora preserved within concretions has been discovered recently in Poland in Sosnowiec (Upper Silesia). It contains new, hitherto unknown taxa particularly plant reproductive organs. Comparison of the taxonomy and taphonomy of the ironstone concretion flora from Sosnowiec with other similar assemblages from the Carboniferous of Europe and North America has reveals many similarities stemming from a common mode of preservation. Due to the exceptional three-dimensional preservation of the plant fossils, in particular reproductive organs key to the understanding of evolutionary relationships, the locality at Sosnowiec can be regarded as an important new Lagerstätte, and the first such site recognized in Poland. The use of pioneering techniques in high-resolution X-ray microtomography promises to yield yet further information on the biota of this new locality.

KEYWORDS: plant fossils preserved within sideritic nodules, Upper Carboniferous, Sosnowiec, Coseley, Mazon Creek, Fossil-Lagerstätten, Konservat-Lagerstätten

INTRODUCTION

The occurrence of exceptionally well preserved fossils within ironstone concretions accompanying Carboniferous coal seams of coal-fields of Europe and North America has been known and described since the 19th Century (Brongniart 1828–1837). Few of these specimens were subjected to detailed palaeobotanical analysis by modern standards and techniques. Greater attention was paid to the fauna appearing in these concretions and there are more papers on this theme (Nitecki 1979, Shabica & Hay 1997). Sideritic nodules often contain splendidly preserved land

animals, which otherwise are seldom found in a good state of preservation (Garwood & Sutton 2010, Garwood et al. 2009, Legg et al. 2012). As well as marine animals, especially these with a very low fossilization potential, such as jellyfishes, hydroids, polychetes etc. (Nitecki 1979, Shabica & Hay 1997). Some animal fossils have also been described from the Sosnowiec nodules (Filipiak & Krawczyński 1995, 1996, Krawczyński et al. 1997, Pacyna et al. 2004, Stworzewicz et al. 2009, Prokop et al. 2012). Carboniferous ironstone concretions create a taphonomic window permitting

the recognition of the fauna and the flora to a degree comparable only with the best palaeontological sites from other geological epochs, e.g. Burgess Shale, Chengjiang, Hunsrück Slate, Solnhofen Lithographic Limestones, etc. (Baird 1990). For these reasons, Carboniferous localities with fossil preserved within sideritic nodules are universally recognized as Fossil-Lagerstätten (Baird 1990, Baird et al. 1985a, b, 1986, Schellenberg 2002, Nudds & Selden 2008). The use of new research techniques such as high-resolution X-ray microtomography reveals new, previously undiscovered details in such fossils (Garwood & Sutton 2010, Garwood et al. 2009, Legg et al. 2012, Spencer et al. 2013).

In the 1990s, on the dump of the “Porąbka-Klimontów” coal mine in Sosnowiec-Zagórze (Upper Silesian Coal Basin) sideritic concretions have been found containing plant and animal fossils (Filipiak & Krawczyński 1995, 1996, Krawczyński et al. 1997, Pacyna 2002a, b, 2003, 2004, 2007a, b, c, 2008a, b, Pacyna & Wojciechowski 2004, Pacyna et al. 2004, Pacyna & Zdebska 2001, 2002, 2005, 2010, Stworzewicz et al. 2009, Prokop et al. 2012). Though ironstone concretions are frequent in rocks accompanying coal seams in Upper Silesia (Porzycki 1972) and they were exploited even as source iron ores (Tryjefaczka 1982), regrettably the fossils preserved within them were mentioned earlier only sporadically (Feistmantel 1874, Roemer 1866, Bocheński 1939), and a few described fossils (only animals) are now lost. This new locality in Sosnowiec provides an opportunity to describe completely such preserved fossil assemblage for the first time in Poland.

The purposes of this article are the discussion of taxonomical composition and taphonomical aspects of fossil floras preserved within sideritic nodules and comparison between these floras and the new flora uncovered in Sosnowiec alongside discussion on future directions in the study of such exceptionally preserved floras.

THE GENESIS OF IRONSTONE CONCRETIONS

The formation of ironstone concretions is tied inseparably with the water environment. As a consequence of the accumulation of large

volumes of organic material (e.g. plant material), the basin water formed reducing conditions above a consolidated sediment base. The bacterial decay of organic debris quickly laid down in the loamy sediment locally changed the reaction of the environment around them, in special cases enabling the precipitation of the ironstone (Chodyniewska 1973, Woodland & Stenstrom 1979, Sellés-Martínez 1996). Then the ironstone concretion formed quickly and protected the organic remains, terminating decomposition and protecting the resultant fossil from compaction through sediment loading.

Ironstone concretions form syngenetically with the sediments in which they appear. In sphaerosiderites the early diagenesis preceding the compaction provides the opportunity for the three-dimensional preservation of the fossil (Baird 1997). The mode of preservation of plants in concretions belongs to the type of preservation of fossil called authigenic cementation (Schopf 1975, 1979). A very early cementation in soft sediment by iron and carbonate compounds preserves the surface configuration of organic parts, even very delicate structures. Thanks to this the three-dimensional shapes of plant morphological-anatomical details are recorded in exquisite detail. Most soft tissues, even if originally present, are postdiagenetically degraded, and the spaces which remain after them could be secondarily filled, e.g. with pyrite or calcite. Of the original organ of the plant only the coal film on walls of the three-dimensional gap most often remains. This gap is often secondarily filled with kaolinite which covers many details and makes the investigation of specimens very difficult. The genesis of this mineral in concretions has not as yet been explained (Baird et al. 1985b).

REVIEW OF THE UPPER CARBONIFEROUS FLORAS PRESERVED WITHIN IRONSTONE CONCRETIONS OF EUROPE AND NORTH AMERICA

Carboniferous floras preserved within sideritic nodules are rare from a global perspective. Though at least several floras preserved within ironstone concretions are known from the Upper Carboniferous strata of Europe and North America, their modern complex taxonomic and taphonomic descriptions and interpretations are lacking. Every locality of such

exceptional preservation invokes broad interest from palaeobotanists, because the plants preserved in them provide a great deal of valuable information. The most famous, richest and best recognized locality with Carboniferous plant fossils preserved within ironstone concretions is Mazon Creek in Illinois, USA. In spite of the fact that this locality has been known since the second half of 19th Century, and has been described in many palaeobotanical papers (Lesquereux 1866, 1870, 1879, 1880, 1884, Noe 1925, Schopf 1938, 1941, Janssen 1940, Langford 1958, 1963, Darrach 1970, Horowitz 1979, Pfefferkorn 1979), to this day new taxa of plants from Mazon Creek are still being described, often later recognized to be unique to this locality (Pigg & Taylor 1985, Drinnan & Crane 1994). Several similar, though significantly taxonomically poorer localities from North America still await full elaboration (Baird et al. 1985b). A review of these localities primarily focusing on the fauna was made by Baird et al. (1985b). A comprehensive review of European localities is currently lacking. In terms of European localities, ironstone concretion lagerstätte have been primarily scrutinised for their faunal content (Moysey 1910, Anderson et al. 1997, 1999).

The mode of preservation in ironstone concretions presents a range of problems when trying to extract information and interpret fossils. Recently however, advances in the use of high resolution X-ray tomography in the study of faunal and some floral remains preserved in such concretions has allowed the extraction of much more information from these exceptional fossils (Garwood & Sutton 2010, Garwood et al. 2009, Legg et al. 2012, Spencer et al. 2013).

Floras preserved within sideritic nodules from North America and European Pennsylvanian localities are discussed and compared below.

NORTH AMERICA (USA)

Illinois

Numerous well preserved floras from shales and coal balls are known from the Middle Pennsylvanian Carbondale Formation, Kewanee Group, Illinois. Horizons containing ironstone concretions are particularly frequent in this formation and several such preserved floras have been described from them, particularly the famous Mazon Creek flora.

Mazon Creek

The Mazon Creek locality is situated in the north-east part of Illinois. It belongs among the most famous palaeontological localities in the world, first of all because of its unusually preserved softbodied fauna (Richardson 1966, Schram & Nitecki 1975, Nitecki 1979, Baird et al. 1885a, b, Baird et al. 1986, Baird 1990, Shabica & Hay 1997, Schellenberg 2002, Wilson 2006, Bethoux 2009). Though the flora from this locality is as equally well known as the fauna, it still awaits a full modern description (Lesquereux 1866, 1870, 1879, 1880, 1884, Noe 1925, Darrach 1936, 1937, 1938, Janssen 1940, Langford 1958, 1963, Darrach 1970, Peppers & Pfefferkorn 1970, Horowitz 1979, Pfefferkorn 1979, Pigg & Taylor 1985, Drinnan & Crane 1994). Ironstone concretions are found in the Francis Creek Shale Member, overlying the Colchester (No. 2) Coal seam. According to North American Carboniferous stratigraphy, the age of the concretions is Middle Pennsylvanian – Desmoinesian Series, which correlates with Westphalian D according to the West-European division.

The fossil assemblage at Mazon Creek preserves over three hundred species of animal taxa and as many plants are also known. The fossil remains represent two kinds of environments: swampy, forested delta plains referred to as 'Braidwood' after the typical locality of occurrence and shallow waters of sea surrounding the delta referred to as 'Essex' type environments and biotas. The terrestrial and freshwater deposits include plants, and also insects, myriapods, spiders, scorpions, fish, amphibians and reptiles. The marine assemblage contains remains of jellyfishes, polychaete worms, mollusca, sea cucumbers and crustacea, as well as pelagic cephalopods and fish (Schram & Nitecki 1975, Nitecki 1979, Shabica & Hay 1997).

The flora preserved within ironstone concretions from the Mazon Creek area has been known since the beginning of coal mining activity there in 1855 (Horowitz 1979). The first collection gathered there was sent for investigation and study to Leo Lesquereux who published the findings in several extensive works (Lesquereux 1866, 1870, 1879, 1880, 1884), which were classical texts in North American palaeobotany. Since Lesquereux's work has not appeared in full, professional revisory elaboration of this flora, though it is known that

nomenclature used by Lesquereux is currently outdated; numerous new specimens have been found, and many of Lesquereux's taxonomic determinations are incorrect and require verification.

In the 20th century, the Mazon Creek flora was illustrated and very briefly described in several popularized scientific works for amateur collectors (Noe 1925, Janssen 1940, Langford 1958, 1963). These works are now known to contain some errors and do not bring new data to the knowledge of this flora. Only Darrah (1970) in his revision of the Upper Pennsylvanian flora of the USA devoted more space to the Mazon Creek flora, but concentrated predominantly on common species and stratigraphically useful taxa.

The latest summary of this flora is the work of Pfefferkorn (1979). According to Pfefferkorn the Mazon Creek flora is characterized by the large number of species, with a large variability in size of the most frequent species and excellent preservation. The large diversity of taxa is related to the variety of subenvironments in the deltaic setting. Plants were preserved as fossils as result of quick submersion during storms, when the sea flowed over the area of the delta. This also caused considerable mixing of disarticulated plant debris. The Mazon Creek flora belongs to the taxonomically richest Pennsylvanian floras in North America (Peppers & Pfefferkorn 1970, Pfefferkorn 1979). This results not only from intensive collecting of specimens, but also from favourable conditions for plants of during their life and taphonomic processes favoring fossil preservation. It is interesting to note the occurrence of the gigantism of some plant forms whose fossils outside Mazon Creek are significantly smaller.

The number of described species of plants from the Mazon Creek locality is over three hundred; however, this figure inflates the diversity artificially since many of these species represent isolated organ morphotaxa (Peppers & Pfefferkorn 1970, Pfefferkorn et al. 1975, Pfefferkorn 1979). Pfefferkorn made an attempt to evaluate the real diversity of the Mazon Creek flora. For every group of plants he chose the organ which showed the greatest diversity, and also appeared often in concretions and provided a relatively large amount of taxonomical information. These are stems for lycopods, the foliage for sphenopsids, fertile

leaves for ferns, the foliage for seed ferns and ovules for cordaites. Pfefferkorn concluded that the minimum-number of recognized natural taxa in Mazon Creek equals 96 species belonging to 41 genera.

Pfefferkorn (1979) mentioned only the most frequently appearing genera and concentrated on the evaluation of the age of the flora, variously given earlier. Based on recognition of index species of the macroflora (the occurrence *Neuropteris ovata* together with more than ten species of *Pecopteris*, and also the occurrence of Stephanian aged species higher in the profile) he found that this flora paralleled floras of Upper Westphalian D in Europe.

In the second half of the 20th Century there appeared several short works revising or describing single new taxa from Mazon Creek. These materials were also taken into account in descriptions of the flora at large or within descriptions of particular systematic groups: Abbott 1958 (*Asterophyllites*, *Annularia* and *Shenophyllum* from Mazon Creek), Pfefferkorn 1976 (he described and illustrated stem specimens of arborescent ferns belonging to genera *Caulopteris*, *Megaphyton* and the new genus *Artisophyton*), Pigg and Taylor 1985 (description of a new stem base of the lycopsid – *Cormophyton mazonensis*).

The separate chapter in research of the Mazon Creek flora constitutes monographic elaborations of diversified plant reproductive organs of different, numerous and well preserved taxa. These monographs appeared from the beginning of the 20th century (e.g. Sellards 1903) and were based on single specimens from the huge (counting above 16 thousand concretions with plant fossils) collection deposited in the Illinois State Museum and the Field Museum of Natural History (Photos of specimens from the Illinois State Museum collection are available on the website <http://www.museum.state.il.us/databases/geology/mazoncreek>, unfortunately most often still with Lesquereux's designations).

Based primarily on materials from Mazon Creek (Lesquereux specimens), Chaloner (1958) carried out revisions of the genus *Polysporia*. Kosanke (1955) described *Mazostachys pendulata*, a fragment of stem and new genus of calamite cone known from a concretion. Good (1975) again described this specimen and recognized it as a basis for a new genus

– *Mazostachys* and referred to this genus as yet another species coming from Francis Creek Shale – *M. noei*.

Taylor (1967) described the new species of the fertile leaf of fern – *Radstockia kidstonii*. Pfefferkorn et al. (1971) described extremely rich and splendidly preserved specimens of fertile fern leaves, isolated spores *in situ* from the sporangia, illustrated and compared them with dispersed species. Pfefferkorn (1973) described buds serving the vegetative reproduction of the fern as the new genus and species – *Kankakeea grundyi*, he also revised similar specimens of Lesquereux, which should be referred to this new taxon. Jennigs and Millay (1979) described rich fertile material of *Pecopteris unita*. This species is common in the Mazon Creek flora. Owing to the use of the combination of different techniques e.g. sectioning of the concretion in suitable planes, followed by polishing and subsequently acetate peeling the sectioned blocks providing information on the anatomical structure of synangia, sporangia and spores. On the basis of the spore morphology that was isolated, they found that this morphological species represented numerous different biological species.

Delevoryas (1964) described the new genus and species of the pollen organ of Medullosales – *Schopfitheca boulayoides* on the basis on one specimen from the concretion, isolated from it prepollen grains. Drinnan and Crane (1994) published a valuable work discussing pollen organs of Medullosales from Mazon Creek flora from the genera *Codonothea*, *Schopfitheca*, *Dolerotherca* and one not generically determinable pollen organ. In particular they isolated from pollen organs prepollen grains and produced detailed illustrations of them. Drinnan et al. (1990) described ovules *Stephanospermum konopeonus* containing prepollen grains in the micropyle (such specimens enable the connection of pollen organs with their corresponding ovules).

Schopf published two works (1975, 1979) devoted to the mode of preservation of plants in ironstone concretions on the example of specimens from Mazon Creek, this special mode of preservation he named the type *authigenic cementation*.

A recapitulation of history of research of the Mazon Creek flora and the full list of publications until the year 1979 was published by Horowitz (1979).

Carterville

The second famous flora from the Carbon-dale Formation preserved within the ironstone concretions was discovered in the town of Carterville in the south of the state of Illinois. The concretions appeared in the Energy Shale and Anna Shale Members, over the coal seam Herrin (No. 6) Coal and are dated from the Middle Pennsylvanian – Desmoinesian Series, they appear to be higher in the profile of the Carbon-dale Formation rather than the concretions from the Mazon Creek and are somewhat younger than them as well, furthermore according to the West-European division also belong to the Westphalian D.

The flora preserved within Carterville concretions was already known about since 1875. One of the specimens from these concretions recognized as *Dolerotherca* sp. was described by Schopf (1948), while another specimen, of calamite cones, was described in 1965 by Hibbert and Eggert and discovered to be a new species – *Paracalamostachys cartervillei* (Hibbert & Eggert 1965). The plant specimen preserved within this concretion consisted of an axis onto which a dozen or so perfectly preserved cones were cyclicly arranged while still preserving the spores within their sporangia. Hibbert and Eggert (1965) isolated the spores from the sporangia in order to trace their variability within the cones, which they recognized belonging to a dispersed species of *Calamospora breviradiata*.

In 1977 Gastaldo described a large collection of plants preserved within the ironstone concretions from Carterville, which originated from the roof shales of Herrin (Nr. 6) Coal (Gastaldo 1977). The collection that Gastaldo had at his disposal consisted of 2500 specimens of concretions containing remains of plants: from which 1475 concretions were chosen for study purposes, from these 24 genera and 52 species of plants were determined.

Within the flora, the ferns from the orders Filicales and Marattiales dominated numerically (44% specimens were recognized as different species of the genus *Pecopteris*), medullosalean seed ferns constituted almost 25% of the flora (the foliage: *Neuropteris*, *Alethopteris*, *Odontopteris*, *Callipteridium*; the ovules *Trigonocarpus schutzianus*), while the lyginoteridalean seed ferns, which were very rare within the assemblage (1%), were represented by only

one species called *Renaultia* (*Sphenopteris*) *chaerophylloides*. Amongst the relatively high number of sphenopsids, representatives from the order of Calamitales were mainly found (the foliage *Annularia*, *Asterophyllites*; stems of *Calamites*; 1 cone), while Sphenophyllales were proved to be rare in number (in other words sphenopsids – 14% of the assemblage).

Isolated sporophylls dominated numerically amongst the lycopsids (10% of the assemblage), and were determined as: *Lepidostrobopsis* cf. *missouriensis*, *Lepidostrobophyllum lanceolatum*, *L. brevifolium*, *L. hastatum*, *L. fallax*, *L. cf. tumidum*, and *Lepidocarpon major* (this species was particularly numerous and constituted 5% of the entire assemblage). The remaining 6% of the assemblage constituted a multitude of taxonomically differentiated thin leafless branches of lycopsids, determined variously as several species of the genus *Lepidodendron*, stems of *Lepidophloios* and *Asolanus*, the leaves *Lepidophylloides*, the isolated sporangia *Lepidocystis*, the cones *Lepidostrobos ornatus*, the rootstocks *Stigmaria ficoides* and the herbaceous lycopsids *Lycopodites*. Cordaites in turn were represented by one specimen of *Artisia*.

Three taxa of plant reproductive organs with exceptionally well preserved details as found within the flora, was the next subject of Gastaldo's detailed works. In 1978 in collaboration with Matten (Gastaldo & Matten 1978) they described the largest seed ever found (10 cms in length) in the Carboniferous strata of North America, which they recognized as the new species *Trigonocarpus leeanus*. In 1981 Gastaldo (Gastaldo 1981a) described the new species from the genus *Palaeostachya* – *P. dircei*. Gastaldo performed many cross-sections to the concretion in the purpose of establishing a detailed diagnosis of the new species. Subsequently, Gastaldo (Gastaldo 1981b) described the isolated sporangia of the lycopsid *Lepidocystis* sp. containing *in situ* megaspores *Valvisporites auritus*, the specimen came from the Anna Shale Member.

Jennings and Millay (1978) described a new species – *Scoleopteris macrospora*, which were found in the ironstone concretions of Anna Shale above the coal seam Herrin near Carterville. They demonstrated for the first time that the use of suitable techniques in the study of ironstone concretions e.g. the sectioning of the concretion in cross-sections of suitable planes,

followed by its polishing and the application of the acetate film method, one could obtain comparable level of information to that derived from the study of coal balls. What is more, within sideritic concretions single large specimens are preserved, as opposed to a mixture of many different plants as observed within coal-balls. The ironstone concretions also delivered valuable morphological information which was difficult to obtain from coal-balls, such as three-dimensional gross morphology of plant organs.

Gorgetown

Ironstone concretions in the Carbondale Formation can also be found in yet another location, this time in the central-eastern state of Illinois, near a town called Georgetown (Vermilion Country). These concretions were found within the Energy Shale Member, above the Herrin (No. 6) Coal Member like those found in Carterville and likewise were dated from the Middle Pennsylvanian – Desmoinesian Series (Westphalian D). The numerous specimens were preserved in large concretions and are of a taxonomically similar composition to those of the Mazon Creek flora (Baird et al. 1985b).

Indiana

Terre Haute and other locations

Concretions containing fossil assemblages (flora and fauna) similar to those of the Braidwood in Mazon Creek were discovered in the open cast coal mine near Terre Haute (Vigo Country) in Indiana (Baird et al. 1985b). They appeared in the Busseron Sandstone Member of the Shelburn Formation, in shales above the coal seam Coal (No. 7) and were dated from the Middle Pennsylvanian, which correlates with the Westphalian D. The flora found within this location and described by Boneham (1975) has much in common with the famous Mazon Creek Flora, especially abundant in *Annularia stellata*, *Ptychocarpus unitus*, pectopterids with an absence of sphenopterids. Approximately 25% of the concretions from this location contained well preserved specimens. Within the floral assemblage, sterile organs predominate the area with lycopods stems and leaves, sphenopsid stems and leaves, fern and seed fern leaves. Plant reproductive organs such as the cones of lycopsids and sphenopsids, fertile leaves of ferns, pteridosperm pollen organs were rare in

number, and belonged to the same taxa as in Mazon Creek.

Ironstone concretions were also discovered in numerous coal mines that exploited Pennsylvanian coals in the state of Indiana. The plant remains that were found in these concretions prevailed in numbers over animal fossils (Baird et al. 1985b). Canwright (1959) described floras preserved within these concretions and also plant fossils from shales having concretions. The floras are both taxonomically rich and well preserved.

Wood (1963) described a flora contained primarily within the ironstone concretions of the Stanley Cemetery in Greene County, Indiana. This was a well preserved and taxonomically rich flora dating back to the Early Pennsylvanian – Westphalian B, with many plant reproductive organs, all beautifully preserved. Wood (1963) noted the similarities between this flora and the Mazon Creek flora, but these similarities likely resulted from the mode of preservation in sideritic nodules. Taxonomically speaking the flora was similar to the Westphalian A and B floras of Great Britain and Poland. This was especially visible in the very similar morphology of the *Lepidostrobus* cones, the lycopsid leafless twigs and stems, and the sphenopsid cones. The species of seed fern leaves were however typical for the Westphalian B floral assemblages.

Iowa

The flora which was preserved within the ironstone concretions of the Pennsylvanian strata of south-eastern Iowa (near Dunerath) was described by Spencer (1894) and Condit and Miller (1951). Only a few leaves of seed ferns and sphenopsid leaves from this site were illustrated (Condit & Miller 1951). The fossil assemblage was found to be similar in composition to that found at Mazon Creek (Baird et al. 1985b). The flora included the same taxa as in Mazon Creek and are of stratigraphically equivalent ages (Westphalian D).

Missouri

Windsor

This taxonomically rich and fossil abundant flora comes mainly from the ironstone concretions and also grey shales of the region of Windsor (Henry Country) in central-western Missouri (Bode 1958, Cridland & Darrah 1968,

Baird et al. 1985b). Concretions were found in the shales above the coal seams of the Croweburg Coal and New Castle Coal within the lowest part of the Verdegris Formation, and were dated back to the Middle Pennsylvanian – Desmoinesian Series, which correlated with the Westphalian D, they were however slightly older than the Mazon Creek concretions (Bode 1958). Bode (1958) was the first to study this flora, but the study was limited to listing taxa of the stratigraphically important seed fern leaves and some of the sphenopsid taxa. Cridland and Darrah (1968) described only one new species of the pollen organ – *Crossotheca urbani* preserved within the concretion, which they found in a dump, their entire collection of nodules contained 1500 specimens. The fossil assemblage (animal fossils were also found in this location) was very similar to the Braidwood type community in the Mazon Creek (Baird et al. 1985b).

Knob Noster

Knob Noster (Johnson Country, Missouri) is relatively new Pennsylvanian site uncovered in 1990 containing a flora and fauna preserved within ironstone concretions (Hannibal et al. 2003). Its fossil assemblage was found to be similar in composition to the Windsor and Braidwood of Mazon Creek sites. The concretions were found to originate from either the delta area or the estuary area while the plants were represented by the foliage of ferns, stems, seeds, cones and the trunks of arborescent plants. Investigations of this site are in progress and could potentially yield new findings.

Oklahoma

Henryetta and Morris

From the mudstones and siltstones above the coal seam of Croweburg Coal, within the lower part of Senora Formation (Middle Pennsylvanian – Westphalian D) in the town of Henryetta and Morris (Okmulgee Country), eastern Oklahoma State, another site yielding concretions has been unearthed but is yet to be described. Preliminary reconnaissance indicates that the flora is similar to that of the Braidwood biota of Mazon Creek (Baird et al. 1985b).

Sallisaw

Numerous plant and animal fossils from another concretion assemblage have been

discovered in dark grey mudstones above the coal seam of Stigler Coal, the McAlester Formation, the Cabaniss Group (the base of the Desmoinesian series, Middle Pennsylvanian, Westphalian C) within the eastern Oklahoma State town of Sallisaw (Sequoyah Country). This flora, which was different from the flora that was found at the Francis Creek Shale, is yet to be described. Its assemblage of fauna is similar to Braidwood in Mazon Creek (Baird et al. 1985b).

NORTH AMERICA (CANADA)

Nova Scotia

Stellarton Basin

Sideritic concretions and atypical siderite-dolomite coal balls with preserved anatomically plants have been found in the Foord Seam (Stellarton Basin, Nova Scotia) in coal and shale splits (Lyons et al. 1995, Zodrow et al. 1996, Zodrow & Cleal 1999). The plant tissue preservation was rather poor in sideritic nodules with only *Stigmaria* rootlets recognizable (Zodrow & Cleal 1999). The age of Foord Seam was estimated at Bolsovian (Middle Pennsylvanian, Upper Carboniferous) based on palynomorphs.

EUROPE

Great Britain

Coseley

Ironstone concretions accompany many coal seams in Great Britain from the roofs of which many are known to hold well preserved plant fossils within sideritic nodules. There is only one flora however which was found to be preserved this way and it is yet to be described in details. Kidston (1914) described the flora from the coal basin of Staffordshire, which was located in the town of Coseley near Dudley. Most of the ironstone concretions that were discovered came from the level Ten Foot Ironstone above coal seam Thick Coal, while the rest of the described specimens came from shales accompanying the coal seams. The age of the flora was estimated at Westphalian B (Lower/Middle Pennsylvanian). It was the first time in Europe that a complete description of a flora preserved within ironstone concretions was given. Some specimens

from the Coseley nodules were described by Kidston in earlier monographic papers about selected taxa, as well as taxa from other sites (Kidston 1903, 1905a, b, 1906a, b). In these papers the importance of this locality was already recognized by Kidston's description of new species of seed fern reproductive organs. Specimens of this flora were gathered by Kidston as well as other workers of the geological survey at the end of 19th century, most of the specimens were splendidly preserved three-dimensionally within ironstone concretions, especially differentiated reproductive organs, this became the basis for Kidston (1914) from which he described a dozen or so new taxa. Within the flora preserved in ironstones, among the taxonomically differentiated representatives of ferns belonging to genera, the following specimens were discovered: *Sphenopteris*, *Boweria*, *Sphyropteris*, *Adiantites*, *Pecopteris*, *Dactylothea*, the fertile leaves of the *Zeilleria avoldensis* have also been recognized.

The richest of taxonomical diversity can be found in the reproductive organs of seed ferns. Pollen organs were found in the numbers of several dozen specimens: 2 species of *Crossotheca*, *Telangium asteroides*, a new genus and species of pollen organ *Coseleya glomerata* (description based on large material). New species of pollen organ – *Neuropteris Carpentieri* (currently *Potoniea carpentieri*) was described based on specimen in which pollen organs were connected with axes. Kidston also isolated prepollen grains from this same organ. Smaller and more simply built pollen organs that were not connected with axes were described as *Whittleseya* (?) *fertilis* (currently *Boulayatheca fertilis*). Kidston illustrated the organs' variabilites and isolated in situ prepollen grains for analysis. Ovules found in connection with the *Neuropteris heterophylla* leaves were referred to this species. Other, isolated ovules were described as the new species: *Hexagonocarpus hookeri*, *Lagenostoma oblonga*, *L. (?) urceolaris* (fully preserved three-dimensionally specimen with all internal details), *Polypterosperrum orantum*, *Rhabdocarpus elongatus*, *R. renaulti*, *R. olivieri*, *R. wildi*, *Trigonocarpus noeggerathi*, *Trigonocarpus* sp., *Tripterosperrum ellipticum*, *T. johnsonii*. Within many concretions seed fern leaves were found, the following genera were recognized: *Mariopteris*, *Alethopteris*, *Aphlebia*, *Lonchopteris*, *Odontopteris*, *Neuropteris*, *Spiropteris*.

Lycopsid cones were found: *Lepidostrobus variabilis*, *L. triangularis*, *Sigillariostrobus* sp., as well as cones connected with branches of *Lepidodendron ophiurus*. One of the most remarkable specimens in the entire collection was a three-dimensional fully preserved small fragment of lycopsid cone described by Kidston as the new species *Lepidocarpon westphalicum*. This specimen was preserved so perfectly that Kidston noticed even the integumented sporangia (which were also well illustrated on his photographs). In no material referable to this genus, with the exception of specimens preserved within coal-balls, had anybody to date recognized integuments with such certainty. The lycopsid stems that were found in the Coseley nodules were referred by Kidston (1914) as belonging to the genera *Sigillaria* and *Bothrodendron*.

The sphenopsid remains contained within concretions predominantly consisted of sterile organs: *Equisetites*, *Calamites*, *Annularia*, *Asterophyllites*, *Sphenophyllum*, *Pinnularia*, few cones belong to *Calamostachys* and *Palaeostachya elongata*.

The cordaites were represented by the different species of *Cordaites* leaves, *Artisia* piths, cones *Cordaianthus volkmanni* and *Cordaianthus* sp., and ovules *Samaropsis gutbieri*.

The specimens originating from the Coseley preserved in the ironstone concretions were eventually described and illustrated in different papers (Kidston 1923–1925, Crookall 1955–1976, Halle 1933, Stockmans & Williere 1961, Kurmann & Taylor 1984, Taylor & Kurmann 1985), most of which contained Kidston's specimens, along with other specimens found at later times. Cleal and Thomas (1994) also illustrated the Coseley concretions containing: *Asterophyllites longifolius*, *Aulacotheca hallei*, *Boulayatheca fertilis*, *Potoniea carpenteri*. Cleal and Shute (2003) in the monograph of the genus *Laveinopteris* illustrated a well preserved yet to be recognized by Kidston, specimens of *Cyclopteris orbicularis*.

Currently animal fossils preserved within sideritic nodules from Coseley are being examined intensively with the use of the newest techniques, e.g. scanning using high-resolution X-ray microtomography (μ CT) (Dunlop 1999, Wilson & Almond 2001, Wilson 2005, Garwood et al. 2009, Garwood & Sutton 2010, Garwood & Dunlop 2011, Legg et al. 2012).

Bickershaw

In 1997 Anderson and co-authors reported the discovery of a new site rich in both flora and fauna preserved in ironstone concretions (Anderson et al. 1997). Nodules were found in the shales above the coal seam Haigh Yard Coal in Bickershaw (Lancashire) and numerous plant remains were found within the ironstone concretions. Anderson et al. (1997) identified on the basis the Cleal and Thomas (1994) key the following genera and species: *Alethopteris decurrens*, *Annularia radiata*, *Sphenophyllum cuneifolium*, *Maripteris muricata*, *Stigmaria ficoides*, *Cyperites*, *Lepidodendron*, *Lepidostrobus*, *Trigonocarpus*, *Calamites*, *Neuropteris*, *Pecopteris* and *Sphenopteris*. This assemblage of plants was typical for late Westphalian A (Lower Pennsylvanian). Plants within the ironstone concretions were preserved mainly as coalified remains. Only the *Lepidostrobus* cones were occasionally piritized, and are also sometimes filled with a calcite and a kaolinite. The concretions in Bickershaw were found on a dump similar to the one from Sosnowiec.

Westhoughton

In 1999 Anderson et al. (Anderson et al. 1999) reported a discovery in the region of Westhoughton (Lancashire) of another well preserved site of plants and animals within ironstone concretions, dating from the Uppermost Westphalian A (Lower Pennsylvanian). A lower number of plant fossils however were found in these concretions in comparison to those in Bickershaw, seed fern leaves were discovered to be very rare, with only the genus *Mariopteris* being recognized. Surprisingly one of the more common plants that were found within the nodules was the *Lepidostrobus* cones. Genera *Trigonocarpus* and *Cyperites* were also recognized. The location of this site was discovered in a working opencast coal-pit from which the concretions were collected *in situ* from shales above the coal seam Wigan Four Foot. Within these shales stems of *Calamites*, *Stigmaria ficoides* root systems with preserved anatomical structure and standing trunks of *Sigillaria* were found. Paleobotanical analyses of this site have yet to be undertaken.

Other British localities

Besides the described specimens mentioned above, a variety of Carboniferous plants

preserved within sideritic nodules have also been known to originate from British coal measures and were discovered as early as the 19th century. Many of them were described along with compression and impression fossils with added comments that they were preserved within sideritic nodules (mostly exclusively in plate captions).

Special attention should be given to the holotype of the typical species of genus *Lepidostrobus* – *L. ornatus*, preserved within an ironstone concretion from the Upper Carboniferous of Derbyshire. This specimen was illustrated for the first time by Parkinson in 1804, and then described by Brongniart (1828–1838), while furthermore revised by Brack-Hanes and Thomas (1983) who isolated *Lycospora granulata* spores from the specimen.

Cleal and Thomas (1994) illustrated the *Cordaitanthus* sp. found preserved within the concretion from above the coal seam Crow Coal in Crawcrook, the Rhyton, County Durham (Westphalian B, Lower/Middle Pennsylvanian).

Cleal and Shute (2003) illustrated within the monograph of the genus *Laveineopteris*, the well preserved in concretions specimens of *Cyclopteris orbicularis* from Westphalian B (Lower/Middle Pennsylvanian) of Coalbrookdale, Shropshire.

FRANCE

Montceau-les-Mines

This well preserved flora from the Upper Stephanian (Upper Pennsylvanian) shales in the area of Montceau-les-Mines (Massif Central) in France has been known since the 19th century (Grand'Eury 1877), and the flora and fauna preserved within the ironstone concretions of the area had been known since the early 1980's (Rolfe et al. 1982, Heyler & Poplin 1988). The perfectly preserved land and freshwater fauna that were found within these concretions instigated the greatest of interests (e.g. Racheboeuf et al. 2002, Vannier et al. 2003, Racheboeuf et al. 2008, Racheboeuf et al. 2009), although the flora itself has been described in detail only comparatively recently (Charbonnier 2004, Charbonnier et al. 2008). The material worked upon was collected *in situ* in three opencast coal-pits, where 6812 concretions containing remains of plants were

found, from which 51 taxa were determined. Within the plant fossils assemblage the species *Annularia stellata* (59%, 4041 specimens) dominated in number, with the remainder sphenopsids: *Calamites*, *Calamostachys tuberculata* and *Sphenophyllum* constituted 10% of assemblage. Ferns constituted 22% of the assemblage, particularly numerous were the magnificently preserved fertile specimens of different *Pecopteris* species. Seed ferns constituted somewhat less than 6% of the assemblage, and were represented by only their foliage. Some specimens were found to be fertile (*Dicksonites pluckenetii*). Lepidodendrolean lycopsids constituted 3% of the assemblage, represented mainly by *Cyperites* leaves, poorly preserved trunks of *Asolanus* and *Syringodendron* and one tree-dimensionally preserved specimen of *Sigillariostrobus*. Cycadales (*Taeniopteris jejuna*) and Cordaitales constituted each 1% of the assemblage. Particularly interesting are the as yet indeterminate small specimens of *Cordaitanthus* cones. An attempt to isolate the spores from fertile organs has yet to be undertaken.

POLAND

The fossils preserved within the ironstone concretions that were found in Poland have been barely recognized, even though the site in Upper Silesia was already known to Roemer (1866). From the concretions found in the area of Katowice, Roemer (1866) described a new genus and species of one of the oldest spiders *Protolycosa anthracophila*. In the same work he also mentioned the discovery of plant remains preserved within ironstone concretions. According to Roemer, the flora that was discovered in the Katowice nodules consisted of *Sigillaria*, calamites and ferns, unfortunately however, none of these were either described by him or illustrated.

Feistmantel (1874) was also familiar with the floras preserved within the sideritic nodules of the Upper Silesia, as he determined numerous preserved taxa within concretions found in Mysłowice, Katowice, Załęże, Orzesze, Pszczyna and Zagórze in Sosnowiec. The specimens described by Feistmantel were deposited in the Mineralogical Museum in Wrocław. Feistmantel however did not know the exact stratigraphic position of these specimens, but only their place of origin, and in spite of his

plans to properly describe and illustrate them, he only published short notes about them. These specimens, as described by both Roemer and Feismantel, are believed to be by now probably lost.

Some specimens of plants found preserved within sideritic nodules from the Westphalian strata (Lower/Middle Pennsylvanian) in the Jaworzno mine were collected by B. Rydzewski in early 20th century but unfortunately they were never published.

Bocheński (1939) illustrated two cone fragments of *Sigillariostrobus* as preserved within ironstone concretion, but he did not describe them in his text, even though they were the only three-dimensionally preserved specimens in his collection.

Outside the area from the Upper Silesia to the Upper Carboniferous strata of Poland only Zimmerman (1962) mentioned in his unpublished work of several species of sphenopsid and seed fern leaves preserved within sideritic nodules. These concretions were found in the neighbourhood of Okrzeszyn in the Lower Silesia, however, Zimmerman (1962) did not describe nor illustrate any of these specimens.

Sosnowiec

Concretions with plant remains preserved within the Sosnowiec site were collected from a waste dump of an already closed coal mine “Porąbka-Klimontów” in Sosnowiec (Zagórze district) between 1998–2006. The area of research was located within the Upper Silesia Coal Basin, in its north-east part, called the Dąbrowa region (Pacyna 2022a, b, 2003, 2004, Pacyna & Zdebska 2001, 2002, 2005, 2010).

Numerous concretions with preserved plants within them that were found in the Ignacy mine in Zagórze (later called the Ignacy shaft in Mortimer mine, the Mortimer-Porąbka mine, and the Porąbka-Klimontów mine) were already known to Feismantel (Feismantel 1874). Unfortunately Feismantel only gave a list of taxa, without any detailed descriptions or illustrations. Furthermore A. Kotasowa – the author responsible for the description of the flora which were found within the mentioned above coal mine (Kotasowa 1968), also made her own discoveries of concretions with preserved plants within them (A. Kotasowa per. comm.), but however never did she describe them.

The so far assembled collection of concretions from Sosnowiec counts about 1500 specimens with plant remains, from which 500 of them were found to have taxonomically diversified reproductive organs (Pacyna 2002a, 2007c).

The size of the concretions which hold the plant fossils range from two centimeters in diameter, to more than twenty centimetres in diameter, while their colour scheme ranges from darkgray, to beige, to brick-red.

Most of the plants within the concretions were found to be well preserved in their three-dimensional form, either coalified or mineralized. When remains are coalified then a film of carbon covers the walls of the empty space that remains from the biological degradation of the soft tissues of the three-dimensional organs. Mineralized plant fossils on the other hand are filled with a calcite, pyrite or with the kaolinite. Mixed mineralisation of fossils are also frequent e.g. calcitically – kaolinitic, whereby such preserved fossils could also have some of their parts coalified (Pacyna & Zdebska 2001, 2002).

Concretions with remains of plants and animals as found in Sosnowiec originate from the Mudstone Series, Załęże Beds. The particularly frequent occurrence of ironstone concretions in the Mudstone Series, unparalleled in the remaining Carboniferous beds of the Upper Silesia, has been a known fact for a long time (Porzycki 1972). Within the first half of 20th century they have been even exploited as a source of iron ores (Porzycki 1972, Tryjefaczka 1982). The ironstone concretions often appeared irregularly within strata and were not connected with any specific stratigraphical levels. They could be found in all types of sedimentary rocks, frequently in coal seams, but most often they accompanied mudstones. They appeared commonly in the form of single nodules, most often regular in shape with a diameter ranging about from 3 to 20 cm, however some specimens have been found reaching in sizes up to 1 meter in diameter (especially in the Dąbrowa region where such nodules have been described). The Mudstone Series, dated at Westphalian A-B, is divided into the Załęże and the Orzesze Beds. It is a monotonous series in respect of its lithology, mudstones and claystones dominate its thickness, with some local intercalations of sandstones, while intra-formational conglomerates are found to be rare.

Within the Mudstone Series a large number of coal seams appear. Many well preserved coalified plant remains were found within this series (Kotasowa 1968).

The flora preserved within the concretions from Sosnowiec was mainly allochthonous in origin. Plant debris must have been transported through fluvial action into the sedimentary basin, where concretions then formed. Some plant fragments were also probably carried by the wind e.g. some fragments of leaves. These changes of location must have been probably very short however, since many of the very delicate structures (e.g. microsynangia of seed ferns, lycopsid cones) were found perfectly preserved and intact. Only calamites, which could be found at the borders of channels and lake banks and constituted a large part of recognized plant fossils, could grow there *in situ*. Large nodules with three-dimensional internal casts of calamite stems and the stem bases that were preserved within concretions, give evidence to this interpretation. The dimensions of the plant remains from the other systematic groups were usually significantly smaller.

The floristic assemblage from the ironstone concretions as found in the Sosnowiec was generally similar in nature to the flora described in the mudstones from which the concretions originated (Kotasowa 1968), the organs which prevailed in these concretions however were seldom found in mudstones. Most interesting is the particularly frequent occurrence of reproductive organs and small plants that were generally seldom found within these strata (Pacyna 2002a, b, 2003, 2007a, b, c, Pacyna & Zdebska 2001, 2010). Fossils from the concretions were also preserved three-dimensionally, as opposed to the flora from the shales where as a result of the strong diagenetic mudstone compaction, fossils were flattened. This three-dimensionality was particularly visible in the case of lycopod cones that are preserved within the concretions (Pacyna 2007c).

Palaeoecological reconstructions place lycopods as the dominant component of the landscape of the flora. Most numerous within the concretions were their leafless twigs which represented a new taxon (Pacyna & Zdebska 2005). Cones and isolated sporophylls from the new species of *Lepidocarpon* genus could be very frequently found, possibly belonging to the same plant as the leafless twigs. Stems and cones of other lycopsid species were less

numerous. Sphenopsid diversified stems, whorls of leaves and cones were also found. Ferns and seed ferns and their reproductive organs were differentiated taxonomically, but are less numerous than the other groups mentioned earlier. The presence of cordaites was marginal, represented mainly by cones and rare leave fragments (Pacyna 2002a, b). Particularly interesting and of exceptional value to this location, and not unlike that which could be found in Coseley (Kidston 1914), was the large presence of various reproductive structures and small plant forms that have seldom been described at all (Pacyna & Zdebska 2001, Pacyna 2003).

With the last salt water ingressions into the Upper Silesia having been dated at Namurian A, the described fossil assemblage having been represented by both land and freshwater environments therefore, and Sosnowiec could be perceived as a parallel counterpart to the flora and fauna type from Braidwood in Mazon Creek. Its faunistic assemblage hitherto described consisted of horseshoe crabs, eurypterids, insects and bivalves (Filipiak & Krawczyński 1995, 1996, Krawczyński et al. 1997), with subsequent searches bringing forth the discovery of various animal groups (Pacyna et al. 2004, Stworzewicz et al. 2009, Prokop et al. 2012).

The age of the fossil assemblage was determined using the same method as that used at Mazon Creek. Unfortunately, earlier palynological attempts at an age evaluation that were undertaken did not yield conclusive results (Krawczyński et al. 1997). On the basis of macroscopic plant remains the age of the concretions could be evaluated explicitly towards the late Langsettian (late Westphalian A), Lower Pennsylvanian, with subzone Laveineopteris loshii, which resulted in the floristics assemblage VIII within the Carboniferous floral succession of Upper Silesia, as in accordance with the Kotasowa and Migier (1995) division. Within the flora from Sosnowiec concretions were found following index species for the Upper Silesia Carboniferous strata: *Lepidodendron aculeatum*, *L. obovatum*, *Sigillaria mamillaris*, *S. rugosa*, *Mesocalamites ramifer*, *Stylocalamites cisti*, *S. suckowii*, *S. undulatus*, *Sphenophyllum cuneifolium*, *Annularia radiata*, *Asterophyllites charaeformis*, *A. equisetiformis?*, *Sphenopteris (Renaultia) schwerini*, *Pecopteris (Senftenbergia) pulmosa-dentata*,

P. (Asterotheca) miltoni, *Lyginopteris hoeninghausii*, *Neuropteris heterophylla*, *Neuraethopteris schlehanii*, *N. rectinervis*, *Paripteris gigantea*, *P. pseudogigantea*, *Mariopteris muricata*, *Karinopteris acuta*, *Margaritopteris pseudocoemansi*, *Alethopteris decurrens* (Pacyna 2002a, b). These species were typical for the assemblage VIII in the Carboniferous floral succession of Upper Silesia, in accordance with the Kotasowa and Migier (1995) division.

In the case of the age estimation of the concretions from Sosnowiec the most essential elements of study were species extinct from the end of Westphalian A stage or such species whose stratigraphical occurrence were limits exclusively to that of the Westphalian A stage. In examining the available material four such species were recognized: *Lyginopteris hoeninghausii*, *Neuraethopteris schlehanii*, *N. rectinervis*, *Karinopteris acuta* and *K. beneckeii*. From these, the most important was the species *Lyginopteris hoeninghausii*, which was exclusively limited to the stratigraphical range of Westphalian A. This became the main index species for Westphalian A, as found not only in Poland, but also for entire European Carboniferous (Kotasowa 1975). The species *Neuraethopteris schlehanii* and *Karinopteris acuta* first appeared in fossil records at the Namurian, and eventually achieved full quantitative culmination at the occurrence of Westphalian A towards the end of which they became extinct (Kotasowa & Migier 1995). The species *Karinopteris beneckeii* first appeared in Namurian B in which it was very frequently found, as well as in Westphalian A towards the end of which they became eventually extinct. The species *Neuraethopteris schlehanii* had the same stratigraphical range in Upper Silesia as it did in Western Europe and was well index species (Goubet et al. 2000). *N. rectinervis* appeared exclusively in the upper part of Westphalian A. Presence of those species indicating that the concretions originated from Westphalian A stage, the *Lyginopteris hoeninghausii* zone (the fossil plants assemblage VIII in the Carboniferous floral succession of Upper Silesia according to the Kotasowa and Migier (1995) division, the floristic assemblage IV according to the local Kotasowa division (Kotasowa 1968) for the Dąbrowa region). In addition to the species that were typically part of this floral assemblage, including the ones mentioned above,

the following species were also determined as belonging to the Sosnowiec concretions: *Sigillaria mamillaris*, *S. rugosa*, *Sphenopteris (Renaultia) schwerini*, *Pecopteris (Senftenbergia) pulmosa-dentata*, *P. (Asterotheca) miltoni*, *Neuropteris heterophylla*, *Paripteris gigantea*, *Paripteris pseudogigantea*, *Mariopteris muricata*, *Margaritopteris pseudocoemansi* (Pacyna 2002a, b).

Three of the recognized species in the Sosnowiec nodules appeared in the Westphalian A stage, each successively higher within their profile. These were: *Margaritopteris pseudocoemansi*, *Neuropteris heterophylla* and *Neuraethopteris rectinervis* (Kotasowa & Migier 1983, 1995), these are index species for the upper part of Westphalian A stage, subzone *Laveineopteris loshii*, enabling therefore to pinpoint the specific age of the concretions at late Westphalian A (late Langsettian), subzone *Laveineopteris loshii*. These results also confirm the numerous occurrences in the concretions of the species *Neuropteris heterophylla* which species first appeared in this subzone and the relatively few occurrences of *Lyginopteris hoeninghausii* and the genus *Neuraethopteris* what is characteristic for this subzone (Cleal & Thomas 1994).

Presumably as it was the case in Montceau-les-Mines, the lake in Sosnowiec was the point of origine for the concretions as discussed above (Doktor & Gradziński 1985, Vannier et al. 2003). While allochthonous plant remains drifted down channels of crevasses or during greater floods, the calamites in turn, which constituted a larger fraction among the vegetable remains, related to the borders of channels and lakes banks, they were the only species to grow as such *in situ*. Large nodules with three-dimensional internal casts of calamite stems, as well as the very frequent occurrence of the whorls of *Asterophyllites* leaves, both not unlike those found in Montceau-les-Mines, gave evidence to such an interpretation (Charbonnier 2004). The dimensions of the plant remains from the other plant groups remained usually significantly smaller. As a result of such a palaeoenvironmental interpretation it is interesting to note such a large presence, of otherwise rare in fossil record, isolated megasporophylls of genus *Lepidocarpon*. *Lepidocarpon* sporophylls were able to travel to the lake, where concretions were formed during the greater flood. Numerous occurrences of this type of

sporophylls were recognized in the Mazon Creek and Carterville nodules (Schopf 1938, 1941, Gastaldo 1977, Pfefferkorn 1979).

A very early cementation of soft sediment by iron and carbonate compounds can preserve the surface configuration of organic parts, but nonetheless most tissues, even those initially preserved have been degraded and the voids which remain after could be secondarily filled in. The structure of the epidermis is generally not well preserved, this phenomenon was well observed in the Mazon Creek flora (Pfefferkorn 1979). However, with this particular mode of fossil preservation the delicate structures can preserve itself, e.g. such as it was the case with the microsynangia of seed ferns which were described from Mazon Creek and Cosley (Kidston 1914, Drinnan & Crane 1994), and also found in Sosnowiec and described as the new species *Codonothea silesiaca*, *Boulayatheca ciliata* and *Dolerothea migierii* (Pacyna 2007a, b, c, Pacyna & Zdebska 2010). Since such similar morphological structures were preserved often in ironstone concretions such as its been discovered in the different sites (in Mazon Creek, in Sosnowiec), and since these types of plant structures were rarely, if ever, found within rocks accompanying coal seams, therefore it could be deduced that some types of morphological structures were predisposed more than others to become the nucleus of the concretion. An example of such type of plant organ could be the thin lycopod twig, which has an aggregation of leaves on its apex. Such types of fossils have been found in the Sosnowiec concretions and could probably be referred to a new species, very similar in nature, but different taxonomically from those described in the Mazon Creek and Carterville floras (Noe 1925, Gastaldo 1977, Pfefferkorn 1979, Pacyna & Zdebska 2005).

The Mazon Creek flora was characterized by a large number of species with large intraspecific size ranges. The occurrence of gigantism in some of the forms is interesting, such as it was the case with some of the species found outside of the Mazon Creek nodules, which tend to be significantly smaller in sizes (Pfefferkorn 1979). In Sosnowiec on the contrary, the large presence of small forms was striking, the size of the lycopod and the sphenopsid cones being there significantly smaller in comparison to such similar cones as those found in the coeval shales. The lycopod cones, which

were preserved within the sideritic nodules in Sosnowiec are common as fossils, as is the case with the Bickershaw and Westhoughton sites (Anderson et al. 1997, 1999). Interestingly concretions often formed around these spherical reproductive organs.

The number of recognized plant organ species found in the Mazon Creek flora have now reached up to three hundred (Pfefferkorn 1979). An attempt has been made to compare the diversity of the flora from the Mazon Creek and from the Sosnowiec, and this to this day this operation is still in progress, as not all the taxa have yet been determined in the Sosnowiec flora. In Sosnowiec the amount the pteridophyte reproductive organs have been discovered to be greater in number, particularly the lycopsid cones, while the amount of leaves of seed ferns significantly smaller. To this day only one fertile fern leaf have been discovered in Sosnowiec, while in Mazon Creek the fertile fern leaves were diversified and abundant (Pfefferkorn et al. 1971, Pacyna & Zdebska 2002).

Pfefferkorn (1979) postulated that on the basis of fossils found in Mazon Creek the mode of preservation of plants in the concretions did not have an influence on the specific composition contained within them flora, while on the other hand the occurrence of rare forms of specimens within the concretions intensified the collections of specimens, hence within a suitably large collection one would have the chance of finding increasingly more and more rare forms of specimens. Unfortunately the composition of the flora from Sosnowiec does not confirm such an interpretation. The collection of plants from Sosnowiec nodules, though quite large in number with about 1500 specimens, is disparately smaller than the one from Mazon Creek. In the Museum of Illinois can one find above 16 thousands specimens of concretions containing plants. Among the plants within Sosnowiec nodules almost half constituted rare or unknown forms of species as found within the shales (various reproductive organs, lycopsid thin twigs). It is worth noticing that similar and delicate morphological structures were often preserved within sphaerosiderites, but rarely were they ever found in the shales. One can thus perhaps conclude that some types of organs are predisposed to become the nucleus of the concretion. An example of such types of delicate organs are the seed fern microsynangia, which appeared in great numbers

in the Mazon Creek as well as in Sosnowiec (Pacyna 2007a, b, c, Pacyna & Zdebska 2010), another example could be the thin lycopsid twigs with leaves aggregated onto their apices, as discovered in Mazon Creek (Noe 1925), as well as recently the concretions in Sosnowiec (Pacyna & Zdebska 2005).

Since such delicate organs decayed the quickest, one could suppose that their preservation in the concretions was a result of a surplus in feedback, whereby the delicate organ quickly decomposed, and changed the local conditions of the environment so as to favour the necessary formation of a concretion. As result of this process the concretion thus arises, the more such plant remains the more easily concretions will therefore form (Baird 1997). Of course organisms of this type, which were frequently preserved in the shales (e.g. leaves, fragments of twigs), also appeared frequently within the concretions themselves, with the proportions of the organisms being either often present or sporadically present within the shales, the latter of which was of much greater important to the concretions.

The fossils assemblage from the Sosnowiec concretions was identical in respect to the taxonomic composition within the assemblage described by Anderson et al. (1997) in Bickershaw. Such taxonomical compositions were typical for the Europaeen late Westphalian A floras, and permitted the evaluation of the age of the fossils to be made not only from Bickershaw but also from Sosnowiec, confirming that both concretions had indeed the same correct age. Plants preserved within the ironstone concretions from Bickershaw were discovered as being mainly coalified, only the cones of *Lepidostrobus* were sometimes piritized, as they could also be filled with calcite and kaolinite. Identical modes of preservation were found in Sosnowiec. Similarly, the concretions from Bickershaw were found on the spoil tip, as were the ones from Sosnowiec.

Within the shales that were found in the spoil tip in Sosnowiec from which the concretions were likely derived, stems of *Calamites*, *Stigmaria ficoides* root systems and fragments of the bark from trunks of *Sigillaria* were found. These taxa were also recognized in the shales from which came the concretions in Westthoughton (Anderson et al. 1999).

The flora from Sosnowiec was allochthonous in origin, meaning it contained drifted

and mixed plants presumably from different places of origin. For this reason the palaeoenvironmental reconstruction for this flora was deemed to be very difficult (Baird et al. 1986, Pacyna 2004). However the frequency of the occurrences of the plant remains from the different taxa, the differences in sizes of the preserved organs, the degree of the disintegration of the seed fern complex leaves, can give us some clues as to the kind of environments from which these plants came from. One can therefore try to relate some of the found taxa to the otherwise described taxa as found in the literature of the palaeoenvironment coal forests.

Generally known reconstructions of the Carboniferous coal forests have little in common with the truth. They present coal-forming plants growing side by side on a peatbog, which we know today is false, since they did not appear growing together at all. The environments of Carboniferous lowlands were also much more differentiated, which can be well observed on the basis of the sedimentological research (e.g. Doktor & Gradziński 1985). Although some have tried to reconstruct the Carboniferous "forests" from the very beginning of palaeobotany development, these reliable environmental reconstructions of the Carboniferous lowlands based on plant macroremains have had a relatively short history (DiMichele & Phillips 1985). Only the pioneering works by Gastaldo (1987, 1991, 1996) contributed to the modern reconstruction of such Carboniferous lowlands, as well as the observations made by Scheihing and Pfefferkorn (1984) during their expeditions to the Orinoco delta, which permitted a better understanding of the taphonomic aspects of the Carboniferous lowlands environment.

Palaeogeographical reconstructions place the Upper Silesia in the Carboniferous period only several degrees north of the equator in the area of the tropical climate. The environment for the deposition of the Mudstone Series was an extensive, flat river plain, subjected to constant subsidences, formed by meandering and anastomosing rivers. Fine-grained sediments were deposited mostly on the forested areas outside river channels and only in the small part in shallow, relatively short-termed lakes. Sands were deposited mainly in the river channels and in the areas of crevasse splays. Peatbogs were developed on badly drained swamp areas of the external flood

plane, with significantly limited deliveries of clastic materials being made to the peatbogs (Doktor & Gradziński 1985).

Plants that were preserved within the concretions represent different environments of the river-plain as occupied through the meandering rivers. Most often in the concretions thin leafless lycopsid twigs were found which belong probably to a new pseudoherbaceous rizomorphic lycopsid taxon (Bateman & DiMichele 1991, Bateman 1992, Bateman et al. 1992, DiMichele & Bateman 1996, Pacyna & Zdebska 2005). Presumably this was a plant which formed compact thicket, as it had a very short, lignified trunk growing out of its repeatedly divided stigmata, while from its trunk branches grew out across the surface of the ground. This lycopsid grew probably within the area of a flood plane. Flood plains were most often covered and grew by congeneric communities of lycopsids resistant to stagnant water (Phillips 1979, DiMichele & Phillips 1994). Probably most of the cones and isolated sporophylls that were found within the concretions from Sosnowiec belonged to this new species of lycopsid, mature megaspore cones disintegrated onto single sporophylls, which were adapted to the distribution of water (Bateman et al. 1992). At least during part of the vegetative season these plants were submerged in water, be it during a flood or a rainy season. The most characteristic feature of this plant was its quick shedding of leaves, some leaves remained only on the very ends of twigs, and displayed not unlike that of brush. Shedded lycopsid leaves (*Cyperites bicarinatus*) were frequent in concretions.

Within the area which is known today as Sosnowiec, in sediments formed in river bars, a taxonomically distinct flora once grew, composed of several species of Lepidodendrales: *Lepidodendron aculeatum*, *L. dichotomum*, and *L. obovatum*, from which concretions containing imprints of bark scales, twigs and leaves.

The environment of river bars – taxonomically rich among environments of Carboniferous lowlands (DiMichele & Phillips 1994) was represented in the concretions by fragments of the bark of lycopsids and the leaflets of complex leaves of ferns and seed ferns. Lycopsids from the genus *Sigillaria* (*S. mamillaris*, *S. rugosa*) lived there, among them grew arborescent ferns (*Sphenopteris* sp., *Pecopteris plumosa-dentata*, *P. miltoni*, *P. avoldensis*) as

well as herbaceous ferns (e.g. *Renaultia schwernerini*). Seed ferns recognized in Sosnowiec were mainly representatives of the Medullosales group. Their leaves were found to be: *Neuropteris obliqua*, *Neuraethopteris schlehani*, *N. rectinervis*, *Paripteris gigantea*, *P. pseudogigantea*, and *Alethopteris decurrens*, as well, it so appears, their reproductive organs, e.g. microsynangia *Codonotheca silesiaca*, *Boulayatheca ciliata*, *Dolerotheca migieri*. Less numerous were the seed ferns from the family of Maropteridaceae (*Karinopteris acuta*, *K. beneckeii*, *Mariopteris muricata*). There representatives of Lyginopteridales could also be found: the leaves *Lyginopteris hoeninghausi* and pollen organs *Silesiatheca formosa*. The Seed ferns were climbing plants, their slender stems holding on to the trunks of *Sigillaria* and arborescent ferns (Gradziński & Doktor 1995). They could also form thick thickets in which their thin trunks covered the tangle of roots and produced 4-metre huge leaves supported by each other. In the undergrowth there surely grew thickly herbaceous horsetails from the genus *Sphenophyllum*.

As they quickly grew during the floods crevasse splays delivered sediments to the flood plain area. Under these circumstances pioneer species were calamites from the group *Stylocalamites* e.g. *S. cistii*, *S. suckowii*, and *S. undulatus* (Gradziński & Doktor 1995). Calamites created also “bulrush” communities over banks of lakes. Within the concretions taxa were found which could have created these communities: *Diplocalamites paleaceus*, *Mesocalamites cistiformis*, *M. ramifer*, *Annularia radiata*, *A. sphenophylloides*, *Asterophyllites charaeformis* – particularly often found together with the cones *Calamostachys charaeformis*, *Asterophyllites equisetiformis?* (Pacyna 2002a, b, Pacyna & Zdebska 2001, 2002).

Cordaitales were still rare element of coal-forming forests in Westphalian A (DiMichele & Phillips 1994), however by then they already had occupied different ecological niches from the thicket of the mangroves type, to the mountainous forests (Falcon-Lang & Scott 2000). Their participation in the concretions from Sosnowiec was small. The specimens were represented by only a few leaves from the genus *Cordaites* and differentiated themselves, but only ever so slightly in comparison the described in literature cones, by a complete lack of seeds. In the landscape of Sosnowiec

they could appear far from the flood plain (Florin 1938–1945, Meyen 1987, 1997, Gastaldo 1991, 1996, Šimůnek 2000, Šimůnek & Libertín 2006).

CONCLUSIONS

The preservation of an organism within an ironstone concretion was due to its quick formation, and enabled the preservation of the original three-dimensional shapes of the organisms as well the preservation of its delicate morphological elements.

The floras preserved within the ironstone concretions united in a very interesting way: its allochthonic origin with unusual taphonomical aspects resulting from syngenetic with the surrounding sediment formation of ironstone concretions (Baird et al. 1986, Schopf 1975, 1979).

Most of the floras preserved within ironstone concretions from Europe and North America originated from the Westphalian stage – the period with the greatest diversity of tropical Carboniferous floras. Similarities in their taxonomic composition are likely the result of a taphonomical filter during the formation of the concretions, which favoured the compartment of delicate and rare taxa, particularly the reproductive organs.

The assemblage of plant remains from the Sosnowiec ironstone concretions was very differentiated and contained forms that are yet to be described. The assemblage was exceptional because among the remains of the plants, reproductive organs that were seldom found in other fossil plant sites dominated the area, as well as many other small forms of well preserved plants. Such small plant forms as found in the Carboniferous shales and mudstones were commonly poorly preserved and therefore treated in the literature as detritus and very rarely described, even though they often carried much important information about the morphology and the anatomy of small taxa. Within nodules from Sosnowiec an intriguing fauna of land and freshwater animals have been also found, such animals were described up to now from only several locations in the world (Filipiak & Krawczyński 1995, 1996, Krawczyński et al. 1997, Pacyna & Zdebska 2001, Pacyna et al. 2004, Stworzewicz et al. 2009, Prokop et al. 2012).

Sites with fossils preserved within the ironstone concretions, particularly the Mazon Creek site, are recognized universally as examples of fossil assemblages carrying a lot of information about extinct organisms, the sites characterizing themselves by their huge wealth and completeness. They are examples of Konservat–Lagerstätten (Nitecki 1979, Baird et al. 1885a, b, Baird et al. 1986, Baird 1990, Shabica & Hay 1997, Shields 1998, Schellenberg 2002, Nudds & Selden 2008). However, none of these, as of yet described Carboniferous palaeontological sites in Poland have gained the recognition of being named a Lagerstätte. The locality in Sosnowiec is significant as the first example of a Carboniferous Lagerstätte in Poland (Pacyna 2008b). The exceptionally well preserved three-dimensional fossils are important specimens which elucidate new information on the morphology of plant reproductive organs. The Sosnowiec site is a significant Konservat – Lagerstätte from a region of middle Europe that is at present relatively understudied (Pacyna & Zdebska 2002, Zatoń & Marynowski 2004).

New research techniques like high-resolution X-ray microtomography which has been used to extract detailed anatomical information in plant fossils from deposits elsewhere promise future discoveries from this locality (Spencer et al. 2013).

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