The Mazon Creek Lagerstätte: a diverse late Paleozoic ecosystem entombed within siderite concretions

Thomas Clements1,2*, Mark Purnell1 & Sarah Gabbott1*
1 Department of Geology, University of Leicester, Leicester LE1 7RH, UK
2 School of Biological, Earth and Environmental Sciences (BEES), University College Cork, Ireland
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Abstract: One of the best records of late Paleozoic ecosystems, the Mazon Creek Lagerstätte is world famous for its striking flora and fauna preserved within siderite concretions. Distinct from other late Carboniferous concretionary Lagerstätten because of the remarkable fidelity of soft tissues and pigments that are frequently preserved, the Mazon Creek has seen a revival in investigations during the last 10 years using modern palaeontological techniques. However, many of these modern investigations build upon a literature that incorrectly interprets the palaeoenvironment of the Mazon Creek and the separate biotas: there is a lack of evidence to support a distinct freshwater fauna. Here, we present a detailed overview of the Mazon Creek Lagerstätte, including the palaeoenvironmental conditions, organisms present and the complex taphonomic processes involved in fossil formation. Investigation into the formation of siderite concretions and the complex taphonomic processes controlling soft-bodied preservation are still continuing but are reviewed in detail.

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The late Carboniferous (Pennsylvanian) Mazon Creek Lagerstätte, Illinois, USA, is exceptional for the diversity and abundance of preserved fauna and flora found within siderite concretions. It hosts the highest diversity of Carboniferous terrestrial plants (Horowitz 1979) and exceptionally preserved 3D animals representing over 300 species from 11 phyla and 23 classes (Shabica & Hay 1997; see Table 1 and Box 1). Unlike most Lagerstätten, it includes fossil organisms that inhabited a number of closely connected habitats including terrestrial swamps, nearshore and fully marine environments. This means that the Mazon Creek provides a unique ‘window’ into multiple Carboniferous animal and plant communities. Exceptionally preserved fossils from the Mazon river area have been known since the mid-19th century (see Nitecki 1979), but it was only after intensive strip mining for coal began in the 1940s that the importance of the Mazon Creek Lagerstätte (Mazon Creek) was truly realized. The fossiliferous concretions of the Mazon Creek Occur within the Francis Creek Shale Member of the Carbondale Formation, removed as overburden to one of the largest and most profitable coal seams in the northern USA (Wright 1979). Records indicate that over 83 shaft mines and 15 strip mines operated between the 1900s and 1980s across a 250 km² geographical area in northern Illinois (Shabica & Hay 1997). Several companies, including the ‘Peabody Coal Company’ (which operated the largest and most famous strip mine, the 14 km² ‘Pit 11’) extracted coal for over 50 years, resulting in the accumulation of immense spoil heaps that were picked over for fossil-bearing siderite (iron carbonate, FeCO₃) concretions by collectors and researchers for decades. This resulted in huge collections of fossil material being amassed; it is not uncommon for collectors to own tens of thousands of fossiliferous concretions, with many hundreds of thousands of Mazon Creek fossils being donated to museums worldwide or sold privately.

Owing to the flat topography of Illinois, very few natural exposures exist; the banks of the Mazon River reveal some outcrop (Fig. 1e); however, high river discharge, vegetation overgrowth and land ownership make collecting problematic. Unfortunately for palaeontological research, the majority of the coal mines were closed and back-filled during the 1990s. Because of this, collecting localities are greatly diminished, especially the largest, Pit 11, which was deliberately flooded to create a fishing reserve and cooling lake for a nuclear power station. Nevertheless, study of the Mazon Creek is currently undergoing a revival (e.g. Sallan & Coates 2014; Clements et al. 2016; Cotroneo et al. 2016; Gabbott et al. 2016; Locatelli et al. 2016; McCoy et al. 2016; Murdock et al. 2016), predominantly utilizing the huge collections of fossiliferous material at several North American institutions such as the Field Museum of Natural History, Chicago, USA and the Royal Ontario Museum, Toronto, Canada.

Site location and age

The Mazon Creek is named after a tributary of the Illinois River SW of Chicago (Illinois, USA), that flows close to the town of Morris, Grundy County, Illinois, USA (Fig. 1). The fossiliferous concretions are found across an area of c. 150 km² spanning several counties; when found in situ, the concretions occur within the lower 3–8 m of the Francis Creek Shale Member.

Baird (1979) stated that the Francis Creek Shale Member was deposited at 290 Ma based on Eysinga (1975), whereas later work and reviews (i.e. Baird et al. 1985a; Shabica & Hay 1997; Schellenberg 2002) used an age of 296 Ma based on Harland et al. (1982). However, nearly all subsequent literature (i.e. Baird et al. 1985b, 1986; Sallan & Coates 2014; Clements et al. 2016; Cotroneo et al. 2016; McCoy et al. 2016, etc.) cited the Francis Creek Shale Member as having an age of 306–311 Ma. The latter age is based on studies utilizing palynological and palaeobotanical data (Pfefferkorn 1979; Wagner 1984; Peppers 1996), which indicate an age that equates to the upper part of the Moscovian stage, the top of which has been dated at 307.0 ± 0.1 Ma (Cohen et al. 2013).

Carboniferous Illinois

Late Carboniferous global-scale geological processes were dominated by the collision of Laurussia and Gondwana and the onset of
Table 1. Fauna found in the Mazon Creek (amended from Shabica & Hay 1997, Appendix B)

<table>
<thead>
<tr>
<th>Phylum</th>
<th>Class</th>
<th>Orders represented</th>
<th>Number of sp.</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cnidaria</td>
<td>Cuboza</td>
<td>1</td>
<td>1</td>
<td>Sea wasps and box jellyfish</td>
</tr>
<tr>
<td></td>
<td>Scyphozoa</td>
<td>1</td>
<td>4</td>
<td>‘True’ jellyfish</td>
</tr>
<tr>
<td></td>
<td>Hydrozoa</td>
<td>1</td>
<td>2</td>
<td>Hydras and siphophores</td>
</tr>
<tr>
<td></td>
<td>Anthozoa</td>
<td>1</td>
<td>1</td>
<td>Sea anemones and corals</td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
<td>?</td>
<td>11?</td>
<td></td>
</tr>
<tr>
<td>Nemertea</td>
<td></td>
<td>1</td>
<td>1</td>
<td>Ribbon worms</td>
</tr>
<tr>
<td>Nemotoda</td>
<td></td>
<td>1</td>
<td>1</td>
<td>Nematodes</td>
</tr>
<tr>
<td>Priapulida</td>
<td></td>
<td>1</td>
<td>1</td>
<td>Penis worms</td>
</tr>
<tr>
<td>Chaetognatha</td>
<td></td>
<td>1</td>
<td>1</td>
<td>Arrow worms</td>
</tr>
<tr>
<td>Annelida</td>
<td>Polychaeta</td>
<td>7</td>
<td>16?</td>
<td>Segmented worms</td>
</tr>
<tr>
<td>Onychophora</td>
<td></td>
<td>1</td>
<td>1</td>
<td>Velvet worms</td>
</tr>
<tr>
<td>Arthropoda</td>
<td>Chelicerata</td>
<td>12</td>
<td>43</td>
<td>Horseshoe crabs, arachnids and sea spiders</td>
</tr>
<tr>
<td></td>
<td>Euthycarcinoidea†</td>
<td>1</td>
<td>3</td>
<td>Extinct arthropod group</td>
</tr>
<tr>
<td></td>
<td>Diplopoda</td>
<td>2</td>
<td>17?</td>
<td>Millipedes</td>
</tr>
<tr>
<td></td>
<td>Chilopoda</td>
<td>2</td>
<td>3</td>
<td>Centipedes</td>
</tr>
<tr>
<td></td>
<td>Arthropilureidea†</td>
<td>1</td>
<td>2</td>
<td>Extinct giant millipedes</td>
</tr>
<tr>
<td></td>
<td>Insecta</td>
<td>11</td>
<td>210+</td>
<td>Insects</td>
</tr>
<tr>
<td></td>
<td>Remipedia</td>
<td>1</td>
<td>1</td>
<td>‘Oar-footed’ marine crustaceans</td>
</tr>
<tr>
<td></td>
<td>Malacostraca</td>
<td>8</td>
<td>14</td>
<td>Crabs, lobsters, shrimps, etc.</td>
</tr>
<tr>
<td></td>
<td>Phyllopoidea</td>
<td>3</td>
<td>4</td>
<td>Fairy and clam shrimp</td>
</tr>
<tr>
<td></td>
<td>Maxillopoda</td>
<td>3</td>
<td>7</td>
<td>Copepods, barnacles and tongue worms</td>
</tr>
<tr>
<td></td>
<td>Thylacoccephala†</td>
<td>2</td>
<td>3</td>
<td>Extinct ‘head pouch’ arthropods</td>
</tr>
<tr>
<td>Mollusca</td>
<td>Polyplacophora</td>
<td>1</td>
<td>1</td>
<td>Clitons</td>
</tr>
<tr>
<td></td>
<td>Gastropoda</td>
<td>1</td>
<td>5</td>
<td>Slugs and snails</td>
</tr>
<tr>
<td></td>
<td>Bivalvia</td>
<td>8</td>
<td>24</td>
<td>Bivalves</td>
</tr>
<tr>
<td></td>
<td>Cephalopoda</td>
<td>4?</td>
<td>11?</td>
<td>Cephalopods</td>
</tr>
<tr>
<td>Brachiopoda</td>
<td>Inarticulata</td>
<td>2</td>
<td>2</td>
<td>Non-hinged brachiopods</td>
</tr>
<tr>
<td></td>
<td>Articulata</td>
<td>1</td>
<td>1</td>
<td>Hinged brachiopods</td>
</tr>
<tr>
<td>Echinodermata</td>
<td>Holothuroidea</td>
<td>1</td>
<td>1</td>
<td>Sea cucumbers</td>
</tr>
<tr>
<td></td>
<td>Crinoidea</td>
<td>1</td>
<td>1</td>
<td>Crinoids</td>
</tr>
<tr>
<td>Hemichordata</td>
<td>Enteropneusta</td>
<td>1</td>
<td>1</td>
<td>Acorn worms</td>
</tr>
<tr>
<td>Chordata</td>
<td>Cyclostomata</td>
<td>3</td>
<td>4?</td>
<td>Jawless fish</td>
</tr>
<tr>
<td></td>
<td>Chondrichthyes</td>
<td>6</td>
<td>15?</td>
<td>Cartilaginous fish</td>
</tr>
<tr>
<td></td>
<td>Osteichthyes</td>
<td>3</td>
<td>14</td>
<td>Ray finned fish</td>
</tr>
<tr>
<td></td>
<td>Sarcopterygi</td>
<td>2</td>
<td>11</td>
<td>Lobe finned fish</td>
</tr>
<tr>
<td></td>
<td>Amphibia</td>
<td>6</td>
<td>9</td>
<td>Amphibians</td>
</tr>
<tr>
<td></td>
<td>Reptilia</td>
<td>1</td>
<td>1</td>
<td>Reptiles</td>
</tr>
<tr>
<td>Incertae sedis</td>
<td></td>
<td></td>
<td>9+</td>
<td></td>
</tr>
<tr>
<td>Trace fossils</td>
<td></td>
<td></td>
<td>7+</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td></td>
<td>103</td>
<td>465+</td>
</tr>
</tbody>
</table>

†, extinct

Box 1 The Mazon Creek is exceptional for its fossil diversity and abundance

The flora and fauna of the Mazon Creek is exceptionally diverse with 350+ species of plant and 465+ animal species representing more than 100 orders (Table 1). Some of the organisms, like the famous Tullimonstrum gregarium and Escumasia roryi, are unique to the deposit; others, such as the lamprey Mayomyzon pieckoensis and chiton Glaphurochiton concinnus (see Fig. 3), are among the best-preserved fossil representatives of their groups. For other taxa, such as scolopendromorph centipedes Mazoscolopendra richardsoni and Palenarthrus impressus (Wilson 2003), the Mazon Creek provides some of the only known Paleozoic occurrences.

The concretions also preserve many remarkable aspects of ecology: direct evidence of invertebrate–plant interactions as well as some of the oldest examples of mimacy and structural camouflage. Similarities of the spines of the horseshoe crab Euproops danae and the foliage of the arborescent lycopod Lepidodendron, and the wing covers of the cockroach-like insects and Odontopteris pinnules have been suggested to be the earliest known examples of crypsis in the fossil record (Fisher 1979).

The abundance of juvenile and diminutive fish and sharks has led some researchers to suggest that the Mazon Creek is a ‘nursery’ habitat (Baird et al. 1986; Sallan & Coates 2014), similar to modern estuaries where shallow, calm waters are used as spawning grounds and hatcheries (Gillanders et al. 2003). Indeed, the Mazon Creek contains the most diverse fossil record of chondrichthyan egg cases, with nine types currently described (Wittry, pers. comm., 2015). Evidence of ontogeny is also preserved in the Mazon Creek: spawn, hatching and juveniles (with egg yolks still attached) have been discovered as well as sub-adult forms of several sharks and fish groups, further supporting the hypothesis of a nursery environment (Baird et al. 1986). However, there is also evidence for the presence of larger animals inhabiting this environment; ichthyoliths representing adult remains, large scales of dipnoans, individual adult shark teeth and hefty coprolites are regularly found within concretions. The near-absence of large body fossils has been explained by their ability to escape burial (Baird et al. 1986); alternatively, the sediment may have lacked the required interstitial iron for concretions to form around large carcasses (Baird 1990). That some concretions contain plants over a metre long counters this explanation.

A full description of the fauna found in the Mazon Creek is beyond the scope of this review; however, there are several excellent guides to the organisms from the Mazon Creek Lagerstätte (e.g. Shabica & Hay 1997; Wittry 2012) with illustrations of all major organisms found to the class level. A faunal list can be found in Table 1.
the Late Paleozoic Ice Age. Several discrete glaciations in both the southern and northern hemispheres and intermittent warming periods (Montañez & Poulsen 2013) caused sea-level oscillations during the late Carboniferous (Heckel 1986; Veevers & Powell 1987). The Francis Creek Shale Member containing the Mazon Creek Lagerstätte was deposited on the NE margin of the Illinois Basin, which during the late Carboniferous was situated c. 4–10° south of the palaeo-equator (Fig. 1) (Ziegler et al. 1979; Baird et al. 1985a, b; Rowley et al. 1985) in a vast epeiric sea that covered most of Illinois and the adjoining states (Vanless 1975; Wright 1979; Cecil et al. 2003). The unit underlying the Francis Creek Shale Member, the Colchester Coal (no. 2) Member, represents an extensive lycopod-dominated swampy forest found close to the palaeo-coastline (Pfefferkorn 1979; Phillips et al. 1985; Winston 1986) that grew in a warm, humid and wet climate (Schopf 1979a; Phillips & DiMichele 1981; Phillips et al. 1985; DiMichele 2014). Ultimately, a marine transgression inundated and drowned much of the forest adjacent to the palaeo-coast (Baird et al. 1985b). As this transgression occurred, the continuing Alleghanian orogeny to the NE disrupted atmospheric conditions and led to increased precipitation (Phillips et al. 1985; Cecil et al. 2003), which resulted in powerful erosive rivers that eventually deposited their load into newly formed shallow seas (Potter & Pryor 1961). In northern Illinois, the washout resulting from this upland flooding formed the Francis Creek Shale Member, an expansive and vertically thick member (25 m maximum thickness). The NE-flowing river delta systems created a large ‘wedge-shaped’ fan of terrigenous sediment (Baird et al. 1985b) that pinches out to the south and west (Baird 1997a). The Francis Creek Shale Member is overlain by stratigraphic units representing the continuing sea-level rise throughout the late Carboniferous (Baird 1979; Baird et al. 1985b).

Mazon Creek: fossils entombed in siderite

Fig. 1. (a) Locality of the Mazon Creek (brown box) in relation to major cities and towns in Illinois. (b) Illinois during the Pennsylvanian showing the epeiric sea and approximate landmasses in relation to the Mazon Creek Lagerstätte (brown box). (c) Illinois (highlighted) and surrounding US states (grey outline) during the Late Carboniferous (Heckel 1986; Veevers & Powell 1987). The Francis Creek Shale Member containing the Mazon Creek Lagerstätte was deposited on the NE margin of the Illinois Basin, which during the late Carboniferous was situated c. 4–10° south of the palaeo-equator (Fig. 1) (Ziegler et al. 1979; Baird et al. 1985a, b; Rowley et al. 1985) in a vast epeiric sea that covered most of Illinois and the adjoining states (Vanless 1975; Wright 1979; Cecil et al. 2003). The unit underlying the Francis Creek Shale Member, the Colchester Coal (no. 2) Member, represents an extensive lycopod-dominated swampy forest found close to the palaeo-coastline (Pfefferkorn 1979; Phillips et al. 1985; Winston 1986) that grew in a warm, humid and wet climate (Schopf 1979a; Phillips & DiMichele 1981; Phillips et al. 1985; DiMichele 2014). Ultimately, a marine transgression inundated and drowned much of the forest adjacent to the palaeo-coast (Baird et al. 1985b). As this transgression occurred, the continuing Alleghanian orogeny to the NE disrupted atmospheric conditions and led to increased precipitation (Phillips et al. 1985; Cecil et al. 2003), which resulted in powerful erosive rivers that eventually deposited their load into newly formed shallow seas (Potter & Pryor 1961). In northern Illinois, the washout resulting from this upland flooding formed the Francis Creek Shale Member, an expansive and vertically thick member (25 m maximum thickness). The NE-flowing river delta systems created a large ‘wedge-shaped’ fan of terrigenous sediment (Baird et al. 1985b) that pinches out to the south and west (Baird 1997a). The Francis Creek Shale Member is overlain by stratigraphic units representing the continuing sea-level rise throughout the late Carboniferous (Baird 1979; Baird et al. 1985b).

Mazon Creek: a river today and in the Carboniferous?

Untangling the depositional environment

The Mazon Creek Lagerstätte is characterized as an obrution deposit. Geological investigations have stated that the Francis Creek Shale Member represents a river delta system (e.g. Baird et al. 1985a, b, 1986). Subsequently, the Mazon Creek Lagerstätte has been hypothesized as resulting from a large-scale cataclysmic
event such as bursting levees during storm events resulting in freshwater and sediment inundation and rapid burial of organisms (see Baird 1990; Shabica & Hay 1997; Schellenberg 2002). Other models include episodic incursion of turbid freshwater during periods of flash flooding (Baird et al. 1986) or storm surges (Johnson & Richardson 1966). Although these ideas are consistently cited in subsequent reviews, there are substantial issues with all these hypotheses.

These palaeoenvironmental interpretations are based on the entire 25 m thickness of the Francis Creek Shale Member, but the fossiliferous Mazon Creek concretions are found only within the basal 3–8 m of the Francis Creek Shale Member. Sedimentary structures in this subsection indicate rapid deposition in a calm marine environment (Fig. 2) (Baird 1979). Scale left in metres and right in millimetres (mm). (c) Hypothesized sequence of events required for preservation in siderite concretions. (i) After rapid burial, decay of the organisms creates a geochemical microenvironment around the carcass and depletes interstitial sulphate. (ii) Siderite precipitation creates a ‘proto-concretion’ that acts to entomb the organism and resists compaction. (iii) Lithification of the concretion completes. Syneresis within the concretions can cause septarian fractures to occur. Secondary minerals may precipitate and fill voids left by decaying tissues. Tidal laminae are often compressed around concretions, suggesting that compaction of the sediment occurred after lithification of the proto-concretion (Kuecher et al. 1990). Based on Baird et al. (1986). (d) A schematic illustration of the so-called ‘taphonomic discontinuity’ seen in the Mazon Creek. Increased geographical distance from the river mouth correlates with an increase in the percentage of ‘dud’ or barren concretions (Fig. 2a (iv)). Similarly, soft-tissue preservation also dramatically decreases with distance from the shore. The most distal zone has no fossils found in concretions but poorly preserved ‘normal’ Carboniferous marine shelf fauna (Fig. 2a (v)). It is postulated that, in the distal region, high bioturbation and/or presence of epifaunal animals may have prevented or limited the formation of siderite concretions, increasing likelihood of pyritic cores forming and obliterating fossiliferous remains.

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submerged SW-sloping peat deposits. This rapidly deposited sediment smothered organism carcasses and engulfed the already drowned lycopod trees in life position, as seen at the base of Pit 11 (Shabica 1979).

Further evidence of this calmer embayment palaeoenvironment comes from the Braidwood biota (Kuecher 1983; Baird et al. 1985b; Kuecher et al. 1990; Feldman et al. 1993), these ‘pinstripe’ laminations record daily and twice a month neap–spring tidal cycles (Baird et al. 1985b; Kuecher et al. 1990) in both marine and freshwater areas (Fig. 2b) (Kuecher 1983; Kuecher et al. 1990), indicating that the entire Mazon Creek area was tidally influenced. It should be noted that the ebb tide band is far thicker than the flood band, suggesting a high sediment discharge rate (Baird et al. 1986). The presence of tidal laminae and rapid sedimentation rates, and the absence of high-energy sedimentary structures within the fossiliferous zone indicate that the organisms of the Mazon Creek inhabited an area around a river delta system that discharged large amounts of sediment and freshwater into a shallow, non-turbulent, brackish marine basin (Archer & Feldman 1994).

Palaeo-environmental information from organisms?

Much of the literature concerning the Mazon Creek considers the biota in terms of separate faunas (e.g. Johnson & Richardson 1966; Baird et al. 1985a, b, 1986; Baird 1997b; Baird & Anderson 1997; Schellenberg 2002; Selden & Nudds 2012; Sallan & Coates 2014). Historically these biotas are based on communities found in distinct geographical localities: terrestrial wash-in and freshwater ecosystems. In fact, only freshwater bivalves and amphibians are considered autochthonous representatives of a freshwater biota (Milner 1982). However, poor preservation of the bivalves makes identification difficult; furthermore, their occurrence with known marine organisms (i.e. polychaetes) demonstrates that they are not good freshwater indicators (Baird et al. 1985b; Schultz 2009). Moreover, amphibians are not good salinity indicators either; some Devonian amphibians are known to be marine (George & Bleich 2011) and Carboniferous forms had the capability to disperse through coastal marine environments and may have spawned there (Godfrey 1992; Parker & Webb 2008).

Currently, there is no clear evidence, fossil or sedimentological, to support that a distinct truly freshwater ecosystem extended into the bay. Investigations have not identified any distinct geographical demarcation between freshwater and marine organisms (Baird 1997a; Schultz 2009) nor have any sedimentary structures that differentiate these environments been identified (Schultz 2009); in fact, tidal laminae have been described throughout ‘Braidwood’ areas (Kuecher et al. 1990; Baird 1997c). Previous work on the ‘one-directional mixing’ between the Braidwood and the Essex faunas is based not on animal fossils, but on fossilized terrestrial plant remains decreasing in size, abundance and diversity distally from the palaeo-coastline (Baird et al. 1985b, 1986). Most of the major groups found in the Mazon Creek could tolerate varying degrees of salinity; these groups include palaeoniscoid fish (Schultze & Bardack 1987), horseshoe crabs (Fisher 1979; Anderson 1994), syncarid shrimps, polychaetes, eurypterids (Kjellesvig-Waering 1963), ostracods and shark egg cases (Palaoxyris). Stenohaline organisms have been found within the ‘Braidwood’ fauna (Schultz 2009), further diminishing the argument for a distinct freshwater biota. Therefore, rather than a distinct freshwater biota, it is more likely that the Mazon Creek represents a brackish marine environment.

Areas that have previously been identified as freshwater (i.e. Braidwood) are actually part of the bay closer to the palaeo-coast (Schopf 1979b). This area was most probably influenced by the freshwater discharge of nearby rivers, with the discharge, sedimentary load and tidal influence acting as biogeographical filters, explaining why benthic organisms in the northern Mazon Creek have ‘patchy’ distributions occurring in dense concentrations locally (Baird et al. 1985b; Baird & Anderson 1997). Where large river systems enter the sea, the freshwater often exists as a hypopycnal plume overlying marine water. In this situation, marine faunas, both benthic and nektonic, can rapidly colonize and inhabit areas with normal marine salinity that occur beneath freshwater (Moura et al. 2016). These areas tend to exhibit lower biodiversity than ‘true’ marine environments (e.g. Carriker 1967) and this reduced diversity has been noted in northern Mazon Creek fossil assemblages (Baird 1997b). Pit 11, famous for its ‘true’ marine fossils, is bioturbated by benthic invertebrates such as polychaetes and holothurians, but only in the northern section of the pit. Only nektonic organisms, including fish, shrimp and Tullimonstrum (Box 2), are found in the southern end, which exhibits very little bioturbation and is deemed to be closer to the palaeo-coast (Baird et al. 1985b). Similar patterns of distributions have been observed in modern marginal marine environments (Moura et al. 2016). The brackish and sediment-rich water of the Mazon Creek would also explain why typical Carboniferous marine communities of corals, articulate brachiopods, bryozaans, trilobites and mucicid bivalves are found only in areas distal to the palaeo-coast, where the Francis Creek Shale Member pinches out, and are not preserved in concretions (see fig. 1a (iv) of Baird et al. 1986).
Fig. 3. A selection of fossils within siderite concretions from the Mazon Creek Lagerstätte. (a) Rhabdoderma sp. (ROM56774). (b) Chiton Glaphurochiton concinnus (PE29045). (c) Rhabdoderma (exigum?) (Burpee/Lauer Foundation LF836). (d) Polychaete Esconites zelus (ROM47529). (e) Priapulid Priapulites konecniorum (FMNHP25135). (f) Actinopterygian Platsomus circularis (FMNHP7333). (g) Unidentified trigonotarbid arachnid, most probably Aphantomartus pustulatus. (BMRP2014MCP850). (h) The seed fern Athlopteris sp. (ROM43584). (i) Asterophyllites sp. ROM 43376. (j) Annularia stellata(?) that has been overgrown with sphalerite (LEIUG83622). (k) Chondrichthyan tooth; Phoebodus? (ROM56812A) demonstrates, that despite an absence of large fossils, larger animals lived in the Mazon Creek area. (l) Concretion with pyritic core from pit 11 (not accessioned). (m) Holothurian Achistium? (P69TG22a). (n) Saurerpeton obtusum (ROM56804B). Scales: 20 mm. Accurate locality data for fossils are often sparse, and most are often referred to by the associated strip-mine ‘pit’ number; however, some pits (such as Pit 11) are geographically wide, making this information less useful.
Box 2 Tullimonstrum gregarium

Fig. 4. The holotype of *Tullimonstrum gregarium* (PE 10504). Image by Paul Mayer (FMNH).

In contrast to other famous Lagerstätten, such as the Burgess Shale or Chengjiang, the flora and fauna of the Mazon Creek are largely recognizable but an extraordinary exception is *Tullimonstrum gregarium* (Figure 4). Discovered in 1955 by a local collector, Francis Tully, and found only in the Mazon Creek Lagerstätte, the enigmatic ‘Tully Monster’ is a popular fossil organism, recognized by the public as the State fossil of Illinois and by its use in advertising campaigns by U-Haul™. The ‘Tully Monster’ is an anatomically bizarre animal. Described in 1966 (Richardson 1966), *Tullimonstrum* has a long slender segmented body, broad flattened asymmetrical tail, a distinctive ‘transverse bar’ that runs perpendicular to the body with associated organs at either end and an anterior elephantine proboscis that terminates in a claw or jaw lined with teeth (Johnson & Richardson 1969). Over the last five decades numerous studies have allied it to a suite of disparate phyla including Mollusca (Foster 1979), Annelida (Johnson & Richardson 1969; Schram 1991), Nemotoda (Johnson & Richardson 1969; Foster 1979) and Chordata (Beall 1991).

Recently, two studies have reclassified *Tullimonstrum* as a vertebrate. McCoy et al. (2016) reinterpreted a suite of anatomical features of *Tullimonstrum* by examining thousands of specimens and using synchrotron X-ray images to propose new hypotheses of homology, identifying a notochord, arcula, dorsal fin, keratinous teeth, a single nostril and the presence of tectal cartilage. A phylogenetic analysis using these new data placed *Tullimonstrum* as a stem-lamprey. A separate and contemporaneous study investigated the transverse bar organs, identifying dark structures found terminally on stalks as being eyes (Clements et al. 2016). The eyes of *Tullimonstrum* were found to contain melanosomes, the intracellular organelles that synthesize and store the pigment melanin. Importantly, Clements et al. identified two distinct melanosome morphologies, each occurring in distinct layers. These layers reflect preservation of the reticulated pigmented epithelium (RPE: a screening layer of the retina). This microanatomical complex was interpreted as an synapomorphy of total group vertebrates, and suggested that *Tullimonstrum* could form a clear visual image with its stalked eyes.

However, these findings have been questioned. Miyashita & Diogo (2016) noted that placing *Tullimonstrum* as a stem vertebrate, stem cyclostome or stem gnathostome (Clements et al. 2016) would question the traits identified on the basis of a lamprey model (McCoy et al. 2016). More recently, Sallan et al. (2017) also questioned the placement of *Tullimonstrum*, disagreeing with most of the anatomical characters described by McCoy et al. (2016). Sallan et al. (2017) noted that eye structures and characters exhibit high levels of homoplasy, convergence and parallel evolution across the tree of life, although they were unable to demonstrate that the RPE character complex has been identified in non-vertebrates.

With the public interest in such a unique fossil and the current controversy in its identification, more research on the ‘monster’ is sure to follow.

Poland (Krawczyński et al. 1997; Pacyna & Zdebska 2002), Montceau-les-Mines, France (Perrier & Charbonnier 2014), and Cosley (Wilson & Almond 2001; Garwood et al. 2009), Crock Hey (Prokop et al. 2006; Garwood & Dunlop 2011) and Bickershaw, UK (Anderson et al. 1997), the Mazon Creek is distinctive, not only for the high diversity of organisms, but also because the fidelity of highly labile soft tissues preserved is unparalleled in the other Carboniferous concretionary fossil deposits.

The controls on concretion formation (Box 3) and the taphonomic pathways before, during and after concretion growth are under renewed investigation. Rapid and constant terrigenous sedimentary input from the upland peaty forests created the ideal scenario to bury organic matter and carcasses quickly, preventing scavenging and retarding aerobic decay. It is important to note that the kill mechanism that caused the mortality of Mazon Creek organisms is unclear, although pulses of freshwater, water column anoxia or water poisoning could be conceivable stresses on marine life. The burial of organisms obliguably to bedding planes suggests that some organisms were, however, smothered and buried in situ. The high fluxes of terrigenous sediment supply also had the secondary effect of suppressing bacteria with sufficient intestinal iron for siderite formation. In normal marine conditions pyrite is the primary reduced-iron precipitate as it is thermodynamically and kinetically favourable for iron to form sulphide minerals at the expense of carbonate precipitation (Cotroneo et al. 2016). However, in environments lacking sulphate, such as freshwater, or marine systems where sulphate is exhausted, iron carbonate (siderite) will preferentially precipitate (see Cotroneo et al. 2016, and references therein).

Although the presence of marine communities and the occurrence of tidally influenced sedimentary structures indicate that a...
persistent head of freshwater did not exist above the sediment (Kuecher et al. 1990), the Francis Creek Shale Member is dominated by illite–chlorites, which reflect deposition in low-salinity oxygen-rich water (Hughes 1970). Rapid deposition, tidal pumping and limited bioturbation probably limited the penetration of seawater into the sediment. This scenario would restrict sulphate supply (sulphate poisons the precipitation of siderite) and minimize the diffusion of oxygen, creating a reducing environment ideal for siderite formation. Furthermore, waters from upland forests would have decreased Eh and pH, further enhancing Fe$^{	ext{2+}}$ activity, increasing the likelihood of siderite formation (Woodland & Stenstrom 1979), although oxygen isotope studies suggest that the concretions formed in marine waters (Cotroneo et al. 2016). Although oxygen levels in the Mazon Creek are poorly constrained, it is likely that the muds were anoxic: studies on modern estuaries demonstrate that high bacterial and detrital content of the sediment can generate varying, but significant, levels of anoxia (Jonas 1997).

Decay of soft tissues was probably retarded by inhibition of both oxidant diffusion and bacterial activity by rapid authigenic precipitation of ‘proto-concretions’ around organic-rich remains (Fig. 2c). Oxygen, carbon and sulphur isotopic signals indicate that the closed environmental conditions were depleted of sulphate, swiftly changing from the precipitation of pyrite to siderite and forcing methanogenesis to become the dominant metabolic pathway for anaerobic bacteria (Cotroneo et al. 2016). Subsequently, methane fermentation is posited to have cemented the proto-concretion by supplying the carbonate required for diagenetic siderite to form (Cotroneo et al. 2016). Siderite tends to form pervasively within the sediment rather than concentrically, filling pore space and resisting compression, protecting the fossil from compaction or obliteration (Raiswell & Fisher 2000). Post-lithification, minerals including kaolinite, galena and sphalerite fill cracks and overgrow fossils, although it is not known if this happens during late diagenesis or as a result of weathering. The high carbonate content, isotopic stability and fossilized soft tissues establish that the concretions formed rapidly (Woodland & Stenstrom 1979; Baird 1990; Cotroneo et al. 2016). It has been suggested that tidal pumping may have been important to the rapid growth of the concretions (Allison & Pye 1994).

What initiated the formation of a concretion is not fully understood. The close relationship between concretion size and shape and the fossil within suggests that organic remains acted as passive nuclei (Baird 1997c). Large amounts of macerated, compressed and carbonized plant matter and infrequent fragments of insect or crustacean cuticle are found in the Francis Creek Shale Member along bedding planes (Baird et al. 1986), suggesting that the sediment was saturated with organic remains. It has been suggested that the decay of larger ‘juicer’ organic remains may have created geochemical microenvironments that triggered siderite precipitation (Baird et al. 1986; Baird 1997c), but the preservation of small animals and plant fragments brings this into question. Moreover, many concretions in the Mazon Creek are ‘dud’ (barren) and seemingly devoid of fossil material.

Such barren concretions may have nucleated around detrital organic remains or small carcasses, and the lack of organic carbon may have limited the bacterial respiration required for the lithification of the proto-concretion (Baird et al. 1986; Cotroneo et al. 2016). Potential retardation of the formation of a proto-concretion and prolonged aerobic bacterial activity prior to entombment in siderite would allow organic remains to decay before preservation. The formation of barren concretions is likely to have been exacerbated by the slower deposition and higher bioturbation commonly seen distally from the sedimentary source. This hypothesis is supported by analysis of fossiliferous versus barren concretions; in the areas closer to the palaeo-coastline 40% of concretions are barren ($n = 56,974$), whereas in the marine section 63% are barren ($n = 229,979$) (Baird & Anderson 1997).

Distance from the palaeo-coast also considerably affected the preservational fidelity of organisms (see Fig. 2d). Concretions found close to the palaeo-coast mouth are rich in soft-tissue fossils (Baird et al. 1985b, 1986; Baird 1997b) whereas areas up to 50 km west of this are characterized by concretions that preserve only small bivalve shells or are barren (Baird 1997a). Towards the towns of Galesburg and Peoria, 170 km SW of the Mazon River, the Francis Creek Shale Member thins, and comprises a highly bioturbated and non-concretionary marine siltstone containing a more typical Carboniferous marine shelf fossil fauna, including trilobites, bryozoans, brachiopods and bivalves (Smith et al. 1970; Shabica 1979; Baird et al. 1985b; Baird 1997b; Baird & Anderson 1997). Between the concretion zone and this ‘normal’ non-concretionary deposit, the Francis Creek Shale Member contains pyritic/calcite concretions almost completely devoid of any fossils, except for a few poorly preserved marine organisms (see fig. 1a of Baird 1979). These areas are typified by high levels of bioturbation that obliterated the tidal laminae that probably slowed the formation of concretions either by aerating or allowing sulphate-rich marine waters into the sediment, or both (Baird et al. 1986). Coupled with the slower rates of sedimentation around the outer margins of the delta fan, this may explain the taphonomic variation (termed a ‘taphonomic discontinuity’) by Baird et al. 1986) observed within the Francis Creek Shale Member.

Recent isotope analysis of Mazon Creek concretions has yielded some interesting preliminary results. Concretions found in the Braidwood area tend to have very little sulphide mineral content compared with Essex concretions, suggesting different diagenetic pathways (Cotroneo et al. 2016). This may be due to proximity to the palaeo-coast; however, further geochemical investigation with a rigorous sampling strategy with more than one Braidwood site is required to accurately constrain this.

### Summary and future work

The Mazon Creek represents a marine bay where allochthonous terrestrial and native marine organisms were buried in an environment favourable for siderite concretion formation. Rapid entombment of the flora and fauna led to exquisite soft-tissue preservation, fossilizing entire organisms rarely seen in the fossil record such as polychaetes, chitons and holothurians. In areas distal to the sedimentary source, burial was slower and increased bioturbation retarded the formation of siderite, preventing exceptional preservation and creating a taphonomic bias. In the most distal areas, where sedimentary input was extremely low, ‘typical’ offshore shelf communities flourished but were not preserved in concretions, nor are any fossils with soft tissues found in these areas.

The Mazon Creek is arguably the most complete record of a late Carboniferous equatorial ecosystem, and renewed research on familiar and in some cases commonly found fossils is providing new insights. For example, recent work on the Tully Monster (Tullimonstrum) has shown the benefits of using modern analytical techniques for detailed anatomical re-evaluation of taxa that have been largely neglected since their original descriptions. The current revival of Mazon Creek research has highlighted several gaps in our current understanding of how this marvellous fossil deposit formed. Investigation of modern estuarine environments has elucidated some of the controls on the formation of siderite concretions, which can now be applied to the Mazon Creek. This work, in particular, will lead to a better understanding of the unique mode of preservation seen in this Lagerstätte when compared with other Carboniferous sideritic concretionary deposits. Additional high-resolution geochemical investigations through the interval and across the geographical area have yet to be attempted; these would complement and validate the isotope studies that...


