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Patterns in Palaeontology: Exceptional Preservation of Fossils in Concretions

by Victoria McCoy[*1]

Introduction:

Have you ever seen a geode — a boring-looking ball-shaped rock that, when split open, reveals a remarkable crystalline interior? For most people, the first reaction to the dazzling crystal interior is to marvel at its beauty. But for some — and perhaps you fall into this group, since you are reading this article — the second and more important reaction is to wonder how it got that way. The people who ask this question understand that the beauty of nature is far greater when we understand it deeply and see it more fully; in short, they are scientists at heart.

If you are a scientist at heart, I have very good news for you. There is something out there that is like a geode, but perhaps even more interesting, at least to fossil lovers: the curious rocks known as concretions.

Concretions are like geodes in that they are fairly ordinary looking ball- or egg-shaped rocks whose interiors contain wonderful surprises. Concretions are different from geodes, however, in that their interiors do not contain crystals; instead, they can, on occasion, contain beautiful, remarkable fossils of organisms that lived many millions of years ago (Fig. 1) — fossils that are unmatched in terms of their three-dimensional preservation of soft tissue, and that tell us a great deal about life on Earth hundreds of millions of years ago. (Note that the similarities between geodes and concretions are only superficial — they actually form through very different processes and are very different in specific details of composition and structure.)

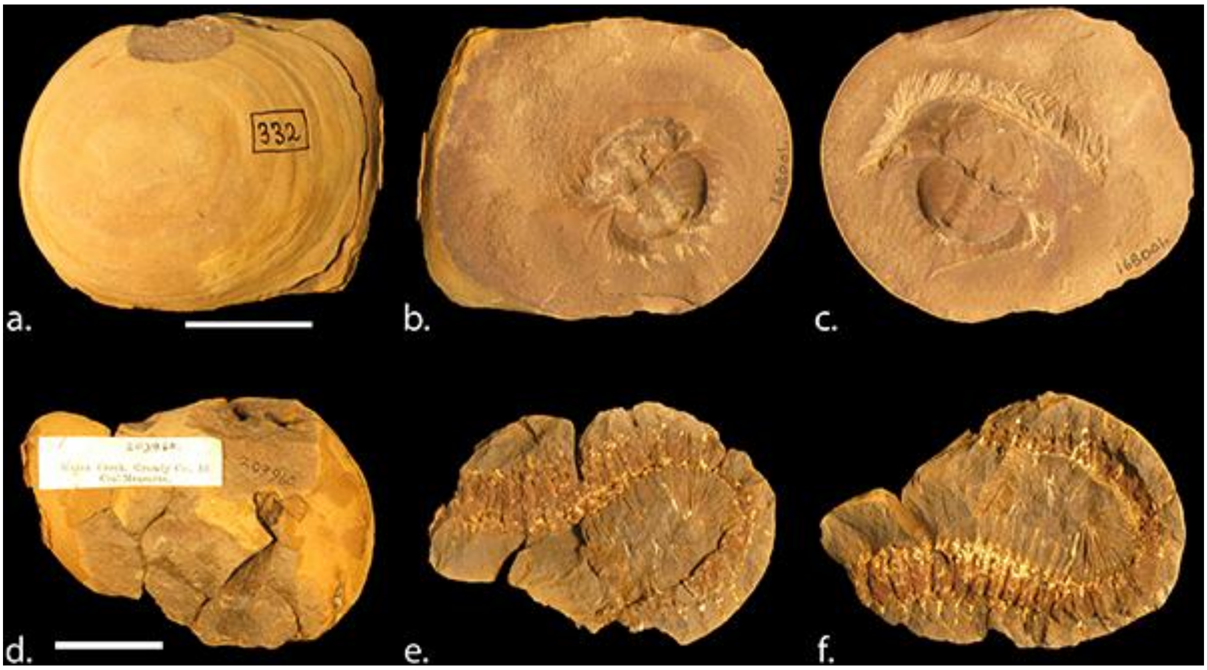

FIGURE 1 — EXAMPLES OF FOSSIL-BEARING CONCRETIONS FROM THE 300-MILLION-YEAR-OLD MAZON CREEK SITE. ALL SCALE BARS ARE 3 CM. (A) A CONCRETION VIEWED FROM OUTSIDE. NOTE THE NON-DESCRIPT APPEARANCE. (B, C) THE SAME CONCRETION CRACKED OPEN, REVEALING THE PRESERVED REMAINS OF BELLINURUS DANAE, A HORSESHOE CRAB. (D) ANOTHER CONCRETION

VIEWED FROM THE EXTERIOR. (E, F), THE SAME CONCRETION CRACKED OPEN, EXPOSING THE PARTIAL FOSSIL OF THE MILLIPEDE ACANTHERPESTES MAJOR.

By this point, you are probably already thinking, “How did that happen?”, “How do we study these fossils?” and “What can they tell us about the ancient world?” Those are large questions, which can occupy a lifetime; here, I merely provide an introduction to some of the most fascinating aspects of concretions. Perhaps it might inspire you to try to answer these questions!

Concretions are individual structures, distinct from the surrounding sediment (Fig. 2), and typically formed through the localized deposition of mineral cement. They are extremely common in sedimentary rocks. Almost 150 concretion sites have been described in the scientific literature, ranging all across the world and throughout time, with many more mentioned in passing but not described in detail. It seems likely that the majority of sedimentary rock units contain concretions.

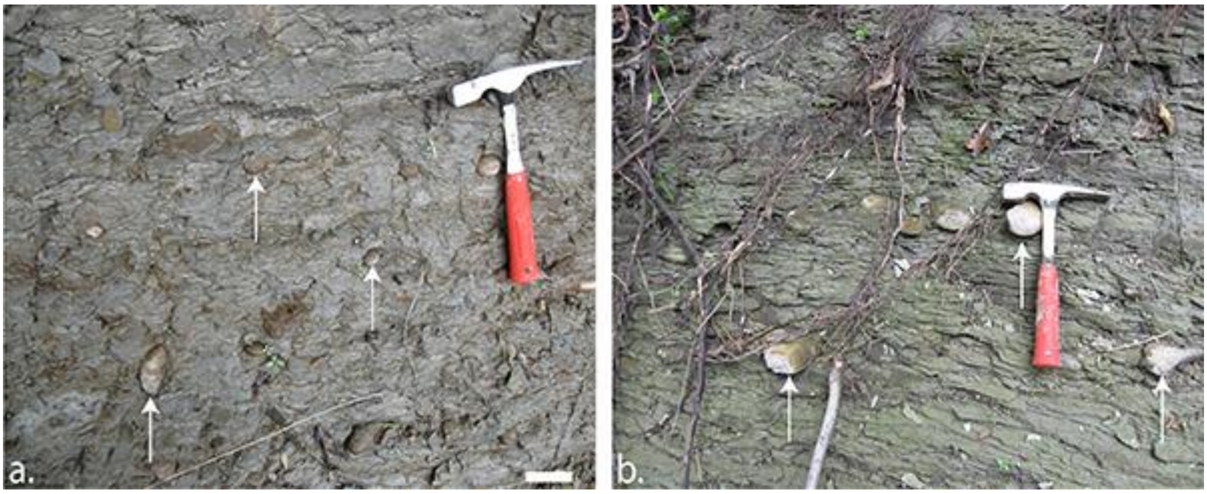

FIGURE 2 — CONCRETIONS IN AN OUTCROP AT THE MAZON CREEK FOSSIL SITE, WITH SOME EXAMPLES INDICATED BY WHITE ARROWS. THE HAMMER IS 28 CM. (A) CONCRETIONS IN OUTCROP ALONG THE BANKS OF THE MAZON RIVER ON THE KODAT FARM. (B) CONCRETIONS IN OUTCROP ALONG THE MAZON RIVER ON THE HIGGINS FARM.

Most often, the fossils in concretions are simply skeletal debris, but there are a few exceptional sites where the concretions contain many and various highly detailed, three-dimensional fossils of soft-bodied animals. These include a few of the most famous fossil sites in the world, three examples of which are outlined below.

Mazon Creek (Francis Creek Shale formation)

Age: Carboniferous period, approximately 307 million to 305 million years ago.

Location: The major outcrops of this fossil site are in Illinois, in the central United States. This is also where the best fossils occur. However, rocks of similar age, depositional environment and fossil content are present across the United States and in Europe.

Depositional environment (what the area was like when the rocks were laid down): A river estuary, covering the transition from fresh water to brackish water to purely marine.

Taxa (groups of animals and plants represented): The fossils of Mazon Creek include mostly soft-bodied forms such as plants, insects, millipedes, arachnids, crustaceans, horseshoe crabs, worms such as polychaetes, jellyfish, ray-finned fish, sharks, coelacanths and early vertebrates with four limbs, called tetrapods (Figs 1, 3, 7). These can be separated into distinct freshwater and brackish-water groups.

FIGURE 3 — ESSEXELLA ASHERAE, A JELLYFISH FROM THE MAZON CREEK FOSSIL SITE THAT RESEMBLES A DISCOLOURED 'BLOB'. THE SCALE BAR IS 3 CM

Method of fossilization: Fossils are preserved in ironstone (siderite, or iron carbonate) concretions, often as impressions or discolouration of the rock. In some cases, the fossils are remineralized, meaning that the organic bodies are replaced with minerals such as kaolinite (a type of clay), pyrite (iron sulphide) or calcite (calcium carbonate). The animals' original cuticle is also occasionally preserved.

Fun facts: One unusual feature of the brackish-water fauna at Mazon Creek is that it is dominated by jellyfish, with one taxon in particular, *Essexella asherae* (affectionately called 'the Blob' for its relatively featureless appearance), making up more than 40% of all specimens (Fig. 3).

FIGURE 4 — RECONSTRUCTION OF THE TULLY MONSTER, BASED ON MAZON CREEK FOSSILS. THE SCALE BAR IS 5 CM.

Mazon Creek is also home to the mighty Tully Monster, *Tullimonstrum gregarium* (Fig. 4). The Tully Monster is not mighty in the traditional sense, being a foot-long, soft-bodied worm-like creature, but rather in the amount of mystery attached to it. Despite more than 50 years of study, and the discovery of hundreds of specimens, the Tully Monster has still not been identified even to the phylum level. Nonetheless, it has captured the imagination of palaeontologists and the general public alike: it is the state fossil of Illinois, is pictured on the side of some U-Haul trucks and is commemorated in the name of a bar in Morris, Illinois.

Santana formation

Age: Cretaceous period, approximately 125 million to 99 million years ago.

Location: Araripe basin in northeastern Brazil.

Depositional environment: Still disputed; probably estuarine.

Taxa: The Santana formation is best known for its diverse fish. However, there are rare occurrences of other tetrapods, such as pterosaurs, crocodilians, turtles and dinosaurs, as well as invertebrates such as copepod, ostracod and decapod crustaceans; gastropod and bivalve molluscs; and sea urchins.

Method of fossilization: The fossils are preserved inside limestone concretions with hard parts preserved and soft tissues replaced with calcium phosphate.

Fun facts: The concretions here are famous for growing as thin layers of calcium carbonate around the outside of a fish, resulting in a concretion that is shaped very much like the fish it contains. There are even stories of experienced collectors identifying the enclosed fossil to the species level without ever cracking open the concretion!

The Santana formation is a strong contender for the best preservation of any fossil site. When the concretions are split, the fish look almost freshly dead, with bones, muscles, skin, scales and even their last meals commonly preserved.

Herefordshire (Wenlock Series)

Age: Silurian period, approximately 430 million to 422 million years ago.

Location: Herefordshire, UK.

Depositional environment: Volcanic ash beds in the outer edge of a continental shelf under the sea.

Taxa: The fossils are mostly soft-bodied organisms such as worms and arthropods, a few centimetres across at most.

Method of fossilization: The fossils are preserved mainly as calcite infills in calcite concretions. The calcite of the fossil and the concretion can be told apart because they have different crystal structures.

Fun facts: The fossils inside these concretions are difficult to study using traditional methods for several reasons: (1) the organisms are too small to significantly weaken the concretions, and so the concretions are difficult to break open along the fossil; (2) they are hardly flattened at all, so the shape of the fossil is preserved in three dimensions, and even when the concretion does break open on the fossil, not enough detail is visible to fully understand how the organism looked (Fig. 5); and (3) the calcite of the fossils is too similar to the calcite of the concretions for the fossils to be investigated using non-destructive techniques that scan for differences between the minerals, such as X-ray computed tomography. Thus, most of the research on fossils from this site is done by grinding away a tiny section of the concretion, digitally photographing the exposed surface and then repeating this process many times (Fig. 6). The organism(s) in the photographs are then virtually reconstructed on a computer.

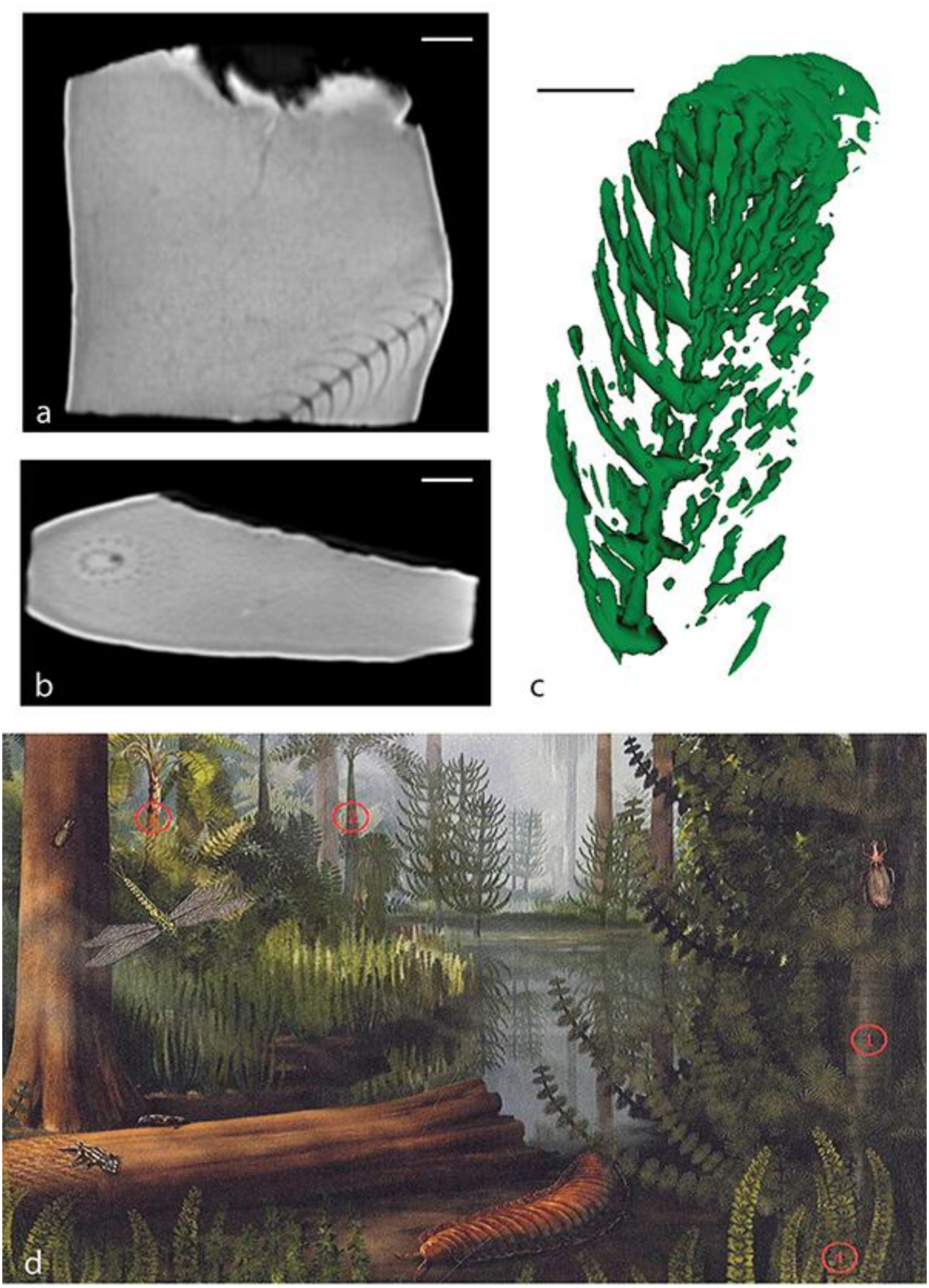

Figure 5 – 3D preservation within concretions – as well as the associated difficulty of fully understanding the fossil from a 2D plane view — is very common, as shown in this example from Mazon Creek, fossil foliage from the genus Calamites. (a) A CT scan of the concretion, showing one possible plane view of the fossil. Notice how it appears to be a central stem, with narrow leaves at regular intervals. (b) A CT scan of the same concretion,

showing a different possible plane view of the fossil. Notice now that it looks very different, and appears to be concentric circles of spots. (c) A 3D reconstruction from the CT scan. Now, seeing the fossil in 3D, it is apparent that it is composed of a central stem, with thin leaves branching away from it in regularly spaced circles. (d) A reconstruction of a carboniferous ecosystem, showing this tree, Calamites, on the right (label 1). This painting is from The Mazon Creek Fossil Flora, by Jack Wittry.

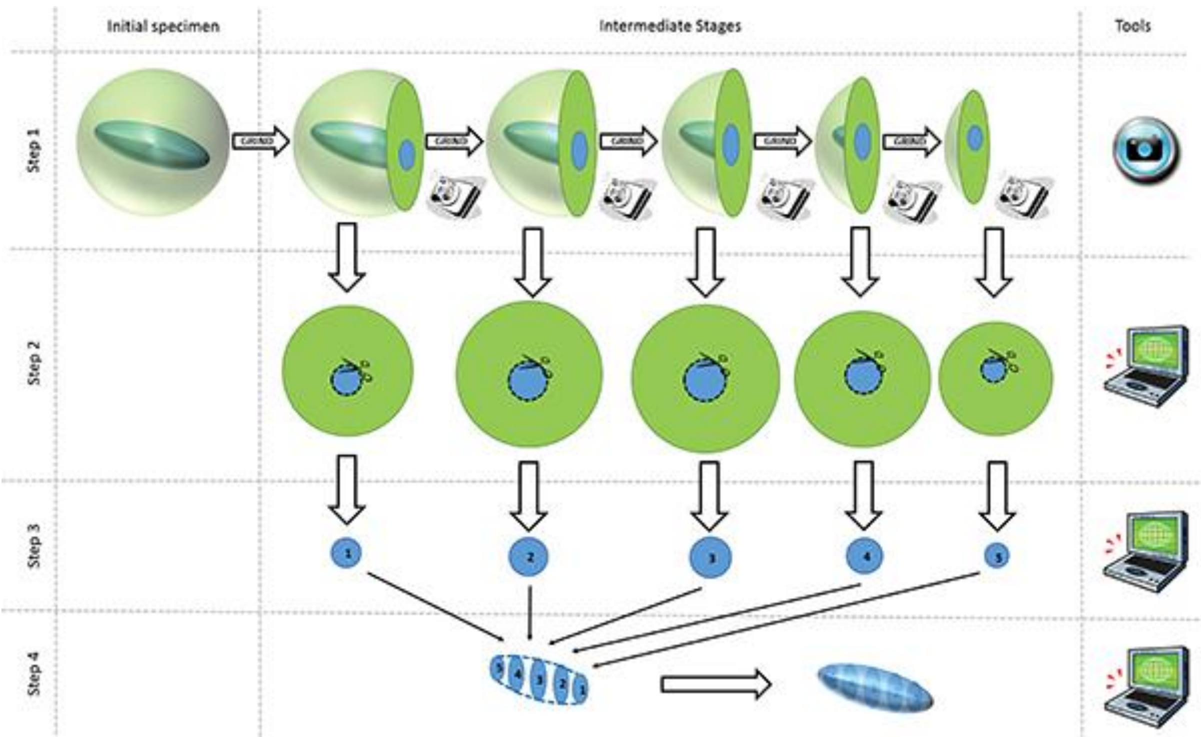

Figure 6 – The process of reconstructing a fossil inside a concretion through grinding, photographing, and digitally reconstructing. At the start, the concretion is a green sphere containing a blue oblong fossil. The concretion is shown as transparent, so the fossil can be seen. The first step is grinding away a small part of the concretion, photographing the near surface, then grinding more of the concretion away, photographing the new surface again, and continuing until the concretion is gone. Step 2 involves looking at the photos on a computer, and cutting out the part of interest, in this case, the blue circles corresponding to the fossil. Step three is taking the isolated fossil images and placing them back in their approximate position. Step four is filling in the missing space to reconstruct the fossil minus the surrounding concretion.

My own experiences doing fieldwork at Mazon Creek (see Fig. 7 for an example of one of my field sites) show that collecting fossils from concretion sites is similar to an Indiana Jones adventure . . . or maybe I exaggerate slightly. A typical field season is full of difficult journeys into strange locales (such as driving into central Illinois, then hiking for a mile through some woods), dangerous animals (excited farm dogs) and weeks of work sweating in the field (a few hours wading barefoot in the stream, picking up concretions until I have as many as my field assistants, my car and I can hold). Then we head back to the hotel, spend the rest of the day hanging out, and are done with fieldwork for the year.

FIGURE 7 — THE MAZON RIVER, ALONG WHICH (AND UNDER WHICH) MANY CONCRETIONS ARE FOUND THAT CAME ORIGINALLY FROM THE MAZON CREEK FOSSIL SITE. ALTHOUGH CALLED A RIVER, IT IS BARELY ONE METRE DEEP AND OFTEN DRIES UP COMPLETELY IN THE SUMMER; HENCE, PALAEONTOLOGISTS CALL THIS DEPOSIT THE MAZON CREEK SITE, RATHER THAN THE MAZON RIVER SITE.

In fact, this illustrates one of the most interesting features of collecting fossils from a concretion site. A stream or other weathering force does most of the work by washing or wearing away the rocky outcrop, separating out the concretions. The fossils are all in concretions, but there is normally no good way of finding out in the field which concretions contain fossils. (The fish-shaped concretions from the Santana formation are a rare exception; even at this site, most fossils are in oval concretions, and there are many empty oval concretions.) The concretions need to be cracked open; the best way to do this without damaging the fossil is to repeatedly freeze and thaw the concretions until they naturally break open along a line made weak by the presence of the fossil. This might take as long as a few years, if it is done by leaving the concretion out in the weather rather than putting it in a freezer. So, in contrast to other methods of fossil collecting — in which a fossil is found quickly in the field, and then laboriously excavated — collecting concretions requires little work, but finding the fossils is time and labour intensive.

Studying fossilization in concretions:

The fossils preserved in concretions are an important source of information about ancient ecosystems. However, even the best fossil assemblages are not exact replicas of their source ecosystem (see the article by Simon Darroch, 'Who's there and who's missing?'). The difference between the two is mostly attributable to the process of fossilization, so before we can interpret fossil sites correctly, it is important to understand how fossilization happens.

A number of minerals can hold together the concretion, including silica (silicon dioxide), apatite (a type of calcium phosphate) or carbonate minerals — all of which have been found to preserve exceptional fossils. Here, I will focus on carbonate concretions. The process of fossilization in carbonate concretions seems theoretically simple. Decay of a recently dead organism (buried in sediment under water) changes the local environment (in a number of ways) to encourage carbonate crystals to grow. In particular, decay changes the carbon in organic material into carbon bound into carbonate ions (CO_3^{2-}), so that carbonate ions become more concentrated in the waters in the sediment pore spaces around the dead organism. Water, especially seawater, will already contain some carbonate ions, and carbonate ions produced through decay will add to this. There are six reactions involved in decay (Fig. 8): aerobic decay, denitrification, manganese reduction, iron reduction, sulphate reduction and methanogenesis. The first five of these break down organic material and produce, among other things, bicarbonate ions (HCO_3^-) or carbon dioxide (CO_2), both of which react with water to produce carbonate ions. Once the local environment reaches appropriate conditions (sufficiently high concentrations of carbonate ions, high pH, and a lack of factors that stop carbonate crystal growth, such as sulphur), carbonate crystals start growing and the concretion forms around the dead organism. Some aspect of concretion formation then slows decay, promoting fossilization. Usually, the fossil is preserved in three dimensions, sometimes with soft tissues. To summarize, decay of an organism triggers concretion formation, which inhibits further decay and leads to fossilization.

1. Aerobic decay: $CH_2O + O_2 \rightarrow \boxed{CO_2} + H_2O$
2. Denitrification: $5CH_2O + 4NO_3^- \rightarrow 2N_2 + \boxed{4HCO_3} + CO_2 + 3H_2O$
3. Manganese reduction: $CH_2O + 2MnO_2 + 3CO_2 + H_2O \rightarrow 2Mn^{+2} + \boxed{4HCO_3}$
4. Iron reduction: $CH_2O + 4Fe(OH)_3 + 7CO_2 \rightarrow 4Fe^{+2} + \boxed{8HCO_3}$
5. Sulfate reduction: $2CH_2O + SO_4^{-2} \rightarrow H_2S + \boxed{2HCO_3}$
6. Methanogenesis: $\left\{\begin{array}{l} 2CH_2O + 2H_2O \rightarrow 2CO_2 + 8H \\ 8H + CO_2 \rightarrow CH_4 + 2H_2O \end{array}\right.$

FIGURE 8 — THE DECAY REACTIONS THAT RESULT IN THE RELEASE OF CARBONATE IONS.

One way to test this model is to try to replicate the process experimentally. This requires some initial study of the concretions to work out what sort of experimental environment to use. Laboratory experiments are limited by both space and time — they must be able to fit in the lab, and the process must occur in what is known as laboratory time, the non-specific maximum length of time that can reasonably be devoted to any one set of experiments.

Fortunately, concretion formation and fossilization should fit well in lab constraints on both space and time. Concretion formation is a localized process, with the end result rarely bigger than one metre in diameter and often only a few centimetres. Moreover, multiple concretions often occur just a few centimetres apart (Fig. 2b). In rare cases, I have seen concretions in outcrops at Mazon

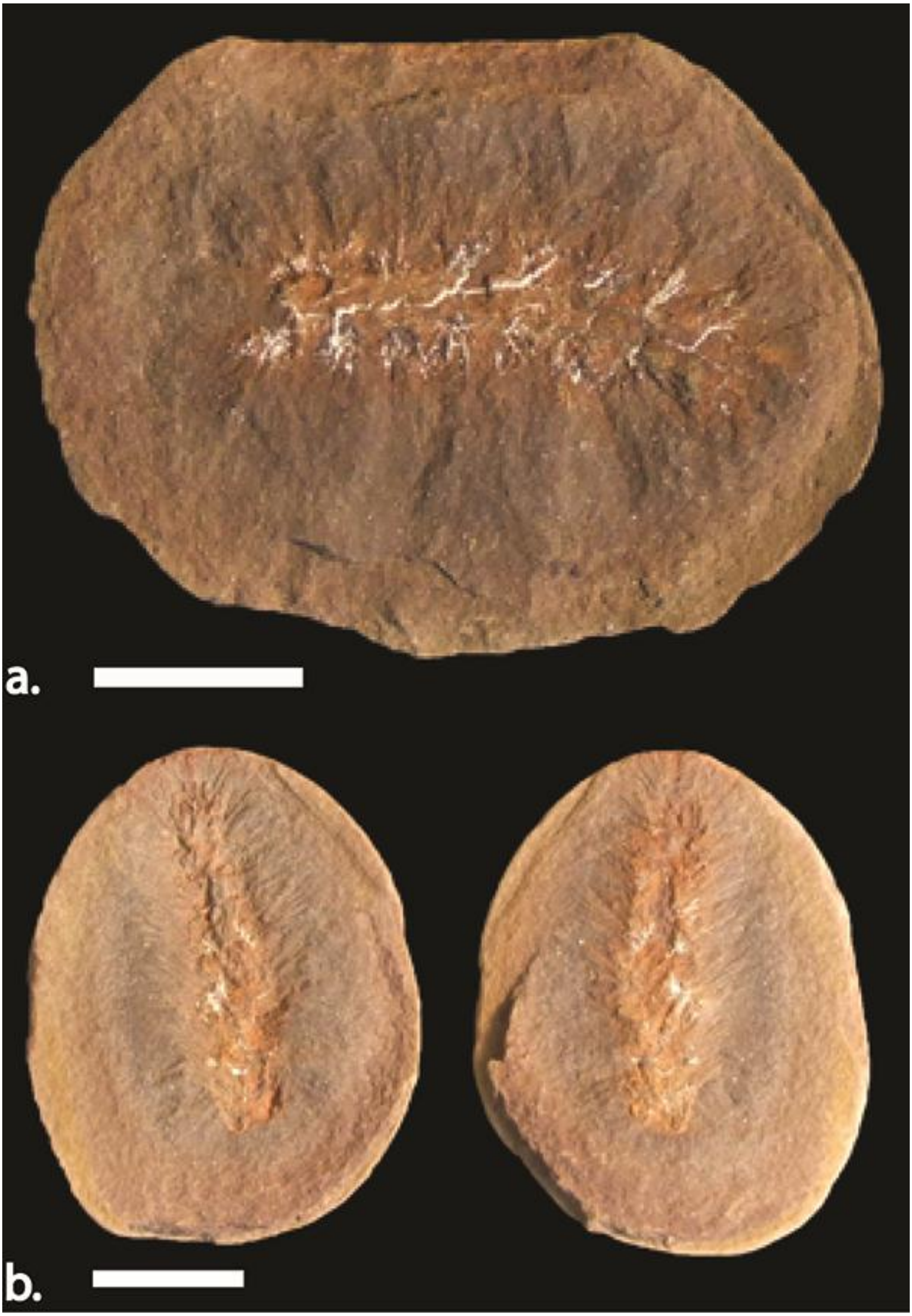

FIGURE 9 — (A, B) TWO SPECIMENS OF PALAEOCAMPA ANTHRAX, A POLYCHAETE FROM THE MAZON CREEK FOSSIL SITE. THE SCALE BARS ARE 1 CM

Creek surrounded in all directions by other concretions, all separated by less than 20 centimetres. Thus, the total concretion-forming system, including everything necessary for the development of one concretion, should fit in a relatively small area. There is also evidence that concretions form on laboratory time scales. At Mazon Creek, there are concretions containing beautifully preserved bristle worms (polychaetes, Fig. 9), which have been experimentally shown to decay to essentially nothing within a few days. Concretion formation and fossilization must occur within the first few days after death, before the worm rots away.

The composition of ancient concretions can also put limits on the experimental environment. The concretions I work on are made of carbonate, and require carbonate ions and ions that bind to them (such as Ca^{2+} or Fe^{2+}) to form carbonate minerals (such as calcite, $CaCO_3$). Decay of an organism can release carbonate ions, but not enough to produce the amount of carbonate seen in a concretion, so some carbonate must already be present in the local environment. Analyses of certain types of chemical elements (isotopes) show that concretionary carbonate contains mainly inorganic carbon from the surrounding sediment or water in pores in the sediment, but not from the organism itself. Sea water typically contains all the ions necessary for concretion formation. For most other conditions, such as pH and temperature, typical seawater values should be fine.

Thus, the experimental set-up can be fairly simple: a freshly killed organism placed in a typical marine environment, contained in even a small space, should form a concretion in a fairly short amount of time. Unfortunately, experiments with this set-up have never exactly replicated what we see in the geologic record (Fig. 10).

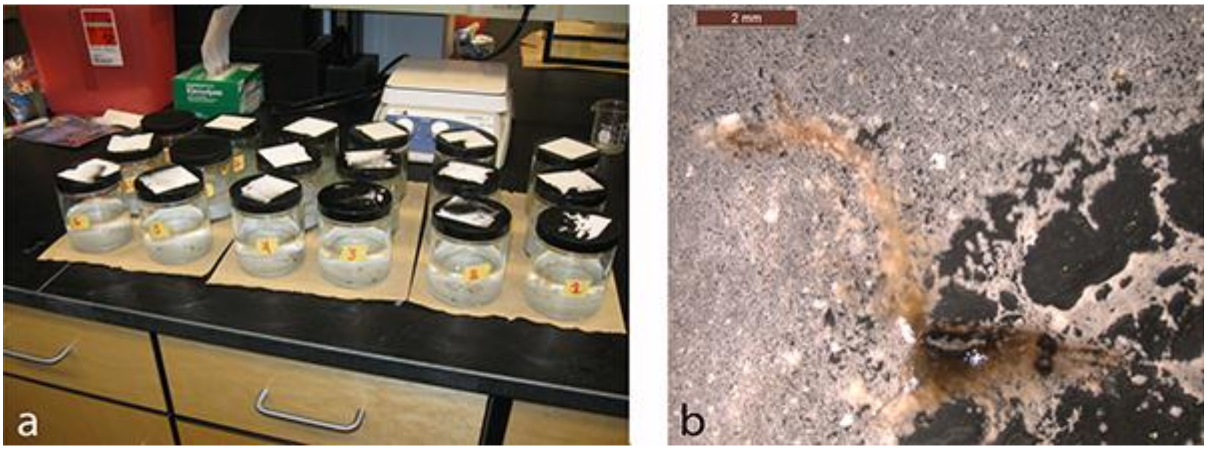

Figure 10 — A typical concretion-forming experimental set-up. (a) Jars filled with sea water, various sediments and freshly killed shrimp. (b) A shrimp after 2 days of decay, with no surrounding concretion (some salt has formed on the bottom of the container, giving it the appearance of frosted glass, but there is no carbonate and nothing surrounding the decaying organism). Photograph courtesy of Robert Young.

The most successful attempt to replicate fossilization in concretions was by Robert Berner, a palaeontologist at Yale University in New Haven, Connecticut, who in the 1960s sealed small fish in jars filled with sea water. The expected chemical changes all took place – increased bicarbonate ions, carbonate ions, ammonia, volatile amines and pH — but there was no deposition of carbonate minerals. Instead, the fish became encased in calcium salts of fatty acids, and natural soaps. Of course, part of the problem in comparing experimental results with ancient concretions is that even if the experiments exactly replicate the process, the experimental result is the product of less than 1 year of the process, whereas the concretions can be millions of years old. There is no guarantee that

FIGURE 11 — A MODERN CONCRETION FROM WEST HAVEN, CONNECTICUT, WITH PRESERVED SHELL PIECES. THE SCALE BAR IS 1 CM.

this extra time did not cause significant changes to the developing concretion. Berner suggested this, with the idea that his calcium soap concretions are the precursors of a more typical rocky carbonate concretion.

One way to try to reconcile these differences is to look for more recent concretions in the geological record. As it turns out, some very young concretions are known. Concretions from West Haven, Connecticut (Fig. 11) have been carbon dated to a few thousand years old, and some concretions in the Norfolk marshes, UK, are estimated to be less than 50 years old. Unfortunately, they are all indistinguishable from more ancient concretions, so all they tell us about a possible transition from a calcium soap concretion to a carbonate concretion is that it happens in less than 50 years. Nonetheless, these recent concretion sites suggest a promising new research direction — observing the growth and development of concretions in their natural habitat. More specifically, researchers could plant dead organisms in marked locations, and check on them yearly to see if concretions are growing around them. A few decades is within the time range of a long-term study.

Conclusion:

Understanding the process by which fossils are preserved in concretions is crucial to unlocking the secrets of many exceptional fossil sites. The disconnect between theory and reality is frustrating yet tantalizing, suggesting that we are close to putting all the pieces together. It may be that slight variations in the experimental conditions — so that they resemble natural environments just a little bit more — would push the results out of soap-concretion territory and into carbonate-concretion territory. Alternatively, the theory could be missing some small but significant component that prevents the experimental results from matching up well. It may even be that there is a major component of the process that is not yet adequately understood. Only time — and more research — will tell.

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http://www.museum.state.il.us/exhibits/mazon_creek/ and http://fieldmuseum.org/explore/multimedia/mazon-creek-fossil-invertebrates — ***Fantastic websites with photos and information about the Mazon Creek fossil site***.

http://palaeo.gly.bris.ac.uk/Palaeofiles/Lagerstatten/santana/fauna.html andhttp://www.fossilmuseum.net/Fossil_Sites/Santana-Formation.htm — ***Great sources of information about the Santana formation fossil site***.

http://bioteaching.wordpress.com/2012/06/11/the-exceptional-silurian-herefordshire-fossil-locality/ — ***A wonderful website describing the Herefordshire fossil site***.

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