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Fossil Focus: Stuck in time — life trapped in amber

by Leyla J. Seyfullah[*1] and Alexander R. Schmidt[1]

Introduction:

Some of the most extraordinary fossils ever discovered, from insects to plants and feathers, are preserved in amber. Amber is the term for various solidified forms of plant resin that occur in the rock record. It can be found in many different colours, shapes and sizes (Fig. 1). Until the past decade, it was thought to be very rare, but new discoveries have shown that it is more abundant in terms of both geographical coverage and presence through time than was previously thought.

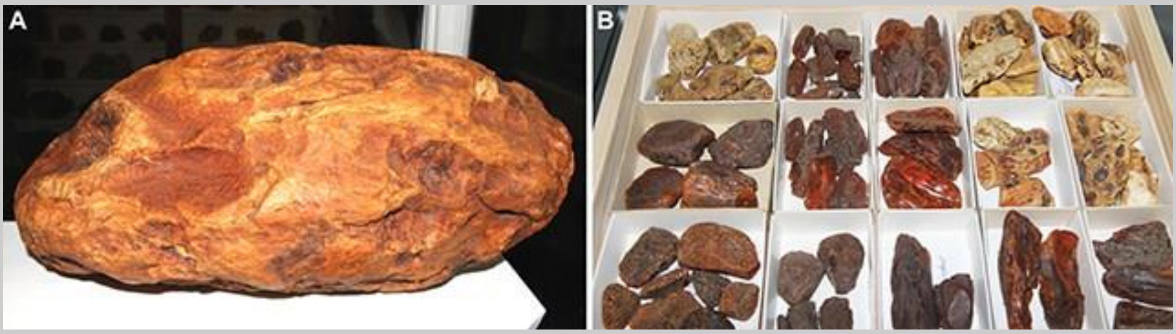

Figure 1 — Amber varies! (A) 9.75 kilogram piece of Baltic amber on display in the Museum für Naturkunde, Berlin. (B) Variation in colour and shape of unpolished amber from conifer trees. This is Bitterfeld amber found in upper Oligocene (around 24 million years old) strata from central Germany, on display in the Museum of the Town of Bitterfeld. Image credits: A. Schmidt.

Although many amber deposits do not contain fossils, some do. Fossils (also known as inclusions) in amber often have exquisite, three-dimensional preservation, retaining fine surface and structural details, and are frequently preserved at least roughly in a position that they would have had in life, and before much decay has set in. Many of the inclusions are arthropods, although a lot of other organisms are sometimes found (Fig. 2), including snails, lizards, plants, fungi, bacteria and, in a few cases, marine organisms like diatoms. In fact, some organisms, such as slime moulds, only have a fossil record in amber. The collection of organisms preserved in amber gives us great insights into the resinous-forest ecosystems of the past and has shed light on the evolution of groups that are otherwise rarely preserved in the fossil record.

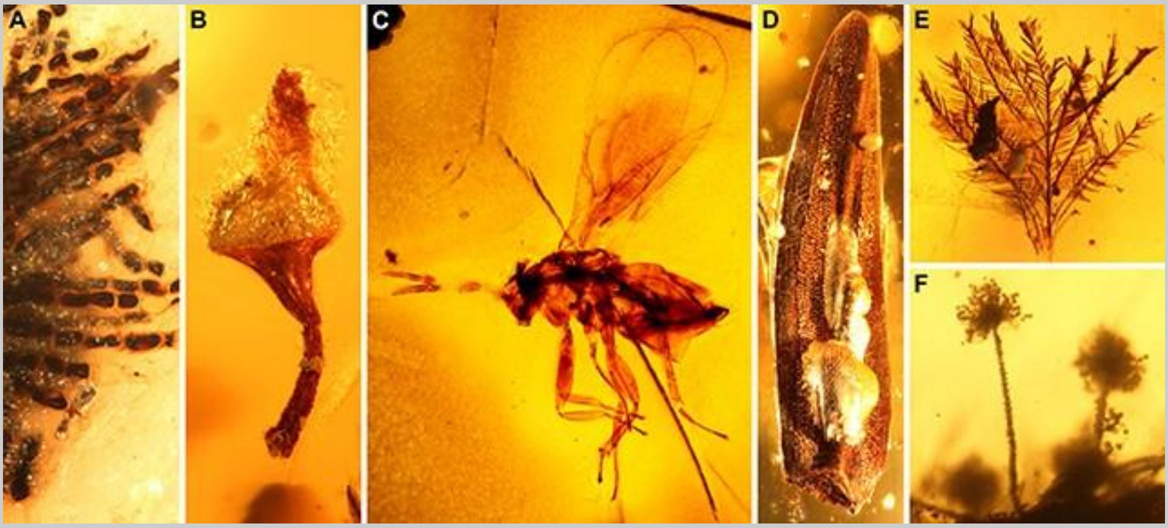

Figure 2 — Amber preserves many groups of organisms, terrestrial, aerial or even aquatic. (A) Filaments of cyanobacteria in mid-Cretaceous (about 100 million years old) amber from France (filaments about 20 micrometres in diameter, Geosciences Collection Rennes IGR.CDL9L). (B) Fossil fruiting bodies of myxomycetes (slime moulds) are only found in amber. Shown is *Arcyria sulcata* from Eocene Baltic amber (about 43 million to 35 million years old; 0.9 millimetres in height, Senckenberg Amber Collection F230/BB/FUN/CJW). (C) Trichogrammatid wasp, a parasitic hymenopteran, in amber from Ethiopia (roughly 0.8 millimetre body size, Museum für Naturkunde, Berlin MB. I 5654). (D) Leaf from Baltic amber (1 centimetre long, Geological-Palaeontological Institute and Museum Hamburg GPIH 294). (E) Remains of a feather in mid-Cretaceous amber from Myanmar (1 millimetre, Geoscience Collection Göttingen GZG.BST.21891). (F) *Aspergillus*-like fungus on plant remains in Bitterfeld amber (conidiophores, which are specialized structures bearing asexual spores, are around 0.3 millimetres long, Grabenhorst Amber Collection LI-5). Image credits: A. Schmidt.

Transforming plant resin into amber:

Resin is just one type of plant secretion, and not all plants produce it. Today, resins are secreted by certain conifers, in particular those from the families Araucariaceae (Fig. 3) and Pinaceae (pines), and some flowering plants, for example Hymenaea in the legume family and *Shorea* in the dipterocarp family. Some extinct plants, such as the Cheirolepidiaceae conifers, also produced resins that became amber. Not all plants that do make resin make the kind that can get preserved as amber; for example, most pine resins will not become truly polymerized amber, due to their chemistry. Furthermore, not all of the right kind of resin gets preserved, because it is relatively soft and easily destroyed in the local environment or when washed into rivers, for example. As a result, the chances of amber being preserved in the rock record are typically very low.

Figure 3 — Fresh resin oozing out of a trunk of *Agathis lanceolata* in New Caledonia. Image credit: C. Beimforde.

Resins are made up of complex mixtures of distinctive types of chemical, usually terpenoids and phenolic compounds. Both types of compound are produced by plants through complex metabolic pathways. Terpenoids are found in all living organisms and form the largest and most diverse class of plant compounds; they are derived from isoprene elements (chemicals based on five carbon atoms linked in a chain). Phenolic compounds contain an aromatic ring of carbon atoms with at least one hydroxyl (OH) group. They are also very diverse plant products. Resins are usually sticky secretions, produced by plants for many different reasons, such as sealing wounds or stopping insect attacks or diseases. They retain traces of the environment that the plant was growing in when the resin was secreted, and so ambers also contain environmental signals, although work to decode these traces is at a relatively early stage. To form amber, resins have to harden (Fig. 4) and become polymerized, and then mature during burial in sediments, ultimately becoming chemically altered but relatively stable as amber.

Figure 4 — Exceptionally large (3.5-centimetre) drop of Baltic amber with original surface structure still preserved, indicating short and low-energy transportation from the source forest to the marine sediment. Image credit: A. Schmidt.

Most ambers are found in sediments laid down by rivers and seas, so it has been suggested that resin falls to the ground near the source tree and is buried in the soil, then is later washed into rivers by erosion. Soil-litter organisms have been found in some ambers. The buoyant resin is washed downstream along with logs, and many pieces collect together on the ocean shore, in lagoons or at the river delta. There, the resin and logs are buried by sediments, and in time the resin becomes amber and the wood becomes lignite (an early stage of coal). Clay or sand deposits keep oxygen away, preventing the oxidation and degradation of the amber.

Therefore, four factors are particularly important for the formation of amber: (1) a near-shore forest that serves as the source of large amounts of resin; (2) forest plants that produce resin with the right type of chemistry to become amber; (3) concentration of the resins during transportation; and (4) appropriate burial in sediments, excluding oxygen that would weather the resin.

How do organisms become inclusions in amber?

The stickiness of the original resin is key to understanding how organisms become trapped and, ultimately, turn into inclusions in amber. When the resin flows out of the plant, various organisms or parts of them (including pollen, spores, wing scales from butterflies, feathers of birds and hairs of mammals) can stick to it. More resin flows over the top, sealing in the trapped objects, and eventually hardens (Fig. 5). If the resin has the right sort of chemistry and the right sort of burial in sediments, it becomes an amber with inclusions (Fig. 6).

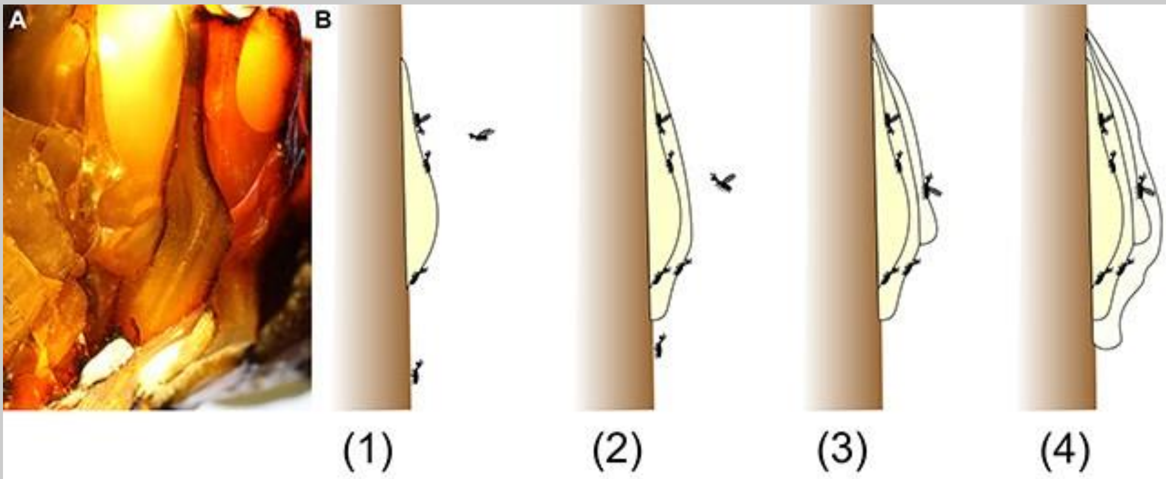

Figure 5 — Amber pieces built of several resin flows are particularly rich in inclusions. (A) A stratified (layered) piece of resin from the early Miocene (about 23 million to 20 million years ago) of New Zealand (Geology Museum of the University of Otago OU 33636). Shining light through it highlights the borders of successive resin flows. (B) Entrapment of organisms in resin: (1) a fresh outpouring of resin occurs, here on a tree trunk. The smell of might be attractive to some organisms, which become stuck on the resin's surface. (2) A second resin outpouring occurs, sealing in the previous resin layer and the organisms stuck to it. (3) and (4) more resin flows may happen, providing more sticky trapping surfaces, and sealing previous sticky surfaces and their victims, allowing the preservation of the trapped organisms. Image credit (A): A. Schmidt. (B) Adapted from Krumbiegel and Krumbiegel (1996).

There are limits to the sorts of organism that can be trapped in amber. Any creature that has the strength to pull itself out of a resin flow, and not be suffocated in it, will typically escape and hence not be preserved. Furthermore, anything that is not completely covered by subsequent resin flow will be accessible to predators, scavengers and weathering, and will probably not end up as an inclusion. Size can hence be a limiting factor, so we are extremely unlikely to find a dinosaur, for example, stuck in amber. Ambers tend to preserve mostly small organisms and fragments of life in a resinous habitat.

Figure 6 — Styles of preservation in amber vary, from perfect cellular details and in life position to shrunken and mummified or completely replaced by crystal growth. (A) Filaments of the alga *Palaeozygnema spiralis* (Zygnematophyceae) from mid-Cretaceous (about 100 million years old) amber of Germany. Chloroplasts are perfectly preserved in some cells (filaments 0.15 millimetres in diameter, Herbarium Haussknecht Jena (JE): Schliersee Amber Collection 65). (B) Liverwort of the genus *Frullania* from Miocene (20 million to 15 million years old) Dominican amber. The plant tissue shows cellular preservation (plant around 2.5 millimetres long, Museum für Naturkunde, Berlin MB.Pb.2009-348). (C) *Frullania cretacea* from mid-Cretaceous amber from Myanmar. This liverwort specimen underwent secondary replacement of organic tissue by the iron mineral pyrite, and small details were lost (branches around 0.1 millimetres wide, American Museum of Natural History New York AMNH Bu-FB-1). (D) Moss *Hypnodontopsis mexicana* (about 3 millimetres total height) with preserved sporophyte from the historic Kühl Collection housed at the Museum für Naturkunde, Berlin (MB, sine numero). The amber considerably darkened over time but the inclusion stayed in cellular preservation. (E) Fern remain from Dominican amber, embedded in resin as dried leaf fragment (some 2 centimetres long, AMNH DR-10-1879). (F) Lizard tail (plus a partial footprint on the left edge) with preservation of skin and bones. After entrapment, the dead lizard was probably opened up by carrion-feeding insects and the exposed vertebrae were later finely preserved by another resin flow. (G) Close-up of the lizard tail with amber-preserved vertebrae and skin scales at a distance (around 1 millimetre diameter, Hoffeins Amber Collection). Image credits: A. Schmidt.

Where and when is amber from?

The largest and most famous amber deposit in the world is the Baltic amber deposit. It is estimated that 640,000 tonnes of amber have been deposited here, and the deposit is thought to be from the late Eocene epoch (around 43 million to 35 million years ago). The oldest amber occurs as tiny droplets in Carboniferous sediments from 320 million years ago; microscopic fragments of ambers (resinites) can occur in lignites of various ages. These are thought to come from resinous structures inside the plants that formed the coals, and so will not preserve fossils. The first outpouring of resin with inclusions comes from the Triassic (230-million-years-old) amber from the Italian Dolomites, which was produced from the canopies of extinct Cheirolepidiaceae trees and contains various microorganisms, midges and distant relatives of extant gall mites (Fig. 7). The entire Jurassic Period (201 million to 145 million years ago) is very poor in amber, but recent work has described hundreds of Cretaceous deposits from across the globe (145 million to 66 million years old). Some of the most significant ambers are derived from between the Eocene epoch (56 million to 34 million years ago) and the Miocene epoch (23 million to 5 million years ago).

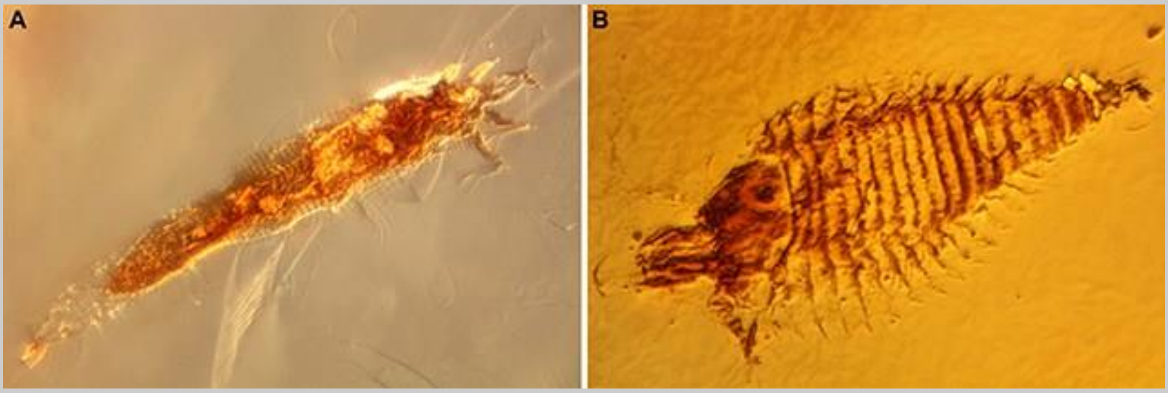

Figure 7 — These two little plant-feeding mites are among the oldest amber inclusions found so far. Millimetre-sized resin droplets from the Triassic (230 million years old) of the Italian Dolomites are the sole known source of early Mesozoic amber inclusions. (A) *Triasacarus fedelei* is about 0.2 millimetres long (Museum of Geology and Paleontology Padova MPG 31343). (B) *Ampezzoa triassica* reached only around 0.12 millimetres (MPG 31344). Image credits: A. Schmidt.

How do we image the life trapped inside amber?

To get the best view of an inclusion, a scientist will typically start by using a light microscope. Frequently, it is best to shine light both onto and through the amber at the same time. The amber is usually polished on wet abrasive papers by hand, just enough to reduce refractions (light scattering) from within the amber and to remove scratches and fissures ‘blocking’ the view without exposing or damaging the inclusion. Sometimes the fossils are removed entirely from the amber, either by dissolving the amber or by physically cutting them out, and then imaged with a scanning electron microscope to get a closer view. More advanced imaging techniques can mean that the amber does not have to be prepared at all. For example, computed tomography (CT) scanning (Figs 8 and 9) or the high-powered beam of X-rays of a synchrotron particle accelerator (Fig. 10) scan the fossils and then allow a 3D model to be built from the data gained (even if the amber is opaque).

Figure 8 — Transparent ambers do not always show all the preserved details clearly, so here X-ray micro CT has been used to reveal the remains of *Anolis* lizards from Dominican amber (20 million to 15 million years old). (A) A reconstructed amber-preserved lizard. (B) The same fossil showing skeletal information (and breaks!) scanned using X-ray CT. (C) An obscured amber-entrapped lizard and (D) the image of the obscured lizard's skeleton generated by X-ray CT scanning (see Sherratt *et al*. 2015 for more information). Image credits: E. Sherratt.

Figure 9 — Apparently unpromising amber specimens can now yield their secrets, even when light microscopy fails. Here, highly detailed information is provided by phase-contrast-enhanced X-ray CT of an Eocene (43 million to 35 million years old) Baltic amber piece containing a Huntsman spider (*Eusparassus crassipes*) that was so darkened and oxidized that the specimen was barely visible. (A) Oblique view at the lower side of the spider's pedipalps (the legs have been virtually cut off for a better view). (B) Frontal view of the prosoma showing fine hairs. (C) Well-preserved detail of the chelicerae and fangs. All images of specimen MB.A. 1604, held at the Museum für Naturkunde, Berlin (see Dunlop *et al*. 2011 for more information). Image credits: J. Dunlop.

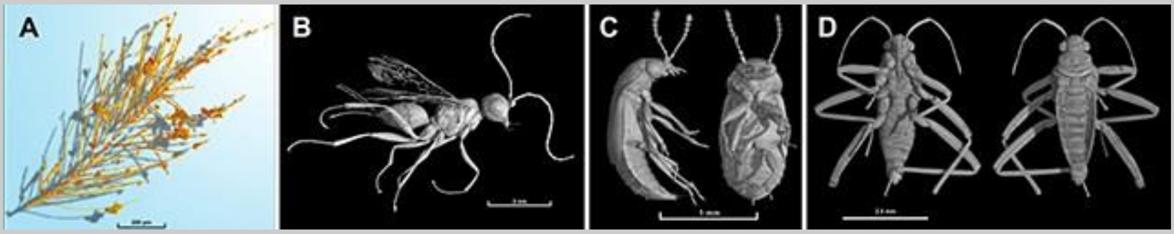

Figure 10 — Visualizing amber-preserved fossils from mid-Cretaceous (about 100 million years old) French opaque ambers using phase-contrast X-ray synchrotron imaging. (A) A primitive feather, possibly from a dinosaur (Geosciences Collection Rennes IGR.ARC-115.6; see Perrichot *et al*. 2008 for more information). (B) *Guyotemaimetsha enigmatica*, a parasitic wasp (Hymenoptera: Maimetshidae; IGR.ARC-370.7). (C) Two views of *Duocalcar geminum*, a rove beetle (Coleoptera: Staphylinidae; IGR.ARC-370.6). (D) *Arcantivelia petraudi*, a water strider (Heteroptera: Veliidae; IGR.ARC-271.1). Image credits: V. Perrichot (Univ. Rennes 1) / ESR.

Amber and the preservation of biological molecules:

The often exceptional preservation of amber inclusions means that subcellular details can sometimes be found. This includes organelles (small components inside cells) and cell membranes. This begs the question, can original biomolecules be preserved in amber? It seems unlikely but some studies have shown that even highly resistant large molecules such as amber-preserved lignin, found in plant woody tissues, and melanin (from fungi in amber) are significantly degraded.

Many studies show that DNA (the genetic material inside all living things) degrades quickly after an organism has died. A study of Holocene (less than 11,700 years old) moa bones showed that DNA has a half-life of only a couple of hundred years, meaning that it is extremely unlikely to survive for more than a few million years. It has also been shown that insect DNA does not even survive in copal, a younger and chemically less mature state of amber. So what about the hype of the 1990s, when DNA was said to have been extracted from amber? Sadly, the various published results were not reproducible and newer work shows that the DNA discovered is the result of modern contamination. Bacteria and fungi contaminate every surface around us, and some are thought to live on amber in museum collections, using either the amber or organic debris inside fissures (cracks) as a food source. Ultimately, this means that recreating dinosaurs or other ancient animals from DNA entrapped in amber is simply not possible — sorry!

How do we preserve amber for the future?

Amber can be thought of as a hardened biological plastic, and depending on the hardness of the individual amber, it can become scratched. This can usually be remedied by careful surface polishing, as long as you do not polish away the inclusion underneath. However, some ambers, especially those that are less mature, can be melted if exposed to heat. Moreover, some can be dissolved in various organic compounds, including oils, which can quickly destroy the inclusions. Probably the biggest problem is weathering, in which ambers left exposed to the elements darken and develop fissures, allowing progressively more damage to occur from oxidation. This can even happen to amber stored in museum collections if the temperature and humidity is not strictly controlled. One way around weathering and degradation is to embed the amber pieces in epoxy resins, which then form an airtight barrier around the amber and its inclusion. If you want to take a closer look at the piece later, you may have to polish off the epoxy, but it does preserve amber without discolouration or further degradation.

Summary:

Amber is both a chemofossil in itself and a fossil-preserving medium. There are often exquisitely preserved organisms in ambers, giving us insight into past forest ecosystems, and sometimes providing a fossil record for organisms that do not normally get preserved in sediments. With sophisticated imaging techniques, even fossils thought to be hidden in weathered or opaque amber are being revealed to great effect. Amber research is going through a renaissance as new deposits have been recognized, particularly in the Southern Hemisphere, broadening both the geographical and the temporal spread of amber deposits worldwide. The resulting improved access to certain rare groups of fossil organisms at different periods of Earth history allows us to trace the evolutionary history of otherwise rarely preserved lineages through time; analyses of entire amber deposits and their inclusions sometimes allows detailed insight into past terrestrial ecosystems.

Suggestions for further reading:

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