Fossils

Mike Viney

Hermanophyton Taylorii
Permineralized Seed Fern

The word fossil is derived from the Latin *fossilis*, which means "dug up". Initially, the term fossil applied to any strange or interesting material found within rock whether or not it was of organic origin (Prothero, 2004, p. 5). Most modern definitions include the concept that fossils are evidence of ancient organisms, which have become a part of the Earth's crust. The word ancient is arbitrary. To some, ancient applies only to extinct organisms while, to others, it implies time limits. Grimaldi and Engel (2005) point out many would like to restrict the term fossil to species that have become naturally extinct. They argue that having this knowledge is problematic. Grimaldi and Engel suggest the following practical definition, "...a fossil is the remains or workings of any species, living or extinct, that have been naturally preserved for several thousand years or more (p. 62). A more common time limit defines fossils as being prehistoric thus; fossils preserve remains or activities of ancient organisms older than 10,000 years (Garcia & Miller, 1998, p. 14; Schopf, 1975, p. 27).

The majority of fossils are found in sedimentary rocks. Organisms become trapped within sediment layers due to the action of water, wind or gravity. Fossils can sometimes be found in metamorphic rocks formed from fossiliferous sedimentary rocks altered by heat and pressure. Fossils can even be found in igneous rock created from lahars or pyroclastic flows that entomb trees or other organisms.

Two major types of fossils are recognized. Body fossils reveal the structure of an organism, while trace fossils reveal the activities of organisms. There are many reasons to study fossils. The fossil record indicates that different life forms have existed at different times revealing the evolution of life on Earth. Fossils and rock types serve as clues to determining ancient environments. Finally, fossils are the most practical way of telling time in geology (Prothero, 2004, p. vii). How do fossils form and how are they classified into different preservation types?

Taphonomy

A Fossil represents evidence of past life that is found in the Earth's crust. Taphonomy ("laws of burial") is the term used to describe the process that results in the formation of a fossil. Taphonomy or the transition of an organism or part of an organism from the biosphere to the lithosphere is accomplished in basically two steps. The process of burial or entombment is referred to as biostratinomy. After burial or entombment, diagenesis begins; the conversion of sediments or other deposits to rock. Biostratinomic and diagenetic processes destroy most traces of organisms. The extent of preservation depends upon what happens during biostratinomy and diagensis. The biostratinomy and diagensis associated with a fossil can reveal much about the environment in which the organism lived. In other words, how fossils form can often provide clues to past environments.

Lagerstätten

Fossilization often occurs as a result of rapid burial, usually by water-borne sediment, followed by chemical alteration. Rapid burial and specific chemical environments help to reduce decomposition from bacteria and fungi. Decomposition, erosion, deposition and rock formation are processes that often destroy soft tissue, so it is the hard parts of organisms such as shells, bones and teeth, which are most often preserved. Occasionally conditions exist that allow for preservation of organisms in environments that rarely produce fossils. Exceptional conditions may also help to preserve soft tissue or impression of soft body parts.

Fossil deposits with soft-bodied organisms well preserved or with terrestrial animals, such as dinosaurs in the Morrison formation are termed Lagerstätten. Lagerstätten is a German word used in mining that denotes a particularly rich seam and has been adopted by paleontologist to signify these rare fossil deposits because they give us a window into past environments seldom preserved in the fossil record (Selden & Nudds, 2004, p. 7). Two types of fossil lagerstätten are recognized. Deposits that contain vast numbers of fossils represent Concentration Lagerstätten. The preservation may not be exceptional, but the great numbers can be very informative. Conservation Lagerstätten contain fossils with soft body preservation, impressions of soft tissue or fossils of well-articulated skeletons without soft tissue preservation. Conservation Lagerstätten are particularly important because they provide knowledge of soft-bodied organisms, allow paleontologists to reconstruct paleoecosystems, and give insights into the morphology and phylogentic relationships of organisms (Nudds & Selden, 2008, pp. 8-9).

Preservation Types

The science of taphonomy explores the environmental conditions that promote fossilization. Both body and trace fossils can form under a variety of circumstances representing multiple modes of preservation. Compare several books on fossils off any library or bookstore shelf and you will soon realize there is no standard for categorizing types of fossil preservation. In this paper we will briefly describe modes of preservation that one is likely to find in both scientific papers and popular books.

Molds & Casts

Casts & Molds of Trilobites
Ellipsocephalus hoffi

Organisms buried in sediment may decay or dissolve away leaving a cavity or mold. If the space is subsequently filled with sediment, an external cast can be made. Molds and casts are three dimensional and preserve the surface contours of the organism. A mold preserves a negative imprint of the surface, while a cast preserves the external form of the organism (Taylor, Taylor & Krings, 2009, p. 22).

Sometimes a shell can be filled with minerals and then dissolve away. The internal cast that remains is termed a steinkern, which in German means "stone cast" (Pothero, 1998, p. 7). Steinkerns are most often represented by the internal molds of mollusks. The pith cast of *Calamites* is the most common plant steinkern. As a *Calamites* tree matured the

Calamites Pith Cast (Steinkern)

center of the stem (pith) became hollow, developing into a tube-shaped air cavity. The pith cast preserves an impression of the pith cavities outside surface, which represents the inside vascular and cortex tissue (Taylor, Taylor & Kring, 2009, p. 23).

Most molds and casts do not contain the actual remains of an organism. Shells, bone, and wood often form as molds or casts. Some trace fossils (ichnofossils), such as tracks and burrows can form as casts or molds. Tracks and burrows can provide clues to the behavior and biomechanics of an organism while it was alive.

Concretions often encapsulate a fossil mold and cast. The siderite (iron carbonate) nodules of Mazon Creek, Illinois preserve Carboniferous aged animals and plants as molds and casts (Nudds & Selden, 2008, p. 120). It should be noted that some authors classify the fossils in Mazon Creek nodules as impressions (Janssen, 1979, p. 24; Rich, Rich, Fenton & Fenton, 1996 pp. 4-6). Limestone concretions in Ft. Collins, Colorado contain the molds and casts of Cretaceous aged mollusks. As kids, my friends and I collected multiple *Inoceramus* clams from a 3-foot diameter concretion. These fossils are found as molds and casts with the cast filling the mold.

It is important to realize that many fossil specimens represent more than one mode of preservation. For example, the cast in a Mazon Creek nodule also represents fossilization by authigenic mineralization, a type of replacement. Subtle pH changes created by the decaying body of the buried organism caused available iron carbonate to precipitate. Thus, the organism became its own nucleation site for the formation of a siderite nodule. Some of the shells found in the limestone nodules of Ft. Collins retain altered shell material, which represents recrystallization. Aragonite (calcium carbonate) in the shell recrystallized to calcite, a more stable form of calcium carbonate.

We usually think of casts and molds as exhibiting obvious three-dimensional character. The thin leaves of plants or the wings of insects can produce shallow casts and molds. Shallow casts and molds may take the form of imprints, or impressions, preserving the three dimensional character of an organism. Impressions of wings are a common insect fossil. Even some of the relief, like pleating on the wings can be preserved. This is important because the veins on a wing can be used to key an insect to the family level (Grimaldi, D. & Engel, M.S., 2005, pp 42-45).

Imprints, impressions and many trace fossils, such as, burrows, insect galleries, and tracks, may represent types of molds or casts if they retain their three-dimensional character. Molds and casts are important because they can faithfully replicate the external form of an organism in a three-dimensional fashion, giving paleontologist information about surface anatomy.

Impressions, Compressions & Carbonization

When organisms become trapped and squeezed between sediments they may form compressions. Larger organisms can be distorted by compression. However, good fossils of fish, leaves and insects are often formed by compression.

Carbonized Insects
Insect Compressions

Fish, Insect and plant compressions retain organic material. The organic matter making up the body of the organism may be altered during decay and rock formation. The distillation of volatile compounds and the polymerization of lipids chemically transform the organic structures and leave a thin film. The thin, dark, film is made of stable, polymerized carbon molecules that remain after more volatile and unstable compounds get dissolved away, hence the name carbonization. A compression fossil represents a type of carbonization.

The thin carbon layer on a plant compression is known as a phytoleim (Cleal & Thomas, 2009, p. 4). The phytoleim may retain original cuticle, which resists decay. The cuticle is the protective non-cellular waxy covering of the epidermis. When removed and studied the cuticle may reveal the arrangement of epidermal cells and stomata, which can sometimes aid in species identification (Tidwell, 1998, p. 27).

As organisms are squeezed into compressions they may form an imprint or impression. Thus, fossils discovered by splitting bedding planes may reveal two fossils from a single specimen. The side with more organic material is called a compression. Compressions often show the external surface of an organism flattened in a two dimensional fashion. The side with little or no organic material is called an impression (Tidwell, 1998, p. 27; Taylor, Taylor & Krings, 2009, p. 21; Schopf, 1975, p. 37). Impressions often represent a negative imprint of a compression.

Imprint & Compression of Fish
Knightia eocaena

Imprints are shallow external molds or voids left by animal or plant tissue. When the siltstone pictured above was split into two slabs the organic matter adhered to one side. The top picture represents an imprint in which bones and scales left a shallow external mold. The lower picture is a compression because it possess organic residue left from scales, original bone, and bone reinforced with calcite. Fish, leaves and insects are often found as imprints and compressions.

The compression is referred to as the part (positive side) and the impression as the counterpart (negative side). The impression in this case shows all the surface details of the compression and represents an imprint (Taylor, Taylor & Krings, 2009, p. 21). The counterparts of Green River fish that represent imprints can be used to make positive laytex casts to study external surface features (Grande, 1984, pp. 119 & 120). If the layer of carbon is lost on the compression through weatherning or further diagenesis then it is also known as an impression (Cleal & Thomas, 2009, p. 4). Thus, an impression, unlike an imprint, can be positive or negative.

For the paleontologist that studies insects, impressions are like casts and molds, which may preserve some relief like pleating on wings (Grimaldi & Engel, 2005, p. 43). This is important because wing venation can be used to identify an insect. Many Mazon Creek nodules do not retain organic material and so both the part and counterpart are referred to as impressions (Janssen, 1979, p. 24; Rich, Rich, Fenton & Fenton, 1996 pp. 4-6). Sometimes parts of a specimen are preserved as a compression while other parts are an impression. In this case the term adpression may be used. Adpressions form when the matrix of a fossil is soft and the phytoleim has fallen off in some places (Cleal & Thomas, 2009, p. 4).

Insects and leaves preserved in the Eocene aged Florissant beds of Colorado are often carbonized. It is believed that leaves and insects became entangled in diatom mucus mats (formed by aggregates of diatoms under stress). Insects and leaves were incorporated into layers of sediments and volcanic ash at the bottom of Lake Florissant. Many of these insects and leaves decomposed leaving imprints. As the sediments compacted and hardened into shale the imprints became impression fossils. Some organisms only partially decayed retaining a dark colored carbon residue to become compression fossils (carbonization). Many insects have their wings preserved as impressions and their bodies as dark compressions. Compressions are often flattened, having a two-dimensional appearance. However, the preservation in diatom layers allows some organisms to retain their three-dimensional character. Some insects are found with organs and appendages. Some leaves can be found with internal structures (Meyer, 2003, pp. 35-37).

Cone & Needle Compression of *Metasequoia*

Feathers are often preserved through compression and carbonization. It is believed that the carbon residue is the result of feather degrading bacteria. An analysis of a Cretaceous aged fossil feather showing a banded color pattern from Brazil produced interesting results. The light areas of the feather represented an impression (no organic residue). The dark areas, representing a compression, consisted of 1-2 micrometer oblate carbonaceous bodies. These objects turned out to be carbonized melanosomes; molecules that were responsible for the original feather color. The fact that the structure of the melanosomes is preserved opens up the possibility of determining the original feather color (Vinther, J., 2008, p. 522).

Fusainized *Lithocarpus sp.*

Most fossils found in coal deposits are compressed and carbonized or coalified. Coal balls are the exception and are discussed under permineralization. Plant and animal remains may also be Charcoalified or Fusainized. Many believe that fusainized organisms are transformed to charcoal by ancient forest fires. Although evidence of fire is associated with some fusainized plant tissues there are exceptions. Some fusainized remains preserve cuticle and resins, which does not seem consistent with an origin that includes fire (Schopf, 1975, p. 45). Fusainized remains are three-dimensional and may be replicated to the cell level by carbon (Grimaldi & Engel, 2005, pp. 49-50).

Permineralization

Permineralized Oak
Quercus sp.

Permineralized fossils form when solutions rich in minerals permeate porous tissue, such as bone or wood. Minerals precipitate out of solution and fill the pores and empty spaces. Some of the original organic material remains, but is now embedded in a mineral matrix

(Schopf, 1975, p. 31). Bone and wood tissues act as excellent frameworks to preserve cell structure. Silicates, iron oxides, metal sulfides, native elements, carbonates, and sulfates can be involved in permineralization. Permineralization is one of the most faithful modes of fossil preservation. In fact, scientists have tried to replicate the process in the laboratory, but no artificial permineralization is equal to the best natural preservation by cryptocrystalline silica or calcium carbonate (Schopf, 1975, p. 33).

Formation of the finest petrified wood involves permineralization with silica, usually from a volcanic source, along with replacement and recrystallization. During the initial stages of permineralization amorphous silica infills pits connecting cells and precipitates on cell walls. At this early stage no replacement has occurred. Replacement of cellulose in cell walls may occur as permineralization continues. Cellulose that degrades leaves room for the emplacement of silica between and within cells walls. The more decay resistant lignin that remains in the cell walls continues to act as a guiding framework to preserve structure. Later silica is deposited in cell lumina, the cavity enclosed by the cell walls and voids left by wood degradation.

Silica that initially permeates the porous tissue and that which replaces cell wall material is amorphous. This amorphous silica is unstable and slowly crystallizes to more stable forms over millions of years. The transition to more stable forms of silica involves continued polymerization and water loss. Higher ordered forms of opal are created through this process and eventually lead to the thermodynamically more stable silica quartz (Stein, 1982, p. 1277). The quality of preservation usually, but not always, declines during successive stages of silicification (Mustoe, 2003, p. 36). In some instances higher order forms of opal and chalcedony may act as the initial replicating minerals (Mustoe, 2008, p. 138).

Permineralized *Palmoxylon*

Petrified forests, representing small to large deposits of permineralized wood, capture people's imagination. What processes allow wood structure to be preserved in stone?

How long does it take to form petrified wood? You can explore these questions in more depth by reading our article on Permineralization.

Petrified wood and petrified dinosaur bone are probably the best known permineralized fossils among the general public. Although not as well known, the coal ball represents a very informative permineralized fossil. A special type of fossil, the coal ball, can be found in the coal deposits of the Pennsylvanian and Permian periods. Coal balls contain swamp vegetation, which has been permineralized with calcium carbonate, preserving 3-D cellular structure. Coal balls are studied in serial section using the cellulose acetate peel method to reveal microscopic structure. Serial sections can be used to reconstruct organs and entire plants. The five major groups of plants found in coal balls include: Lycophytes, sphenopsids, ferns, seed ferns, and cordaiteans (Rothwell, 2002, p. 40). The in situ preservation of plant materials in coal balls allows paleontologist to study plant associations that tell us something about the palaeoecology of the coal swamps. Coal balls reveal that the arborous fern *Psaronius* became the dominant canopy tree after the extinction of Lepidondendrales near the Middle Pennsylvanian. Certain species of small ferns and horsetails have been found, which grew in association with the roots of *Psaronius* (Rothwell, 2002, p 42).

Amber

Wasp in Baltic Amber

Amber is referred to as petrified tree resin or sap. I prefer petrified tree resin as the term sap refers to fluids transported by xylem or phloem tissues (Raven, Evert, & Curtis, 1981, p. 659). Conifers and some deciduous trees produce resin in response to injury. Resins are viscous liquids that contain volatile terpene compounds and organic solids. Under the right conditions resins polymerize and harden with age, turning into copal. After several million years or more, copal matures into amber.

Tree resin breaks down when exposed to drying and oxidation within just a few thousand years. It is not surprising then that amber deposits do not represent forest floor environments. Amber deposits usually represent marine environments. Amber deposits form when resins produced in forests are transported by water to oceans or lakes, where they are deposited into the sedimentary layers. Quick transport and deposition protects the resin from weathering. Once deposited, the resin chemically matures into intermediate forms called copals and finally into amber after millions of years. The amberization process is estimated to take between 2 and 10 million years. However, the type of depositional environment may also affect the time needed for amberization. Amber from Borneo is found in sand and clay sediments deposited in a deep ocean 12 million years ago. The material that comes out of the sandstone has matured into amber, while the specimens from the clay are still copal (Ross, 2010, pp 8-9).

Petrified resins have been found in Carboniferous, Triassic, and Jurassic deposits, but represent minute amounts of resins produced inside trees. Resin that collects inside trees does not act as an insect trap. The first occurrence of fossil containing amber is Cretaceous in age. The majority of amber deposits that contain fossils were formed during the Cenozoic (Weitschat & Wichard, 2002, pp.9-10).

Fossils entombed in amber are referred to as inclusions. Although the organisms often look complete, most appear to be thinly lined hollow spaces (Weitschat & Wichard, 2002, p. 29). However, under the right conditions the internal organs can be well preserved. The preserved internal organs of a bee exhumed from Dominican amber have been imaged using an electron microscope (Grimaldi & Engel, 2005, p. 59). Studies using scanning electron microscopes as well as transmission electron microscopes have revealed internal organ preservation in Baltic amber spiders and gnats. It seems that many organisms in amber are preserved through mummification. In the process of mummification, dehydration results in up to a 30% decrease in volume of tissues. The decrease in tissue volume gives the organisms the appearance of an empty husk (Selden & Nudds, 2004, p. 134).

The shape of a specimen can be a clue to whether the amber formed inside the tree as an internal resin accumulation or outside the tree as an external resin accumulation. Resin can collect inside the void of a tree, drip off a branch, or flow along the outer bark. Resin that collects inside a tree usually does not contain fossils. Resin that accumulates on the outside of a tree can act as an insect trap. Fossils are almost exclusively found in specimens formed by successive resin flows that collected on the outside of the tree. These specimens are referred to as Schlaube (Weitschat & Wichard, 2002, p. 12). Organisms become trapped in the resin and are then covered by a successive resin flow. You can usually see the plane representing a successive resin flow; it often looks like a fracture in the amber.

Amber can represent a brief snapshot in time. Amber has preserved insect developmental stages, mating, egg laying, brood care, feeding, as well as various symbiotic relationships. Amber with and without fossils can be quite valuable so, it is often faked. See Ross (2010) for an excellent discussion regarding materials used to make fake amber and tests that can be used to distinguish real amber from imitations (pp. 11-15).

Chemical Preservation

Hydrophilus beetle in Tar Sand

Peat bogs, oil seeps, paraffin, tar pits and asphalt are good sources for fossils that have been chemically preserved (Garcia & Miller, 1998, p. 15). Paraffin mines and peat bogs can preserve soft tissue. Tar pits or asphalt preserve only hard parts such as bones, shells or exoskeletons. In 1907, a paraffin mine in Poland produced the head, forelegs, and skin of a woolly rhinoceros (Rich, 1996, p. 3). The Rancho La Brea Tar Pits in California, Big Bone Lick in Kentucky, and Talara, Peru are well known sites for fossils preserved in tar pits (Garcia & Miller, 1998, p. 15).

Rancho La Brea literally translates to "the tar ranch". The naturally occurring petroleum based substance is more properly referred to as asphalt (Nudds & Selden, 2008, p. 262). Rancho La Brea within the city of Los Angeles is one of the richest deposits of ice aged animals. The sabre-toothed cat *Smilodon fatalis*, the imperial mammoth *Mammuthus imperator*, the American mastodon *Mammut americanum*, and the giant ground sloth *Glossotherium harlani* are just some of the ice aged mammals that capture the public's imagination. However, hundreds of plant and animal species have been found trapped within these asphalt deposits providing a window into a North American Pleistocene ecosystem.

Most of the fossils excavated at Rancho La Brea are carbon dated at between 11,000 and 38,000 years old. The asphalt rich sediments that contain this concentration lagerstätte were deposited during the last ice age (Wisconsinan Glaciation), which places them in the Upper Pleistocene Epoch. Shallow asphalt pools formed animal traps during the summer. During the winter these pools may have solidified. As seasons changed, heat from the summer sun would once again set the traps for foraging herbivores.

Interestingly, there is a preservation bias for carnivores, young and maimed individuals. Young and maimed animals were more susceptible to becoming trapped in the asphalt pools. Scavengers were attracted to the carcasses accumulating in the pools. Although soft tissue is not preserved the bones retain much of their original composition. Rapid burial followed by asphalt permeation accounts for the excellent bone preservation (Nudds & Selden, 2008, p 262-268). The bones are black with tar and have the smell of petroleum. Scientists have extracted DNA from the bones to compare these extinct organisms with their living relatives (Prothero, 2004, p. 9).

Replacement

Pyritized Ammonite

Minerals can replace bone, shell, wood, and even soft body parts as they dissolve away due to the action of water and decay. Replacement and mineralization are terms used to describe this fossilization process (Garcia & Miller, 1998, p. 15). Part of the ammonite shell above has been replaced by the mineral pyrite. The replacement of soft or hard body parts may occur when minerals precipitate out of solution due to the action of bacteria or pH changes. During replacement coats of bacteria quickly mineralize the decaying tissue. If replacement results in a fossil that is completely articulated with three-dimensional fidelity the process is referred to as mineral replication (Grimaldi and Engel, 2005, p. 45). Grimaldi and Engel also classify permineralization as a type of mineral replication that is a result of microbial decay. Organic residue on compression fossils can be replaced by minerals leaving an impression coated with a mineral. Pyrite is a common replacement mineral. In pyritization sulfur reducing bacteria facilitate the precipitation of pyrite during decay.

The Lagerstätten known as Beecher's Trilobite Bed in New York is famous for its pyritized trilobites. Trilobite exoskeletons as well as soft body parts, including antennae, legs, muscles, and digestive tract, have been preserved with the mineral pyrite (Etter, 2002, p. 131).

In the Orsten deposits of Sweden the meiofauna making up the paleoecosystem of a flocculent-layer just above the seabed is exquisitely preserved by phosphatization. Eyes, hairs, spines, muscle scars, joints, pores, and soft body parts have been preserved on miniature late Cambrian arthropods. Exoskeletal replacement and or coating by calcium phosphate occur only on specimens less than 2 mm is size. The Orsten Lagerstätten is important because it helps to deepen our understanding of arthropods as many larval stages are preserved (Tang, 2002, pp. 117-121).

Exquisite examples of leaves, stems, cones, and seeds of Carboniferous plants along with animal life can be found in the Lagerstätten known as Mazon Creek, which is just 150 km southwest of Chicago, Illinois. The soft and hard parts of plants and animals are replaced with the mineral siderite (iron carbonate). Subtle pH changes created by the decaying body of the buried organism caused available iron carbonate to precipitate. Thus, the organism became its own nucleation site for the formation of a siderite nodule. When these nodules are split open, the fossil appears as a 3-D external cast and mold. Mold surfaces may be coated with kaolinite, pyrite, calcite or sphalerite. Plant material is sometimes covered with a carbonaceous film (Nudds & Selden, 2004, p. 120).

Siderite Nodule with Seed Fern Leaf

Plant material preserved in barite sand nodules can be found near the town of Steinhardt Germany in an Oligocene aged deposit. When split open some of these nodules reveal molds and casts of plant material replaced with the mineral barite (barium sulfate).

Cone Cast in Barite Nodule

The process that forms a concretion or nodule, which may contain a replacement fossil, is called authigenic cementation or authigenic mineralization (Prothero, 2004, p. 437; Cleal & Thomas, 2009, p. 7). Authigenic minerals grow in place rather than being transported or deposited. Thus, the concretions or nodules are found in the place they formed or in situ (Latin for "in the place").

Recrystallization

Recrystallized Fossil Clam *Mercenaria permagna*

Some shells are made of aragonite. During the fossilization process aragonite reverts to a more stable form of calcium carbonate called calcite. Thus, recrystallization from aragonite to calcite represents a type of replacement. Some shells are made of layers of calcite and aragonite. The small crystals of calcite in shells may recrystallize into larger calcite crystals. The overall shape of the shell may remain, but the effect of recrystallization on microscopic texture is evident (Prothero, 2004, p. 9).

Freezing

Mammuthus primigenius Hair

Woolly mammoths and woolly rhinoceroses from the Pleistocene can sometimes be found in the permafrost of Alaska and Northern Siberia. The entire organism is sometimes preserved in this frozen soil.

During the last Ice Age some of these animals died in areas that have remained cold. Eventually, in rare instances, organisms were buried in what became permafrost soil. Bones, muscles, internal organs, partly digested food, skin and hair can sometimes be found. Both the course guard hair and soft underwool of the mammoth is represented in the specimen above. Some of the 30,000 year old woolly mammoths found are so fresh that they could be eaten by humans and animals (Prothero, 2004, p. 9).

In the spring of 2007 Yuri Khudi, a Nenet reindeer herder, discovered a baby *Mammuthus primigenius* exposed on a sandbar of the Yuribey River in Siberia. The 40,000 year old fossil mammoth was named Lyuba after Khudi's wife.

Lyuba, nicknamed the Ice Baby, represents one of the best preserved fossils found to date in the permafrost of Siberia. Lyuba was one month old when she drowned in soft sediments of silt and clay. Paleontologist Dan Fisher has determined that more than just the frozen permafrost was essential in Lyuba's excellent preservation (Miller, 2009, p. 41).

Lactobacilli colonized her tissues after death. The lactic acid produced by these bacteria acted as a preservative, pickling Lyuba's tissues. As new sediments accumulated above

Lyuba the layers in which she was entombed turned to permafrost. Eventually, floodwaters eroded the permafrost that encased Lyuba and transported her downstream. The lactic acid that originally helped to preserve the tissues now protected the fossil from present day scavengers as it lay exposed on the sandbar. Thus, for Lyuba preservation by both chemical means and freezing were critical factors in the fossilization process.

Encapsulation

Encapsulation occurs when minerals form around an organism. Late Miocene gypsum deposits in the Alba area in Piedmont, Northern Italy contain dragonflies (mostly larvae) entombed in single clear gypsum crystals. The insects became trapped in the gypsum as the evaporate deposit formed. The entombed insects, like most inclusions in amber, are thinly lined hollow spaces (Schluter, Kohring, & Gregor, 2003, p. 374).

Organisms may also become entombed in microcrystalline material. The Devonian aged Rhine Chert near the Aberdeenshire villiage of Rhynie in Scotland represents an ecosystem near a sinter terrace. The area was periodically flooded with silica rich solution from hot springs and geysers (Selden & Nudds, 2004, p. 52 and Kenrick & Davis, 2004, p. 24). Organisms were permeated with silica and entombed before any cellular decay could occur. Insects have also been found encapsulated in Miocene aged onyx from Arizona (Grimaldi & Engel, 2005, pp. 49-50).

Desiccation

Desiccation occurs when an animal dies in a very dry environment. Water is drawn out of the tissues slowing the process of decay. The drying process may also reduce the probability of scavenging. This process is similar to human mummification. In fact, some authors use the term mummification to describe this process. Ground sloths preserved through desiccation have been found in South America (Garcia & Miller, 1998, p. 15). Moa remains preserved through desiccation have been found in New Zealand (Walker & Ward, 2002, p. 13). Many of these specimens have been found in dry caves. Naturally mummified insects have been found in association with Pleistocene mammals frozen in tundra permafrost. Insects preserved through desiccation have also been found in Egyptian mummies and the stomachs of Eocene aged bats (Martinez-Delclos & Jarzembowski, 2000).

When is a preserved remain considered a fossil? Walker and Ward (2002) do not consider organisms preserved through desiccation to be fossils because they are only temporarily spared from decay (p. 13). Earlier we discussed that some limit the definition of fossils to the remains of a species that have become naturally extinct. Many definitions have time limits, which are set somewhat arbitrarily. Gimaldi and Engel (2005) suggest that evidence of any organism which has been naturally preserved for several thousand years or more constitutes a fossil (p.62). Under this definition desiccation may be considered a fossilization process.

As discussed earlier, desiccation also seems to play a role in the preservation of some organisms encapsulated in amber. Tree resin provides a micro-environment in which mummification can take place. As the resin matures into amber the mummified remains continue to be protected from decay.

Unaltered Remains

Mammuthus primigenius molar

The concept of unaltered remains can refer to multiple modes of preservation. Freezing, encapsulation in amber (tree resin), desiccation, and chemical preservation, such as entombment in petroleum containing sediment, are examples explored in our museum. The term unaltered remains is a bit misleading. It does not mean that the organism is unchanged. Nucleic acids (DNA and RNA), proteins, pigments, and soft tissues may be degraded. Tissues, if present, have usually lost water. However, organic matter that is present has not changed into another substance. Freezing, mummification (desiccation), oil seeps, and amber can preserve both soft and hard tissues. Sometimes the soft tissues decay, but the hard parts remain unaltered. Teeth, bones, and shells may be preserved in this way. Forty thousand year old bones encased in the asphalt of Rancho La Brea in Los Angeles retain their original composition. Mollusk shells of the Pleistocene are known that retain their mother-of-pearl aragonite layer. Even some Cretaceous aged mollusks are found with their aragonite intact (Prothero, 2004, p. 9).

The mammoth tooth pictured on this page retains original enamel, dentine, and bone. Unaltered teeth, bones, and shells may also exhibit some signs of permineralization with calcium phosphate, pyrite or other minerals.

Chemical Fossils

Crude Oil

Chemical fossils are chemicals found in rocks that provide an organic signature for ancient life. Molecular fossils and isotope ratios represent two types of chemical fossils.

Molecular fossils are often referred to as biomarkers or biosignatures and represent products of cellular biosynthesis that are incorporated into sediments and eventually into rock. Many of these chemicals become altered in known ways and can be stable for billions of years.

Nucleic acids (DNA & RNA), proteins, and carbohydrates do not survive long in the geologic environment. The majority of biomarkers are hydrocarbons derived from membrane lipids, which under certain conditions can be stable over billions of years. Molecules derived from pigments, such as chlorophyll, can also act as biomarkers. In 1936 Alfred Teibs recognized that vanadyl porphyrin was a molecular fossil of chlorophyll. Teibs discovery helped support a biologic origin for petroleum (Knoll, summons, Waldbauer, & Zumberge, pp. 134-135).

The fossil fuels petroleum (crude oil), coal, and natural gas are the result of biologic activity and contain chemical fossils. Major coal deposits represent plant material that grew primarily during the Carboniferous period. Crude oil and natural gas formed primarily from prehistoric algae and zooplankton that were deposited on the ocean floor under anoxic conditions. Natural gas can also form from fossil plant material. During sedimentary rock formation the remains of algae and zooplankton are converted into a mixture of organic hydrocarbons known as kerogen. Over geologic time heat and pressure can convert kerogen into oil or natural gas. The majority of oil deposits are Mesozoic or Cenozoic in age.

It is interesting to contemplate the origins of fossil fuel energy. Ancient plants and algae converted solar energy into the chemical bond energy of carbohydrates. Converted energy from the Sun was then passed through the food chains of these prehistoric ecosystems. Organic chemicals from these organisms were incorporated into sediments and eventually rock. So, the fossil fuels we humans have come to depend upon represent ancient sunshine stored within the Earth's crust.

Fossil fuels currently provide more than 85% of all the energy consumed in the United States. Crude oil supplies 40% of our energy needs and accounts for 99% of the fuel for cars and trucks. Coal is the major source of energy for generating electricity worldwide (U.S. Department of Energy). We depend upon fossil fuel energy for our agriculture. Some studies estimate that without fossil fuels the United States could only sustain two thirds of its current population (Pfeiffer, D.A., 2006, p. 41). Our dependence upon these nonrenewable resources should be a wake up call to invest in and develop alternative energy sources. At present, it is clear that coal, oil and natural gas, chemical fossils in the form of fossil fuels, are the lifeblood of America's economy.

For paleontologists and geobiologists the information provided by molecular fossils varies greatly. Some molecular fossils can help to determine what organisms were present, while others can indicate what biosynthetic pathways were in operation; still others provide information regarding the depositional environment (Knoll, Summons, Waldbauer, and Zumberge, 2007, p. 135).

Isotope ratios represent another type of chemical fossil and result from metabolic processes that preferentially utilize one form of an isotope over another (Cowen, R. p. 16). Molecular fossils represent biomolecules or their derivatives that were once part of a living organism. In this way, molecular fossils are similar in concept to conventional body fossils. Isotope ratios are not preserved bits of an organism, rather they result from activities during life and in this way are analogous to trace fossils.

The first chemical evidence of photosynthesis, in the form of C-12 to C-13 ratios, can be found in Archean rock of 3.8 Ga from Isua, Greenland (Kenrick & Davis, 2004, pp 10-11; Johnson & Stucky, 1995, p 22). The process of photosynthesis preferentially utilizes C-12 over C-13 when removing CO_2 from the air to synthesize carbohydrates, creating ratios of these carbon isotopes that differ from normal background ratios. Thus, carbon compounds processed by photosynthetic organisms are enriched with C-12 (Rich & Fenton, 1996, p 91). The enrichment of C-12 in rocks is a test for the presence of life. Carbon isotope ratios consistent with presence of cyanobacteria are widespread in rock dated at 3.5 Ga (Johnson & Stucky, 1995, p. 22). One problem with the evidence above is the fact that chemical pathways in non-photosynthetic autotrophs and nonautotrophs can produce C-12 enrichment (Blankenship, Sadekar, & Raymond, 2007, pp 22-23).

Molecular fossils have been a key to understanding the evolution of primary producers in Earth's oceans. Microfossils and molecular fossils have helped to establish that Earth's oceans have experienced two major shifts in the composition of primary producers. Initially, cyanobacteria along with other photosynthetic bacteria were the primary producers during the Proterozoic eon. The first shift occurred during the early Paleozoic era when eukaryotic green algae joined cyanobacteria in being major primary producers. The second shift would occur during the Mesozoic era when dinoflagellates and coccolithofores would be joined by diatoms in the Jurassic. Diatoms, dinoflagellates, and coccolithophores would assume their dominant role as the base of many modern marine ecosystems by Cretaceous times. (Knoll, Summons, Waldbauer, and Zumberge, 2007, p. 155).

Trace Fossils

Trilobite Tracks

Fossils do not always represent a part of the organism. Trace fossils record the activities of organisms. Tracks, burrows, eggshells, nests, tooth marks, gastroliths (gizzard stones), and coprolites (fossil feces) are examples of trace fossils or ichnofossils. Trace fossils represent activities that occurred while the animal was alive. Thus, trace fossils can provide clues to diet and behavior. Ichnology (ichn "trace or track, -ology "the science of") is the study of trace fossils. Trace fossils represent multiple modes of preservation and are considered here as a category for convenience.

Tracks represent animals going about their day-to-day activities and may provide insight into the dynamic behavior of extinct organisms. Tracks are formed in situ, that is they are found in the place were the organism made them. The rocks containing tracks provide clues to the environment in which the imprints were made.

Footprints making up a track can reveal the pace (steps), stride (the distance between consecutive steps made by the same foot), and trackway width or straddle. Steps and stride can reveal anatomical features, such as, number of toes or whether the organism was a biped or quadruped. Straddle can be used to measure the extent to which the animal sprawls or walks erect (Lockley & Meyer, 2000, pp3-4). Pace angulation can (angle between step line segments) help to determine the body width of an animal (Prothero, 1998, p. 413).

Mathematical relationships between stride length and hip height (measured by footprint length) of some vertebrates can help us to establish relative velocity.

$$\text{Velocity (V) m/s} = (0.25g^{0.5})(SL^{1.67})(h^{-1.17})$$

In 1976 R. McNeil Alexander, a British zoologist, proposed the most widely used formula for estimating the speed of animals from their trackways where g is the acceleration due to gravity, SL the stride length, and h hip height (footprint length x 4). Relative stride length is a ratio of stride length divided by hip height. A ratio of greater than 2.0 for most terrestrial tetrapods marks the point at which an animal changes from walking to trotting. A ratio of greater than 2.9 marks the point at which an animal is running (Prothero, 1998, p. 412). Paleontologists have also attempted to use tracks as an indicator of metabolism; was the organism endothermic ("warm blooded") or ectothermic ("cold blooded")? Trackways can provide clues to the social nature of the animal, was it gregarious (social), and did the animal travel in herds? Trace fossils can be combined to provide multiple lines of evidence. Dinosaur nesting sites and trackways support the idea that some herbivorous dinosaurs were gregarious. This same evidence may also point to migrating behavior. Tracks of multiple organisms (footprint assemblage or ichnocoenosis) combined with an analysis of rock formation can help to build an ecological picture of ancient environments. Trackways at Davenport Ranch in Texas record a herd of 23 sauropods apparently being tracked by 5 theropod dinosaurs (Prothero, 1998, p. 414)

The system for naming footprints (ichnotaxonomy) runs somewhat parallel to the taxonomy for body fossils. A track made by *Tyrannosaurus* would be given the formal name *Tyrannosauripus*. Footprint names end in -pus ("a foot"), -podus ("foot"), or -ichnus ("track or trace") (Borror, 1988, pp 47, 78, & 82). Determining who made tracks is a prime objective of tracking. Looking at body fossils from the same time period to compare foot anatomy to the track is the key. For example, Pterosaur feet (body fossils) are an excellent match for *Pteraichnus* (footprints).

In very rare instances the tracks are found with the maker. A specimen of *Kouphichnium walchi* (a horseshoe crab), found in the Solnhofen strata, is preserved at the end of its track (Boucot, 1990, p. 314). Bivalves with escape trails have been found in siderite nodules from Mazon Creek (Nudds & Selden, 2008, p. 123).

Patterns of tracks through time, known as palichnostratigraphy corresponds well with biostratigraphic zones (time intervals defined by fossils). The longevity of the average dinosaur species, defined by appearance and disappearance from the geologic record, is 7 to 8 million years. Ichnologists find essentially the same span of time, 7 to 8 million years for changes in the footprint record (Lockley & Meyer, 2000, p. 10).

The Reverend William Buckland (1784-1856), an English geologist/paleontologist, was the first scientist to recognize the true nature of fossilized feces. Buckland coined the term coprolite or "dung-stone" to describe these trace fossils. The oldest known vertebrate coprolites come from Silurian deposits and represent fish feces (Eschberger, 2000, Coprolite Article). Coprolites attributed to arthropods are known from the Ordovician (Taylor, Taylor & Krings, 2009, p. 1007).

Crocodile Coprolite

Dr. Karen Chin, curator of paleontology at the University of Colorado Museum in Boulder identifies several criteria for coprolite identification. Coprolites often have high calcium phosphate content (Williams, 2008, p. 47). Phosphate helps mineralize feces. This may help to explain why there is a preservation bias for carnivore coprolites over those of herbivores. Carnivore's coprolites contain their own source of phosphate in the bones and teeth of the consumed prey. Herbivorous coprolites contain the cellulose and lignin of plants and require an outside source of phosphate, usually in the form of marine sediments. The need for phosphate does not apply to all coprolite preservation unlike vertebrates, the coprolites of terrestrial arthropods, have been found in the Rhynie chert, permineralized coal balls and fossil wood (Taylor, Taylor, & Krings, 2009, pp. 1007-1011).

Shape can also be an important clue. Sharks and many primitive fish produce spiral-shaped coprolites. The shape of coprolites from larger organisms such as dinosaurs may be affected by splatting issues, trampling, weathering and dung consumers. Shape can also be misleading.

Salmon Creek in the state of Washington produces beautifully shaped siderite (iron carbonate) deposits, which resemble feces. These structures are sold as turtle or even ground sloth Miocene-aged coprolites. There is some debate about the nature of these deposits. Adolf Seilacher of Yale University suggests they may represent intestinal casts or cololites (Seilacher, 2001, p. 1). George Mustoe of Western Washington University points out that there is a real lack of evidence as to an animal origin for these deposits. First, they lack calcium phosphate. Second, they lack internal clues such as pollen, scales, seeds, bones or plant fibers. Third, the deposit in which they are found lacks fossils. These siderite deposits most likely do not represent coprolites. The real value in coprolites is what they contain.

Salmon Creek Pseudocoprolite?

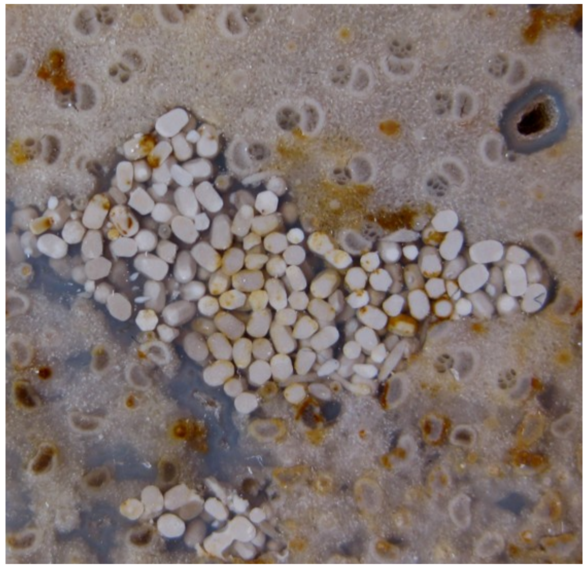
Coprolite research is carried out primarily with thin sections. Herbivorous dinosaur coprolites studied by Chin have established a relationship between plant eating dinosaurs and tunneling insects related to dung beetles (Eschberger, 2000, Coprolite Article). Dr. Chin has also established that *T-rex* pulverized its victims from studying microscopic bone fragments found in a coprolite. Indian and Swedish scientists have found grass phytoliths in dinosaur coprolites. This helps to establish that dinosaurs and grasses coexisted (Williams, 2008, p. 51). Coprolites of arthropods recovered from rock material, such as the Rhynie chert, are composed of spores as well as plant and fungal remains (Taylor, Taylor & Krings, 2009, p. 1007). These Devonian-aged arthropods were probably detritus feeders. Coprolites provide important insight into diet, physiology as well as the geologic and geographic distribution of plants and animals.

Insect ichnofossils (trace fossils) can be helpful in determining what types of insects were present at a particular time and provide information about the nature and persistence of past plant-insect associations.

Evidence for herbivory in insects appears in the Carboniferous. Like vertebrates, the first insects were carnivores and detritivores. Herbivory requires hosting cellulose-digesting bacteria through a symbiotic relationship within the gut. The oldest examples of marginal and surface feeding are on Carboniferous seed fern leaves of *Neuropteris* and *Glosspteris* (Grimaldi & Engel, 2005, p. 52). It is estimated that only 4% of the leaves in Carboniferous deposits exhibit damage from feeding. Herbivores do not make a significant impact on plant life until the Permian (Kenrick & Davis, 2004, pp. 166-167).

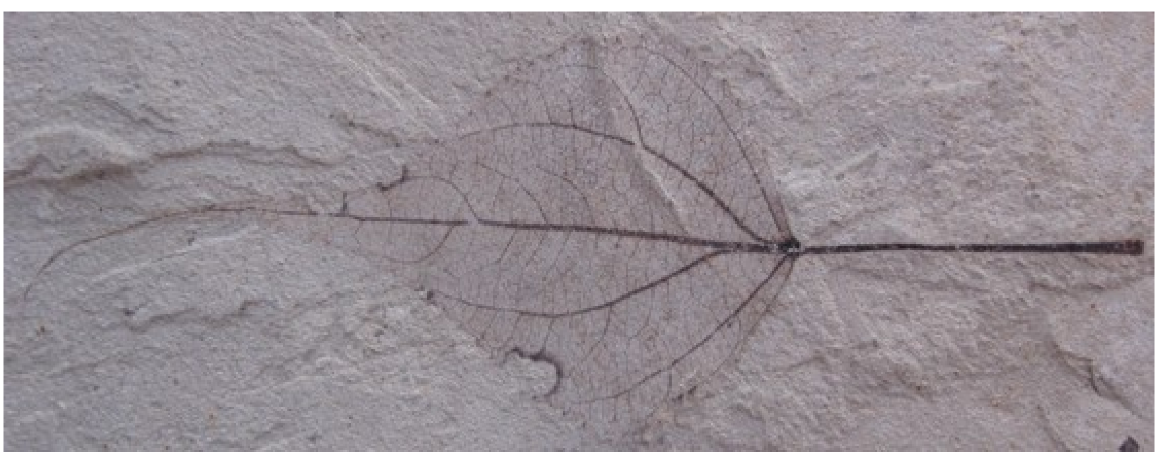
Galls are excessive growths on stems, leaves, cones, and flowers caused by insect feeding or egg-laying. The earliest fossil galls are found on the petioles of *Psaronius* tree ferns of the Late Carboniferous. Insect gall fossil diversity and abundance takes off with the advent of flowering plant evolution in the Cretaceous (Grimaldi & Engel, 2005, p. 53).

Insects produce tunnels in wood known as borings or galleries. Some insects eat the cambial layer while others eat fungus that grows within the galleries; still others eat the wood itself. The oldest borings and galleries in wood, attributed to mites, are known from the Carboniferous. The first definitive beetle borings are from the Triassic. There are some borings in permineralized Triassic-aged wood from Arizona that are attributed to termites or bees; however, they may be beetle borings (Grimaldi & Engel, 2005, p. 54 & 55).



Permineralized Termite Coprolites in *Palmoxylon*

Leaf mines are meandering tunnels produced by the feeding larvae of some beetle, fly, and sawfly species. The first definitive leaf mines first appear in the leaves of Triassic conifers and pteridosperms. Interestingly, the abundance and diversity of fossil leaf mines coincides with the radiation of flowering plants (Angiosperms) during the Cretaceous. Leaf mines have been used to establish the persistence of insect and plant associations. For example, the larvae of certain moth families have been eating the leaves of *Quercus* (oak) and *Populus* (poplars) for 20 million years and hispine beetles have been eating the leaves of *Heliconia* for 70 million years (Grimaldi & Engel, 2005, p. 52).



Carbonized Poplar Leaf Exhibiting Marginal Feeding

Caddisfly larvae live in lakes, ponds, and rivers. Many build distinctive protective cases from bits of sand, shells and vegetation. Fossil caddisfly cases can often be identified to the family or even genus level. The oldest larval caddisfly cases (Trichoptera) are found in the Jurassic (Grimaldi & Engel, 2005, p. 51).

Celliforma is a fossil bee nest (in the form of subterranean excavations) that is first found in Late Cretaceous deposits. *Celliforma* is found from the Cretaceous to the Pliocene (Grimaldi & Engel, 2005, p. 51). Termite borings appear in the Cretaceous and represent the oldest undisputed fossil nest for social insects (Grimaldi & Engel, 2005, p. 54). *Coprinisphaera* is the fossil burrow of a scarabaerine dung beetle, which makes its first apperance during the Paleocene. *Coprinisphaera* lived from the Paleocene to the Pleistocene and had a wide geographic range being found in South America, Antarctica, Africa and Asia. *Coprinisphaera* coincide with the evolution of the first ecosystems to have abundant mammalian herbivores. Evidence for the first scarab tunnels are found in the coprolites of herbivorous dinosaurs from the Late Cretaceous of Montana (Grimaldi & Engel, 2005, p. 50).

Trace fossils can also help to establish evolutionary trends. Deep burrows in marine sediments first appear in the fossil record during the late Precambrian and indicate the presence of soft-bodied coelomates (Prothero, 1998, p. 227). The earliest evidence for herbivory in insects appears in the Carboniferous. Specimens of *Neuropteris* and *Glossopteris* seed fern leaves have been found that show signs of marginal and surface feeding. Definitive leaf mines, which are produced only by insects with complete metamorphosis, first appear in the Triassic. The first undisputed bee nests and termite borings appear in Cretaceous deposits adding evidence to body fossils that social insects had evolved by this time (Grimaldi & Engel, 2005, pp 50-55).

Trace fossils representing marine environments are used to determine animal behavior as well as establishing the type of sedimentary environment in which the rock formed. In fact, marine trace fossils are often classified into behavioral categories; does the trace fossil represent resting, dwelling, crawling, grazing or some other type of feeding behavior (see Prothero, 1998, p 406 for more details)? Perhaps the most practical way to classify marine trace fossils is by their associations with a particular sedimentary environment or ichnofacies. In marine environments different ichnofacies are associated with different water depths, physical energies (wave & current conditions), or even type of substrate. Ichnofacies have become a standard tool for sedimentary geologists as well as paleontologists (Prothero, 1998, p. 406).

Ophiomorpha (Shrimp-Like Organism) Burrow

Ichnofossils are important tools that help geologists interpret sedimentary environments, paleobathymetry, and provide clues to the diagenetic history of some sedimentary rocks. For the paleontologist and fossil collector ichnofossils represent fossilized behavior and provide important clues to paleoecology and paleoenvironments.

Pseudofossils


Manganese Dendrites on Sandstone

Pseudofossils are objects that do not have a biologic origin, but may be mistaken as a fossil. Mineral and rock patterns of inorganic origin formed purely by natural geological processes may be mistaken for fossils. Dendrites deposited by mineral rich water percolating through rock layers may have the appearance of a well preserved plant. Concretions may look like eggs or other objects that have a biologic origin (Ivanov, Hrdlickova, & Gregorova, 2001, p. 10).

Conclusion

Fossils reveal that different organisms have lived at different times. Different modes of preservation are a testament to the fact that environments have changed through time. The different life forms represented by the fossil record appear in an irreversible and thus, knowable order. The history of life on Earth is a true revelation from the fossil record that throws light on extinction, evolution and the continued creation of life.

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