How to Make a Fossil: Part 2 – Dinosaur Mummies and Other Soft Tissue

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ABSTRACT

There are many misconceptions about fossils, including that fossils only represent bones and shells of extinct animals. Yet, scientists have long known that under certain conditions soft tissues (i.e., non-bone parts) of extinct vertebrates may be preserved. These conditions require that scavenging and bacterial decay did not occur because of freezing, mummification, and embalming. Minerals can also replace soft tissue thus producing a replica. Chemical and microbial causes are involved in making these replicas, sometimes in multiple-step processes. Soft tissue fossils chiefly include skin, internal organs, muscles, vessels, and blood cells. Most examples of dinosaur "skin" are impressions rather than the actual skin. The processes in replicating dinosaur skin are illustrated using the famous Sternberg dinosaur "mummy." The basic conditions require drying of the carcass, relatively rapid burial, and deposition of minerals on the skin by bacteria before it has decayed away. These minerals duplicate the coarser features of the skin, including scales, wrinkles and folds. In contrast, flexible dinosaur tissue preservation may have involved encapsulation by minerals, as well as chemical alteration of the cell membrane.

INTRODUCTION

Misconceptions about the fossilization process occur even among professional paleontologists (Yeoman 2006). Fossils are usually hard parts (bones and shells) or traces (footprints, burrows) of extinct animals. Previously, I discussed the events that typically occur in the fossilization of bone (Carpenter 2007). But vertebrates, even extinct forms, are more than a collection of bones. Their bodies are encased in skin, which protects the muscles and internal organs from drying out and which provides a barrier to disease microbes. Movement is made possible by muscles connecting bones across joints. Food is digested and metabolized to give energy to the muscles and internal organs. All of these activities are made possible because the skeleton provides a framework for the organs. However, the non-bone parts of the body, called the soft tissue, are easily decomposed by bacteria or may be consumed by scavengers or predators. Therefore, such tissue is rare in the fossil record. Under unusual conditions, however, even these tissues can be preserved for millions of years. The methods for this include freezing, drying (mummification) or embalming (e.g., amber), all of which stop oxidation and bacterial

activity. Besides preserving the actual soft tissue, minerals can also replicate tissue in extremely fine detail (down to the cellular level). The understanding of how these replicas or pseudomorphs of tissue formed is still in its infancy, but experimental work indicates that mineral deposition by bacteria is crucial in most cases. Some examples of various preserved soft parts are given in Table 1.

Figure 1. Extinct Steppe Bison, Bison priscus, *found frozen in Alaska. As with most frozen carcasses, this specimen shows signs of pre-burial decay. On display at the National Museum of Natural History, Washington DC.*

The classic cases of frozen soft tissue are those of mammoths and other Pleistocene mammals in Siberia and northern Alaska (Fig. 1). The most detailed study of the Siberian mammoths was by Tolmachoff (1929) and the most detailed study of a frozen bison was by Guthrie (1990). Although Guthrie admitted to eating a part of the neck muscle in a stew, eating of the frozen mammoths by contemporary humans is an urban myth (although, dogs and wolves will eat the carcasses). Interestingly, this myth occurs in both Russia (where mammoth meat was allegedly served in St. Petersburg) and the United States (where it was allegedly served at the Explorers Club in New York City).

Tolmachoff noted that one of the best ways to find a mammoth is by a distinctive decay smell, even when no trace of the carcass appears at the surface. All specimens of mammoths found to date show some decay. None are flash-frozen as alleged by Velikovsky (1956) and by some Creationists (e.g., Brown 1995). The levels of decay show that there was some passage of time between death and burial by sediments; and none of the specimens occur frozen in ice, although ice wedges are occasionally found in the surrounding sediments.

Studies of DNA from the various frozen mammal carcasses (e.g., Greenwood and others 1999) show some breakdown so that no complete DNA strands remain. However, by overlapping segments on paper, it is possible to reconstruct the DNA sequence for many of these extinct mammals. These results show that the mammoth is more closely related to the Asian elephant than to the African elephant (Greenwood and others 1999).

Mummification involves removal of water from the tissues through dehydration. The best examples of mummification are the 13,000-year-old partial carcasses of ground sloths from Mylodon Cave, Ultima Esperanza, Chile. The specimens retain fur attached to pieces of skin (Hoss and others 1996). As might be expected, the specimens are ideal for DNA studies. However, as with the frozen mammoth carcasses, no complete DNA strands are present, but enough segments have been extracted to reconstruct part of the sequence on paper. The results showed that the DNA was most similar to that of the two-toed sloth (*Choloepus*) from South America.

The breakdown of the DNA in both the frozen and dehydrated carcasses is a natural process that begins after death, and for the mammoths, clearly shows a passage of time between death and freezing of the carcass. Enzymes called nucleases, which separate the nucleic acids of the DNA to their smaller components or mononucleotides (Hofreiter and others 2001), cause the breakdown. Other processes, such as oxidation (a chemical reaction involving oxygen) and hydrolysis (a chemical reaction involving water), break down DNA at a much slower rate. The breakdown in both the frozen and mummified carcasses is the reason why no complete DNA strains in these fossils are known. This makes it unlikely that we shall ever see living dinosaurs in zoos, only in the movies.

Embalming in amber is another method of preserving the original soft tissue. Amber is well known for containing insects within, but small vertebrates have also been found in amber from the Upper Eocene of the Dominican Republic, including a green anole lizard (Rieppel 1980) and a frog (Poinar and Cannatella 1987). A gecko was found in Baltic amber from the Lower Eocene of Russia (Bauer and others 2005). Coniferous tree resins are ideal for preserving tissue because resin chemicals, such as terpenes (which include turpentine), penetrate into the body and dehydrate it, thus stopping decay. As the resin ages, air and sunlight cause a hardening of the resin due to loss of lighter chemicals and the formation of long, three-dimensional chains of organic molecules. All of these organic molecules are identical (therefore are called monomers) and are attached to each other in a linear chain, called a polymer. The process that connects monomers into long chains called polymers is polymerization. Polymerization continues while the resin is buried changing it to a homogenous, chemically inert solid, which is amber. Plastic is a polymer, so amber can be thought of as nature's plastic. All vertebrates found in amber were too small to get themselves out of the sticky resin (so do not expect to find a *T. rex* in amber).

Figure 2. Carcass of the wooly rhinoceros, Coelodonta antiquitatis *found embalmed in tar and salt near Starunia, Poland. Cast on display at the Natural History Museum, London.*

Another embalmed specimen is that of a wooly rhinoceros found in Poland (Fig. 2). The specimen was in sediments impregnated with salt and tar that were thought to have been the preserving agents. There is doubt about this mode of preservation because soft tissue is not found in other tar pits, such as La Brea in California. A more likely solution is that the specimen was initially frozen, like the mammoths of Siberia, but was freeze-dried (meaning the water was removed during the frozen state, much like an old piece of meat in the back of the freezer; see also Fig. 1). Then near the end of the last glaciation (about 11,500 years ago), with the ground defrosted, oil seeped upwards into the encasing sediments and embalmed the carcass. A new study of the specimen is needed to test this two-

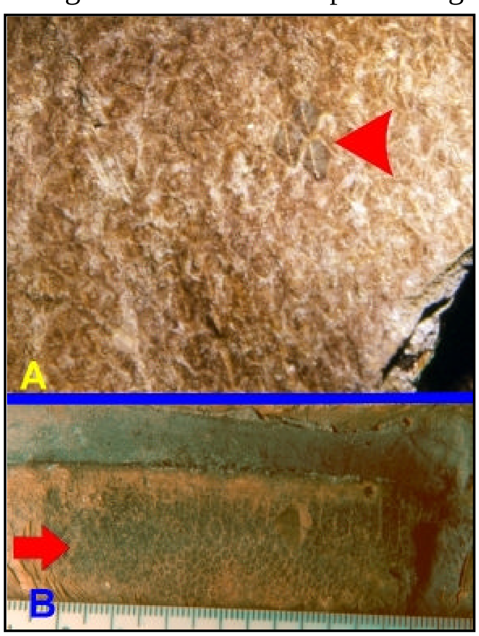

Figure 3. Soft tissue fossilization from marine environments include Tylosaurus *skin (A) and leg scales of* Hesperornis *(B). Arrow in A shows the scale pattern enhanced. Note the midline ridge of the diamond-shaped scales, and their alternating pattern. Specimens on display at the University of Kansas Museum of Natural History, Lawrence.*

stepped hypothesis. Soft tissue can also be replicated by minerals, either as three-dimensional structures (such as the muscles in fish, Schultze 1989) or as localized deposits (such as the skin halos surround ichthyosaurs, Martill 1987).

Figure 4. Soft tissue of a "feathered dinosaur" Sinosauropteryx prima *showing the feather-like structures on the body and intestine (arrow). This specimen shows fossilization of feathers from a biofilm coat on the outside of the body, as well as phosphate mineralization from intestinal bacteria. NIGP 127586.*

Paradoxically, the very bacteria responsible for decay of soft tissue are also responsible for its fossilization as shown by experimental work (Briggs and Kear 1994; Briggs 2003) and by fossilized bacteria associated with the replicas (Martill and Wilby 1994; Briggs 2003). Some of the most important bacteria, as well as other microbes, in fossilization form vast, very thin colonies that are encased in a protective gel-like secretion (Briggs 2003). These colonies, called biofilms, appear as a scum or slime layer on coffee left in a mug for several days (for more information, see: http://en.wikipedia.org/wiki/Biofilm). They form in wet environments and are especially prevalent on lake and ocean bottoms. In the bottom of the Western Interior Seaway, they were responsible for the preservation of mosasaur skin (Fig. 3A; Williston 1898b) and the leg scales of a *Hesperornis* (Fig. 3B; Williston 1898a). In lake bottoms, biofilms played a key role in the fossilization of feathers (Davis and Briggs 1995), including the feathered dinosaurs of China (Fig. 4), as well as the fur surrounding the Eocene mammals of Messel, Germany (Fig. 5).

A bird carcass sinking to the bottom of a lake is soon enshrouded by a biofilm. Because biofilms have an interesting property in their ability to concentrate ions, such as iron or calcium, a thin mineral veneer (often iron carbonate, or siderite) a few microns thick is formed. Once the feather tissue decays, the veneer remains as a replica of the feather surface. Because biofilms coat the outside of the bird, decay renders the inside of the body

Figure 5. Bat showing the silhouette of the body as an indecipherable carbon smudge due to the decay of the internal organs beneath a biofilm veil. DMNH 2728

*Figure 6. Positive impression of dinosaur skin (*Saurolophus angustifrons*). Note the large scales interspersed among the more abundant smaller ones. On display in Tokyo by the Hayashibara Museum of Natural History.*

into an indecipherable dark smudge of organic carbon lso seen in the bat of Fig. 5). This same basic principle apparently occurred at Messel, Germany, where a halo of fur is seen around the carcasses of small mammals (Wuttke 1988b). In some instances, however, the fur did not completely decay thus preserving its protein. Bacteria and biofilms, as we shall see in the next section, also play a key role in the replication of dinosaur skin (Fig. 6).

THE DINOSAUR MUMMY

How dinosaur "skin" gets fossilized has been a mystery ever since S.H. Beckles described a patch impression of sauropod skin in 1852. Since then, numerous examples of skin impressions have been found for almost every type of dinosaur. The most common and best examples are of hadrosaurs and include the nearly complete "mummy" discovered by

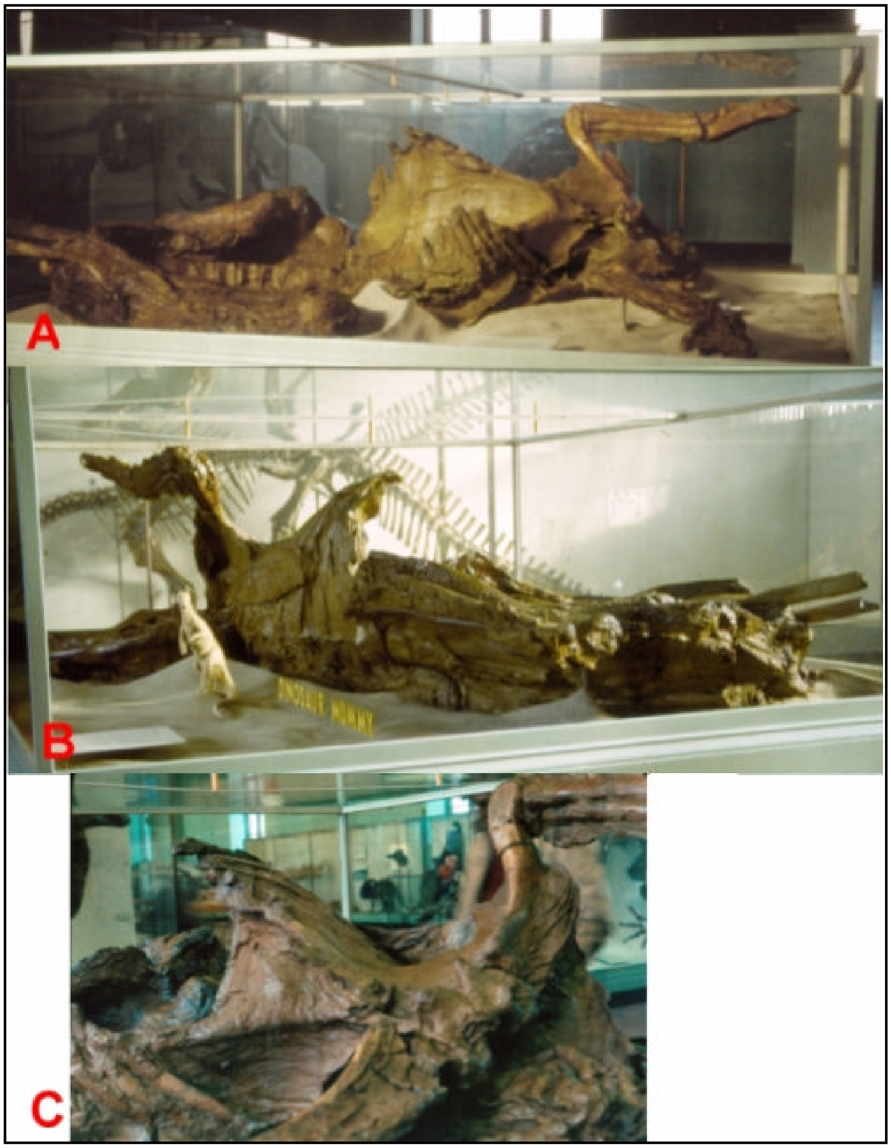

*Figure 7. The Sternberg hadrosaur "mummy" (*Edmontosaurus annectens*). Mineral deposits that were probably formed by an enveloping biofilm have replaced the original skin. A, belly view, B, back view, C, chest view from front. Note the preservation of skin folds suggesting mummification prior to burial. On display at the American Museum of Natural History.*

G.M. Sternberg in 1908. That specimen (AMNH 5060), currently on display at the American Museum of Natural History (AMNH), remains one of the best examples of a dinosaur "mummy" known (Fig. 7). In describing the specimen, Henry Osborn (1912) suggested that the sun dehydrated the carcass prior to rapid burial by a sudden flood:

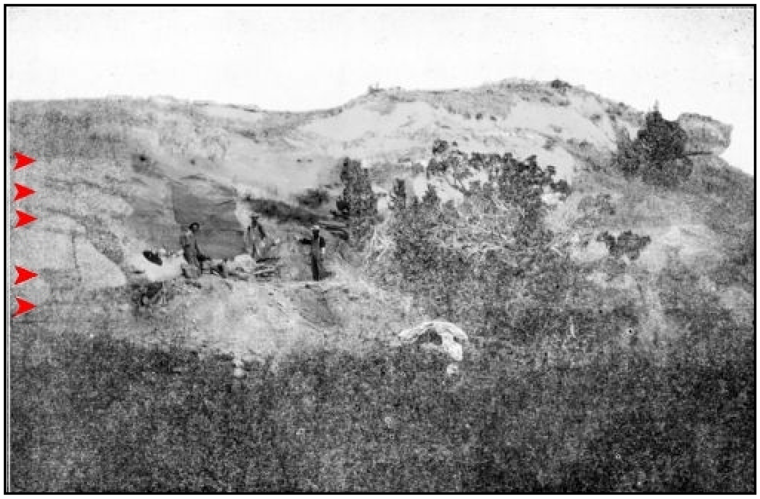

Figure 8. The only known photograph of the Sternberg hadrosaur "mummy" site at the time of its excavation. Arrows denote the different sandstone layers. Note that the lowermost bedding surface is horizontal, whereas the overlying ones are angled. This shows that the carcass was buried on a point bar. Photograph from Sternberg 1909 for an article actually published in 1908.

> *"...the epidermis is shrunken around the limbs, tightly drawn along the bony surfaces, and contracted like a great curtain below the chest area. This condition of the epidermis suggests the following theory of the deposition and preservation of this wonderful specimen, namely: that after dying a natural death the animal was not attacked or preyed upon by its enemies [i.e., was not scavenged], and the body lay exposed to the sun entirely undisturbed for a long time, perhaps upon a broad sand flat of a stream in the low-water stage; the muscles and viscera thus became completely dehydrated, or desiccated by the action of the sun, the epidermis shrank around the limbs, was tightly drawn down along all the bony surfaces, and became hardened and leathery; on the abdominal surfaces the epidermis was certainly drawn within the body cavity, while it was thrown into creases and folds along the sides of the body owing to the shrinkage of the tissues within. At the termination of a possible low-water season during which these processes of desiccation took place, the 'mummy' may have been caught in a sudden flood, carried down the stream, and rapidly buried in a bed of fine river sand intermingled with sufficient elements of clay to take a perfect cast or mold of all the epidermal markings before any of the epidermal tissues had time to soften under the solvent action of the water. In this way the markings were indicated with absolute distinctness, ... although of course there is no trace either of the epidermis itself, which has entirely disappeared, or of the pigmentation or coloring, if such existed."* (Osborn 1912, p. 7, 9).

As Osborn noted, the sediments made a mold or impression of the skin before it was softened by water. Therefore, the "mummy" is actually an impression of the skin rather than the preservation of actual material. This dessication-hypothesis has been extended to explain other examples of "mummified" dinosaur skin (e.g., Carpenter 1987).

BURIAL ENVIRONMENT

Rapid burial of the carcass before complete decay occurs is the key to the preservation of the "mummy," as was suggested by Osborn (1911, 1912). Therefore, we need to know something about the sediments, or matrix, encasing the specimen because these provide some of the most fundamental clues to how the "mummy" was preserved. Unfortunately, little of the encasing rock remains on the specimen today, but fortunately Sternberg (1908, 1909) and

Osborn (1912) gave that information. Sternberg reports removing over 10 feet of sandstone overburden to get at the specimen, and this is substantiated by a photograph of the quarry (Fig. 8). Osborn reports that the specimen was encased in "fine river sand intermingled with ... clay..." Such a sand-clay mixture is common in sandstones of the Lance Formation (Connor 1992) where we know the specimen was collected (Osborn, 1912; Sternberg 1908). The Lance Formation consists of sediments deposited in fresh water environments, including river channel, point bar, crevasse splay, levee, and flood plain. The thick sandstones in the Lance, such as at the "mummy" site, were sands deposited either in river channels, point bars or portions of the levee adjacent to the channel.

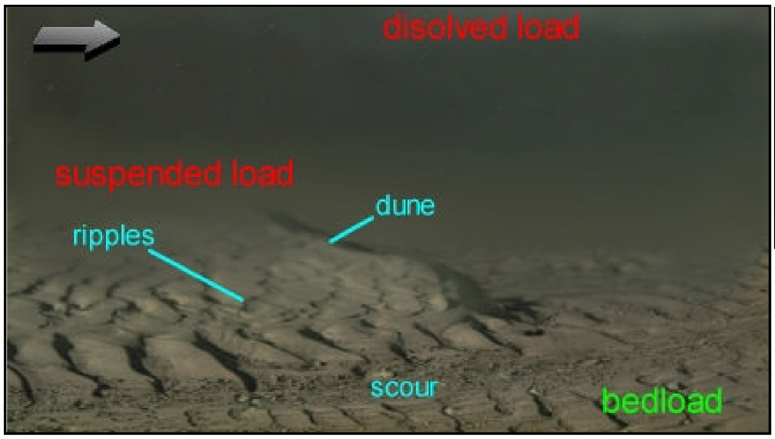

Figure 9. Rivers carry sediment dissolved, suspended, and pushed along the bottom as bed load. Which of these three methods the sedimentary particle is carried by is dependent on its size and the water velocity.

How can we decide which type of deposit was at the "mummy" site? First, we need some background in the sedimentology of rivers. Rivers move sediment in three major ways: As bed load pushed along the bottom of the river channel, as suspended, fine-grained sediments (mostly as silts and clays which give flood waters the brown, murky look), and dissolved minerals in the water (Fig. 9). As we shall see, all three transport groups play a role in the formation of the "mummy". Rivers get their sediments through erosion of weathered rock or by erosion of previously deposited sediments (Fig. 10). Erosion of weathered rock is an important source for dissolved load, whereas erosion of previously deposited sediments is an important source for bed load and suspended sediments. Dissolved load is easily transported, even by the slowest flowing rivers, but suspended, and especially bed load, require faster moving water. Consequently, transportation of these sediments is highest during floods. Why is that so? Water velocity has long been known (e.g., Wolman and Leopold 1957) to be dependent on the gradient of the river channel (steeper in the mountains than in the plains) and/or on the volume of water flow (volume is more important to our story, so we will concentrate on it).

The more water put into a channel, especially runoff during heavy rain, the faster it will flow (the increased mass pushes water ahead of it). Faster flowing water has more energy and can support larger particles in suspension. Furthermore, faster flowing water has more erosive energy and removes sediment from the riverbanks, especially from the outer bank at a river bend (Fig. 10B, 11). It is during floods, then, that rivers carry most of their sediment load. For example, the Rio Beni River, Bolivia, carries 82%-90% of its annual 212 million tons of sediment during the rainy reason (January-March) when the river is prone to repeated floods (Gautier and others 2007). Floods do not last forever and eventually wane, causing a gradual

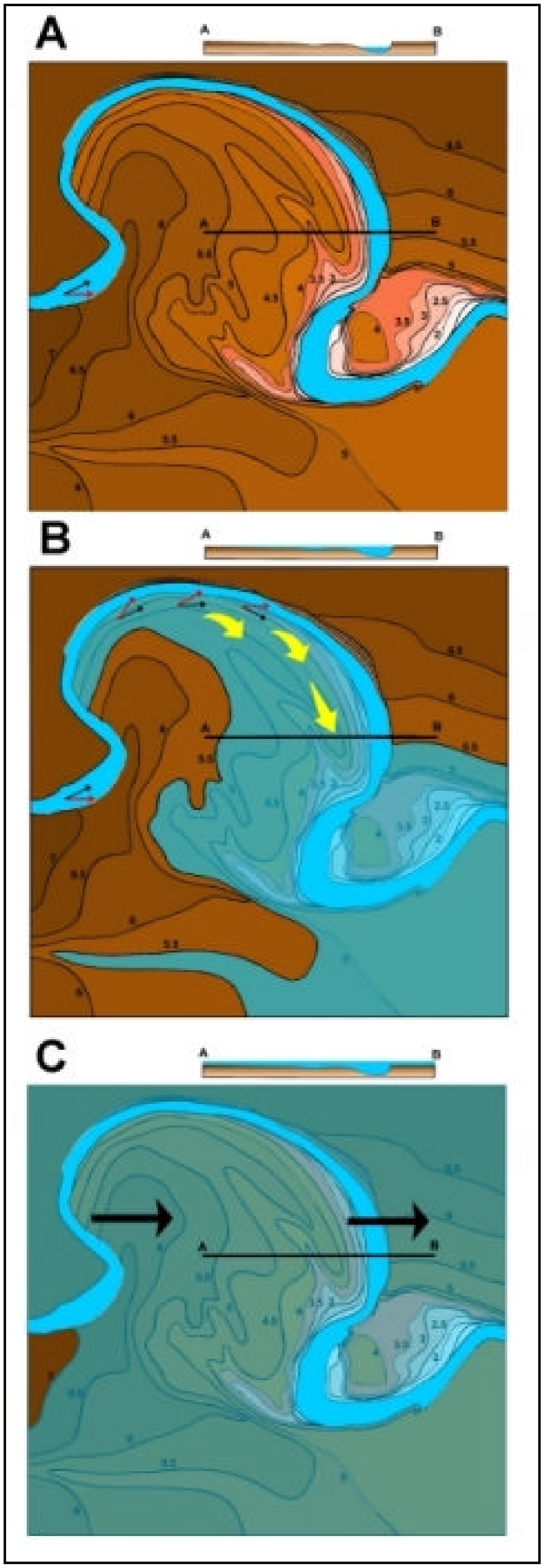

Figure 10. Schematic diagrams showing the effects of floods. A, preflood flow, the river meanders around a point bar. B, river during early stages of flood. Small red vector arrows show that the energy of the water flow is towards the outer bank where it erodes the sediments; the small black vector arrows shows the effective direction the water flows because it is deflected by the bank. The undercut bank collapses dumping large amounts of sediment into the river, which then pushes it downstream (yellow arrows). Note that the downstream side of the point bar is lower than the upstream side allowing water to spread over a wider area. Water velocity drops, thus depositing sediment. Growth of the point bar, then, is on the downstream side. C, at maximum flood, the river is no longer confined to the channel and the river flows over the banks and point bar. The energy of the flood is no longer concentrated at the riverbank.

drop in both water velocity and volume. With this decrease of potential transportation energy, the sediment begins to settle, beginning with the heavier (usually larger) particles.

The amount of sediment deposited of course depends on the amount transported by the flood. Most deposits are only a few feet thick, but on occasion can exceed tens of feet deep within or near the channel. These sediments are deposited in a matter of hours or few days, and this is what is meant by “rapid burial” of a bone or carcass. It is not surprising then that the best dinosaur “mummies” are found in sandstone several feet thick. But this burial was not just by passive deposition of sediments in a waning flood. Simple experimental work shows that a carcass (or bone) can be an obstacle in flowing water (Fig. 12). Two simultaneous processes can bury this obstacle: Scouring of sand from around the object and by migrating underwater sand dunes (more on this below). These dual processes can entomb an obstacle in less than a day, and often in a matter of hours. The piling of water on the upstream side of the obstacle causes the water velocity to increase as it squeezes around the sides because

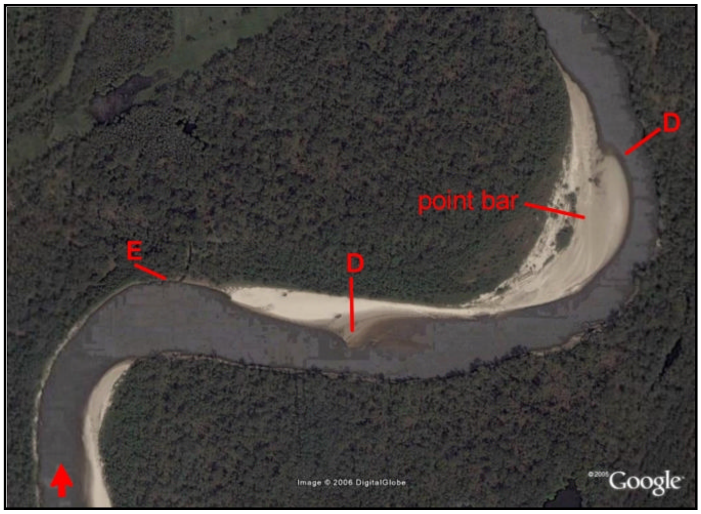

Figure 11. Satellite image of a river meander showing where erosion (E) of the bank occurs, downstream deposition (D), and location of the point bar. Heavy arrow shows direction of stream flow. Pearl River, Mississippi. Image

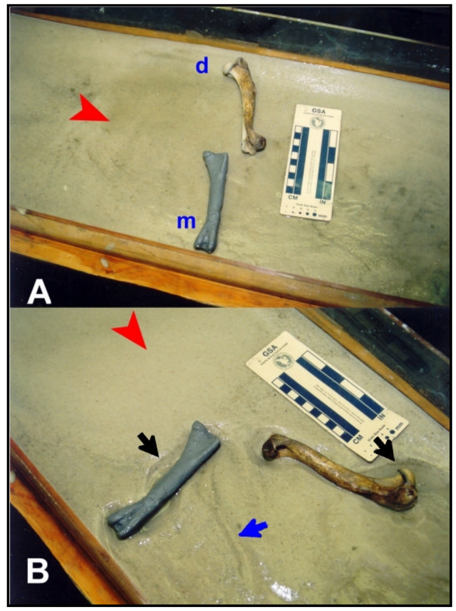

Figure 12. Simple experiment showing the effects of flowing water on bone. A, pre-flow position of bones (d – dog humerus; m – cast of juvenile Maiasaura *femur). B, after flow dispersal note erosion on the upstream side (black arrows) because the bone acts as a barrier, and deposition on the downstream side (blue arrow) in the flow shadow. Red darts indicate stream flow direction. Sediment used is fine sand.*

it is constrained by the water trapped between the object and the riverbank. This fast flowing water scours the sand from around the upstream portion and sides of the object (Fig. 12B). Eventually, so much of the sand is removed that the obstacle slides into the depression. Meanwhile, the sand that was scoured is pushed by water to the lee-side, or "shadow"-side, of the object where water velocity is considerably less. Here, the sand is deposited as a downstream tapering wedge (Fig. 12B). Thus, a carcass or bone can actually set up the conditions for its own burial (Fig. 13). When river velocity is high, added sediment hastens burial.

So what was the environment of deposition at the "mummy" site? The photograph of the quarry shows that the specimen lay at the boundary between the lowermost inclined sandstone beds in a stack of at least five beds (Fig. 8). These sandstones lack the features typically seen in sand deposited at the bottom of the river channel. In a river channel, sediment too heavy to be suspended in the flowing water is

Figure 13. Cow carcass on a point bar, northwestern Colorado. The carcass sets up the conditions for its own burial by impeding water flow. Note how the carcass has trapped vegetation on the upstream side, and provided a shadow for deposition on the downstream side.

Figure 14. Satellite image showing bed load of sand being moved as dunes downstream during a flood on the Platte River Nebraska. Water pushes sand from the downstream side up the dune surface until it cascades down the steeper upstream side. This process can bury a carcass within a few hours. Arrow denotes river flow direction.

pushed along the river bottom as bed load (Fig. 9). This bed load moves downstream in “waves” or underwater dunes (Figs. 9, 14), which produces cross-bedding seen in sandstone. The height of these dunes is largely dependent on river depth and sediment supply. Downstream movement occurs because sediment is scoured from the upstream side and deposited on the downstream side of the dune. As a result, the tops of the dunes are frequently truncated or eroded flat. Truncation is especially prevalent as water level begins to drop. This causes a constriction of water flow and an increase in the erosive power of the water. In contrast, on a point bar (the sediments deposited on the inside of a river bend), sediment is deposited on the downstream portions so that truncation or other erosional features are less common (Fig. 11). Furthermore, because each flood event buries the point bar surface with new sediment, the original surfaces can be seen in cross section as angled beds called lateral accretions. Because each layer shifts the riverbed away from the point bar, the upper, thinner parts of the point bar overlay lower, thicker parts deposited during the proceeding flood. Thus, a vertical section generally shows successively thinner sand layers. The angled, thinning beds seen in the Sternberg photograph (Fig. 8) tells us that the mummy was buried in a point bar. But where did all of the sand to bury the carcass come from?

One of the most important sources for large quantities of sediment during a flood is from the collapse of the riverbank into the channel caused by river erosion of fine-grained flood plain deposits (e.g., Gautier et al. 2007). Bank collapse occurs mostly at the outer bends of rivers where water flow undercuts the steep bank (Fig. 10). A collapsing bank does not remain intact as a single block of sediment, but rather fragments into smaller blocks and loose soil. This mound of debris impedes water flow so it is immediately eroded by the constricted flow. Sandy soil erodes quickly thus adding to the volume of sediment being transported by the water as bed load. Clay-rich soil, however, tends to form clumps because water increases the cohesiveness of the clay particles. These clumps are pushed downstream as part of the bed load and are rounded into mud “pebbles.” They are deposited anytime or anywhere along the channel where water velocity drops enough that it cannot push the bed load along. Within the channel, winnowing of finer grain particles concentrates the mud pebbles, whereas on the lee side of a point bar, the mud pebbles may become suspended in sand. The undercutting of riverbanks and ultimate collapse increases in frequency as water flow (hence velocity) rises, but peaks before river flow spills onto the flood plain (Wolman and Leopold, 1957). The decrease in bank collapse once the flood flows onto the flood plain occurs because the water is so deep in the channel that it passes directly over the bends and the energy of the flowing water is no longer concentrated at the banks (Fig. 10C). The abundance of mudstone pebbles in the sandstones of the Lance Formation (Connor 1992) indicates that erosion, followed by bank collapse was a common occurrence. All of the evidence, then, indicates that the hadrosaur "mummy" was on the downstream side of a point bar that was building out into a channel. Burial was rapid (a few hours or at most a few days) by the mass influx of sediment dumped into the river by bank collapses upstream.

CAUSE OF DEATH

We cannot be certain what killed the hadrosaur, but several lines of evidence and analogy with modern events suggest that death was due to starvation during a prolonged drought. First, as Osborn (1912) noted, "*...the muscles and viscera had thus become completely dehydrated or desiccated by the sun, and that the epidermis, hardened and leathery, shrank around the limbs and was tightly drawn down along the bone surfaces... [T]he skin is tightly drawn in around the scapula and thrown up into ridges, precisely as we have observed it in existing lizards after exposure and desiccation by the action of the sun.*" The description is similar to that given by Hillman and Hillman (1977: 5) for carcasses seen in an African drought: "*The skin dried hard within a few days and could only be cut with a hacksaw. This was followed by crinkling and contraction, so that an increased prominence of the bones was noticeable in carcasses that had been dead for some time.*" Second, the hadrosaur carcass shows no signs of scavenging, which would be expected for three tons of hadrosaur meat lying around. This absence suggests unusual conditions, perhaps similar to those reported by Hillman and Hillman (1977) and Walker et al (1987) who report that during a drought the supply of carcasses may exceed the capacity of scavengers. Haynes (1991) has observed that elephant carcasses may be left untouched because drought has forced scavengers out of the area or that they preferentially scavenge certain taxa. Microbial scavenging or decomposition also stops during droughts because microbial metabolism requires water. Third, the hadrosaur carcass appears to have been rapidly buried in a point bar, suggesting that it had remained near water or at least a river channel at the time of death. Death in such a setting is common. Numerous studies report that drought mortality of large ungulates is due to starvation, not thirst (e.g., Conybeare and Haynes 1984, Hillman and Hillman 1977; Walker et al. 1987; Haynes 1991). Large ungulates must wallow in water during droughts to prevent death from overheating (Haynes 1991). This tie to water restricts the distance they may range for food and causes a depletion of vegetation near the waterhole or river channel from overgrazing and trampling. Cornfield (1973), Conybeare and Haynes (1984) and Haynes (1991) have mapped the distribution of elephant carcasses during droughts and they noted a strong correlation between carcass density and proximity to water sources; i.e., that the number of carcasses decreases with distance. The probability of these carcasses being preserved in the fossil record is high because of the higher rates of erosion due to the near absence of ground cover near the river channel at the end of the drought (Walker et al. 1987). It seems very probable that, at over three tons, hadrosaurs were also tied to water to prevent overheating during droughts.

BURIAL AND FOSSILIZATION

The increased erosion and accompanying bank collapse that would have occurred at the end of the drought would have provided the great volume of sediment necessary to bury the hadrosaur before the tissue softened and was scavenged or decayed. The enormous volume of water that most likely flowed down the river channel during the flood that followed the drought may have moved the carcass some. But its large multi-ton mass was probably not moved far, perhaps tens of feet, before coming to rest on the downstream side of the point bar where water velocity was less (Fig. 15, 16). There, waves of sediment would have rapidly buried the carcass within a few floods. Once buried, the carcass was in a more stable, wet environment. The carcass would have slowly re-hydrated from the outside in, and in the process would have reactivated microbial decay. It is not until the bacteria have been revitalized that the process of fossilization can begin. Remarkably, decay and mineralization of tissue go hand-in-hand because almost all bacteria can precipitate minerals in their surrounding environment (called authigenic mineralization) or within their cell walls (autolithification) (see Carpenter 2007). Both processes can occur on the same specimen depending on bacterial species, as well as the immediate microenvironment. The rate of mineralization is largely controlled by the amount of ions (an atom or molecule with either a negative or a positive charge) available for use in metabolism. For the revitalized bacteria, possibly forming a biofilm, a constant supply of ions was available from the ground water seeping through the point bar, as well as from the carcass.

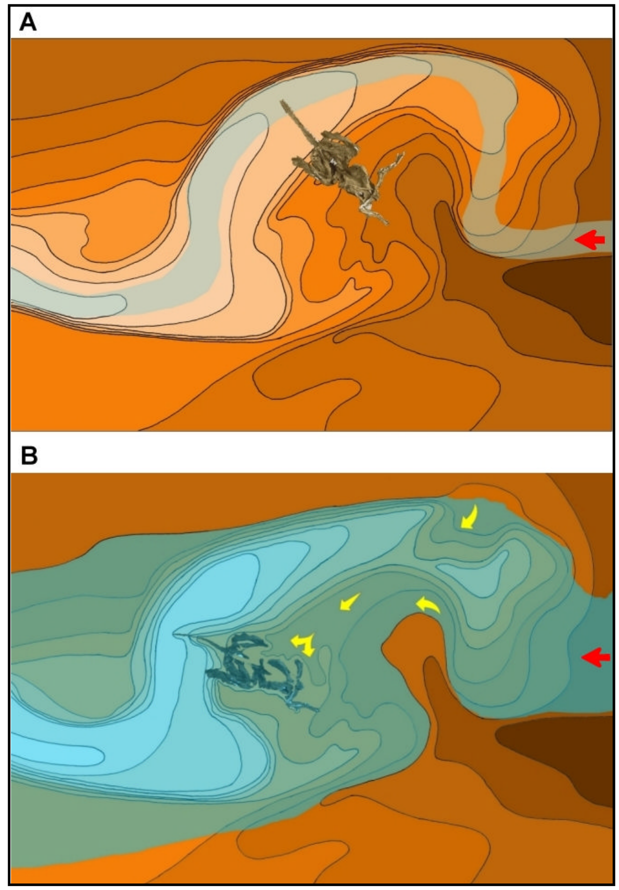

Figure 15. Reconstructing how the Sternberg dinosaur "mummy" was buried. A, the hadrosaur dies near or on a point bar during a drought. Death was probably due to starvation. B, when the drought finally breaks, the river flooded. Erosion was high due to the landscape being stripped of vegetation. The force of the water may have been enough to move the carcass on the downstream side of the point bar where water velocity was less. Burial began almost immediately from sediments (yellow arrows) originating from erosion of the banks at river bends. Red arrows show water flow direction.

Figure 16. Reconstruction of the Sternberg hadrosaur "mummy" between flood events. This restoration is based on my observations of the cow carcass in Figure 13.

As can be seen in Figure 7, the hadrosaur carcass retains most of its original shape. Such three-dimensionality is unusual and indicates that, as the tissue decayed, the surrounding sediments had to have been "frozen" in place. This was achieved by a halo of mineralization formed by bacteria on the surface of the skin (this same principle also forms concretions). Unfortunately we do not know what minerals were formed or how extensive the halo was because no record or samples were kept when the encasing rock was removed from the "mummy" during preparation. Calcium carbonate ($CaCO_3$) is typically the cement forming the concretions in the Lance Formation (Connor 1991), so it was probably present in some quantity in the halo as well. It is, in fact, the most common mineral precipitated by bacteria (Carpenter 2005), especially in the presence of decaying organic material (Berner, 1968). Another mineral that we do know was deposited on the skin surface was siderite, an iron carbonate mineral. This mineral gives the rust color to the "mummy" and exposed bones. In the only analysis of "mummified" hadrosaur skin, Wegweiser and others (2004) report the presence of pyrolusite, a manganese oxide mineral. They incorrectly assumed its precipitation due to the presence of marine water, rather than by bacteria (Myers and Nealson 1988). Many minerals can form spontaneously under certain conditions (inorganic mineralization), but bacteria can produce the same minerals (biomineralization) in a less restrictive setting and often in a much shorter time (e.g., Konhauser 1998).

The cementing of the sand encasing the "mummy" by bacterially produced minerals essentially formed a mold of the skin surface, thus preserving the body shape. Later, this mold was filled with sand, although how it did so is unknown. It is a cast in sand that we see on display. The position of the skeleton within the cast shows that the bones did not disarticulate in a pile at the bottom of the mold of the carcass once the soft tissue decayed. Because the skeleton remains in correct anatomical position relative to the outer shape of the body, early mineralization must have occurred to "lock" the bones in place. This mineralization was probably simultaneous with decay. The rate of this decay and mineralization was probably controlled by tissue type (e.g., bone, ligament, muscle, glandular tissue, etc.), which decompose at very different rates (Clark and others 1997). Furthermore, these events took place in an oxygen-free (i.e., anaerobic) environment at very slow rates. Most likely the ions used in early mineral formation by bacteria were those liberated from tissue (e.g., iron from blood, etc.). It is certainly possible that early mineralization of internal organs may have occurred, but this remains unknown without detailed analysis by x-ray and computerized tomography (CT) of the body.

OTHER DINOSAUR SOFT TISSUE

The early mineralization that occurred internally in the Sternberg hadrosaur mummy may have also occurred in a specimen of *Thescelosaurus* reported to have a fossilized "heart" (Fig. 17; Fisher and others, 2000). Despite some skepticism about the identity of the concretion in the chest as a fossilized heart (e.g., Dalton 2000; Rowe and others 2001), there is reason to believe the object is correctly identified (CT movies of the "heart" are available here: http://www.dinoheart.org/insideout/index.html). The heart may very well have acted as the nucleus for precipitation of minerals by bacteria. Possibly, the inner and outer surfaces of the heart were initially coated with siderite, an iron carbonate mineral, at the same time that the heart muscle was decaying. Later, this siderite may have altered to iron oxyhydroxide (goethite) as suggested by Rowe and others (2001). This possible mineral change highlights the caution needed in the chemical studies of fossils: What we see today may not necessarily have been the original mineral precipitated. Given the millions of years fossils remain underground at different physical and chemical environments, even slow processes that take thousands or millions of years can eventually alter the original fossilizing mineral. The apparent absence of other soft tissue concretions within the body cavity or absence of other fossilized soft tissue highlights the non-uniform conditions for bacteria within the carcass. This non-uniform condition for bacteria within the same specimen has been noted before (e.g., Davis and Briggs 1995, p. 784).

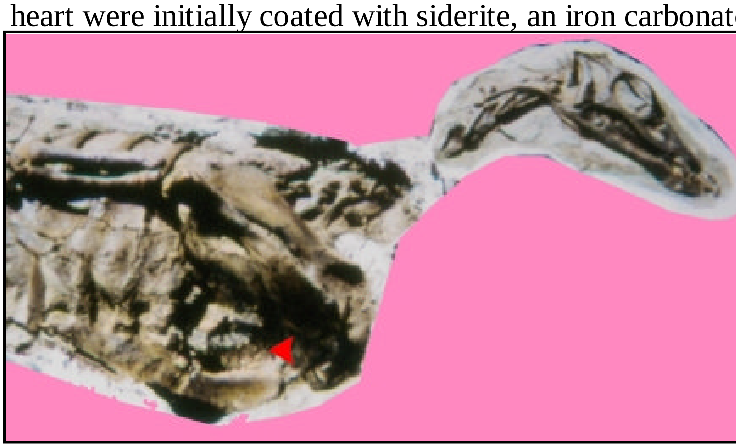

Figure 17. One of the more controversial examples of soft tissue preservation is the alleged heart (red arrow) in the chest region of this specimen of Thescelosaurus. *Currently on display at the North Carolina Museum of Natural Sciences*.

Fossilized blood cells have long been known (Seitz 1907), including from dinosaur bones (Moodie 1920), but have been in the news again recently because of the report of blood cells of *Tyrannosaurus rex* (Schweitzer and Horner 1999). How blood cells can be preserved for millions of years is an area of research that is only now being examined. Schweitzer and others (2007) have presented a hypothesis that can be experimentally tested. First, it is important to understand that not all cells break down or decompose at the same time. Even the same type of cells in different parts of the body can decompose at different rates depending on the local temperature. Furthermore, one major component of blood called heme (or haeme), the iron-bearing molecule which carries oxygen, can block enzymes that break down cells after death.

Their hypothesis involves a series of steps. First, heme is released from some of the blood cells that break down early. Some of this heme is further broken down, releasing its iron atoms, which can form siderite or other iron minerals. These minerals grow around segments of blood vessels, thus trapping blood serum and other blood cells. Some of the heme does not break down (although it would if not encapsulated by minerals), but remains in the blood serum, where it prevents further destruction of the blood cells. The molecules of the blood vessels and cell membranes become more orderly arranged because of the presence of chemically reactive molecules, called radicals. These radicals cause polymerization of the vessels and cell membranes making them chemically stable. Although one form of polymerization transforms flexible resin into stiff amber, another form apparently allows blood vessels to remain pliable and cell membranes intact.

Figure 18. Coprolites, or fossilized feces, involve early mineralization by bacteria in order to be preserved. Carnivore coprolites are most common because of the abundant supply of phosphate from the bones. Temporary display at the National Science Museum of Japan

Coprolites or fossilized feces are the product of digestion. Bone fragments of incompletely digested prey are common in such fossils, including a recently discovered specimen, which, based on its large size, is believed to have been from a tyrannosaurid (Fig. 18; Chin and others 2003). Remarkably, a microscopic study discovered short fragments of fossilized muscle from its prey. Considering how soft feces are, how did this specimen become preserved? Studies of carnivore coprolites show them to be high in phosphate, which most likely originates from the prey, especially the skeleton. Because feces are full of bacteria, the agents of fossilization were already in place. The bacteria readily combined the negative phosphate ions (PO_4^{3-}) and the positively charged calcium ions (Ca^{2+}), which may be present in the soil or groundwater (after burial by a flood), to form the mineral calcium phosphate ($Ca_3(PO_4)_2$). This mineral is easy to form and is relatively stable. Consequently, it is a common mineral in soft tissue fossilization (e.g., Martill 1988; Schultze 1989; Briggs and others 1997; Sagemann and others 1999).

CONCLUSIONS

Fossilized soft tissue, whether frozen, mummified, embalmed, or replicated in minerals, is common in the geological record. Frozen, mummified and embalmed soft tissue is dependent on halting microbial decay. Such fossils retain much of the organic material in its original state, thus leaving little need for speculation about these animals as living creatures. Soft tissue replicas, on the other hand, depend on decay bacteria to create the chemical environment needed to precipitate the fossilizing minerals. Such fossils seldom replicate the animal in its entirety. Rather, selected portions may be fossilized. These regions appear to be those to which bacteria have the easiest access shortly after death. Thus, the intestine may be fossilized because of the high numbers of bacteria naturally present in the gut, or the body or leaf may appear as a silhouette because biofilms may easily form across the body. The fossilization of plants shares some similarities with the fossilization of vertebrates, as well as some differences. This will be my topic in the next article.

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Table 1. Examples of Soft Tissue Fossils in Vertebrates (not an exhaustive list, heavy on dinosaurs).

Taxon	Soft Tissue Type	Reference
Fishes		
Atacamichthys greeni	muscle	Schultze 1989
Bobbichthys opercularis	muscle, intestine	Schultze 1989
Chongichthys sp.	gills	Schultze 1989
Domeykos profetaensis	muscle, blood vessels	Schultze 1989
Protoclupea chilensi	muscle, swim bladder	Schultze 1989
Varasichthys ariasi	muscle, swim bladder	Schultze 1989
Amphibians		
Chelotriton robustus	skin	Wuttke 1988a
Eleutherodactylus	carcass	Poinar & Cannatella 1987
Messelbatrachus tobieni	skin, eyeballs	Wuttke 1988a
tadpole	body outline	Toporski & others 2002
Reptiles		
Anolis sp.	carcass	Rieppel 1980
Anurognathus ammoni	skin	Frey & others 2003
Batrachognathus volans	skin	Unwin 2006
Germanodactylus sp.	skin	Frey & others 2003
?*Ichthyosaurus*	skin collagenous fibers	Lingham-Soliar 1999
Jeholopterus ningchengensis	skin	Unwin 2006
Pterodactylus kochi.	skin, throat pouch, "fur"	Frey & others 2003
Rhamphorhynchus muensteri	skin	Frey & others 2003
Scaphognathus crassirostris	skin, "fur"	Frey & others 2003
Sordes pilosus	skin, "fur"	Unwin 2006
Tapejara navigens	horny beak, skin	Frey & others 2003
Tapejara imperator	skin	Frey & others 2003
Tylosaurus proriger	skin	Williston 1898b
Yantarogekko balticus	carcass	Bauer & others 2005
Dinosaurs (non-avian)		
Anatotitan copei	skin	Lull & Wright 1942
Archaeopteryx lithographica	feather	Wellnhofer 2004
Beipiaosaurus inexpectus	integumentary structures ("feathers"),	Xu & others 1999a
Brachylophosaurus canadensis	blood vessels	Schweitzer & others 2007
Caudipteryx zou	integumentary structures ("feathers")	Qiang & others 1998
Centrosaurus apertus	skin	

Chasmosaurus belli	skin	Sternberg 1925
Corythosaurus casuarius	skin	Lull & Wright 1942
dinosaur	muscle, connective tissue, capillaries?	Chin & others 2003
dinosaur	yolk?	Carpenter 1999
Diplodocus sp.	skin ornamentation	Czerkas 1993
Edmontosaurus annectens	skin, horny beak, frill	Osborn 1912; Morris 1970; Horner 1984
Gryposaurus incurvimanus	frill	Lull & Wright 1942
Gryposaurus notabilis	skin	Lull & Wright 1942
Lambeosaurus lambei	skin	Lull & Wright 1942
Microraptor gui	feathers	Xu & others 2003
Parasaurolophus walkeri	skin	Lull & Wright 1942
Pelecanimimus polyodon	muscle, skin	Pérez-Moreno & others 1994
Protarchaeopteryx robusta	feathers	Qiang & others 1998
Psittacosaurus sp.	tail bristles, skin	Mayr & others 2002
Saurolophus angustirostris	skin	this paper
Scipionyx samniticus	muscle, intestine, liver, trachea	Dal Sasso & Signore 1998
Seismosaurus hallorum	protein	Gurley & others 1991
Shuvuuia desreti	integumentary structures ("feathers")	Schweitzer 2001
Sinornithosaurus millenii	integumentary structures ("feathers")	Xu & others 1999b
Sinosauropteryx prima	integumentary structures ("feathers"), liver	Chen & others 1998
theropod	intestine	Martill & others 2000
Thescelosaurus sp.	heart	Fisher & others 2000
titanosaur	skin	Chiappe & others 1998
Triceratops horridus	blood vessels, osteocytes	Schweitzer & others 2007
Tyrannosaurus rex	osteocytes, blood vessels, blood cells?	Schweitzer & others 2007
Birds		
Aegialornis szarskii	feathers, body outline	Peters 1988
birds	feathers, body outline	Peters 1988
Changchengornis hengdaoziensis	feathers, body outline	Qiang & others 1999
Eoalulavis hoyasi	feathers, body outline	Sanz & others 1996
Eoenantiornis buhleri	feathers, body outline	Hou & others 1999
Hesperornis regalis	skin	Williston 1898a
Mammals		
Bison priscus	carcass	Guthrie 1990

Hassianycteris messelensis	body outline	Habersetzer & others 1988
Macrocranion tupaiodon	fur	Wuttke 1988b
Mammut americanum	osteocytes, blood vessels, fibrous material	Schweitzer & others 2007
Mammuthus columbi	osteocytes	Schweitzer & others 2007
Masillamys beegeri	fur, body outline	Koenigswald & others 1988b
Mylodon darwinii	skin	Hoss & others 1996
Palaeochiropteryx tupaiodon	body outline	Habersetzer & others 1988
Pholidocercus hassiacus	fur, body outline	Koenigswald & others 1988a