Quo Vadis?

Paleoenvironmental and Diagenetic Constraints on Late Cretaceous Dinosaur Skin from Western North America

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ABSTRACT

Upper Cretaceous sandstone deposits of the Western Interior Seaway include fossil skin (integument) associated with the skeletal remains of some dinosaurs. Skin preserves as thin pyrolusite (manganese oxide) coatings on sandstone molds and casts. Pyrolusite is an authigenic marine mineral used to map paleoshorelines, thus the dinosaur fossil is inferred to have been deposited in a nearshore marine environment. Rapid burial of the dinosaur remains in marginal-marine settings in the presence of seawater resulted in the inhibition of scavenging activity by other creatures. Seawater mixed with freshwater promoted the natural embalming of the corpse. Thus, it effected changes in the microbial consortia responsible for decay leading to an increase in pH allowing for preferential precipitation of pyrolusite as a replacement for dinosaur integument.

INTRODUCTION

Fossilization of non-biomineralized anatomy of terrestrial animals and the circumstances under which it occurred are of great importance to our understanding of the processes that have led to exceptional preservation. Fossilization processes provide proxy evidence in the interpretation of paleoenvironments. Evidence is provided of environmental toxins, salts, cold, or dry conditions and other principal factors aside from burial rate and early diagenesis that lead to soft tissue preservation in vertebrate animals (e.g., Briggs et al., 1997; Babcock, 1998; Babcock et al., 2000; Chamberlain and Pearson, 2001).

Paleoenvironmental and diagenetic processes combined during the Late Maastrichtian in Wyoming's Lance Formation resulting in exceptional preservation of dinosaur skin. Instances of fossilized dinosaur skin impressions are usually explained by desiccation and subsequent burial in sediment (e.g., Cope, 1885; Osborn, 1912; Brown, 1916; Sternberg, 1925; Czerkas, 1997; Anderson et al., 1999; Murphy et al., 2002). This explanation requires rapid onset of desiccation because it assumes fossilization in an arid setting and presumes desiccation occurs mere hours to days after death to effectively restrict scavengers and microbes responsible for decay prior to burial. Whereas this argument could be compelling for corpses of relatively small mass, it is less convincing for corpses of large mass. New laboratory and field evidence associated with a corpse of large mass, namely a hadrosaur dinosaur found in the Lance Formation of Wyoming, suggests that paleoenvironmental settings combined with diagenetic processes to play key roles in the fossilization of soft tissues (Wegweiser et. al., 2003). Soft-part preservation occurred preferentially after the dinosaur was buried rapidly in sediments saturated with seawater in nearshore marine settings. Integument was replaced by beta-manganese dioxide (pyrolusite) mediated by activity of some marine-adapted microbial consortia occurring relatively soon after burial, and prior to extensive compaction and dewatering of the host sediment.

In this paper, we summarize results of field studies and laboratory analyses concerning the taphonomic history of dinosaur integument from a new occurrence in the Lance Formation from This Side of Hell Quarry located northwest of Pitchfork and Hell's Half Acre, Wyoming. Questions addressed in this paper are: 1) How was dinosaur integument preserved? 2) What was the depositional environment in the Lance Formation that preserved dinosaur integument? 3) How rapidly did fossilization of dinosaur integument occur? Preservation of hadrosaur integument in the Lance Formation in northwestern Wyoming by pyrolusite provides new and intriguing paleoenvironmental evidence for the exceptional preservation of non-biomineralized tissue.

MATERIAL AND LOCATION

Material described here is from the Lance Formation (Upper Cretaceous, Maastrichtian)

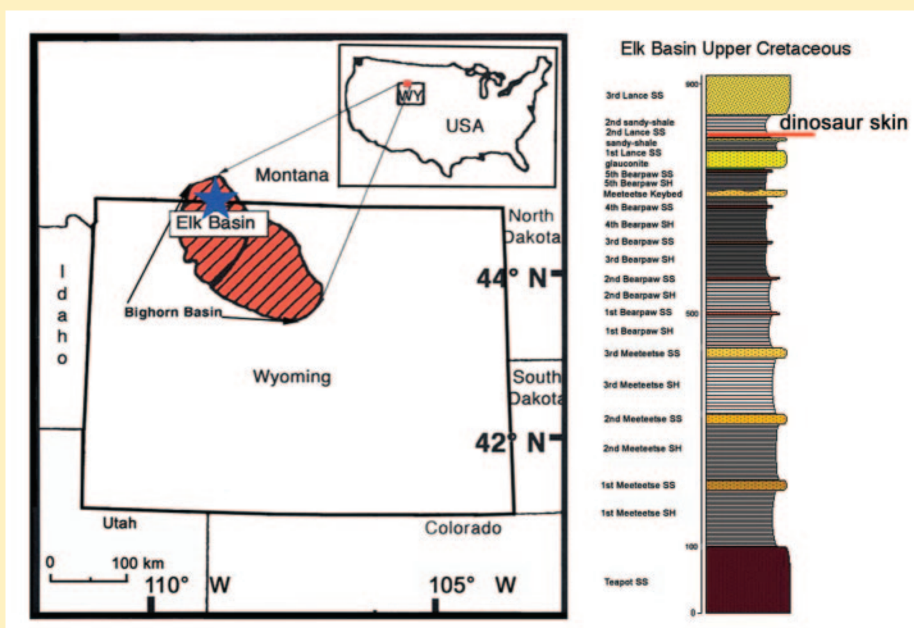

Figure 1: *Location of This Side of Hell Quarry in Elk Basin Anticline, Wyoming and Upper Cretaceous stratigraphy within Elk Basin.*

Figure 2: *An example of lambeosaurine (hadrosaur) bones in the process of excavation, located in the This Side of Hell Quarry, Wyoming.*

and is found in This Side of Hell Quarry, located in the Elk Basin Anticline in the northwestern Bighorn Basin in Park County, Wyoming (Figure 1). Dinosaur skin and skin impressions associated with lambeosaurine dinosaur bone (Figure 2) described herein occur in the second sandstone interval of the Lance Formation in Park County, Wyoming (Wegweiser, 2002). Specimens of dinosaur skin casts and molds (Figures 3) are reposited in the collections of the University of Wyoming.

SEM-EDX ANALYSIS

Samples of dinosaur skin, dinosaur skin impressions, associated bone, and associated matrix were examined using the JEOL JSM-820 scanning electron microscope with Oxford eXL energy dispersive X-ray analyzer of the Microscopic and Chemical Analysis Research Center (MARC) of The Ohio State University (Figure 4). The samples were left uncoated and subjected to an acceleration voltage of 10 keV. SEM-EDX analysis shows significant evidence of Mn on the dark portions of the skin impression, but effectively none on portions that lack this material. Bone material lacks any evidence of Mn, while the surrounding matrix contains only an isolated, small trace.

STRATIGRAPHY AND SEDIMENTOLOGY

The Lance Formation in Elk Basin Anticline, Wyoming, consists of coastal dune deposits and fluvial to marginal-marine deposits (Wegweiser, 2002). Fine-grained overbank deposits are interbedded with delta lobe deposits that were at times subaerially exposed. The Lance Formation in Elk Basin is dominated by pale orange, bentonitic, silty arenaceous sandstone interbedded with silty sandstone, sandstone, silty shale, and occasional beds of siderite containing trace fossils (such as inferred arthropod dwelling traces) and nodules exhibiting desiccation cracks. Lenticular and vertically stacked sandstone, shale, and siltstone bodies are interbedded with sheet-flood sandstones.

Bedding plane exposures of sheet sandstones, back-barrier deposits, coastal dune deposits, and lagoonal deposits, some with organic lags containing charcoal, iron-carbonate beds, and thin lenses of conglomerate are present near the This Side of Hell Quarry. In the quarry, strata range through beds of mudrock, silty mudrock, bentonitic muddy siltstone, and bentonitic silty fine-grained sandstone. Flaser bedding and very fine-grained clay drapes occur in the quarry. Flaser bedding is an indicator of fluctuating hydraulic conditions with transport and traction followed by periods of quiescence. Flasers are thus commonly considered to be indicators of tidal flat settings. Sandstone containing dinosaur skin impressions is fine-grained bentonitic litharenite containing abundant mica and volcanic fragments punctuated by micaceous flasers and almost white clay drapes. Micro-ripple marks occur in the quarry in the finer grained intervals. In general, the region contains stratigraphic units that imply deposition in a low topographic area, such as on a delta lobe consisting of sandy braidplain fluvial deposits interspersed with shallow intertidal bays that were occasionally subjected to volcanic ash-falls, channel abandonment, and regular marine incursions.

Fluvial deposits in the Lance Formation in Elk Basin consist of large-scale, wedge-shaped cross-trough bedded sands exhibiting intermittent very thin narrow conglomerate lenses and large-scale soft sediment deformation structures. These deposits interfinger with marginal-marine deposits characterized by thin, laminar fine-grained bentonitic sandstone beds exhibiting reactivation surfaces, mud drapes, and flaser bedding. Fine-grained overbank units are interbedded with these delta lobe braid-plain deposits.

Thin (1 to 2 mm) clay drapes and truncated lenses of light gray shale occur in direct associ-

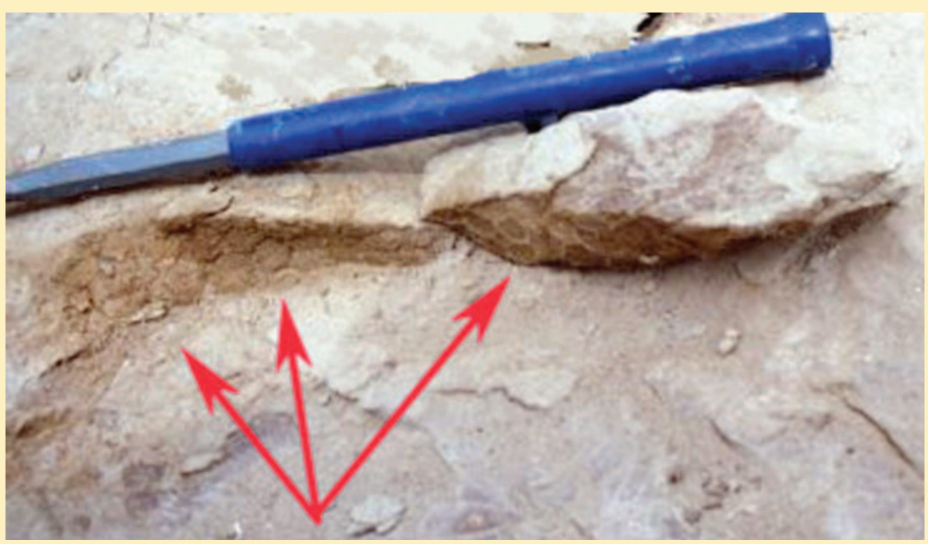

Figure 3: *Section of pyrolusite (ß-MnO2) preserved dinosaur skin in situ, in the Lance Formation. The location of the skin is from the scapular area of a lambeosaurine (hadrosaur) dinosaur whose ribs are shown in Figure 2.*

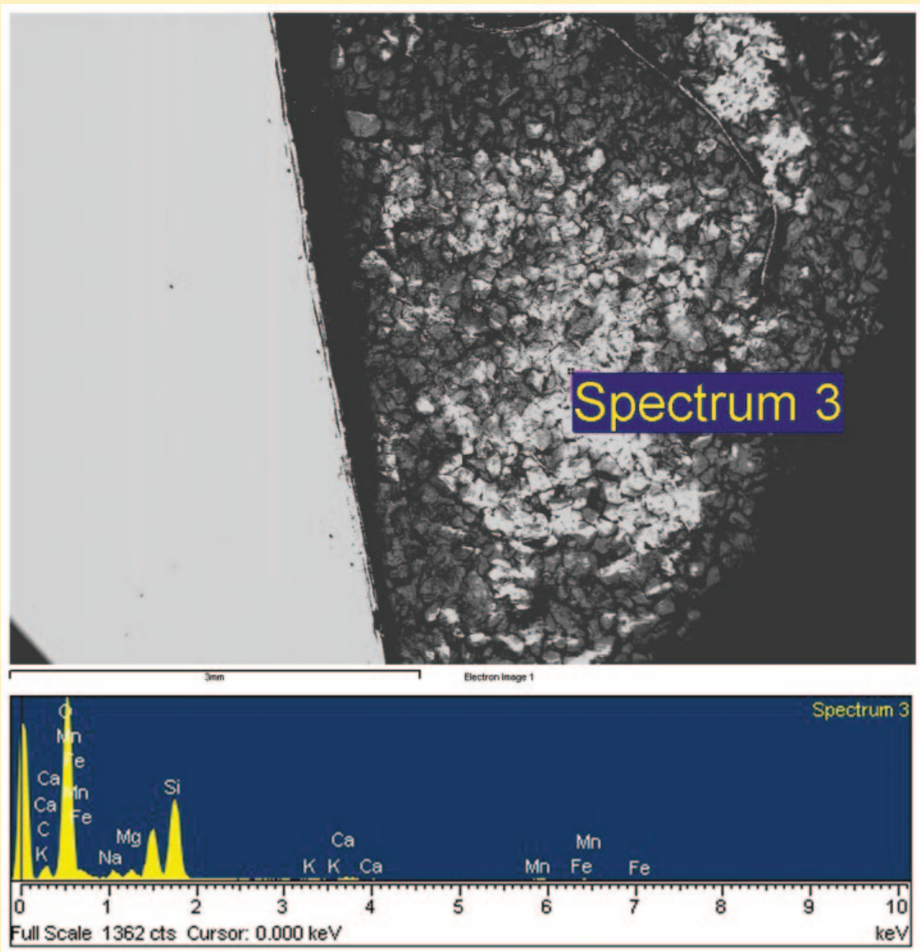

Figure 4: *Backscattered electron image of dinosaur skin with EDX analysis. The brighter regions of the image represent pyrolusite.*

ation with the dinosaur remains. Sheet-flood sandstone deposits underlying the quarry represent episodic deposition and proximal crevasse splay and interfluvial channel paleoenvironments, as well as coastal dune deposits in which organisms were deposited during recession of floodwaters. Finer grained deposits, with higher percentages of organic material, represent lagoons and back barrier bar environments, and contain fossils of vertebrate and invertebrate organisms. Sheet-flood sandstone deposits make up approximately 60 percent of the outcrop. Another 20 percent are composed of thinner, friable siltstone, silty sandstone, and fine-grained sandstone, some with desiccation features. Another 5 percent of the outcrop are composed of strata containing siderite and manganese nodules, and fossils replaced by siderite and manganese. Approximately 15 percent are finer grained interfluve deposits.

Elongate log-like and ribbon-like lenticular structures cemented by iron minerals are common in the sheet-flood sandstone units of the Lance Formation (Connor, 1992). Elongate log-like concretions with distorted bedding and ribbon-like lenticular structures are indicators of paleochannel and paleoshoreline positions (Connor, 1992), and are here interpreted as the upper parts of transverse bars found in non-braided, low sinuosity streams of lower delta plains.

The Lance Formation contains one of the best known and diverse Late Cretaceous vertebrate faunas from North America (Cope, 1872; Clemens, 1964, 1966, 1973; Estes, 1964; Breithaupt, 1982, 1985, 1997, 2001; Whitmore, 1985; Whitmore and Martin, 1985; Derstler, 1994; Archibald, 1996; Webb, 1998). Remains of cartilaginous and bony fishes, amphibians, champsosaurs, turtles, lizards, snakes, crocodilians, pterosaurs, dinosaurs, birds, and mammals are known from this unit. In addition, the Lance Formation is the source of the some of the best-known Cretaceous dinosaurs from North America (e.g., Triceratops, Thescelosaurus, Ankylosaurus, Edmontonia, Edmontosaurus, Pachycephalosaurus, Ornithomimus, Troodon, and Tyrannosaurus). Most vertebrate fossils from the Lance Formation are biomineralized bones and teeth. Reported instances of exceptional preservation of skin surrounding skeletal material are rare. These occurrences have been primarily reported as coming from hadrosaur dinosaurs (e.g., Sternberg, 1909; Osborn, 1912; Lull and Wright, 1942; Derstler, 1994; Czerkas, 1997).

TIMING AND STYLE OF INTEGUMENT PRESERVATION

Dinosaur integument (Figure 3) in the Lance Formation has been preserved through a combination of molds and casts in sandstone and thin (1 to 2 mm) voids filled by pyrolusite (MnO2). Skin impressions consist of small (1 to 2 mm) to large (5 to 10 mm) diameter polygonal, primarily hexagonal, non-overlapping scales. Grooves between the scales range in depth from 1 to 4 mm. Skin relief ranges from 2-5 mm in thickness. Skin fossils and impressions come from the area of the quarry surrounding the scapula of a lambeosaurine (hadrosaur) dinosaur. Pyrolusite preferentially covers moldic integument, and has not been observed to coat either adjacent bones or adjoining sediment. This indicates that the mineral is an early replacement product that affected only the integument.

Precipitation of pyrolusite occurs in environments that became more strongly alkaline through a combination of microbial decay (Kothny, 1983) and mixing of slightly acidic fresh water with more alkaline marine water. Fresh and marine water would be expected to mix in marginal-marine environments where streams enter the ocean. In order for manganese oxides to precipitate, Fe and Al ions must first be preferentially removed from the sediment, pH must be at least 8.0, and Eh must be at least 0.75 (Figure 5). Once formed, pyrolusite is virtually insoluble (Krauskopf, 1957). Manganese commonly precipitates in nearshore and marine paleoenvironments, recording such events as periods of transgression, delta-lobe abandonment, or storm breaching (Curtis and Coleman, 1986; Guilbert and Park, 1986; Blatt et al., 1991; Connor, 1992). Even small amounts of foreign ions (e.g., Fe, Al) present in soils from the weathering of minerals prevent the formation of pyrolusite (McKenzie, 1976).

Ion exchange of MnO2 is strongly controlled by Eh and pH (Guilbert and Park, 1986). Anions of manganese are commonly released and precipitate when river waters reach oxic marine conditions with higher pH values (generally exceeding 8.0). The isoelectric point for common colloidal particles of manganese is 4.0 to 4.5. As groundwater interacts with seawater within the phreatic zone, pyrolusite precipitates (Curtis and Coleman, 1986). Burial of organic remains under these conditions results in deposition of

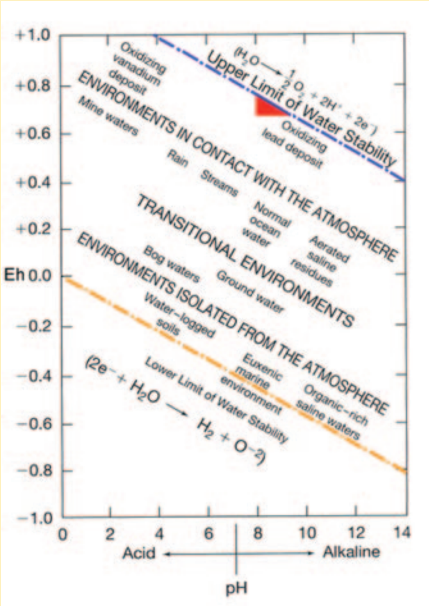

Figure 5: Phase equilibria diagram for depositional environments of iron oxide minerals. The red triangle indicates the window of environmental parameters necessary for the precipitation of pyrolusite to occur.

manganese into voids left by the biological material within the paleo-phreatic zone (Curtis and Coleman, 1986). Fe and Al are removed first by the movement of groundwater in different Eh and pH conditions (Figure 5), leaving Mn that will precipitate given the appropriate oxidizing conditions.

DISCUSSION

Preservation of soft tissue in the fossil record is a relatively rare occurrence globally, requiring a narrow set of paleoenvironmental and diagenetic conditions. Preservation of soft parts can begin to occur once the decomposing animal is buried below the taphonomically active zone. Occurrence of pyrolusite in the voids where the dinosaur skin decomposed after burial in the Lance Formation is indicative of extraordinary geochemical conditions in the sediment shortly after burial.

Pyrolusite (ß-MnO_2) replacement of the Lance Formation dinosaur skin from the This Side of Hell Quarry in Elk Basin, Wyoming resulted in 3-D preservation and suggests that precise oxidizing Eh and pH conditions existed in the sediments around the dinosaur during decomposition. Such conditions had to occur almost immediately after burial and were sustained during diagenesis and the fossilization process. A sustained pH of at least 8.0 and an Eh of at least 0.75 (Figure 5) was reached. These constrained conditions had to be sustained in pore waters surrounding the dinosaur carcass during diagenesis for a few weeks to at least a few months (see Lynn and Bonatti, 1965; Burns and Burns, 1979; Curtis and Coleman, 1986; Guilbert and Park, 1986; Blatt et al., 1991; Connor, 1992).

Replacement of integument by pyrolusite probably began within hours to days of burial and continued over a period of weeks to months (see Mackenzie, 1976). Integument is usually preserved three-dimensionally, meaning that skin diagenesis occurred before the occurrence of significant compaction and dewatering of surrounding sediment. Cobalt and nickel commonly occur in association with other manganese oxides and sometimes with pyrolusite formed in soils, but cobalt and nickel are not associated with material analyzed by SEM-EDX from the Lance Formation. These results suggest that replacement of dinosaur skin by pyrolusite did not likely occur in a soil horizon. Furthermore, the ratio of Mn/Fe is higher when acidic groundwater percolates through soils depositing much of the ferric oxide in the B soil horizon, thereby enriching the B-horizon in manganese (Krauskopf, 1957). A near lack of Fe in the EDX Lance Formation material suggests that replacement of the dinosaur skin took place below the B-paleosoil horizon. Replacement of skin probably occurred after the carcass was buried in a marginal-marine setting, possibly in the marine phreatic zone.

Paleosols in the Lance Formation would have formed regionally during emergent conditions within deltaic complexes, and being naturally rich in Fe, Al, Mn, and CO2, would have become leached as a consequence of net downward movement of acidic water during deposition, provided Eh and Ph conditions combined properly. Thus, the paleosols could have provided a source of Mn and eventual precipitation of pyrolusite.

SUMMARY AND IMPLICATIONS

The dinosaur in This Side of Hell Quarry in the Lance Formation fossilized in tightly constrained paleoenvironmental conditions resulting in replacement of integument by pyrolusite. Sediments provided an environment in which sustained contact between the marine-fluvial interface and dinosaur integument occurred during diagenesis and fossilization. This suggests dinosaur skin replacement occurred near to a source of marine water that mixed with fluvial water. Replacement of integument was relatively rapid, having to occur prior to total dissolution by decay and prior to the invasion of carrion eating meiofauna. The apparent preferential preservation of hadrosaur dinosaur skin and the association and partial articulation of the skeleton (Figure 2), suggests that this dinosaur lived close to the environment in which exceptional preservation of soft tissue could occur (Figure 6). It further suggests rapid and nearly complete burial that occurred in this instance in fine-grained sandstone. The presence of pyrolusite is proxy evidence that the environment in which fossilization and diagenesis occurred was influenced by the marine-fluvial interface.

This Side of Hell Quarry is located relatively far to the west of the generally accepted Maastrichtian paleogeography, which places the ancient shoreline well to the east (Figure 7). Other Maastrichtian dinosaur skin occurrences (Figure 7) should be examined and investigated for the mineralogy of the skin and

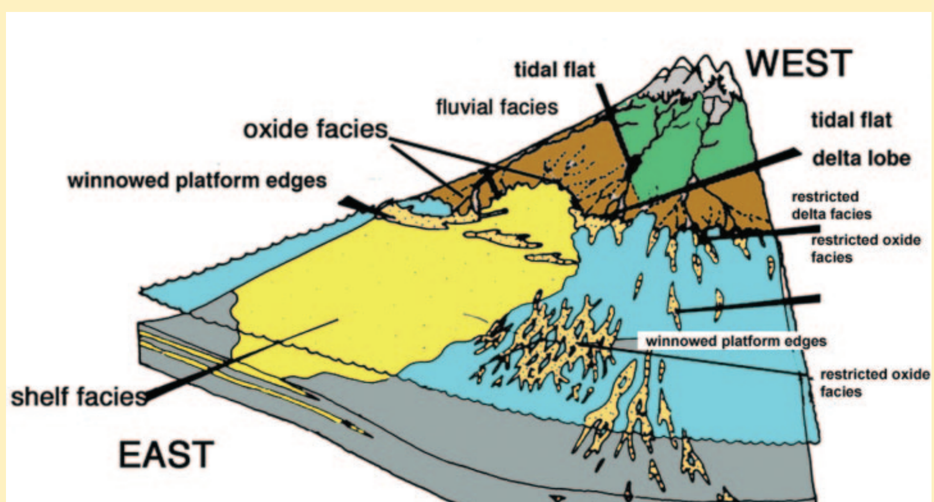

Figure 6: Paleoenvironmental model for the deposition of Lance Formation and related strata in the present-day Elk Basin, Wyoming.

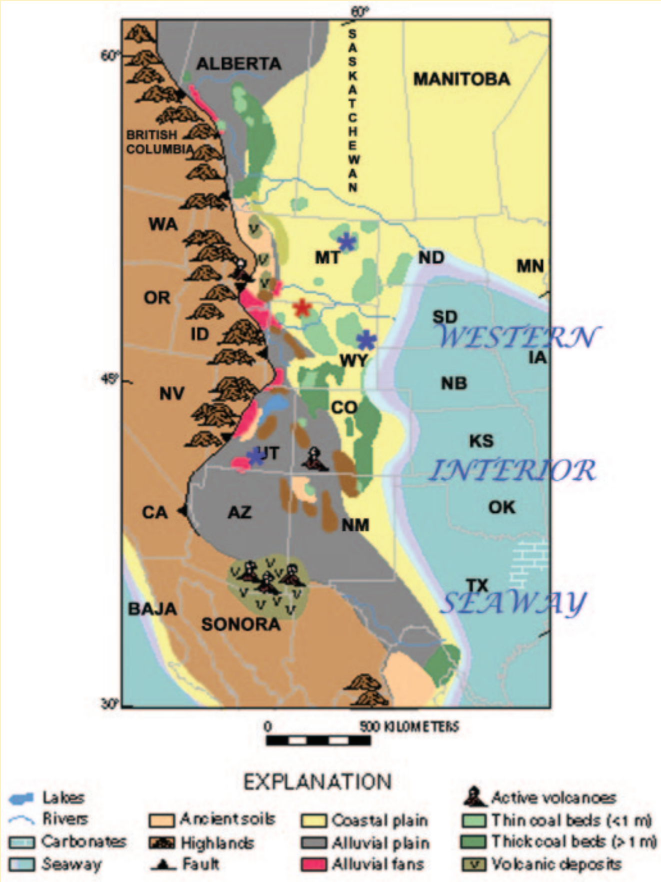

***Figure 7:** Generalized partial Late Maastrichtian paleogeography map of North America. The "This Side of Hell, Wyoming Quarry" with pyrolusite replacement of dinosaur skin is shown in a red asterisk. Representative localities of additional Maastrichtian dinosaur skin occurrences are shown in blue asterisks (e.g., Sternberg, 1925; Horner, 1984; Gillette, 2002). Only the "This Side of Hell, Wyoming Quarry" dinosaur skin has undergone SEM-EDX thus far to test for replacement mechanisms. Modified from http://energy.usgs.gov/factsheets/cret.coals/maas.gif.*

thus, the potential geochemistry of the sedimentary environment surrounding the fossils. In the Lance Formation, in the This Side of Hell Quarry, possibilities that could result in this mixing of marine and fluvial waters include the following: 1) Replacement by pyrolusite occurred because marine water could mix with fluvial water, all in sustained contact with the dinosaur carcass during decomposition. 2) The dinosaur was buried in sediments indirectly influenced by marine conditions such as a salt marsh, tidal-flat, or deltaic complex during fossilization processes. 3) Replacement by pyrolusite during decomposition can (and in this case probably did) happen in a matter of weeks to a few months, so preservation took place relatively rapidly during diagenesis as 3-D preservation of hadrosaur dinosaur integument has occurred.

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