Unusual, Fossiliferous Concretions from the Lower Jurassic Moenave Formation of St. George, Utah, USA: Implications for Ancient Fish Mass Mortalities

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UNUSUAL, FOSSILIFEROUS CONCRETIONS FROM THE LOWER JURASSIC MOENAVE FORMATION
IN ST. GEORGE, UTAH, USA: IMPLICATIONS FOR ANCIENT FISH MASS MORTALITIES

by

ALLISON REBECCA VITKUS

B.A., Carleton College, 2010

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Unusual, Fossiliferous Concretions from the Lower Jurassic Moenave Formation of St. George Utah, USA: Implications for Ancient Fish Mass Mortalities

Written by Allison Rebecca Vitkus

Has been approved for the Department of Museum and Field Studies

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
ABSTRACT

Vitkus, Allison Rebecca (M.S. Museum and Field Studies)

Unusual, Fossiliferous Concretions from the Lower Jurassic Moenave Formation of St. George Utah, USA: Implications for Ancient Fish Mass Mortalities

Thesis directed by Associate Professor Karen Chin

Two types of unusual concretions with similar contents but markedly different shapes and distributions were found in close stratigraphic proximity within the Whitmore Point Member of the Moenave Formation. Roughly cylindrical, elongate concretions were found in parallel and regularly spaced rows, and a layer of irregularly shaped and distributed fossiliferous concretions was discovered only a few centimeters above the cylindrical concretions. Both sets of concretions contain abundant hematite as well as enameloid fish scales. In addition, the concretions contain numerous ostracod carapaces and what appear to be rip-up clasts. Microprobe and Raman analyses of representative concretion samples reveal that the cylindrical concretions have a groundmass largely composed of silica while the irregular concretions have a groundmass largely composed of dolomite, and the ostracods within each type of concretion have been altered and match the chemistry of the surrounding groundmass. Evidence of multiple cement precipitation events is present within each concretion. These unusual concretions suggest mass fish mortality events in the large lake that occupied the St. George area in the early Jurassic.
For my family and friends – thank you for your encouragement and support.
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CHAPTER I

INTRODUCTION

Highly unusual, iron-rich concretions found in the Lower Jurassic Moenave Formation in St. George, Utah present an intriguing geologic conundrum. Two types of iron-rich concretions containing abundant enameloid fish scales were found in lacustrine sediments. Although the concretions have similar contents and were found stratigraphically within 4 centimeters of each other, they have markedly different shapes and distributions. The lower horizon contains meters-long concretions that are cylindrical, parallel in arrangement, and regularly spaced. In contrast, the concretions above are irregularly shaped and distributed. Parallel, elongate concretions like the cylindrical Moenave concretions are unusual on their own; it is baffling that they occur in stratigraphic proximity to the irregular concretions and have comparable contents, yet are strikingly different. The goal of this study is to examine and compare the structure and chemistry of the cylindrical and irregular concretions, and in so doing look for evidence that can help explain how they formed. In addition, information from the concretions may provide information about the paleoenvironment in which they originated.

In order to investigate the formation of the Moenave concretions, it is necessary to review previous studies concerning the origins of concretions with similar characteristics. Concretions are cemented mineral masses within unconsolidated sediments. A concretion is typically formed when cement precipitates around a nucleus, accreting sediment grains; common cements include iron, calcium, magnesium, and bicarbonate (Chan et al., 2007; Curtis and Coleman, 1986). Many concretions form around inorganic nuclei, but fossils serve as
nucleation centers for others. The Mazon Creek deposits in Illinois produce many examples of siderite concretions with fossils as their nucleation centers (Baird et al., 1986).

Chan et al. (2005) suggested a model for the formation of iron oxide concretions that was summarized as a three step process. First, iron is dispersed throughout the rock, either during burial or early in diagenesis. Then, a reducing fluid flows through the sediment, mobilizing the iron. Finally, the reduced iron-rich fluids in the rock encounter oxygenated water, causing iron oxide precipitation. This model for concretion formation relies on advection, or bulk fluid flow, and suggests that sediments containing iron oxide concretions are permeable and that enough groundwater disseminated iron through the sediment. Unlike those composed of different materials, recognizable nucleation centers are rare in iron-oxide concretions.

An example of recent hematite concretion formation was documented by Bowen et al. (2008) in Lake Brown in Western Australia, a shallow, ephemeral, hypersaline, acidic lake. Unlike Chan et al.’s model for the formation of concretions in the dune sediments of the Navajo Sandstone, these concretions form in a subaqueous depositional environment. Bowen et al. described the cement of these newly formed concretions as being massive instead of layered; the cementing minerals seem to have surrounded and somewhat displaced grains of quartz and gypsum from the surrounding sediment. Most of the Lake Brown concretions are spheroidal, though they are not quite spherical – the average aspect ratio (longest/shortest dimension) is about 1.5, with the longest concretion having an aspect ratio of 3.2. Some of these concretions contain a goethite-hematite mixture.
Most concretions discussed in the literature do not exhibit a parallel distribution, however, evenly distributed (but non-parallel) concretions have been reported. Abdel-Wahab and McBride (2001) described massive spherical concretions that were found to be regularly spaced in Cretaceous sediments in Egypt. Fossil shell material in the same sediments probably contributed the calcite that cemented the concretions. Bjørkum and Walderhaug (1990) proposed models for the formation of evenly spaced calcitic marine concretions based on a review of concretions from several locations. They suggested that the reason for the even spacing was saturation of calcite within the sediment; calcite accretion around nucleation points would have lowered the concentrations of dissolved calcite around them, preventing concretions from growing very close together.

Evenly spaced and iron-rich spheroidal concretions were found with plinthite nuclei in Venezuela (Herrera and Chacón, 2013). A plinthite is a humus-poor, iron-rich mixture of clay, quartz and other highly weathered materials that hardens irreversibly when exposed to repeated wetting and drying (Soil Survey Staff, 2010). These Venezuelan concretions were found within fluvial sediments which are submerged for much of the year. The concretions are large (0.5 m), and their interior structures are characterized by concentric rings with depletion zones in between them. The sediment surrounding these concretions is made up of kaolinite, quartz, hematite, and goethite.

While descriptions of spherical and sub-spheroidal concretions are common, elongate concretions are relatively rare in the literature. Of these, most are composed of calcite. Ferruginous, horizontally oriented, elongate concretions have been described, however, in
recent soils in Australia. These are much smaller than the Moenave concretions; most are less than 16 millimeters in diameter (Löhr et al., 2010).

Elongate vertical calcite concretions have also been described. Giant, tubular, calcite-cemented sandstone concretions from Eocene sediments in Bulgaria are several meters long like the Moenave concretions, but are oriented vertically. These concretions are thought to have been formed by changing subsurface water chemistry in reaction to anaerobic oxidation of methane by microbes (De Boever et al., 2009).

Beckner and Mozley (1998) described Miocene-age, elongate calcite concretions from New Mexico that were several meters long and oriented subparallel to bedding. Some of these were found alone while others were found in groups with similar orientations, somewhat parallel to each other. However, unlike the Moenave concretions, these New Mexico concretions are not regularly spaced.

Models for elongate calcite concretion growth were proposed by Mozley and Davis (2005), who compared numerous elongate calcite concretions. Examination of some of these concretions indicated growth at multiple nucleation sites throughout the structures. The authors concluded that many of these concretions were probably formed in elongate zones of groundwater whose chemistry was affected by microbial activity.

Many researchers have considered microbial activity to be very important in the formation of concretions. De Boever et al. (2009) and Mozley and Davis (2005) both suggested microbial involvement in their models of elongate concretion formation. Stromatolites and microbially induced sedimentary structures (MISS) are known to be formed by microbial activity when benthic biofilms interact with the grains of the host sediment on which they live. Biofilms
and microbial mats are communities of microorganisms held together by extracellular polymeric substances (EPS; Noffke and Awramik, 2013; Riding, 1999), and can interact with sediment by trapping, binding, baffling, and/or stabilizing the grains. These microbial interactions with the sediment create MISS, whereas stromatolites are formed when carbonate precipitation happens within the EPS and successive layers of carbonate precipitation occur (Noffke and Awramik, 2013).
CHAPTER II
GEOLOGIC SETTING

The Moenave Formation extends from northwestern Arizona to southwestern Utah on the Colorado Plateau (Kirkland and Milner, 2006; Tanner and Lucas, 2007). It is the stratigraphically lowest portion of the Glen Canyon Group, which unconformably overlies the Late Triassic Chinle Formation (Kirkland and Milner, 2006). The Glen Canyon Group also includes the Wingate Sandstone, The Kayenta Formation, and the Navajo Sandstone Formation (Blakey, 1994; Milner et al., 2011).

The thickest sections of the Glen Canyon Group (including the area around St. George) form a thick band of sediment called the Zuni Sag along the southwest edge of the Colorado Plateau (Blakey, 1994). River systems in the Early Jurassic are thought to have flowed from the southeast to the northwest along the Zuni Sag, depositing sediment. These rivers likely were the source of the sand in the extensive ergs which formed the Wingate Sandstone (Blakey, 1994). The Wingate inter-tongues with the lacustrine to fluvial Moenave Formation to the northeast (Milner et al., 2011; see Figure 1).

The Moenave Formation is approximately 74 m thick at the St. George Dinosaur Discovery Site. The formation is divided into the lower Dinosaur Canyon Member (approximately 53 m thick) and the upper Whitmore Point Member (around 17 to 19 m thick), in which the fish scale-filled concretions were discovered (Kirkland et al., 2014). The Dinosaur Canyon Member is largely composed of fluvial and floodplain deposits, whereas the Whitmore Point Member is predominantly composed of lacustrine sediments (Kirkland and Milner, 2006;
Figure 1. A: Generalized cross-section of lower to middle Jurassic rocks at Utah-Arizona border. B: Map of outcrops and geographic distribution of the Moenave and Wingate Formations at the Utah-Arizona Border. Diagram from Milner et al., 2011.
The Springdale Sandstone was once considered to be the uppermost member of the Moenave, but has since been determined to be a member of the unconformably overlying Kayenta Formation (Kirkland and Milner, 2006).

The Whitmore Point Member of the Moenave Formation was deposited by an ancient body of water known as Lake Dixie. This member incorporates a complex series of limestones, siltstones, mudstones, shales, and sandstones that represent two major lacustrine cycles (Tanner and Lucas, 2007; Kirkland and Milner, 2006; Kirkland et al., 2014). The base of the Whitmore Point Member is marked by a dolomitic limestone layer, which is overlain by dark gray shales as well as red-brown to mauve-colored, track-bearing sandstones and mudstones. The upper layers are largely composed of red-purple and greenish-gray mudstones and shales with some fine-grained sandstones and siltstones. The fish scale-filled concretions that are the subject of this paper were found in mauve and green colored mudstones of the upper Whitmore Point Member. The cylindrical concretions occur approximately 68 meters above the contact between the Moenave and the Chinle Formations (Kirkland and Milner, 2006; Kirkland et al., 2014; see Figure 2).

Milner and Kirkland (2006) described Lake Dixie as an aerially extensive lake system based on the presence of large coelacanths as well as on the geographic extent of Moenave Formation exposures. The fish fauna in Lake Dixie is dominated by semionotid taxa, such as *Lophionotus kanabensis* (Gibson, 2013). Other fish found within the Whitmore Point include the lungfish *Ceratodus stewarti*, the aforementioned coelacanth (similar to *Chinlea*), a palaeoniscoid, and the freshwater shark, *Lissocus johnsonorum*, (Milner and Kirkland, 2006).
Figure 2. Stratigraphic section at the St. George Dinosaur Discovery Center, modified from Kirkland et al., 2014. Red rectangle highlights where the fish scale concretions were found.
Freshwater ostracods have been found within the Moenave Formation as well – the most common ostracod found in the Whitmore Point Member is *Darwinula*, a freshwater genus. *Darwinula* is sometimes found in sediments deposited in hypersaline environments, though it is debated whether they actually lived in such environments or were instead transported (Shudack, 2006). Stromatolites are also found within the upper levels of the Whitmore Point (Kirkland and Milner, 2006; Kirkland et al., 2014). Some of the most famous fossils from St. George are the vertebrate tracks within the Whitmore Point, including the dinosaur track *Eubrontes* (Kirkland and Milner, 2006; Kirkland et al., 2014). Kirkland et al. (2014) noted puckering on the main track bearing surface, which may indicate the presence of fossilized microbial mats.

The stromatolite horizons, along with ripple cross-bedded sandstones and mud-cracked intervals within the Whitmore Point Member, suggest that the portions of Lake Dixie recorded in outcrops of the Moenave Formation were fairly shallow and fluctuated in depth (Kirkland et al., 2014). Lake Dixie has been compared to Botswana’s modern Okavango Delta, which is an inland delta fed by rivers (Kirkland et al., 2014). Evaporites are rare within the Whitmore Point Member, indicating that Lake Dixie’s waters did drain out at least some of the time, probably into a drainage configuration existing to the northwest (Blakey and Ranney, 2008; Kirkland et al., 2014).

The age of the Moenave formation has been debated by several authors. Pipiringos and O’Sullivan (1978) considered the boundary of the Triassic and the Jurassic to be at the base of the Moenave Formation (and at the base of the Wingate Sandstone to the northeast). Other authors, however, have placed the boundary between the Triassic and Jurassic within the
Moenave formation (Donohoo-Hurley et al., 2010; Kirkland and Milner, 2006; Lucas and Tanner, 2006; Milner et al., 2011; Tanner and Lucas, 2007), though the exact stratigraphic location of the boundary is debated. An Early Jurassic age for the Whitmore Point has been supported by palynostratigraphy and the biostratigraphy of semionotid fish, dinosaurs, and fossil tracks (Kirkland and Milner, 2006; Milner and Kirkland, 2006; Cornet and Waanders, 2006; Lucas and Heckert, 2001). Fossils associated elsewhere with Triassic sediments have been discovered within the lower sections of the Wingate Sandstone. As the Wingate is thought by some to have been deposited concurrently with the Moenave, these fossils have been used as evidence for the Triassic-Jurassic boundary being located within the Dinosaur Canyon Member. However, there are no exclusively Triassic dinosaurs or other tetrapods in the Moenave Formation.

According to Milner et al. (2011), the tetrapod body fossils and trace fossils in the Moenave all appear to post-date the end Triassic extinction (ETE), which occurred before the Triassic-Jurassic transition.

The conchostracan fauna within the Whitmore Point Member also provides information about the age of the unit. This fauna is dominated by *Euestheria brodieana* but also includes *Bulbilimnadia killianorum*. Some of these specimens were found about 3.5 meters below the Springdale Member of the Kayenta Formation (Kozur and Weems, 2010). Kozur and Weems correlated these occurrences to basal Hettangian strata in Poland. *Euestheria brodieana*, another species of conchostracan, was found about 6 m above the contact with the Dinosaur Canyon Member. This species on its own is characteristic of the Upper Rhaetian, leading Kozur and Weems to infer that the Triassic-Jurassic boundary occurs within the Whitmore Point Member.
CHAPTER III
MATERIALS AND METHODS

In 2001, the two concretion-bearing strata within the Moenave Formation were exposed by heavy equipment preparing the site for construction of a new school. Before construction began, the area was gridded and the concretions were photographed \textit{in situ}. These overhead images were stitched together with Adobe Photoshop software to create a composite map showing the spatial distributions of the concretions (Figure 3). Representative samples of both the cylindrical and irregular concretions were collected. The distances between the cylindrical concretions and the lengths of concretions that were not collected were determined from the composite image.

The specimens analyzed in this study are housed in the University of Colorado Museum of Natural History (UCM) and include two cylindrical concretions (UCM 96682 and UCM 96683), two irregular concretions (UCM 95892 and UCM 95712), and a portion of a stromatolite (UCM 98247).

Portions of cylindrical concretion UCM 96683, irregular concretion UCM 95892, and stromatolite UCM 98247 were selected for thin section analysis. These pieces were impregnated with a 9:1 mixture of acetone and Struers Epoes epoxy (1:1 epoxy resin to hardener) in order to prevent portions of attached host sediment from falling off during the cutting process. Each of these samples was cut perpendicular to the bedding plane using an Isomet slow speed saw with a 5 inch diamond-impregnated blade. Most pieces of cylindrical concretion UCM 96683 were cut perpendicular to the long axis of the concretion. To examine
Figure 3. Plan view showing the distribution of cylindrical concretions (indicated by turquoise lines) and irregular concretions (yellow) in situ in the Whitmore Point Member of the Moenave Formation at the St. George site. The lighter sediment shows the top of the indurated strata that contain both types of concretions. The darker, reddish sediments are artificial breaks in the concretion-bearing strata caused by heavy equipment, which ripped trenches through the indurated concretion-bearing strata, exposing the sediments below. Image provided by Karen Chin.
the orientation of enameloid scales within the cylindrical concretion, one piece of UCM 96683 was cut parallel to the long axis.

Cut surfaces of the specimens were polished with 600 grit grinding paper before being mounted onto clean glass slides with Devcon 2-ton epoxy (1:1 epoxy resin to hardener). Specimens were then ground down to an appropriate thickness for transmitted light microscopy with a series of diamond imbedded grinding discs and grinding papers ranging in size from 120 to 600 grit. Polishing for microprobe analysis was done with Buehler 5 μm aluminum oxide powder on Tex-MEP perforated cloth followed by Buehler 0.05 μm Masterprep polishing compound on Mastertex velvet cloth. All together four thin sections of cylindrical concretion UCM 96683 (FSF-C-a, FSF-C-b, FSF-C-e, and FSF-C-f), three slides of irregular concretion UCM 96892 (SP4-b, SP4-c, and SP4-d), and four slides of stromatolite UCM 98247 (98247-a, 98247-b, 98247-c, and 98247-d) were made.

Microscopic features in thin sections were examined with a Leica MZ125 stereomicroscope and a Leica DMRX compound microscope and photographed with a Canon 5D Mark ii digital camera. Thin sections FSF-C-b (UCM 96683), SP4-b (UCM 95892), and 98247-c (UCM 98247) were carbon-coated and analyzed for elemental composition using EDS (energy-dispersive spectrometry) spot analysis and backscattered electron imaging with a JEOL JXA-8600 electron microprobe maintained at the Electron Microprobe Laboratory in the Department of Geological Sciences at the University of Colorado Boulder. Spot analyses were collected using an accelerating potential of 15KV and a 20 nA probe current. Data were analyzed using dPict software, interfaced to the microprobe with Geller microprobe automation.
Concretion samples were also analyzed with Raman spectroscopy. Analyses of petrographic slides FSF-C-b (UCM 96683) and SP4-d (UCM 95892) were conducted with a Horiba LabRAM HR Evolution confocal Raman microscope-spectrometer maintained at the Micro-Raman Imaging Laboratory in the Department of Geological Sciences at the University of Colorado Boulder. Carbon coating was removed from the cylindrical concretion thin section, FSF-C-b, with Metadi Buehler 1 μm diamond paste prior to Raman analysis. A frequency doubled Nd-YAG (532 nm) excitation laser, 600 gr/mm grating, 100 μm confocal pinhole, and a 1024 x 256 pixel thermoelectrically-cooled CCD detector were used, resulting in a spectral resolution of about 4.5 cm-1 as measured by the full width at half maximum of the 585 nm neon emission line. Raman shift was calibrated daily prior to analysis using the 520.7 cm-1 Raman peak of silicon. Spots approximately 1 μm in diameter were analyzed using an Olympus 100x 0.90 NA dry objective lens and 0.15-1.5 mW laser power at the sample surface. Raman generated elemental maps of cylindrical concretion slide FSF-C-b (UCM 966823) and irregular concretion slide SP4-d (UCM 95892) were collected with an Olympus 50x 0.75 NA objective, 2.9 mW laser power, and a 2μm step size corresponding to the approximate laser spot diameter. Spectra collected from the samples in this study were compared to reference spectra from the RRUFF Raman spectrum database after a polynomial baseline was subtracted to remove background florescence. Raman spectra, chemical images, and maps were processed using LabSpec 6.3 software.

The areal densities of enameloid scales within the two types of concretions were calculated from digital photographs of cut and polished surfaces of cylindrical concretion UCM 96683 and irregular concretions UCM 95892 and UCM 95712. Four sample surfaces from
cylindrical concretion UCM 96683 were analyzed [FSF-B-pA-a, FSF-B-pB-a, FSF-B-pB-b (cut parallel to long axis), and FSF-C-pB-a], along with two surfaces of irregular concretions (UCM 95892 SP2-a and UCM 95712). These surfaces were photographed with a stereo microscope. For the purpose of determining the density of scales in each specimen, scales within designated 1 by 2cm rectangles on the surfaces were counted, and digitally outlined with Adobe Photoshop. The relative percentages of enameloid scales and sediment clasts within the sampled areas were then determined using Image J software.

The relative abundances of elements within concretion, sediment, and stromatolite specimens were measured using an ARL 3410+ inductively coupled plasma optical emission spectrometer (ICP-OES) maintained in the Department of Geological Sciences at the University of Colorado Boulder. Samples of cylindrical concretions UCM 96682 and 96683, irregular concretions UCM 95712 and 96892, sediment immediately surrounding these concretions, and stromatolite UCM 98247 were selected for analysis; samples of both oxidized and reduced sediments were collected around cylindrical concretion UCM 96683. These samples were pulverized into powder with a mortar and pestle, dissolved with acids, and mixed with water before analysis. Oxide weight percents were calculated based on the assumption that the elements were present in specific oxide compounds within the samples.
CHAPTER IV
DESCRIPTIONS OF SPECIMENS

Cylindrical Concretions

Macroscopic Description

The cylindrical concretions were distributed in parallel rows in sediments exposed by heavy equipment at the St. George site. The encasing sediments are red to mauve siltstone capped by gray green siltstone. Although the host siltstone is not well indurated, the concretions themselves are well cemented. The concretions were intermittently exposed along the bedding plane, but formed rows of somewhat continuous segments of cylindrical concretions. A limited extent of the bedding plane was exposed, but ten rows formed by seventeen multi-segmented linear concretions were observed in this area (see Figures 3, 4, and 5). The in situ rows of concretions ranged from 60 to 130 cm apart averaging 90 cm apart between rows. Segments of the cylindrical concretions are 49 to 305 cm in length (see Appendix A), and their diameters range from about 4 to 10 cm.

Sample cylindrical concretion UCM 96683 collected from the site is 130 cm long and averages 7.3 cm in diameter. Natural breaks reveal diameters ranging between 6.2 and 11.5 cm in width (horizontal to the bedding plane and perpendicular to the parallel lines of the concretions) and 4.0 and 9.3 cm in height (perpendicular to the bedding plane). Most, but not all, cross sections of this concretion segment are wider than they are tall. A second collected cylindrical concretion (UCM 96682) is 158 cm long. Both concretions contain numerous natural
Figure 4. View of Moenave Formation section containing cylindrical concretions and irregular concretion. The concretion layers were found in the section between the red dotted lines. Photograph taken by Andrew Milner.

Figure 5: Two collected cylindrical concretion segments viewed from above. Edited from a photograph taken by Karen Chin.
vertical breaks (Figure 6), many of which are covered with a coating of calcite that may have been deposited as an evaporite on the broken surfaces. The outer surfaces of these concretions are distinguished by abundant, centimeter-sized, semispherical protrusions.

**Microscopic Description**

Analyses of thin sections of cylindrical concretion slide FSF-C-b (UCM 96683) reveal a conspicuous hematite border enveloping the concretion. The outer iron oxide border typically ranges from 200 – 400 μm thick, and also contains silica, dolomite, and calcite (Figures 7 and 8). Hematite is also concentrated around some of the inclusions inside the concretion. These internal concentrations of hematite vary widely in thickness.

The cylindrical concretion contains numerous enameloid fish scales, and Raman analysis indicates that the scales are composed of apatite. Probable bone fragments are present as well. Hematite surrounds most of the fish scales and bone fragments, and is also present within what appear to be tiny circulatory channels in the scales (Figure 9). Few, if any, scales or bone fragments are found in the sediment outside of the iron-rich border.

Abundant ostracod carapaces are also present within cylindrical concretion UCM 96683 (Figure 9). These carapaces are identified by their ovate shapes which commonly show a split into two similarly sized and overlapping valves. The ostracod carapaces also display a prismatic microtexture. A small number of ostracod carapaces are found in the sediment outside of the hematite border, though the vast majority of ostracods are found within the concretion. Small sediment chips are also present within the cylindrical concretion. These sediment clasts are
Figure 6. View of a broken surface and side of a collected cylindrical concretion.
Figure 7. Backscattered electron microprobe image of cylindrical concretion slide FSF-C-b showing fish scales and the iron rich border near the top. The brightest areas in the image are iron-rich.
Figure 8. Raman maps showing the distribution of elements in cylindrical concretion slide FSF-C-b. Top: Center of cylindrical concretion slide, which is primarily composed of silica (blue), calcite (green), and hematite (red). An apatite (yellow) scale takes up most of the upper right corner, and a small amount of feldspar (pink) is present on the left. Bottom: Iron-rich border of concretion slide FSF-C-b, largely made of hematite (red) and silica (blue). Dolomite (turquoise) and calcite (yellow) are also present.
Figure 9. Photomicrograph of cylindrical concretion slide FSF-C-b viewed with transmitted light and a lambda plate. Notice the ostracod carapaces in the upper half of the image and the fish scales in the lower half. Iron oxide seems to fill tiny circulatory channels within the scales.
generally elongate, and are similar in size, shape, and orientation to the enameloid fish scales. These clasts appear to be made up of the same type of sediment surrounding the concretion, and are interpreted here as rip-up clasts. The fish scales, ostracod carapaces, and rip-up clasts inside the concretion are supported by a groundmass largely composed of silica cement with some calcite (Figure 8). The abundant ostracod carapaces have been replaced by silica.

An unusual siliceous structure was found in the groundmass of slide FSF-C-b (Figure 10). The structure contains what appear to be tiny (less than 30 μm) round inclusions, or blebs, composed of goethite and arranged in concentric rings. Between the rings of goethite blebs are thin (about 10 μm thick) rings of hematite. The structure is surrounded by an uneven rim of calcite and hematite, at least 60 μm thick.

There does not appear to be any evidence of sediment baffling or trapping around the edges of the concretion, as is typically found in the outer edges of microbially induced sedimentary structures, or MISS (Noffke, 2001). The sediment surrounding the cylindrical concretion is largely siliceous with crystals and veins of calcite.

Counts of fish scales in four cross-sectional surfaces of cylindrical concretion UCM 96683 (FSF-B-pA-a, FSF-B-pB-a, FSF-B-pB-b, and FSF-C-pB-a) show an average of 15.4 enameloid scales per cm². The average cross-sectional surface area taken up by enameloid scales is 23.1% within the central portions of the concretion surfaces observed. If FSF-B-pB-b – the only surface oriented along the long axis of the concretion – is omitted, the other three surfaces average 35.33 scales per cm² and the average surface area covered by scales is 21.8%. There is an average of 4.5 rip-up clasts per cm² on the same concretion surfaces. The average cross-
Figure 10: Reflected light photomicrograph image showing an unusual silica structure with goethite blebs in concentric rings, found within cylindrical concretion slide FSF-C-b. Hematite and calcite are concentrated at the edge of the structure (upper left).
sectional surface area composed of sediment clasts is 12.7%, or 12.4% if the longitudinal FSF-B-pB-b surface is omitted (see Figure 11 and Table 1).

Chemical compositions determined by optical emission spectroscopy show that there are noticeable differences between the elemental concentrations in the cylindrical concretions and the host sediment (Figure 12 and Table 2). Based on the averaged analyses of three cylindrical concretion samples and four associated sediment samples, several elements occur in higher concentrations in the cylindrical concretion samples. These elements include phosphorus (P₂O₅; 2.97 wt.% cylindrical concretion versus 0.17 wt.% host sediment), iron (Fe₂O₃; 11.8 wt.% cylindrical concretion versus 5.3 wt.% host sediment), silicon (SiO₂; 52.1 wt.% cylindrical concretion versus 48.1 wt.% host sediment), and calcium (CaO; 25.2 wt.% cylindrical concretion versus 16.2 wt.% host sediment). In contrast, aluminum (Al₂O₃) was found to be considerably higher within the surrounding sediment (12.3 wt.%) than within the cylindrical concretions themselves (2.20%). Magnesium (MgO) is also higher on average in the sediment surrounding the cylindrical concretion samples (11.6 wt.%) than within the cylindrical concretions themselves (7.16 wt.%).

Irregular Concretions

Macroscopic Description

The irregular concretions were found in situ in a layer approximately 1-4 cm above the parallel cylindrical concretions. These flattened masses are typically 2 cm to 5 cm thick, and have irregular shapes ranging between 5 cm and 150 cm in lateral dimensions (Figures 5 and
Figure 11: Cross section of cylindrical concretion surface FSF-B-pA-a. Enameloid fish scales (red) and elongate sediment clasts (green) are outlined in the lower image and cover 21.3% and 9.8% of the surface respectively.
<table>
<thead>
<tr>
<th>Cut Surface</th>
<th>Specimen number</th>
<th>Cylindrical or irregular concretion</th>
<th>Enameloid scales per cm²</th>
<th>Scale area as % of total area observed</th>
<th>Sediment clasts per cm²</th>
<th>Clast area as % of total area observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSF-B-pA-a</td>
<td>UCM 96683</td>
<td>Cylindrical</td>
<td>17.5</td>
<td>21.3</td>
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<td>9.8</td>
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<td>UCM 96683</td>
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<td>14.0</td>
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<td>UCM 95712</td>
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<td>7.5</td>
<td>16.6</td>
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<tr>
<td>SP2-a</td>
<td>UCM 95892</td>
<td>Irregular</td>
<td>12.5</td>
<td>36.5</td>
<td>3.5</td>
<td>9.7</td>
</tr>
</tbody>
</table>

*Cut surface oriented along long axis of concretion

**Table 1.** Concentrations of enameloid scales and sediment clasts in observed cylindrical and irregular concretion cut surfaces.
Figure 12. Average oxide weight percents in cylindrical concretions, irregular concretions, and the host sediment immediately surrounding these concretions. See text and Table 2 for more information.
<table>
<thead>
<tr>
<th>Powdered sample</th>
<th>UCM #</th>
<th>Type of specimen</th>
<th>$P_2O_5$ wt. %</th>
<th>MnO wt. %</th>
<th>Fe$_2$O$_3$ wt. %</th>
<th>MgO wt. %</th>
<th>SiO$_2$ wt. %</th>
<th>Al$_2$O$_3$ wt. %</th>
<th>CaO wt. %</th>
<th>TiO$_2$ wt. %</th>
<th>Na$_2$O wt. %</th>
<th>K$_2$O wt. %</th>
<th>Total wt. %</th>
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</thead>
<tbody>
<tr>
<td>96682-QC</td>
<td>96682</td>
<td>CC</td>
<td>2.74</td>
<td>0.18</td>
<td>15.03</td>
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<td>0.12</td>
<td>0.45</td>
<td>1.27</td>
<td>103.25</td>
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<td>0.20</td>
<td>2.23</td>
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<td>43.21</td>
<td>11.57</td>
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<td>5.53</td>
<td>98.51</td>
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<td>CC</td>
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<td>6.48</td>
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<td>12.83</td>
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<td>0.09</td>
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<td>Strom.</td>
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<td>0.24</td>
<td>20.01</td>
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<td>47.00</td>
<td>0.05</td>
<td>0.21</td>
<td>0.36</td>
<td>0.36</td>
<td>77.99</td>
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</table>

**Table 2.** Weight percent of oxides within specimens, calculated on the assumption that the elements whose concentrations were detected by ICP-OES were present in the measured oxides. Some of the total percentages are considerably above or below 100%, likely because not all of the iron present occurs in Fe$_2$O$_3$ and some of the calcium and magnesium are present as dolomite. **CC** = cylindrical concretions, **CCS** = sediment around cylindrical concretions, **CCOS** = oxidized sediment around cylindrical concretions, **CCRS** = reduced sediment around cylindrical concretions, **IC** = irregular concretions, **ICS** = sediment around irregular concretions, **Strom.** = stromatolite, **DL** = detection limits of ICP-OES.
They were found in red to mauve siltstone topped by very light gray-green siltstone (Kirkland et al., 2014; see Figures 13 and 14).

The top surfaces of irregular concretions UCM 95712 and UCM 95892 have an outer texture showing semicircular protrusions that are similar to those occurring on the cylindrical concretions. These small protrusions are also similar to those covering flat, reddish, fossil fish filled concretions found sparsely elsewhere within the Whitmore Point Member (Kirkland et al., 2014). Although the outer sediment around the irregular concretions is not well-indurated, the concretions themselves are so well cemented that acid preparation of them proved difficult without destroying the semionotid scales within (Milner, personal comm., 2013).

Microscopic Description

Thin sections of the irregular concretion slides SP4-b and SP4-d (UCM 95892) have an outer rim of hematite and silica that is similar to that present in the analyzed cylindrical concretion (Figure 15). However, the iron-rich border is much thicker than in the cylindrical concretion slides; in places it is over 1000 μm, in contrast to the approximately 200 to 400 μm thick rim in the analyzed cylindrical concretion. There are also concentrations of hematite in the groundmass and surrounding inclusions within the concretion.

As in the cylindrical concretions, the irregular concretions contain numerous enameloid scales and what may be fragments of bone. Raman analyses indicate that the scales are composed largely of apatite and show hematite in fine interior channels. Abundant ostracod carapaces within both irregular concretion slides have been heavily dolomitize and some appear to have been partially replaced with hematite (Figure 16). Cut surfaces of irregular
Figure 13: Collected irregular concretion (UCM 95892) sample in plan view.

Figure 14: Side view of piece of collected irregular concretion (UCM 95892).
Figure 15: Backscattered electron microprobe image of irregular concretion slide SP4-b showing the iron-rich border. A fish scale largely composed of apatite is in the upper right corner. Most of the brightest areas are iron-rich.
concretions UCM 95712 and 95892 show numerous elongate sediment clasts, many with similar sizes, shapes, and orientations to the fish scales. These are interpreted to be rip-up clasts similar to those found in the cylindrical concretions.

The interior groundmasses of irregular concretion slides SP4-b and SP4-d are mostly composed of dolomite and calcite (Figure 16). Silica and feldspar clasts and traces of barium oxide were also present. As with the cylindrical concretion, the sediment surrounding the irregular concretion is largely siliceous with crystals and veins of calcite. A zircon crystal was found in the surrounding sediment of slide SP4-b.

Examination of a cut surface of irregular concretion UCM 95712 reveals 13.0 enameloid scales per cm$^2$, covering approximately 23.7% of the total central area observed. Surface SP2-a UCM 95892 has 12.5 enameloid scales per cm$^2$, which cover 36.5% of the total central area observed. In addition, the surface of UCM 95712 shows 7.5 sediment clasts per cm$^2$, covering 16.6% of the total area observed, while surface SP2-a of UCM 95892 has 3.5 sediment clasts per cm$^2$, covering 9.7% of the area observed (see Figure 17 and Table 1).

Characterization of the elemental compositions of three irregular concretion samples and their host sediments show that the concretions have considerably higher percentages of phosphorus and iron than the encasing sediments (see Figure 12 and Table 2). The irregular concretions have average concentrations of 3.08 wt.% phosphorus (P$_2$O$_5$) compared to 0.13 wt.% in the host sediment, and 29.7 wt.% iron (Fe$_2$O$_3$) in the irregular concretions versus 3.09 wt.% in the host sediment. Conversely the host sediments contains more aluminum (Al$_2$O$_3$; 8.47 wt.% in the host sediment versus 3.26 wt.% in the irregular concretions) and potassium
Figure 16: Raman image showing a portion of the interior of irregular concretion slide SP4-d, which shows a dolomite (turquoise) and calcite (green) ground mass. The circular structure is an ostracod carapace that is being replaced with hematite (red). Silica (blue), and a portion of an apatite (yellow) fish scale are also apparent in this image.
Figure 17: Cut irregular concretion surface 95712. Enameloid fish scales (red) and elongate sediment clasts (green) are outlined in the lower image and cover approximately 23.7% and 16.6% of the surface respectively.
(K\textsubscript{2}O; 3.59 wt.% in the host sediment versus 1.31% in the irregular concretions) than the irregular concretions.

**Stromatolites**

Stromatolites were found less than two vertical meters above the cylindrical and irregular concretions in stratigraphic section (Kirkland et al., 2014). These stromatolites have a green-gray surface on top, which is the same color as the reduced sediments in the vicinity of the concretions. A pebbly texture (tiny, tightly-packed semi-spheroidal protrusions) is evident on the upper green-gray surface. The sediment below the stromatolites changes color abruptly from mauve-red to green-gray, indicating a redox boundary.

Cut cross section surfaces of the stromatolite reveal that small pieces of green-gray sediment, each generally less than 1 millimeter in width, appear to have been trapped in the upper layer of the stromatolite (Figure 18). EDS spot checks with the electron microprobe showed the stromatolite to be largely composed of calcite. In thin section, the sampled stromatolite shows banding, likely reflecting the layers of calcite that were deposited on the stromatolite over time and helped cement the structure.

Optical emission spectroscopy analysis of the stromatolite sample reveals a chemical composition that is strikingly different from both types concretions and their host sediments (Table 2). The sample contains much lower concentrations of iron (Fe\textsubscript{2}O\textsubscript{3}; 0.24 wt.%)) and silicon (SiO\textsubscript{2}; 8.88 wt.%), and has no detectable phosphorus. At the same time, the stromatolite has much higher levels of calcium (CaO; 47.0 wt. %) and magnesium (MgO; 20.0 wt.%).
**Figure 18.** Cut surface of stromatolite (UCM 98247). Note the millimeter scale sediment clasts.
CHAPTER V

DISCUSSION

The distinctive and unusual characteristics of the Moenave concretions and the nature of their geological context must be considered when trying to reconstruct the origins of the two types of concretions. Important contextual information comes from the fact that these concretions were formed in sediments deposited in ancient Lake Dixie, a large lake which varied widely in depth. Lake Dixie also supported a variety of fish and invertebrates (Kirkland and Milner, 2006; Milner et al., 2006; Schudack, 2006; Kirkland et al., 2014).

The long (up to ~3 meter) cylindrical concretions were distributed in situ in mostly parallel rows and were spaced approximately one meter apart. Abundant enameloid fish scales (and possibly, bone fragments), ostracod carapaces, and what appear to be rip-up clasts were found inside both types of concretions, yet very few fish scales were found in the sediment between the concretions in either concretion-bearing stratum. Although the inclusions are similar, the groundmasses of the two types of concretions are different: largely silica in the cylindrical concretions and predominantly dolomite in the irregular concretions. However, both cylindrical and irregular concretions have outer coatings of hematite cement, which show some layering. Both types of concretions also have concentrations of hematite inside, often surrounding and infiltrating inclusions.

The chemical composition of the ostracods in the concretions generally matches the composition of the surrounding groundmass, being silicified in the cylindrical concretions and dolomitized in the irregular concretions. The outer iron-rich surfaces of both types of
concretions are distinguished by the presence of semi-spheroidal protrusions; some of this surface texture seems to reflect underlying inclusions of fish scales and rip-up clasts, though some of it may also reflect uneven distributions of hematite.

Taking into account the specific characteristics of the Moenave concretions, the following must be considered to investigate the concretions’ formation: 1) the sources of the skeletal debris present within the concretions, 2) the methods of distribution, aggregation, and accretion of fish scales in the concretion beds, and 3) the mechanisms for concretion formation that correspond with the patterns of mineralization evident in the cylindrical and irregular concretions.

**Source of fish debris**

The abundance of enameloid fish scales within the Moenave concretions is one of their most conspicuous features. In order to fully investigate the concretions’ origins, it is important to consider possible sources of this fish material. Little to no phosphorus was found in the groundmass between the fish scales, suggesting that their source was unlikely to be fecal matter (Chin, 2002). The fish skeletal debris could have accrued after mass mortality events or during slow accumulations of fish material over time.

Mass fish mortalities, or fish kills, have been determined to be caused by various biotic and abiotic physical and chemical factors. These include changes in pH, toxic algal blooms, hypoxia, droughts, parasite infections, floods, sediment loads, and changes in temperature. Sometimes, fish kills are the result of multiple adverse conditions (Betts et al., 2014; Closs and Lake, 1996; Hallegraeff, 1993; Leivstad and Muniz, 1976; Reifel et al., 2002; Whitfield, 1995).
Investigating possible causes of fish kills in the fossil record can be difficult, as much of the evidence has long since disappeared. Lake Dixie was subject to frequent changes in depth (Kirkland et al., 2014), which could have brought about conditions that caused fish kills. Climatic factors may have also played a role in making the lake uninhabitable for fishes.

As discussed in the introduction, microbial activity is thought to contribute to concretion formation (De Boever et al., 2009; Mozley and Davis, 2005). Mozley and Davis proposed a model of elongate calcitic concretion formation in which bacteria create an environment conducive to mineral precipitation. A fish kill in ancient Lake Dixie would have generated considerable amounts of decaying organic material, and provided far more resources for multiplying bacteria at once than slow accumulations of dying fish.

**Aggregation and adherence of fish debris**

Formation of the distinctively-shaped concretions would have required mechanisms to aggregate the abundant fish debris and other inclusions. The high density of fish scales in the concretion groundmasses, combined with the near lack of fish scales found in sediments between the concretions, suggest that some mechanism of adherence was an important initial step that helped keep the skeletal debris together.

One method of accretion might have involved microbial mats. These communities of microorganisms are connected by a sticky matrix of extracellular polymeric substance (EPS) forming a cohesive mat that adheres to a surface. Falling fish debris may have stuck to microbial mats at the sediment-water interface in this area of the lake. Fish kills would have provided abundant nutrients for microorganisms in microbial mats to feed upon. Furthermore,
the ostracods found in the Moenave concretions could have been feeding on such microbial mats, because some extant ostracods have been shown to prefer mat-forming cyanobacteria as a food source over animal remains (Schmidt et al., 2007).

The rip-up clasts within the concretions may be microbial mat chips, which are described by Noffke (2001) as flake-like pieces torn from microbial mats by turbulent waters. If the rip-up clasts within the Moenave concretions are indeed mat chips, they are likely to be the remnants of an older microbial mat torn up before the formation of the mat the fish material and ostracod carapaces may have adhered to. The small, flat sediment pieces within the Moenave stromatolite may also be microbial mat chips (see Figure 18). Clusters of microbial sand chips from the Precambrian of Namibia and South Africa were described by Pflüger and Gresse (1996), who thought it likely that they were aggregated by wave action and adhered together by microbial tissue.

Another possible source of adhering substances would be the considerable amounts of fat and oil are released from decaying carcasses after mass fish kills. Adipocere is a waxy substance produced from the breakdown of fat, and Betts et al. (2014) described adipocere spheres filled with fish scales and bones around the edges of the Salton Sea in California after a modern mass fish kill. In the hypersaline Salton Sea, high wind events sometimes cause lake turnovers, drastically reducing oxygen in the upper layers of the lake when they are mixed with the anoxic lower layers, thus causing mass fish kills. Bacteria multiply to consume the fats in the dead fish, creating free fatty acids which form bouyant adipocere around skeletal material (Betts et al., 2014; Malenda et al., 2012). The generation of adipocere, at least in the Salton
Sea, has been seen only after mass fish kills as opposed to being associated with individual dead fish (Betts et al., 2014).

In general, adipocere has mostly been referenced in literature relating to medicine and forensics (Betts et al., 2014; Kumar et al., 2009). However, some studies have discussed the role of adipocere in taphonomy. Waxy adipocere is known to naturally harden cadavers, so Smith and Wuttke (2012) proposed formation of adipocere as a mechanism for stabilizing the bones in some exceptionally preserved lizards from the Eocene of Germany. After conducting actualistic experiments on decaying modern fish in seawater, Berner (1968) proposed that the formation of calcium-rich adipocere around organic material was a key step in the creation of calcite concretions around fossils. Photomicrographs of Moenave concretion thin sections show gaps between clusters of inclusions, filled with large mineral crystals (Figure 19). It is possible that these gaps are indicative of areas where organic substances like adipocere were mineralized.

**Shaping of aggregated fish debris**

The distinctive shapes of the Moenave concretions make it necessary to consider how the accumulations of enameloid fish scales became what are now the cylindrical and irregular concretions. The elongate morphologies and parallel arrangements of the cylindrical concretions are especially striking in contrast to the variable morphologies and distributions of the irregular concretions that occur only a few centimeters higher in section. The presence of rip-up clasts within both types of concretions provides clues to the conditions of the lakebed because they indicate strong, physical disturbance of the sediment.
Figure 19. Photomicrograph of petrographic slide FSF-C-b from cylindrical concretion UCM 96683. Gaps between clusters of inclusions appear to be filled with large mineral crystals.
In an actualistic study, Hagadorn and McDowell (2012) examined the effects of unidirectional water flow on sands inoculated with microbial communities. They found that, in some cases, microbial communities in sediments prevented the formation of ripples or dunes. Instead, the shear stress from unidirectional flow resulted in roll-up, flip-over, and rip-up structures. The sediments that formed roll-up structures were those which contained thick microbial films and were subject to water flow with a velocity of around 35-40 cm/s. Higher velocities ripped up sediment chips within microbial mats of any thickness. Velocities below 35 cm/s but above 25-30 cm/s would sometimes result in flip-over structures depending on the microbial community present in the sediment.

It therefore seems likely that the Moenave cylindrical concretions are mineralized roll-up or flip-over structures that were initially formed by the shear stress of unidirectional water flow over sediments bound with microbial films or mats. In contrast, the masses of aggregated fish material that formed the irregular concretions do not appear to have been shaped by strong, unidirectional water flow.

**Mineralization and diagenesis**

At least four different major digenetic episodes occurred within both sets of concretions: 1) hematite precipitated around and inside the individual fish scales and other accreted debris; 2) authigenic cements formed a groundmass between the inclusions, lithifying the concretions; 3) hematite was precipitated around the exterior of the lithified or partially lithified concretions; and 4) diagenetic alteration changed the minerals in the concretions to their present chemistry. Some of these processes might have been concurrent. However, it
seems logical that the outer hematite cement rim was precipitated after the initial mineralization of the concretions because silicification and dolomitization generally rely on the flow of groundwater to introduce new minerals (Butts and Briggs, 2011; Hanshaw et al., 1971), and the hematite rim would likely have affected permeability.

Possible mechanisms for the formation of the Moenave concretions can be considered in view of previously described models for concretion development. Mozley and Davis’s (2005) model proposed that some of the concretions they investigated were formed by post depositional cement precipitation at multiple nucleation centers in elongate zones of groundwater influenced by microbial activity. In Chan et al.’s 2005 model of iron concretion formation, it is the redox reactions within the groundwater that drive precipitation of iron cement. Chan et al. (2005) suggested that the precipitated hematite in the Navajo Sandstone Formation coated grains of sand which then served as nuclei for concretion growth.

It is possible that similar processes may have helped drive the formation of the Moenave concretions. Hematite precipitated around the numerous fish scales and other inclusions, which provided multiple nucleation points. Both groundwater chemistry and microbial activity probably contributed to the authigenic mineral precipitation around and between the inclusions.

Decaying organic tissues from fish kills would have supported considerable microbial activity, and advection of cations through groundwater flow would have provided the components for mineral precipitation. The iron oxide, semicircular protrusions on the outer surfaces of both types of concretions may reflect multiple nucleation points for mineralization and concretion growth, as in Mozley and Davis’s model for concretion formation (2005).
Potential model for concretion formation

The following model for the formation of the Moenave concretions proposes a series of five steps (Figure 20) that are consistent with the contents, chemistry, morphology, and distribution of both the cylindrical and irregular concretions. Two steps differ in the formation of the two types of concretions – shaping of the accumulated material (step 3) and diagenetic alteration (step 5).

**Step 1 – Source of fish skeletal debris:** Mass fish mortalities were brought about by adverse conditions in Lake Dixie.

**Step 2 – Aggregation and adherence of material:** Sticky microbial mats along the sediment-water interface served to bind disarticulated fish debris along with ostracods and rip-up chips from wave-damaged microbial mats. Waxy adipocere formed from decaying fats and oils may have also contributed to the adherence of the fish material, rip-up chips, and ostracods.

**Step 3 – shaping of accumulated material:** Accumulations of fish material embedded within microbial mats were rolled and shaped into elongate configurations by strong, sustained, unidirectional water flow, possibly caused by strong winds. These parallel accumulations were later mineralized and became the cylindrical concretions. In contrast, the irregular concentrations of skeletal material were formed by multidirectional water flow.

**Step 4 – Burial and mineral precipitation:** After burial, hematite precipitated around and within the fish skeletal material and ostracods. Authigenic minerals also precipitated between the fish scales and other inclusions, forming a groundmass with relatively few clastic grains.
Figure 20. Flow chart of proposed model for formation of cylindrical and irregular Moenave concretions. Most of the steps for formation of the cylindrical and irregular concretions are similar, except for steps 3 (shaping of accumulated material) and 5 (diagenetic alteration). See text for more explanation.
Groundwater chemistry and the metabolic activities of microbes facilitated mineral precipitation.

Step 5 – Diagenetic alteration of the groundmass minerals and precipitation of the outer hematite rim: The groundmass cements were altered to their present form: a predominance of silica in the cylindrical concretions and dolomite in the irregular concretions. A hematite cement rim precipitated around the external surfaces of both the cylindrical and irregular concretions.
The cylindrical and irregular concretions found in the Whitmore Point Member of the Moenave Formation are highly unusual due to their distinctive shapes, distributions and contents. These specimens preserve a record of a series of physical and biological events in the history of ancient Lake Dixie because their contents, morphology, chemistry, and geological context shed light on the paleoenvironmental conditions that led to their formation.

Certain events, most likely mass mortalities, led to the abundance of fish skeletal material and ostracods within the concretions. This fish debris, along with ostracods and rip-up chips, was probably bound together with sticky substances – within microbial films and, possibly, waxy adipocere. Specific physical conditions, such as strong winds, must have created water flow with high velocities that rolled up and overturned the fish debris within microbial mats – thereby forming the aggregated fish material into the shapes that would later define the cylindrical and irregular concretions. The chemistry of the groundwater and the metabolic activities of microorganisms would have facilitated precipitation of minerals around and within the fish material masses, and later diagenetic changes gave rise to the present chemical composition of the concretions.

The cylindrical and irregular concretions can both be considered amalgam concretions. The fish scales and other inclusions surrounded by hematite cement can be viewed as numerous miniature concretions that were cemented together as multinucleate compound concretions. A series of fortunate events (from the geologist’s perspective) appears to have
caused the formation of these peculiar concretions. The specific set of circumstances required to form the Moenave concretions are presumably why nothing quite like them have been so far described in the literature.


Cornet, B. and Waanders, G. 2006. Palynomorphs indicate Hettangian (Early Jurassic) age for the middle Whitmore Point Formation, Utah and Arizona in Harris et al., eds., The Triassic-Jurassic Terrestrial Transition: New Mexico Museum of Natural History and Science Bulletin, no. 37, p. 390-406.


Kirkland, J.I. and Milner, A.R.C. 2006. The Moenave Formation at the St. George Dinosaur Discovery Site at Johnson Farm, St. George, Southwestern Utah in Harris et al., eds., The Triassic-Jurassic Terrestrial Transition: New Mexico Museum of Natural History and Science Bulletin, no. 37, p. 289-309.


APPENDIX A

Lengths of segments of cylindrical concretions

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<th>Cylindrical Concretion Number</th>
<th>Length (cm)</th>
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