The Distribution, Composition, and Formation of Sahara Desert Microbialites From the Base of the Meski Plateau, outside Erfoud, Morocco

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THE DISTRIBUTION, COMPOSITION, AND FORMATION OF
SAHARA DESERT MICROBIALITES FROM THE BASE OF THE
MESKI PLATEAU, OUTSIDE ERFOUD, MOROCCO

A Thesis Presented

by

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THE COMPOSITION, DISTRIBUTION, AND FORMATION OF SAHARA DESERT MICROBIALITES FROM THE BASE OF THE MESKI PLATEAU, OUTSIDE ERFOUD, MOROCCO

A Thesis Presented

by

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DEDICATION

To my best friend and partner, Leigh.

&

To my parents for providing a well cemented foundation.
ACKNOWLEDGMENTS

This research would not have been possible without Dr. Jorge Wagensberg, director of the CosmoCaixa Museum of Science, Barcelona, Spain, and the museum staff. I thank Dr. Wagensberg for asking us to collaborate on this project and develop the museum exhibit, and for graciously giving us the original samples to analyze. I thank Maria Jose Ruiz de Loizaga and the late Andreu Sole for their original field work. I am especially grateful to Embarek Segaoui for granting us access to his concretion collection, and for his invaluable guidance and assistance with field work at the research sites. I thank Mike Dolan, Celeste Asikainen, Bruce Scofield, Jim MacAllister, Melishia Santiago, and the entire Margulis lab staff over years for their support. I thank Robert DeConto, Mark Leckie, and Richard Yuretich for recognizing potential. I thank Mike Jersinovic, Steven Burns, Mark Leckie, and Sheila Seamna for their guidance during the committee process, and the Department of Geosciences for intelectual, emotional, and financial support. I thank Mike Dolan, Penny Boston, and Tom Kieft for their guidance throughout the NASA Planetary Biology Internship, a crucial component of my graduate research. Finally I thank Lynn Margulis for her unconditional love, support, guidance, and
inspiration. The Graduate School, the College of Natural Sciences, the Department of Geosciences, and Lynn Margulis of the University of Massachusetts, and the NASA Space Grant Consortium and NASA Planetary Biology Internship financially supported this research.
ABSTRACT

THE COMPOSITION, DISTRIBUTION, AND FORMATION OF SAHARA DESERT MICROBIALITES FROM THE BASE OF THE MESKI PLATEAU, OUTSIDE ERFOUD, MOROCCO

SEPTEMBER 2010

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Seven distinctly different museum-quality concretionary morphotypes of elongate, spheroidal, banded, botryoidal, columnar, rosette, and speleothem in regolith at two small sites at the base of the Meski Plateau near Erfoud, Morocco are described. Although most are isolated hand samples, the largest concretions are meter-sized blocks. Not one sample resembles any surrounding outcrop or bedrock. The barite rosettes formed first via periodic mixing of $\text{Ba}^{2+}/\text{SO}_4^{2-}$-saturated solutions. They provided nuclei for cyclical precipitation-based concentric concretion development. The speleothem formed via precipitation from a carbonate-saturated solution
in a large void within porous sandstone. The sand concretions formed when calcite precipitated around grains in unconsolidated quartz sands with cyclic fluctuation of Ca$^{2+}$/CO$_3^{2-}$ saturated ground water. Petrographic analyses, stable isotope data, sample morphology, coupled with light and scanning electron microscopy indicate that microbial processes induced the periodic cement precipitation that produced the unique concretions.
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CHAPTER 1
INTRODUCTION

The role of microbial mediation during diagenesis leading to the formation of concretions and nodules within sediments has been debated since new tools allowed analysis of sedimentary structures at high resolution. Fossilized microbes and organic residues, so-called “biomarkers”, have led geologists to hypothesize and prove the biogenicity of certain sedimentary structures such as stromatolites and ooids (Noffke et al. 2008; Brehm et al. 2004). However, the genesis of similar sedimentary structures is still debated (McLoughlin et al. 2008) or claimed to be abiogenic (Collin et al. 2005).

Seven distinctly different morphotypes of museum-quality concretions are abundant in regolith only at two sites of limited area at the base of the Meski Plateau c. 30 km east of Erfoud, Morocco (Figure 1); they include many elongate, spheroidal, banded, botryoidal, columnar, and rosette hand samples, and one speleothem (Figures 2-8).
Figure 1: The Meski Plateau.

Figure 2a: Internal view of elongate sample MS3. Note concentric lamina.
Figure 2b: External view of elongate sample MS3.

Figure 3: Spheroidal sample MS8. Note concentric lamina.
Figure 4: Banded sample MS4. Note concentric lamina.

Figure 5: Botryoidal sample MS7.
Figure 6a: Columnar sample MS11a.

Figure 6b: Columnar sample MS11b. Note bedding planes.
Figure 7: Barite rosette sample MS10.

Figure 8a: External view of speleothem sample MS12.
Most concretions are isolated pebble- to cobble-sized, but a few are larger blocks of cemented concretions (Figures 9-12). The meter-sized samples we refer to as block samples. That not a single sample resembles any surrounding outcrop or bedrock, yet all are limited to a small area within the large Saharan locality is evidence for our hypothesis that the concretions are diagenetic structures produced post-depositionally whose genesis required microbial activity.
Figure 9: Excavated block of cemented concretions. Note discontinuity. Hammer for scale.

Figure 10: Excavated block of cemented concretions. Moroccan Dirham (~2cm) for scale.
Figure 11: Lynn Margulis and the author look at an excavated block of cemented concretions.

Figure 12: Possible *in situ* block of cemented concretions. Hammer for scale.
The seven distinct concretion morphologies, their limited geographical extent, chemical composition, and microbial association are described here in the geologic literature for the first time. Our studies were designed to determine if the concretions might be “microbially induced sedimentary structures” (MISS, Noffke et al. 2008). That high-ordered mineral precipitation form similar bizarre abiogenic structures (De Wit et al. 1982), leads to debate about the role, if any, of life (e.g. McLoughlin et al. 2008). The variety of at least seven distinguishable concretion morphologies in the same limited area, even within a single block sample, and absence of any samples elsewhere in the area led us to hypothesize that these sedimentary structures are microbialites.

The literature is replete with examples of biological precipitation of calcite. Calcium carbonate is one of the most common cementing agents in sandstones and diagenetic sand concretions. Bacterial-mediated calcite precipitation has been described both in nature and in the laboratory (Lowenstam & Wiener 1989; Van Lith et al. 2003; Chekroun et al. 2004; DeJong et al. 2006;). Microorganisms, chiefly bacteria, influence diagenesis in sedimentary rock-forming processes (Noffke 2008; Noffke et al. 2008). Both field and laboratory preliminary observations led to this study to elucidate the probable formation of the seven concretion morphotypes, and
to label them for a museum exhibit (CosmoCaixa Museum of Science, Barcelona, Spain, directed by Dr. Jorge Wagensberg).
CHAPTER 2
GEOLOGICAL SETTING

2.1 Research sites

Both research sites are located at the base of the Meski Plateau, one of a series of plateaus in a large basin to the east and south of the High Atlas Mountains at the edge of the Western Sahara near the Moroccan/Algerian border (Figure 13). A surficial geology map of the same general area with accompanying rock unit lithologies is provided in Figure 14. Four sites along the Moroccan/Algerian border contain deposits of the concretions analyzed here. Unfortunately two of the four sites are inaccessible due to military restrictions (local field guides, personal communication). The two accessible sites were named Bou lalou (Arabic for “end of the road”, Figure 15) and Saf saf (Figure 16), after a type of local tree.
Figure 13. Physical map of the general area of the two research sites (red star).
Figure 14. Surficial geology map of the general area of the two research sites (red star) with rock unit lithologies. Map provided by Mohammed Et-Touhami.
Figure 15: Field guide Embarek points towards the Bou lalou research site with the Meski Plateau in the background.

Figure 16: The Saf saf research site with the Meski Plateau in the background. Bag for scale.
2.2 High Atlas Mountains

The High Atlas Mountains (Figure 17) began forming in the Late Mesozoic (Alpine Orogeny) and are primarily composed of volcanics, sandstones, carbonates, and clays, and their metamorphic end members, and more recent Cenozoic sediments that have been continuously uplifted, folded and weathered (Barbero et al. 2007). The supercontinent of Pangea had rifted apart to form ocean precursors to the Mediterranean and the Atlantic by the Early Cretaceous. Sands, clays, limey sediments, and evaporite layers (e.g. gypsum, halite) had been deposited in those early oceans.

Figure 17: The High Atlas Mountains.
2.3 Guir and Meski Plateaus

The High Atlas Mountains are covered by Middle Cretaceous and Cenozoic rocks that [extend out to] form the great plains of the northwestern Sahara, including the Guir and Meski Plateaus (Wendt et al. 1984). A view from the Meski Plateau looking towards the Guir Plateau is seen in figure 18.

Figure 18: A view of the Guir Plateau from the Meski Plateau.
CHAPTER 3
METHODS

3.1 Sample collection

The original samples we subjected to detailed analyses were collected in the 1980’s and donated to us by Dr. Jorge Wagensberg. The other samples were collected in January 2008 by S.F and M.Et-T. during a reconnaissance trip to Erfoud with Lynn Margulis. At least two samples of all five morphotypes of sand concretions, several barite rosettes, and the speleothem were returned for detailed study to the University of Massachusetts-Amherst. Analytical equipment used in this study is located at the Department of Geosciences, UMass-Amherst unless otherwise noted.

3.2 Petrography

Petrographic sections were cut, at least three from each of the seven morphotypes, to a total of 31 (outsourced to Texas Petrographic, Houston, TX & Tulsa Sections, Tulsa, OK). The grain and cement mineralogy, fabric, and estimated intergranular volume (IGV) were determined by white light microscopy (Leitz Laborlux Pol 12). Images were taken with an attached Olympus Q Imaging Micropublisher 5 RTV digital color camera. Thin
sections were cut through concentric lamina from center-to-edge and/or bedding planes where possible. Clean portions were cut from the cores, centers, and edges of the samples. To decipher any trends from the cores to edges of concentrically laminated concretions, and across bedding planes for the columnar samples approximately 2 g of each sample was taken from each section (center-middle-edge) and powdered for x-ray fluorescence (XRF, Siemens MRS 400) analysis of major elements. Compositional data for the barite rosettes and speleothem was obtained by XRF analysis.

3.3 Stable isotopes

Stable isotopes of carbon and oxygen were measured by use of an isotope ratio mass spectrometer (Finnigan Delta+XL) with automated preparation systems for all morphotypes except the banded concretion and barite rosettes. Duplicate transects were drilled with a micro-drill from the center to the edges for concentric concretions or across the entire length of laminated samples to obtain representative data throughout the entire sample. A total of 148 powdered sample points were drilled from the five morphotypes (duplicates of 74 powdered sample points) and plotted for analyses of the possible water source, solution temperature during calcite precipitation, concretion burial depth, and indications of microbial activity.
3.4 Scanning electron microscopy

For detection of possible microfossils, to confirm compositional analysis, compare biogenic and abiogenic textures, analyze grain and cement fabrics, and to map elemental distributions of calcium, aluminum, iron, magnesium and carbon we used high-resolution scanning electron microscopy imaging (SEM, Carl Zeiss EVO50 XVP) equipped with energy-dispersive X-ray spectrometry (EDS, Bruker AXS X-Flash silicone drift detector). Operating conditions for SEM observations were a 10-20 kV beam and a ~50 nA beam current.

Representative thin sections of all seven morphotypes were placed in 1% 1N HCl solutions for 30 seconds to dissolve the top few microns of cement, and coated with a ~100 Å thick coating of a gold/palladium (Au-Pd) mix for detection of entombed microfossils and biofilms by SEM. Quartz grains, more resistant to acid dissolution, remain in place while the carbonate cement slightly dissolves. This yields 2-10 μm relief between the grains and the cement. Dissolution reveals objects not visible in thin section due to burial by calcite precipitate making them accessible for analysis (Figure 19).
Figure 19: Petrographic thin sections were acid-etched for microfossil detection. Note raised relief of etched portion in bottom half of the section. EHT = extra high tension; WD = working distance; SE = secondary electron; Mag = magnification.
CHAPTER 4

RESULTS

4.1 Concretion age constraints

The Meski Plateau that overlies Devonian and Carboniferous bedrock is composed of continental Late Cretaceous (Cenomanian Age ~99-93.5 MaBP) Fe-bearing sandstones capped by Early Miocene (Aquitanian Age ~23.8-20.5 MaBP) lacustrine carbonates. More specifically, according to Moroccan surficial geology maps of the research area provided by M.Et-T. (Figure 14), the Cenomanian sandstones are red detrital facies that consist of allochthonous gravel, sand, silt, clays, and organic matter delivered to the basin by tectonic, fluvial, and eolian processes. These materials lithified.

During the early Miocene the Meski sandstones were flooded by a freshwater lake large enough to cover the Cenomanian sandstones with >1m-thick layer of carbonate. Freshwater algae and bacteria, especially cyanobacteria, probably cyclically produced these lacustrine carbonates (Figure 20). Over the course of the Neogene these deposits were eroded into what is now a series of plateaus that include the Meski and Guir.
4.2 Composition *(Note: All compositional data in Table 1; XRF in Table 2)*

4.2.1 Calcite-cemented sands concretions

The same relative mineral composition prevailed in every sample of the five sand concretion morphotypes for which quartz sand comprises 60-70% of the grains on average, followed by feldspars, and rock fragments (Table 1). Eroded material from the Cenomanian Age sandstones, the
surrounding High Atlas Mountains, and the Aquitanian Age lacustrine carbonates is the likely source of the sediment that comprise the concretions.

Rock fragments consist of volcanic minerals (e.g. pyroxenes, zircons, iron-oxides) and metamorphic grains (e.g. biaxial quartz). The intergranular matrix that occurs as micritic calcite cement between and along sand grain boundaries and/or pore spaces is consistent in all five calcite-cemented sand morphotypes.

Table 1: Petrographic data.

<table>
<thead>
<tr>
<th>Type</th>
<th>ID#</th>
<th>Max. size (largest dimensions in mm)</th>
<th>Roundness</th>
<th>Sorting</th>
<th>Grain size (sand)</th>
<th>Composition</th>
<th>Calcite% wt.</th>
<th>IGV% / IGM</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elongate*</td>
<td>MS3</td>
<td>158 x 102</td>
<td>A-R</td>
<td>MWS-MS</td>
<td>VF-M</td>
<td>Q,F,R,Z, Fld, Ilm, Zeo, Mc</td>
<td>21.7</td>
<td>≥ 50</td>
<td>Irregular concentric laminations</td>
</tr>
<tr>
<td></td>
<td>MS5</td>
<td>210 x 102</td>
<td>A-R</td>
<td>MWS-MS</td>
<td>VF-M</td>
<td>Q,F,R,Z, Fld, Ilm, Zeo, Mc</td>
<td>21.7</td>
<td>≥ 50</td>
<td>Irregular concentric laminations</td>
</tr>
<tr>
<td>Spheroidal</td>
<td>MS8</td>
<td>210 x 102</td>
<td>A-R</td>
<td>MWS-MS</td>
<td>VF-M</td>
<td>Q,F,R,Z, Fld, Ilm, Zeo, Mc</td>
<td>21.7</td>
<td>≥ 50</td>
<td>Irregular concentric laminations</td>
</tr>
<tr>
<td>Banded</td>
<td>MS4</td>
<td>55 x 48</td>
<td>A-R</td>
<td>MWS</td>
<td>VF-M</td>
<td>Q,F,R,Z, Fld, Ilm, Zeo, Mc</td>
<td>21.7</td>
<td>≥ 50</td>
<td>Ilmenite bands</td>
</tr>
<tr>
<td>Botryoidal</td>
<td>MS7</td>
<td>100 x 78</td>
<td>A-R</td>
<td>MS</td>
<td>VF-M</td>
<td>Q,F,R,Z, Fld, Ilm, Zeo, Mc</td>
<td>21.7</td>
<td>≥ 50</td>
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<tr>
<td>Columnar</td>
<td>MS11a</td>
<td>48 x 68</td>
<td>A-R</td>
<td>MS</td>
<td>VF-F</td>
<td>Q,F,R,Z, Fld, Ilm, Pyx, FeO</td>
<td>21.7</td>
<td>≥ 50</td>
<td>Clear bedding planes</td>
</tr>
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<td></td>
<td>MS11b</td>
<td>56 x 74</td>
<td>A-R</td>
<td>MS</td>
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<td>21.7</td>
<td>≥ 50</td>
<td>Clear bedding planes</td>
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<td>MS10</td>
<td>20-100 in diameter</td>
<td>A-R</td>
<td>MS-WS</td>
<td>VF-F</td>
<td>Barite% = 57</td>
<td>≥ 50</td>
<td>Clays, FeO</td>
<td>MS10Sul/Cal reveals transition from tabular barite to sparry calcite</td>
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<td>MS12</td>
<td>102 x 149</td>
<td>See text</td>
<td>See text</td>
<td>M-F</td>
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<td>See text</td>
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</table>

MWS = moderately well sorted; MS = moderately sorted; WS = well sorted; PS = poorly sorted; WR = well rounded; R = rounded; SR = sub-rounded; SA = sub-angular; A = angular; VA = very angular; VF = very fine; F = Fine; M = medium; IGV = inter-granular volume; IGM = inter-granular matrix (* denotes different cuts from same sample)

Qtz = quartz; Fld = feldspars; Pyx = pyroxenes; Cal = calcite; Ilm = ilmenite; Zeo = zeolite; Mic = micrite; Spar = sparry calcite; FeO = iron oxides; Bar = barite

Table 1: Petrographic data.
Calcite cement that accounts for nearly 25% on average of each sand concretion sample is the only cement present in significant volume in any sample. Minimal quartz overgrowth occurs and iron oxides are present in small volume. Both may account for some sand grain cementation. Micritic calcite is common around grain boundaries and other intergranular areas of increased clays and silty matrix in all five sand concretion samples (Figure 21), but large poikilotopic sparry calcite crystals predominate (Figure 22).

Figure 21: Cement in the elongate sample (MS3/9) consists of micritic calcite, clays, organic material, and iron oxides.
4.2.1.1 Elongate & spheroidal

These two classes of morphotypes (≤210 x 102 mm) are spheroidal to slightly elongate, concentrically ringed concretions (Figures 2 & 3). Both morphotypes are composed of angular to rounded, moderate to moderately-well sorted, very fine to medium grains of quartz, feldspar, ilmenite, zeolite, and microcline with an average composition of $Q_{94}F_{4}R_{2}$. Intergranular matrix is composed of clays, detrital calcite, and silt-sized particles. The elongate sample is composed of 21.7% calcite cement by average weight. The spheroidal sample is composed of 25.1% calcite cement by average weight.
weight. The irregular concentric laminations (≤0.5 to 3 mm), visible in the hand sample, show an uneven pattern of deposition.

4.2.1.2 Banded

This morphotype (≤55 x 48 mm) is unusual in that it is not similar in shape to any of the other samples, but does display concentric rings, and does have a nucleus (Figure 4). Although composed mostly of angular to rounded, moderately well sorted, very fine to medium grains of quartz and feldspar, this sample displays the highest variance and wt.% of heavy mineral species (ilmenite, zircons, zeolite, hematite) of any sample, as seen by the clear ilmenite bands (Figure 23). This sample has an average composition of $Q_{84}F_{6}R_{10}$. Intergranular matrix is composed of clays, detrital calcite, and silt-sized particles.
4.2.1.3 Botryoidal

This morphotype (≤100 x 78 mm) is an aggregate of smaller-sized nodules with no apparent concentric pattern (Figure 5). This sample is composed of angular to rounded, moderately sorted, very fine to medium sand sized grains of quartz, feldspar and zeolite, and has an average composition of Q_{94}F_{4}R_{2}. Intergranular matrix is composed of clays, detrital calcite, and silt-sized particles. The botryoidal sample is composed of 22.6% calcite cement by average weight. The nodules are very similar to the highly weathered barite rosettes found at the same site, however, compositional
analysis reveals no barite in these samples. Each individual nodule varies in size, but not more than a few mm. There is no apparent fabric to the grains.

4.2.1.4 Columnar

These morphotypes (≤ 56 x 74 mm) are elongate and display horizontal bedding planes rather than concentric laminations. Although both samples are columnar, these two samples are unique: one displays a fleur-de-lis morphology (MS11a, Figure 6a) and one a stromatolitic morphology (MS11b, Figure 6b). These samples are composed of angular to rounded, moderately sorted, very fine to fine sand sized grains of quartz, feldspars, pyroxenes, ilmenite, and other iron oxides with the average composition of Q\textsubscript{94}F\textsubscript{4}R\textsubscript{2}. MS11a and MS11b are 24.4% and 21.6% calcite by weight, respectively. Poikilotopic calcite crystals predominate, but micrite, clays, detrital calcite, and silt-sized particles constitute intergranular matrix along grain boundaries and pore spaces. MS11b has smaller poikilotopic spar crystals and contains more heavy metal grains like ilmenite as well as significantly more micrite and other intergranular matrix along and between grains.
4.2.2 Barite rosettes

Barite rosettes (Figures 7 & 24) at the two research sites occur both isolated in regolith and as concretion nuclei (Figure 25). The barite rosettes vary in shape and size externally. All of the 50+ rosettes studied share a common radial or rosette crystal arrangement. Internally they display a common mineralogy and texture, but vary (55-70%) with respect to intergranular volume. The barite rosettes are composed of angular to rounded, moderately to well sorted, very fine to fine sand grains of quartz, feldspars, pyroxenes, barite, and other volcanic and metamorphic minerals with an average composition of Q$_{90}$F$_8$R$_2$. Large poikilotopic crystals of barite, some exceeding 4 mm in size cement sand grains, although small poikilotopic barite crystals cement some sand grains. Varying amounts of intergranular matrix occur as a function of minus-cement porosity, which is as high as 70%.
Figure 24: Barite rosette sample MS10sul/cal has a transition zone from barite (tabular crystals) to calcite (rounded crystal). Rock eyepiece for scale.

Figure 25: Barite rosettes occur as nuclei in many larger blocks of cemented concretions. Moroccan Dirham (~2 cm) for scale.
4.2.3 Speleothem

This sample (≤ 102 x 149 mm) is the most anomalous of all the samples collected at either site with a composition of mostly calcite (92%). Other significant major elements associated with this sample are Mg (1.06% wt.) and Si (0.87% wt.). Although the speleothem sample resembles in external morphology the elongate and columnar samples at both sites, its composition is primarily calcite (Figure 8). The speleothem is extremely bulbous, with relatively small (≤2 cm) mammaries that protrude from each side. Externally it resembles secondary cave formations found worldwide (Hill & Forti 1997), and even displays the alternating micrite/spar laminations common to most speleothems. Internally dense laminations of micrite with varying amounts of clay, silt, and iron oxides alternate with large columnar crystals of spar (Figure 26). This arrangement creates irregularly concentric lamina about a barite or calcite nucleus, which terminate at contact zones. Laminae extend from distinct nucleation sites. Calcite-cemented sand concretion block samples are similar (Figure 25).
Figure 26: Petrographic thin section of speleothem sample MS12. Note the similarities between the fusing concentric concretions in the block sample from Figure 23 and the fusing nuclei seen here.
Table 2: X-ray fluorescence data showing elemental abundances (in oxides) from seven samples from six morphotypes (C= center; M= middle; E= edge).

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4.3 Intergranular volume

Intergranular volume (IGV) values are high. All 31 thin sections exceed 40% (e.g. Figure 19 & compiled in Table 1). A few large concretions with septarian structures like those from Utah and Wyoming (McBride et al. 2003) were discovered among the excavated Moroccan morphotypes, but none in situ. Details are not described here. Although XRF measurements aided in compositional analyses, no major-element trend was apparent (Note: XRF data in Table 2).

4.4 Stable isotope data

Stable isotope data compiled from all five concretion samples is in Table 3. Oxygen isotope fractionation values show no trends from center to edge or across laminae on any. Delta (δ) ¹⁸O values range from −6 ‰ to −12 ‰ Pee Dee Belemnite standard (PDB). Carbon fractionation values also show no apparent trend from center to edge or across laminae. δ¹³C fractionation values range from −3 ‰ to −9 ‰ PDB. Plots of oxygen data v. carbon data are compiled in Table 4.
## Table 3: Stable isotope data

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*MS8 is a cut from MS9

** Table 3: Stable isotope data. **
4.5 Scanning electron microscopy

The concentric laminations macroscopically visible in hand samples do not correlate with visible light or electron microscopic images, except in texture and fabric of grains and cements. The speleothem sample clearly displays internal laminae both macroscopically and microscopically due to the sharp transition between micrite and spar lamina (Figure 26).

Several areas within the calcite cement and along grain boundaries and pore spaces contain objects of size, shape, and numbers consistent with
the presence of bacteria. Rod-shaped, coccoid, and filamentous objects we interpreted to be remnants of bacterial cells, colonies and/or biofilms (Figure 27). Biofilms wrap around sand grains in and around calcite cement in Figure 27b. Clay occurs in all sand concretions around grain boundaries, pore spaces, and along bedding planes of the columnar samples (Figure 27c).

Figure 27: Collage of scanning electron micrographs of calcified biofilms (27a-b), clays (27c), and calcified biofilms and bacteria (27b-d).
EDS confirmed heightened levels of relict carbon not associated with chlorine (an epoxy effect). The elemental distributions of calcium, aluminum, iron, magnesium and carbon are distributed along grain boundaries and in pore spaces (aluminum example, Figure 28). These data suggest remnant bacteria. Calcite cementation around the sand grains is incomplete or has been dissolved in areas of highest aluminum concentration (Figure 29). These observations confirm secondary infill with clays due to hydration.

Figure 28: Elemental map of thin section from elongate sample MS3 (cut from MS9). Aluminum is examined here. Note the dissolution pit infill.
Figure 29: Secondary electron image used for elemental mapping (same as in Figure 28). Note dissolution pits caused by mineral dissolution upon hydration.
CHAPTER 5
DISCUSSION

5.1 Paleoenvironment

The formation of seven distinctive morphotypes of the same grain composition cemented by calcite independently concentrated in two small isolated basins is highly unlikely. Outcrops of in situ samples of sand concretions to collect for laboratory analyses were sought by the authors, but not found. Neither have local geologists or collectors, which abound in the Erfoud area famous for its fossils, seen any. The lack of bedrock that contains in situ concretions, with the possible exception of the block sample (Figures 30-32) contrasts with conspicuous striking examples of limited areas replete with concretions and barite rosettes that litter the desert floor.
Figure 30: Close-up image of possible in situ block of cemented concretions. This outcrop displays three different depositional settings. Hammer for scale.

Figure 31: Close-up image of block from figure 30. Note the bedding planes, columnar structures, and concentric structures, all representative of different depositional settings. Hammer for scale.
Figure 32: Close-up image of top left of figure 31. Note irregular concentric lamina and terminating individual concretions, similar to the speleothem sample.

A shallow marine setting during the Late Cretaceous, produced by inlet seas, dominated the landscape in the area that encompasses the research sites (de Lamotte et al. 2009). These marine sands lithified and subsequently eroded into what are now a series of plateaus that line the western edge of the Sahara Desert. During the Late Cretaceous, the Alpine orogeny created the High Atlas Mountains, uplifting sedimentary deposits to the east and creating topography conducive to drainage, eventually creating alluvial settings, which transported material from the surrounding High Atlas Mountains into the basins (Figure 33).
Figure 33: Plateaus are uplifted over time delivering sediment to local basins.

During the Early Miocene, lacustrine carbonates were deposited. The sand that comprises the Cenomanian Age Fe-bearing sandstones of the Meski Plateau area, and volcanic and metamorphic material from the surrounding High Atlas Mountains was weathered, eroded, and transported to the basins via tectonic, fluvial, and eolian processes as evidenced from placer deposits found within the banded morphotypes. The carbonate was supplied by Aquitanian Age lacustrine carbonates and/or carbonates found throughout the region in sediments from previous marine settings entrained by tectonics, fluvial, and eolian processes (Figure 20).
The ilmenite bands deposited along bedding planes within the banded concretion (Figure 23) are relevant to the reconstruction of the Saharan depositional environment. Heavy durable mineral particles from weathered debris, e.g. gold and/or ilmenite concentrate and deposit in ways characteristic of placers in an alluvium and represent surficial fluvial deposits. Ilmenite grains were simply transported from older volcanics and metamorphics. It is not their origin, but their more recent depositional pattern in the banded concretion that is unusual.

The occurrence of clay yields insight into post-depositional dissolution processes within the pore spaces, such as evidence of a consistent water source, mineral weathering, and/or organic matter decay. Clay inclusions and iron oxides (~1-5% of all samples by volume), concentrated around grain edges and the remaining pore spaces are evidence of mineral-saturated water penetration of sandstone and subsequent concretion pore spaces. Clays, volcanics, and detrital carbonate were a likely Ca$^{2+}$ source for carbonate precipitation.
5.2 Concretion composition and age constraints

5.2.1 Concentric samples (MS7, MS8, MS9)

All five calcite-cemented sand concretions are composed of angular to rounded quartz and volcanic grains with low to high sphericity; they are so well cemented by calcite cement that IGV is 40-60% in every sample with porosity \( \leq 5\% \). Such high IGV associated with low porosity are evidence early cementation in concretion development and/or that they formed at the surface or at shallow depths. No trend of decreasing IGV from center to edge was seen in any of the concentric concretions suggestive of pervasive rather than progressive growth. During progressive growth concretion cement occurs at the center at shallow depths, and decreases towards the margins during progressive burial (McBride & Milliken 2006). The limited number of point contacts and near absence of long contacts between grains (petrographic thin sections, Appendix A) that indicates shallow burial correlates with our IGV data and inferred concretion ages.

5.2.2 Columnar (MS11)

The columnar sample displays the same external texture, and in some samples the same bulbous external morphology as the concentrically
laminated sand concretions, but lack concentric laminations. Instead, the columnar samples display bedding planes that suggest calcite cement precipitated in a low-energy system such as standing water. IGV in the columnar samples is analogous to the concentric samples.

5.2.3 Barite rosettes (MS10)

The barite rosettes are interpreted to be related to upwelling of basinal brines along subterranean fractures, leading to lateral migration of fluid along permeable beds and bedding surfaces (London 2008). The formation of barite requires only oxidation of basinal brines. At Stanley Draper Lake, northeast of Norman, Oklahoma, barite rosettes similar to the Moroccan rosettes are studied by David London (Univ. of Oklahoma). Reduced deep basinal brines rich in Ba$^{2+}$ and HS$^-$ migrated after prior regional uplift. When the vadose zone of local porous sandstones was reached, mixing and concomitant oxidation of sulfide to sulfate by meteoric water led to the precipitation of the barite roses (London 2008). The rosettes are fracture- and bedding-controlled and cement vertical solution pipes in Oklahoma. Rosettes of barite form most abundantly in breccias; they disperse along bedding as lateral mantos and the frequency of formation decreases with distance from the vertical pipes and mineralized breccias. The similarities in
geological setting and paleoenvironment make it plausible to infer that similar abiogenic processes at the two Moroccan sites formed the barite rosettes.

5.2.4 Speleothem (MS12)

The speleothem resembles carbonate speleothems found worldwide in caves (Hill & Forti 1997). Speleothems that involve the precipitation of CaCO$_3$ from a saturated solution, either by the evaporation of dripping water from a saturated soil onto a substrate, or by autotrophic CO$_2$ degassing in a solution, may be produced biogenically or abiogenically (Boston et al. 2001). The occurrence of alternating micritic/sparry laminations in speleothems is indicative of biogenesis (Figure 26). Structures similar to speleothems called pool fingers form in caves (Melim et al. 2001). Caves are classically defined as voids within subterranean rock, usually limestone, large enough to permit human passage. We consider here a void large enough to produce a $\sim$1700 cm$^3$ speleothem to be a cave. This unique sample amongst the abundant carbonate-cemented sand concretions are inferred to have formed in a large pore space during alternating phreatic conditions in the same way as the cemented concretions by precipitation out of solution, but on a larger scale.
5.2.5 Concretion age constraints

In concert with the IGV data the ages of the samples are constrained; the concretions are not older than 23 Ma as such diagenetic sedimentary structures take on the order of 10s of thousands to millions of years to form (McBride et al. 2003). Over 90% of the grains are recycled quartz, regardless of the roundness; therefore the sand grains comprising the cemented concretions were recycled (from the Cenomanian sandstones). From the level of sorting and wide range of roundness and sphericity (petrographic thin sections, Appendix A), the history of the grains that comprise these rocks can only be categorized as eolian and alluvial.

5.3 Stable isotope fractionation processes

Stable isotopic fractionation analyses have been applied to several similar studies and provide a suite of data used to determine the genesis of diagenetic carbonate deposits such as information on the water source (e.g., meteoric), the depth of formation (i.e., water temperature of formation), and microbial activity (Mozley & Carothers 1992; Mozley & Burns 1993; Klien et al. 1999; Abdel-Wahab & McBride 2001; McBride & Parea 2001; McBride et al. 2003; McBride & Milliken 2006).
5.3.1 Oxygen isotopes

Fractionation of oxygen isotopes can yield information about the water source from which the calcite precipitated, or even the burial history of the rocks in question. The “light” $\delta^{18}O$ values reported here can be attributed to three possibilities: prior burial, bacterial sulfate reduction, or an isotopically light water source. In the first scenario, according to the oxygen isotope fractionation data and related temperature relationship standards of O’Neil and Epstein (1966), these values suggest a prior burial depth of 2-3.4 km assuming a 25°C/km geothermal gradient (fractionation values of $–6 \%$ to $–12 \%$ PDB correlate to a water source temperature of ~50-85°C, respectively). This is highly unlikely considering the lack of grain compaction within the concretions, and the amount of sediment transport required to remove at least 2000 meters of sediment in less than 20 Ma, the inferred age maxima for these sedimentary rocks based on similar structures (McBride 2003) and surficial geology maps.

$^{18}O$-depletion can also result from $^{18}O$-depletion of pore waters during sulfate reduction. This depletion results from the incorporation of $^{18}O$-depleted oxygen from sulfate and organic matter into the pore-water bicarbonate reservoir (Mozley & Burns 1993); this scenario would correlate with sulfate respiration induced calcite precipitation.
Another likely scenario is one that involves a high-altitude water source. The High Atlas Mountains (Figure 17), also partially the detritus source, has presumably delivered cyclic seasonal melt water to the local basins for 10s of millions of years, probably commonly in large volumes of water in short periods, such as flash floods produced by seasonal storms. Relationships between depleted $\delta^{18}$O values, cold temperatures, and carbonate production (i.e. foraminifera tests) have been clearly demonstrated (e.g. Shackleton 1987). Water vapor carried to high altitudes will become isotopically depleted in the “heavy” isotope, $^{18}$O, which is reflected by precipitation (snow) enriched in $^{16}$O. Subsequently, when this snow and ice melts and drains into the basins, the water will still contain this depleted $^{18}$O signature, which will eventually be incorporated into the precipitated carbonates.

The $\delta^{18}$O values are consistent with a high-altitude water source, and seasonal melt water influxes into area basins would explain the cyclic groundwater table fluctuation. These $\delta^{18}$O values are representative of pedogenic calcites, which can precipitate from multiple processes, but always due to the phenomenon known as increased carbonate alkalinity (Mozley & Davis 2005). During this process, carbonate and bicarbonate ions are released into solution by any number of methods (often through
microbial oxidation of organic matter or via autotrophic sulfate reduction), raising the pH of said solution. If the solution contains sufficient Ca\(^{2+}\) ions, calcium carbonate will precipitate.

5.3.2 Carbon isotopes

The depleted \(\delta^{13}C\) values (\(\delta^{13}C = -3\, \%_o\) to \(-9\, \%_o\) PDB) found in these concretions and the speleothem are typical of average freshwater carbonates, however, they are also well within the range of carbonates precipitated by two common metabolic processes: oxidation of organic matter by heterotrophic bacteria and sulfate respiration by anaerobic bacteria (Mozley & Burns 1993). These \(\delta^{13}C\) values are consistent with low rates of organic carbon oxidation and low sedimentation rates, suggesting relatively stable and similar conditions in this basin throughout the Neogene into the present. These \(\delta^{13}C\) data also fall within the range of sulfate-reduction processes, and if depleted \(^{18}O\) values are interpreted to be the product of \(^{18}O\)-depletion of pore waters during sulfate reduction as described by Mozley & Burns (1993), the data suggests microbial sulfate-reduction may have induced calcite precipitation.

Considering that isotopic fractionation of inorganic carbon is consistent with bacterial organic carbon oxidation and sulfate reduction, and
based on our assumption of relatively shallow burial depth, we conclude again that bacterial oxidation of organic matter and/or heterotrophic sulfate reduction must have been responsible for inducing initial calcite precipitation in pore spaces between sand grains. The hydrogen sulfide gas produced by these metabolic reactions could produce acids, however, it’s just as plausible the gas could have dissipated considering the shallow depths of concretion genesis.

5.4 Concentric laminae as evidence for biogenicity

The concentric nature displayed by samples MS3 and MS8 is potential evidence of biogenicity simply based on depositional patterns (Figures 2 & 3). Stratifications yielding uneven lamina are synonymous with biogenicity because these stratifications are temporal and suggest cyclicity, usually seasonal and/or annual, like the lamina seen in stromatolites (Noffke 2008). Physical-chemical (abiotic) precipitation of minerals out of solution should produce smoother lamina, such as the case with geodes, suggesting that irregular lamina could be evidence for biogenecity in other rocks (Mozley & Davis 2005). This is observed macroscopically as one can see alternating darker and lighter laminations in both concentrically laminated concretions (Figure 2). Less commonly, one can also see alternating lamina with light
microscopy as alternating degrees of grain compaction that mimic the concentric lamina and bedding planes of the hand samples that display these macroscopic sedimentary structures.

5.5 Bacterially induced calcite precipitation

Microbially induced calcite precipitation is well documented (Golubic 1973, Krumbein 1979, Lowenstam & Weiner 1989, Bosak & Newman 2003, Chekroun et al. 2004, DeJong et al. 2006), and is both induced and controlled processes (Lowenstam & Weiner 1989). Induced biomineralization occurs when metabolic end products that alter the environment sufficient for the precipitation of certain minerals are excreted (Lowenstam & Weiner 1989; Boston et al. 2001). Controlled biomineralization occurs with genetic enzymatic control determining the time, place, and morphological details of a mineral precipitate, as in vertebrate bones, mollusk shells, or magnetite in magnetotactic bacteria (Lowenstam & Weiner 1989).

*Bacillus pasteurii*, a common soil bacterium, was documented inducing the precipitation of calcite, which cemented quartz sand grains in laboratory experiments (DeJong et al. 2006). Two processes in particular, hydrolysis of urea and sulfate reduction, have been documented to occur in
environments analogous to the present study (quartz sand substrate, alternating saturation/evaporative conditions: Van Lith et al. 2003; Chekroun et al. 2004, DeJong et al. 2006).

Aerobic heterotrophic bacteria can oxidize organic carbon releasing CO$_2$(g) into solution; subsequent bicarbonate production will lead to the precipitation of CaCO$_3$ in the presence of Ca$^{2+}$ ions in an alkaline solution. This metabolism occurs in oxic environments where abundance of free O$_2$ is available as terminal electron acceptor.

In anoxic sulfur-rich environments, often within millimeters of the sediment/subaerial contact as well as in the deeper subsurface, anaerobic heterotrophic bacteria use SO$_4^{2-}$ as a terminal electron acceptor and release bicarbonate. Preliminary results of experiments designed to quantify calcite cement precipitation via bacterial sulfate reduction are being prepared for publication.

Hydrolysis of urea induces the precipitation calcium carbonate in a similar process, as does autotrophy in the photic zone. Since the concretions and the speleothem grew subaerially photosynthetic metabolism is not possible.

Organic matter for these reactions may have been supplied from above via microbial mats, plant material, dead organisms, and animal urea
and feces during precipitation events, or from penetrating groundwater containing microbial remains and/or dissolved organic material. During episodes of shallow standing water it is likely phototrophic bacteria produced extensive mats via the release of extra polysaccharides that bind microbes and fine-grained sediment. These bacteria would produce photosynthate, much like cyanobacteria do in modern microbial mats today (Noffke 2008). Also like in modern mats, the photosynthate produced could have been metabolized by anaerobic sulfur bacteria living in the subsurface. Concretions could not have developed in areas of intense hydration, so the conditions for concretion genesis must have been dry, like today; however, modern oases in the Moroccan Sahara are evidence for localized autochthonous organic material even in the most arid of climates (Figure 34). The microbial mats and scums that occur at these oases have been occurring in these areas for as long as there has been enough water to generate biofilms (Figure 35).
Figure 34: Oasis near the Saf saf research site. These oases provided organic material to the system.

Figure 35: Photosynthetic microbial scum at the edge of a stream at an oasis.
With regards to the ilmenite bands in sample MS4, workers have implicated bacteria, via the production of metabolic end-products, in the precipitation of a variety of heavy metals (Dyer et al. 1994, Tebo et al. 2004, Fortin & Langley 2005) and formation of gold placer deposits (Watterson 1992), similar processes might have occurred with other heavy metals of varying oxidation states such as titanium, etc. Microbial processes could have produced the ilmenite grains and unusual grain depositional pattern, especially considering the lack of an abundance of ilmenite, or any depositional pattern of said mineral in any of the other samples.

With regard to the production of sulfate used in the formation of barite rosettes, sulfide-oxidizing bacteria mediate this oxidation process chemolithoautotrophically. This may have been the case with the Moroccan rosettes. Barite rosettes were grown in the lab where water-soluble organic compounds like acetates, oxalates, and proteins are specifically implicated in forming the rose clusters and crystal habits (London 2008), showing that biogenic compounds can play crucial roles in barite rosette formation. Upon mixing in a solution pipe or along saturated bedding planes within the porous sandstone, barites could have precipitated. Sulfide-oxidizing bacteria living within the pores of the sandstone may have produced the sulfate used
in the barite production, but no evidence exists to make or refute such a
claim.

If the laminated concretions formed from an abiogenic flow
mechanism, one would expect the concretions to have an orientation
representing the fluid flow at the time (Mozley & Davis 2005). The
concretions in this study lack an orientation, and therefore, led us to suspect
that these structures formed from fluctuating ground water moving up and
down through the sediments rather than directional flow of water through the
sandstone in a direction, e.g. from a higher elevation to the basin. During
snowmelt or high precipitation events the water table level would respond by
rising; the opposite is also true for periods of decreased precipitation or
drought, causing the water table to recede. This fluctuation would present
phreatic (saturated) and vadose (unsaturated) conditions within the sediment
(Mozley & Davis 2005).

5.6 Conclusions

Although strictly physical-chemical systems, e.g. gaseous mud pools
in hydrothermal vent fields (De Wit et al. 1982), can produce similar
sedimentary structures, the calcite-cemented sand concretions and
speleothem analyzed here are likely microbialites, i.e. microbially induced
sedimentary structures. Petrographical analyses, concretion morphology, geochemical data, and SEM imaging all support a microbial origin; such evidence for the barite rosettes is speculative.

The detritus that comprises the Cenomanian Age Fe-bearing sandstones of the Meski Plateau area, and volcanic and metamorphic material from the surrounding High Atlas Mountains was weathered, eroded, and transported to the basins via eolian and fluvial processes, as evidenced from placer deposits found within the banded morphotype. The carbonate was supplied by Aquitanian Age lacustrine carbonates and/or weathered carbonate grains and dust found throughout the region entrained by fluvial and eolian processes. Although no in situ outcrop samples were found, it is plausible that some or all of these rocks formed in the Cenomanian sandstones that comprise the Meski Plateau and were weathered and eroded out over time. The example seen in figures 30-32 could have been produced in situ, however, many similarly sized loose block samples were encountered (Figure 9-11), and no other evidence exists other than horizontal bedding planes to confirm or refute the block sample seen in figures 30-32 as in situ.

The inferred depositional sequence is as follows: The barite rosettes formed first, probably from the mixing of two briny waters saturated in
barium and sulfate, respectively, or possibly by induced microbial processes, and commonly acted as nucleation sites for subsequent calcite precipitation. Either process (solution mixing or microbial processes) could explain the rare occurrence of nearly contemporaneous barite and calcite. Bacterial organic carbon oxidation or heterotrophic sulfate reduction induced the initial precipitation of calcite cement, which precipitated and eventually bound detrital grains in the sand concretions.

Initial calcite precipitated along grain boundaries was microcrystalline (micrite); subsequent precipitation of larger sparry calcite may have been an abiogenic process, although large poikilotopic crystals of sparry calcite may have precipitated along biofilms. A common abiogenic process for carbonate development within sediments, especially in arid environments, is simple evaporation of a saturated solution. The microbialites developed in porous sands as a function of cyclic ground water fluctuation and subsequent flow direction and rate induced by seasonal melt water transported from the surrounding High Atlas Mountains and by increased carbonate alkalinity within those ground waters due to microbial activity. Depending on microbial mediation and groundwater flow dynamics, concretions would develop, as seen in figures 30-32. Alternating phreatic (solution) and vadose (precipitation) conditions in concert with microbial processes may explain
the concentric lamina of some of the samples. Slow fluid flow could also produce concentric concretions; vertical flow could produce the columnar samples.

Larger voids analogous to the tiny pore spaces still visible in the rocks could have provided an environment similar to a cave, which allowed the speleothem to grow by continual precipitation of carbonate layers about a nucleus and subsequent substrate (preceding calcite layers). Micritic calcite precipitation in the speleothem was induced by bacteria and created an environment conducive to abiogenic precipitation of larger poikilotopic crystals of sparry calcite. These layers alternated cyclically until cessation of carbonate precipitation, most likely a function of a diminished or terminated water source, or contact with an impurity such as mineral or organic matter.

The microbialites and barite rosettes of the Meski Plateau in the Moroccan Sahara represent a distinct sedimentary deposit, now on display at the CosmoCaixa Museum of Science, Barcelona, Spain. These unique rocks link microbial and diagenetic processes. They should aid in the analysis and reexamination of other laminated and/or concentric sedimentary structures in the future.
APPENDICES
APPENDIX A

PETROGRAPHIC THIN SECTION IMAGES
Figure A-1: Thin section MS3B from elongate sample MS3/9. Note the oversized pore (center). This is evidence of pre-compaction cementation.

Figure A-2: Thin section MS4C from banded sample MS4. Note ilmenite bands.
Figure A-3: Thin section MS8J from spheroidal sample MS8.

Figure A-4: Thin section MS10C from barite rosette sample MS10.
Figure A-5: Thin section MS12B from speleothem sample MS12.

Figure A-6: Thin section MS12C from speleothem sample MS12.
APPENDIX B

IMAGES FROM THE BOU LALOU RESEARCH SITE
Figure B-1: Concretions cover the desert floor at the Bou lalou site. Field guide Embarek stands in the background.

Figure B-2: Concretion patterns are evidence for what the paleo-groundwater flow direction may have been as the water migrated to the basin.
Figure B-3: Field guide Embarek (top) and Prof. Et-Touhami (left) examine a wall of cemented concretions at the Bou lalou site.

Figure B-4: Solitary concentrically laminated calcite concretion at the Bou lalou site from above. Rock eye-lens for scale.
Figure B-5: Profs. Et-Touhami and Margulis examine the only possible in situ block of cemented concretions. See text for details.

Figure B-6: The author and Prof. Margulis climb over a deposit of cemented concretions at the Bou lalou site.
Figure B-7: Field guide Embarek sits on a wall of cemented concretions at the Bou lalou site.

Figure B-8: A thick (1.5m+) wall of cemented concretions at the Bou lalou site. Note the bedding planes. Hammer for scale.
Figure B-9: Close-up image of B-8. Hammer for scale.

Figure B-10: Small grapestone concretions and barite rosettes cover the desert floor at the Bou lalou site. These were formed by standing water, as evidenced by the lack of microbialite pattern. Moroccan Dirham (~2 cm) for scale.
APPENDIX C

IMAGES FROM THE SAF SAF RESEARCH SITE
Figure C-1: Driving through an oasis towards the Saf saf site.

Figure C-2: Microbial scum covers the stream at the oasis near the Saf saf site.
Figure C-3: The oasis from above. The Guir Plateau stands out in the background.

Figure C-4: A Nomadic gravesite lies among grapestone concretions at the base of the Meski Plateau at the Saf saf site.
Figure C-5: Close-up image of the Nomadic gravesite seen in C-4.

Figure C-6: Grapestone concretions form large mounds at the Saf saf site. Bag for scale.
Figure C-7: Close-up image of grapestone concretion from the Saf saf site in C-6.

Figure C-8: Series of small concretions, flat sandstone beds, and grapestone concretions (from bottom up) at the Saf saf site. Larger concretions lie on the cross-beds, which was more permeable. Hammer for scale.
Figure C-9: Grapestone concretions and barite rosettes occur together and overly flat sandstone beds at the Saf saf site.
APPENDIX D

IMAGES FROM THE FERME AUBERGE MERZANE, OUTSIDE

ERFOUD, MOROCCO
Figure D-1: The High Atlas Mountains.

Figure D-2: The gate at the Ferme Auberge Merzane, our place of residence during our research trip to Erfoud, Morocco.
Figure D-3: A collection of concretion morphotypes at the Ferme Auberge Merzane coy pond. Quarter for scale.

Figure D-4: Columnar sample on artistic display at the Ferme Ubergé Merzane.
Figure D-5: Weathered concretions display internal irregular lamina. Quarter for scale. See text for details.

Figure D-6: Concretions with septarian structures are on artistic display at the Ferme Auberge Merzane. Moroccan Dirham (~2 cm) for scale.
Figure D-7: Grapestone concretions on the vertical face of a carbonate block at the Ferme Auberge Merzane.

Figure D-8: Columnar sample from the Ferme Auberge Merzane. Note bedding planes within the columnar structures. See text for details.
Figure D-9: Concretions and barite rosettes cover an excavated slab of concretions from one of the research sites. Moroccan Dirham (~2 cm) for scale.

Figure D-10: Lunch and tea in the Sahara Desert with (left to right): field guide and local hero Embarek, Prof. Et-Touhami, Prof. Margulis, and the author.


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