Origin of Jurassic Carbonate Nodules in Southeastern Wyoming

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The Morrison Formation of the Western United States is famous for the dinosaurs and other fossils that have been excavated from its beds. It was deposited during the Late Jurassic in a semi-arid, savannah-like environment. The Morrison Formation is remarkably extensive, with outcrops across eight states; however attempts to correlate between Wyoming and the Colorado Plateau have proven difficult. The goal of this research is to determine the origin of carbonate rocks from the Morrison Formation beds exposed on the Spring Creek Preserve in southeastern Wyoming, and to assess their potential for lithostratigphic correlations. A wide range of research techniques were employed, ranging from macroscopic observations in the field to geochemical and isotopic analyses. Field relationships and macro- and microtextures of nodular and calcareous units are consistent with carbonate mineral deposition of freshwater lacustrine muds and the development of palustrine limestones, nodules and calcrete as the micritic muds were exposed and desiccated. Strontium isotope data suggest that the nodules developed from alteration of nearby lacustrine carbonates with little exogenous input. The thickness and level of development of the nodular carbonate units below the mid-Morrison unconformity at 42 m and observed in nearby localities suggests an extended period of subaerial exposure and desiccation in the study area during middle Morrison time. If the presence of these palustrine carbonates found throughout Wyoming is the result of a synchronous regional lake-level lowstand, it is plausible that this nodular horizon correlates to the Mid-Morrison paleosol unconformity identified Utah and Colorado. The strontium isotope composition of a belemnite from the

underlying Sundance Formation corresponds to a Late Jurassic Oxfordian age (161-157 million years ago) for this unit and places a maximum age for the Morrison Formation in the Spring Creek Reserve study area.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

I would like to thank my advisors Dr. Rosemary Capo and Dr. Brian Stewart, as well as the rest of my committee, Dr. Charles Jones and Dr. Matt Lamanna. I would also like to thank James Gardiner, Mandi Lyon, Dr. Edward McCord, and Dr. Kelli Trujillo for all of their help along the way. This project was funded with financial support from the University of Pittsburgh Honors College and the University of Pittsburgh Office of Experiential Learning.

1.0 INTRODUCTION

The Late Jurassic Morrison Formation is remarkably extensive, with surficial outcrops in eight states across the Mountain-West region from Montana in the north to New Mexico and Arizona in the south (Trujillo 2003). It has been studied by scientists since the 1870's when fossils were first discovered in its beds. Since then, the formation has remained of interest to paleontologists and paleoecologists alike. The Morrison Formation is best known for yielding one of the richest dinosaur faunas in the world, including familiar taxa such as *Camarasaurus*, *Apatosaurus*, *Diplodocus*, *Allosaurus*, and *Stegosaurus* (Dodson, et al. 1980). Today there also exists a great deal of interest in the mammalian fossils from these beds, because the Late Jurassic was a time of rapid diversification of early mammals (Luo and Wible 2005). Because the Morrison Formation offers a rare window into the terrestrial world of the Jurassic, a number of recent studies have been devoted to reconstructing its ecosystem (Turner and Peterson 2004, Carrano and Velez-Juarbe 2006, Farlow, et al. 2010). In general, the paleoclimate of the area during the deposition of the Morrison Formation has been interpreted as semi-arid or at least seasonally dry, and it has been suggested that a high groundwater table supported much of the plant and animal life in the low-lying areas of the Morrison depositional basin.

As a result of its broad geographic extent, the strata of the Morrison Formation do not represent a homogeneous depositional environment. This point is evidenced by the fact that the named members in Utah, Colorado, and New Mexico are not found in Wyoming. This variability has made long-distance correlations within the Morrison Formation difficult, especially into its northern reaches. Correlations into southeastern Wyoming are particularly important because of the limited number of microvertebrate sites that exist within the Morrison Formation. Microvertebrate localities probably account for less than 10% of all known Morrison fossil localities, and two of the most productive microvertebrate sites, Como Bluff and Ninemile Hill, are located in southeastern Wyoming (Carrano and Velez-Juarbe 2006).

In an attempt to resolve this correlation problem, some workers turned to the clay minerals found within the Morrison Formation, that have been studied since the middle of the 20th century due to the presence of uranium ore deposits (Keller 1962). Workers in the late 1990's proposed that a shift from non-smectitic clays to smectitic clays could be found at most Morrison Formation localities (Turner and Peterson 1999). This was interpreted as a synchronous event resulting from an increase in ash fallout from a distant volcanic source. Turner and Peterson (1999) proposed that this clay-change could be used to correlate Morrison localities throughout Utah, Colorado, New Mexico, and Wyoming. However, this idea came under some scrutiny when another study illustrated that Morrison Formation clays are highly variable both laterally and vertically (Trujillo 2006). While the clay-change us a useful datum for correlating local sites, it does not work as well when attempting long-distance correlations.

More recently, workers in Colorado and Utah described a mid-Morrison paleosol (fossil soil) unconformity that they used to correlate between sites on the Colorado Plateau and the Front Range (Demko, et al. 2004). The paleosol was described as a laterally extensive, reddish argillic Calcisol with distinctive termite trace fossils; a similar paleosol was observed in the San Juan Basin of New Mexico. Demko et al. (2004) interpreted this unconformity paleosol as a horizon representing a significant change in fluvial style, groundwater levels, and paleoclimate throughout the Morrison depositional basin. They also suggested that this mid-Morrison paleosol unconformity is traceable into central and southeastern Wyoming, where it represents a regional lake-level lowstand, and is possibly equivalent to the "Boundary Caliche," named and described by Allen (1996).

"Caliche" is a term associated with arid environments that has been used in numerous contexts and can imply the presence of carbonate and/or sodium nitrate minerals. Allen (1996) used it to refer to a laterally extensive, pedogenically modified palustrine-lacustrine limestone. He described three types of "caliche" including an immature and thin micritic limestone-pebble horizon with smaller nodules below, a more mature "caliche" with four layers of a massive micritic limestone, and a massive limestone of a huge pan evaporative depocenter nearly ten feet thick. Allen (1996) used the "Boundary Caliche," which falls roughly in the middle of the Morrison Formation, as a marker bed to correlate Morrison sites throughout southeastern and central Wyoming.

These carbonate mineral-rich horizons in southeastern Wyoming offer a potential means of correlation with the Morrison Formation of the Colorado Plateau if they do indeed represent an extended period of sub-aerial exposure. Terrestrial carbonates (e.g. travertine, lacustrine limestone) can be formed in a variety of depositional environments, and provide insight into the paleoenvironment in which they formed. The carbonate units in the study area could be related to pedogenic calcrete (a soil horizon of cemented carbonate grains), groundwater carbonate cement, or palustrine carbonates that are found widely distributed over floodplains and distal regions of alluvial basins, and their presence is indicative of periods of reduced clastic input (Alonso-Zarza 2003). Calcretes are associated with arid to semi-arid climates whereas palustrine carbonates tend to form in semi-arid to sub-humid climates (Alonso-Zarza 2003 and references therein). By studying the terrestrial carbonates in the Morrison Formation of the Spring Creek area in southeastern Wyoming, both their correlation potential and paleoenvironmental implications could be better understood.

2.0 PROJECT OBJECTIVES

The objectives for this research were threefold. The first goal of this research was to construct a measured lithostratigraphic section of the Morrison Formation at the Allen L. Cook Spring Creek Preserve, with special attention paid to any carbonate rocks encountered. This will allow all samples collected from the field to be placed in an accurate stratigraphic context. Second, this project aimed to determine the origin of carbonate nodules found within the section. Finally this study evaluated the potential for lithostratigraphic correlations between the Morrison Formation throughout Wyoming and the Colorado Plateau. A wide range of research techniques ranging from macroscopic observations in the field to geochemical and isotopic analyses were employed to achieve these objectives.

3.0 STUDY SITE

The fieldwork for this research project was conducted on the University of Pittsburgh Honors College's Allen L. Cook Spring Creek Preserve in southeastern Wyoming. The Spring Creek Preserve is located approximately ten miles to the east of Rock River, Wyoming (Figure 1). It sits at an elevation of 7,000 feet in the Laramie Basin with the Laramie Mountains to the East and the Medicine Bow Mountains to the Southwest.

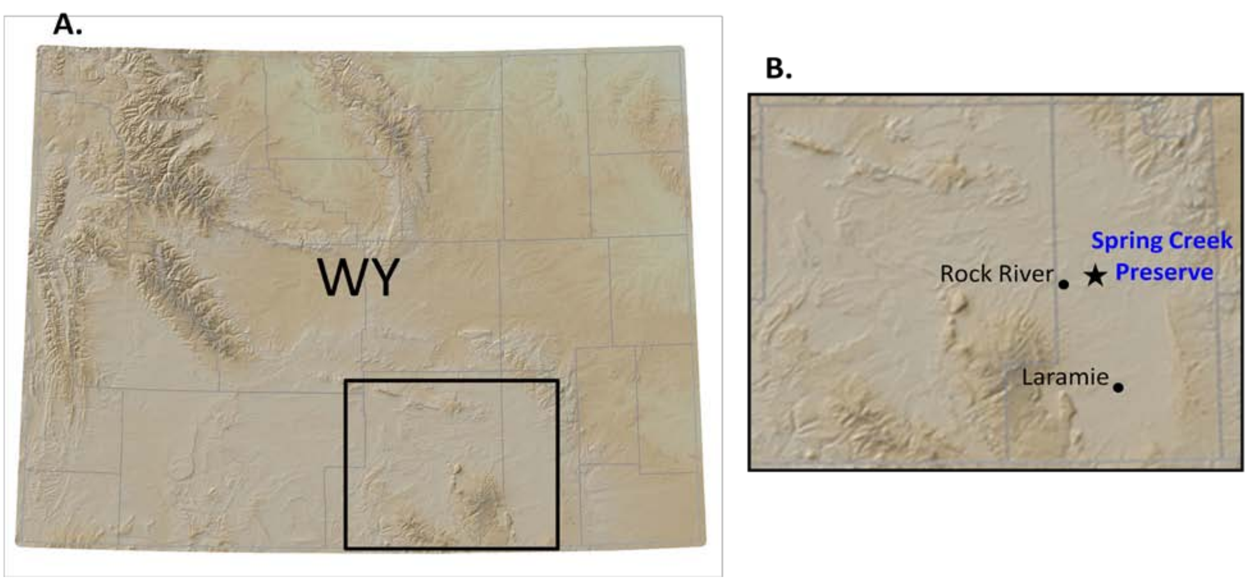

Figure 1. Location of Study Site. (A) Map of Wyoming. (B) Inset of Albany and Carbon Counties showing the location of the Spring Creek Preserve in Relation to the towns of Rock River and Laramie

3.1 GEOLOGY OF THE SPRING CREEK PRESERVE

The Spring Creek Preserve is centered on McGill anticline, which is an asymmetric fold that plunges to the west-southwest (Houlette, 1947). The southern limb of the of the anticline dips between 10° and 15°, whereas the more steeply dipping northern limb dips between 30° and 40°. There are seven formations exposed on the Preserve, with the oldest being the Triassic Chugwater Formation at the core of the anticline. Moving up section are two Late Jurassic units, the Sundance and Morrison Formations. Above these two formations are four Cretaceous units: the Cloverly, Thermopolis, Mowry and Frontier Formations. This paper will focus on the Morrison Formation and the units directly above and below

The Sundance Formation sits stratigraphically below the Morrison. But unlike the Morrison, it was deposited when a shallow epicontinental sea transgressed into the region from the north. The Sundance Formation dates from the early to middle Oxfordian (Kowallis, et al. 1998). It is characterized on the Spring Creek Preserve by fine grained sandstones and shales, and belemnite fossils are also commonly found within its beds. The uppermost beds of the Sundance Formation compose the Windy-Hill Member, a near-shore facies of fine-grained sandstones interbedded with shales. Some authors have placed the Windy-Hill Member in the Morrison Formation based on the presence of an unconformity at its base (Kowallis, et al. 1998, Turner and Peterson 2004); this would place the age of the Windy-Hill Member as Kimmerigian. However, recent workers in Wyoming still place the Windy-Hill member in the Sundance Formation (Trujillo 2003, Connely 2006).

The Morrison Formation is characterized by a variety of environments, including fluvial, overbank, lacustrine, and wetland deposits (Turner and Petereson 2004). The majority of the rocks that compose the Morrison on the Spring Creek Preserve are fine-grained mudstones and shales. Interspersed throughout are freshwater limestones, sandstone lenses, paleosols, and carbonate nodules. The base of the Morrison is marked by a laterally extensive, freshwater limestone bed. The Morrison Formation, being terrestrial in origin and lacking significant volcanic deposits, has proven difficult to date. It can be said that the Morrison is roughly Kimmeridgian to Tithonian in age (Trujillo 2003, Turner and Peterson 2004).

Sitting unconformably on top of the Morrison is the Cloverly Formation. Like the Morrison, the Cloverly Formaiton was deposited in a terrestrial environment and has also proven difficult to date. It can be coarsely dated as between Barremian and Albian, which would imply a gap of at least 15 million years in the sedimentary record (Kowallis 1998). Cloverly exposures on the Spring Creek Formation consist of well indurated sandstones and conglomerates as well as organic rich mudstones.

4.0 METHODOLOGY

Fieldwork for this research was conducted during July of 2009 at the Allen L. Cook Spring Creek Preserve in southeastern Wyoming. A measured section of the Morrison Formation was constructed by use of a Brunton compass, Jacob's staff, and measuring tape. Samples were collected of Morrison Formation carbonate nodules, freshwater limestones, sandstones, and mudstones. Marine belemnite fossils were also collected from the basal Sundance Formation for the purpose of acquiring a Jurassic marine isotopic signature. Every sample collected was photographed in the field and Munsell color and GPS coordinates were also recorded.

Thin sections for this study were prepared by Burham Petrographics, LLC. Standard 30 μm thin sections were made of the carbonate nodules, mudstone matrix, freshwater limestones, belemnite, and sandstones. For all of the sandstones, an additional thin section was prepared with blue epoxy impregnation as well as alizarin red and ferrous carbonate stains. Thin sections were analyzed on a Leica polarizing petrographic microscope.

Analytic work was carried out at the University of Pittsburgh Department of Geology and Planetary Science geochemistry laboratories. Carbonate samples for geochemical analysis were first broken apart to expose fresh surfaces; samples were then crushed and powdered with a Diamonite mortar and pestle. In order to analyze different mineral components of the samples, a sequential extraction procedure was used (Figure 2). Powdered samples were first leached with ammonium acetate (NH_4OAc) to remove any exchangeable/soluble salts. Samples were then leached with 8% acetic acid (HOAc) in order to extract the carbonate mineral fractions. Sandstones and mudstone matrix samples underwent an additional 2N hydrochloric acid (HCl) extraction to approximate a silicate weathering component. All leachates were then dried down before being redissolved in dilute nitric acid (HNO_3). Elemental concentrations (Mg, K, Mn, Sr, Al, Si, S, Na, and Ca) were determined for each of the leachates by ICP-AES. Strontium (Sr) was concentrated and purified under clean lab conditions by use of a Sr-selective chromatographic resin, and the $^{87}Sr/^{86}Sr$ ratios were measured using a Finnigan MAT 262 thermal ionization mass spectrometer (TIMS).

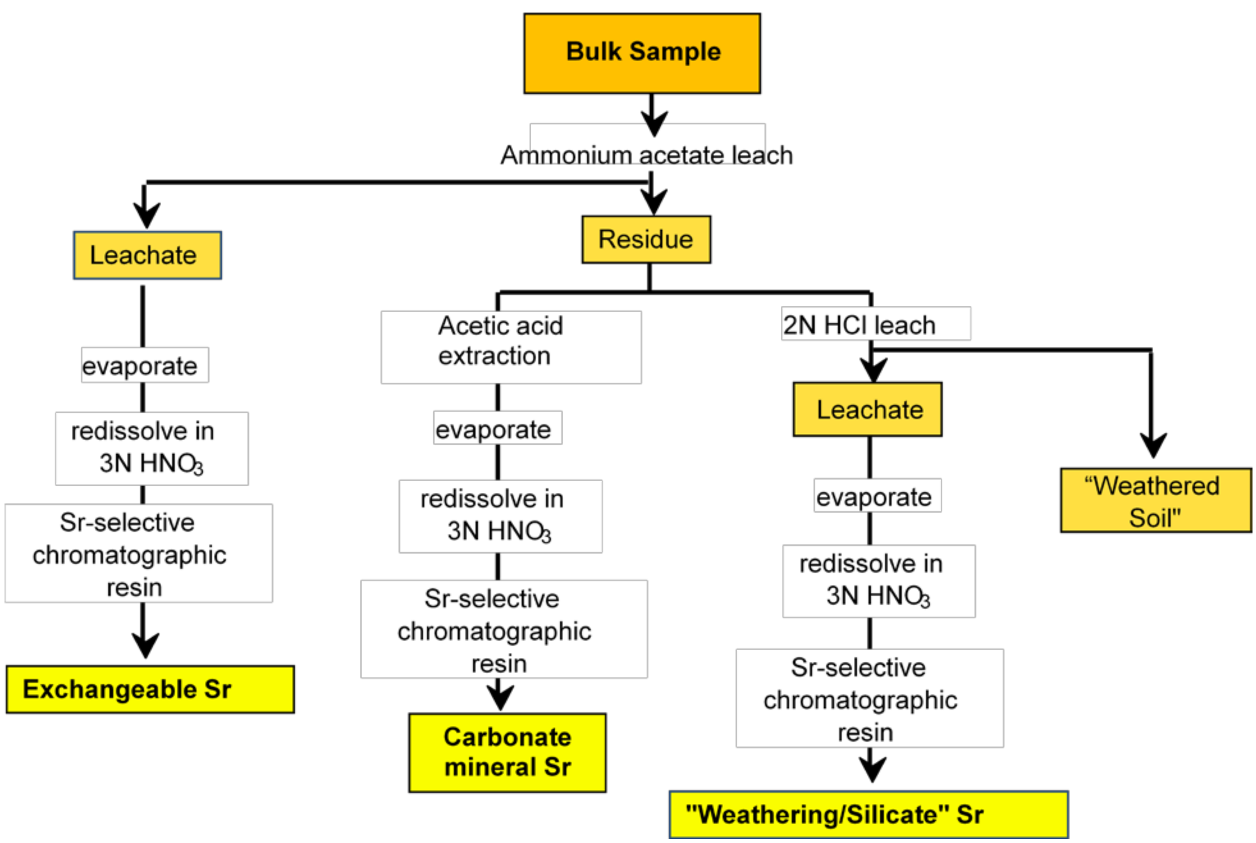

Figure 2. Flow diagram illustrating sequential extraction procedure.

5.0 RESULTS

5.1 STRATIGRAPHY

The measured section constructed on the Spring Creek Preserve totaled 108 meters in thickness (Figure 3). The Morrison Formation in the study area is 82.5 meters thick. The first three meters of the measured section encompass the uppermost part of the Windy-Hill member of the Sundance Formation. The top 22.5 meters of the section represents the lower part of the Cloverly Formation. The base of the Morrison Formation was marked by a laterally extensive massive, freshwater limestone bed. Ten limestone beds were encountered in total, and they were all located in either the first or last 20 meters of the Morrison Formation. Eight sandstone lenses were included in this section, all of which exhibited cross-bedding. The four sandstone lenses located in the middle 40 meters of the Morrison Formation all contained rip-up clasts of the underlying green mudstone. Most of the sandstone lenses and upper limestone beds did not appear to be laterally extensive. The rest of the section consisted of mudstones ranging in color from grayish green (10GY 5/2) to grayish red (5R 4/2). Two distinct nodular zones within the Morrison Formation were also identified.

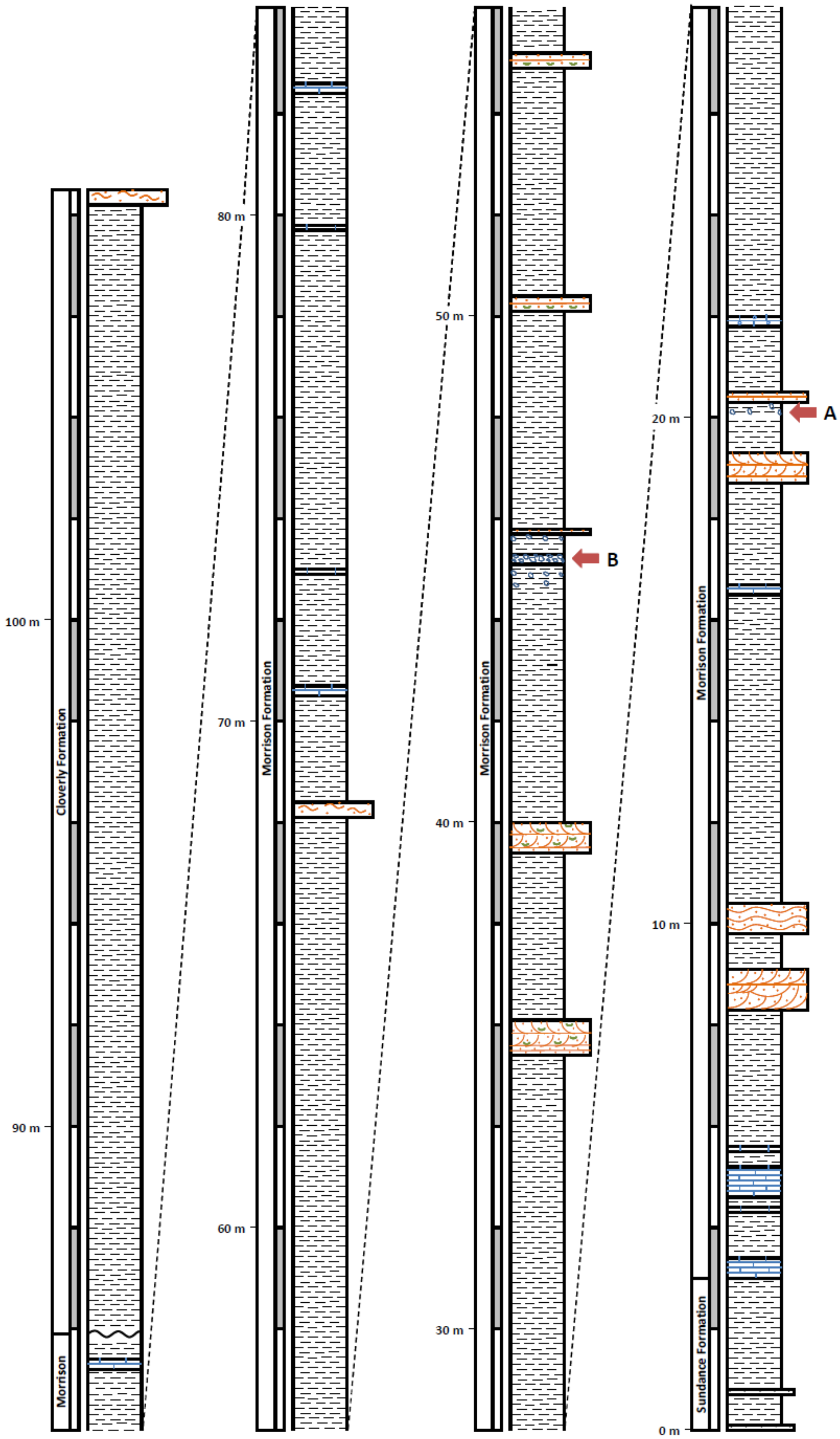

Figure 3. Measured Section of the Spring Creek Preserve. (A) First Nodular Zone. (B) Second Nodular Zone

The first nodular zone is located 19.3 meters up from the base of the Morrison. The mudstones within this zone are mottled, with Munsell colors ranging from dark greenish gray (5GY 4/1) to pale red purple (5RP 4/2) (Figure 4A). Carbonate nodules, 1.5 cm in diameter, were found within the dark greenish gray zones. The mottled mudstone is overlain by a green mudstone that is immediately followed by a red mudstone. The dip of the contact between these two mudstones is consistent with the rest of the section and there is an angular unconformity where they were cut by overlying Quaternary deposits (Figure 4B).

The second nodular zone is located 42.2 meters above the base of the Morrison. At this height in the section, the slopes of the modern gullies are covered with thousands of carbonate nodules weathering out from the hillside (Figure 5). Most of these nodules can be traced up to a 20 cm thick, well-indurated nodular horizon. The carbonate nodules are mottled in color, ranging from a Dusky Yellow Green (5GY 5/2) to a Grayish Red (5R 4/2). Once the nodules are exposed, they weather to white. More isolated carbonate nodules in a green, silty mudstone matrix are found 20 cm below the indurated nodular horizon (Figure 6A). These nodules are more elongate and oriented vertically. Carbonate nodules are also found 60 cm above the indurated nodular horizon. These nodules are also in a green silty matrix and are unconformably capped by a sandstone lens. This sandstone contains rip-up clasts of both the green mudstone matrix as well as small carbonate nodules (Figure 6B).

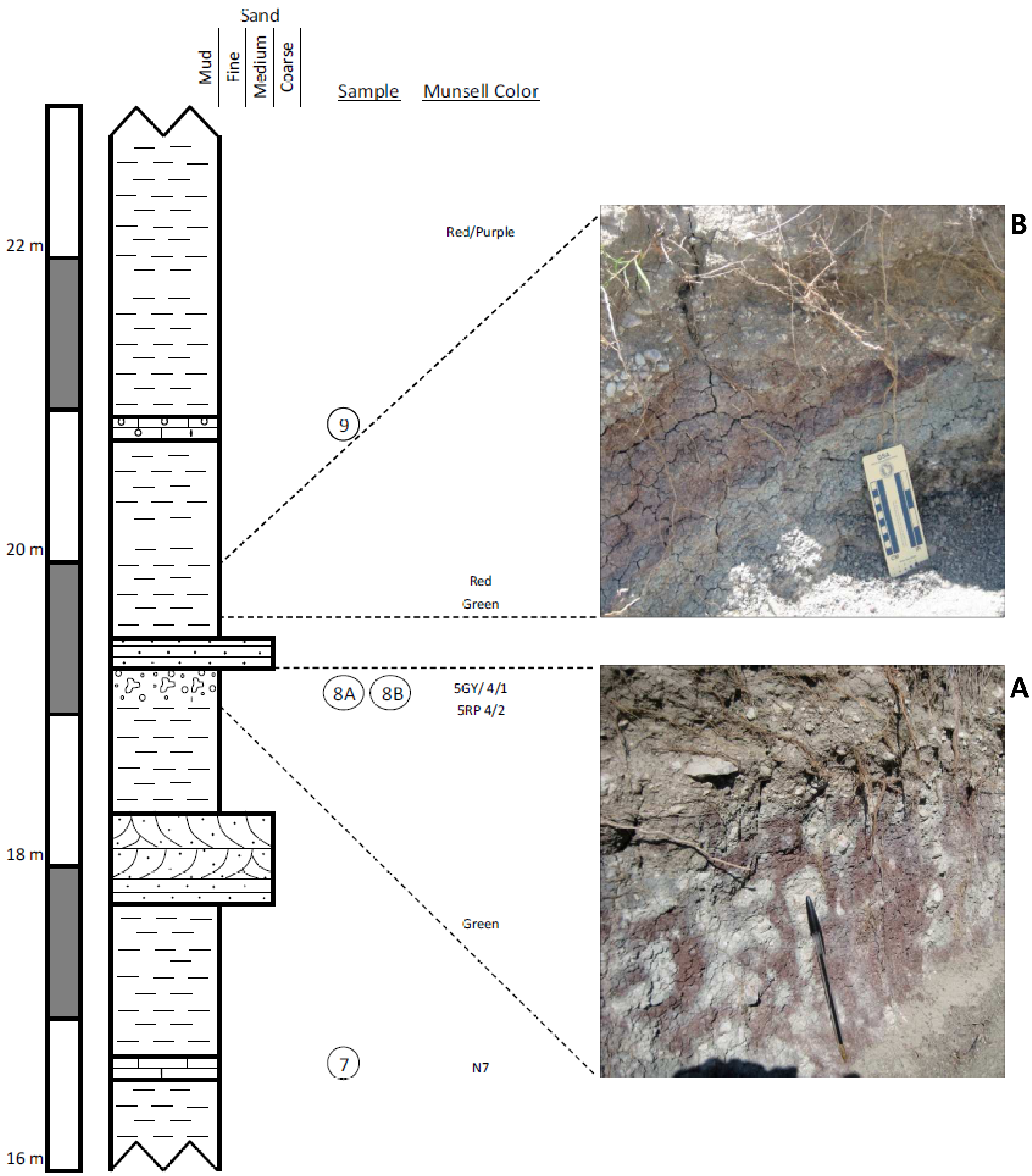

Figure 4. First Nodular Zone. (A) Mottled mudstone matrix with carbonate nodules. (B) Green and red mudstone beds with Quaternary deposits sitting unconformably on top.

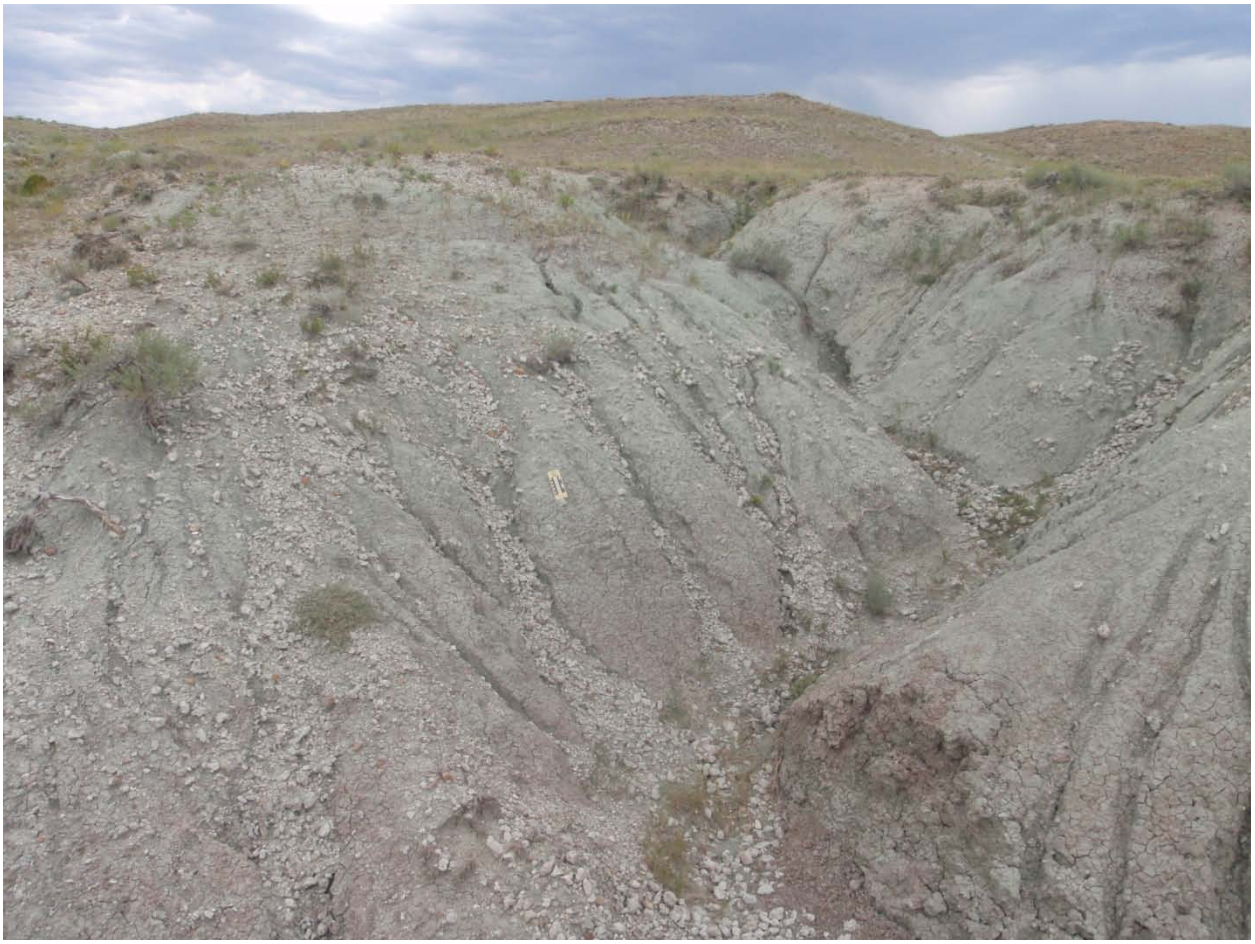

Figure 5. Carbonate nodules weathering out of the second nodular zone.

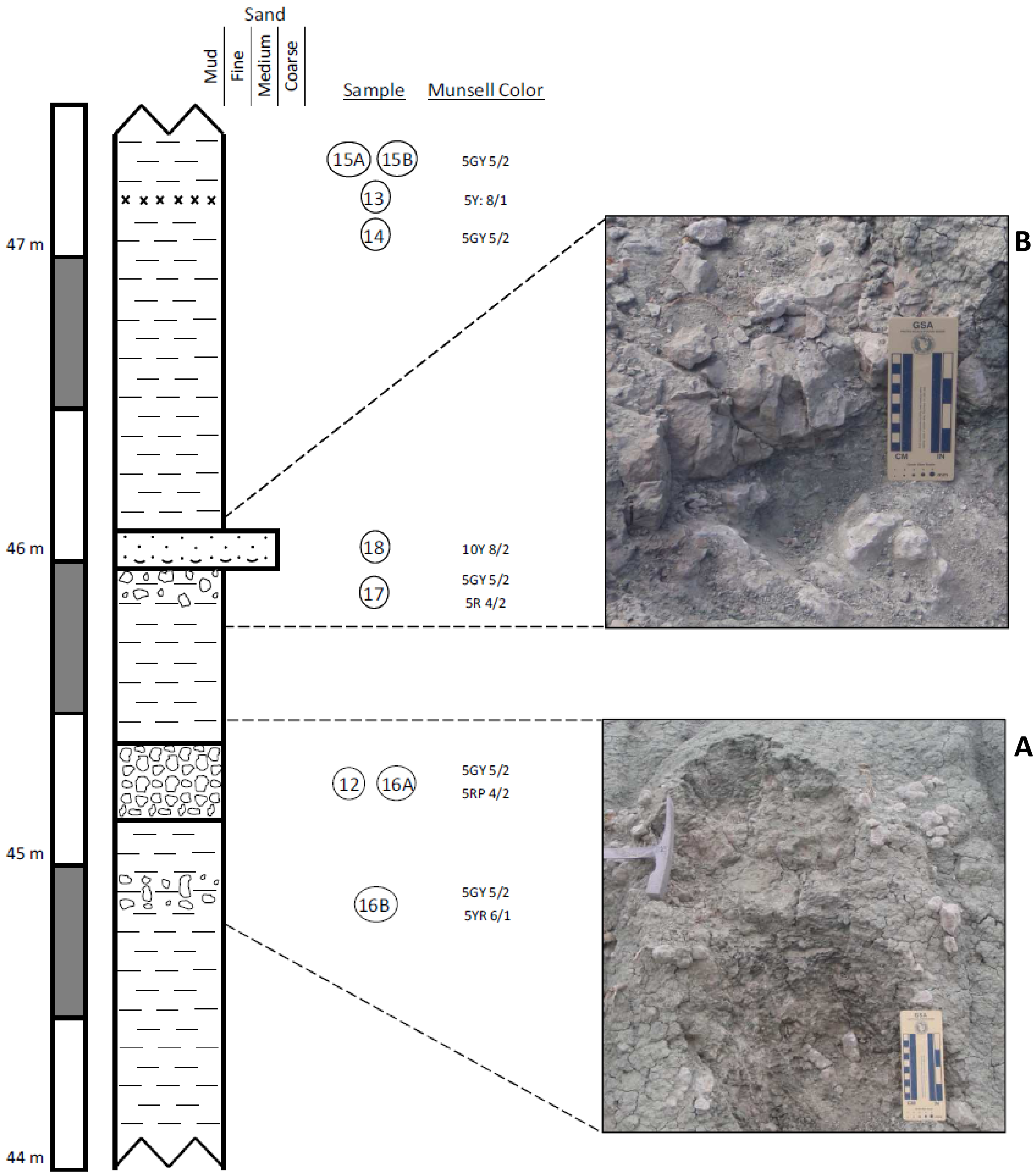

Figure 6. Second Nodular Zone. (A) Second nodular horizon marked by hammer with elongate carbonate nodules below. (B) Carbonate nodules above the second nodular zone capped unconformably by a sandstone.

5.2 MICROMORPHOLOGY

In order to help assess the depositional environment in which the carbonate nodules formed, petrographic thin sections were made. The carbonate nodules from the first nodular zone are composed of a peloidal limestone with spar occupying the pore spaces (Figure 7). The carbonate nodules from the second nodular zone are a brecciated peloidal micrite (Figure 8). These nodules exhibit both irregular and circumgranular cracks, which were subsequently filled with a sparry (possibly phreatic) cement. There are also isolated quartz and microcline grains found throughout the nodules. The nodules found 60 cm above the well-indurated horizon contain clasts of the surrounding mudstone matrix.

The fabric of the carbonate nodules differs from that of either the freshwater limestone or the marine belemnite fossils (Figure 9). The freshwater limestone is composed of nearly entirely of micrite, and does not have a peloidal fabric. Fossils of ostracods, gastropods, and other freshwater organisms are preserved in the limestone. The belemnite fossil is composed of sparry calcite with a radiating fabric.

The green mudstone matrix is made up of approximately 70% fine clays and 30% quartz (Figure 10). The quartz grains range in size from silt to very fine sand, and they are sub-angular to sub-rounded. There are also a few isolated microcline grains. Plasmic fabric is preserved within the clays. The Morrison sandstones range from fine to very fine grained and are composed mostly of quartz, with accessory minerals of microcline, plagioclase, and biotite. Most of the sandstones have some percentage of carbonate cement, with some completely cemented by calcite (Figure 11). The existence of green mudstone and carbonate rip-up clasts within the sandstones in the middle of the Morrison Formation is evidence for sub-aerial exposure of the green mudstone.

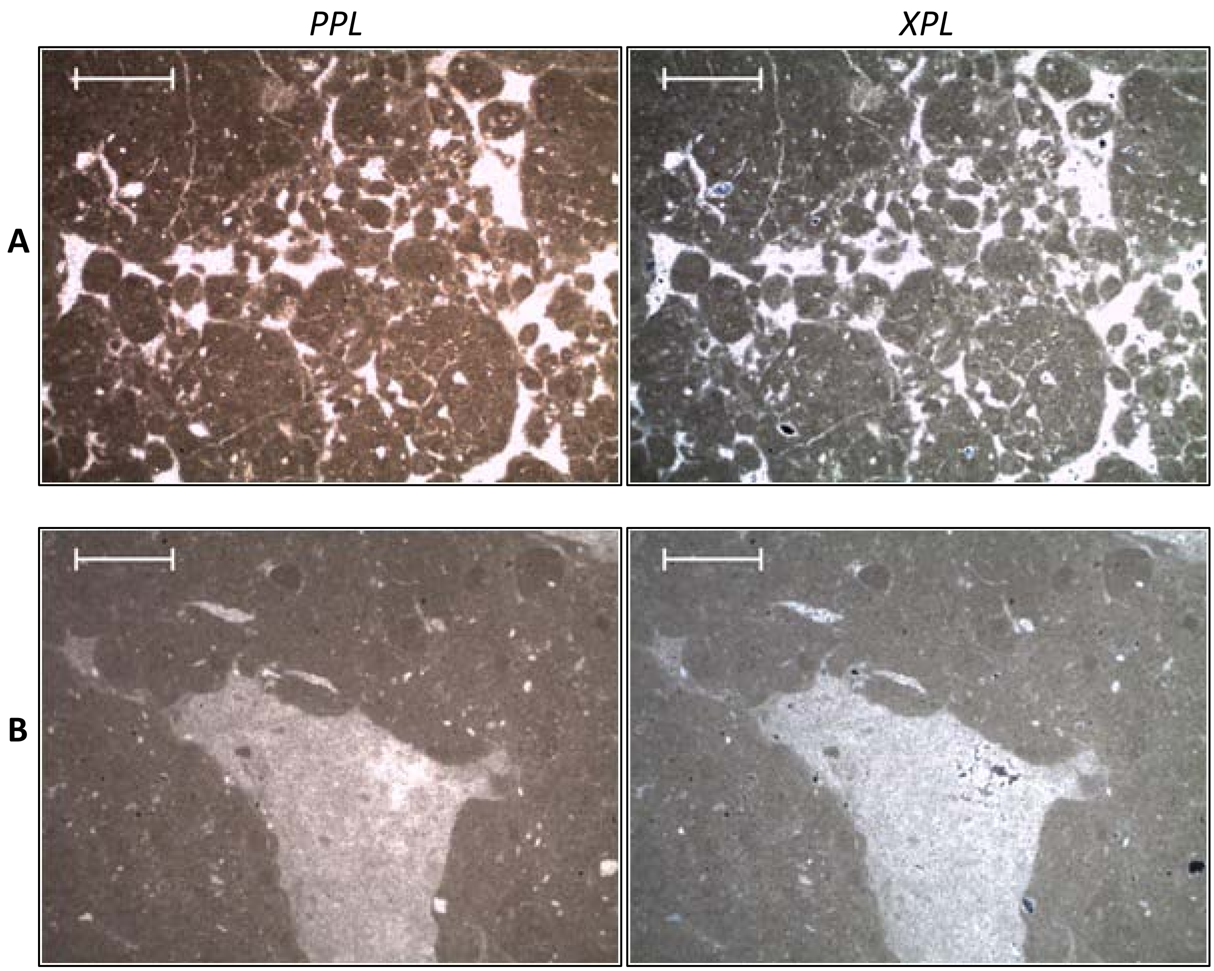

Figure 7. Photomicrographs of the first nodular zone. (Scale Bar= 500 μm)

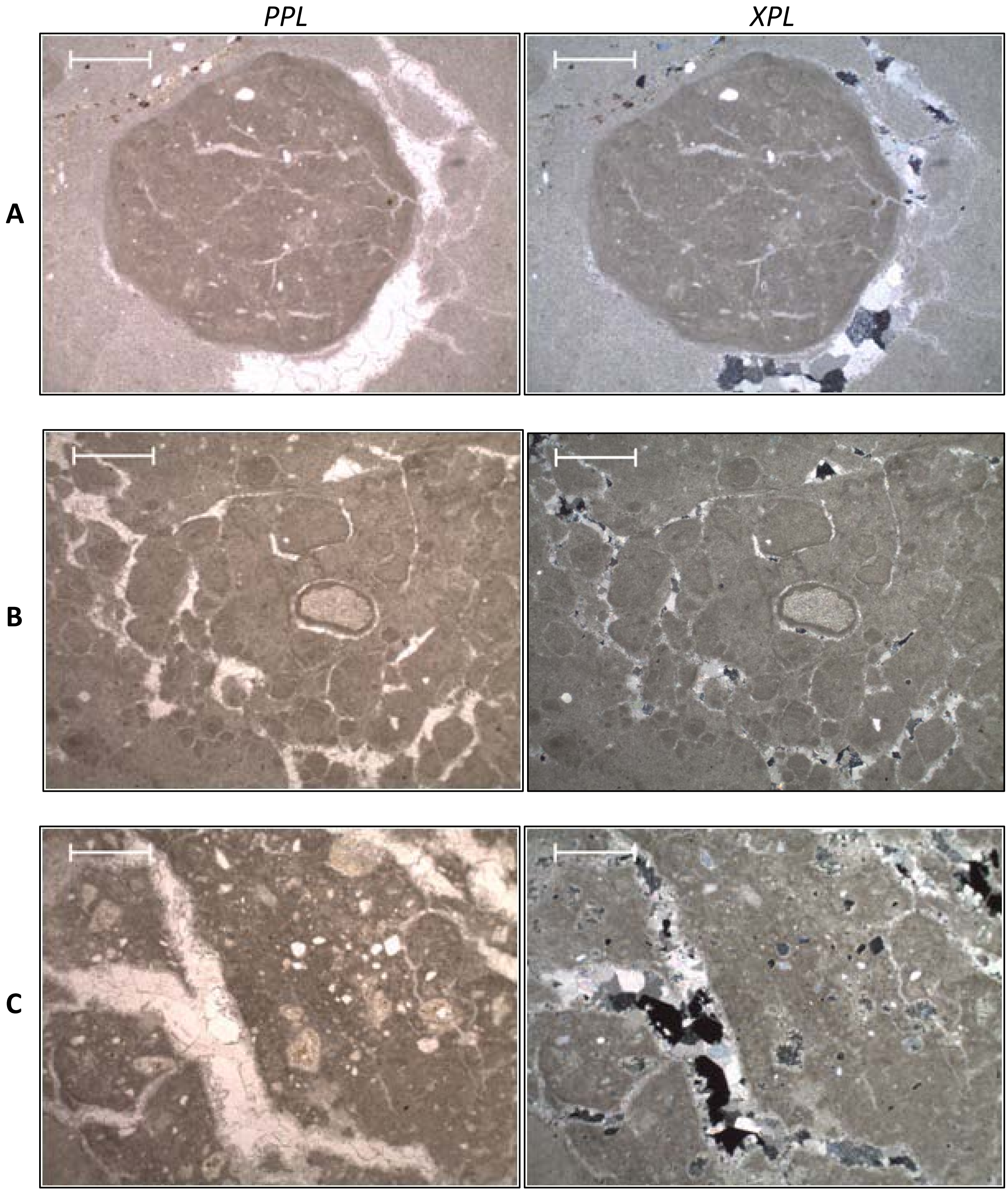

Figure 8. Photomicrographs of the second nodular zone. (A) Well-indurated nodular horizon. (B) Nodular zone 20 cm below the well-indurated horizon. (C)Nodular Zone located 60 cm above the well-indurated horizon. (Scale Bar= 500 μm)

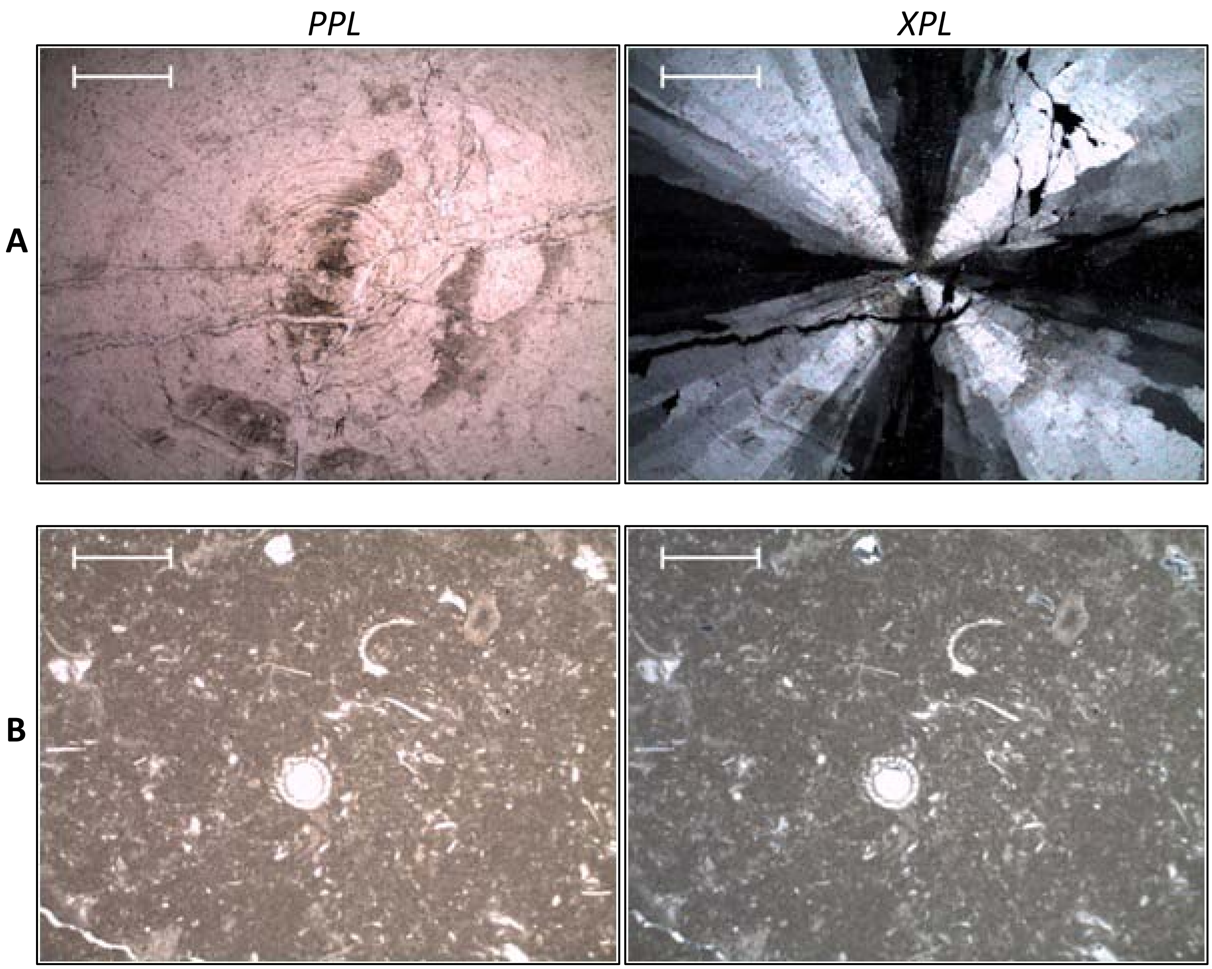

Figure 9. Photomicrographs of (A) a belemnite fossil and (B) a freshwater limestone (Scale Bar= 500 μm)

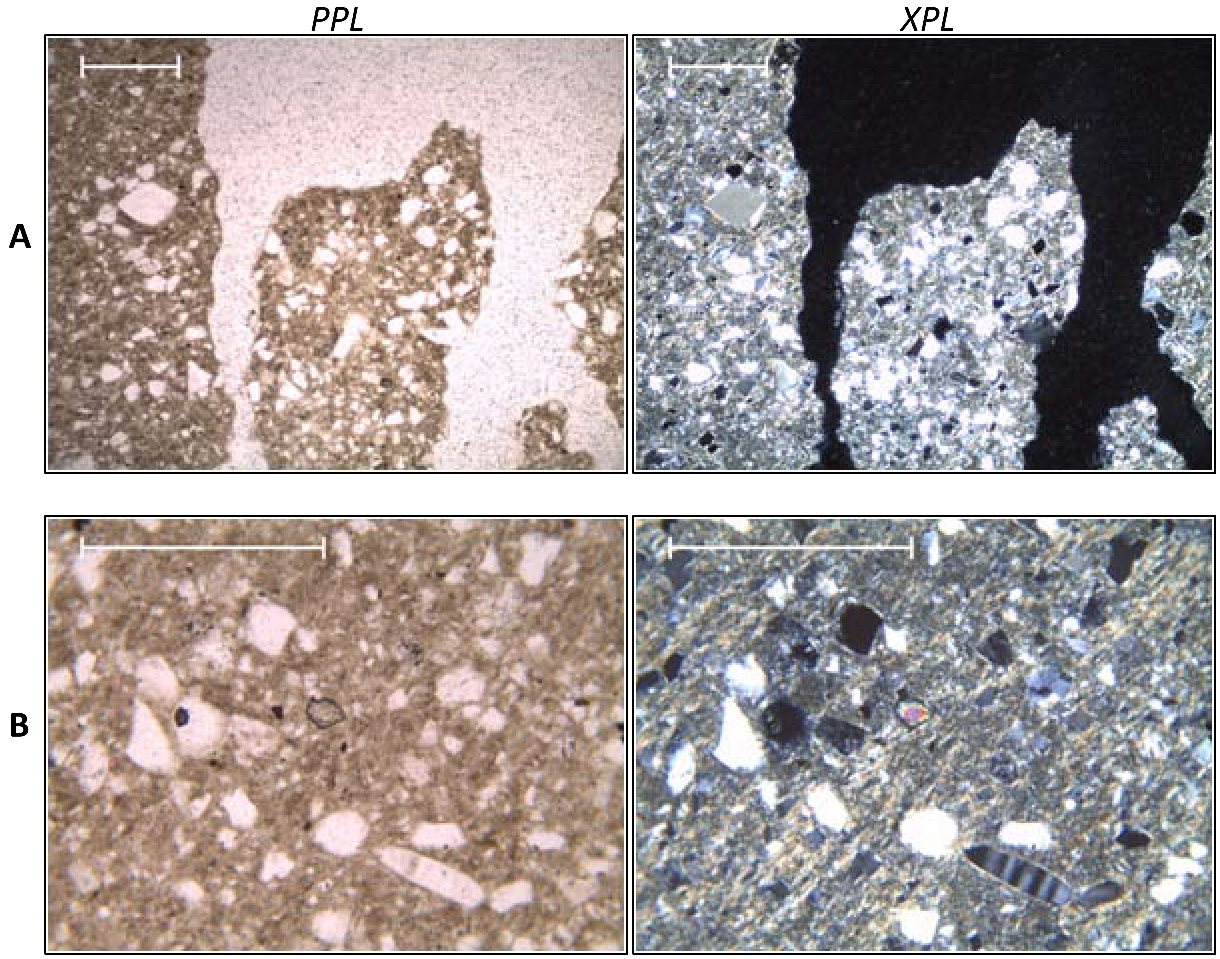

Figure 10. Photomicrographs of the mudstone matrix. (Scale Bar= 500 μm)

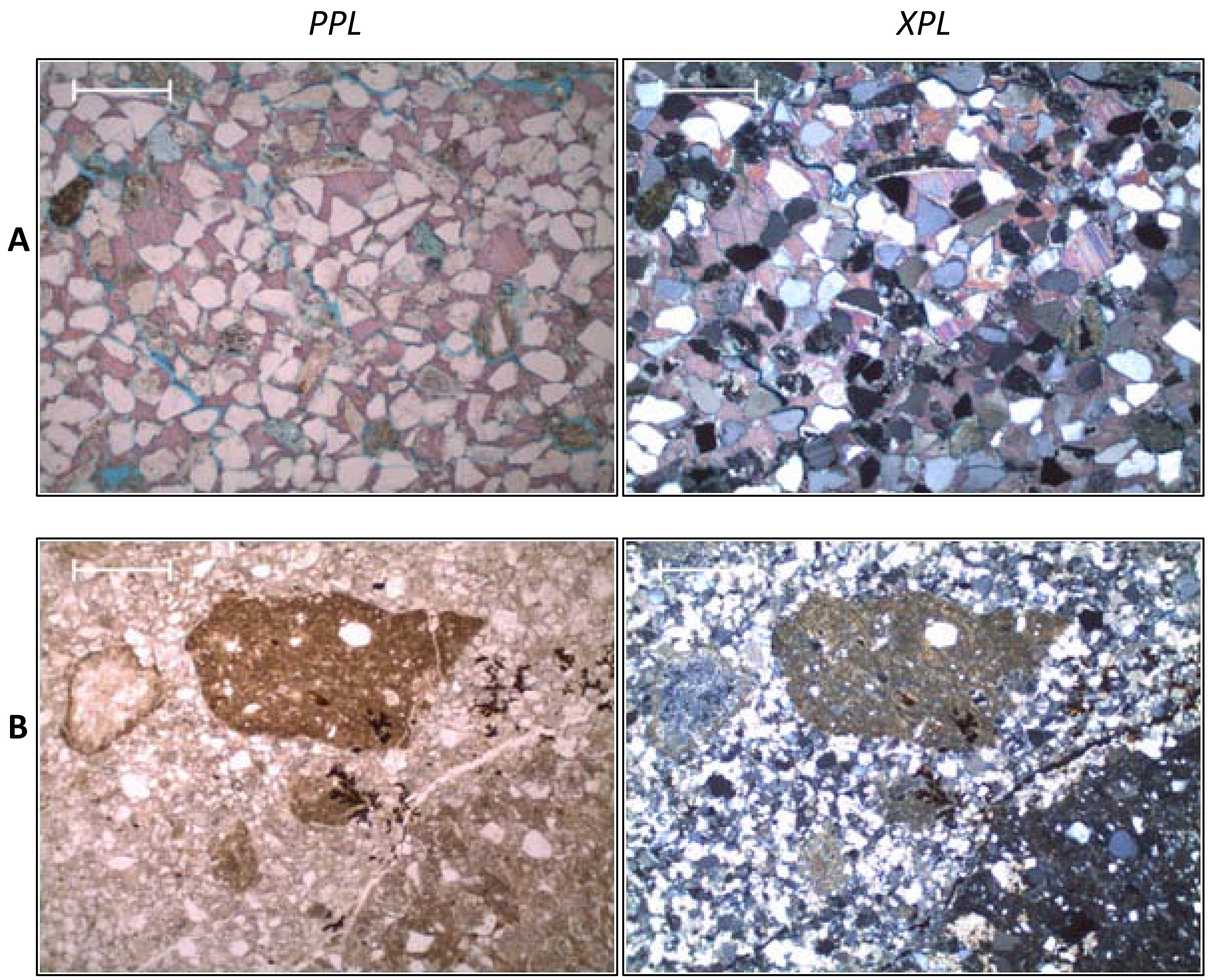

Figure 11. Photomicrographs of sandstones. (A) Carbonate cemented sandstone from the middle of the Morrison, carbonate minerals are stained pink. (B) Sandstone with rip-up clasts from just above the second nodular zone. (Scale Bar= 500 μm)

5.3 ISOTOPIC GEOCHEMISTRY

Strontium (Sr) isotope signatures can be used as a tracer to understand the sources of Sr and other cations in both marine and the terrestrial environments (see reviews by Capo et al., 1998; Banner 2004 and references therein). Differences in strontium isotope ratios (expressed as $^{87}Sr/^{86}Sr$) within carbonate minerals arise from variation in the Rb/Sr ratio of their sources. In contrast to the stable isotopes of oxygen and carbon, natural mass fractionation effects are small, and the Sr isotope ratio reflects only the relative contributions from isotopically distinct sources. Because of the long residence time of Sr in the oceans, the $^{87}Sr/^{86}Sr$ of seawater is extremely homogeneous (within ±10 ppm). Unaltered marine carbonates (e.g., limestones and calcareous fossils) record the $^{87}Sr/^{86}Sr$ of the seawater that they precipitated in; this has been used to develop chemostratigraphic correlations of Sr isotopic composition with time (e.g., Burke et al. 1982).

Previous work has demonstrated the utility of Sr isotopic analysis in pedogenic studies of calcrete (e.g., Capo and Chadwick, 1999). The primary sources of Sr in paleosols are primary minerals in the original parent material and exogenous materials introduced by wind and precipitation. These are cycled through the soil system and preserved in secondary minerals (e.g., pedogenic carbonate and clay minerals). If the sources of Sr have distinct and relatively constant $^{87}Sr/^{86}Sr$ ratios, the isotopic composition of the different system components can then be used to identify and calculate the magnitude of fluxes from the endmember sources.

Strontium isotopic ratios were determined for selective sequential extractions of seven samples. These samples were chosen with the objective of establishing potential sources that the carbonate nodules could be compared to. This includes Jurassic seawater (HOAc leachate of the belemnite fossil), the terrestrial/lacustrine carbonate (HOAc leachate of the freshwater limestone), and the silicate weathering signature (HCl fraction from the terrigenous sediment and mudstone matrix).

The results are shown in Table 1. The $^{87}Sr/^{86}Sr$ of the belemnite is low (0.70863) and reflects the composition of Jurassic seawater (Jones, et al. 1994). The $^{87}Sr/^{86}Sr$ values from the carbonate nodules are equivalent with that of the freshwater limestone. The samples representing the silicate weathering end member all had higher $^{87}Sr/^{86}Sr$ values (Figure 12).

Table 1. $^{87}Sr/^{86}Sr$ Results

Sample	**Type**	**$^{87}Sr/^{86}Sr$**		
		NH_4OAc Leachate	*HOAc Leacahate*	*HCl Leachate*
00	Belemnite (Marine)	-	0.70683	-
07	Freshwater Limestone	-	0.70779	-
13	Terrigenous Sediment	0.70894	-	-
14	Mudstone Matrix	0.70900	-	0.70845
16A	Carbonate Nodule	-	0.70778	-
17	Carbonate Nodule	-	0.70779	-
18	Sandstone	0.70902	-	0.70789

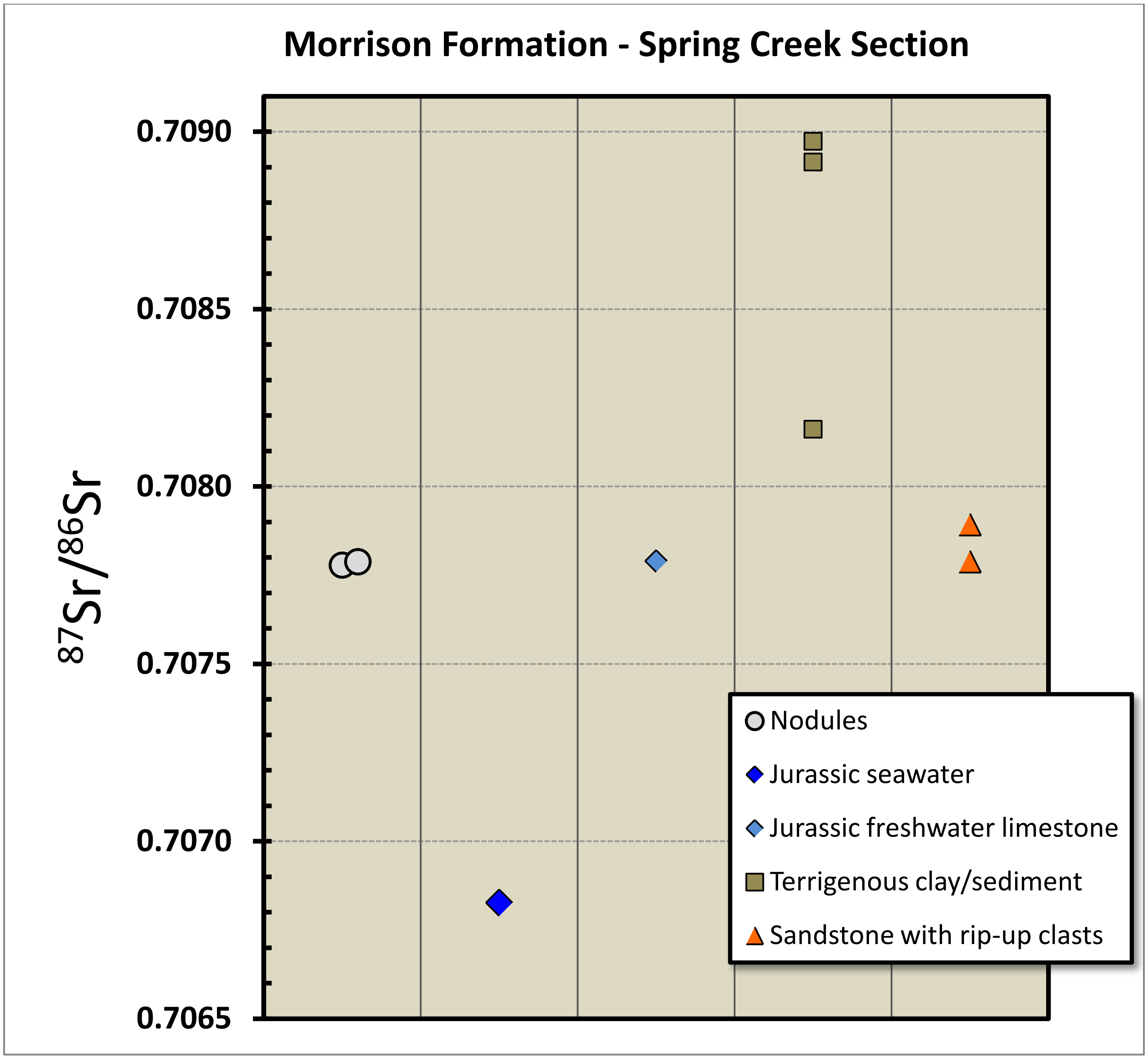

Figure 12. Strontium Isotope Results

6.0 DISCUSSION

6.1 STRATIGRAPHIC CORRELATION

In order to assess the correlative potential of the carbonate nodules from the Spring Creek Preserve with Allen's "Boundary Caliche," comparisons were drawn with his Como Bluff section because of its close proximity (Figure 13). A measured section from Ninemile Hill, another nearby Morrison Formation locality, was also included in this comparison (Trujillo 2006). The thicknesses of all three sections are similar, ranging between 82.5 and 86.5 meters (Table 2). The "Boundary Caliche" at Como Bluff sits 43 meters from the base of the Morrison Formation. This is very close to the location of the second nodular horizon, which sits 42.2 meters above the base of the Morrison Formation. A nodular horizon is also present at Ninemile Hill at a height of 44 meters in the section, although there is no available description of this horizon. In the upper part of the Morrison Formation, a chert bed also sits a similar height in all three sections. These locations of this bed fall within a range of 7 meters. However, this bed may not be ideal for lithostratigraphic correlations. Its lateral extent at the Spring Creek Preserve could not be determined, and detailed descriptions of this bed are not available from either Como Bluff or Ninemile Hill.

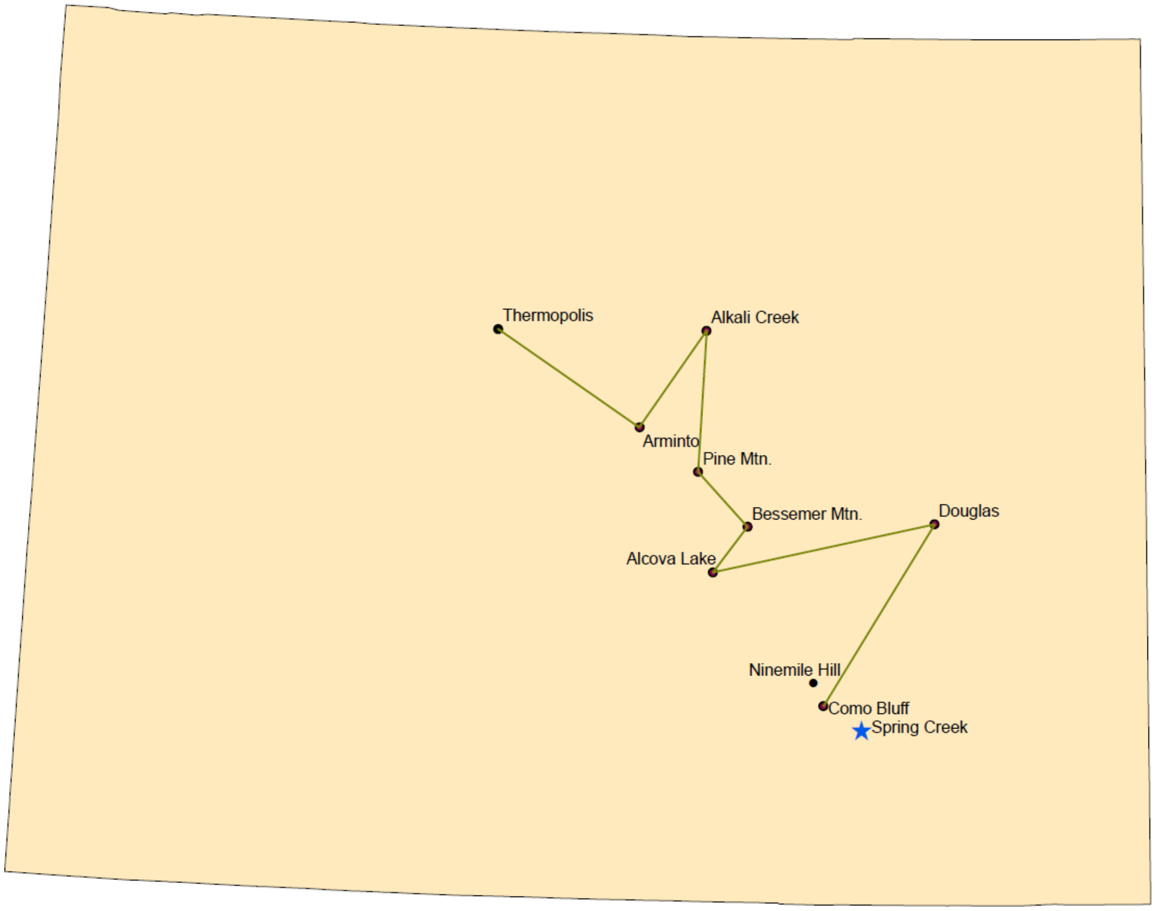

Figure 13. Morrison Formation localities in central and southeastern Wyoming. The sites connected by the solid line represent the sections measured by Allen (1996). Ninemile Hill was measured by Trujillo (2003).

Table 2. Stratigraphic Comparison between the Spring Creek Preserve, Como Bluff, and Ninemile Hill.

	Spring Creek Section *(This Study)*	**Como Bluff Section** *(Allen 1996)*	**Ninemile Hill Section** *(Trujillo 2006)*
Nodular Horizon: (Height in Section, m)	42.2	43	44
Chert Bed: (Height in Section, m)	68.1	74	75
Total Thickness of Section (m)	82.5	84	86.5

A carbonate nodular horizon exists at a nearly identical stratigraphic height in the middle of all three of these sections. In addition to this point, the nodular horizons at all three sites are underlain by a red mudstone. This suggests that the second carbonate nodule horizon from the Spring Creek Preserve is a potential stratigraphic marker that can be used for correlations between sites in Wyoming.

6.2 INTERPRETATION OF MORRISON FORMATION CARBONATES IN THE SPRING CREEK PRESERVE STRATIGRAPHIC SECTION

The Morrison Formation was deposited in a terrestrial setting, thus carbonates in the study area would be lacustrine (lime mud; travertine, tufa), karstic, or of groundwater or pedogenic origin (calcrete). If the carbonate units are paleosol related, they developed either on primary lacustrine carbonates (palustrine) or as the result of alteration of other carbonate or silicate parent material and/or the atmospheric introduction of calcium in precipitation or dust.

In uppermost limestone bed, the micritic texture (~1 micron diam carbonate crystals) and ostracod fragments indicate that this is a freshwater lacustrine carbonate, formed by the lithification of lime mud in a freshwater lake (Figure 9B).

Palustrine carbonates are the result of subaerial exposure and pedogenic alteration of primary lacustrine lime muds and limestone; evidence includes root traces, desccation, pedogenic textures (Freytet 1984). Characteristic palustrine microfabrics (described by Freytet and Verrechia 2002 and Alonso-Zarza 2003) that are present in the Spring Creek nodular beds and associated units include:

1. *Nodular and brecciated limestones* (as single beds in this case); cm-scale irregular micrcrystalline carbonate nodules; sometimes tightly packed and cemented; sometimes embedded in clay-rich siltstone. Brecciated clasts of micrite are found within the nodules (Figure 6C).

2. *Mottled zones* are observed in the field. This is likely due to the redox-related remobilization of iron under changing water table depths (Figure 4A).

3. Cracks infilled with *blocky sparry calcite* are evidence of desiccation and later possibly phreatic carbonate cementation. Circumgranular cracking is evidence of multiple generations of cracking that indicate repeated wet-dry cycles (Figure 14).

4. The *vertically-oriented nodular* (cm-scale in diameter) texture seen below the indurated limestone layer, could potentially be the remnants of calcified vertical roots (Figure 4B). Some of the elongated nodules below the indurated limestone layer contain micritic peloids, loose micrite matrix, and spar cement and are similar to those described by Alonso-Zarza (2003) (Figure 14).

5. *Peloids* (*sensu* Freytet and Verrecchia (2002) of are coated roughly 50µm to 1 mm-sized grains of rounded micrite that can have several origins: true fecal pellets, bacterial, or purely mechanical (Figures 7 and 8).

6. Clotted textures (~10-20 µm diameter homogeneous micritic objects of possible microbiologic origin) were also observed (Figures 8 and 14).

7. *Subangular ripup clast*s and carbonate *intraclasts* of material with microtextures similar to that found in the palustrine carbonate are also observed in the siltstone deposited above the nodular carbonate units (Figure 11B); these are evidence that the micritic carbonates are not the result of post-depositional diagenetic processes or an artifact of recent exposure, but had been

subaerially exposed, altered and semi-lithified prior to erosion and integration into the fluvial silt- and sandstone that buried them during Morrison time.

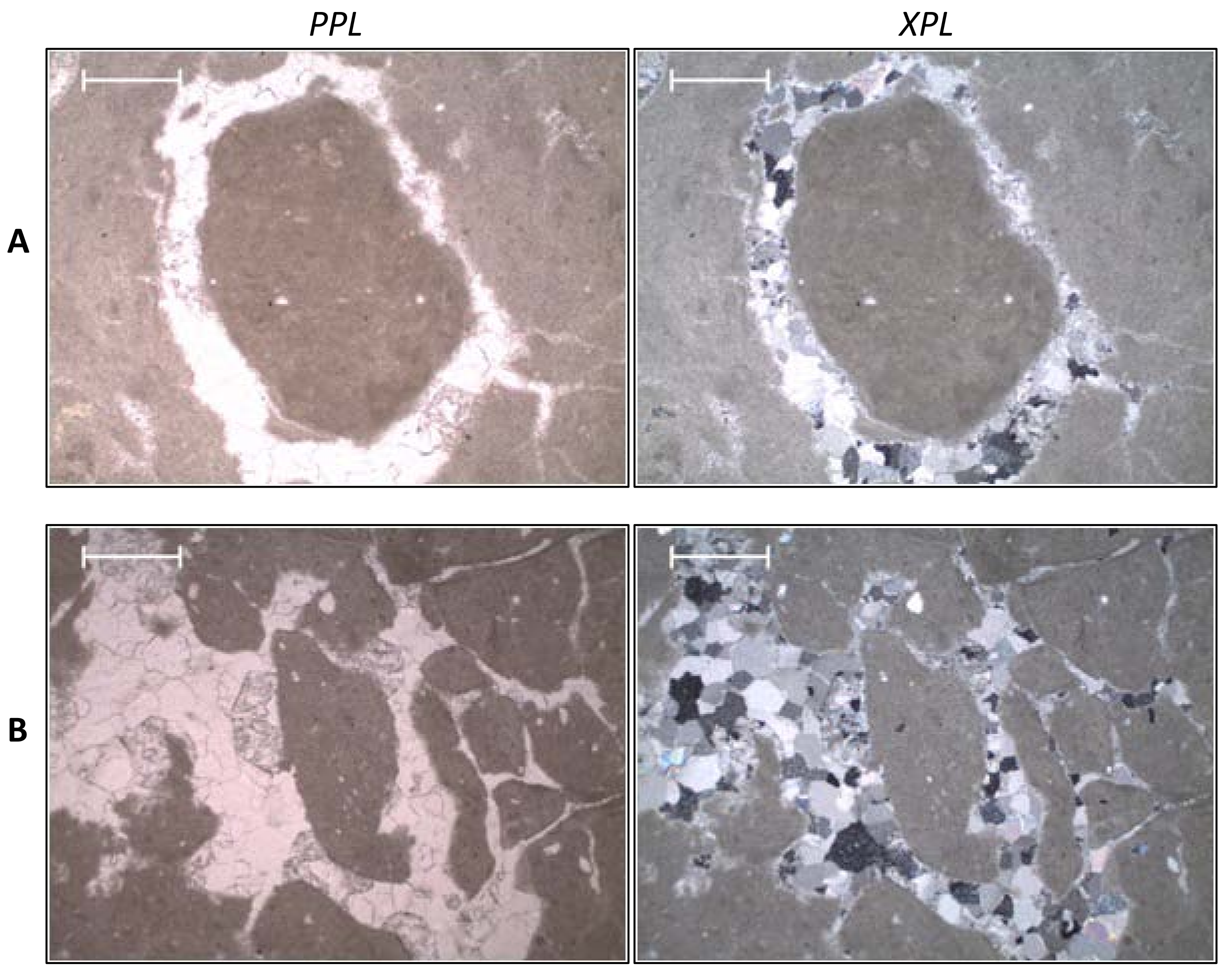

Figure 14: Photomicrographs exhibiting circumgranular cracking, and clotted textures. (A) Well-indurated nodular horizon. (B) Nodular zone 20 cm below the well-indurated horizon. (Scale Bar= 500 μm)

The strontium isotopic composition of sequential extractions of Morrison Formation carbonates and siltstones from the Spring Creek section suggest that there was minimal input to carbonate mineralization from silicate weathering or from exogenous atmospheric deposition. The nodules were most likely formed from a regional carbonate source that was altered by pedogenic and groundwater processes, resulting in secondary carbonate precipitation (sparry infillings and calcrete). The second nodular zone at 42.2 m in the section is a distinct horizon that sits at the correct stratigraphic height to correlate with Allen's "Boundary Caliche" throughout central and southeastern Wyoming. If the presence of these palustrine carbonates found throughout Wyoming is the result of a synchronous regional lake-level lowstand as suggested by Currie (1997), it is plausible that this nodular horizon correlates to the Mid-Morrison paleosol unconformity identified by Demko, et al. (2004) in Utah and Colorado.

Strontium-isotopic analysis of a belemnite fossil from a marine limestone within the Sundance Formation in the study area yields an 87Sr/86Sr ratio of 0.7068XX±0.000001, which correlates with seawater Sr-isotope data obtained from the Oxfordian stage of the British Late Jurassic (Jones et al. 1994). Gradstein et al. (2004) assign ages of 161 and 157 Ma to the lower and upper boundaries of the Oxfordian, respectively. The Oxfordian age is consistent with the Kimmeridgian and Tithonian biostratigraphic assignments given to the overlying Morrison Formation, plus the 148-150 Ma 39Ar/40Ar dates obtained from sanidine crystals taken from the Brushy Basin Member of the Morrison Formation in Utah and Colorado (Kowallis et al, 1998).

7.0 CONCLUSIONS

Field relationships and macro- and microtextures of nodular and calcareous units within the Spring Creek Preserve stratigraphic section of the Morrison Formation are consistent with carbonate mineral deposition of freshwater lacustrine muds and the development of palustrine limestones, nodules and calcrete as the micritic muds were exposed and desiccated. This likely occurred in a semiarid environment in topographically low-gradient, low energy ponds, lakes and seasonal wetlands that were easily affected by subaerial exposure and subsequent pedogenic and groundwater-related processes under fluctuating water table conditions. The palustrine nodules and calcretes developed from alteration of nearby lacustrine carbonates with little exogenous input. The thickness and level of development of the nodular carbonate units below the mid-Morrison unconformity at 42 m and observed in nearby localities by Trujillo (2006) suggests an extended period of subaerial exposure and desiccation in the study area during middle Morrison time, consistent with the observations of Allen (1996) for other parts of southwestern and central Wyoming, and with paleosols associated with a mid-Morrison unconformity occurring in other parts of the Colorado Plateau (Demko et al 2004). A belemnite fossil within the underlying Sundance Formation puts a Late Jurassic Oxfordian maximum age for the overlying Morrison Formation in the study area.

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