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STRATIGRAPHY, PETROLOGY, AND PALEONTOLOGY OF THE
LATE CRETACEOUS (CAMPANIAN) MESAVERDE GROUP
IN NORTHEASTERN UTAH

By

Christopher J. Ward

A report submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Applied Environmental Geoscience

Approved:

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ABSTRACT

Stratigraphy, Petrology, and Paleontology of the late Cretaceous (Campanian) Mesaverde Group
in Northeastern Utah

by

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Major Professor: Dr. Benjamin J. Burger

Department: Geology

This project examines a poorly studied sandstone ridge called Snake John Reef located 22 miles southeast of Vernal, in northeastern Utah. Previously this ridge was mapped as exposures of late Cretaceous, undifferentiated Mesaverde Group, and recently unidentified dinosaur fossils have been found along the ridge by the Utah Field House of Natural History State Park Museum. Stratigraphic sections, petrographic thin sections, and collection and study of fossils from Snake John Reef were undertaken to understand the stratigraphic relationship as well as to reconstruct the depositional environment of the dinosaur bearing units. Snake John Reef represents exposures of three late Cretaceous formations, the lower Sego Sandstone, middle Iles Formation, and upper Williams Fork Formation which can be diagnosed on differences in lithology. The units are capped by an unconformity with the Eocene Colton Formation. Fossil shark teeth (*Scapanorhynchus*, *Cretolamna*, and *Squalicorax*) are found in the lower Sego Sandstone, while dinosaur bones are located in the middle Iles Formation, and represent fragmentary but provisionally identified bones of ornithischian and tyrannosaurid dinosaurs. Fossil conifers (*Geinitzia* sp.) were also found in the Iles Formation, while fossil wood bored by *Teredo* (shipworms) is found in the upper Williams Fork Formation indicating close proximity to the ocean. This shows a marine to terrestrial transitional sequence, and an overall regression of

the coastline. Petrographic study of the sandstone units indicate that they are best classified as calcilithites composed of crystalline limestone with bituminous coal clasts. The absence of quartz grains indicate that the area represented a localized sediment starved coastal system, that may have been protected by barrier islands along a forested coastline. The presence of coal beds in the upper Williams Fork Formation indicate the presence of swamps higher in the section. Angularity of grains, abundance of poorly sorted fossil wood fragments, as well as sedimentary and paleontological evidence supports the interpretation that the coastline was prone to tropical storms that may have frequented the Western Interior Seaway during the Cretaceous Period. A major sequence boundary is found at the contact between the Sego Sandstone and Iles Formation representing a subaerial unconformity with an abundance of bioturbation 175.5 meters above the lower contact with the Mancos Shale. The Iles Formation represents a low stand system tract during a forced regression, with the upper Trout Creek Sandstone Member of the Iles Formation representing a short term transgressive system tract. In conclusion, the ridge along Snake John Reef presents a unique coastal depositional system during the final regression of the Western Interior Seaway that preserves dinosaur and plant fossils along a storm prone coastline during the Cretaceous.

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INTRODUCTION

Geologic and Geographic Context of Project Area

During the late Cretaceous (Campanian to Maastrichtian) the Western Interior Seaway regression left behind a thick set of sedimentary rocks in northeastern Utah (sandstones, coal, and mudstones; Roberts and Kirschbaum 1995). The Mesaverde Group was deposited as a laterally extensive complex of shallow water facies, including coastal-plain, flood-plain, barrier islands, and marine-shelf, with depositional environments that transition between offshore marine to fully terrestrial coastal plain fluvial influenced deposits (Roehler 1990). The Mesaverde Group is broadly defined as the sedimentary rock layers above the Mancos Shale, and below the fully terrestrial latest Cretaceous and early Cenozoic mudstones and siltstones, representing the Fort Union, Wasatch, Colton, and North Horn Formations. Because of the complex lateral variation of sedimentary facies, the Mesaverde Group has been subdivided into numerous formations and members depending on geography. In northwestern Wyoming, the unit is divided into the Fales Member, an “unnamed middle member,” and the Teapot Sandstone Member (Demar and Breithaupt 2006). However, in southwestern Wyoming in the Rock Springs Uplift, the unit is subdivided into the Rock Springs, Blair, Haystack Mountains, Allen Ridge, Iles, Almond and Williams Fork Formations (Roehler 1990). In northwestern Colorado, the group is divided into the Sego Sandstone, Iles Formation, and Williams Fork Formation (Dien and Archibald 2005). In central Utah, near Price the Mesaverde Group is divided into the Star Point Sandstone, the Blackhawk Formation, the Castlegate Sandstone, and the Price River Formation, while along the Book Cliffs the Buck Tongue of the Mancos Shale overlays the Castlegate Sandstone, with the Sego Sandstone, Neslen Formation, Farrer Formation, and Tuscher Formation overlaying the Buck Tongue Member of the Mancos Shale (Hettinger and

Kirschbaum 2002). The numerous geological terms applied to the Mesaverde Group reflect a complex of near-shore environments that resulted in laterally disconnected depositional facies that range from sand dominated deltaic environments, to coal-rich flooded ox-bows, to near shore littoral environments, and tidal-influenced mud flats. All these units were deposited during the final regression of the Western Interior Seaway during the Late Cretaceous.

In northeastern Utah, the Mesaverde Group is exposed along a ridge called Snake John Reef which extends across the Utah-Colorado border east of Jensen, Utah. The ridge is formed by erosion resistant sandstone, which dips toward the south, and was folded from the late rise of the Uinta Mountains to the north during the Laramide Orogeny. The farthest western edge of exposures of the Mesaverde Group is along the base of Asphalt Ridge forming the western edge of Ashley Valley near Vernal, Utah. Further to the west the Mesaverde Group is covered by Eocene deposits that bury the Cretaceous rocks along the southern flank of the Uinta Mountains. The Mesaverde Group in northeastern Utah has not been well studied, and unlike other regions has not been subdivided into smaller lithological units.

Paleontology of the Mesaverde Group

The recovered flora of the Mesaverde Group indicates that the climate was subtropical, with similarities to today's southeastern coast of Louisiana (Tidwell 2007; Young 1966). The Mesaverde Group has been dated to the late Campanian using ammonite biozones (Roberts and Kirschbaum 1995), but in some places likely extends up into the early Maastrichtian. Dinosaur fossils have been sporadically discovered from the unit. Outcrops near Rangely, Colorado have produced a chasmosaurine ceratopsian skull (Diem and Archibald 2005), an oviraptor humerus (Hunt-Foster and Foster 2015), and a nearly complete hadrosaur skeleton currently being excavated by a team led by Dr. Elizabeth Johnson of Colorado Northern Community College

(personal communication with Dr. Johnson). Fossils from other areas include a chasmosaurine ceratopsian skull, unassociated frill fragment (Farke 2004) and a partial skeleton of *Saurolophus* (Gates and Farke 2009) from the Rock Springs Uplift, Wyoming and hadrosaur trackways near Price, Utah and Grand Mesa, Colorado (Carpenter 1992).

Purpose of Study

The purpose of this study was to reconstruct the depositional environment of northeastern Utah during Late Cretaceous by examining the stratigraphy and petrology, as well as recovered fossils of the sedimentary rocks that compose the Mesaverde Group. The project area was limited to the Snake John Reef, a prominent ridge that extends east from Jensen, Utah across the Utah-Colorado border near highway 40. This report includes a stratigraphic column, thin-section analysis, and a description of fossils, including dinosaur bones recovered from the ridge. Data from the project area improves our understanding of the environments found along the coast of the Western Interior Seaway during the late Campanian, and how this area fits within the larger context of what we know about the geology of the Mesaverde Group throughout the western states of North America.

MATERIALS AND METHODS

In order to reconstruct the depositional environment of the Mesaverde Group along Snake John Reef, I measured a stratigraphic section using a Jacob Staff, starting at GPS coordinates N 40°17.702' W 109°14.966' and ending at N 40°17.384' W 109°15.005'. The stratigraphic section begins at the contact between the Mancos Shale and the first sandstone, and ends at the base of the Eocene Colton Formation, which was confirmed by the presence of perissodactyl mammal teeth.

Rock samples were collected from lithologic units measured in the Mesaverde Group,

and thin sections were made and studied at the USU Uintah Basin Geology Lab in Vernal, Utah. Eighteen rock samples were collected; fifteen from the sandstones, two from mudstones, and one coal seam. Sandstones were analyzed with a polarizing light microscope for grain characteristics and lithologic composition. Fossils were collected and documented when found. The dinosaur fossils in this study were previously collected by Steve Sroka and housed at the Utah Field House of Natural History State Park Museum in Vernal, Utah.

RESULTS

Stratigraphic Column

The measured stratigraphic column is 421.5 meters thick, with a lower sandstone unit and an upper interbedded sandstone, mudstone and coal unit. The basal sandstone in contact with the Mancos Shale forms a prominent resistant ridge, whereas the overlying units form a more gradual sloping hill to the south. Snake John Reef is a sinuous ridge, trending roughly east/west, but at the measured section it strikes 80° NE, with a dip of 60° south.

The basal unit of the Mesaverde Group is a 175.5 m thick massive sandstone containing a thin zone of small scale (< 15 cm) cross-beds 15 m from the top. The top contact of this lower unit is an abrupt surface with heavy bioturbation, which is interpreted as a widespread subaerial erosional surface representing a sequence boundary during the low stand of the shoreline. Marine fossils (shark teeth, fish vertebrae and bone; Fig. 7) are found low in this unit near the road cut just west of the Colorado/Utah border along highway 40, 10 miles east of the main study locality (Fig. 1). The fossil-rich basal unit at this location is a coarse-grained sandstone, with a fossiliferous zone about 8 centimeters thick. This fossil bearing layer does not extend to the main study locality.

Above the sequence boundary is a 246 m thick mudstone dominated sequence, with thick

(1 - 45 m) mudstone layers alternating with thin (0.2 - 3 m), sometimes discontinuous sandstones, and occasional thin coal seams. Some mudstone units contain very high quantities of iron concretions. Petrified wood is common throughout the mudstone units, and occasionally found in the sandstones as well. The sandstones commonly contain mudstone rip-up clasts and iron concretions, though the iron concretions are much less numerous than in the mudstones.

A thin sandstone layer 23 m above the sequence boundary (unit 14) contains centimeter-scale cross-bedding, rip-up clasts, and has produced fossilized conifer branches preliminarily identified to the Campanian-aged fossil *Geinitzia* (known in Eastern Europe and New Jersey; Burger and Ward 2016). Fragmentary dinosaur fossil material occurs between 49 m and 86.5 m above the sequence boundary.

Higher in the section, the sandstones become thinner and more sparse. Above 277.5 m from the basal contact with the Mancos Shale there are no sandstones over 0.5 m thick. Most of the sandstones are heavily stained with hematite, giving them a rusty-red color. One sandstone in particular, unit "Upper 6" on the stratigraphic section (Fig.3), is composed of about 30% petrified wood. The wood is preserved in random orientations, very jagged, and pieces range from a few millimeters long to over 4 cm. Additionally, the larger pieces sometimes exhibit small burrow casts about 0.5 cm long, attributed to *Teredo*, or shipworms (Fig. 6). Another rust-colored sandstone, unit 45, contains millimeter thick bands of lighter and darker hematite stained laminate bedding.

The Mesaverde Group at Snake John Reef is truncated by a substantial unconformity, overlain by the Eocene aged Colton Formation. The unconformity itself is not visible along most of Snake John Reef, with grey mudstone both above and below the unconformity surface. However, there is a local marker bed of white sandstone adjacent to the stratigraphic section

measuring path that is about 15 m wide and 4.5 m thick. This white sandstone and the equivalent mudstone strata to the east and west cap the Mesaverde Group at Snake John Reef. The discovery of *Eohippus* and other perissodactyl teeth in the mudstone layer above the marker bed indicate the mudstone above the marker bed is Eocene in age.

Petrographic Analysis

Petrographic analysis with a polarized light microscope revealed that the sandstones within the Mesaverde Group of Snake John Reef are calcilithites, composed of limestone fragments and bituminous coal, with varying small percentages of hematite, usually as a stain or cement. Higher percentages of bituminous coal were found in the lower units, with a gradual decrease in coal clasts upward in the section. There is a complete absence of allogenic clasts, such as quartz or feldspar within the calcilithites. The calcilithites are highly reactive to HCl acid, and likely only formed the ridge called Snake John Reef due to northeastern Utah's arid environment.

Grain sizes range from silt to fine-grained sand, with the exception being Unit 5 with a grain size of 200 - 400 μm , which places it in the medium sand grain size range. The clasts are highly angular across the entire sequence, and all well to very-well sorted except for Unit 25, which with its grain size range of 40 - 250 μm is moderately-well sorted. Resistance to weathering across the sequence ranges from virtually absent to strong, correlating with the degree of cementation, with the more resistant layers containing more cement between grains. Interestingly, the basal ridge-forming sand unit is only moderately well cemented, while multiple thinner sands higher in the section are strongly cemented, and do not form ridges.

Patterns of hematite staining differ across the sequence boundary separating the lower shallow-marine unit and the upper terrestrial unit. Hematite staining is found on the surfaces of

specific clasts in the lower shallow-marine unit, with the matrix and other clasts being clean. However, in the upper terrestrial unit the hematite stain appears to be diagenetic, crossing clast and matrix boundaries, except for in Unit 33, a calcilithite with clast-specific hematite staining. Starting with Unit 35, most of the calcilithites at the top of the section are heavily stained with hematite, such that they are rust colored in hand sample and opaque in thin section. Characteristics and thin section photographs for each stratigraphic unit sampled can be found in Appendix 1.

Dissolution tests were conducted on the rock samples using 23% HCl solution to confirm the identification of the major lithologic component as calcite. However, results were highly inconsistent, with dissolution percentages ranging from 18% up to 90%. The hematite in the rock samples also reacted to the HCl acid producing iron(III) chloride ($\text{Fe}_2\text{O}_3 + 6\text{HCl} \rightarrow 2\text{FeCl}_3 + 2\text{H}_2\text{O}$), which is an exothermic reaction. If heated on a hot plate to evaporate reactant water, glass beakers would break under the extra heat. Hence digestion of the rock samples using HCl acid required slow evaporation over several weeks. While hematite nodules within the samples are uncommon, hematite is also observed as a stain on particular grains or within the cement when the samples are viewed in thin section. So while total hematite content by percent sample mass may be low, estimates of total carbonate content may be flawed or grossly underestimated when using acid digestion while hematite is present.

Paleontology

Nine unidentified dinosaur fossils have been found from the Mesaverde Group in the study area. They were found between 224 m and 262 m from the basal contact with the Mancos Shale (Fig. 3). The largest specimen, FHPR 4268, is a vertebral centrum 20 cm in diameter and 6 cm thick (Fig. 4A). FHPR 9625 is a 20 cm long bone fragment that is missing both ends (Fig.

4B). It most likely represents the distal end of a tyrannosaurid metatarsal II. The deep groove at what would be the distal end closely matches the tyrannosaurid metatarsal II labeled D in Fig. 3 of Thomson et al. (2013). In both specimens the groove shallows proximally into a slightly concave flat bone surface, while the opposite side of the bone shaft is rounded. FHPR 9623 (Fig. 4C) is a 4 cm wide distal ungual. The distal rim is chipped, but the bases of the lateral protrusions of the bone are present on each side. FHPR 2717 (Fig. 4D) is a complete pes III-1, 5 cm wide at the proximal end and 4 cm wide at the distal end. FHPR 2718 (Fig. 4H) is a maxillary jaw fragment, possibly from the rear end of the tooth battery. The medial side of the alveoli are exposed as grooves, which are heavily weathered and coated in iron oxide, and meet a wall of bone on one side. However in cross-section, two sequential replacement teeth are visible (Fig. 4H2) behind this bone wall, and based on their broad-based triangular cross-section, the teeth identify the jaw as ceratopsian.

The rest of the specimens are smaller vertebral elements. FHPR 2721 (Fig. 4F) is a partial vertebral centrum with a partial neural arch 4 cm in diameter and 3.5 cm long. FHPR 2715 is a very small vertebral centrum, 2 cm in diameter and 3 cm long. FHPR 2725 (Fig. 4G) is a slightly larger partial vertebral centrum, 7 cm long, 5 cm in diameter at the anterior end and 5.5 cm in diameter at the posterior end. The dorsal surface shows the rugose sutural surface for the neural arch on each side of the canal for the spinal cord. Unfortunately the neural arch was not found with it.

Lastly, FHPR 2720 (Fig. 4I) is a flat bone fragment about 8 cm long, 4 cm wide and 1 cm thick. The museum labels it as a jaw fragment, but it contains no tooth elements. As it is an isolated and incomplete specimen, it cannot be identified.

The following description of the *Geinitzia* sp. fossils recovered from Snake John Reef

(Fig. 5) is reproduced from Burger and Ward (2016). The recovered fossil described here was found on a single large sandstone block, and shows the branching pattern, with four terminal branches and an isolate branch in the same slab (Figure 1). The fossil conifer branches compare closely with figures in Kunzmann (2010) and Halamski (2013) of *Geinitzia reichenbachii* from the Campanian of Europe. The branching pattern is less symmetrical and dense, and similar to modern *Sequoia* in habit. The fossils exhibited on the slab show both curved needlelike leaves extending from a wider scale-like base near the stem. This feature resembles some of the modern *Araucaria* species which show needles with a wider leaf base. The needles measure about 1 cm in length, with a wider scale-like leaf base making up about 3 mm of the total leaf length. The leaves are spirally arranged on each branch.

DISCUSSION

Depositional Environment

The overall stratigraphic sequence of the Mesaverde Group at Snake John Reef fits the sequence reported in other areas, exhibiting a transition from shallow-marine to terrestrial deposits as the Western Interior Seaway receded eastward during the late Campanian. Despite lacking any marine fossils, the lower massive calcilithite unit is thought to be shallow marine due to its stratigraphic position; overlying the marine Mancos Shale and underlying terrestrial deposits. The top of this unit exhibits a bioturbated subaerial unconformity, followed by an abrupt lithologic change to a mudstone dominant unit containing abundant terrestrial fossils such as petrified wood and dinosaur bones, none of which is found in the lower calcilithite unit. The identification of the lower unit as marine is strengthened by the presence of marine fossils such as *Scapanorhynchus*, *Cretolamna*, and *Squalicorax* shark teeth and fish vertebrae contained in equivalent strata in the nearby Roadcut locality (Fig. 2 for locality, Fig. 7 for fossils).

The Snake John Reef outcrop appears to be contiguous, if not continuous with the Mesaverde Group outcrops in Rangely (Fig. 1), Colorado, which share the same shallow-marine to terrestrial sequence, therefore the stratigraphy of Diem and Archibald (2005) will be adopted here. The lower shallow-marine massive calcilithite unit is assigned to the Segó Sandstone, a littoral sandstone at the base of the Mesaverde Group in Rangely, Colorado. The upper terrestrial unit represents the Iles Formation and Williams Fork Formations. Both formations are described as interbedded fine-grained sandstone, shale, carbonaceous shale, and coal, divided by the Trout Creek Sandstone, a “whitish-grey, fine-grained, cross-bedded sandstone ranging from 0 to 30 m in thickness” (Dyner 1968). Unit 33 in the stratigraphic section, a 10.5 m thick fine-grained calcilithite, is the thickest calcilithite in the upper terrestrial block, and tentatively identified as the Trout Creek Sandstone, with the top of Unit 33 marking the contact between the lower Iles Formation and upper Williams Fork Formation. This identification is based upon a lithologic change found across the Unit 33 boundary. Above Unit 33, all but one of the calcilithites are less than one-meter-thick and stained rust colored from their high hematite content, while calcilithites of this nature are not found below Unit 33. Additionally, the mudstone layers between the calcilithites quickly increase in thickness above Unit 33, from a range of 1 to 12 m below, to a range of 5 to 45 m above.

The subaerial unconformity 175.5 m from the basal contact with the Mancos Shale at the top of the lower Segó Sandstone represents a major sequence boundary with the overlying Iles Formation. The Iles Formation represents a low stand system tract during a forced regression, with the upper Trout Creek Sandstone Member of the Iles Formation representing a short term transgressive system tract. The Williams Fork Formation represents a return to seaway regression that continues to the top of the Mesaverde Group at the unconformity with the

overlying Eocene aged Colton Formation.

Sequence stratigraphic analyses of the Mesaverde Group have been conducted in both the Book Cliffs, UT (Legler et al 2014) and Rangely, CO (Painter et al 2013) areas. In the Book Cliffs, the Segó Sandstone is interpreted as containing four regressive-transgressive tongues of deltaic sediment. In Rangely, the lower Segó Sandstone contains fluvio-deltaic deposits that transition into a passive tide-influenced shoreline higher in the formation after large-scale river avulsion. Despite some degree of agreement between these two areas, their geographic distance and substantial lithologic differences from Snake John Reef lead me to believe that the Snake John Reef stratigraphic sequence is unrelated to what is found at the Book Cliffs or in Rangely. However, the single stratigraphic section measured for this report does not lend itself well to correlation, and a more complete sequence stratigraphic analysis of the entire ridge line may add further detail to the local sequence stratigraphy of the area as well as allow better correlation between Snake John Reef and other Mesaverde Group outcrops.

The limestone composition of the area lends itself to some interpretations atypical of Mesaverde Group deposits elsewhere in the US. The rapidly uplifting Sevier Orogeny just west of the area should have been contributing a substantial quantity of erosive quartz and arkosic sediment to the area. Roehler (1990) reported lithologic compositions from the Green River Basin of 46.5% - 72% quartz, 3 - 10% feldspar, and 16.5 - 25% lithics, and abnormal sandstone compositions have not been reported from the Mesaverde Group in neighboring areas (Roberts and Kirschbaum 1995; Hettlinger and Kirschbaum 2002). The limestone dominant clasts in the calcilithites of Snake John Reef indicate a sediment starved depositional system lacking any rivers contributing erosive sediment from nearby orogenic events. The area would also have to have been protected from any longshore currents that could bring quartz sediment to the area,

perhaps by other geologic or sedimentological structures that are not preserved.

Further complicating the sediment source is the high angularity of the grains. Typical shallow-marine sediment has been thoroughly tumbled by wave action and become well rounded. Highly angular calcite grains, a much softer mineral than quartz, indicates wave energy was low with minimal clast transport. The sediment must be locally derived, but a source of nearby limestone has not been identified. Furthermore, the locally low energy conditions must have persisted through to the end of Mesaverde deposition, because the terrestrial calcilithite deposits in the Iles and Williams Fork Formations possess the same limestone composition and high angularity as the lower shallow-marine Segó Sandstone.

The thin calcilithites in the terrestrial Iles and Williams Fork Formations are, other than variations in grain size, lithologically the same as the underlying shallow-marine Segó Sandstone. If they represented short term transgressions of the Western Interior Seaway and were littoral sands, the grains would be expected to be more rounded from being tumbled by waves. However, they are just as angular as in the Segó Sandstone, indicating a similar lack of wave-action and tumbling. An alternative explanation is that they are storm deposits. The climate along the coast of the Western Interior Seaway during the late Cretaceous was subtropical, similar to the gulf coast of the U.S., and should have been subjected to tropical storms just like the southern states are today. Powerful storms wash marine sediment well inland (Keen and Stone 2000), where it drops out of suspension once the energy of the storm fades. This type of deposition does not cause a significant amount of grain tumbling; the grains are picked up and moved quickly, then redeposited and do not move much afterwards. This allows the grains to stay angular, as observed at the Snake John Reef locality. Modern storm deposits form bars and berms well away from the coast (Keen and Stone 2000), which may explain the inconsistent thickness and

discontinuity of these calcilithite layers. The storm deposits also decrease in frequency up section, which fits with the seaway retreating eastward from the area.

The other peculiar aspect of the calcilithites of Snake John Reef are the bituminous coal clasts found throughout the sequence. The upper terrestrial units contain 3 coal seams and abundant petrified wood, indicating that the coastline was most likely swampy. In describing Mesaverde Group stratigraphy in the Book Cliffs of Utah and Colorado, Young (1966) described a cycle of coastal lagoons forming behind barrier beaches and then filling in with swamps that were eventually buried under new beaches as the coastline advanced seaward, leaving peat deposits below the surficial littoral sands. In the sediment-starved local depositional environment of Snake John Reef, these peat deposits would not have been buried deep enough to coalify during the Cretaceous, but total sediment accumulation over time may have been low enough that powerful storms could scour down to the peat beds, eroding them and working organic matter back into the local sediment. This organic matter would later coalify when the Mesaverde Group was buried under Cenozoic sediment, creating the coal clasts present in the deposits today. Since the barrier beaches/islands integral to this scenario are also involved in explaining the high grain angularity of the deposits at Snake John Reef (by dampening wave energy in the area), they provide two-fold support for this interpretation. The resulting picture is a coastline very far from any rivers, lined with a chain of barrier beaches that protect the coastal swamps behind them from wave action, which is also protected from longshore currents that could bring quartz sand to the area. One possible reconstruction can be found in Fig. 8.

Paleontology

The fossil material of Snake John Reef serves as an initial indicator of the potential for the area to produce more fossil material in the future. All fossil material collected from the area

to date has been collected at the surface. As the material is exposed by erosion from annual winter rain and snow, quarrying may produce more complete material that hasn't been subjected to present day erosive forces.

During the late Campanian around 75.5 Ma, new Laramide uplift east of the Sevier Orogeny created a north/south biogeographic boundary, segregating, among many animal groups, the hadrosaurian dinosaurs. This boundary placed *Maiasaura*, *Prosaurolophus*, and later *Saurolophus* on the north side, and *Gryposaurus* and *Kritosaurus* on the south side (Gates et al. 2012). Based on their identification of *Saurolophus* material from Barnum Brown's 1937 expedition to the Campanian aged Almond Formation in southern Wyoming, Gates and Farke (2009) predicted that the segregation boundary would be found in the northern Utah/northern Colorado region. The Snake John Reef locality sits squarely within this region, and material recovered from this area that could be identified to genus or species may provide important geographic data points for the delineation of this biogeographic boundary hypothesis.

Currently, all fossil material recovered from the Snake John Reef locality are isolated, fragmentary specimens that cannot be identified to genus or species. But the presence of fossil material indicates the potential for the area to produce more complete specimens in the future. To date, all fossil material recovered from Snake John Reef has been found via prospecting. The material appears to be exposed by erosion from annual rain and snow, as fossils are found most abundantly at the beginning of each summer. It's possible that more complete material lays further underground, and discovery of a suitable quarry may produce material identifiable to genus or species.

CONCLUSION

Examining the previously undescribed Mesaverde Group at Snake John Reef in northeastern Utah has revealed a marine to terrestrial transitional sequence typical of the Mesaverde Group. However, it represents a protected, sediment starved coastal depositional system that is atypical of the Mesaverde Group, completely lacking quartz sediment and instead containing calcilithites composed of crystalline limestone. The area was occasionally hit with tropical storms that left thin discontinuous calcilithite deposits over the coastal plain. The area is sparsely fossiliferous, and has produced fragmentary dinosaur material, as well as conifer branch fossils referred to *Geinitzia*.

There is a high potential for future research in the area. Conducting a full sequence stratigraphic analysis, as well as correlating the area to Mesaverde Group outcrops in other regions requires additional stratigraphic sections. Additionally, future prospecting for fossils could help reveal a new dinosaur record from northeastern Utah. This research highlights the transitional nearshore marine and terrestrial depositional environment during the final regression of the Western Interior Seaway in northeastern Utah, along a late Cretaceous storm-prone coastline.

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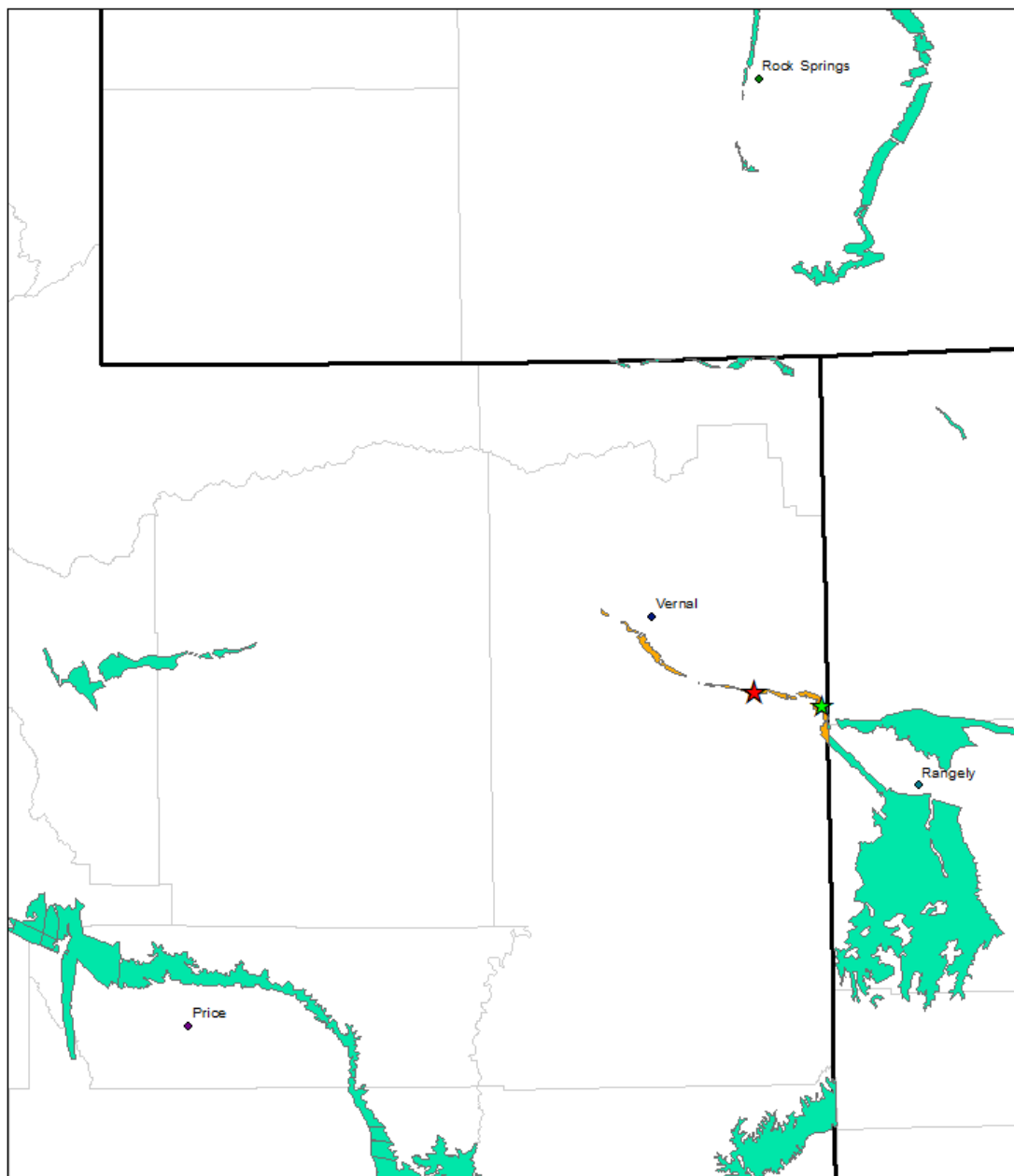
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Fig. 1: Regional map of the Mesaverde Group.



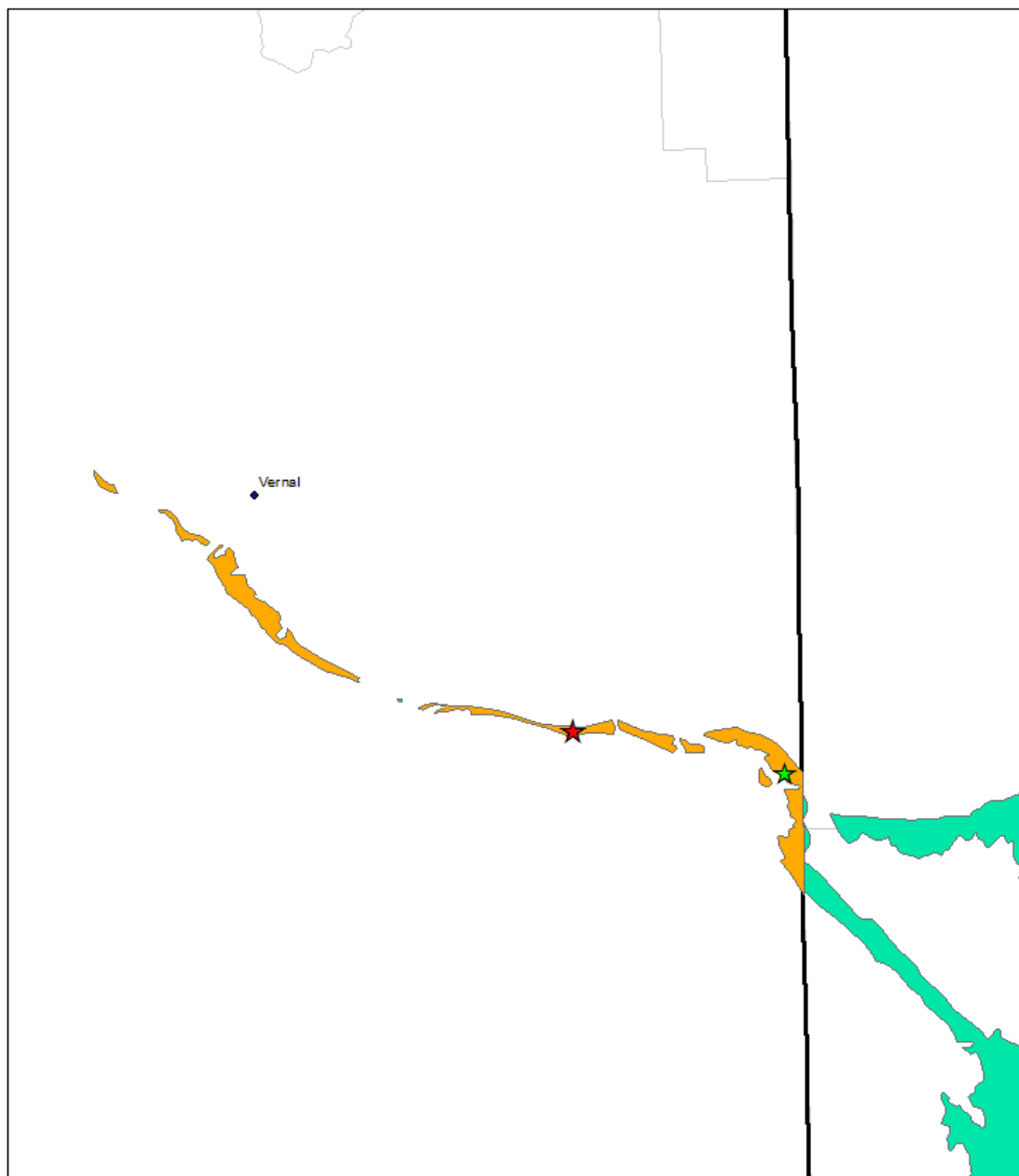
Mesaverde Outcrops of northeastern Utah

Legend

- ★ SJR Locality
- ★ Roadcut Locality
- Orange Snake John Reef
- Green Mesaverde Outcrops

Data provided by the Utah Geological Survey,
Colorado Geological Survey, and Wyoming Geospatial Hub
Map by Chris Ward 6/26/16

Fig. 2: Local map of the Mesaverde Group and study area.



Mesaverde Outcrops of northeastern Utah

Legend

- ★ SJR Locality
- ★ Roadcut Locality
- Snake John Reef
- Mesaverde Outcrops

Data provided by the Utah Geological Survey,
Colorado Geological Survey, and Wyoming Geospatial Hub
Map by Chris Ward 6/26/16

Fig. 3: Stratigraphic section. Many lithologic units are too thin to show at this scale. For field descriptions of each unit, see Table 1. Credit to Ben Burger for digitizing my sketch.

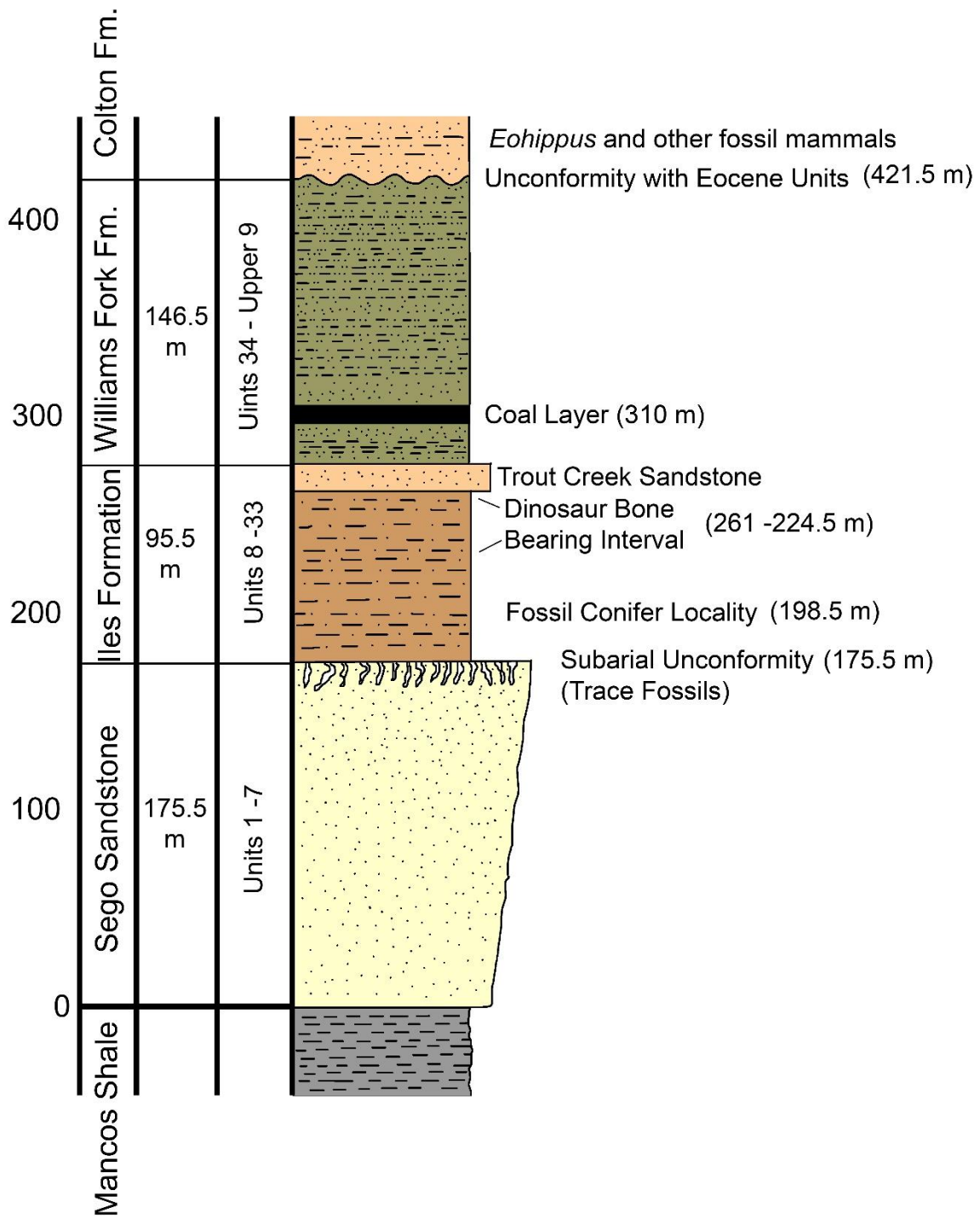


Table 1: Lithologic descriptions of each unit.

Unit #	Thickness (m)	Description
1	10.5	Tan/grey calcilithite, lenticular beds, very fine grained, forms the ridge at the basal contact with the Mancos Shale
2	12	Tan/grey calcilithite, mostly covered, fine grained
3	21	Grey fine grained calcilithite
4	4.5	Tan/grey fine grained calcilithite
5	112.5	White/grey calcilithite, coarsening upwards from fine grained to medium grained. Hematite staining is sparsely distributed throughout. The top meter contains substantial decimeter-scale cross-bedding. Steve Sroka calls this the "Uranium Sand," referring to an abandoned uranium mine found at the base of this unit. The hole is deeper than the eye can see - don't fall in!
6	15	White/grey calcilithite, medium grained, bioturbation, heavy organic matter content. Subaerial unconformity and sequence boundary.
7	1.5	White/grey calcilithite, medium grained, bioturbation, heavy organic matter content. Subaerial unconformity and sequence boundary.
8	1	Light brown mudstone.
9	0.7	Tan calcilithite, fine grained.
10	2.5	Coal
11	4.5	Light brown mudstone.
12	3	Tan calcilithite, very fine grained. Underside shows dissolution holes, bioturbation/burrows, petrified wood, rip-up clasts. The first "Temple Wall."
13	9	Tan mudstone.
14	1	Tan calcilithite; despite forming a wall of resistant rock about 3 meters tall, the grains range in size from 20-40 μ m, which technically falls within the grain size range for silt. Contains <1cm iron concretions, rip-up clasts, lithics, 3cm crossbeds. The Geinitzia branch fossils are found in this layer.
15	1.5	Tan/grey silty calcilithite.
16	1.5	Tan calcilithite, fine grained, thin shingly bedding.
17	4.5	Light brown mudstone. Petrified wood.
18	3	Grey calcilithite, grain size range 30-60 μ m, placing it in the grain size range for silt. <1cm iron concretions.
19	7.5	Tan calcilithite, grain size range 20-60 μ m, placing it in the grain size range for silt.
20	3.5	Light brown mudstone. Petrified wood.
21	0.3	Tan calcilithite, fine grained.
22	3	Light brown mudstone.
23	1.1	Orange/brown calcilithite, fine grained. Makes a prominent wall stretching across much of the area, with roughly rectangular fractures throughout. The second "Temple

		Wall." Current lower boundary of dinosaur bone bearing interval.
24	11	Mottled grey, tan, and reddish mudstone. Numerous bands of broken iron concretions, so it may count as a paleosol. Abundant petrified wood.
25	1	Brown calcilithite, fine grained. Very hard and resistant to weathering. Inconsistent exposure, more like a row of individual calcilithite blobs.
26	6.5	Tan mudstone. Petrified wood.
27	0.5	Brown calcilithite, fine grained. Thin beds, inconsistent exposure.
28	5	Tan mudstone.
29	0.5	Brown calcilithite, fine grained. Thin beds, seems to contain softball sized concretions of the same brown calcilithite sediment. Inconsistent exposure.
30	12	Tan mudstone, abundant iron concretions in layers.
31	0.7	Brown calcilithite, very fine grained. Thin beds. Inconsistent exposure. Current upper boundary of dinosaur bone bearing interval.
32	3	Moved about 30 meters west due to lack of exposure. Tan/grey mudstone, abundant iron concretions in layers.
33	10.4	Tan calcilithite, fine grained. Mudstone rip-up clasts, 1-2m wide concretions of brown calcilithite.
34	2.6	Tan mudstone containing a 0.3m thick coal seam 1m from the base, iron concretions.
35	0.2	Brown calcilithite, fine grained, inconsistent exposure.
36	12.4	Tan mudstone, abundant iron concretions in layers. Contains a 0.2m thick coal layer at the top.
37	0.2	Rust-colored calcilithite, grain size ranges 20-40 μ m, placing it in the grain size range for silt. Heavily stained with hematite.
38	6	Grey mudstone, contains a 0.5m thick coal seam near the top.
39	2	Coal.
40	5	Grey mudstone, abundant iron concretions.
41	0.2	Rust-colored calcilithite, heavily stained with hematite.
42	4	Grey mudstone, iron concretions.
43	2	Coal.
44	8	Grey mudstone.
45	0.5	Rust-colored calcilithite, heavily stained with hematite. Night had begun to fall back at layer 38, and it was now quite dark. The yips and howls of the large pack of coyotes were growing closer, so I hurried back to the car - thus the following change in unit nomenclature.
Upper 1	12	Grey mudstone.
Upper 2	0.5	Rust-colored calcilithite, heavily stained with hematite, millimeter-scale bedding visible in cross-section. Pond?
Upper 3	5	Grey mudstone. Petrified wood.

Upper 4	2.5	Lower half-meter is yellow, patches of hematite staining. Upper 2 meters is white/grey. Very fine grained calcilithite.
Upper 5	33.5	Grey mudstone. Petrified wood.
Upper 6	0.5	Dark rust-colored calcilithite, heavily stained with hematite, very fine grained. About a third petrified wood by volume. Some of the larger pieces of petrified wood contain Teredo(shipworm) burrow casts.
Upper 7	3.5	Grey mudstone.
Upper 8	0.3	Rust-colored calcilithite, heavily stained with hematite, very fine grained. Also contains iron concretions.
Upper 9	45	Grey mudstone. Contains a 15m wide white very fine grained calcilithite that tapers in thickness at both ends, possibly a channel sandstone (except it's a calcilithite). Exhibits hematite staining, especially at the upper surface. I later marked this as the contact between the Mesaverde Group and Colton Formation.
Upper 10	31.5	Light grey mudstone. An Eohippus tooth was found 12m from the base of the unit, and a lag deposit containing other mammalian tooth fragments was found 22.5m from the base of the unit.
Upper 11	0.1	Tan calcilithite, very fine grained. Once I discovered that I had reached the Eocene, I stopped measuring.

Fig. 4: Fossil Specimens. **A**, FHPR4268 large centrum; **B**, FHPR9625 ulna; **C**, FHPR9623 distal ungual; **D**, FHPR2714 pes-III 1; **E**, FHPR2715 small centrum; **F**, FHPR2721 small centrum; **G**, FHPR2725 partially fused centrum; **H1**, FHPR2718 jaw fragment lingual side; **H2**, FHPR2718 jaw fragment posterior side; **I**, FHPR2720.

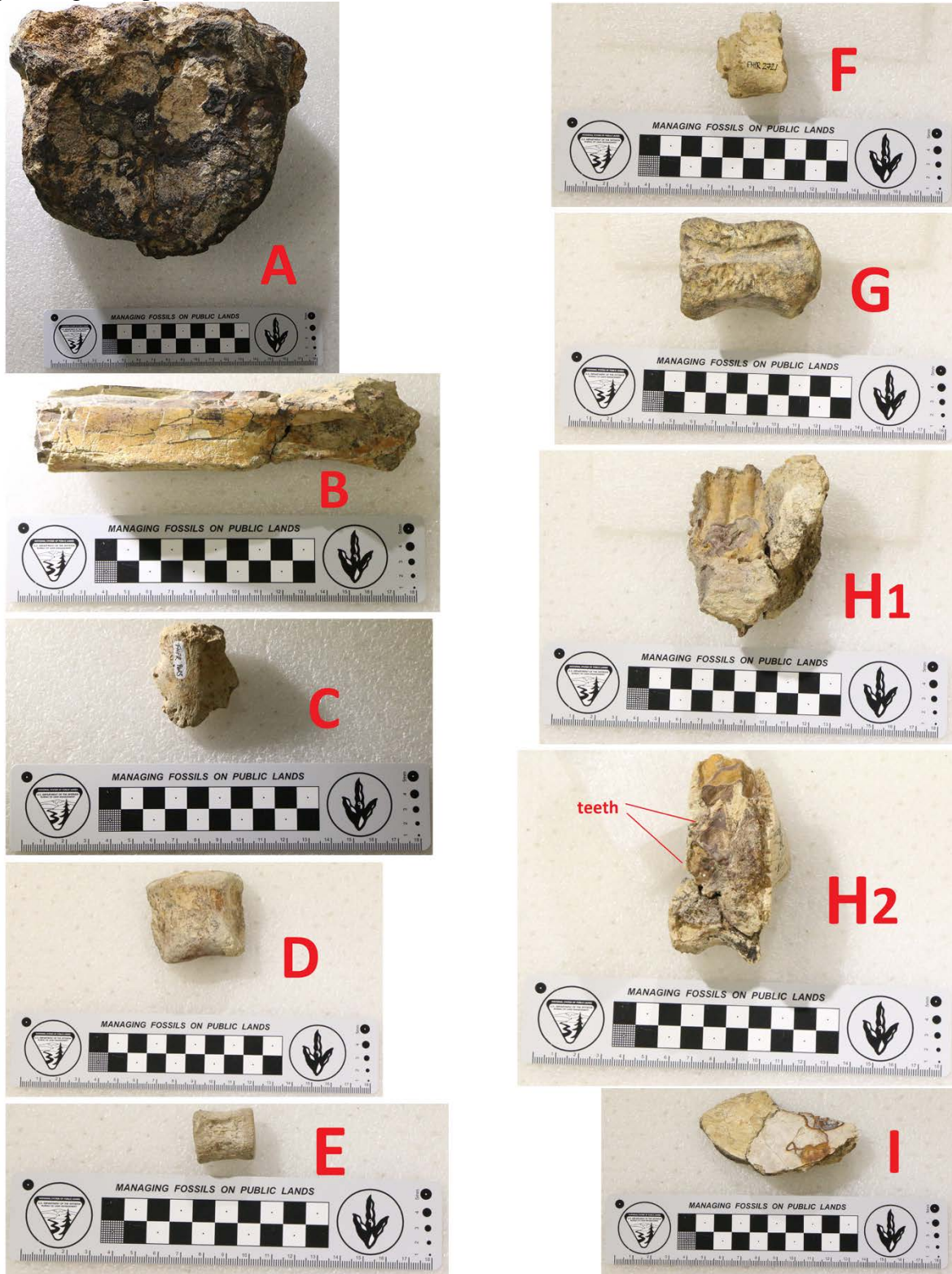


Fig. 5: *Geinitzia* branch fossils from Unit 14, reproduced from Burger and Ward 2016.

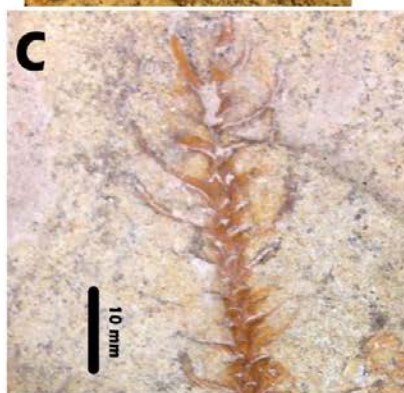
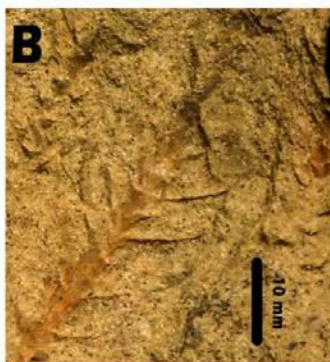


Fig. 6: *Teredo* borings from Unit Upper 6.



Fig. 7: The Roadcut locality contains a fossiliferous band containing *Scapanorhynchus*(above), *Cretolamna*(middle), and *Squalicorax*(below) shark teeth, and fish vertebrae.

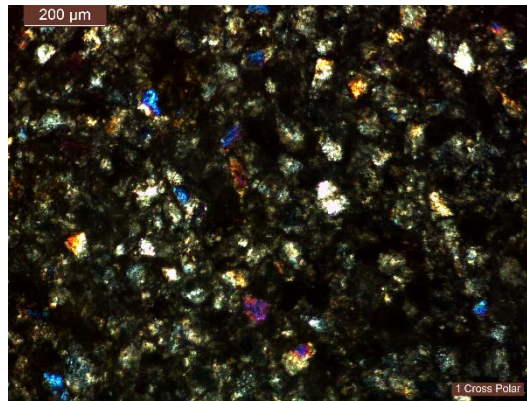
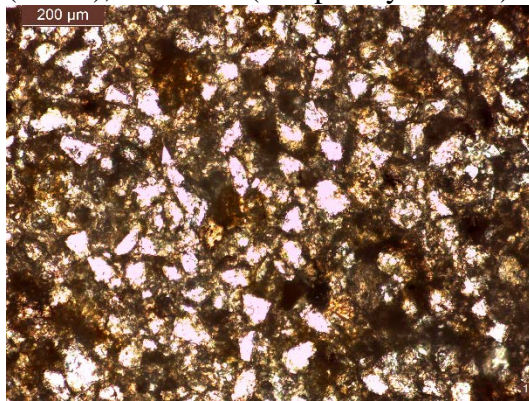


Fig. 8: Reconstruction of the Snake John Reef depositional environment.



APPENDIX 1

Appendix 1: Rock sample thin sections under normal and polarized light with lithologic characteristics. The hematite staining parameter approximates the following values: very light (1% of average microscope view exhibits hematite stain), light (5%), moderate (10%), heavy (20%+), extensive (completely stained).



Unit 1: Sego Sandstone

Color: yellow-tan

Grain Wear: angular

Sorting: very well sorted

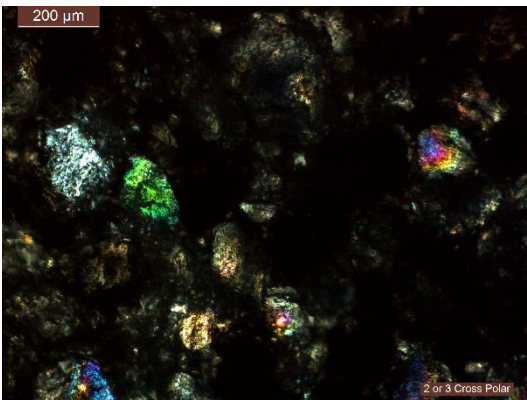
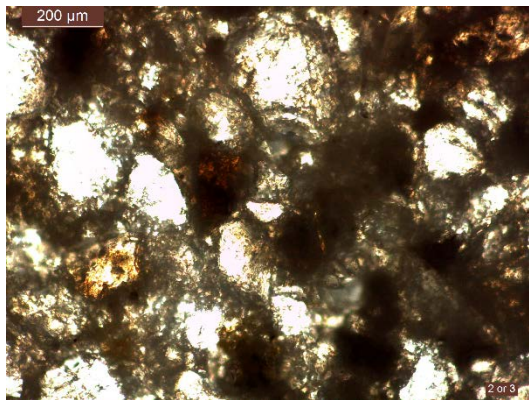
Cementation: medium

Grain Size (μm): 50-100

Lithologic Composition: 5% organic, 95% calcite

Degree of Hematite Staining: light, confined to specific grains, while other grains and matrix clean

Macro: 2-5mm hematite concretions producing bumps on surface of hand samples



Unit 2 or 3: Sego Sandstone

Color: grey-tan

Grain Wear: angular

Sorting: very well sorted

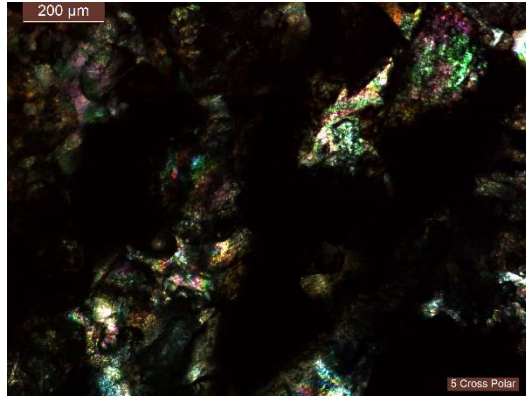
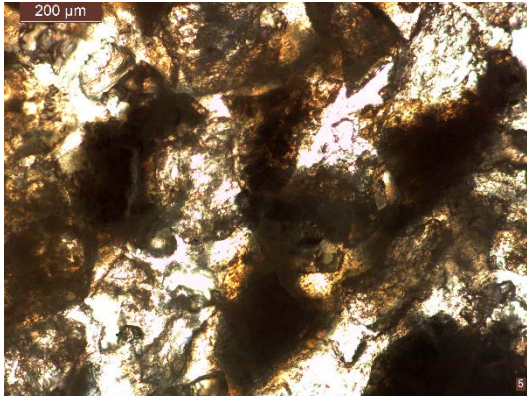
Cementation: medium

Grain Size (μm): 120-200 microns

Lithologic Composition: 5% organic, 95% calcite

Degree of Hematite Staining: light, confined to specific grains, while other grains and matrix clean

Macro: flaser bedding



Unit 5: Sego Sandstone

Color: very light grey

Grain Wear: angular

Sorting: well sorted

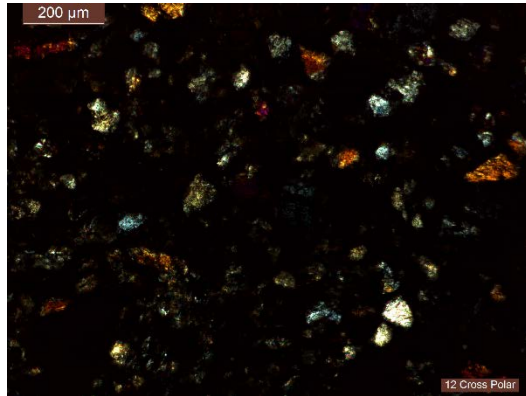
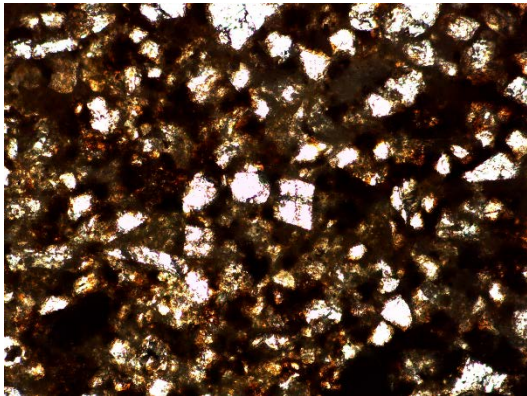
Cementation: poor

Grain Size (μm): 200-400

Lithologic Composition: 10% organic, 90% calcite

Degree of Hematite Staining: light, confined to specific grains, while other grains and matrix clean

Macro: 10-30cm cross-beds



Unit 12: Iles Formation (Note: Non-polarized picture has the same scale)

Color: brown-tan

Grain Wear: angular

Sorting: well sorted

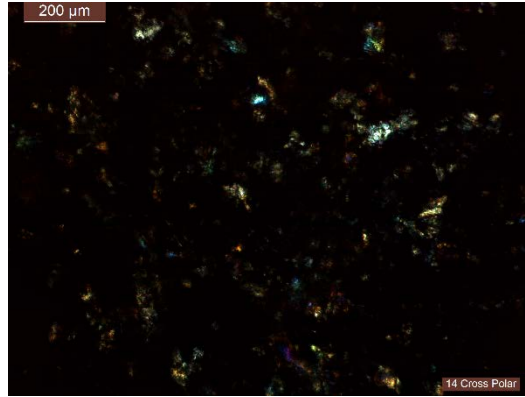
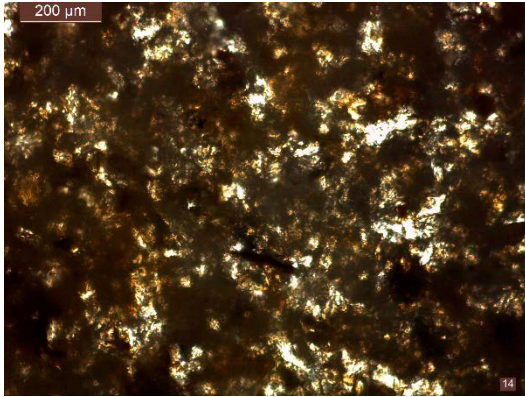
Cementation: strong

Grain Size (μm): 30-100

Lithologic Composition: 15-20% organic, 80-85% calcite

Degree of Hematite Staining: heavy, independent of specific grains or matrix

Macro: bioturbation, petrified wood fragments, mudstone rip-up clasts



Unit 14: Iles Formation

Color: tan

Grain Wear: angular

Sorting: very well sorted

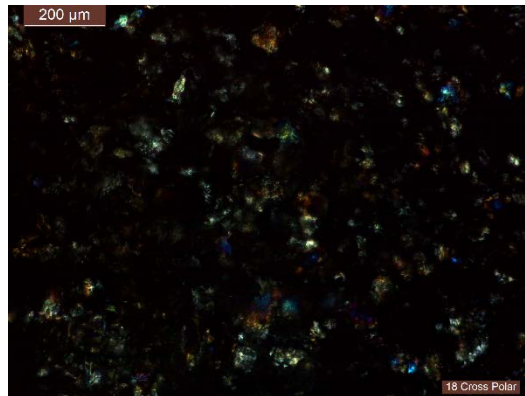
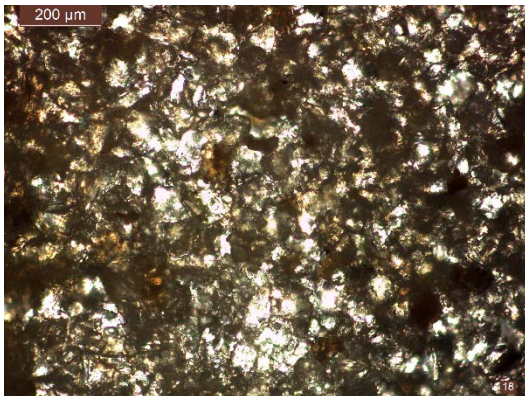
Cementation: poor

Grain Size (μm): 20-40

Lithologic Composition: 5% organic, 95% calcite

Degree of Hematite Staining: light, independent of specific grains or matrix

Macro: <1mm hematite concretions, 2-6cm petrified sticks, mudstone rip-up clasts, ~3cm cross-beds



Unit 18: Iles Formation

Color: tan

Grain Wear: angular

Sorting: very well sorted

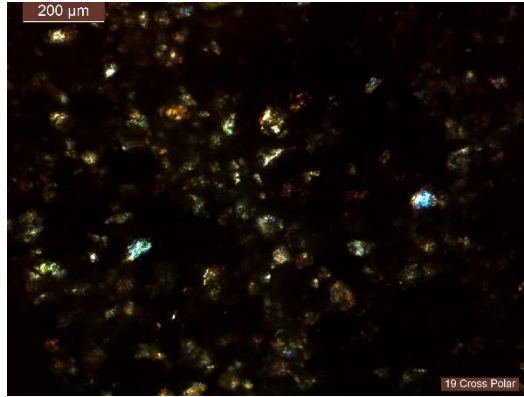
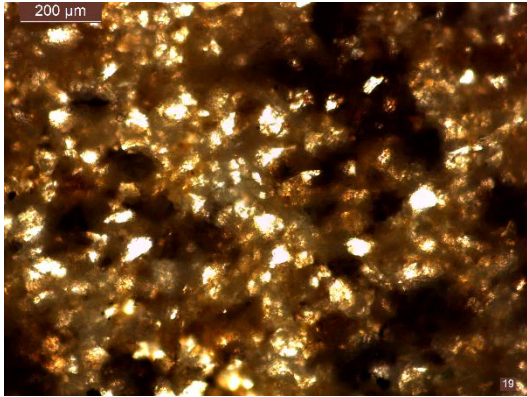
Cementation: poor

Grain Size (μm): 30-60

Lithologic Composition: 1% organic, 99% calcite

Degree of Hematite Staining: bands of moderate non-grain specific staining, otherwise clean

Macro: none



Unit 19: Iles Formation

Color: tan

Grain Wear: angular

Sorting: well sorted

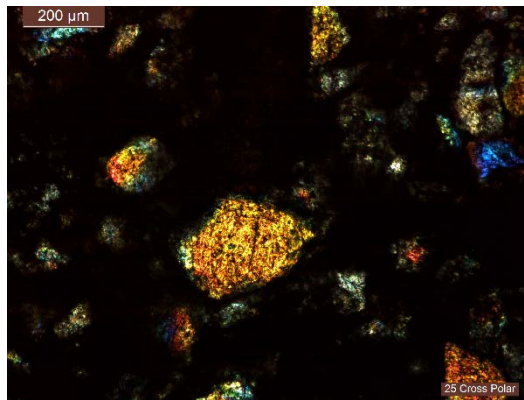
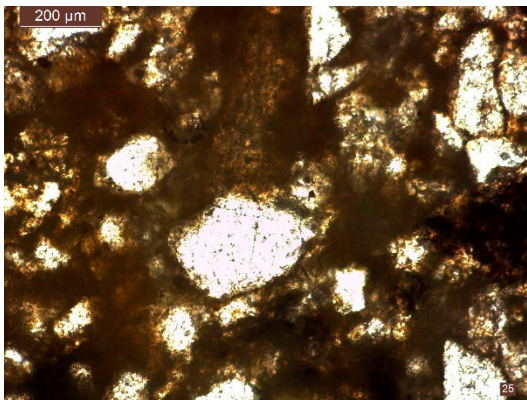
Cementation: strong

Grain Size (μm): 20-60

Lithologic Composition: 10% organic, 90% calcite

Degree of Hematite Staining: moderate, independent of grains or matrix

Macro: sample contains one 5mm hematite concretion



Unit 25: Iles Formation

Color: grey-tan

Grain Wear: angular

Sorting: moderately well sorted

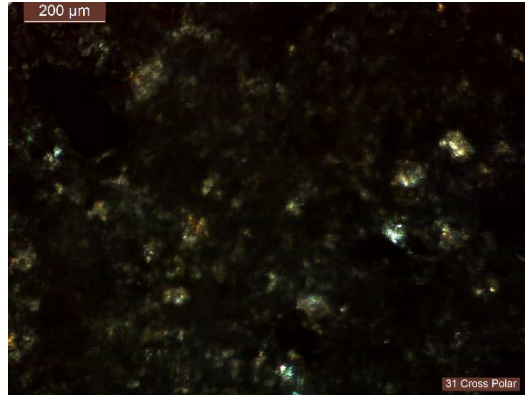
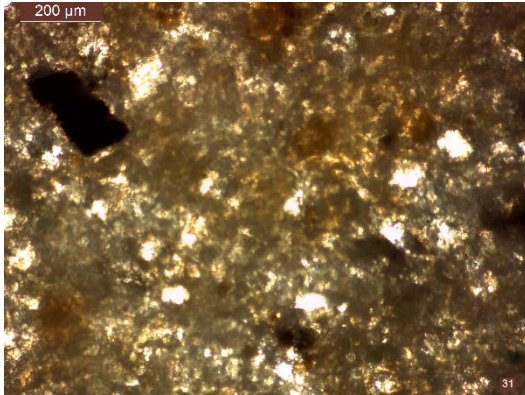
Cementation: strong

Grain Size (μm): 40-250

Lithologic Composition: 5% organic, 95% calcite

Degree of Hematite Staining: light, independent of grains or matrix

Macro: unit contains large pieces of petrified wood and dinosaur fossils



Unit 31: Iles Formation

Color: light tan

Grain Wear: angular

Sorting: very well sorted

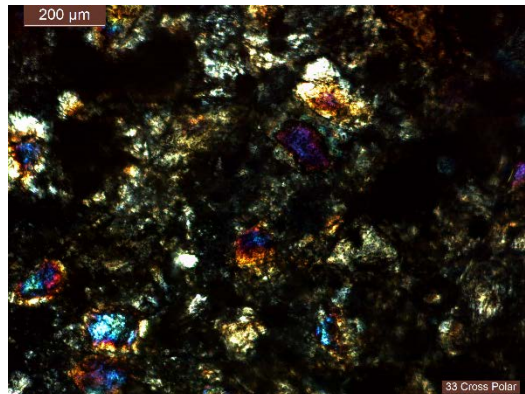
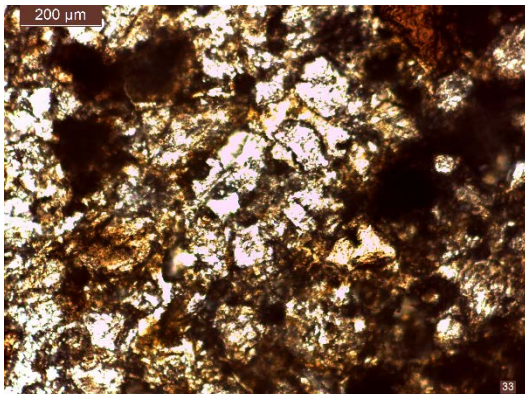
Cementation: strong

Grain Size (μm): 40-80

Lithologic Composition: 1% organic, 99% calcite

Degree of Hematite Staining: light, independent of grains or matrix

Macro: extensively cemented such that distinguishing grain boundaries is difficult, organics and hematite content confined to small patches, contains dinosaur fossils



Unit 33: Iles Formation (Troutcreek Sandstone)

Color: tan

Grain Wear: angular

Sorting: very well sorted

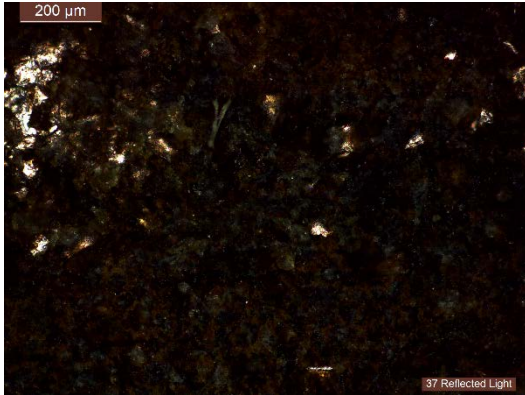
Cementation: very poor, fell apart under the rock saw coolant water spray

Grain Size (μm): 100-200

Lithologic Composition: 5% organic, 95% calcite, rare tan opaque grains (mudstone?), one muscovite grain

Degree of Hematite Staining: moderate, confined to specific grains

Macro: mudstone rip-up clasts



Unit 37: Williams Fork Formation

Color: rust

Grain Wear: angular

Sorting: very well sorted

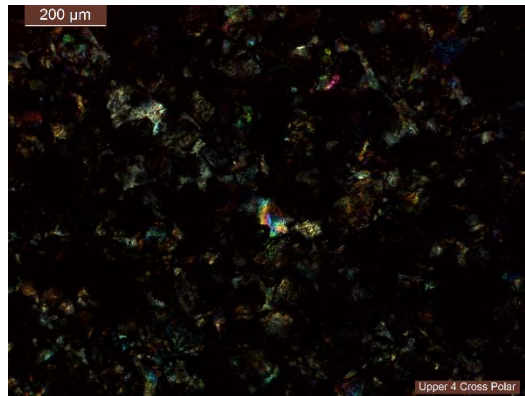
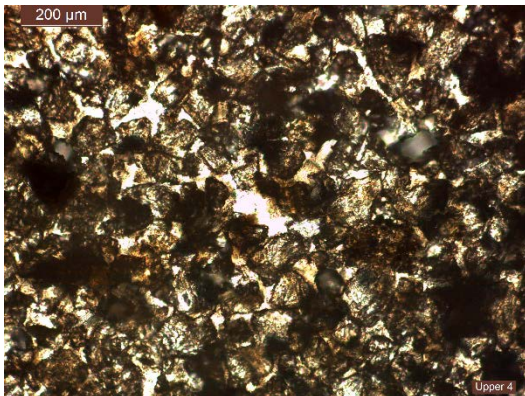
Cementation: strong

Grain Size (μm): 20-40

Lithologic Composition: ~100% calcite

Degree of Hematite Staining: extensive, the entire rock is heavily stained with hematite; “ferrous calcite”

Macro: laminate pattern, algal mat or pond deposit



Unit Upper 4: Williams Fork Formation

Color: light tan

Grain Wear: sub-angular

Sorting: very well sorted

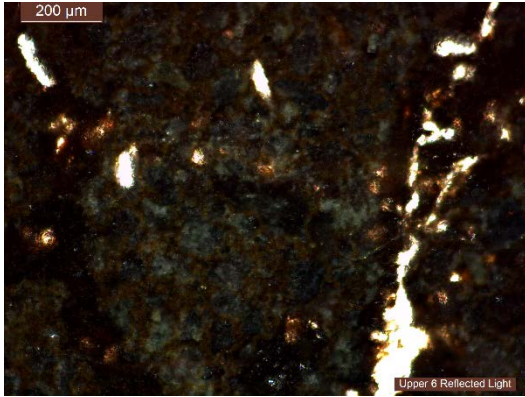
Cementation: poor

Grain Size (μm): 60-120

Lithologic Composition: <1% organic, 99% calcite

Degree of Hematite Staining: very light

Macro: none



Unit Upper 6: Williams Fork Formation

Color: rust

Grain Wear: angular

Sorting: well sorted?

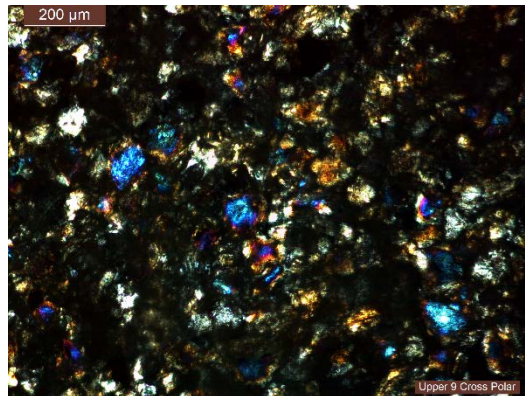
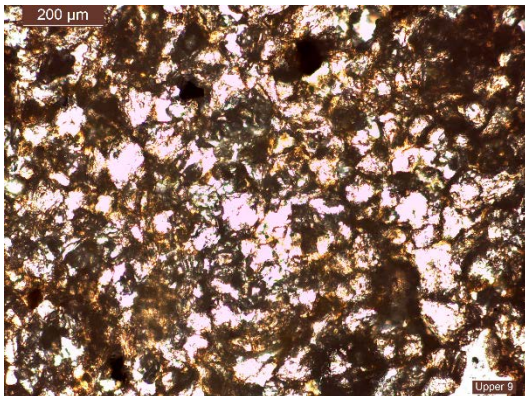
Cementation: strong

Grain Size (μm): 20? - 80?

Lithologic Composition: 95+% calcite

Degree of Hematite Staining: extensive, “ferrous calcite.” The hematite stain is so dark that distinguishing individual grains and composition with any confidence is impossible.

Macro: abundant petrified wood shards with random orientations



Unit Upper 9: Williams Fork Formation (cap unit of Mesaverde Group)

Color: light tan

Grain Wear: angular

Sorting: very well sorted

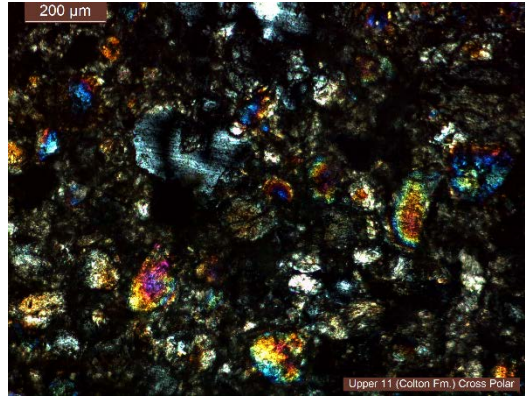
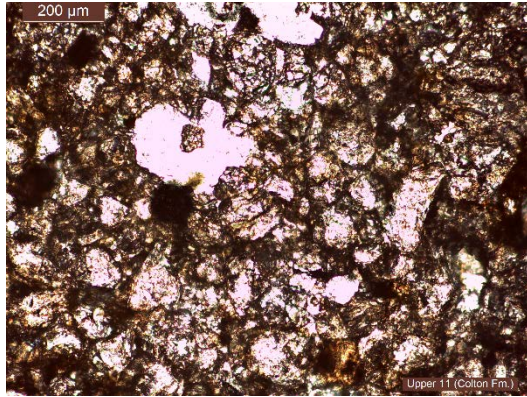
Cementation: poor

Grain Size (μm): 60-120

Lithologic Composition: 1% organic, 99% calcite

Degree of Hematite Staining: very light

Macro: collected from a river channel deposit at the top of a large stack of siltstone



Unit Upper 11: Colton Formation

Color: tan

Grain Wear: angular

Sorting: well sorted

Cementation: poor

Grain Size (μm): 60-150

Lithologic Composition: 1% organic, 99% calcite

Degree of Hematite Staining: very light

Macro: Eocene, still calcite, rare <1mm hematite concretions