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CONTINENTAL SALINE ENVIRONMENTS INTERPRETED FROM BEDDED GYPSUM OF THE TRIASSIC RED PEAK FORMATION (CHUGWATER GROUP), NORTHCENTRAL WYOMING

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in
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keywords: gypsum, Triassic, Chugwater, Red Peak Formation, red beds, sedimentology, petrography

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ABSTRACT

Continental saline environments interpreted from bedded gypsum of the Triassic Red Peak Formation (Chugwater Group), northcentral Wyoming

Maya Yamei Bradford

Bedded evaporites and associated red bed siliciclastics record saline lake and groundwater systems from Permo-Triassic Pangea. A major component of these red bed and evaporite systems is bedded gypsum. However, little attention has been paid to the textures of ancient gypsum. Observations of gypsum textures can refine interpretations of depositional environment and diagenetic history. This project describes textures of bedded gypsum from an outcrop of the Triassic Red Peak Formation (Chugwater Group) near Greybull, Wyoming.

This thesis uses fieldwork, petrography, and x-ray diffraction to describe an outcrop of the upper Red Peak Formation, with a focus on textures of bedded gypsum, to make interpretations about depositional environments. The study outcrop is comprised of alternating units of bedded gypsum and red bed siliciclastic mudstone. The red mudstone units are massive, rich in blocky peds, host abundant cross-cutting gypsum veins, and are interpreted to be paleosols. Three distinct lithologies of bedded gypsum are described and identified: bottom-growth gypsum, laminated gypsum, and clastic gypsum. Bottom-growth gypsum is interpreted to have precipitated at the bottom of shallow saline surface water bodies. Laminated gypsum likely formed in shallow saline lakes and mudflats; here, gypsum cumulates precipitated and were later reworked. Clastic gypsum units are composed of eolian-reworked bottom growth gypsum crystals deposited in sandflats and dunes. The study section of the Red Peak Formation was formed in shallow saline lakes and associated mudflats, sandflats, dunes, and desert soils.
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Appendix C. Additional petrographic photos
INTRODUCTION

Bedded evaporites and associated red bed siliciclastics from the mid Permian through early Triassic periods are widespread across equatorial Pangea. These rocks are representative of extensive continental acid-saline lake and groundwater systems in arid, desert landscapes (e.g., Benison et al. 1998; Benison and Goldstein 2002). Workers have interpreted continental ephemeral and perennial acid-saline lake and groundwater systems from bedded evaporites and red beds of the Permian and Triassic periods in Kansas and Oklahoma, North Dakota, South Dakota, northern Brazil, and Northern Ireland (Benison et al. 1998; Benison and Goldstein 2000; Benison and Goldstein 2001; Abrantes et al. 2016; Andeskie et al. 2018; Andeskie and Benison 2020; Knapp 2020; Petras 2021).

It is interesting that so many hot, dry environments are marked by extreme concentrations of salt and acid across equatorial Pangea during the late Permian and early Triassic. These end-member environments appear to have made up a long-lived regional system, representing a major component of Permo-Triassic continental settings. The late Permian – early Triassic depositional record of northern Wyoming, which consists of red beds and bedded evaporites, has yet to be described in terms of detailed sedimentology. The geographic extent and longevity of these extreme continental saline environments of Pangea, and the extent to which they were interconnected, can be further refined. Knowledge of continental environmental, biological, and climatic conditions during the Permo-Triassic is relevant: the late Paleozoic was the last time there was a major icehouse to greenhouse transition since the current transition from Pleistocene icehouse to modern global warming (Gastaldo et al. 1996; Montañez and Poulsen, 2013; Penn et al. 2018). Therefore, knowledge about Permian-Triassic environments, life, and climate can help to predict future Earth system trends (i.e., Payne and Clapham 2012; Dietl et al. 2015).

The Red Peak Formation (Chugwater Group) is composed of early Triassic red beds and bedded gypsum. While the red beds of the Triassic Chugwater Group and their distinctive bright-red color are well-known to geologists familiar with Wyoming geology, the depositional environments of the Chugwater Group remain contentious (Cavaroc and Flores 1917, High and Picard 1969, Picard 1967, Irmen and Vondra 2000, Lovelace and Lovelace 2012, Knapp et al. 2015, Knapp et al. 2016, Knapp 2020). The bedded gypsum of the Chugwater Group has not yet been described in sedimentological detail; ancient bedded gypsum in general is understudied.
The objective of this thesis was to make detailed observations of bedded gypsum from an outcrop of the Red Peak Formation (Chugwater Group) in northcentral Wyoming. These observations were used to make interpretations of the depositional environments and diagenetic conditions under which the gypsum formed. Results include a refined depositional environment of the Red Peak Formation, as well as an expanded understanding of both Pangean continental systems and ancient bedded gypsum.

BACKGROUND

Textures of bedded gypsum

Gypsum textures are geological snapshots in time of specific depositional environments. Bottom-growth gypsum, which are rows of vertically oriented acicular, bladed, or twinned “swallowtail” gypsum crystals, precipitate only at the bottoms of saline surface waters. Cumulate gypsum, acicular gypsum crystals that precipitate in the water column, settle at the bottom, creating a felted texture of flat-lying crystals. Displacive gypsum, which are acicular or lath-shaped gypsum crystals, randomly oriented in mudstone, precipitate only from shallow Ca-SO$_4$-rich groundwaters in uncemented sediment (e.g., Schreiber and Kinsman 1975; Casas and Lowenstein 1989; Smoot and Lowenstein 1991; Benison et al 2007; Andeskie and Benison 2020).

The textures of gypsum have been well-documented from modern environments, as well as Pleistocene and Miocene deposits (i.e., Schreiber and Kinsman 1975; Schreiber 1987; Benison et al. 2007; Kiro et al. 2016; Knapp et al. 2016; Benison 2019). For example, beds of vertically-oriented gypsum crystals in Egypt were interpreted to have formed by in situ bottom growth precipitation at the bottom of a saline water body during the Miocene (Attia et al. 1995). Miocene gypsum formations in Italy are characterized by both vertical, bottom-growth textures, as well as laminated textures (i.e., Manzi et al. 2009; Dela Pierre et al. 2011). However, here remains a paucity of published studies of the textures of bedded gypsum from the Mesozoic, Paleozoic, and Precambrian.
The Chugwater Group

The early Triassic Red Peak Formation is part of the Chugwater Group. The Chugwater Group is subdivided into four formations, with the Red Peak Formation comprising most of the Chugwater in thickness and in volume (Fig. 1). Rocks of the Chugwater Group are well exposed around the flanks of Laramide uplifs in northern and central Wyoming. Descriptions of the Chugwater note its distinctive red color, fine grain size, its assumed lateral continuity and consistent thickness, reptile trackways, and the presence of gypsum (Picard 1967, High and Picard 1969, Irmen and Vondra 2000, Lovelace and Lovelace 2012).

Figure 1: The Red Peak Formation in northcentral Wyoming. Left, cross-sectional view of recently excavated wall at the Georgia-Pacific Gypsum mine near Greybull, Wyoming. In this view, the pale-tan Alcova Limestone overlies the alternating red bed and bedded gypsum units of the Red Peak Formation. Right, stratigraphic column of the Chugwater Group and its four formations, modified after Knapp 2020.

Detailed sedimentological observations of the Chugwater Group and underlying Goose Egg Formation show that much of the red bed siliciclastics that make up these formations are sheet flood deposits that underwent pedogenesis (Knapp 2020). The abundance of paleosols strongly suggests a continental origin for this sequence of Permo-Triassic red beds and bedded gypsoms. Yet, the textures of the bedded gypsoms of these rocks remained undescribed.

The Red Peak Formation of the Chugwater Group around Greybull, Wyoming is characterized by alternating units of bedded gypsum and red bed siliciclastic mudstone (Fig. 1). Are depositional textures preserved in this ancient bedded gypsum? Is all bedded gypsum the
same? Can we interpret depositional environments from the bedded gypsum units? Or, has all or some gypsum succumbed to diagenetic alteration that obliterates depositional textures? The main objective of this thesis is to make detailed petrographic descriptions of the bedded gypsum units at one outcrop of the Red Peak Formation, and from those descriptions, interpret depositional environments.

METHODS

I visited multiple exposures of the Red Peak Formation near Greybull in northcentral Wyoming. The Red Peak Formation is well-exposed in an anticline here and is exposed as outcrops and mine walls. Each exposure of the Red Peak Formation in this area was composed of red bed siliciclastics and bedded gypsum. I chose one outcrop for this project. I performed a centimeter-scale measured section of the outcrop, collecting representative hand samples from which I made 16 large-format thin sections. X-ray diffraction bulk analysis was performed on three samples of bedded gypsum. Combining field and petrographic observations, I described lithologies of the bedded gypsum and red bed siliciclastics.

Fieldwork

Fieldwork was conducted in June of 2021. One outcrop of the Red Peak Formation was chosen for a detailed measured section. The outcrop is approximately 8 km north of Greybull, Wyoming. It is closest to Greybull County Road #26. The outcrop is near, but stratigraphically above, a Wyo-Ben, Inc. stucco plant. This Wyo-Ben location mines gypsum for stucco. The GPS coordinates for this outcrop are 44°34’52.06” north, 108°7’38.22” west.

This outcrop was measured at a centimeter scale. Color, sedimentary textures, sedimentary structures, diagenetic features, and stratigraphic contacts were described. Color was determined in the field using a Munsell Soil Chart. HCl was used to test for any carbonate minerals. Digital photography and detailed field notes documented the rocks. Samples were collected from representative units.
Petrography

Representative samples collected in the field were slabbed on a rock saw and made into 16 large-format thin sections. Thin sections were observed and photographed under transmitted, reflected, and polarized light with an Olympus BX53 microscope (6.3-63x magnification). Sedimentary textures, sedimentary structures, colors, minerals, and diagenetic features were described and documented with a Spot 5 digital imaging system.

Mineral identification

Representative rock samples collected in the field were powdered and analyzed using x-ray diffraction (XRD) to identify minerals. Three samples of representative bedded gypsum units were analyzed using the bulk analysis by K/T Geoservices. In the field, some bedded gypsum was tested for elemental composition with a Bruker handheld XRF. Additional mineralogy data was reported from local miners.

RESULTS AND INTERPRETATIONS

The study outcrop is composed of alternating units of bedded gypsum and red siliciclastic mudstone (Fig. 2). Based on field and petrographic observations, three lithologies of bedded gypsum and one lithology of red beds were described (see Appendix A for measured section.)

Figure 2: Left the study outcrop is composed of alternating units of bedded gypsum and red bed siliciclastic mudstone. Right, generalized stratigraphic column of the study measured section. Units from which thin sections were made are indicated with a star. Units from which X-ray diffraction data were obtained are indicated with a triangle. The red bed siliciclastic units were too friable to make thin sections.
Lithologies and interpreted depositional environments

**Bottom-growth gypsum lithology: Saline lake lithofacies.***---

*Results:*

This bedded gypsum lithology is pale orange (5 YR 8/4) in outcrop and grey (GLEY 2 7/1 10B) to yellowish white (7.5 YR 8/1) on fresh exposures. The most prominent feature of these rocks are beds comprised of vertical crystals. The vertical crystals are seen in outcrop and in thin section.

![Image](https://via.placeholder.com/150)

**Figure 3.** Bottom-growth gypsum lithology. In outcrop, the lithology has a vertical texture (A). The vertical texture is from multiple rows of bottom-growth gypsum. In thin section, there is a row of bladed and swallowtail-shaped bottom-growth gypsum crystals (B), and a row of acicular bottom-growth gypsum crystals (C).

In outcrop, this lithology is characterized by multiple beds with vertical texture. In thin section, the vertically oriented crystals are bladed, or acicular gypsum (Fig. 3). Many crystals are twinned to form a swallowtail shape. The beds have flat bottoms and pointy tops. Thin (~0.05 cm) wavy laminations of gypsum mudstone form the base of the beds of vertical gypsum crystals and drape over their pointy tops (Fig. 3). There are multiple beds of vertical gypsum crystals. There is one 42 cm-thick unit of this lithology, although this texture is also seen in another bedded gypsum lithology.

*Interpretations:*

X-ray diffraction bulk analysis of rocks containing this texture indicate that the vertical crystals are composed of gypsum. Gypsum is known to form beds of vertically oriented gypsum crystals that are acicular, bladed or swallowtail shaped; this texture is called bottom-growth
gypsum (Benison et al. 2007; Hardie and Eugster 1971). This bedded gypsum lithology is composed of bottom-growth gypsum. Bottom-growth gypsum precipitates only in Ca-SO₄-rich saline surface waters, growing upward from the sediment-water interface. Bottom-growth gypsum forms beds of vertically-oriented gypsum crystals that are acicular, bladed, or swallowtail shaped (Benison et al. 2007; Hardie and Eugster 1971). Bottom-growth gypsum crystals will use any substrate at the bottom of the water body as growth nuclei. The laminations of gypsum mud that underlie the bottom-growth gypsum beds and drape over their pointy crystal tops may be composed of tiny (sub mm scale) cumulate gypsum crystals, which precipitate in the water column and settle to the bottom.

Bottom-growth gypsum only forms in saline surface waters. The one unit consisting solely of bottom-growth gypsum lithology is both underlain and overlain with red siliciclastic mudstone paleosols. Therefore, surface waters are interpreted to be lakes rather than oceans or lagoons. In addition, if precipitated by evapoconcentrated seawater, calcite and/or aragonite would be expected to have precipitated prior to gypsum; no carbonate minerals were detected (Hardie 1984; Benison and Goldstein 2002). The bottom-growth gypsum units represent saline lake deposits.

**Clastic gypsum lithology: Dune/sandflat lithofacies. ---**

*Results:*

The clastic gypsum lithology is dull reddish yellow (5YR 6/6) on weathered surfaces and pure white, vitreous, and sugary on fresh surfaces. The clastic gypsum lithology is composed of bladed and abraded gypsum grains that are abraded crystals (Fig. 4).

![Figure 4. Clastic gypsum lithology. In outcrop, textures cannot be observed on weathered surfaces (A). On fresh surfaces, the gypsum is white, sugary, and vitreous (B). Under the microscope, the grains are bladed, abraded, and bimodally distributed (C).](image)
The clastic gypsum has bimodal grain size distribution (medium sand-sized (0.3 – 0.4 mm) and very fine sand-sized grains (0.1 mm; Fig. 4). Grains are randomly oriented and flake off the rock easily. Microscopic observations show that the grains are abraded crystals with alternating bands of fluid inclusions and clear gypsum.

Analyses of fresh surfaces by a portable XRF in the field detected only calcium and sulfur. Mine workers report that their lab analyses confirm this lithology is pure gypsum. There are three units of this lithology at this outcrop. They range in thickness from 60 cm to 96 cm. The beds are massive (structureless). Clastic gypsum units are interbedded with red siliciclastic mudstones.

Interpretations:

Based on the bimodal grain size distribution, the abraded nature of the bladed grains, and growth bands of primary fluid inclusions, the clastic gypsum lithology is interpreted as originally bottom-growth gypsum crystals that were reworked and deposited as clastic grains by wind in sandflats and dunes. Bottom-growth gypsum are bladed crystals that precipitate at the bottoms of Ca-SO\textsubscript{4}-rich surface waters. If these water bodies experience desiccation, the bottom-growth gypsum crystals are exposed to eolian processes. Wind erodes and entrains the bladed gypsum crystals and reworks them as clastic gypsum grains, depositing them in sandflats and dunes near the saline lakes (Benison et al. 2007; Benison 2017; Benison 2019).

The clastic gypsum lithology is interpreted to be an eolian deposit despite the absence of cross-bedding. High-angle, trough, and tangential cross-bedding forms in eolian deposits of rounded and spherical quartz grains. Eolian-style cross-bedding has also been documented in deposits of rounded and spherical gypsum grains, but the extent to which cross-bedding forms and is preserved in deposits of abraded gypsum bladed crystals is not yet well-studied (McKee 1966). The bladed nature of the gypsum grains that compose the clastic gypsum lithology may account for the lack of cross-bedding.

Laminated gypsum lithology: Ephemeral saline lake and saturated mudflat

Results:

The laminated gypsum lithology is characterized by planar, convolute, and crinkly thin and thick laminations of pale grey (GLEY 2 7/1 10B) and pure white gypsum mudstone. Several
textures of gypsum were observed, including thin, discontinuous beds of bottom-growth gypsum with mud drapes; crinkly, doming laminations in the shapes of mounds; and clastic gypsum mud. Several syndepositional textures of gypsum are documented from thin section, including displacive gypsum and blocks of gypsum mud with vertical cracks (Fig. 5).

There are three units of the laminated gypsum lithology. The units range in thickness from 60 cm to 82 cm. Laminated gypsum units are interbedded with red siliciclastic mudstones. X-ray diffraction bulk analysis across three units of the laminated gypsum indicated that this lithology is composed of 97% gypsum and 3% clay minerals; there is no anhydrite (Table 1).

Figure 5. Laminated gypsum lithology. (A) In outcrop, there are many textures in the laminated gypsum. In thin section, there are two important syndepositional textures: (B) displacive gypsum and (C) autoclastic breccia.
Table 1. X-ray diffraction bulk analysis results of three representative samples of the laminated gypsum lithology.

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<th>Anhydrite (wt%)</th>
<th>Bassanite (wt%)</th>
<th>Celestine (wt%)</th>
<th>Total Clay (wt%)</th>
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Interpretations:

Planar laminations of clastic gypsum mud form from settling and low-energy suspension fall-out of muds in shallow gypsum-precipitating lakes (i.e., Abrantes et al. 2016). Crinkly laminations and dome-shaped laminations are interpreted to represent microbial mats, which may grow in shallow surface waters (i.e., Noffke et al. 2013). Convolute laminations are the products of soft sediment deformation. Clastic gypsum mud laminations, bottom-growth gypsum, and thin laminations of cumulate gypsum crystals likely formed in the shallow lake at the same time.

Several diagenetic textures are also present in the laminated gypsum lithology. When Ca-SO₄-rich groundwaters precipitate gypsum crystals in pore spaces in unconsolidated muds, the resulting texture is acicular gypsum crystals randomly-oriented in a mud matrix. This texture is called displacive gypsum and is indicative of saline mudflats adjacent to saline lake deposits (Casas and Lowenstein 1989, Smoot and Lowenstein 1991, Benison et al. 2007; Fig. 5). Vertically cracked gypsum mud is interpreted as autoclastic breccia, which is a product of desiccation of saturated mud (Fig. 5). The sedimentary textures and sedimentary structures in the laminated gypsum lithology together indicate formation in shallow lakes and saturated mudflats that experienced stages of flooding and desiccation, causing lake levels to fluctuate over short time spans (likely days to years).

Ped-rich siliciclastic mudstone lithology: Desert soil lithofacies. ---

Results:

Interbedded with each unit of bedded gypsum there is a unit of red (5 YR 4/6) siliciclastic mudstone. Red mudstone units range from 16 cm to 74 cm in thickness. The units are massive and structureless. These red mudstone units are characterized by abundant blocky peds (Fig. 6).
Figure 6. Ped-rich mudstone lithology. A, the red mudstone is characterized by abundant blocky peds, reduction spots, and root features that are filled with gypsum cement. B, contacts of red mudstone underlying and overlying a laminated gypsum unit.

Blocky peds are structures in mudstone that are areas where the silt-sized grains appear arranged in clustered clumps. In the red siliciclastic mudstone units, each clump is no more than 2 cm in diameter and are sub-rectangular and blocky.

The red mudstone is riddled with cross-cutting veins filled with gypsum cement. The gypsum veins are no wider than 2 cm and branch from a principle horizontal vein and have tapered ends. Localized blue-grey (GLEY 2 8/1 5B) mudstone surrounds the gypsum veins and in randomly oriented patchy spots (Fig. 6).

Interpretations:

Blocky peds are the product of wetting and drying of soils. The blue-grey areas are interpreted to be reduction zones, places where iron oxides were reduced most likely by decaying organics. The cross-cutting gypsum veins are interpreted to have formed when late-stage saline groundwaters precipitated gypsum cement in cracks that likely originated as root features and/or as desiccation cracks. Based on the blocky peds and root features, the ped-rich siliciclastic mudstone is interpreted to represent a paleosol.

Summary of interpreted depositional environments

Summary of lithologies and lithofacies. --- The study section of the Red Peak Formation is composed of alternating units of bedded gypsum and red paleosols (Fig. 2). There are three distinct lithologies of the bedded gypsum: clastic gypsum, bottom-growth gypsum, and
laminated gypsum. Bedded gypsum units are interbedded with units of red bed siliciclastic mudstone that are interpreted as paleosols. At the bottom of the section, the bedded gypsum is clastic. It is interpreted as sandflat and dune deposits composed of reworked bottom-growth gypsum material. Moving up section, the bedded gypsum is increasingly laminated and bottom-growth gypsum is more common (Fig. 7). These are interpreted as shallow saline lake and saturated mudflat deposits. The study section of the Red Peak Formation was formed in shallow saline lakes and associated mudflats, sandflats, dunes, and desert soils.

Figure 7. Stratigraphic column with field and petrographic observations, lithologies, and depositional environment interpretations. At the bottom of the section, the bedded gypsum is clastic and interpreted to have formed in sandflats and dunes adjacent to gypsum-precipitating lakes. Moving up section, the gypsum becomes increasingly laminated and bottom-growth gypsum appears. These units of bedded gypsum are interpreted to have formed in shallow saline lakes and brine-saturated mudflats. Units of bedded gypsum alternate with units of red desert paleosols.
Because the succession of vertically adjacent lithologies in the Red Peak Formation represent laterally adjacent facies documented at modern saline lake-mudflat/sandflat-dune-soil environments, we can say that the stratigraphic sequence follows Walther’s Law (Middleton 1973). In other words, the lithologies in the Red Peak Formation represent depositional environments that may have co-existed at the same time. This suggests that there were no major interruptions in sedimentation or major changes in climate over the time of formation of the outcrop that was the focus of this study.

**A shallow saline lake system.** --- The lithologies and textures described from this study fit well within the model for shallow saline lakes and associated environments (i.e. Lowenstein and Hardie 1985, Benison et al. 2007, Benison 2017; Fig. 8). Bottom-growth gypsum grows from the bottom of the shallow saline lake when the lake undergoes evapoconcentration. Lamination gypsum may also form in saline lakes. When and if the lake undergoes desiccation, beds of bottom-growth gypsum crystals are subaerially exposed and vulnerable to eolian processes. Wind entrains, abrades, sorts, and deposits the bottom-growth gypsum crystals as clastic grains in nearby sandflats and dunes. The mudflats surrounding the gypsum-precipitating lake are saturated with shallow calcium sulfate-rich groundwaters, which precipitate displacive gypsum crystals in the shallow subsurface (centimeters below surface) in the unconsolidated mud. The gypsum mud in these mudflats likely originated as lake precipitates or displacive gypsum that were reworked. Another source of gypsum mud was likely efflorescent crusts, which form tiny (sub-mm) crystals on desiccated lake surfaces; while textures indicative of remnant efflorescent crusts were not observed, they are not well-preserved in ancient rocks (Benison and Goldstein 2000; Benison et al. 2007). The sediments undergo wetting and drying, driven by both rainfall, drought, and the rising and falling of the water table, which results in autoclastic breccia in mudflats and blocky peds in desert soils.

This shallow saline lake system is heavily influenced by the relative height of the groundwater table (Fig. 9). Depending on the relative height of the groundwater table, the lake undergoes stages of flooding and desiccation. During flooding stages, the lake is surrounded by saturated mudflats. Bottom-growth gypsum forms at the lake bottom, cumulative gypsum forms in the water column of the lake, and displacive gypsum forms in the wet mudflats. During stages of desiccation, the bottom-growth gypsum crystals are entrained by wind and deposited as clastic...
sand grains in the surrounding sandflat and dune facies. If desiccation persists, the sandflat and dune facies will encroach on the mudflat facies. When the groundwater table is rejuvenated by a rare precipitation event, the lake and saturated mudflat facies reappear.

Figure 8. Sedimentary textures suggest this model of a shallow saline lake system. Bottom-growth gypsum forms in the lake. The bottom-growth crystals are exposed to wind when the lake undergoes desiccation. The wind reworks the crystals and deposits them as clastic grains in nearby sandflats and dunes. The lake is surrounded by wet and dry saline mudflats. The laminated gypsum lithology contains textures of both lake environments as well as mudflat environments, and is interpreted to represent the lake’s dynamic shoreline, which reflects subaqueous and subaerial conditions depending on the height of the water table.

Figure 9. The system is highly influenced by the height of the groundwater table. During relative highs, a shallow saline lake exists (A). As evapoconcentration occurs, the lake shrinks, and dunes may encroach on the lake (B). As the groundwater table lowers, the lake undergoes complete desiccation and is covered by sandflats and dunes (C). If dry conditions persist, the sand may form crescent-shaped dunes (D). Rare precipitation events reinvigorate the groundwater table and system experiences a flooding stage, reinstating the lake and mudflat facies (A). These changes occur rapidly; all four stages illustrated above can occur at one location within one month.
There are thousands of shallow saline lakes across Western Australia that are modern analogs for this ancient gypsum-precipitating system (Benison et al. 2007, Bowen et al. 2012). These lakes precipitate gypsum and are surrounded by reworked gypsum material in mudflats, sandflats, and dunes. These lakes are extremely dynamic and dependent on the height of the groundwater table. The lakes experience stages of flooding, evapoconcentration, and desiccation. The gypsum-precipitating lakes and surrounding gypsum mudflats, sandflats, and dunes are further surrounded by red desert soils. These red desert soils that surround the saline environments provide an analog to the red paleosol in the Red Peak Formation in northcentral Wyoming.

**Paragenetic Sequence**

The most identifiable diagenetic textures observed in the study outcrop are seen in the laminated gypsum lithology and ped-rich mudstone lithology. These features include displacive gypsum, autoclastic breccia, blocky peds, reduction spots, and cross-cutting gypsum veins.

In the laminated gypsum lithology, there is abundant displacive gypsum, which forms relatively early from Ca-SO$_4$-rich groundwaters just centimeters below the surface in saturated mudflats. Blocky, vertically cracked gypsum mudstone likely formed as autoclastic breccia are also documented in the laminated gypsum lithology.

Blocky peds, reduction spots, and cross-cutting gypsum veins are diagenetic features that characterize the ped-rich red mudstone lithology. Vein-filling gypsum cements likely formed at a moderate depth, deeper than several centimeters below the surface. Based on cross-cutting relationships, the vertical gypsum cement that fills veins and fractures is the last diagenetic feature to form; vein-filling gypsum cement forms after the cementation of the host rocks (Holliday 1970). Figure 10 shows the paragenetic sequence interpreted for this outcrop of the Red Peak Formation.
DISCUSSION

Textures in ancient gypsum

This study describes textures and interprets depositional environments from textures in bedded gypsum that is approximately 240 million years old. Until now, the oldest well-preserved gypsum to be described texturally and with depositional environment interpretations is Miocene in age. Before this study, we did not know if the textures seen in modern and Miocene gypsum
could be seen in ancient gypsum and we did not know if we would observe textures reflecting depositional environments in these bedded gypsum units of the Red Peak Formation. The Red Peak Formation gypsum appears well-preserved, relatively unaltered by heat and subsurface waters. This shows the promise that ancient gypsum from outcrop may be mined for specific environmental indicators such as surface water temperature and chemistry through fluid inclusion studies (i.e., Benison et al. 1998, Benison and Goldstein 1999, Zambito and Benison 2013).

Modern and ancient chemical sediments contain details of climate, environment, and life in fluid inclusions. Primary fluid inclusions in modern bottom-growth and cumulate halite and gypsum from Western Australia contain unaltered lake water (Benison et al. 2007, Conner and Benison 2013). Fluid inclusion studies of this modern halite show the presence of Archaea and/or Bacteria, as well as Dunaliella algal cells, and fungi (Conner and Benison 2013, Benison 2019, Benison et al. 2022). Clusters of microorganisms and sulfate crystals known as “hairy blobs” are seen in these fluid inclusions (Benison et al. 2008). Fluid inclusions also contain organic compounds including beta-carotene (Benison et al. 2022). Fluid inclusion studies of modern bottom-growth gypsum from northern Chile also show unaltered surface waters, algal cells, organic compounds, and various prokaryotes (Benison and Karmanocky 2014, Karmanocky and Benison 2016).

Fluid inclusion studies of ancient bottom-growth halite show the pH of some Permian lake waters was less than zero (Benison et al. 1998). Fluid inclusions from Permian bottom-growth halite also show that ancient surface water temperatures were as high as 73°C; surface water temperatures are known to be good proxies for air temperature in modern analog settings (Zambito and Benison 2013). Because primary fluid inclusions in halite are aligned along diurnal growth bands, they also provide evidence of climate. A large diurnal temperature range of 30°C from fluid inclusions in diurnal growth bands indicate an arid, desert climate during the Permian (Zambito and Benison 2013).

Ancient gypsum has generally been excluded from fluid inclusion studies because ancient gypsum is often subject to dehydration and rehydration, and transitions multiple times between gypsum and anhydrite, thus destroying primary fluid inclusions (Benison 2013). The ancient bedded gypsum described this study is remarkable in its preservation; there is no petrographic or mineralogic evidence that this gypsum experienced dehydration and rehydration. In particular,
the gypsum grains composing the clastic gypsum lithology are original, unaltered (aside from physical weathering due to eolian entrainment and transport) bottom-growth gypsum crystals. The results of this study emphasize the potential for ancient bedded gypsum to contain information of environment, climate, and life in fluid inclusions. Additionally, the fluid inclusion-containing lithology in this study are eolian deposits (other bedded gypsum lithologies have not yet been evaluated for fluid inclusions). Previous fluid inclusion studies of ancient evaporites were limited to bottom-growth and cumulate halites and gypsins. This study is the first to demonstrate the potential of ancient windblown gypsum to contain primary fluid inclusions.

*Comparison to other Permo-Triassic red beds and bedded evaporites*

The Red Peak Formation is atypical because the association of red beds and bedded evaporites is relatively rare in the rock record. The Red Peak Formation is similar in age and lithology to bedded gypsum and associated red beds from the Permian and Triassic of Kansas and Oklahoma, North Dakota and South Dakota, northern Ireland, and northern Brazil. Figure 11 shows the paleogeographic location of these rocks and their interpreted environments on Pangea.

The Permian Nippewalla Group from Kansas and Oklahoma consists of bedded halite, bedded gypsum, displacive halite, and red mudstones and red sandstones that likely formed in extremely acid saline lakes, mudflats, sandflats, desert soils, and dunes (Benison et al. 1998, Benison and Goldstein 2001, Sweet et al. 2013, Zambito and Benison 2013, Foster et al. 2014, Benison et al. 2015). Like the Red Peak Formation, the Nippewalla Group has bottom-growth gypsum. But, the Nippewalla Group bottom-growth gypsum has been entirely replaced by anhydrite. As a result, the crystals are blocky and fine detail has been lost.

The Permian Opeche Shale from North Dakota and South Dakota consists of bedded and displacive halite and red fine-grained siliciclastics that together represent a saline lake system and red desert paleosols (Benison and Goldstein 2000). The Opeche Shale contains rare bedded gypsum, unlike the Red Peak Formation, which contains abundant bedded gypsum. The red mudstone of the Opeche Shale is characterized by paleosol features including blocky peds and root features. The red mudstone of the Red Peak Formation is similarly characterized by blocky peds and interpreted as a desert paleosol.
Figure 11. The Red Peak Formation and other Permo-Triassic stratigraphic groups and formations composed of red beds and bedded evaporites. A. Paleogeographic map of Pangea 240 mya, with relevant groups and formations plotted as colored dots (modified from Blakey and Ranney 2018). B. Relevant groups and formations with main peer reviewed papers, descriptions, and interpretations.
The Triassic Mercia Mudstone Group from Northern Ireland is interpreted to have formed in shallow saline lakes, saline mudflats, dry mudflats, and desert soils (Andeskie et al. 2018). These environments are also represented in the Red Peak Formation. However, the Mercia Mudstone contains abundant halite, including bedded halite, displacive halite, and replacement halite after gypsum. Like the Red Peak Formation, the Mercia Mudstone contains bottom-growth gypsum. However, the bottom-growth gypsum in the Mercia Mudstone has been replaced by halite, while the bottom-growth gypsum in the Red Peak Formation retains its original composition.

The Permian-Triassic Motuca Formation from northern Brazil is also composed of red siliciclastic mudstones and bedded gypsum (Abrantes et al. 2016). Lithologies of the bedded gypsum include a laminated gypsum and a clastic gypsum. The laminated gypsum is characterized by planar to wavy thick and thin laminations of white and grey gypsum mudstone and is interpreted as shallow saline lake deposits. The clastic gypsum is called a “gypsarenite” and is interpreted as gypsum crystals reworked in subaqueous conditions. The laminated bedded gypsum of the Motuca Formation is very similar to the laminated gypsum of the Red Peak Formation. However, the Motuca Formation may lack eolian deposits similar to the clastic gypsum in the Red Peak Formation.

The Red Peak Formation is similar to other Permo-Triassic red bed and evaporite deposits from Pangea in that all are composed of fine-grained red bed siliciclastics and bedded evaporites that formed in continental saline settings. Carbonate minerals are unusual in these rocks, and exist mainly as replacement phase of gypsum (Benison et al. 2017). Fossils are uncommon and constrained to microorganisms in bedded halite and suspect insect traces. This collection of Permo-Triassic units are lithologically equivalent and maybe time equivalent across Pangea. Placing temporal constraints on these rocks is challenging for several reasons. Igneous rocks used for absolute dating are not existent in these rocks. The ages of these rocks are mainly understood with relative dating methods; they are underlain by rocks containing early Permian fossils and overlain by rocks containing Jurassic fossils (Zambito et al. 2012). The only absolute date from these rocks comes from the identification of the Kaiman Superchron recorded in iron-oxide minerals (Foster et al. 2014). This places a 267 my age on the Dog Creek Shale near the top of the Nippewallla Group.
Unlike many previous studies which described sedimentological evidence from cores, this study of the Red Peak Formation relies solely on evidence preserved in outcrop. While similar in depositional interpretations, the Red Peak Formation is different from other comparable deposits in its well-preserved gypsum composition and texture. The fact that the bedded gypsum units of the Red Peak Formation are composed almost entirely of gypsum and no anhydrite means that the Red Peak Formation did not undergo heating or deformation the extent needed to remove the waters from the calcium sulfate or chemically replace the gypsum. The unusual preservation of this ancient gypsum indicates that it did not undergo dehydration to anhydrite.

**Halite.** --- The Red Peak Formation is composed of primarily gypsum and contains no evidence of halite. Possible explanations for this absence of halite are: (1) halite effectively never existed in this system, (2) halite existed in this sample but is no longer present in the rock record, or (3) halite existed in the system but was ephemeral.

It is possible that the gypsum-precipitating lakes and groundwaters that formed the Red Peak Formation never precipitated a significant amount of halite. In modern analogues from Western Australia, lakes primarily precipitate either gypsum or halite. Lakes that precipitate one mineral only precipitate a negligible amount of the other; most lakes are either gypsum-rich with minor halite, or halite-rich with minor gypsum (Benison et al. 2007).

Another possibility is that halite existed in the system but was dissolved from outcrop. Halite is more susceptible to dissolution than gypsum; the Permian Nippewalla Group, which is halite-rich in core, lacks halite in outcrop (Benison et al. 2015). However, textures indicative of halite that was later dissolved, such as halite casts and pseudomorphs, were not observed in this study of the Red Peak Formation.

Lastly, halite might have existed in the system but was ephemeral. If the climate was too wet, meteoric waters would dissolve any existing halite prior to burial and diagenesis. Autoclastic breccia, abundant red paleosols, and eolian deposits suggest that the system was relatively arid; it seems unlikely that meteoric waters were abundant enough at the time of deposition to dissolve existing halite. It is most likely that the saline lakes and groundwaters of the Red Peak Formation had a chemistry that favored gypsum.
**Acidity.** --- Late Permian and early Triassic red beds and bedded evaporites were likely formed in acid lake and groundwater systems (i.e., Benison et al. 1998, Benison and Goldstein 2002, Benison et al. 2015, Andeskie et al. 2018). Raman spectroscopy of fluid inclusions in the Permian Nippewalla Group and Opeche Shale shows sulfate peaks indicative of pH less than one (Benison et al. 1998, Benison and Goldstein 2002). Although this master’s thesis did not employ Raman spectroscopy, there are other indicators that the early Triassic lake waters and groundwaters of Wyoming were likely acid. In modern settings, lake and groundwater systems that precipitate gypsum, do not precipitate carbonates, and are associated with iron-rich sediments are acidic (Benison and Goldstein 2002). Acidity may be interpreted in the Red Peak Formation based on the presence of gypsum, the absence of carbonates, and the presence of iron-oxides (Benison and Goldstein 2002).

**A long-lived regional system.** --- Bedded evaporites and associated red bed siliciclastics interpreted as shallow saline lakes and associated mudflats, sandflats, dunes, and desert soils have been documented in the Permian of Kansas, Oklahoma, North Dakota, and South Dakota, the Triassic of Northern Ireland, and the Permo-Triassic of Northern Brazil (Benison et al. 1998, Benison and Goldstein 2000, Benison and Goldstein 2001, Abrantes et al. 2016, Andeskie et al. 2018, Andeskie and Benison 2020). This study adds to our understanding of what seems to be a long-lived, regional landscape consisting of shallow saline lakes surrounded by mudflats, sandflats, dunes, and desert soils that existed in equatorial Pangea during the late Permian and early Triassic. Further documentation of Permo-Triassic bedded gypsums and their textures will further refine what we know about the temporal and regional extent of continental saline systems on Pangea.

*Marine vs. non-marine controversy*

**Early marine interpretations of the Chugwater Group.** --- The Chugwater Group has historically been interpreted as a marine deposit due to the presence of bedded gypsum and rare carbonates (Branson 1915; Tomlinson 1916; Picard 1967; High and Picard 1969). The Chugwater Group is also remarkable in its uniformity of thickness and fine grain size across wide areas. The widespread regularity of planar beds and fine grains is another reason why
workers have assigned the Chugwater a marine depositional interpretation (Branson 1915; Irmen and Vondra 2000).

Early marine interpretations of the Chugwater Group were made before workers established an acceptable framework of red bed deposition and evaporite deposition in continental environments using comparative sedimentology (Walker 1967; Hardie 1985; Lowenstein and Hardie 1985; Benison et al. 2007). Since then, the processes by which evaporites and red beds accumulate in modern and ancient continental settings have been established (i.e., Benison et al. 2007; Benison and Goldstein 2000, 2001; Foster 2014). Today, there is a large body of work describing both modern and ancient evaporites and red beds that have formed in continental saline lake and groundwater systems. Most ancient examples of extreme acidic saline settings existed from the middle Permian to early Triassic, corresponding roughly to the biotic crisis in which ~90% of all existing species on Earth went extinct.

The case for continental deposition of the Chugwater Group. --- Hardie (1984) established a framework for discerning between marine and continental origins of evaporite deposits. Detailed descriptions of modern and ancient evaporite depositional settings also provide guidelines for the recognition of continental versus marine evaporites (e.g. Benison and Goldstein 2000; Benison et al 2007). Evidence of continental deposition include the paucity of carbonate minerals and stratigraphic setting.

There were no carbonate minerals found in this study’s outcrop of the Red Peak Formation. The absence of calcite and aragonite is interesting because bedded and displacive gypsum indicate that the saline surface waters and groundwaters contained Ca (Andeskie and Benison 2020). It is possible that any carbonate minerals that originally existed in the Red Peak Formation were dissolved or replaced by gypsum. However, no shapes, grains, or textures that would be left behind by original carbonate grains or minerals were observed. It is more likely that carbonate minerals simply were rare in the depositional environment of the Red Peak Formation. The lack of carbonates in this section of the Red Peak Formation is evidence that the depositional setting of the Red Peak Formation is continental and not marine.

The Red Peak Formation is overlain by the Triassic Alcova Limestone and underlain by the mid-Permian Goose Egg Formation. There is no convincing evidence that the Alcova Limestone has a marine origin; it has been interpreted as a saline lake deposit (Knapp 2015). A
detailed sedimentological study of the Goose Egg Formation yielded no evidence of marine influence; the presence of paleosols is strongly indicative of a continental setting (Knapp 2020).

Sedimentary structures that are indicative of marine or marginal marine settings such as tidal bundles have not been found the Red Peak Formation or in other formations of the Chugwater Group or underlying Goose Egg Formation (Knapp 2020). Bedded evaporites have been used as evidence that marine waters inundated the northern U.S. midcontinent, despite the fact that most modern evaporites form in lakes. An alternative interpretation of these evaporites suggest that the northern U.S. midcontinent remained an inland continental setting during the late Permian and Early Triassic (Benison and Goldstein 2000). There is no evidence found in this study to suggest that the Red Peak Formation had any marine influence on deposition. The depositional environments of the Red Peak Formation interpreted in this study are continental.

**Implications for a modern climate catastrophe**

The end-Permian mass extinction event is known as the most severe of all mass extinctions in Earth history (Erwin 2006; Payne and Clapham 2012). For example, up to 92% of all marine species did not survive (Sepkoski 1992; 2002). The largest recorded eruption of flood basalts in Earth history occurred at this time; many workers agree these flood basalts pumped massive amounts of carbon dioxide and other greenhouse gasses into the atmosphere by combusting recently deposited Carboniferous coal (Erwin 2006; Knoll et al. 2007; Svensen et al. 2009; Grasby et al. 2011; Jurikova et al. 2020; Cui et al. 2021; Dal Corso et al. 2022). This massive increase in atmospheric carbon dioxide is proposed to have directly resulted in several global kill mechanisms, including acid rain, forest fires, global warming, and ocean anoxia and acidification (Knoll et al. 2007; Tabor and Poulsen 2008; Chen et al. 2013; Jurikova et al. 2020; Vajda et al. 2020). Modern conditions are similarly characterized by acid rain, forest fires, global warming, and ocean anoxia and acidification that are the results of anthropogenic inundation of carbon dioxide into the atmosphere (Barnett et al. 2001; Karl and Trenberth 2003; Rosenzweig et al. 2008; Hansen and Stone 2015; Abatzoglou et al. 2016; Burns et al. 2016; Masson-Delmotte 2018; Fox et al. 2020).

Modern extinction rates are exceptionally high due to humanity’s impact on climate; current extinction rates suggest that a mass extinction is under way (Barnosky et al. 2011;
This mass extinction would be the sixth of its kind in Earth’s 4.6 billion year history, and the first that is entirely anthropogenic (Tabor and Paulsen 2008; Ceballos et al. 2015; Ceballos et al. 2017; Ceballos and Ehrlich 2018). The evidence is incontrovertible that recent extinction rates are highly unusual in the context of Earth’s history. Human society has started to destroy species of other organisms at an accelerating rate, initiating a mass extinction episode unparalleled for 65 million years.

This study adds to a growing understanding of what continental environments looked like during a period of catastrophic climate change that caused tremendous biological loss. Current trends in climate and extinction indicate that humans will experience an earth system comparable to the Permo-Triassic world in its climate and loss of life. Perhaps understanding environment-climate-ecosystem interactions in the Permo-Triassic will be meaningful for future conditions. In each instance throughout geologic time where massive amounts of carbon were rapidly injected into the atmosphere, there was dramatic ocean acidification, global warming, and mass extinction (Tabor and Poulsen 2008; Chen et al. 2013; Jurikova et al. 2020). Knowing what environments looked like during the Permo-Triassic is critical for predicting what’s to come.

**Ancient gypsum and the search for life on Mars**

The potential of ancient gypsum to preserve microorganisms in primary fluid inclusions is pertinent to the search for life on Mars. Mars has many sulfate deposits, which could contain fluid inclusions. The Mars 2020 return sample mission has collected several sulfate-rich sediments and sandstones which likely contain fluid inclusions in gypsum (Benison et al. 2023). Because gypsum is known to preserve microorganisms and microfossils within fluid inclusions from as far back as the Permian, there is added promise for Martian gypsum to retain clues of past life (Benison and Karmanocky 2014).

**Recommendations for future work**

This study examines a single outcrop of the Red Peak Formation in the Greybull area. The Permo-Triassic red beds and bedded gypsums in this area are undescribed. I recommend a study that interprets depositional environments from multiple outcrops that expand the complete
Permo-Triassic depositional record in this area in order to fully understand the regional extent, longevity, and environmental trends of these continental saline environments. Methods demonstrated in this study, such as combining field and petrographic observations to describe lithologies, should be applied to this larger project.

CONCLUSIONS

The Red Peak Formation in northcentral Wyoming is characterized by alternating units of red bed siliciclastics and bedded gypsum. Although the Red Peak Formation makes up most of the well-known Chugwater Group, the bedded gypsums of the Red Peak Formation had not yet been described. Detailed sedimentology of the bedded gypsums from one outcrop of the Red Peak Formation showed three distinct lithologies of bedded gypsum, with three different implications for depositional environment. The bedded gypsum of the Red Peak Formation in northcentral Wyoming is interbedded with red mudstones that are interpreted to be paleosols. The association of the bedded gypsum units with paleosol units strongly suggests a continental origin for the bedded gypsum. The bedded gypsum lithologies are bottom-growth gypsum, clastic gypsum, and laminated gypsum. The bottom-growth gypsum is characterized by a vertical texture from multiple rows of bottom-growth gypsum crystals and formed in the bottoms of shallow saline lakes. The clastic gypsum is composed of bladed and abraded gypsum grains with a bimodal grain size distribution and formed in sandflats and dunes adjacent to gypsum-precipitating lakes. The laminated gypsum is characterized by planar, convolute, and wrinkly laminations of gypsum mudstone and formed in shallow saline lakes and saturated mudflats. The Red Peak Formation in northcentral Wyoming formed in shallow saline lakes and associated mudflats, sandflats, dunes, and desert soils.

Textures of bedded gypsum from the Red Peak Formation include bottom-growth gypsum, displacive gypsum, and clastic gypsum. These bedded gypsum textures, which are associated with red desert paleosols, are interpreted to have formed in continental saline lakes, and associated saline mudflats, sandflats, and dunes. Similar continental saline environments have been described from the Permian of South Dakota, Oklahoma, and Kansas, and the Triassic of Northern Ireland and northern Brazil (Benison et al. 1998; Benison and Goldstein 2000;
Abrantes et al. 2016; Andeskie et al. 2018; Andeskie and Benison 2020). Gypsum precipitating lakes in Western Australia, which are surrounded by reworked gypsum material in mudflats, sandflats, and dunes, and further surrounded by red desert soils, are modern analogs for these Permo-Triassic environments. These lakes experience stages of desiccation and flooding. This study adds another example of an acid saline environment in western equatorial Pangea during Permo-Triassic time and increases our understanding of the extent and longevity of these continental acid-saline systems.
REFERENCES


Andeskie, A.S. and Benison, K.C., 2020, Using sedimentology to address the marine or continental origin of the Permian Hutchinson Salt Member of Kansas: Sedimentology, v. 67, p. 882-896.


Benison, K.C. and Bowen, B.B., 2015, The evolution of end-member continental waters: The origin of acidity in southern Western Australia: GSA Today, v. 25, no. 6, p. 4-10.


Ceballos, G., Ehrlich, P.R., Dirzo, R., 2017, Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines: PNAS, v. 114, no. 30, p. E6089-E6096.


Hansen, G. and Stone, D., 2015, Assessing the observed impact of anthropogenic climate change: Nature Climate Change, v. 6, p. 532-537.


McKee, E.D., 1966, Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas): Sedimentology, v. 7, no. 1, p. 3-69.


Appendix A. DESCRIPTION OF MEASURED SECTION

This outcrop is 10 km north of the town of Greybull, Wyoming. It is located at 44°34’52.06”N, 108° 7’38.22”W. Units A-G were measured from base to top of the east side of the outcrop. Unit G can be traced to the base of the west side of the outcrop. Units 1-10 were measured from base to top of the west side of the outcrop. Unit 1 conformably overlies Unit G on the west side of the outcrop.

- Unit A
  - Unit A is the basal unit exposed at this outcrop
  - Unit A is a massive gypsum sandstone composed of moderately sorted, subrounded grains. In the hand, the grain size is mostly coarse sand (0.5 mm) but some grains are very coarse sand (1 mm) and some grains are medium-fine sand (0.1 mm). The grains are sugary and have a vitreous luster. The sandstone is white on fresh exposures but has a 1 mm-thick weathering rind that is burnt orange (5YR 6/6). The grains slough off easily, but you can’t crumble the rock with your hands – friable but not too friable. The unit is massive and retains no sedimentary structures.
  - The lower and upper contacts of this unit are concealed by interbed and rubble; the thickness of this unit is estimated to be around 95 cm.

- Unit B
  - Unit B is an orangey brown (5YR 4/6) mudstone with bluish grey (GLEY 2 8/1 5B) contacts. The grain size is fine silt (0.005 mm). The mudstone is riddled with branching vein networks. The veins are filled with medium-fine sand sized grains that are white, sugary, and have a vitreous luster. The veins are no wider than 2 cm and branch from a principle horizontal vein and have tapered ends.
  - Unit B appears to conformably overlie Unit A and pinches out to the east between Unit A and Unit C. The maximum thickness of Unit B is 40 cm.

- Unit C
  - same as A, with a thickness of 96 cm
- **Unit D**
  - Unit D is an orangey brown mudstone riddled with gypsum stringers like Unit B. Here a clotty, nodular texture appears in the mudstone. The silt-sized grains are arranged in clustered clumps. Each clump is no more than 2 cm in diameter and are rounded and spherical or sub-rectangular and blocky. The clumps are clustered together creating a clotty, nodular texture. Bluish grey (GLEY 2 8/1 5B) spots appear in the blocky orange mudstone near the cross-cutting white gypsum stringers.
  - Unit D conformably overlies unit C and has an undulating contact with Unit E. Unit D is 44 cm thick.

- **Unit E**
  - same as A, C, with a thickness of 60 cm

- **Unit F**
  - same as B, D
  - pinches out to the east between Unit E and Unit G, with a maximum thickness of 42 cm

- **Unit G**
  - Unit G has the same lithology as A (massive gypsum sandstone), with the appearance of a 1 cm-thick wavy discontinuous bed filled with vertically oriented, sparry gypsum crystals.
  - Although Unit G is effectively massive, the weathering profile is noticeably different than the units of bedded gypsum beneath it. You can almost begin to see laminations and bedding planes in the weathering profile of this unit.
  - We traced this unit from the top of the east side of the outcrop to the base of the west side of the outcrop.
  - Unit G is 42 cm thick
- **Unit 1**
  - same as B, D, F
  - connects in some places to lithologic-equivalent Unit 3 above it
  - pinches and swells, with a maximum thickness of 44 cm

- **Unit 2**
  - Unit 2 is a hard gypsum mudstone with suspect remnant beds. The mudstone is comprised of fine silt to clay sized grains of gypsum. It has a 1 mm-thick rind that is reddish yellow (5YR 7/6) and is yellowish white (7.5YR 8/1) to pale grey (GLEY 2 7/1 10B) on fresh exposures.
  - This unit of bedded gypsum is significantly harder than the units of bedded gypsum below it. It has a slightly undulating upper surface and suspect remnant beds.
  - Unit 2 is 28 cm thick.

- **Unit 3**
  - same as B, D, F, 1
  - Unit 3 pinches out completely in some places, and is 16 cm thick at most.

- **Unit 4**
  - Unit 4 is a laminated and thinly bedded gypsum mudstone. It is well-cemented and comparatively hard. It has a 0.05 mm-thick rind that is pale orange (5YR 8/4) and orangey brown (5YR 4/6). On fresh exposures it is yellowish white (7.5YR 8/1) and pale grey (GLEY 2 7/1 10B). There are wavy, discontinuous beds and laminations composed of white gypsum grains. These wavy, discontinuous beds and lamina are enveloped by orangey brown beds and laminations composed of siliciclastic mud. There are rare instances of tightly packed, polygonal gypsum nodules, 1-3 cm$^2$ in diameter, separated by mm-thin stringers of the orange siliciclastic mud. There are gypsum laminations with a vertical texture that is characteristic of bottom growth crystals.
  - This unit is 182 cm thick.
- **Unit 5**
  - same as B, D, F, 1, 3, with a thickness of 33 cm

- **Unit 6**
  - Unit 6 is a beautifully laminated and thinly bedded gypsum mudstone like Unit 4.
  - There are mudcracks at the base of this unit.
  - Unit 6 is 60 cm thick.

- **Unit 7**
  - same as B, D, F, 1, 3, 5, with a thickness of 32 cm

- **Unit 8**
  - same as 4, 6
  - There are thin wavy laminations and weathered surfaces appear to have an almost conchoidal fracture texture. It is extremely well-cemented, to the point of being chert-like.
  - Unit 8 is 82 cm thick.

- **Unit 9**
  - same as B, D, F, 1, 3, 5, 6, with a thickness of 74 cm

- **Unit 10**
  - This gypsum cap unit was out of reach, so we were not able to carefully describe its textures, but there was no indication that it was distinct from the bedded gypsums of Units 4 and 6.
  - About 6 m above this outcrop, there is a cliff-forming outcrop of a buff-colored carbonate mudstone. We think this is the Alcova Limestone.
Appendix B. ADDITIONAL FIELD PHOTOS

Contact between Unit 3 (red paleosol) and Unit 4 (bedded gypsum) with pencil for scale

Undulating, mounding contact between a unit of red mudstone and a unit of bedded gypsum
Block of laminated gypsum showing multiple depositional textures with sharpie for scale
View of study outcrop with shovel for scale

Laminated gypsum in outcrop
Figure 1. Unit 6, under transmitted and partially polarized light (A) and reflected light (B)

Figure 2. Unit 6, under transmitted and partially polarized light (A) and reflected light (B)
Figure 3. Unit 8, under transmitted light (A) and reflected light (B)

Figure 4. Unit 8, under transmitted and partially polarized light (A) and transmitted and cross polarized light (B)
Figure 5. Unit 8, under transmitted and partially polarized light (A) and reflected light (B)

Figure 6. Unit 4, under transmitted and cross-polarized light (A), and reflected light (B)
Figure 7. Unit 6, under transmitted and partially polarized light (A), and reflected light (B)

Figure 8. Unit 6, under reflected light (A) and transmitted and partially polarized light (B)
Figure 9. Unit 2, under transmitted and partially polarized light (A), reflected light (B), and transmitted and cross-polarized light (C)
Figure 10. Unit 2, under transmitted and partially polarized light (A), reflected light (B), and transmitted and cross-polarized light (C)
Figure 11. Unit 2, under transmitted and partially polarized light (A), reflected light (B), and transmitted and cross-polarized light (C)
Figure 12. Unit 4, under transmitted light (A), reflected light (B), and transmitted and cross-polarized light (C)
Figure 13. Unit 2, under transmitted light (A), reflected light (B), and transmitted and cross-polarized light (C)
Figure 14. Unit 4, under transmitted and partially polarized light (A), reflected light (B), and transmitted and cross-polarized light (C)
Figure 15. Unit C, under transmitted and partially polarized light (A), and cross-polarized light (B)