2017

Improving Seeding and Mulching Specifications In West Virginia and Creating a Materials Estimate Tool

Forrest N. Pritt

The depositional and diagenetic history of the Permian Quartermaster Group of western Kansas

Joseph James Pritt

Thesis submitted
to the Eberly College of Arts and Sciences
at West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science in
Geology

Kathleen C. Benison, Ph.D., Chair
Katherine R. Bruner, Ph.D.
Jaime Toro, Ph.D.

Department of Geology and Geography

Morgantown, West Virginia

2016

Keywords: Big Basin Formation; Day Creek Dolomite; Kansas; Permian;
Quartermaster Group; Whitehorse Sandstone

ABSTRACT

The depositional and diagenetic history of
the Permian Quartermaster Group of western Kansas

Joseph James Pritt

Permo-Triassic red beds and evaporites can be found in a variety of locations around the world. Largely deposited once the supercontinent Pangea formed, many of these units have historically been interpreted as marine to marginal marine deposits due to their association with evaporites. Evaporites, however, can also form in continental settings. Recent studies of red beds and evaporites within the Leonardian-Guadalupian Nippewalla Group of Kansas suggest some red beds and evaporites were deposited in acid saline lakes and associated environments. The middle to late Permian Quartermaster Group, which overlies the Nippewalla Group, has not been as extensively studied. The main goal of this thesis was to determine the depositional and diagenetic history of the Quartermaster Group of Kansas.

This research focused on the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation of the Quartermaster Group as observed in the Amoco Rebecca K. Bounds core no. 1 from Greeley County, west-central Kansas. Petrography and mineralogical identification were used to characterize the depositional and diagenetic features of these rocks. Field observations from south-central Kansas (Clark and Barber Counties) provided supplementary data.

Sedimentary features observed in the Quartermaster Group suggest the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation were deposited in continental settings. The Whitehorse Sandstone consists of red sandstone, siltstone, and mudstone with observable ped structures, root features, ripple cross-stratification, mud drapes, mudcracks, and soil slickensides. These features suggest deposition in mudflats and fluctuating water tables in adjacent soils. The Day Creek Dolomite consists of bedded gypsum/anhydrite and finely laminated red siltstones. Ripple cross-stratification, mudcracks, and planar laminae observed in bedded gypsum/anhydrite indicate deposition in ephemeral saline lake environments while ripple cross-stratification, mud drapes, soil slickensides, and root features in red siltstones indicate mudflats and soils. The Big Basin Formation consists of dark red sandstone, siltstone, and mudstone characterized by soft sediment deformation, ripple cross-stratification, mudcracks, and soil slickensides. These features suggest deposition in mudflats and the development of paleosols. In general, early and late diagenetic features observed within the Quartermaster Group suggest substantial influence from wetting and drying processes at or near the surface.

Evidence for acidity in the Quartermaster Group is based on suspect to problematic criteria. Acid saline lake deposition is postulated from indirect criteria such as unusual yellow hues observed in halite and other evaporites within bedded gypsum/anhydrite layers of the Day Creek Dolomite. Additionally, the absence of carbonates, abundance of red beds, and similarities to the underlying Nippewalla Group, a known acid system, suggest that units within the Quartermaster Group were likely influenced by acid lake waters and groundwater.

The Quartermaster Group signifies deposition in an arid to semiarid continental setting. Comparisons between these units and the underlying Nippewalla Group suggest conditions became more humid and less saline towards the end of the Permian. Additional use of highly recoverable core in future studies will help to refine understanding of the stratigraphy, nomenclature, paleogeography, depositional environments, and diagenetic history of other red bed and evaporite sequences in Kansas and throughout the western midcontinental United States.

ACKNOWLEDGEMENTS

I would like to thank the many individuals that have helped to contribute to this research and others that have made lasting impressions on my life. My desire to become a geologist would not have been possible had it not been for my previous undergraduate advisors Dr. Stephen C. Kuehn and Dr. David L. Matchen. Their passion for geology made me reconsider my initial desires of becoming a geographer, lawyer, or meteorologist. Additional thanks should be given to my longtime friend and mentor William "Bill" K. Jones who to this day provides sound advice about carbonates and academia.

Of course, none of this research would have been made possible had it not been for the inspiration, encouragement, and support provided by my mentor and advisor Dr. Kathleen C. Benison. The Kansas Geological Survey allowed Benison and myself to study and sample the Rebecca K. Bounds no. 1 core. This study of the Quartermaster Group would not have been made possible had it not been for the preliminary work by her and her colleagues James J. Zambito, IV, Gerilyn S. Soreghan, Tyler M. Foster, and Molly J. Kane. Additional help in this research was provided through suggestions from committee members Dr. Katherine R. Bruner and Dr. Jaime Toro. I understand everyone has tight schedules and I am forever grateful that you all took the time out of your days to make mine a little better.

I would also like to thank all friends, many of which are current and past graduate students of WVU that have provided me peace of mind in times of distress including (but not limited to): John "Alex" Haney, Zach Barnhill, Victoria Hilliard, John Baird, Amanda Delisle, Mollie Kish, Sofia Andeskie, Lynnette Eichenlaub, Jonathan Knapp, Travis Wilson, Shuvajit Bhattacharya, and Kory Wiley. These brave, loving souls have also provided ears, beds, and brews whenever I've needed them.

Pets, in addition to people, can provide comical relief in times of thesis preparation and writing. Many thanks to my cats in Virginia and other feline friends throughout West Virginia for providing such relief in times of need.

Financial woes of this research have been eased by the NSF grant EAR-1053025 to Dr. Kathleen C. Benison and assistance provided by West Virginia University. Additional thanks is given to West Virginia University for providing a sedimentary petrology course and lab that were overall helpful throughout this research.

Last, but not least, I would have never made it this far in life without my father and mother, Roy and Linda Pritt. They taught me at an early age that hard work, humility, and appreciation can take me places. Their lessons and loving support are what truly make me who I am today. I have been many places throughout my 26 years of life and I hope that continues.

"One does not discover new lands without consent to lose sight of shore for a very long time."

- André Gide

TABLE OF CONTENTS

INTRODUCTION

Permo-Triassic red bed and evaporite sequences have historically been interpreted as marine to marginal marine deposits because of their association with evaporites. Evaporite units, however, are known to also form in continental settings (Lowenstein and Hardie, 1985; Benison et al., 1998; Benison and Goldstein, 2001; Benison et al., 2007). Recent studies suggest that some Permian red beds and evaporites of the western midcontinental United States formed in arid continental settings with extremely acidic saline lakes and associated environments such as mudflats with acid saline groundwater (Benison and Goldstein, 2000, 2001). Continental sedimentary rocks deposited during the formation of Pangea suggest a transition from icehouse earth to greenhouse earth conditions from early to late Permian (Parrish, 1993).

Red beds and evaporites can be found extensively throughout the western midcontinental United States (Fig. 1). Composed of red, organic-poor sandstone and shale, and evaporites (gypsum/anhydrite and/or halite), these units are highly friable and poorly preserved at the surface. Outcrops can undergo dissolution and alteration by meteoric waters. In the subsurface these units are susceptible to dissolution and alteration if buried too shallow or deeply, respectively. Red beds and evaporites within approximately 1000 ft of the surface can undergo dissolution if rock units interact with groundwater. Original rock textures of evaporites may be lost if buried deeper than approximately 10000 ft (Benison et al., 2015). Factors such as these have made studying red beds and evaporites historically difficult (Benison et al., 2013).

Permo-Triassic red bed and evaporite studies are important for a variety of reasons. Evaporites can serve as subsurface marker beds because of their distinct petrophysical signatures in well logs (Zambito et al., 2012; Soreghan et al., 2015). Subsurface evaporite-bearing units can also serve as stratigraphic traps/seals (i.e. Buckner Anhydrite; Lowenstein, 1987). Red beds at shallow depths (within 1000 ft of the surface), which interact with groundwater, can potentially serve as aquifers (i.e. red beds of Kansas and Oklahoma; Wood and Stacy, 1965). Lastly, red bed and evaporite sequences can help determine paleoclimate and depositional environments as they tend to form in specific environmental conditions.

Though many outcrops and cores of red beds and evaporites are poorly preserved due to dissolution, alteration, and poor drilling methods, the Amoco Rebecca K. Bounds core no. 1 (API 15-071-20446), also known as the Becky Bounds core, is exceptional in that it exhibits 99.1% recovery despite containing many units that are evaporite and/or evaporite cemented (Zambito et al., 2012; Benison et al., 2013). Drilled in Greeley County, Kansas (38.48963ºN latitude, -101.97456ºW longitude), from March to early April 1988, this core provides an opportunity at obtaining significant information concerning the Permian of western equatorial Pangea. Permian units found in the Becky Bounds core from the Council Grove to Nippewalla Group have been studied for factors such as magnetostratigraphy, geochemistry, fluid inclusion microthermometry, detrital zircon geochronology, mineralogy, and petrography (Soreghan et al., 2015). Units above the Leonardian-Guadalupian Nippewalla Group, which are thought to complete the Permian series in Kansas, are not as well documented. These units, the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation, seemingly equivalent to the Quartermaster Group of northern Texas, will be the main focus of this thesis and referred to as the Quartermaster Group herein (Fig. 2).

The main purpose of this study was to determine the depositional and diagenetic history of the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation as observed in the Becky Bounds core through a detailed petrographic analysis. Each formation's mineralogy, sedimentary textures, sedimentary structures, fossils, and diagenetic features were documented.

Stratigraphic contacts bounding the Quartermaster Group were also analyzed. This study is the first of its kind specifically detailing the sedimentology, stratigraphy, depositional environments, and diagenetic history of the Quartermaster Group of western Kansas.

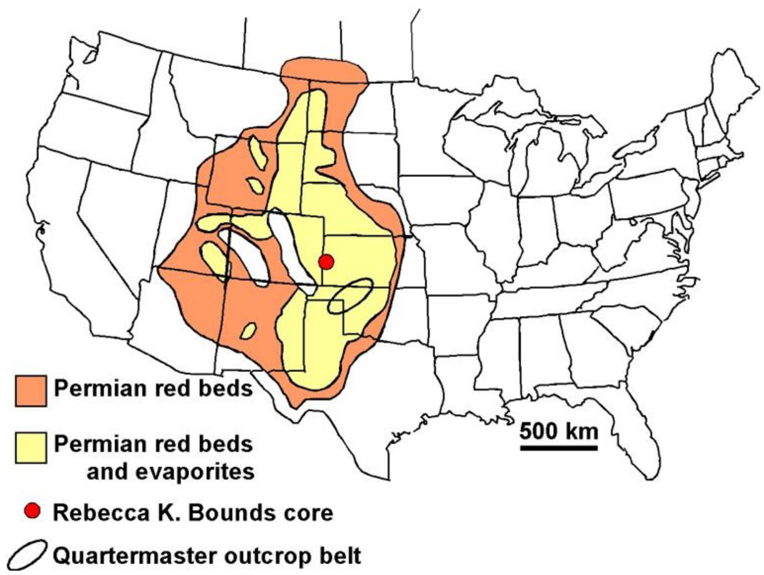


Figure 1. Spatial distribution of Permian red beds and evaporites throughout the midcontinental United States. (Modified after Pritt and Benison, 2015 and Walker, 1967)

BACKGROUND

STATEMENT OF RESEARCH PROBLEM

The depositional history of many middle to late Permian red beds and evaporites of the western midcontinental United States has been debated. Evaporites have been used as evidence for marine to marginal marine depositional environments for the Nippewalla Group and other Permian red beds and evaporites (e.g. Hills, 1942; Fay, 1964; Maughan, 1966, 1967; Mudge, 1967). Many modern evaporites, however, have been noted to form in continental settings (Lowenstein and Hardie, 1985; Benison et al., 1998; Benison and Goldstein, 2001; Benison et al., 2007). Interpreted paleosol and eolian dune deposits in many of these red beds contradict historically suggested marine to marginal marine interpretations (Benison and Goldstein, 2000, 2001; Poland and Simms, 2012; Sweet et al., 2013; Foster et al., 2014). Of particular importance in contradicting marine to marginal marine deposition are fluid inclusion data from bedded halite in the Nippewalla Group of Kansas and Opeche Shale of North Dakota, which demonstrate that middle Permian lake waters and groundwater had extremely low pHs (some less than 0) and high concentrations of Al, Fe, and Si (Benison et al., 1998; Benison and Goldstein, 2002). These recent findings suggest Permian red beds and evaporites of the Nippewalla Group were deposited in extremely acid saline lakes and associated continental environments (Benison et al., 1998; Benison and Goldstein, 2000, 2001, 2002). Earlier accounts describing red beds and evaporites throughout the western midcontinental United States have also considered continental deposition of the Nippewalla Group. Holdoway (1978) interpreted a continental, closed-basin depositional environment through use of petrography and bromine analysis of halite in one core. Evidence supporting her conclusions included sedimentary and early diagenetic features in the Nippewalla Group indicative of eolian deposition and paleosol formation. Low bromine values were also observed. Environmental interpretations of red beds and evaporites throughout the western midcontinental United States, which vary in interpretation from marine/marginal marine to continental deposition, suggest a need for more detailed studies (i.e., Sweet et al., 2013). This thesis, which petrographically details the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation in the Becky Bounds core, will provide interpretations of depositional environments and paleoclimate in western equatorial Pangea during the middle to late Permian (Fig. 2).

System/Period	Series/Epoch	Stage/Age	Group	Formations
PERMIAN	Guadalupian ? Ochoan		Quartermaster	Big Basin
				Day Creek Dolomite
				Whitehorse Sandstone
	Leonardian		Nippewalla	Dog Creek
				Blaine
				Flower-pot Shale
				Cedar Hills Sandstone
				Salt Plain
				Harper Sandstone
			Sumner	Stone Corral
				Ninnescah Shale
				Wellington
	Wolfcampian		Chase	Nolans Limestone
				Odell Shale
				Winfield Limestone
				Doyle Shale
				Barneston Limestone
				Matfield Shale
				Wreford Limestone
			Council Grove	Speiser Shale
				Funston Limestone
				Blue Rapids Shale
				Crouse Limestone
				Easly Creek Shale
				Bader Limestone
				Stearns Shale
				Beattie Limestone
				Eskridge Shale
				Grenola Limestone
				Roca Shale
				Red Eagle Limestone

Figure 2. Stratigraphic nomenclature of Permian units observed in Kansas (Zambito et al., 2012). The Leonardian-Guadalupian boundary is estimated at 265-267 ma (Foster et al. 2014). Areas of main interest to this thesis are highlighted in yellow while areas shaded in orange represent the Nippewalla Group. The depositional environments of the Quartermaster Group will be compared to those observed in the Nippewalla group for this thesis. (modified from Sawin et al., 2008)

Two hypotheses were tested in this research:

1) The Quartermaster Group of western Kansas was deposited in an acid saline system similar to the one observed in the underlying Nippewalla Group. Expected depositional environments that would support this hypothesis may include saline lake, mud flat, eolian dune and/or sandflat lithofacies and development of paleosols.
2) The Quartermaster Group of western Kansas represents a change in environmental conditions to a different continental system than that of the underlying Nippewalla Group or marine/marginal marine systems. Expected depositional environments that would support a different continental system may include perennial freshwater lake or fluvial lithofacies. Depositional environments that would support marine/marginal marine systems may include delta, lagoon, tidal flat, and/or estuary lithofacies.

CHALLENGES OF STUDYING RED BEDS AND EVAPORITES

Investigating Permian red beds and evaporites of the western midcontinental United States can be problematic for a variety of reasons. Correlation between core and outcrop has proven extremely difficult. Evaporite and evaporite bearing rocks exposed to surface conditions can undergo dissolution and alteration at great rates, but can remain well-preserved in highly recovered core (Benison et al., 2013). Halite, in many cases, is not preserved in outcrop except for molds and casts. Halite-cemented siliciclastics, however, can be well preserved in core, potentially exhibiting sedimentary structures and textures not observed in outcrop. Cores are rare, however, as few are drilled in red beds and evaporites. Those that are drilled tend to use fresh water muds for drilling, which lead to the dissolution of many evaporite bearing units (Soreghan et al., 2015). These differences between core and outcrop have led to significant issues concerning the stratigraphy of middle to late Permian strata in Kansas and their correlation to units in Oklahoma and the northern northern Texas panhandle (Baars, 1990; Sawin et al., 2008; Zambito et al., 2012). Limited preservation of outcrops and minimal quantities of well recovered core have left the lithological details of many red bed and evaporite sequences such as the Quartermaster Group poorly understood (Benison et al., 2013).

A lack of volcanic ash and fossils in some Permian red beds has left age-dating difficult. The Leonardian-Guadalupian boundary (~270 Ma) falls within the Dog Creek Formation which conformably underlies the Whitehorse Sandstone (Foster et al., 2014). Stratigraphically overlying the Big Basin Formation in the Becky Bounds core are late Triassic-early Jurassic rocks. Lithological similarities and conformable contacts between the Leonardian-Guadalupian Nippewalla Group as well as several disconformities between the Big Basin Formation and overlying late Triassic-early Jurassic rocks suggest that the three formations comprising the Quartermaster Group are likely middle to late Permian (Guadalupian-Ochoan) in age. Recent detrital zircon work by Smith et al. (2015) on rocks identified as the Big Basin Formation at Point of Rocks indicate a youngest single detrital zircon age of 263 $\pm$ 12.1 Ma.

Nomenclature concerning these units is also challenging. Late stage diagenesis of many red beds and evaporites at the surface renders them vastly different to their subsurface equivalents (Soreghan et al., 2015). Type localities of the Quartermaster Group and associated red beds and evaporites are generally based on surface exposures (Cragin, 1896, 1897; Gould, 1905, Norton, 1939) despite the fact that many evaporite bearing units are better preserved in the subsurface. This poses problems for the petroleum industry as surface and subsurface descriptions of these units tend to vastly differ. For example, dissolution experiments were conducted on six displacive halite samples from the Becky Bounds core to determine the amount of rock thickness (height) and rock mass lost to dissolution. Results of this study showed rock height and rock mass losses to dissolution ranged from 53.2% to 88% and 68.2% to 93.3%, respectively (Benison et al., 2015). Additionally, the limited economic value of red beds to the petroleum industry has resulted in scarce high quality continuous coring, ultimately limiting the study of these units (Soreghan et al., 2015). Minimal recognition of these rocks in the subsurface can potentially result in loss of equipment at drill sites should subsurface halite and evaporite bearing units undergo dissolution and collapse as a result of conventional drilling fluids (Benison et al., 2013).

Despite containing an abundance of evaporite-bearing units, the Becky Bounds core's 99.1% recovery provides an exceptional record and opportunity for high resolution studies concerning the Permian of western Kansas.

GEOLOGIC SETTING

Midcontinental North American red bed and evaporite rocks of the middle to late Permian can be generally observed from Texas to Saskatchewan (south-north) and Wyoming through Kansas (west-east). Mountains surrounding this region during time of deposition included the Ancestral Rocky Mountains to the west, the Ouachita Mountains to the south, and the Appalachian Mountains to the east (Soreghan et al., 2015; Fig. 3). Dips of these beds are relatively shallow (~0.5^o) indicating little to no structural control on deposition (West et al., 2010). Estimates of western Kansas paleolatitude during time of deposition range from 5-15^oN (i.e. Benison and Goldstein, 2001; Foster et al., 2014).

More specifically, the Rebecca K. Bounds core drilling site is found in what is known as the Hugoton Embayment, a northward extension to the Anadarko Basin of Oklahoma and Texas

(Maher and Collins, 1948). This feature plunges southward, with thickest units towards its axis and towards the Anadarko Basin (Merriam, 1963). Paleozoic sediments are thought to have been deposited in low relief settings (Fay, 1964). Tectonics are not thought to have played a crucial role during this time period. The development of the Hugoton Embayment, however, suggests subsidence influence (Merriam, 1963). Leonardian-Guadalupian rocks on the Northern Shelf of the Anadarko Basin experienced burial depths no greater than 1000 m (Carter et al., 1998). It can be presumed from these values that Leonardian-Guadalupian rocks of the Rebecca K. Bounds core experienced no greater than 1000 m burial depths as well.

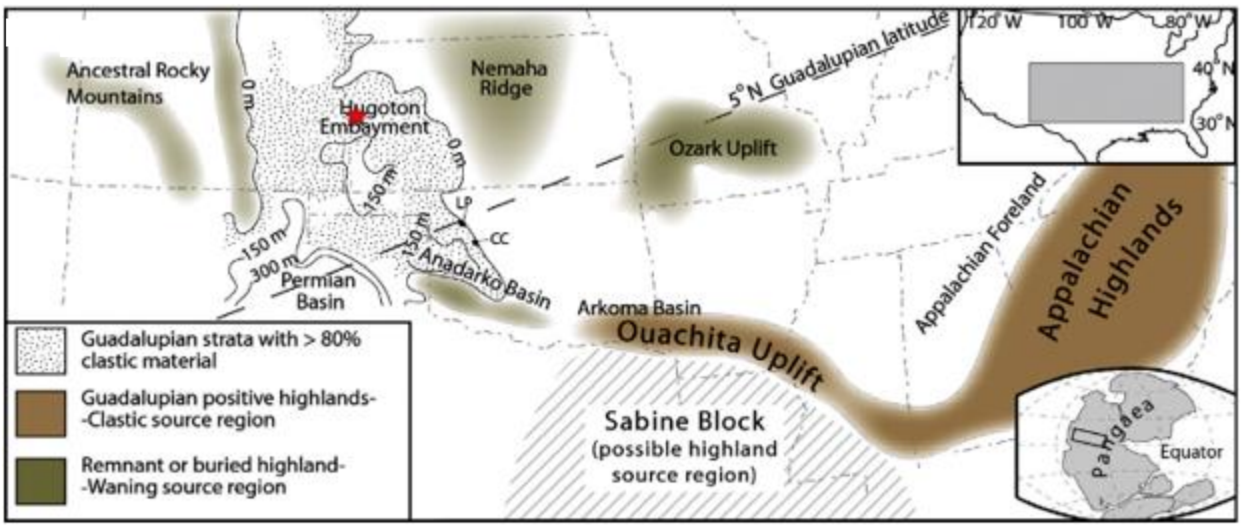


Figure 3. Paleogeographic reconstruction of the midcontinental United States (western equatorial Pangea) during the Guadalupian. This reconstruction depicts the overall orogenic systems that were prevalent during deposition of Guadalupian rocks. The approximate location of the Becky Bounds core drilling location has been designated by a red star on the figure. (modified from Sweet et al., 2013)

ENVIRONMENTAL CONDITIONS

Significant climatic shifts occurred in Kansas during the Permian (Parrish, 1993). Lithological characteristics observed in the Council Grove Group through Nippewalla Group suggest conditions transitioned from an icehouse earth to greenhouse earth, respectively (West et al., 1997, 2010). Olszewski and Patzkowsky (2003) related eustatic and climatic changes observed in late Carboniferous and early Permian rocks to icehouse conditions. Monsoonal circulation is indicated from models and data by the early Permian (Parrish, 1993; Soreghan et al., 2002; Tabor and Montanez, 2002). Greenhouse conditions, however, were predominant during the middle to late Permian. Evidence for greenhouse conditions is gathered from homogenization temperatures obtained from primary fluid inclusions of 24 chevron halite beds spanning from the Harper Sandstone to Blaine Formation of the Nippewalla Group (Benison and Goldstein, 1999; Zambito and Benison, 2013). Results showed homogenization temperatures as high as 73^{o}C with daily temperature ranges as high as 32^{o}C. Homogenization temperatures of this degree and range indicate western Kansas was an extremely warm environment during the middle to late Permian. Modeling studies further support a dry paleoclimate during this time (West et al., 1997, 2010; Poulsen et al., 2007).

Extremely acidic waters were also observed in halite fluid inclusions from various intervals of bedded halite within the Nippewalla Group (Benison and Goldstein, 1999, 2013). Acidity was determined from HSO_4^- peaks from laser Raman spectroscopy (LRM) data of halite fluid inclusions. These peaks are only observed when pH is less than 1 (Benison et al., 1998). Additional evidence of acidity within these units was gathered from leachate analyses of fluid inclusions in halite which showed abundant Al, Fe, and Si. Though Fe and Si can be found in moderate amounts in some alkaline waters, high concentrations of Al have been considered diagnostic criteria for extremely acid waters (Benison, 1997; Benison and Goldstein, 2002). Environmental conditions during the deposition of the Quartermaster Group of western Kansas are not described in reviewed literature but will be interpreted in this thesis.

HISTORICAL STUDIES OF THE QUARTERMASTER GROUP

Historically, very few studies have been conducted on units of the Quartermaster Group of Kansas. Notable works that briefly mention the Quartermaster Group and associated units in Kansas and Oklahoma include Cragin (1896), Gould (1905), Evans (1931), Norton (1939), Swineford (1955), and Fay (1964) . These studies largely relied on field observations and rotary cuttings for description. In contrast, the well-preserved Becky Bounds core provides a greater opportunity for gathering details concerning western Kansas throughout the middle to late Permian.

First described by Cragin (1896) as the Red Bluff Sandstone, the Whitehorse Sandstone was named by Gould (1905) for surface exposures observed in Whitehorse Springs, Woods County, Oklahoma. Field exposures of this unit in Kansas can be found in Barber, Clark, Comanche, and Kiowa Counties (Zeller, 1968). Norton (1939) described the Whitehorse Sandstone as very fine-grained sandstone to siltstone with few shale beds and localized dolomites in south-central Kansas. Zeller (1968) described it as red beds of shale, siltstone, and feldspathic sandstone with minor amounts of dolomite. Subsurface cuttings indicate that it may also contain thin veins (stringers) of dolomite and anhydrite (Swineford, 1955). Zeller (1968) divided this unit into four members (from bottom to top): the Marlow Sandstone Member, the Relay Creek Dolomite Member, an unnamed member (referred to by Norton (1939) as the Even-Bedded Member), and the Kiger Shale Member. These four members were not confidently distinguishable in the Becky Bounds core and, as such, were not used in this thesis. Thickness of this unit in subsurface and outcrop can range as much as 400 ft and 270 ft thick, respectively, with thickest units found in southwestern Kansas (Merriam, 1963).

The Day Creek Dolomite was named by Cragin (1896) for field exposures at the Day Creek in Clark County, Kansas. It is described in outcrop as a pale, dense single-bedded gray to pink fine-grained dolomite with localized chert nodules and disseminated chert (Zeller, 1968). Field exposures of these units are poor and often found as rubble at the bottom of slopes (Swineford, 1955). This unit in the subsurface, however, is lithologically variable and indurated. In some locations, where the units are thickest (e.g. northeastern Morton County, Kansas), it is predominantly found as anhydrite while in other subsurface locations it is represented as bedded anhydrite mixed with very fine shale (Swineford, 1955). Maximum thicknesses of this unit in the subsurface and outcrops of Kansas range from 65 ft and 3 ft, respectively (Merriam, 1963).

The Big Basin Formation, recognized interchangeably with the Taloga Formation among earlier accounts (Cragin, 1897), was named by Cragin (1896) for field exposures observed in Big Basin, Clark County, Kansas, and Taloga, Dewey County, Oklahoma, respectively. Field exposures of this unit in Kansas can be found in Clark County and southeastern Meade County (Zeller, 1968). Early accounts of this formation describe it as a red siliciclastic consisting of silty shale, siltstones, and very fine-grained sandstones (Norton, 1939). Zeller (1968) described it as shale, siltstone, dolomitic siltstone, and feldspathic sandstone. Previous subsurface accounts of the Big Basin Formation (northeastern Morton County, Kansas) indicate it consists of fine red silty sandstone, red sandy shale, and thin beds of anhydrite and dolomite (Swineford, 1955). Maximum subsurface and outcrop thicknesses range from 300 ft to 45 ft, respectively (Merriam, 1963). Red, tan and grey shale, siltstone, and sandstone, overlain by white beds of the Neogene Ogallala Formation at Point of Rocks in Morton County, Kansas, were recently identified as the Big Basin Formation. Detrital zircon ages from this locality suggest a youngest single zircon age for these units of 263 $\pm$ 12.1 Ma (Smith, 2015; Smith et al., 2015).

Correlating the Quartermaster Group of Kansas to seemingly equivalent rocks elsewhere in Oklahoma and Texas has proven historically difficult. The Whitehorse Sandstone of Kansas has been considered equivalent to the Whitehorse Group of both Oklahoma and Texas. This group, separated into the Marlow Formation and Rush Springs Sandstone, is primarily a reddish-brown sandstone, with thicknesses reaching 560 ft in Custer County, Oklahoma. Thicknesses of this unit in Hall County, Texas, reach 270 ft. A greenish-grey sandstone is reported at the base of the Whitehorse Group regionally (Fay, 1972). The Day Creek Dolomite of Kansas is considered to be equivalent to the Cloud Chief Formation of Oklahoma and Alibates Dolomite of Texas (Rascoe, 1968). The Cloud Chief Formation in Custer County, Oklahoma, is a mix of gypsum and dolostone which grades into shale totaling 310 ft thick in the subsurface (Fay, 1972). Early studies suggested the Cloud Chief Formation rested above the Day Creek Dolomite (Gould, 1924). Later studies, however, refuted these claims and suggested the Cloud Chief was below the Day Creek Dolomite and that it should be recognized as a member of the Whitehorse Group (Evans, 1931). The Alibates Dolomite, however, is described by Gould (1907) as a white, massive dolomite, shale, and flinty dolomite in northern Texas. Tabor (2011) describes the Alibates as a rare dolomite with laminated to massive gypsum and red mudstone. Massive to laminated siltstones and sandstones are also observed. Lastly, the Big Basin Formation of Kansas is considered stratigraphically equivalent to the Quartermaster Formation of Oklahoma and northern Texas (Norton, 1939). The Quartermaster Formation in the Palo Duro Basin is described as a red bed unit, up to 210 ft thick, composed of fine sandstones which grade into massive to rippled mudstones (Tabor, 2011). These correlations, however, are debatable.

BECKY BOUNDS CORE HISTORY

The Amoco Rebecca K. Bounds core no. 1 provides an excellent opportunity for gathering data concerning the Permian of the midcontinental United States (Zambito et al., 2012; Soreghan et al., 2015). Drilled by Amoco Production Company in March-April 1988 in west-central Kansas (Greeley County), approximately four miles east of the Colorado border, this core provides substantial recovery of Permian red beds and evaporites that are crucial to a variety of studies for this time period (Soreghan et al., 2015; Fig. 4). Spanning from Mississippian to Cretaceous rock, a 99.1% recovery of the Becky Bounds core is considered to be the result of using salt-saturated drilling fluids (diesel-based drilling mud) during drilling (Zambito et al., 2012; Benison et al., 2013). The core has been stored in Tulsa, OK, as well as Denver, CO, but is currently located at the Kansas Geological Survey core repository in Lawrence, Kansas, where it has resided since 2001 (Zambito et al, 2012). The core was originally drilled with the intent of testing Amoco's (then) newly developed SHADS (slim-hole advanced drilling system) rig. Studies of this core have focused on the sedimentology, biostratigraphy, and well log character of the Mississippian-lowest Permian and Mesozoic strata (Soreghan et al., 2015). It wasn't until recently that studies concerning middle to upper Permian units were conducted. Sections of this core relevant to this study were not slabbed or described until November 2011 by K. Benison and J. Zambito (i.e. Zambito et al., 2012; Benison et al., 2013). Rock saws used for slabbing were modified so that water was directed to the back of the saw blade to limit dissolution of bedded evaporites and evaporite cements. Units were also described, photographed, and measured during this time (Zambito et al., 2012; Benison et al., 2013; Fig. 4). Preliminary thin section and XRD analysis of the Quartermaster Group was done by Benison and became the foundation for this thesis.

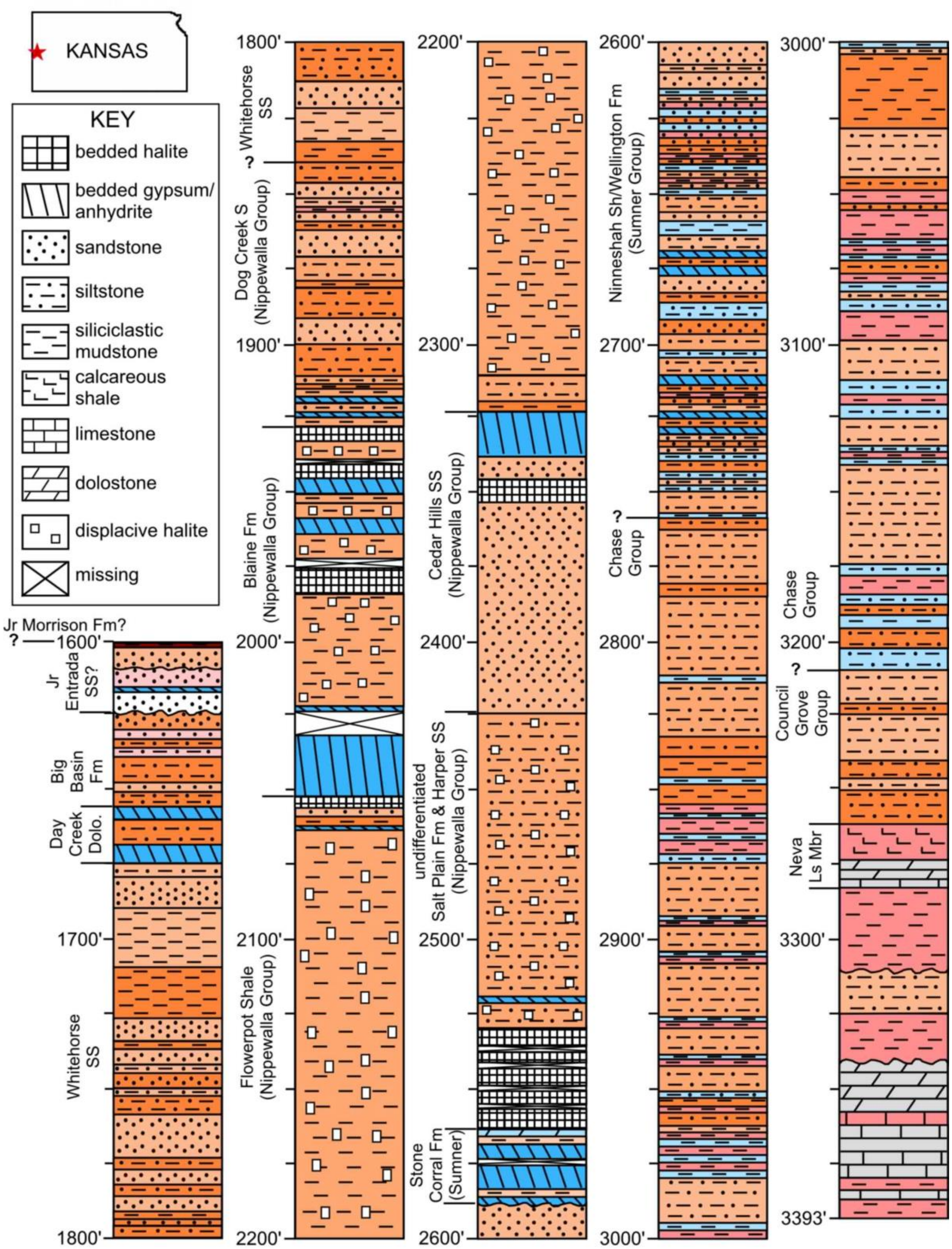


Figure 4. Stratigraphy of Permian units observed in the Becky Bounds core. Colors represented in stratigraphic column represent approximate colors of rocks in core. Drilling location of core is denoted by a red star on the Kansas map. (taken from Benison et al., 2013)

METHODS

Methods used in conducting this study included the use of petrography and XRD mineral identification from the Becky Bounds core to determine the depositional and diagenetic history of the Quartermaster Group of western Kansas. A detailed measured section of the Becky Bounds core published by Zambito et al. (2012) was used. Additionally, supplemental data was gathered from field observations of the Quartermaster Group in south-central Kansas. The following paragraphs provide additional insight into the methods for gathering data for this thesis.

The Becky Bounds core from 1627 ft to1840 ft depth was studied for this thesis. This interval spans from the base of the Whitehorse Sandstone, up through the Day Creek Dolomite, and to the top of the Big Basin Formation. Additionally, units directly above the Big Basin Formation, as well as the underlying Dog Creek Formation, were observed to evaluate contacts between formations. Thirty core slabs, 38 thin sections, and a measured section were made available at the start of this research by Dr. Kathleen C. Benison. The Kansas Geological Survey core repository was visited from May 5th-6th, 2014, to view the entirety of the Quartermaster Group of the Becky Bounds core, make core descriptions, photograph units, and gather additional samples. Overlying and underlying units were also observed at this time. Selected core samples were shipped back to West Virginia University and prepared for an additional 12 thin sections. A total of 50 thin sections (43 large format and 7 standard format) and 74 hand samples were examined for this thesis.

Field work was conducted on May 8th- 9th, 2014, at the Clark State Fishing Lake, the Big Basin Prairie Reserve, and along Route 160 in Clark and Barber Counties in south-central Kansas. Outcrops within these areas are approximately 180 miles southeast of the Becky Bounds drill site and represent some of the locations these three formations have been documented at the surface in Kansas (Norton, 1939). Field work goals included comparing and contrasting outcrops with the Becky Bounds core, as well as comparing and contrasting the Nippewalla Group (particularly the Dog Creek Formation) with Quartermaster Group outcrops. Due to poor confidence in stratigraphic context of these rocks, thin sections were not made for outcrop samples.

Seventy four hand samples from the Becky Bounds core, including 13 from the Dog Creek Formation, were used for this study. Hand samples were described by eye and hand lens observations. Colors of the units were described by use of a Munsell Soil Color Chart. Sedimentary textures and sedimentary structures were documented during this process. Additionally, samples were tested for saltiness (taste test) and effervescence (via HCl reaction). Detailed observations can be found in the appendices.

A total of 50 thin sections (43 large format and 7 standard format) were petrographically described for this thesis. Two microscopes were used in Kathleen Benison's Red Earth Observatory lab at WVU's Brooks Hall for this research. The Olympus SZX10 binocular microscope has magnification capabilities of 6.3x to 63x in plane transmitted, reflected, and polarized lighting. In addition, the Olympus BX53 microscope can magnify from 20x to 2000x in plane transmitted, reflected, polarized, and UV-vis light sources. Samples were viewed under various magnifications and light settings (plane transmitted, reflected, and polarized lighting) for grain size range, grain size composition, sorting, roundness, sphericity, mineralogy, porosity, fossils, sedimentary structures, and diagenetic features. High quality photomicrographs were obtained for each studied thin section through use of SPOT 5 digital imaging software on the

Olympus SZX10 binocular microscope. SPOT 5 digital imaging software was also available on the Olympus BX53 microscope but not used in obtaining high quality photomicrographs.

Viewing thin sections from core under various light settings and magnifications garnered a variety of detailed information concerning the mineralogy, sedimentary structures, sedimentary textures, and diagenetic features of these rocks. The assemblage of observed features in each thin section, coupled with core slab observations was used to make depositional and diagenetic interpretations. A comparative sedimentology approach was used in evaluating petrographic data. An example of this approach would be documenting a well-sorted sandstone with bimodal grain size distribution and tangential, high angle cross-stratification. This sandstone would be indicative of an eolian dune lithofacies because it meets diagnostic criteria of modern eolian dune settings (Ahlbrandt and Fryberger, 1982). Additionally, features such as cements, replacement fabrics, and dissolution features were documented to make interpretations about diagenetic processes. The relative order of observed diagenetic features was used to determine paragenetic sequence. Notes were made for depositional and early diagenetic features that may have been influenced by weather and/or climate. These features led to paleoweather and paleoclimate interpretations.

RESULTS

FIELD OBSERVATIONS

Field work was conducted on May 8th- 9th, 2014, at the Clark State Fishing Lake, the Big Basin Prairie Reserve, and along Route 160 in Clark and Barber Counties in south-central Kansas. Outcrops observed for this thesis are approximately 180 miles southeast of the Becky Bounds drill site and represent some of the localities these three formations have been documented at the surface in Kansas (Norton, 1939). Due to poor confidence in stratigraphic context of these rocks, thin sections were not made for outcrop samples. Notes describing each formation in outcrop, however, were taken.

The Whitehorse Sandstone is a red bed unit composed of finely laminated to massive bedded sandstone, siltstone, and mudstone. Quartz is the predominant mineral within this formation. The Whitehorse Sandstone crumbles in a blocky nature when handled. Samples of this unit are not salty when licked. Additionally, this formation shows a variety of red and white layers at the surface. Members of this unit could not be confidently differentiated in outcrop (Fig. 5).

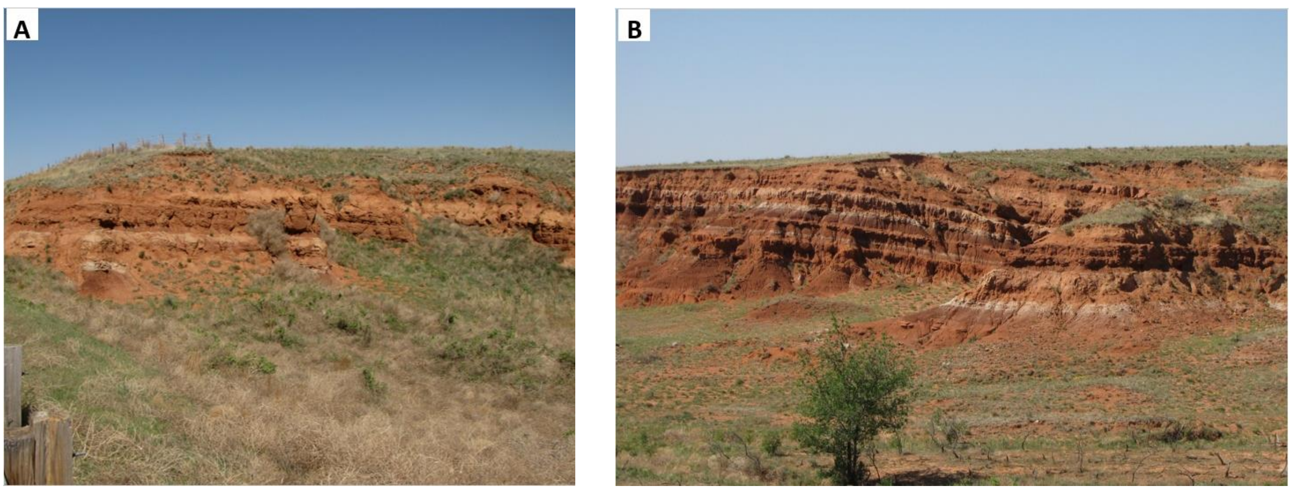


Figure 5. Photographs of the Whitehorse Sandstone in outcrop. (A) Image of the Whitehorse Sandstone near Kiger Creek along Route 160. Variance in color is minimal. (B) Image of the Whitehorse Sandstone along Route 160 in Clark County, Kansas. White and red layers of rock are shown in image. Tree for scale. Photographs courtesy of K. Benison.

The Day Creek Dolomite in outcrop is a ~2 ft unit and is a mix of wavy laminated globular chert and dolomite (Fig. 6). Colors of this unit range from peach to grey. Calcite is considered the predominant cement of this unit at the surface because of the rock’s vigorous effervescence when exposed to HCl.

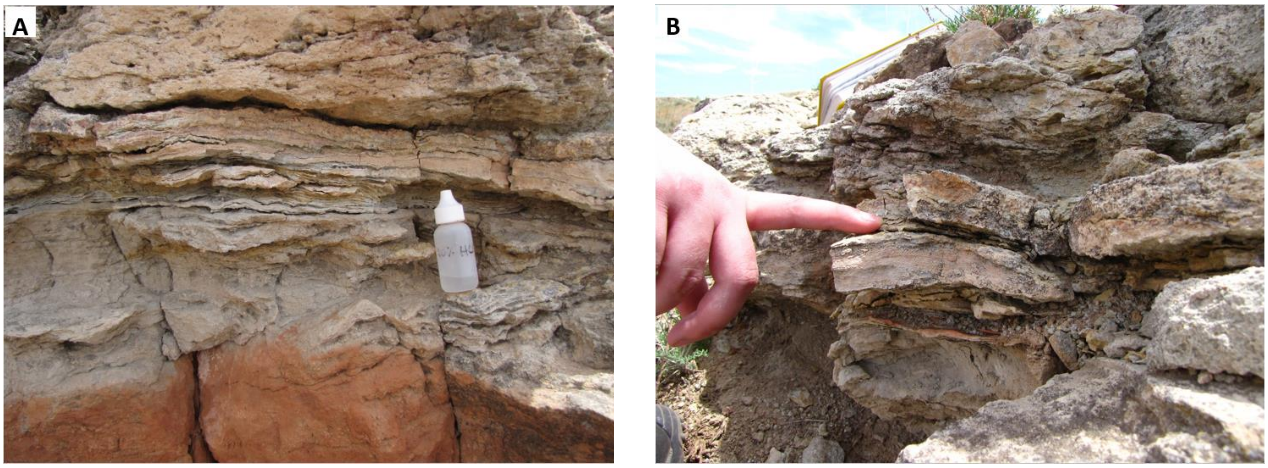


Figure 6. Photographs of the Day Creek Dolomite in outcrop at the Big Basin Prairie Reserve. (A) Image of the Day Creek Dolomite within the Big Basin Prairie Reserve. Formation is ~2 ft thick in outcrop. HCl bottle for scale. (B) Close up image of wavy chert and dolomite within outcrop. Finger for scale. Photographs courtesy of K. Benison.

The Big Basin Formation is a friable, finely-laminated to massive bedded siltstone and sandstone. Color of this unit, however, is slightly darker than all other red bed outcrops observed (Fig. 7). The unit is mainly composed of sand to silt sized quartz grains. Gypsum veins were uncommonly observed.

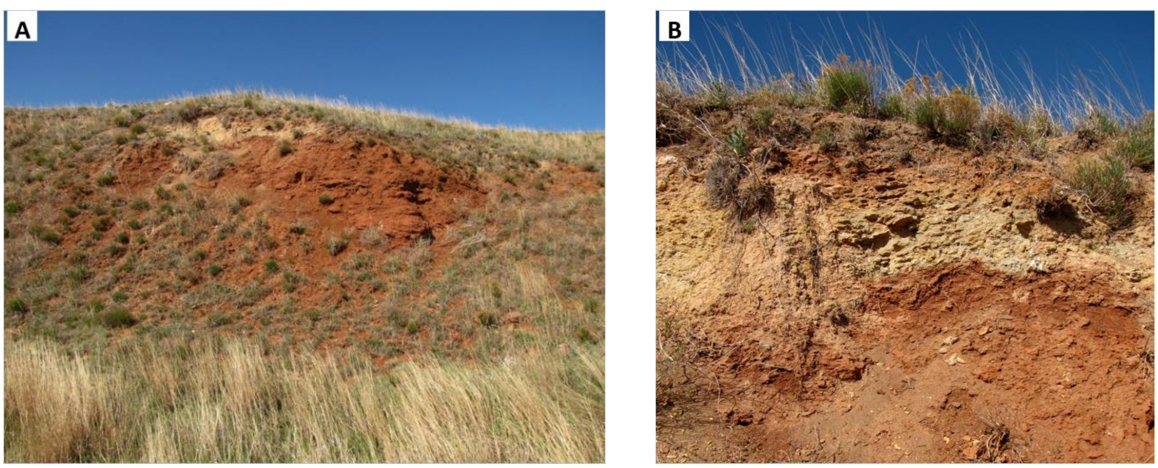


Figure 7. Photographs of the Big Basin Formation in outcrop. (A) Image illustrating the thickness of the Big Basin Formation in outcrop. (B) Close up image of contact between the Big Basin Formation and Cretaceous Cheyenne Sandstone in outcrop. Photographs courtesy of K. Benison.

CORE AND PETROGRAPHIC OBSERVATIONS

Whitehorse Sandstone

The Whitehorse Sandstone, extending 1676 ft to 1840 ft, conformably overlies the Dog Creek Formation of the underlying Nippewalla Group. Three lithologies are observed in this formation: red siltstone/mudstone, red well-sorted sandstone, and red mud clast conglomerate. This formation has not been subdivided in core as it has in outcrop (Norton, 1939; Zeller, 1968) because members couldn't be confidently differentiated in core. The samples exhibit varying degrees of salt content. The Whitehorse Sandstone, despite its name, generally transitions between siltstone and mudstone deposition throughout a majority of the formation. Salt content roughly follows this trend as mudstone does not exhibit saltiness while siltstones and sandstones do. Samples do not effervesce when exposed to HCl. Porosity, mainly intergranular, ranges from less than 1% to 10%. Cements are intergranular halite, intergranular to blocky gypsum, and clay.

Red siltstone/mudstone comprises 96% of the Whitehorse Sandstone in this core (Fig. 8). Colors range between 2.5YR 4/6 and 2.5YR 5/8. This lithology is characterized as a mix of moderate to well-sorted siltstone that grades into mudstone. Silt grains are mostly subangular to subrounded. The beds are typically uniform in composition consisting, on average, of ~80% quartz with the remaining ~20% consisting of variable amounts of gypsum, dark opaque grains, and clay. Dark opaque grains shimmer/glimmer in reflected light and will be referred to as specular hematite herein. In general, specular hematite grains (~0.1 mm and smaller) are angular to well rounded. Some of these grains are elongate in nature exhibiting low sphericity. Trace minerals include feldspar and mica.

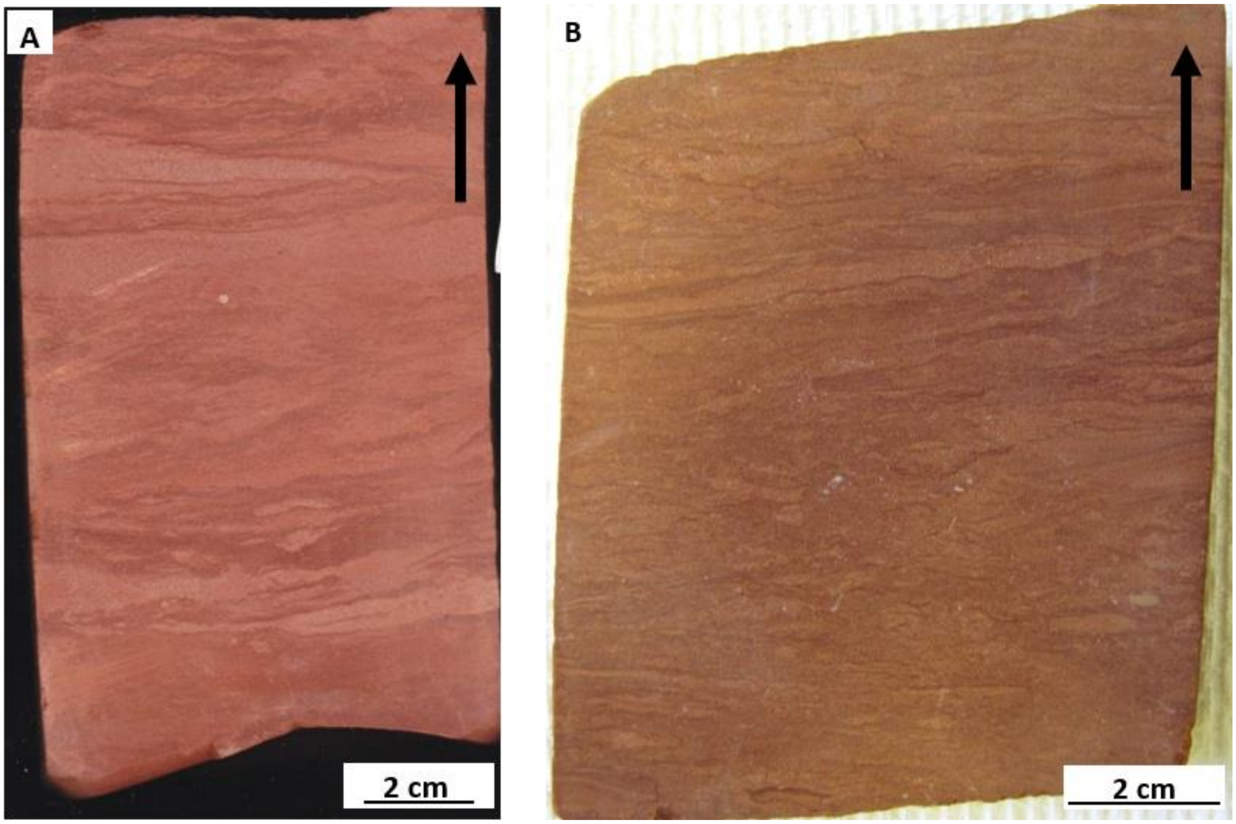


Figure 8. Photographs of Whitehorse Sandstone hand samples from the Becky Bounds core. (A) Hand sample from 1823’9”-1824’2”; fine grained siltstone with wavy discontinuous laminae and mud clasts. Photograph courtesy of K. Benison. (B) Hand sample from 1730’6” depth; fine grained siltstone with wavy discontinuous laminae and ripple cross-stratification.

Planar laminae, wavy discontinuous laminae, soft sediment deformation, ripple cross-stratification, mudcracks, and mud drapes are found within red siltstone/mudstone. Additional features observed in hand sample and thin section include soil slickensides, ped structures, mud clasts/rip-up clasts, water escape features, and root features. Reduction spots, halite cement, and displacive gypsum crystals are diagenetic features observed in this lithology (Fig. 9). Reduction spots range from 0.1 mm to 3 cm in size and often crosscut bedding. Though a majority of these features are uniformly greyish green, some reduction spots contain dark nuclei at their centers. A majority of these reduction spots are associated with coarser grained zones (i.e. fine sands and coarse silts) though they also occur in association with smaller grain sizes (i.e. fine silts and clay).

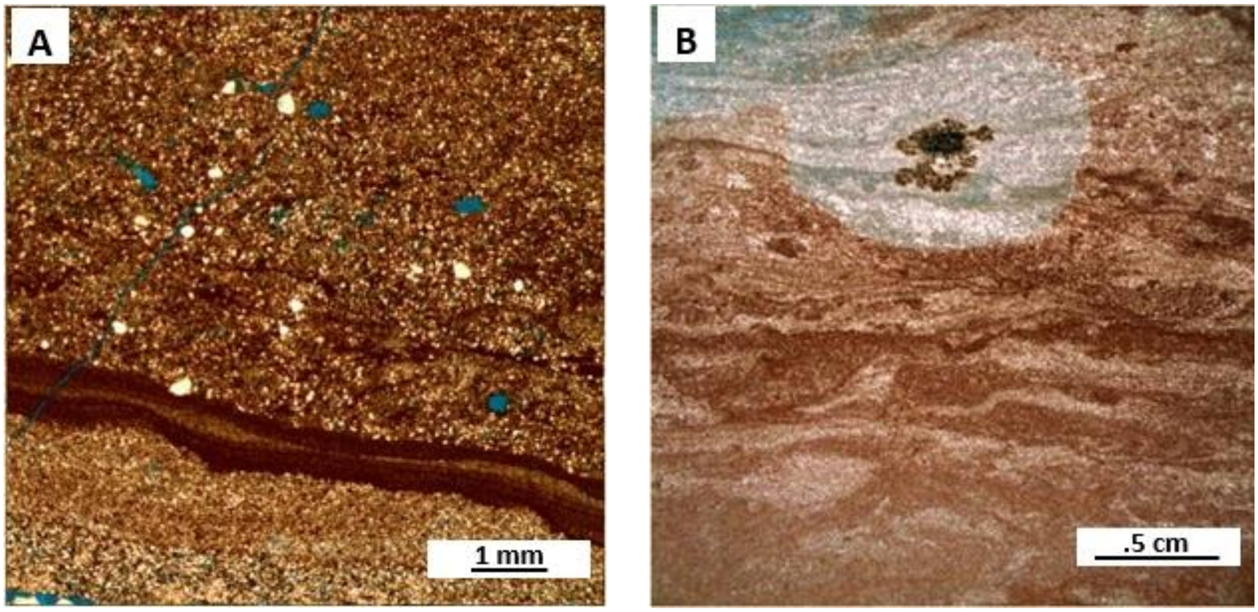


Figure 9. Photomicrographs of the Whitehorse Sandstone from the Becky Bounds core. (A) Photomicrograph from 1745'2" depth under plane transmitted light; mud laminations over sand and silt sized grains. Note the "floating" medium sand grains above the mud beds surrounded by fine sand and silt grains. (B) Photomicrograph from 1709' depth under plane transmitted light; wavy discontinuous laminae and a specular reduction spot with dark central nuclei. Both photomicrographs are shown oriented with respect to stratigraphic "up".

Red well-sorted sandstone comprises ~1% of the Whitehorse Sandstone in this core (Fig. 10). This lithology composed of well-sorted very fine sand and silt grains (2.5YR 4/8 to 2.5YR 5/6). The grains also exhibit high sphericity and bimodal grain size. Compositionally, this lithology is mainly quartz (~80%). Additional minerals include gypsum (~<10%), feldspar (~<5%), mica (~< 1%), clay (~<5%), and specular hematite (~<5%). Cements include intergranular halite and iron oxide.

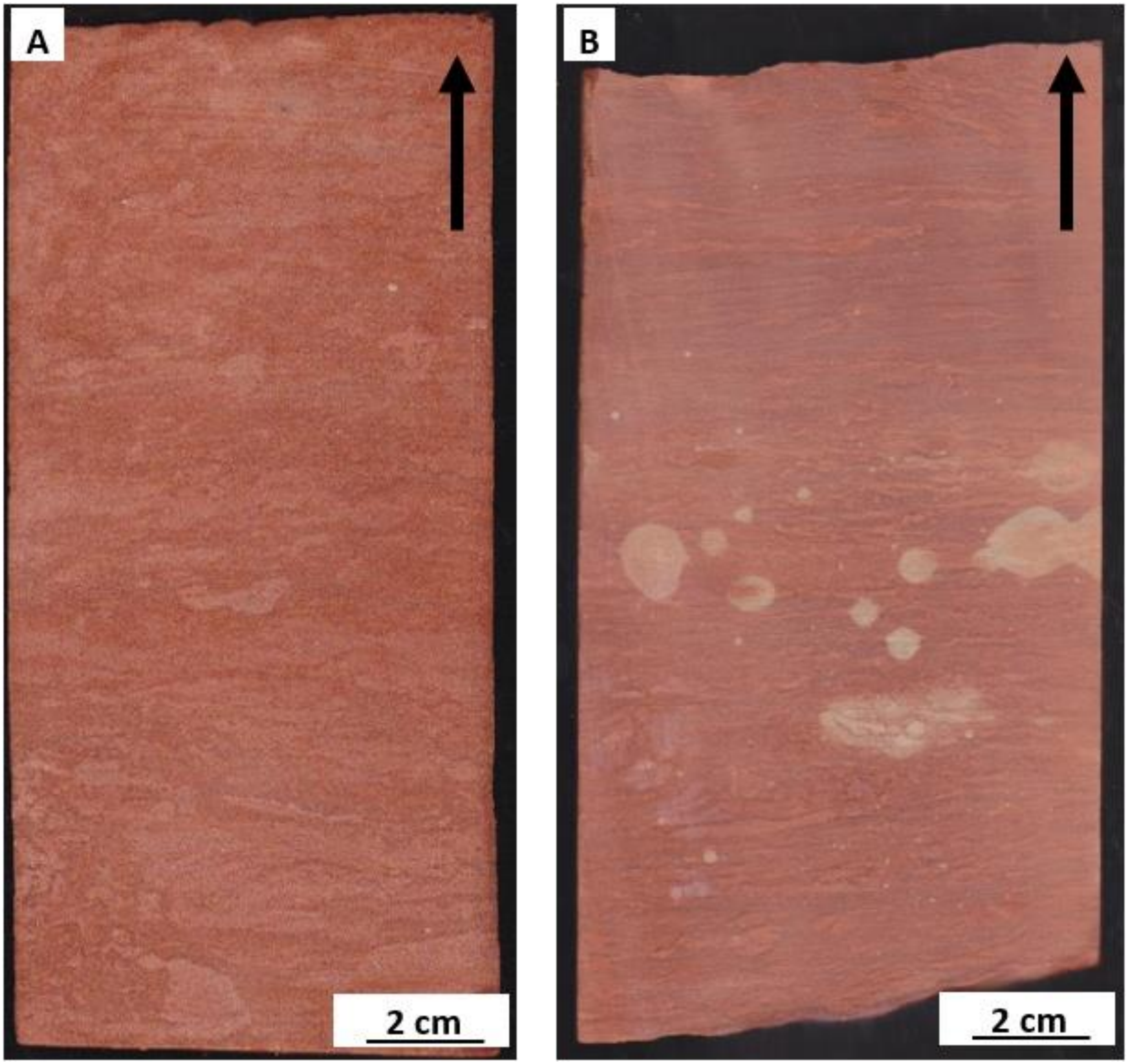


Figure 10. Photographs of Whitehorse Sandstone hand samples from the Becky Bounds core. (A) Hand sample from 1758'5"-1759'; wavy discontinuous laminae with mud clasts and mudcracks in fine sand and silt grains. (B) Hand sample from 1742'-1742'6" depth; wavy discontinuous laminae with reduction spots in fine sand and silt grains. Photographs courtesy of K. Benison.

Planar laminae, wavy discontinuous laminae, ripple cross-stratification, and mudcracks are observed in red well-sorted sandstone. Mud clasts/rip-up clasts and root features are also observed. Reduction spots, halite cement, and displacive gypsum crystals are diagenetic features within this lithology (Fig. 11).

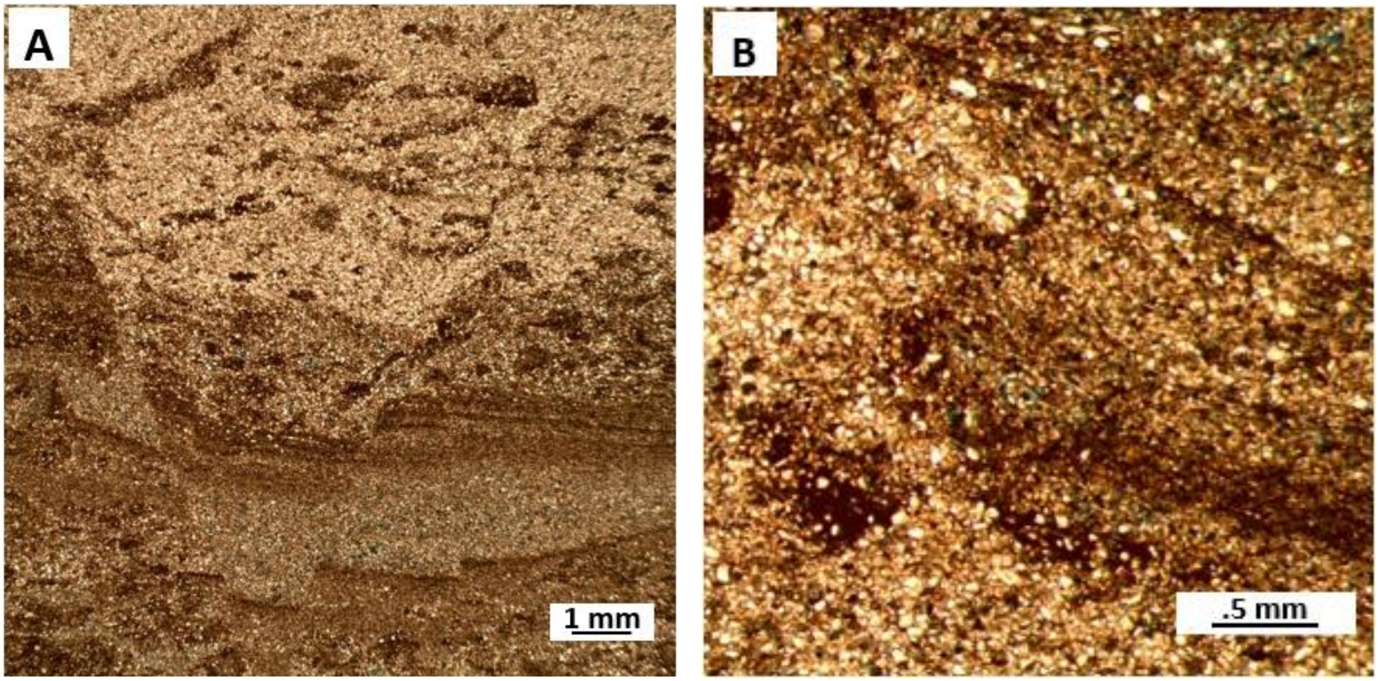


Figure 11. Photomicrographs of the Whitehorse Sandstone from the Becky Bounds core. (A) Photomicrograph from 1759' depth under plane transmitted light; planar to disrupted fine sands. Note the rip-up clasts directly above the disrupted laminae. (B) Photomicrograph from 1758'6" depth under plane transmitted light; Faint, needle-like features in photomicrograph are displacive gypsum crystals. Both photomicrographs are shown oriented with respect to stratigraphic "up".

Red mud clast conglomerate comprises ~3% of the Whitehorse Sandstone in this core (Fig. 12). Colors range between 2.5YR 5/6 and 2.5YR 6/6. Grain size ranges significantly from coarse gravel (~2 cm) to clay. Compositionally, this lithology is mainly quartz and mud clast lithics (~40% and ~45%, respectively). Grains are subangular to subrounded and poorly-sorted. Additional minerals include clay (~10%), gypsum (~<5%), and specular hematite (~<5%). Cements include intergranular and blocky gypsum.

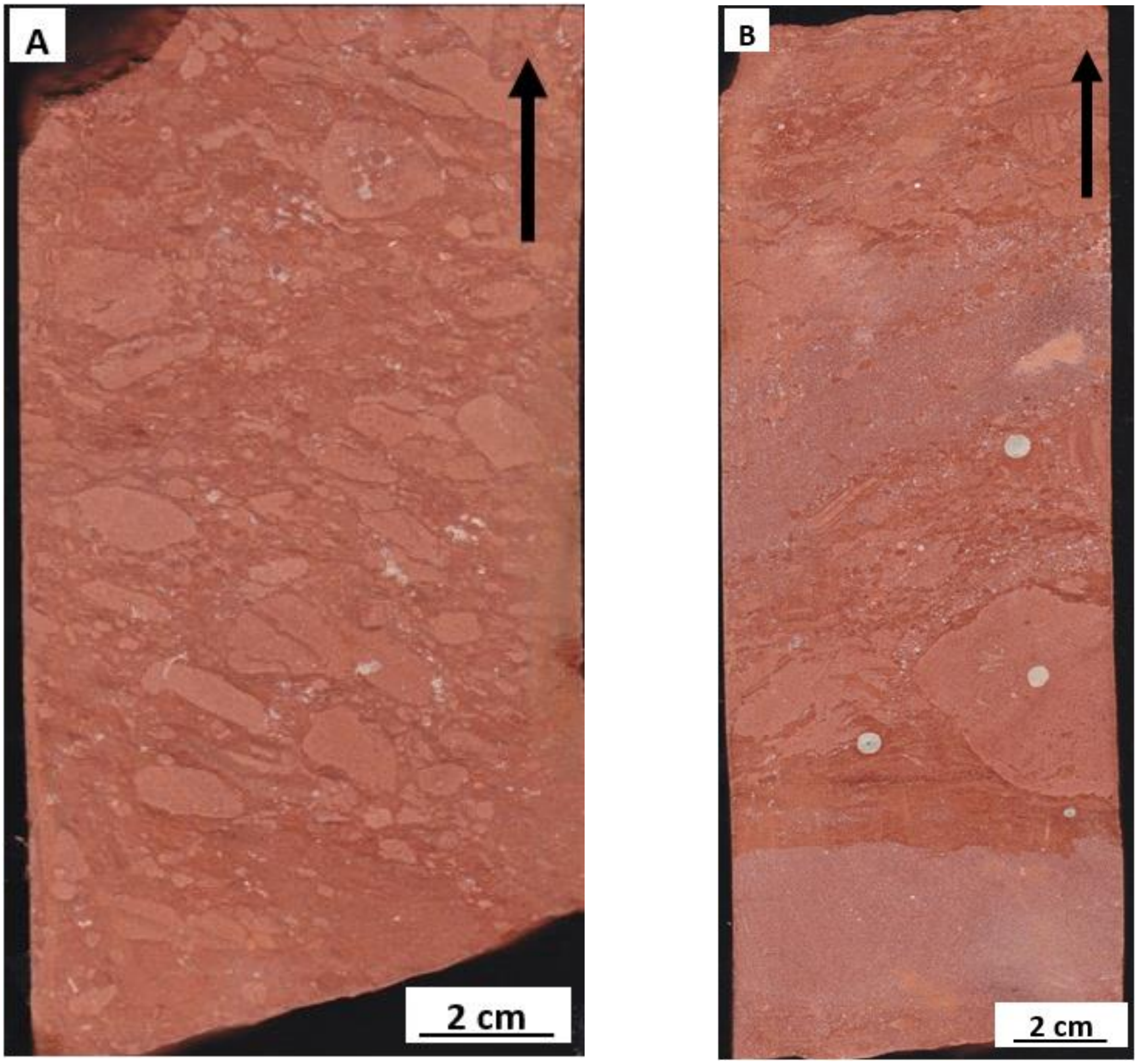


Figure 12. Photographs of Whitehorse Sandstone hand samples from the Becky Bounds core. (A) Hand sample from 1685’5”-1685’11”; mud clasts exhibiting a preferred orientation. (B) Hand sample from 1682’-1682’9”; mud clast conglomerate with reduction spots. Photographs courtesy of K. Benison.

Mudcracks, ripple cross-stratification, and soft sediment deformation are observed within red mud clast conglomerate. Soil slickensides and root features are also observed. Reduction spots, gypsum cement, and displacive gypsum crystals are diagenetic features observed within this lithology (Fig. 13).

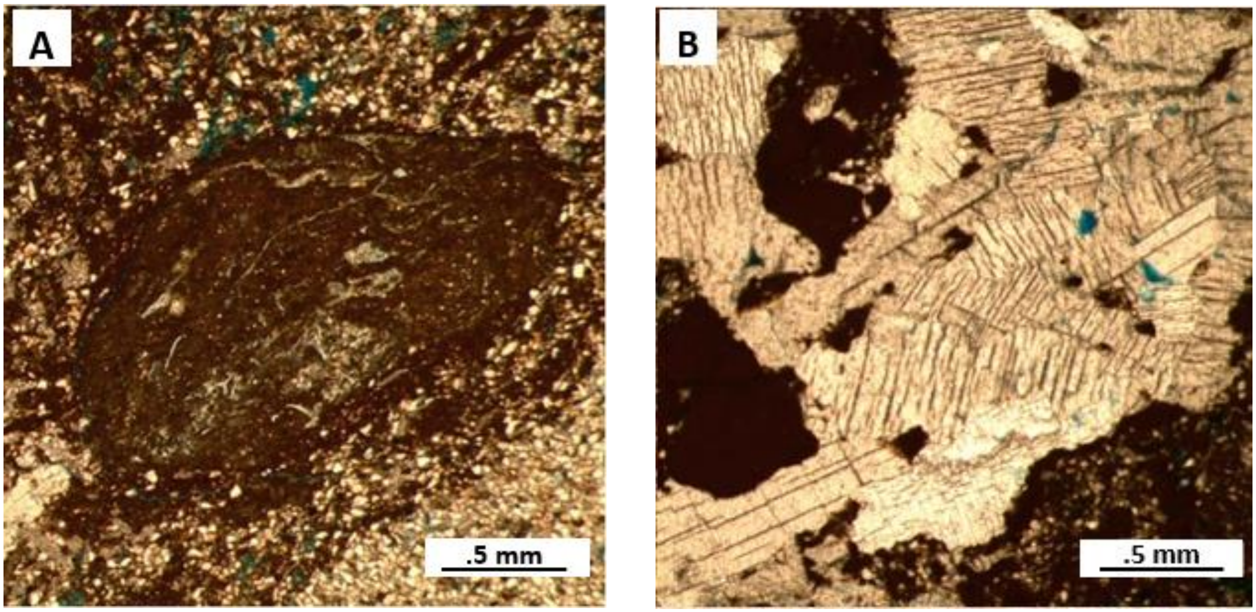


Figure 13. Photomicrographs of the Whitehorse Sandstone from the Becky Bounds core. (A) Photomicrograph from 1685'8" depth under plane transmitted light; root feature (rhizocretion) surrounded by clay and silt sized grains. (B) Photomicrograph from 1685'8" depth under plane transmitted light; blocky gypsum cement surrounded by clay and silt sized grains. Both photomicrographs are shown oriented with respect to stratigraphic "up".

Day Creek Dolomite

Extending 1659 ft to 1676 ft in the Becky Bounds core, the Day Creek Dolomite consists of two lithologies: bedded gypsum/anhydrite and red siltstone/mudstone. More specifically, three crystalline gypsum/anhydrite beds (totaling 10 ft 2 inches) sandwich two red siltstone/mudstone beds (totaling 6 ft 10 inches). Salt content is evident (via taste test) at the boundaries between bedded gypsum/anhydrite and red siltstone/mudstone. Boundaries between bedded gypsum/anhydrite and red siltstone/mudstone also have a slightly metallic taste. Dolomite is not present in the formation despite the formation's name. Porosity ranges from ~<1% (for bedded gypsum/anhydrite) to ~5% (for red siliciclastic units). Intergranular gypsum is the predominant cement throughout this formation.

Bedded gypsum/anhydrite comprises ~60% of the Day Creek Dolomite in this core (Fig. 14). Found at the base, center, and top of the formation, this lithology is whitish-pink to blue (2.5YR 6/1). In these crystalline units, mineralogy is uniform consisting mainly of bedded gypsum/anhydrite with trace amounts of iron oxide. Crystals are vertical to near vertical. Halite with a yellowish hue is found as small crystals towards the tops of these bedded features. Gypsum ooids are also found towards the tops of some localized gypsum/anhydrite beds.

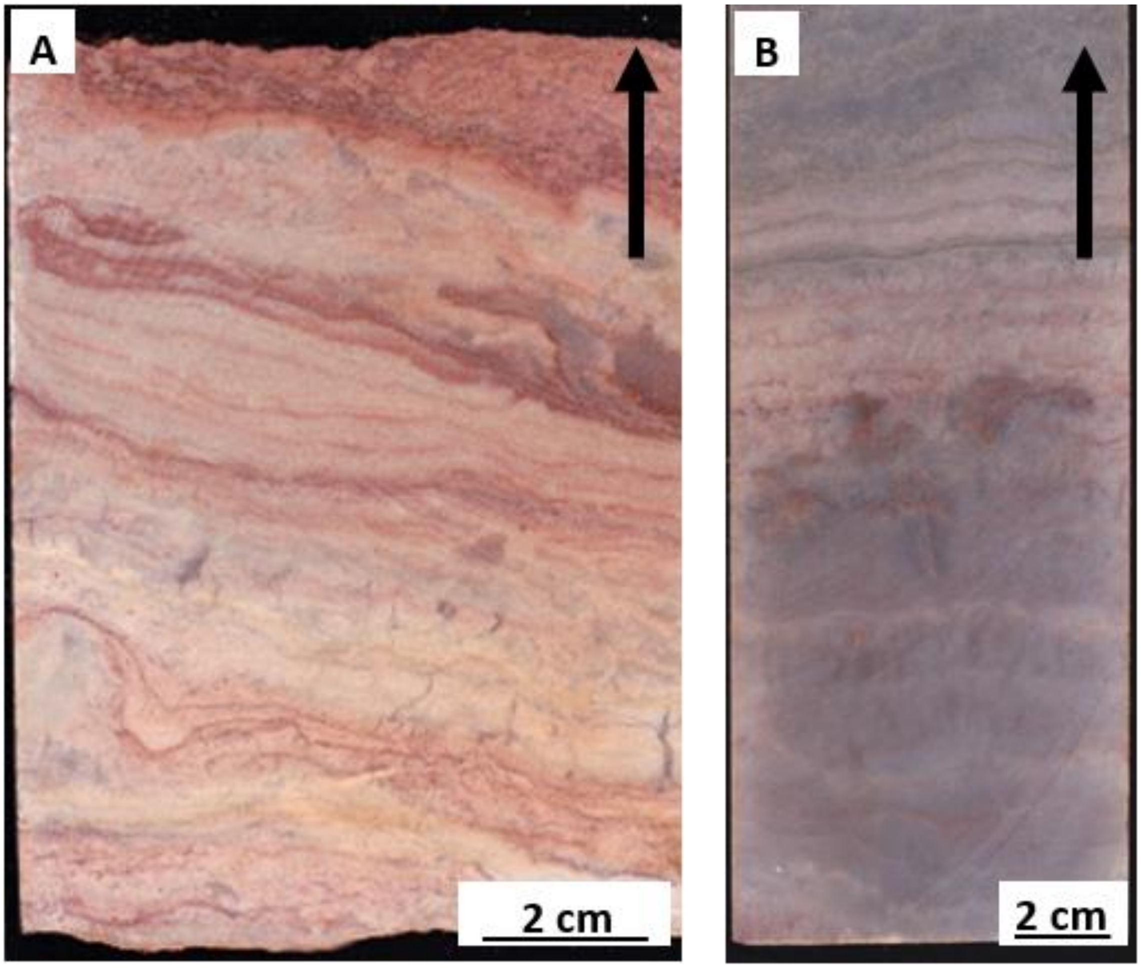


Figure 14: Photographs of Day Creek Dolomite hand samples from the Becky Bounds core. (A) Hand sample from 1674’3”-1674’8” depth; wavy discontinuous red siliciclastic laminae in bedded gypsum/anhydrite. Mudcracks are also visible towards the base of the hand sample. (B) Hand sample from 1662’2”-1663’ depth; Note the thick lamina of vertically oriented gypsum crystals. Photographs courtesy of K. Benison.

Mudcracks, planar laminae, and wavy discontinuous laminae are observed in bedded gypsum/anhydrite. Gypsum alteration to anhydrite, anhydrite alteration to gypsum, and dissolution pits in evaporite are diagenetic processes which influenced this lithology (Fig. 15). Dissolution of gypsum/anhydrite is commonly found at contacts between bedded gypsum/anhydrite and red siliciclastics.

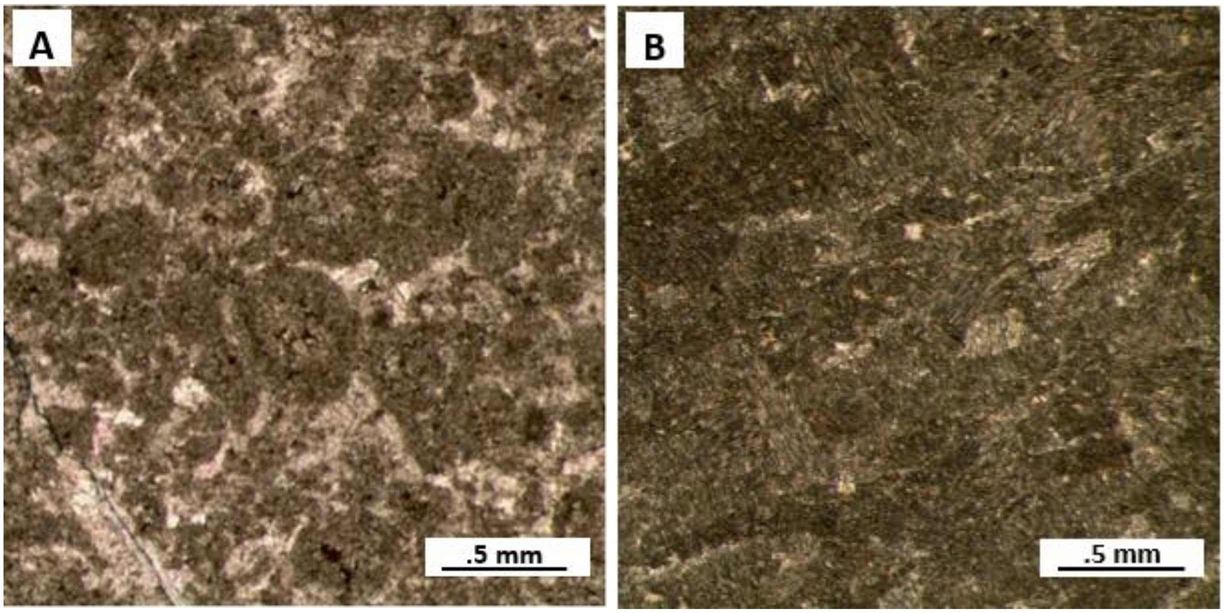


Figure 15. Photomicrographs of the Day Creek Dolomite from the Becky Bounds core. (A) Photomicrograph from 1660' depth in plane transmitted light; rare, suspect ooids in gypsum/anhydrite. (B) Photomicrograph from 1659'6" depth in plane transmitted light; bedded gypsum/anhydrite with suspect yellow hues throughout the photomicrograph. These yellow hues can be found in and around cubic, isotrophic minerals (halite). Both photomicrographs are shown oriented with respect to stratigraphic "up".

Red siltstone/mudstone comprises ~40% of the Day Creek Dolomite in this core (Fig. 16). Grain sizes range from medium sand to clay though silt sized grains dominate. Color is typically uniform (2.5YR 5/6). Compositionally, grains are subrounded to rounded, well-sorted quartz (~80%) and gypsum clasts (~20%). Specular hematite comprises less than 1% of the lithology.

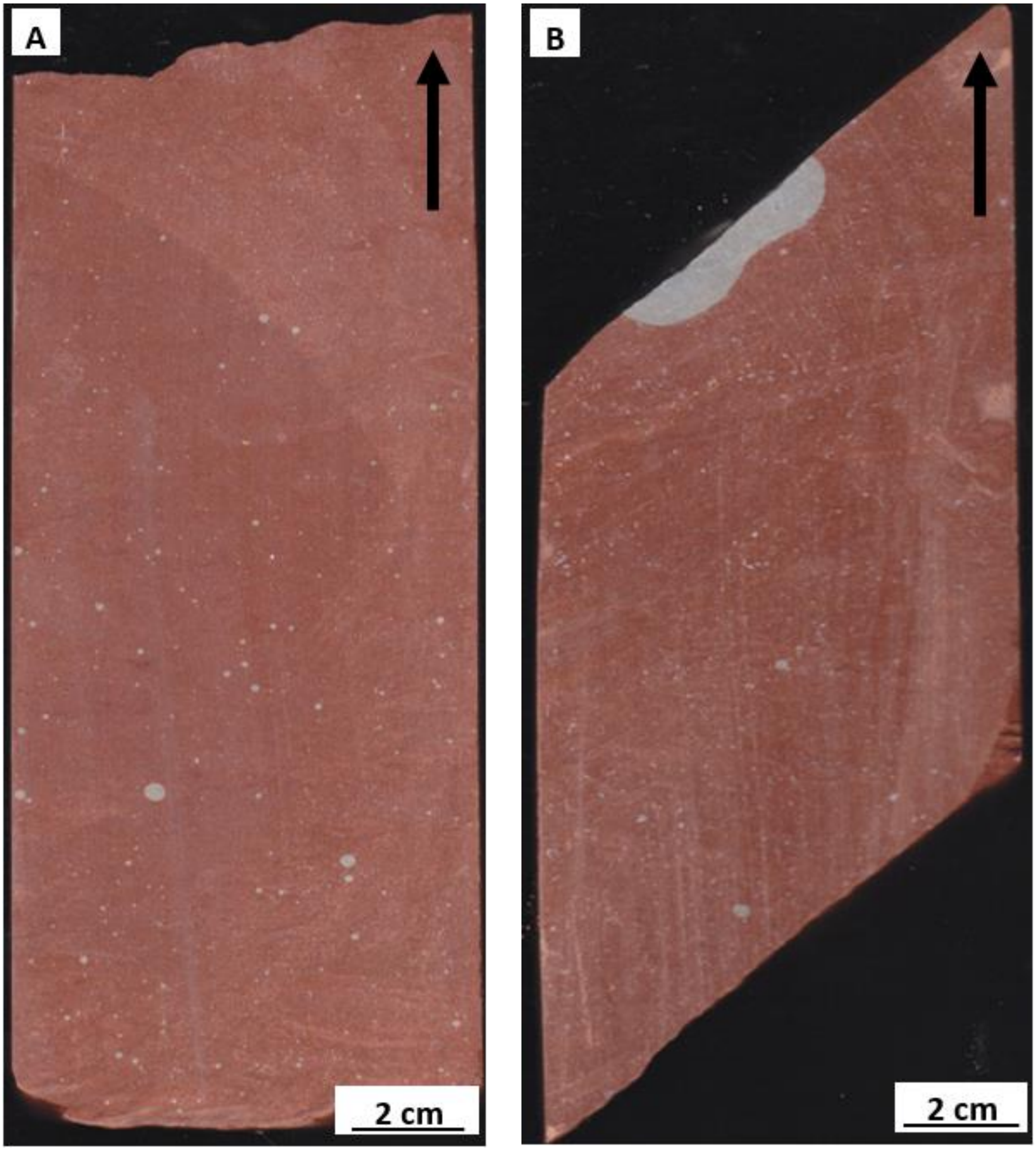


Figure 16: Photographs of Day Creek Dolomite hand samples from the Becky Bounds core. (A) Hand sample from 1664’4”-1665’depth; red siltstone with reduction spots. (B) Hand sample from 1668’-1668’7” depth; red siltstone with reduction spots. Boundaries between oxidized and reduced zones are gradational. Photographs courtesy of K. Benison.

Ripple cross-stratification, mudcracks, mud drapes, water escape features, planar laminae, and wavy discontinuous laminae are observed within red siltstone/mudstone. Additional features include soil slickensides, ped structures, rip-up clasts, and root features. Diagenetic features include reduction spots and displacive gypsum crystals (Fig. 17). Reduction spots, range in size from 0.1 mm to 3 cm in size. These features also crosscut bedding. Though a majority of these features are uniformly greyish green, some reduction spots contain dark nuclei at their centers. Contacts between reduction spots and red bed host rock are gradational.

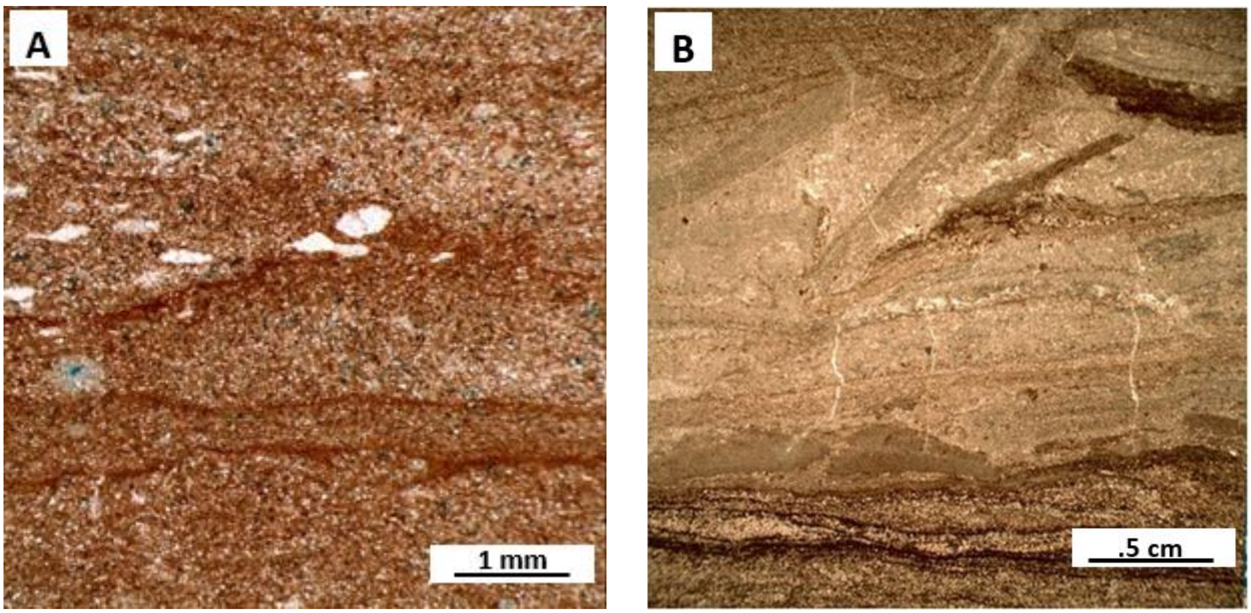


Figure 17. Photomicrographs of the Day Creek Dolomite from the Becky Bounds core. (A) Photomicrograph from 1668' depth in plane transmitted light; gypsum-filled root casts in red siltstone. (B) Photomicrograph from 1662' depth in plane transmitted light; contact between wavy laminated siltstone and gypsum/anhydrite. Note the mudcracks and water escape features towards the center of the photomicrograph. Both photomicrographs are shown oriented with respect to stratigraphic "up".

Big Basin Formation

The Big Basin Formation consists of two lithologies: dark red, poorly-sorted sandstone and dark red siltstone/mudstone. This formation extends from 1627 ft to 1659 ft and is unconformably overlain by white, calcareous Mesozoic sandstones in the Becky Bounds core. Units do not effervesce when exposed to HCl. Grain size ranges from coarse sand to clay. Color of this unit is a somewhat darker red than the red siliciclastics found in the Day Creek Dolomite and Whitehorse Sandstone (5 YR 4/4). Porosity ranges from 1% to 5%. Intergranular gypsum and iron oxide cement the Big Basin Formation.

Dark red, poorly-sorted sandstone, comprising ~20% of formation, is only found towards the base of the Big Basin Formation in this core (Fig. 18; 5YR 4/4). This lithology is composed of subangular to well rounded fine sand grains which uncommonly surround medium and coarse grained "floating" sands. Compositionally, grains are quartz (~80%), gypsum (~<10%), clay (~5%) and specular hematite (~<5%).

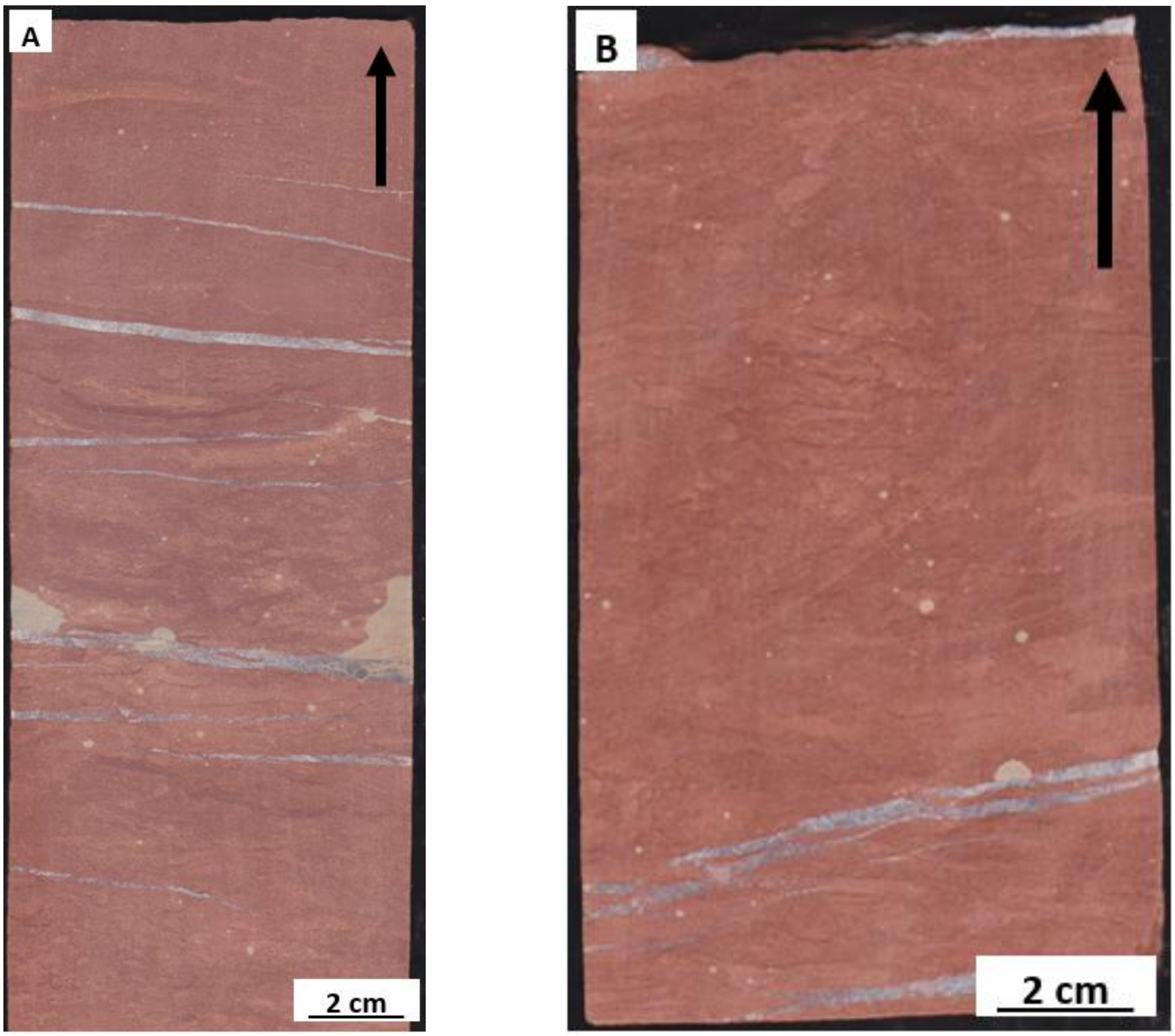


Figure 18: Photographs of Big Basin Formation hand samples from the Becky Bounds core. (A) Hand sample from 1656'7"-1657'depth; dark red sand grains with reduction spots and gypsum veins (stringers). (B) Hand sample from 1653'2"-1654' depth; dark red sandstone with reduction spots and gypsum veins (stringers). Photographs courtesy of K. Benison.

Sedimentary structures include wavy discontinuous laminae, soft sediment deformation, and mudcracks. Mud clasts are also found within this lithology. Reduction spots and subhorizontal gypsum veins are diagenetic features observed within this rock type (Fig. 19). Cements include intergranular gypsum and iron oxide. Reduction spots, though ranging from 0.1 mm to 1.5 cm in size, are a common diagenetic feature throughout the Big Basin Formation. These features tend to crosscut bedding and are sometimes found surrounding gypsum veins ("stringers"). Though a majority of reduction spots are uniformly greyish green, some contain dark nuclei at their centers. Contacts between reduction spots and red bed host rock in core are gradational showing little to no lithologic changes between zones. A majority of these reduction spots are associated with coarser grained zones (i.e. fine sands and coarse silts) though they also occur in association with smaller grain sizes (i.e. fine silts and clay). Gypsum veins (stringers) are subhorizontal to vertical.

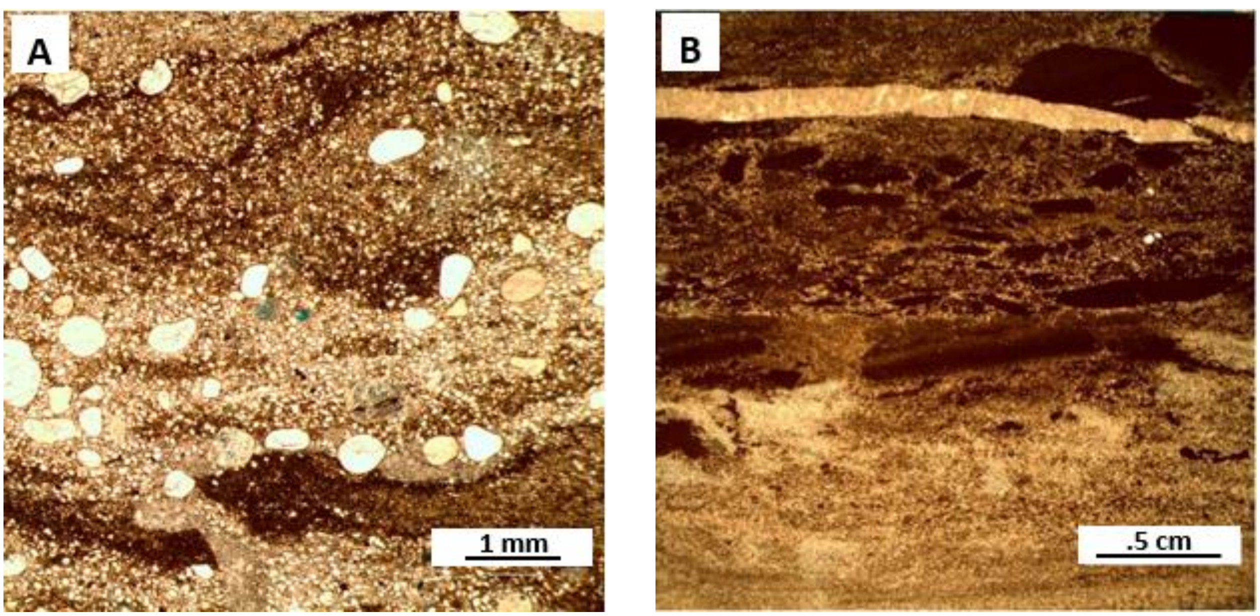


Figure 19. Photomicrographs of the Big Basin Formation from the Becky Bounds core. (A) Photomicrograph from 1659' depth in plane transmitted light; medium to coarse grained sand "floating" in finer grained sands, silts, and clay. (B) Photomicrograph from 1651'9" depth in plane transmitted light; dark red sandstone with mud clasts/rip-up clasts and gypsum veins (stringers). Both photomicrographs are shown oriented with respect to stratigraphic "up".

Dark red siltstone/mudstone comprises ~80% of the Big Basin Formation in this core (Fig. 20). Colors range from 5YR 4/4 to 5YR 5/3. Fine sand and silt grains are mostly subangular to subrounded. Grains are moderate to well sorted and are mainly quartz (~80%). Additional minerals that are observed include gypsum (~<10%), clay (~<5%) and specular hematite (~<5%). Cements include intergranular gypsum and iron oxide.

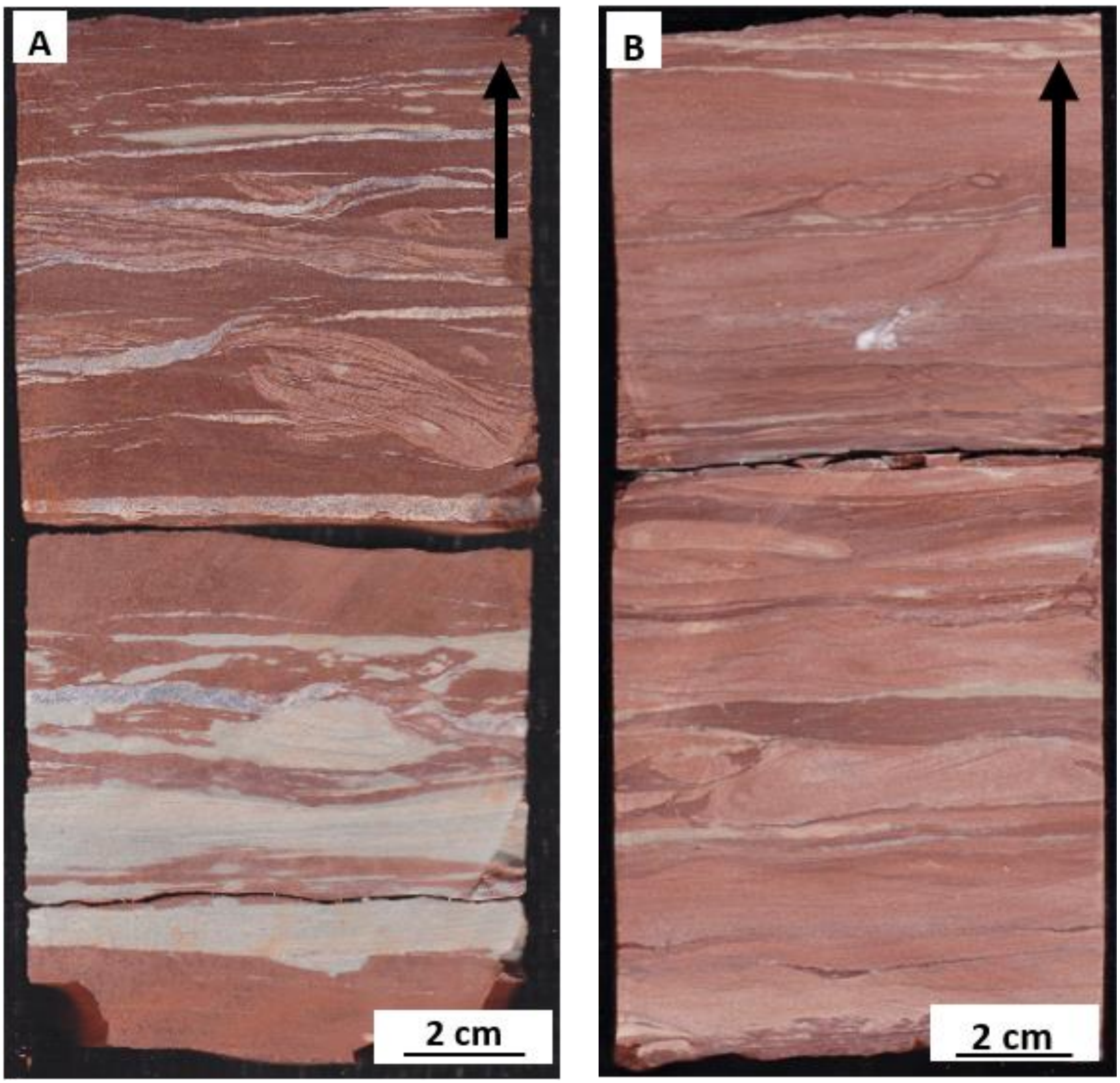


Figure 20. Photographs of Big Basin Formation hand samples in the Becky Bounds core. (A) Hand sample from 1634’1”-1634’7” depth; soft sediment deformation and ripple cross-stratification in dark red siltstone. Gypsum veins (stringers) and reduction spots are also observed in hand sample. (B) Hand sample from 1629’2”-1629’9” depth; ripple cross-stratification and soft sediment deformation in dark red siltstone. Note the decrease of gypsum veins (stringers) moving up section. Photographs courtesy of K. Benison.

Mudcracks, ripple cross-stratification, and soft sediment deformation are observed within dark red siltstone/mudstone. Mud clasts/rip-up clasts, ped structures, halite casts, and soil slickensides are also observed. Diagenetic features include reduction spots, displacive gypsum crystals, gypsum nodules, and subhorizontal to vertical gypsum veins (Fig. 21).

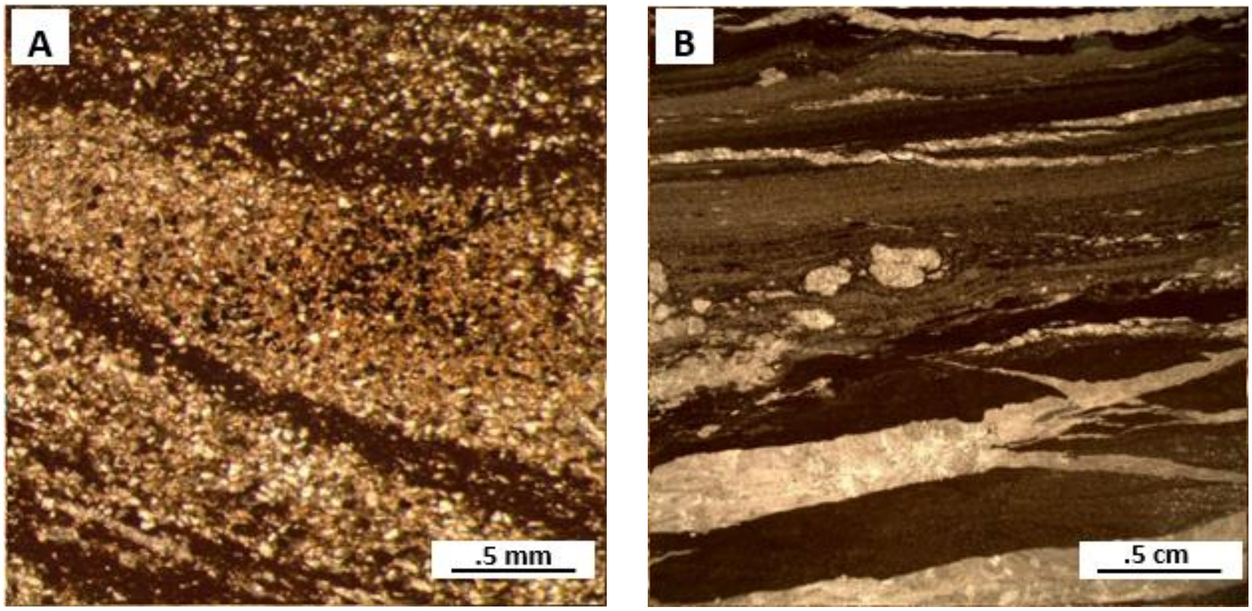


Figure 21. Photomicrographs of the Big Basin Formation in the Becky Bounds core. (A) Photomicrograph from 1634’4” depth in plane transmitted light; close up of specular hematite concentrated in wavy discontinuous laminae. (B) Photomicrograph from 1637’5” depth in plane transmitted light; gypsum veins (stringers) and gypsum nodules alongside planar laminae, ripple cross-stratification, and rip-up clasts. Both photomicrographs are shown oriented with respect to stratigraphic “up”.

Based on the results of this study, a stratigraphic column has been constructed (Fig. 22). Please refer to appendices for further details regarding the Quartermaster Group.

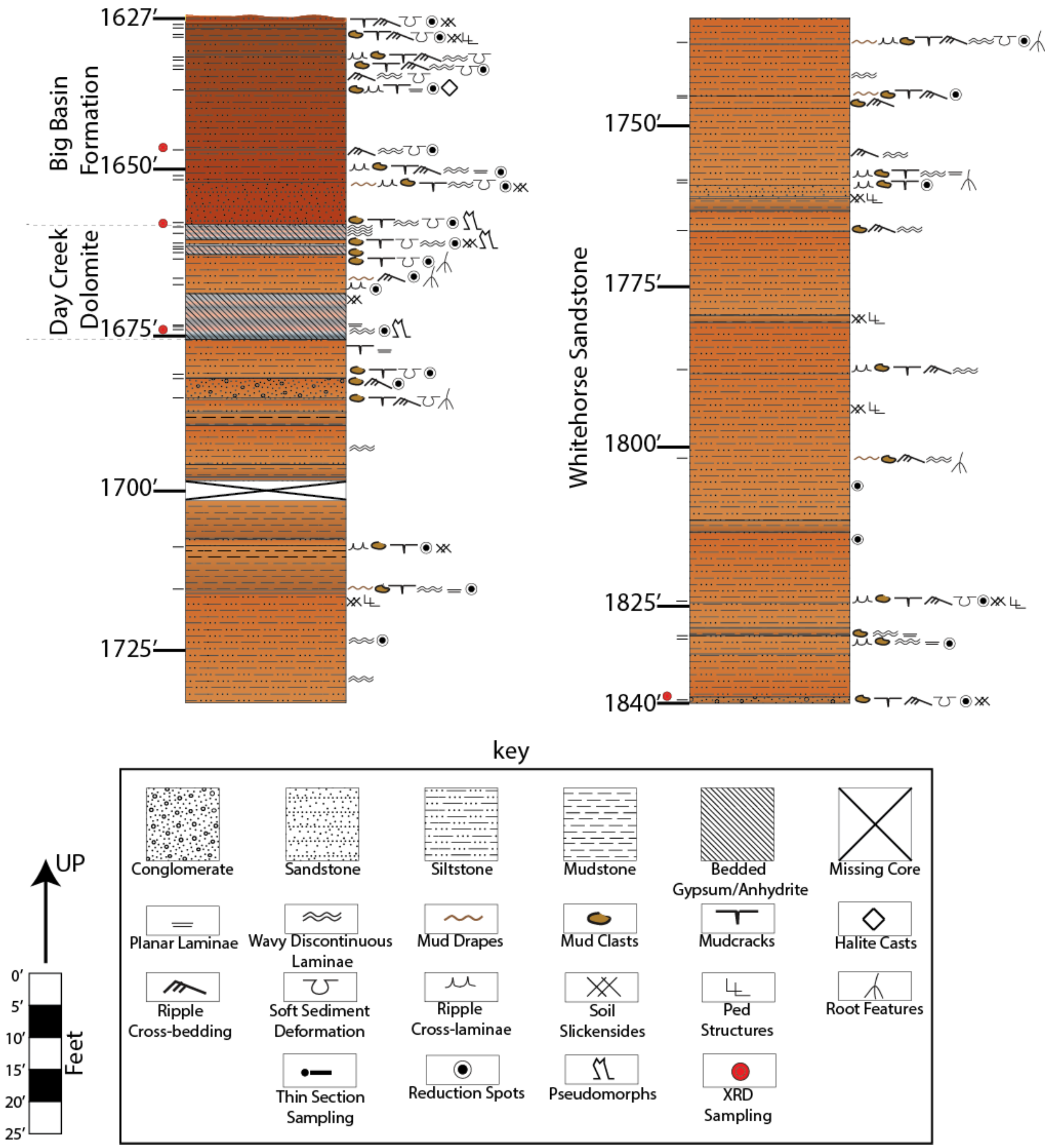


Figure 22. Stratigraphic column detailing the Quartermaster Group of western Kansas and its features as observed in the Becky Bounds core. Colors represent approximations of actual colors of rocks within the Becky Bounds core. Note the disconformity at the top of the Big Basin Formation. (modified after Zambito et al., 2012)

INTERPRETATIONS

FIELD INTERPRETATIONS

Due to poor confidence in stratigraphic context of the Quartermaster Group in outcrop, few interpretations can be made regarding these rocks at the surface. Units identified as the Quartermaster Group in outcrop consist of planar bedded red siliciclastics for the Whitehorse Sandstone and Big Basin Formation and dolomite/chert for the Day Creek Dolomite. These and other features observed in outcrop indicate that Quartermaster units found in south-central Kansas formed in similar depositional environments as Quartermaster Group units observed in the Becky Bounds core.

There are, however, differences between rocks in the Quartermaster Group observed in outcrop and core. Halite, though present in core as intergranular cement, is not preserved in outcrop. Additionally, thickness of these units in outcrop is much thinner than observed in the Becky Bounds core. These differences are considered to be the result of late stage dissolution of halite when units are at or near the surface. Evidence for late stage dissolution includes collapse features throughout south-central Kansas and halite saturated groundwater predominantly found throughout the region (Benison et al., 2015).

DEPOSITIONAL ENVIRONMENTS AND DIAGENESIS OF THE QUARTERMASTER GROUP IN THE BECKY BOUNDS CORE

Whitehorse Sandstone

Lithofacies and Depositional Environments

Three lithologies are observed in the Whitehorse Sandstone: red siltstone/mudstone, red well-sorted sandstone, and red mud clast conglomerate. Red siltstone/mudstone is interpreted to have formed in mudflats with development of paleosols. This lithofacies represents 96% (~157.5 ft) of the 164 ft section of the Whitehorse Sandstone in the Becky Bounds core. Red silt and clay, based on their gradational nature, are interpreted to have been deposited by both wind and water. Mud drapes alongside mud clasts indicate deposition during sheet flooding events while the well-sorted, high sphericity nature of some grains indicate minute eolian signatures (Ahlbrandt and Fryberger, 1982). Varying salt content of this lithofacies suggests saline groundwater table fluctuations or meteoric water influence. Mudcracks are evidence of wetting and drying events or low water table throughout deposition (Reading, 2002; Legler et al., 2005). The presence of displacive gypsum crystals in this lithofacies, however, indicates the unit was likely saturated by waters enriched in calcium and sulfate throughout deposition (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002). Grey reduction spots, many of which having dark nuclei, are evidence of organic decay in an otherwise oxidizing setting (Benison and Goldstein, 2001). Soil slickensides, ped structures, and root features are all lines of evidence for paleosol development (Retallack, 1988, 1990). Soil formation, however, was relatively short lived throughout this lithofacies as these features, though routinely common, do not exhibit significant thickness throughout the Becky Bounds core.

Red, well-sorted sandstone is interpreted to have formed in a dune to interdune depositional environment. This lithofacies represents 1% (~1.6 ft) of the 164 ft section of the Whitehorse Sandstone in the Becky Bounds core. The well-sorted, high sphericity, well rounded nature of fine sand grains found within this lithofacies is typical of eolian transport. Bimodal grain size also supports this lithofacies interpretation. Clastic subrounded to well rounded gypsum is interpreted to have been carried in as sand to silt sized grains reworked from crystals in nearby saline lakes. The presence of mud clasts, mudcracks, and small-scale ripple cross-stratification in fine sands indicate deposition in a wet interdune environment. Both mudflat and dune/interdune lithofacies can be associated with saline lake environments (Ahlbrandt and Fryberger, 1982; Glennie, 1987).

Red mud clast conglomerate is interpreted to have formed in mudflats during significant sheet flooding events (Hardie et al., 1978; Smoot, 1983). This lithofacies represents 1% (~5 ft) of the 164 ft section of the Whitehorse Sandstone in the Becky Bounds core. Soft sediment deformation indicates deposition occurred on already wet sediment. A significant lack of salt content in this lithofacies may indicate wet conditions during time of deposition. Mudcracks, however, indicate episodic wetting and drying (Reading, 2002; Legler et al., 2005). Subaerial exposure can occur frequently in mudflat settings (Eugster, 1980).

Diagenesis

Early diagenetic features include reduction spots, halite cement, and displacive gypsum crystals. Reduction spots observed in this formation are the result of organic matter undergoing reduction (Benison and Goldstein, 2001). This reduction would then allow for the bleaching of localized regions within sediment as groundwater moved through. Large reduction spots, which show greater lateral extent than their smaller reduction spot counterparts, are interpreted to have also undergone reduction via organic decay. Decaying organics in this case, however, are interpreted to be root horizons within weakly formed paleosols.

Halite cement is another early diagenetic feature found within the Whitehorse Sandstone. A pervasive saltiness occurs throughout much of the formation.

Displacive gypsum crystals are also an early diagenetic feature. These crystals are found throughout the formation in sandstone, siltstone, and mudstone. These features are interpreted to have formed in near surface sediments situated in waters enriched in calcium and sulfate (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002).

A late diagenetic feature is dissolution of halite. Though most of the formation is salty there are some zones within the formation that do not exhibit saltiness. Gypsum appears to be the predominant cement within these areas of the core. Initial cements may have been halite that later got replaced by gypsum as a result of late stage dissolution by meteoric waters. A paragenetic sequence for the Whitehorse Sandstone is presented below (Fig. 23).

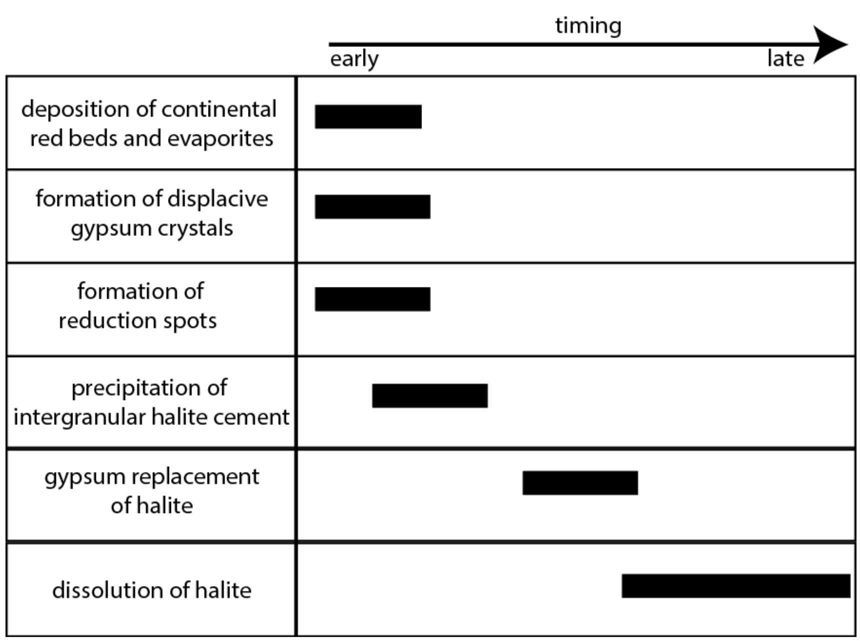


Figure 23. Proposed paragenetic sequence of diagenetic and depositional events in the Whitehorse Sandstone. Timing is relative for these events.

Day Creek Dolomite

Lithofacies and Depositional Environments

Two lithologies are present within the Day Creek Dolomite: bedded gypsum/anhydrite and red siltstone/mudstone. Bedded gypsum/anhydrite is interpreted to have formed in an ephemeral saline lake environment. This lithofacies represents 60% (~10 ft) of the 17 ft section of the Day Creek Dolomite in the Becky Bounds core. The upright nature of gypsum/anhydrite crystals within this lithofacies indicates that these units formed in a shallow subaqueous, saline setting (Lowenstein and Hardie, 1985; Hovorka, 1987). The presence of gypsum ooids towards localized tops of this lithofacies also suggests enhanced salinity during evapoconcentration (Tekin et al., 2008). Red silt sized siliciclastics (red siltstone/mudstone lithofacies) are found between the bedded gypsum/anhydrite lithofacies and are interpreted to have been deposited by sheet flooding events when the ephemeral saline lake had less standing water and was more characteristic of a mudflat. Wetting and drying events indicated by mudcracks within these lithofacies transitions could be seasonal or episodic (Glennie, 1987). Halite exhibiting a yellowish hue is considered as indirect evidence that this ephemeral saline lake was also acidic (Jagniecki and Benison, 2010).

Red siltstone/mudstone is interpreted to have formed in mudflats with adjacent soils. This lithofacies represents 40% (~7 ft) of the 17 ft section of the Day Creek Dolomite in the Becky Bounds core. Red silt and clay, based on their gradational nature, are interpreted to have been deposited during sheet flooding events with minute eolian signatures (Ahlbrandt and Fryberger, 1982). Varying salt content of this lithofacies is considered to be a result of saline groundwater table fluctuations or meteoric water influence (Hardie et al., 1978; Rosen, 1978). Mudcracks are evidence of wetting and drying events or low water table throughout deposition (Reading, 2002;

Legler et al., 2005). The presence of displacive gypsum crystals in this lithofacies, however, indicates the unit was saturated with saline groundwater at times before lithification (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002). Soil slickensides, ped structures, and root features are all lines of evidence for paleosol development (Retallack, 1988, 1990). Soil formation, however, was relatively short lived throughout this lithofacies as these features, though routinely common, show insignificant thickness throughout the Becky Bounds core.

Diagenesis

Early diagenetic features observed include reduction spots, replacement of gypsum to anhydrite, and displacive gypsum crystals. Reduction spots observed in this formation are the result of decaying organic matter, carried in by wind and/or water, undergoing reduction. This reduction would then allow for the bleaching of localized regions within sediment as groundwater moved through.

Replacement of gypsum to anhydrite is another early diagenetic feature observed in this formation. A majority of the crystals observed within bedded gypsum/anhydrite seem to have undergone competitive growth as some vertical gypsum/anhydrite crystals are surrounded by crystals that are slightly tilted. The upright nature of these crystals indicates that they were originally bottom-growth gypsum crystals that formed in a shallow brine pool (Lowenstein and Hardie, 1985; Hovorka, 1987). The overall texture of these crystals, which are complicated to observe in cross polarized and plane transmitted lighting, suggests gypsum to anhydrite alteration. Potential causes of alteration include variations in water content (waters drawn off from original gypsum), salinity (enhanced salinity provides greater chance of anhydrite formation), and temperature (temperatures above 37^{o}C are considered by some to be optimal for anhydrite formation; Schreiber and Walker, 1992; Hovorka, 1992).

Displacive gypsum crystals are found throughout the mudstones/siltstones of this formation. These features are suggested to have formed in near surface waters saturated in calcium and sulfate (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002). Calcium and sulfate could have potentially been leached from bedded gypsum/anhydrite within the formation.

Late diagenetic features observed in the Day Creek Dolomite include dissolution of gypsum/anhydrite and replacement of anhydrite to gypsum. These features are interpreted to be the result of meteoric waters interacting with bedded gypsum/anhydrite at or near the surface (Benison and Goldstein, 2001). Lastly, bedded gypsum/anhydrite is interpreted to have undergone multiple episodes of dehydration and hydration resulting in replacement of anhydrite to gypsum. This late stage diagenetic feature, much like dissolution of gypsum/anhydrite, can also occur at or near the surface (Schreiber and Walker, 1992; Hovorka, 1992). A paragenetic sequence for the Day Creek Dolomite is presented below (Fig. 24).

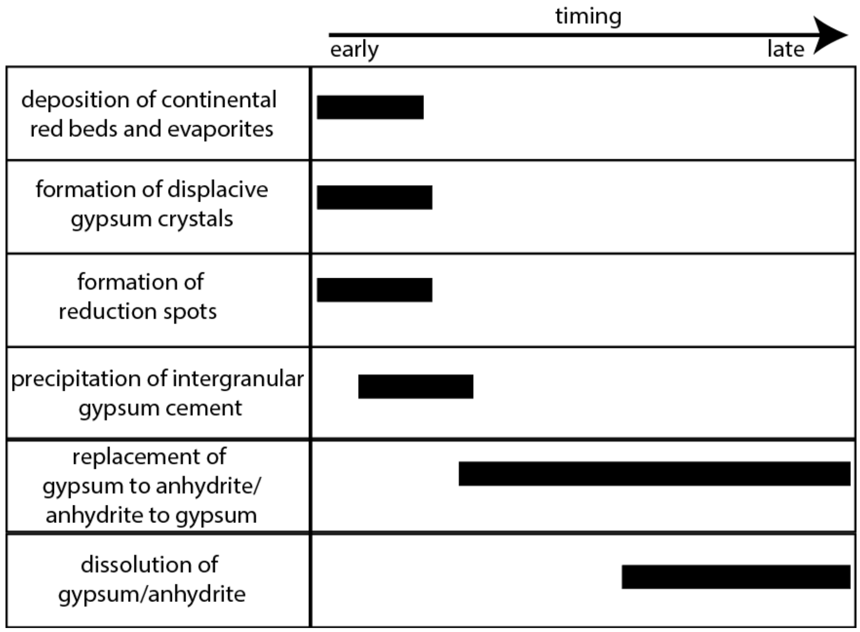


Figure 24. Proposed paragenetic sequence of diagenetic and depositional events in the Day Creek Dolomite. Timing is relative for these events.

Big Basin Formation

Lithofacies and Depositional Environments

Two lithologies are present in the Big Basin Formation: dark red, poorly-sorted sandstone and dark red siltstone/mudstone. The dark red, poorly-sorted sandstone is interpreted to have formed in an overall wet setting greater than most other lithologies previously described. Most of the sedimentary features observed in this formation indicate a mudflat depositional environment. This lithofacies represents 20% (~6.5 ft) of the 32 ft section of the Big Basin Formation in the Becky Bounds core. Massive sheet floods are interpreted to be the cause of many sedimentary structures observed within this lithofacies. Soft sediment deformation (e.g. ball and pillow structures) indicates sediment was deposited in an already wet setting. Mud clasts and mudcracks, however, indicate episodic wetting and drying (Reading, 2002; Legler et al., 2005). Gypsum veins (stringers), a late diagenetic feature, are interpreted to have formed when these rocks interacted with water saturated in calcium and sulfate at or near the surface. A lack of salt content throughout this lithofacies also supports greater precipitation during deposition.

Dark red siltstone/mudstone is interpreted to have formed in mudflats. This lithofacies represents 80% (~25.5 ft) of the 32 ft section of the Big Basin Formation in the Becky Bounds core. Unlike the lithofacies interpreted from the red siltstone/mudstone of the Whitehorse Sandstone and Day Creek Dolomite, this lithofacies seems to have been deposited in wetter conditions than observed during the deposition of the Whitehorse Sandstone. Soft sediment deformation indicates sediment was deposited in an already wet setting. Mudcracks are evidence of wetting and drying events or low water table throughout deposition (Reading, 2002; Legler et al., 2005). The presence of displacive gypsum crystals in this lithofacies, however, indicates the unit was likely moist throughout deposition (Last and Schweyen, 1983; Smoot, 1983, 2015;

Reading, 2002). Soil slickensides are lines of evidence for interstitial paleosol development (Retallack, 1988, 1990). These features also indicate the expansion and contraction of clays during wetting and drying events (Smoot and Olsen, 1994). Soil formation, however, was limited throughout this lithofacies as these features, though routinely common, show insignificant thickness throughout the Becky Bounds core.

Diagenesis

Early diagenetic features observed in core include reduction spots, halite cement, and displacive gypsum crystals. Reduction spots observed in this formation are the result of organic matter undergoing reduction (Benison and Goldstein, 2001). This reduction would then allow for the bleaching of localized regions within sediment as groundwater permeated through the sediments.

Halite cement is another early diagenetic feature proposed within the Big Basin Formation. The Big Basin Formation exhibits a lack of salt content throughout the entire formation. Halite casts, however, indicate halite was once present and may have acted as an initial cement.

Displacive gypsum crystals are found throughout the formation in sandstone, siltstone, and mudstone. They are interpreted to have formed in near surface sediments situated in waters enriched in calcium and sulfate (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002).

Late diagenetic features observed in the Big Basin Formation include dissolution of halite, gypsum nodules, and gypsum veins (stringers). It is interpreted that initial cements were halite that later got replaced by gypsum as a result of late stage dissolution by meteoric waters. Original halite cement is interpreted from halite casts observed in core. Dissolution of halite is interpreted to have caused the many microfaults observed within this formation. Gypsum nodules are found in a variety of areas throughout core and are interpreted to have formed in sediments beneath the surface in calcium and sulfate concentrated waters (Reading, 2002; Legler et al., 2005). Lastly, gypsum veins (stringers) are found throughout the Big Basin Formation and are considered to be the result of extensional stresses acting on these rock units. Waters enriched in calcium and sulfate likely followed along joint and faulting surfaces. In time, this interaction resulted in the gypsum veins (stringers) observed throughout the Big Basin Formation. Similar gypsum veins can be found in the Quartermaster Formation of the Texas panhandle (Goldstein and Collins, 1984). A paragenetic sequence for the Big Basin Formation is presented below (Fig. 25).

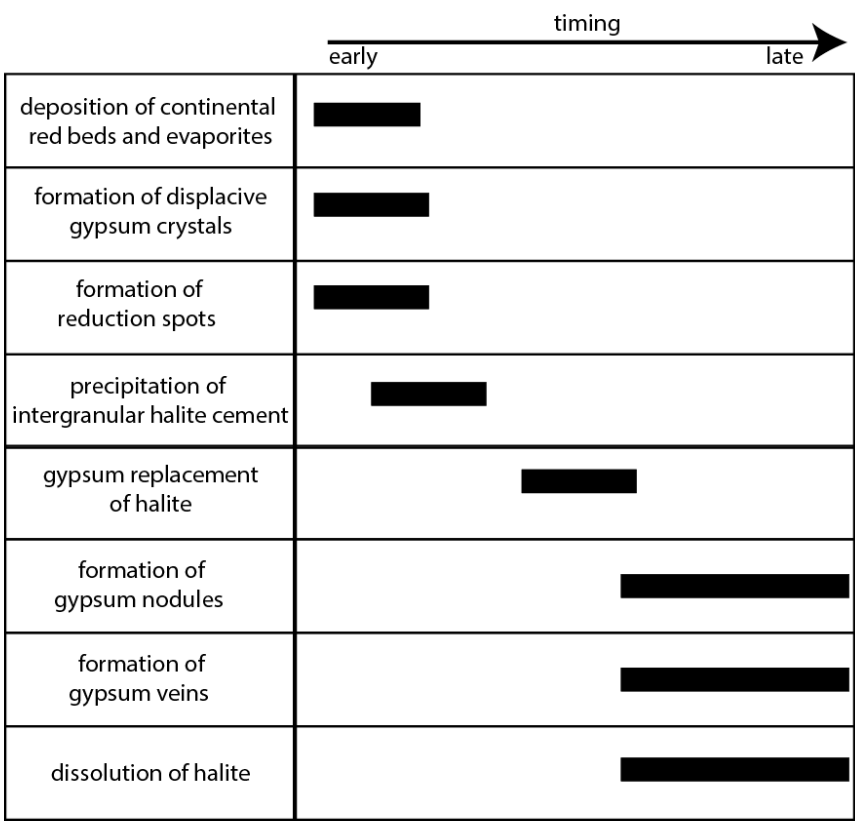


Figure 25. Proposed paragenetic sequence of diagenetic and depositional events in the Big Basin Formation. Timing is relative for these events.

DISCUSSION

MARINE/MARGINAL MARINE DEPOSITIONAL ENVIRONMENT DEBUNKED

Sedimentary features observed in the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation indicate the Quartermaster Group was deposited in ephemeral saline lakes and associated continental environments. Depositional environments interpreted within the Quartermaster Group include mudflats, dune, interdune, and ephemeral saline lake. Soil slickensides, ped structures, and root features suggest paleosol development at various times during the deposition of the Quartermaster Group.

Deposition of the Quartermaster Group in marine/marginal marine environments such as tidal flats, deltas, estuaries, and lagoons, however, is considered. Tidal flats occur on open coasts in low relief/low energy settings and are typically associated with lagoons, estuaries, and deltas. Generally, tidal flats are similar to one another in that their formation relies on measurable tidal range and absence of strong waves. Characteristically, however, there is much variety in tidal flats (Weimer et al., 1982). These depositional environments are typically subdivided into three zones: subtidal, lower intertidal, and upper intertidal. Interlayered sand and mud are typically found in these subdivisions. Quartz, feldspar, mica, gypsum/anhydrite, and carbonates can all be found within this depositional environment. Sands are mainly deposited during current flow while muds are deposited during slack water periods. In the Chandipur tidal flat, upper regions are mostly composed of medium to fine sand while distal regions contain more than 80% very fine sand (Chakrabarti, 2005). Megaripples, ripple laminae, longitudinal cross-beds, lenticular bedding, wavy bedding, and flaser bedding are all common sedimentary structures found in subtidal deposits. Intertidal zones are mainly characterized by flaser bedding, lenticular bedding, wavy bedding, and herringbone cross-stratification. Horizontal laminations, climbing ripple laminations, hummocky cross-stratification, interference ripples, and scour and fill laminations are also common (Chakrabarti, 2005). In addition, bioturbation (worm burrows), shell lags, trace fossils (gastropods), mudcracks, and algal mats may all be preserved in tidal flat deposits (Reineck and Singh, 1980; Clifton, 1982). Despite this variety of sedimentary features, none appear to be restricted to this facies alone. Tidal rhythmites, however, are considered diagnostic to this depositional environment. Though many of these features are observed in the Quartermaster Group, the cyclicity of sedimentation observed in tidal rhythmites isn't one of them. Bioturbation, shell lags, and algal mats aren't observed in the Quartermaster Group either. These features among others suggest the Quartermaster Group formed in depositional environments other than tidal flats.

Deltas occur when sediments influenced by fluvial processes meet with larger water bodies (ocean or lake; Wright, 1985). They are categorized as fluvially dominated, wave-dominated, and tide-dominated (Coleman, 1976). Deltas are characterized as largely clastic accumulations which transition from offshore facies to fluvial facies upsection (Reading and Collinson, 2002). As such, variable features can be produced in deltas. Grain size can range from gravel to clay with coarsest grain sizes near river mouths (Wright, 1985). Compositionally, clastics are mainly observed within this depositional environment. Evaporites, however, can form in deltas with high tide range in arid climates. Slump structures, ripple cross-stratification, mudcracks, parallel bedding, lenticular bedding, wavy bedding, and diapiric structures are all associated with deltaic deposition (Wright, 1985). In addition, bioturbation, shell remains, algal mats, peat deposits, and wood fragments may also be present. Despite this variety of sedimentary features, none appear to be restricted to this facies alone. Vertical sequences that coarsen upward, however, are typical of prograding deltaic deposits (Coleman and Prior, 1982). A variety of these features are shared between Quartermaster Group and deltaic deposits but there are differences. Bioturbation, shell lags, coarsening upward sequence, and algal mats are not observed within the Quartermaster Group. In addition, sediments are finely laminated in the Quartermaster Group, a feature which contrasts greatly with thick packages of sediment observed in deltas. These features suggest the Quartermaster Group formed in depositional environments other than deltas.

Estuaries are marginal marine environments where a semi-enclosed body of water is influenced by river discharge. The specific character of estuary deposits is directly influenced by setting, processes operating in the area, as well as what sediments are available from the surrounding environment. As such, a variety of sedimentary features can be observed within this facies (Clifton, 1982). Sediments in modern estuaries are typically green, brown, black, or grey. Sedimentation is dominantly influenced by tidal effects. Grain size typically ranges from fine sand to mud. One to ten centimeter sand deposits can be found sporatically through sequences of planar laminated silts and clays (Nichols and Biggs, 1985). The sands may be introduced from the ocean while mud accumulates from river discharge. Compositionally, clastics, evaporites, and carbonates can all be observed within this depositional environment. Sedimentary structures such as planar laminae, wavy bedding, flaser bedding, herringbone cross-stratification, ripple laminations, slump structures, mud drapes, and lenticular bedding can be observed within estuarine deposits (Clifton, 1982). Additional features may include bioturbation (burrows), wood fragments, shell remains, root features, and mud clasts (Terwindt et al., 1963; Terwindt, 1971). A variety of these features are observed in the Quartermaster Group, but the lack of bioturbation, shell remains, and bimodality of cross-stratification among other features suggests the Quartermaster Group formed in depositional environments other than estuaries.

Lastly, lagoons are shallow water bodies which run parallel to the coast with restricted connection to the open sea. The specific character of lagoon deposits is directly influenced by their setting, processes operating in the area, as well as what sediments are available from the surrounding environment. Lagoons in tidal regions share a variety of similarities to tidal flats and estuaries (Reading and Collinson, 2002). Grain size, because of the typical low energy setting, ranges between sand and mud. Compositionally, clastics, evaporites, and carbonates can all be observed within this depositional environment. Sedimentary structures such as planar laminae, wave ripple cross-stratification, mudcracks, soft sediment deformation, wavy bedding, and lenticular bedding may all be observed within lagoon deposits. Additional features may include algal mats, bioturbation, restricted marine fauna, and coal deposits (Reineck and Singh, 1980). Black shales may also develop in these highly reducing settings (Reading and Collinson, 2002). A variety of these features are observed in the Quartermaster Group, but the lack of bioturbation, algal mats, and organics among other features suggests the Quartermaster Group formed in depositional environments other than lagoons.

The case for nonmarine deposition is a more appropriate interpretation for the Quartermaster Group. Fossils and carbonates, generally plentiful in marine to marginal marine depositional environments, are absent throughout the Quartermaster Group. More importantly, sedimentary features found throughout the Quartermaster Group reinforce deposition in a terrestrial environment. Features found within these red beds indicate units were subaerially exposed long enough for mudcracks, ped structures, soil slickensides, and root features to develop. Lastly, displacive gypsum crystals and evidence of halite cement are found in the red beds of the Quartermaster Group indicating deposition of sediments in environments influenced by saline groundwater (i.e. mudflats, etc.; Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002).

Sedimentary features observed within the Quartermaster Group coincide with features other geologists have described within the underlying Nippewalla Group. Holdoway (1978) interpreted the underlying Nippewalla Group as forming in a closed basin continental setting. She used bromine analysis and petrographical observations to support her conclusions. Low bromine values (ranging from 0 to 20 ppm, though mostly 5 ppm) obtained from halite samples of the Nippewalla Group indicate deposition occurred within a continental setting where halite formed in non-marine waters or was recrystalized. Additionally, sedimentary and early diagenetic features observed within the red beds of the Nippewalla Group indicate eolian deposition and paleosol formation. Additional studies support these conclusions and suggest the possibility of acidity within ephemeral saline lake and associated environments (Benison et al., 1998; Benison and Goldstein 2001). With few differences in sedimentary features to those observed in the underlying Nippewalla Group, the Quartermaster Group seems to have also been deposited in a continental setting characterized by ephemeral saline lakes and associated environments. A depositional model for the Quartermaster Group has been added to the following page (Fig. 26).

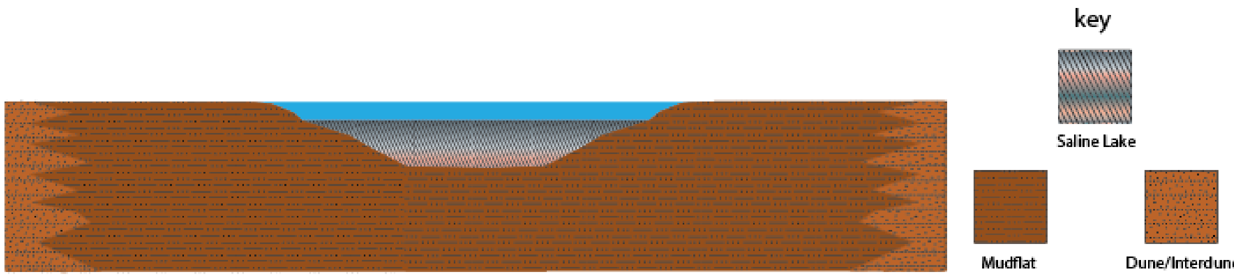


Figure 26. Generalized schematic depositional cross-sectional model for the Quartermaster Group. Sediments were deposited in ephemeral saline lakes and adjacent environments (mudflats, dunes, etc.) by sheet floods and wind. The Whitehorse Sandstone was deposited in dune/interdune and mudflat environments. Thick bedded gypsum was deposited in a saline lake which underwent stages of flooding, evapoconcentration, and desiccation during the deposition of Day Creek Dolomite. Deposition also occurred in mudflats during this time. The Big Basin Formation was deposited in mudflats. Paleosols developed interstitially in each formation.

TRENDS IN THE QUARTERMASTER GROUP

A variety of trends can be observed within each formation of the Quartermaster Group within the Becky Bounds core. The Whitehorse Sandstone, in contrast to what its name suggests, generally transitions between siltstone and mudstone deposition throughout the entirety of the formation. Salt content roughly follows this trend as mudstones do not exhibit salty taste while siltstones and sandstones do. This trend indicates fluctuations in precipitation or the groundwater table (i.e. salty during drier times).

The Day Creek Dolomite transitions between bedded gypsum/anhydrite and red siltstone indicating periods of flooding, evapoconcentration, and dessication. Some contacts of bedded gypsum/anhydrite within this formation are salty and contain unusual yellow hues near observed halite. These features suggest the evaporation of an ephemeral saline lake that may have potentially been acidic (Jagniecki and Benison, 2010).

Lastly, the Big Basin Formation is seemingly darker red than other red beds observed within the Quartermaster Group. The sample is not salty throughout the formation though is interpreted to have contained halite at some point throughout depositional history (halite casts observed). Gypsum veins (stringers) are subhorizontal to vertical and are interpreted to have formed along joints and faulting surfaces. These joints and faulting surfaces were likely caused by the dissolution of halite when sediments interacted with meteoric waters at a near the surface (Norton, 1939).

PALEOCLIMATE/PALEOWEATHER

The Quartermaster Group illustrates conditions which were initially arid that later transitioned to semiarid and/or temperate. The Whitehorse Sandstone exhibits halite cement throughout a majority of the formation within the Becky Bounds core. The presence of intergranular halite cement indicates evaporation exceeded precipitation throughout deposition or that sediments were influenced by sodium- and chloride-rich fluids. The presence of displacive gypsum crystals throughout the formation suggests the climate was arid, with waters enriched in calcium and sulfate normally below the surface (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002). Mudstones of the Whitehorse Sandstone suggest periods during deposition where evaporation outweighed precipitation. Groundwaters, enriched in saline minerals, were likely deeper beneath the surface during drier times. Precipitation events likely came as sheet floods of various intensities as indicated by rip-up clasts and mud clast conglomerates within the formation (Smoot, 1983). Mudcracks, however, indicate episodes of wetting and drying (Reading, 2002; Legler et al., 2005). These mudstones are mainly associated with soil slickensides and ped structures indicating pedogenesis during times when the environment was more hospitable (Kraus, 1999).

Evapoconcentration of saline waters led to the deposition of bedded gypsum/anhydrite (ephemeral saline lake lithofacies) within the Day Creek Dolomite. The vertical nature of gypsum/anhydrite crystals supports shallow water deposition in brine pools (Hovorka, 1987).

The presence of mudcracks and gypsum ooids within this lithology suggests waters shallowed through time eventually leading to dessication of the lake (Benison and Goldstein, 2001). Mudflat deposits developed during times of dessication (Lowenstein and Hardie, 1985). Similar mudflat-ephemeral saline lake-mudflat transitions have been observed in core descriptions from Death Valley, California (Lowenstein et al., 1999).

Features observed in the Big Basin Formation express a continuation of instability. Poorly-sorted sandstone at the base of the formation was likely deposited by massive sheet floods. High sphericity, well rounded “floating” medium to coarse sand grains are also at the base of this unit suggesting some eolian transport (Ahlbrandt and Fryberger, 1982). Conditions were likely semiarid to temperate as halite cements, though initially considered to have cemented Big Basin Formation sediments, were not preserved but replaced by gypsum and clay in the Becky Bounds core. Big Basin mudflats were deposited in wetter conditions than Whitehorse Sandstone mudflats. This is interpreted by relative abundance of soft sediment deformation in the two formations. Soil slickensides in the Big Basin mudflats indicate the expansion and contraction of clays from wetting and drying events (Smoot and Olsen, 1994). These features may also indicate pedogenesis (Retallack, 1988, 1990). Their occurrence in the Big Basin Formation is much less than observed in the Whitehorse Sandstone, suggesting sediments were likely much more saturated throughout Big Basin deposition.

COMPARING THE QUARTERMASTER GROUP TO THE NIPPEWALLA GROUP

A variety of similarities are observed between the units of the Quartermaster Group and Nippewalla Group. The Quartermaster Group and Nippewalla Group are both red bed and evaporite sequences interpreted to have been deposited in continental settings characterized by lacustrine and eolian deposition (Benison and Goldstein, 2001; Poland and Simms, 2012; Foster et al., 2014). Evidence of pedogenesis is also observed in both the Nippewalla Group and Quartermaster Group. Lastly, carbonates and fossils are absent throughout the Quartermaster Group and Nippewalla Group.

Though many features are shared between the Quartermaster Group and Nippewalla Group, bedded halite and displacive halite (also known as chaotic halite) lithofacies are only observed in the Nippewalla Group (Benison and Goldstein, 2001). The only lines of evidence of halite in the Quartermaster Group are halite cements interpreted from the saltiness of the Whitehorse Sandstone and Day Creek Dolomite and halite casts in the Big Basin Formation. The overall absence of bedded halite and chaotic halite in the Quartermaster Group when compared to the underlying Nippewalla Group indicates that conditions were likely more humid when sediments of the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation were deposited.

CORE VS. OUTCROP

Differences are observed between the Quartermaster Group at the surface and within the Becky Bounds core. Quartermaster units within core are indurated when compared to their surface counterparts. Halite, though present in core, is not preserved in outcrop. Additionally, thickness of these units in core is much greater than observed in their outcrop equivalents. A majority of these differences are considered to be the result of late stage dissolution of halite when units are at or near the surface.

These stark differences between outcrop and core observations have historically resulted in issues regarding the stratigraphy, nomenclature, interpretation, and understanding of the

Quartermaster Group and other red bed and evaporite sequences (Benison et al., 2015). The use of the Becky Bounds core and potential use of other cores exhibiting substantial recovery can improve efforts at mitigating these acknowledged issues. Additional use of high resolution petrophysical logging would also help in these efforts.

DOES THE QUARTERMASTER REPRESENT ACID SALINE ENVIRONMENTS?

Benison and Goldstein (2002) described criteria for the recognition of acid saline environments in the rock record. They determined the presence of extremely acidic waters in halite fluid inclusions from various intervals of bedded halite within the Nippewalla Group (Benison and Goldstein, 1999, 2013). With many sedimentary similarities with the underlying Nippewalla Group, there is a possibility that the Quartermaster Group may have been deposited in acid saline environments as well. Diagnostic criteria for acid saline environments in the Nippewalla Group were determined from HSO_4^- peaks from laser Raman spectroscopy (LRM) data of fluid inclusions in halite. These peaks are only observable when pH is less than 1 (Benison et al., 1998). Additional evidence of acidity for these units was gathered from leachate analyses of fluid inclusions in halite, which showed abundant Al, Fe, and Si (Benison and Goldstein, 2002). Studies of modern acid environments show an inverse relationship between the abundance of Al, Fe, and Si and pH (Benison, 1997; Benison and Goldstein, 2002). Though the Quartermaster Group has no bedded halite to test for these diagnostic criteria, other indirect and possibly problematic criteria of acid saline environments are observed. Red beds, though not exclusive to acidic environments, are a characteristic of acidic environments in modern and ancient settings (Benison and Goldstein, 2002; Benison et al., 2007). An overall paucity of carbonates within each formation of the Quartermaster Group within the Becky Bounds core may be indicative of acidic environments because evaporites in neutral or alkaline environments are typically accompanied by carbonates (Benison and Goldstein, 2002). Lastly, the presence of halite exhibiting a yellowish hue observed in the crystalline units of the Day Creek Dolomite may represent acidic conditions. This unusual hue has been observed in modern acid saline settings and is interpreted to be caused by waters enriched in metals such as aluminum trapped within the halite (Jagniecki and Benison, 2010). Additionally, rock types and sedimentary features observed in the Whitehorse Sandstone are similar to those observed in the Dog Creek Formation of the underlying Nippewalla Group (a known acid system). Though not confirmed, it can be proposed from these criteria and the sedimentological similarities with the underlying Nippewalla Group and modern acidic settings that units within the Quartermaster Group were also likely deposited in acid saline environments.

If truly acidic, the ephemeral saline lakes and associated environments of southern Western Australia can be viewed as a potential modern analog to the Quartermaster Group. Located on the Yilgarn Craton, a tectonically stable and low relief setting, these ephemeral saline lakes range from acidic to alkaline, though most are acidic (Benison et al., 2007). Salinities as high as 32% total dissolved solids and pH values as low as 1.4 have been observed within these lakes (Benison and Bowen, 2015). Some lakes are halite-dominated while others, comparable to the ephemeral saline lake lithofacies observed in the Day Creek Dolomite, are gypsum-dominated. Surrounding these lakes are mudflats which compositionally range from quartz rich to intermixed quartz/gypsum deposits. Orange hematite, which actively precipitates in these acidic settings, tends to coat sand and silt sized grains. Displacive gypsum crystals form within these environments in near surface sediments enriched in calcium and sulfate (Last and Schweyen, 1983; Smoot, 1983, 2015; Reading, 2002). A lack of carbonates is also observed within these arid to semiarid settings (Benison et al., 2007). In time, extensive deposits of red beds and evaporites will likely form in the acid saline lake systems of the Yilgarn Craton comparable to those observed in the Quartermaster Group and Nippewalla Group of Kansas.

CONCLUSIONS

Detailed field observations and petrographical observations from the Becky Bounds core of the middle to late Permian Quartermaster Group indicate the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation were deposited in arid to semiarid continental settings. Red mudstone, siltstone, and sandstone as well as bedded gypsum/anhydrite observed within the Quartermaster Group are interpreted to have been deposited in dune, interdune, ephemeral saline lake, and mudflat depositional environments. Soil slickensides, ped structures, and root features suggest paleosol development.

Diagenetic features within the Whitehorse Sandstone, Day Creek Dolomite, and Big Basin Formation reinforce these conclusions. Early and late diagenetic features observed within these units in field and core suggest substantial influence from waters at or near the surface in arid and oxidizing settings.

Historically, many red bed and evaporite sequences have been interpreted as marine or marginal marine deposits. Soil features and significant absence of carbonates and marine fossils within the Quartermaster Group indicate western Kansas was terrestrial during the middle to late Permian. An absence of carbonates throughout the Quartermaster Group, yellow hues observed in halite of the Day Creek Dolomite, and striking similarities with the underlying Nippewalla Group are suspect/problematic criteria which may indicate these terrestrial environments were possibly acidic.

The use of highly recoverable core is an exceptional tool to better understand the stratigraphy, lithology, nomenclature, paleogeography, diagenetic history, and depositional environments of red bed and evaporite sequences throughout the western midcontinental United States and elsewhere (Soreghan et al., 2015).

REFERENCES CITED

Ahlbrandt, T.S. and Fryberger, S.G., 1982, Introduction to eolian deposits. *In:* Scholle, P.A., and Spearing, D. eds., Sandstone depositional environments: American Association of Petroleum Geologists, Memoir 31, p. 11-47.

Baars, D.L., 1990, Permian chronostratigraphy in Kansas: Geology, v. 18, no. 8, p. 687-690.

Benison, K.C., 1997, Acid water deposition and diagenesis of Permian red bed hosted evaporites, midcontinent, United States of America: Proquest Dissertations Publishing.

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, p. 4-10, doi: 10.1130/GSATG231A.1

Benison, K.C., and Goldstein, R.H., 1999, Permian paleoclimate data from fluid inclusions in halite: Chemical Geology, v. 154, no. 1, p. 113-132, doi: 10.1016/S0009-2541(98)00127 -2.

Benison, K.C., and Goldstein, R.H., 2000, Sedimentology of ancient saline pans: An example from the Permian Opeche Shale, Williston Basin, North Dakota, U.S.A.: Journal of Sedimentology Research, v. 70, no. 1, p. 159-169, doi: 10.1306/2DC 40907-0E47-11D7-8643000102C1865D.

Benison, K.C., and Goldstein, R.H., 2001, Evaporites and siliciclastics of the Permian Nippewalla Group of Kansas, USA: A case for non-marine deposition in saline lakes and saline pans: Sedimentology, v. 48, no. 1, p. 165-188, doi:10.1046/j.1365-3091.2001.00362.x.

Benison, K.C., and Goldstein, R.H., 2002, Recognizing acid lakes and groundwaters in the rock record: Sedimentary Geology, v. 151, no. 3, p. 177-185, doi:10.1016/S0037-

0738(02)00155-0.

Benison, K.C., Goldstein, R.H., Wopenka, B., Burruss, R.C., and Pasteris, J.D., 1998, Extremely acid Permian lakes and ground waters in North America: Nature, v. 392, no. 6679, p. 911-914. doi: 10.1038/31917.

Benison, K.C., Bowen, B.B., Oboh-Ikuenobe, F.E., Jagniecki, E.A., LaClair, D.A., Story, S.L. Mormile, M.R., and Hong, B., 2007, Sedimentology of acid saline lakes in southern Western Australia: Newly described processes and products of an extreme environment: Journal of Sedimentary Research, v. 77, no. 5, p. 366-388, doi:10.2110/jsr.2007.038.

Benison, K.C., Zambito IV, J.J., Soreghan, G.S., Soreghan, M.J., Foster, T.M., and Kane, M.J., 2013, Permian red beds and evaporites of the Amoco Rebecca K. Bounds core, Greeley County, Kansas: Implications for science and industry, *In:* Dubois, M.K., and Watney, W.L., eds., Midcontinent core workshop: From source to reservoir to seal: Kansas Geological Survey and Kansas Geological Society, Lawrence, KS, p. 9-14.

Benison, K.C., Zambito IV, J.J., and Knapp, J., 2015, Contrasting siliciclastic-evaporite strata in subsurface and outcrop: An example from the Permian Nippewalla Group of Kansas, U.S.A.: Journal of Sedimentary Research, v. 85, no. 6, p. 626-645, doi: 10.2110/jsr.2015.43.

Carter, L.S., Kelley, S.A., Blackwell, D.D., and Naeser, N.D., 1998, Heat Flow and Thermal History of the Anadarko Basin, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 82, no. 2, p. 291-316.

Chakrabarti, A., 2005, Sedimentary structures of tidal flats: A journey from coast to inner estuarine region of eastern India: Journal of Earth System Science, v. 114, no. 3, p. 353-

368, doi: 10.1007/BF02702954.

Clifton, H.E., 1982, Estuarine deposits. *In:* Scholle, P.A., and Spearing, D. eds., Sandstone depositional environments: American Association of Petroleum Geologists, Memoir 31, p. 179-189.

Coleman, J.M., 1976, Deltas: Processes of deposition and models for exploration: Continuing Education Publishing Company, Champaign, IL, 102 p.

Coleman, J.M., and Prior, D.B., 1982, Deltaic environments of deposition. *In:* Scholle, P.A., and Spearing, D. eds., Sandstone depositional environments: American Association of Petroleum Geologists, Memoir 31, p. 139-178.

Cragin, F.W., 1896, The Permian system in Kansas: Colorado College Scientific Society, Colorado College Studies, v. 6, p. 1-54.

Cragin, F. W., 1897, Observations on the Cimarron Series: American Geologist, v. 19, p. 351-363.

Eugster, H.P., 1980, Geochemistry of evaporitic lacustrine deposits: Annual Review of Earth and Planetary Sciences, v. 8, no. 1, p. 35-63, doi: 10.1146/annurev.ea.08.050180.000343.

Evans, N., 1931, Stratigraphy of Permian beds of northwestern Oklahoma: American Association of Petroleum Geologists Bulletin, v. 15, p. 405-439.

Fay, R.O., 1964, The Blaine and related formations in northwestern Oklahoma and southern Kansas: Oklahoma Geological Society Bulletin, v. 98, 238 p.

Fay, R.O., 1972, Stratigraphy and general geology of Custer County: Oklahoma Geological Bulletin, v. 114, p. 1-46.

Foster, T.M., Soreghan, G.S., Soreghan, M.J., Benison, K.C. and Elmore, R.D., 2014, Climatic and paleogeographic significance of eolian sediment in the Middle Permian Dog Creek

Shale (Midcontinent U.S.): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 402, p. 12-29, doi: 10.1016/j.palaeo.2014.02.031.

Glennie, K.W., 1987, Desert sedimentary environments, present and past- A summary: Sedimentary Geology, v. 50, no. 1, p. 135-165, doi: 10.1016/0037-0738(87)90031-5.

Goldstein, A.G., and Collins, E.W., 1984, Deformation of Permian strata overlying a zone of salt dissolution and collapse in the Texas panhandle: Geology, v. 12, no. 5, p. 314-317.

Gould, C.N., 1905, Geology and water resources of Oklahoma: U.S. Geological Survey Water-Supply Paper 148, 178 p.

Gould, C.N., 1907, The geology and water resources of the western portion of the panhandle of Texas: U.S. Geological Survey Water-Supply Paper 191, 88 p.

Gould, C.N., 1924, A new classification of Permian redbeds of southwestern Oklahoma: American Association of Petroleum Geologists Bulletin, v. 8. p. 322-341.

Hardie, L.A., Smoot, J.P., and Eugster, H.P., 1978, Saline lakes and their deposits: A sedimentological approach. *In*: Matter, A., and Tucker, M.E., eds., Modern and ancient lake sediments. International Association of Sedimentology Special Publication, v. 2, p. 7-41.

Hills, J.M., 1942, Rhythm of Permian seas- A paleogeographic study: American Association of Petroleum Geologists Bulletin, v. 26, no. 2, p. 217-255.

Holdoway, K.A., 1978, Deposition of evaporites and red beds of the Nippewalla Group, Permian, western Kansas: Kansas Geological Survey Bulletin, v. 215, 43 p.

Hovorka, S.D., 1987, Depositional environments of marine-dominated bedded halite, Permian San Andres Formation, Texas: Sedimentology, v. 34, p. 1029-1054.

Hovorka, S.D., 1992, Halite pseudomorphs after gypsum in bedded anhydrite-Clue to gypsum-anhydrite relationships: Journal of Sedimentary Petrology, v. 62, no. 6, p. 1098-1111.

Jagniecki, E.A., and Benison, K.C., 2010, Criteria for the recognition of acid-precipitated halite: Sedimentology, v. 57, no. 1, p. 273-292, doi:10.1111/j.1365-3091.2009.01112.x.

Kraus, M.J., 1999, Paleosols in clastic sedimentary rocks: their geologic applications: Earth Science Reviews, v.47, no. 1, p. 41-70.

Last, W.M., and Schweyen, T.H., 1983, Sedimentology and geochemistry of saline lakes of the Great Plains: Hydrobiologia, v. 105, p. 245-263.

Legler, B., Gebhardt, U., and Schneider, J.W., 2005, Late Permian non-marine-marine transitional profiles in the central southern Permian Basin, northern Germany: International Journal of Earth Sciences, v. 94, no. 5, p.851-862, doi: 10.1007/500531-005 -0002-5.

Lowenstein, T.K., 1987, Evaporite depositional fabrics in the deeply buried Jurassic Buckner Formation: Journal of Sedimentary Petrology, v. 57, p. 108-116.

Lowenstein, T.K., and Hardie, L.A., 1985, Criteria for the recognition of salt-pan evaporites: Sedimentology, v. 32, no. 5, p. 627-644, doi:10.1111/j.1365-3091.1985.tb00478.x.

Lowenstein, T.K., Brown, C., Roberts, S.M., Ku, T., and Yang, W., 1999, 200 k.y. paleoclimate record from Death Valley salt core, Geology, v. 27, no. 1, p. 3-6, doi: 10.1130/0091-7613 (1999)027C0003:KYPRI.

Maher, J. C., and Collins, J.B., 1948, Hugoton Embayment of Anadarko Basin in southwestern Kansas, southeastern Colorado, and Oklahoma Panhandle: American Association of Petroleum Geologists Bulletin, v. 32, p. 813-816.

Maughan, E.K., 1966, Environment of deposition of Permian salt in the Williston and Alliance

Basins. *In:* 2nd symposiom on salt, v. 1, p. 35-47, Northern Ohio Geological Society, Cleveland, Ohio.

Maughan, E.K., 1967, Eastern Wyoming, eastern Montana, and the Dakotas. *In:* McKee, E.D., and Oriel, S.S. eds., Paleotectonic Investigations of the Permian System in the United States, United States Geological Survey Professional Paper, v. 515, p. 125-152.

Merriam, D.F., 1963, The geologic history of Kansas. State Geological Survey Kansas Bulletin, v. 162, 317.

Mudge, M.R., 1967, Central midcontinent Region. *In:* McKee, E.D., and Oriel, S.S. eds., Paleotectonic Investigations of the System in the United States, United States Geological Survey Professional Paper, v. 515, p. 91-123.

Nichols, M.M., and Biggs, R.B., 1985, *In:* Davis, Jr., R.A. eds., Coastal sedimentary environments: Springer-Verlag, New York.

Norton, G. H., 1939, Permian red beds of Kansas: American Association of Petroleum Geologists Bulletin, v. 23, p. 1751-1819.

Olszewski, T.D., and Patzkowsky, M.E., 2003, From cyclothems to sequences: The record of eustasy and climate on an icehouse epeiric platform (Pennsylvanian-Permian, North American midcontinent): Journal of Sedimentary Research, v. 73, p. 15-30.

Parrish, J.T., 1993, Climate of the supercontinent Pangea: Journal of Geology, v. 101, no. 2, p. 215-233, doi: 10.10861648217.

Poland, Z.A., and Simms, A.R., 2012, Sedimentology of an erg to an erg-margin depositional system, the Rush Springs Sandstone of western Oklahoma, U.S.A.: Implications for paleowinds across northwestern Pangea during the Guadalupian (middle Permian): Journal of Sedimentary Research, v. 82, no. 5-6, p. 345-363, doi: 10.2110/jsr.2012.32.

Poulsen, C.J., Pollard, D., Montanez, I.P., and Rowley, D., 2007, Late Paleozoic tropical climate response to Gondwanan deglaciation: Geology, v.35, p.771-774.

Pritt, J.J, and Benison, K.C., 2015, Depositional environments of the Quartermaster Group: Evidence of acid saline lakes and soils in west-central Kansas during the late Permian?: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 361.

Rascoe, B., Jr., 1968, Permian system in western mid-continent: The Mountain Geologist, v. 5, p. 127-138.

Reading, H.G., 2002, Sedimentary environments: Processes, facies, and stratigraphy, 3rd edn, Blackwell Sciences, Oxford.

Reading, H.G, and Collinson, J.D., 2002, Clastic Coasts, In: Reading, H.G. eds., Sedimentary environments: Processes, facies, and stratigraphy, 3rd edn, Blackwell Sciences, Oxford.

Reineck, H.E., and Singh, I.B., 1980, Depositional sedimentary environments with reference to terriginous clastics, 2nd edn, Springer-Verlag, Berlin, 542 p.

Retallack, G.J., 1988, Field recognition of paleosols: Geological Society of America Special Paper, v. 216, p. 1-20.

Retallack, G.J., 1990, Soils of the past: An introduction to paleopedology. Boston: Unwin Hyman.

Rosen, M.R., 1994, The importance of groundwater in playas: A review of playa classificiations and the sedimentology and hydrology of playas. *In:* Rosen, M.R. eds, Paleoclimate and basin evolution of playa systems: Geological Society of America Special Publication, v. 289, p. 1-18.

Sawin, R.S., Franseen, E.K., West, R.R., Ludvigson, G.A., and Watney, W.L., 2008, Clarification and changes in Permian stratigraphic nomenclature in Kansas: Current research in earth sciences: Kansas Geological Survey Bulletin, v. 254, p. 1-4.

Schreiber, B.C., and Walker, D., 1992, Halite pseudomorphs after gypsum: A suggested mechanism: Journal of Sedimentary Petrology, v. 62, no. 1, p. 61-70, doi: 0022-4472/92/0062-61/$03.00.

Smith, John J., 2015, Chronostratigraphic assessment of enigmatic redbeds at Point of Rocks, Cimarron National Grassland, Kansas: U-PB age constraints from detrital zircons: Geological Society of America Annual Meeting Abstracts with Programs, v. 47, no. 7, p.803.

Smith, J.J., Platt, B.F., Ludvigson, G.A., Sawin, R.S., Marshall, C.P., and Olcott-Marshall, A., 2015, Enigmatic red beds exposed at Point of Rocks, Cimarron National Grassland, Morton County, Kansas: Chronostratigraphic constraints from uranium-lead dating of detrital zircons, Kansas Geological Survey Bulletin, v. 261, p. 1-16.

Smoot, J.P., 1983, Depositional subenvironments in an arid closed basin: the Wilkins Peak Member of the Green River Formation (Eocene), Wyoming, U.S.A.: Sedimentology, v. 30, no. 6, p. 801-827, doi: 10.1111/j.1365-3091.1983.4b00712x.

Smoot, J.P., 2015, Advances in the sedimentology of desert basin mudflats: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 504.

Smoot, J.P. and Olsen, P.E., 1994, Climatic cycles as sedimentary controls of rift basin lacustrine deposits in the early Mesozoic Newark basin based on continuous core. *In:* Lomando, T., and Harris, M. eds., Lacustrine Depositional Systems: SEPM Core Workshop Notes, v. 19, p. 201-237.

Soreghan, M., Soreghan G.S., and Hamilton, M., 2002, Paleowinds inferred from detrital-zircon geochronology of upper Paleozoic loessite, western equatorial Pangea: Geology, v. 30, no. 8, p. 695-698, doi: 10.1130/0091-7613(2002)03020695:PIFDZ.

Soreghan, G.S., Benison, K.C., Foster, T.M., Zambito IV, J.J., and Soreghan, M.J., 2015, The paleoclimatic and geochronologic utility of coring redbeds and evaporites: A case study from the RKB core (Permian, Kansas, USA): International Journal of Earth Sciences, v. 104, no. 6, p. 1589-1603, doi: 10.1007/500531-014-1070-1.

Sweet, A.C., Soreghan, G.S., Sweet, D.E., Soreghan, M.J., and Madden, A.S., 2013, Permian dust in Oklahoma: Source and origin for middle Permian (Flowerpot-Blaine) redbeds in western tropical Pangea: Sedimentary Geology, v. 284, p. 181-196, doi: 10.1016/j.sedgeo.2012.12.006.

Swineford, A., 1955, Petrography of upper Permian rocks of south-central Kansas: State Geological Survey of Kansas Bulletin 111, 179 p.

Tabor, N.J., and Montanez, I.P., 2002, Shifts in late Paleozoic atmospheric circulation over western equatorial Pangea: Insights from pedogenic mineral $\delta^{18}O$ compositions: Geology, v. 30, no. 12, p. 1127-1130.

Tabor, N.J., 2011, Ochoan Quartermaster Formation of north Texas, USA, part 1: Litho- and Chemostratigraphy: Geological Society of America Abstracts with Programs, v 43, no. 5, p. 383.

Tekin, E., Varol, B., and Ayyildiz, T., 2008, A rare natural gypsum ooid (gypsolites) in an evaporitic playa lake of late Miocene (?) to Pliocene age in central Anatolia, Turkey: Carbonates and Evaporites, v. 23, p.50-59.

Terwindt, J. H. J., de Jong, J.D., and van der Wilk, E., 1963, Sediment movement and sediment properties in the tidal area of the Lower Rhine (Rotterdam Waterway): Geology, v. 21, no. 1, p. 244-258.

Terwindt, J. H. J., 1971, Litho-facies of inshore estuarine and tidal-inlet deposits: Geology Mijnbouw, v. 50, p. 515-526.

Walker, T.R., 1967, Formation of red beds in modern and ancient deserts: Geological Society of America Bulletin, v. 78, no. 3, p. 353-368, doi: 10.1130/0016-7606(1967)78(353:For BIM).

Weimer, R.J., Howard, J.D., and Lindsay, D.R., 1982, Tidal flats and associated tidal Environments. *In:* Scholle, P.A., and Spearing, D., eds., Sandstone depositional environments: American Association of Petroleum Geologists, Memoir 31, p. 191-245.

West, R.R., Archer, A.W., and Miller, K.B., 1997, The role of climate in stratigraphic patterns exhibited by late Palaeozoic rocks exposed in Kansas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 128, no. 1, p. 1-16, doi: 10.1016/50031-0182(97) 81127-3.

West, R.R., Miller, K.B., and Watney, W.L., 2010, The Permian system in Kansas: Kansas Geological Survey Bulletin 257, 82 p.

Wood, P.R., and Stacy, B.L., 1965, Geology and ground-water resources of Woodward County, Oklahoma: United States Geological Survey Professional Paper, v. 21, 128 p.

Wright, L.D., 1985, River Deltas. *In:* Davis, Jr., R.A. eds., Coastal sedimentary environments: Springer-Verlag, New York.

Zambito IV, J.J., and Benison, K.C., 2013, Extremely high temperatures and paleoclimate trends recorded in Permian ephemeral lake halite: Geology, v. 41, no. 5, p. 587-590, doi: 10.1130/G34078.1.

Zambito IV, J.J., Benison, K.C., Foster, T.M., Soreghan, G.S., Soreghan, M.J., and Kane, M., 2012, Lithostratigraphy of Permian red beds and evaporites in the Rebecca K. Bounds core, Greeley County, Kansas: Kansas Geological Survey Open-File Report 2012-15. p. 1-45.

Zeller, D.E., ed. 1968, The stratigraphic succession in Kansas: Kansas Geol. Survey Bulletin, v. 189, 81. p.

APPENDICES

Petrographic Data of the Dog Creek Formation and Quartermaster Group

<u>Dog Creek Formation</u>

Hand Sample: 1915'

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of very fine sand and silt sized grains of quartz, halite, and gypsum
- Salty: yes
- Reaction to HCl: no
- Sample looks to have gypsum cements throughout
- Sedimentary structures: mudcracks
- Diagenetic features: specular reduction spots

<u>Dog Creek Formation</u>

Hand Sample: 1913'

Hand Sample Notes

- Possible paleosol feature (ped structures and slickensides)

<u>Dog Creek Formation</u>

Thin Section: 1897'

Hand Sample: 1897'

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of fine sand and silt sized grains
- Sample looks to be composed of quartz, halite, and gypsum
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~10%, silt: ~65%, clay: ~20%
- Sorting: well-sorted
- Roundness: subrounded-well rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, and dark opaque grains
- Porosity: ~5% or less
- Cement: gypsum and/or halite
- Sedimentary structures/features: rip-up clasts, mud drapes, graded bedding, ripple cross-stratification, mud clasts, mudcracks, and possible water escape features

- Diagenetic features: localized specular reduction spots and displacive gypsum crystals

Other Notes

- finer grained material observed in darker colored areas of the sample
- boundaries between light and dark grains are observed as both sharp and smooth
- finely laminated throughout
- dark opaque grains widely distributed throughout the sample

Dog Creek Formation

Hand Sample: 1895'4"-1895'11"

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no
- Sedimentary structures/features: planar laminae and wavy discontinuous laminae

Dog Creek Formation

Thin Section: 1892'

Hand Sample: 1892-1893'

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of fine sand and silt sized grains
- Sample looks to be composed of quartz, halite, and gypsum
- Salty: yes
- Reaction to HCL: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller though most at ~0.1 mm)
- Grain Size Range: fine sand: ~10%, very fine sand: ~35%, silt: ~45%, clay: ~10%
- Sorting: well-sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, dark opaque grains, and traces of lithics with feldspar (?)
- Porosity: ~3% or less
- Cement: halite and/or gypsum
- Sedimentary structures/features: mudcracks and ripple cross-stratification
- Diagenetic features: displacive gypsum crystals

Other Notes

- Observed cubic minerals with yellowish hue in plane lighting throughout the sample. Could these be halite crystals?
- Dark opaque grains are widely distributed throughout the thin section though some areas of the sample seem to show higher concentrations of them. These grains glimmer in reflected light and are likely specular hematite or pyrite.
- Bedding is not apparent in sample though grains look to be reworked
- Gypsum can be found as detrital grains, cements, and displacive crystals in the sample
- Darker areas of sample seem to also have smaller grain size
- Some areas of the sample look to be better cemented than other areas of the sample

<u>Dog Creek Formation</u>

Thin Section: 1880'

Hand Sample: 1879'6"-1880'5"

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand to very fine sand and smaller (~0.16 mm though most at ~0.1 mm)
- Grain Size Distribution: fine sand: ~10%, very fine sand: ~30%, silt: ~30%, clay: ~30%
- Sorting: well-sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, mica, dark opaque grains, and polycrystalline quartz
- Porosity: ~3% or less
- Cement: halite and/or gypsum
- Sedimentary structures/features: wavy discontinuous laminae, rip-up clasts, mudcracks, and flame structures
- Diagenetic features: specular and globular reduction spots and displacive gypsum crystals

Other Notes

- Very fine discontinuous lamina observed throughout the thin section
- Alternating fine and coarse bands of sediment are found throughout the sample with coarser grains generally lighter in color than finer grains
- Dark opaque grains are widely distributed throughout the sample but some areas have a higher concentration and greater preferential orientation than other areas of the sample.
- Some minerals are cubic in shape and isotropic in plane light interpreted to be halite

- Gypsum can be found as elongate crystals (displacive gypsum) in areas throughout the sample. No preferential orientation.
- High porosity areas in sample can be found around coarser grain sizes. Possible dissolution of preexisting cement in these areas.
- Detrital gypsum can be found within coarser grained area of the sample. Possible rip-up clasts from preexisting gypsum bedding?
- Drusy cements observed in bottom right corner of thin section (halite?)

Dog Creek Formation

Thin Section: 1879’8”

Hand Sample: 1879’6”-1880’5”

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller though most at ~0.1 mm)
- Grain Size Distribution: fine sand: ~10%, very fine sand: ~30%, silt: ~40%, clay: ~20%
- Sorting: moderately sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, and dark opaque grains
- Porosity: ~5% or less
- Cement: halite and/or gypsum
- Sedimentary structures/features: wavy discontinuous laminae, rip-up clasts, and ripple cross-stratification
- Diagenetic features: specular reduction spots, globular reduction spots, and displacive gypsum crystals

Other Notes

- Sample overall is reworked with wavy discontinuous laminae throughout.
- Dark opaque grains are widely distributed throughout the sample and glimmer in reflected light. These grains (?) could be specular hematite or pyrite though uncertain.
- Multiple reduction spots of various shapes and sizes can be found throughout the thin section. Coincidentally these reduction spots are found around areas of high porosity and are found to have gradational boundaries.
- Halite can be observed as a cement throughout the thin section though some areas look to be better cemented than other areas in the sample
- Gypsum can be found as detrital grains, displacive crystals, and cement in the sample.

<u>Dog Creek Formation</u>

Thin Section: 1875'2"

Hand Sample: 1875'2"-1876'

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 4/6) composed of fine sand and silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and very fine sand (~0.16 mm and smaller though most at ~0.1 mm)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~45%, silt: ~40%, clay: ~10%
- Sorting: well-sorted
- Roundness: mostly subrounded-well rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, and dark opaque grains
- Porosity: ~8% or less
- Cement: halite and/or gypsum
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: globular reduction spots and displacive gypsum crystals

Other Notes

- Large reduction spot found in center of thin section. This reduction spot takes up the whole field of view at .63x magnification for the microscope (~3.7 cm).
- Relatively high porosity in sample though most shown within the reduction spot
- Dark opaque grains are widely distributed throughout the sample with some areas of sample showing greater concentrations of them.
- Dark fractures (?) found throughout rock. Could these be root casts?
- Some areas of the sample look better cemented than other areas observed in the sample.

<u>Dog Creek Formation</u>

Hand Sample: 1866'

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: specular reduction spots

<u>Dog Creek Formation</u>

Hand Sample: 1860'3"-1860'7"

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 4/6) composed of silt and clay
- Quartz and gypsum composition
- Salty: no
- Reaction to HCl: no
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: specular reduction spots throughout sample

<u>Dog Creek Formation</u>

Thin Section: 1854'

Hand Sample: 1853'-1854'

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~30%, silt: ~40%, clay: ~25%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, and dark opaque grains
- Porosity: ~7% or less
- Cement: halite and/or gypsum
- Sedimentary structures/features: wavy discontinuous laminae, rip-up clasts, mudcracks, and ripple cross-stratification
- Diagenetic features: localized specular reduction spots surrounding coarser grains and displacive gypsum crystals

Other Notes

- Sample overall looks chaotic with grain size ranging from fine sand/silt to clay.
- Sample overall composed of iron oxidized quartz but there seems to be some gypsum cement and halite cement throughout. Additionally, gypsum can be found as displacive crystals as well as detrital grains.
- Dark opaque grains found throughout sample and do not seem to show any preferred orientation. They glimmer in reflected light so likely specular hematite or pyrite. Shapes are relatively rounded in this sample.
- Reduction spots have smooth, gradational boundaries.

<u>Dog Creek Formation</u>

Thin Section: 1853'

Hand Sample: 1853'-1854'

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 4/6) composed of very fine sand and silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~25%, silt: ~50%, clay: ~20%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, halite, feldspar, mica, and dark opaque grains
- Porosity: ~5% or less
- Cement: halite and/or gypsum
- Sedimentary structures/features: wavy discontinuous laminae, mud clasts, rip-up clasts, flame structures, mud drapes, and mudcracks. There is also a possibility of cross-stratification though it's not well preserved.
- Diagenetic features: specular reduction spots displacive gypsum crystals

Other Notes

- Porosity is concentrated around the coarsest sediments of the thin section. Some areas of porosity look to be cubic in shape as if halite was originally in sample but removed via dissolution or plucking during thin section making.
- Some areas of the sample look to be better cemented than other areas of the sample. Cements observed in the sample include halite as well as drusy gypsum.
- Feldspar, though minimal, is found in the sample.
- Gypsum can be found as drusy cement and displacive crystals in the sample. Displacive crystals often show random orientation but there are some areas in the thin section that look imbricated.
- Dark opaque grains are widely distributed throughout the sample and seem to glimmer in reflected light. They are interpreted to be specular hematite or pyrite.

<u>Dog Creek Formation</u>

Hand Sample: 1848-1848'6"

Hand Sample Notes

- Reddish rock (2.5YR 4/6, 2.5YR 3/6) composed of very fine sand and silt grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes

- Reaction to HCl: no
- Sedimentary Structures/features: wavy discontinuous laminae and mudcracks
- Diagenetic features: specular and globular reduction spots

<u>Whitehorse Sandstone</u>

Hand Sample: 1840'

Hand Sample Notes

- Reddish rock(2.5YR 4/6) composed of silt and clay sized grains with possible fine sands as well
- Looks to be composed of clay, quartz, gypsum, lithics, and iron oxides
- Salty: no
- Reaction to HCl: no
- Cement: gypsum (?)
- Sample is very smooth with signs of possible soil slickensides

<u>Whitehorse Sandstone</u>

Thin Section: 1839'6"

Hand Sample: 1839'6"-1839'8"

Hand Sample Notes

- Reddish brown rock (2.5YR 6/6) composed of silt and clay sized grains of quartz and gypsum
- Salty: No
- Reaction to HCl: No
- Gypsum seems to be acting as cement fill in some areas as sample contains unusual shapes of the mineral

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm-smaller)
- Grain Size Distribution: very fine sand: ~5%, silt: ~75%, clay: ~20%
- Sorting: poorly-sorted-moderately sorted
- Roundness: subangular-subrounded
- Sphericity: moderate-high sphericity
- Composition: minute quartz, mica, lots of clay (?), possible gypsum (may be dolomite as cement takes on blocky shape), lithics (observed as mud clasts) and dark opaque grains.
- Porosity: ~2% or less though more if considering the epoxy openings
- Cement: gypsum
- Sedimentary structures/features: soft sediment deformation, mud clasts (angular and well rounded), cross-stratification (?), and mudcracks,
- Diagenetic features: specular reduction spots, globular reduction spots and displacive gypsum crystals

Other Notes

- What was initially interpreted to be gypsum cement may actually be dolomite. These areas seem to have a very blocky look as well as it doesn't show pink and green in birefringence that's typical in gypsum. This may be due in part to sample thickness, however.
- There seem to be traces of displacive gypsum in the finer areas of the sample, however. This displacive mineral may be observed in other areas of the sample just not as poignant.
- Dark opaque grains show no preferential orientation in the sample.

<u>Whitehorse Sandstone</u>

Hand Sample: 1833'

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt sized grains
- Quartz and gypsum composition
- Salty: no
- Reaction to HCl: no
- Laminae are chaotic

<u>Whitehorse Sandstone</u>

Thin Section: 1830'

Hand Sample: 1829'6"-1830'2"

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt sized grains of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~25%, silt: ~65%, clay: ~10%
- Sorting: moderately-well-sorted (depends on where you are in the sample)
- Roundness: subangular-subrounded
- Sphericity: moderate-moderately high sphericity
- Composition: quartz, gypsum, and dark opaque grains
- Porosity: ~5% or less
- Cement: undistinguished though suspected to be gypsum
- Sedimentary structures/features: planar laminae, wavy discontinuous laminae, mud clasts, and possible ripple cross-stratification
- Diagenetic features: reduction spots and displacive gypsum crystals

Other Notes

- Reduction zone observed midway through the sample (could this be a remnant of organic decay?).
- Gypsum often bladed/tabular
- Silt-sized grains are moderate-highly spherical, subangular-subrounded light-colored quartz and gypsum.
- Red mud is either too fine-grained to distinguish individual grains or in rounded fine sand-sized clasts.
- Silt and mud in patches; no beds remaining, patches appear to be ripped-up and reworked clasts
- Gypsum found in a couple of forms: displacive needles, reworked grains, and cement filling large-irregular shapes
- Rare calcite as a possible late-stage blocky cement?

Whitehorse Sandstone

Thin Section: 1829'6"

Hand Sample: 1829'6"-1830'2"

Hand Sample Notes

- Reddish rock (2.5YR 5/4) composed of very fine sand, silt, and clay
- Looks to be composed of quartz, gypsum, and clay
- Salty: no
- Reaction to HCl: no
- Dark opaque grains (?) are concentrated at the center of a reduction spot. Could these potentially be remnant organics or pyrite?

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.2 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~5%, silt: ~50%, clay: ~40%
- Sorting: moderate-well-sorted
- Roundness: angular-subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum (?), dolomite? (potentially though unlikely), clay (?), and dark opaque grains
- Porosity: ~1% or less
- Cement: gypsum
- Sedimentary structures/features: mud clasts, wavy continuous laminae, wavy discontinuous laminae, and planar laminae
- Diagenetic features: displacive gypsum crystals

Other Notes

- Bottom half of thin section seems to be lighter in color than upper portion of thin section.
- Lots of epoxy fill in the sample (more porosity than originally suggested).

- Dark opaque grains glimmer under reflected light suggesting these grains to be pyrite or specular hematite.
- Many grains (?) take on obscure shapes so may actually be cements. Possible cements include gypsum, clay, or dolomite…may or may not be gypsum because in XPL minerals don't show diagnostic pink/green birefringence. Also, these areas take on a more blocky appearance than what is typically seen in gypsum….this leads me to suggest that these "cements" could be dolomite or calcite.

<u>Whitehorse Sandstone</u>

Hand Sample: 1825'

Hand Sample Notes

- Possible paleosol feature (ped structures and slickensides)

<u>Whitehorse Sandstone</u>

Thin Section: 1824'

Hand Sample: 1823'9"-1824'2"

Hand Sample Notes

- Reddish brown rock (2.5YR 4/4) composed of very fine sands and silt
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.2 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~70%, silt: ~20%, clay: ~5%
- Sorting: well-sorted
- Roundness: subangular-subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz, clay (?),gypsum, and dark opaque grains
- Porosity: ~5% or less (though grains look plucked)
- Cement: undistinguished
- Sedimentary structures/features: mud clasts, mudcracks, ripple cross-stratification, and soft sediment deformation
- Diagenetic features: specular reduction spots and displacive gypsum crystals

Other Notes

- Dark opaque grains do not show a preference in where they are located in the sample. Overall, though, some areas show higher concentrations than others.

<u>Whitehorse Sandstone</u>

Hand Sample: 1822’5”-1823’4”

Hand Sample Notes

- Reddish rock (2.5YR 4/4) composed of fine sand and silt sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

<u>Whitehorse Sandstone</u>

Hand Sample: 1815’

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains
- Composed mostly of quartz though possible halite and gypsum
- Salty: yes
- Reaction to HCl: no
- Bedding not apparent in sample
- Diagenetic features: specular reduction spots

<u>Whitehorse Sandstone</u>

Hand Sample: 1807’7”-1808’5”

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no
- Sedimentary structures/features: wavy to planar laminae
- Diagenetic features: specular reduction spots

<u>Whitehorse Sandstone</u>

Hand Sample: 1803’

Hand Sample Notes

- Reddish rock (2.5YR 4/6, 2.5YR 4/8) composed of very fine sand and coarse silt grains
- Sample seems to be a mixture of quartz, gypsum, clay, (?) and halite
- Salty: yes
- Reaction to HCl: no
- Bedding not apparent in a variety of places
- Dark, vein-like zones are found throughout the sample…could these be organic rich mudcracks or are they examples of root casts?

- Most striking feature for this sample is the presence of knob-like features covering the surface of this rock. These features tend to be ~.2 mm in diameter and are lumpy. Could these be the sand blebs Norton refers to in his 1939 publication? Other guess are root features, ant/termite nest remnants, magnetized areas of the sample, or halite cement growths

Whitehorse Sandstone

Thin Section: 1802'

Hand Sample: 1802'

Hand Sample Notes

- Reddish rock (2.5YR 5/8) with medium sand sized grains that's overall very brittle
- Mostly composed of quartz though possible traces of gypsum and halite
- Salty: yes
- Reaction to HCl: no
- Rock with undistinguishable beds or observable reduction spots

Thin Section Notes

- Grain Size Range: medium sand and smaller (~0.3 mm and smaller)
- Grain Size Distribution: very fine sand: ~20%, silt: ~70%, clay: ~10%
- Sorting: moderate to well-sorted
- Roundness: angular-subrounded
- Sphericity: low-moderate sphericity (high in some places)
- Composition: quartz with iron rich clay (?), dark opaque grains, halite, and possible gypsum or mica
- Porosity: ~7% or less (some grains look to have been plucked out during thin section making)
- Cement: halite
- Sedimentary structures/features: wavy discontinuous laminae, mud clasts, cross-stratification, and mud drapes
- Diagenetic features: none observed

Other Notes

- Some areas preferentially have more fine-grains/clay than others….seem to form unusual shapes in the thin section.
- Some lighter colored areas of the sample do not seem to be reduced at all so likely lithic quartz (sandstone) from elsewhere.
- Clay found in sample are very wavy and discontinuous.
- Dark opaque grains found in sample scattered throughout though some areas the grains are more highly concentrated. They glimmer in reflected light suggesting they're either pyrite or specular hematite.

<u>Whitehorse Sandstone</u>

Hand Sample: 1796'

Hand Sample Notes

- Reddish rock (2.5YR 5/6)composed of fine sand and silt sized grains
- Quartz, gypsum, and halite composition
- Salty: yes
- Reaction to HCl: no
- Rock with undistinguishable beds or observable reduction spots

<u>Whitehorse Sandstone</u>

Hand Sample: 1794'

Hand Sample Notes

- Possible paleosol feature (ped structures and slickensides)

<u>Whitehorse Sandstone</u>

Thin Section: 1788'

Hand Sample: 1788'

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains of quartz and gypsum
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~.2 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~5%, silt: ~70%, clay: ~20%
- Sorting: poor-moderately sorted
- Roundness: angular-subrounded
- Sphericity: low to high sphericity
- Composition: quartz, clay (?), dark opaque grains, gypsum found preferentially in finer grains, and feldspar
- Porosity: ~10% or more. I suspect a lot of this porosity comes from the dissolution of halite cements in preparation of this sample. The reason I suggest this is because open pore spaces, intergranular as is, take on strange shapes that are unusual for grains to take on. Additionally, this seems to be far too much porosity to be natural for this sample when compared to surrounding lithology.
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae, mud clasts, ripple cross-stratification, and mudcracks
- Diagenetic features: displacive gypsum crystals

Other Notes

- This thin section seems to contain the most immature sediments observed to this point. The grains are overall not well rounded and sphericity is minimal at best. This suggests provenance was close by and likely sourced from nearby areas.
- Dark opaque grains found to glimmer under reflected light suggesting this is likely pyrite or specular hematite. Undistinguished where it is all coming from, however.
- Possible liesegang banding throughout so very weary of calling some features crossbeds.
- Seems to have very fine bands of clay and sand sized grains.
- Overall shapes of features suggest periods of turbulent moisture (very strong storms).

<u>Whitehorse Sandstone</u>

Hand Sample: 1780'

Hand Sample Notes

- Possible paleosol feature (ped structures)

<u>Whitehorse Sandstone</u>

Hand Sample: 1778'

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of silt and clay sized grains though mostly silt
- Composition: quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no
- Wavy laminae throughout the sample with no observable reduction spots.

<u>Whitehorse Sandstone</u>

Hand Sample: 1774'10"-1775'7"

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Whitehorse Sandstone

Thin Section: 1766’4”

Hand Sample: 1766’2”-1767’

Hand Sample Notes

- Reddish rock (2.5YR 4/8, 2.5YR 5/8) composed of sand and silt sized quartz and gypsum grains
- Salty: no
- Reaction to HCl: no
- Sample initially looks to have no apparent bedding.
- Sample doesn’t seem to contain any reduction spots though there are darker patches found on the surface of the sample….could these be organics?

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.15 mm and smaller)
- Grain Size Distribution: fine sand: ~<1%, very fine sand: ~20%, silt: ~75%, clay: ~5%
- Sorting: moderately-well-sorted
- Roundness: subangular-well rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, clay (?), mica, and feldspar
- Porosity: ~5% or less
- Cement: undistinguished
- Sedimentary structures/features: mud clasts, cross-stratification, and wavy discontinuous laminae
- Diagenetic features: displacive gypsum crystals

Other Notes

- Grains seem to be both mature and immature as grains are both angular and well rounded.
- Some areas of the sample seem to be better cemented than other areas. Could this mean multiple cements or processes or does this mean that these better cemented areas were blown in from elsewhere?
- Gypsum/mica seems to be preferentially found in finer grained areas of the sample.
- Feldspars can be found as individual grains in this sample whereas in many other samples it is found in what look to be igneous lithics.
- Dark opaque grains are scattered throughout the sample though there are areas where dark opaque grains have a preferential orientation to their deposition.These grains sparkle so likely pyrite or specular hematite.

Whitehorse Sandstone

Hand Sample: 1760’

Hand Sample Notes

- Possible paleosol feature (ped structures and slickensides)

<u>Whitehorse Sandstone</u>

Thin Section: 1759'

Hand Sample: 1758'5"-1759'

Hand Sample Notes

- Red to grayish rock (2.5YR 5/6) composed of fine sand and silt sized grains.
- Composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller…bimodal grain size?)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~50%, silt: ~25%, clay: ~20%
- Sorting: well-sorted
- Roundness: subrounded-well rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, halite, dark opaque grains, and traces of mica
- Porosity: ~5% or less
- Cement: halite though undistinguished
- Sedimentary structures/features: mud clasts, mud clasts, rip-up clasts, ripple cross-stratification, and mudcracks
- Diagenetic features: speckled reduction spots and displacive gypsum crystals

Other Notes

- Darker colored areas seem to contain finer sediment while lighter colored areas contain coarser sediments.
- Decent amount of elongate minerals in the sample (displacive gypsum?).
- Dark opaque grains are minimal though scattered throughout sample. Seem to be smaller than surrounding grains (density variation?). These grains glimmer in reflected light and are interpreted to be specular hematite or pyrite.
- Sample seems to show sharp distinct boundaries in areas of sample.

<u>Whitehorse Sandstone</u>

Thin Section: 1758'6"

Hand Sample: 1758'5"-1759'

Hand Sample Notes

- Reddish rock (2.5YR 4/8, 2.5YR 5/6) composed of fine silt and clay sized grains.
- Rock looks to be composed of quartz, gypsum, clay (?), and halite.
- Possible root features
- This rock seems to also have speckled brown dots all over it (comparable to 1802')
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~25%, silt: ~50%, clay: ~25%
- Sorting: poorly-sorted to well-sorted
- Roundness: subrounded
- Sphericity: overall high sphericity
- Composition: quartz, clay (?), gypsum, feldspars, mica (minute amounts) and dark opaque grains.
- Porosity: ~5% or less
- Cement: halite and/or hematite
- Sedimentary structures/features: wavy discontinuous laminae, ripple cross-stratification, mudcracks, ball and pillow structures, soft sediment deformation, and rip-up clasts.
- Diagenetic features: specular reduction spots, globular reduction spots, and displacive gypsum crystals

Other Notes

- Sample contains a lot of immature grains that are elongate bladed/tabular while others are well rounded. I'm finding this to be common of the lower Whitehorse as the sample becomes more mature (or at least seems) moving up section.
- Fine, needle like gypsum is found throughout the sample but seems to be preferentially located in finer grained areas.
- Dark opaque grains do not seem to show any preferential deposition in sample as they are scattered throughout. Grains (?) are overall well rounded though some are angular and are, at times, found to take on the shape of the cement. These grains (?) shine/glimmer under reflected light suggesting the dark opaque grains are either specular hematite or pyrite.
- Feldspars have been found in the sample though they are minimal at best (grain here or there).
- Possible graded bedding throughout sample. This could mean a flood/sheet flood deposit. I have taken photomicrographs of each.

<u>Whitehorse Sandstone</u>

Hand Sample: 1754'8"

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt grains
- Quartz, gypsum, and halite composition
- Salty: yes
- Reaction to HCl: no
- Sedimentary structures/features: Wavy discontinuous laminae and possible cross-stratification

<u>Whitehorse Sandstone</u>

Thin Section: 1745’7”

Hand Sample: 1745’6”

Hand Sample Notes

- Reddish rock (2.5YR 4/6, 2.5YR 5/6) composed of fine sand and silt sized grains
- Sample looks to be composed of quartz and minute amounts of gypsum
- Salty: yes
- Reaction to HCl: no
- Sample doesn’t seem to contain reduction spots and a large majority of hand sample looks massive. I can vaguely point out individual laminae but not to a great extent.
- Sample laminations range from horizontal to crossbedded with grains that look slightly buffed as well. Could this represent an eolian environment?

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.2 mm and smaller)
- Grain Size Distribution: fine sand: ~10%, very fine sand: ~40%, silt: ~40%, clay: ~10%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: moderate sphericity
- Composition: quartz, hematite, gypsum, dark opaque grains, feldspar (more than seen in other samples), and mica
- Porosity: ~7% or less
- Cement: halite
- Sedimentary structures/features: rip-up clasts and ripple cross-stratification
- Diagenetic features: displacive gypsum crystals

Other Notes

- Looks to be two generations of isotropic cement (halite?).
- Dark opaque grains seem to sparkle under reflected light and are interpreted to be either pyrite or specular hematite.
- Dark opaque grains come in a variety of shapes including well rounded to angular…some have high sphericity while others have low sphericity. Have these formed as concretions in place or blown in as detrital grains?
- Many of the quartz grains found in this sample are elongate, lacking sphericity, and overall tabular in shape. Could this mean some other mineral rather than quartz?
- Many areas in sample show intergranular porosity (between grains). Some porosity seems natural while other areas seem to be secondary porosity (dissolution of halite cement?). This amount of porosity is not common in other formations observed.
- Most grains in sample are silt sized though some grains would constitute as fine sand grains.
- Areas that are redder in color preferentially have more needle like crystals than areas that are lighter in color. Could these gypsum crystals be associated with the formation of clay in place?

- Redder areas in some areas seem to have formed in place while other areas have more definite boundaries. Areas of more definitive boundaries are interpreted to be rip-up clasts from elsewhere. Some are well rounded while other areas have more tabular/bladed shapes.

<u>Whitehorse Sandstone</u>

Thin Section: 1745'2"

Hand Sample: 1745'6"

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 5/8) composed of fine sand and silt sized grains of what look like quartz and gypsum.
- Salty: yes (minimal)
- Reaction to HCl: no
- One portion of the sample seems to contain coarser-grained sediment (bottom left of the sample)
- Few grains look slightly buffed in appearance

Thin Section Notes

- Grain Size Range: medium sand and smaller (~0.3 mm and smaller)
- Grain Size Distribution: medium sand: ~5%, fine sand: ~5%, very fine sand: ~30%, silt: ~50%, clay: ~10%
- Sorting: poorly-sorted to very well-sorted depending on the area of the thin section
- Roundness: subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, mica, possible feldspar, dark opaque grains, and clay
- Porosity: ~7% or less (may or may not be natural as many grains looked to be plucked from thin section)
- Cement: halite
- Sedimentary structures/features: mud clasts, rip-up clasts, mud drapes (angular and well rounded), ripple cross-stratification, and mudcracks
- Diagenetic features: none observed

Other Notes

- Sample contains both large and small grains. I would say this contains some of the largest grain sizes of all samples studied.
- Porosity seems typical of what I have found of other Whitehorse sandstone sample. I think a good portion of this porosity is primary as these sand/shale seem poorly cemented. On the other hand, I think some porosity is a result of thin section making. Some of the cement observed included halite and hematite. Halite may have been lost to dissolution during the thin section making process. Also, some grains (larger ones) seem to have been plucked out during thin section making processes contributing to the observed increase in porosity.

- As I’ve moved up in thin section I’ve found the amount of low sphericty grains to have decreased. Could this be because of maturation of sediment or a loss of grains that appear tabular/bladed as one moves up section (loss of feldspars?).
- In general, dark opaque grains can be found relatively smaller than grains that surround them (quartz?) and approximately ½ the size. Grains can be angular to well rounded and at times takes shape of cement. These grains/cements seem to overall be scattered throughout the sample though at times show a preferential deposition. These grains glimmer in reflected light suggesting they are either specular hematite or pyrite.
- Some areas of the sample look better cemented than other areas. Could this mean two separate series of cements in the sample?
- Some darker areas of the sample seem to have definitive boundaries while others do not
- I am tentative of calling the sedimentary structure cross-stratification as it may just be liesegang banding.

Whitehorse Sandstone

Hand Sample: 1742’-1742’6”

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt grains
- Quartz, gypsum, and halite composition
- Salty: yes
- Reaction to HCl: no
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: specular reduction spots

Whitehorse Sandstone

Hand Sample: 1739’8”-1740’8”

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains
- Looks to be composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no

Whitehorse Sandstone

Thin Section: 1737’

Hand Sample: 1737’

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of silt and clay sized grains of quartz, clay (?), and gypsum
- Salty: no
- Reaction to HCl: no

- Possible root structure observed with hand lens
- Lighter zones of the sample seem to have gradational boundaries (nothing definitive)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~20%, silt: ~60%, clay: ~20%
- Sorting: moderate-well-sorted
- Roundness: subrounded-rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, feldspar, mica, gypsum, clay (?), and dark opaque grains
- Porosity: ~7% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae, rip-up clasts, mudcracks, mud drapes, flame structures, and ripple cross-stratification
- Diagenetic features: specular reduction spots and displacive gypsum crystals

Other Notes

- Mica or detrital gypsum at the bottom of thin section as these areas show high birefringence with unusual shapes.
- May or may not be ripple cross-stratification as this may just be liesegag banding.
- The darker areas of the sample have definitive layer as well as gradational layers so there may be some rip-up clasts in this sample as well.
- Dark opaque grains are scattered throughout and do not show any preferential orientation in sample. They shine in reflected light and are interpreted to be specular hematite or pyrite.

<u>Whitehorse Sandstone</u>

Hand Sample: 1730'6"

Hand Sample Notes

- Reddish rock (2.5YR 3/6, 2.5YR 4/6) composed of fine sand and silt sized grains
- Composed of quartz, gypsum, and halite
- Salty: yes
- Reaction to HCl: no
- Sedimentary structures/features: wavy discontinuous laminae, ripple cross-stratification, tee-pee structures, and water escape features

<u>Whitehorse Sandstone</u>

Hand Sample: 1723'-1724'

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 4/6) composed of fine sand to silt sized grains
- Composed of quartz, halite, and gypsum
- Salty: yes

- Reaction to HCl: no
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: reduction spots

<u>Whitehorse Sandstone</u>

Hand Sample: 1718'

Hand Sample Notes

- Possible paleosol feature (ped structures and slickensides)

<u>Whitehorse Sandstone</u>

Thin Section: 1715'6"

Hand Sample: 1715'

Hand Sample Notes

- Reddish rock (2.5YR 4/6, 2.5YR 5/6) composed of silt and clay grain sizes
- Composed of quartz, gypsum, hematite, and clay (?) upon first glance
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~10%, silt: ~60%, clay: ~30%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, hematite, dolomite (?), mica, dark opaque grains
- Porosity: ~4% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae, ripple cross-stratification, mud drapes, soft sediment deformation, mud clasts, rip-up clasts, and mudcracks
- Diagenetic features: reduction spots (minimal) and displacive gypsum crystals

Other Notes

- Dark iron rich zones of the sample have mostly definitive boundaries though some boundaries are gradational.
- Dark opaque grains deposited throughout sample and are slightly smaller than non-dark grains. They seem to glimmer in reflected light and are interpreted to be specular hematite and pyrite. Dark opaque grains take on multiple shapes (rounded, angular, elongate, etc.) while at times look to be acting as cements (filling in void spaces).

<u>Whitehorse Sandstone</u>

Thin Section: 1709'

Hand Sample: 1709'

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of very fine sand and silt sized grains of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~5%, silt: ~50%, clay: ~40%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, lots of gypsum, clay (?), mica (?), and dark opaque grains
- Porosity: ~3% or less. Some areas look to be filled with epoxy so that may have been porosity beforehand though this dimension has been excluded from the presented porosity value.
- Cement: gypsum (?)
- Sedimentary structures/features: ripple cross-stratification, mudcracks, and mud clasts
- Diagenetic features: reduction spots (takes on unusual shapes) and displacive gypsum crystals

Other Notes

- First sample with organic residue found at the center of a reduction spot. Reduction spots found in this sample are round in shape…not speckled throughout. There is a lot of gypsum in these reduction spots. Could this be sulfate reduction as a result of gypsum formation?
- Darker areas of sample have gradational boundaries as well as rigid boundaries.

<u>Whitehorse Sandstone</u>

Hand Sample: 1694'

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of sand and silt sized grains
- Quartz and gypsum composition
- Salty: yes
- Reaction to HCl: no
- Cement: gypsum and/or halite
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: none observed

<u>Whitehorse Sandstone</u>

Hand Sample: 1686'5"-1686'11"

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of silt and clay sized grains though possible gravel sized lithics from elsewhere
- Looks to be composed of quartz and gypsum
- Satly: yes (minimal)
- Reaction to HCl: no
- Bedding indistinguishable though looks to be composed of gravel sized mud clasts (conglomerate?)
- Cement: gypsum (?)

<u>Whitehorse Sandstone</u>

Thin Section: 1685'8"

Hand Sample: 1685'5"-1685'11"

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 5/8) composed of silt and clay sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Areas of gypsum in sample seem to take on unusual shapes.

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.1 mm and smaller though may be some lithics)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~35%, silt: ~30%, clay: ~30%
- Sorting: poorly-sorted-moderately sorted
- Roundness: subangular-subrounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, lithics, clay (?), dolomite (?) (though potentially confused with gypsum) and dark opaque grains
- Porosity: ~5% or less though much porosity seem to be artifacts of thin section making
- Cement: gypsum
- Sedimentary structures/features: soft sediment deformation, mud clasts, rip-up clasts, cross-stratification (?), and mudcracks
- Diagenetic features: displacive gypsum crystals

Other Notes

- Most chaotic sample observed.
- Strangely, all rip-up clasts, etc. seem to be preferentially oriented as if the sample were but a piece of a much larger example of cross-stratification (angled down slope).

- Dark opaque grains glimmer in reflected light so likely specular hematite or pyrite. One thing to note is that these grains are minimal in the sample.
- Sharp boundaries exist between light and dark areas of thin section.
- Likely gypsum cement. Seems to be a secondary cement that came through and filled excess intergranular spaces of sample. Gypsum looks well developed here and can also be found as displacive gypsum in some regions of sample. This gypsum seems to follow a preferred orientation much like the lithics and mud clasts observed in the sample.
- Could this be an example of substantial flooding or environment change?

Whitehorse Sandstone

Thin Section: 1682’9”

Hand Sample: 1682’-1682’9”

Hand Sample Notes

- Light reddish rock (2.5YR 6/6, 2.5YR 6/8) composed of very fine sand and silt
- Concretionary layer
- Looks to be composed of quartz and gypsum though there may be additional trace minerals in sample
- Salty: no
- Reaction to HCl: no
- Some parts of sample look to be more cemented than other areas…possible concretionary processes observed?

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller)
- Grain Size Distribution: fine sand: <~1%, very fine sand: ~20%, silt: ~70%, clay: ~10%
- Sorting: moderate to well-sorted
- Roundness: subrounded-rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, clay (?), dark opaque grains, feldspar, and possible dolomitic areas seem to be replacing original minerals (gypsum) in sample
- Porosity: ~2% or less
- Cement: gypsum
- Sedimentary structures/features: mud clasts, rip-up clasts, and cross-stratification (?)
- Diagenetic features: specular reduction spots and displacive gypsum crystals

Other Notes

- Bedding not apparent in sample.
- Possible chalcedony cement in this sample (bottom right mud clast)
- Reduction spots seem to have a gradational boundaries.
- Some areas of the sample look to be more cemented than other areas of the sample. I have observed some areas of the sample to have an almost dolomitic look to them.
- Another observation I’ve made while looking at this sample is that there are some areas that are more oxidized that not only have rounded grains but also distinctly sharp

boundary ones too. Cubic shapes like halite or pyrite are also observed…could these just be open areas where the minerals once were?
- Dark opaque grains are both rounded and elongate in sample. Areas glimmer under reflected light suggesting this is either specular hematite or pyrite
- Gypsum in sample is observed in the sample as both displacive crystals and cement (takes on strange shapes as if filling up intergranular porosity) though looks to be being replaced by some other mineral though.

Whitehorse Sandstone

Thin Section: 1682'

Hand Sample: 1682'-1682'9"

Hand Sample Notes

- Light red rock (2.5YR 6/6, 2.5YR 7/6) composed of fine sand to silt sized grains
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.125 mm and smaller)
- Grain Size Distribution: fine sand: ~10%, very fine sand: ~30%, silt: ~40%, clay: ~20%
- Sorting: poorly-sorted-moderately sorted
- Roundness: subangular-subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, clay (?), halite (?), and dark opaque grains
- Porosity: ~3% or less (found in cracked areas of sample)
- Cement:
- Sedimentary structures/features: mudcracks, circumgranular cracks, water escape features, mud clasts, and rip-up clasts
- Diagenetic features: specular reduction spots

Other Notes

- More oxidized clay areas are found with both gradational and sharp, distinct boundaries.
- Dark opaque grains throughout sample are likely specular hematite or pyrite.

Whitehorse Sandstone

Hand Sample: 1677'

Hand Sample Notes

- Reddish rock (2.5YR 4/6, 2.5YR 5/6) composed of sand and silt sized grains
- Composed of quartz and gypsum
- Sample is very brittle and "delicate"
- Salty: no
- Reaction to HCl: no
- Sedimentary structures/features: planar bedding and mudcracks

Whitehorse Sandstone

Hand Sample: 1676'-1676'6"

Hand Sample Notes

- Reddish rock (2.5YR 4/6) composed of fine sand and silt sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Day Creek Dolomite

Thin Section: 1675'

Hand Sample: 1675'-1675'4"

Hand Sample Notes

- Reddish gray rock (2.5YR 6/1) composed of crystalline evaporite material
- When scratched it produces a white-gray powder
- Sample contains very faint red laminae in addition to the grey crystalline rock
- Sample looks to have a welded crystal texture
- Salty: no
- Reaction to HCl: no
- Sample is flakey and tasteless

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A
- Roundness: N/A
- Sphericity: N/A
- Composition: gypsum/anhydrite (birefringence is off and not high, however) and possible dark opaque grains (minimal at best)
- Porosity:~1% or less (sample is highly crystalline)
- Cement: gypsum/anhydrite (?)
- Sedimentary structures/features: none observed
- Diagenetic features: gypsum/anhydrite alteration

Other Notes

- This sample is crystalline, whitish grey, and cracked throughout. I am unsure if cracks were a result of thin section making or some cracks look to have healed and filled in by cement of some sort. The "cement" looks different than what has been observed of the rest of the sample.
- The birefringence confuses me more than anything in these sample as it seems in many areas to have a lower order than typical gypsum. This may be a result of gypsum/anhydrite thickness, though. There are also areas of the sample that show extinction not typical of gypsum/anhydrite as it goes completely extinct despite sharing

many favorable qualities of this mineral. Could there be some kind of replacement/conversion going on in the minerals here?

- There are many unusual shapes observed in this sample though the most interesting are areas that are of cubic shape. These areas look much like halite though seem to be replaced by gypsum?
- There is a dark diagonal line of material that cuts through the lower half of this sample. At first I thought it was iron of some sort but shining reflected light on it makes me question this. Could this be some other mineral or an artifact of thin section making?

Day Creek Dolomite

Thin Section: 1674’8”

Hand Sample: 1674’3”-1674’8”

Hand Sample Notes

- Reddish rock (2.5YR 7/1, 2.5YR 7/2) that looks crystalline with some siliciclastics. The siliciclastics look to be fine sand sized
- Difficult to scratch sample though some can be scratched off. Sample seems to actually scratch item used for scratching.
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A
- Roundness: N/A
- Sphericity: N/A
- Composition: gypsum, blocky crystals (?), quartz (?), and dark opaque grains (there are very few of these)
- Porosity: ~2% though crystalline
- Cement: gypsum
- Sedimentary structures/features: wavy discontinuous bedding
- Diagenetic features: specular reduction spots and gypsum alteration

Other Notes

- Sample looks to be dolomitized but seems to have undergone some alteration
- Possible fossil alteration?
- Iron oxide seems to be trapped in areas of dolomite. There is a total absence of dark opaque grains in sample.

Day Creek Dolomite

Thin Section: 1674’3”

Hand Sample: 1674’3”-1674’8”

Hand Sample Notes

- Reddish rock (2.5YR 7/1) that looks to be crystalline though possible granular input from outside sources that give the sample its slight pinkish color.
- Looks to be well developed beds of gypsum/anhydrite in sample
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A
- Roundness: N/A
- Sphericity: N/A
- Composition: gypsum and iron oxide though some areas of the sample look to be recrystallized or cements of some sort. The blockyness of these areas suggest these minerals are either calcite or dolomite but VERY uncertain
- Porosity: ~2% or less
- Cement: gypsum
- Sedimentary structures/features: none observed
- Diagenetic features: gypsum conversion to anhydrite

Other Notes

- This sample is crystalline with thin veneers of iron oxide localized around cracks in the rock. There are some areas around these cracks that seem to have quartz grains suggesting this iron oxide was likely blown in rather than diagenetically forming due to infiltrating waters. Some areas, however, look to have formed the iron oxide diagenetically as it can be found in obscure areas of the sample.
- “Cements” seem to be filling cracks in the sample and tend to be more crystalline than surrounding areas of the rock. Could this be the result of storms enriched in calcium/magnesium waters?

<u>Day Creek Dolomite</u>

Hand Sample: 1673’6”

Hand Sample Notes

- Reddish gray rock (2.5YR 6/1) that is crystalline
- Looks to be gypsum/anhydrite with slight amounts of red siliciclastics
- Salty: no
- Reaction to HCl: no
- Cement: undistinguished
- Sedimentary structures/features: planar bedding
- Diagenetic features: undistinguished

Day Creek Dolomite

Hand Sample: 1670’11”-1671’1”

Hand Sample Notes

- Pale red crystalline rock (2.5YR 7/2) composed of gypsum and laminations of red siliciclastic (quartz?)
- Salty: yes
- Reaction to HCl: no
- Possible slickensides (?) In red siliciclastics
- Bedding hard to distinguish though red siliciclastics overall look chaotic

Day Creek Dolomite

Thin Section: 1668’

Hand Sample: 1668’-1668’7”

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of very fine sand and silt sized grains of what seem to be quartz and gypsum.
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: silt: ~95%, clay: ~5%
- Sorting: moderate- well-sorted
- Roundness: well rounded
- Sphericity: very high sphericity
- Composition: quartz, gypsum, and dark opaque grains though minimal
- Porosity: ~3% or less
- Cement: gypsum
- Sedimentary structures/features: none observed
- Diagenetic features: specular reduction spots, globular reduction spots, halite to gypsum pseudomorphs, and displacive gypsum crystals.

Other Notes

- Siliciclastic rock with large, blocky gypsum cements.
- Boundaries between light and dark areas of sample are gradual.
- Some areas look to be dolomitized in the sample (very fine-grained zones with potential crystal mosaics).
- Dark opaque grains are scattered throughout the sample and take on multiple shapes and sizes including elongate and rounded. These glimmer in reflected light and are interpreted to be specular hematite or pyrite.

<u>Day Creek Dolomite</u>

Thin Section: 1668'

Hand Sample: 1668'-1668'7"

Hand Sample Notes

- Reddish rock (2.5YR 5/6) composed of very fine sand and silt sized grains of what seem to be quartz and gypsum.
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: silt: ~95%, clay: ~5%
- Sorting: poor-moderately sorted
- Roundness: subrounded-rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, and dark opaque grains
- Porosity: ~5% or less
- Cement: undistinguished
- Sedimentary structures/features: ripple cross-stratification (?)
- Diagenetic features: specular reduction spots, globular reduction spots, displacive gypsum crystals, and halite to gypsum pseudomorphs

Other Notes

- Sample is red with reduction spots that are both large and small.
- Reduction spots have gradational boundaries.
- Gypsum found in this sample is both clastic and displacive.
- Some areas of the sample look to have been altered or recrystallized as many gypsum samples take on shapes of calcite/dolomite grains.
- Dark opaque grains take on a variety of shapes from rounded to elongate. They glimmer in reflected light suggested they're specular hematite or pyrite.
- Some areas look to have been cemented quicker than other areas in the sample.
- Some of the grains found in this sample are very red (ruby colored). Could this be siderite?

<u>Day Creek Dolomite</u>

Thin Section: 1667'

Hand Sample: 1667'

Hand Sample Notes

- Reddish brown rock (2.5YR 4/3, 2.5YR 4/4) composed of very fine sand and silt sized grains
- Looks to be composed of quartz and detrital gypsum

- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: coarse silt and smaller (~.05 mm to .06 mm and smaller)
- Grain Size Distribution: silt: ~70%, clay: ~30%
- Sorting: moderate to well-sorted
- Roundness: subrounded-rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, dark opaque grains, and deep red opaque grains
- Porosity: ~3% or less
- Cement: gypsum
- Sedimentary structures/features: ripple cross-stratification and mud drapes
- Diagenetic features: specular reduction spots and gypsum alteration

Other Notes

- Displacive gypsum is much smaller in this sample than in other samples observed.
- Color of red siliciclastic resembles that of the Whitehorse samples.
- Dark opaque grains scattered throughout sample and have little to no preferential distribution.
- Dark opaque grains, much like elsewhere, glimmer in reflected light and are smaller than surrounding grains. Could this be pyrite or specular hematite?
- Many areas in sample look to be areas where roots once were that were later filled with gypsum cement? Possible gypsum alteration.

<u>Day Creek Dolomite</u>

Thin Section: 1664'

Hand Sample: 1664'

Hand Sample Notes

- Reddish rock (2.5YR 4/4) composed of very fine sand, silt, and slight amounts of clay
- composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: medium sand and smaller (~0.3 mm and smaller)
- Grain Size Distribution: medium sand: <~1%, fine sand: <~1%, very fine sand: ~10%, silt: ~80%, clay: ~10%
- Sorting: moderately sorted
- Roundness: subrounded-well rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, dark opaque grains, and lithics (polycrystalline quartz though not many at all)

- Porosity: ~3% or less
- Cement: gypsum
- Sedimentary structures/features: water escape features, mudcracks, and mud clasts
- Diagenetic features: specular reduction spots and displacive gypsum crystals

Other Notes

- Color of sample is similar to that of Big Basin though slightly lighter shade.
- Possible concretions formed in sample though medium sands may have been plucked out.
- Root feature with circumgranular cracks and cement that oddly looks to be filling in for a root.
- Some features have sharp edges while others are very smooth/rounded.

<u>Day Creek Dolomite</u>

Thin Section: 1663’

Hand Sample: 1662’2”-1663’

Hand Sample Notes

- Crystalline rock (2.5YR 6/1) composed of gypsum/anhydrite
- Wavy bedding of siliciclastics found in between gypsum/anhydrite
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A
- Roundness: N/A
- Sphericity: N/A
- Composition: nearly all bedded gypsum
- Porosity: ~1% or less

Other Notes

- This sample is wholly gypsum/anhydrite (bedded).

<u>Day Creek Dolomite</u>

Thin Section: 1662’6”

Hand Sample: 1662’2”-1663’

Hand Sample Notes

- Reddish rock (2.5YR 7/1, 2.5YR 6/1) composed of crystalline material. There seem to be minor siliciclastics in the sample if any.
- Salty: no
- Reaction to HCl: no
- Sample does not show bedding (massive)

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A
- Roundness: N/A
- Sphericity: N/A
- Composition: gypsum with possible organics and iron oxides.
- Porosity: ~2% or less
- Cement: undistinguished
- Sedimentary structures/features: none observed
- Diagenetic features: none observed

Other Notes

- Sample is gypsum/anhydrite.
- Possible unconformity preserved in the rock as gypsum crystals seem to change size and shape across boundary.
- Possible iron oxides and organics trapped in gypsum. "Organics" seem to have a yellowish brown hue around them whereas iron oxides look red to black in this sample
- Much less iron oxide in this sample than others previously observed in Whitehorse and Big Basin.
- Speckled brown and yellow stains can be found in random places throughout the sample with decent amounts of what looks to be gypsum in the sample.
- Possible yellow stained halite in sample.

<u>Day Creek Dolomite</u>

Thin Section: 1662'2"

Hand Sample: 1662'2"-1663'

Hand Sample Notes

- Reddish grey rock (2.5YR 6/1, 2.5YR 7/1) composed of crystalline material. There seem to be minor siliciclastics in the sample if any.
- Salty: no
- Reaction to HCl: no
- Sample does not show bedding (massive)

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller)
- Grain Size Distribution: very fine sand: ~20%, silt: ~70%, clay: ~10%
- Sorting: poor-moderately sorted
- Roundness: subangular-rounded
- Sphericity: high sphericity
- Composition: gypsum, quartz, clay (?), and dark opaque grains
- Porosity: ~2% or less
- Cement: undistinguished
- Sedimentary structures/features: rip-up clasts

- Diagenetic features: displacive gypsum crystals

Other Notes

- Sample is gypsum with a small interbed of red siliciclastic in between.
- Siliciclastics are ranging in size from fine sand to clay and is overall poorly-moderately sorted.
- Sample looks to be bedded gypsum though some may be clastic.
- Possible crystal mosaic found in the sample while some cracks filled with red siliciclastics.
- Dark opaque grains are minimal at best in this sample.
- Strange air bubble shapes observed in the sample…noticed these in red siliciclastics early in the Day Creek.

<u>Day Creek Dolomite</u>

Thin Section: 1662’

Hand Sample: 1662’11”-1661’1”

Hand Sample Notes

- Reddish rock (2.5YR 5/6, 2.5YR 6/6) composed of fine sand and silt sized red siliciclastics (quartz/gypsum?)
- Edges of sample seem to show a variety of paleosol characteristics (soil slickensides?)
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: fine sand and smaller (~0.16 mm and smaller though one grain at ~.32 mm)
- Grain Size Distribution: fine sand: ~5%, very fine sand: ~10%, silt: ~80%, clay: ~5%
- Sorting: moderately to well-sorted (more moderate though)
- Roundness: angular-subrounded with some well rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, dark opaque grains, and some amber colored grain that is currently unknown
- Porosity: ~5% or less
- Cement: gypsum
- Sedimentary structures/features: mudcracks, possible rip-up clasts, water escape features, and wavy discontinuous laminae
- Diagenetic features: specular reduction spots and gypsum alteration

Other Notes

- Midway through sample and up is a mix of what looks to be quartz grains, possible crystal mosaic by dolomite coating many areas, gypsum, and limited iron oxide/ dark opaque grains.
- Gypsum veins are found in the sample and oddly look like voids that were once where rocks were.

<u>Day Creek Dolomite</u>

Thin Section: 1660'

Hand Sample: 1660'-1660'5"

Hand Sample Notes

- Pale red rock (2.5YR 6/1, 2.5YR 6/2) composed of crystalline rock with fine wavy laminations of red siliciclastics
- Very heavy for its size
- Looks like it has a welded crystal texture
- Salty: yes (minimal)
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A
- Roundness: N/A
- Sphericity: N/A
- Composition: looks like a mix of gypsum/anhydrite and dolomite as localized crystal mosaics. Possible halite as well
- Porosity: ~2% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: pseudomorphs

Other Notes

- Though crystalline, this sample looks to have dolomitized areas that are far too spherical to be a feature…they resemble ooid and pisoid shapes.
- Iron oxides are preferentially found along cracks in the sample.
- A lot of yellow areas found in the sample…much more than what were previously observed in the last crystalline sample with yellow.
- Halite crystals are cubic and yellow.

<u>Day Creek Dolomite</u>

Thin Section: 1659'6"

Hand Sample: 1659'3"-1659'8"

Hand Sample Notes

- Reddish crystalline rock (2.5YR 4/1, 2.5YR 5/1) composed of crystals and very fine red siliciclastics (gypsum and quartz?)
- Salty: yes
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: N/A
- Sorting: N/A

- Roundness: N/A
- Sphericity: N/A
- Composition: gypsum/anhydrite, halite pseudomorphs (?), and halite
- Porosity: ~2% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae
- Diagenetic features: pseudomorphs

Other Notes

- A majority of this thin section is gypsum/anhydrite though seem to have lots of halite pseudomorphs as well as some areas that have been overprinted by dolomite (crystal mosaic?).
- Yellow areas in sample coupled alongside iron oxides sparsely found throughout sample.

Day Creek Dolomite

Hand Sample: 1659'-1659'3"

Hand Sample Notes

- Reddish gray crystalline rock (2.5YR 5/1)
- Looks to be composed of gypsum/anhydrite though possible additional minerals like halite. There's also red siliciclastic in the sample
- Salty: yes (minimal)
- Reaction to HCl: no
- Diagenetic features: gypsum stringers (?)

Big Basin Formation

Thin Section: 1659'

Hand Sample: 1658'10"-1659'

Hand Sample Notes

- Reddish rock (2.5YR 4/6, 2.5YR 5/6) composed of coarse sand to silt sized grains
- Composed of quartz and gypsum
- Salty: yes (minimal)
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: coarse sand and smaller (~0.5 mm and smaller though mostly smaller)
- Grain Size Distribution: coarse sand: ~5%, medium sand: ~10%, fine sand: ~20%, very fine sand: ~30%, silt: ~30%, clay: ~5%
- Sorting: poorly-sorted-moderately sorted
- Roundness: subangular-very well rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, lithics, clay (?), dark opaque grains
- Porosity: ~5% or less though lots of grain plucking
- Cement: gypsum (?)

- Sedimentary structures/features: wavy discontinuous laminae, soft sediment deformation, ball and pillow structures, mudcracks, and mud clasts
- Diagenetic features: specular reduction spots and subhorizontal gypsum stringers

Other Notes

- Could have seen recrystallized brachiopod shell (unlikely though).
- Gravel sized grains are found throughout thin section and has not been apparent until now. One seems to be a granitoid lithic with monocrystalline quartz, polycrystalline quartz as well as only feldspar in entire Big Basin.
- This is considered the boundary between Big Basin and Day Creek.

<u>Big Basin Formation</u>

Hand Sample: 1656’7”-1657’

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of medium sand and silt
- Composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

<u>Big Basin Formation</u>

Hand Sample: 1653’2”-1654’

Hand Sample Notes

- Reddish rock (5YR 4/4) composed of fine sand and silt sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

<u>Big Basin Formation</u>

Thin Section: 1651’9”

Hand Sample: 1651’-1651’11”

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt to clay sized quartz
- Salty: no
- Reaction to HCl: no
- On exposed surface there seem to be soil slickensides. Could this be indication of paleosol?

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: medium sand: < ~1%, fine sand: < ~1%, very fine sand: ~30%, silt: ~50%, clay: ~20%

- Sorting: poorly-sorted-well-sorted
- Roundness: subangular-very well rounded
- Sphericity: moderate-very high sphericity
- Composition: quartz, gypsum, dark opaque grains, lithics (?), clay (?)
- Porosity: ~2% or less
- Cement: gypsum
- Sedimentary structures/features: wavy discontinuous laminae, mud clasts, mudcracks, mud drapes, ripple cross-stratification, rip-up clasts, ball and pillow structures
- Diagenetic features: specular reduction spots, globular reduction spots, displacive gypsum crystals, and gypsum stringers (subhorizontal and vertical)

Other Notes

- Reduction spots seem to show sharp contacts with oxidized zones in some places.
- Mudcracks seem to sometimes not cut across reduction spots.
- Dark opaque grains shine in reflected light and seem to show no orientation in thin section. Could this be pyrite or specular hematite?
- Rip-up clasts and mud clasts seem to show a preferred orientation.
- Very well rounded grains can be found in the thin section…could these be lithics of some sort?
- Clay most predominant in top of thin section. I am starting to see pattern of quartz layer, dark muds/clay, light muds/clay and repeat.
- Gypsum seems to be filling cracks in clay.
- Some stringers seem to be filled with clay from surrounding area.

<u>Big Basin Formation</u>

Thin Section: 1651'

Hand Sample: 1651'-1651'11"

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt to clay sized quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Sample seems to show paleosol features (soil slickensides on exposed surfaces)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: medium sand: <~1%, fine sand: <~1%, very fine sand: ~10%, silt: ~70%, clay: ~20%
- Sorting: moderate-well-sorted
- Roundness: angular-well rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, oxidized clay (?), gypsum, and dark opaque grains
- Porosity: ~3% or less
- Cement: undistinguished

- Sedimentary structures/features: planar laminae, wavy discontinuous laminae, mud clasts, ripple cross-stratification, graded bedding (?), rip-up clasts, circumgranular cracks
- Diagenetic features: specular reduction spots, globular reduction spots, displacive gypsum crystals, and gypsum stringers (subhorizontal and vertical)

Other Notes

- Possible unconformity observed in thin section towards the base.
- Very unusual well rounded grains around the first gypsum stringers. In XPL range from white to yellowish-orange color.
- Gypsum found as cement and displacive crystals. Displacive gypsum preferentially found in finer sediment zones.
- Dark opaque grains are shiny under reflected light but dark otherwise. Could this be pyrite? There seems to be no preferential orientation of where these dark opaque grains are found in the sample.

<u>Big Basin Formation</u>

Thin Section: 1647’

Hand Sample: 1647’-1648’

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt to clay sized quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: <~1%, silt: ~70%, clay: ~30%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: moderate-very high sphericity
- Composition: silt to clay sized quartz, clay (?), dark opaque grains, and gypsum
- Porosity: ~3% or less
- Cement: gypsum
- Sedimentary structures/features: wavy discontinuous laminae, cross-stratification, and ball and pillow structures,
- Diagenetic features: specular reduction spots, globular reduction spots, displacive gypsum crystals, and gypsum stringers (subhorizontal and angular)

Other Notes

- Clay and quartz grains show no specific orientation and are intermixed.
- Unusual concentration of dark opaque grains can be found in localized zones of the thin section.
- Stringers are observed as subhorizontal as well as crosscutting zones of clay and quartz grains.
- Areas of porosity are irregularly shaped as though grains were plucked from these areas (artifacts of thin section making?).

- Gypsum in sample is found as cement, clastic grains, and displacive crystals that are preferentially found in clay dominated regions of the sample.
- Some gypsum stringers seem to be broken up by sand and clay sized grains.
- Dark opaque grains seem to shine in reflected light. Could this be specular hematite or pyrite?

<u>Big Basin Formation</u>

Hand Sample: 1643'10"-1644'5"

Hand Sample Notes

- Reddish brown to red rock (2.5YR 5/4, 2.5YR 5/6) composed of fine sand and silt
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Sample seems to be mix of laminar and discontinuous (wavy) bedding and laminations.
- Diagenetic features seen in sample include gypsum stringers and specular reduction spots dotted throughout the sample.
- Possible two generations of gypsum stringers in sample.

<u>Big Basin Formation</u>

Hand Sample: 1638'-1638'4"

Hand Sample Notes

- Reddish brown rock (2.5YR 4/3, 2.5YR 4/4) composed of silt and clay sized grains
- Samples seem to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Cement: undistinguished
- Sedimentary structures/features: cross-stratification
- Diagenetic features: globular reduction spots and gypsum stringers

<u>Big Basin Formation</u>

Thin Section: 1637'5"

Hand Sample: 1637'3"-1638'

Hand Sample Notes

- Reddish brown rock (2.5YR 4/3, 2.5YR 4/4) composed of silt and clay sized grains
- Composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~10%, silt: ~70%, clay: ~20%
- Sorting: well-sorted
- Roundness: well rounded
- Sphericity: high sphericity
- Composition: quartz, gypsum, and very fine dark opaque grains
- Porosity: ~3% or less
- Cement: gypsum
- Sedimentary structures/features: planar laminae, rip-up clasts, ripple cross-stratification, and mudcracks
- Diagenetic features: specular reduction spots, globular reduction spots, displacive gypsum crystals, and gypsum stringers (subhorizontal and angular)

Other Notes

- 2 or more generations of gypsum stringers observed in thin section.
- Reduction spots preferentially found around gypsum cements.
- Dark opaque grains scattered throughout sample. These grains glimmer in reflected light and are interpreted to be specular hematite or pyrite.
- Gypsum in many areas of the sample looks chaotic as though detrital (gypsum nodules?).
- Red siliciclastics at times are trapped within gypsum stringers.

<u>Big Basin Formation</u>

Thin Section: 1634’4”-1634’5”

Hand Sample: 1634’1”-1634’7”

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt and clay sized quartz, clay, and gypsum
- Salty: no
- Reaction to HCl: no
- Smell odorless
- Exposed surfaces vaguely resemble paleosol features (ped structures?)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~5%, silt: ~75%, clay: ~20%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: moderate to high sphericity
- Composition: quartz, gypsum, clay (?), and dark opaque grains (pyrite?)
- Porosity: ~2% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae, wavy continuous laminae, ball and pillow structures, and cross-stratification

- Diagenetic features: globular reduction spots, displacive gypsum crystals, and gypsum stringers

Other Notes

- Gypsum is observed as clastic, cement, and displacive crystals.
- Dark opaque grains seem to show no preference in thin section locality.
- Low-angle cross-stratification observed in thin section.
- Cracks observed in sample seem to be artifacts of thin section making.
- Zones between oxidized and reducing zones seem to be gradational rather than abrupt.
- Gypsum stringers seem to cut across or abruptly stop at reduction spots.

Big Basin Formation

Thin Section: 1634’-1634’3”

Hand Sample: 1634’1”-1634’7”

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt and clay sized quartz, clay, and gypsum
- Salty: no
- Reaction to HCl: no
- Exposed surfaces vaguely resemble paleosol features (ped structures?)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~5%, silt: ~70%, clay: ~25%
- Sorting: moderate-well-sorted
- Roundness: subangular-rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, clay (?), black opaque grains
- Porosity: ~3% or less likely the result of thin section making, however
- Cement: gypsum
- Sedimentary structures/features: wavy discontinuous laminae, wavy continuous laminae, ball and pillow structures, cross-stratification, mud clasts, and mudcracks
- Diagenetic features: globular reduction spots, displacive gypsum crystals, and gypsum stringers

Other Notes

- Gypsum looks strange in XPL, particularly bottom one of sample. I also noticed a gypsum stringer that seems to split in two (right side of thin section).
- Reduction spots seem to abruptly stop when next to gypsum stringers.
- Most definitely is a bimodal grain size between lighter, coarser grains and darker, finer grains.
- In areas of light grains there seems to be a fining upward sequence with finer grains at the top of the thin section.
- Gypsum found as a cement, clastic sediment, and displacive crystal in sample.

- Very unusual concentration of detrital, dark opaque grains towards the top/middle right of sample.

Big Basin Formation

Hand Sample: 1633'7"-1634'

Hand Sample Notes

- Reddish brown to dark reddish brown rock (2.5YR 3/3, 2.5YR 4/4) composed of fine sand, silt, and clay sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae and ripple cross-stratification
- Diagenetic features: globular reduction spots and gypsum stringers
- Possible paleosol features (ped structures?)

Big Basin Formation

Thin Section: 1632'7"-1632'10"

Hand Sample: 1632'6"-1632'11"

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt to clay sized grains of quartz and gypsum
- Salty: no
- Reaction to HCl: no

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~10%, silt: ~70%, clay: ~20%
- Sorting: moderate-very well-sorted
- Roundness: moderate-well rounded
- Sphericity: moderate-high sphericity
- Composition: quartz, mica (?), and gypsum, gypsum comes in many forms here with dark opaque grains.
- Porosity: ~5% (more than units above)
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous bedding, ripple cross-stratification (?), ball and pillow structures, flame structures, soft sediment deformation, rip-up clasts, mud clasts, and mudcracks
- Diagenetic features: specular reduction spots, globular reduction spots, displacive gypsum crystals, and gypsum stringers (subhorizontal and vertical)

Other Notes

- The sample seems to contain pyrite that seems to fill in irregularly shaped areas. Quartz grains are much larger and directly contrast with finer grain sizes found within darker, muddy clay areas of sample.
- Gypsum can be found as clastic grains, cement, and displacive crystals.

Big Basin Formation

Thin Section: 1632'6"-1632'7"

Hand Sample: 1632'6"-1632'11"

Hand Sample Notes

- Reddish brown to white rock (5YR 4/4) composed of silt to clay sized quartz and gypsum (very smooth to the touch)
- Salty: no
- Reaction to HCl: no
- Apparent bedding/laminations observed as light and dark colored reddish-brown patches
- Exposed, fresh surface looks to almost have soil slickensides (paleosol features)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: <~1%, silt: ~85%, clay: ~15%
- Sorting: moderate-very well-sorted
- Roundness: subangular-rounded
- Sphericity: moderate-high sphericity
- Composition: quartz and gypsum with traces of dark opaque grains
- Porosity: ~3% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy discontinuous laminae/beds, cross-stratification, ball and pillow structures, rip-up clasts, mudcracks
- Diagenetic features: globular reduction spots, displacive gypsum crystals, and gypsum stringers (subhorizontal to vertical)

Other Notes

- Seems to show distinct grain size difference between light and dark bands with lighter laminae having exceptionally larger grain sizes.
- Two main gypsum types: cement and displacive crystals.
- Possible two generations of cement observed in gypsum stringer.
- Microfaulting along some stringers.
- Reduction spots cut across stringers.
- Reduction spots cut by stringers mostly.

<u>Big Basin Formation</u>

Hand Sample: 1631'2"-1632'

Hand Sample Notes

- Reddish rock (5YR 4/4) composed of very fine sand and silt sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Sedimentary structures/features: mudcracks, wavy discontinuous laminae, and ball and pillow structures
- Diagenetic features: specular reduction spots

<u>Big Basin Formation</u>

Hand Sample: 1630'6

Hand Sample Notes

- Reddish rock (5YR 4/4) composed of very fine sand, silt, and clay sized grains
- Looks to be composed of quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Sedimentary structures/features: planar laminae, wavy discontinuous laminae, and ball and pillow structures
- Diagenetic features: gypsum stringers (minute)

<u>Big Basin Formation</u>

Thin Section: 1629'5"-1629'8"

Hand Sample: 1629'2"-1629'9"

Hand Sample Notes

- Reddish brown rock (5YR 5/3) composed of very fine-grained silt to clay sized quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Easily scratched and breaks off in flakes (could this be evidence of paleosol?)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: silt: ~70%, clay ~30%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz and gypsum
- Porosity: ~3% or less

- Cement: undistinguished
- Sedimentary structures/features: rip-up clasts, cross-stratification, flame structures, ball and pillow structures, and mudcracks
- Diagenetic features: specular reduction spots and minimal gypsum stringers

Other Notes

- Veins in sample filled with gypsum and sometimes silica.
- Sample contains opaque tabular features that resemble skeletal grains. Look somewhat like shells but could be pyritization. Mica?
- Dissolution vug in the corner of sample?

Big Basin Formation

Thin Section: 1629'2"-1629'4"

Hand Sample: 1629'2"-1629'9"

Hand Sample Notes

- Reddish brown rock (5YR 5/3) composed of very fine-grained silt to clay sized quartz and gypsum
- Salty: no
- Reaction to HCl: no
- Easily scratched and breaks off in flakes (could this be evidence of paleosol?)

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~5%, silt: ~75%, clay: ~20%
- Sorting: moderate-well-sorted
- Roundness: subangular-subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz, gypsum, and dark opaque grains
- Porosity: ~5% or less
- Cement: gypsum (?)
- Sedimentary structures/features: rip-up clasts, cross-stratification, flame structures, and ball and pillow structures
- Diagenetic features: none observed

Other Notes

- Sample contains soft sediment deformation, mudcracks, veins, cross-stratification, as well as pillow structure (?). Sample seems to get coarser as moving up section in thin section. Dark opaque grains that could be organics that have undergone pyritization, mica or iron oxide of some sort.

Big Basin Formation

Thin Section: 1628'

Hand Sample: 1627'-1627'6" (1628?)

Hand Sample Notes

- Grey to Reddish brown rock (5YR 5/2 sharply transitioning to 10YR 7/2) composed of silt and clay sized grains
- Salty: no
- Reaction to HCl: no
- Sample coarsens upward in what seems to be sandstone with potentially large amounts of feldspar (feldspathic wacke?). This is interpreted to be the Permian-Jurassic boundary

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: silt: ~60%, clay: ~40%
- Sorting: well-sorted (some laminae observed)
- Roundness: angular-subrounded
- Sphericity: moderate-high sphericity
- Composition: quartz and gypsum with traces of dark opaque grains
- Porosity: ~5% or less
- Cement: undistinguished though considered gypsum
- Sedimentary structures/features: rip-up clasts, cross-stratification, and mudcracks
- Diagenetic features: reduction spots and gypsum stringers

Other Notes

- Reduction spots cut across stringers, sometimes not.
- Quartz coated in iron but gypsum is not.

<u>Big Basin Formation</u>

Thin Section: 1627’5”-1627’6”

Hand Sample: 1627’-1627’6”

Hand Sample Notes

- Reddish brown rock (5YR 4/4) composed of silt to sand sized quartz and gypsum. Some clay sized material in sample as well
- Lighter colored part of hand sample is composed of quartz and pink colored grains (could these be feldspar?).
- Salty: no
- Reaction to HCl: no
- Boundary between dark and light is highly gradational.
- Dark portion of sample seems to show indications of paleosol features though no signs of reduction in sample.

Thin Section Notes

- Grain Size Range: very fine sand and smaller (~0.1 mm and smaller)
- Grain Size Distribution: very fine sand: ~10%, silt: ~80%, clay: ~10%
- Sorting: moderate-very well-sorted

- Roundness: subangular-subrounded
- Sphericity: moderate-very high sphericity
- Composition: quartz, gypsum, dark opaque grains, and very high birefringent mineral (blue?)
- Porosity: ~2% or less
- Cement: undistinguished
- Sedimentary structures/features: wavy continuous laminae, ball and pillow structures, cross-stratification, and mudcracks
- Diagenetic features: displacive gypsum crystals

Other Notes

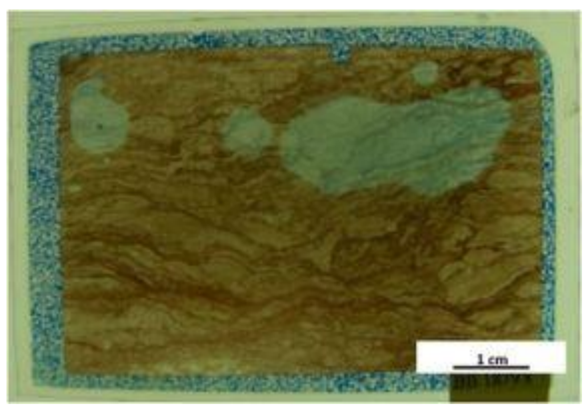
- Gypsum found in sample seems to be windblown as well as displacive. Displacive gypsum found in both darker and lighter portions of sample.
- Dark opaque grains are both rounded and elongate. They sparkle under reflected light suggesting they are either specular hematite or pyrite.
- Large unusual shaped grain in top right of sample that is very orange in XPL

Large Format Thin Section Photographs

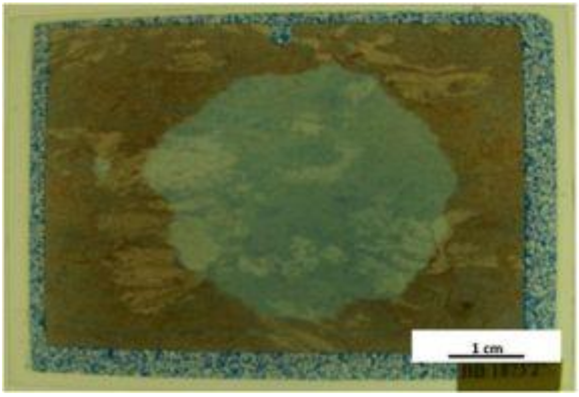
BB1897' (Dog Creek)

BB1892' (Dog Creek)

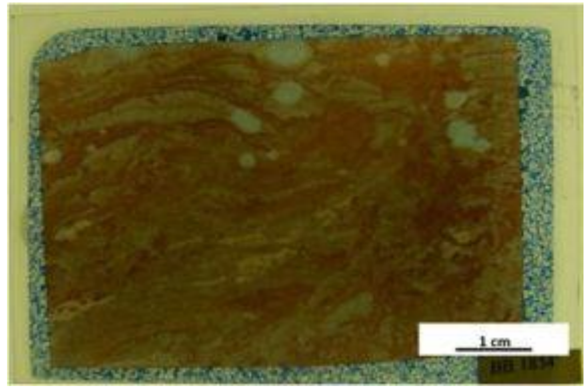
BB1880' (Dog Creek)



BB1879'8" (Dog Creek)

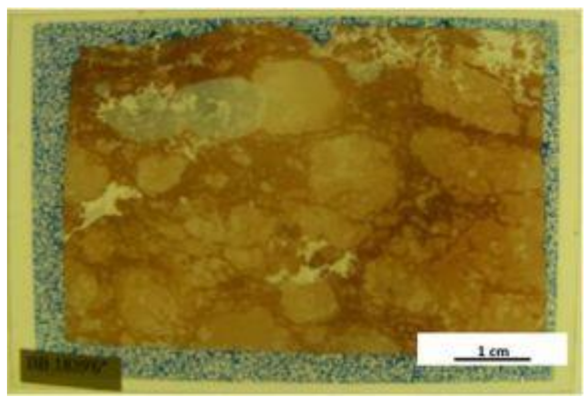


BB1875’2” (Dog Creek)

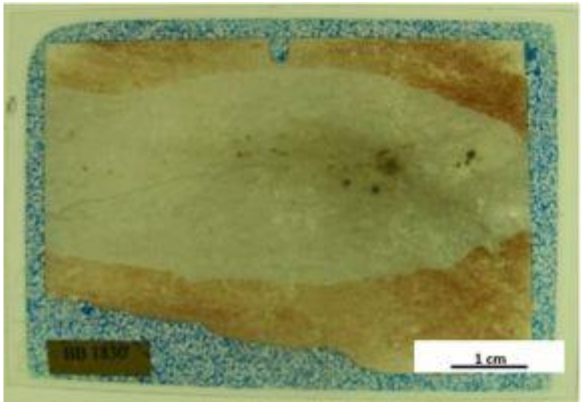


BB 1854’ (Dog Creek)

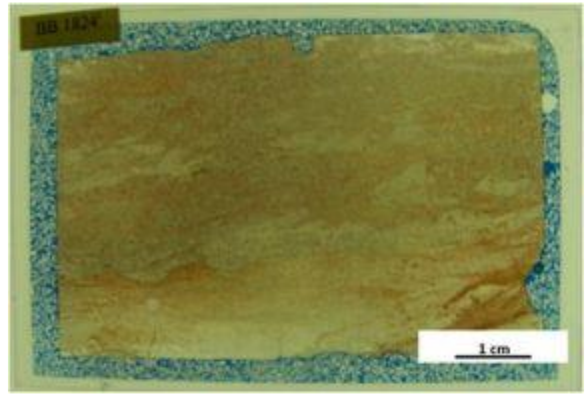
BB1853’ (Dog Creek)



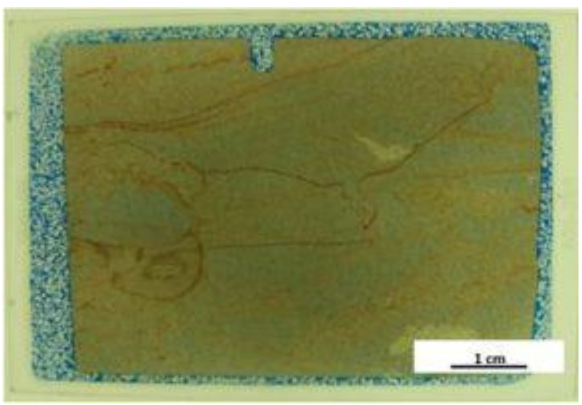
BB1839’6” (Whitehorse Sandstone)



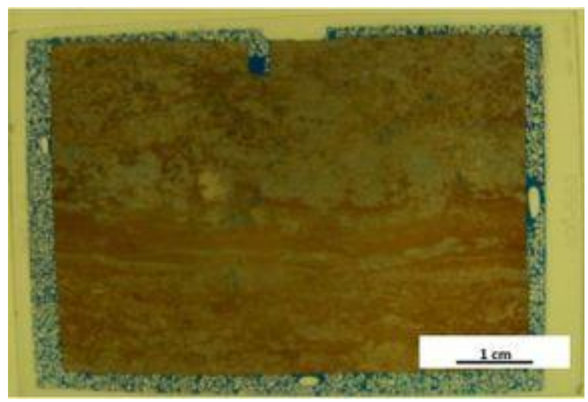
BB1830' (Whitehorse Sandstone)



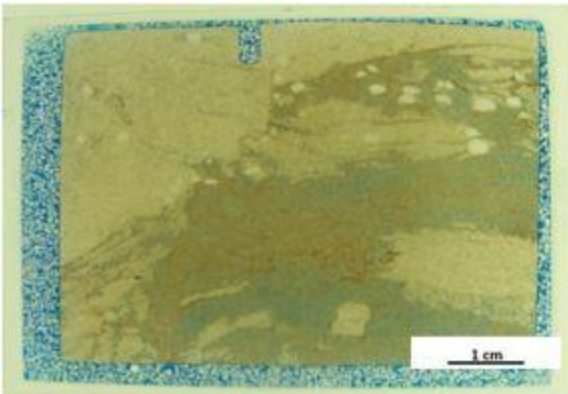
BB1824' (Whitehorse Sandstone)



BB1802' (Whitehorse Sandstone)

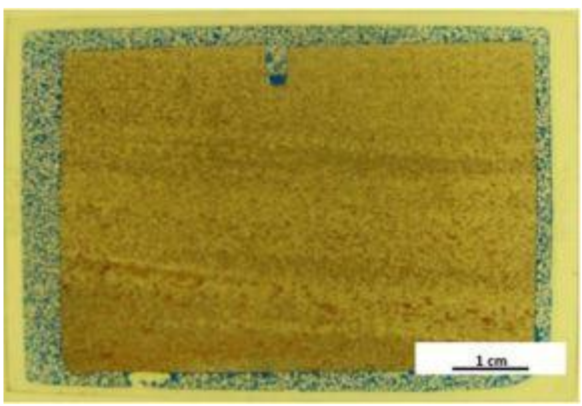


BB1788' (Whitehorse Sandstone)

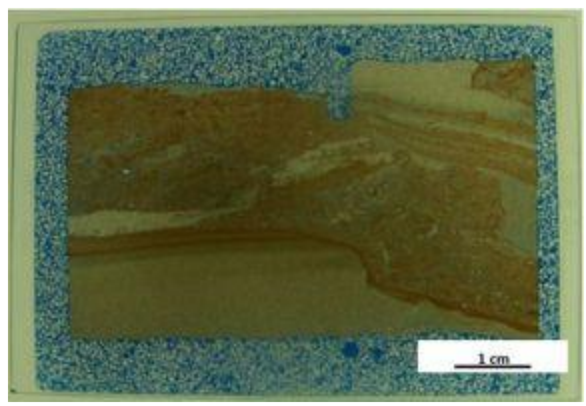


BB1766’4” (Whitehorse Sandstone)

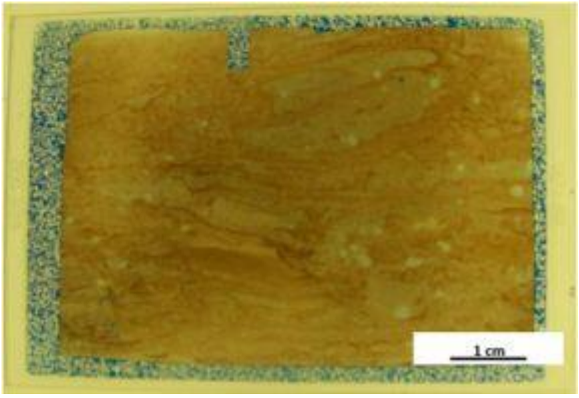
BB1759’ (Whitehorse Sandstone)



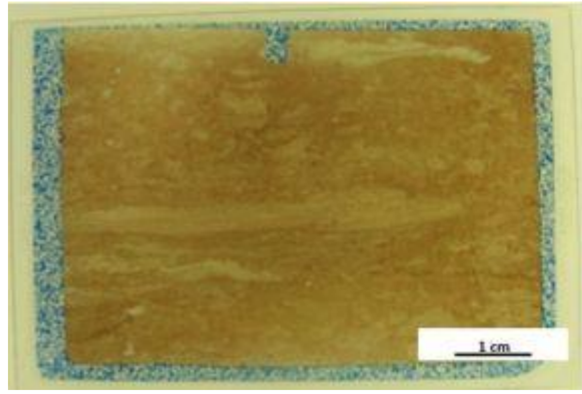
BB1745’7” (Whitehorse Sandstone)



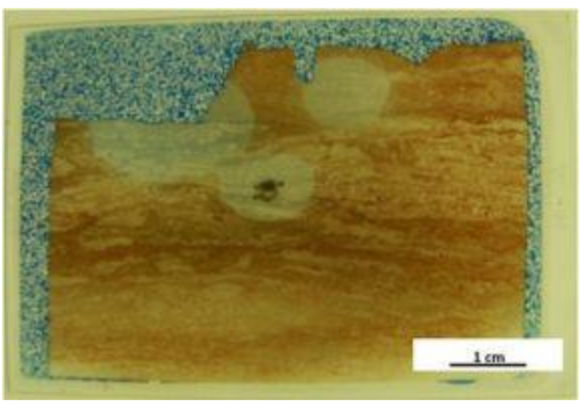
BB1745’2” (Whitehorse Sandstone)



BB1737’ (Whitehorse Sandstone)

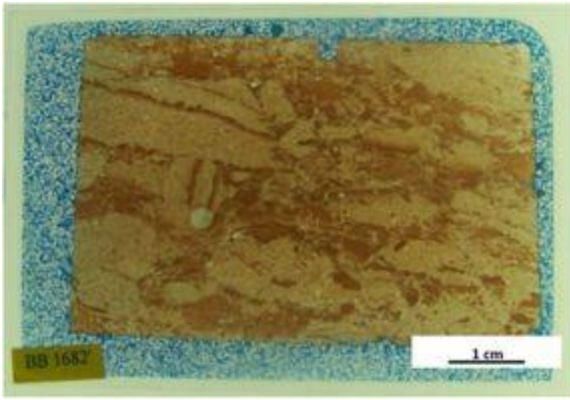


BB1715’ (Whitehorse Sandstone)

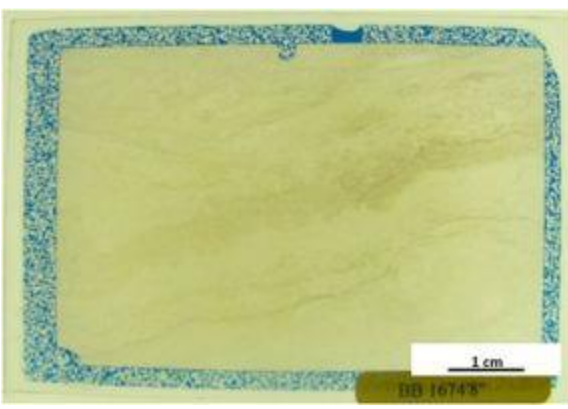


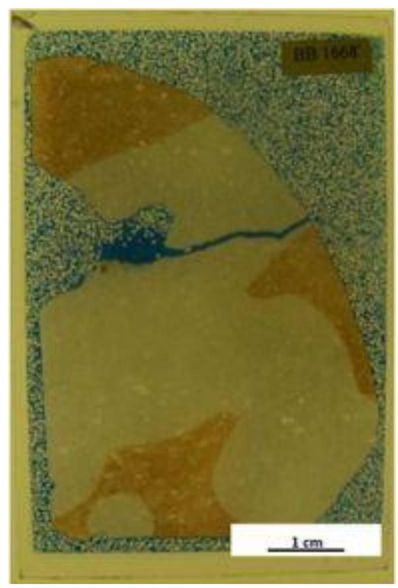
BB1709’ (Whitehorse Sandstone)

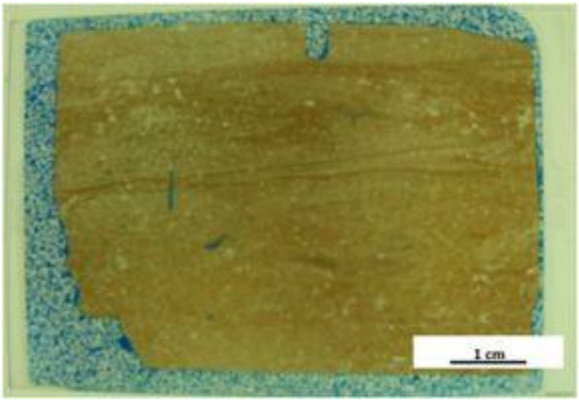
BB1685’8” (Whitehorse Sandstone)


BB1682’ (Whitehorse Sandstone)


BB1675’ (Day Creek Dolomite)


BB1674’8” (Day Creek Dolomite)

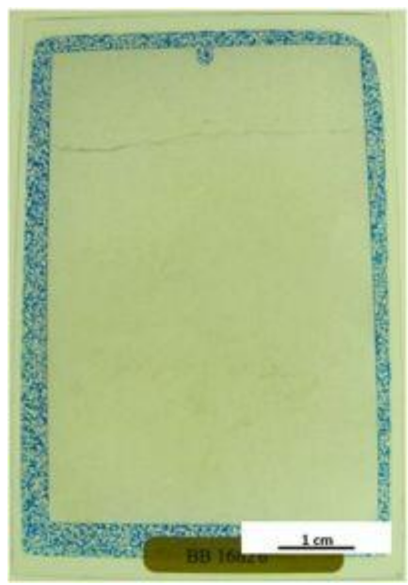

BB1668’ (Day Creek Dolomite)



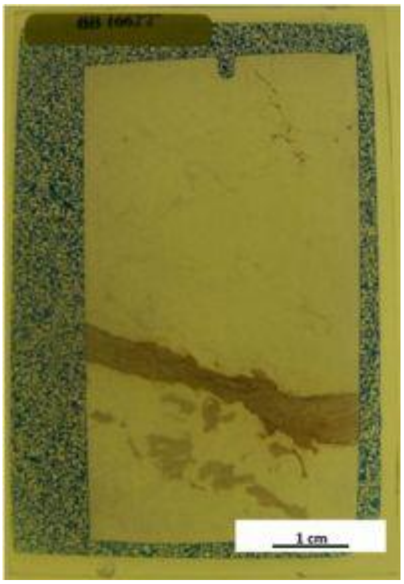
BB1667' (Day Creek Dolomite)

BB1664' (Day Creek Dolomite)

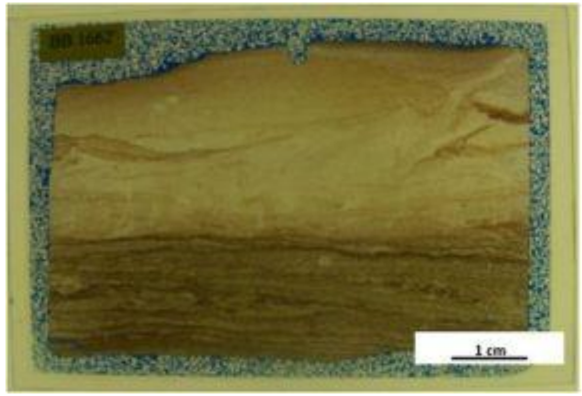
BB1663' (Day Creek Dolomite)



BB1662'6" (Day Creek Dolomite)



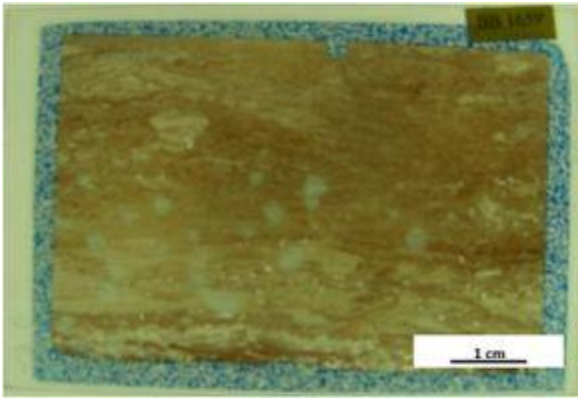
BB1662'2" (Day Creek Dolomite)



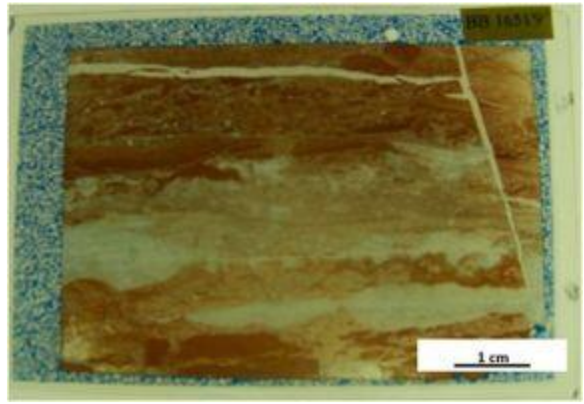
BB1662' (Day Creek Dolomite)

BB1660' (Day Creek Dolomite)

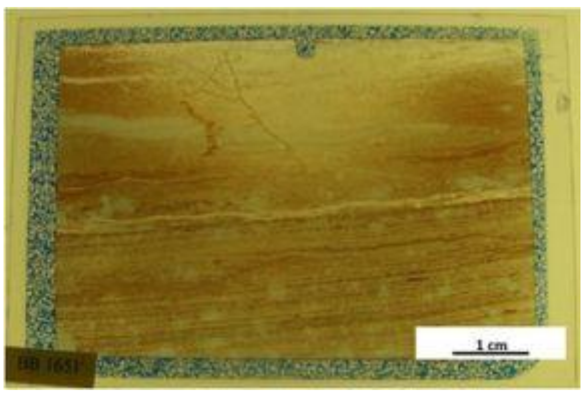
BB1659'6" (Day Creek Dolomite)



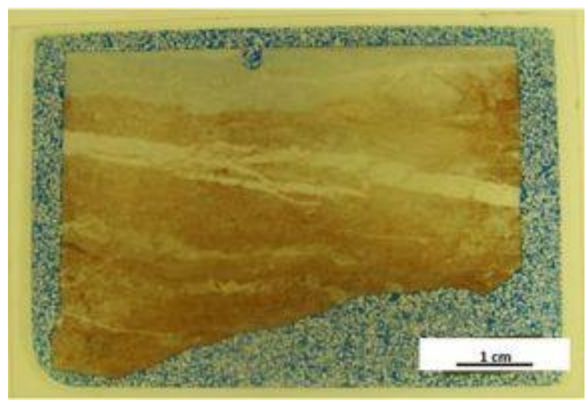
BB1659’ (Big Basin)



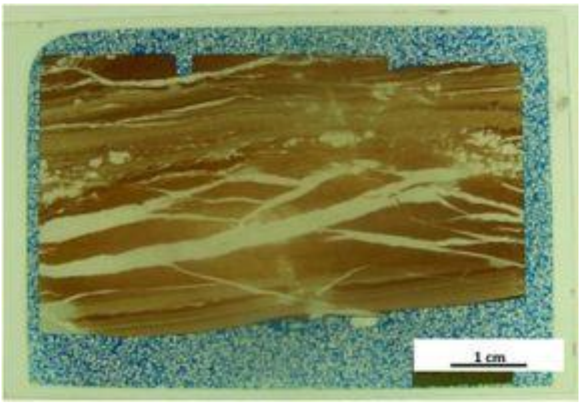
BB1651’9” (Big Basin)



BB1651’ (Big Basin)



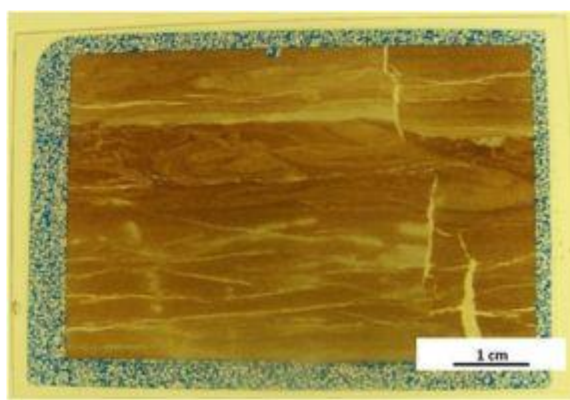
BB1647’ (Big Basin)



BB1637’5” (Big Basin)

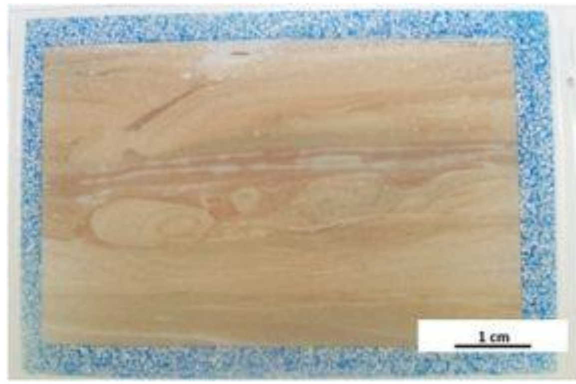
BB1634’-1634’2” (Big Basin)

BB1632’7”-1632’10” (Big Basin)

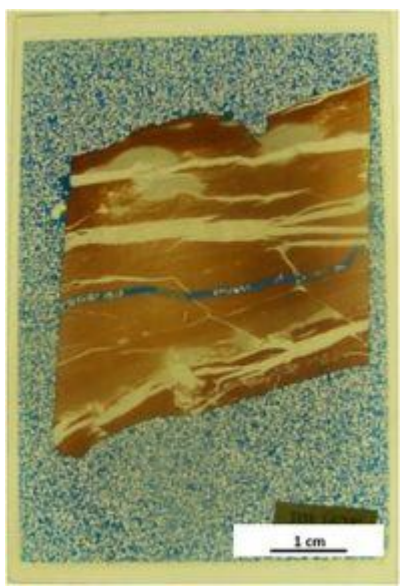


BB1632’6”-1632’7” (Big Basin)

BB1629’5”-1629’8” (Big Basin)



BB1629’2”-1629’4” (Big Basin)



BB1628’ (Big Basin)

XRD DATA

Depth	1647’	1647’	1659’6”	1674’3”	1839’6”
Quartz	41.3	48.1	0.2	0	0.6
K-Feldspar	11.6	7.7	0	0	0
Plagioclase	0	0	0	0	0
Calcite	0	0	0	0	0
Dolomite	17	21	8.3	69.6	57.5
Hematite	0	1.1	0	0.2	1.4
Gypsum	0	0	0	0.3	0
Anhydrite	11.7	0	87.7	25.6	0.3
Halite	0	0	0	0	0
Total Clay	18.4	22.1	3.8	4.3	41.2
RO-M-L I/S 90S*	0	0	0	0	33.7
R1 M-L C/S 50S**	1.9	0.8	0	0	0
R3 M-L I/S 15S***	0	0	0	0	0
Illite & Mica	11.9	17.3	3.8	4.3	6
Kaolinite	0.7	1	0	0	0
Chlorite	3.9	3	0	0	1.5
Total	100	100	100	100	100

* RO-M-L I/S 90S- Randomly Ordered Mixed-Layer Illite/Smectite with 90% Smectite Layers
** R1 M-L C/S 50S- R1 Ordered Mixed-Layer Chlorite/Smectite with 50% Smectite Layers
*** R3 M-L I/S 15S- R3 Ordered Mixed-Layer Illite/Smectite with 15% Smectite Layers