The Sequence Stratigraphic Context of Mixed Basin Margin Evaporites in the Harrisburg Member of the Permian Kaibab Formation, Northern Arizona and Southern Utah

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The Sequence Stratigraphic Context of Mixed Basin Margin Evaporites in the Harrisburg Member of the Permian Kaibab Formation, Northern Arizona and Southern Utah

By

Cole Edward Hendrickson, BS Geology

Presented to the Faculty of the Graduate School of Stephen F. Austin State University
In Partial Fulfillment
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The Sequence Stratigraphic Context of Mixed Basin Margin Evaporites in the Harrisburg Member of the Permian Kaibab Formation, Northern Arizona and Southern Utah

By

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ABSTRACT

The Kaibab Formation is a mixed carbonate system including evaporites and siliciclastics deposited on a westward dipping epeiric carbonate ramp during the middle Permian in northern Arizona, southern Utah, and eastern Nevada. It consists of the Fossil Mountain Member deposited in open-marine conditions and the overlying Harrisburg Member deposited in restricted conditions. The Harrisburg Member includes facies and depositional environments ranging from open-marine shallow-subtidal wackestone - packstone, restricted subtidal dolomitic mudstone, dolomitic sandstone, peritidal oolitic grainstone as well as gypsum and red siltstones deposited in a sabkha environment.

Fourteen stratigraphic sections were measured across northern Arizona and southern Utah to analyze the sequence stratigraphic context of the Harrisburg Member. This study interprets four parasequences making up systems tracts of two depositional sequences. The lower two parasequences are indicative of the highstand systems tract of depositional sequence H1. Facies of the lower parasequences consist of the open-marine wackestone - packstone, restricted subtidal dolomitic mudstone, dolomitic sandstone and oolitic-pelletal grainstone. An erosional surface between the second and third parasequence is denoted by a chert pebble conglomerate and represents a sequence boundary.
SB1. The third and fourth parasequences represent the transgressive systems tract of the second depositional sequence H2, and have a stacking pattern indicative of a landward migration of facies with gypsum and red siltstone facies overlain by a shallow-marine wackestone - packstone. The Permo-Triassic Unconformity truncates the Harrisburg Member and represents a major sequence boundary SB2 separating it from the overlying Triassic sediments of the Rock Canyon Conglomerate and Moenkopi Formation.
ACKNOWLEDGEMENTS

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I would also like to thank the rest of my thesis committee. Dr. Kevin Stafford was always available for questions and stimulating conversation. Dr. Mindy Faulkner always had words of encouragement. Thanks also to Dr. Joseph Musser for his edits.

Besides my thesis committee, I would like to thank Dr. Timothy Walsh at the Geology Department of Wayland Baptist University. He allowed me to use petrographic equipment that was very useful in this study. His advice and encouragement is greatly appreciated as well. I would also like to thank David Scholman for inspiring conversations on carbonate sequence stratigraphy.

My friends also deserve to be recognized. They have held me up and supported me in times of need and pushed me through times of procrastination, I would specifically like to thank Jonathan Woodard and Austin Wilkerson of whom I had the pleasure of attending both undergraduate and graduate school with. I
would also like to thank Ryan Silberstorf, Robert Schoen, and Jensen Angelloz. Last but not least is Garrett Williamson who had the harshest words of encouragement for me during times of slow progress in this project. Garrett also helped me in editing the manuscript and was also took a week off of work to be a field assistant. My time in graduate school would not have been this much fun without my friends and I thank them for their comradery.

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INTRODUCTION

The Kaibab Formation was deposited during the Middle Permian on a carbonate ramp in an epeiric seaway and represents the upper portion of the Permian sequence that is present in the Grand Canyon region across northern Arizona and southern Utah (Cheevers and Rawson, 1979; figure 1). Fossils in the Kaibab Formation cause it to be considered Leonardian to Guadalupian in age (McKee, 1938). The formation consists of the Fossil Mountain and Harrisburg members; they mainly consist of limestone but are also interbedded with siltstones, sandstones, and thick gypsum deposits (McKee, 1938; Sorauf and Billingsly, 1991).

The Kaibab Formation has been the subject of several detailed studies over the years such as McKee (1938), Sorauf (1962) and Nielson (1980). These works have focused on the stratigraphic and sedimentological aspects of the Kaibab Formation through petrographic description, facies analyses and lithostratigraphic correlations. The first series of studies on the Kaibab Formation also included the underlying Toroweap Formation before it was informally recognized by McKee (1938). Nomenclature as it is applied to the Toroweap and Kaibab formations today did not become formally recognized under the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) until the work of Sorauf and Billingsley (1991).
Several problems exist in the current understanding of the stratigraphy of the Harrisburg Member: 1) the contact between the Harrisburg Member and the underlying Fossil Mountain Member is gradational; nomenclature is arbitrarily based on a general change in slope and color, making it difficult to pick a specific surface on which the Harrisburg Member begins; and 2) the use of facies maps by past authors (McKee, 1938; Cheevers and Rawson, 1979) which classified lithofacies based on the dominant lithology in the area rather than observing facies stacking patterns relative to unconformities. The use of this method lead to the interpretation of an unusual facies arrangement of dolomitic mudstone facies being found far shoreward of the gypsum facies (McKee, 1938; Cheevers, 1980), which may be better explained through the use of sequence stratigraphy. Measured sections and petrographic analyses of this study have provided more data on the Harrisburg Member; by applying the sequence stratigraphy, this study serves to better explain its stratigraphy and facies relationships.
Figure 1: Map of study area and transect lines with measured section locations.
LITERATURE REVIEW

Geologic Setting

During the Paleozoic, the western margin of Laurentia transitioned from stable to active and subduction-dominated (Burchfiel et al, 1992); southeastern Laurentia also underwent collision with Africa during assembly of Pangea, leading to the uplift of the Ancestral Rocky Mountains (Kluth, 1986). During the Permian, the Grand Canyon region was located on the western margin of Laurentia. Paleomagnetic data indicates that the continent was between the equator and the Tropic of Cancer which led to the development of a warm, dry climate (Utriskey, 1973). This is supported by the presence of extensive red beds and evaporites in the Grand Canyon region. These climatic conditions continued into the Mesozoic.

During the middle to late Permian, thick marine successions were deposited during sea-level highstands (Blakey and Middleton, 2012) in a series of complex environments consisting of shallow-marine, shoreline, and continental settings (McKee, 1938; Blakey and Middleton, 2012). This system consists of five formations. The lower most Permian aged formation is the Supai Group, consisting of sandstone interbedded with mudstone and gypsum (Blakey and Middleton, 2012). Much of this sandstone is interpreted to have formed in eolian
environments with mudstones forming in coastal-plain settings and gypsum in the coastal sabkhas (Blakey, 2003). The Supai Group is overlain by the Hermit Formation which consists of sandstone, mudstone, and localized conglomerates. This unit formed on a broad coast in a fluvial dominated setting with some scattered eolian deposits (Blakey, 2003). The Coconino Sandstone overlies the Hermit Formation and is made up of yellow, cross-stratified sandstone deposited in an arid eolian environment (Blakey, 1990).

During the late Leonardian – earliest Guadalupian, seas fluctuated due to glaciation in the southern hemisphere causing a shallow epeiric sea to cover a broad, flat coastal plain (Blakey, 2012). Marine conditions became dominant, depositing the Toroweap and Kaibab formations (figure 2). Both of these formations consist of limestone, dolostone, sandstone, and bedded gypsum (Blakey, 2012; Nielson, 1986; Sorauf, 1991; McKee, 1938). Findings from McKee (1938) indicate that the sea transgressed from the west.

The Kaibab Formation was deposited on a broad, shallow-dipping carbonate ramp in an epeiric seaway (Goolsby, 1988; figures 2). The paleoshoreline trends in a north-south direction from Page, Arizona to Flagstaff, Arizona (Sorauf and Billingsley, 1991). Because authors of previous works have never described a reef or a shelf edge which would indicate a
rimmed carbonate platform, the shallow-dipping rimless platform is more representative of a carbonate ramp (Goolsby, 1988). The Kaibab Formation lacks a high energy facies belt offshore like traditional rimmed platforms have under the description of Schlager (2005). Wave-action also likely dissipated due to friction across the broad platform (Irwin, 1965; Cheevers and Rawson, 1979; figure 3). Depositional environments in the Kaibab Formation range from shallow-
marine, sabkha, restricted coastal-plain, and local continental environments (Blakey and Middleton, 2012). The seas receded in the late Permian, leaving the carbonate ramp exposed to a period of erosion which extended into the Triassic forming the Permo-Triassic unconformity; this marks a significant sequence boundary in the region.

Between the late Permian and early Triassic, fluvial processes were dominant, depositing the Rock Canyon Conglomerate in incised channels across northern Arizona and southern Utah (Nielson, 1986). Erosion continued until a shallow seaway returned to the area later in the Triassic, unconformably depositing the Moenkopi Formation on the eroded topography of the Kaibab Formation (Nielson, 1986). The Moenkopi Formation is characterized by shallow marine and broad tidal flat deposition with limestones, red sandstones, siltstones, and mudstones. Ripple marks, scour marks, and mud cracks are common in this formation (Blakey, 2012).
Regional Structure

The structural geology of the Grand Canyon Region has evolved significantly; the western portion of Laurentia experienced deformation from Mississippian through Permian time during the uplift of the Ancestral Rocky Mountains, which served as a significant source of clastic material (Maughan, 1990). Further deformation and uplift is related to the Laramide orogeny such as the Colorado Plateau on which numerous smaller plateaus formed like the Kaibab Plateau.

The Colorado Plateau is a prominent uplift covering western Colorado, New Mexico, eastern Utah and northern Arizona (figure 4). It consists of a 30 mile thick slab of crust that has uplifted the rocks at the surface over one mile above sea level (McQuarrie and Chase, 2000); today, Permian rocks of the Grand Canyon region lie on the western portion of this structural feature. Several models have been proposed for the formation of the Colorado Plateau such as crustal thickening through horizontal shortening, magmatic injection (Morgan and Swanberg, 1985), and displacement of lower crust (Bird, 1984). The timing of the uplift has stirred controversy in the scientific community for years. Hypotheses present evidence for Oligocene-Miocene or a Pliocene-Pleistocene uplift of the Colorado Plateau (McQuarrie and Chase, 2000).
The Kaibab Plateau is a north-south trending asymmetrical anticline on the western portion of the Colorado Plateau (Tindall and Davis, 1999) running from northern Arizona into southern Utah; it provides extensive exposures of the Kaibab Formation. The eastern limb of this Laramide fold is known as the East Kaibab Monocline (figure 5). Like other monoclinal features found on the Colorado Plateau, the formation of this fold is the result of drape folding of sedimentary rocks over near-vertical basement faults that were likely reactivated during the Laramide Orogeny (Tindall and Davis, 1999). It is important to note
that sedimentary formations are known to thin significantly where drape folding takes place (Tindall and Davis, 1999).
Figure 5: Left: structural geology of the Grand Canyon region highlighting the study area of Tindall and Davis (1999) which refers to the detailed map in the right figure. Right: a detailed structure map of the East Kaibab Monocline with an easterly dip, caused by reactivation of a Precambrian fault (Tindall and Davis, 1999).

Stratigraphy
a study on the Kaibab Plateau where he designated the type locality of the Kaibab Formation in Kaibab Gulch, now known as Buckskin Wash, on the north side of the Grand Canyon.

Work by McKee (1938) was the first to recognize the Toroweap Formation and separate it from the Kaibab Formation. McKee (1938) inconveniently used the Greek letters alpha (α), beta (β), and gamma (γ) (figure 6) when naming the three members of both the Toroweap and Kaibab Formations; the Greek letters made the members ineligible for formalization under the North American Stratigraphic Code. Sorauf (1962) presented formalized names for all members of the Toroweap and Kaibab formations. The Toroweap Formation now consists of the Seligman, Brady Canyon, and Woods Ranch members; with the Fossil Mountain and the Harrisburg members formally making up the Kaibab Formation (figure 6). Nielson (1986) later added the East Clear Creek Member and the Hurricane Cliffs Tongue to the nomenclature and also declared the Rock Canyon Conglomerate to be an independent formation from the Moenkopi Formation due to being of different depositional origins (figure 6).
### Figure 6: Nomenclature of the major studies of the Kaibab Formation, compared with Nielson's study in far right column (from Nielson, 1986).

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- Rock Canyon Cong.
- Fossil Mtn.
- Clear Creek Mbr.
- Hurricane Cliffs Tongue
- Woods Ranch Member
- Brady Canyon Member
- Seligman Member
- Coconino Sandstone
- Hermit Formation
- Queontaweap Sandstone
- Supai G.
Toroweap Formation

The Toroweap Formation overlies the Coconino Sandstone (Cheevers and Rawson, 1979) and consists of limestone, dolostone, sandstone, bedded gypsum, and sandy mudstone (Blakey and Middleton, 2012). The Toroweap Formation is overlain by the Kaibab Formation and consists of the Seligman, Brady Canyon, and Woods Ranch Members. It was deposited during a single marine transgression and regression (Kunkle, 1965; Nielson, 1986; figure 7). East of the Grand Canyon, all three members grade into cliff-forming dolomitic sandstone with low-angle crossbedding (Rawson and Turner Peterson, 1979; Billingsley et al, 1985). McKee (1938) separated the Toroweap into eastern and western phases based on general lithological changes. The eastern phase consists of beach facies and littoral sandstone facies; the western phase is made up of marine carbonates and evaporites (McKee, 1938; Irwin, 1987). The gradational change between the two phases made this a difficult method of division and would be represented in cross-section with a vertical zig-zag cutoff. A north-south trending paleoshoreline was noted in the work of Sorauf and Billingsley (1991) where limestone grades eastward into sandstone.

Seligman Member. This member is named after its type section in Seligman Arizona. Gypsum is very common in this unit and in some places, makes up a significant volume of the rock (Rawson and Turner-Peterson, 1979). In the Grand Canyon region, it is recognized by Sorauf and Billingsley (1991) and
Nielson (1986) as a slope-forming unit containing lenses of gypsum, siltstone, sandstone, dolomite, and gray limestone.

Brady Canyon Member. This member makes up a massive limestone cliff in the middle of the Toroweap Formation (Neilson 1986) and is named after its type locality in Brady Canyon on the east side of Toroweap Valley (McKee, 1938). It consists of thick to very thick beds containing round chert nodules and silicified fossil fragments (Nielson, 1986). The Brady Canyon Member contains abundant poorly preserved crinoids and brachiopods that are disarticulated,
broken, and abraded. This unit grades into a buff to pale-red, fine-graned, thin-bedded, quartz sandstone with carbonate cement to the southeast (Sorauf and Billingsley, 1991).

**Woods Ranch Member.** The Woods Ranch Member is the uppermost member of the Toroweap Formation. It forms a slope made up of a gypsiferous siltstone and sandstone (Sorauf and Billingsly, 1991). Nielson (1986) describes the Woods Ranch Member as a pale orange, blocky, thin-bedded dolostone at its base, with a gypsiferous siltstone overlying it. Dissolution of some of the gypsum is suggested by its variation in thickness. It also contains diapiric structures and clastic dikes (Nielson, 1986). Loading, caused by the deposition of the overlying Fossil Mountain Member of the Kaibab Formation, may also have affected the thickness of the Woods Ranch Member across southern Utah (Nielson, 1986). McKee (1938) documented the presence of a disconformity between the the Toroweap Formation and the Kaibab Formation which was supported by Nielson (1986).

**Kaibab Formation**

The Kaibab Formation is characterized by both open-marine, and restricted-marine environments. The lower Fossil Mountain Member was deposited in open-marine conditions (figure 7). The upper Harrisburg Member was deposited during a regression and is represented by restricted-marine conditions. Both the Fossil Mountain and the Harrisburg members grade
eastward into almost pure sand and become indistinguishable as they reach what has been interpreted as the relative paleo-shoreline (Mckee, 1938).

**Fossil Mountain Member.** The Fossil Mountain Member consists of a light gray, cherty limestone associated with deposition during a transgression (figure 7), and correlated with the massive cliff that it forms across the region (Reeside and Bassler, 1922; Nielson, 1986; Sorauf and Billingsley, 1991). Its type locality is located on the Bass Trail on the south rim of the Grand Canyon (Sorauf and Billingsley, 1991); the cherty limestone is interbedded with sandy limestone and contains abundant Leonardian fossils. Nielson (1986) classified it as a biomicrite to biosparite with an average thickness of 300 ft. The base of the Fossil Mountain Member is identified where massive limestone cliffs overlie the gypsum-rich Woods Ranch Member of the Toroweap Formation (Cheevers and Rawson, 1979).

Cheevers and Rawson (1979) followed the work of McKee (1938), by splitting the Fossil Mountain Member into western and eastern phases, with both of the phases gradually grading into one-another. The western region is mostly fossiliferous limestone with abundant bryozoans, crinoids, and sponges (Cheevers and Rawson, 1979; McKee, 1938). The eastern region is characterized by a decrease in bedding thickness and the eventual gradational combination of both the Fossil Mountain Member and the overlying Harrisburg Member. The study done by Cheevers and Rawson (1979) differed from many
past works on the Kaibab Formation in that it analyzed petrographic textures rather than biostratigraphy. Using this method, they identified four major facies within the Fossil Mountain Member based on the dominant lithology from west to east (figure 8): 1) the dolomitic skeletal waskestone (dsw); 2) dolomitic skeletal mudstone (dsm); 3) dolomitic mudstone facies (dm); and 4) a sandstone facies (ss). Cheevers and Rawson (1979) also identified five major changes in stacking patterns consisting of three transgressions and two regressions in the Kaibab Formation. However these shifts in stacking patterns are not represented in the facies maps.
Petrologic studies of the Fossil Mountain Member indicate that at the time of deposition, it was a poorly washed biosparite with mud deposited behind the shadow of allochems; infilling of sparry calcite occurred later (Nielson, 1986). Dissolution of fossils followed, along with partial dolomitization. The newly formed secondary porosity was then filled in by silica (Nielson, 1986). The percentage of clastic material in this member is highly variable throughout all of the facies (Cheevers and Rawson, 1979). Sandstones found in the eastern region of the Fossil Mountain Member contain mostly quartz with trace amounts of feldspar.

Figure 8: Map of facies of the Fossil Mountain Member showing its maximum extension. Abbreviations: dm – dolomitic mudstone; dsw – dolomitic wackestone; dsm – dolomitic skeletal mudstone; ss – sandstone (after Cheevers and Rawson, 1979).
due to the discontinuity of gypsum (Sorauf and Bilingsley, 1991). The Harrisburg Member was split into eastern and western phases by (McKee 1938) which was followed by Cheevers and Rawson (1979). The western phase is mostly made up of dolomite, gypsum and limestone. The eastern phase does not contain any evaporites and is more dominated by limestones and siliciclastics.

The common method of facies analysis in past works included facies mapping; lithofacies were classified by determining the dominant lithology in an area to create general maps. McKee (1938) identified five facies (figure 9) in the Harrisburg Member with facies 1-3 being the broadest in extent. These divisions were made based on lateral changes in dominant lithology and fauna. The most westward facies (facies 1) contains red beds, gypsum, and thin-bedded limestones. Faunas of this facies are mostly mollusks with some brachiopods. To the east, facies 2 lacks evaporites and contains red beds and thin-bedded limestones; It is also noted to be thinner than facies 1; Facies 3 is found to the south and southeast of the Grand Canyon where the Harrisburg contains mostly thin-bedded, magnesian limestones but lacks gypsum and red beds. Fossils are poorly preserved in facies 3 and are preserved mostly as internal or external molds of pelecypods, scaphopods, and gastropods (McKee, 1938).

Cheevers and Rawson (1979) also mapped facies in the Harrisburg Member using dominant lithologies. They documented dolomitic mudstone facies surrounding the gypsum facies in a seaward and shoreward direction;
McKee (1938), Edie (1958) and Irwin (1965) both documented similar facies configurations. Cheevers and Rawson (1979) noted that this arrangement of facies indicates a discrepancy in the depositional model for the Harrisburg Member (figure 10). Two hypotheses were presented to explain the presence of dolomitic mudstone shoreward of the gypsum facies: 1) large volumes of fresh water influx from the continent diluting hypersaline brines; and 2) the sea is
thought to have transgressed far enough to connect the Kaibab Formation to the San Andres Formation of New Mexico, diluting hypersaline brines (Baars, 1962).

Permo-Triassic Unconformity

The contact between the Harrisburg Member and the overlying Triassic Moenkopi Formation is marked by an erosional unconformity representing a gap in time possibly starting in the Leonardian (figure 11). Large erosional channels are cut into the Kaibab Formation throughout northwestern Arizona. In southwestern Utah, conglomerates and breccias have been deposited in channels and karst depressions. Such units are represented by the Rock Canyon...
Conglomerate or other basal conglomerates (Nielson, 1986; Cheevers and Rawson, 1979). Some erosional channels are cut as deep as 200 feet (Reeside and Bassler, 1922). The exact time span represented by the unconformity is unknown; this high magnitude regression could have been caused by tectonic uplift, basin subsidence to the north, or withdrawal related to Permian glaciation (Irwin, 1971).

Figure 11: The Permo-Triassic unconformity (red dashed line) truncating the Kaibab Formation and overlain by fluvial deposits of the Rock Canyon Conglomerate. Scale bar 2ft.
Rock Canyon Conglomerate

The Rock Canyon Conglomerate (figure 11) overlies the Permo-Triassic unconformity and was named for exposures in Rock Canyon, Arizona by Reeside and Bassler (1922). Clastic material consists of boulder, cobble, and pebble sized clasts in a sandy matrix; sedimentary structures indicate deposition in fluvial channels (Nielson, 1986). Nielson (1986) noted its fluvial origins; separating it from overlying and underlying marine rocks; he therefore suggested that it be elevated to formation status.

Moenkopi Formation

The Moenkopi Formation unconformably overlies the Kaibab Formation throughout northern Arizona and southern Utah. Lithologies consist of red and yellowish-gray siltstone, sandstone, mudstone, and limestone (Blakey, 1973; Nielson, 1986). This formation is part of an extensive red bed sequence formed as a result of the uplift of the Ancestral Rocky Mountains. Much of the clastic material was sourced from the Uncompahgre Uplift composed of Precambrian gneiss, schist, and granite (McKee, 1954; Blakey, 1973). The Timpoweap and Lower Red members the Moenkopi Formation are all known to make contact with the underlying Kaibab Formation across the region (figure 12). After the Permian, erosion of the Kaibab formation produced topography that was filled in by the members of the Moenkopi Formation as a shallow sea returned to the area, ending a period of subaerial erosion (Nielson, 1986).
Figure 12: Stratigraphy of the Moenkopi Formation.
STUDY AREA

The study area crosses the Grand Canyon region of northern Arizona and southern Utah (figure 1; see Table A1 for locations), which today is located on the western Colorado Plateau. Uplift of this prominent feature and other Laramide folds produced extensive outcrops of the Kaibab Formation in various canyons and fault scarps. The study was conducted across various branches of public land, including Vermillion Cliffs National Monument, the Kaibab National Forrest and public land managed by the Arizona Strip Office of the Bureau of Land Management (BLM). Data collection required reliable means of transportation due to the extreme remoteness of several locations.

A centralized portion of the study area was focused on the east side of the Kaibab Plateau just north of the Grand Canyon; this area is known as House Rock Valley, lying between the Kaibab National Forrest and Vermillion Cliffs National Monument. The eastern limb of the Kaibab Plateau, called the East Kaibab Monocline, provided numerous outcrops in canyons. This feature could be followed for over thirty miles in a northward direction which also resembled depositional strike of the Kaibab Formation. Highway 89A provided access to several outcrops measured in this area with minimal hiking required. House Rock Road provided the best access to sections north of Highway 89A; this gravel
BLM road stretches roughly 40 miles north into southern Utah where it connects to Highway 89. It follows the East Kaibab Monocline for nearly the entire distance. The Kaibab Plateau is also home to the type section of the Kaibab Formation, located in Buckskin Wash, once known as Kaibab Gulch. The type section is located in southern Utah along the East Kaibab Monocline.

Data was collected at other various locations across northern Arizona and southern Utah. The eastern most section was measured in a tributary called Soap Creek that connects to the Grand Canyon. On a map, this section is in close proximity to Cliff Dwellers, Arizona. A section measured on the west side of the Kaibab Plateau was located in a road cut on Highway 89A. Kanab Creek, located southwest of Fredonia, Arizona, is a large tributary of the Grand Canyon and is mentioned by several past authors in their research; a section was measured at the North Kanab Mine, a reclaimed uranium mine, which sits on the rim of the canyon. A range of Permian rocks is visible at Kanab Creek, ranging from the Supai Group to the Kaibab Formation. This section was chosen based on accessibility provided by the mining road. More data was collected along the Hurricane fault escarpment just south of Hurricane, Utah. The fault scarp provides a continuous exposure of both the Toroweap and Kaibab formations. A final section was measured just south of St. George, Utah in Mohave County, Arizona. The section was located on the south bound side of Interstate 15 at the exit on Black Rock Road. This area appeared to be affected by Laramide deformation and gypsum diapiric structures. Weathering of the thick gypsum
units in this area produces small, rolling hills covered in gypsum soil, covering significant portions of available outcrops making it a difficult area to find complete outcrops.
METHODS

This study incorporated outcrop, thin-section, and scanning electron microscopy (SEM) data to help better understand deposition, lithofacies and their relationships in the Harrisburg Member. Outcrop measurements and descriptions were used to develop a stratigraphic framework; thin-sections provided further information on lithofacies and diagenesis; and imaging via scanning electron microscopy yielded higher resolution of samples when needed.

Fourteen stratigraphic sections were measured across northern Arizona and southern Utah. A thirty mile long, north-south transect consisting of eight sections was measured following depositional strike on the East Kaibab Monocline. Six sections were measured along depositional dip of the carbonate ramp in a 100 mile long east-west transect. Section locations were chosen based on: accessibility; the possible presence of a complete section determined by satellite imaging and topographic maps; and locations measured in past works. All measurements were made using a Brunton Compass and a Jacob’s staff. At locations where beds dipped at an angle greater than five degrees apparent dip was used to acquire the most accurate measurement possible.

While measuring outcrops, observations of each lithologic unit were recorded in detail using criteria from the United States Geological Survey
Stratigraphic Nomenclature and Description: 1) general lithology, 2) specific lithology, 3) color of a fresh surface, 4) color of a weathered surface, 5) bedding thickness, 6) presence of sedimentary structures, 7) clast descriptions, 8) unique minerals present, 9) weathering profile of unit (cliff or slope), 10) fossils present, and 11) conformity or nonconformity of the lower contact. Data was not collected on covered slopes except for approximate thickness measurements. Hand samples of each lithologic unit were also collected; later twenty one samples were chosen for thin-section analyses.

In order to provide more information on the depositional environment and complex diagenetic history of the Harrisburg Member, twenty-one thin sections were analyzed using a petrographic microscope to supplement the facies analyses. Thin sections are described based on: 1) grains present, 2) texture, 3) cements present, 4) replacements, 5) dolomite, 6) evidence of compaction, and 7) porosity. Billets were cut from samples collected in the field and were sent to Tulsa Sections in Tulsa, Oklahoma to be cut into thin-sections. Carbonate samples were half stained with alizarin red S to differentiate calcite from dolomite. Scanning electron microscopy was also used to image samples which required higher resolution.

Outcrop and thin section analyses aided in the identification of six lithofacies which were put into a stratigraphic framework. Correlations were made to identify stratal-surfaces, parasequences and sequences. Together they shed
light on the overall shoreward or landward migration of facies as well as their relationships.
RESULTS

Lithofacies

Observations in the field and petrographic analyses lead to the identification of six lithofacies: 1) oolitic-pelletal grainstone, 2) dolomitic mudstone, 3) skeletal wackestone-packstone, 4) dolomitic sandstone, 5) red siltstone, and 6) gypsum lithofacies. Designation of these lithofacies was based on constituents and their percentages in both carbonate and siliciclastic sediments; the method of Dunham (1962) was used to classify carbonate rocks and the Dott classification scheme (1964) was applied to siliciclastic sediments.

Petrographic analyses and scanning electron microscopy also provided insight on the complex diagenesis that each lithofacies underwent. Dolomitization has affected both members of the Kaibab formation and was observed in several lithofacies pervasively replacing carbonate mud, degrading original textures, and appearing as cement. Replacement of carbonate mud and later dolomite cementation indicates dolomite precipitated in at least two diagenetic events. Multiple models could be responsible for the pervasive dolomitization of the Kaibab Formation.
Oolitic-pelletal grainstone.

This facies consists of concentrically coated fecal pellets and ooids with sparse skeletal fragments found in the upper-most unit of the section at Soap Creek, Arizona (figure 13). The unit is well washed with very little mud present and is held together by fine-grained dolomitic cement. The lack of mud suggests that the environment was subject to enough energy that it was winnowed away; it is believed to be a tidal related deposit. Cross-laminations also suggest some type of tidal deposit with enough energy to transport the grains, but not to form a large cross-bedded shoal type deposit. The presence of ooids is indicative of elevated salinities according to Lees (1975).

Figure 13: Oolitic-pelletal grainstone found at Soap Creek Arizona, likely representing nearshore deposition with higher energy, washing away mud. All grains appear to be coated and were later pervasively dolomitized. Red arrows indicate ooids, yellow arrows indicate fecal material. Red is staining of calcite, white is porosity. Scale at 500 microns.
This facies has been altered by multiple diagenetic events. A period of meteoric diagenesis took place, leading to partial dissolution of allochems. Lack of significant dissolution indicates relatively shallow burial. Dolomite cement infills several of the intrapartical pores left behind by meteoric dissolution; this constrains the timing of dolomite cementation in this facies. Dolomite cement also infills the primary porosity of this facies.

**Dolomitic mudstones**

The dolomitic mudstone facies is a dominant lithofacies in the Harrisburg member. It contains very few marine fossils indicating deposition in restricted marine conditions. Algal remains were also found in thin-sections of the dolomitic mudstone facies, indicating that precipitation of calcite occurred through both organic and chemical processes (Scholle and Ulmer-Scholle, 2003; figure 14). Quartz sand grains are also scattered throughout the facies. Quartz was observed to be both randomly scattered and in laminations. Bioturbation is found locally along the East Kaibab Monocline represented by vertical burrows filled in with brown chert; sand laminations are also interrupted by bioturbation. Sparse intraclasts are present in several of the samples and are likely products of storm events.

Carbonate mudstones were observed in thin-section to be pervasively replaced by fine-grained sucrosic dolomite; rhombs have an average size of ten microns and are anhedral-subhedral in shape. The lack of preservation of original
fabrics due to alteration to fine-grained dolomite is supported by the findings of Cheevers and Rawson (1979). Laminations are sometimes present in hand samples but very faint due to dolomitization. Replacement of the carbonate mud occurred early in the diagenetic process; large dolomite rhombs were observed in pore spaces indicating a second dolomitization event related to cementation (figure 15). Meteoric diagenesis also emplaced sparry calcite and aragonite cements after dolomitization.
Figure 14: Dolomitic mudstone with an algal fragment (red arrow) and quartz grains. 100 µm
The skeletal wackestone-packstone facies is found throughout the study area representing open-marine deposits and indicative of deeper water (figure 17). Skeletal material decreases upwards in the Harrisburg Member indicating increasingly restricted conditions; however skeletal material also increases westward in a seaward direction. Faunal assemblages are split between the lower and upper portions of the Harrisburg Member. Fossils in the lower Harrisburg Member include brachiopods, bryozoans, and crinoids (figure 17). The upper most unit in the Harrisburg Member covers a broad area with fossils that consist of brachiopods, gastropods, cephalopods, and bivalves; skeletal

Figure 16: Meteoric diagenesis indicated by dissolution leaving a pore space that was filled in with isopachous rim cement (green arrow) and gypsum cement (red arrow).
material is often fragmented and disarticulated. Quartz sand is also common in the upper Harrisburg Member where this facies is present.

![Image](image.png)

**Figure 17:** A bryozoan (red arrow) found in the lower Harrisburg Member at Kanab Mine in Unit H1. Refer to the measured section in figure A7.

The carbonate mud matrix was replaced by fine-grained dolomite and fossils were replaced by silica and sparry calcite. Skeletal fragments in the Fossil Mountain and lower Harrisburg member were dissolved away leaving moldic porosity, some of which was later filled in with white silica. In the upper most unit of the Harrisburg Member, fossils were replaced with sparry calcite and red-orange botryoidal silica (figure 18). Replacement with botryoidal silica cement is likely related to formation of the Permo-Triassic sequence boundary during prolonged exposure to subaerial conditions and meteoric diagenesis.
Dolomitic Sandstone

The dolomitic sandstone facies (figure 19) was found in the eastern portion of the study area and was found as far west as the section at Kanab Mine. Cheevers and Rawson (1979) believed the sandstones in the Kaibab Formation to be from a northern source and transported southward by longshore currents. This facies is classified as a well sorted quartz arenite with subangular to subrounded grains and occasional intraclasts. Quartz grains are cemented together by fine-grained dolomite. Cheevers and Rawson (1979) report the sand
grains to be bimodal with sizes ranging from 0.04 to 0.20 mm. Cross and planar laminations are common in this facies.

This facies contains thin to thick bedded white-gray chert. In thin section, the contact between the chert and the dolomitic sandstone is separated by a narrow dissolution surface; quartz grains at the contact are in a micritic matrix or “muddy” transition zone which quickly cleans outward to quartz arenite. This indicates that carbonate mud was dissolved away and replaced with silica; the dissolution of carbonate mud and silicification appear to have occurred contemporaneously. Laminations of sandstone wrap over and under the wavy character of the chert beds, indicating that chert had to be present before compaction. Scanning electron microscopy was used to further observe the silica and rule out primary deposition of silica by siliceous organisms. Imaging revealed that the chert consists of microcrystalline quartz with dolomite rhombs in pore spaces; no remains of siliceous organisms were found. The dolomite found in the pore spaces of the bedded chert also indicate that a stage of dolomitization occurred after silicification.
The red siltstone facies is a quartz wacke consisting of thinly bedded silt-sized quartz grains with trace amounts of feldspar in a clay matrix (figure 20). The red color is a product of the presence of iron-oxides. This facies is also noted by several authors to be gypsiferous (Nielson, 1986; Sorauf and Billingsley, 1991) which associates it with the gypsum facies in a sabkha environment. This association can be directly observed near St. George, Utah. The red siltstone facies was difficult to study due to usually occurring as a slope, but it was observed under overhangs of carbonate ledges, and in road cuts on the East Kaibab Monocline. This facies is often absent of sedimentary structures, however planar and cross-laminations are present in thin-section.
Gypsum

The gypsum facies was only found in the western portion of the study area. The section measured just south of St. George, Utah contained a seventy foot thick section of gypsum which was likely interbedded with other carbonates and red beds; however much of it was covered by weathered gypsiferous soil. This facies suggests hypersaline conditions at the time of deposition. Nielson (1974) reported rain drop impressions and mudcracks in the gypsum facies indicating that it was periodically subaerially exposed. The gypsum facies of the Harrisburg Member is reported to be interbedded with carbonate mudstone and red siltstone (Cheevers and Rawson, 1979; Nielson, 1986; Sorauf and Billingsley, 1991). This interbedding has also been observed in this study near St. George, Utah (figure 21).
Lithostratigraphic Units

This study includes measured sections in transects that trend down depositional dip, as well as along depositional strike. Carbonate platforms are known for the range of depositional environments they contain and their direct relation to the lateral facies changes that occur across a platform. Therefore, the transect that trends down dip encounters all of the facies of this study where little to no change in facies is found along depositional strike. The lithostratigraphic units in this study will be discussed in this section.

The transect along depositional strike was measured along the East Kaibab Monocline which trends north-south. Eight sections were measured over
roughly thirty miles. This transect encountered many of the same
lithostratigraphic units throughout the sections. The main facies include the
dolomitic mudstone, dolomitic sandstone, red siltstone, and dolomitic
wackestone-packstone facies. Variability between facies is minimal along strike
except for the dolomitic sandstone facies. Changes in the amount of sand
present along the transect is likely related to variability in sediment supply along
depositional strike. The dolomitic wackestone-packstone facies is the uppermost
unit of the Harrisburg Member but is also difficult to study along the East Kaibab
Monocline due to erosion. Its position in the section has made it the most
susceptible to erosion during the Permo-Triassic and present-day erosional
cycles. Therefore, it is not always present across the East Kaibab Monocline.

Stacking along the East Kaibab Monocline normally consists of four
limestone ledges forming a stair-stepping topography. The number of units in a
section is commonly between ten and twelve and have a general facies stacking
pattern listed from bottom to top as the following: dolomitic skeletal wackestone,
dolomitic mudstone, dolomitic sandstone interbedded with chert, dolomitic
mudstone, dolomitic sandstone interbedded with chert, locally bioturbated
dolomitic mudstone, red siltstone, and dolomitic wackestone-packstone facies.
This transect was useful to observe stacking patterns along strike. However, it is
difficult to develop a full sequence stratigraphic context along this transect alone.
The transect measured along depositional dip trends east-west and contains all lithofacies. Lateral facies changes and observation of unconformities across the dip of the platform make this transect very useful in developing the sequence stratigraphic context of the Harrisburg Member. Stacking patterns change across this transect due to lateral facies changes, making every section different from east to west. The eastern-most section at Soap Creek, Arizona is closest to the relative paleo-shoreline mapped by Sorauf and Billingsley (1991). The high amount of sand in the section at Soap Creek supports that model. Sand content also decreases from east to west indicating greater distance from the shoreline. The amount of fossil material in the Harrisburg Member also increases to the west, indicating deeper water and more open-marine conditions. A noticeable thickening of sections occurs to the west as well.

The section at Soap Creek consists of units stacked from bottom to top: sandy dolomitic wackestone, dolomitic mudstone, dolomitic sandstone interbedded with chert, a covered section, dolomitic mudstone, dolomitic sandstone, capped with an oolitic-pelletal grainstone.

Kaibab contained ten units stacked in the order of: skeletal wackestone, cherty dolomitic mudstone, dolomitic mudstone, dolomitic sandstone interbedded with chert, a dolomitic sandstone, a covered section, a bioturbated dolomitic mudstone, unconformably overlain by a chert pebble conglomerate, red and yellow siltstone, and a dolomitic mudstone.
A short and incomplete section was measured on the west side of the Kaibab Plateau at a roadcut along Highway 89A. This section was most useful for documenting the interbedding of carbonate mudstones in the red siltstone facies. The section contains four carbonate mudstones interbedded with three red siltstone beds.

The locality at Kanab Mine offered one of the most complete sections of the Harrisburg Member and contains thirteen units. These units are listed from bottom to top as: dolomitic wackestone-packstone, dolomitic mudstone, a covered section, dolomitic sandstone interbedded with chert, a second cherty sandstone bed, a covered section, a cherty dolomitic mudstone, unconformably overlain by chert pebble conglomerate, a medium grained sandstone, a dolomitic mudstone, a red siltstone, a dolomitic wackestone, and dolomitic packstone. The top unit is truncated by Permo-Triassic unconformity and is overlain by deposits of the Rock Canyon Conglomerate.
The section at Mollies Nipple is located along the Hurricane Cliffs outside of Hurricane, Utah. This is also one of the most complete sections. The fourteen units are listed from top to bottom as: skeletal wackestone, dolomitic mudstone, lime mudstone, another lime mudstone, skeletal wackestone, lime mudstone, a covered section, skeletal wackestone, skeletal packstone, dolomitic mudstone, a covered section, dolomitic mudstone, unconformably overlain by a chert pebble conglomerate, and a gypsiferous lime mudstone.
At St. George, Utah, observations were made at the measured section and the immediate surrounding area. The measured section contains a mudstone, a very thick section of gypsum, much of which was covered, a dolomitic mudstone and a cherty dolomitic mudstone. Observations of the immediate surrounding area found a chert pebble conglomerate stratigraphically lower than the gypsum. This conglomerate is presumed to be correlative to the intraformational chert pebble conglomerate mentioned in previous measured sections.

**Sequence Stratigraphy**

Many of the detailed works on the Kaibab Formation pre-date the development of sequence stratigraphy and others coincide with a time when sequence stratigraphy was not yet refined or widely accepted in the field of stratigraphy. Therefore, the Kaibab Formation has not yet been studied using a sequence stratigraphic method; this study offers a new look at nearly half of the Kaibab Formation using this method.

**Terminology**

Sequence stratigraphy is the analysis of repetitive, genetically related depositional units bounded by surfaces of nondeposition or erosion, otherwise known as unconformities (Galloway, 1989). Parasequences are shoaling upward successions and can be observed in both siliciclastic and carbonate sequence
stratigraphy as the building blocks of systems tracts (Van Wagoner, 1990).

Parasequences are defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative conformities (Van Wagoner et al., 1988). Parasequences can be also be bound above, or below by sequence boundaries. Marine flooding surfaces are surfaces separating younger from older strata across which there is evidence of an abrupt increase in water depth rather than erosion by subaerial processes (Van Wagoner, 1990).

The Harrisburg Member

The data gathered in this study was interpreted to contain two depositional sequences, H1 and H2, separated by an erosional surface or a sequence boundary, SB1. Sequence H1 consists of two parasequences, P1 and P2, and sequence H2 consists of another two parasequences, P3 and P4. Each depositional sequence has a unique facies association (figure 23). These shoaling upward parasequences are observed in this study with flooding-surfaces marked where shallow-water facies are overlain by deeper-water facies. P1 and P2 have a progradational stacking pattern; P3 and P4 have a retrogradational stacking pattern (figure 24).
Figure 23: Top diagram shows depositional environments and facies associations of parasequences 1 and 2. Bottom diagram indicates environments and facies associations of parasequences 3 and 4.
Sequence H1 (figures 25-26) consists of P1 and P2 which have a generally shallowing-upward stacking pattern indicative of a highstand systems tract (HST). Facies are representative of subtidal to intertidal environments. The eastern portion of the study area contains sections from Kanab Mine, the U.S. 89A roadcut, Kaibab Gulch, and Soap Creek, Arizona. P1 begins in the Fossil

Figure 24: Diagram showing the measured section at Kanab Mine highlighting the four parasequences (P1-P4) during the third order regression of the Kaibab Formation.
Mountain Member as a skeletal wackestone and shallows upward into the Harrisburg Member with dolomitic mudstone shallowing upward to dolomitic sandstone. P2 shallows from a dolomitic mudstone to dolomitic sandstone overlain by a tidal deposit of the oolitic grainstone facies at Soap Creek. At Kaibab Gulch, the shallowest facies present is a locally bioturbated mudstone with vertical burrows. H1 is significantly thicker at Kanab Mine but parasequences have similar stacking patterns. Along strike, P1 and P2 have variable amounts of sand which is likely attributed to differences in sediment supply along the shoreline. The dolomitic sandstone facies in P1 has a broader distribution than the sand found in P2. Parasequences P1 and P2 exhibit varying thicknesses along strike which are presumed to be due to different rates of sedimentation or possibly compaction. Inlets, paleo-lows or paleo-highs could have considerable effect stratigraphic units present along strike.

To the west at the Hurricane Cliffs, parasequences P1 and P2 contain facies and stacking patterns indicative of deeper water and more open-marine conditions with crinoids, bryozoans, and brachiopods. P1 shallows upward from a
Figure 25: Dip transect trending from east to west (A-A'). Correlations show parasequences P1 and P2 beneath SB1, overlain by P3 and P4 and SB2.
Figure 26: Strike transect along the East Kaibab Monocline (B-B') showing mostly facies of P1 and P2. Facies of P3 and P4 are not always present. A projected SB1 surface is chosen as the datum.
the Hurricane Cliffs. It is possible that it could have been deposited around a peleo-topographic high or eroded away and therefore not found in the section. Near St. George, Utah, gypsum interbedded with dolomitic mudstone represents a development of a sabkha environment. The chert pebble conglomerate was found near the incomplete section and stratigraphically lower than the gypsum.

P4 overlies P3 and consist of a dolomitic skeletal wackestone-packstone with different fossil assemblages than those found in P1, P2. This parasequence is found as far east as the East Kaibab Monocline representing a rather widespread transgression. The presence of fossils indicate the return of deeper, more open-marine conditions overlying the sabkha related facies and displays a generally shoreward migration of facies. The transgression of H2 was short-lived due to a following forced regression truncating the Harrisburg Member. For this reason, P4 is eroded away and only present at a few localities like Kanab Mine and the East Kaibab Monocline.

The Permo-Triassic Boundary or SB2 has a complex relationship with the underlying Kaibab Formation, the overlying Rock Canyon Conglomerate and Moenkopi Formation. The Rock Canyon Conglomerate represents an unknown amount of time in which fluvial deposition was dominant. The Moenkopi Formation represents a transgression following the subaerial erosion of the Kaibab Formation. Both the Timpoweap Member and Lower Red Member are known to contact the Kaibab Formation across northern Arizona and southern
Utah (Nielson, 1986). Deposition of the different members could be related to the paleo topography of the underlying Kaibab Formation. The Timpoweap Member is a carbonate unit that has been interpreted as filling in paleo-lows and is overlain by the Lower Red Member (Nielson, 1986).
DISCUSSION

The Kaibab Formation has undergone a great deal of study for over a hundred years. However, the concept of sequence stratigraphy has not yet been applied and serves to possibly aid in explaining its stratigraphy, the cyclicity of depositional environments, and lithofacies relationships. Prior works on the Kaibab Formation were conducted using lithostratigraphic correlation methods and facies analysis which were turned into mapped lithofacies (McKee, 1938; Cheevers and Rawson, 1979; Nielson, 1986; figure 10). The use of lithostratigraphy, which goes back to the work of Wheeler and Mallory (1953; 1956), have also had an effect on the way nomenclature is applied to the member of the Kaibab Formation. The following topics will be discussed in this section: the third-order sequence of the Kaibab Formation; the classification of a sabkha depositional environment; the problem with nomenclature as it is applied to the members of the Kaibab Formation; and the issue with the use of lithofacies and lithostratigraphy by past authors.

Third-Order Sequence

Although it is not within the scope of this study to interpret the sequence stratigraphic context of the entire Kaibab Formation, there is enough information available through the work of this study and others to make a general interpretation that estimates where third-order systems tracts lie. The work of
Abbott (1998) states that the Toroweap and Kaibab formations are each third-order sequences and together make up a second-order sequence (figure 27). The Kaibab third-order sequence is bounded by regional unconformities. It is bound at the base by a disconformity between it and the underlying Toroweap Formation and it is bound at the top by the Permo-Triassic Unconformity. The third-order sequence consists of facies stacking patterns that indicate a transgression and a following regression.

Using the general information provided in past works, it is possible that the systems tracts of the Kaibab Formation can be identified. Irwin (1976) indicates that the basal portion of the Fossil Mountain Member is made up of a sandy transgressive facies. The transgressive facies was also identified by McKee (1938) as the gamma member. This could be interpreted as a third-order transgressive systems tract (TST). The highstand systems tract (HST) likely includes the much of the Fossil Mountain Member and the overlying Harrisburg Member.

It is possible that the Kaibab Formation can be further divided into smaller, fourth-order sequences or parasequence sets through the work of Cheevers and Rawson (1979) and Cheevers (1980). This work was not focused on sequence stratigraphy. However, Cheevers and Rawson (1979) made progress in the study of the cyclical deposition of the Kaibab Formation by identifying five “kickbacks” or changes from transgression to regression.
The study identified three transgressions and two regressions. With more work on the Kaibab Formation, these kickbacks recorded by Cheevers and Rawson...
(1979) could be interpreted as three fourth-order sequences or parasequence sets. This study identifies two parasequences representing a seaward shift in facies, and two parasequences showing a shoreward shift in facies. Under this interpretation, the Harrisburg Member could be correlative to the second regression and third transgression of Cheevers and Rawson (1979).

Depositional Environment

Several past works on the Kaibab Formation state that the Harrisburg Member was deposited in a sabkha environment, resulting in thick evaporites (McKee, 1938; Cheevers and Rawson, 1979; Nielson, 1986). This study was unable to produce detailed observations and descriptions of the gypsum in the Harrisburg Member due to its weathering profile; however it was concluded that gypsum occurs in layers of at least six inches or more. Cheevers and Rawson (1979) reported bedding in the gypsum indicates precipitation in a standing body of water such as a brine pan. Mudcracks, raindrop impressions, and chicken-wire structures are said to indicate periodic subaerial exposure of the gypsum (Nielson, 1978; Mathews, 1974). A sabkha is defined by Warren (2005) as a salt-encrusted, supratidal mudflat where intrasediment evaporate growth occurs via ground-water driven capillary processes; although this description does not seem to define the evaporites in the Harrisburg Member. Consideration should be given to a salina depositional model as the possible cause of thicker beds of gypsum in the Harrisburg Member. Salinas fill with subaqueous evaporites with
no surface connection to the sea and brines are supplied by seawater seepage and fresh-water influx (Warren, 2005). However, more work is required to further classify the Harrisburg evaporites as salina deposits.

Nomenclature

The Harrisburg Member is separated from the Fossil Mountain Member at a change in weathering profile and color. It is known to begin at the first break in slope above the cliffs of the Fossil Mountain Member and color changes from gray to yellow (Nielson, 1986). However, the boundary between the Fossil Mountain and Harrisburg Members is gradational without definitively determining a top or base of either member on a particular surface. Fossil material slowly disappears between the upper Fossil Mountain and lower Harrisburg members. This formal nomenclature has resulted in lithostratigraphic units that are not chronostratigraphic in nature. Problems with nomenclature go back to the study of Reeside and Bassler (1921) when they named only the gypsum bearing beds of the Kaibab Formation the Harrisburg Gypsiferous Member. The name Harrisburg was later generally applied to all rocks representative of restricted conditions after realizing that the gypsum was not continuous. The lack of an unconformity or sequence boundary indicates that member nomenclature is an arbitrary surface which is crossed by conformable sedimentation.

It may be more efficient to apply member names specifically to units that are bound by unconformities or erosional surfaces to avoid confusion. The name
Fossil Mountain could be applied to strata below SB1 and the name Harrisburg would be applied to strata in sequence H2. Not only is sequence H2 bound by unconformities, but all of the sabkha-related lithofacies that the Harrisburg Member is known for are well constrained within this sequence.

**Past use of lithostratigraphy and lithofacies**

A significant issue with past works is the method of lithofacies classification. McKee (1938) and Cheevers (1980) designated lithofacies on the basis of dominant lithology at a location (figure 28). This method may have been detrimental to the understanding of the Harrisburg Member for several reasons: 1) it ignores the presence of other lithofacies present at a section; 2) it ignores the vertical relationships of these facies; and 3) it does not account for stratigraphically significant surfaces such as sequence boundaries like SB1. In comparison, the sequence stratigraphic method accounts for vertical and lateral facies relationships and also accounts for the presence of unconformities like SB1.
Figure 28: Lithostratigraphic and facies concepts of Wheeler and Mallory (1956). A) uses arbitrary vertical cutoffs to define lateral contacts. B) Lithofacies of this model are defined by the average gross lithology across several formations and defined are defined by arbitrary cutoffs. C) Conformable lithostromes with diachronous lithosomes which corresponds more with the modern usage of lithofacies. A and B are methods that have been applied to the Kaibab Formation which this work attempts to reconcile (after Bhattacharya and Abreau).
Past use of the lithofacies model eventually led authors to develop facies maps which outlined facies relationships that are uncharacteristic of carbonate depositional environments. Several works (McKee, 1938; Edie, 1958; Irwin, 1965; Cheevers and Rawson, 1979) acknowledged a facies arrangement of dolomitic mudstone surrounding a gypsum lithofacies and particularly shoreward of the gypsum. Edie (1958) and Baars (1962) both presented models to justify this arrangement. However, by using sequence stratigraphy and considering the possibility of a salina depositional environment, lithofacies relationships may be better explained both vertically and horizontally.

This study has highlighted the presence of two depositional sequences H1 and H2 during deposition of the Harrisburg Member and the overall regression of the Kaibab Formation. The lack of gypsum beds, signs of replaced gypsum, or even gypsum cement in sequence H1 suggests that it was deposited under mostly subtidal conditions without precipitation of gypsum. The author is led to believe that sabkha conditions became well developed later, strictly during deposition of sequence H2. This is supported by the following: 1) the gypsiferous red siltstone is only found in sequence H2; 2) gypsum cements were only found in sequence H2, and 3) thick gypsum deposits were only found in sequence H2. The red siltstone and gypsum facies are both associated with sabkha or salina deposition and both only occur above SB1 (figure 25-26 and 29). This constrains sabkha development in time, with deposition occurring strictly in sequence H2.
Figure 29: The map shows the facies model mapped by Cheevers (1980) showing the gypsum facies surrounded by dolomitic mudstone. To the right of the map is a lithofacies model showing the facies relationships displayed on the map. The bottom cross-section is a sequence stratigraphic explanation of the facies relationships between the restricted marine facies tract of sequence H1 and the Sabkha facies tract of sequence H2 (red lines are sequence boundaries SB1 and SB2). The facies of Cheevers (1980) were mapped based on dominant lithology at a given location. Notice in the sequence model that sabkha conditions did not develop until after SB1.
CONCLUSION

This study applied sequence stratigraphic methods to the Harrisburg Member to better explain its facies relationships. The Kaibab Formation was deposited on a broad rimless carbonate platform that is very representative a ramp architecture. The Harrisburg Member was deposited in environments that range from open-marine subtidal to a supratidal sabkha or salina. Facies that were identified were: 1) open-marine skeletal wackestone-packstone containing crinoid columns, bryozoans, brachiopods, and pellets, 2) restricted subtidal dolomitic mudstone that is locally bioturbated, 3) dolomitic sandstones interbedded with chert, 4) oolitic-pelletal grainstone, 5) red siltstone, and 6) gypsum.

Petrographic studies of the Harrisburg Member confirm the classification of these facies and provide information on its complex diagenetic history. Observations of carbonate mud concur with those of McKee (1938), concluding that it is a product of chemical and organic origins. Algal material found in thin-section indicates that organic precipitation of carbonate mud occurred along with chemical precipitation. Thick white-gray chert beds and nodules found in the dolomitic sandstone facies consist of microcrystalline quartz and lack spicules...
and other signs of organic origin. The white-gray chert is believed to be a secondary replacement of micritic mud that was dissolved during an early stage of diagenesis before compaction. Silica has also replaced many of the fossils in the entire Kaibab Formation. The Harrisburg Member was also subject to pervasive dolomitization which appears to have occurred early on in its diagenetic history. Dolomitization is thought to have occurred in two separate events. Fine-grained dolomite has replaced most of the micrite and is also found as cement.

Although it was not the focus of this study, factors observed in thin-section indicate a diagenetic order of the following: 1) dolomitization of carbonate mud; 2) dissolution of micrite and contemporaneous replacement with silica in the dolomitic sandstone facies; 3) dolomite cementation; 4) meteoric dissolution of allochems and pore spaces; 5) cementation emplacing equant sparry calcite, aragonite, isopachous, and gypsum cements; and 6) replacement of skeletal material with botryoidal silica cement. Future works will provide more information to further constrain the complex diagenetic history of the Harrisburg Member.

Lithofacies were grouped into four shallowing upward parasequences (P1-P4) that are bound by flooding surfaces. P1 and P2 consist of facies that were deposited in subtidal open-marine, subtidal restricted-marine and tidal environments. Stacking patterns in sequence H1 show a seaward migration of facies indicative of normal regression likely during a HST. A chert pebble
conglomerate represents an erosional surface and a sequence boundary (SB1) that separates H1 from H2. P3 represents supratidal sabkha or salina deposition and is overlain by P4 deposited in more open-marine conditions. Together P3 and P4 show a shoreward migration of facies representative of a TST. The Permo-Triassic boundary represents SB2, and also makes up a major regional unconformity truncating the Harrisburg Member.

By recognizing surfaces like SB1, sequence stratigraphy is likely a more useful method of interpretation and has shed new light on the Harrisburg Member. The nomenclature of the members of the Kaibab Formation used in past works is not representative of depositional sequences. It may be beneficial to future works on the Kaibab Formation to identify members based on depositional sequences rather than an arbitrary boundary represented by a change in color and topography. Sequence stratigraphic correlations show that the entire Harrisburg Member was not deposited in a sabkha depositional environment; sequence H1 was deposited in a subtidal environment and sabkha conditions did not develop until deposition of sequence H2. This is a new interpretation of the Harrisburg Member that may better explain its facies relationships.
FUTURE WORKS

More work can be done on the Kaibab Formation. A more detailed thin-section analysis is needed to constrain the orders of diagenetic events. Further analysis of the different types of cherts could be a subject of future research. Further analyses could prove the bedded cherts to be more significant. Analysis using x-ray fluorescence or isotope analysis could shed more light on the origin of the chert and the mechanism of emplacement. Stratigraphic sections should be measured further to the west to gain a fuller picture of the stratigraphic context of the different facies in the Kaibab Formation. Past works cite locations in the Beaver Dam Mountains to the west of St. George where sections have been measured. They should be revisited to hopefully take into account the presence of SB1 of this study and further observe the facies stacking patterns between the Fossil Mountain and Harrisburg Members. Ultimately the Kaibab Formation should be correlated with its basinward equivalent which is likely found further west in Nevada. This would provide a more complete stratigraphic framework of carbonate deposition during the Leonardian of the Western United States.
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APPENDIX A

Description of Measured Sections

Figure A1: Map of study area including transect lines A-A’ and B-B’.
Table A1: List of coordinates for locations of measured sections across northern Arizona and southern Utah. Coordinate System: WGS84.

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<th>Symbol</th>
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<td></td>
<td>Planar cross bedding</td>
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<td>Horizontal planar lamination</td>
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<td>Gastropods</td>
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<td>Cephalopods</td>
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<td>Crinoids</td>
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<td>Bryozoa</td>
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<td>Vertical burrows</td>
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<td>Nodules and concretions</td>
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<td>Infraclaste</td>
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<td>Load casts</td>
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<td>Shells</td>
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Figure A2: List of symbols for measured section descriptions.
Figure A3: Description of measured section at Soap Creek, AZ

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<th>SCALE (m)</th>
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<td>10</td>
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Measured Section at Soap Creek, Arizona: Location
Figure A3: Description of measured section at Soap Creek, AZ continued.
Figure A4: Topographic map including location of measured section at Soap Creek, AZ. Location is just south of Highway 89A near Cliff Dwellers AZ.
Figure A5: Description of measured section at St. George, UT.

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<th>SCALE (m)</th>
<th>FORMATION</th>
<th>STRATIGRAPHIC UNIT</th>
<th>LITHOLOGY</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
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<tbody>
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<td>30</td>
<td>H4</td>
<td></td>
<td>Limestone, silty mudstone, fresh color 5Y7/6 moderate yellow, weathered color 5Y7/2 yellowish gray, thick bedding, cherty, weathers to a slope, contact not visible.</td>
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<td>25</td>
<td>H3</td>
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<td>Limestone, gypsum mudstone, fresh color 10YR6/2 pale yellowish brown, weathered color 5Y7/2 yellowish gray, thick bedding, brown chert, weathers to a slope, contact not visible.</td>
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<td>20</td>
<td>H2</td>
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<td>Gypsum, weathered and fresh surface color N0 white, thick bedding, weathers to a slope, contact conformable.</td>
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<td>15</td>
<td>H1</td>
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<td>Limestone, mudstone, fresh color 10YR6/2 pale yellowish brown, weathered color 10YR6/2 pale yellowish brown, thin bedding, weathers to a slope, contact not visible.</td>
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Figure A6: Topographic map including location of measured section near St. George Utah. Location is just south of the Arizona-Utah border on Interstate 15 at the first southbound exit on Black Rock Road.
**Figure A7**: Description of measured section at Kanab Mine along Kanab Creek, outside of Fredonia, AZ.

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<th>SCALE (m)</th>
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<td>Rock Canyon Conglomerate</td>
<td>RC1</td>
<td>Conglomerate, sandy lithic conglomerate, fresh color 10YR8/6 pale yellowish orange, weathered color 10YR8/6 pale yellowish orange, massive bedding, cross-bedding, quartz grains are medium and angular, chert pebbles are angular, weathers to a cliff, lower contact erosional</td>
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Limestone, packstone, fresh color 10YR8/2 very pale orange, weathered color 10YR8/6 pale yellowish orange, massive bedding, fragmented fossils, weathers to a cliff, fossils include gastropods, cephalopods, and brachiopods, contact is conformable.

Limestone, wackestone, fresh color 10YR8/6 pale yellowish orange, weathered color 10YR8/2 very pale orange, massive bedding, fragmented chertified fossils, weathers to a cliff, fossils include gastropods, cephalopods, brachiopods, contact is conformable.

Limestone, mudstone, fresh color 5Y8/4 grayish yellow, weathered color 5Y8/4 grayish yellow, thick bedding, wavy bedding, nodular chert, weathers to a slope, contact not visible.

Sandstone, quartz arenite, fresh color 5Y7/2 yellowish gray, weathered color 10YR8/2 very pale orange, massive bedding, cross-bedding, medium sized grains, angular to sub-angular, chert clasts, weathers to a slope, erosional contact.

Limestone, mudstone, fresh color 5Y7/2 yellowish gray, weathered color 10YR8/2 pale yellowish brown, thin bedded, interbedded chert, weathers to cliff, contact not visible.
Figure A7: Description of measured section at Kanab Mine along Kanab Creek, outside of Fredonia, AZ continued.
Figure A8: Topographic map including location of measured section at Kanab North Mine. This section is along a large canyon called Kanab Creek in Arizona. The section can be found by heading west on the Zion Scenic Byway from Fredonia, AZ, then turning south on Mt. Trumbell Road, and then turning left on an unnamed well graded dirt road to the mine.
Measured Section along the Hurricane Cliffs

Figure A9: Description of measured section along the Hurricane Cliffs outside of Hurricane, UT.
Figure A9: Description of measured section along the Hurricane Cliffs outside of Hurricane, UT continued.
Figure A10: Topographic map including location of measured section on the Hurricane Cliffs just south of Hurricane, UT. This section is preserved under a tertiary basalt flow from a volcanic neck called Mollies Nipple which sits just above the town of Hurricane and is very easily located.
### Measured Section at Kaibab Gulch

**Figure A11:** Description of measured section at Kaibab Gulch in southern Utah on House Rock Road.

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<tr>
<th>SCALE (m)</th>
<th>FORMATION</th>
<th>STRATIGRAPHIC UNIT</th>
<th>LITHOLOGY</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
</tr>
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<tbody>
<tr>
<td>31</td>
<td>H9</td>
<td></td>
<td>Limestone, mudstone, fresh color 5Y5/4 grayish yellow, weathered color 5Y6/4 dusky yellow, massive bedding, weathers to a cliff, contact not visible.</td>
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<td>30</td>
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<td>29</td>
<td>H8</td>
<td></td>
<td>Siltstone, quartz wacke, color 5Y7/6, thin bedded, laminations, weathers to a slope, contact not visible.</td>
<td></td>
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<tr>
<td>26</td>
<td>H7</td>
<td></td>
<td>Conglomerate, sandy lithic conglomerate, color 10YR6/6 dark yellowish orange, thin-thick bedded, cross-stratification, grains are angular pebbles, weathers to a cliff, contact is erosional.</td>
<td></td>
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<tr>
<td>23</td>
<td>H6</td>
<td></td>
<td>Limestone, bioturbated mudstone, fresh color 5Y7/6 moderate yellow, weathered color 5Y7/6 moderate yellow, massive bedding, brown silica infills burrows, weathers to a cliff, burrows are trace fossils, contact not visible.</td>
<td></td>
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</table>
Figure A11: Description of measured section at Kaibab Gulch in southern Utah on House Rock Road continued.
Figure A12: Topographic map including location of measured section at the type section of the Kaibab Formation. It was originally named Kaibab Gulch but has been renamed Buckskin Gulch on newer maps. This location is in southern Utah on House Rock Road south of Hwy 89.
Figure A13: Description of measured section in a road cut on the East Kaibab Monocline along Highway 89A.

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<thead>
<tr>
<th>SCALE (m)</th>
<th>STRATIGRAPHIC UNIT</th>
<th>LITHOLOGY</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Limestone, mudstone, weathered color 10YR8/6 pale yellowish orange, weathers to a cliff (note: unable to properly observe due to high position in roadcut).</td>
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</tbody>
</table>
Figure A13: Description of measured section in a road cut on the East Kaibab Monocline along Highway 89A continued.
Figure A14: Topographic map including location of measured section on the west side of the Kaibab Plateau in a road cut along Hwy 89A. Both sides of the road were observed at this location.
Section 1: House Rock Canyon

Figure A15: Description of a measured section in House Rock Canyon on the East Kaibab Monocline.
Figure A15: Description of a measured section in House Rock Canyon on the East Kaibab Monocline.
Figure A16: Topographic map including location of measured section near the scenic lookout on the East Kaibab Monocline along Hwy 89A.
Figure A17: Description of measured section at Section 2 along the East Kaibab Monocline.
Figure A17: Description of measured section at Section 2 along the East Kaibab Monocline continued.

Limestone, mudstone, fresh color N6 medium light gray, weathered surface 5Y7/6 moderate yellow, thick bedding, calcite, weathers to a cliff, contact not visible.

Limestone, wackestone, fresh color 10YR8/2 very pale orange, weathered color 10YR8/6 pale yellowish orange, thin bedded, nodular chert, weathers to a cliff, fossils include crinoids, contact is conformable.

Limestone, mudstone, fresh color N7 light gray, weathered color N4 medium dark gray, thick bedded, nodular chert, weathers to a cliff.
Figure A18: Topographic map including location of measured section on the East Kaibab Monocline off of Hwy 89A.
Section 3

Figure A19: Description of measured section 3 along the East Kaibab Monocline just north of section 2.
Figure A19: Description of measured section 3 along the East Kaibab Monocline.
Figure A20: Topographic map including location of measured section on the East Kaibab Monocline off of Hwy 89A.
## Section 4

Figure A21: Description of measured section 4 along the East Kaibab Monocline.
Figure A21: Description of measured section 4 along the East Kaibab Monocline continued.

- **Formation**: H1, H2, H3, Fossil Mountain Member

<table>
<thead>
<tr>
<th>Scale (m)</th>
<th>Lithology</th>
<th>Structures / Fossils</th>
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</thead>
<tbody>
<tr>
<td>21-20</td>
<td>Sandstone, quartz arenite, fresh color N8 very light gray, weathered color 10YR8/2 very pale orange, thin bedded, laminations, chert interbeds, weathers to a slope, contact not visible.</td>
<td></td>
</tr>
<tr>
<td>17-16</td>
<td>Limestone, wackestone, fresh color 5Y8/4 Grayish yellow, weathered color 5Y7/2 yellowish gray, thick bedding, interbedded chert, weathers to a slope, fossil include crinoids, contact is conformable</td>
<td></td>
</tr>
<tr>
<td>15-12</td>
<td>Dolomitic wackestone. 10YR 8/2. Bedding is thick with cannonball chert nodules, weathers to a slope with identical faunas to Fossil Mountain member, brachiopods, crinoids, bryozoa.</td>
<td></td>
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<tr>
<td>11-6</td>
<td>Limestone, sandy wackestone, fresh color 10YR8/2 very pale orange, weathered color N3 dark gray, thick bedding, quartz grains are sounded-subrounded, nodular chert present, weathers to a cliff, fossils include brachiopods, bryozoa, and crinoids, contact is conformable.</td>
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</table>
Figure A22: Topographic map including location of measured section on the East Kaibab Monocline accessible by hiking from House Rock Road.
Section 5

Figure A23: Description of measured section 5 along the East Kaibab Monocline.

Conglomerate, lithic conglomerate, 5YR4/6 light brown, thick bedding, cross-bedding, chert clasts are angular, quartz sand grains are subangular-subrounded, weathers to a cliff, unconformable contact.

Limestone, mudstone, fresh color 10YR6/6 pale yellowish orange, massive bedding, chert, weathers to a cliff, conformable contact.

Limestone, mudstone, fresh color 10YR8/6 pale yellowish orange, massive bedding, red/brown chert in burrows, weathers to a cliff, contact is conformable.

Limestone, mudstone, fresh color 5Y8/4 grayish yellow, weathered color 10YR3/6 pale yellowish orange, very thin bedding, chert, weathers to a slope, contact not seen.

Limestone, mudstone, fresh color 10YR8/2 very pale orange, weathered color 10YR8/2 very pale orange, massive bedding, calcite in fractures, weathers to a cliff, contact not visible.

Sandstone, quartz arenite, fresh color N8 very light gray, weathered color N3 dark gray, thin bedding, bedded chert, weathers to a cliff, contact not visible.
Figure A23: Description of measured section 5 along the East Kaibab Monocline continued.

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<tr>
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<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
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<tbody>
<tr>
<td>11</td>
<td>Harrisburg Member</td>
<td>HS</td>
<td>Sandstone, quartz arenite, fresh color 5GY8/1 light greenish gray, weathered color 5GY8/4 light greenish gray, thin bedded, chert interbeds, weathers to a cliff, contact not visible.</td>
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<tr>
<td>10</td>
<td>Harrisburg Member</td>
<td>HT</td>
<td>Limestone, skeletal mudstone, 10YR8/2, very pale orange, weathered color 5Y3/2 grayish brown, thick bedding, ribbon chart at bedding planes, weathers to a slope, fossils include crinoids, contact not visible.</td>
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<tr>
<td>9</td>
<td>Harrisburg Member</td>
<td>HT</td>
<td>Limestone, mudstone, fresh color 10YR8/2 very pale orange, weathered color 10YR8/2 very pale orange, massive bedding, nodular chart, no fossils, contact not visible.</td>
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Figure A24: Topographic map including location of measured section on the East Kaibab Monocline accessible from House Rock Road.
### Figure A25: Description of measured section at Trail Canyon along the East Kaibab Monocline.

<table>
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<tr>
<td>36</td>
<td>Hb</td>
<td>Hamsburg Member</td>
<td>Limestone, mudstone, fresh color 5Y8/4, grayish yellow, weathered color 5Y8/4, grayish yellow, massive bedding, red/brown chert, weathers to a cliff, conformable.</td>
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<tr>
<td>35</td>
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<td>Hb</td>
<td>Limestone, mudstone, fresh color 10YR6/6, darkish orange, massive bedding, red/brown chert in burrows, weathers to a cliff, trace fossils include vertical burrows, contact not visible.</td>
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<td>34</td>
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<td>Hamsburg Member</td>
<td>Limestone, mudstone, weathered color 10YR5/5, thick/massive bedding, sparry calcite in fractures, weathers to a cliff, contact not visible.</td>
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NOTES
Figure A25: Description of measured section at Trail Canyon along the East Kaibab Monocline continued.
Figure A26: Topographic map including location of measured section on the East Kaibab Monocline off House Rock Road.
Section 7

Figure A27: Description of measured section 7 along the East Kaibab Monocline.
Figure A27: Description of measured section 7 along the East Kaibab Monocline continued.
Figure A28: Topographic map including location of measured section on the East Kaibab Monocline off House Rock Road.
Figure A29: Description of measured section 8 along the East Kaibab Monocline.

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<td>41</td>
<td>H8</td>
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<td>Limestone, mudstone, 5Y7/6 moderate yellow, weathered color 5Y7/6 moderate yellow, massive bedding, red/brown chert, weathers to a cliff, vertical burrows, contact not visible.</td>
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Figure A29: Description of measured section 8 along the East Kaibab Monocline continued.
Figure A30: Topographic map including location of measured section on the East Kaibab Monocline off House Rock Road.
APPENDIX B

Description of Thin-sections and Photos

Kaibab Gulch – Unit H4

Figure B1: A porespace in the dolomitic mudstone facies filled with equant sparry calcite (green arrow) and secondary bladed and botryoidal calcite cement. Notice the calcite in the porespace is stained red while the dolomitic matrix is not. Calcite cements are likely a result of meteoric diagenesis, occurring after dolomitization. Matrix (yellow arrow) consists of entirely euhedral to subhedral fine-grained dolomite Scale 500 microns.
Figure B2: Unit H4 composed of almost completely of euhedral to subhedral dolomite that likely replaced micrite. Dolomite rhombs are approximately 0.2-0.3 mm. Signs of the original fabric or laminations cannot be seen. Equant sparry calcite (stained red) can be seen filling in pore spaces as a product of meteoric diagenesis. Scale at 500 microns.
Figure B3: Soap Creek Unit H6 in the dolomitic sandstone facies with fine-grained quartz sand in a dolomitic cement. Cement was likely micritic before being replaced by fine-grained dolomite. Rhombs are euhebral and different sizes appear to have formed over the course of two separate dolomitization events. Poor quality of the slide and thickness causes different extinction colors in this specimen. Scale at 500 microns.
Figure B4: A carbonate clast in the conglomerate at SB1. Contains pellets (red arrows) and other unidentifiable allochems. Clast size is approximately 2 cm. Clast is angular and poor sorting in this specimen is indicated by the presence of quartz sand (yellow arrows) grains, chert clasts (green arrow) and this carbonate clast. Matrix is micrite that has been replaced by dolomite. Scale at 500 microns.
Figure B5: Photomicrograph of the dolomitic wackestone-packstone facies with a brachiopod fossil that has been replaced by silica. The cavity is being filled with radiating silica cement that is possibly chalcedony. The orange color is likely due to inclusion of iron-oxide in the diagenetic fluids. This event likely took place during burial diagenesis. Matrix is micrite replaced by euhedral-subhedral dolomite rhombs which likely occurred in the early stages of diagenesis. Scale at 100 microns.
Figure B6: Oolitic-pelletal grainstone facies found at Soap Creek Arizona, likely representing nearshore deposition with higher energy washing away mud. Pelets (yellow arrows) have a more ellipsoidal shape while ooids (red arrows) are more circular. All grains are concentrically coated and were later pervasively dolomitized. Grains reach sizes up to 1 mm. Pellets (yellow arrows) consist of dark micrite. A brachiopod fragment (green arrow) is seen in the center of the sample. Fine-grained euhedral dolomitic cement is found around and between allochems. Sample is well-sorted and well-washed. Intrgranular porosity is likely a product dissolution during meteoric diagenesis. Scale at 500 microns.
Hurricane Cliffs – Unit H12

Figure B7: Photomicrograph of Mollies Nipple H12 showing a pelletal grainstone with graded bedding that fines upward. Pellets (yellow arrows) consist of micrite and are well sorted. Ellipsoidal shape is indicative of pellets. Pore spaces have developed an isopachous cement (red arrow) around their rims and were later filled in with gypsum cement (green arrow). Dissolution of pore spaces and later cementation is a product of meteoric diagenesis. Unlike most of the Harrisburg Member, this unit has not been dolomitized. Scale at 500 microns.
Figure B8: Dolomitic mudstone facies. Original fabric poorly preserved after dolomitization. Original laminations (red lines) can barely be seen. Unidentified fossils (green arrows) have their long axis oriented parallel with laminations. Micrite was replaced by fine-grained dolomite. Size of dolomite rhombs increases to the top left of the sample. Pore spaces (yellow arrow) are filled with sparry calcite. Scale at 500 microns.
Figure B9: Fine quartz grains in a micritic matrix. Grains are subrounded to subangular and appear well sorted. A single sand lamination (red line) can be seen at the base of the sample. The zone in the center of the slide (green) shows signs of bioturbation. Secondary porosity (blue) in the micritic matrix was dissolved out during diagenesis. Scale at 500 microns.
Figure B10: A second photomicrograph of H11 from section 7. Quartz grains in a micritic matrix (opaque). Smaller grains are subangular-subrounded. Larger quartz grains are well rounded. Laminations (red line) are present indicating episodic deposition of sand. Porosity (blue) is secondary due to dissolution during meteoric diagenesis. Scale at 500 microns.
Figure B11: Allochem is a brachiopod fossil. Orange botryoidal silica cement (red arrows) was emplaced inside the fossil before it was dissolved. The orange color is likely due to the inclusion of iron-oxide in the cementing fluid. The remaining cavity in the center was filled with white-gray silica cement (green arrow). Porosity is blue. The remaining porosity Scale at 500 microns.
Figure B16: Allochem is a brachiopod fossil. Orange botryoidal silica cement (red arrows) was emplaced inside the fossil before it was dissolved. Gray silica cement filled in. The orange color is likely due to the inclusion of iron-oxide in the cementing fluid. Porosity is blue. The remaining porosity Scale at 500 microns.
Figure B13: Quartz arenite (bottom) and white chert (top) of the dolomitic sandstone facies. Quartz grains are very-fine, approximately 0.1 – 0.2 mm. Quartz grains are in a micritic matrix that has been replaced by fine-grained dolomite. Poor quality of thin-section sample does not allow an accurate measurement of the rhombs and does not allow a great deal of resolution of the white chert. Dissolution has taken place between the quartz grains and the chert leaving porosity (blue). Chert is likely a product of early diagenesis and replaced micritic mud. Chert has small needle-like rods but do not appear to be sponge spicules, therefore, chert is not primarily deposited but a product of diagenesis. Scale at 500 microns.
Figure B14: Quartz arenite in the dolomitic sandstone facies. Quartz grains sit in a micritic matrix that has been replaced by fine-grained dolomite. Sandstone cleans upwad as there is no micrite in the upper portion of the sample. Grains in the upper portion of the sample are cemented together by dolomite rather than sitting in a matrix. Scale at 500 microns.
Section 8 H8:Sandy Dolomitic Mudstone

Figure B15: A sample from the dolomitic mudstone facies with very-fine quartz grains (green arrows) in the micritic matrix. Quartz grains are subangular to subrounded. Micrite has been replaced by fine-grained dolomite. Allochem in the center of the sample is believed to be an algal fragment (red arrow). It is not clear whether it is blue or green algae. Small amounts of iron-oxide cement (yellow arrow) are scattered throughout the sample. Scale is 100 microns.
Figure B16: A sample from the red siltstone facies that has been classified as a quartz wacke. Silt-sized quartz grains sitting in a clay matrix. Roughly 5% of the slide consists of feldspar grains while 95% is quartz. A large chert grain also sits in this matrix (green arrow). Micro cross-laminations (red arrows) indicating current flow. Scale 500 microns.
Figure B17: A large chert clast in the red siltstone facies. Grains consist of silt size quart grains and sit in a clay matrix (brown). Chert clast sits in a clay lamination. This sample is classified as a quartz wacke. Scale 500 microns.
Kanab Mine – Unit H1

Figure B18: A thin-section of a dolomitic mudstone. Matrix is fine-grained dolomite. A pore space has been filled with large dolomite rhombs (red arrow) after the initial dolomitization of the micritic matrix, supporting the hypothesis of two dolomitization events. Scale at 100 microns.
Figure B19: SEM photo of a pore space within the bedded chert of the dolomitic sandstone facies with dolomite rhombs (red arrow) growing on micro-crystalline quartz (yellow arrow).
VITA

Cole Hendrickson was born and raised in Hawaii where he attended Kamehameha Schools in Pukalani, Maui. After graduating high school in 2011, he moved to Texas where he earned a Bachelor’s Degree in geology from Tarleton State University in Stephenville, Texas in 2015. Upon completion of his work as an undergraduate he enrolled at Stephen F. Austin State University to complete a Master’s Degree. During the summer of 2017 he completed a geoscience internship at a small oil and gas company in Enid Oklahoma called Maverick Brothers Resources. He received the degree of Master of Science in December of 2017 and accepted a summer internship at Anadarko Petroleum for the summer of 2018. He went on to pursue a career in the oil and gas industry.

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Styled after the Geological Society of America

This thesis was typed by Cole Hendrickson