Lithofacies and Sequence Architecture of the Upper Desert Creek Sequence (Middle Pennsylvanian, Paradox Formation) in the Greater Aneth Field, Southern Paradox Basin, Utah

Evan R. Gunnell
Brigham Young University

Follow this and additional works at: https://scholarsarchive.byu.edu/etd
Part of the Physical Sciences and Mathematics Commons

BYU ScholarsArchive Citation
Gunnell, Evan R., "Lithofacies and Sequence Architecture of the Upper Desert Creek Sequence (Middle Pennsylvanian, Paradox Formation) in the Greater Aneth Field, Southern Paradox Basin, Utah" (2018). All Theses and Dissertations. 7095.
https://scholarsarchive.byu.edu/etd/7095

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in All Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.
ABSTRACT

Lithofacies and Sequence Architecture of the Upper Desert Creek Sequence
(Middle Pennsylvanian, Paradox Formation) in the Greater Aneth Field,
Southern Paradox Basin, Utah

Evan R. Gunnell
Department of Geological Sciences, BYU
Master of Science

The Greater Aneth Buildup (GAB) is comprised of the 3rd-order middle Pennsylvanian
(Desmoinesian) Desert Creek sequence of the Paradox Formation. A hierarchy of 4th- and 5th-
order, carbonate-dominated cycles comprise the Upper Desert Creek (UDC) 4th-order sequence.
A SE to NW trending transect line, utilizing core and petrophysical data from six oil and gas
wells (from SE to NW wells R-19, Q-16, O-16, J-15, K-430, E-313), revealed deposition of
seven carbonate facies within four 5th-order parasequences in the UDC. While each of the seven
carbonate facies are present across the transect line, the UDC parasequences are dominated by a
shallow-water oolite facies. Laterally and vertically, a general facies transition is evident in each
of the four parasequences from a dominantly deeper-water succession of facies in the SE, to a
more shallow-water, open marine to restricted lagoon, succession of facies to the NW.
Parasequence UDC-3 contains the best representation of this facies transition with the SE wells
(R-19, Q-16, and O-16) displaying the deeper-water/mixed algal facies grades into the shoaling
oolite facies in the NW wells (J-15, K-430, and E-313). Within UDC strata, porosity and
permeability correlate well to each other, but poorly to facies type. Porosity and permeability are
predominantly controlled by diagenesis. Minor appearances of fibrous isopachus rim cements,
and more common micritization (both whole grain and envelope) suggest that early-marine
diagenesis occurred within the oolite facies. Meteoric diagenesis is demonstrated by abundant
calcite spar, and drusy dogtooth cements within oomoldic pores, intraparticle pores, and
interparticle pores, in addition to neomorphism of early marine diagenetic fabrics. Spastolithic
oolids, stylolitization, and grain brecciation are representative of burial diagenesis within these
strata. Dolomitization is present in each of the six studied core, but only in minor amounts.
The Upper Desert Creek 3rd-order sequence has preserved laminamoldic diagenetic fabric
that is the oldest known example of selective leaching in a meteoric vadose environment.
Lithofacies trends along transect line A to A’ demonstrate an increase in ooid-rich grainstone
NSCF both vertically and laterally from the SE to the NW. Lithofacies type, combined with
diagenesis, are the major drivers for porosity and permeability creation and destruction within
Upper Desert Creek strata. NSCF, specifically ooid grainstones, have the greatest diagenetic
potential of the seven UDC lithofacies.

Keywords: Aneth, Upper Desert Creek, carbonate, spastolith, diagenesis, Paradox Basin, laminamoldic
ACKNOWLEDGEMENTS

As completion of this project nears I wish to thank many individuals. Special thanks goes to my graduate advisor, Scott Ritter. Scott has been a great mentor to me as an undergraduate as well as during this graduate research project. His knowledge and expertise have been invaluable, and he is very generous with his time and wisdom. In addition, he has become a great friend, and someone I thoroughly enjoy spending time with. Having the opportunity to attend every course he teaches during my time at BYU, especially the week long field trip to Andros Island in the Bahamas, and another trip to the Guadalupe Mountains, has set the foundation for my love of carbonate sedimentology.

Tom Morris and Sam Hudson have both been great instructors and mentors, and they have eagerly shared their experience and expertise. Their time teaching in the classroom and in the field are invaluable to me.

This project would not have been possible without the resources and help of the Utah Geological Survey, and more specifically Peter Nielsen, Thomas Dempster, Thomas Chidsey and Louis Wersan. These men were always ready to help us with the core analysis, and are great men to work with. Additionally, I wish to thank Resolute Energy, and specifically Jason Burris, for their core donation, which was invaluable to my core selection, analysis and research, and will continue to be essential in future projects in the Greater Aneth Field moving forward.

Chanse Rinderknecht, Trevor Tuttle, Geoff Ritter, and Chris Perfili are all solid geologists, who have helped me become a better one myself, and are great friends. It was great working through different problems, and learning together with each of them.

My wife and children are my greatest support, and my reason for all I do. My wife especially, has been the best support I could ask for. We have struggled through difficult
semesters together, and long days of homework and research, but she has been loving and
supportive of me pursuing my dream all along the way. I couldn’t have completed this without
her.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>GEOLOGIC SETTING</td>
<td>3</td>
</tr>
<tr>
<td>Tectonic History</td>
<td>3</td>
</tr>
<tr>
<td>Stratigraphic History</td>
<td>6</td>
</tr>
<tr>
<td>METHODS</td>
<td>8</td>
</tr>
<tr>
<td>LITHOFACIES DESCRIPTIONS</td>
<td>9</td>
</tr>
<tr>
<td>Black Laminated Mudstone</td>
<td>9</td>
</tr>
<tr>
<td>Algal Facies</td>
<td>12</td>
</tr>
<tr>
<td>Intermediate Facies</td>
<td>15</td>
</tr>
<tr>
<td>Skeletal Capping Facies</td>
<td>20</td>
</tr>
<tr>
<td>Non-Skeletal Capping Facies</td>
<td>22</td>
</tr>
<tr>
<td>Restricted Lagoon Facies</td>
<td>24</td>
</tr>
<tr>
<td>Quartz Sand Facies</td>
<td>26</td>
</tr>
<tr>
<td>SEQUENCE STRATIGRAPHY</td>
<td>28</td>
</tr>
<tr>
<td>Contextual Background</td>
<td>28</td>
</tr>
<tr>
<td>Paradox Basin Sequences</td>
<td>28</td>
</tr>
<tr>
<td>Upper Desert Creek Systems Tracts</td>
<td>29</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1- Greater Aneth Buildup Index Map ................................................................. 2
Figure 2- Paleogeographic Map of the Paradox Basin ................................................... 4
Figure 3- Paleolatitude Map of the Paradox Basin ......................................................... 5
Figure 4- Stratigraphic Column ...................................................................................... 7
Figure 5- Black Laminated Mudstone Thin-Section Photomicrographs ......................... 11
Figure 6- Algal Facies Thin-Section Photomicrographs .................................................. 14
Figure 7- Intermediate Facies Heterozoan Thin-Section Photomicrographs .................. 17
Figure 8- Intermediate Facies Photozoan Thin-Section Photomicrographs .................... 19
Figure 9- Skeletal Capping Facies Thin-Section Photomicrographs ............................... 21
Figure 10- Non-Skeletal Capping Facies Thin-Section Photomicrographs ..................... 23
Figure 11- Restricted Lagoon Facies Thin-Section Photomicrographs ......................... 25
Figure 12- Quartz Sand Facies Thin-Section Photomicrographs .................................... 27
Figure 13- Greater Aneth Buildup Cross Section .......................................................... 34
Figure 14- Marine Diagenetic Fabric Thin-Section Photomicrographs ......................... 38
Figure 15- Meteoric Diagenetic Fabric Thin-Section Photomicrographs ....................... 42
Figure 16- Meteoric Oomoldic Diagenetic Fabric Thin-Section Photomicrographs ......... 43
Figure 17- Burial Diagenetic Fabric Thin-Section Photomicrographs ............................. 45
Figure 18- Porosity and Permeability Cross-Plot for Well R-19 ................................... 47
Figure 19- Porosity and Permeability Cross-Plot for Well Q-16 .................................... 47
Figure 20- Porosity and Permeability Cross-Plot for Well O-16 .................................... 48
Figure 21- Porosity and Permeability Cross-Plot for Well J-15 .................................... 48
Figure 22- Porosity and Permeability Cross-Plot for Well K-430 ................................. 49
Figure 23- Porosity and Permeability Cross-Plot for Well E-313 .........................................49
APPENDIX A- Fossil Abundance and Diagenesis Distribution Along A-A’ .........................56
APPENDIX B- Detailed Stratigraphic Columns and Geophysical Logs Along A-A’ ..........62
INTRODUCTION

Middle Pennsylvanian (Desmoinesian) strata in the Paradox Basin of southeastern Utah, contain some of the largest petroleum resources in the state of Utah (Weber et al., 1995). This thesis focuses on the middle Pennsylvanian rocks in the Greater Aneth Field. The petroleum history of the Paradox Basin (and the Greater Aneth Field), including exploration and extraction, dates back to the early 1900’s when surface features were originally used to locate potential petroleum targets. This exploration method offered limited success, until two of the major production companies in the field narrowed the main productive interval in the basin to the middle Pennsylvanian Paradox Formation’s upper carbonate strata in the mid 1950’s (Stevenson and Wray, 2009). Subsequent exploration and production within Paradox Formation carbonates outlined the lateral extent of the Greater Aneth Buildup. The buildup is horseshoe-shaped, opening to the west and covering an area of approximately 115 square miles (Fig. 1). Production to-date totals over 600 million barrels of oil. The Desert Creek interval, divided into a lower dominantly algae-rich wackestone to grainstone (Algal Facies), and upper dominantly oolitic grainstone (Non-Skeletal Cap Facies accounts for more than two-thirds of all the production within the Greater Aneth Field (Peterson, 1992).
A donation to the Utah Geologic Survey (UGS) of core from over 100 wells, many with complete representation of the Desert Creek sequence, was made by Resolute Energy Corp. in 2017. This core donation rounded out the core suite already available at the UGS, and has allowed for an improved characterization of the middle Pennsylvanian strata in the Greater Aneth Field with respect to sedimentology, biofacies, sequence stratigraphy, carbonate petrography, diagenesis, and reservoir characterization (porosity/permeability trends). Former characterization studies were conducted by Weber et al. (1995), Peterson (1966), and Peterson (1992). This study applies the sequence-stratigraphic-based approach adopted by Weber et al. (1995) in the Aneth unit, to a broader transect trending SE to NW across the Greater Aneth Buildup. The added core resources permit more detailed petrographic and diagenetic studies of
the Greater Aneth Buildup than have previously been possible. This thesis is focused on the strata comprising the Upper Desert Creek 4\textsuperscript{th}-order sequence, and is the companion study to that done by Chanse Rinderknecht (2017) focused on the Lower Desert Creek 4\textsuperscript{th}-order sequence along the same transect. These simultaneously conducted studies are the first of many planned studies to provide a more detailed and comprehensive diagenetic and depositional model of the entire Greater Aneth Buildup.

GEOLOGIC SETTING

Tectonic History

The Greater Aneth Buildup is a middle Pennsylvanian (Desmoinesian) carbonate buildup located in the Paradox Basin of southeastern Utah. The Paradox Basin is an intracratonic basin, with a northwest-southeast orientation, that extends from east-central Utah to northwestern New Mexico and into southwestern Colorado (Barbeau, 2003). The basin has an areal extent of approximately 10,000 miles\(^2\) (16,000 km\(^2\)) (Stevenson and Baars, 1988). Although the majority of active subsidence occurred during middle Pennsylvanian (Desmoinesian) time, the tectonics influencing the basin trace back to the Precambrian (Baars and Stevenson, 1981; Kelley, 1958; Stevenson and Baars, 1986). Topographic highs surrounding the basin during the Pennsylvanian include the Uncompahgre and San Luis Uplifts to the east, the Defiance/Zuni Uplift to the south, and the Monument Upwarp/Emery High to the west (Fig. 2) (Blakey, 2009; Guthrie and Bohacs, 2009; Ohlen and McIntyre, 1965). The Oquirrh Basin to the northwest, and the Cabezon Accessway to the southeast connected the Paradox Basin to the Panthalassa Ocean during glacio-eustatic sea-level highs, resulting in deposition of black shale and normal-marine carbonates. During intervening lowstands of sea level, basin restriction resulted in deposition of evaporites and fine-grained, quartz sandstone.
Three major facies belts developed in the basin (Fig. 3): marine black shale, with associated anhydrite and halite on the inner shelf, and in the basin center; thick alluvial deposits shed off the Uncompahgre and San Luis uplifts to the northeast; and on the southwest, cyclic
Figure 3. Paleolatitude map of the Paradox Basin during late middle Desmoinesian (Desert Creek) time. Illustration shows major depositional facies distribution in the basin. Modified from Weber et al. (1995).
shelf carbonates. The Paradox Basin sedimentary fill records a complex interplay between basement uplift, loading, creation of accommodation through subsidence and compaction, differential sedimentation, and salt movement (Peterson, 1966).

Stratigraphic History

Pennsylvanian strata in the Paradox Basin has formerly been split into complimentary lithostratigraphic and sequence stratigraphic subdivisions (Fig. 4). 

Lithostratigraphy- In the Paradox Basin, both formal and informal terminology have been used for Pennsylvanian strata beginning with Woodruff (1910), who assigned the entire succession of Pennsylvanian strata exposed along the San Juan River, to the Goodrich Formation. Wengerd (1958) abandoned Woodruff’s (1910) terminology, opting instead to subdivide the mixed Atokan through Missourian strata into the Paradox and Honaker Trail formations. The former was established for shelf strata and correlative basin-center salt cycles of latest Atokan and lower and middle Desmoinesian age. The Honaker Trail Formation was established for overlying late Desmoinesian to early Missourian carbonate shelf strata that lacked coeval basin-center evaporites and that transitioned upward into mixed carbonate-siliciclastic beds.

The Paradox Formation was further subdivided into informal subsurface zones bounded by easily correlated (on gamma logs) black shales by petroleum geologists (Wengerd, 1963). In ascending order the subsurface zones are: the Alkali Gulch, Barker Creek, Akah, Desert Creek, and Ismay zones. The black shales that defined the bases of the Desert Creek, Lower Ismay and Upper Ismay zones are named the Chimney Rock, Gothic and Hovenweep shales, respectively.

Sequence Stratigraphy- Combined studies of Goldhammer et al. (1991), Weber et al. (1995), and Gianniny and Simo (1996) resulted in the division of the Paradox Formation into a hierarchy of four 3rd-order depositional sequences. These sequences correspond largely with the Barker
Creek, Akah, Desert Creek and Ismay zones (Fig. 4) and are named accordingly. However, the bases of the informal lithostratigraphic zones and corresponding sequences do not exactly coincide. Whereas the lower boundary of the lithostratigraphic zones are placed at the base of the easily recognizable black shale beds, the sequence boundaries are placed a few meters lower, coincident with sequence-bounding exposure surfaces. The few meters of strata between the exposure surface and overlying black shale constitute the transgressive systems tracts of the respective sequences and are generally comprised of a meter-thick sandstone bed overlain by a thin (1 to 2 meters) upward deepening transgressive limestone.

![Stratigraphic column](image)

Figure 4. Stratigraphic column of upper Paleozoic chronostratigraphic, lithostratigraphic, and sequence stratigraphic intervals. Modified from Baars and Stevenson (1982).

The 3rd-order sequences, have been further subdivided by Goldhammer et al. (1991), Weber et al. (1995) into fourth-order depositional sequences based upon a) the occurrence of subaerial exposure surfaces, b) presence of continuous to discontinuous lowstand quartz sandstone bed, c) cycle stacking patterns replicating the deposition of successive lowstand, transgressive stage, and highstand systems tracts, and d) lowstand evaporites onlapping the highstand shelf and carbonate buildups. Fourth order cycles are named, in ascending order, the Lower Barker Creek,
Upper Barker Creek, Lower Akah, Upper Akah, Lower Desert Creek, Upper Desert Creek, Lower Ismay, and Upper Ismay sequences. The fundamental building blocks of these fourth-order sequences are higher-order, 5th-order parasequences. These parasequences are 2-7 meter-thick, shallowing-upward cycles reflecting high-frequency, high-amplitude “ice house” sea-level oscillations (Goldhammer et al., 1991).

METHODS

Upon evaluation of the core made available both from the Resolute Energy donation, and those already at the Utah Geological Survey, 11 slabbed cores were initially selected from the Aneth and McElmo Creek units of the Greater Aneth Field. Of the 11 cores studied, six were chosen (from SE to NW: McElmo Creek R19, McElmo Creek Q16, McElmo Creek O16, McElmo Creek J15, Aneth K-430, and Aneth U E-313) with their associated core and well log data to establish vertical cyclicity patterns, in addition to lateral facies heterogeneities of the Upper Desert Creek sequence. The six well locations were chosen to define a transect across the Greater Aneth Buildup, that offers an evaluation of facies pattern variation from the “windward” (southeast) to the “leeward” (northwest). Additionally, these wells were chosen to afford the most continuous and complete core available. The transect is approximately 22 km long (13.7 miles), with the distance between each well averaging 2 miles. These cores were described with respect to composition, texture, color, significant surfaces, and sedimentary structures and subdivided into facies and parasequences. Thin sections of representative facies and surfaces were prepared (n=197) and analyzed using standard petrographic techniques. This allowed for an accurate analysis of facies extent and faunal distribution. Stages of diagenesis were also evaluated as recorded by marine and meteoric cement growth. Well-log data were used to
evaluate and correlate lithofacies and sequence-stratigraphic trends from well to well across the transect.

When intervals of core were missing, well logs were particularly instrumental in delineating regional correlations.

LITHOFACIES DESCRIPTIONS

A five-part facies classification was developed by Pray and Wray (1963) to describe the Ismay sequence, which overlies the Desert Creek sequence. This classification portrayed the characteristic shallowing-upward trend of Paradox Basin carbonate cycles. Goldhammer et al. (1991), Weber et al. (1995), and Grammar and Eberli (2000) expanded the classification of Pray and Wray (1963) in their subsequent studies of the Paradox Basin. The current study closely follows nomenclature from these stratigraphers in defining the following seven facies found in the Upper Desert Creek sequence. These are presented in a more-or-less offshore (deeper) to onshore (shallower) succession.

Black Laminated Mud Facies (BLM)

*Description-* The black laminated mudstone facies (BLM) is dark-gray to black silty dolomitic shale and shaley mudstone that extends into black sapropelic shales in the basin (Goldhammer et al., 1991; Guthrie and Bohacs, 2009). Goldhammer et al. (1991) first introduced this facies to characterize black shales (including the Chimney Rock Shale) found in the Honaker Trail section in southeastern Utah. Grammar and Eberli (2000) and Guthrie and Bohacs (2009) reported the total organic carbon (TOC) of the Chimney Rock Shale to range from 2-5%. Using thin-section analyses from core samples within the McElmo and Aneth Units of the Greater Aneth Field, it has been determined that the BLM is composed of 40-60% dolomitic carbonate...
mud, 20-35% angular to sub-rounded quartz silt (10-100µm diameter), 5-10% organic rich mud, and 2-5% clay minerals.

**Interpretation**- This facies has been interpreted as the deepest water facies found in the Desert Creek strata due to the high mud and clay content, preservation of laminae, relatively high TOC values, and scarcity of benthonic fossils (Goldhammer et al., 1991; Ritter et al., 2002). These characteristics suggest deep-water, dysoxic, low-energy conditions unfavorable to benthonic organisms. The bedding-plane occurrences of fish teeth and “deep-water” conodont elements (*Idiognathodus* spp; Ritter et al., 2002) indicates open marine conditions contrasting to the “shallow-water” mesohaline model proposed by Weber et al. (1995). This facies represents the maximum flooding of the 3rd-order Desert Creek sequence. Although it is only found at the base of the Lower Desert Creek sequence, it is of note in this study as it is a hydrocarbon source rock for the Aneth Field (Rasmussen and Rasmussen, 2009), and it was used as a datum when correlating core and well logs across the Aneth Field (Fig. 5).
Figure 5. Representative thin-section photomicrographs of the Black Laminated Mudstone (BLM) carbonate mudstone facies as found in the Desert Creek 3rd-order sequence. A) and B) E-313 5899.4’. C) E-313 5931’. D) K-430 5729.3’. E) J-15 5651’. F) R-19 5866.7’. Scale bar equals 1mm.
Algal Facies (AF)

*Description*- Rocks characterized by predominance of phylloid-algal thalli display a range of textures that includes wackestone, packstone, and bafflestone. Characterized by visible macro-porosity, this facies comprises the largest reservoir intervals found in the Desert Creek 3rd-order sequence, and is most commonly and extensively found in Lower Desert Creek strata. The AF is found, however, in Upper Desert Creek strata in core R-19, Q-16, O-16, and K430, but only in 1-3 ft. thick intervals. The phylloid thalli are generally highly altered or broken, with two examples of less altered and broken thalli present from core R-19 and K430 (Fig. 6). Frond margins are commonly micritized with the intraparticle porosity filled with sparry calcite. It is generally accepted that these phylloids are of the genus *Ivanovia*, largely due to preserved supporting examples of diagnostic internal structure from core Q-16 and R-19 (Torres, 1995) (Fig. 6). This facies is split into three categories. 1) phylloid bafflestone facies with abundant shelter porosity. The shelter pores are commonly cement reduced. The characteristic feature of this facies is the phylloid fronds’ ability to baffle mud, partitioning it into grain-supported fabrics in which interstices are filled with variable abundances of sediment and calcite cement. 2) phylloid packstone facies is characterized by grain-supported accumulations of broken algal plates. In general, sparry calcite cementation occurred between the broken fronds. 3) phylloid wackestone facies generally has well-preserved to fragmentary phylloid fronds suspended in a mud matrix. Other skeletal contributors such as small foraminifera, encrusters, brachiopods, and corals are present, but are generally rare (Fig. 6).

*Interpretation*- The phylloid bafflestone is interpreted as forming *in-situ*, in an open-marine depositional environment within the photic zone. The growth of algal mounds depended on their ability to keep pace with sea-level rise. The predominance of phylloid algae is attributed to the
rapid production and accumulation of algal thalli relative to other biotic contributors. The phylloid-algal packstone is interpreted to be deposited in shallow water where the phylloid chips are broken and can be a major grain constituent in packstone. The phylloid wackestone is interpreted as the start of a phylloid algal mound, also referred to as an incipient mound. The phylloid wackestone often grades upward into a phylloid bafflestone.
Figure 6. Representative thin-section photomicrographs of Algal Facies (AF) as found in Upper Desert Creek strata. A) Algal wackestone facies, this algal frond is an example of the preserved internal structure that is characteristic of phylloids, sample Q-16 5507'. B) Algal grainstone facies in the upper half of the image, sample K-430 5616.11'. C) Algal bafflestone facies, representing the partitioning of mud at the top of the image from the mud below; also shows the “unzipping” of the fronds, sample K-430 5608.3'. D) Algal bafflestone facies partitioning mud above and below the fronds, sample J-15 5629'. E) Algal packstone to grainstone facies, sample R-19 5735.7'. F) Algal wackestone to mud-dominated packstone, the left of the larger frond also shows internal structure indicative of phylloids, sample R-19 5767.2'. Scale bar equals 1mm.
Intermediate Facies (IF)

Coined by Pray and Wray (1963), and broadened by Goldhammer et al. (1991), the descriptive term “intermediate facies” is used to describe strata that are normal marine, muddy, and that contain skeletal constituents. Additionally, it describes strata that are deposited in intermediate positions of shallowing-upward cycles within the Honaker Trail and Paradox formations between deep-water black shales or spicule-rich limestone below and high-energy grainstone above. Common components of this facies include crinoid, brachiopod, bryozoan, coral, foraminifera, and sparse phylloid algae fragments (both whole or fragments). The “intermediate facies” description was further subdivided by Grammar and Eberli (2000) into “intermediate-restricted” and “intermediate-diverse” subfacies, dependent on diversity of the skeletal constituents. Rocks of the “intermediate-restricted” subfacies, as the name suggests, contain a relatively low diversity of skeletal constituents, specifically crinoids, brachiopods, bryozoans and ostracodes. Conversely, rocks of the “intermediate-diverse” subfacies not only contain elements of the “restricted” fauna, but also include the addition of small foraminifera, molluscs, fusulinids, rugose corals, Chaetetes, and phylloid algae. In this study of the Upper Desert Creek strata, we have likewise chosen to differentiate between skeletal limestones with higher or lower diversity of skeletal components. Using the terms “restricted” and “diverse” are nonspecific to factors of a physical or biological environment, thus unlike previous stratigraphers we have chosen to differentiate on the basis of light-dependent and light-independent fauna in the intermediate transitional facies. Following the definitions proposed by James (1997), our differentiation results in a lower diversity “intermediate facies-heterozoan,” for rocks with light-independent crinoids, brachiopods, and bryozoans; and a higher diversity “intermediate facies-photozoan,” for rocks including both light-independent and light-dependent fauna.
Intermediate Facies- Heterozoan (IF-H)

Description- The intermediate heterozoan facies (IF-H) is typically characterized by wackestone to mud-dominated packstone that have a heterozoan fossil assemblage containing articulate brachiopods, echinoderms, bryozoans, ostracodes, bivalves, rare trilobites, and rare phosphatic inarticulate brachiopods. Rocks of this facies may be dominated by skeletal elements of a predominant taxon, articulate brachiopods or crinoids, for example, or may also contain remains of multiple heterozoan taxa. The matrix is typically a dense, dark gray to black carbonate mud, and may include laminae in deeper parts of the section, and also contains disarticulated and whole fossils, ranging from coarse sand to gravel size (Fig. 7).

Interpretation- This facies has been interpreted to represent deposition below fair-weather wave base under normal-marine conditions, with intermittent light restriction clouded through turbidity and depth. Updip depositional environments shed microbioclasts that made their way into this depositional environment through storm action. With the presence of a heterozoan fossil assemblage, it is interpreted by James (1997) and Beauchamp and Desrochers (1997), to be evident of a cool-water depositional environment. Due to the low paleo-latitudinal setting of the Paradox Basin during the Pennsylvanian Period however, cool water conditions would be unlikely (Fig. 3) (Roylance, 1990). Low-light conditions may have resulted from presence of air-fall silt or other suspended sediment in the water column.
Figure 7. Representative thin-section photomicrographs of Intermediate Facies Heterozoan (IF-H) found in Upper Desert Creek and Lower Desert Creek strata for reference. A) Skeletal wacke-mud-dominated packstone, sample O-16 5889'. B) Mud-dominated skeletal packstone, sample K-430 5618.4'. C) Poorly sorted mud dominated skeletal packstone, sample J-15 5639.3'. D) Wacke-mud-dominated packstone, sample Q-16 5577.5'. E) Skeletal mud-dominated packstone, sample R-19 5785'. F) Skeletal mud-dominated packstone, sample R-19 5860' (cross polarized). Scale bar equals 1mm.
Intermediate Facies- Photozoan (IF-P)

Description- The “intermediate photozoan facies” (IF-P) is most commonly mud-dominated packstone and wackestone, with a photozoan grain assemblage. The photozoan fossils that are most prevalent in this facies are fusulinids, foraminifera and phylloid algae. The fusulinids are largely representatives of the genus *Beedeina*, though rare occurrences of *Wedekindellina* have been found as well. The foremost smaller foraminifera in this facies are *Endothyra, Tubertina, Paleotextularia, Tetrataxis, Biseriella, Earlandia, Staffella, Bradyina,* and irregular encrusting foraminifera. The IF-P is highly variable and can include the full photozoan fossil assemblage, or be dominated by only a single fossil taxon, and the fossils found in this facies can be whole or disarticulated. Heavy bioturbation is evident in rocks of this facies, with many of the muds having a peloidal matrix that is often clotted with minor shelter pores reduced by sparry calcite (Fig. 8).

Interpretation- The IF-P represents deposition in well-lit marine waters of normal salinity and variable energy as indicated by the presence of light-dependent calcareous algae and fusulinids and variable amounts of matrix mud. The “intermediate facies-photozoan” of this study is largely synonymous with the “intermediate facies-diverse” of Grammar and Eberli (2000). This facies is characterized by bioturbation, diverse skeletal grains, wackestone or packstone textures, and thin undulatory beds.
Skeletal Capping Facies (SCF)

*Description*- The skeletal capping facies (SCF) consists of grain-dominated packstone and grainstone, with disarticulated to whole skeletal grains comprising the dominant grain type. Microbioclasts are also present. Primary interparticle porosity has been partially to completely filled with sparry calcite cement, as a result of minimal mud matrix. This facies is subdivided into three main subfacies categories. A) “crinoidal skeletal cap”: capping facies dominated by disarticulated crinoid columnals. Common characteristics include grain-to-grain dissolution and cement-filled interparticle porosity. B) “foraminiferal skeletal cap”: capping facies dominantly comprised of foraminifera tests and rare peloids. This facies has only been found in one of our six cores (Q-16). The majority of the foraminifera found in this lone example are irregular encrusting foraminifera. C) “diverse skeletal cap facies”: capping facies comprised of a range of skeletal grains. The most common constituents are: *Beedeina*, small foraminifera, crinoids, and rare peloids. Micritization and abrasion are noted in the grain appearance of each of the subfacies categories, also with instances of gradational neomorphism (Fig. 9).

*Interpretation*- Goldhammer et al. (1991) indicated a shallow subtidal or shoaling environment for this facies based on grain-supported textures, observed micritization and abrasion of skeletal debris, and the presence of encrusting foraminifera. This facies developed in 1-5 meter-deep, high-energy channels between the algal mounds. This facies shares similarity with the “intermediate facies-photozoan,” but is unique in its lower carbonate mud content. The SCF is represented in all six cores (R-19, Q-16, O-16, Navajo J-15, K430 and E313).
Figure 9. Representative thin section photomicrographs of Skeletal Capping Facies (SCF) found in Upper Desert Creek and Lower Desert Creek strata for reference. A) Foraminifera-rich skeletal packstone-grainstone, sample R-19 5731′. B) Foraminifera-rich grainstone, sample Q-16 5447.2′. C) Peloidal grainstone, sample K-430 5561′. D) Foraminifera-rich packstone-grainstone, sample J-15 5584.2′. E) and F) Skeletal mud-dominated packstone, sample O-16 5789.8′. Scale bar equals 1mm.
Non-Skeletal Capping Facies (NSCF)

Description- The non-skeletal capping facies (NSCF) is texturally similar to the skeletal capping facies (grain-dominated packstone to grainstone), however the main constituents are non-skeletal grains. In the Greater Aneth Field, the NSCF is subdivided into two main subfacies categories: A) “oolitic non-skeletal cap facies” comprised of ooid grainstone and rare ooid-grain-dominated packstones. Due to the relatively high primary interparticle porosity, diagenetic fabrics found in this subfacies contain a wide range of features. The most common diagenetic features are cement-reduced to cement-filled interparticle porosity, and oomoldic porosity. The matrix is commonly neomorphosed to microspar, with rare occurrences of selective dolomitization. Occurrences of this subfacies are represented in each of the six cores (R-19, Q-16, O-16, Navajo J-15, K430 and E313). B) “peloidal non-skeletal cap facies” similar to the subfacies “A” above, is also most commonly a grainstone to grain-dominated packstone, but is comprised predominantly of peloids. Interparticle pores are partially to wholly filled with calcite cement or mud. Occasional skeletal grains, most commonly brachiopods and foraminifera, are rare components of this facies. In Upper Desert Creek strata this subfacies was only observed in core E313 (Fig. 10).

Interpretation- This facies represents a shallow, high- to low- energy depositional environment, with ooids representing a high-energy, shoal-water environment. Ooids found in the NSCF had an original aragonitic composition, as indicated by the replacement of cortices by equant sparry calcite or selective dissolution of oocortical layers of the entire ooid to form oomoldic pores. Additionally, these ooids would have developed at a time of “aragonite seas” according to Sandberg (1983). The peloidal skeletal cap facies represents a variable-energy, shallow-water depositional environment created by shoaling or a fall in sea level. Peloid-rich
limestones often form in restricted lagoons where circulation is poor. This facies is thin, no more than two meters thick, and is found only in core E-313.

Figure 10. Representative thin-section photomicrographs of Non-Skeletal Capping Facies (NSCF) found in Upper Desert Creek strata. A) Ooid grainstone with laminamoldic porosity, sample R-19 5695.4'. B) Peloidal grainstone, sample E-313 5769.8'. C) Ooid grainstone, sample K-430 5536.9'. D) Ooid and peloid grainstone, sample J-15
Restricted Lagoon Facies (RLF)

Description- The “restricted lagoon facies” (RLF) is chiefly non-skeletal grain wackestone to mud-dominated packstone. Rare disarticulated skeletal grains are observed, usually brachiopod and ostracode fragments. The non-skeletal grains are typically peloids, with minor occurrences of irregular encrusting foraminifera. The restricted lagoon facies is indicated by a clotted texture resulting from microbial-induced mud precipitation, and includes the presence of rare small (2-4 mm) silt-filled burrows (Fig. 11).

Interpretation- The interpreted depositional environment for this facies was a low-energy, restricted-marine lagoon that developed during the onset of the TST or the end of the HST when phylloid build ups or marginal sand bodies dampened energy transfer into the interior banktop lagoon. In Upper Desert Creek strata, this facies is found in cores Q-16, O-16, Navajo J-15, and E313.
Figure 11. Representative thin-section photomicrographs of Restricted Lagoonal Facies (RLF) found in Upper Desert Creek strata. A) Silty mudstone-wackestone, clotted fabric, rhizolith features present, sample Q-16 5467'. B) Peloid grainstone, sample Q-16 5468.1'. C) Peloid packstone-grainstone, sample Q-16 5398.3'. D) Clotted peloid packstone, sample E-313 5872.6'. E) Neomorphosed peloid mudstone-wackestone, sample K-430 5553.8' (scale bar equals .5mm). F) Peloid packstone, sample O-16 5732'. Unless otherwise stated, scale bar equals 1mm.
Quartz Sand Facies (QSF)

Description- The quartz sand facies (QSF) was originally named by Pray and Wray (1963), and has been further used by Goldhammer et al. (1991) and Grammar et al. (1995) to describe strata that are dominated by well-sorted, angular to sub-rounded, coarse silt to fine-grained quartz sand (50-150 µm diameter). There is effectively no clay, but up to 30% calcareous material in the form of peloids, ooids or worn skeletal grains (Goldhammer et al., 1991). Of the six described cores there are four containing 1-2 ft.-thick QSF packages (Q-16, O-16, Navajo J-15, R-19) (Fig. 12).

Above 3rd-order sequence boundaries, thin (1 to 2 meters) beds of QSF are laterally continuous and display trough- and hummocky cross stratification. Above the 4th-order sequence boundary that divides the Desert Creek succession into the Lower and Upper Desert Creek sequences, the QSF ranges from 0 to 50 cm in thickness (Appendix B).

Interpretation- Size, shape, and sorting indicate a distal eolian source for the quartz grains. Concentration of quartz grains occurred on the shelf and on the Aneth Buildup at times of exposure. Hence this facies is interpreted as a lowstand accumulation of wind-blown grains, that was reworked during the ensuing transgression, whether 3rd order or 4th order in duration (Goldhammer et al., 1991). We have interpreted this QSF layer to mark the base of the Upper Desert Creek 4th-order sequence. The best evidence for this interpretation of the stacking relationship, and the associated systems tract is found in core Q-16, as the QSF layer is deposited atop a rhizolith-bearing exposure surface.
Figure 12. Representative thin-section photomicrographs of Quartz Sand Facies (QSF) found in Upper Desert Creek strata. A) and B) Sample J-15 5532’. C) and D) Sample O-16 5717.4’. E) and F) Sample Q-16 5466.6’. Samples represent well-sorted, angular to sub-rounded, coarse silt to fine grain quartz sand. Scale bar equals 1mm.
SEQUENCE STRATIGRAPHY

Contextual Background

When determining stratigraphic packaging at the cycle and sequence scale, different orders of eustatic sea-level rise and fall are integral. The hierarchy of these sea-level oscillations are determined by the duration and characteristic amplitudes of each order. The succession of the stratigraphic forcing subsequent to these oscillations is as follows: 3rd-order oscillations have a 1-10-million-year duration; 4th-order oscillations have a 100,000 year-1-million-year duration; and 5th-order oscillations have a 10,000 year-100,000-year duration (Vail et al., 1977). Schlager (1981) proved that long-term subsidence rates in a shallow-shelf setting are relatively constant with a rate of 1-25 cm/1,000 years. Likewise, Schlager (1981) demonstrated that the collection of carbonate sediment is also relatively constant at a rate of 0.1-1meter/1,000 years. With the rates of long-term subsidence and carbonate sediment accumulation staying relatively constant through geologic time, eustatic sea-level oscillations remain the major forcing mechanism controlling the lithofacies stacking configurations. Climate controls the type of carbonates deposited as well as the presence/absence of evaporites and composition/texture of associated siliciclastics.

Paradox Basin Sequences

Sequence hierarchies for Atokan through Virgilian strata of the Paradox Basin have been proposed by Goldhammer et al. (1991), Weber et al. (1995), Gianniny and Simo (1996), and Rasmussen and Rasmussen (2009). Each of these largely complementary stratigraphies subdivide the Paradox and lower part of the Honaker Trail formations into six 3rd-order composite sequences named (in ascending order) the Barker Creek, Akah, Desert Creek, Ismay, Lower Honaker Trail and Upper Honaker Trail sequences. These are bounded at the base by
regional exposure surfaces that are overlain by a meter-scale “lowstand quartz sandstone”, a thin (1 to 2 meters), carbonate-dominated transgressive systems tract, a maximum-flooding black shale (e.g. Chimney Rock, Gothic, Hovenweep), and overlying highstand to falling stage carbonate accumulation, often rich in phylloid algae or non-skeletal carbonate grains. These are comprised of two or more 4th-order sequences that are in turn comprised of three to four thinner, higher-order (3 to 10 meter) parasequences (5th-order cycles). Fourth-order sequence boundaries are marked by incipient to moderately well-developed exposure surfaces with little or no erosional relief. These may or may not be overlain by thin lowstand quartz sandstone beds. The maximum-transgressive facies of these 4th-order Upper Barker Creek, Upper Akah, and Upper Desert Creek sequences are not black shale, but are comprised of muddy limestone in the 5th-order cycle superjacent to the sequence boundary. The stacking of constituent 5th-, 4th-, and 3rd-order cycles reflect the complex interplay between climate, subsidence, eustatic sea-level oscillations, and sediment accumulation rates across the breadth of the Paradox Basin.

**Upper Desert Creek Systems Tracts**

Representative systems tracts in the Upper Desert Creek strata are the Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), and the Highstand Systems Tract (HST).

**LST:** Designating the boundary between the Lower Desert Creek sequence and the Upper Desert Creek sequence is a subaerial exposure surface marked by calcrete and rhizolith features. These features underlie a LST sandstone found in wells K-430, J-15, and Q-16. Sub-angular, fine-grained quartz grains that are well sorted are indicative of an eolian source for these sand grains.

**TST:** The TST is defined as rocks deposited above the sequence boundary and below the superjacent maximum-flooding surface. During transgression, lowstand quartz sand was
reworked and redeposited. The basal sandstone, where present is overlain by carbonate mudstone, intermediate heterozoan limestone, or peloidal mud depending the position on the buildup. Hence, the TST is variable and poorly represented in this 4th-order sequence.

**HST**: The Highstand Systems Tract comprises the majority of the *UDC* 4th-order sequence as studied in core sample. This ranges in thickness from 45 to 69 feet, and is characterized by a variation in lithofacies types, with the ooid grainstone NSCF representing the dominant facies type volumetrically.

**Description of Individual 5th-Order Parasequences**

The Upper Desert Creek sequence is comprised of four parasequences labeled (in ascending order) UDC 1 through UDC 4. *UDC* 1 is comprised of the LST and TST, and the HST in the UDC sequence comprises the upper part of UDC 1 and overlying parasequences UDC 2-UDC 4 (Appendix B) (Fig. 13). Variations in lithofacies and lateral extent of of these parasequences are discussed below in stratigraphic order from southeast the (“windward”) to northwest (“leeward” side of the Greater Aneth Buildup). These are illustrated in Figure 13 and described below.

**UDC 1**: In well R-19, this parasequence is seven feet thick and is comprised of the following succession of facies: four feet of AF; two, one-foot-thick beds of IF-P, capped by a one-foot-thick interval of carbonate mudstone. Parasequence *UDC 1* in well Q-16 is characterized by a one- to two-foot-thick layer of QSF, representing the reworked LST sand. The QSF is overlain by six to seven feet of restricted RLF. Capping the RLF in this parasequence are four, two-to five- foot thick IF-P layers, with an interbedded layer (two feet) of AF. In well O-16, this parasequence is represented by 10 feet of NSCF, dominated by ooid grainstone. Well J-15, is similar to Q-16, beginning with a one to two-foot-thick QSF, which then transitions to one
to two feet of intermediate IF-H, and is capped by 10 feet of IF-P. Well K-430 begins with three, one to three-foot-thick layers of carbonate mudstone transitioning to 11 feet of missing section, capped by two thin (one to two-foot-thick) layers of NSCF (oolite). Finally, UDC 1 in well E-313 is composed completely of 16 feet of IF-P consisting of peloid, crinoid, brachiopod and foraminifera grain-rich packstone (Appendix B).

UDC 2: In well R-19, the IF-H capping layer from UDC 1 transitions to four feet of shallower IF-P making up the UDC 2 parasequence. In well Q-16, the UDC 2 is characterized by eight feet of shallowing-upward AF wackestone. Well O-16 similarly contains a shallowing-upward succession of strata, beginning with one to three feet of IF-P, with minor occurrences of algal fragments. The IF-P is capped by six feet of RLF. This parasequence is missing in well J-15. In well K-430 this parasequence begins as four feet of AF packstone overlain by one to two feet of IF-P. The initial layers transition to nine feet of missing core that are capped by two, one-to two-foot-thick layers of peloidal grainstone-dominated NSCF. In well E-313, UDC 2 begins with seven feet of missing core, and is capped by nine feet of ooid grainstone NSCF (Appendix B).

UDC 3: In well R-19, UDC 3 is dominated by 12-14 feet of carbonate mudstone facies, that includes minor brachiopod and crinoid constituents. Capping the carbonate mudstone are two, one-to two-foot-thick layers of IF-P dominated by fusulinid-, brachiopod-, ooid- and peloid-bearing mud-dominated-packstones. UDC 3 in well Q-16 begins with seven feet of IF-H, overlain by three to four feet of AF wackestone to packstone, and capped by two, one-to three-foot-thick layers of NSCF dominated by ooid and peloid grainstone. This parasequence in well O-16 differs significantly from well Q-16, which is geographically nearby. UDC 3 in well O-16 coarsens upward from two to three feet of AF, overlain by 10 feet of IF-H, containing minor
crinoid and brachiopod constituents. Atop the IF-H layer is a seven-foot-thick RLF layer dominated by peloid-rich, mud-dominated packstones, capped by three to four feet of NSCF ooid grainstone. Parasequence UDC 3 in well J-15 is comprised entirely of 12-14 feet of coarsening upward NSCF ooid grainstone. Well K-430 contains two NSCF layers of ooid/peloid grainstone totaling eight feet. Finally, in well E-313 this parasequence contains a single four-foot-thick layer of NSCF ooid grainstone (Appendix B).

UDC 4: The initiation of this parasequence in well R-19 is marked by a maximum flooding surface designated by two to three feet of carbonate mudstone deposited atop the underlying IF-P layers. The carbonate mudstone coarsens upward to 12-15 feet of NSCF ooid grainstone. In well Q-16, this parasequence contains four layers of NSCF, the lower being a peloid packstone overlain by three successive layers of ooid packstone-grainstone totaling in 20-21 feet. Well O-16 has an overall coarsening upward trend containing alternating layers of NSCF and RLF ranging from one to nine feet thick. The NSCF are predominantly ooid-rich grainstones, with minor peloid and skeletal constituents; and the RLF are mostly peloid-rich carbonate mudstones or wackestones. Deposition in well J-15 begins with RLF which transitions to three feet of missing core, capped by two layers, three to four feet thick, of IF-P dominated by peloid and skeletal wacke-packstones. UDC 4 in well K-430 begins with three alternating, coarsening upward one foot thick layers of carbonate mudstone and NSCF followed by eight to ten feet of missing core. The missing core interval is capped by two to three feet of NSCF, mostly ooid/peloid packstone-grainstone. Two facies types comprise UDC 4 in well E-313, six to eight feet of RLF dominated by peloidal grainstones, four feet of missing core, and four feet of oolitic grainstone NSCF (Appendix B).
To summarize, the trend of the stacked lithofacies show a general depositional shift of shallow facies (mostly NSCF, RLF and SCF) over time from the windward side (SE) of the Greater Aneth structure early in the 3rd-order sequence deposition, to the leeward side (NW) late in the 3rd-order sequence deposition (Fig. 13).
Figure 13. Greater Aneth Buildup cross section transect of the entire Desert Creek 3rd-order sequence. This illustrates lithofacies distribution and trends, and sequence stratigraphic surfaces from the SE (right) to the NW (left) of the cross section.
BIOFACIES ANALYSIS

This study heavily employed the use of thin-section analysis to determine and delineate trends in fossil abundance, in addition to trends in lithofacies types, sequence stratigraphic systems tracts, and diagenesis. Fossil abundance allows for an evaluation of paleoenvironments during deposition, otherwise unavailable. Overall, the fossil abundance trends support that there is a general shallowing upward nature of the lithofacies in each well except E-313. In well E-313 the shallowing-upward trend is not as apparent, which can likely be attributed to its location on the northern flank of the Greater Aneth Buildup. The increase, and subsequent decrease in fossil abundance, also aid in the placement of the sequence stratigraphic surfaces. In wells Q-16 and J-15, this was utilized when interpreting the presence of a QSF facies, and the placement of the sequence boundary at the bottom of the Upper Desert Creek 3rd-order sequence. (Appendix A)

DIAGENSIS

Heckel (1980) and Heckel (1983) created a paragenetic model, based upon study of classic Midcontinent Pennsylvanian strata, that characterized that timing and influence of marine, meteoric, and burial fluids on lithologic/stratigraphic components of a cyclothem as a function of sea-level rise and fall. Longman (1980), Roylance (1990), and Gournay (1999) each discussed the effects of diagenesis on Pennsylvanian carbonate lithofacies in the Paradox Basin. Herein, five main diagenetic environments will be described in relation to the exposure of the sediments to diagenetic waters as a consequence of sea-level fall. Between initial 4th-order sea-level rise that initiated deposition of the Upper Desert Creek sequence and the 3rd-order sea-level fall that bounds the upper surface of the sequence, sediments were exposed only to marine water resulting in micritization of selected grains and precipitation of modest amounts of marine cement in grain-rich sediments. The sediments were modified by meteoric water only after the
ensuing (sequence-terminating) fall of sea level. A more in-depth discussion of these environments and their effects on the Upper Desert Creek strata will follow.

**Marine Phreatic Diagenetic Environment**

Located at, or below the sediment/water interface, the marine phreatic environment is defined as the zone where all pore space is fully saturated by normal marine fluids. Most carbonate sediment is produced and deposited in this zone, lending to the greatest diagenetic effects those sediments undergo through subjection to boring, micritization, breakage, disarticulation and cementation (chemical) processes. Within the marine phreatic environment there are active and stagnant zones that influence the sediment differently.

*Active Zone:* The fluid-forcing mechanism in this zone includes waves, tides and currents that drive marine fluids through the carbonate sediment. Degassing, photosynthesis and CO2 loss occur in this zone as the marine fluids interact with coarse-grained carbonate sediment most commonly, and often on surfaces with topographic relief, which oversaturates the marine fluid with respect to CaCO3. This oversaturation drives the precipitation of carbonate cements within the sediment (Heckel, 1983). Through geologic time, the oceans have oscillated between production of aragonite marine cements and ooids and calcite cements and ooids, giving rise to the concept of “aragonite seas” versus “calcite seas (Sandberg, 1983). Relative to this study, conditions promoting aragonite seas prevailed during the deposition of the Upper Desert Creek sequence.

The most characteristic imprint of phreatic “active” zone diagenesis in the Upper Desert Creek sequence is the presence of cloudy, fibrous cements on skeletal and non-skeletal grains, best seen in grainstone and grain-dominated packstone intervals (Fig. 14). These cements can be
seen in all wells in the transect, and are most commonly present in facies containing algal (AF), foraminifera (IF-P, SCF), and/or ooid grains (NSCF).

*Stagnant Zone:* This zone, as used herein, occurs where water either moves too slowly to allow for cement precipitation between sediment grains or where grains remain in place over long enough periods of time to be encrusted by organisms or develop micritic coatings. Micritization is pervasive in Upper Desert Creek strata, and in this study is represented by complete micritization of grains, often ooids, to partial enveloping of select grains, ooids and various skeletals (Fig. 14). Encrustation of skeletal elements is present, but relatively rare.

**Marine Vadose Diagenetic Environment**

Within this environment cement precipitation occurs rapidly as CO₂ degasses. Degassing occurs as pores are partially filled by tide or wave-driven marine water along this narrow shoreline zone. Cements precipitated in this environment range from micritic to fibrous aragonitic and high-Mg calcite. Normally meniscus and pendant cements dominate this environment with minor occurrence of isopachous rim cements. The Upper Desert Creek strata however, has little evidence of these cement types.
Figure 14. Representative thin-section photomicrographs of marine diagenetic fabrics found in Upper Desert Creek strata. A) and B) Marine isopachous rim cements on irregular encrusting foraminifera, sample R-19 5731’ (scale bar equals .5mm). C) Marine isopachus rim cements and sparse micritic envelopes, sample R-19 5712.1’. D) Marine isopachous rim cements, sample Q-16 5456’. E) Marine isopachous rim cements, sample Q-16 5451.9’ (scale bar equals .5mm). F) Marine isopachous rim cements and whole to partial micritization of grains, sample K430 5574.2’. Unless otherwise stated, scale bar equals 1mm.
Meteoric Vadose Diagenetic Environment

Halley and Harris (1979), Allan and Matthews (1982), James and Choquette (1984), and Moore and Wade (2013) explained the processes by which meteoric water transforms aragonite and high-Mg calcite sediments into low-Mg calcite limestone through solid-solid calcitization or mineral-controlled dissolution/precipitation reactions.

Exposure to the meteoric vadose diagenetic environment results from the terrestrial exposure of carbonate sediment, either through shoaling or a relative drop in sea level. During this exposure, pore spaces are filled with air and also, intermittently, with meteoric water. The intermittent infilled meteoric water moves downward through the carbonate sediment while dissolving, most commonly, the aragonite and high-Mg calcite, and creating a “zone of solution”. Similar to the Lower Desert Creek time, an arid environment was present during Upper Desert Creek deposition. Any meteoric fluids moving downward through the deposited sediments in this environment would have moved slowly resulting in partial to complete dissolution of aragonite grains (e.g. dissolution of oocortical layers to form laminamoldic pores, Fig. 15 and 16) and cements. Laminamoldic pores result specifically from slow, surgical and selective leaching of ooid cortical layers, often resulting in preservation of the concentric cortical structure. Hazard et al. (2017) investigated this leaching behavior in Pleistocene sediments. Similarly, Cantrell (2006) described laminamoldic leaching within Jurassic ooid sediments of Saudi Arabian shoals. Laminamoldic diagenetic fabric found in the middle Pennsylvanian Desert Creek 3rd-order sequence is the oldest known example of this selective leaching in a meteoric vadose environment.

Conversely to the “zone of solution,” the “zone of precipitation” can be found anywhere in the meteoric vadose diagenetic environment. Meteoric water flowing through carbonate
sediment becomes saturated, with respect to CaCO$_3$, over time. This saturation results in precipitation of calcite cement within interparticle, intraparticle, and evolving moldic pore spaces. The cements that precipitate are low-Mg calcite, and are meniscus or pendant cements, due to the precipitation concentration at grain-to-grain contacts. As crystal terminations are only able to develop at the air-water interface, they are not present in mud-bearing carbonates in the Upper Desert Creek sequence.

**Meteoric Phreatic Diagenetic Environment**

The meteoric phreatic diagenetic environment exists below the water table where pore spaces are completely filled with meteoric water. This fresh water will be saturated in varying amounts with respect to CaCO$_3$. Within this diagenetic environment, there are two sub-environments: the “undersaturated” and “active-saturated” environments. As would be expected, the “undersaturated” environment is characterized by water that is largely undersaturated with respect to CaCO$_3$, thus causing the dissolution of aragonite and high-Mg calcite. This results in vug and moldic pores. Conversely, the “active-saturated” environment occurs where water is saturated with respect to CaCO$_3$, and thus low-Mg calcite cements dominate. Cement precipitation here is not discriminative of primary or secondary porosity, though it will initially fill primary pores, and varies in cement texture from dogtooth rims to blocky spar montages. Furthermore, neomorphism can occur where water moves slowly through the sediment in what Heckel (1983) called the “stagnant-saturated” environment. Minor cementation occurs here. Upper Desert Creek strata in the Aneth Field contain large amounts of neomorphosed cement/sediment.
Meteoric Diagenesis of Upper Desert Creek Strata

Upper Desert Creek strata are most commonly characterized by the presence of cement-reduced porosity through the precipitation of equant sparry calcite, in the form of drusy dogtooth or blocky spar calcite cement. These cements are most prevalent in inter- and intraparticle pores where pores reduced by isopachus rim cements have been further reduced or filled through the precipitation of blocky sparry calcite, similar to recent and Pleistocene oolites studied in south Florida and the Bahamas by Robinson (1967) (Fig. 16). Additionally, another common meteoric diagenetic feature present in these strata is “porosity inversion” where carbonate material is dissolved from aragonitic ooids and skeletal grains and precipitated between constituent grains. This occurs most commonly in the ooid-dominated variety of NSCF rocks. When inverted porosity occurs, reservoir-quality porosity may be created, depending on the connectivity of the leached pores, and whether or not the pores have been further reduced by later stages of cementation.
Figure 15. Representative thin-section photomicrographs of meteoric diagenetic fabrics found in Upper Desert Creek strata. A) Partial to complete dissolution (leeching) of ooid grains, inverted porosity, with precipitated intraparticle calcite cement, sample J-15 5480'. B) Partial to complete dissolution (leeching) of ooid grains, inverted porosity, with precipitated intraparticle calcite cement, sample J-15 5492.5'. C) Pore reducing equant sparry calcite, rhyzolith soil horizon, sample Q-16 5467'. D) Peloidal clotted grainstone with precipitated intraparticle calcite cement, sample Q-16 5468.1'. E) Pore reducing equant sparry calcite within moldic pores, sample O-16 5758.3' 1x. F) O-16 5739.2’ 1x. Scale bar equals 1mm.
Figure 16. Representative thin section photomicrographs of meteoric oomoldic and laminamoldic fabrics found in Upper Desert Creek strata. A) Selective calcitization through selective dissolution and cementation of ooids, sample O-16 5727.3’. B) Selective calcitization through selective dissolution and cementation of the ooids in the middle of the image, and complete leaching of ooids around the edges of the image, sample Q-16 5414.3’. C) Dissolution removed much of the outer cortex, in addition to the nucleus on the right ooid, sample R-19 5695.4’. D) Selective calcitization through selective dissolution and cementation of ooids, sample J-15 5480’. E) Partial dissolution of micritized ooids, sample E-313 5767.6’. F) Selective calcitization through selective dissolution and cementation of ooids in the center, in addition to whole dissolution of ooids on the left, and selective dissolution or cortical layers in ooids in the upper left and bottom right of the image, sample K-430 5536.9’. Scale bar equals 1mm.
Burial Diagenesis

The deep burial diagenesis environment occurs where marine sediments are deeply buried in the marine phreatic environment. As this burial occurs, substantial compaction (mechanical) can occur prior to significant cementation, leaving minimal pore space for cement precipitation (Heckel, 1983).

Evidence of mechanical compaction is represented by partially dissolved and/or deformed ooids (spastoliths) present in core E-313 and K-430, as well as dissolution seams, stylolites, grain to grain suturing (commonly in skeletal cap facies), and brecciation of skeletal constituents found to some degree in each of the six studied core (Fig. 17). With the exception of examples of spastoliths in core E-313 and K-430, no significant mechanical compaction is observed in the predominant ooid facies, likely due to early marine and/or late meteoric cement precipitation within pore spaces. Brecciation and stylolite presence mark the most dominant feature of mechanical compaction in the Upper Desert Creek strata.
Figure 17. Representative thin section photomicrographs of burial diagenetic fabrics found in Upper Desert Creek strata. A) Paritally micritized ooids with meteoric intraparticle cements, represents ooid spastoliths, sample E-313 5785.1'. B) Skeletal packstone indicating grain-to-grain suturing, sample J-15 5555.5'. C) Brecciation of grain constituents, sample O-16 5758.3'. D) Ooid spastoliths and stylolitization, sample O-16 5732'. E) Algal grainstone representing brecciation of algal fronds, and grain-to-grain suturing, sample R-19 5735.7'. F) Skeletal packstone with representative grain-to-grain sutures, sample Q-16 5499.8'. Scale bar equals 1mm.
POROSITY AND PERMEABILITY

In addition to the core donated by Resolute Energy, all the associated thin section and porosity and permeability data were also donated, making this a very rich data set. Utilizing the porosity and permeability data collected from core plugs has allowed for creation of porosity and permeability logs that have been further correlated to the lithofacies descriptions made in our core analysis.

Porosity types include inter- and intra- particle, moldic (including oomoldic), some vugs, and minor shelter pores. Highest porosity values are generally found in NSCF, more specifically in ooid grainstones, but minor instances of high porosity are also found in RLF and IF-P. Well Q-16, for example, illustrates poor correlation between porosity and facies type, as the lowest (~3%) and highest (~22%) porosity values in this core are both found within the NSCF ooid grainstones, illustrating that porosity, permeability and lithofacies don’t always have strong correlation. Porosity, permeability and lithofacies, in general however, do share a strong correlation to each other, and also to lithofacies type (Fig. 18- Fig. 23) (Appendix B).
Figure 18. Porosity and permeability cross-plot from well R-19.

Figure 19. Porosity and permeability cross-plot from well Q-16.
Figure 20. Porosity and permeability cross-plot from well O-16.

Figure 21. Porosity and permeability cross-plot from well J-15.
Figure 22. Porosity and permeability cross-plot from well K-430.

Figure 23. Porosity and permeability cross-plot from well E-313.
Overall, porosity and permeability share a strong correlation to each other, but weakly to lithofacies type. As a result, they alone could be considered poor indicators to designate facies in an effort to find petroleum resources and reservoir quality zones. Thus, the conclusion has been reached that diagenesis greatly determines porosity and permeability, and thus creates or destroys reservoir quality and petroleum resource producibility.

CONCLUSIONS

As a result of the newly available core suite, partially donated from Resolute Energy Corporation, the possibility of an improved characterization of the middle Pennsylvanian Upper Desert Creek sequence in the Greater Aneth Field was realized and conducted. This characterization was completed through further detailed analysis of core, sedimentology, biofacies, sequence stratigraphy, thin sections, diagenesis, and porosity/permeability. Comprised of seven lithofacies, similar to those outlined by Weber et al. (1995), the Upper Desert Creek sequence can be divided into 4 5th-order parasequences. *UDC 1* commonly contains layers of IF-P, as in wells R-19, Q-16, J-15 and E-313, with occurrences of NSCF, carbonate mud, and AF. *UDC 2*, where present in core, is representative of a laterally shallowing succession from SE to NW. *UDC 2* grades from a dominantly AF to wholly NSCF to the NW, with minor layers of IF-P and RLF along the transect. *UDC 3* in the three southeastern most wells shallows from a carbonate mud in R-19, to IF-H in Q-16 and O-16, to NSCF in K-430, J-15 and E-313 in the three northwestern most wells. *UDC 4* is heavily dominated by RLF and NSCF all across the transect, often as alternating layers shallowing to a NSCF cycle cap. One exception is in well J-15, where the parasequence is dominated by IF-P, likely due to its position on the Greater Aneth Buildup. In general, the lateral and vertical shifts in facies along the transect, all support the shallowing upward stacking nature of the 5th-order parasequences.
Just as lithofacies distribution across the Greater Aneth Buildup allow for interpreting a
shallowing upward signature of the 5th-order cycles, faunal distribution further supports this
interpretation, and also further aids lithofacies delineation. Additionally, diagenesis is the major
driver in the creation and/or destruction of porosity and permeability, especially within the ooid-
rich reservoir rocks of the Upper Desert Creek sequence. Early-marine cementation resulted in
isopachus rim cements on non-skeletal and skeletal grains. Pervasive leaching, represented
commonly by laminamoldic porosity, occurred predominantly in the ooid grainstone NSCF near
or at the top of the 5th-order cycles during meteoric diagenetic episodes. The Upper Desert Creek
3rd-order sequence has preserved laminamoldic diagenetic fabric that is the oldest known
element of this selective leaching in a meteoric vadose environment. Further meteoric diagenesis
is evident in the presence of calcite spar and drusy dogtooth cements in IF-P, IF-H and NSCF
across the buildup. Burial diagenesis is limited to compaction (represented predominantly by
grain to grain suturing, skeletal grain brecciation and ooid spastoliths), and stylolitization.

Lithofacies trends along transect line A to A’ demonstrate an increase in ooid-rich
grainstone NSCF both vertically and laterally from the SE to the NW. Lithofacies type,
combined with diagenesis, are the major drivers for porosity and permeability creation and
destruction within Upper Desert Creek strata. NSCF, specifically ooid grainstones, have the
greatest diagenetic potential of the seven UDC lithofacies.
REFERENCES


Baars, D.L. and Stevenson, G.C., 1981, Tectonic evolution of the paradox basin, Utah and
Colorado, In Wieand, D.L. (eds.), Geology of the Paradox basin. Rocky Mountain

Baars, D.L, and Stevenson, G.M., 1982, Subtle stratigraphic traps in Paleozoic rocks of the
Paradox Basin, In Halbouty M.T. (ed.), The deliberate search for subtle traps, American
Association of Petroleum Geology (AAPG), v. 32, p. 131-158.

Barbeau, D.L., 2003, A flexural model for the Paradox basin: implications for the tectonics of the

Beauchamp, B., and Desrochers, A., 1997, Permian warm- to very cold- water carbonates and

Blakey, B.C., 2009, Paleogeography and geologic history of the western Ancestral
RockyMountains, Pennsylvanian-Permian, southern Rocky Mountains and Colorado
Plateau The Paradox Basin Revisited – New Developments in Petroleum Systems and

Cantrell, D.L., 2006, Cortical fabrics of Upper Jurassic ooids, Arab Formation, Saudi Arabia:
Implications for original carbonate mineralogy: Sedimentary Geology, v. 186, p. 157-
170.

example from Middle Pennsylvanian shelf carbonates of the Paradox Basin, In,

Gournay, J.P., 1999, Phylloid algal bioherms and ooid grainstones: characterization of reservoir
facies utilizing subsurface data from the Aneth Platform and outcrop data along the San
Juan River, Paradox Basin Southeastern Utah, unpublished dissertation, University of

Gianniny, G.L. and Simo, J.A.T., 1996, Implications of a unfilled accommodation space for
sequence stratigraphy on mixed carbonate-siliciclastic platforms; an example from the
lower Desmoinesian (Middle Pennsylvanian), southwestern Paradox Basin, Utah, In
Region, Rocky Mountain Section Society for Sedimentary Geology (SEPM), p. 213-
234.


Kelley, V.C., 1958, Tectonics of the region of the paradox basin, In. Sanborn, A.F (ed.), Guidebook to the geology of the paradox basin: Intermountain Association of Petroleum Geologists, p. 31-38


APPENDIX A

Fossil abundance and diagenesis presence and distribution for each well along transect line A-A’.

R-19
APPENDIX B

Detailed stratigraphic columns from analysis of each core along transect line A-A', including analyzed geophysical logs and porosity and permeability data.