PETROLOGY AND DIAGENESIS OF THE DAD SANDSTONE,
LEWIS SHALE, WASHAKIE BASIN, WYOMING

By
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ABSTRACT

The Cretaceous Lewis Shale of south-central Wyoming in the Washakie Basin contains significant natural gas resources. While recent research has included the development of a high frequency stratigraphic framework for the Lewis, the controls on reservoir quality remain poorly defined. This study describes the paragenetic sequence for the Dad sandstone, Lewis Shale using petrographic data from different wells and depths in the Washakie basin.

A better understanding of the characteristics of the Dad sandstone, which is the reservoir rock in the Lewis Shale, was accomplished using thin section petrology, X-ray diffraction and scanning electron microscopy (SEM) using energy dispersive X-ray spectrometer (EDX). Forty thin sections were point counted to determine parameters including grain size, porosity, framework grain mineralogy, sorting, angularity, matrix, cementation, and organic content. Samples were analyzed using x-ray diffraction methods for whole rock and clay mineralogy. SEM analysis defined pore geometry, pore filling minerals, cementation patterns, microporosity, and general rock morphology.

Observations show that the Dad sandstone is a fine-grained, poorly sorted and are texturally immature rock. Dad sandstones are dominantly detrital quartz and detrital feldspar (i.e. plagioclase), with an important lithic component comprised mainly of carbonate clasts, organic matter and other rock fragments. The lithic component of these sandstone’s are observed altered, replaced, and dissolved during burial.

Four major diagenetic processes that occur in the Dad sandstone include: compaction, cementation and development of secondary and microporosity. Compaction plays a major role on reservoir quality in the Dad sandstone due to the ductile framework grains that deform and reduce intergranular porosity with increasing burial. During later diagenesis, the cements, mainly clays and carbonate, account for additional porosity reduction in the Dad sandstone. However, late stage porosity enhancement is observed due to the dissolution of lithic grains and feldspars. A strong positive correlation
between the porosity and permeability in the Dad sandstone, suggests that reservoir quality may be directly related to porosity.
TABLE OF CONTENTS

ABSTRACT..................................................................................................................iii
LIST OF FIGURES.......................................................................................................viii
LIST OF TABLES.........................................................................................................xv
ACKNOWLEDGEMENTS............................................................................................xvi
CHAPTER 1 INTRODUCTION.........................................................................................1
  PURPOSE OF STUDY.................................................................................................1
  LOCATION...............................................................................................................1
GEOLOGIC BACKGROUND..........................................................................................4
  Petroleum Geology...................................................................................................5
  General Stratigraphy...............................................................................................8
  Tectonics.................................................................................................................15
  Depositional Environment.......................................................................................15
CHAPTER 2 DIAGENESIS............................................................................................20
  PREVIOUS WORK....................................................................................................20
    Diagenetic Background.........................................................................................20
    Cretaceous Sandstones in the Study Area..........................................................23
METHODS..................................................................................................................28
  Lithofacies Descriptions.......................................................................................29
RESULTS.....................................................................................................................31
  Sample Description...............................................................................................31
# PETROGRAPHY

- Detrital Mineralogy ................................................................. 35
- Detrital Quartz ................................................................. 35
- Feldspars ................................................................. 36
- Rock Fragments ................................................................. 41
- Clays ................................................................. 44
- Carbonate Cement ................................................................. 53
- Quartz Cement ................................................................. 53
- Porosity ................................................................. 58
- Microporosity ................................................................. 58
- Primary Porosity ................................................................. 64
- Secondary Porosity ................................................................. 64

## CHAPTER 3: SUMMARY OF RESULTS

## DIAGENESIS

- Compaction ................................................................. 69
- Minus Cement Porosity ................................................................. 70
- Cementation ................................................................. 78
- Paragenesis ................................................................. 84
- Reservoir Quality ................................................................. 87

## CONCLUSIONS

 vi
LIST OF FIGURES

Figure 1-1. Wyoming topographic map showing key features within the Washakie Basin. .................................................................2

Figure 1-2. Basemap showing thin section sampling locations for this project as well as completed and current Lewis Shale research. .........................3

Figure 1-3. The Cretaceous Western Interior Seaway of North America extended from the Arctic to the Gulf of Mexico. The square is the approximate location of the study area (After Witton, 1999). ........................................6

Figure 1-4. Depositional model of a mud-rich submarine fan system. ..................7

Figure 1-5. Stratigraphic column showing the Lewis Shale Formation. ...............11

Figure 1-6. Diagrammatic section displaying how the Lewis Shale overlies and intertongues with the Almond formation and is also overlain by and intertongues with the Fox Hills and Lance formations (after Van Horn and Shannon, 1989). ............12

Figure 1-7. West to east diagrammatic cross-section of the Lewis Shale between Rock Springs and Rawlins, Wyoming. See figure 5 for location. Diagram displays how the Lewis represents the final regression and transgression of the late Cretaceous Seaway (after Van Horn and Shannon, 1989). .................13

Figure 1-8. Diagrammatic north-south cross-section of south-central Wyoming (after Van Horn and Shannon, 1989). .................................................13

Figure 1-9. Map showing the locations of cross-sections. Also note the
isopach from the Hay Reservoir area to the north. ..................................14

Figure 1-10. Type log for the Lewis Shale is seen on the left of this figure.

The log to the right is a composite log of the Lewis Shale in the Hay Reservoir
Area showing sandstone nomenclature used by Van Horn and Shannon, 1989. .......14

Figure 1-11. Map displaying the major tectonic features of south-central

Wyoming (After Van Horn and Shannon, 1989). .........................................16

Figure 1-12. Paleogeographic map from Lower Maastrichtian time (~69.4 Ma). The

embayment located to the south of the Lost Soldier Anticline was formed during the

Lower Maastrichtian time as the Lost Soldier Anticline became active, at the beginning

of the Laramide Orogeny (McGookey, 1972). .............................................17

Figure 1-13. Stratigraphic cross section of the Lewis Shale, Fox Hills

Sandstone, Lance Formation, Mesaverde, and underlying Steele Shale. Note

that the Lewis Shale unconformably overlies the Mesaverde Group. See figure 9 for

location of cross section (after Pyles, 2000). .............................................18

Figure 2-1. QFL Diagram produced using percent quartz, feldspar, and lithic

grains in all of the samples examined..........................................................37

Figure 2-2. Twinning fabric of plagioclase feldspar. Sample CD2-4 from

outcrop. ........................................................................................................39

Figure 2-3. Twinning fabric still seen in samples from Powder Mountain 1-13 E,

sample #2 at 13332.4 feet. ...............................................................40

Figure 2-4. Dissolution fabric of a rock fragment creating secondary porosity.
Sample from outcrop. .................................................................42

Figure 2-5. Carbonate replacement of a lithic grain from Strat Test #61 well sample #43 at 411.7 feet. .........................................................43

Figure 2-6. Authigenic pore occluding material, including, illite, quartz cement, and chlorite. Sample from the Creston SE #5 well, at 8,193 feet. .........................45

Figure 2-7. Clay coating grains, believed to be chlorite. Sample from the Creston SE #5 well at 8226 feet. .........................................................46

Figure 2-8. Photo taken from sample at 8,000 feet. Image shows mixed-layer illite/smectite (I/S) clay lining grains. Location of the mixed-layer clay denoted by I/S symbol. .................................................................47

Figure 2-9. SEM image of mixed layer illite/smectite forming a bridge between to grains. .................................................................48

Figure 2-10. SEM EDAX plot of the elemental make-up of the illite-smectite bridge in the photo above. The small amount of calcium present in this plot indicates that this is not a pure illite and that it is mixed-layer illite-smectite clay. ....49

Figure 2-11. X-ray diffraction pattern multiple display, gray= air dried, blue= glycolated, and green= heated to 550°C. Sample number CD2-4, from outcrop channel facies. Pattern shows smectite, illite, kaolinite, and chlorite. ........50

Figure 2-12. X-ray diffraction multiple display pattern, gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from outcrop sheet
facies, sample number SD2-1. Plot of XRD peaks displays normal pattern of illite, smectite, kaolinite, and chlorite. .................................................................50

Figure 2-13. X-ray diffraction multiple display pattern, gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from the Strat Test #61 well, sample number 26 from 395 feet. Peaks of XRD plots displays normal pattern of detrital illite, smectite, kaolinite, and chlorite. .................................................................51

Figure 2-14. X-ray diffraction multiple display pattern gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from 8,213 feet and is from the Creston SE#5 well. Plot of XRD peaks displays a normal pattern of illite, smectite, kaolinite, and chlorite. .................................................................51

Figure 2-15. X-ray diffraction multiple display pattern gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from 13,356.6 feet and is from the Powder Mountain 1-13E well. Pattern displays mixed layer illite-smectite clay where illite constitutes 90% of the mixed layer clay, kaolinite, and chlorite. .........................52

Figure 2-16. X-ray diffraction multiple display pattern gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from 13,277.5 feet and is from the CEPO Lewis 21-18 well. Pattern displays mixed layer illite-smectite clay where illite constitutes 90% of the mixed layer clay, kaolinite, and chlorite. .........................52

Figure 2-17. Plot of percent quartz cement versus depth. ..............................................54

Figure 2-18. SEM image showing quartz growing around illite, representing late quartz cement. Photo from Powder Mountain 1-13E well at 13367.5 feet. ......55
Figure 2-19. Image is showing the irregular quartz grain boundaries as a result of opaque pore filling and grain lining material, which seems to be inhibiting the precipitation of quartz overgrowths in this sample. Sample taken from the Powder Mountain 1-13E at 13330.6 feet. .................................................................56

Figure 2-20. Photo from approximately 13,000 feet, displays nicely how quartz cement is inhibited by opaque material in between grains. .........................................................57

Figure 2-21. Depth vs- He-porosity (%), values include microporosity. .......................59

Figure 2-22. Plot of depth versus He-porosity from data collected from 1031 core plugs from the Dad sandstone (Thyne et al., 2002). .................................................................60

Figure 2-23. SEM image of a microporous grain. Sample is from the Strat Test #61 sample #15 from approximately 207 feet. .................................................................61

Figure 2-24. Relationship of He-porosity vs. thin section porosity. .........................63

Figure 2-25. Plane light image shows secondary dissolution porosity, where the grain is almost completely dissolved. Sample is from Strat Test sample # 26 from approximately 395 feet. (CL=Clay), (SP=Secondary Porosity), (LG=Lithic Grain), (C=Carbonate).An example of deep secondary porosity (SP) from the CEPO 21-18, (Q=Quartz). .................................................................65

Figure 2-26. Image from CEPO 21-18 displaying secondary porosity at depth. .........66

Figure 2-27. Ghost grain, where the grain is completely dissolved and all that remains is a clay rim and some remnant grain material. Sample is from outcrop sample #CD2-4. .................................................................67
Figure 3-1. Uncompacted sample from outcrop, showing approximately 25-30% porosity. Sample CD2-8. .................................71

Figure 3-2. Sample is from 8,200 feet. Compaction and carbonate cementation both reduce the amount of intergranular porosity. ........................................72

Figure 3-3. Compaction increase with depth, showing <10% porosity. .................73

Figure 3-4. Plot of depth versus minus cement porosity. .......................74

Figure 3-5. COPL versus CEPL plot for all samples showing relative contributions of compactional and cementation processes in porosity loss. The figure was plotted for values calculated with minus-cement porosity equal to thin section porosity plus cement volume. .................................................................76

Figure 3-6. COPL vs. CEPL for all samples showing relative contributions of compactional and cementation processes in porosity loss. The figure was plotted for values calculated with minus-cement porosity equal to thin section porosity plus cement volume. .................................................................77

Figure 3-7. Poikilotopic carbonate cementation from outcrop sample #SD2-1. .........81

Figure 3-8. Carbonate replacement of a lithic grain, complete replacement is seen in this photograph. Sample is from the Creston SE #5 well at 8213 feet. .................82

Figure 3-9. Dissolution of the lithic grain, then precipitation by carbonate within this plagioclase feldspar grain. Sample from the Powder Mountain 1-13E well at 13330.6 feet. .................................................................83

Figure 3-10. Paragenetic sequence of diagenetic events of the Dad Sandstone,
Lewis Shale, Washakie Basin, Wyoming. .................................................................84

Figure 3-11. Photomicrograph from Powder Mountain 1-13 sample #4 taken from
13343.5 ft. Lewis framework grains are ductile in nature causing increased
compaction under burial. .................................................................86

Figure 3-12. Illite lining grains/precipitation on the edges of grains and filling small
pore space in between grains (Plane light–left and cross nickels–right). Sample
is from the Creston well at 8,213 feet. (C = carbonate and Q = Quartz grain). ...............88

Figure 3-13. Plot of He-porosity vs. K (mD), displays a relationship between porosity
and permeability, where as porosity decreases so does permeability. .................90

Figure 3-14. Plot of He-porosity versus permeability (k) in milldarcies (mD) from data
collected from 1031 core plugs from the Dad sandstone (Thyne et al., 2002). ........91

Figure 3-15. Dissolution of grains. Sample #4 from CEPO 21-18 core, 13,260.4
feet, k = 0.01 mD. .................................................................92
LIST OF TABLES

Table 1-1. Table representing the total amount of Lewis Shale gas resource, reserves, and production as of 1996 (GRI Report-1997). ........................................8

Table 2-1. Average quartz volume percentage for each sample location/well. ........35

Table 2-2. Average percent plagioclase, k-spar, and average total feldspar percent. ....38

Table 2-3. Feldspar composition based on the Michel-Levy method of measuring maximum extinction angles between plagioclase twin lamellae. .........................38

Table 2-4. Average percent lithic grains broken out and average total percent lithics in samples from outcrop to 13,000 feet, calculated using point count data. .................41

Table 2-5. Table displaying total percent of carbonate clasts, carbonate cement, and carbonate replacement broken down, as well as the total carbonate from outcrop to 13,000 feet (See Appendix for raw data). .................................................53

Table 2-6. Summary table of both thin section and He-porosity results. ..................62

Table 3-1. Minus cement porosity values. ..............................................................70

Table 3-2. Summary of total percent cement for all samples. ..............................78
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In memory of my grandfather Geoffrey Spencer.
CHAPTER 1: INTRODUCTION

PURPOSE OF STUDY

This study documents the major diagenetic processes that have occurred within the Dad sandstone member of the Lewis Shale and how those processes have affected the reservoir quality over time using outcrop and core samples. The samples were analyzed using petrographic methods, including thin-section standard point counting, x-ray diffraction, and SEM analysis.

Location

The project area is located within the Washakie Basin, which lies in south-central Wyoming and is surrounded by the Great Divide Basin to the north and the Sand Wash Basin of northern Colorado to the south (Figure 1-1). The Washakie Basin is part of the eastern Greater Green River Basin. The formation of interest is the Lewis Shale, which crops out along the eastern portion of the Basin and trends along the 60-mile Rawlins-Sierra Madre uplift that extends south to the town of Baggs, Wyoming. The study area encompasses the area between Rawlins and Baggs Wyoming and includes wells in T19N-R91W-sec1, T14N-R96W-sec13, T14N-R95W-sec18, and T16N-R92W-sec 25.

Figure 1-1 shows the Wyoming topographic map of project area and displays key features such as the Washakie and Great Divide Basins and the Wamsutter Arch, which separates the two basins. The Rawlins Uplift defines the eastern margin of the Great Divide Basin. The southern and eastern limits of the Washakie Basin are defined by the Cherokee Rim (south), Atlantic Rim, Sierra Madre Uplift and the Hatfield and Miller Anticlines (east), respectively (Pyles, 2000). Figure 1-2 shows thin section sampling locations for this research study as well as the extent of supporting studies by the Lewis Shale Project.
Figure 1-1. Wyoming topographic map of project area, displaying key features within the Washakie and Great Divide Basins. The geographic units are in NAD83, State Plane meters (State of Wyoming Geographic Information Council web page).
Figure 1-2. Basemap showing ongoing and completed Lewis Shale Project studies as well as sampling locations for this project which are denoted by a black diamond.
GEOLOGICAL BACKGROUND

Figure 1-2 shows a project basemap with ongoing and completed Lewis Shale Consortium studies as well as sampling locations for this project, which are denoted by a blue diamond. The Lewis Shale of south central Wyoming was deposited during the Late Cretaceous in the Western Interior Cretaceous seaway. This Late Cretaceous seaway extended from the Arctic Ocean to the Gulf of Mexico (Winn et al., 1985) (Figure 1-3). Most of the interior seaway was located over a large depositional basin into which Mesozoic sediments were deposited in excess of 20,000 feet (6,096 meters) in some locations (Winn et al., 1985). The Lewis Shale was deposited during Maastrichtian time in a transgressive-regressive eustatically controlled cycle (Winn et al., 1985). The Lewis basin fill is largely shale and was derived from large delta systems that once existed within the basin (Weimer, 1970).

The Lewis Shale is largely composed of mudstones and siltstone with a hydrocarbon producing deepwater sandstone interval known informally as the Dad sandstone (McPeek, 1981). The Lewis Shale has produced at the Wamsutter, Hay Reservoir, Table Rock, and Desert Springs fields as well as other areas (Figure 1-2). Porosity and permeability in the Dad sandstone are low; the unit has been designated a tight gas sand by the Federal Energy Regulatory Commission (Winn, et al, 1985). The deepwater sandstones vary in lateral continuity, vertical connectivity, and rock quality (Slatt, 2000). Witton (1999) divided the Dad sandstone into two major types: 1) a turbidite and sandy debris-flow channel-fill sandstone, that was deposited within a paleo-slope environment; 2) a layered and amalgamated sheet sandstone, deposited in a depositional down-dip, basinal environment (Figure 1-4). Witton (1999) also observed general trends between the channel and sheet sandstones that include the following; the channel sandstones tend to be more laterally discontinuous and of relatively poor reservoir quality, whereas the sheet sandstones tend to be more continuous and of better reservoir quality.
The depositional environment determines the initial pore system distribution (porosity and permeability) as it relates to the different facies described by Witton (1999) and Goolsby (2001). Diagenetic processes during burial modify this original pore system, and thus the capacity of the reservoir to host or transmit fluids.

Petroleum Geology

The Lewis Shale, along with the Almond and Ericson formations, is one of the major productive intervals of the Washakie and Great Divide Basins of Wyoming. The Upper Cretaceous sandstone reservoirs of the Washakie and Great Divide Basins are overpressured and may hold an estimated 2.2 TCF of gas reserves and an estimated undiscovered gas resource of 18.2 TCF (after Van Horn and Shannon, 1989). According to the 1997 report by the Gas Research Institute (GRI Report-1997), the Lewis Shale has produced only 6 percent of its 10.7 TCF gas resource, compared to the Mesaverde Group (8 % produced), the Frontier (17% produced), and the Muddy/Dakota Sandstone (16 % produced). The Lewis Shale potentially has 10.1 TCF of remaining gas supply (0.4 TCF remaining reserves and 9.7 TCF undiscovered resource) (Table 1-1). This amount is nearly a quarter of the 46.9 TCF total remaining gas supply (reserves plus undiscovered resources) for these four major reservoirs. Although the Lewis is a major gas resource, the reservoirs are difficult to locate due to the discontinuous nature of the Dad sandstones.

The source rocks for the Lewis Shale in south-central Wyoming are not clearly defined; one possible source of the Lewis Shale may be from coals of the Mesaverde and Lance Formations (after Surdam, 1984). Traps have been defined as stratigraphic and structural in this study area and seals may be from the overlying shales and adjacent impermeable lithologies (after Surdam, 1984).
Figure 1-3. The Cretaceous Western Interior Seaway of North America extended from the Arctic to the Gulf of Mexico. The square is the approximate location of the study area (After Witton, 1999).
Figure 1-4. Depositional model of a mud-rich submarine fan system. Scales are for a major river distributary and turbidite system. (After Reading and Richards 1994).
General Stratigraphy

The Lewis Shale type section is located near Fort Lewis, just east of Mesa Verde National Park in southwest Colorado. However, Weimer (1960) showed that the Lewis Shale of Wyoming was younger than and not an extension of the Lewis Shale of southwest Colorado. The Lewis Shale in the Washakie Basin is approximately 762 m (2500 ft) thick and consists of shale, siltstone, and sandstone (Winn et al., 1985; Gill et al., 1970). Pyles (2000) informally defined the Lewis Shale as having three internal members, a lower, Dad, and upper members.

The lower Lewis was deposited within the *Baculites eliasi* and *Baculites grandis* ammonite biozones (Perman, 1990). The lower Lewis consists mainly of a few hundred feet of black organic rich shale. Generally black carbonaceous shale without distinct lamination, it locally displays contorted layers and contains minor interbedded siltstone.

<table>
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<th>Undisc. Resource</th>
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<th>Well Completions</th>
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</table>

Table 2.4. Status of the Greater Green River Basin Gas Resource. Only 0.6 TCFG has been produced from the Lewis Shale, leaving 10.7 TCFG of producable reserves. (After Doelger and Barlow, 1997)

Table 1-1. Table representing the total amount of Lewis Shale gas resource, reserves, and production as of 1996 (GRI Report-1997).
and very thin sandstone beds of lower-to-upper, very fine grain size. These units can be interpreted as bioturbated marine shale or highly dewatered marine shales. Part of the lower Lewis, informally named the Asquith marker, defines the maximum flooding surface and is interpreted as a third-order condensed interval (McMillen and Winn, 1991; Pyles, 2000) which is composed of carbonaceous shale with an average thickness of 18 m (6 to 28 m range; 60 feet, 20 to 90 ft range) and a relatively high organic content (Pyles, 2000; Escalante, 2002).

The middle Lewis or Dad sandstone, was deposited within the Baculus grandis and probably continued into the Baculites clinolobatus ammonite biozone (Perman, 1990). The Dad sandstone contains interbedded sandstones and shales, and subdivides the Lewis into upper and lower shale units. It is a lower very-fine to fine grained sandstone package interbedded with minor shale beds, which are gray locally white (Van Horn and Shannon, 1989). The thickness reported for the Dad sandstone is variable; according to Hale (1961) it varies from 305 to 427 m (1000 to 1400 ft) in the Rawlins area. Perman (1987) reported thicknesses of 136 to 221 m (445 to 725 ft) on the south-southeast side of the Rawlins area with a maximum thickness in the Washakie basin of 397 m (1302 ft). The upper Lewis interval is a dark gray, silty sand, which locally contains fossiliferous limestone or siltstone concretions (Pyles, 2000 and Gill et al., 1970).

The Lewis Shale conformably overlies and intertongues with the Almond Formation (a nearshore sequence) and is also overlain by and intertongues with the Fox Hills and Lance Formations, which are shoreline and continental deposits (Figure 1-5). Deposition of general sedimentation in the Lewis (Winn et al, 1985), was controlled by intrabasin tectonics and eustacy. Sedimentation was controlled by deltas entering the Lewis Sea from the northeast and later from the south. As a result, sands and muds prograded from the west and northwest (Weimer, 1965, 1966, 1970; Winn et al, 1985).

The lower most Lewis Shale is a westward thinning sequence of marine derived sediments, which records the final transgression-regression of the Late Cretaceous
seaway in southwest Wyoming (Figures 1-6, 1-7 and 1-8). Van Horn and Shannon (1989) describe the Lewis Shale as having a lower transgressive member, associated with the Almond Formation and an upper regressive member associated with the Fox Hills and Lance Formations. According to Van Horn and Shannon (1989) a bentonite bed denoted by low resistivity on electric logs can be used as the subdivision between the upper and lower portions of the Lewis Shale, and can be correlated throughout the Great Divide and Washakie Basins (Figures 1-9 and 1-10). According to Winn et al, (1985), the Almond Formation sandstone is a near-shore sequence deposited during early Lewis sedimentation, that underlies the Lewis Shale Formation. The Fox Hills and Lance Formations, deposited in shoreline and continental environments, overlie the Lewis and are partly equivalent to the upper portions of the Lewis Shale Formation. See Appendix A for cross-sections from within the study area running north-south and east-west (Suryanto, 2003).

Time stratigraphic units have been interpreted within this regressive Lewis Shale Formation, defined by a series of clinoforms first recognized by Asquith, (1970). These clinoforms demonstrate the Lewis time equivalence with the non-marine and transitional marine Lance and Fox Hills lithologies to the northeast (Van Horn and Shannon, 1985). Using these correlations three major time-stratigraphic units have been described, which when mapped record the southwest progradation of the regressive Lewis (Van Horn and Shannon, 1985).
Figure 1-5. The Lewis Shale is located stratigraphically above the Almond Formation and below the Lance and Fox Hills is 66.5-73 million years old (after Escalante, 2002).
Figure 1-6. Diagrammatic section displaying how the Lewis Shale overlies and intertongues with the Almond formation and is also overlain by and intertongues with the Fox Hills and Lance formations. Diagram displays how the Lewis represents the final regression and transgression (after Van Horn and Shannon, 1989).
Figure 1-7. West to east diagrammatic cross-section of the Lewis Shale between Rock Springs and Rawlins, Wyoming. See Figure 1-9 for location (after Van Horn and Shannon, 1989).

Figure 1-8. Diagrammatic north-south cross-section of south-central Wyoming (after Van Horn and Shannon, 1989). See Figure 1-9 for location of cross-section.
Figure 1-9. Map showing the locations of cross-sections. Also note the isopach from the Hay Reservoir area to the north.

Figure 1-10. Type log for the Lewis Shale is seen on the left of this figure. The log to the right is a composite log of the Lewis Shale in the Hay Reservoir Area showing sandstone nomenclature used by Van Horn and Shannon, 1989.
Tectonics

The Western Interior Basin was the locus of deposition of the Cretaceous Interior seaway, which extended from the present-day Arctic Ocean to the Gulf of Mexico. The Western Interior Basin was formed through a composite of many foreland basins that occurred throughout the Mesozoic. This foreland basin persisted from the Late Jurassic to the early Eocene (Pyles, 2000; Baars et al., 1988). Subsidence occurred within the basin caused by gravitational loading, thermal decay and contraction, stress-induced, isostatic subsidence by crustal loading and cooling caused by low-angle subduction of oceanic crust from the Farallon plate (Pyles, 2000; Cross and Pilger, 1978).

The Laramide Orogeny, which took place from late Mesozoic to early Tertiary, is thought to be responsible for most of the structural features in the study area (Figure 1-11) (Pyles, 2000; Baars et al., 1988). In south-central Wyoming, the Laramide Orogeny uplift commenced during the early to lower Maastrichtian causing the last phase of the ancestral Lost Soldier anticline to form (Weimer, 1960, McGookey et al., 1972; Reynolds, 1976). Uplift began to cause erosion of the Lower Lewis Shale and the Mesaverde Group and resulted in the formation of an embayment within the seaway (Figure 1-12). At this location the Lewis unconformably overlies the Mesaverde Group (Figure 1-13). This basin is a product of horizontal compression, and fragmentation of the craton that occurred during the Laramide Orogeny (Pyles, 2000 and Baars et al., 1988).

Depositional Environment

The Upper Cretaceous Lewis Shale of south-central Wyoming was deposited during the final transgression and regression of the Western Interior Seaway (which lasted approximately 2.4 Ma in the study area). This seaway was located over a depositional basin, which in places received over 6000 m of Mesozoic sediments. Most
Figure 1-11. Major tectonic and structural elements of the Greater Green River basin and adjacent areas (after Minton, 2002; Baars et al. 1988; Karlstrom et al. 1988).
Figure 1-12. Paleogeographic map from Lower Maastrichtian time (~69.4 Ma). The embayment located to the south of the Lost Soldier Anticline was formed during the Lower Maastrichtian time as the Lost Soldier Anticline became active, at the beginning of the Laramide Orogeny (McGookey, 1972).
Figure 1-13. Stratigraphic cross-section of the Lewis Shale, Fox Hills Sandstone, Lance Formation, Mesaverde and underlying Steele Shale. The Baculites clinobatus zone, which occurred 69.4 Ma, is at the base of the Fox Hills Sandstone (After Reynolds, 1977 and Pyles, 2000). Sampling for this research are located within the Dad sandstone of the Lewis Shale.
of the clastics were deposited along the basins western margin (Winn et al, 1985; McGookey et al 1972).

The Lewis Sea rapidly advanced from the east, which created a shallow marine embayment, (Figure 1-12). The entire Rock Springs uplift area was submerged near the head of this embayment. A slow final retreat of the Late Cretaceous Sea from the Rock Springs uplift area is confirmed by the clinoform depositional pattern of the shallow marine sandstones of the basal Lance Formation and the Fox Hills Sandstone. After the final regression of the Lewis Sea, continental Lance deposition commenced until the Laramide orogeny (WGA, 1965). Even though the Lewis Shale unit is mainly composed of siltstone and mudstone, sandstone is present and the unit contains significant hydrocarbons (Winn, et al., 1985; McPeek, 1981).

The Lewis Shale is approximately 762 m (2500 ft) thick in south-central Wyoming. Turbidity currents and related sediment-gravity flow processes, along with major deltas deposited major portions of the Lewis Shale Formation. Sedimentation was controlled by both intrabasin tectonics and eustacy. According to Winn et al. (1985), most of the Lewis deposition during the early stages of the transgression occurred on a muddy shelf. This shelf extended over a broad area that included the modern Red Desert and Washakie Basins and Rawlins and Sierra Madre Uplifts. The Lewis Basin was ultimately filled with sands and muds prograding form the west and northwest, (Winn et al., 1987).

The Dad Sandstone member of the Lewis Shale Formation, which is the primary focus of this research, is described as a prograding unit of sandstone with minor shale that divides the Lewis Shale into lower and upper members that are composed predominantly of shale (Perman, 1987). The Dad Sandstone member was named and first described by (Hale, 1961). The Dad Sandstone has been identified in south-central Wyoming along the eastern margins of the Washakie and Great Divide Basins. In this location, the Dad Sandstone may be related to either the Sheridan delta to the north or a north-trending uplift to the south (Perman, 1987).
CHAPTER 2: DIAGENESIS

PREVIOUS WORK

Diagenetic Background

Porosity is as an aspect of texture, and is defined as the total of all void spaces within a rock. Porosity is of particular interest to the economic geologist, because it is in the pore spaces that contain fluids such as oil, gas or water. Primary porosity is formed at or before the time of deposition: it occurs between and within the grains. Secondary porosity is formed during diagenesis, usually by solution/dissolution of components of the rock. Both primary and secondary porosity are progressively destroyed as sediments are buried by processes of compaction and cementation (Boggs, 1995).

There are four major porosity types that occur within clastic rocks (Boggs, 1995):

1) Primary intergranular – Interstitial void space between framework grains
2) Dissolution- Partial or complete dissolution of framework grains or cement.
3) Micropores- Small pores mainly between detrital or authigenic clays; can also occur within grains (ex. microporous chert).
4) Fracture- Breakage due to earth stress

Pittman (1979) stated that dissolution porosity might be a result of one or all of the following: leaching of carbonate, feldspar, sulfate, or other soluble material. “Sandstones with significant amounts of clay mineral usually have microporosity, high surface area, small pore apertures, low permeability, high irreducible water saturation, and an increased sensitivity to fresh water” (Pittman, 1979). Porosity type and/or pore geometry change with diagenesis. For example, macropores may become micropores, minerals may dissolve creating voids in between the grains, and pores may become partly to completely occluded by precipitation of minerals. Knowledge of pore geometry is important for an understanding of fluid production rates.
Intergranular porosity occurs between detrital grains. The best sandstone reservoirs from the viewpoint of storage volume and deliverability have predominantly intergranular porosity. Sandstone reservoirs with intergranular porosity range from a cutoff for pay of about 5% for compacted sandstone to totally unconsolidated sands with porosities exceeding 40%.

Original porosity of sand was evaluated by Pryor (1973), who measured porosity, permeability, and textural characteristics of sands from river point bars, beaches, and eolian dunes adjacent to beaches. Porosity values were found to vary considerably within deposits of each environment indicating that deposition environment controls initial porosity. After deposition, sediments undergo compaction during burial. Well-sorted sands have greater porosity than poorly sorted sands. Angular sands have greater initial porosities and are more compactable than rounded sands of the same size. A rock that consists of a framework of strong minerals, such as quartz, tends to undergo only minor porosity and permeability reduction during compaction due to grain rotation and rearrangement into a tighter packing configuration (McBride, 1984). During early compaction, particle size may be as important an influence on porosity as overburden load. As overburden accumulates, the finer sands are compressed more rapidly than the coarser sediments and the relationship between particle size and porosity becomes less pronounced. At even greater overburden loads, the relation between particle size and porosity changes from inverse to direct.

McBride (1984) discussed how compaction reduces the porosity and permeability of a rock by: (1) grain rotation and rearrangement into a tighter packing configuration, (2) plastic deformation of ductile grains that flow into adjacent pores and pore throats, (3) fracturing and crushing of brittle grains, and (4) pressure solution in the form of grain suturing and stylolitization. Lundegard (1992) states that compaction (mechanical and chemical) may be the dominant mechanism of porosity loss in most sandstones. A complicating factor in the calculation of compactional porosity loss is that true intergranular volumes may be underestimated by point counting procedures because
microporosity is not easily visible in thin sections (Pittman, 1979). This underestimation of microporosity may lead to an overestimation of compactional porosity loss.

Lundegard (1992) found that there is a direct relationship between content of lithic grains and intergranular volume. The greater the lithic content, the lower the intergranular volume and the higher the compaction index (equal to compactional porosity loss / (compactional porosity loss + cementational porosity loss). Relationships between compaction indices and sandstone composition clearly show that sandstone lithic content strongly influences susceptibility to compaction.

According to Houseknecht (1987), the best porosity preservation is in samples that have undergone the least intergranular pressure solution. Houseknecht (1987) discussed the relative importance of compaction and made some general observations. During burial diagenesis porosity is reduced by mechanical compaction, intergranular pressure solution, and cementation. Mechanical compaction and intergranular pressure solution are both considered compactional processes because they irreversibly reduce the intergranular volume of sand. In contrast, cementation occludes, but does not reduce, intergranular volume. Relative importance of compactional processes can be quantified using a graph of intergranular volume vs. cement.

Dissolution porosity tends to be especially important in sandstones that are deeply buried. Dissolution porosity may play a significant role in the preservation of porosity during burial resulting from removal of carbonates, feldspars, sulfates, and other soluble materials (Pittman 1979). Typical soluble components include detrital grains, authigenic mineral cement and replacement minerals.

Sandstone reservoirs with only dissolution porosity range from poor to excellent, depending on amount of porosity and interconnection of pores. Sandstones with only dissolution porosity may have essentially no measurable matrix permeability if the soluble grains are disseminated, because upon leaching they formed isolated pores with microporous interconnections. Excellent reservoirs develop where carbonate cement has been dissolved to form secondary intergranular porosity (Pittman, 1979).
According to Pittman (1979), feldspars commonly affected by dissolution are sanidine, orthoclase, and plagioclase. In contrast, microcline, which is also present in sandstones with partly dissolved other feldspar usually lacks any sign of dissolution. This may be explainable because of the relative temperature of formation stability for the (potash) feldspar group. Sanidine and orthoclase form at higher temperatures than microcline as does plagioclase. Therefore, they are not as stable under diagenetic conditions (Pittman, 1979).

Cretaceous Sandstones in the Study Area

Pryor (1961) described the petrography of Mesaverde Sandstones in Wyoming. The main purpose of his study was to determine the rock types, the distribution pattern, and the provenance of the Mesaverde Group clastics in Wyoming. Pryor generalizes the Mesaverde group as a “genetically related series of chiefly coarse clastic materials that reflect a regressive-transgressive phase of sedimentation in the Cordilleran geosyncline during Late Cretaceous.” The major mineral components of the sandstones were found to be: quartz, feldspar (orthoclase, microcline, and plagioclase), carbonate (calcite and dolomite), clay matrix, muscovite, biotite, chlorite, rare glauconite, and rock fragments (schist, shale, siltstone, chert, polycrystalline quartz, and igneous). After classification Pryor found that Mesaverde sandstones range in rock type from protoquarzite to subgraywacke and lithic greywacke. He noted that detrital clay and silt matrix was abundant, chiefly kaolinite and fine quartz (Pryor, 1961).

Pryor’s work had several major implications. Some of the major petrographic implications that Pryor (1961) describes include first, the abundance of sedimentary rock fragments (especially chert) suggested that pre-existing sediments contributed significant quantities of material to the Mesaverde sedimentary system. In addition, the observation of the presence of fresh feldspar grains, and igneous and metamorphic rock fragments suggested a significant contribution of sediment by igneous and metamorphic rocks.
Provenance interpretations of Mesaverde sandstones and adjacent Cody and Lewis formation sandstones indicate that the source areas were composed of both crystalline (igneous and metamorphic) and sedimentary rocks. Based on observations from mineral association maps, Pryor (1961) suggested separate basins receiving detrital materials from two separate source areas, with a small amount of mixing at the borders of the basins. Pryor concluded that the closely related upper Cody and Lewis sandstones are identical in composition to those of the Mesaverde group.

Dutton (1993) discussed the influence of provenance and burial history on diagenesis of Middle Cretaceous Frontier sandstones, Green River Basin. Dutton found that framework-grain composition of Frontier sandstones varies with both depositional environment and stratigraphic position. On the basis of petrographic evidence, the relative sequence of major events in the diagenetic history of Frontier sandstones was identified by Dutton as follows: (1) mechanical compaction by grain rearrangement and deformation of ductile grains; (2) formation of illite and mixed-layer illite smectite (MLIS) rims; (3) precipitation of quartz overgrowths; (4) precipitation of calcite cement; (5) generation of secondary porosity by dissolution of feldspar, chert, biotite, and mudstone grains and calcite cement; (6) precipitation of kaolinite in primary and secondary pores; and (7) chemical compaction by intergranular pressure solution and stylolitization and additional precipitation of quartz cement. Dutton concluded that many of these events overlapped in time.

Dutton (1993) determined relative timing of authigenic phase, without using radiometric dating. Authigenic illite and mixed layer illite-smectite (MLIS) rims, the earliest cements to precipitate, probably formed in the shallow subsurface, perhaps within the first 0.3 km of burial. The illite probably formed from meteoric water because of the apparent predominance of meteoric fluids during early diagenesis of Frontier sandstones (Dutton, 1993). Tangentially oriented illite and MLIS crystals may be authigenic, or they may have entered the sandstone by mechanical infiltration (Matlock et al., 1989) and been subsequently recrystallized during burial diagenesis (Dutton, 1993). Late-stage
diagenesis included albitization of feldspar, formation of secondary pores by dissolution of silicate grains, and precipitation of kaolinite, chlorite, illite, and quartz. Because much of the secondary porosity in the Frontier was formed by feldspar dissolution, sandstones that contained greater initial volumes of feldspar developed more secondary porosity (Dutton, 1993).

Very few petrographic studies have been performed on the Lewis Shale of south-central Wyoming. Van Horn and Shannon (1989) describe the sandstone within the Lewis Shale in Hay Reservoir field as very-fine to fine-grained sandstone composed of arkosic arenites with porosities of 5-12 % and permeabilities of 0.01-0.6 md. Van Horn and Shannon (1989) and Thomas et al., (1980) describe the diagenetic history of the Dad sandstone in the following general order; deposition, initial dewatering, and compaction of feldspathic-quartzose grains with primary intergranular porosity in the range of 40%. Initial chloritization of iron-rich volcanic rock fragments, partial decay of micaceous grains and the possible initial dissolution of lithic and feldspathic fragments were also important diagenetic processes that were observed in the Dad sandstone of the Hay Reservoir field. The following paragenetic sequence was derived from Van Horn and Shannon (1989) and Thomas et al., (1980).

1. Partial quartz cementation and compaction of soft lithic fragments into pseudomatrix.

2. Local precipitation of calcite and continued dissolution of feldspar.

3. Scattered calcite cementation and partial infilling of intragranular pore-space in leached feldspars.

4. Partial dissolution (second stage) of calcite cement and intragranular spar.

5. Second stage of precipitation of authigenic clays, principally illite and lesser amounts of chlorite.

6. Formation of pyrite associated with organic material.

Van Horn and Shannon (1989) determined that Dad sandstones consist of 57% quartz, 27% feldspar and 16% lithic grains. Porosity comprises up to 12 % of the rock
and includes 73% intergranular primary porosity, 21% intragranular secondary porosity and 6 % microporosity. They also conclude that sandstone exhibits multiple phases of burial diagenesis including mechanical and chemical compaction followed by porosity enhancement with partial dissolution of porefilling cements and more labile feldspar grains and lithic fragments. Finally, they conclude that porosity preservation appears to be greater in the structurally highest portion of the sandstone.

Brown et al. (1981) described the macroporosity in the Lewis Sandstones in the Hay Reservoir area as being comprised of solution and intergranular porosity. Solution porosity occurs in partially decomposed feldspar grains and rock fragments. Intergranular porosity forms at the junction of several detrital (clasts) or grains. Significant microporosity was observed where solution pores or intergranular pores were partially filled by clays. According to the authors, porosity that is seen on a properly prepared thin section should be considered total effective porosity.

Brown et al. (1981) created a reservoir model of Lewis sandstones in the Hay Reservoir area. They describe the reservoir as primarily fine grained sandstone with mean grain size ranging from 0.10 mm to 0.26 mm and fairly uniform sorting. They found several potential problems that may affect reservoir interpretations completion, and production performance in these sandstones, mainly: 1) microporosity due to clay; 2) water sensitivity of the clays; 3) acid sensitivity; and 4) formation depth. By far the most important factor is microporosity. The authors observed that fine authigenic hair-like illitic clay crystals grow in place as pore linings, corresponded to an extensive amount of localized microporosity. The reservoir model of the Lewis sandstones in the Hay Reservoir area concluded that the primary influence on the reservoir is the clay development, which creates microporosity. They suggested that wells higher on structure in a particular interval have a higher productivity. In the downdip portion of the reservoir increased clay development causes increased microporosity, and correspondingly higher water saturation. Reservoir matrix permeability ranged from 0.0085 md to 0.082 md (Brown et al., 1981).
Cain (1986) described the depositional environment of Upper Cretaceous Sandstones of the Lewis Shale in the Sand Wash Basin of Colorado. She described the petrography of the Lewis Shale using two cores. Fine-grained sandstones in the cores have an average mean grain size of 0.13 mm. They have an overall average detrital content of 41% mono-crystalline quartz, 15% feldspar, 20% rock fragments, 8% other minerals, and 16% matrix. Rock fragments are predominantly chert fragments and volcanic rock fragments. Other minerals include thin flakes of carbonaceous debris and carbonate grains. Cements (mostly calcite) comprise an average of 23% of the bulk composition of the sandstones.

Using plots of porosity versus calcite cement, Cain (1986) suggested that decreases in porosity correlate with increases in calcite cement. She interpreted the facies/depositional environment of the sandstones of the Lewis Shale of the Sand Wash basin as being deposited under conditions of decreasing flow regime by turbidity currents. This was based on the repetitive, ordered bedsets in the sandstones, as well as textural gradation within the bedsets. The less complete turbidite sequences, which characterize these sandstones, are similar to those recognized in other turbidites (Bouma, 1962; Walker, 1967).

Weaver (1961) studied the clay mineralogy of the Lewis Shale. X-ray diffraction analysis of the clay size fraction (less than 2 microns) of the Late Cretaceous rocks of the Washakie Basin showed that the most common clay minerals were illite, kaolinite, montmorillonite, chlorite, and mixed-layer illite montmorillonite. Weaver also noted that most samples contained all five of these clays listed above, and that chlorite could be predominant. He related clay content to lithology, environment, and depth with kaolinite content usually much greater in the sandstones than in adjacent shales. According to Weaver (1961), this type of kaolinite distribution may be related to either segregation of the clay mineral types during deposition or to post-depositional alteration by fluids. He found that in open marine depositional environments, the average kaolinite was only 6%, in the shallow marine to lagoon environments 16%, and in a marshy to continental
environments 27%. This distribution may be related to grain size and transport distance. Weaver also found that montmorillonite is the most abundant clay in the Lewis Shale open marine deposits, and he noted that this might reflect the tendency for bentonite to be preserved in marine environments. Bentonite forms from volcanic ash decomposition and is largely composed of montmorillonite. Plotting kaolinite for the Lewis Shale showed a decrease in kaolinite percent towards the lower-middle part of the Lewis Shale. Lastly, Weaver showed that at a depth of 10,000 feet, no discrete montmorillonite remained in the Lewis Shale of the Washakie Basin.

METHODS

Four cores and two outcrops were sampled for petrographic analysis. The wells include: Strat Test #61 CSM well, located in T16N R92W, Creston SE #5 well located in T19N, R91W section 1, Powder Mountain Unit 1-13E well located in T14N R96W Section 13, and the CEPO Lewis 21-18 located in T14N, R95W section 18. These wells have depths ranging from 162.3’-895.1, 8,193’-8,237’, 13,330.6’-13368.5’, and 13,250.5’-13,282.5’, respectively. Eight samples were taken from each core and outcrop to be point counted and analyzed for clay content. Samples were chosen from outcrop to 13,000 feet based on previously described sedimentary facies (Witton, 1999; Goolsby 2001) and display an array of porosity and permeability values collected from He-porosity core plug data which was analyzed in a laboratory using standard gas (He) displacement methods. The samples represent the entire range of facies and depths from outcrop to 13,000 feet. However, the outcrops do not represent surface conditions as they were once buried and then uplifted. All thin sections were impregnated with blue epoxy to highlight porosity and stained for K-feldspar and calcite cement.

Composition of Dad sandstones was determined from 40 thin sections selected from different facies in each core and outcrop. The chemical compositions of detrital and authigenic components of sandstone was determined by standard thin-section
petrography, scanning electron microscopy (SEM) using and energy dispersive X-ray spectrometer (EDX). For each thin section, 300 counts were performed with a petrographic microscope, using an automatic point-counting stage, for framework grain mineralogy, replacement and intergranular cementation, intergranular and intragranular porosity, grain size, angularity, sorting, matrix, ductile rock fragments, feldspar composition and organic content. Feldspar composition was determined using the Michel-Levy method. Raw petrographic data are included in Appendix A. Relationships observed in thin section data have been used in the final construction of the paragenetic sequence for the Lewis Shale.

Initially, samples were analyzed using X-ray diffraction for whole rock mineralogy, and then the < 2-micron fraction for clays. All clay fraction samples from outcrop to 13,000 feet were analyzed using techniques described by Moore and Reynolds (1997) including air drying, glycolation for 24-48 hours to determine whether expandable smectite is present, and heating to 550°C for two hours to determine whether kaolinite was present. NewMod was then used in the final analysis of mixed-layer clay to determine the ratio of illite to smectite in the 13,000-foot samples only.

Ten samples were analyzed, two from each sample depth, using the SEM in order to describe the authigenic pore material, cementation (intergranular and replacement fabrics), microporosity, and general morphology of these rocks. Identification of cementation fabrics aided in reconstructing the diagenetic history and allowed for more accurate interpretation of the factors that influence permeability and porosity.

Lithofacies Designations and Descriptions

Samples in this study were collected to represent the different facies of the Lewis Shale in order to identify if there is any correlation between lithofacies and diagenesis. The following section describes the major lithofacies that occur throughout the Lewis Shale. Lithofacies refers to “a facies characterized by particular lithologic features”. It is
“a lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of lithology, including all mineralogical and petrographic characters and those paleontologic characters that influence the appearance, composition, or texture of the rock” (AGI, 1997). There have been three lithofacies descriptions made on the Lewis Shale over the last few years and those include Witton (1999), Goolsby (2001) and Bracklein (2001). Witton (1999) identified four major lithofacies in outcrop and those are described as follows:

1. LFA (continuous thick-bedded sandstones),
2. LFB (discontinuous thick-bedded sandstones with rip-up clasts),
3. LFC (thin bedded sandstones), and
4. LFD (thin bedded laminated mudstones and shale).

Goolsby et al. (2001) identified three additional lithologic units in the CSM Strat Test #61 well. Those are as follows:

1. LFAch (discontinuous thick-bedded sandstones, channels dominated by turbidite deposits),
2. LFAd (continuous carbonaceous-rich thick-bedded sandstones, distal sheet sandstones), and
3. LFDt (laminated carbonaceous mudstones, fourth-order transgressive shales).

Bracklein (2000) described six different lithofacies, in outcrop, south of Witton (1999)’s thesis area and those are as follows:

1. high-density turbidite current (HDTC),
2. low-density turbidite current (LDTC),
3. mudstone,
4. slump, and
5. thin-bedded facies.

The Bracklein (2000) and Goolsby et al. (2001) classification of the major lithofacies present in the Lewis Shale are genetic and process-oriented, with mixed
designations (descriptive and interpretative). In this study sheet and channel lithologic
descriptions of Witton (1999) and Goolsby (2001) are used.

RESULTS

Sample Descriptions from Core

CSM Strat Test #61

The CSM Strat Test #61 well is located in T16N, R92W section 25 in Carbon
County, Wyoming. It was cored from 150-937 feet in depth. Samples were chosen based
on facies changes described by Witton (1999) and were taken at depths of 162.3 ft, 207.2
ft, 395.3 ft, 411.7 ft, 569.1 ft, 577.5 ft, 868.2 ft, and 892.2 ft. All samples are from the
Dad sandstone member of the Lewis Shale. The samples will be described below and are
numbered 6, 15, 26, 43, 87, 94, 121, and 145, respectively in order to maintain consistency
with numbering in point counting. All sample descriptions for the Strat Test #61 well
were taken from core descriptions by Goolsby (2002).

Sample #6 was taken at 162.3 ft depth and is a light gray-brown sandstone, and is
lower very-fine to upper-fine grained, angular, and moderately to poorly sorted and is
part of a fining upward package. The dominant grains seen in core appear to be quartz
and lithic grains. The bed is massive with faint signs of soft-sediment deformation. This
sample is part of sheet facies, previously defined by (Witton, 1999).

Sample #15 was taken at a depth of 207.2 ft and is a light gray-brown massive
sandstone, and is part of a coarsening upward sequence. Grains are middle fine-grained,
angular, and poorly sorted in nature. This sample is part of the sheet facies.

Sample #26 was taken at a depth of 395.3 ft and is massive sandstone with very
small rip-up clasts. Sand grains are middle fine, angular and poorly sorted. This sample
is part of the channel facies previously described by Witton (1999).

Sample #43 was taken from a depth of 411.7 ft and is a medium to light brown to
gray sandstone, containing dewatering structures at the top portion of the interval. The
sandstone package appears to be amalgamated with occurrence of thin discontinuous laminations and carbonaceous debris. The grains are fine, poorly sorted, and angular. This sample is part of the channel facies.

Sample #87 was taken from a depth of 569.10 ft and is a brown gray sandstone, and capped by a dark gray siltstone with carbonaceous laminations. The grains are fine, poorly sorted, and angular. This sample is part of the channel facies.

Sample #94 was taken from a depth of 577.5 ft and is within a massive brown gray sandstone package, with faint but mostly featureless bedding. Faint ripple laminations and disseminated plant debris are also present. Grains are fine, poorly sorted, and angular. This sample is part of the channel facies.

Sample #121 was taken from a depth of 868.2 ft and is a brown gray sandstone. The interval is capped by finely laminated shale and some carbonaceous matter, then thin carbonate siltstone, and lastly, coaly sandstone with coal fragments to 25 mm by 5mm in size. The remainder of the section is mostly massive. Grains are fine, poorly sorted, and angular. This sample is part of the channel facies.

Sample #145 was taken from a depth of 892.2 ft and consists of two thin sandstone/shale units with carbonate material and laminations with fine disseminated coaly material and rip-up clasts. The grains are fine, poorly sorted, and angular. This sample may be part of a sheet flow facies.

Creston SE #5

The Creston SE #5 well is located in T19N, R91W section 1 Sweetwater County, Wyoming. The Creston SE #5 core represents the Dad sandstone and runs from 8,190-8,248 feet. Samples were only taken from 8,190-8,226 feet because below this depth the core is dominantly siltstone. The stratigraphic description and sample locations for this core is in Appendix B. Turbidity current and fluidized flow depositional processes as well as deposition by pelagic settling dominate the Creston SE #5 core (Minton, 2002). The inferred depositional environment for the Creston interval is a sandy basin/slope
break, with channel-lobe transition deposits (Minton, 2002). Massive bedding, shale clasts, small intervals of interbedded siltstone dominate the interval from 8,190-8,226 feet, with planar to wavy laminated zones, as well as minor convolute bedding, and a dewatering fracture from 8,206-8,208 feet.

Powder Mountain Unit 1-13E

The Powder Mountain Unit 1-13E well is located in T14N R96W Section 13 in Sweetwater County, Wyoming. The core represents the Dad sandstone, from 13,329 to 13,378 feet. The stratigraphic column and sample locations are located in Appendix B. The cored interval in Powder Mountain 1-13E is dominantly deposited by turbidity currents, inferred to represent base of slope to deep-water hemipelagic depositional environments (Minton, 2002). Interbedded siltstone separates larger intervals of fine-grained sandstone containing dish and flame structures (dewatering features), floating shale clasts (<0.5 mm thick), calcite-lined fractures, convolute bedding, and slump features within the siltstone intervals. Small pyrite crystals are found within the siltstone intervals between 13,334.5 and 13,337.5 feet.

CEPO Lewis 21-18

The CEPO Lewis 21-18 is located in T14N, R95W section 18 within Sweetwater County, Wyoming. The CEPO core represents the Dad sandstone interval from a depth of 13,249-13,283 feet. The stratigraphic column and sample locations for this interval are located in Appendix B. The cored interval is dominated by turbidity current and fluidized flow depositional processes and represents a depositional environment from slope to base of slope to deep-water environments. The sand package is void of any sedimentary features until approximately 13,276 feet, where dish structures, dewatering features, flame structures, floating shale clasts (<0.5 mm thick), and calcite-lined fractures are seen to 13,281 feet. Pyrite crystals also occur within the siltstone interval. The remainder of the core is dominated by massive sand packages separated by a very
small-interbedded siltstone interval from 13,276.7-13,277.4 feet containing a minor slump feature. The CEPO core interval begins with basal massive sandstone and sharply changes into a laminated siltstone from 13,250.5 feet to 13,256.6 feet containing such sedimentary features as climbing ripples, floating clay clasts, and dewatering structures.

According to observations made by Minton (2002), the CEPO Lewis 21-18 and the Powder Mountain 1-13E cores show lithologic differences. The grain size in the CEPO Lewis 21-18 core is slightly larger than that of the Powder Mountain 1-13E core. Grain size in the Powder Mountain core ranges from clay to fine sand with very-fine sand being the dominant sand grain size, whereas the CEPO Lewis core ranges from clay to lower-medium sand. Minton (2002) also noted the presence of small clay clasts (0.1 to 1 cm) in the massive sandstone intervals of both wells, but fewer clasts are present in the CEPO core. The sandstone intervals in the CEPO core shows repetitive, amalgamated Bouma cycles with internal fluid escape structures. The sandstone intervals in the Powder Mountain well also have amalgamated Bouma cycles with internal fluid escape structures. However, thin-bedded sandstones, flame structures, ripples, clay clasts and distorted bedding are more common in the Powder Mountain well (Minton, 2002).

The Powder Mountain well displays both sub-vertical and sub-horizontal calcite-lined fractures. The CEPO Lewis well has similar calcite-filled fractures only in the bottom 1 ft (0.3 m) of the core (Minton, 2002). The Powder Mountain and CEPO Lewis wells both represent sheet facies (Witton, 1999).

PETROGRAPHY

Data from 40 thin sections have been compiled and analyzed from outcrop to 13,000 feet. Results are listed in Appendix B file, (pointcountingtable.xls) and are summarized in Tables 2-1-2-6. Data has been grouped by geographic location. Grain size was taken using a standard grain size chart where fine grained equals 125-250 microns and very fine equals 62-125 microns. The Dad sandstone samples in this study
consist of fine-grained, poorly sorted and texturally immature sandstone containing many ductile lithic fragments and angular to sub-angular grains. In general, shallow samples of the Dad sandstone tend to be fair-to-poorly sorted. The deeper samples are moderately well-sorted, but never become well-sorted sands.

Detrital Mineralogy

The Dad sandstone, Lewis Shale rocks are lithic arenites with a variable lithic component (Figure 2-1). Many of these sandstone samples fall on the border of classification schemes as seen in Figure 2-1. The deeper samples are more quartz-rich than the other samples, but they are located the farthest west in the basin.

Detrital Quartz

Detrital quartz is the most abundant framework grain in the Dad sandstone (Table 2-1). Quartz appears in two general forms: grains showing undulatory extinction and non-undulatory extinction. The percentage of quartz increases significantly with depth: 35% in outcrop and shallow burial to near 50% at depths of 13,000 feet.

<table>
<thead>
<tr>
<th>Sample Location/Well</th>
<th>Average Quartz (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>34.97</td>
</tr>
<tr>
<td>Strat Test #61</td>
<td>31.51</td>
</tr>
<tr>
<td>Creston SE #5</td>
<td>41.00</td>
</tr>
<tr>
<td>CEPO 21-18</td>
<td>20.30</td>
</tr>
<tr>
<td>Powder Mountain 1-13E</td>
<td>49.19</td>
</tr>
</tbody>
</table>

Table 2-1. Average quartz volume percentage for each sample location/well.
Feldspars

The second most abundant grain type is feldspar (Table 2-2). Total feldspar (K-feldspar plus plagioclase feldspar) averages between 12-17%. There is no apparent trend between feldspar and depth. Plagioclase feldspars are 2 to 3 times more abundant than K-feldspars. Differentiation between K-feldspars and plagioclase feldspars was achieved by staining samples for K-feldspar as well as observation of twinning textures on the plagioclase feldspars. Composition of the plagioclase grains was determined using the Michel-Levy Method (Table 2-3). Microcline is present in some of the samples, but is extremely rare. Twinning planes are seen in all samples from outcrop to 13,000 feet (Figure 2-2 and 2-3).

The lack of apparent trend with depth is not typical for reactive minerals such as feldspar, however, the deepest samples are from the CEPO 21-18 and Powder Mountain 1-13E wells. These wells are located in the western portion of the Washakie basin and there is evidence that the sediment sources in that portion of the basin are different than those for sediments in the northern portion of the basin (Escalante, 2003). Escalante showed that the western wells had significantly more mono-cytstalline quartz than the samples from the northern (Crestone) and eastern (outcrop and Strat Test well #61) portion of the study area. This is probably the main reason for the differences in the detrital composition seen in Figure 2-1.
Figure 2.1. QFL Diagram produced using percent quartz, total feldspar, and total lithic grains in all of the samples examined (n = 40). Data are shown in the point count data table (Appendix B).
## Table 2.2. Average percent plagioclase, K-spar, and average total feldspar percent.

<table>
<thead>
<tr>
<th>Sample/Well</th>
<th>Ave. K-Spar (%)</th>
<th>Ave. Plag. (%)</th>
<th>Ave. Feldspar (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>2.49</td>
<td>15.11</td>
<td>17.61</td>
</tr>
<tr>
<td>Strat Test #61</td>
<td>3.73</td>
<td>8.48</td>
<td>12.21</td>
</tr>
<tr>
<td>Creston SE #5</td>
<td>2.00</td>
<td>13.00</td>
<td>15.00</td>
</tr>
<tr>
<td>CEPO 21-18</td>
<td>4.32</td>
<td>9.47</td>
<td>13.79</td>
</tr>
<tr>
<td>Powder Mtn. 1-13E</td>
<td>4.10</td>
<td>13.40</td>
<td>17.50</td>
</tr>
</tbody>
</table>

## Table 2.3. Feldspar composition based on the Michel-Levy method of measuring maximum extinction angles between plagioclase twin lamellae.

<table>
<thead>
<tr>
<th>Sample/Well</th>
<th>Anorthite (%)</th>
<th>Max. Extinction Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>45</td>
<td>26.5</td>
</tr>
<tr>
<td>Strat Test #61</td>
<td>35</td>
<td>19</td>
</tr>
<tr>
<td>Creston SE #5</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>CEPO 21-18</td>
<td>31</td>
<td>16</td>
</tr>
<tr>
<td>Powder Mtn. 1-13E</td>
<td>26</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 2-2. Twinning fabric of plagioclase feldspar. Sample CD2-4 from outcrop. 
(Q=quartz), (Plg. F=Plagioclase Feldspar), (LG=Lithic Grain), and (M=Mica)
Figure 2-3. Twinning fabric still seen in samples from Powder Mountain 1-13 E, sample #2 at 13332.4 feet. (Q=Quartz), (OM=Opaque Material), and Plg. F=plagioclase feldspar).
Rock Fragments

Lithic grains and rock fragments include carbonate grains, igneous rock fragments (IRF), sedimentary rock fragments (SRF), volcanic rock fragments (VRF), and metamorphic rock fragments (MRF), they make up a significant percentage of the grains within the Dad sandstone and are dominantly ductile in nature (Table 2-4). Rock fragments make up 8-17% of the essential framework grains. Carbonate grains comprise the majority of these rock fragments.

<table>
<thead>
<tr>
<th>Sample/Well</th>
<th>Ave. Carbonate (%)</th>
<th>Ave. IRF (%)</th>
<th>Ave. VRF (%)</th>
<th>Ave. SRF (%)</th>
<th>Ave. MRF (%)</th>
<th>Other Lithics (%)</th>
<th>Ave. Total Lithics (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>7.39</td>
<td>2.85</td>
<td>0</td>
<td>1.77</td>
<td>1.97</td>
<td>10.75</td>
<td>24.73</td>
</tr>
<tr>
<td>Strat Test #61</td>
<td>9.25</td>
<td>1.37</td>
<td>0.33</td>
<td>3.68</td>
<td>1.66</td>
<td>5.00</td>
<td>21.29</td>
</tr>
<tr>
<td>Creston SE #5</td>
<td>10.00</td>
<td>1.00</td>
<td>0</td>
<td>1.00</td>
<td>1.00</td>
<td>4.00</td>
<td>17.00</td>
</tr>
<tr>
<td>CEPO 21-18</td>
<td>5.18</td>
<td>0.30</td>
<td>0.33</td>
<td>0.90</td>
<td>0.20</td>
<td>5.40</td>
<td>12.31</td>
</tr>
<tr>
<td>Powder Mtn. 1-13E</td>
<td>4.07</td>
<td>0.25</td>
<td>0.63</td>
<td>0.91</td>
<td>1.24</td>
<td>3.13</td>
<td>10.22</td>
</tr>
</tbody>
</table>

Table 2-4. Average percent total lithic grains and individual categories in samples from outcrop to 13,000 feet. (Note: Powder Mountain and CEPO represent half of the eastern samples)
Figure 2-4. Dissolution fabric of a rock fragment (RF) creating secondary porosity (SP). Sample from outcrop. (C=Carbonate Grain), (CL=Clay Coating), (Org. M=Organic Matter), (CC=Carbonate Cement)
Figure 2-5. Carbonate replacement (CR) of a lithic grain from CSM Strat Test #61 well, sample #43 at 411.7 feet. (Q=quartz)
Clays

Kaolinite, chlorite, illite, smectite and a mixed-layer illite/smectite were observed in samples from the Dad sandstone. Total percent clay is the amount of authigenic clay plus the amount of detrital clay present in these samples. Total clays were low in most samples (4-13%). Authigenic clays accounted for at least 50% of clay in all samples and were present as pore-filling and in some places grain-coating (Figure 2-6 and 2-7). Kaolinite is observed mainly fills pore spaces, and chlorite commonly coats grains (Figure 2-7).

Chlorite is present in all samples from outcrop to 13,000 feet. It is found dominantly coating grains, but also occludes pore spaces. Chlorite forms most commonly during diagenesis and low-grade metamorphism (Drever, 1997). As used here, the term illite includes all clay-sized (< 2 micron) minerals belonging to the mica group, that is, clay minerals that show a 10-Å basal spacing in X-ray diffraction (Grimm et al., 1937). Pure detrital illite, which is only seen in samples from outcrop to 8,000 feet, mainly coats grains as well as fills pore space (Figure 2-8). Smectite is present in its expandable state in outcrop only. The term smectite is used to describe any clay with a basal spacing (the thickness of the 2:1 sheet plus the interlayer space) that expands to 17-Å on treatment with ethylene glycol (Drever, 1997). Mixed-layer illite (0.9)/smectite, is observed only in samples at 13,000 feet (Figures 2.2-2.7). Mixed-layer illite/smectite clay forms bridges between grains, and lines grains, and occludes pore space (Figure 2-9). The energy dispersive X-ray fluorescence (EDAX) and clay x-ray diffraction pattern, show that this clay is an illite-smectite mixed-layer clay (Figures 2-10 and 2-16). The small amount of calcium present along with the broad reflection at approximately 8 degrees on the clay X-ray pattern in Figure 2-16 indicates mixed-layer clay. Authigenic clay material may be an important cause of porosity and permeability reduction in Dad sandstone reservoir sandstones.
Figure 2-6. Authigenic pore occluding material, including, illite, quartz cement, and chlorite. Sample from the Creston SE #5 well at 8,193 feet.
Figure 2-7. Clay coating grains, believed to be chlorite (Chl). Sample is from the Creston SE #5 well at 8226 feet. (Org. M=Organic Matter), (P=Porosity), (Q=quartz), and carbonate is stained in pink.
Figure 2-8. Photo taken from Creston SE #5 at 8,000 feet. Image shows I (.90)/S mixed-layer clay lining grains. Location of I (.90)/S denoted by I/S symbol. (L=Lithic grain), (C=Carbonate).
Figure 2-9. SEM image of mixed layer illite (.90)/smectite forming a bridge between two grains.
Figure 2-10. SEM EDAX plot of the elemental composition of the illite-smectite bridge in the photo in Figure 2-9. The small amount of calcium present in this plot indicates that the sample is a mixed-layer illite-smectite clay.
Figure 2-11. X-Ray diffraction pattern multiple display, gray= air dried, blue= glycolated, and green= heated to 550°C. Sample number CD2-4, from outcrop channel facies. Pattern displays smectite, illite, kaolinite, and chlorite.

Figure 2-12. X-ray diffraction multiple display pattern, gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from outcrop sheet facies, sample number SD2-1. Plot of XRD peaks displays normal pattern of illite, smectite, kaolinite, and chlorite.
Figure 2-13. X-ray diffraction multiple display pattern, gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from the Strat Test #61 well, sample # 26, 395 feet. Peaks SHOW detrital illite, smectite, kaolinite, and chlorite.

Figure 2-14. X-ray diffraction multiple display pattern gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from 8,213 feet (Creston SE#5 well). Plot displays a normal pattern of illite, smectite, kaolinite, and chlorite.
Figure 2-15. X-ray diffraction multiple display pattern gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from 13,356.6 feet (Powder Mountain 1-13E well). Pattern shows mixed layer illite-smectite clay where illite constitutes 90% of the mixed layer clay, kaolinite, and chlorite.

Figure 2-16. X-ray diffraction multiple display pattern gray= air dried, blue= glycolated, and green= heated to 550°C. Pattern is from 13,277.5 feet (CEPO Lewis 21-18 well). Pattern displays mixed layer illite-smectite clay where illite constitutes 90% of the mixed layer clay, kaolinite, and chlorite.
Carbonate Cement

Calcite is the most abundant cement in the Dad sandstone, ranging from 0-8% (Appendix A). Total carbonate, which includes calcite grains, cement, and replacement fabrics, ranges from 4-18% from outcrop to 13,000 feet (Table 2-5). Grains were at least 50% of the total carbonate in most samples.

<table>
<thead>
<tr>
<th>Sample/Well</th>
<th>Carb. Clasts (%)</th>
<th>Carb. Cement (%)</th>
<th>Carb. Replacement (%)</th>
<th>Total Carb. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>7.29</td>
<td>6.25</td>
<td>0.38</td>
<td>14.02</td>
</tr>
<tr>
<td>Strat Test #61</td>
<td>9.25</td>
<td>6.63</td>
<td>0.75</td>
<td>16.62</td>
</tr>
<tr>
<td>Creston SE #5</td>
<td>10.00</td>
<td>7.00</td>
<td>1.00</td>
<td>18.00</td>
</tr>
<tr>
<td>CEPO 21-18</td>
<td>5.18</td>
<td>2.40</td>
<td>0.00</td>
<td>7.58</td>
</tr>
<tr>
<td>Powder Mtn. 1-13E</td>
<td>4.07</td>
<td>0.00</td>
<td>0.00</td>
<td>7.58</td>
</tr>
</tbody>
</table>

Table 2-5. Total percent of carbonate grains, carbonate cement, and carbonate replacement, as well as the total carbonate from outcrop to 13,000 feet (Appendix A) (Note: Powder Mountain and CEPO represent half of the eastern samples)

Quartz Cement

Quartz cement plays a volumetrically minor role in the reservoir quality of the Dad sandstone (2-6% by volume). The normal trend of increasing quartz cement with depth is not well developed (Figure 2-17). Cement in the deeper samples (Figure 2-18) appears to have been inhibited by grain coatings with clay or ductile matrix (Figure 2-19 and 2-20).
Figure 2-17. Plot of percent quartz cement versus depth, n=40.
Figure 2-18. SEM image showing quartz growing around illite, representing a later quartz precipitation event. Photo from Powder Mountain 1-13E well at 13367.5 feet.
Figure 2-19. Photomicrograph shows irregular quartz grain boundaries resulting from opaque pore filling and grain lining material, which seems to be inhibiting the precipitation of quartz overgrowths in this sample. Sample taken from the Powder Mountain 1-13E at 13330.6 feet. (Q=Quartz), (OM=Opaque Material)
Quartz overgrowth – inhibited growth pattern. Quartz rims inhibited by opaque material within seams of grains.

Figure 2-20. Photo from approximately 13,000 feet, displays how quartz cement may be inhibited by opaque material coating grains (OM=Opaque Material), (Q=Quartz), (C=Carbonate).
Porosity

Porosity is an aspect of texture and is defined as the total of all void spaces within a rock (Boggs, 1995). Porosity is important in defining the reservoir quality of a rock. Figure 2-21 shows the He-porosity (core plug porosity determined by gas (He) displacement) versus depth trend for the 40 samples from this study. The relationship between porosity and depth from this study are very similar to data collected from other Dad sandstone samples (Figure 2-22) (Thyne et al., 2002). Three major forms of porosity observed in the Dad sandstone are: (1) microporosity, (2) primary (intergranular) porosity, and (3) secondary (dissolution) porosity, discussed in more detail below.

Microporosity

Microporosity, consists of small pores (i.e. aperture radii less than 5 microns) occurring between detrital or authigenic clays as well as within grains (Figure 2-23). Macropores may become micropores as minerals dissolve creating voids, and other pores become partly or completely occluded by precipitation of product minerals (Pittman, 1979). Micropores occur among clay minerals or at pore throat restrictions in sandstones. Based on observations, authigenic clay minerals and associated microporosity are common in the Dad sandstone. Pore throats in the Dad sandstone are partially or completely occluded by authigenic materials.

Microporosity is believed to be the cause of the higher He-porosity values compared to thin section porosities (in some cases). The He-porosity in the Dad sandstone ranges from 25-31% from 100-900 feet to 2-11% to 8,200 feet and from 6-11% at 13,300 feet. Thin section porosity values from the two shallower wells were often much lower than the He-porosity values (Figure 2-24 and Table 2-6).
Figure 2-21. Depth versus He-porosity (%); values include microporosity.

\[ y = 41866e^{-0.1489x} \]

\[ R^2 = 0.9239 \]
Figure 2-22. Plot of depth versus He-porosity from data collected from 1031 core plugs from the Dad sandstone (Thyne et al., 2002).
Figure 2-23. SEM image of a microporous grain. Sample is from the CSM Strat Test #61, sample #15 from approximately 207 feet.
Table 2-6. Summary of both thin section and He-porosity results, represented by sample location and depth. NM = not measured.
Figure 2-24. Relationship of He- and thin section porosity. Note the greater amount of underestimation for point counted values relative to He-porosity for the shallower samples (CSM Strat Test #61 and Creston SE #5).
Primary Porosity

Primary porosity (intergranular porosity) is defined as the percentage of void space between framework grains and is formed at or before the time of deposition (Boggs, 1995). Primary porosity was noted in point counts of the Dad sandstone samples. The results show that primary intergranular porosity is highly variable in the samples, but values in shallow samples were as high as 16%, while the deeper samples had values ranging from 4-9% (Table 2-6).

Secondary Porosity

Secondary porosity (intragranular porosity) is defined as the partial or complete dissolution of framework grains or cement and is formed during diagenesis, usually by solution/dissolution of framework grains within the rock (Boggs, 1995). The amount of secondary porosity ranges from 0-7% and is present in all samples from outcrop to 13,000+ feet (Figures 2-25 and 2-26). However, secondary porosity is 46% (mean value) of total porosity in the deep samples versus 24% (mean value) of the total in the shallow samples.

The most common form of secondary porosity is partial dissolution of grains (Figure 2-25 and 2-26), which occurs in samples from outcrop to 13,000 ft. Although feldspars, and less commonly VRF’s, are more susceptible to dissolution in Dad sandstone, there are some minor amounts of partial quartz dissolution are present as well. Although less common, secondary porosity is seen in the form of ghosts of grains (Figure 2-27) or remnant dissolved grains of uncertain identity in which dissolution has almost removed the grain completely, leaving behind an oversized pore space.
Figure 2-25. Plane light image shows secondary dissolution porosity, where the grain is almost completely dissolved at SP. Sample is from CSM Strat Test, sample # 26 from approximately 395 feet. (CL=Clay), (SP=Secondary Porosity), (LG=Lithic Grain), (C=Carbonate).
Figure 2-26. An example of secondary porosity (SP) from the CEPO 21-18, at 13,265 ft (Q=Quartz).
Figure 2-27. Ghost grain, where the grain is almost completely dissolved. All that remains is a clay rim and some remnant grain material. Sample #CD2-4, from outcrop channel facies. (SP=Secondary Porosity), (CL=Clay).
CHAPTER 3: SUMMARY OF RESULTS

Dad sandstones are dominantly detrital quartz and detrital feldspar (i.e. plagioclase), with an important lithic component comprised mainly of carbonate clasts, organic matter and other rock fragments. The lithic component of these sandstone’s are observed altered, replaced, and dissolved during burial (Figures 2-25 and 2-26).

Detrital quartz abundance increases in the deeper samples, which may be a result of dissolution removing feldspars and lithic grains and/or due to the proximity to a source of more quartz-rich sediments. Quartz grains show both undulatory and non-undulatory extinction patterns. Those showing undulatory extinction may be derived from a metamorphic or plutonic origin rather than a volcanic origin (McCullough, 1995). Feldspar abundance neither decreases nor increases as sample depth increases. However, dissolved feldspar grains leave only remnants of plagioclase and orthoclase. Microcline is extremely rare.

Twinning planes are seen in feldspar from outcrop to 13,000 feet (Figures 2-2 and 2-3). The presence of the twinned lattices and lack of dissolution textures in some grains, especially at greater depths, suggests that a coating on grain surfaces kept feldspars from reacting with the surrounding material/fluids during burial.

DIAGENESIS

Four major diagenetic processes that occur in the Dad sandstone include: compaction, cementation and development of secondary and microporosity, discussed in the following section. The result of these diagenetic processes influences the reservoir quality of sandstones.
Compaction

Figures 3-1, 3-2, and 3-3 show the systematic loss of porosity during burial. The most visible mechanism appears to be physical compaction. Porosity is reduced during burial diagenesis by mechanical compaction, intergranular pressure solution and cementation (Houseknecht, 1987). Compaction works in conjunction with cementation, to reduce porosity. Mechanical compaction irreversibly reduces the intergranular volume of sand (Houseknecht, 1987). Relationships between compaction indices and sandstone composition clearly show that sandstone lithic content strongly influences susceptibility to compaction (Lundegard, 1992). A rock consisting of dominantly rigid minerals, such as quartz, tends to undergo only minor porosity and permeability reduction during compaction due to grain rotation and rearrangement into a tighter packing configuration (McBride, 1984). Sandstones containing a greater volume of ductile grains will experience more porosity loss by mechanical compaction early in their burial history (Dutton, 1995). The Dad sandstone’s lithic component is predominantly ductile in nature and therefore, will be more susceptible to compaction with burial.

A quantitative estimation of porosity loss due to compaction and cementation using point-count data on cement and pore space abundance was made using the Dad sandstone data (Lundegard, 1992). Errors associated with this method come from uncertainty in initial sandstone porosities, the amount of local grain dissolution and precipitation during burial, and accuracy of the porosity values (Lundegard, 1992). Initial porosity for the Dad sandstone was estimated at 45% and used in the calculation of compaction. Houseknecht (1987) calculated the percent original porosity destroyed by compaction equal to 40%, however 45% was used for initial porosity because this value was observed from He-porosity data in the shallow samples. Compactional porosity loss may be underestimated by using porosity values from point counting procedures because microporosity is not easily visible in thin sections (Pittman, 1979). This underestimation of true porosity due to microporosity may lead to an overestimation of compactional
porosity loss. This may be the case for the Dad sandstones in CSM Strat Test #61 well samples where point-counting data was much lower than He-porosity (Figure 2-23). In spite of the uncertainties, it was worthwhile to evaluate compactional effects because it is potentially the most important mechanism of porosity loss in these sandstones.

The Dad sandstone compaction index was calculated using the following methodology from Lundegard (1992):

Compactional porosity loss (COPL) = ((100 - Pi) * (Pmc))/(100 - Pmc).
Cementational porosity loss (CEPL) = (Pi – COPL) * (Total cement/Pmc)
Where: Pi is initial porosity and Pmc is minus cement porosity

Minus-Cement Porosity

Minus-cement porosity (intergranular porosity + intergranular mineral cement) indicates the amount of compaction in sandstone (Dutton, 1995). Minus-cement porosity averages 20 % and ranges from 11%-41% (Table 3-1). The upper values are used as an estimate of porosity during the time of deposition of the rock (Higley et al., 1997). The minus-cement porosity versus depth trend (Figure 3-4) shows that near-surface porosity of 40-45% decreases rapidly to less than 10-20% by 8000 feet. The trend of declining minus-cement porosity with increasing depth is more gradual than that of measured porosity versus depth, because minus-cement porosity better represents the compactional component of porosity loss.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Depth (ft)</th>
<th>Range (%)</th>
<th>Mean (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>0</td>
<td>18-35</td>
<td>24</td>
</tr>
<tr>
<td>Strat Test Well #61</td>
<td>160-900</td>
<td>15-41</td>
<td>24</td>
</tr>
<tr>
<td>Creston SE #5</td>
<td>8190-8230</td>
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<td>20</td>
</tr>
<tr>
<td>CEPO 21-18</td>
<td>13258-13282</td>
<td>15-21</td>
<td>18</td>
</tr>
<tr>
<td>Powder Mtn. 1-13E</td>
<td>13332-13358</td>
<td>11-13</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 3-1. Minus cement porosity values represented by location and depth.
Figure 3-1. Uncompacted sample from outcrop, showing approximately 25-30% porosity. Sample CD2-8 from outcrop channel facies, (Org. M=Organic Matter), (P=Porosity – Blue Areas), (F=Feldspar), (C=Carbonate Grain), (Q=Quartz).
Figure 3-2. Sample is from Creston SE #5 core at 8,200 ft. Compaction and carbonate cementation both reduce the amount of intergranular porosity.
Figure 3-3. Sample from Powder Mountain 1-13 core sample #7. Compaction increased with depth to 13346.5 ft, showing <10% porosity in blue, (Q=Quartz), (SP=Secondary Porosity), (Cm=Cement), (Org. M=Organic Matter).
Figure 3-4. Plot of depth vs. minus-cement porosity calculated using core plug (He) porosity.

\[
y = 1E+08x^{-3.1535} \\
R^2 = 0.7614
\]
Figure 3-5 shows the COPL versus CEPL values using the thin section porosity to calculate the minus-cement porosity. Examination of the figure reveals that all the samples have significant porosity loss including the outcrop and CSM Strat Test #61 well samples. Outcrop samples with a high value for compactional porosity loss may be influenced by microporosity that skews the values toward higher compactional contribution, since the minus-cement porosity is underestimated causing the COPL value to be too high. Figure 3-6 shows the difference in the plot if the helium porosity values are used to calculate the minus-cement porosity. Outcrop samples are omitted since there were no core plug porosity values from outcrop samples. Figure 3-6 shows that for the Dad sandstone samples, the following observations can be made:

1. The shallow samples from the CSM Strat Test #61 well (162 ft to 892 ft sampling depth) have modest overall porosity loss (10-15%), with approximately equal amounts from cementation and compaction.

2. In the Creston SE #5 well (8,193 ft to 8,218 ft sampling depth), the overall porosity loss was higher (35-40%), but compaction was the more important mechanism.

3. In the CEPO 21-18 and the Powder Mountain 1-13E wells (13,250 ft to 13,360 ft sampling depth), the porosity loss was as large as the Crestone well, but mostly due to compaction.

Compactional porosity loss in the Dad sandstone exceeds 30% in the deeper samples suggesting the ductile portions of the rocks are deformed to fill intergranular pore spaces. In the Creston SE #5 well, the overall porosity loss is similar to the deeper wells, but a larger portion is due to cementation, mostly by carbonate. Based on the results summarized above, the Dad sandstone the most important mechanism of porosity loss is compaction with depth, while the role of cementation is of lesser significance.
Figure 3-5. COPL vs. CEPL for all samples showing relative contributions of compactional and cementation processes in porosity loss. The figure was plotted for values calculated with minus-cement porosity equal to thin section porosity plus cement volume.
Figure 3-6. COPL vs. CEPL for all samples showing relative contributions of compactional and cementation processes in porosity loss. The figure was plotted for values calculated with minus-cement porosity equal to core plug (He) porosity plus cement volume.
Cementation

Cementation occurs when chemical precipitates form in the pores of a sediment or rock, binding the grains together (Boggs, 1995), which reduces porosity by filling in the pore spaces between the grains. However, it is reversible (Boggs, 1995). Precipitation of authigenic minerals usually reduces reservoir quality; however, early formation of some authigenic minerals can preserve the original porosity by protecting the rock from later degradation by compaction or cementation (Wilson and Pittman, 1977). In this study, carbonate, MLIS, illite, and chlorite were the most common cements in the Dad sandstone (Table 3-2), with small amounts of quartz cement.

<table>
<thead>
<tr>
<th>Quartz Cement (%)</th>
<th>Carbonate Cement (%)</th>
<th>Clay Cement (%)</th>
<th>Micaceous Cement (%)</th>
<th>Other Cement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>37</td>
<td>35</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3-2. Summary of total percent cement for all samples.

Petrographic evidence suggests that carbonate precipitation may have occurred in multiple stages during the burial of the Dad sandstone. An early precipitation event may have worked to preserve original porosity, observed in the form of poikilotopic cement (Figure 3-7). This pattern is generally observed to occur in samples from shallow cores and outcrop located in the eastern portion of the basin. The source of carbonate cement was not determined for these samples. A later carbonate cementation (precipitation) event may have occurred during the burial mainly in the form of a replacement fabric (Figures 3-8 and 3-9), in which carbonate precipitated and replaced the grain (i.e. carbonate precipitation on a twinned plagioclase grain, preserving the twinned fabric after burial). Poikilotopic carbonate cement dominates samples ranging from 400-8,500 feet, but is rare in samples at 13,000 feet. However, grain replacement fabrics are still observed at 13,000 ft.
Clays occlude pore throats as well as coat and replace grains in the samples analyzed in this study. Clay replacement may increase overall porosity of the rock; however, the pores associated with clay minerals tend to be micropores that contain irreducible (bound) water. Primary porosity in Dad sandstones has been significantly reduced as a result of clays in the form of authigenic clays and detrital pore filling clays. Illite and smectite or a MLIS mix are the dominant forms of clay cement occluding pore throats; whereas chlorite, which is seen in all samples generally coats and replaces grains.

The Dad sandstone appears to contain no trend of increasing quartz cement with depth (Figure 2-18). As depth increases, quartz grain boundaries sometimes appear less defined due to dissolution-like textures. Quartz cement also appears to be inhibited by clay coatings, opaque pore coating and grain lining material (Figure 2-19, 2-20). However, grain coating by authigenic chlorite does not appear to be the mechanism by which quartz precipitation under burial is inhibited in these rocks (Ehrenberg, 1993). In contrast, at shallower depths quartz grains have sharp boundaries and display thin quartz overgrowths. Quartz cement shows an inverse trend in these sandstones.

In summary, compaction plays a major role on reservoir quality in the Dad sandstone due to the ductile framework grains, which reduces intergranular porosity under increased compaction and burial as opposed to a system with a more rigid framework. Physical compaction accounts for most initial porosity loss. During later diagenesis, the cements, mainly clays and carbonate, account for additional porosity reduction; therefore, the diagenetic factors are of secondary importance on reservoir quality in the Dad sandstone. However, late stage porosity enhancement is observed due to the dissolution of lithic grains and feldspars that may double primary porosity.

Cementation also plays an important role in reducing reservoir quality in the Dad sandstone. Carbonate cementation is seen in two major forms: 1) poikilotopic cement and 2) replacement fabrics. The carbonate cement fills voids within grains themselves that were originally created by dissolution. Cement occurs in the form of authigenic clay and clay coatings on grains. Authigenic clay cement fills pore space and as a result
reduces porosity values under burial. Clay coatings do not appear to greatly contribute to intergranular porosity reduction but do however reduce intragranular porosity. Unstable grains (VRF and feldspars) commonly are altered by compaction and crushing of grains creating additional fresh surfaces, which then can react with formation fluids. Some of these grains alter to authigenic clays. The authigenic clays precipitate after dissolution and alteration of grains within pore spaces. Authigenic clays documented in the Dad sandstone are kaolinite, chlorite, illite, and a mixed layer illite (0.90)/smectite.
Figure 3-7. Poikilotopic carbonate cement (PC) from outcrop (sheet) sample #SD2-1. (Org. M=Organic Matter), (F=Feldspar).
Figure 3-8. Carbonate replacement (CR) of a feldspar grain. Sample is from the Creston SE #5 well at 8213 feet.
Figure 3-9. Dissolution of the feldspar grain, then replacement by carbonate within this plagioclase feldspar grain. Sample from the Powder Mountain 1-13E well at 13330.6 feet. (F = Feldspar and CR = Carbonate Replacement).
Paragenesis

On the basis of petrographic evidence and combining the relative sequence of major events in the diagenetic history of the Dad sandstone of south-central Wyoming is summarized as follows: 1) mechanical compaction by grain rearrangement and deformation of ductile grains; 2) formation of illite and mixed-layer illite smectite (MLIS) rims; 3) precipitation of calcite cement; 4) precipitation of quartz overgrowths; and 5) generation of secondary porosity by dissolution of feldspar, chert, biotite, and mudstone grains and calcite cement. Many of these events overlapped in time based on the observations made for the Dad sandstone. Figure 3-10 below summarizes the petrographic relationships observed in thin section and SEM analysis.

<table>
<thead>
<tr>
<th>Diagenetic Occurrences</th>
<th>Early ← Relative Time → Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Compaction</td>
<td></td>
</tr>
<tr>
<td>Authigenic Clay (Illite/MLIS Rims)</td>
<td></td>
</tr>
<tr>
<td>Precipitation of Calcite Cement</td>
<td></td>
</tr>
<tr>
<td>Secondary Porosity Development by Dissolution</td>
<td></td>
</tr>
<tr>
<td>Precipitation of Clay in Pores</td>
<td></td>
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<tr>
<td>Precipitation of quartz cement at depth</td>
<td></td>
</tr>
<tr>
<td>Precipitation of clay (chlorite) coatings</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3-10. Paragenetic sequence of diagenetic events. Dashed lines represent uncertainty in timing of events.
The events that occurred relatively early in the paragenetic sequence are physical compaction, calcite cementation (pre-and post-compaction events), secondary intragranular dissolution porosity, authigenic clay formation, and alteration of grains. Mechanical compaction begins early and continues to mid-diagenesis, reducing primary porosity to less than 25%, due to the ductile grains (Figure 3-11). Further burial causes chemical compaction to occur that produces sutured contacts as pressures increase.

It is possible that two calcite precipitation events exist in the sample set. Calcite cementation in the form of poikilotopic cement occurs in shallow samples where it may preserve primary porosity and produce minus-cement porosity values greater than 35%. However, the deeper Crestone well samples also have similar cement, but with reduced minus-cement values indicating precipitation during deeper burial. Thus, there could be two events or a single event could be responsible. More detailed examination is required including stable isotope and CL data. The amount of carbonate cement is proportional to the amount of carbonate rock fragments.

Grain alteration and secondary intragranular dissolution porosity appear to have started relatively early in the sequence of events. Grains that were most susceptible to alteration and dissolution were volcanic and feldspar grains. Dissolution of these grains can be seen in samples from outcrop to 13,000 feet. Dissolution in shallow samples may be related to near surface processes, where partially dissolved grains were cemented, no later alteration especially in samples with 30-40% minus cement porosity (Table 3-1). Alteration (typically in the form of feldspars altering to clay) begins shortly after dissolution of grains and continues throughout the burial, evidence is seen by observing cross-cutting relationships. The shallow samples show dissolution such as ghost grains and intragranular porosity that would be lost to physical compaction if the rocks had been deeply buried after dissolution. Other common alteration features include clay-rim remnants and carbonate dissolution.
Figure 3-11. Photomicrograph from Powder Mountain 1-13 sample #4 taken from 13343.5 ft. Lewis framework grains are ductile in nature causing increased compaction under burial.
Late-stage diagenesis included the albitization of feldspar, formation of secondary pores by dissolution of framework grains, and precipitation of chlorite, illite, and quartz. Much of the secondary porosity in the Dad sandstone may have been formed by feldspar, and lithic grain dissolution. As dissolution and alteration of framework grains continued, authigenic clay precipitated in narrow pore spaces and lined grains with early detrital clay rimming grains that was later altered to illite during burial (Figure 3-12). Quartz is seen growing around authigenic clay material, indicating late quartz cement precipitation.

No correlation was observed between facies and diagenesis as a result of this study. However, samples from shallow cores and outcrop (CSM Strat Test #61 and Creston SE #5) located in the eastern portion of the basin display poikilotopic cementation patterns where this pattern is not observed in deep samples (CEPO 21-18 and Powder Mountain 1-13E) from the western side of the basin. Samples from deep western cores (CEPO 21-18 and Powder Mountain 1-13E) are observed to contain more detrital quartz and shallow samples contain a greater lithic component.

Reservoir Quality

The quality of a petroleum reservoir is directly related to porosity and permeability (Primmer et al., 1997). Within the sandstones of the Lewis Shale, the reservoir quality may be controlled by initial sediment composition, burial history, and the mineral precipitation and dissolution that occur during burial and lithification (Primmer et al., 1997). Figure 3-13 shows there is a strong positive correlation between the porosity and permeability in the Dad sandstone, which suggests that reservoir quality may be directly related to porosity. This correlation pattern between porosity and permeability is very similar to other data collected from the Dad sandstone (Figure 3-14) (Thyne et al., 2002).

Primary porosity in the Dad sandstone has been significantly reduced as a result of compaction, cementation (both calcite and quartz) and clays (in the form of authigenic
Figure 3-12. Illite lining grains and/or precipitating on the edges of grains and filling small void space in between grains (plane light-B and cross polars-B). Sample from Creston SE #5 sample from 8,213 feet. (C = carbonate, Q = Quartz grain, and I = Illite).
and detrital clays). Although cementation may have occurred throughout the burial history of these sands, it was not pervasive enough to have protected primary porosity during increased burial. Quantification of compactional porosity loss is complicated by not being able to determine the exact initial porosity and by underestimation of present porosity by point counting due to microporosity, which is not easily seen in thin sections (Lundegard, 1992; Pittman, 1979).

The large amount of secondary porosity in shallow samples may be from leaching by meteoric water creating secondary porosity (Pittman, 1979). Secondary porosity in the deeper Dad sandstone is an important component of reservoir quality in deep wells since approximately one-half of the total porosity is secondary, but of a different origin than that of shallow samples. In the Dad sandstone, it appears that secondary porosity is mainly formed from dissolution of more soluble grains, such as feldspars (i.e. orthoclase and plagioclase) and rock fragments (Figure 3-15).

Surdam et al. (1989) developed a predictive model for sandstone diagenesis that may be applicable to the Dad sandstone. They suggested a working hypothesis that generation of organic acids during burial controls the enhancement of porosity of sandstones in the 80º to 120º C thermal window just before liquid hydrocarbon generation. The ideal scenario for maximizing porosity preservation and/or enhancement includes: (1) close proximity to organic-rich source rocks and potential reservoir rocks (short migration routes); (2) availability of organic-rich source rocks that either contain types II and III kerogen with associated mineral oxidants (clay minerals and/or polysulfides); (3) rapid evolution from organic acid/phenol generation to hydrocarbon maturation (overpressuring); (4) adequate fluid flux (clay diagenesis or other dehydration reactions are necessary; and (5) available conduits into potential reservoir rocks. The organic-rich portions of the lower Lewis are ideally positioned to provide organic acids. The source rocks are distributed in a broad areal extent (eastern side of GGRB), with Type II and III kerogen reaching the oil window at burial depths of approximately 8,000 feet (Escalante, 2002), at about the same depth as overpressuring (Suryanto, 2003).
Figure 3-13. He-porosity versus permeability (k) in milldarcies (mD) from the 40 conventional core plugs from this study.
Figure 3-14. Plot of He-porosity versus permeability (k) in millidarcies (mD) from data collected from 1031 core plugs from the Dad sandstone (Thyne et al., 2002).

\[ y = 3 \times 10^{-7}x^{5.7828} \]

\[ R^2 = 0.8665 \]
Figure 3-15. Dissolution of grains. Sample #4 from CEPO 21-18 core, 13,260.4 feet, $k = 0.01$ mD.
CONCLUSIONS

Based on the results summarized above the following conclusions can be made about the Dad sandstone member of the Lewis Shale:

- As depth increases, compaction becomes the dominant process in controlling the reservoir quality, in particular the systematic reduction in porosity and permeability as depth is increased, of these rocks where, the role of cementation is secondary. Early cementation is not pervasive enough to preserve the reservoir quality of these sandstones. Overall, compaction is the major contributor to primary porosity loss in these rocks.

- Microporosity, is one of the major contributing factors for thin section porosity underestimating He-porosity values, because of micropores that occur between detrital or authigenic clays but also seen within some clay grains.

- Diagenetic alterations and authigenic minerals have played a role in Dad sandstone reservoir quality by occluding pore throats and reducing primary porosity. Primary porosity in the Dad sandstone has also been reduced as a result clays in the form of authigenic clays and detrital pore filling clays, and cementation (both calcite and quartz).

- Secondary porosity in the Dad sandstone is a significant component of total porosity in the deep samples.

- Porosity enhancement is primarily caused by the later dissolution of feldspars and other soluble detrital grains. Secondary porosity in these rocks can be identified by the dissolution textures including oversized pores.

- There is no observed correlation between facies and diagenetic occurrences of the Dad sandstone.

- Shallow samples located in the eastern portion of the Washakie Basin display poikilotopic cementation patterns, where this pattern is not observed in deep
samples from the western side of the basin. Observations also show that samples from deep western cores contain more detrital quartz than in the shallow eastern samples.
REFERENCES


