THESIS

FACIES DISTRIBUTION, ITS IMPLICATIONS FOR CLIMATE SIGNALS, AND HYDROCARBON POTENTIAL OF THE PERMIAN LYONS SANDSTONE, FRONT RANGE BASIN, NORTHERN COLORADO, USA

Submitted by

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ABSTRACT

FACIES DISTRIBUTION, ITS IMPLICATIONS FOR CLIMATE SIGNALS, AND HYDROCARBON POTENTIAL OF THE PERMIAN LYONS SANDSTONE, FRONT RANGE BASIN, NORTHERN COLORADO, USA

The Permian Lyons Formation consists of mostly fine- to medium-grained sandstones with minor silt- and mudstone intercalations. The formation shows six siliciclastic facies that are grouped into two Facies Associations: Facies Association 1 consists of high-angle cross-laminated sandstones (Facies 1), low-inclined cross-laminated sandstones (Facies 2), horizontally-laminated sandstones (Facies 3), and chaotically-bedded to folded sandstones (Facies 4), while Facies Association 2 is mainly characterized by wavy- to irregularly-laminated silty sandstones (Facies 5) and massive to wavy-laminated silt-rich mudstones (Facies 6) with minor amounts of high-angle cross-laminated sandstones (Facies 1), low-inclined cross-laminated sandstones (Facies 2) and horizontally-laminated sandstones (Facies 3). Facies Association 1 deposits dominate the southern part of the study area whereas Facies Association 2 sediments are more common towards to north. Stratigraphically, Facies Association 1 and 2 deposits occur intercalated with each other, and generally show two time Facies Association 2 sediments overlain by Facies Association 1 deposits. This intercalation of Facies Associations is best observed in the central part of the study area. In the south, Facies Association 1 deposits strongly dominate the succession, and in the north Facies Association 2 deposits are much more common, and do not show intercalation clearly.

In the Lyons Formation, high-angle cross-laminated sandstones (Facies 1) are interpreted as remnants of fossil eolian dunes. Between these dunes, nearly flat to low-inclined dry interdunal areas occur and they are characterized by low-inclined cross-laminated sandstones (Facies 2) and horizontally-laminated sandstones (Facies 3). Chaotically-bedded to folded sandstones (Facies 4) represent internal deformation of dune deposits in the lower portion of dune flanks. Deposition of wavy- to irregularly-laminated sandstones (Facies 5) reflects wet to damp conditions in interdune areas. Massive to wavy-laminated silt-rich mudstones (Facies 6) indicate the presence of small ponds or lakes between dunes. Facies Association 1 deposits overall represent dry eolian conditions, and Facies Association 2 deposits represent wet eolian conditions. The distribution of Facies Association therefore indicates that dry and wet climates were generally alternating but overall dry climate conditions dominated the southern part of the study area whereas wet conditions were more prevalent in the north. Stratigraphically, the north to south transect reflects an expansion of dry conditions northwards despite the climate fluctuations, and a “Goldilocks” window of where to best observe climate cycles in the central part of the study area. This change in depositional conditions is exclusively observed along a north-south transect but not evident in an east-west direction. This study interprets the parts of the succession where Facies Association 1 sediments dominate as the paleo-erg center, and the portions where wet Facies Association 2 deposits are more prevalent as a paleo-erg margin environment.

In the Lyons Formation, dry eolian deposits show good reservoir quality because of overall excellent sorting and roundness of the grains, while wet eolian deposits contains more fine-grained sediment which causes poorly sorting and reduction of porosity. Therefore, this study interprets that the main Lyons Formation plays are in the southern part of the study area within the paleo-erg center where dry eolian deposits are strongly dominating.

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TABLE OF CONTENTS

1.0 INTRODUCTION

Eolian facies are characteristic for arid climates, yet they can also reflect less dry and more humid environmental conditions (Loope, 1985). Eolian strata are often arranged in distinct cycles that are thought to be the product of climate fluctuations, and these cycles may therefore also provide a time-frame for the duration of sedimentation (Clemmensen et al., 1994). Nevertheless, all previous studies have shown that such cycles can be traced laterally throughout an eolian system and connect a range of different eolian depositional environments (Loope, 1985; Clemmensen et al., 1994; Scherer and Lavina, 2005; Mountney, 2006). Such a pattern, however, may not be recognizable in all fossil examples of eolian strata and should therefore be scrutinized critically.

Here, we present data from the Lyons Formation of northern Colorado, an eolian system that does not follow this general assumption. Even though climate cyclicity is well documented in the succession, portions of it do not reflect any climate fluctuations. This study suggests that eolian depositional environments may in part not record changes from humid to arid, and therefore climate models should be built on a sufficiently robust data set that incorporates all lateral facies variations, and not expect every section to reflect all climate fluctuations.

Recognizing climate cycles builds on the documentation and interpretation of a variety of eolian facies in the succession. This study therefore started with a detailed sedimentary facies description, documented the lateral and vertical distribution of facies throughout the basin in northern Colorado, and used the resulting data set as a basis for interpreting possible climate signals for this part of the Permian throughout northern Colorado. The investigations focus on twenty-two drill cores taken from the Lyons Formation (present in the subsurface of the northeast Colorado) in Weld and Larimer Counties, Colorado, which are available at the USGS

Core Research Center at the Federal Center in Lakewood, Colorado (Table 1; Fig. 1). The aim of this study are: (1) to determine and describe facies and facies associations in the Lyons Formation and present the facies architecture along a north-south and east-west transect through the basin; (2) to develop a detailed depositional model for the Lyons Formation in order to understand and predict sediment distribution in this sedimentary system laterally and vertically; (3) to determine how climate changes influenced sedimentation throughout the Lyons Formation and detect changes in the different parts of the basin, and (4) to determine reservoir facies in this unit, and document their lateral and vertical variations throughout the succession in order to predict reservoir geometries and reservoir rock distribution.

Table 1. List of drill cores logged in this study. (x^1) indicates the cores used for cross section, and (x^2) indicates cores have porosity and permeability analyses.

Original Operator	Original Well Name	Field	USGS Library #
Amoco Production[1]	Clara A Bacon 1	Wattenberg	B571
Coquina Oil[1,2]	Berthoud State 2	Berthoud	A739
Hamilton Bros Oil Co	Carroll 1-30	Baxter Lake	D337
Viking Petroleum[1]	Cactus Hill State 2	Unnamed	A839
Viking Petroleum	Cactus Hill State 1	Wildcat	A840
Apache Corporation	Black Willow 1	Wildcat	B190
California Oil	Brownell 1	New Windsor	B355
Apache Corporation[2]	Rodenberger 1	Wildcat	C130
Amoco Production	Champlin 1A 312	Wildcat	A774
Crystal Oil	Crystal Amoco 21-13	Wildcat	A900
Tiger Oil[1,2]	Wadleigh 34-21	Wildcat	B187
Amoco Production[1]	Champlin 410	Wildcat	B290
California Oil[2]	Pierce 1	Pierce	B356
General American Petroleum	Uprr Turner 1-7	Wildcat	D030
Pomeroy Production	Community 6	Fort Collins	D485
Chevron Oil[2]	Pierce 3	Pierce	D926
Hamin Jake L[2]	Beatty 1	Wildcat	E783
Shell Oil Company[1]	Colorado National Bank 1	Wildcat	F033
Chevron Oil[1]	Vern Woods 1	Pierce	S722
California Oil[1]	Lee Ray Walker 1	Pierce	S781
Amoco Production	Champlin Amoco A 491	Wildcat	B316
Hilliard O&G Inc.[1]	Amoco Uprr 1	Wildcat	E739

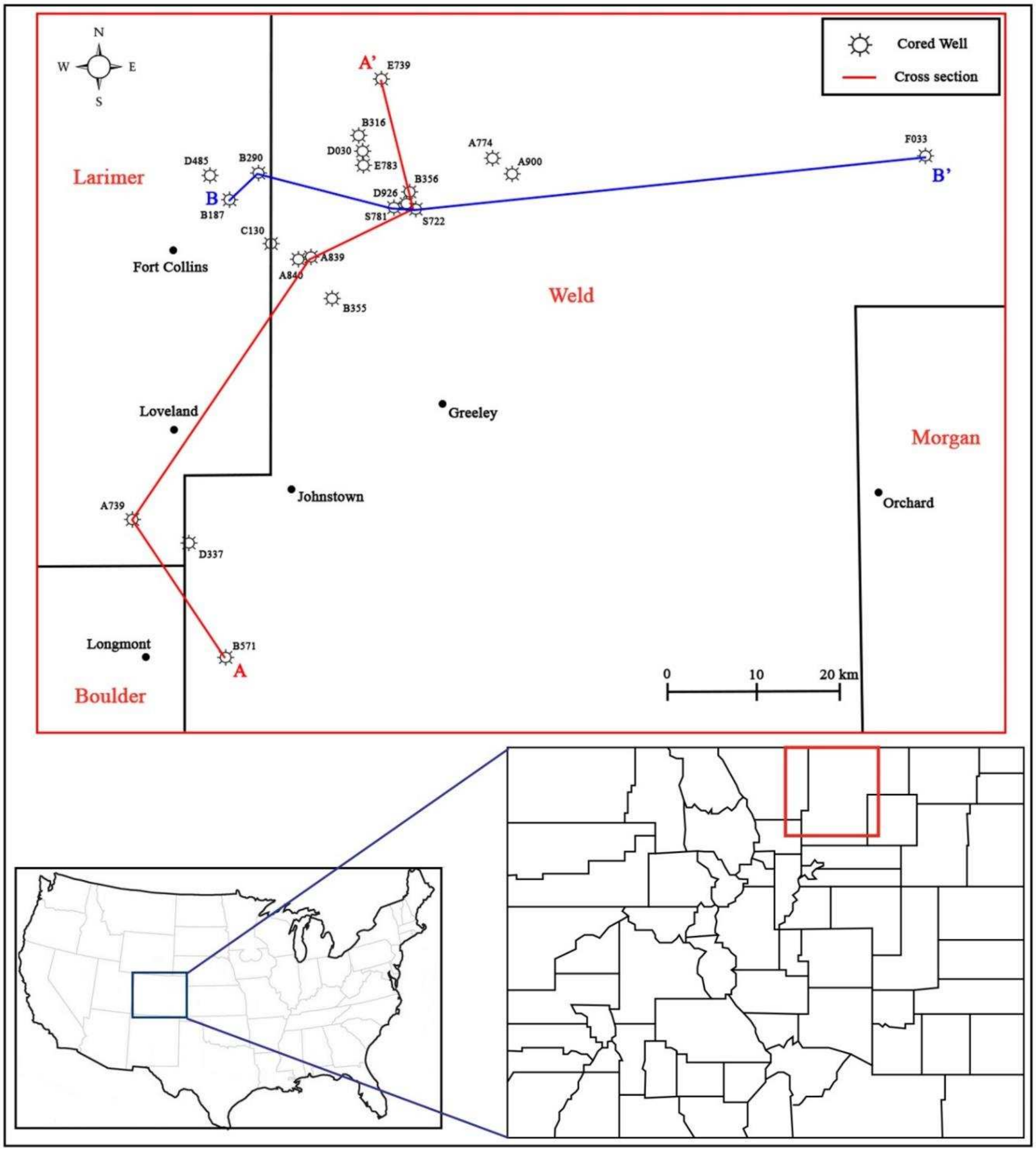

Figure 1. Map showing the location of the study area and drill cores, and north-south and east-west transects.

2.0 GEOLOGICAL SETTING

During the Mississippian, a compressional, likely small-scale foreland basin formed in the area now occupied by the Front Range and further to the east in northern Colorado (cf. Dickinson and Lawton, 2003; Lawton et al., 2015) here referred to as the Front Range Basin (Fig. 2).

This depositional trough was bounded to the west by the Ancestral Rocky Mountains and was initially filled by the continental red beds of the Mississippian to Pennsylvanian Fountain Formation (Maughan and Wilson, 1963; Maughan, 1980) (Fig. 3). The overlying Ingleside Formation exhibits the transition into the Permian, as well as the first marine ingressions into Colorado, coming from the north (Heaton, 1933; Maughan and Wilson, 1963). The fine-grained, partly gypsum-rich Owl Canyon Formation conformably overlies the Ingleside Formation and represents partly continental and partly restricted marine deposition (Maughan, 1980). Still in the Permian, the Lyons Formation, interpreted as either fully or partly continental (Adams and Patton, 1979; Tieje, 1923; Vail, 1917; Walker and Harms, 1972), shows sedimentation from eolian dunes above an unconformity with the underlying Owl Canyon Formation. Its top exhibits another unconformity to the Lykins Formation that straddles the Permian-Triassic boundary (Walker and Harms, 1972; Weimer and Land, 1972). It is unlikely, however, that the overlying Triassic to Jurassic Jelm, Sundance, and Ralston Creek Formations still reflect deposition into the Front Range Basin formed by the Ancestral Rocky Mountain uplifts as these movements are thought to have ceased latest in the Permian (Dickinson and Lawton, 2003).

The Permian Lyons Formation is a sand-dominated unit, distributed throughout the Front Range Basin and shows varying thickness from around 1 to 20 m. In early studies (Fenneman, 1905; Heaton, 1933; Thompson; 1949), the Lyons Formation is described as undivided, whereas Blood (1970) and Weimer and Erickson (1976) suggest a subdivision into three distinct stratigraphic members, in both cases based on data from Morrison, Colorado (Fig. 4). An even more detailed subdivision is presented by Adams and Patton (1979) comprising nine members labeled Unit A to I (Fig. 4).

From a depositional standpoint, the Lyons Formation was interpreted as both continental as well as shallow-marine. The Lyons Formation was described as beach bar deposits by Fenneman (1905) and Thompson (1949), and near-shore deposits by Heaton (1933) and Blood (1970). However, it was re-interpreted as fluvial by Weimer and Land (1972), and as a combination of fluvial and eolian by Weimer and Erickson (1976). Early studies by Vail (1917) and Tieje (1923), in contrast, suggested a purely eolian depositional environment for the Lyons Formation. These ideas were reiterated in the 1970s by Walker and Harms (1972), and Adams and Patton (1979).

It is generally assumed that the Permian in the central US was characterized by dry climatic conditions (Peterson, 1980), and especially in Colorado, climate was thought to be arid during that time span (Vail, 1917). The assumed arid climate led Adams and Patton (1979) to suggest that the Lyons Formation was most likely deposited in a desert-like and/or sabkha environment.

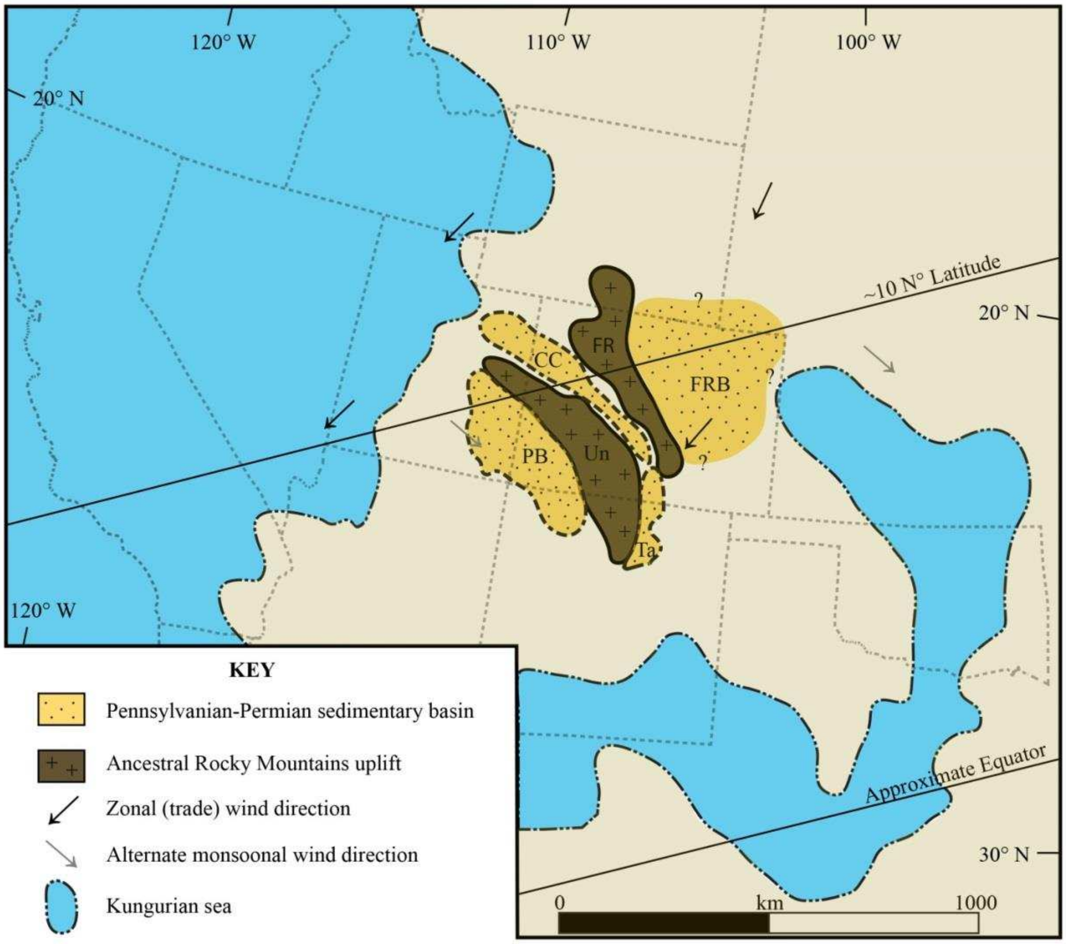

Figure 2. Paleogeography of Colorado during Permian times highlighting Pennsylvanian-Permian sedimentary basins, the Ancestral Rocky Mountains uplifts, the shoreline of the Kungurian Sea, and zonal (trade) and alternate monsoonal wind directions. Pennsylvanian-Permian sedimentary basins: CC, Central Colorado trough; FRB, Front Range Basin; PB, Paradox Basin; Ta, Taos trough. Ancestral Rocky Mountain uplifts: FR, Front Range; Un, Uncompahgre. Modified from Lawton et al. (2015). The border of the Front Range Basin is not well known and therefore labeled with question marks.

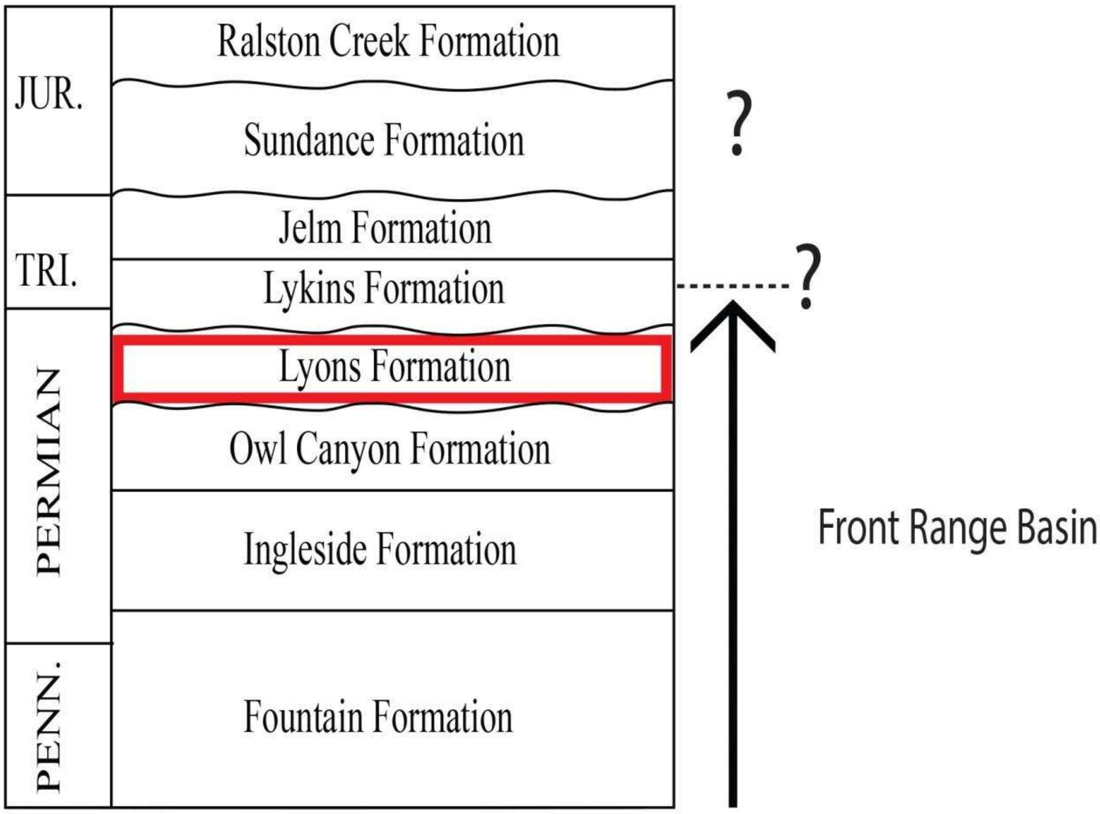

Figure 3. Stratigraphic column of the Front Range Basin. The red rectangle highlights the Lyons Formation which is the focus of the present study, and wavy lines show unconformities. Modified from Fishman (2005).

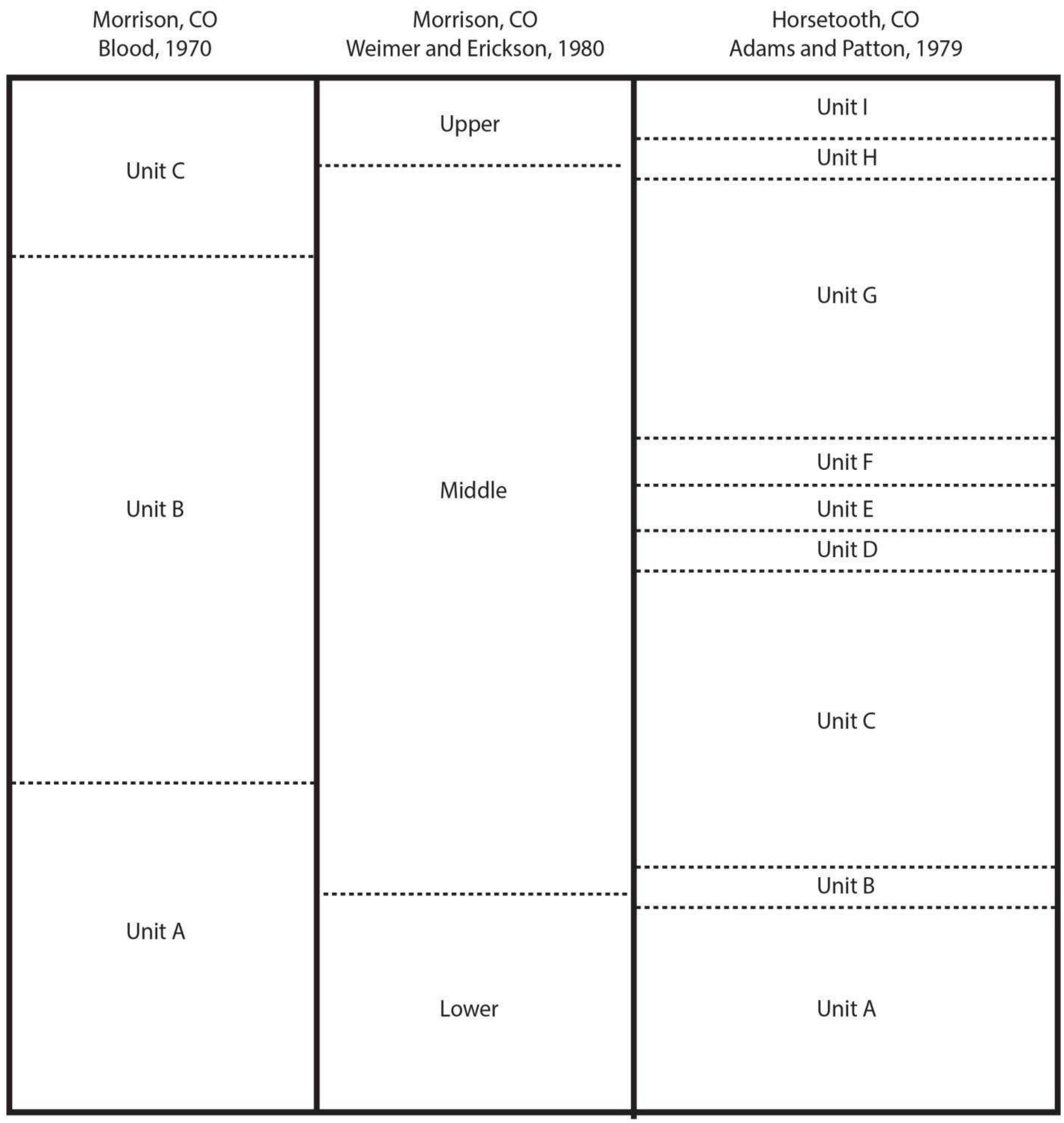

Figure 4. Stratigraphic subdivision of the Lyons Sandstone in the Morrison and Horsetooth areas, Colorado. Not to scale.

3.0 SEDIMENTOLOGY

3.1 Sedimentary Facies

3.1.1 Facies 1: High-angle cross-laminated sandstone

Description

Facies 1 consists of fine- to medium-grained, well-sorted, poorly- to well-cemented, high-angle cross-laminated sandstones (Fig. 5-A). Individual cross-bed sets are 0.5 to 10 m thick, and laterally mostly continuous. The grains are subrounded- to well-rounded, and more than 95% of them are made of quartz. The cross-laminations show alternations of fine- to medium-grained sand laminae (Fig. 6-A). Each of the fine-grained laminae is between 1 and 5 mm thick, internally massive, and well-sorted; the laminae consisting of medium-grained sandstones, in contrast, are 4 to 43 mm thick, and internally either inversely graded or massive, and well-sorted. Generally, the massive to inversely graded thick and coarse-grained laminae are more common in the upper part of cross-bed sets, and show dips of up to 30^{o}. The fine-grained thin laminae are generally more common at the base of individual cross-bed sets. Some convolute lamination and vertical microfaults (filled with calcite and dead oil residue) occur sporadically in this facies. This facies includes some oil-stained portions.

Interpretation

The large-scale high-angle cross-lamination, good-sorting and roundness of quartz grains are very characteristic of eolian dune deposits (e.g. Walker and Harms, 1972; McKee, 1966). It is assumed in this study that the very fine-grained sandstone laminae represent grainfall deposits as described by Hunter (1977). As wind is only able to pick up a limited range size of grains, these laminae are very-well sorted and massive because of a lack of grain size variations that could result in visible grading. The distal fine-grained massive sandstone laminae tend to be more common in the low-inclined portion of individual dunes, represented by the basal portion of beds (Bagnold, 1954; p. 259). The inversely graded fine- to medium-grained sandstone laminae, in contrast, most likely reflect deposition by grain flows as described by Hunter (1977). This is indicated by the inverse grading which is typical for sediments deposited from grain flows but uncommon to absent in all other deposits (Inman et al., 1966). A grainflow origin of the inversely-graded laminae would also explain well why they are preserved mostly in the upper, high-inclined portion of individual beds, representing an area adjacent to the crest or on the flank of the former dunes. As the internal friction of grainflow deposits "freezes" individual flows before they can reach distal low-inclined parts of the dune, it seems reasonable that there should be few, if any, grainflow deposits in the distal part of the dunes.

3.1.2 Facies 2: Low-inclined cross-laminated sandstone

Description

Facies 2 consists of well-sorted, well-rounded, very fine- to medium-grained, 0.15 to 4 m thick, low-inclined cross-laminated sandstones (Fig. 5-B). Medium-grained laminae are intercalated with fine-grained laminae. Laminae are 1 to 3 mm thick, mostly planar but wavy in places, parallel, and laterally continuous. Laminae are mostly internally massive with some inversely-graded lamina consisting of very fine-grained to medium-grained sand. Some anhydrite-cemented laminae are present, and these laminae are intercalated with oil-stained laminae in places. Vertical fractures are common, filled by calcite and/or dead oil residue.

Interpretation

The low inclination of cross-lamination in combination with the presence of well-sorted and well-rounded sand grains suggest that this facies was deposited by wind processes (Hunter, 1981; Sharp, 1963; Ellwood et al., 1975). Hunter (1977) describes similar low-inclined cross-lamination as climbing-ripple structures formed by migrating of ripples in an eolian environment. It is interpreted in this study that the stratification type in this facies reflects subcritically climbing translatent strata (wind ripples) because of the absence of ripple-foreset cross-lamination, and the fact that the relation between the angles of ripple climb is much lower than the inclination of the ripple stoss slope. Most of the individual laminae are massive because of the narrow range of grain sizes wind can carry resulting in little to no visible internal structure within individual laminae. However, during the migration of eolian ripples, inversely graded laminae can form because of the migration of the slightly coarse-grained ripple crests over the fine-grained sheltered ripple troughs (Sharp, 1963; Fryberger et al., 1988; Mountney, 2006).

3.1.3 Facies 3: Horizontally-laminated sandstone

Description

Facies 3 consists of well-sorted, well-rounded, very fine- to medium-grained, horizontally-laminated sandstone beds that are between 0.2 and 3.5 m thick (Fig. 5-C). Horizontal laminae are planar, massive, 1 to 10 mm thick, and laterally continuous. Fine-grained sandstone laminae are intercalated with medium-grained sandstone laminae. The boundaries between these fine-grained and medium-grained sandstone laminae are straight and sharp. Vertical fractures are common, and filled by calcite and/or dead oil residue.

Interpretation

This facies is interpreted to have been deposited by wind processes based on its excellent sorting and rounding of the grains (e.g. Reineck and Singh, 1975; p. 211) and lack of clearly water-formed sedimentary structures. Horizontal laminations are formed in eolian environments, similar to subaquatic planar lamination, by high velocities of the depositing flow; Hunter (1977) states that from around 18 m/s of velocity, strong winds form horizontal lamination in eolian settlings. Nevertheless, horizontal laminations can also be the product of wind modifying previously formed structures: e.g., wind can flatten ripples to form horizontal laminations both on the windward and the leeward sides of the dune (Glennie, 1972; Hunter, 1977).

3.1.4 Facies 4: Chaotically-bedded to folded sandstone

Description

Facies 4 consists of well-sorted, well-rounded, chaotically- to contorted-bedded very fine-grained sandstones (Fig. 5-D). Beds are 0.35-1 m thick showing a chaotic internal structure or folding. Some internally massive, 5 to 10 mm thick, irregular- to wavy-laminae are present, and they vary in thickness laterally. If present, folds can be locally overturned. Beds are mostly cemented by anhydrite. Remnants of low-angle cross-laminae and high-angle cross-laminae are rarely present.

Interpretation

Excellent rounding and sorting of the sediment points to a high energy processes that constantly or repeatedly moves the grains for extended periods of time resulting in a very mature sediment, both compositionally as well as structurally. In this study, it is assumed that the process responsible for maturing the sediment was wind action and that the sediment represents an eolian deposit (cf. Reineck and Singh, 1975; p. 211). Nevertheless, the chaotic bedding and the folding most likely represents gravity failure of dune deposits with capillary water as by light rain or heavy dew (Doe and Dott, 1980; Hunter, 1981; Kocurek, 1981; Fefchak and Zonnevald, 2010).

3.1.5 Facies 5: Wavy- to irregularly-laminated silty sandstone

Description

Facies 5 consists of reddish to tan, poorly sorted, silty to very fine-grained sandstones. Individual sand grains in this facies exhibit good rounding (Fig. 5-E). Beds of facies 5 are between 0.2 to

3.05 m thick and internally characterized by wavy to irregular laminations that can be continuous or discontinuous, and parallel to non-parallel. Individual laminae of this facies are generally in the range of 2 mm thick. Rarely, this facies shows mm-thick irregular laminae of medium- to coarse-grained sandstone, and mudstones. Rarely, this facies shows downfolding of laminae into a through between 0.01-0.3 m wide with the amount of deformation decreasing downsection over several tens of a millimeter. Facies 5 sandstones also often show well-developed stylolites that are lined by sub-mm thick siliciclastic mudstones.

Interpretation

The poor sorting of facies 5 reflects the input of several different grains sizes into the area of deposition and therefore varying energy conditions during sedimentation: the silt-sized grains reflect relatively low-energy conditions, and the sand-size grains high-energy conditions. Similar to over- and underlying strata, and also reflected in the good roundness of the sand grains, this facies interpreted to be eolian in origin. It is most likely that the depositional environment allowed for the mixing of the two grain assemblages because of fluctuations in energy, e.g. during wind gusts. Changes in the waviness of the laminae are envisioned to reflect variations in the wetness of the surface: the wetter the surface, the more irregularities can be expected to form in individual laminae (Ahlbrandt and Fryberger, 1981).

The wavy- and irregularly-laminated beds most likely represent adhesion ripples (Ahlbrandt and Fryberger, 1981). Adhesion ripples are thought to form when wind blows over a wet depositional surface with sand grains sticking to it, building these structures (Kocurek, 1981a and b). The wetness is a result of a rising groundwater table producing an irregular depositional surface leading to the observed depositional irregularity and unevenness of the laminae. In places, also mud was trapped on the damp surface leading to the observed thin mudstone laminae in facies 5.

The coarse-grained sandstone laminae, in contrast, have been most likely deposited from bed load processes such as creep and some saltation (Kocurek and Fielder, 1982). It is most likely that if they were originally deposited together with fine- and medium-grained sand, then the small grain sizes must have been blown away leaving behind only the coarse-grained sand as a lag. The local synsedimentary folding with down-warping laminae and a decrease in the amount of deformation down-section is interpreted to represent the effects of an animal foot sank into sediment. As animals can only walk either on land or in very shallow water this feature additionally suggests that it is likely that the depositional environment of this facies was subaerially exposed. The mudstone layers following stylolites are interpreted to reflect dissolution of quartz and the subsequent accumulation of insoluble residue along the stylolites.

3.1.6 Facies 6: Massive to wavy-laminated silt-rich mudstone

Description

Facies 6 consists of massive to wavy-laminated silt-rich mudstones (Fig. 5-F). These poorly-sorted fine-grained sediments vary in silt content between 10 and 70% form beds that are between 20 and 50 mm thick, and locally contain mm-thick structureless silt- and sandstone lenses. Sand and some of the silt grains, when present, are generally well-rounded. In siltier portions of this facies, the silt-rich wavy laminae are very distinct and clay-rich portions of the bed form mm-thick continuous to discontinuous wavy laminae that in outcrop weather back significantly. In places when overlain by sandy sediments, facies 6 can form several tens of a millimeter-high flame structures intruding into overlying strata. Contacts of this facies to both over- and underlying sediments are mostly sharp or gradationally in places.

Interpretation

The fine-grained nature of facies 6 suggests that these sediments have been deposited in an overall tranquil and low-energy setting. Nevertheless, the depositional environment of this facies must also show some fluctuations in depositional energy as reflected in siltstone laminae as well as silt- and sandstone lenses intercalated into the mudstones, the coarse grains indicating relatively high-energy conditions. Discontinuous mudstone laminae most likely reflect local erosion of mudstones and are therefore also an indicator of high-energy episodes during sedimentation of this facies.

In this study, Facies 6 is interpreted to reflect deposition by eolian processes because of the well-rounded sand and silt-grains it contains, as well as its exclusive intercalation into eolian sediments throughout the study area. In order to deposit fine grain sizes in an overall quiet environment in eolian surroundings, the place of deposition must have been a somehow protected location, nevertheless also prone to at times slightly elevated energy conditions forming the siltstone laminae and siltstone/sandstone lenses. Fine grain sizes such as clay and silt are often transported by wind (Mountney, 2006) yet will be preferentially trapped and deposited in standing water bodies (Ahlbrandt and Fryberger, 1981). It is therefore assumed in this study that facies 6 mudstones represent a humid portion of this eolian system in relatively close proximity to dunes that would have supplied the sand and silt grains.

Even though no classical bed load sedimentary structures such as ripples are well preserved, the lenticular nature of the siltstone laminae as well as the silt- and sandstone lenses suggest that this facies was majorly deposited by bed load processes. However, the sheet-like nature of the fine-grained, clay-rich mudstones suggests suspension settling, likely in a standing body of water.

Figure 5. Facies of the Lyons Formation. (A) Core photograph of high-angle cross-laminated sandstone (Facies 1) (Coquina Oil Berthoud State 2, 4977 ft). (B) Core photograph showing low-inclined cross-laminated sandstone (Facies 2) (Tiger Oil Wadleigh 34-21, 7808 ft). (C) Core photograph illustrating horizontally-laminated sandstone facies is overlying low-inclined cross-laminated facies (Facies 3) (Tiger Oil Wadleigh 34-21, 7795 ft). (D) Core photograph of chaotically-bedded to folded sandstone (Facies 4) (Viking Petroleum Cactus Hill 2, 8989 ft) (E) Core photograph showing wavy- to irregularly-laminated silty sandstone (Facies 5) (Coquina Oil Berthoud State 2, 4992 ft). (F) Core photograph illustrating massive to wavy-laminated silt-rich mudstone (Facies 6) is overlying wavy to irregularly-laminated silty sandstone (Facies 5) (Amoco Production Champlin 410, 8526 ft).

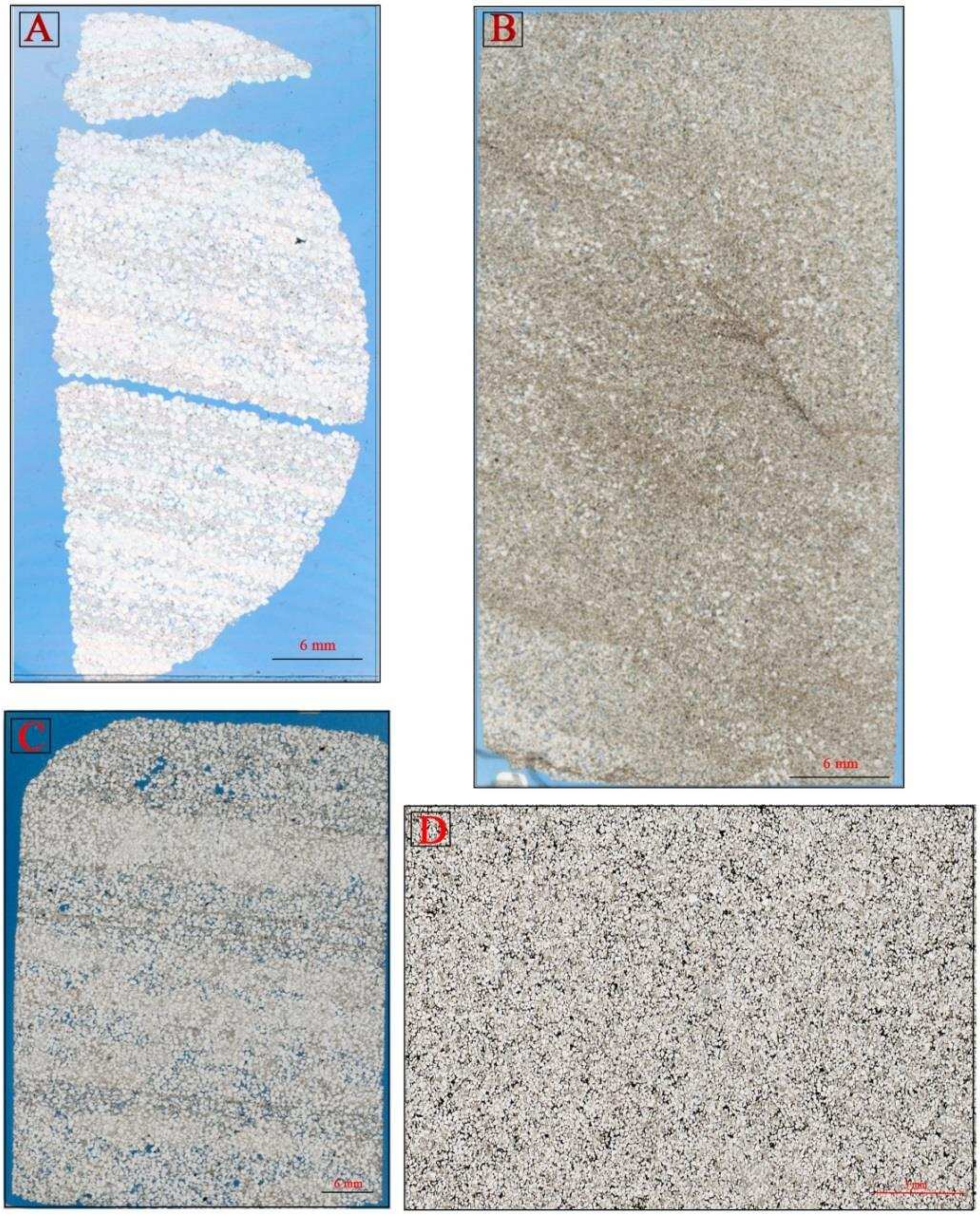

Figure 6. Thin section examples from the drill cores taken from Lyons Formation. (A) High-angle cross-laminated sandstone (Facies 1). Note the intercalation of very fine-grained laminae with medium-grained laminae, and well-sorting and well-rounding in the individual laminae (Apache Corporation Antelope 1-17 – 9026.1 ft). (B) Wavy- to irregularly-laminated poorly-sorted silty sandstone (Facies 5) (Shell Oil Company Colorado National Bank 1 – 8132.4 ft). (C) Low-inclined cross-laminated**,** well-rounded and well-sorted sandstone (Facies 2) (Amoco Production Champlin 1A-312 – 9275.3 ft). (D) Well-sorted and well-rounded, oil-stained sandstone. (Viking Petroleum Cactus Hill State 1 – 8967 ft). Thin section photographs are available at Core Research Center website (Well Catalog-Lyons Formation, 2013).

4.0 FACIES ARCHITECTURE

The Lyons Formation is characterized by thicknesses between 7 and 25 m throughout the study area, and is also highly variable over the 82 km along the north-east transect (Fig. 7). In contrast, its facies architecture is fairly uniform along the east-west transect (Fig. 8).

In the study area, the Lyons Formation shows two different sediment packages or facies associations that reflect the co-occurrence of distinct facies in the field: Package #1/Facies Association 1 consists of mostly high-angle cross-laminated sandstone (Facies 1) and low-inclined cross-laminated sandstone (Facies 2) with some horizontally-laminated sandstone (Facies 3) and very rare chaotically-bedded to folded sandstone (Facies 4). Package #2/Facies Association 2, in contrast, contains mainly wavy- to irregularly-laminated sandstone (Facies 5) and massive to wavy-laminated silt-rich mudstone (Facies 6) together with thin high-angle cross-laminated sandstone (Facies 1), low-inclined cross-laminated sandstone (Facies 2), and horizontally-laminated sandstone (Facies 3). The contacts between these packages are generally sharp and well defined.

Throughout the northern-central part of the study area, best reflected in the Viking Petroleum Cactus Hill State 2, and the Chevron Vern Wood 1 wells, the Lyons Formation is characterized by an intercalation of packages (1-7 m) of Facies Association 1 and Facies Association 2. Throughout the study area, two packages of facies association 1 and two packages of intercalated facies association 2 sediments are evident (Fig. 7). Nevertheless, the distribution of facies is not uniform across the study area:

The northernmost well (Hillyard Oil and Gas Amoco Uprr 1) is entirely dominated by a thick package of facies association 2 in its lower portion, and only about 7 feet of Facies Association 1 at the very top. However, the southernmost two wells (Amoco Clara A Bacon 1, and Coquina Oil

Berthoud State 2) are strongly or completely dominated by Facies Association 1 sediments, and only the Coquina Oil Berthoud State 2 well contains about 8 feet of Facies Association 2 in its lower portion. This change in lateral facies distribution is pronounced in the north-south correlation (Fig. 7) but not well expressed along the east-west transect (Fig. 8).

Similarly, a change in the distribution of facies trough stratigraphy is distinctly expressed along the north-south transect (Fig. 7), yet not noticeable in the east-west transect (Fig. 8): Facies Association 2 sediments are more common in the lower part of the Lyons Formation, whereas Facies Association 1 deposits dominate the upper portion of the succession. The abundance of Facies Association 1 sediments generally increases upsection throughout the study area. The Coquina Oil Berthoud State 2 well contains only Facies Association 1 sediments in the top two thirds of the core whereas the Hillyard Oil and Gas Amoco Uprr 1 well in the very north of the study area shows only Facies Association 1 sediments at the very top of the succession.

Furthermore, there are also distinct lateral changes in the thickness of individual facies from the southern to the northern part of the basin. While high-angle cross-laminated sandstones (facies 1) form beds that are up to 5 m thick in the south, this same facies shows units less than a meter thick in the northern part of the study area. Likewise, low-inclined cross-laminated (facies 2) and horizontally-laminated sandstone (facies 3) deposits are slightly thicker in the southern part of the study area than in the north. Another distinct thickness change is also observed in wavy- to irregularly-laminated silty sandstone (facies 5) deposits. While they are only 0.2-0.3 m thick in the south, they are up to 4.5 thick in the northern part of the basin. Nevertheless, massive to wavy-laminated silt-rich mudstone (facies 6) deposits are very thin (only up to 0.1 m) in the succession, and there are no distinct thickness changes along neither the north-south nor the east-west transect.

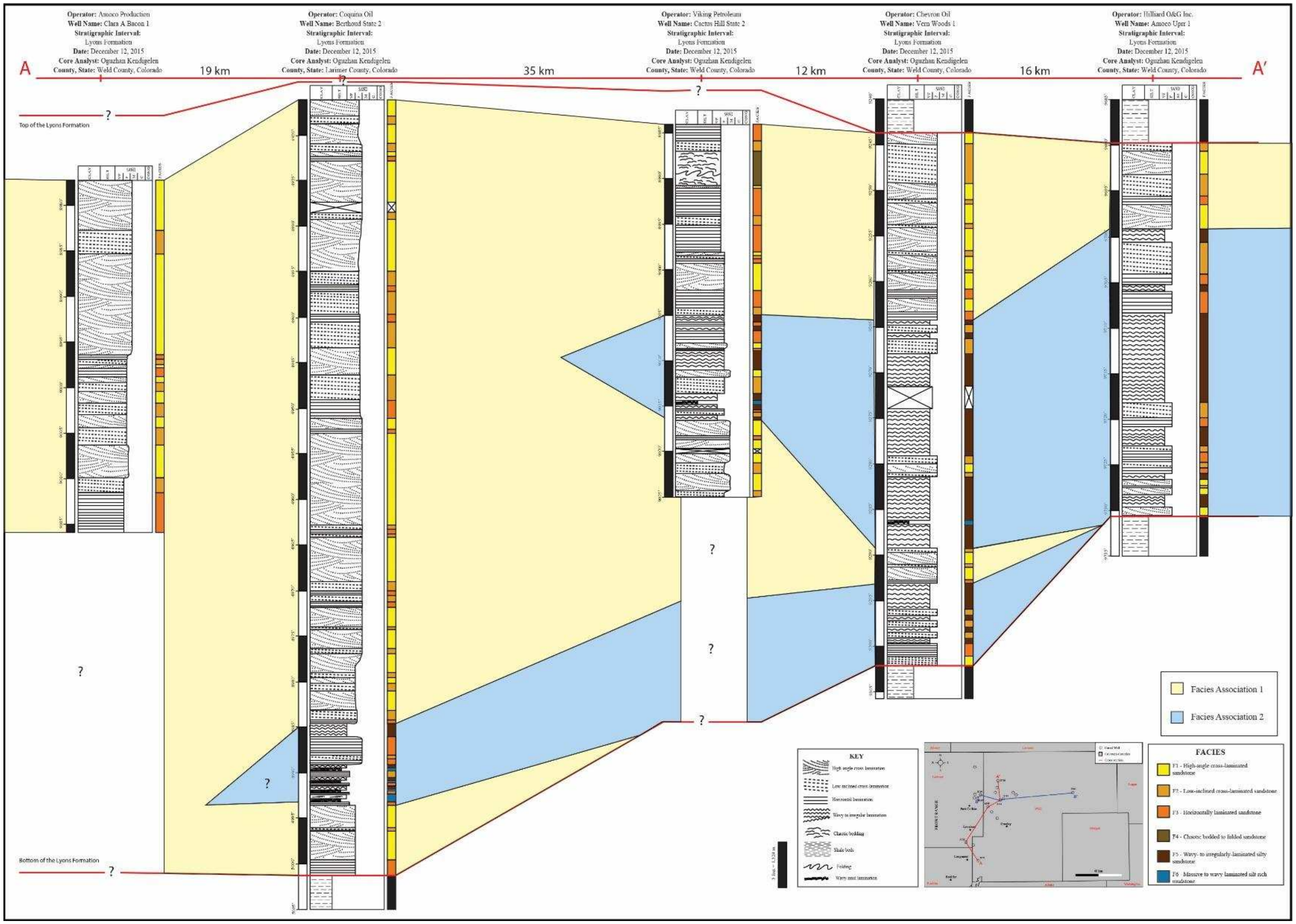

Figure 7. South-north transect consisting of five drill core samples trough the Lyons Formation in the Front Range Basin, Colorado, showing sedimentary structures, sedimentary facies and correlation of sedimentary packages/facies associations.

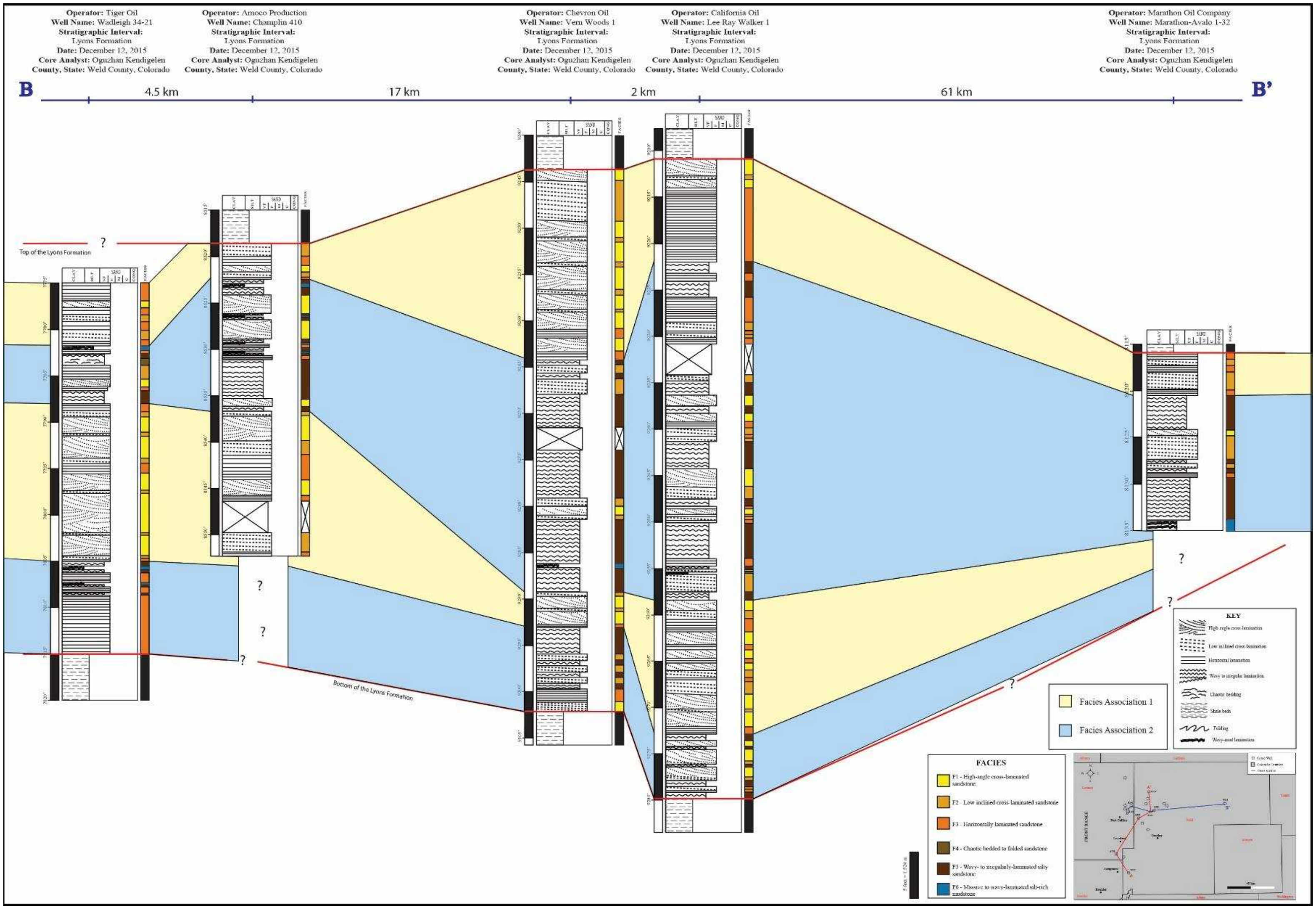

Figure 8. Northwest-northeast transect consisting of five drill core samples trough the Lyons Formation in the Front Range Basin, Colorado, showing sedimentary structures, sedimentary facies and correlation of sedimentary packages/facies associations.

5.0 DEPOSITIONAL MODEL

In this study, the Lyons Formation is interpreted entirely as an eolian unit deposited under partly dry to slightly wet conditions, the water mostly reflecting the position of the groundwater table, and only to a minor degree precipitation. The six different facies defined in this study reflect a variety of sub-settings within the wind-dominated, continental environment. Nevertheless, as the facies expression is strongly controlled by the presence or absence of water these facies are interpreted as two different scenarios, one where nearly no water is influencing sedimentation and therefore dry conditions, and one where water is present in places, and may it only be at times and therefore slightly wet conditions.

During dry conditions (Facies Association 1), large eolian dunes with large-scale cross beds were abundant in the study area, reflected in the high-angle cross-laminated sandstones of facies 1. These dunes were growing and migrating through both grainflow and grainfall processes as indicated by the internal structures of their laminae. They are often bounded by horizontal erosional surfaces interpreted to reflect maximum groundwater levels (Kocurek and Havholm, 1993) but in places also preserve their original relief, indicated by large-scale wavy upper boundaries (cf. Talbot, 1985 and Kocurek, 1988). The interdune areas were characterized by in places very high wind speeds and less sediment supply than the dunes experienced (Mountney and Jagger, 2004; Mountney, 2006; Jones et al., 2016). This is reflected in the presence of horizontally-laminated sandstone (facies 3) in-between dunes, and the occurrence of low-angle cross-laminated sandstone ripples (facies 2) in places with some amount of sand supply. Occasional precipitation resulted in failure of the uppermost sediment layers on the dunes; they slid down, deformed internally and accumulated in the lower portion of dune flanks (facies 4; Doe and Dott, 1980).

During slightly wet conditions (Facies Association 2), dunes were also present in the study area, reflected by the high-angle cross-laminated sandstones of facies 1 in Facies Association 2 intervals. Nevertheless, as beds of facies 1 are generally rarer than in Facies Association 1, it is assumed in this study that also the dunes may have been less common than during dry times. Similar to dry periods, however, the interdune areas were characterized by high wind speeds reflected in horizontally-laminated sandstones (facies 3) and low-angle cross-laminated sandstone ripples (facies 2). However, because of the presence of some water, especially in the flat interdune areas, ponds could form there and accumulate fine-grained sediment such as the massive to wavy-laminated silt-rich mudstone deposits (facies 6) that reflect deposition in small interdune lakes. At the margin of these lakes, or in slightly wet interdune areas without ponds, wavy- to irregularly-laminated silty sandstone (facies 5) accumulated.

In the north-south transect through the study area, the Lyons Formation shows a progressive change in sedimentary architecture: in the north, the bulk of the sediments has been deposited in a slightly wet environment, whereas in the south, the majority (or all?) of the sediments reflect deposition under overall dry conditions. This change in facies and Facies Associations over a distance of only 82 km is interpreted as the lateral transition from a paleo-erg center, reflected by the cross-bedded sandstone dominated facies in the south, to an eolian-dominated paleo-erg margin, indicated by the mostly fine-grained and partly irregularly bedded sediments in the north.

Nevertheless, the vertical succession shows that the erg is not stationary over time. The stepwise expansion of Facies Association 1 sediments to the north reflects that the erg is most probably growing over time into that direction. Alternatively, the entire erg system may have been migrating to the north as southern limit of the erg is not exposed in the current transect, likely located further south of the study area. The slightly wet interdune areas also showing two growth stages in the north-south transect; however, their environment does retract after the initial expansion, and the second advance of Facies Association 2 sediments does not reach the extension of the first lateral expansion of these deposits. At the top of the succession, only Facies Association 1 sediments remain in all investigated sections and cores, reflecting overall dry conditions for the entire study area.

It is remarkable to see that the Lyons sedimentary system only shows significant changes in a north-south direction but nearly none along the east-west transect. This is tentatively favoring a migration of the entire erg system towards the north rather than an expansion of the erg, and dominant paleo-wind direction with a northern net sediment transport component.

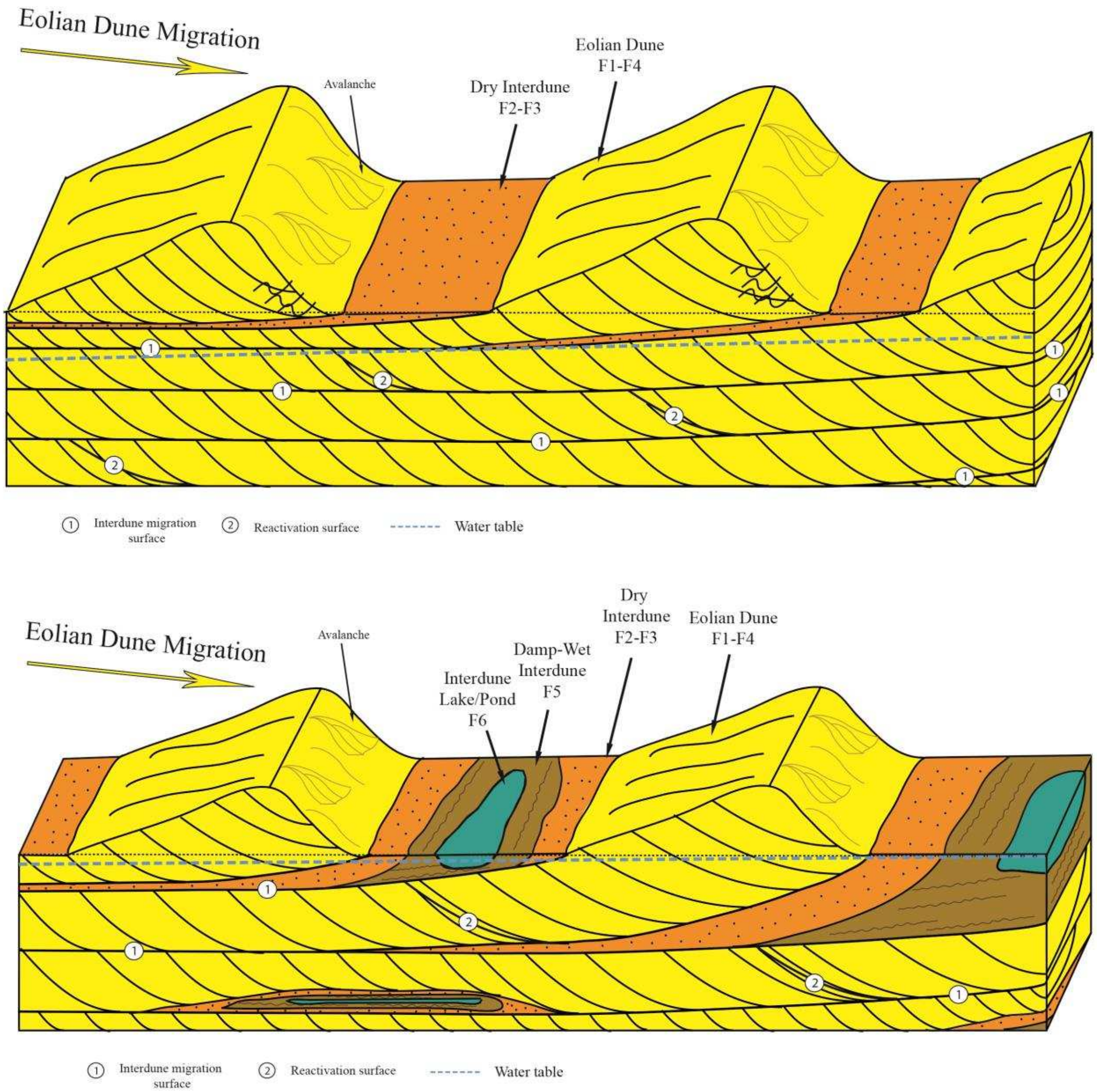

Figure 9. Conceptual models (not to scale) showing dry and wet eolian conditions during deposition of the Lyons Formation.

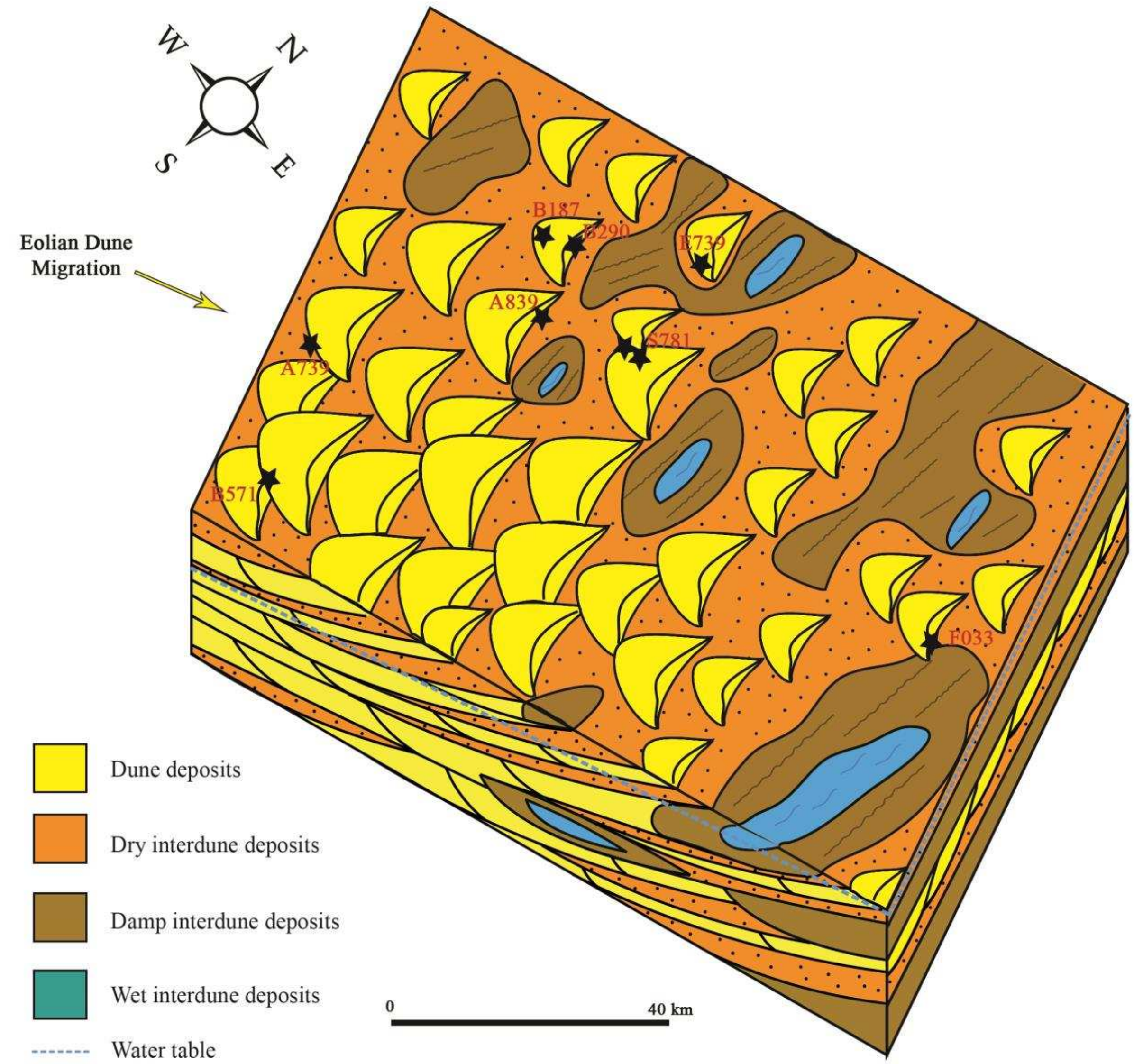

Figure 10. Paleoenvironment of the Lyons Formation in the Front Range basin. Note the changes in stratigraphic architecture from and assumed paleo-erg center in the south-southwest to the eolian dominated paleo-erg margin in the north-northeast. (stars show core locations)

6.0 DISCUSSION

6.1 Depositional Processes of Wavy- to Irregularly-laminated Sandstones and Chaotically-bedded to Folded Sandstones

This study suggests that wavy- to irregularly-laminated sandstone deposits (Facies 5) have been deposited in damp to wet interdune areas. The wavy and irregularly laminae are interpreted as adhesion structures formed by sticking of grains on the damp-wet surface. However, Ahlbrandt and Fryberger (1982), Schreiber et al., (1982) and Dubiel and Brown (2000) claim that wavy to irregularly laminae in eolian deposits may also form as result of the growth of evaporites in sediments, and the crinkling of the laminae results following replacement and removal of the evaporites via dissolution. According to these authors, these kinds of structures are characteristic for sabkha deposition during dry times in wet interdune areas. Nevertheless, in this study no evaporite has been observed growing anywhere in the Lyons Formation. Evaporite nodules that are generally characteristics for sabkha environments are absent throughout this unit, and a lateral transition into marine deposits as expected for sabkha is also lacking.

The present study is suggesting that chaotically-bedded to folded sandstones of Facies 5 have been deposited in the lower portion of the dunes' flanks because of gravity failure of dune deposits after a light rain or heavy dew. However, Rubin and Hunter (1988), and Bryant et al., (2003) state that internal deformation of eolian strata may also form by loading and migrating of dunes over saturated sand deposits when the water table is high. For the chaotically-bedded to folded sandstones (Facies 5) in the Lyons Formation this is not thought to be the case. Facies 5 deposits only occur very locally in the study area and are laterally not continuous. They are generally associated with high-angle cross-laminated dune facies, and they are underlain and overlain by dune and dry interdune deposits which are interpreted as representing times of a low water table in the study area. Therefore, it is most likely that the chaotically-bedded to folded sandstones (Facies 5) have originally been deposited by wind in eolian dunes, and have subsequently been sliding down the dune flanks after having been saturated from above regardless of the position of the paleo-water table.

6.2 Climatic Implications on Depositional Environment

Climate is one of the important agents that have a direct impact on the formation of eolian strata. Changes in climatic conditions from arid to humid or vice versa determine the extent to which dune deposits occur in the rock record, and which type of interdune sediments form (Fig. 11). Therefore, climate is thought to be the main trigger that determines if either wet or dry eolian systems can form. Also this study introduces both dry as well as wet systems for the Permian Lyons Formation in northern Colorado. Nevertheless, this study shows that, at times, both dry eolian and wet eolian deposits can co-exist (Fig. 11) on a transect that spans the northern to southernmost parts in this study. This suggests that the climate signal preserved in eolian strata is not quite as absolute as previously thought. Observing the facies trends displayed in Figure 7, it becomes clear that dry deposits seem to entirely dominate the southern part whereas dominantly wet eolian deposits are characterizing the northern portion of the transect. In the central portion, however, the climate changes from wet to dry and back are best observed. This transect therefore suggest that in eolian systems such as the Lyons Formation, a “Goldilocks window” exists that reflects climate changes the best, in the Lyons Formation located in the central study area. North of it, wet eolian deposits become overwhelmingly dominant, obliterating the signal, and to the south, dry eolianites are prevalent, often not clearly mirroring the climate signals. It is therefore advisable to incorporate abundant sections into studies of eolian systems so that ideal locations showing the “Goldilocks signal” for documenting eolian cyclicity are among the documented sections. Conversely, even though climate cyclicity may characterize a succession, this may not be well reflected throughout the strata of a study area if chosen too small and only in one distinct facies association. Even during relatively wet times, the center of an erg system (in our study area equivalent to the southern outcrops) may preserve mainly to exclusively dry eolian sediments, and not mirror climate changes recorded in wet strata (in our example located in the north).

Despite the prominent lateral facies changes, two distinct cycles, each recording a transition from wet to dry climate conditions, can be observed in the Lyons Formation in northern Colorado. As eccentricity cycles of either 100 kyr or 400 kyr duration are generally thought to be responsible for cyclicity in eolian systems (Clemmensen et al., 1994). Based on this interpretation, the time frame recorded in the deposition of the Lyons Formation is in the range of either 200 kyrs, or 800 kyr, respectively.

6.3 Hydrocarbon Potential and Reservoir Facies

The Lyons Formation is recognized as a minor reservoir in the Front Range Basin (Higley and Cox, 2007). In the study area, major amounts of oil are mostly produced from the Cretaceous "J" sandstone, the "D" Sandstone, and the Niobrara Formation of the overlying Denver Basin succession (Clayton and Swetland, 1980). Nevertheless, the first oil discovery in the Lyons Formation dates back to 1953 and was achieved in Black Hollow and Keota fields, Weld Counties. The three fields with cumulative production greater than 1 million barrels of oil (MMBO) from the Lyons Formation are Black Hollow (10.8 MMBO, 0.330 million cubic feet of gas (MMCFG)), Lake Canal (2.7 MMBO, 0 CFG), and Pierce (11.5 MMBO, 0.500 MMCFG) (Higley and Cox, 2007) (Fig. 12).

It remains unclear as to which unit could be the source rock for the Lyons Formation oils. According to Clayton and Swetland (1980), the Cretaceous and Permian oil are geochemically different and, therefore, they are interpreted to originate from different source bed (Fig. 13). However, the exact source remains enigmatic. There have been different suggestions as to which the source of the oil found in the Lyons Formation could be: (1) adjacent Permian and Pennsylvanian organic-rich shales are one possibility (Levandowski et al., 1973), (2) the Permian Satanka Formation that contains organic-rich strata is also an option (Berman, 1978), and (3) the Permian Phosphoria Formation near the Idaho-Wyoming border (Dimelow, 1972; Momper, 1978) has been claimed to source the Lyons Formation. Yet, none of these units have been confirmed to produce the oil found in the Permian of the Front Range, leaving this riddle to be solved by further studies. Nevertheless, basin modeling suggest that the deepest buried potential sources began to generate oil between about 78 and 50 Ma during the Late Cretaceous or the Early Tertiary (Lee and Bethke, 1994).

The two facies in the Lyons Formation that show good reservoir quality (Fig. 14) are the high-angle cross-laminated sandstones (Facies 1) and the low-inclined cross-laminated sandstones (Facies 2). Both facies, at least when abundant in the succession, represent dry eolian conditions. Excellent sorting and roundness of the grains in this facies result in abundant interparticle porosity and high permeability. In addition, the horizontally-laminated sandstones (Facies 3) and chaotically-bedded to folded sandstones (Facies 4), both also characteristics of dry conditions, also show minor oil residue in places. In contrast, the two facies that are characteristics for wet conditions which are wavy- to irregularly-laminated silty sandstones (Facies 5) and massive to wavy-laminated silt-rich mudstones (Facies 6) do not show good reservoir quality because they are overall poorly sorted and often contain large amounts of fine-grained material significantly reducing their porosities as well as their permeability.

Results of porosity and permeability analyses from Lyons Formation sediments are publically available from the USGS Core Research Center website (Well Catalog-Lyons Formation, 2013). Based on 225 data points derived from the website (Appendix 2), the average porosity of Lyons Formation sediments is 8.17 vol% even though individual porosities vary from 1.9 vol% to 25.3 vol%. Likewise, the permeability of samples from the Lyons Formation ranges from less than 0.1 mD to 583 mD (n=156) (Appendix 2). However, when subdivided into dry versus wet eolian sediments, the discrepancy becomes very apparent: Dry eolian deposits show an average of 8.53 vol% porosity (max 25.3 vol%) (n=201), while sediments deposited under wet eolian conditions show an average of 5.15 vol% porosity (max 9.3 vol%) (n=24). The same trend is reflected in the permeability of the samples: Dry eolian deposits show permeabilities that range from less than 0.1 mD to 583 mD, while wet eolian sediments reflect only permeabilities of less than 0.1 mD. Additionally, all oil-stained parts of the core are in dry eolian sediments, and the main Lyons Formation plays are in the southern part of the study area where dry conditions are thought to be more prominent. Therefore, this study concluded that dry eolian deposits are generally more likely to form good reservoir quality rocks than sediment deposited under wet eolian conditions.

The Lyons Formation is overlain by the anhydrite-rich siltstone beds of the Lykins and Satanka Formations throughout the study area. These non-porous units are likely to create a good seal on top of the porous Lyons Formation. Traps in the Lyons Formation are generally anticlinal closures and show reduction of porosity by occluding cement updip (Levandowski et al., 1973).

In order to recognize suitable reservoir facies also in non-cored wells, the results of this study can be used to interpret geophysical logs from the Lyons Formation in order to identify potential oil reservoirs. Eolian sediments deposited under dry conditions show lower Gamma Ray values as compared to wet eolian deposits (Figure 15) because they do not contain fine-grained muddy sediment. In addition, because dry eolian sediments are dominantly well-sorted and well-rounded sandstones, they show higher porosity values than poorly-sorted wet eolian deposits, and are therefore easily detected and differentiated in porosity logs.

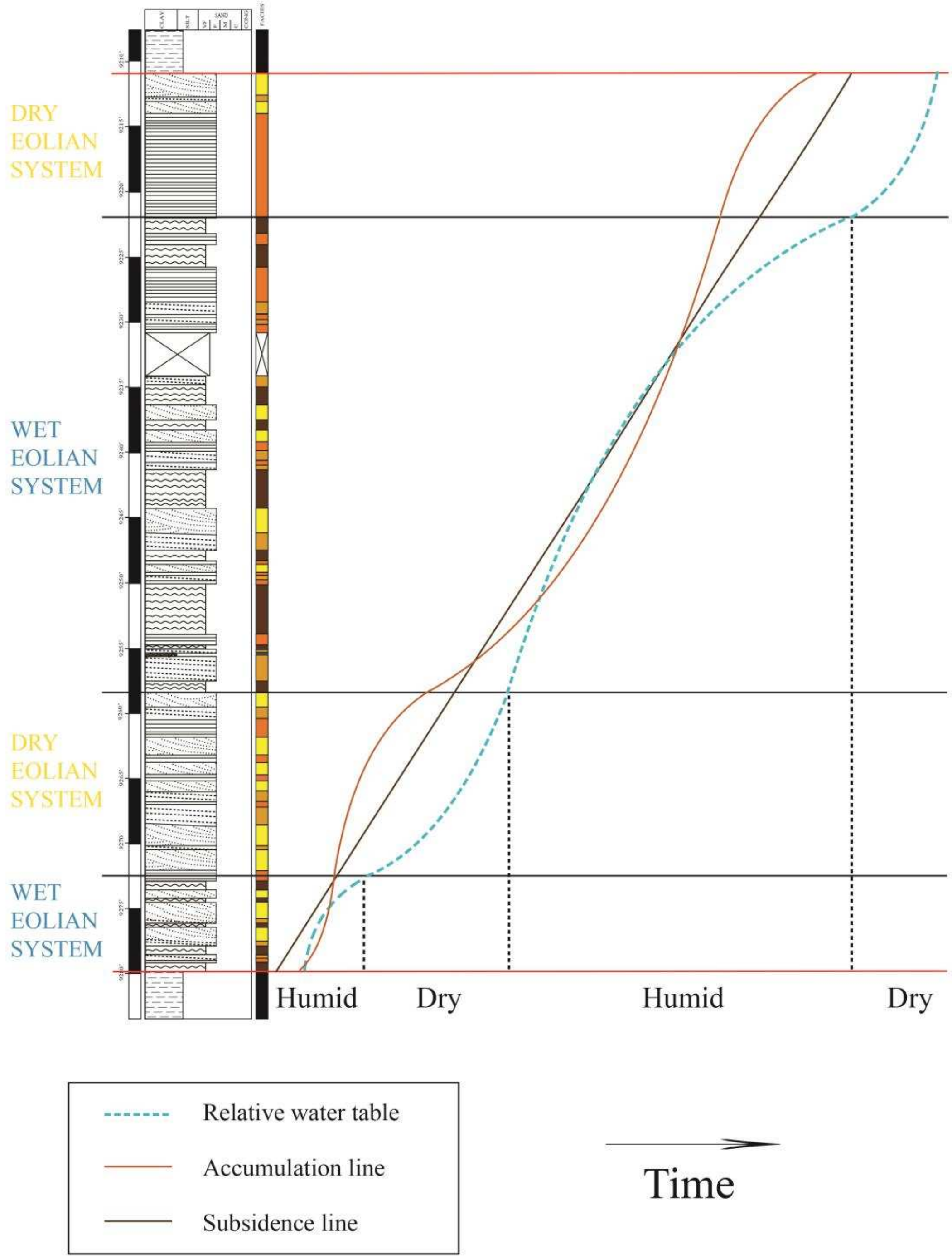

Figure 11. Showing the relationships between relative water table, subsidence and accumulation with climatic changes in the Lyons Formation.

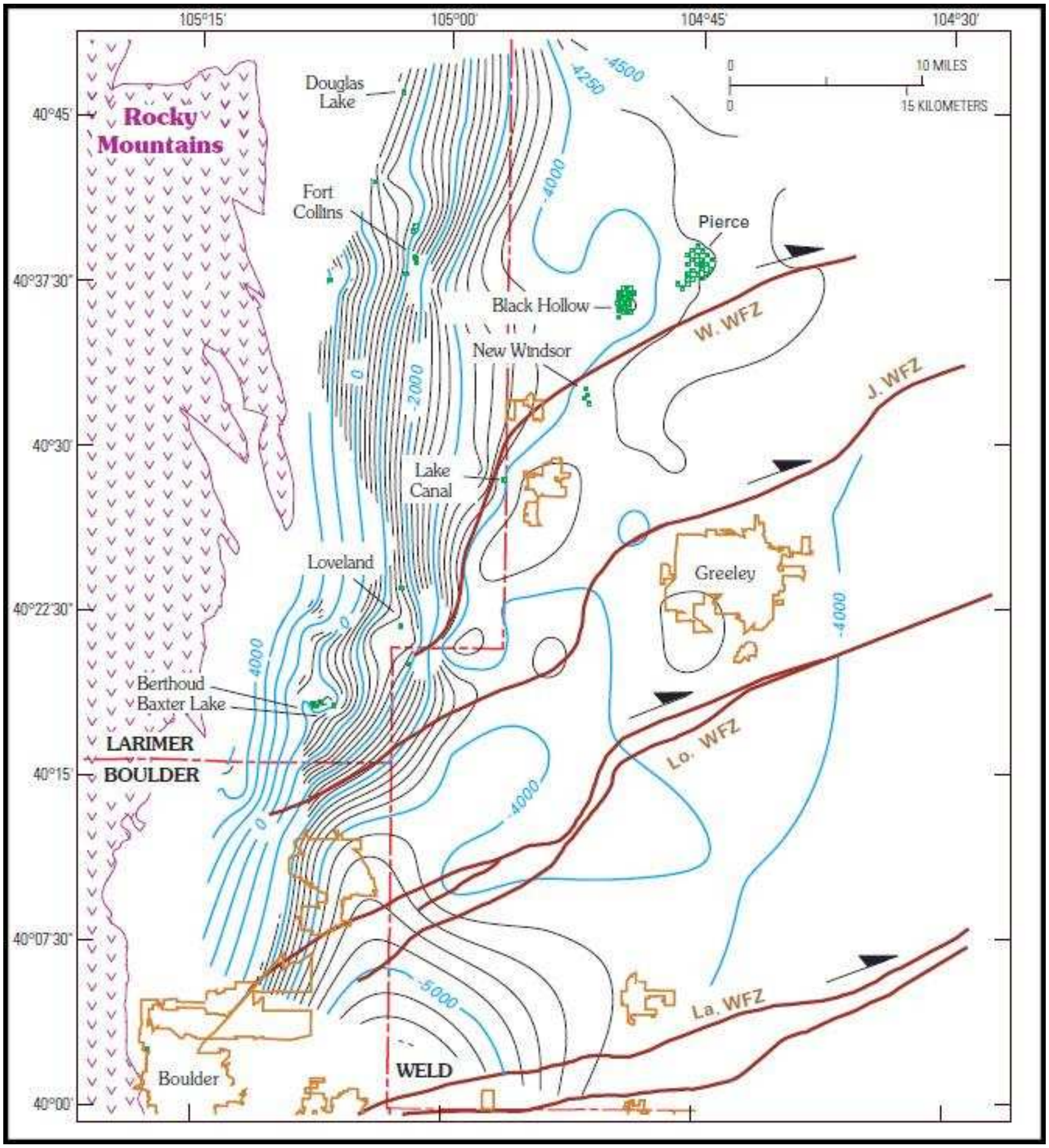

Figure 12. Map showing oil productive Lyons fields (green dots) and wrench faults in the study area. (W.WFZ: Windsor, J.WFZ: Johnstown, Lo.WFZ: Longmont, La.WFZ: Lafayette) (Higley and Cox, 2007).

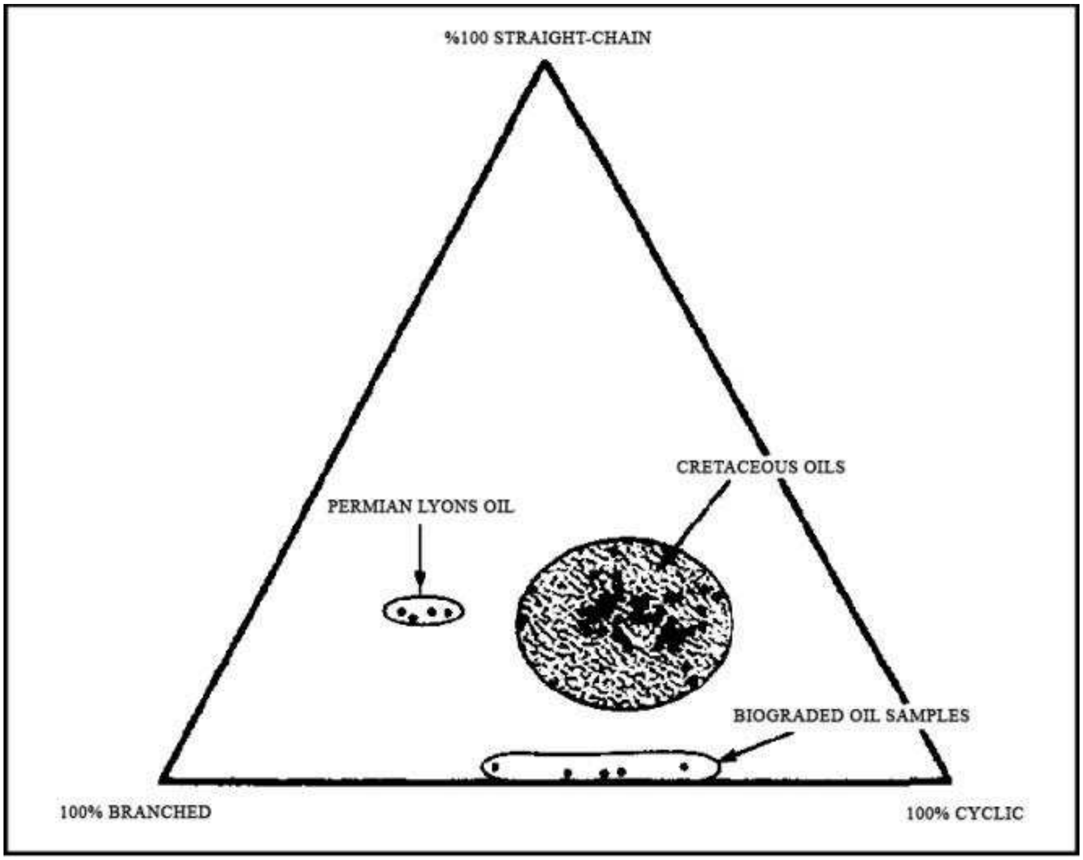

Figure 13. Showing the geochemical difference between Permian Lyons Oil and Cretecous Oils in the study area. (Clayton and Swetland, 1980).

Figure 14. Core photographs showing oil-stained cores in reservoir facies (Facies 1 and Facies 2). A) Viking Petroleum Cactus Hill 2, 8991 ft; B) Coquina Oil Berthoud State 2, 4999 ft).

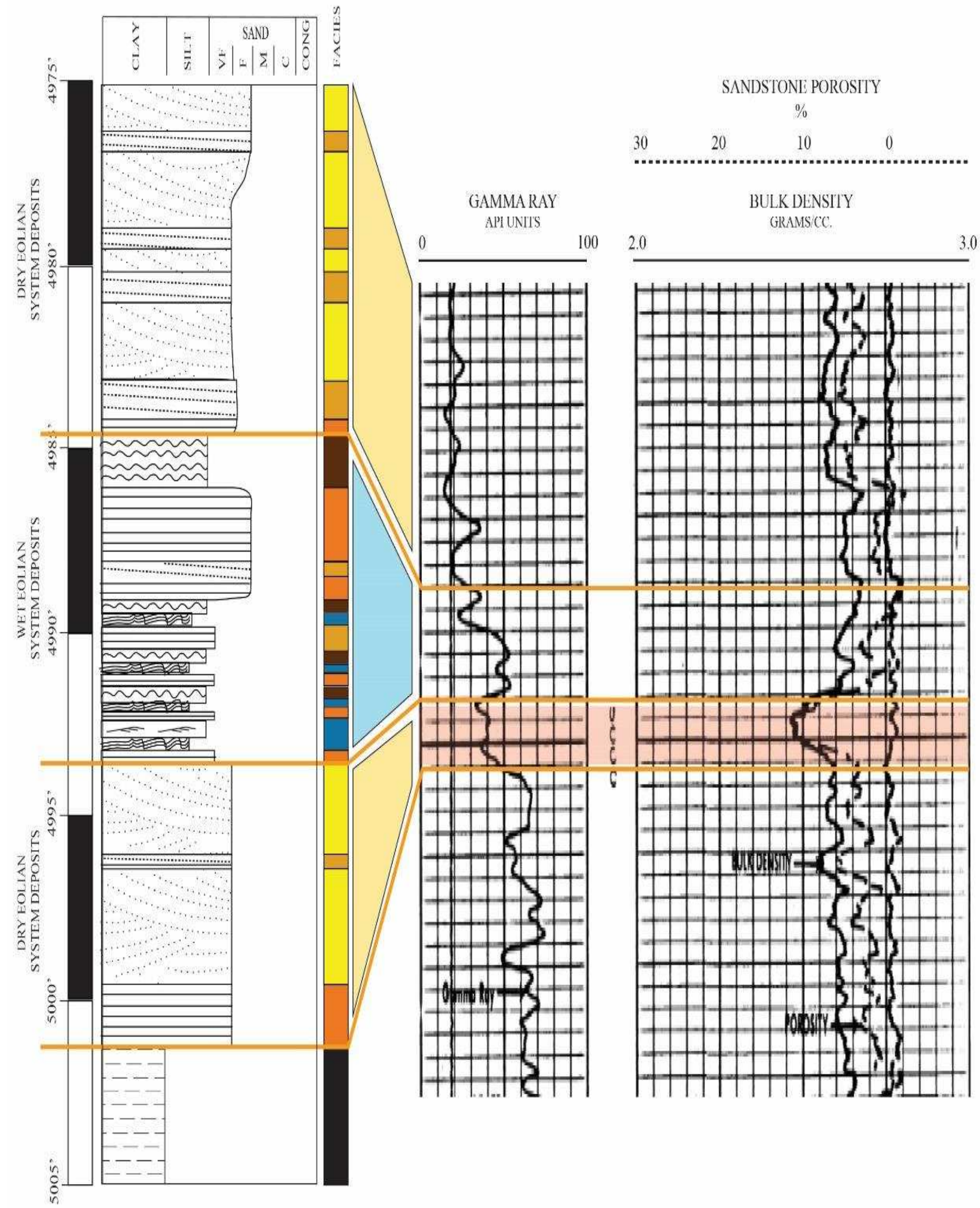

Figure 15. Correlation of dry and wet eolian deposits between a drilling core and geophysical logs (bottom section of Coquina Oil Berthoud State 2). Red highlighted section shows reservoir dry eolian system deposits with high porosity and low bulk density.

7.0 CONCLUSIONS

1. The Lyons Formation consists of six siliciclastic facies. These are: (1) high-angle cross-laminated sandstones, (2) low-inclined cross-laminated sandstones, (3) horizontally-laminated sandstones, (4) chaotically-bedded to folded sandstones, (5) wavy- to irregularly-laminated silty sandstones and (6) massive to wavy-laminated silt-rich mudstones.
2. These six facies described in the Lyons Formation are grouped into two sedimentary packages/Facies Associations. Package #1/Facies Association 1 consists of high-angle cross-laminated sandstone (Facies 1), low-inclined cross-laminated sandstone (Facies 2), horizontally-laminated sandstone (Facies 3) and chaotically-bedded to folded sandstones deposits (Facies 4), whereas Package #2/Facies Association 2 includes wavy- to irregularly-laminated silty sandstone (Facies 5) and massive to wavy-laminated silt-rich mudstone (Facies 6) deposits with minor amounts of high-angle cross-laminated sandstone (Facies 1), low-inclined cross-laminated sandstone (Facies 2) and horizontally-laminated sandstone deposits (Facies 3).
3. The distribution of Facies Associations in the Lyons Formation shows lateral changes along the north-south transect from larger amounts of Facies Association 1 deposits in the south to more Facies Association 2 deposits in the north; however, along the east-west transect, such changes in Facies Associations are not obvious.
4. Stratigraphically, the succession shows only a thin package of Facies Association 2 deposits at the base of the succession in the south; in the central part of the study area, two distinct changes from Facies Association 2 to Facies Association 1 are detected. In the northern part of the study area, only the topmost part of the succession shows Facies Association 1 sediments whereas all underlying deposits are Facies Association 2 deposits.

5. High-angle cross-laminated sandstones (Facies 1) in the Lyons Formation represent the remnants of eolian dunes. The areas between these dunes were characterized by slightly lower wind energy represented by the low-inclined cross-laminated sandstone (Facies 2) and horizontally-laminated sandstones (Facies 3). Both of these facies, if abundant, are thought to reflect mostly dry conditions of the sedimentary environment. The chaotically-bedded to folded sandstones (Facies 4) are thought to have been deposited in the lower portion of dunes' flanks and reflect the internal deformation of dune deposits. If interdune areas show wet conditions they are characterized by wavy- to irregularly-laminated sandstones (Facies 5). In case interdune areas develop small ponds or lakes the respective facies would be massive to wavy-laminated silt-rich mudstones (Facies 6).
6. Based on the two Facies Associations, the Lyons Formation allows distinguishing two different environments; Facies Association 1 deposits represent dry conditions, whereas Facies Association 2 deposits represent wet conditions during deposition. The distribution of Facies Associations in the study area shows that no distinct facies changes are recorded along the east-west profile. However, in the north-south transect does reveal that dry eolian deposits dominated in the southern part of the study area whereas wet eolian deposits were more abundant in the north.
7. As the amount of dune deposits is significantly higher in the southern sections, this part of the study area is interpreted to represent the inner portion of a paleo-erg, whereas the northern part of the study area was characterized by overall wet eolian conditions interpreted to reflect paleo-erg margin conditions. The Lyons Formation in northern Colorado therefore shows a distinct variation in stratigraphic architecture from paleo-erg in the south to paleo-erg margin in the north.

8. Climatic changes in the Lyons Formation are best observed in the center of the study area where dry eolian deposits are intercalated with wet interdune deposits; such facies changes are generally not detected in the paleo-erg center (southern part of the study area) because this specific depositional environment is mostly to entirely dominated by dry eolian deposits.
9. Dry eolian deposits (Facies Association 1) in the Lyons Formation show better reservoir quality than wet eolian deposits because of overall excellent sorting and roundness of the grains. Sediments deposited under dry conditions are characterized by large amounts of interparticle porosity and good permeability. While porosity is on average 8.17 vol% (max. of 25.3 vol%) and permeability ranges between 0.1 to 583 mD in the Facies Association 1 deposits, porosity and permeability values are significantly lower in the Facies Association 2 deposits (porosity is on average of 5.15 vol%, and permeability is generally less than 0.1 mD).

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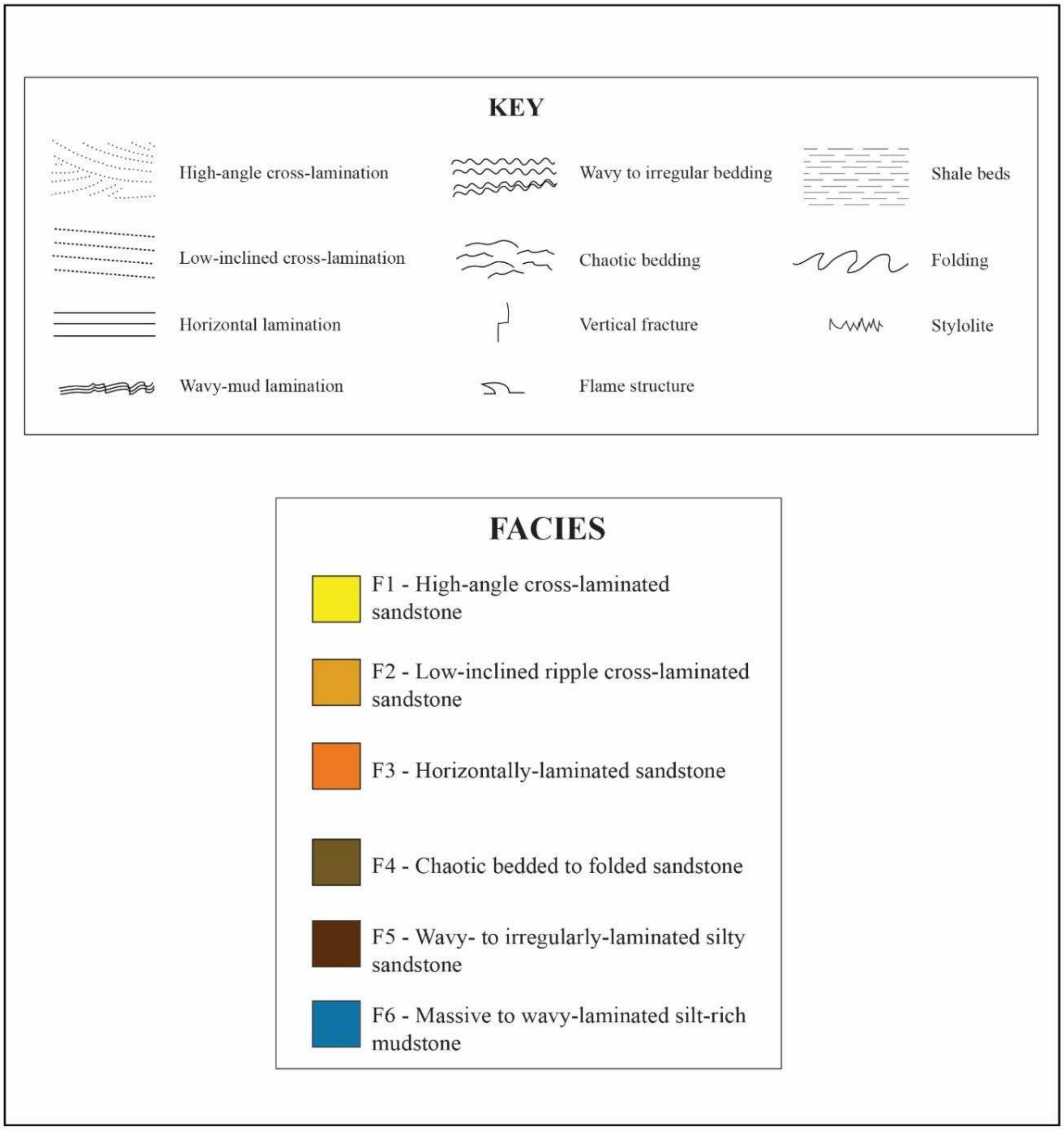
APPENDICES

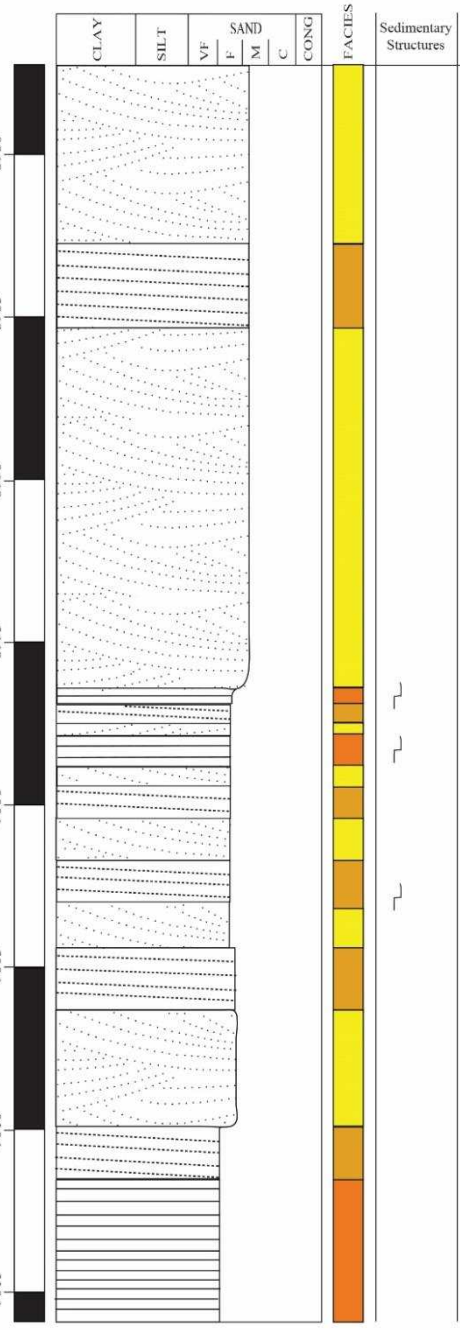
Appendix 1: Core logs



Operator: Amoco Production
Well Name: Clara A Bacon 1

Stratigraphic Interval: Lyons Formation
Date: December 12, 2015

Core Analyst: Oguzhan Kendigelen
County, State: Weld County, Colorado



Description

Dark pink, fine to medium-grained, well-sorted, well-rounded, high-angle cross-laminated sandstones. Intercalation of 1 to 5 mm thick, fine-grained laminae with 4 to 43 mm thick, medium-grained laminae. Medium-grained laminae is internally mostly massive with some inverse grading.

Dark pink, fine to medium-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstones. Laminae are 1 to 4 mm thick.

Dark pink, fine to medium-grained, well-sorted, well-rounded, high-angle cross-laminated sandstones. Laminae are 1 to few mm thick.

Dark pink, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstones. Laminae are 1 to few mm thick. Mm thick vertical fracture is present, and filled with calcite.
Sharp contact between low-inclined cross-laminated sandstone and high-angle cross-laminated sandstone.
Dark pink, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstones. Laminae are 1 to few mm thick. Mm thick vertical fracture is present, and filled with calcite.

Intercalation of dark pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated and high-angle cross-laminated sandstones. Laminae are 1 to few mm thick.

Dark pink, medium-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstones. Laminae are 1 to few mm thick.

Dark pink, medium-grained, well-sorted, well-rounded, high-angle cross-laminated sandstones. Laminae are 1 to few mm thick.

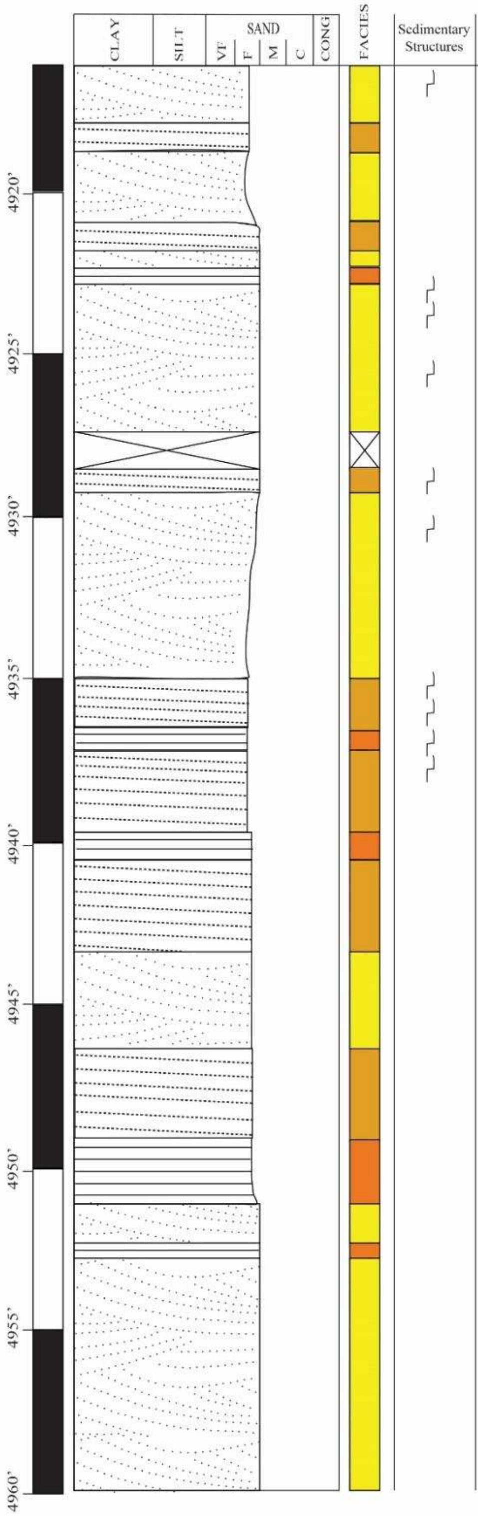
Dark pink, fine to medium-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstones. Laminae are 1 to few mm thick.

Dark pink, fine to medium-grained, well-sorted, well-rounded, horizontally-laminated sandstones. Laminae are 1 to few mm thick.

Operator: Coquina Oil
Well Name: Berthoud State 2

Stratigraphic Interval: Lyons Formation
Date: December 12, 2015

Core Analyst: Oguzhan Kendigelen
County, State: Larimer County, Colorado



Description

Light gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with vertical fractures. Lamina are 1 to few mm thick, either anhydrite cemented or oil-stained.

Light gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated anyhdrite-cemented sandstone. Laminae are 1 to few mm thick, either anhydrite cemented or oil-stained.

Light gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated anhydrite-cemented sandstone. Mm thick anhydrite cemented laminae are intercalated with oil-stained laminae.

Light gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated anyhdrite-cemented sandstone. Laminae are 1 to few mm thick, either anhydrite cemented or oil-stained.

Black, intensely oil-stained, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone.

Light gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with vertical fractures. Lamina are 1 to few mm thick, either anhydrite cemented or oil-stained. Vertical fractures are very common, and they are filled with oil-residue.

Light gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated anyhdrite-cemented sandstone. Laminae are 1 to few mm thick, either anhydrite cemented or oil-stained. Vertical fracture is present, and filled with oil-residue.

Light to dark gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with vertical fractures. Lamina are 1 to few mm thick, either anhydrite cemented or oil-stained.

Dark gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstones are intercalated with very-fine grained horizontally-laminated sandstones. Laminae are mm thick. Vertical fractures are very common, and filled with. anhydrite.

Light gray, very fine to fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Light gray, very fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are mm thick.

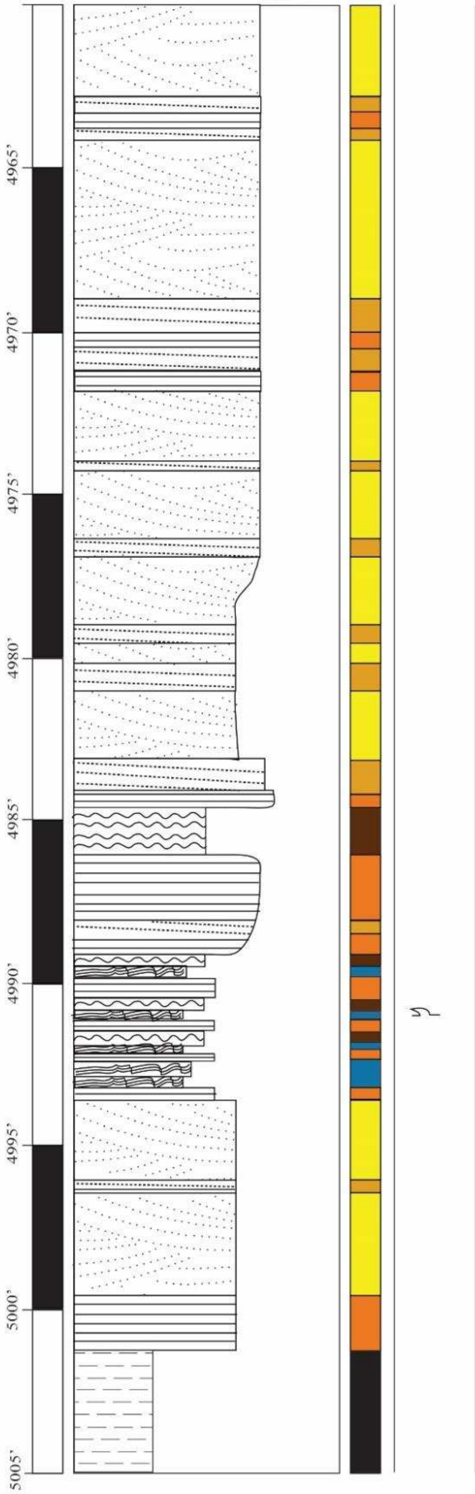
Red, very fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick, internally massive.

Red, fine to fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone.

Red, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Pinkish gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.



Pinkish gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Intercalation of pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated and horizontally-laminated sandstone. Laminae are 1 to few mm thick, internally massive.

Pink, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Intercalation of pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated and horizontally-laminated sandstone. Laminae are 1 to few mm thick, internally massive.

Pink, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.

Pink, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with a 5 inch thick, dark brown, intensely oil-stained part. Laminae are 1 to few mm thick.

Pinkish red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are up to 1 mm thick.

Intercalation of pinkish red to light brown, fine-grained, well-sorted, well-rounded, high-angle cross-laminated and low-inclined cross-laminated sandstones. Laminae are 1 to few mm thick. Contacts between these deposits are sharp to graditional.

Pinkish light brown, medium-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are up to mm thick.

Pink, very fine-grained, poorly sorted, well-rounded, wavy to irregular laminated sandstone. Laminae are up to 1 mm thick.

Pink, medium-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are up to 1 mm thick.

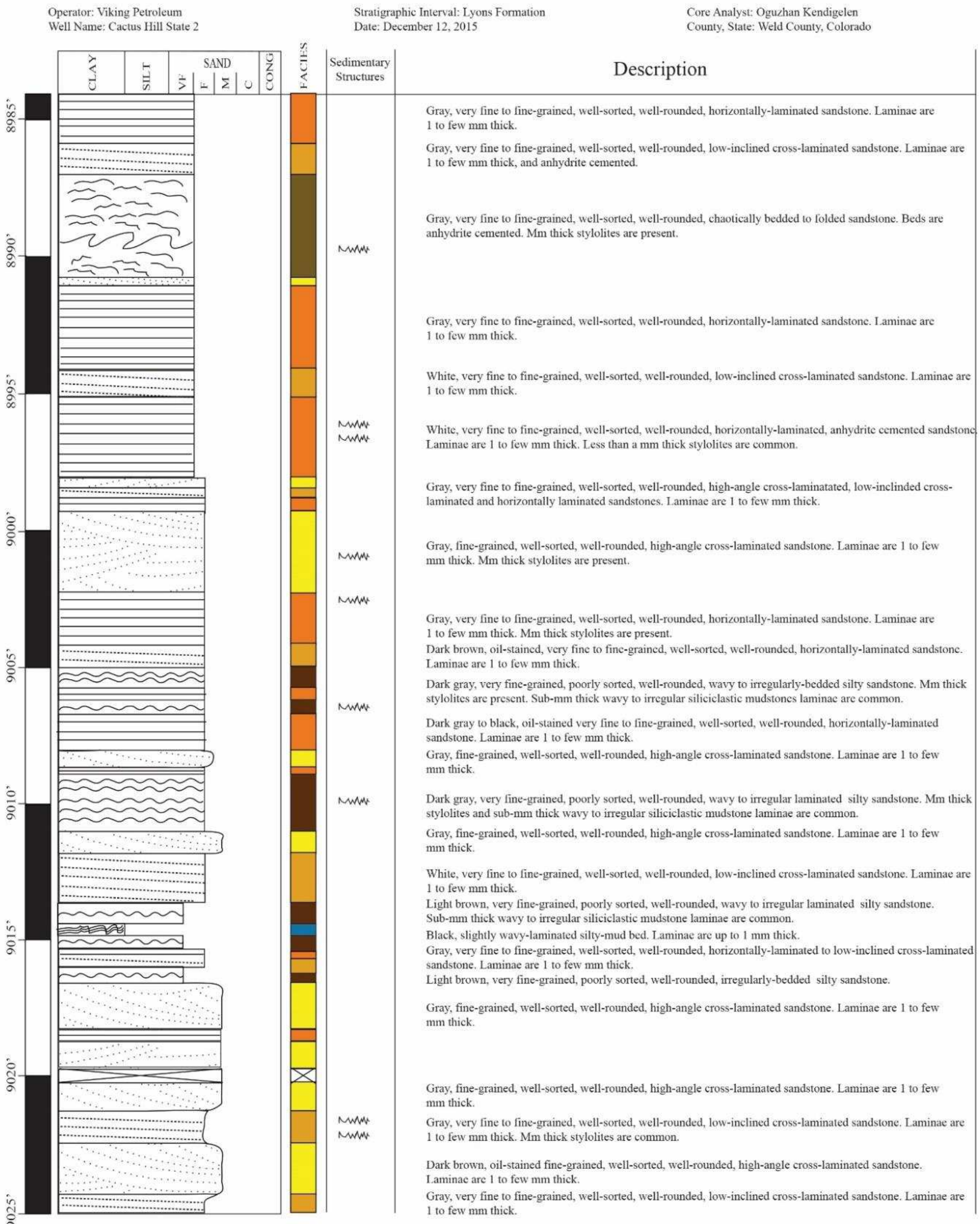
Red, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated to horizontally laminated sandstone. Laminae are up to 1 mm thick.

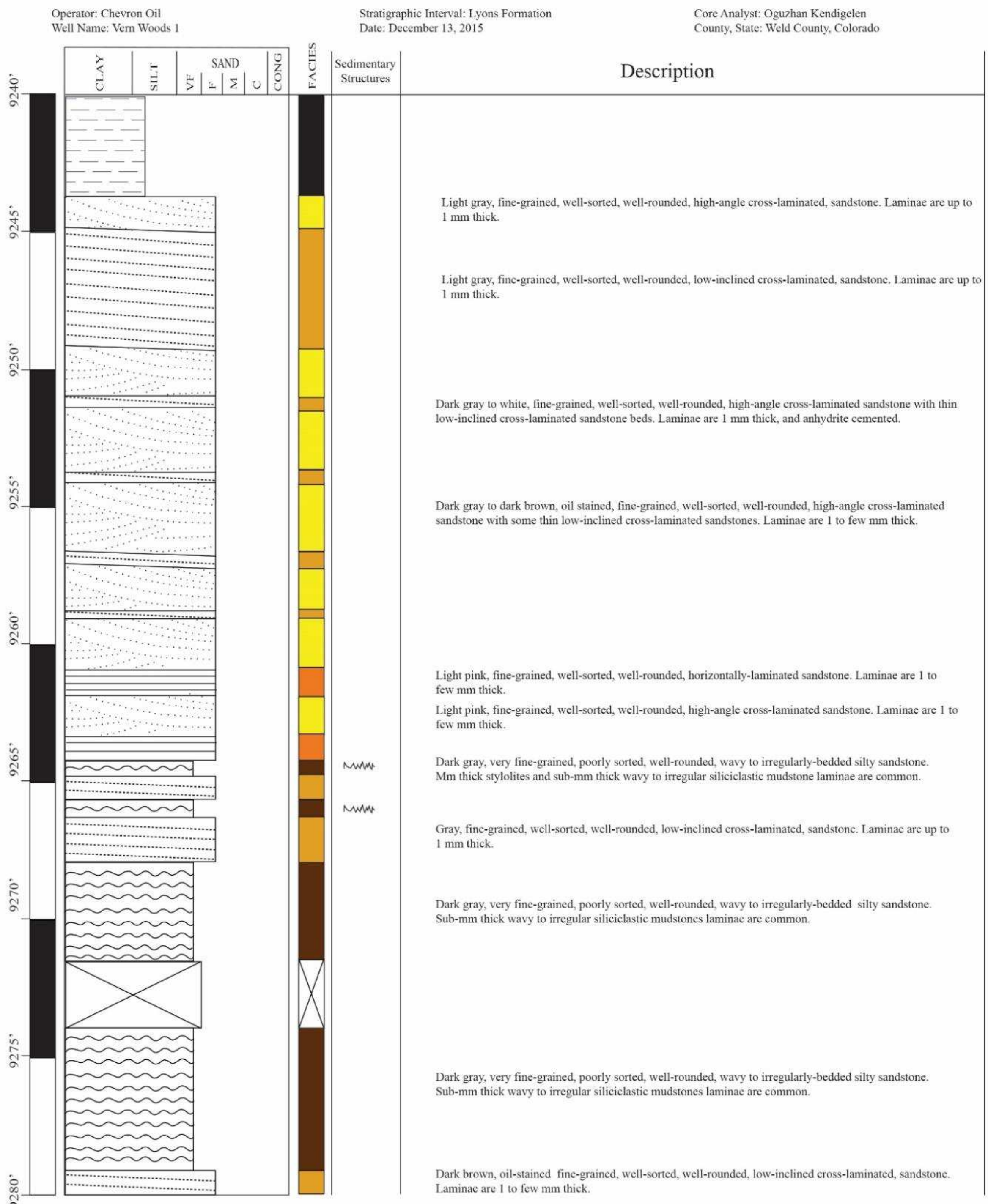
Intercalation of red, very fine-grained, poorly sorted, well-rounded, wavy to irregular laminated silty sandstone and black, thin, massive to wavy-laminated silt-rich mud beds, with thin very fine-grained horizontally-laminated sandstone beds. Few milimeter-high flame structures are observed.

Light pink, very fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

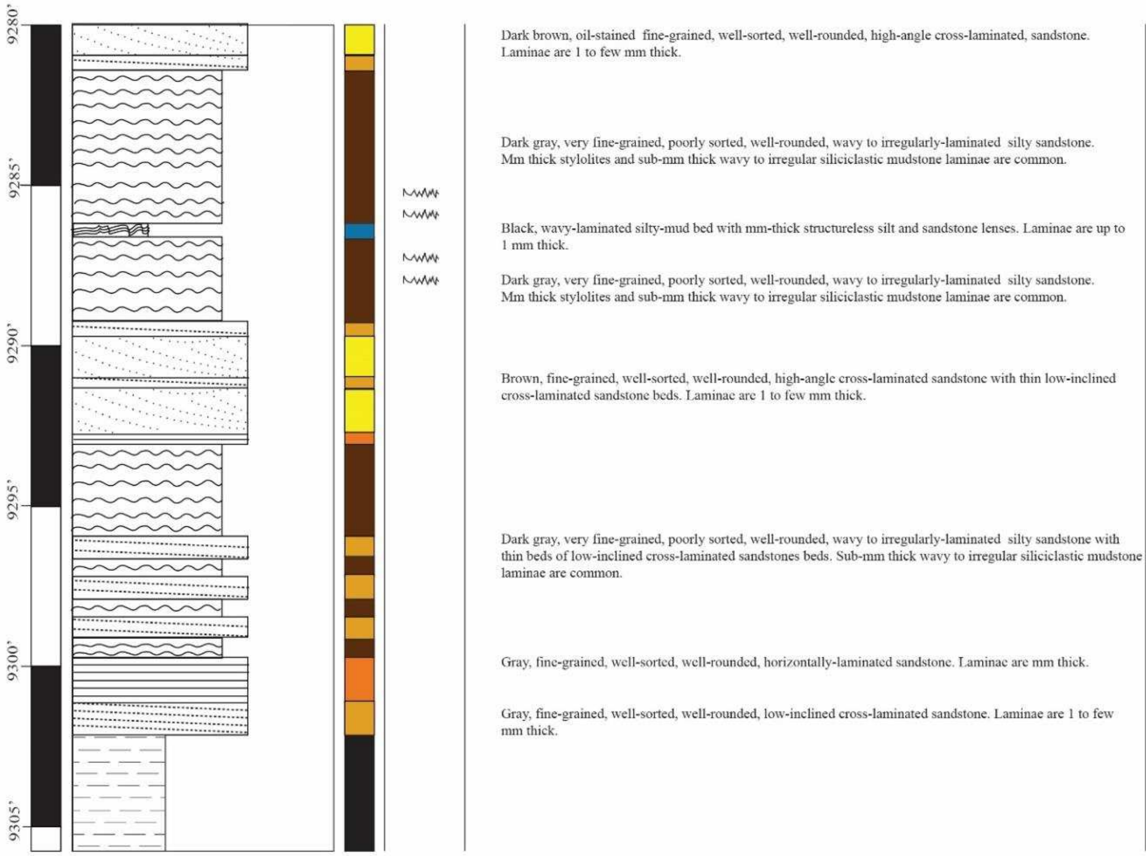
Dark brown, oil-stained, very fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

Light pink, very fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are up to 1 mm thick.

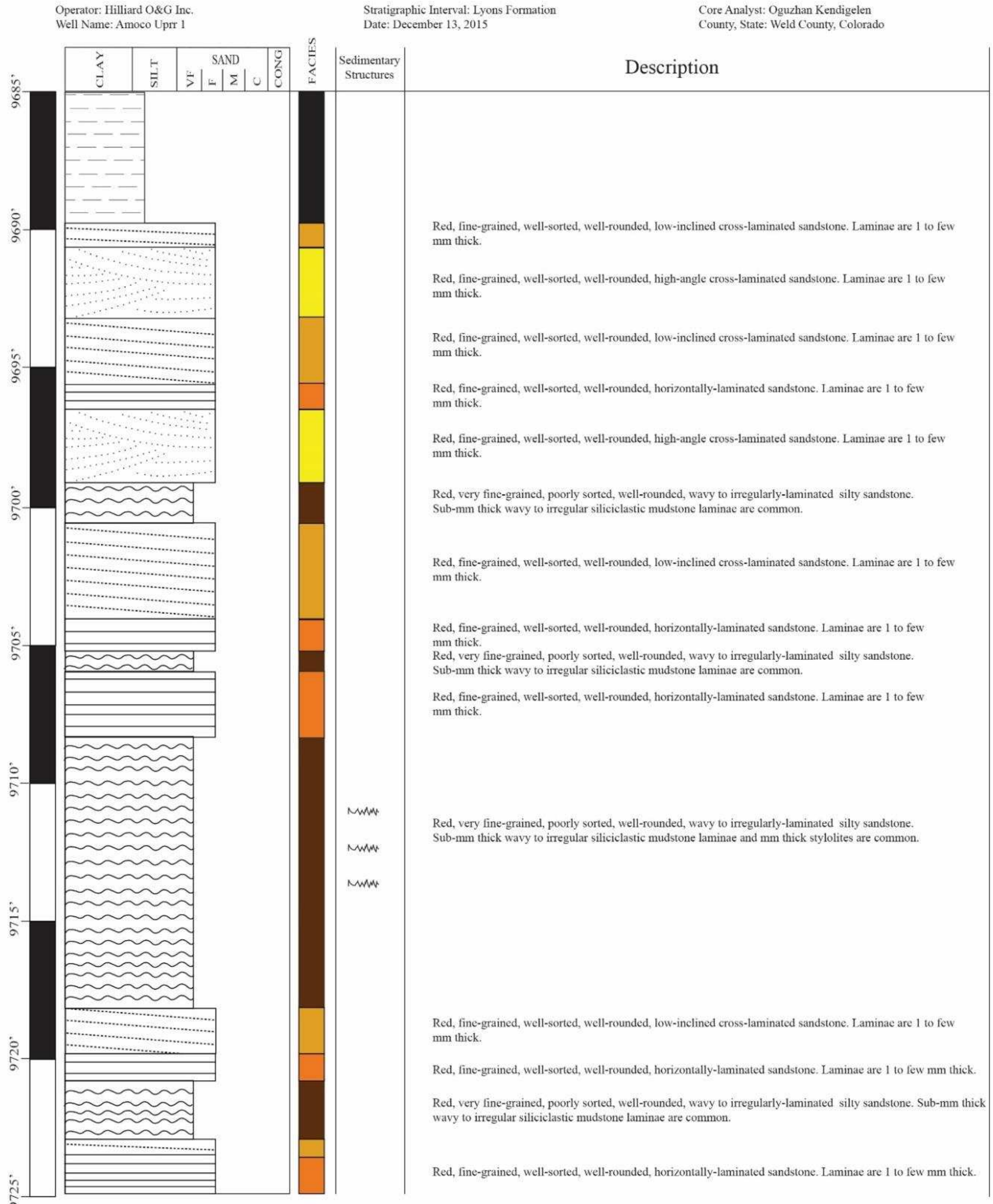

Operator: Viking Petroleum
Well Name: Cactus Hill State 2
Stratigraphic Interval: Lyons Formation
Date: December 12, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Weld County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
8985'
8990'
8995'
9000'
9005'
9010'
9015'
9020'
9025'
Gray, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Gray, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick, and anhydrite cemented.
Gray, very fine to fine-grained, well-sorted, well-rounded, chaotically bedded to folded sandstone. Beds are anhydrite cemented. Mm thick stylolites are present.
Gray, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
White, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
White, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated, anhydrite cemented sandstone. Laminae are 1 to few mm thick. Less than a mm thick stylolites are common.
Gray, very fine to fine-grained, well-sorted, well-rounded, high-angle cross-laminatated, low-inclinded cross-laminated and horizontally laminated sandstones. Laminae are 1 to few mm thick.
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick. Mm thick stylolites are present.
Gray, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick. Mm thick stylolites are present.
Dark brown, oil-stained, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Mm thick stylolites are present. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Dark gray to black, oil-stained very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregular laminated silty sandstone. Mm thick stylolites and sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
White, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Light brown, very fine-grained, poorly sorted, well-rounded, wavy to irregular laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Black, slightly wavy-laminated silty-mud bed. Laminae are up to 1 mm thick.
Gray, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated to low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Light brown, very fine-grained, poorly sorted, well-rounded, irregularly-bedded silty sandstone.
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Gray, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick. Mm thick stylolites are common.
Dark brown, oil-stained fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Gray, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.



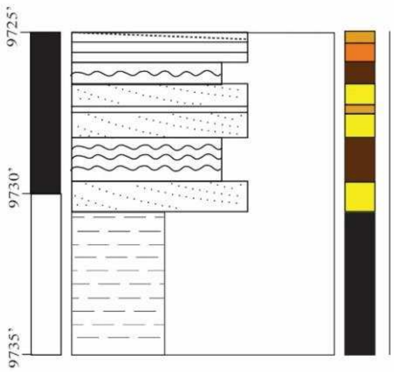
Operator: Chevron Oil
Well Name: Vern Woods 1
Stratigraphic Interval: Lyons Formation
Date: December 13, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Weld County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
9240'
9245'
9250'
9255'
9260'
9265'
9270'
9275'
9280'
Light gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated, sandstone. Laminae are up to 1 mm thick.
Light gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated, sandstone. Laminae are up to 1 mm thick.
Dark gray to white, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with thin low-inclined cross-laminated sandstone beds. Laminae are 1 mm thick, and anhydrite cemented.
Dark gray to dark brown, oil stained, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with some thin low-inclined cross-laminated sandstones. Laminae are 1 to few mm thick.
Light pink, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Light pink, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Mm thick stylolites and sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated, sandstone. Laminae are up to 1 mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Dark brown, oil-stained fine-grained, well-sorted, well-rounded, low-inclined cross-laminated, sandstone. Laminae are 1 to few mm thick.



9280'
9285'
9290'
9295'
9300'
9305'
Dark brown, oil-stained fine-grained, well-sorted, well-rounded, high-angle cross-laminated, sandstone. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Mm thick stylolites and sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Black, wavy-laminated silty-mud bed with mm-thick structureless silt and sandstone lenses. Laminae are up to 1 mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Mm thick stylolites and sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Brown, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with thin low-inclined cross-laminated sandstone beds. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone with thin beds of low-inclined cross-laminated sandstones beds. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Gray, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are mm thick.
Gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.



Operator: Hilliard O&G Inc.
Well Name: Amoco Uprr 1
Stratigraphic Interval: Lyons Formation
Date: December 13, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Weld County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
9685'
9690'
9695'
9700'
9705'
9710'
9715'
9720'
9725'
Red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Red, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Red, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae and mm thick stylolites are common.
Red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.



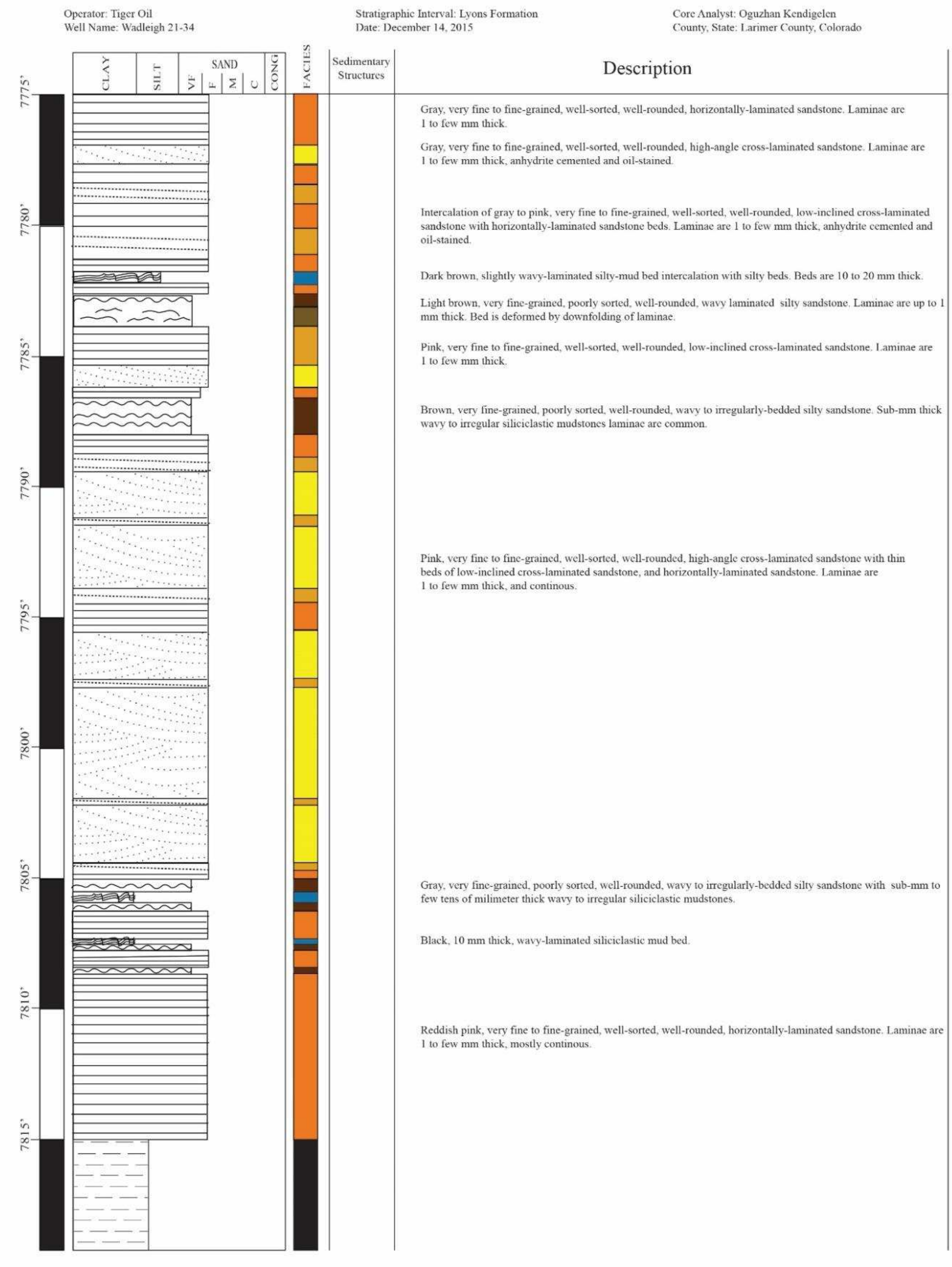
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.

Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.

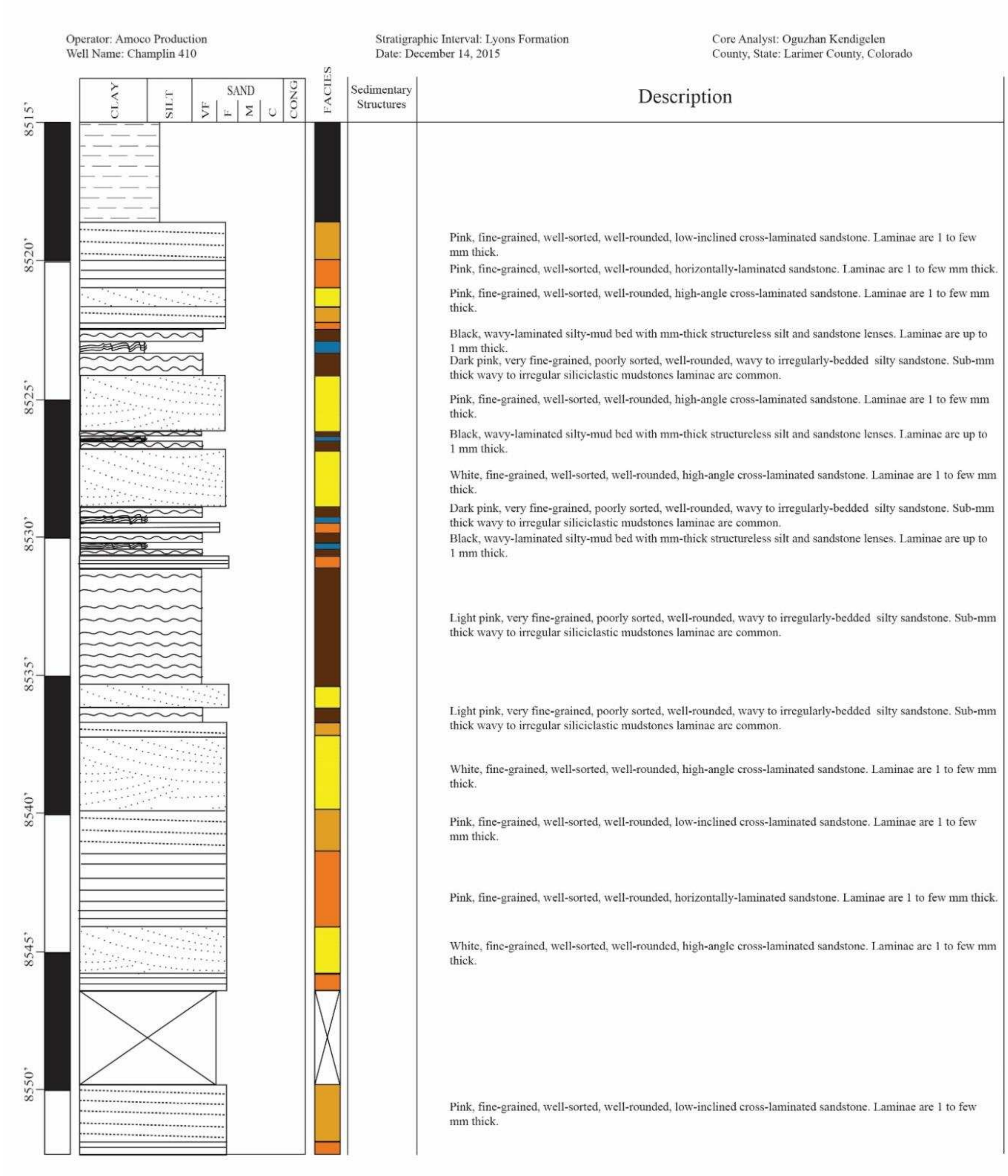
Red, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

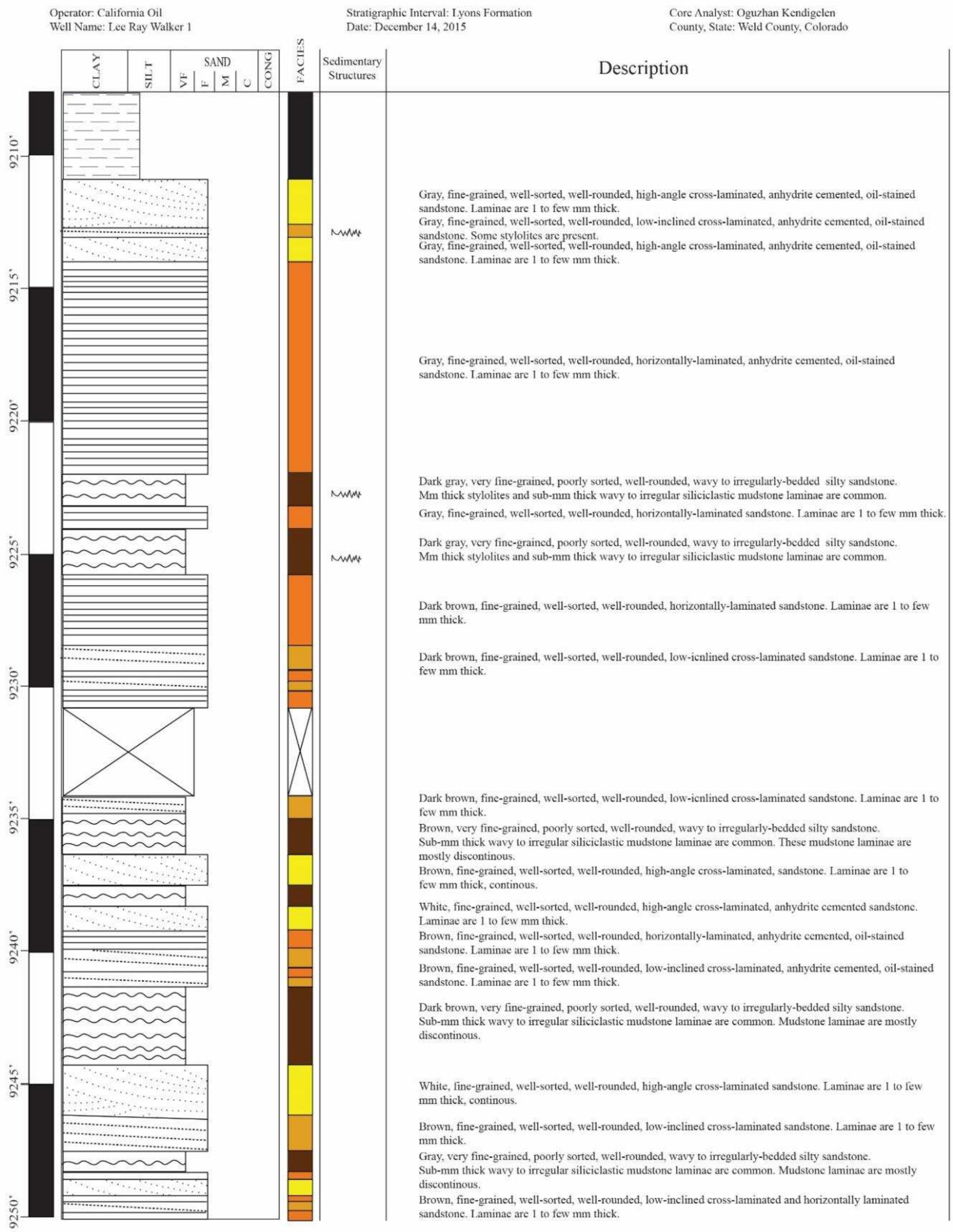
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-laminated silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.

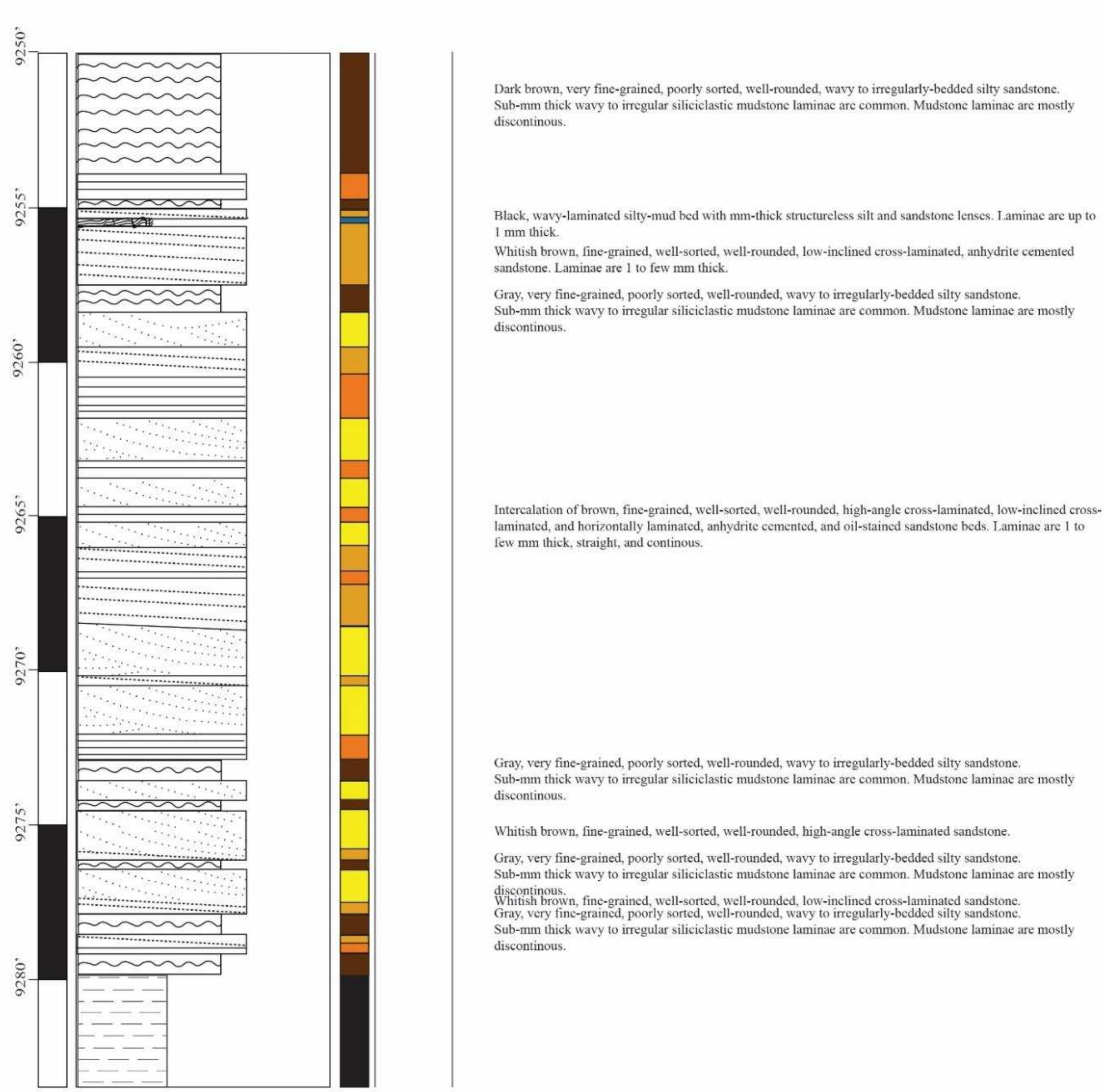
Red, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.

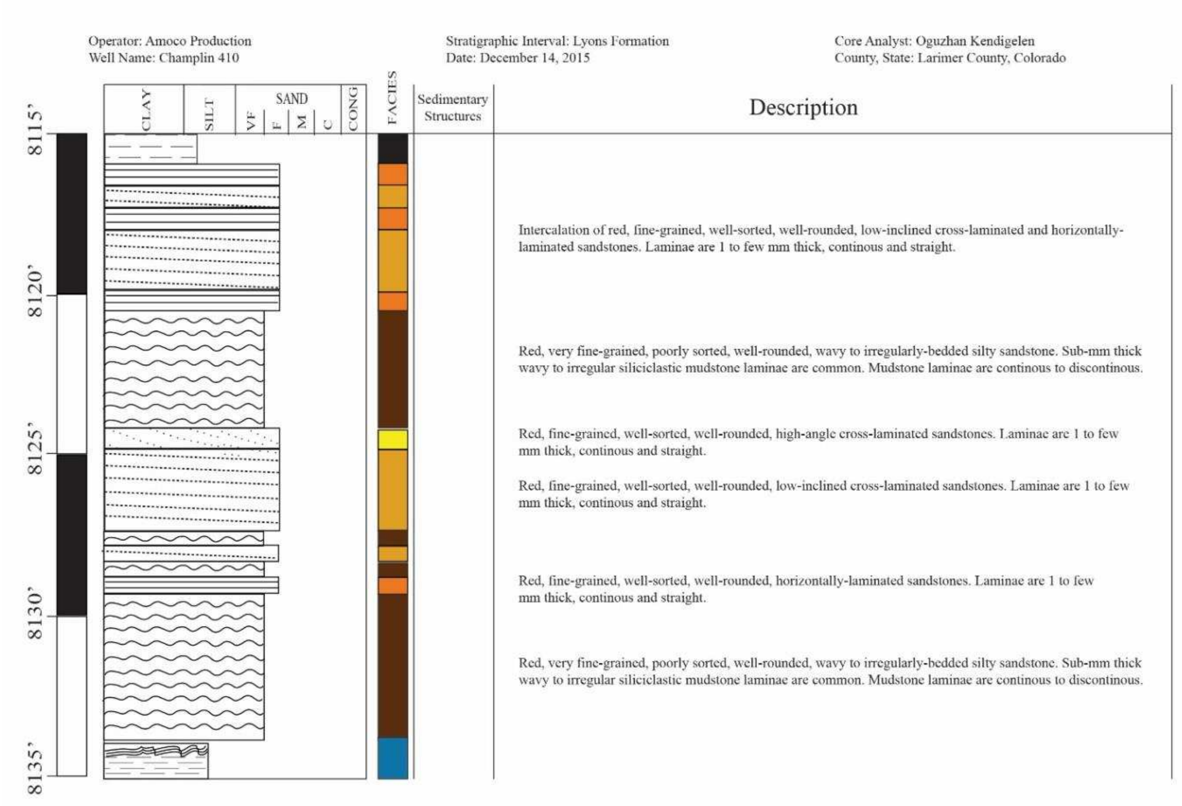


Operator: Tiger Oil
Well Name: Wadleigh 21-34
Stratigraphic Interval: Lyons Formation
Date: December 14, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Larimer County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
7775'
7780'
7785'
7790'
7795'
7800'
7805'
7810'
7815'
Gray, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Gray, very fine to fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick, anhydrite cemented and oil-stained.
Intercalation of gray to pink, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone with horizontally-laminated sandstone beds. Laminae are 1 to few mm thick, anhydrite cemented and oil-stained.
Dark brown, slightly wavy-laminated silty-mud bed intercalation with silty beds. Beds are 10 to 20 mm thick.
Light brown, very fine-grained, poorly sorted, well-rounded, wavy laminated silty sandstone. Laminae are up to 1 mm thick. Bed is deformed by downfolding of laminae.
Pink, very fine to fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Brown, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Pink, very fine to fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone with thin beds of low-inclined cross-laminated sandstone, and horizontally-laminated sandstone. Laminae are 1 to few mm thick, and continous.
Gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone with sub-mm to few tens of milimeter thick wavy to irregular siliciclastic mudstones.
Black, 10 mm thick, wavy-laminated siliciclastic mud bed.
Reddish pink, very fine to fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick, mostly continous.


Operator: Amoco Production
Well Name: Champlin 410
Stratigraphic Interval: Lyons Formation
Date: December 14, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Larimer County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
8515'
8520'
8525'
8530'
8535'
8540'
8545'
8550'
Pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Pink, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Pink, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Black, wavy-laminated silty-mud bed with mm-thick structureless silt and sandstone lenses. Laminae are up to 1 mm thick.
Dark pink, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Pink, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Black, wavy-laminated silty-mud bed with mm-thick structureless silt and sandstone lenses. Laminae are up to 1 mm thick.
White, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Dark pink, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Black, wavy-laminated silty-mud bed with mm-thick structureless silt and sandstone lenses. Laminae are up to 1 mm thick.
Light pink, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
Light pink, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstones laminae are common.
White, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Pink, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
White, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick.
Pink, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.


Operator: California Oil
Well Name: Lee Ray Walker 1
Stratigraphic Interval: Lyons Formation
Date: December 14, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Weld County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
9210'
9215'
9220'
9225'
9230'
9235'
9240'
9245'
9250'
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated, anhydrite cemented, oil-stained sandstone. Laminae are 1 to few mm thick.
Gray, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated, anhydrite cemented, oil-stained sandstone. Some stylolites are present.
Gray, fine-grained, well-sorted, well-rounded, high-angle cross-laminated, anhydrite cemented, oil-stained sandstone. Laminae are 1 to few mm thick.
Gray, fine-grained, well-sorted, well-rounded, horizontally-laminated, anhydrite cemented, oil-stained sandstone. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Mm thick stylolites and sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Gray, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Dark gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Mm thick stylolites and sub-mm thick wavy to irregular siliciclastic mudstone laminae are common.
Dark brown, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstone. Laminae are 1 to few mm thick.
Dark brown, fine-grained, well-sorted, well-rounded, low-icnlined cross-laminated sandstone. Laminae are 1 to few mm thick.
Dark brown, fine-grained, well-sorted, well-rounded, low-icnlined cross-laminated sandstone. Laminae are 1 to few mm thick.
Brown, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. These mudstone laminae are mostly discontinous.
Brown, fine-grained, well-sorted, well-rounded, high-angle cross-laminated, sandstone. Laminae are 1 to few mm thick, continous.
White, fine-grained, well-sorted, well-rounded, high-angle cross-laminated, anhydrite cemented sandstone. Laminae are 1 to few mm thick.
Brown, fine-grained, well-sorted, well-rounded, horizontally-laminated, anhydrite cemented, oil-stained sandstone. Laminae are 1 to few mm thick.
Brown, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated, anhydrite cemented, oil-stained sandstone. Laminae are 1 to few mm thick.
Dark brown, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.
White, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone. Laminae are 1 to few mm thick, continous.
Brown, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone. Laminae are 1 to few mm thick.
Gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.
Brown, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated and horizontally laminated sandstone. Laminae are 1 to few mm thick.


9250'
9255'
9260'
9265'
9270'
9275'
9280'
Dark brown, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.
Black, wavy-laminated silty-mud bed with mm-thick structureless silt and sandstone lenses. Laminae are up to 1 mm thick.
Whitish brown, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated, anhydrite cemented sandstone. Laminae are 1 to few mm thick.
Gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.
Intercalation of brown, fine-grained, well-sorted, well-rounded, high-angle cross-laminated, low-inclined cross-laminated, and horizontally laminated, anhydrite cemented, and oil-stained sandstone beds. Laminae are 1 to few mm thick, straight, and continous.
Gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.
Whitish brown, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstone.
Gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.
Whitish brown, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstone.
Gray, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are mostly discontinous.



Operator: Amoco Production
Well Name: Champlin 410
Stratigraphic Interval: Lyons Formation
Date: December 14, 2015
Core Analyst: Oguzhan Kendigelen
County, State: Larimer County, Colorado
CLAY
SILT
SAND
VF
F
M
C
CONG
FACIES
Sedimentary Structures
Description
8115'
8120'
8125'
8130'
8135'
Intercalation of red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated and horizontally-laminated sandstones. Laminae are 1 to few mm thick, continous and straight.
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are continous to discontinous.
Red, fine-grained, well-sorted, well-rounded, high-angle cross-laminated sandstones. Laminae are 1 to few mm thick, continous and straight.
Red, fine-grained, well-sorted, well-rounded, low-inclined cross-laminated sandstones. Laminae are 1 to few mm thick, continous and straight.
Red, fine-grained, well-sorted, well-rounded, horizontally-laminated sandstones. Laminae are 1 to few mm thick, continous and straight.
Red, very fine-grained, poorly sorted, well-rounded, wavy to irregularly-bedded silty sandstone. Sub-mm thick wavy to irregular siliciclastic mudstone laminae are common. Mudstone laminae are continous to discontinous.

Appendix 2: Porosity and permeability datasets

	Dry eolian deposits					Wet eolian deposits
	2.1	6.3	8.2	15.9	19.9	2.6
	3.1	5.8	4.5	16.5	11.5	4.2
	2.8	3.7	4.4	16.4	11.7	5.3
	2.3	4.9	5.3	8.9	13.4	3.6
	2.6	5.3	5.2	13.2	15.6	3.6
	3.4	5.2	5.2	14.5	15.6	3.3
	3.5	4	4.4	8.9	16.7	9.3
	3.1	2.9	4.8	13.2	22	6.3
	3.8	5.5	6.7	14.5	19.9	7.5
	4.2	5.6	3.9	8.9	23.9	3.5
	6.1	4	5.5	10.2	25.2	5.2
	3.2	4.4	4.4	13.9	23.9	2.2
	6.3	5.2	4.4	10.3	22.1	5.4
	4	4.1	3.8	14	25.3	4.2
	2.6	3.2	5.4	9.1		4.6
	2.8	3.9	5.3	6.4		4.9
	3.8	5.8	5.3	11		5.3
	4.6	3.6	4.1	11.6		7.8
	3.8	4.6	8.4	10.7		3.5
	4.6	5.8	3.9	12.6		3.8
	3.7	2.9	6.1	8.9		3.2
	3.8	2.8	7.3	13.2		8.5
	3.5	4.7	7.1	13.7		7.9
	3.8	3.3	8.2	19.9		8
	3.4	4.1	8.6	10.6		
	3.4	2.5	7.7	14.3		
	3.9	4.2	6.7	12.7		
	4	4.5	3.1	7.3		
	3.9	4.2	3.1	6.6		
	3.5	4.3	3.4	11.1		
	5.1	5.1	8.2	9.8		
	5.1	8.9	18	15.1		
	5.4	13.8	14.3	10.5		
	3.9	13.9	18.8	11.5		
	3.3	12.8	17.3	14.2		
	5.7	15.2	12.4	7.9		
	1.9	12.7	8.6	12.2		
	2.7	5.4	8.7	4.6		
	2.3	4.2	6.9	10.6		
	2.3	4.7	4.3	3.2		
	3.2	7.7	12.5	3.9		
	2.9	7.3	7.9	3.6		
	3.4	5	14.8	5.1		
Average Porosity	8.53 vol%					5.15 vol%
Maximum Porosity	25.3 vol%					9.3 vol%
Total Avarage Porosity (Dry+Wet Eolian Deposits)	8.17 vol%					

	Dry eolian deposits				Wet eolian deposits
	<0.1	<0.1	<0.1	100	<0.1
	<0.1	<0.1	<0.1	523	<0.1
	0.1	<0.1	<0.1	583	<0.1
	0.1	0.1	<0.1	175	<0.1
	<0.1	<0.1	0.14	73	<0.1
	<0.1	<0.1	<0.1	422	<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	0.1	<0.1	<0.1		<0.1
	0.2	0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	0.1	<0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	1.6	2.1		<0.1
	<0.1	0.1	1.8		<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		<0.1
	<0.1	<0.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	0.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	0.1	<0.1		
	<0.1	9.7	<0.1		
	<0.1	39	<0.1		
	<0.1	36	<0.1		
	<0.1	33	104		
	0.1	7.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	<0.1	<0.1		
	<0.1	<0.1	82		
	<0.1	<0.1	234		
	<0.1	<0.1	420		
	<0.1	<0.1	32		
	<0.1	<0.1	30		
	<0.1	<0.1	63		
	<0.1	0.11	176		
Maximum Permeability	583 mD				<0.1 mD