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Sedimentology and Stratigraphy of the Upper Pennsylvanian – Lower Permian Systems of Western Nebraska, USA

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By

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Sedimentology and Stratigraphy of the Upper Pennsylvanian – Lower Permian Systems of Western Nebraska, USA

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Depositional patterns and regional stratigraphic relationships in the carbonate-dominated Pennsylvanian and Permian deposits in western Nebraska are not well established due to poor surface exposure. Examination of petroleum drillcores and wireline logs, along with thin sections and biostratigraphic analysis allow new insight into facies distributions, depositional environment, and regional stratigraphic relationships. Nine shallowing upward cycles are identified that can be correlated across the southern Nebraska Panhandle within the Pennsylvanian (Virgilian)-Permian (Wolfcampian) stratigraphy (Admire, Council Grove, and Chase Groups). These cycles are composed of facies representing deposition from open marine through nonmarine environments. Results show that depositional settings in western Nebraska were shallower and more restricted than in other nearby areas of the Midcontinent and that regional climatic conditions became more arid through time, from the Pennsylvanian into the Permian. Increasing our understanding of these subsurface relationships will be

useful in two primary regards. First, it will aid petroleum exploration efforts in this region by providing a better understanding of depositional patterns and facies variability, and second, it will contribute to our knowledge about regional variations in climate and their increasing aridity through time.

INTRODUCTION

Cyclic variations in relative sea-level due to glacioeustatic fluctuations during the Late Paleozoic are recorded in the North American Midcontinent (Wanless and Shepard, 1936; Momper, 1963; Heckel, 1986; Veevers and Powell, 1987; Olszewski and Patzkowsky, 2003). These carbonate-dominated cyclic deposits, termed cyclothems (Wanless and Weller, 1932), have received a great deal of attention since their discovery in the early 1900s, and are now generally defined as limestone-shale couplets (Olszewski and Patzkowsky, 2003). Specifically, Kansas-type cyclothems are heavily documented and correlated across the US Midcontinent, and have been described in detail by Heckel (1986). Klein and Willard (1989), Momper (1963), Carlson (2007), and Watney et al. (2008) offered discussions on the eustatic and tectonic influences on cyclic deposition in North America during this time. In the Midcontinent, glacioeustasy appears to have been the primary control on deposition in this region, although localized tectonic activity on the inner craton also played a role. The combination of tectonic and glacioeustatic influences on sediment deposition affected the geometries and regional distributions of these deposits, complicating efforts to understand lateral correlations (Carlson, 2007; Watney et al., 2008).

Despite petroleum exploration activity in western Nebraska (Burchett, 1987; Montgomery et al., 1998), the subsurface facies around the Pennsylvanian-Permian boundary and their regional stratigraphic relationships remain poorly documented. The Midcontinent, and especially western Nebraska (Fig. 1), contains sensitive carbonate and evaporite facies that record even slight changes in relative sea-level and reveal information about regional variations in paleoenvironment and response to climate and glacioeustatic fluctuations during this time. This thesis clarifies the sedimentology and stratigraphy of the Pennsylvanian-Permian subsurface deposits of western Nebraska. It contrasts the stratigraphic succession in the Nebraska Panhandle with that in parts of the Midcontinent to the southeast, and reconstructs climatic changes through time by examining petroleum drillcores from three counties in western Nebraska.

GEOLOGICAL SETTING AND STRATIGRAPHY

Location

This study focuses on the Upper Pennsylvanian and Lower Permian carbonate- dominated deposits of the southern Panhandle of Nebraska. The strata recorded in drillcores from three counties (Kimball, Cheyenne, and Garden) of Nebraska are the topic of this research (Fig. 1).

Tectonic History

Glacioeustatic signals are preserved in the stratigraphic record of the Midcontinent more so than in other areas of the US, where active regional tectonics may have played a role in controlling sedimentation patterns (Klein and Willard, 1989). Although the glacioeustatic signal is prominent in the US Midcontinent, it is important to consider what effects local underlying tectonic structures may have had on sediment accumulation in this region.

Montgomery et al. (1998) showed the Transcontinental Arch (TCA) as a through-going feature that extended across the study area (Fig. 2A), and separated the northern Alliance Basin from the southern Sterling Basin. Others (Carlson, 1999) argued that the TCA did not exist, rather they postulated that a series of localized topographic highs better characterized the structure of the area. Carlson (2007) identified both the Morrill County High and the Wattenberg High as positive topographic features extending through the study area (Fig. 2B). He also discussed the potential links between the Precambrian accretionary history of Nebraska and observed Phanerozoic structures throughout the region. Carlson (2007) argued that Phanerozoic patterns of structure and stratigraphy for Nebraska can be attributed to the tectonic history of the Precambrian basement. Watney et al. (2008) argued that simple topographic variability did not adequately account for the facies distribution patterns documented for the US Midcontinent. Rather, it appeared that reactivation of underlying structural features during the Pennsylvanian (also, episodically throughout entire Phanerozoic) such as the Ancestral Rocky Mountain uplift and Ouachita uplift affected depositional geometries. This tectonic influence along with lateral facies variability more accurately account for the geometries and depositional patterns observed in the US Midcontinent than does a single feature, namely a TCA, which created one topographic high across the study area (Fig. 2).

Whether the underlying feature was a large arch that reached across the entire study area (Montgomery et al., 1998) or a series of localized positive features, the creation of which was influenced by the accretionary tectonics of the Precambrian (Carlson, 2007; Watney et al., 2008), it is likely that topographic relief in this region would have contributed to sedimentation patterns evident today in the geometry of deposits. For example, Wolfcampian strata (Fig. 3) are ~900 feet thick and thin to about half this thickness toward the Nemaha Uplift in eastern Nebraska and south-central Kansas (West et al., 2010). Because this thickness trend has been associated with structure and paleotopographically-controlled stratigraphic variation in Kansas, similar patterns would be likely for Nebraska.

Stratigraphic Context

The stratigraphic succession analyzed in this study consists of siliciclastic, carbonate, and evaporite rocks (Heckel, 1986; Montgomery et al., 1998; Mazzullo, 1998; Sawin et al., 2006). Lithologies described by Montgomery et al. (1998) include halite, anhydrite, dolomite, black shale, siltstone, limestone, and arkose. Mazzullo (1998) discussed interpreted paleosols as well as documented mudrocks, shales, wackestones, packstones, and grainstones. Sawin et al. (2006) documented the presence of carbonate muds, wacke- to packstones, and black, fissile shales around the Pennsylvanian-Permian boundary in Kansas at their proposed stratotype locality at the Tuttle Creek Spillway section.

This stratigraphy studied here has been analyzed closely in Kansas. In regions where paleotopography did not exert any control on deposition beds are found to correlate across laterally extensive areas (up to hundreds of km), even where units are as little as ~1 m thick (Olszewski and Patzkowsky, 2003). From this, Olszewski and Patzkowsky (2003) inferred that this stratigraphy was deposited across a wide carbonate ramp with a very low depositional gradient.

In the Midcontinent, the Pennsylvanian-Permian boundary has been established at the base of the Bennett Shale Member of the Red Eagle Limestone, within the Council Grove Group (Ritter, 1995; Sawin et al., 2006) (Fig. 3). The cores under consideration here contain rocks from the Missourian Lansing through the Permian Chase Group. Figure 3 shows this stratigraphy as it is documented for Kansas.

Admire Group

The Virgilian Admire Group consists of black shales, grainstones, microbially laminated dolomite, anhydrite, and halite facies (Montgomery et al., 1998). The Admire Group contains three prominent dolomitic sections, termed “A,” “B,” and “C” by Montgomery et al. (1998). These are separated by thick-bedded anhydrite layers. These “intervening” anhydrite beds are evident within the cores and wireline logs examined in this study. According to Montgomery et al. (1998) the halite is rarely preserved due to erosion during transgression and the anhydrite may be displacive.

Council Grove Group

The Virgilian-Wolfcampian Council Grove Group contains the Pennsylvanian-Permian boundary, positioned at the base of the Bennett Shale Member of the Red Eagle Limestone (Sawin et al., 2006), based on biostratigraphy and a distinct change in the type of cyclic sedimentation observed (Ritter, 1995; Olszewski and Patzkowsky, 2003). Generally, the Council Grove Group is represented by a series of open marine facies such as limestones containing fusulinids and algally coated grains, along with limestone beds with shaly partings and medium to dark gray laminated shales (Sawin et al., 2006). Reddish to greenish calcareous mudrocks were inferred by previous workers as recording episodes of subaerial exposure (West et al., 2010). A diverse spectrum of open marine fauna appear within these strata as well, such as fusulinids, foraminifera, brachiopods, crinoids, bryozoans, bivalves, and gastropods (West et al., 2010).

Chase Group

The upper Wolfcampian Chase Group, described in detail by Mazzullo (1998) and West et al. (2010), is lithologically similar to the Council Grove Group, but differs appreciable in that it also contains significant evaporitic facies. Yellow to gray, green, or black shales and mudrocks, red and green mudrock units, wacke- to packstones (locally dolomitized), and microbial laminites are common. Desiccation polygons, algally coated grains, evaporite nodules replaced with calcite, and a diverse assemblage of open marine fossils including brachiopods, bivalves, fusulinids, crinoids, bryozoans, and echinoids are present.

Olszewski and Patzkowsky (2003) described the depositional setting for these Groups as an arid carbonate ramp. The gradient would likely have been minimal. Both Olszewski and Patzkowsky (2003) and West et al. (2010) cited episodes of subaerial exposure, indicated by the presence of interpreted paleosols.

METHODS

This research represents an integration of core and thin section data from six petroleum drillcores in western Nebraska (Fig. 1; Chevron Compton-Duncan 1, Davis Petroleum Beyer #1, Marathon Oil Brauer 14-1, American Petrofina Ackerman #1, Bass Enterprises Brauer 6-13, and Southland Royalty Withers #1). Lithology, grain size, fossil content, bioturbation, porosity, and sedimentary structures were logged.

Fusulinid biostratigraphy, carried out by Dr. Greg Wahlman of Wahlman Geological Services, LLC, helps constrain stratigraphic relationships for the region (as much as possible, based on fossil preservation; details available in Appendix B). Also, industry picks and wireline logs serve as correlation aids.

Cores are correlated across the study area using a genetic stratigraphic approach to understanding deposition in a peritidal to open marine setting and focused on identifying cycles contained within the rocks. Flooding/transgressive surfaces are identified and used as the basis for correlation. Correlations for this study hang on the Admire "A" dolomite datum.

LITHOFACIES

Lithofacies record conditions ranging from open marine to restricted marine and nonmarine environments (Fig. 4). Table 1 provides detailed descriptions. The complete, detailed, graphic logs of each core are available in Appendix A.

Lithofacies A. Calcareous Shale to Shaly Limestone

This lithology ranges from black calcareous shale to a gray shaly limestone (Fig. 4A). It is laminated in many places and is inferred to contain some organic material, based on its color. Due to its dark color, the presence of laminations, and lack of fossils and bioturbation, Facies A is interpreted to represent deposition in the calmest, and most poorly oxygenated environment of the facies logged in this study. Deposition is also inferred to have been below both fair weather wave base (FWWB) and storm wave base (SWB) in an open marine setting.

Lithofacies B. Skeletal Wackestone

This lithology contains skeletal fusulinid, foraminifera, crinoid, and brachiopod grains, as well as other, unidentifiable skeletal fragments (Fig. 4B). It is tan to gray in color. The original matrix is carbonate mud, and there is variable secondary micritization of skeletal grains. This lithology contains small (< 2.5 cm) anhydrite nodules or iron concretions, and is often stylolitized. This facies represents deposition in a subtidal environment. The biota are diverse and indicate an open marine setting. Depositional depths were restricted to the bottom of the photic zone, based on the presence of photozoan biota such as fusulinids and phylloid algae.

Lithofacies C1. Skeletal Packstone

This lithology consists of skeletal grains from fusulinids, foraminifera, crinoids, brachiopods, and other unidentifiable fragments (Fig. 4C). Its color ranges from tan to gray, and the matrix is micrite. This facies may also contain small (< 2.5 cm) anhydrite nodules or iron concretions, and is often stylolitized. This facies is inferred to represent deposition in a subtidal environment, within the photic zone, based on the presence of photozoan fossil assemblages.

Lithofacies C2. Fusulinid Packstone

In this instance, fossil material is limited to fusulinids (Fig. 4D). Otherwise, it has the same characteristics as Facies C1.

Lithofacies D. Dolomitized Wacke- to Packstone

This lithology is similar to facies B and C (skeletal wackestone and skeletal packstone), but in this case, the matrix material is dolomite, and has a sucrosic texture (Fig 4E). Skeletal grains may be micritized and consist of fusulinids, foraminifera, crinoids, brachiopods, and unidentifiable fragments. The rock contains small (< 2.5 cm) anhydrite nodules and is often stylolitized. The biota are diverse and indicate an open marine setting at the time of deposition. Depositional depths were restricted to the bottom of the photic zone, based on the presence of photozoan fossils such as fusulinids. Good preservation of skeletal grains and the fine nature of the matrix material suggests dolomitization during early diagenesis.

Lithofacies E. Oolitic Grainstone

This lithology is composed of well-sorted, micritized ooids. Primary intergranular pore space is filled with blocky cement or micrite/micritized cement (Fig. 4F). This facies represents deposition in a subtidal environment along a sand shoal, as areas where this facies formed must have had high enough energy to achieve adequate grain agitation for ooid formation and to remove primary micrite.

Lithofacies F. Mudstone

This lithology is a brown to tan dolomitized mudstone (Fig 4G). Local bioturbation is manifest as color mottling. Sparse biota include fusulinids and foraminifera. There are also anhydrite nodules (~2.5 cm) located in ovoid enclaves interpreted as burrows, and intergranular and fracture porosity. This facies is inferred to have been deposited in a subtidal setting, based on fossil content and bioturbation. Fine scale dolomitization and anhydrite fill in burrows suggests a later period of exposure to restricted marine conditions.

Lithofacies G. Calcareous Sandstone

This lithology is a light green-gray, fine- to medium-grained, well-sorted, quartz sandstone with carbonate cement (Fig 4H). It is poorly fossiliferous, but contains brachiopod skeletal material, as well as other unidentifiable skeletal fragments. It is locally laminated or bioturbated and shows intergranular porosity. This facies is likely composed of reworked eolian grains from the adjacent lowlands. Sediment would have been transported and deposited along the coastline, where it was later bioturbated and cemented.

Lithofacies H. Microbial Laminite

This lithology is typically dark gray or black to light brown (at times has slightly pinkish hue) and shows crinkly laminations or crenulations, as are typical of microbial deposits (Fig. 4I). It can contain anhydrite overgrowths (up to several centimeters in width). This facies is inferred to represent an intertidal zone, because of similarity to facies in modern settings such as Abu Dhabi (Butler et al., 1982; Alsharhan and Kendall, 2002). Anhydrite nodules probably originated as displacive gypsum, increasing in volume as conditions became more arid with time, eventually overtaking these units (turning into Facies I). On the basis of previous work by Montgomery et al. (1998) and observations in core, it is clear that in some intervals, microbial laminite has been displaced by growth of anhydrite nodules and transformed into chickenwire anhydrite.

Lithofacies I. Bedded Anhydrite

These rocks are gray to white color, and have a nodular to chickenwire fabric (Fig. 4J). Where it is nodular, this lithofacies can have a dolomicrite matrix. It does not contain any biota. Observations from core and thin sections suggest that anhydrite displaced what was formerly microbial laminite (Facies H). This facies represents deposition in a restricted sabkha or supratidal environment, where chickenwire fabric and association with microbial laminites are known to exist from modern analogs such as Abu Dhabi, UAE (Butler et al, 1982; Alsharhan and Kendall, 2002).

Lithofacies J1. Red Mudrock

This lithofacies is a red, laminated or fissile mudrock that in some cases contains small to medium size (~5-15 cm) anhydrite and/or carbonate nodules (Fig. 4K). Local bioturbation suggests that originally, this facies was deposited in the nearshore marine environment. Later, these units were subaerially exposed, indicated by oxidation and the presence of root structures (Fig. 4L) and slickensides that likely resulted from wetting and drying and shrink-swell cycles involving clay minerals. It is inferred to be the oxidized equivalent of Facies J2.

Lithofacies J2. Green Mudrock

This lithology is a dark green to dark gray massive mudrock (Fig. 4M). Bioturbation can be manifest as color mottling. It locally contains small to medium (~5-15 cm), pink to white colored carbonate and/or anhydrite nodules. It is interpreted as a nearshore marine shale, on the basis of local bioturbation, that was then exposed, allowing soil development to occur (based on root structures and slickensides discussed above, Facies J1). Subsequently, upon burial, reducing fluid flowed through the unit, turning parts of it green (Fig. 4N, 4O). Facies J2 is inferred to be the reduced equivalent of Facies J1.

BIOSTRATIGRAPHY

Fusulinid identifications aided in refining regional stratigraphic correlation, because in many instances, the industry wireline log picks did not correspond to recently revised stratigraphic positions, as indicated by Dr. Wahlman's work. In these instances, preference was given to the biostratigraphic data.

In all cases, fusulinids belonged to taxa characteristic of the middle or upper Shawnee Group (Virgilian). Only two samples could be tied to specific beds in the well-known Kansas stratigraphy. Biostratigraphic evidence indicates that these aforementioned beds approximately correlate to the Topeka Limestone, and the Deer Creek Limestone (Appendix B).

DISCUSSION

1. *Depositional Environment*

The facies represented in these cores are consistent with deposition along a carbonate ramp in an arid setting (Fig. 5) during the Late Pennsylvanian and Early Permian, as suggested previously by Olszewski and Patzkowsky (2003) for strata in Kansas. An excellent modern analog for western Nebraska is the carbonate ramp developed along the southern shore of the Persian Gulf, in the Abu Dhabi area, which has been described by numerous workers (Butler, 1968; Kendall and Skipwith, 1969; Butler et al., 1982; Evans, 1994; Evans, 1996; Alsharhan and Kendall, 2002; Alsharhan and Kendall, 2003). Different lithofacies and facies assemblages for this region can broadly be grouped into the subtidal, intertidal, and supratidal categories, which match the broad depositional regions interpreted to exist in western Nebraska in Pennsylvanian-Permian time. These depositional settings occur in close lateral proximity to one another, therefore they probably had interfingering or overlapping relationships (Alsharhan and Kendall, 2002).

Subtidal Environment

Lithofacies within the subtidal region are typically composed of skeletal wackestones (Kendall and Skipwith, 1969), equivalent to Facies B and C (Fig. 4B, 4C, 4D). Near the shoreline, sediments consist dominantly of shells and shell fragments, as well as aragonitic marine cements (Alsharhan and Kendall, 2002). Alsharhan and Kendall (2002) describe beachrock formation in the subtidal environment, as well as reef and oolite facies. Oolites (Facies E; Fig. 4F) form along shoals, terraces, and offshore banks. These facies are surrounded by carbonate sands and other unconsolidated mudstones and wackestones with diverse skeletal material (Alsharhan and Kendall, 2002). Facies described in Abu Dhabi are similar to skeletal wackestones, packstones, and oolites of western Nebraska (Facies B, C, E; Fig. 4B, 4C, 4D, 4F). Figure 5 illustrates the depositional environment for the facies discussed here.

Intertidal Environment

The intertidal zone can contain the characteristics of both the subtidal and supratidal settings, making the intertidal flats difficult to distinguish at times. In Abu Dhabi, two facies characteristic intertidal zones have been described:

i) Cemented Beachrock and Oolite Facies

Cemented crusts and beachrocks of the lower intertidal zone are principally composed of laterally interfingering carbonate sands and muds (Alsharhan and Kendall, 2003). Kendall et al. (1994) studied the cement coatings on rocks produced within intertidal and subtidal settings of Abu Dhabi and determined that their composition is primarily aragonite. Intertidal sediments include oolites (Facies E; Fig. 4F), as well as sands full of coral material and fragments (Facies B and C; Fig. 4B, 4C, 4D) (Kendall and Skipwith, 1969). These facies can be very similar to those observed in the subtidal environment.

ii) Microbial Mats

The intertidal zone also contains microbial mats (Facies H; Fig. 4I) (Butler et al., 1982). It is the most distinctive facies of the intertidal zone and is interbedded with aragonite muds brought in by storms (Butler et al., 1982; Kendall, 1992). In this study, these deposits are referred to as microbial laminite (Facies H; Fig. 4I). These mats can be in the upper intertidal zone, show polygonal desiccation cracking, and be cemented into beach rock *in situ*. Often, these microbial mats contain gypsum crystals (Alsharhan and Kendall, 2002), which grow displacively within the sediment. Similar features are also observed in the drillcores being studied for western Nebraska.

Supratidal Environment

Alsharhan and Kendall (2003) and Butler et al. (1982) both give a detailed analysis of several distinct facies within the supratidal region at Abu Dhabi, South of Al Qanatir Island.

i) Lower Supratidal: Gypsum Mush Facies

At Abu Dhabi the supratidal gypsum mush facies lies between two microbial mat (Facies H; Fig. 4I) layers and is roughly 30 cm thick (Butler et al., 1982). The sediments here are composed of carbonate muds, generally aragonite, and they locally contain isolated gypsum crystals or nodules, as well as microbial filaments (Butler et al., 1982). In some areas, the lower supratidal region contains water-saturated carbonate muds interbedded with the gypsum mush (Alsharhan and Kendall, 2002). This facies is the equivalent of the microbial laminite (Facies H; Fig. 4I) that contains displacive anhydrite nodules, observed in western Nebraska. Material would begin as displacive gypsum crystals or "mush" as described here, and then, with time in the supratidal environment, progressively coalesce into nodules and, ultimately, beds of anhydrite. Kendall (1992) describes the process by which this "mush" material transforms into anhydrite. The crystals forming within the existing sediment either incorporate sediment into the crystal, or simply displace the sediment as they grow (Kendall, 1992). Usually, initial crystal growth occurs, followed by the formation of secondary gypsum overgrowth. This creates the interlocking, chickenwire texture observed in the bedded anhydrite facies (Facies I; Fig. 4J) documented for western Nebraska. In many cases in western Nebraska, the gypsum formation displaced microbial laminite (Facies H; Fig. 4I), and ultimately transitioned from microbial laminite to bedded anhydrite. Displacive anhydrite is shown in Figure 4P.

ii) Middle Supratidal: Salt-Flat Facies

Alsharhan and Kendall (2002) describe the mid supratidal area at Abu Dhabi as characterized by a halite crust, although it is not typically long lived. Butler et al. (1982) provide a more detailed analysis in which they document several diagenetic processes occurring at the surface. These include precipitation, replacement, and alteration of gypsum to anhydrite, as discussed above. The last of these processes is seen in western Nebraska, where anhydrite can take on a chickenwire texture (Facies I; Fig. 4J), and aragonite muds are often dolomitized (Facies D and F; Fig. 4E, 4G).

iii) Upper Supratidal: Salt-Flat Facies and Eolianite Facies

This area differs from the Middle Supratidal Salt Flats in that it is flooded much less frequently, typically only about twice a decade (Butler et al., 1982). This area is also known to have siliciclastic input derived from eolian process (Butler et al., 1982), which provide a likely explanation for the formation of Facies G (Fig. 4H). It is probable that eolian processes supplied the sediment for formation of the calcareous sandstone (Facies G; Fig. 4H). It was likely transported to the coastline under eolian influences, where it was then bioturbated and cemented.

Diagenesis in this section of the coastal flat is similar to the Middle Supratidal salt flat facies, in that there is a great deal of anhydrite formation (Facies I) and dolomitization of aragonite muds (Facies D and F; Fig. 4E, 4G) (Butler et al., 1982).

The most landward facies is the eolianite facies consisting of recycled siliciclastic and carbonate materials. This facies also contains an abundance of subsurface anhydrite, as well as surficial halite crusts (Butler et al., 1982). Facies J of this study is not represented in this modern analog.

2. *Cycle Expression*

The cycles documented in western Nebraska are shallowing upward cycles (Fig. 6), each of which is truncated by a flooding/transgressive surface. These cycles contain the highstand and regressive portion of the full transgressive-regressive cyclothem typically seen in other areas of the Midcontinent (Fig. 7; Heckel, 1986; Veevers and Powell, 1987; Olszewski and Patzkowsky, 2003). The transgressive deposits are not well-preserved in this area (likely eroded during transgression, or not deposited if sea-level rise was particularly rapid). Therefore the flooding/transgressive surface that delineates the boundary between shallowing upward cycles also represents the transgressive component of the cyclothem. The lack of transgressive deposits also likely represents a loss of stratigraphic units between western Nebraska and the stratigraphic column documented for the US Midcontinent. Cycle character differs from core to core, and stratigraphically (Fig. 6). The lower parts of the cycles are generally composed of an open marine facies such as a wackestone or packstone (Facies B and C), and occasionally a more offshore marine facies such as Facies A, and represent the Highstand Systems Tract (HST). Tops of cycles are observed shallowing upward into paleosols (Facies J1/J2), microbial laminites (Facies H), and bedded anhydrite (Facies I).

Flooding/transgressive surfaces mark the boundary between the top of a shallowing upward cycle and the bottom of the next cycle. In terms of lithostratigraphic expression, this can be seen as a microbial laminite, anhydrite, or paleosol (Facies H, I, J1/J2) topped by an open marine deposit (Facies A, B, C, D, E).

The sequence stratigraphic interpretation of this region is complex. Both flooding/transgressive surfaces and subaerial exposure surfaces can be identified, and often closely coincide. Each shallowing upward cycle can be termed a parasequence, on the basis of terminology proposed by Catuneanu et al. (2009), who defined a parasequence as a set of genetically related beds bounded by flooding surfaces. Deposits created during times of subaerial exposure comprise the Lowstand Systems Tract (LST) of these cyclothems. Flooding/transgressive surfaces represent a relative rise in sea-level, but they also represent the Transgressive Systems Tract (TST) because transgressive deposits are either not preserved or were not deposited across the region, as discussed above. The HST is well preserved throughout the study area. It is recorded by various carbonate deposits, which filled in accommodation created during sea-level rise. The shallowing upward nature of the cycles represents a time of relative sea-level drawdown or regression. Relative sea-level begins to drop, increasing the amount of restricted facies allowed to form. The parasequence sets observed in western Nebraska show a trend toward relative sea-level drawdown at the top of the Admire Group. These parasequence sets are probably a part of one larger sequence, the boundaries of which are not evident in the section analyzed.

Heckel (1986) described the Kansas-type cyclothem in great detail (Fig. 7). This description has largely been adopted for the US Midcontinent. This type of cyclothem is composed of a highly fissile, black, phosphatic ”core” shale, recording the deepest water depths and furthest inundation of the sea during a cycle. This shale is bounded by two open marine units such as mudstones, wackestones, or oolites. The open marine limestone below the core shale represents the TST and the limestone above the core shale represents the HST and the initial stages of regression. Finally, those limestones are each bounded by shales with either blocky mudstone or sand and coal deposits. An ideal cycle records a full transgressive-regressive cycle, and typically records deposition from offshore (represented by core shale) to open marine environments (Fig. 7). Western Nebraska cyclothems do not express the full transgressive-regressive cycle as is documented for Kansas. Western Nebraska cyclothems also lack the black, phosphatic, “core” shale that records deeper water conditions. They also contain prominent restricted marine to nonmarine facies.

Facies A corresponds to the “core” shale of Heckel (1986), in that it represents deposition in the deepest marine environment under dysoxic to anoxic conditions at times. From the restricted and nonmarine facies present in these cycles, it is clear that western Nebraska represents a shallower depositional environment than those which are generally represented in Midcontinent cyclothems. However, the pattern of deposition observed in western Nebraska, of transgressive and regressive deposits that have lateral continuity and that reflect allogenic forcings in deposition, is similar to what is typically described for the Midcontinent.

3. *Regional Correlation*

Fusulinid data and industry formation top picks provide the initial framework for correlations, while wireline log patterns and lithostratigraphy allow for correlation in more detail. The top of the Admire Group "A" dolomite was chosen as the datum for the cross-sections due to its clear signal in the wireline logs of all six cores. The "intervening" anhydrites are particularly prominent within these cores and logs, and provide reliable tools for correlation. Ultimately, for this study, the correlation of cycles is more significant than the correlation of the individual beds or facies. Because these rocks were deposited over potentially variable topography (as previously discussed; Fig. 2) and because peritidal environments can show great lateral variability, the correlation of general shallowing upwards cycles is more reliable and provides a clearer picture of potential glacioeustatic fluctuation than would the correlation of individual stratigraphic units or facies.

Nine shallowing upward cycles were identified and correlated across the region (Figs. 8 and 9). Cycles show thickness changes across their lateral extent. For example, cycle 1 thickens from the west where it is ~40 ft (~12 m) thick, toward the east where it is ~70 ft (~21 m) thick. It shows roughly the same thickness across the N-S transect. Cycle 2 thins from west to east from ~40 ft (~12 m) to ~15 ft (~4.5 m) in thickness, and thickens from north to south from ~20 ft (~6 m) to ~40 ft (~12 m) in thickness. Cycle 3 remains roughly the same thickness from west to east (~35 ft, ~10.5 m), but thickens dramatically from ~25 ft (~7.5 m) to ~70 (~21 m) ft from north to south. However, it is thickest at the center well, American Petrofina Ackerman #1, where its total thickness is ~80 ft (~24 m). Cycle 4 is thinner to the west than the east, showing a thickness change from ~40 (~12 m) ft to ~65 ft (~20 m). It also thickens slightly from ~55 ft (~16.5 m) to ~65 ft (~20 m) from N-S. Cycle 5 is ~80 ft (~24 m) thick to the west and ~ 70 ft (~21 m) thick to the east. It thickens drastically at the center well, with a total thickness of ~140 ft (~43 m). The N-S transect for cycle 5 shows a uniform thickness at ~140 ft (~43 m), except for at the Marathon Brauer 14-1 well, where it thins to ~110 ft (~33.5 m) in thickness. Cycles 6 through 9 are not identified on the N-S transect due to lack of core recovery, and therefore thickness data is only available on the west to east transect. Cycle 6 thickens from ~95 ft (~29 m) in the west to ~125 ft (~38 m) in the east. Cycle 7 shows a fairly consistent thickness from west to east, at ~60 ft (~18 m). However, it does thin slightly to ~45 ft (~14 m) thick in the middle at the Davis Petroleum Beyer #1 well. Cycle 8 thickens from the west where it is ~65 ft (~20 m) thick to the east where it is ~125 ft (~38 m) thick. It is ~30 ft (~9 m) thick in the center at the Davis Petroleum Beyer #1 well. Cycle 9 thins slightly from west to east, decreasing from ~130 ft (~40 m) to ~115 ft (~35 m) in thickness. It is thinner in the center (Davis Petroleum Beyer #1 well) at only ~85 ft (~26 m) thick. Such lateral variations in cycle thickness are attributed to topographic variability throughout the region at the time of deposition, controlled by paleotopographic highs resulting from underlying Precambrian structures (Fig. 2). There is no evidence for a consistent pattern of deposition along topographic highs or lows, but instead it seems that topographic features varied throughout time and space. An alternate interpretation as to why these cycle thicknesses vary as they do is differential compaction. Although not the favored interpretation, it is possible that some of the beds or facies with higher mud content may have been differentially compacted, resulting in cycle thickness variability, as was documented for the Midcontinent by Joeckel (1995).

Because cycles can be correlated across the region despite variations in cycle thickness, this implies that deposition was responding to allogenic factors, chiefly glacioeustasy. At the same time, however, underlying structural features creating topographic variability imposed a regional control over the distribution of subtidal to supratidal facies in western Nebraska.

4. *Conditions Through Time*

Although the correlation of large scale cycles 1-9 is important in understanding the regional stratigraphic relationships, stratigraphic trends in facies recorded in higher-frequency (lower-order) cycles can provide insights into different regional paleoclimate conditions. To distinguish the two cycle orders present here, larger, correlative cycles 1-9 are termed *cycles* while higher-frequency cycles are termed *non-correlative* cycles. Analysis of each of the six petroleum drillcores (available in Appendix A) has shown a general trend of increasing aridity with time. As an example, Figure 6 shows detailed graphic logs through three intervals of the Davis Petroleum Beyer #1 core from Cheyenne County. It displays section from the Late Pennsylvanian, moving toward the Early Permian (deeper depths to shallower depths). The trend described below for this core is evident in all of the cores considered in this study, and this discussion is intended to clarify coarse regional climate patterns.

The first cycle (A) (Fig. 6A) shallows upward into a paleosol (Facies J1/J2). Second (B) (Fig. 6B) is composed of smaller non-correlative cycles that ultimately shallow upward into the microbial laminite facies (Facies H). This is a good example of higher resolution cyclicity within one correlative shallowing upward cycle. The final cycle (C) (Fig. 6C), is also composed of non-correlative cycles that ultimately shallow upward into bedded anhydrite (Facies I). Because anhydrite beds thicken and become so prominent at the top of the Admire Group, a trend of increasing aridity is interpreted. This trend of increasing aridity seems to be regionally relevant (Fig. 8; Fig. 9), in that it can be observed and correlated across the study area. Because this trend can be observed at the top of the Admire Group in each of the six cores studied, it implies that conditions were becoming more arid and restricted regionally and not just in certain areas that sat atop topographic highs.

Montgomery et al. (1998) documented increasingly restricted facies in the Admire Group strata, noting the presence of bedded or displacive anhydrite in western Nebraska. Olszewski and Patzkowsky (2003) discussed cyclic deposits of Nebraska and Kansas, and they also saw evidence for a trend toward aridity in their study. This trend of increasing aridity through time also corresponds temporally to the documented sea-level lowstand for Early Permian (Vail et al., 1977) and the acme of glaciation on Gondwana during the Late Paleozoic Ice Age (Fielding et al., 2008). Koch and Frank (in press) document a sea-level drawdown across carbonate platforms around the world that span the Pennsylvanian-Permian boundary that temporally coincide with the findings of Vail et al. (1977) and Fielding et al. (2008). The interpretation of sea-level and climate signals is rendered difficult by contemporaneous uplift at this time related to the formation of Pangea (Carlson, 2007; Watney et al., 2008), further complicating the relationship between sea-level and climatic signals.

CONCLUSIONS

1. Cyclothems in the Alliance Basin of western Nebraska record deposition in open marine through nonmarine environments on an arid carbonate ramp. Overall, facies and cycles in western Nebraska represent deposition in a more arid and restricted setting than those in Kansas and the majority of the US Midcontinent. Essentially, western Nebraska represents an offset from the deeper, better understood cyclothems from Kansas, to a shallower and more restricted setting. This is partly due to its position further up the shelf (northwest of Kansas), and also as a result of variable paleotopography, which created localized topographic highs throughout the region.
2. Facies are arranged in shallowing upward cycles. These cycles differ from the classic Kansas-type cyclothem described by Heckel (1986) in the following ways:
    a. Highly fissile, black, phosphatic "core" shales are absent. The equivalent facies here is a laminated carbonate rich in organic matter (Facies A).
    b. Restricted, evaporative marine facies such as bedded anhydrite, microbial laminite, and dolomitized mudstone are extensively developed, especially in the Admire Group.

c. Cycles are expressed as asymmetric, shallowing upward cycles rather than transgressive-regressive cycles.

3. Shallowing upward cycles are regionally correlative, which is significant in that it implies allogenic control on deposition.
4. There is a temporal trend toward increasing aridity across the transition from the Late Pennsylvanian to the Early Permian. This climatic signal has been documented by previous workers and also corresponds to global changes, including the maximum expansion of glacial ice in Gondwana.

ACKNOWLEDGEMENTS

This project was supported by NSF CAREER Grant EAR-0645504 to T. Frank at the University of Nebraska-Lincoln. Support was also received from The Nebraska Geological Society Yatkola-Edwards Grant, with a match from the American Association of Petroleum Geologists. I also owe thanks to Jim Rogers who generously supplied funds for thin sections, and to Greg Wahlman for agreeing to help with biostratigraphic analysis. Thanks also go out to my committee, Dr. Christopher Fielding, Dr. Marvin Carlson, and Dr. R. M. Joeckel. They have helped me immensely with core selection and analysis, and provided me with helpful and useful materials, advice, and knowledge. Thank you to my advisor, Tracy Frank, who has helped guide me toward a final product I can be proud of, and who has pushed me to be the best geologist I can be. I cannot thank you enough for teaching, mentoring, and encouraging me through this project. I appreciate all the kind words and support given to me from so many great friends and my boyfriend, Ryan, throughout this process. And lastly, I owe my greatest thanks to my family. I would have never been able to complete this project without their constant love, support, and words of encouragement on all those days when I could have sworn there would never be enough time.

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FIGURE CAPTIONS

Figure 1. Map of USA, Nebraska in gray. Main Figure shows location of six petroleum drillcores used in this study.

Figure 2. A) Isopach map of total Permian section for the Alliance Basin, showing thickness of total Permian section (after Montgomery et al., 1998). Shows regional structure, including the Transcontinental Arch and depocenters of Alliance Basin and Sterling Basin. Red dots represent core localities. B) Map of Nebraska showing several positive structures in Nebraska (after Carlson, 2007). 1. Agate-White River Fault; 2. Morrill County High; 3. Wattenberg High; 4. Ord Arch; 5. North Platte Arch; 6. Cambridge Arch; 7. Eastern Nebraska High.

Figure 3. Regional stratigraphy, as documented for Kansas. The Pennsylvanian-Permian boundary lies at the base of the Bennett Shale Member of the Red Eagle Limestone, within the Council Grove Group (Ritter, 1995; Sawin et al., 2006; Ramezani et al., 2007). Modified from Olszewski and Patzkowsky (2001).

Figure 4. Photographs of core and plane light photomicrographs of thin sections (2x magnification) from core, representing each of the facies described in Table 1. Scales as marked. (A) Photograph of calcareous shale to shaly limestone of Facies A. Gray to black, laminated; (B) Photomicrograph of skeletal wackestone of Facies B. Fusulinids, crinoids, brachiopods in micrite matrix; (C) Photomicrograph of skeletal packstone of Facies C1. Fusulinids, crinoids, brachiopods in micrite matrix; (D) Photomicrograph of fusulinid packstone of Facies C2. Fusulinids in micrite matrix; (E) Photomicrograph of dolomitized wacke- to packstone of Facies D. Sucrosic dolomite matrix; (F) Photomicrograph of oolitic grainstone of Facies E. Micritized ooids in micrite matrix; (G) Photograph of mudstone of Facies F. Light brown to tan, bioturbated, anhydrite fill in voids; (H) Photograph of calcareous sandstone of Facies G. Gray-green, bioturbated, anhydrite growths; (I) Photograph of microbial laminite of Facies H. Dark microbial material with micrite sediment; (J) Photograph of bedded anhydrite of Facies I. Chickenwire texture; (K) Photograph of red mudrock of Facies J1. Shows bioturbation and possible root structures; (L) Close up photograph of root structures within Facies J1; (M) Photograph of green mudrock of Facies J2. Shows bioturbation; (M) Photograph of Facies J1/J2 occurring together; (O) Photograph of Facies J1/J2 occurring together; (P) Photograph of displacive anhydrite overgrowths in microbial laminite.

Figure 5. Block diagram of proposed depositional setting (after Pratt, 2010).

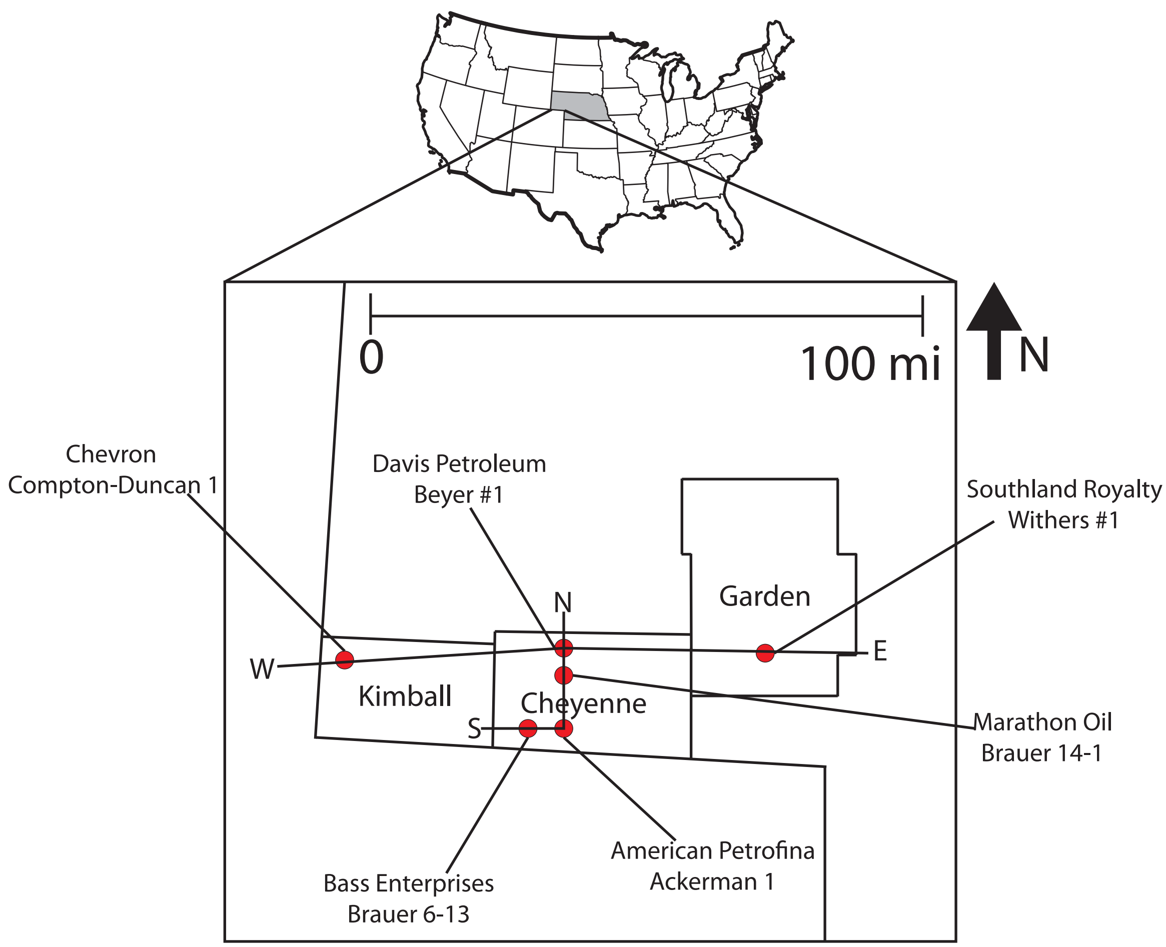
Figure 6. Detailed graphic logs through three intervals of Davis Petroleum Beyer #1 core from Cheyenne County, Nebraska, USA. (A) Shallowing upward cycle characterized by mudstone, skeletal wackestone and paleosol. Shallows up into paleosol (Facies J1/J2), with evidence for vegetation; (B) Composite shallowing upward cycle composed of mudstones, paleosols, and microbial laminite. Overall,

shallows up into microbial laminite (Facies H); (C) Composite shallowing upward cycle composed of paleosols, mudstones, wackestones, microbial laminite, and bedded anhydrite. Overall, shallows up into bedded anhydrite (Facies I).

Figure 7. Kansas-type cyclothem, as described by Heckel (1986). Shows the transgressive-regressive cycle generally recorded in the Midcontinent, and the component, outside shales, middle and upper limestones, and the core shale that make up this type of cyclothem.

Figure 8. W- E cross section. Correlation between the Lansing, Shawnee, Wabunsee, Admire, Council Grove, and Chase Groups as recorded in drillcores and wireline logs of the Chevron Compton-Duncan #1, Davis Petroleum Beyer #1, and Southland Royalty Withers #1 cores.

Figure 9. N-S cross section. Correlation between the Lansing, Shawnee, Wabunsee, and Admire Groups as recorded in drillcores and wireline logs of the Davis Petroleum Beyer #1, Marathon Brauer 14-1, American Petrofina Ackerman #1, and Bass Enterprises 6-13 Brauer cores.


0
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N
Chevron
Compton-Duncan 1
Davis Petroleum
Beyer #1
Southland Royalty
Withers #1
Garden
N
W
E
Kimball
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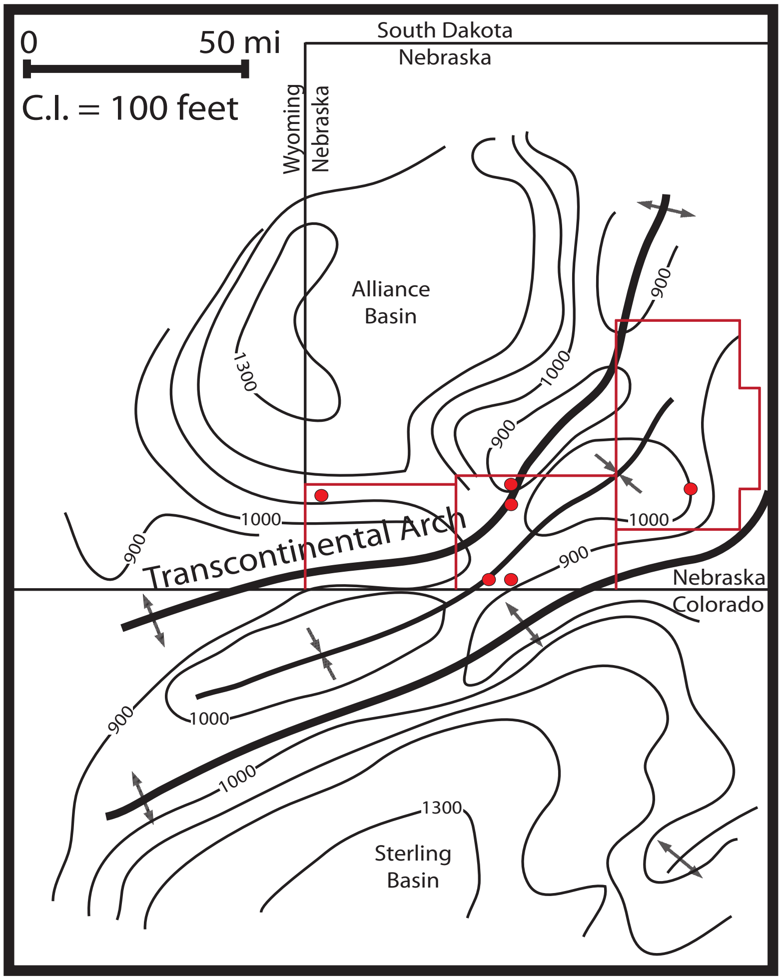
S
Marathon Oil
Brauer 14-1
American Petrofina
Ackerman 1
Bass Enterprises
Brauer 6-13

Figure 1

A


0
50 mi
C.I. = 100 feet
South Dakota
Nebraska
Wyoming
Nebraska
Alliance
Basin
1300
1000
900
1000
900
Transcontinental Arch
900
1000
Nebraska
Colorado
900
1000
1000
1300
Sterling
Basin

B

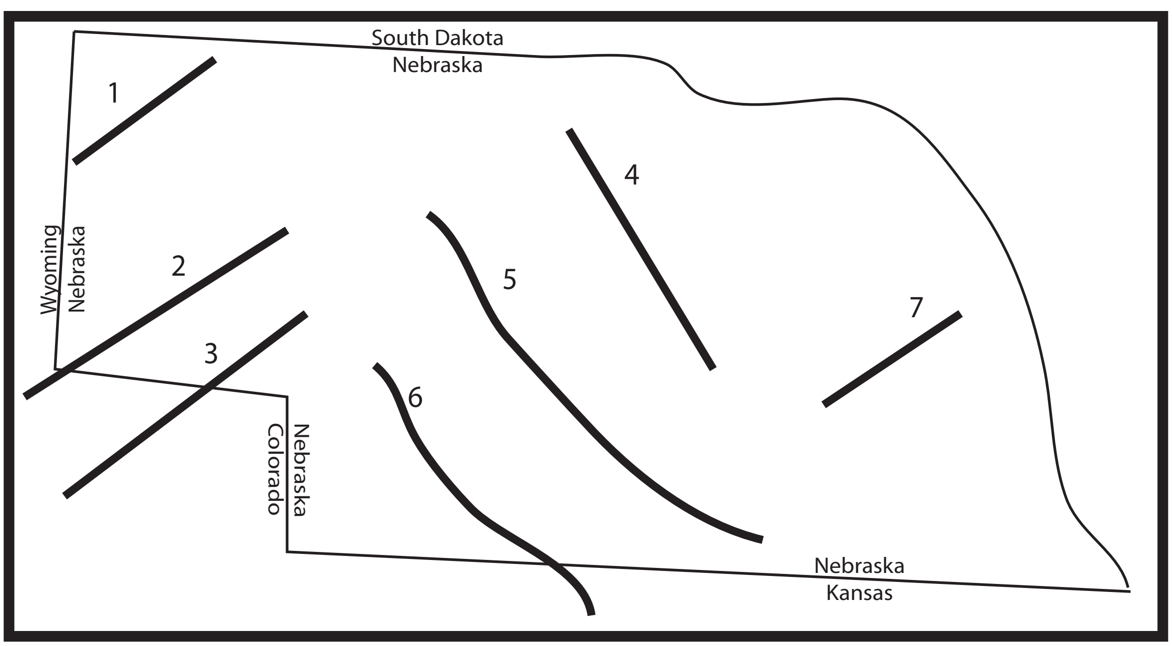

South Dakota
Nebraska
1
Wyoming
Nebraska
2
3
4
5
6
7
Nebraska
Colorado
Nebraska
Kansas

Figure 2

Formation	Group	Series
	Chase	Wolfcampian
Upper Council Grove Gp	Council Grove	
Bader Ls		
Stearns Sh		
Beattie LS		
Eskridge Sh		
Grenola Ls		
Roca Sh		
Red Eagle Ls		Permian 299.0 ± 0.8 Ma
Johnson Sh	Admire	Pennsylvanian
Foraker Ls		Virgilian
Janesville Sh		
Falls City Ls		
Onaga Sh		

Figure 3

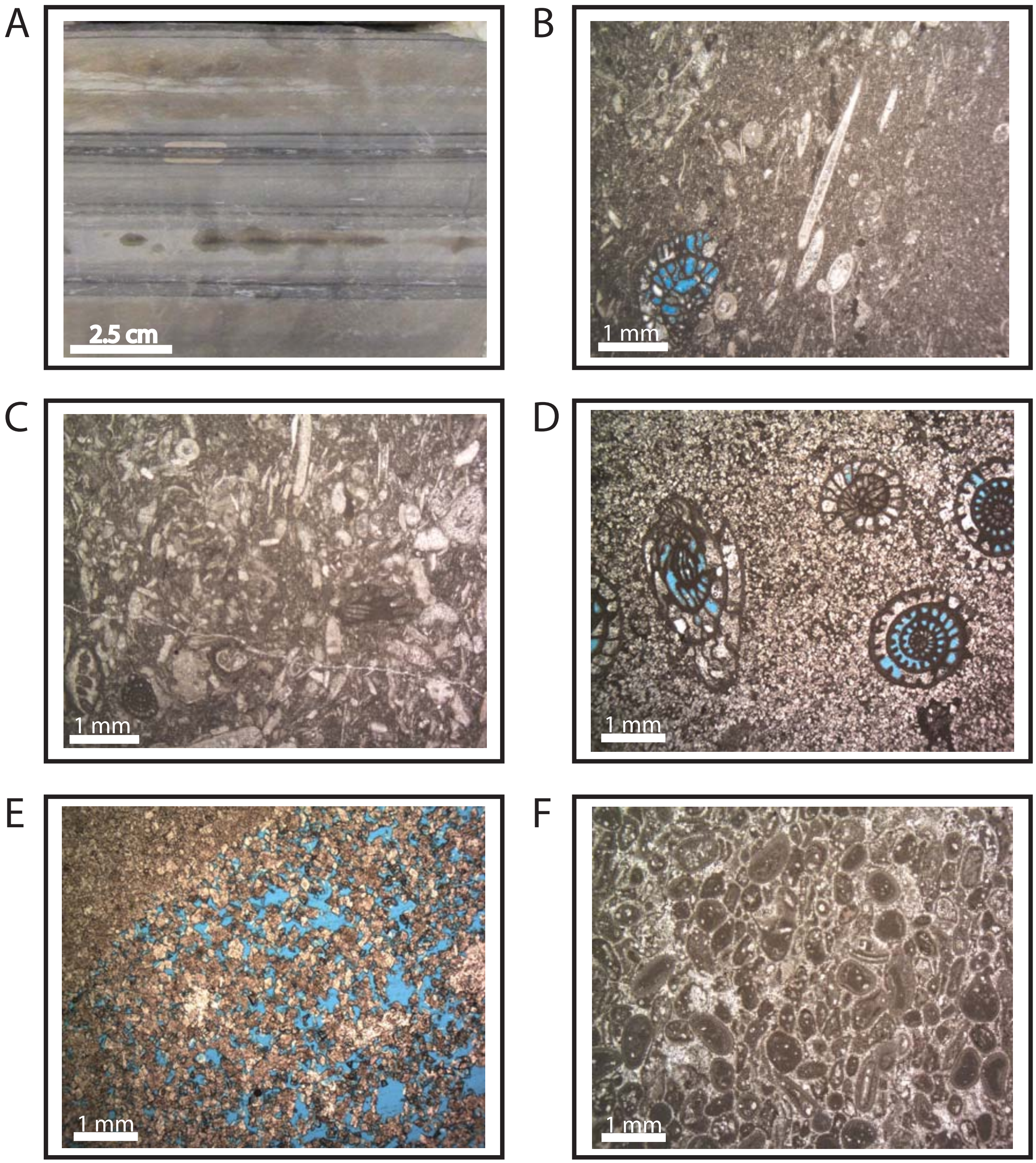


Figure 4

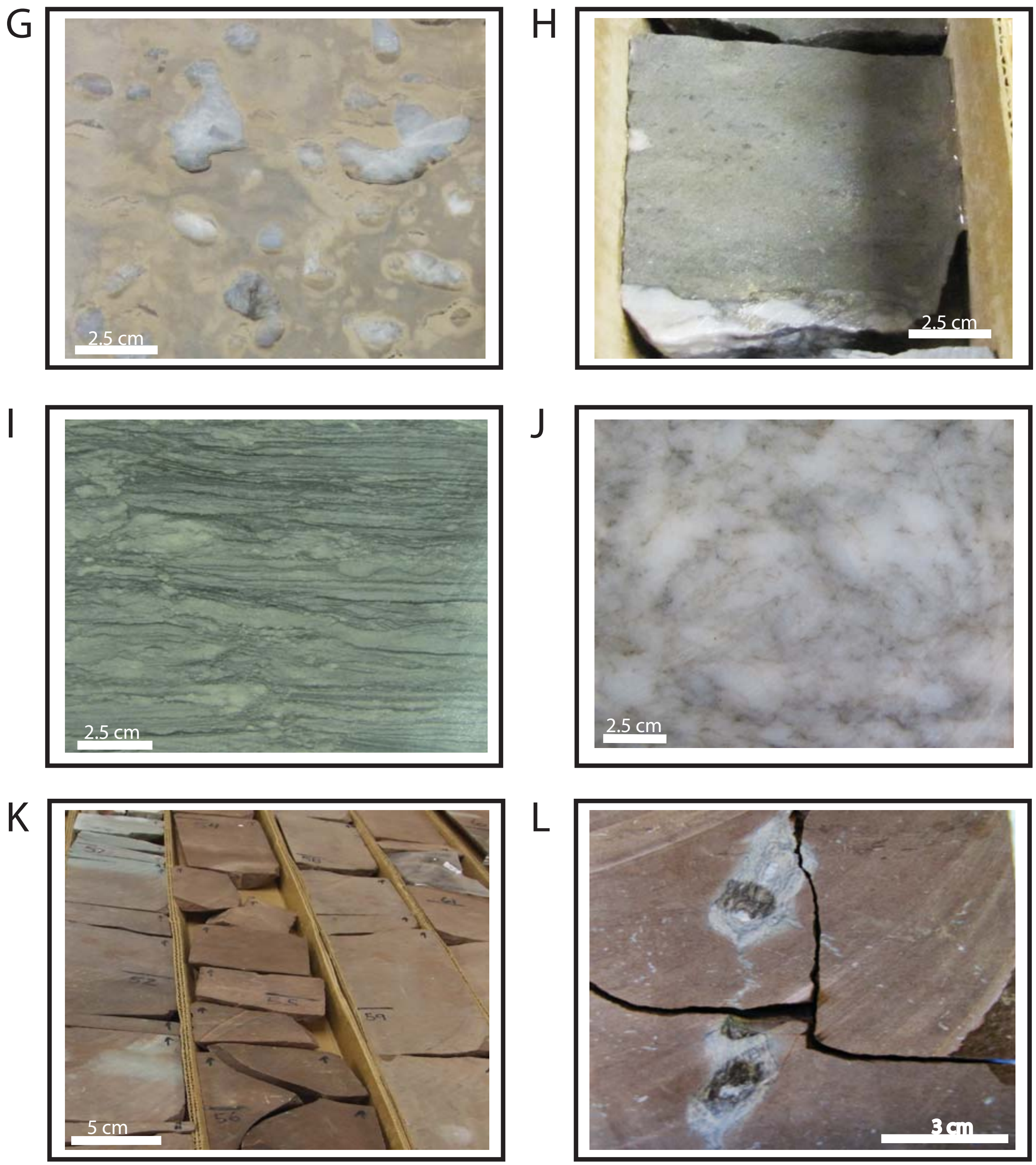


Figure 4 continued

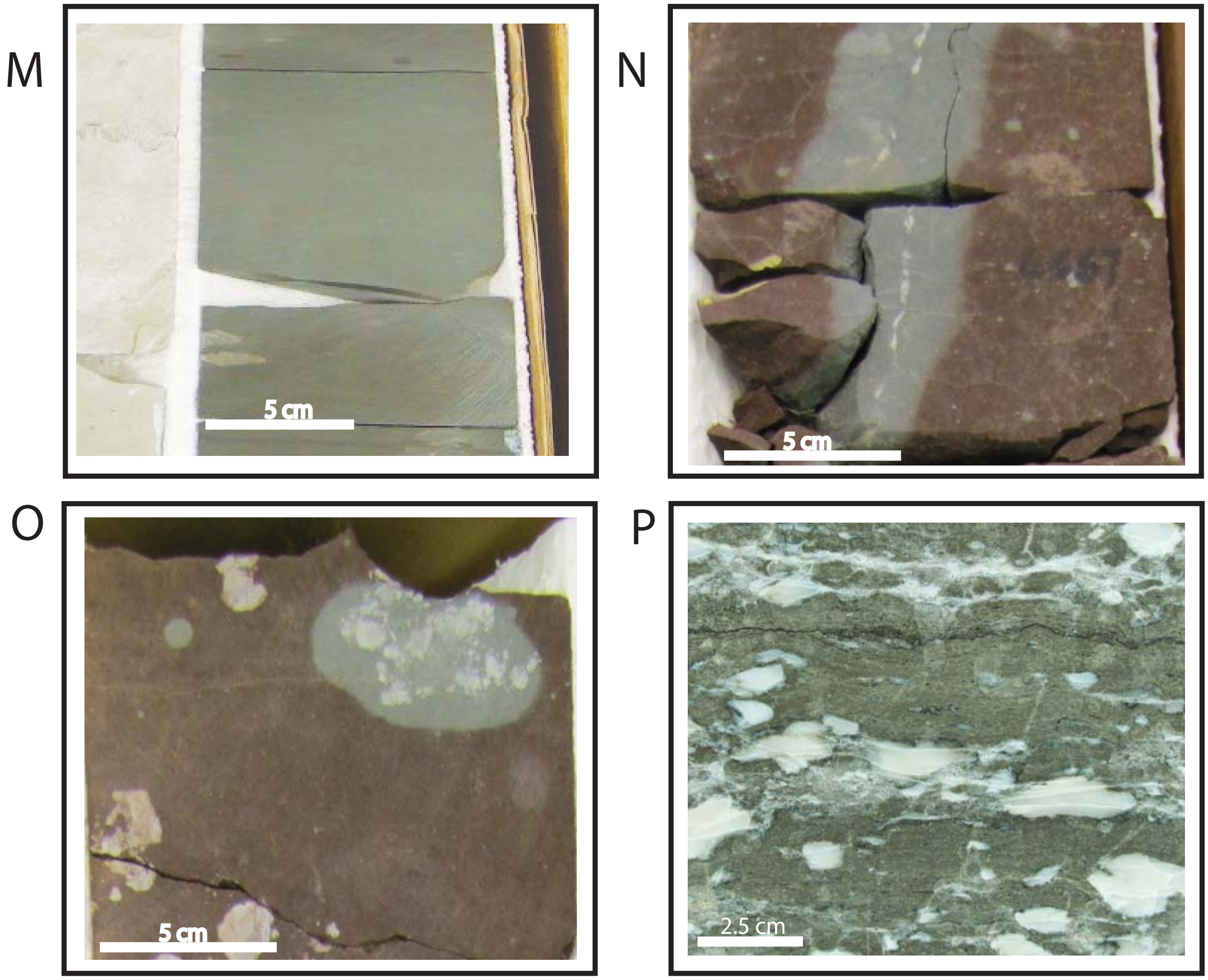
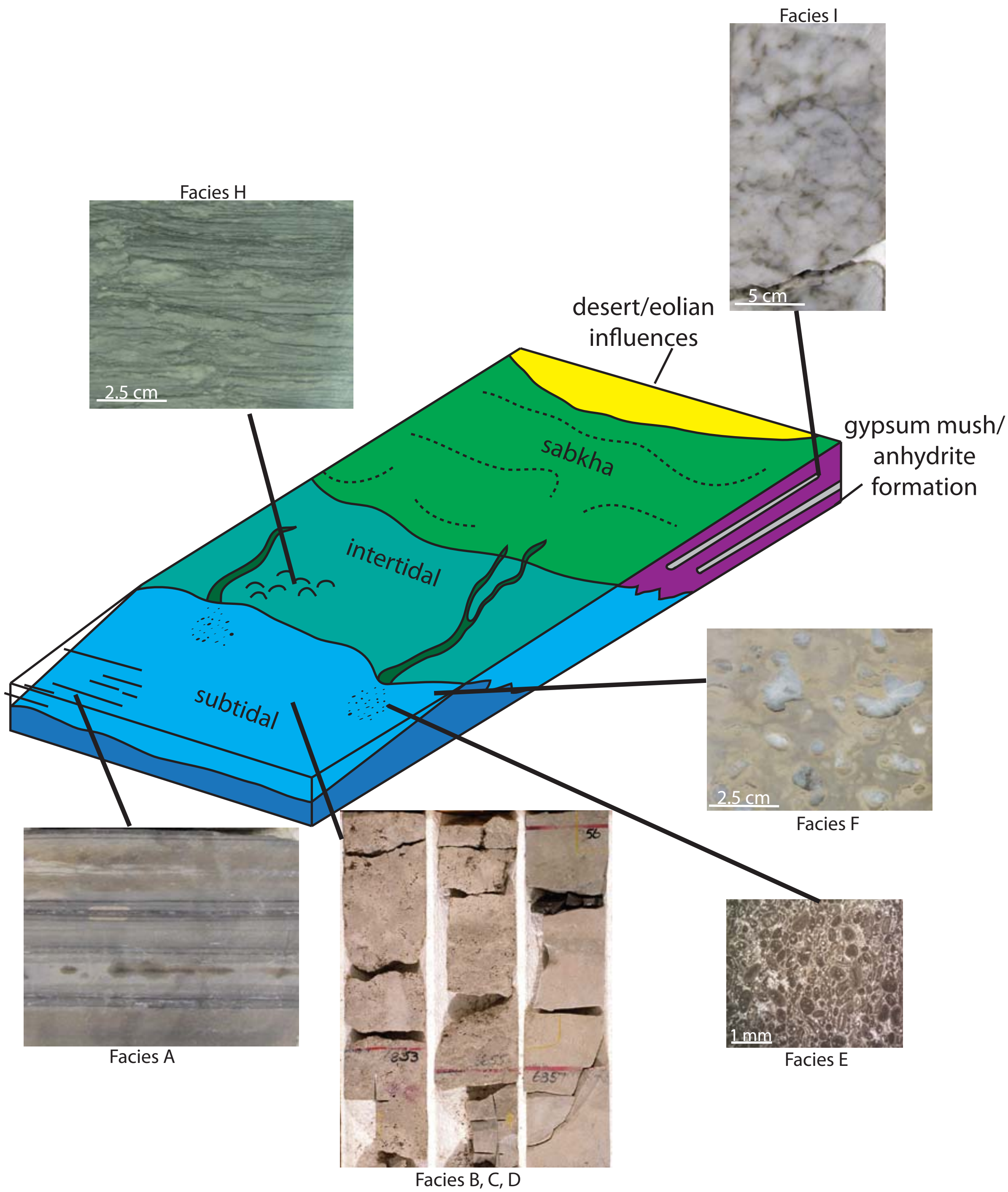
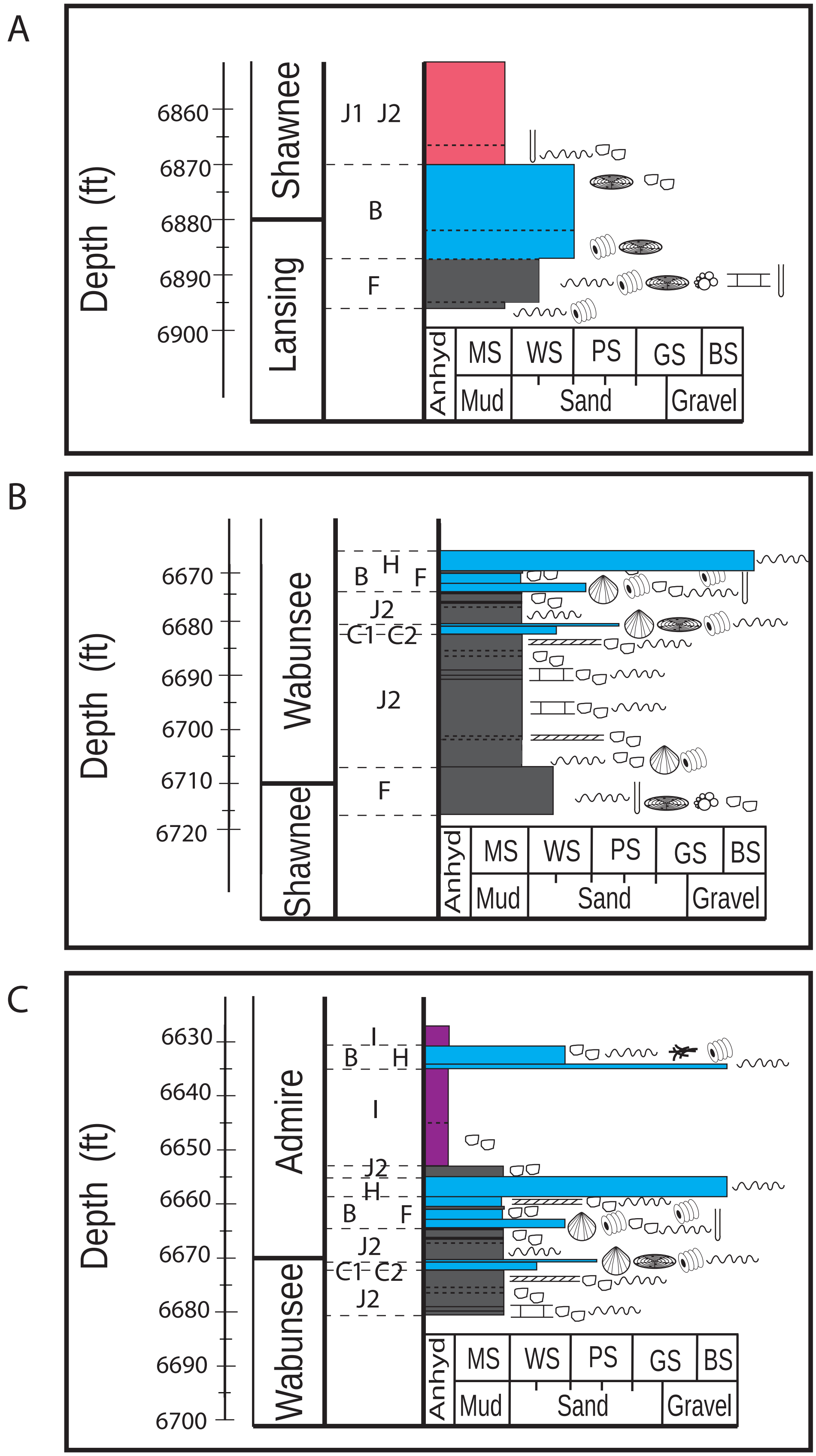


Figure 4 continued



Facies I
5 cm
Facies H
2.5 cm
desert/eolian influences
gypsum mush/ anhydrite formation
sabkha
intertidal
subtidal
2.5 cm
Facies F
1 mm
Facies E
Facies A
Facies B, C, D

Figure 5



A
Depth (ft)
6860
6870
6880
6890
6900
Shawnee
Lansing
J1 J2
B
F
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel
B
Depth (ft)
6670
6680
6690
6700
6710
6720
Wabunsee
Shawnee
H
B F
J2
C1 C2
J2
F
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel
C
Depth (ft)
6630
6640
6650
6660
6670
6680
6690
6700
Admire
Wabunsee
I
B H
I
J2
H
B F
J2
C1 C2
J2
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel

Figure 6

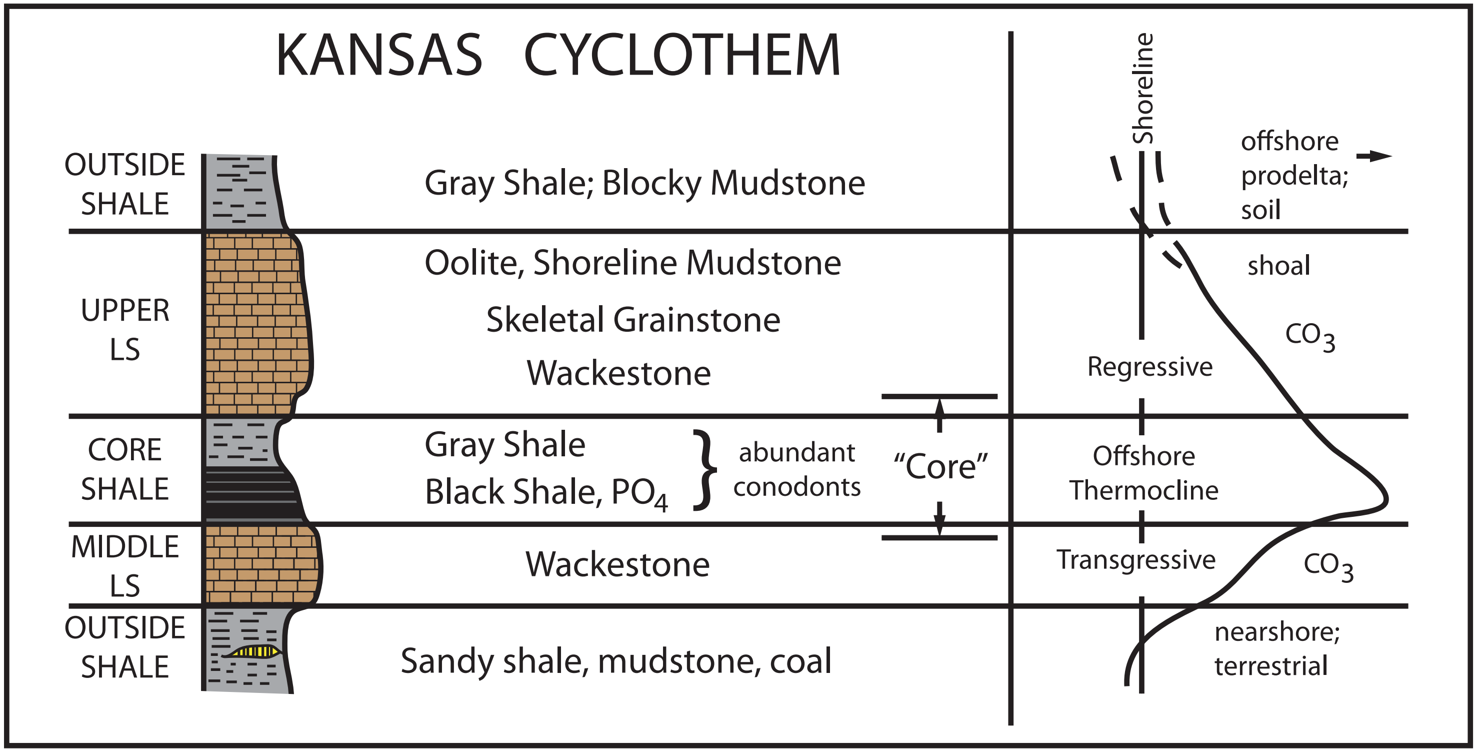

KANSAS CYCLOTHEM
OUTSIDE SHALE
Gray Shale; Blocky Mudstone
UPPER LS
Oolite, Shoreline Mudstone
Skeletal Grainstone
Wackestone
CORE SHALE
Gray Shale
Black Shale, PO_4
abundant conodonts
"Core"
MIDDLE LS
Wackestone
OUTSIDE SHALE
Sandy shale, mudstone, coal
Shoreline
offshore prodelta; soil
shoal
CO_3
Regressive
Offshore Thermocline
Transgressive
CO_3
nearshore; terrestrial

Figure 7

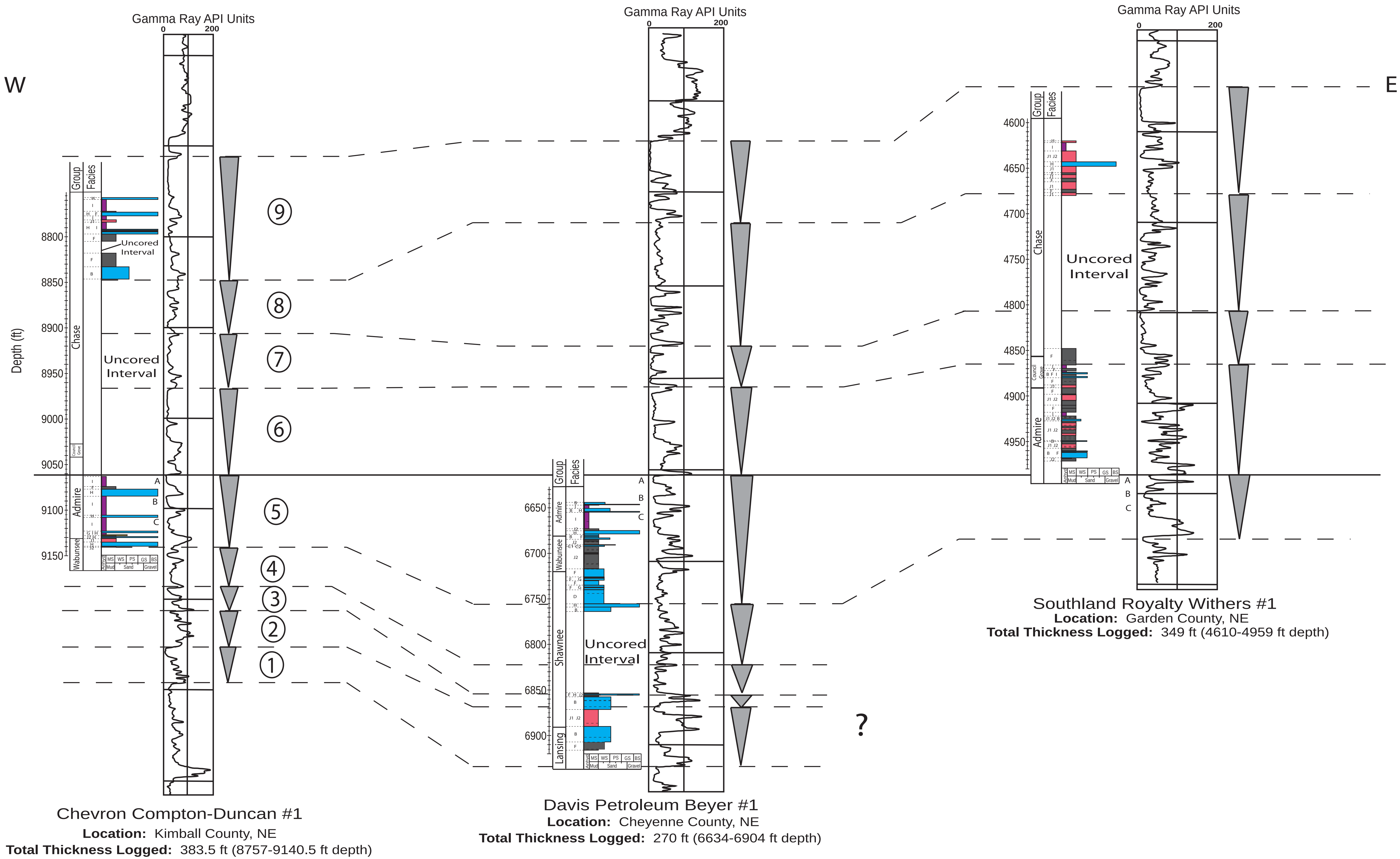

W
E
Gamma Ray API Units
0
200
Depth (ft)
Group
Facies
Chase
Admire
Wabunsee
Uncored Interval
Chase
Admire
Council Grove
Wabunsee
Shawnee
Lansing
MS WS PS GS BS
Mud Sand Gravel
A
B
C
9
8
7
6
5
4
3
2
1
?
Chevron Compton-Duncan #1
Location: Kimball County, NE
Total Thickness Logged: 383.5 ft (8757-9140.5 ft depth)
Davis Petroleum Beyer #1
Location: Cheyenne County, NE
Total Thickness Logged: 270 ft (6634-6904 ft depth)
Southland Royalty Withers #1
Location: Garden County, NE
Total Thickness Logged: 349 ft (4610-4959 ft depth)

Figure 8

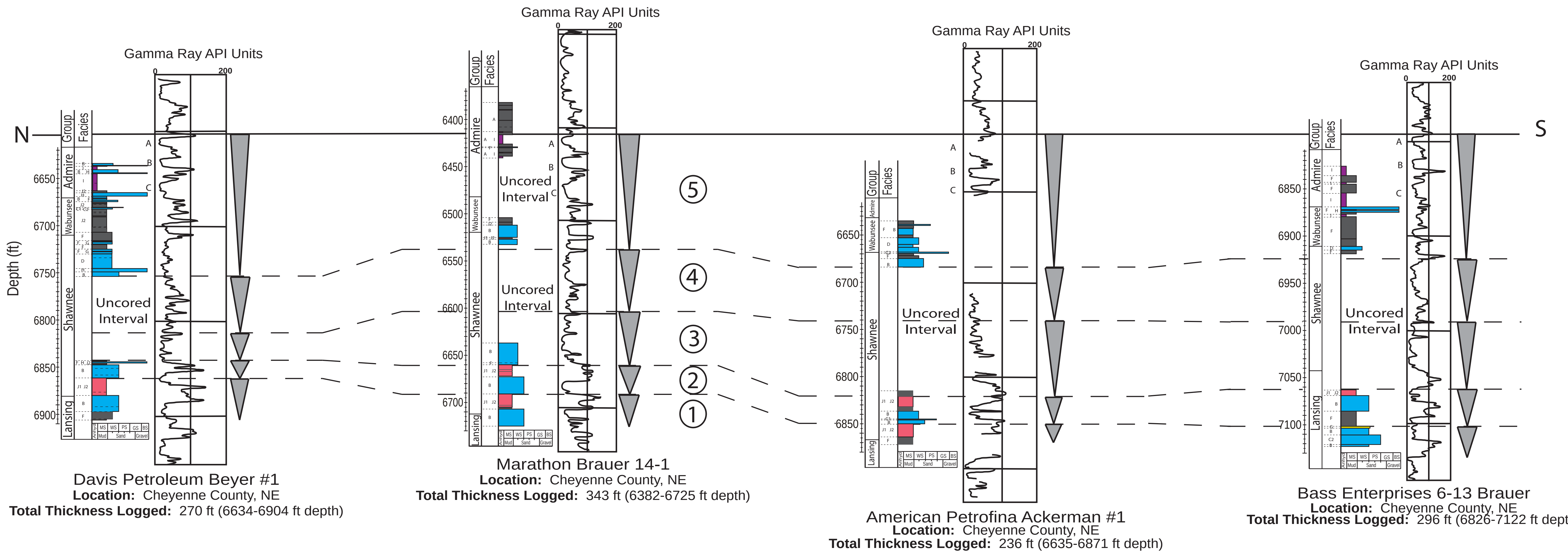

Gamma Ray API Units
N
S
Depth (ft)
Group
Facies
Admire
Wabunsee
Shawnee
Lansing
Uncored Interval
A
B
C
1
2
3
4
5
Davis Petroleum Beyer #1
Location: Cheyenne County, NE
Total Thickness Logged: 270 ft (6634-6904 ft depth)
Marathon Brauer 14-1
Location: Cheyenne County, NE
Total Thickness Logged: 343 ft (6382-6725 ft depth)
American Petrofina Ackerman #1
Location: Cheyenne County, NE
Total Thickness Logged: 236 ft (6635-6871 ft depth)
Bass Enterprises 6-13 Brauer
Location: Cheyenne County, NE
Total Thickness Logged: 296 ft (6826-7122 ft depth)

Figure 9

Table 1. Facies of the Admire, Council Grove, and Chase Groups in western Nebraska, USA. Organized open marine-nonmarine.

FACIES		OBSERVED ATTRIBUTES
A	*calcareous shale to shaley limestone*	gray to black, often laminated
B	*skeletal wackestone*	tan to gray, shows varying degrees of micritization of grains, contains stylolites, small (<2.5 cm) anhydrite nodules or iron concretions, occasionally laminated, shaley partings, foraminifera, fusulinids, crinoids, brachiopods, biofragments, shows moldic, intergranular, intragranular, and fracture porosity
C	**C1.** *skeletal packstone*	tan to gray, shows varying degrees of micritization of grains, contains stylolites, small (<2.5 cm) anhydrite nodules or iron concretions, foraminifera, fusulinids, crinoids, brachiopods, biofragments, shows moldic, intergranular, intragranular, and fracture porosity
	C2. *fusulinid packstone*	tan to gray, shows varying degrees of micritization of grains, may contain stylolites and anhydrite nodules (usually ~2.5 cm), only fusulinids,shows moldic, intergranular, intragranular, and fracture porosity
D	*dolomitized wacke- to packstone*	tan to gray, sucrosic texture, dolomite matrix and skeletal material variably micritized, may contain stylolites, small (<2.5 cm) anhydrite nodules or iron concretions,foraminifera, fusulinids, crinoids, brachiopods, biofragments, shows moldic, intergranular, intragranular, and fracture porosity
E	*oolitic grainstone*	micritized ooids, occasionally with intergranular blocky cement, shows intergranular, intragranular, and fracture porosity
F	*mudstone*	light brown to light tan, mottled, dolomitized, contains anhydrite nodules (~2.5 cm), locally bioturbated, scattered foraminifera and fusulinids, intercrystalline and fracture porosity
G	*calcareous sandstone*	light gray, fine to medium grained, well sorted, quartz sand, carbonate cemented, can be laminated or bioturbated, poorly fossiliferous, intergranular
H	*microbial laminite*	black/dark gray to light brown, shows crinkly laminations or crenulations, may contain anhydrite nodules, microbial mats, anhydrite nodules can be displacive
I	*bedded anhydrite*	gray to white, nodular to chickenwire texture, sometimes with dolomicrite matrix, may contain geopetal structures when anhydrite is clearly displacive, when displacive, anhydrite usually developed in microbial laminite (facies H)
J	**J1.** *red mudrock*	red, laminated or fissile, fractured, may contain small to medium size (~5-15 cm) irregular carbonate nodules and/or anhydrite nodules, noncalcareous, oxidized equivalent of facies J2
	J2. *green mudrock*	dark green, mottled, massive, can be locally heavily bioturbated, often contains pink to white colored, small to medium size (~5-15 cm) irregular carbonate and/or anhydrite nodules, reduced equivalent of facies J1

APPENDIX A: GRAPHIC LOGS

Legend

Lithofacies

- Paleosol
- Anhydrite
- Sandstone
- Siltstone/Mudstone
- Carbonate

Fossils

- Gastropod shell
- Bryozoan
- Crinoid
- Phylloid algae
- Fusulinids
- Brachiopods
- Foraminifera

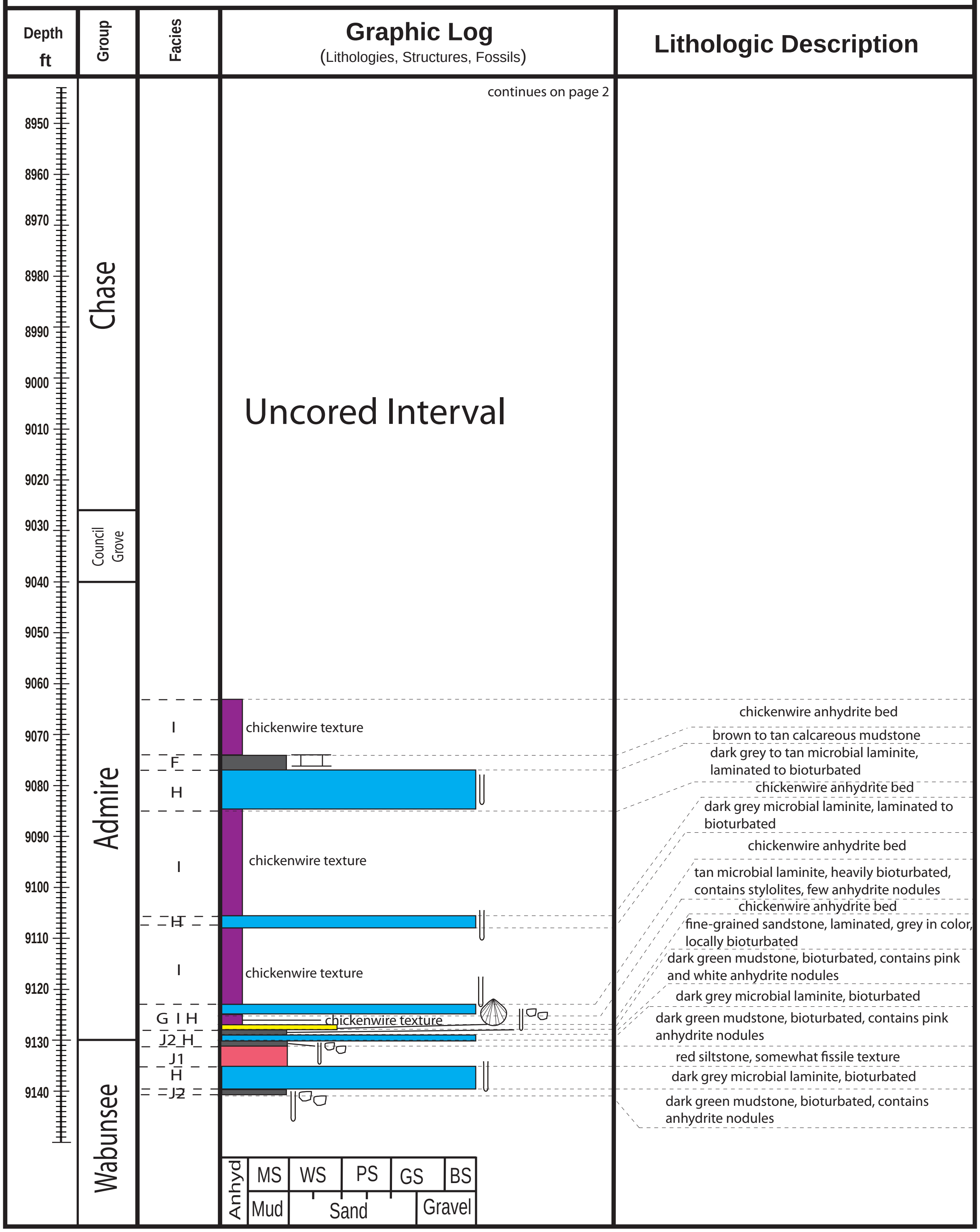
Sedimentary Structures and Other Features

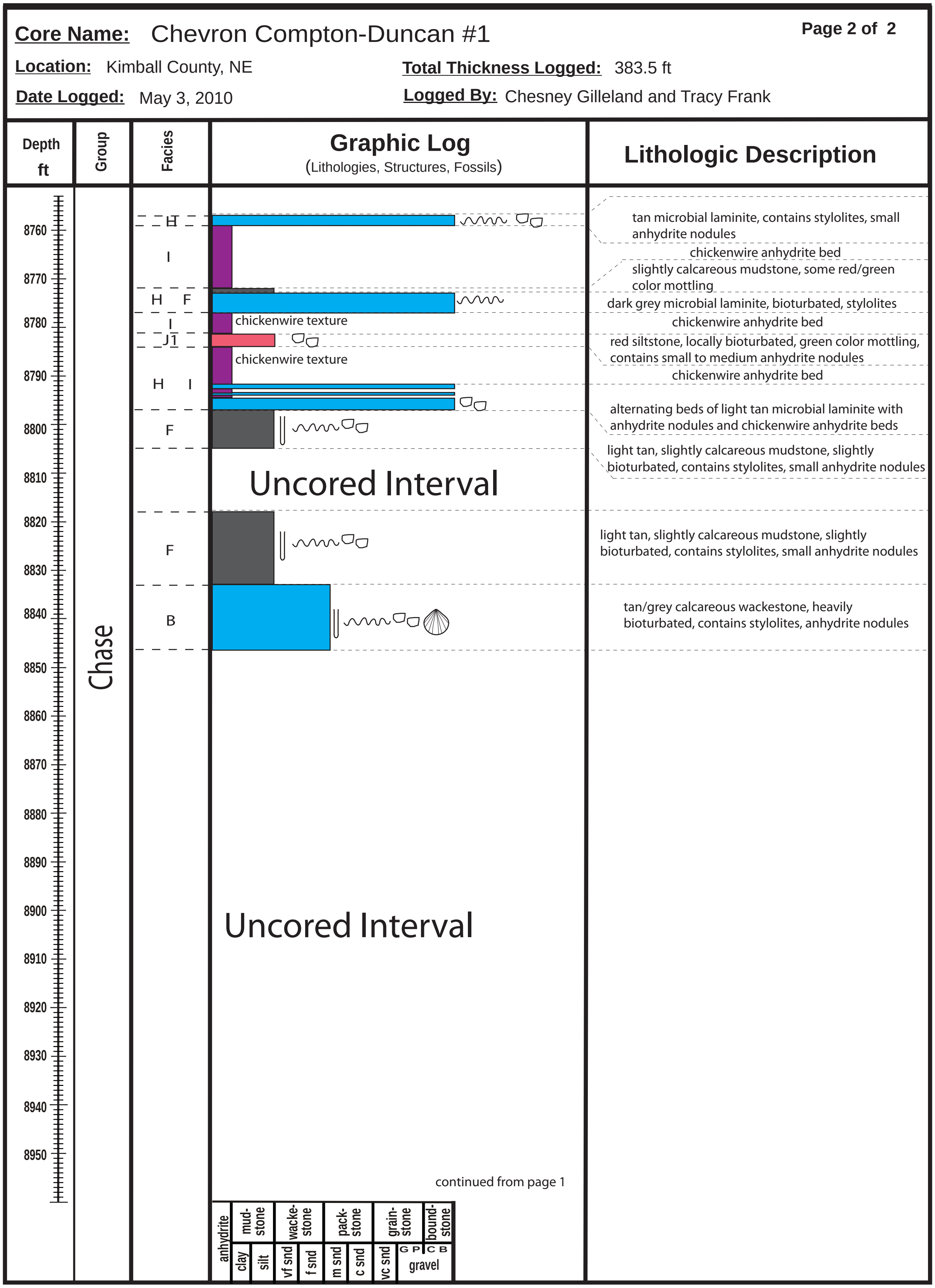
- Horizontal, planar lamination
- Dolomitized
- Evaporite nodules
- Stylolites/stylolitic contacts
- Calcareous
- Ooids
- Bioturbation
- Pyrite

Core Name: Chevron Compton-Duncan #1 — **Page 1 of 2**

Location: Kimball County, NE — **Total Thickness Logged:** 383.5 ft

Date Logged: May 3, 2010 — **Logged By:** Chesney Gilleland and Tracy Frank




Core Name: Chevron Compton-Duncan #1
Page 2 of 2
Location: Kimball County, NE
Total Thickness Logged: 383.5 ft
Date Logged: May 3, 2010
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Group
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
8760
8770
8780
8790
8800
8810
8820
8830
8840
8850
8860
8870
8880
8890
8900
8910
8920
8930
8940
8950
Chase
H
I
H F
I
J1
H I
F
F
B
chickenwire texture
chickenwire texture
Uncored Interval
Uncored Interval
continued from page 1
tan microbial laminite, contains stylolites, small anhydrite nodules
chickenwire anhydrite bed
slightly calcareous mudstone, some red/green color mottling
dark grey microbial laminite, bioturbated, stylolites
chickenwire anhydrite bed
red siltstone, locally bioturbated, green color mottling, contains small to medium anhydrite nodules
chickenwire anhydrite bed
alternating beds of light tan microbial laminite with anhydrite nodules and chickenwire anhydrite beds
light tan, slightly calcareous mudstone, slightly bioturbated, contains stylolites, small anhydrite nodules
light tan, slightly calcareous mudstone, slightly bioturbated, contains stylolites, small anhydrite nodules
tan/grey calcareous wackestone, heavily bioturbated, contains stylolites, anhydrite nodules
anhydrite
mud-stone
wacke-stone
pack-stone
grain-stone
bound-stone
clay
silt
vf snd
f snd
m snd
c snd
vc snd
G P C B
gravel

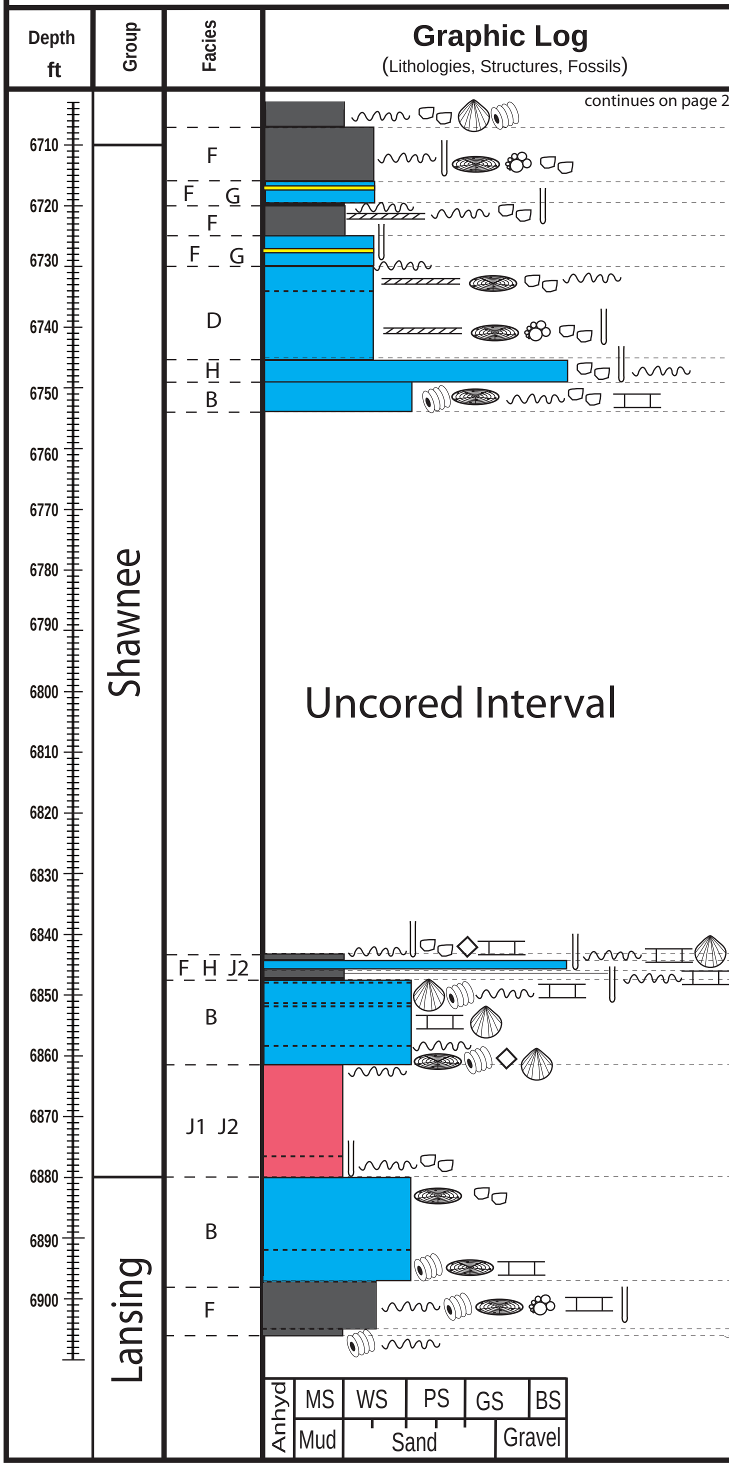
Core Name: Davis Petroleum Beyer #1

Location: Cheyenne County, NE

Total Thickness Logged: 270 ft

Date Logged: September 7, 2010

Logged By: Chesney Gilleland and Tracy Frank



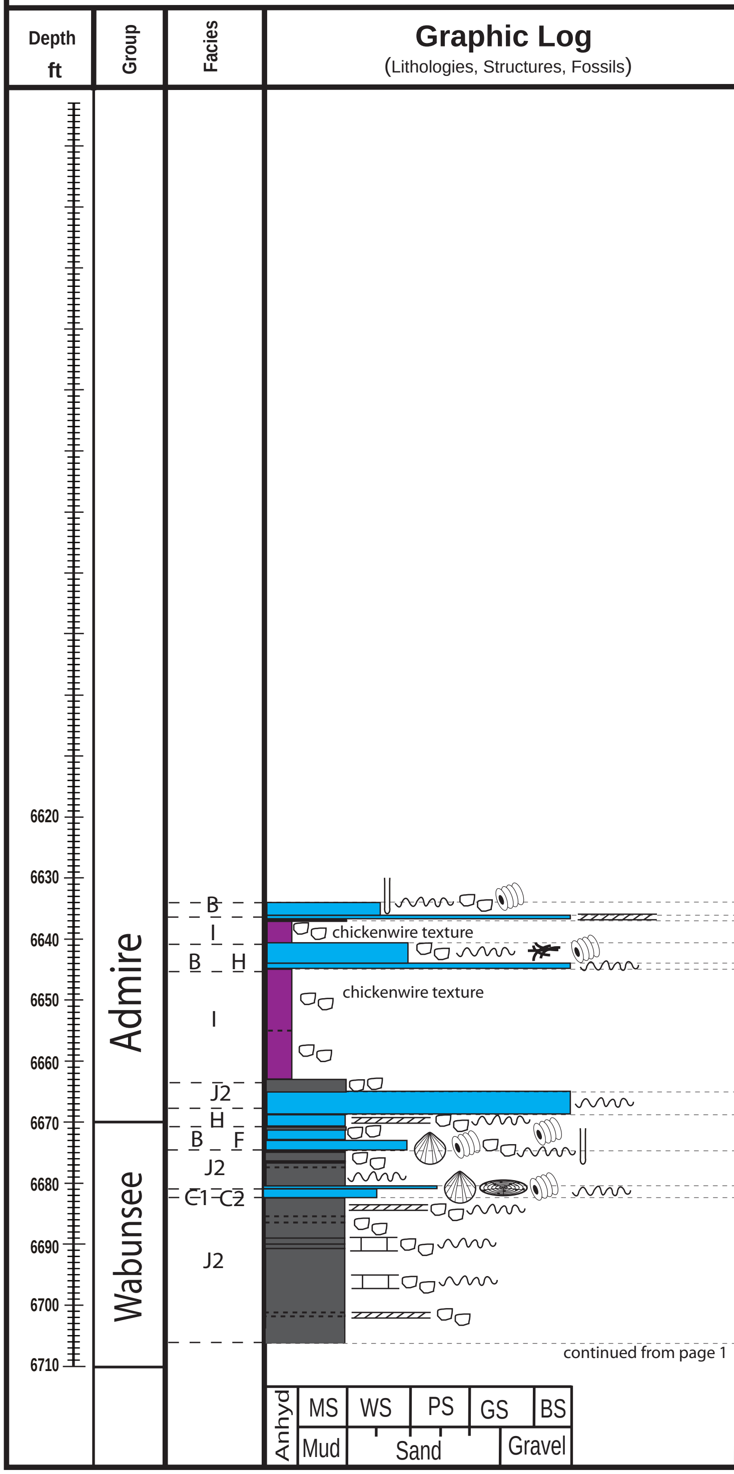
Lithologic Description

- dark grey calcareous mudstone, bioturbated, contains stylolites, anhydrite nodules
- grey mudstone with layers of vf sand, contains anhydrite, bioturbated and mottled
- light grey dolomitized mudstone, bioturbated, contains stylolites, anhydrite nodules
- grey mudstone with layers of vf sand, contains anhydrite, bioturbated and mottled
- light tan mud- to wackestone, contains stylolites, and anhydrite nodules
- alternating bands of microbial laminite (dominant) and skeletal wackestone, contains stylolites and anhydrite nodules
- medium grey skeletal wackestone, locally dolomitized, contains stylolites, small anhydrite
- green mudstone, calcareous, mottled, bioturbated, contains stylolites, anhydrite nodules
- dark grey microbial laminite, calcareous, bioturbated, contains stylolites
- grey mudstone on top of 2 inches of dark grey shale, both are calcareous, the mudstone is bioturbated, and contains stylolites
- light to medium grey skeletal wackestone, contains stylolites, small anhydrite nodules and iron concretions
- red siltstone, green color mottling, bioturbated, contains stylolites and anhydrite nodules, locally calcareous
- light to medium grey skeletal wackestone, contains stylolites, small anhydrite nodules and iron concretions
- dark grey mud- to wackestone, calcareous, slightly bioturbated
- grey mudstone, contains stylolites

Core Name: Davis Petroleum Beyer #1 — **Page 2 of 2**

Location: Cheyenne County, NE — **Total Thickness Logged:** 270 ft

Date Logged: September 7, 2010 — **Logged By:** Chesney Gilleland and Tracy Frank



Lithologic Description

dolomitized mud- to wackestone, contains stylolites, anhydrite nodules, bioturbated, mottled

dark grey microbial laminite, dolomitized, locally calcareous

chickenwire anhydrite bed, covered by fissile black shale

grey wackestone, contains stylolites, anhydrite nodules

dark brown microbial laminite, stylolites

dark green mudstone almost completely overgrown by anhydrite nodules, grading up into chickenwire anhydrite bed

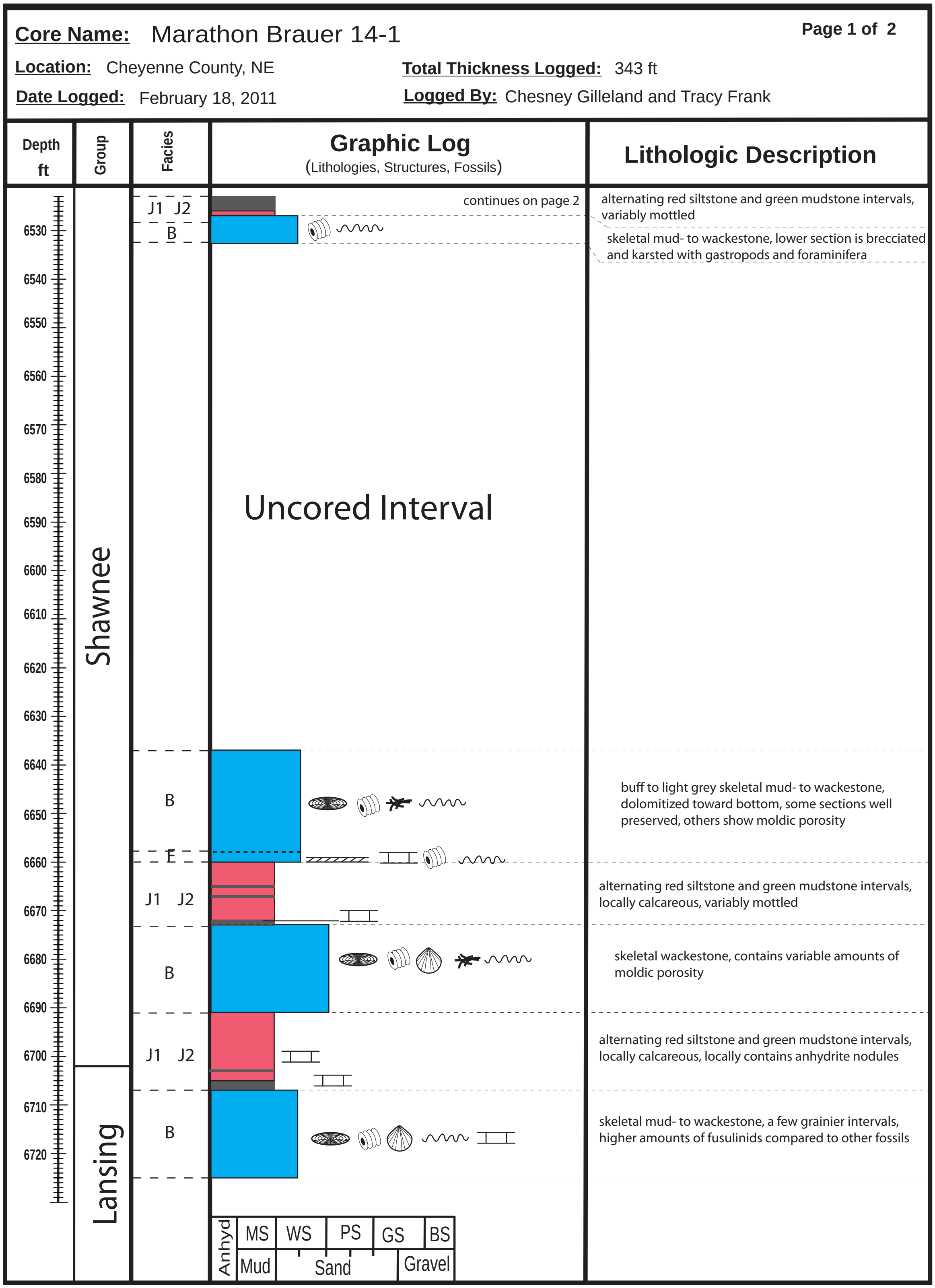
dark grey microbial laminite, calcareous, bioturbated, contains stylolites

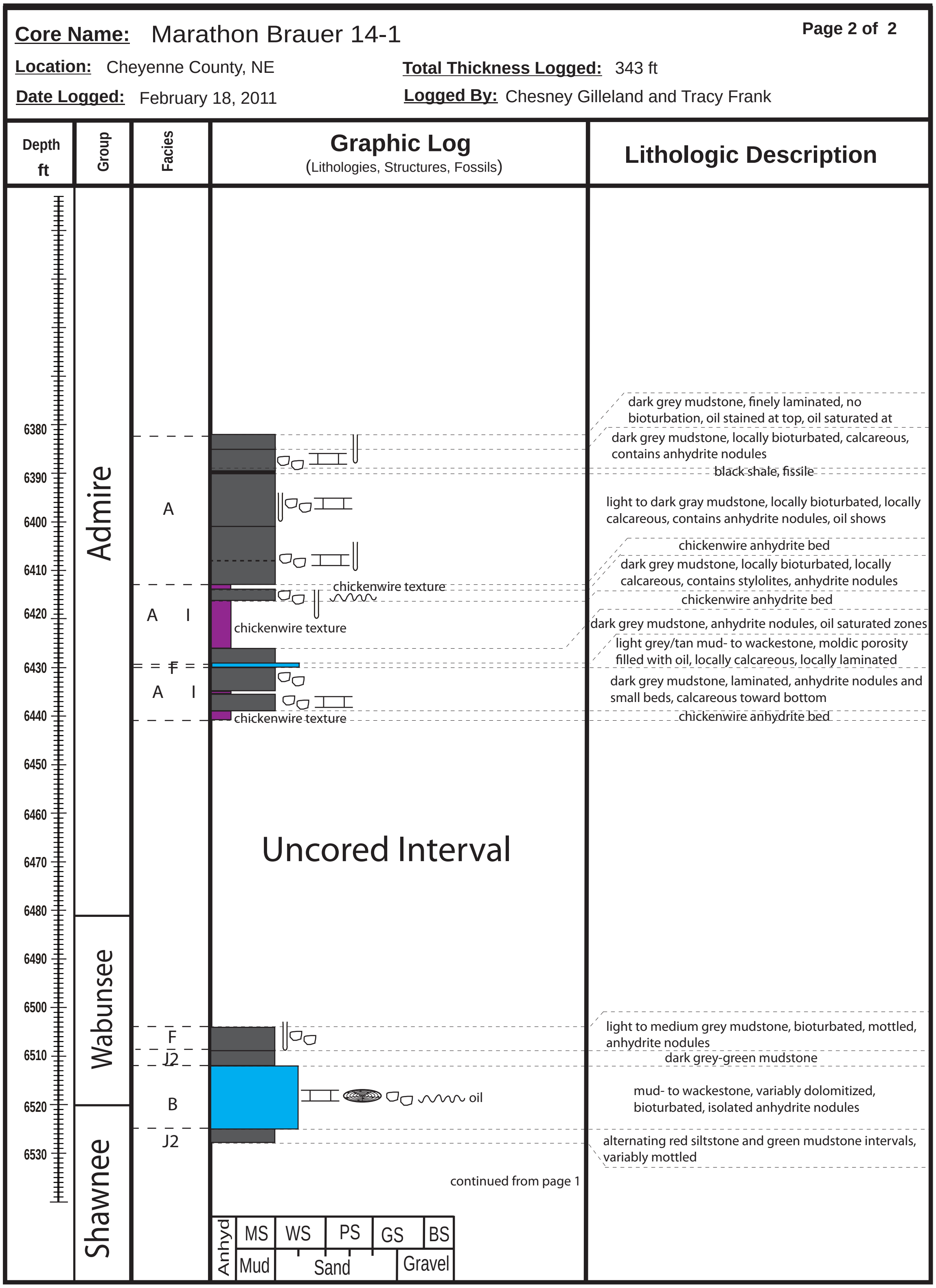
dolomitized mud- to wackestone, still calcareous at bottom, zone of condensed stylolites in middle, small anhydrite nodules

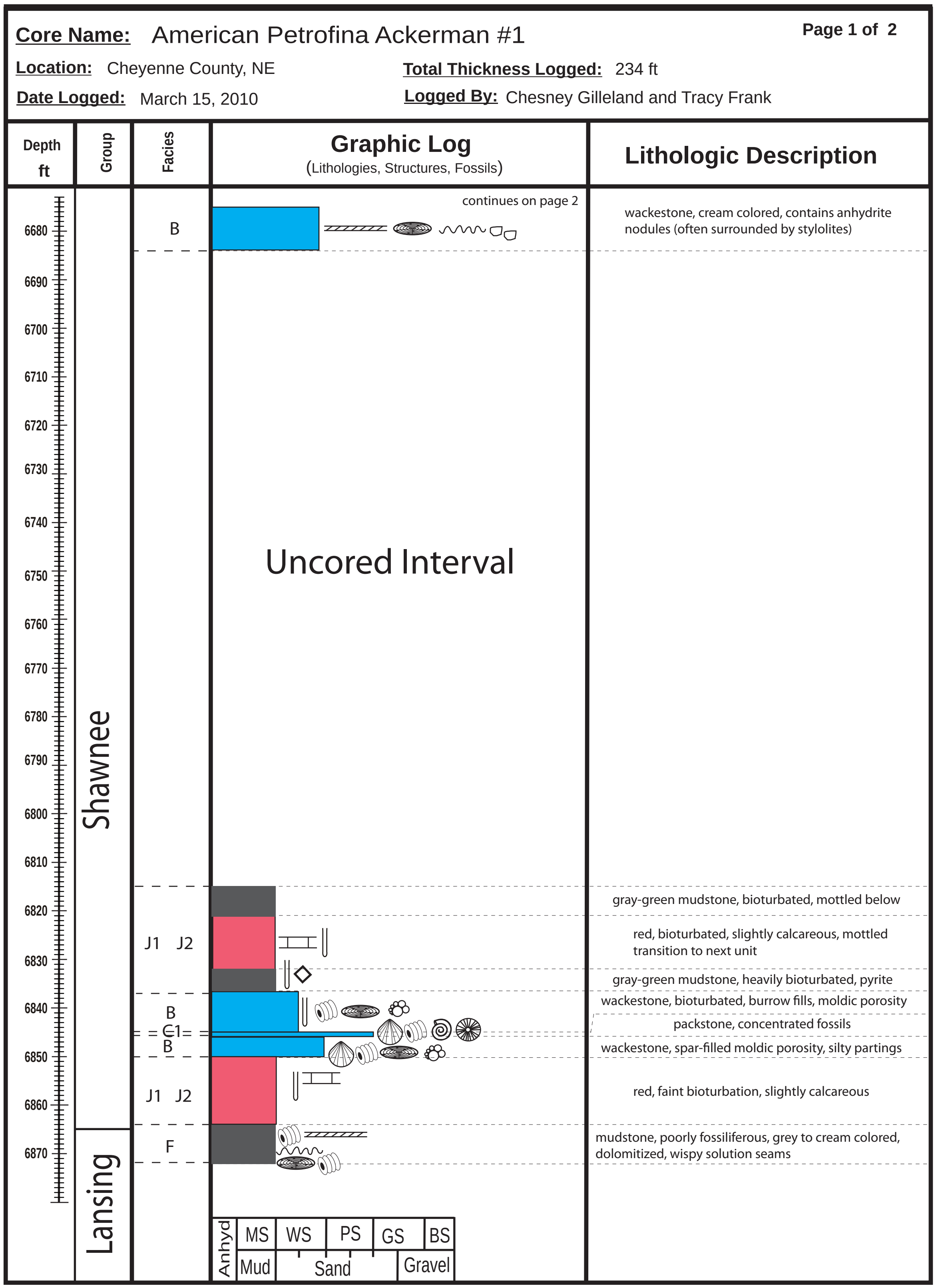
dark green mudstone, locally calcareous, bioturbated, contains stylolites, anhydrite nodules, fissile black shale unit within

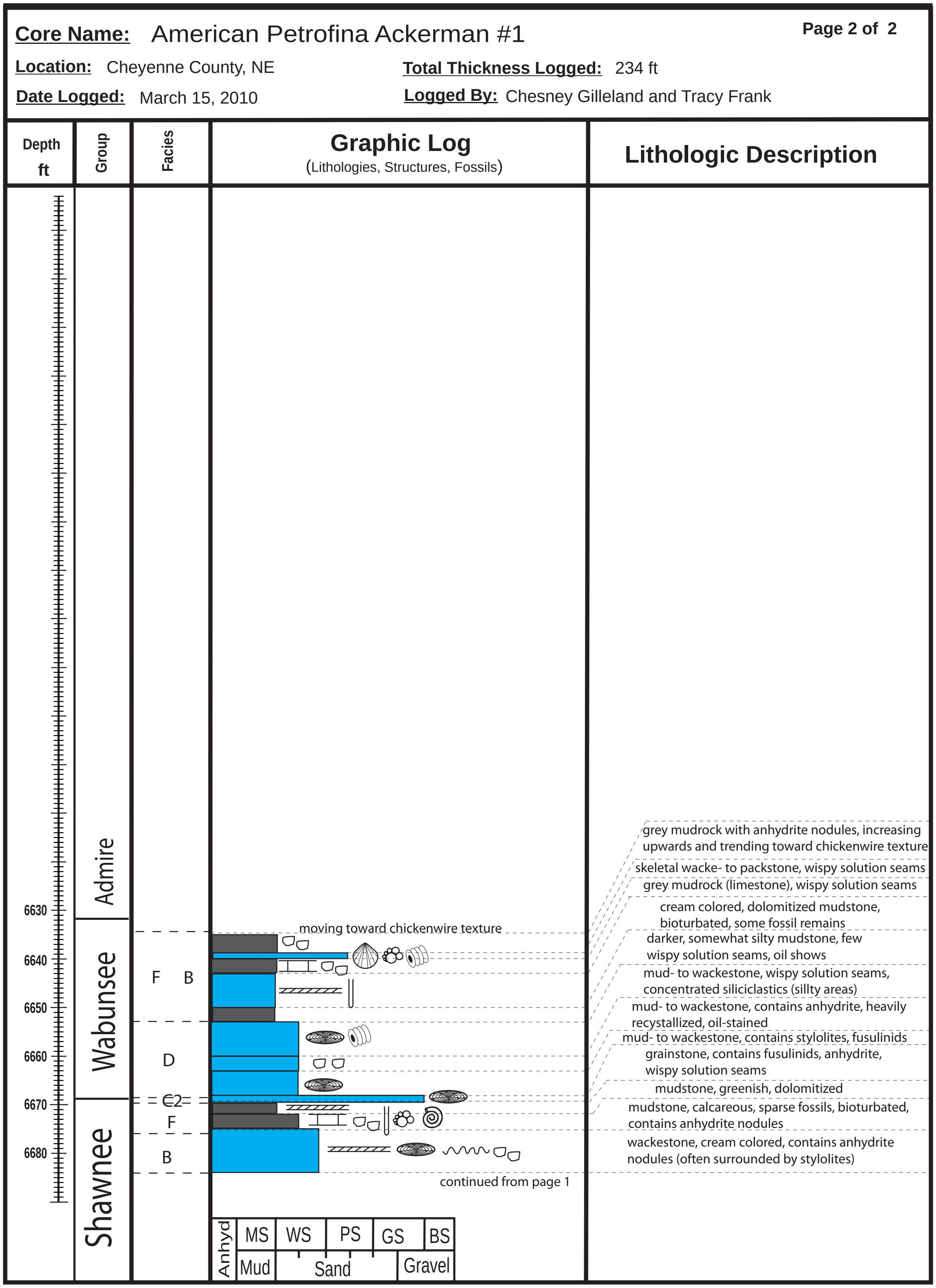
wacke- to packstone, bioturbated, mottled, contains stylolites

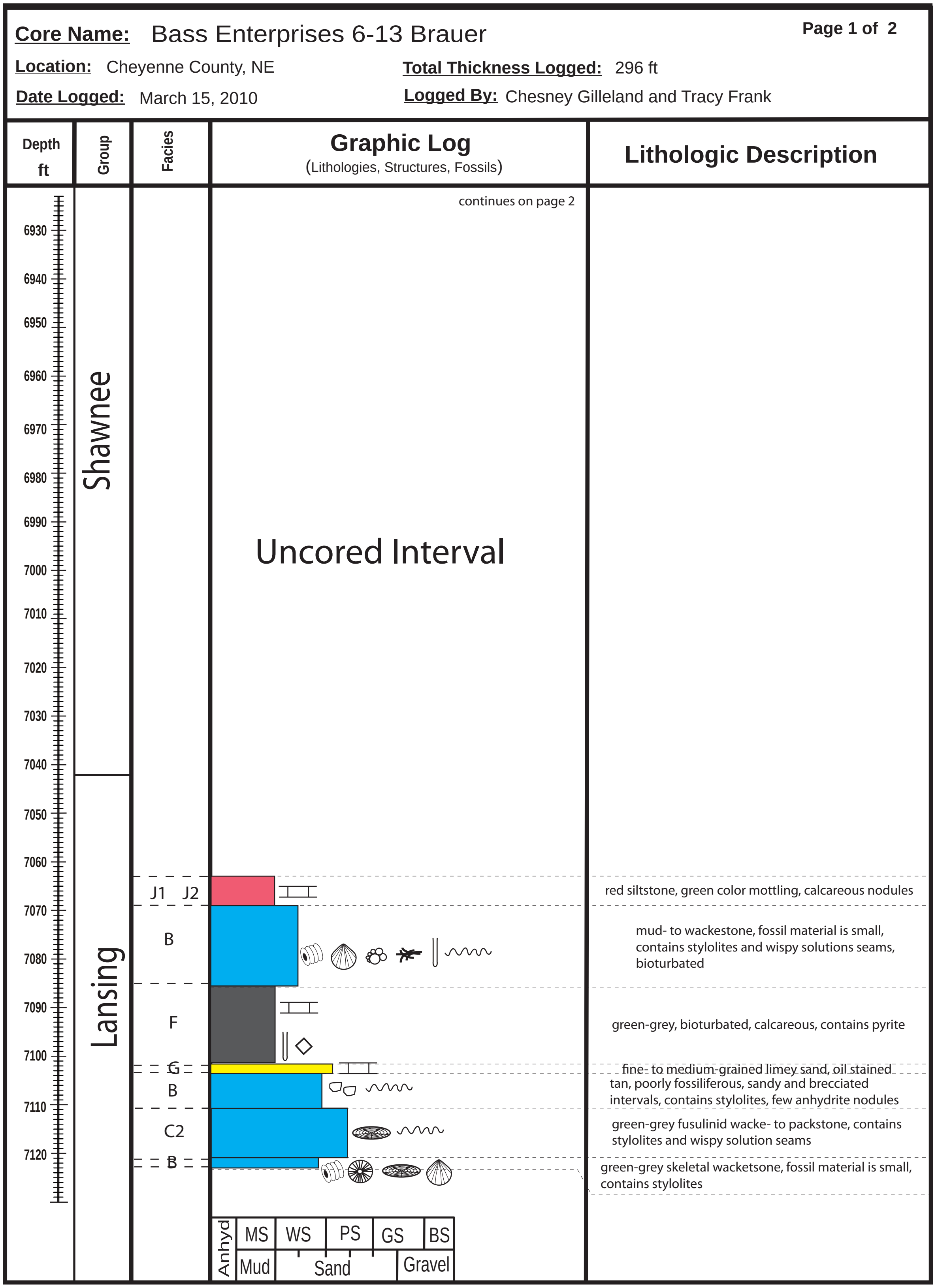
green-grey mudstone, varying amounts of dolomitization, contains stylolites, anhydrite nodules, laminations present in some areas

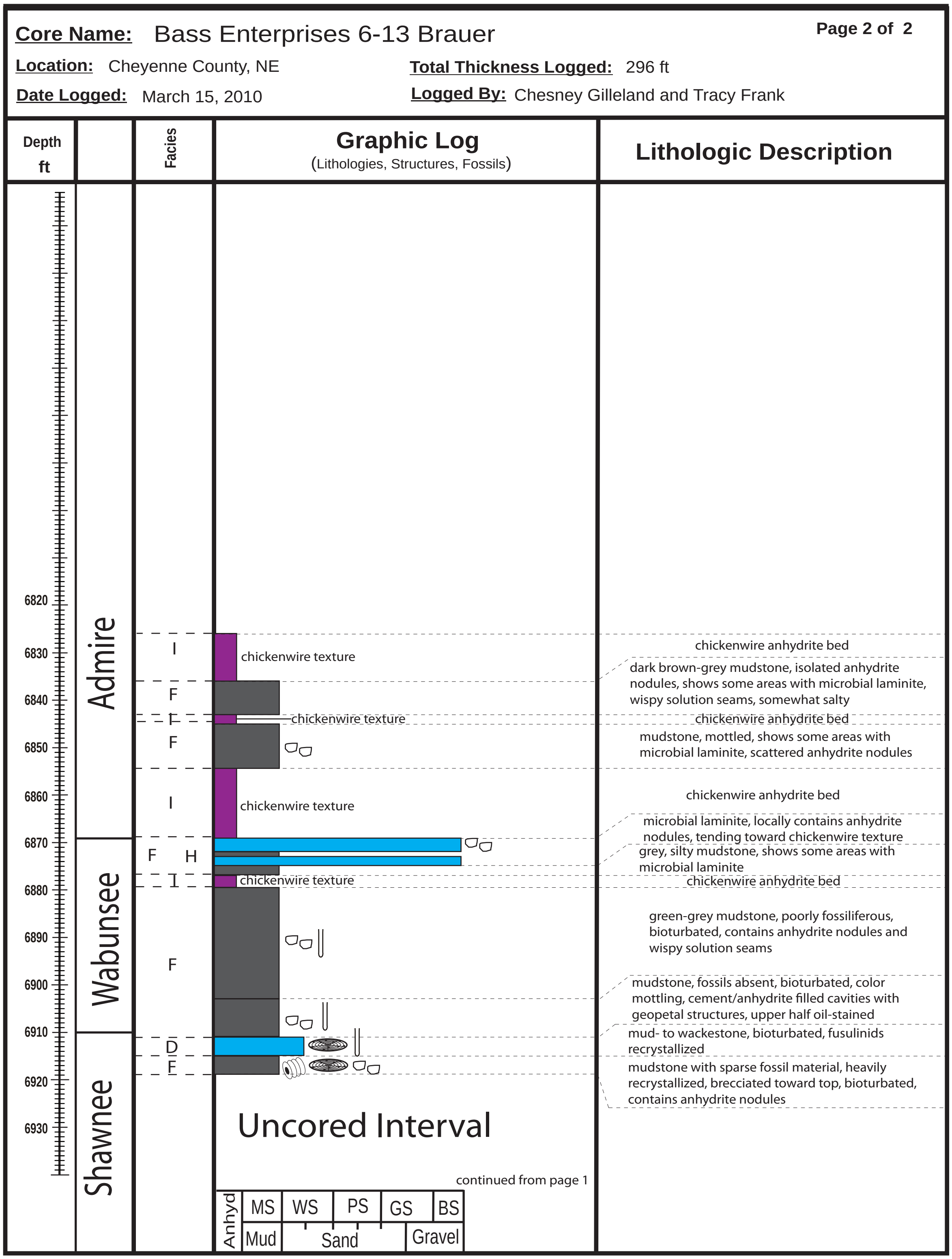

Core Name: Marathon Brauer 14-1
Page 1 of 2
Location: Cheyenne County, NE
Total Thickness Logged: 343 ft
Date Logged: February 18, 2011
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Group
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
continues on page 2
J1 J2
B
alternating red siltstone and green mudstone intervals, variably mottled
skeletal mud- to wackestone, lower section is brecciated and karsted with gastropods and foraminifera
6530
6540
6550
6560
6570
6580
6590
6600
6610
6620
6630
6640
6650
6660
6670
6680
6690
6700
6710
6720
Shawnee
Lansing
Uncored Interval
B
buff to light grey skeletal mud- to wackestone, dolomitized toward bottom, some sections well preserved, others show moldic porosity
E
J1 J2
alternating red siltstone and green mudstone intervals, locally calcareous, variably mottled
B
skeletal wackestone, contains variable amounts of moldic porosity
J1 J2
alternating red siltstone and green mudstone intervals, locally calcareous, locally contains anhydrite nodules
B
skeletal mud- to wackestone, a few grainier intervals, higher amounts of fusulinids compared to other fossils
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel


Core Name: Marathon Brauer 14-1
Page 2 of 2
Location: Cheyenne County, NE
Total Thickness Logged: 343 ft
Date Logged: February 18, 2011
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Group
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
6380
6390
6400
6410
6420
6430
6440
6450
6460
6470
6480
6490
6500
6510
6520
6530
Admire
Wabunsee
Shawnee
A
A I
F
A I
F
J2
B
J2
chickenwire texture
chickenwire texture
chickenwire texture
Uncored Interval
oil
continued from page 1
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel
dark grey mudstone, finely laminated, no bioturbation, oil stained at top, oil saturated at
dark grey mudstone, locally bioturbated, calcareous, contains anhydrite nodules
black shale, fissile
light to dark gray mudstone, locally bioturbated, locally calcareous, contains anhydrite nodules, oil shows
chickenwire anhydrite bed
dark grey mudstone, locally bioturbated, locally calcareous, contains stylolites, anhydrite nodules
chickenwire anhydrite bed
dark grey mudstone, anhydrite nodules, oil saturated zones
light grey/tan mud- to wackestone, moldic porosity filled with oil, locally calcareous, locally laminated
dark grey mudstone, laminated, anhydrite nodules and small beds, calcareous toward bottom
chickenwire anhydrite bed
light to medium grey mudstone, bioturbated, mottled, anhydrite nodules
dark grey-green mudstone
mud- to wackestone, variably dolomitized, bioturbated, isolated anhydrite nodules
alternating red siltstone and green mudstone intervals, variably mottled


Core Name: American Petrofina Ackerman #1
Page 1 of 2
Location: Cheyenne County, NE
Total Thickness Logged: 234 ft
Date Logged: March 15, 2010
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Group
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
continues on page 2
6680
6690
6700
6710
6720
6730
6740
6750
6760
6770
6780
6790
6800
6810
6820
6830
6840
6850
6860
6870
Shawnee
Lansing
B
J1 J2
B
C1
B
J1 J2
F
Uncored Interval
wackestone, cream colored, contains anhydrite nodules (often surrounded by stylolites)
gray-green mudstone, bioturbated, mottled below
red, bioturbated, slightly calcareous, mottled transition to next unit
gray-green mudstone, heavily bioturbated, pyrite
wackestone, bioturbated, burrow fills, moldic porosity
packstone, concentrated fossils
wackestone, spar-filled moldic porosity, silty partings
red, faint bioturbation, slightly calcareous
mudstone, poorly fossiliferous, grey to cream colored, dolomitized, wispy solution seams
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel


Core Name: American Petrofina Ackerman #1
Page 2 of 2
Location: Cheyenne County, NE
Total Thickness Logged: 234 ft
Date Logged: March 15, 2010
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Group
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
6630
6640
6650
6660
6670
6680
Admire
Wabunsee
Shawnee
F
B
D
C2
F
B
moving toward chickenwire texture
continued from page 1
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel
grey mudrock with anhydrite nodules, increasing upwards and trending toward chickenwire texture
skeletal wacke- to packstone, wispy solution seams
grey mudrock (limestone), wispy solution seams
cream colored, dolomitized mudstone, bioturbated, some fossil remains
darker, somewhat silty mudstone, few wispy solution seams, oil shows
mud- to wackestone, wispy solution seams, concentrated siliciclastics (sillty areas)
mud- to wackestone, contains anhydrite, heavily recystallized, oil-stained
mud- to wackestone, contains stylolites, fusulinids
grainstone, contains fusulinids, anhydrite, wispy solution seams
mudstone, greenish, dolomitized
mudstone, calcareous, sparse fossils, bioturbated, contains anhydrite nodules
wackestone, cream colored, contains anhydrite nodules (often surrounded by stylolites)


Core Name: Bass Enterprises 6-13 Brauer
Page 1 of 2
Location: Cheyenne County, NE
Total Thickness Logged: 296 ft
Date Logged: March 15, 2010
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Group
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
continues on page 2
6930
6940
6950
6960
6970
6980
6990
7000
7010
7020
7030
7040
7050
7060
7070
7080
7090
7100
7110
7120
Shawnee
Lansing
Uncored Interval
J1 J2
B
F
G
B
C2
B
red siltstone, green color mottling, calcareous nodules
mud- to wackestone, fossil material is small, contains stylolites and wispy solutions seams, bioturbated
green-grey, bioturbated, calcareous, contains pyrite
fine- to medium-grained limey sand, oil stained
tan, poorly fossiliferous, sandy and brecciated intervals, contains stylolites, few anhydrite nodules
green-grey fusulinid wacke- to packstone, contains stylolites and wispy solution seams
green-grey skeletal wacketsone, fossil material is small, contains stylolites
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel


Core Name: Bass Enterprises 6-13 Brauer
Page 2 of 2
Location: Cheyenne County, NE
Total Thickness Logged: 296 ft
Date Logged: March 15, 2010
Logged By: Chesney Gilleland and Tracy Frank
Depth ft
Facies
Graphic Log
(Lithologies, Structures, Fossils)
Lithologic Description
6820
6830
6840
6850
6860
6870
6880
6890
6900
6910
6920
6930
Admire
Wabunsee
Shawnee
I
F
I
F
I
F
H
I
F
D
F
chickenwire texture
chickenwire texture
chickenwire texture
chickenwire texture
Uncored Interval
continued from page 1
Anhyd
MS
WS
PS
GS
BS
Mud
Sand
Gravel
chickenwire anhydrite bed
dark brown-grey mudstone, isolated anhydrite nodules, shows some areas with microbial laminite, wispy solution seams, somewhat salty
chickenwire anhydrite bed
mudstone, mottled, shows some areas with microbial laminite, scattered anhydrite nodules
chickenwire anhydrite bed
microbial laminite, locally contains anhydrite nodules, tending toward chickenwire texture
grey, silty mudstone, shows some areas with microbial laminite
chickenwire anhydrite bed
green-grey mudstone, poorly fossiliferous, bioturbated, contains anhydrite nodules and wispy solution seams
mudstone, fossils absent, bioturbated, color mottling, cement/anhydrite filled cavities with geopetal structures, upper half oil-stained
mud- to wackestone, bioturbated, fusulinids recrystallized
mudstone with sparse fossil material, heavily recrystallized, brecciated toward top, bioturbated, contains anhydrite nodules

Core Name: Withers #1

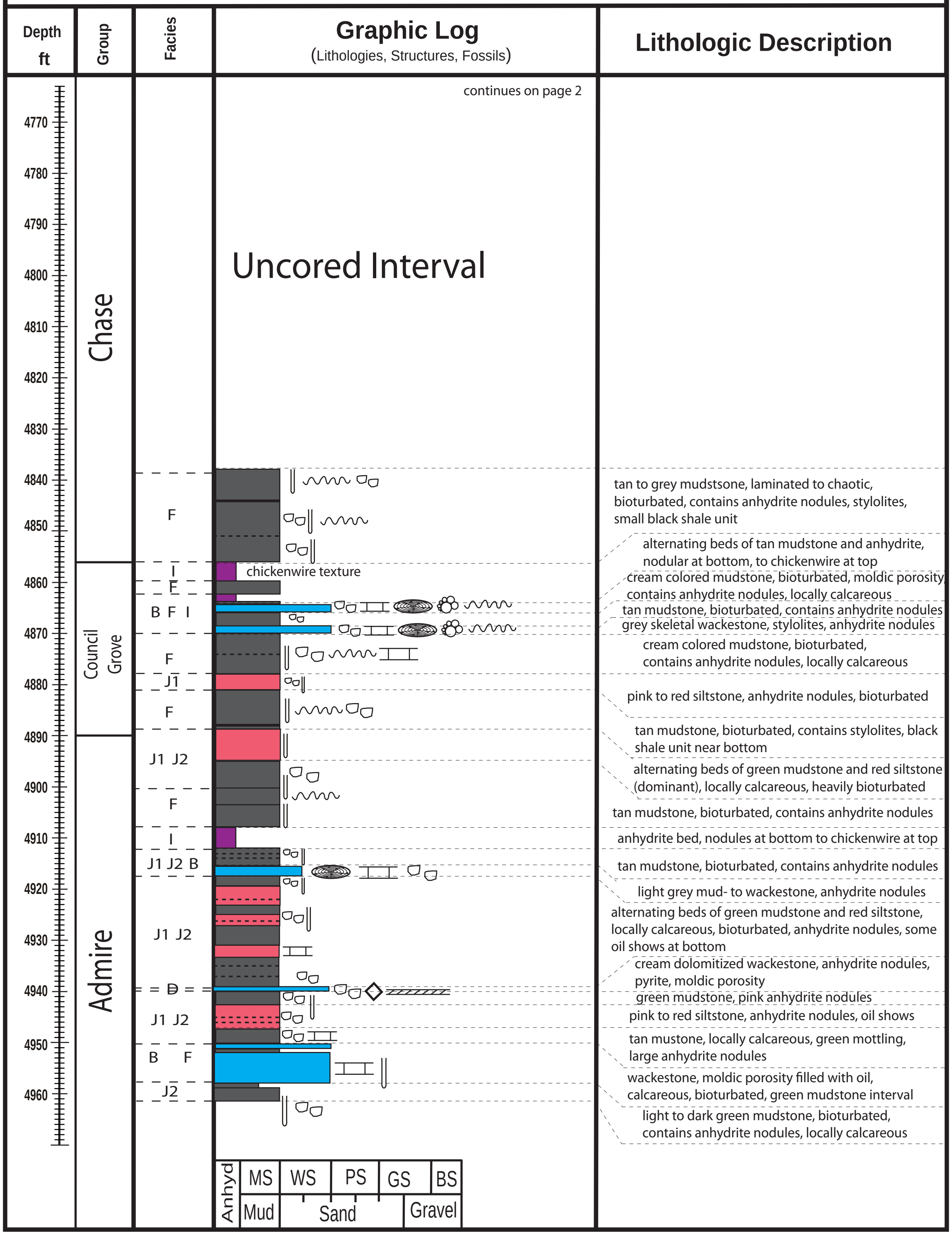
Page 1 of 2

Location: Garden County, NE

Total Thickness Logged: 349 ft

Date Logged: December 9, 2010

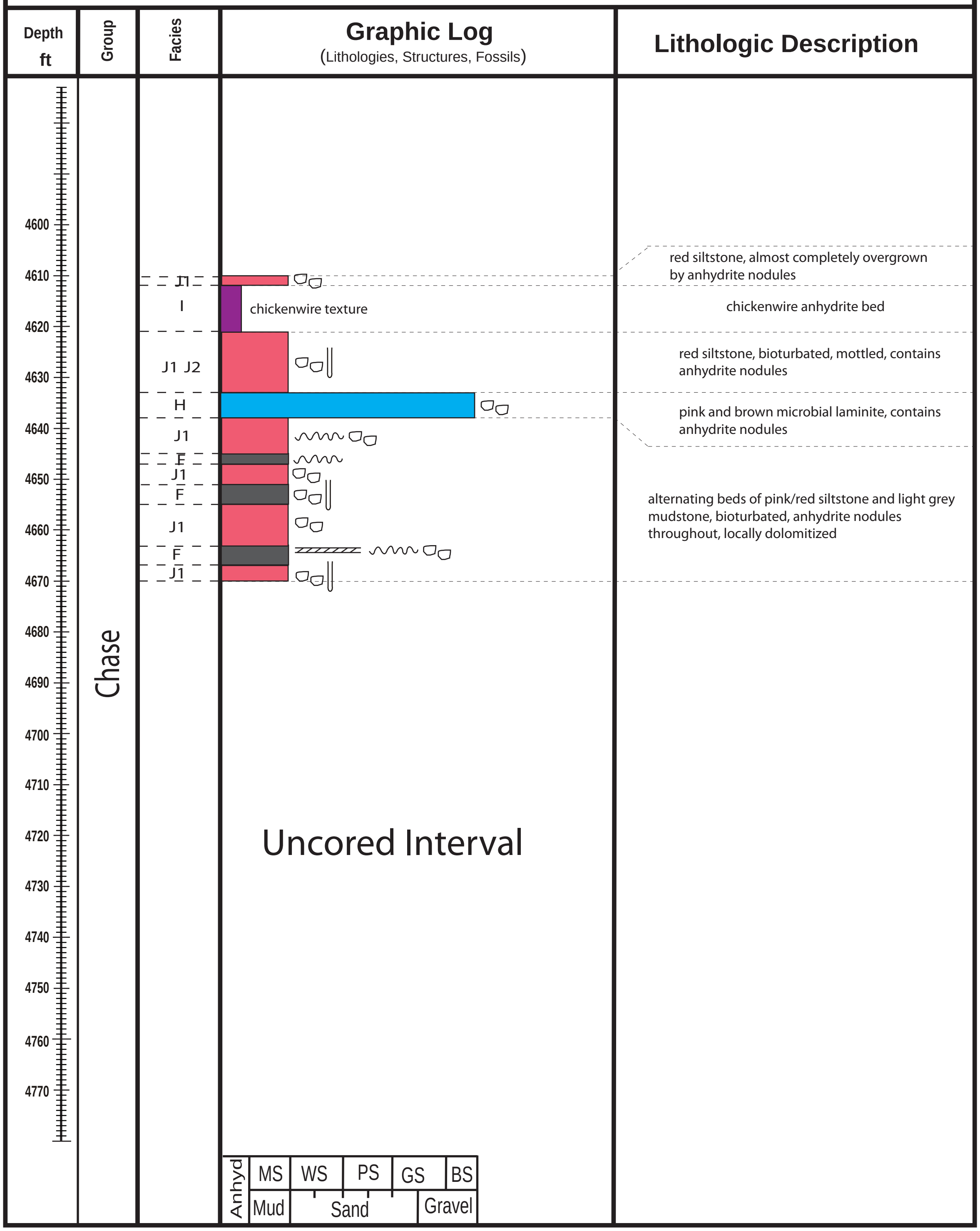
Logged By: Chesney Gilleland and Tracy Frank



Core Name: Withers #1 — **Page 2 of 2**

Location: Garden County, NE — **Total Thickness Logged:** 349 ft

Date Logged: December 9, 2010 — **Logged By:** Chesney Gilleland and Tracy Frank



APPENDIX B: BIOSTRATIGRAPHY

No fusulinids were found in the Chevron Compton-Duncan #1 core from Kimball County, or in the Southland Royalty Withers #1 core from Garden County. The following is a report on the fusulinid species identified in the four remaining cores, which are all located in Cheyenne County.

American Petrofina #1 Ackerman, Cheyenne County- Within the interval from 6667 to 6671 feet depth, thin sections were analyzed at 6667.9 feet, 6668.5 feet, 6669.0 feet, and 6670.8 feet. These sections were found to contain Virgilian-aged fusulinid assemblages, including *Triticites beedi, Triticites cullomensis,* and *Schubertella* cf. *cisoensis*. This particular assemblage correlates with the Middle Virgilian upper Shawnee (approximately the Topeka Limestone). Only one thin section from the interval 6671 to 6684 feet depth contained fusulinid material, and it is from 6678.5 feet depth. It contained sparse and poorly preserved fusulinid fragments that could only be identified as Virgilian-aged *Triticites*.

Bass Enterprises #6-13 Brauer, Cheyenne County- The interval that spans 6826 to 7063 feet depth is mostly anhydritic dolomite for this core. Only one dolomitized, small juvenile *Triticites* sp. (Virgilian type) was identified in the thin sections.

Davis Petroleum #1 Beyer, Cheyenne County- The interval of 6710 to 6754 feet depth was identified as Virgilian (Middle to Upper Shawnee Group). Within this interval, there are three areas of fusulinid bearing carbonates that are partially to completely dolomitized, but a few samples did contain dolomitized fusulinids. At 6710 feet depth, *Triticites cullomensis* and *Triticites beedei* were identified, and indicate a correlation to the middle to upper Shawnee Group in Kansas. Fusulinids from the interval of 6738.9 to 6749 feet depth were identified as *Triticites* cf. *beedei* and *Dunbarinella* sp. indeterminate. These fusulinids indicate a probable correlation to the middle Shawnee (Deer Creek Limestone) in Kansas.

Marathon #14-1 Brauer, Cheyenne County- Two thin section samples were taken from the Middle Virgilian (Upper Shawnee Group) within the interval of 6506 to 6533 feet depth, only one of which was useable (6520.8 feet depth). The fusulinids in this thin section are Virgilian *Triticites cullomensis* and *Triticites beedi*, which correlate with the Virgilian middle to upper Shawnee Group of Kansas.

It is important to note that in some cases, the fusulinid zones identified did not match up with the industry Formation Top picks for certain formations. In these instances, the fusulinids identified were given higher rank than the industry picks for correlation purposes.