THESIS

SEDIMENTOLOGY AND DIAGENESIS OF THE LOWER LODGEPOLE FORMATION, WILLISTON BASIN, NORTH DAKOTA

Submitted by

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ABSTRACT

SEDIMENTOLOGY AND DIAGENESIS OF THE LOWER LODGEPOLE FORMATION,

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The Scallion and overlying False Bakken intervals represent the lowermost portion of the Mississippian Lodgepole Formation, a predominantly carbonate unit located in the Williston Basin of North Dakota (ND) and Montana (MT) in the US, and Saskatchewan and Manitoba in southern Canada. Macroscopic and microscopic observations allow a subdivision of these mostly fine-grained sediments into five carbonate and two siliciclastic facies. These facies form distinct stratigraphic units that can be traced through western ND and easternmost MT with nodular skeletal wackestones and packstones of the Scallion interval at the base showing a distinct coarsening-upward trend, overlain by between one and three black siliciclastic mudstones with interbedded carbonate mudstones of the False Bakken unit. This lowermost part of the Lodgepole Formation represents mid-ramp to basinal settings of a low-inclination carbonate platform system within the half-enclosed intracratonic Williston Basin. The observed stacking patterns reflect relative sea-level changes that influenced facies distribution within the basin throughout its evolution: the coarsening-upward observed within the Scallion interval shows a general shoaling of the setting during progradation, representing a lowstand systems tract. The False Bakken interval consisting of up to three shale beds with intercalated carbonate mudstones shows a significant fining within the lower Lodgepole Formation depositional system and is interpreted as representing the transgressive systems tract. The subdivision into a maximum of three mudstone units reflects three backstepping parasequences during relative sea-level rise. The subsequent renewed onset of fine-grained carbonate deposition on top of the False Bakken interval reflects deposition during highstand conditions. During burial, the Lodgepole Formation experienced a complex series of diagenetic events with nodule formation, dolomitization, and pressure dissolution being the most prominent. The results

of these processes are irregularly distributed both stratigraphically and geographically and play a significant role in reservoir quality of the formation.

TABLE OF CONTENTS

1: Introduction

The Williston Basin in North Dakota and Montana has recently seen a significant resurgence in interest as a location for intense hydrocarbon exploration along with associated scientific studies (Anna et al., 2008, Chen et al., 2009, Gaswirth et al., 2010). Overlying the well-known Bakken Formation is the lesser studied Lodgepole Formation, which forms the basal unit of the Madison Group (Gaswirth et al., 2010, Peterson, 1987, Montgomery, 1996). The Lodgepole Formation was deposited on a westward dipping carbonate ramp system showing shale facies towards the basin center (Young and Rosenthal, 1991, Kerr, 1988). The lower Lodgepole Formation, which is the focus of this study, represents the transition between the carbonate mud-rich mid-distal ramp facies and the basinal siliciclastic-dominated shale facies. Although ramps make up a significant portion of carbonate depositional systems throughout the geologic record, the processes that occur in outer ramp to basinal environments are still poorly understood (Burchette and Wright, 1992).

Several studies have been completed on Waulsortian-type mounds (see Cotter, 1965, 1966, Smith, 1972, Longman, 1996) but detailed and comprehensive studies of the Lodgepole Formation's much more widely distributed non-mound facies are sparse within the published literature (Heck, 1978). The presence of high quality source rocks within the Bakken Formation and the Lodgepole itself make understanding the sedimentology and thus the position of potential reservoir facies economically important (Chen et al., 2009, Jarvie, 2001). The two primary aims of this study therefore are: (1) to understand the sedimentological processes operating at the distal ends of carbonate ramps and (2) to investigate the possibility for Lodgepole facies to serve as unconventional reservoirs in order to better understand the general hydrocarbon potential of basinal carbonate mudstone successions in intracratonic settings. In addition, this study will highlight the diagenetic overprint both the ramp and basin deposits underwent and its implication on reservoir quality. Forty-four cores were measured at both the USGS Core Library in Lakewood, Colorado and the NDGS Laird Core Laboratory in Grand Forks, North Dakota. The location of these cores can be seen in Fig. 1. Representative samples were selected for later thin section preparation from many of the cores. In total, 54 thin sections were described from these cores. Using detailed core and petrographic observations, this report will describe the facies, stratigraphy, depositional processes, and diagenetic suite of the lower Lodgepole Formation from both a scientific and an exploration perspective.

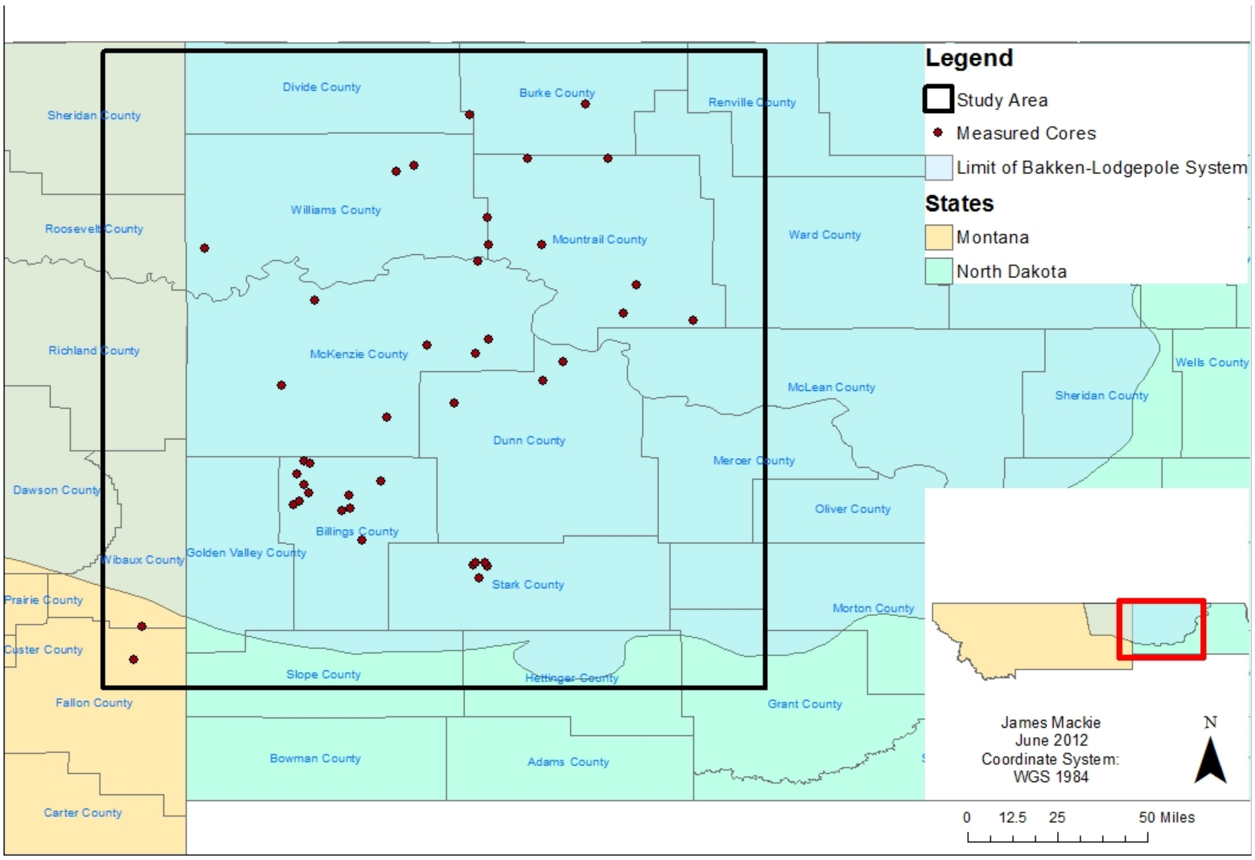

Figure 1. Location of observed lower Lodgepole Formation cores in North Dakota and Montana integrated into the present study

2: Geologic Setting

The Lodgepole Formation occurs in the Williston basin of North Dakota, South Dakota, and Montana, in the United States, and Saskatchewan and Manitoba in Canada. It was deposited in an intracratonic setting located on the western edge of the Canadian Shield Province (Gerhard et al., 1982). The basin underwent episodic subsidence attributed to a wrench style fault system with a primary northeast-southwest shear direction (Brown, 1978). One of these episodes of subsidence occurred around 365 Mya during the Late Devonian, just prior to the onset of Lodgepole deposition (LeFever and Crashell, 1991). Several low relief anticlinal structures are found in the Williston Basin, although the Lodgepole formation thins over only the Cedar Creek anticline indicating that it was the only one of these anticlines with positive relief at the time of Lodgepole deposition (Gerhard et al., 1982, Heck, 1978). During the Mississippian, the basin may have been connected to the Cordilleran foreland basin by either the Central Montana Trough or a seaway located further northwards (Bjorlie and Anderson, 1978; J. LeFever, personal communication 2011). The Williston Basin was isolated from major orogenic events during the Paleozoic which is reflected in the lack of thick siliciclastic sequences and the abundance of carbonates in the basin fill (Kerr, 1988).

The Lodgepole Formation forms part of the Mississippian Madison Group along with the overlying Mission Canyon and Charles Formation and is part of the Kaskaskia sedimentary sequence (Sloss, 1963; Kent, 1987, Kerr, 1988). This carbonate unit was deposited on a generally westward dipping carbonate ramp system with sedimentation that indicates mostly relatively shallow, subtidal, open water conditions (Young and Rosenthal, 1991). Carbonate mud is abundant in most of the facies in this formation, and the skeletal grains represent open water benthic marine organisms like crinoids, brachiopods, bryozoans, and solitary and colonial corals (Young and Rosenthal, 1991). Dark gray to black siliciclastic shales and argillaceous carbonate mudstones are intercalated in the basin's deepest parts in northwest North Dakota and represent deep shelf facies (cf. Peterson, 1987). According to most accepted models, Waulsortian-type mud-mounds occur at the shelf break on the eastern side of the basin and in the Central Montana Trough (Cotter 1965, Johnson 1995). Their location appears to be dependent on the position of paleotopographic highs formed by tectonic activity or differential salt dissolution (Shurr et al., 1988, Gaswirth et al., 2010).

3: Sedimentology

The sedimentological observations summarized in this report are based on both the macroscopic and microscopic study of a total of forty-four cores focusing exclusively on the lower portion of the Lodgepole Formation. Eight of these cores are from the Core Research Center at the USGS in Denver, Colorado, and the remaining thirty-six of the cores were documented at the North Dakota Geologic Survey's Laird Core and Sample Library in Grand Forks, North Dakota. Illustrated sections of these cores can be found in Appendix 1. In total, 54 thin sections were described from the lower Lodgepole allowing for detailed microfacies analysis. The core and thin section observations from the lower Lodgepole interval allow the subdivision of the section into five carbonate and two siliciclastic facies. The Dunham (1962) classification scheme was used in describing these facies.

3.1: Facies Descriptions

3.1.1: Carbonate Facies:

Facies 1: Massive Carbonate Mudstone

Description: This facies is characterized by a medium gray carbonate mudstone(Fig. 2.A) with rare carbonate and siliciclastic grains occurring in abundances of 1% or less. Typical grains are brachiopod and ostracod shells ranging in size from 0.2mm to 0.5mm, calcispheres, and detrital quartz grains with diameters around 0.02mm (Fig. 2.B). Rarely, larger brachiopod shells and crinoid ossicles (up to a few cm long) occur. Grains in this facies are usually randomly oriented and distributed throughout the matrix although in some intervals, shells may be mostly aligned parallel to bedding. This facies is devoid of well-defined sedimentary structures and burrows. In core samples, this facies sometimes varies in color vertically between lighter and darker gray on a decimeter scale.

Interpretation: The abundance of mud and lack of carbonate grains suggest that this facies was deposited in a low energy environment that may have been episodically influenced by high energy storm events. The organisms found in this facies may have either lived there (or higher in the water column in the case of the ostracods) or were transported basinward from their habitat during higher energy events. The quartz grains were either transported to this depositional site by eolian processes or were originally arranged in laminae that were later affected by intense bioturbation. The lack of sedimentary structures and frequently random orientation of grains suggests that this facies underwent extensive diffuse bioturbation. It is therefore more likely that the silt sized quartz grains in this facies do indeed represent a detrital not an eolian component. This environment was most likely well oxygenated at and below the sediment water interface based on the interpreted amount burrowing. The color variations between intervals of this facies probably represent slight changes in the influx of clay into the system.

Facies 2: Carbonate Mudstone with Burrows

Description: Facies 2 is a carbonate mudstone with abundant burrows that are visible in both hand sample and thin section. As with facies one, the primary grains are fine brachiopod shells (0.5-1mm long), calcispheres (around 0.1mm in diameter) and detrital quartz grains (around 0.1mm in diameter). These grains make up one percent or less of the material in this facies. Occasionally, micritic pellets, larger crinoid ossicles, and brachiopod shells are present. Grains are typically randomly distributed throughout the matrix and elongate grains may or may not be horizontally oriented. Distinct laminations are not present, but in places this facies has laterally discontinuous, dark grey-brown clay rich layers. These layers are between 0.1 and 0.3mm thick and extend around 1 mm in length parallel to bedding. The defining characteristic of this facies is the burrows (Fig. 2.C). These burrows are typically less than 1 cm in diameter and can have any orientation ranging from horizontal to vertical. Burrow fills are dark grey or brown in color and may be richer in organic material or clay than the mudstone matrix. The fill of most burrows is homogenous although some display clear backfilling or spreiten (Fig. 2.D).

Interpretation: This facies was deposited in a low energy environment based on the rare presence of large carbonate grains and the extensive amount of carbonate mud. The environmental conditions at the time of deposition must have been favorable for burrowing organisms based on the numerous preserved ichnofossils. The massive texture and lack of laminations and other sedimentary structures suggest considerable diffuse bioturbation. The random orientation of the sparse grains found also indicates extensive bioturbation since elongate grains like brachiopod shells would have been most likely originally deposited laying horizontally. The clay-rich layers probably represent short periods of time with a very high influx of clay that was able to settle from suspension or bedload transport (c.f. Schieber et al. 2007). These layers were then later disrupted and burrowed by infaunal benthic organisms.

Facies 3: Nodular Skeletal Wackestone

Description: This facies is composed of tan to medium grey carbonate mud with interdispersed skeletal fragments that compose anywhere from 10 to 25% of the material. The tan colored rock is slightly more brittle in hand sample than intervals where the matrix is pure grey carbonate mud. Primary grains in order of abundance are: crinoid ossicles, brachiopod shells and shell fragments, and ostracod shells. Less common grains include gastropod shells, rugose corals, and bryozoan fragments. Most grains are in the 0.2-1mm size range and many are broken and disarticulated although some appear to be intact. The valves of ostracods in particular are often still articulated. The large grains generally have random orientations although in several cases grains appear to be aligned along the margins of burrows. Grains can be randomly distributed throughout the matrix or concentrated into patches of higher grain density (Fig. 2.E). This facies is generally devoid of any sedimentary structures. Burrow traces are often visible in thin section and do not have a preferential orientation (Fig. 2.F). Burrow fills are generally finer-grained than the surrounding material. The nodular texture of this facies is made up of lighter gray or tan colored round, irregular- shaped, carbonate-rich concretions surrounded by darker gray material. The nodules range in size from 0.5cm to 3-4cm in diameter. They tend to be longer on their horizontal axis than their vertical axis. Grains appear to be mostly evenly distributed across both the nodules and the surrounding material. In some places, the nodular texture becomes dominated by dark gray, clearly defined anastamosing microstylolites. Where microstylolites are present, the nodular texture is less apparent and the facies instead appears more massive. Grains tend to be more concentrated in close proximity to the microstylolites.

Interpretation: This facies was deposited in a low to moderate energy environment that was capable of transporting larger carbonate grains, at least at times, yet not capable of winnowing away carbonate mud. The carbonate mud settled from suspension likely sourced from the micritization of larger carbonate grains closer to shore. The grains in this facies probably have both an allochthonous and authochthonous origin. Much of the skeletal material in this facies can be attributed to bed load transport from shallower water environments based on the fact that many of the organisms are broken and disarticulated. On the other hand, some shells appear still intact and in the case of many ostracods, still articulated. These organisms likely lived at or near the location where they were deposited. Bioturbation may have then separated brachiopod and ostracod valves after the organism died. The lack of bedding or other well defined sedimentary structures suggests that this facies experienced extensive diffuse bioturbation. This point, combined with the burrow traces that are visible in places, indicates that the environment was hospitable to burrowing organisms and was oxygenated at and below the sediment-water interface. The nodular texture of this facies is an early diagenetic effect (cf. Möller and Kvingan, 1988) as a result of early cementation and later pressure solution (Wanless, 1983).

Areas where microstylolites are more dominant than nodules are a result of more extensive pressure solution (Wanless, 1983).

Facies 4: Nodular Skeletal Packstone

Description: This facies is a skeletal packstone with a nodular texture. The most important grains are crinoid ossicles, brachiopod shells, and ostracod shells. Each of these grains usually consist of 15-25% of the total material and the dominant grain varies between samples. Fenestrate bryozoan fragments, gastropods, trilobites and rarely cephalopods and conodonts are present in some samples and are usually found in concentrations of 5% or less in total. Most grains are 0.5-1mm in length but can be up to a few centimeters. Elongate carbonate grains are generally randomly oriented. In total, skeletal grains make up anywhere from 40-50% of the material in this facies. The matrix material is mostly medium gray carbonate mud but can be tanner in places. This facies is devoid of sedimentary structures (Fig. 2.G) although grains are often concentrated in patches. In some locations, dolomite is also a major constituent in this facies. Fine-grained dolomite rhombs (0.02mm in length) can be found in percentages of up to around 30% locally but usually make up closer to 15% of the total material. The dolomite occurs in patches and is often concentrated along fluid-flow pathways like cracks and dissolution seams or in internal voids in the skeletons of large carbonate grains. The dolomite appears to mostly replace matrix material leaving larger carbonate grains unaltered (Fig. 2.H). This facies has a nodular texture made up of light-medium gray to tan, irregularly shaped concretions that are surrounded by medium to darker gray material. The nodules are 1-3cm in diameter and do not show any internal structure. The distribution and abundance of grains within the nodules and the surrounding material appears to be the same. Swarms of anastomosing microstylolites are present throughout this facies. Moldic, interparticle, and intraparticle porosity (nomenclature according to Choquette and Pray, 1970) can be found in some samples and can be either minus-cement or open. Porosity only appears to occur in this facies when dolomite is present as well.

Interpretation: This facies was deposited in a moderately agitated environment. Conditions were capable of transporting carbonate grains and winnowing much of the carbonate mud. The lack of bedding or any other sedimentary structures and the random orientation of grains suggests that this facies has experienced extensive diffuse bioturbation even though well-defined burrows are absent. This indicates that environmental conditions were favorable for burrowing organisms during deposition of this facies.   Bioturbation may have also contributed to the patchy distribution of grains (e.g. Kidwell et al., 1986). What may have originally been well defined coarse laminations of skeletal grains could have been disrupted by burrowing, leaving coarse patches of concentrated grains.   This facies has experienced significant diagenesis in the form of both dolomitization and the formation of the nodular texture.   The abundance of dolomite in this facies also contributes to how coarse it appears in thin section even though this is unrelated to the energy conditions at the time of deposition. The nodular texture and microstylolites are a result of early differential cementation and is discussed in further detail in chapters 7.7 and 8.

Facies 5: Laminated Skeletal Packstone

Description: This facies is composed of fine-grained skeletal material and carbonate mud of varying abundance organized into thin laminations. It generally appears in discrete intervals that up to 10 cm in thickness. The two major grain types in this facies, in order of importance, are crinoid ossicles and recrystallized shell material likely from brachiopods and ostracods. These grains are typically around 0.5 mm long but can be up to a few millimeters in size. Trilobite, bryozoan, rugose coral, and gastropod fragments are also found but each of these typically makes up less than 5% of the grains. Most of these grains are also around 0.5mm in length but occasionally can be larger.   In several places, authigenic glauconite grains and glauconitic replacement of the carbonate grains dominate this facies. Grains can form up to 70% of this facies in the coarsest portions and around 30% in the more carbonate mud-rich parts (Fig. 2.I). The matrix of this facies is a medium gray carbonate mud. The coarse grains within this facies are concentrated within laminations that are horizontal or inclined at low angles and are typically around 1mm in thickness (Fig. 2.J). In places, laminations are less well defined and grains may have a more patchy distribution. Darker, discontinuous clay-rich stringers occur in places intercalated into the laminations. Elongate grains are usually aligned parallel to bedding. Poorly defined burrow traces are visible in some places and grains adjacent to these burrows appear to be aligned along burrow margins.

Interpretation: Facies 5 represents an environment characterized by high energy events like storms that were capable of mobilizing the skeletal debris to deposit the coarse beds. These high energy time intervals must have been separated by quiet water periods that allowed fine-grained carbonate mud to be deposited before another high energy event deposited another coarse bed. Based on the implied higher energy conditions, the discontinuous clay stringers may have been reworked clay clasts. Alternatively, these clay rich laminae may have been deposited as clay drapes that settled from suspension as quiet water conditions resumed after a storm and were later bioturbated. Although burrow traces are occasionally visible, bioturbation appears to be mostly insignificant in this facies based on the generally well defined beds and horizontal orientation of elongate grains. The lack of bioturbation throughout much of this facies is probably due to a substrate that was generally too coarse to be suitable for burrowing organisms or was deposited and buried too quickly to be bioturbated extensively (Wheatcroft and Drake, 2003).

3.1.2 : Siliciclastic Facies:

Facies 6: Massive Black Siliciclastic Mudstone

Description: Facies 6 is a silt-rich siliciclastic mudstone that only occurs within the False Bakken interval of the lower Lodgepole Formation (Fig. 2.K). The most important grain type within this facies is sub-angular silt-sized quartz grains which are typically around 0.02mm in diameter. These occur in percentages ranging from 10-20% of the facies (Fig. 2.L). Very fine-grained skeletal debris is sparsely distributed throughout this facies in percentages of 1% or less. These skeletal grains are mostly brachiopod shells and are typically up to 0.5mm long and may be fragments or whole shells. Occasionally, larger recrystallized brachiopod fragments are found in sizes up to a few centimeters. The grains are all randomly distributed throughout the matrix and elongate grains are generally horizontally oriented. The matrix material is composed of dark brown-black clay minerals and organic matter. Elemental observations taken from SEM analysis at the USGS Laboratory in Lakewood, Colorado generally are consistent with the composition observed under the standard petrographic microscope. Most grains are composed of either quartz or clay minerals (Fig. 3.A). The clay minerals tend to be more elongate and parallel to bedding while the quartz grains are more equant in shape and do not have a preferred orientation (Fig. 3.B). Additionally, minor amounts (1% or less) of dolomite, phosphate, and calcitic grains occur. Laminations or any other sedimentary structure are not preserved in this facies. *Planolites* burrows are visible in some samples and are typically about 0.5mm in width.

Interpretation: Facies 6 represents a low energy environment where fine-grained siliciclastic deposition dominated. The massive nature of this facies makes it hard to determine whether a majority of the sedimentation was due to settling from suspension or bedload transport. Although there is a significant amount of silt in this facies, it does not appear to have been deposited in discrete laminations. It is possible, however, that the silt may have originally been arranged in laminations formed by currents or suspension that were later destroyed by bioturbation. Rare high energy events could have transported the occasional larger brachiopod fragment into this facies or they may have simply lived there in the case of unbroken shells. The almost entirely siliciclastic composition of the matrix material as supported by the SEM data shows that carbonate deposition was mostly absent from this facies aside from sporadic calcite and dolomite material that was occasionally washed basinward from a more marginal position. Although this is a black mudstone, some level of oxygen must have been present at and below the sediment-water interface due to the presence of *Planolites* and diffuse bioturbation.

Facies 7: Black Siliciclastic Shell-Rich Mudstone

Description: This facies is comprised of fine-grained siliciclastic mud with interbedded laminae of skeletal grains. Brachiopod shells are the most abundant grain type and they are typically around 0.5mm in length but can be up to a few centimeters in size. Less abundant grains include crinoid ossicles and undifferentiated skeletal debris mostly 0.5mm and smaller. The overall abundance of these carbonate grains is about 10-20% but within individual coarse beds as high as 50-60%. Most of the elongate grains are horizontally aligned although some are randomly oriented. Silt sized (0.01-0.02mm) quartz grains are also an important constituent and can be found in concentrations between 5-15%. The silt grains are dispersed throughout the facies and their distribution appears to be independent of the carbonate grains which are mostly found in thin beds. The matrix is very dark gray to black siliciclastic mud (Fig. 3.M). Skeletal material is organized into laminations that are typically around 0.5-1mm thick separated by finer-grained material with scattered large grains (Fig. 2.N). These laminations can be discrete and well defined or discontinuous. Poorly defined tube-shaped burrows with a darker, fine-grained fill are found in places and are typically 0.5mm in width. These burrows do not show a preferential orientation and can be vertical or horizontal.

Interpretation: This facies was deposited during alternating high and low energy conditions with the mudstones representing the low energy, quiet water conditions and the shell beds representing intermittent high energy events. The shells were most likely concentrated at the bases of currents winnowing away finer material, and thereby preferentially accumulating coarse grains in lags. During quiet water periods when these beds were deposited, energy conditions were much lower, only capable of depositing fine, clay sized material through bed load transport (c.f. Schieber et al. 2007) or suspension- settling. The environment at the time of deposition must have been somewhat hospitable for burrowing organisms based on the presence of the poorly defined burrows. Areas where the coarse shell beds have a patchier, discontinuous distribution represent places where bioturbation was likely

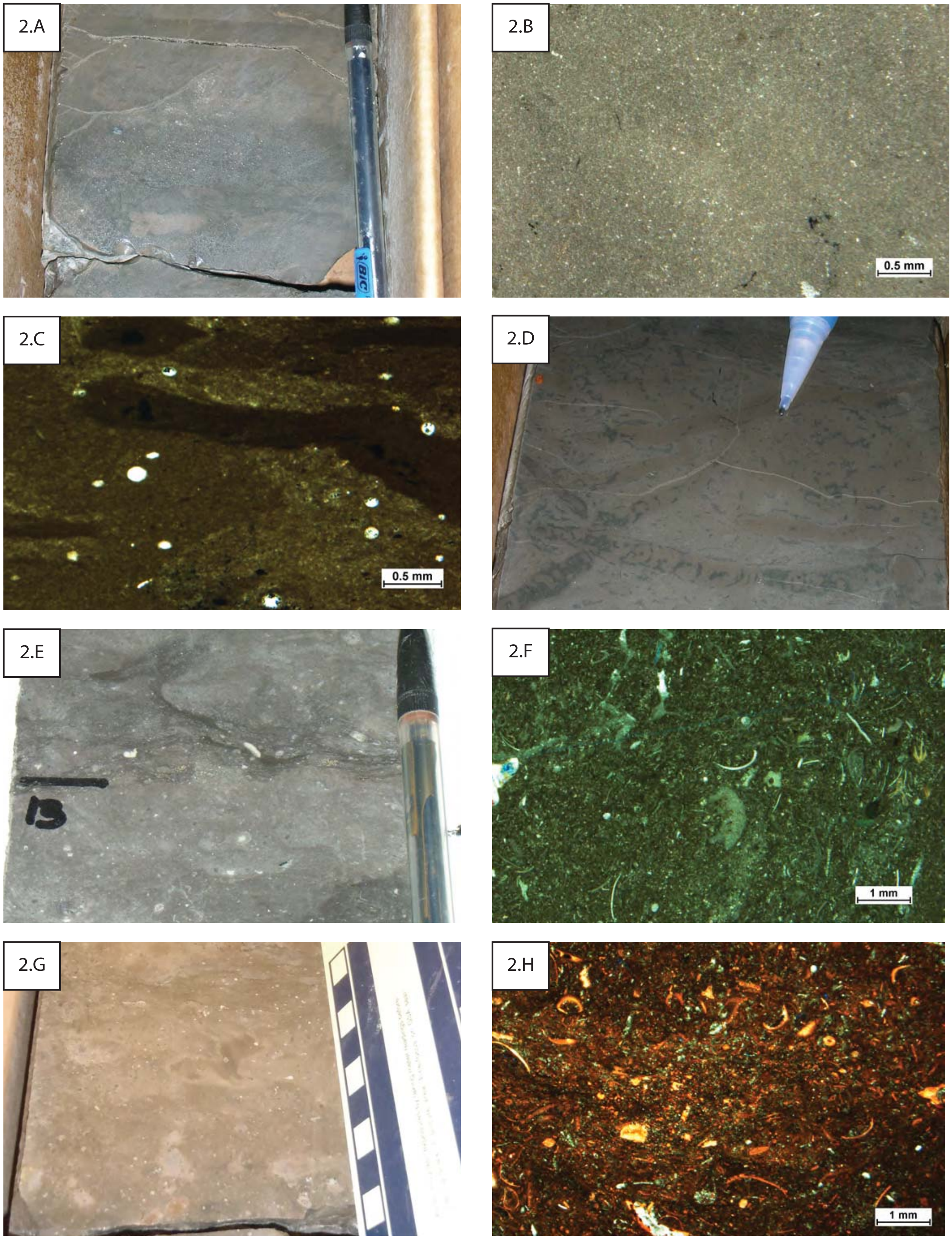

Figure 2 - Facies Photos

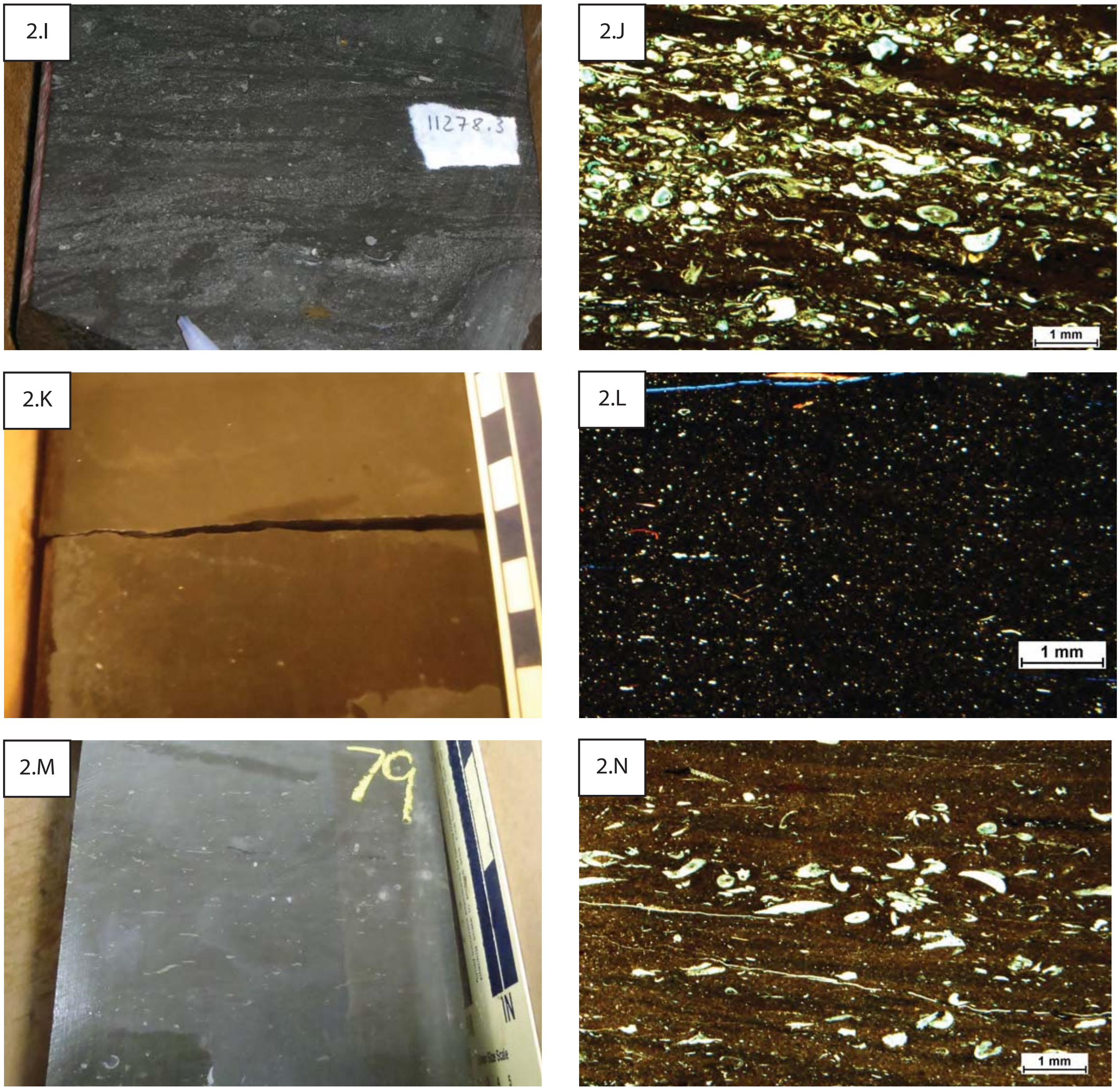

Figure 2 - Facies Photos (Continued)

Figure 2 Captions

- 2.A EOG Sidonia 1-06H at 8654 ft. Massive carbonate mudstone (facies 1). (Pencil for scale)
- 2.B Maxus Energy Carus Fee 21-19 at 11271.5 ft. Massive carbonate mudstone. The visible white grains are calcispheres (facies 1).
- 2.C Pennzoil Spring Creek 27X-31 at 10767.9 ft. Carbonate mudstone with burrows (facies 2) The darker areas are burrows and evidence of backfilling is visible in some places. The visible white grains are calcispheres.
- 2.D Amerada Hess State ND 1-11H at 9411.5 ft. Carbonate mudstone with burrows (facies 2). Note the well-defined spreiten visible in some of the burrows. (Pencil for scale)
- 2.E Conoco Skarphol D #5 at 8913 ft. Nodular skeletal wackestone (facies 3). The lighter gray areas are nodules while the darker areas are the surrounding matrix material. (Pencil for scale)
- 2.F Helis Oil and Gas Co. Linseth 4-8H at 10768.3 ft. Nodular skeletal wackestone (facies 3) Grains include skeletal debris mostly from brachiopods. Note the random orientation of grains likely due to bioturbation.
- 2.G Meridian Oil Co MOI Elkhorn #33-11 at 10400.5 ft. Nodular skeletal packstone facies (facies 4). It is important to note that the distinction between facies 3 and 4 is not readily distinguishable in core. The corresponding thin section from this interval is seen below in photo H. (Centimeter scale on right)
- 2.H Meridian Oil Co MOI Elkhorn #33-11 at 10400.5 ft. Nodular skeletal packstone (facies 4). Note the randomly oriented grains made of mostly brachiopod and crinoid debris. The fine white material is sucrosic dolomite. (Red calcite dye)
- 2.I Maxus Energy Carus Fee 21-19 at 11278.3 ft. Laminated skeletal packstone facies (facies 5). The visible grains are fine crinoid material. Note how the distribution of grains is slightly more patchy lower in the photo. (Pencil for scale)
- 2.J Stephens Energy BR 21-29 at 10661.9 ft. Laminated skeletal packstone facies (facies 5) Laminations of skeletal material consisting of mostly crinoid and brachiopod debris are separated by finer intervals of carbonate mud.
- 2.K Whiting Oil and Gas Teddy 44-13 TFH at 10495.5 ft. Massive black siliciclastic mudstone (facies 6)
- 2.L Stephens Energy BR 21-29 at 10660.0 ft. Massive black siliciclastic mudstone (facies 6) The visible white grains are detrital quartz.
- 2.M Florida Exploration Federal 34-1 at 10479.0 ft. Black siliciclastic shell-rich mudstone. The visible grains are pyritized brachiopods (facies 7). (Inch scale on left)
- 2.N Astral Oil Company Stenehjem 43-27 at 10887.5 ft. Black siliciclastic shell-rich mudstone (facies 7) The coarser intervals consist of fine crinoid and brachiopod debris as well as some detrital quartz.

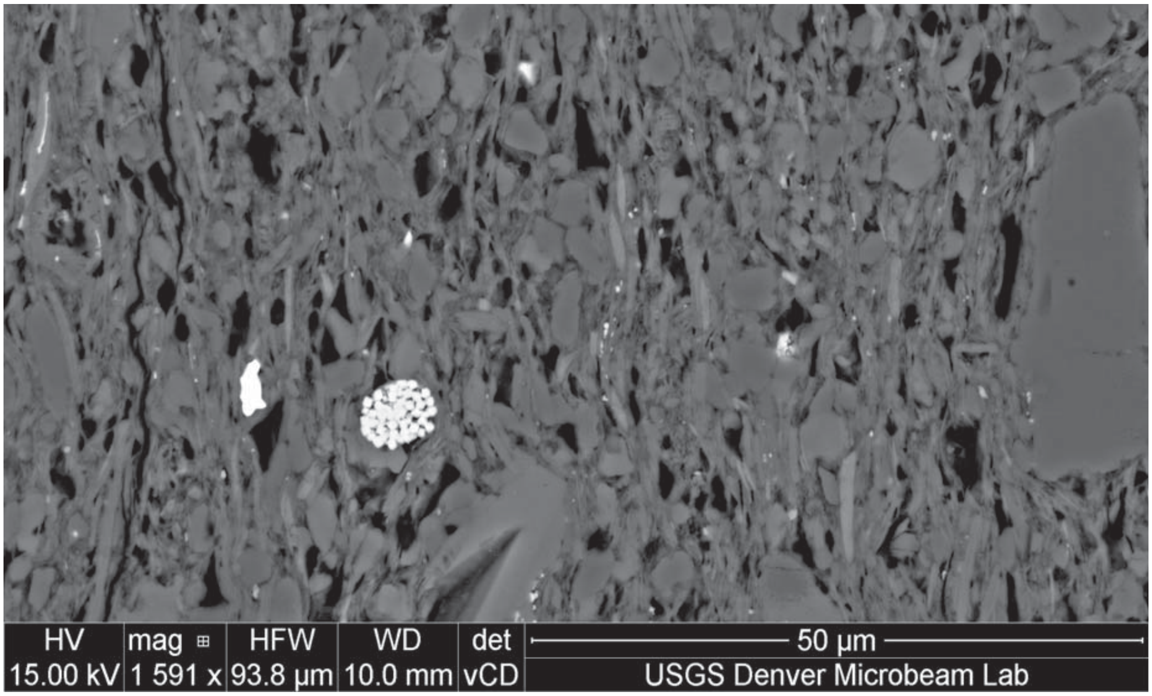

Figure 3. A BSE SEM image of the first False Bakken intervalfrom EOG Liberty 2-11 H well . The equant grains represent quartz while the more platy grains represent clay minerals. The white fromboidal grain is phosphate. (note that this photo is rotated 90 degrees from horizontal)

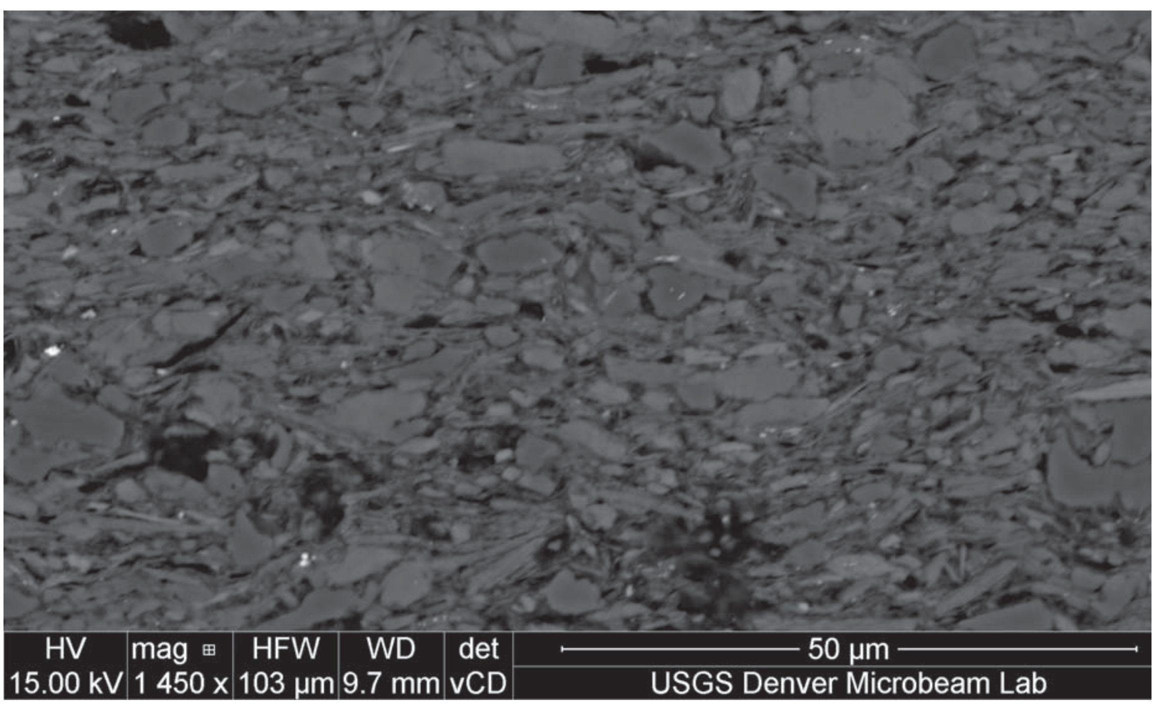

Figure 3. B BSE SEM image of the second False Bakken Intervalfrom Stephens Energy Co. BR-21-29 well. Note that the composition is similar to that of the First Bakken interval seen in Figure 5.A. Elongate grains, particularly clay minerals are aligned parallel to bedding.

Figure 3. False Bakken SEM Imagery

more significant. This bioturbation destroyed well-defined laminations and intermingled mud with the coarse shell beds.

4: Vertical Facies Arrangement

The facies of the lower Lodgepole Formation shows the same general succession in each of the investigated cores. Above the base of the Upper Bakken Shale member the lowermost Lodgepole interval consists of nodular skeletal wackestones or packstones (facies 3 and 4) that mark a sharp contact with the underlying siliciclastic mudstones. This lower portion of the Lodgepole Formation, called the "Scallion" interval (LeFever and Anderson, 1984), varies between nine and fifteen feet (3-5m) in thickness across the basin. The nodular wackestone and nodular packstone facies (facies 3 and 4) are usually found in close association although the relationship between the two is not always well defined by meter- or decimeter-scale coarsening or fining upward sequences. Thin intervals of laminated skeletal packstones (facies 5) are intercalated within the nodular facies in beds that do not exceed a few centimeters. The skeletal packstones become more frequent and thicker as the dominant nodular facies coarsen towards a maximum and subsequently fine upward over the whole thickness of the Scallion interval. The Scallion interval is overlain by the False Bakken mudstones, which are represented by one, two, or three intervals of black to very dark gray siliciclastic mudstones (facies 6) with coarser shell bedded siliciclastic mudstone (facies 7) intervals intercalated in some locations. These dark False Bakken facies are separated by intervals of gray to dark-grey massive carbonate mudstone (facies 1). In some cores, the lowermost False Bakken mudstone interval is replaced by a bed of glauconite-rich bedded skeletal packstone (facies 5). The total thickness of the False Bakken interval, defined by the black siliciclastic mudstone beds (or the glauconitic laminated skeletal packstone interval where it is present) and the carbonate mudstone in between, is typically around six to ten feet (2-3m) with the individual black siliciclastic mudstone intervals usually being a foot thick or less (0.3m). Within the False Bakken facies, thin intervals (1-2 cm thick) of non-glauconitic bedded skeletal packstones (facies 5) are sometimes found in close proximity to the black mudstone facies. The Lodgepole Formation directly overlying the False Bakken interval consists of a thick succession of massive carbonate mudstones (facies 1) and bioturbated carbonate mudstones (facies 2) that show variations of lighter and darker grey bands on a decimeter scale, likely reflecting slightly varying clay content.

5: Depositional Model

The entire lower Lodgepole Formation represents the low-energy part of a carbonate ramp at its distal-most end where carbonate transitioned into siliciclastic basinal deposition. A ramp setting is indicated by generally gradual facies changes and a lack of features suggesting steep inclinations such as synsedimentary deformation or coarse reef debris (e.g. Burchette & Wright 1992). The depositional energy reflected in the facies allows the sedimentary environment to be subdivided into three distinct facies belts. A schematic diagram indicating the distribution of facies and processes is shown below in Fig. 4.

The most proximal facies belt, facies belt 1, is equivalent to a mid-ramp setting (c.f. Burchette and Wright, 1992) and includes facies 1,3,4, and 5. It is especially well developed in the Scallion interval in-between the upper Bakken shale member and the False Bakken mudstones. This belt experienced intermittent high energy conditions during storms that deposited coarser deposits such as those of the bedded skeletal packstone facies (facies 5). During fair-weather conditions, the dominant processes were the deposition of carbonate mud, likely from suspension, and subsequent burrowing and homogenization of the uppermost sediment. The variations in the amount of large grains within facies belt 1 are minor and can be possibly attributed to slight differences in energy or proximity to sediment sources such as water depth and distance to shore or mud mounds.

The transition from facies belt 1 to facies belt 2 marks the point where storm-induced currents were no longer able to regularly transport skeletal grains basinward and carbonate mud instead makes up nearly all of the sedimentation. Facies belt 2 consists therefore largely of carbonate mudstones that are overall devoid of macroscopic fossils showing exclusively facies 1, 2, and rarely facies 5. The lack of large carbonate grains and the predominance of carbonate mud suggest deposition in deeper, calmer water than the more shoreward packstone and wackestones that dominate facies belt 1. However, rarely this calmer environment was interrupted by higher energy events depositing thin intervals of bedded skeletal packstone (facies 5). In facies belt 2, these beds are typically thinner than those found intercalated in facies belt 1. In facies belt 1, they are generally around 5 centimeters in thickness, while in facies belt 2 they often fluctuate around 1-2 centimeters in thickness. The majority of the mud in this facies belt most likely originated from sediment suspended during storms in the upper portions of the ramp that settled out on the distal ramp during calmer fair-weather conditions (Wendte and Uyeno, 2005). The presence of extensive diffuse and well-defined bioturbation in the distal portion of the ramp suggests that even the deeper Lodgepole environments were well oxygenated, even though the substrate or other factors may not have been favorable for large brachiopods or echinoderms to thrive. Alternatively, remnants of large invertebrates may have originally been present in the sediment but degraded over time through boring and decay from acidic nutrient-rich waters entering this half-enclosed basin (cf. Peterhänsel and Pratt 2001).

The onset of facies belt 3 basinward of facies belt 2 is marked by the transition from carbonate mudstone facies to siliciclastic mudstone facies. This facies change represents the outermost limit of abundant carbonate mud transport from shallow water areas, and the shift to distal basin facies with predominantly siliciclastic mud deposition. The presence of thin shell beds within the siliciclastic mudstones (facies 7) shows that high energy events still were capable of occasionally depositing small amounts of larger carbonate grains in this distal setting. Since many of the grains here are fragmented and distributed in laminations, it is likely that most of the shell debris in this facies belt is allochthonous although the occasional isolated intact brachiopod probably lived and perished within this environment.

This most basinward facies belt represents the deepest water environment at the most distal end of the carbonate ramp. However, even in these distal sediments bioturbation is abundant throughout indicating that the entire Williston Basin was oxygenated also in its most remote parts during the entire duration of Lodgepole deposition.

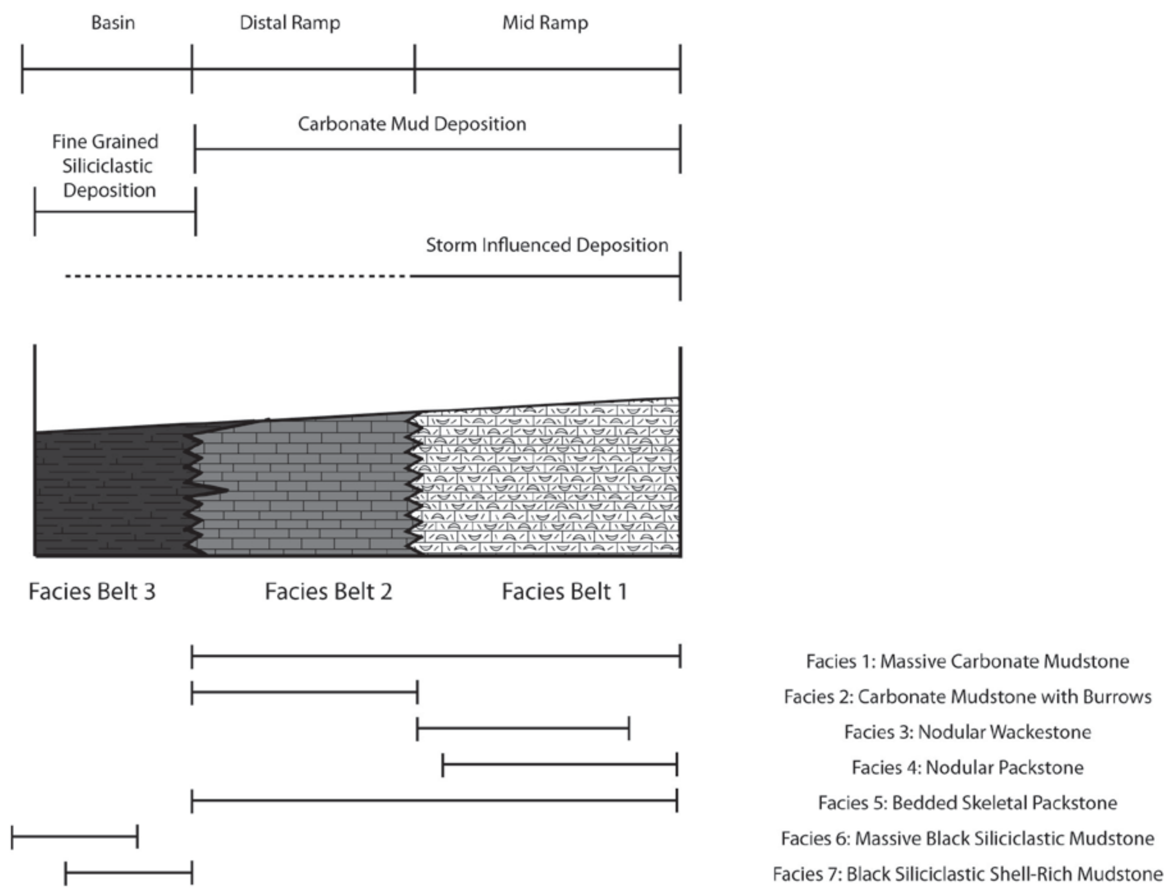

Figure 4. Depositional Model for the middle to distal ramp facies of the Scallion and False Bakken Intervals of the Lodgepole Formation.

6: Sequence Stratigraphic Interpretation

The investigated portion of the lower Lodgepole Formation is interpreted to consist of three systems tracts. The Scallion interval represents a lowstand systems tract based on the abundance of larger grains that are otherwise not as common in the lower portion of the Lodgepole Formation. The lowstand systems tract indicates a significant shift of mid-ramp facies basinwards; however, the transition from the basal Upper Bakken Shale is conformable, indicating a gradual progradation of carbonate over basinal mudstone facies. The top of the Scallion interval is marked by a distinct transgression indicated by a sharp contact of mid-ramp facies and overlying deep shelf False Bakken siliciclastic mudstones. This transition marks the onset of the transgressive systems tract. However, the onset of an increase in accommodation space and initial retrogradation of facies is already notable in the uppermost Scallion interval where most of the measured sections show a well-defined fining-upward trend, and a transition from carbonate wacke- and packstones to mudstones prior to False Bakken deposition.

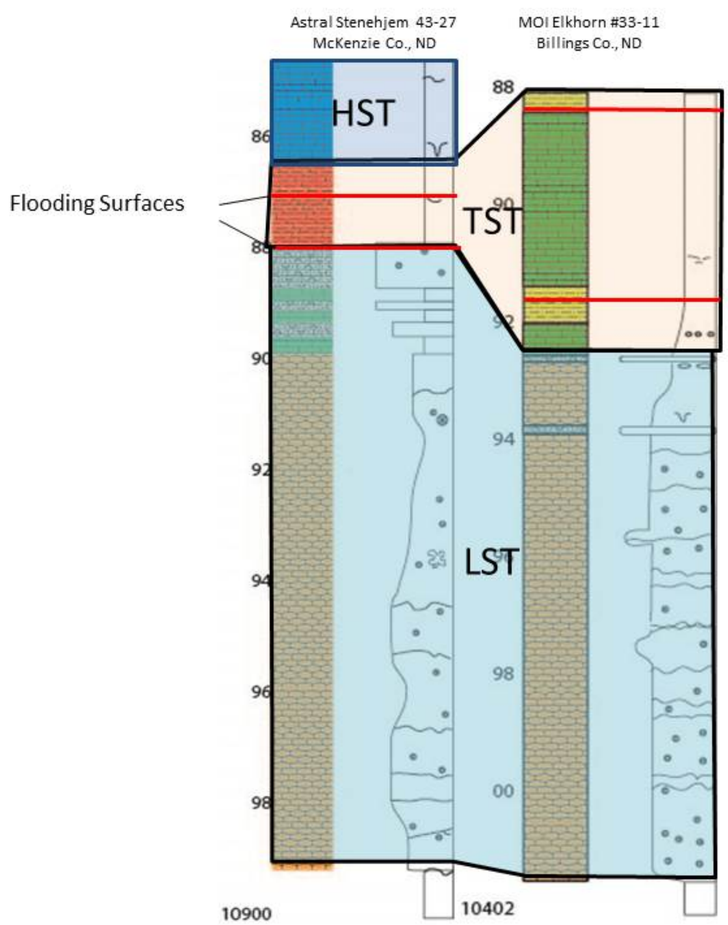

Figure 5. Sequence stratigraphic interpretation of the Lower Lodgepole Formation.

With rising sea level, carbonate production was successively shifted marginwards onto the craton, and therefore carbonate was less likely to reach the most distal portions of the basin. This allowed for the deposition of fine-grained siliciclastic sediment of facies 6 and 7. The stratigraphic level where the lithology shows the finest grain size within these black siliciclastic mudstone facies where sedimentation rates were at their lowest represents flooding surfaces. This transgression appears to have occurred in at least three separate pulses as evidenced by the presence of three separate False Bakken intervals in most cores. One of these False Bakken pulses is sometimes substituted by an interval where glauconite replacement occurred representing a condensed section where very little to no deposition occurred (Amorosi, 1995). In places, there is only one False Bakken interval, most likely in slightly shallower locations where one of the two transgressive pulses did not shift the facies distribution shoreward enough for carbonate deposition to cease. These intervals of False Bakken and glauconite deposition that represent individual transgressive pulses as well as the carbonate mudstone facies intervals in between them are interpreted to be the transgressive systems tract. Fig. 8 below shows the distribution of cores with these variations in the transgressive systems tract. The thick carbonate mudstones overlying the transgressive systems tract represent the renewed onset of prolonged carbonate deposition as the ramp prograded after sea level ceased to rise. The lack of large grains in this interval suggests that sea level was higher at this time than during Scallion interval deposition and lower energy conditions did not permit the transport of these larger grains. The upper carbonate mudstones are therefore interpreted to represent the highstand systems tract. A comparable stratigraphic architecture is observed in the mid-outer ramp deposits of the Upper Jurassic in northeast Spain (Aurell et al., 1998).

7: Diagenesis

The lower Lodgepole Formation shows a number of diagenetic phases and events such as cementation and formation of porosity that have altered the original depositional fabric of the rock and influenced its reservoir characteristics. Most of the data rely on thin section observations, and because of the small scales of cements and porosity only little is based on direct core observations. Nineteen of the thin sections were prepared using UV fluorescent dye in order to detect micro-scale porosity not recognizable with just blue epoxy. Diagenetic phases observed in the Lodgepole Formation are described below.

7.1: Chert

Chert nodules and, less commonly, thin chert beds occur in many of the Lodgepole cores particularly in the carbonate mudstones above the Scallion interval (facies 1 and 2). The nodules are typically rounded and slightly more elongate in a direction parallel to bedding. In hand sample, the nodules appear to be a very light grey to white color that can be either slightly translucent to opaque (Fig. 6.A). The size of the nodules is around 3-5 cm across. Larger carbonate grains are absent within the nodules although some appear dirty due to included carbonate mud. They typically occur in horizons where several nodules are found within a few centimeters of each other. The margins of the nodules may be either smooth or irregular but they are usually well defined from the surrounding carbonate material (Fig. 6.B). A thin, discontinuous bed of chert was observed in one thin section from the E.O.G. Sidonia 1-06H core close to larger nodules chert nodules as described above (Fig. 6.C).

The chert found in the lower Lodgepole formation represents localized supersaturation of quartz in pore waters creating the conditions necessary for microcrystalline quartz to replace microcrystalline calcite cement (Maliva and Siever, 1989). The source of the silica in solution can likely be attributed to dissolved sponge spicules (Noble and Van Stempvoort, 1989). Since the chert is mostly found in the carbonate mudstones overlying the False Bakken Interval, it may be that the source for silica was more abundant during this carbonate mudstone deposition than during the deposition of the underlying Lodgepole Formation intervals. The lone thin bed of chert likely represents a depositional feature where an abundance of silica rich skeletal material was deposited and recrystallized (Maliva and Siever, 1989).

7.2: Dolomitization

Dolomite is often found in abundance within the Scallion interval of the Lodgepole in the nodular skeletal wackestone and packstone facies (facies 3 and 4). Isolated dolomite rhombs are also present within the False Bakken facies (facies 6 and 7). Geographically, the distribution of the dolomite is patchy across the basin (see chapter 8.2). Cores where the nodules of the Scallion interval are more tan than grey have more dolomite that is visible in thin section. The dolomite can comprise of up to 15% of the total rock volume and localized patches of about 1-3mm can consist of 30% dolomite or more. Two distinct types of dolomite are found within the lower Lodgepole Formation. Dolomite I has a sucrosic texture and individual dolomite rhombs range from 0.01-0.03 mm in diameter with most on the smaller end of that range. The rhombs are mostly cloudy and do not show any zonation. Some of the rhombs have clearly defined edges while others overgrow each other and remnant carbonate grains. Where the rhombs have irregular edges, they also tend to be less clear and some dark matrix material appears to be included within the crystals. It is generally found in poorly defined small areas that have varying concentrations of dolomite rhombs (Fig. 6.D). In some cases, the dolomite is focused along cracks, and when this occurs, the margins of the dolomitization are often well defined (Fig. 6.E). Dolomite I appears to exclusively replace matrix material while larger carbonate skeletal grains remain unaltered.

Dolomite II rhombs are usually around 0.1mm across and are noticeably clearer than dolomite I with no visible inclusions. Dolomite II fills large internal voids in bioclasts such as the space in between the septa of rugosan corals, and the central channels of crinoids (Fig. 6.F). In a similar fashion dolomite II also occasionally fills what was formerly shelter porosity underneath brachiopod shells with significant curvature (Fig. 6.G). Where this occurs, there is also a fine calcitic internal sediment below the dolomite crystals (see Section 7.4).

Since it occurs exclusively in the matrix and does not replace carbonate grains, dolomite I likely replaces micrite or fine crystalline calcite cement. Alternatively, the clear, coarse rhombs of dolomite II found in intragranular voids do not replace matrix material and instead likely replace sparry calcite cement (see Section 7.8) that originally filled these spaces or filled pores that were open. Since the sparry calcite cement does not have impurities or incorporated insoluble material, this allowed the dolomite to form as large, clear rhombs. Dolomite formation requires magnesium-rich pore waters to migrate through the rock; the source for the magnesium remains unclear. As clay minerals such as illite and chlorite contain abundant magnesium, some of the magnesium-rich water may have originated in the Bakken Formation shales. This water then migrated into the Lodgepole Formation through fractures and along faults and caused the dolomitization. The variable distribution of these conditions is discussed further in Section 8.2.

7.3: Glauconite

Glauconite replacement of carbonate grains is present within the laminated skeletal packstone facies (Facies 5) substituting the stratigraphically lowest False Bakken interval in eight of the measured sections. Glauconite most commonly occurs as roundish to oval grains measuring about 0.5 to 1 millimeter in diameter. It can also form part of biogenic particles, most commonly crinoid ossicles in which the internal structure is still visible in some of the cases. Some of the biogenic grains are partially composed of glauconite, and partially of carbonate. Stratigraphic intervals containing abundant glauconite are generally in the range of 1 to 3 centimeters thick, and besides the glauconite, these intervals can show some carbonate shell material (Fig. 6.H). Nevertheless, within beds containing glauconite grains, typically all grains are composed of glauconite (Fig. 6.I), and only occasionally carbonate material is present within the form of other grains (Fig. 6.J).

In the Lodgepole Formation, glauconite occurs as primary precipitations in the form of roundish to oval aggregates, likely formed on the sea floor (cf. Odin and Matter 1981). However, the presence of grains that still contain remnants of carbonate and are known to be originally made of carbonate, such as crinoid ossicles, represent a secondary replacement of primary calcitic or aragonitic lithologies. These secondary glauconite occurrences can either have completely changed the original composition of the particles, or only replaced smaller or larger portions of it. The presence of glauconite is believed to indicate condensation (Amorosi 1995) and is therefore often used as an indicator for transgressive conditions (Loutit et al. 1988) when sediment delivery to the deep shelf is strongly reduced.

7.4: Internal Sediment

Internal sediments fill the bottom portion of what was originally open porosity under brachiopod shells. Shelter porosity (Choquette and Pray 1970) that shows internal sediments is rare in the Scallion interval. However, it occurs in both cases where originally open space was present within this unit. The internal sediment consists of calcite. Unlike the surrounding carbonate mud matrix, the internal sediment shows larger and granular-looking grains that are typically about 0.01 mm across (Fig. 6.G). Within shelter pores, internal sediment takes up between 40 and 60% of the total original open porosity with coarse, clear dolomite II cement filling the remaining portion. In places, a few small (~0.01mm) dolomite rhombs are included within the calcitic internal sediment.

The position of the internal sediment on the bottom of shelter pores indicates that this calcitic material was deposited within originally open pore spaces. It did not completely fill them, however, as the leftover portion was occluded by dolomite cement and must have been still open during sedimentation of the internal sediment. The form of the calcite grains as well as their size argues for a formation mechanism distinctly different from the surrounding finer-grained matrix material. It has been suggested (Wilbur and Neumann, 1993) that the clear granular appearance of the internal sediment components reflect precipitation from calcite oversaturated sea-water within pore spaces that were gravitationally laid down in contrast to other cement types that grow attached to pore walls. Internal sediments are not restricted to a distinct water depth but occur in shallow-water platform interior sediments (Egenhoff et al., 1999) as well as on carbonate slopes, e.g. in the Bahamas (Wilber and Neumann, 1993).

7.5: Microcrystalline Carbonate Nodules

The presence of carbonate nodules is prevalent within the Scallion interval of the lower Lodgepole Formation. These nodules are found specifically within the nodular skeletal wackestone and nodular skeletal packstone facies (facies 3 and 4). The nodules are typically medium grey or tan in color and 1-5 cm across. Where the nodular facies are tan, hand samples tend to be more brittle than the purely grey areas. The nodules are usually slightly elongated parallel to bedding but in some cases, their orientation is more random. The margins of the nodules may be well defined or more nebulous (Figs. 6.K and 6.L respectively). The matrix material surrounding the nodules is usually dark grey in color and it does not show any of the tan/brown appearance of the nodules. Within the facies of the Scallion interval (facies 3, 4, 5), there is a continuum stratigraphically between a more nodular Scallion interval texture and a less nodular texture that is instead dominated by microstylolites/dissolution seams. Where the Scallion interval is more nodular (Fig. 10), the color variation between light and dark grey, and in some locations light brown, is pronounced.

The presence/absence of carbonate nodules is generally attributed to differences in cementation during compaction, often relatively early during diagenesis (Choquette and James, 1987). The original cement composition in the nodules is likely microcrystalline calcite that precipitated along distinct layers. Elongation parallel to bedding suggests that ion transport in solution occurred along bedding planes. Precipitation of this cement would have occurred in small open spaces in between carbonate mud particles prior to compaction. Dolomitic replacement of this microcrystalline calcite cement was responsible for the increased resistance to pressure dissolution/microstylitization where present. Jenkyns (1974) suggested that the amount of nodularity is dependent on the amount of clay content with lower amounts of clay yielding less well defined nodules. This aligns well with observations from the Lodgepole Formation because the amount of clay is generally very limited (and not readily visible in core or thin section) causing the nodules to generally be poorly defined relative to surrounding material when compared with other nodular limestone units (Jenkyns, 1974; Möller and Kvignan, 1988; Wanless, 1979).

7.6: Microstylolites/ Dissolution Seams

Swarms of microstylolites occur in all of the carbonate facies of the lower Lodgepole Formation. These swarms are most prominent in the Scallion interval but are less commonly found in the overlying carbonate mudstone facies. Where dissolution seams are more prevalent, the surrounding carbonate mud is a consistent medium grey color (Fig. 6.M) rather than varying between light grey, dark grey, and tan like the more nodular texture. The microstylolites are dark- very dark grey in hand sample and appear black in thin section (Fig. 6.N). Individual microstylolites are about 0.2mm thick and the overall thickness of the swarms is around 1-5 cm. Each stylolite shows sinuosity on two separate scales: a finer scale with wavelengths of 2-3mm and amplitudes of about 1 mm and a larger scale with a wavelength around 5-10 cm and an amplitude of around 5cm. The larger amplitude of sinuosity is less regular in form and can sometimes bound well-defined, isolated carbonate nodules. They are typically anastamosing and can overlap or truncate against other nearby microstylolites. Carbonate grains such as skeletal debris are often more abundant around the swarms but stylolites were never observed to cut through any grains.

The presence of microstylolites is inversely related to the presence of the nodular/early cementation of carbonates. The fact that grains are more concentrated near swarms of microstylolites affirms the fact that they are in fact dissolution structures. Grains such as crinoids and shells are more resistant to pressure dissolution than the fine grained carbonate mud matrix and therefore were excluded from the dissolution that removed the micrite (Wanless, 1983). The darker material that makes up the laminations is insoluble material such as clay minerals that was left behind after the microcrystalline carbonate dissolved (Wanless, 1983). The fact that pressure dissolution structures (microstylolites) are not often found in close proximity to the nodular facies suggests that these areas were more resistant to pressure dissolution than less nodular facies where microstylolites are abundant (Bathurst, 1987). The distribution of microstylitized intervals is patchy within individual cores and across the study area and does not show any clear trends.

7.7: Porosity Formation

The open porosity in the lower Lodgepole Formation is directly connected to the presence of dolomite in the nodular skeletal wackestone and packstone facies (facies 3 and 4) of the Scallion interval. Porosity is not visible macroscopically and is only observable in thin section (Fig. 6.O). Although dolomite can be found without associated porosity, porosity is restricted to only where dolomite is present. In areas where the dolomite concentration is high but porosity is absent, micrite is still prevalent in between the dolomite rhombs and skeletal grains. The porosity associated with the dolomite is intercrystalline in nature and is concentrated locally in patches where the amount of dolomite relative to other carbonate grains is high (30% or more). This condition only occurs in a very limited number of investigated cores (Amerada Hess State ND 1-11H and EOG Resources N & D 1-05H, EOG Sidonia 1-06H; Porosity does not exceed 5-6% overall but in localized millimeter scale patches of dolomite, it can be as high as 20% (Figs. 6.P, 6.Q, 6.R). The dolomite rhombs bordering pores are usually around 0.01-0.02 mm across and so inherently the pores in between the rhombs are this size or smaller. Moldic porosity, mostly in the form of dissolved fine brachiopod/ostracod shell fragments, occurs in minor amounts (Fig 6.S). As with the dolomitic porosity, it was only found in a few samples and it accounted for a maximum of about 1-2% and was usually less than 1% porosity by volume. Moldic porosity was only visible using UV dye under fluorescent light so it is possible that it is more widespread than was actually observed.

The fact that most of the porosity is associated with dolomite occurrence suggests that porosity formation is most likely dependent on dolomitization. The reduction in volume from calcite to dolomite (up to 13%) is responsible for creating the space necessary for open porosity to form (Weyl, 1960). In the lower Lodgepole Formation, the dolomite must have completely replaced carbonate mud where porosity is present because micrite is not found directly adjacent to any pores. The relative lack of dolomite within this part of the formation also explains why porosity values related to dolomitization in the lower Lodgepole are relatively low. Porosity observed in molds were caused by the dissolution of shell material that could have been aragonitic and was therefore more susceptible to slightly acidic pore waters than the calcite of the surrounding matrix (Flügel 2004). However, as this type of porosity is overall rare it indicates that this process did not play a major role in porosity formation within the Scallion interval of the Lodgepole Formation.

7.8: Pyrite

Pyrite is found throughout the lower Lodgepole Formation and typically makes up between one and five percent of the total volume. The pyrite typically has a framboidal form that can either occur independent of any obvious parent grain or replace some or all of carbonate skeletal grains. When pyrite replaces shell fragments, it can either replace the entire grain (Fig. 6.T) or replace the grain in patches independent of internal structure in widely varying percentages. When it replaces a skeletal grain, the size of the pyrite present is dependent on the size of the grain. This type of pyrite appears most commonly around the False Bakken interval where isolated shells or shell beds occur within the siliciclastic and carbonate mudstone facies (Facies 1,2,6,7). Within the Scallion Interval (facies 3,4,5), pyrite also often replaces the internal structure of crinoid ossicles that was formerly composed of organic matter surrounding individual calcite crystals and preserves it in great detail (Fig. 6.U).

The pyrite that occurs independent of skeletal grains ranges in size from silt sized framboids around 0.2mm to aggregates of numerous framboids that can be up to 10mm across These irregular masses of pyrite occur throughout the observed interval of the Lodgepole Formation but are most common in the area immediately above (~10 cm) the contact with the Upper Bakken Formation.

Pyrite likely represents sulfidic conditions in the fluid within the formation due to the decomposition of organic matter in the Upper Bakken and False Bakken or, in the case of the pyritized internal structure of crinoids, within the grain itself (Flügel, 2004). Microbial breakdown of organic matter is a key catalyst for creating the reducing conditions necessary for pyrite precipitation (Raiswell and Berner, 1986). It is likely that amorphous organic matter facilitated the pyrite precipitation that is independent of skeletal grains while organic matter within skeletal material facilitated the precipitation of pyrite associated with these grains.

7.9: Sparry Calcite Cement

Irregular sparry calcite cement occurs in limited amounts throughout the lower Lodgepole Formation. It can be found in any of the carbonate facies but is most common in the carbonate mudstone (facies 1 and 2) and nodular skeletal wackestone and packstone facies (facies 3 and 4). The cement is usually composed of euhedral, blocky crystals that are around 0.1-0.2mm across. These cements are most commonly observed in veins that do not have a preferential orientation and may be vertical or horizontal. Some of these veins show signs of compaction and are slightly contorted towards bedding (Fig. 6.V). The same cement also fills rare shelter porosity that existed underneath brachiopod shells.

The rare sparry calcite veins formed where localized calcite supersaturated pore waters allowed the veins to grow and expand through the force of crystallization (Watts, 1978). This force allowed the cement to expand and displace surrounding micrite. Where the sparry calcite cement fills shelter porosity, the calcite crystals were able to grow uninhibited in open space, allowing for larger crystal sizes than where microcrystalline calcite cement filled micro-pore space in between carbonate mud grains. It is also possible that the calcite precipitated in cracks that were already open as it did in the open voids underneath brachiopod shells.

7.10: Relative Timing of Diagenetic Phases

The eight diagenetic phases described above occur either superimposed in a position to each other that reflects their relative temporal relationship or occur in positions isolated from other diagenetic phases making their relative timing difficult to establish (Fig. 7). This is especially obvious in large open pore spaces that contain several cement and/or pore phases such as shelter porosity, but also holds true for the carbonate matrix that may show earlier carbonate micro-cements that are replaced by dolomitic, glauconitic, and other mineral phases.

From the eight phases observed within the cores selected for in this study the earliest diagenetic phases seems to be the glauconite. While not in contact with other diagenetic phases making relative timing difficult, glauconite formation generally occurs within the uppermost sediment layer before any significant addition of overlying sediment (Odin and Matter, 1981) and hence before burial has even started. Approximately time-equivalent, also occurring within the uppermost sediment layers, but within a carbonate and not a glauconite-forming environment, the calcitic internal sediments formed. Relative timing with respect to (temporally and environmentally restricted) glauconite formation, however, remains speculative as both phases have not been found together. The sparry calcite cement fills the remaining pore space below brachiopod shells and overlies the internal sediment which consequently makes it younger than the calcitic grains accumulated gravitationally at the bottom of larger pore spaces. It remains unclear, however, if the sparry calcite underneath brachiopod shells is time-equivalent with local microcrystalline nodule cement, or whether the latter represents a later stage locally enhanced calcite precipitation within very small pore spaces of the matrix. The fact that calcitic cements observed in fractures within the lower Lodgepole Formation are equivalent in form and size to the calcitic cements fillings shelter pores either suggests that both phases formed around the same time, or that these two calcite cements are indeed similar looking but temporarily different phases that can only be differentiated by their geochemistry, and/or by cathodoluminescence investigations which are beyond the scope of this study.

Nevertheless, the two dolomite phases replace both calcitic matrix and earlier cement and therefore must have formed after all the calcite precipitation in voids and cracks occurring within the lower Lodgepole Formation

Since nodular intervals appear to be more resistant to the pressure dissolution based on the absence of microstylolites in these facies relative to non-nodular facies, the microcrystalline calcite precipitation must have occurred prior to when the pressure dissolution that formed the microstylolites occurred. If the nodular texture that formed as a result of the microcrystalline calcite cement did not provide any resistance to pressure dissolution, then microstylolites would be found in both nodular and non-nodular facies since the overburden pressure that drove the microstylitization would likely be similar where both of these textures are found. This relationship makes determining the temporal relationship between dolomitization and pressure dissolution difficult because the dolomite forms in the intervals with nodular texture where microstylolites are absent. Since it does not appear adjacent to any of the other diagenetic phases, the timing of the chert nodule formation is unclear. Malivas and Siever (1989) suggest that chert nodule formation can occur during both shallow and deep burial, the chertification

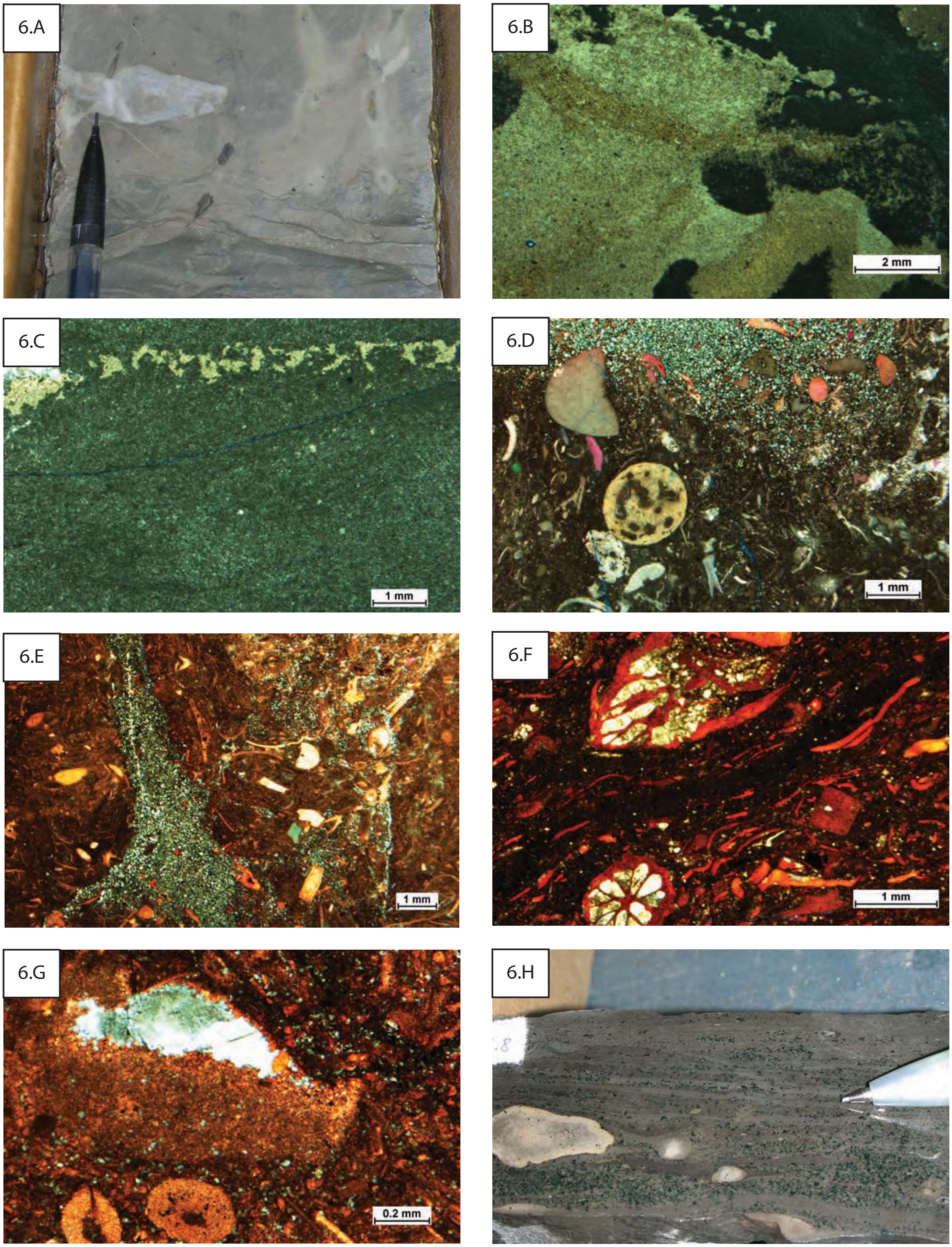

Figure 6. Diagenesis Photos

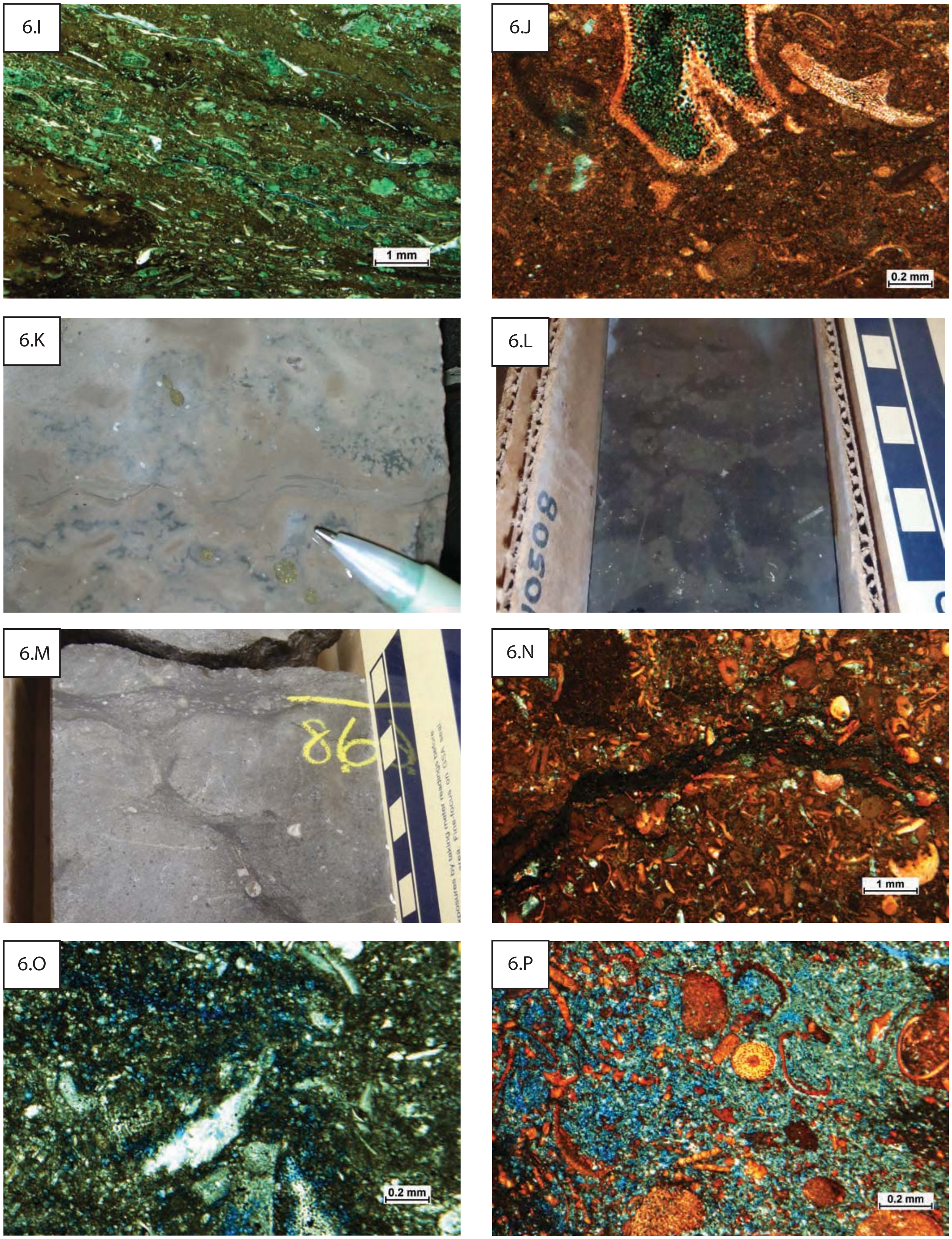

Figure 6. Diagenesis Photos (Continued)

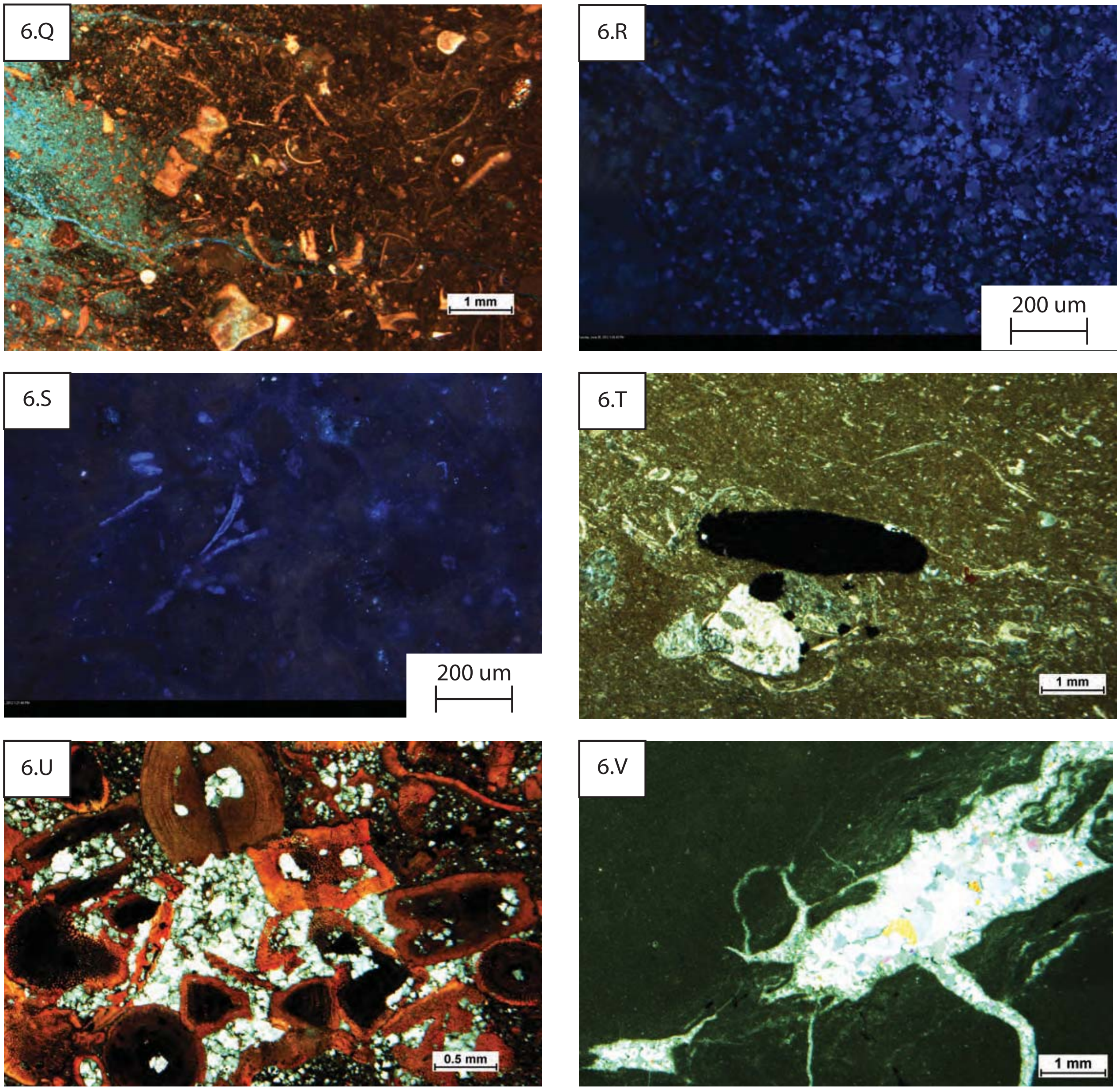

Figure 6. Diagenesis Photos (Continued)

Figure 6 Captions

- 6.A EOG Sidonia 1-06H at 8695.3 ft. Chert nodule surrounded by carbonate mudstone (facies 1 and 2) above the Scallion and False Bakken Intervals. (Pencil for scale)
- 6.B EOG Sidonia 1-06H at 8698.9 ft. Margin of chert nodule (tan) and surrounding carbonate mudstone (dark grey).
- 6.C EOG Sidonia 1-06H at 8675.5 ft. Irregular discontinuous chert bed. This feature was not observed outside of this instance.
- 6.D Brigham Exploration 36-1 2H at 10742.6 ft. Patchy sucrosic dolomite in the nodular skeletal packstone facies. Not how the dolomite is replacing matrix material and leaving larger carbonate grains unaltered.
- 6.E Pennzoil Spring Creek 27X-31 at 10786.5 ft. Intense dolomite along a vertical crack. Diffuse dolomite rhombs in matrix material on the right side of the image. (Red calcite dye)
- 6.F Meridian Oil Co. MOI Elkhorn #33-11 at 10394.5 ft. Coarse dolomite filling internal voids in rugosans skeletons. (Red calcite dye)
- 6.G Stephens Energy BR 21-29 at 10668.0 ft. Geopetal calcite sediment fill with overlying coarse dolomite in umbrella void. (Red calcite dye)
- 6.H Clarion Resources Slater 1-24 at 7878.8 ft. Glauconitic grains in laminated skeletal packstone facies(facies 5). (Pencil for scale)
- 6.I Amerada Hess State ND 1-11H at 9412.0 ft. Photomicrograph of glauconitic replacement of crinoid ossicles and other carbonate grains in laminated skeletal packstone facies (facies 5).
- 6.J EOG Resources N & D 1-05H at 9394.1 ft. Glauconitic replacement of the interior of a crinoid ossicle.
- 6.K Clarion Resources Slater 1-24 7888.5 ft. Nebulous tan carbonate nodules surrounded by medium-dark grey matrix. (Pencil for scale)
- 6.L Socony Vacum Oil Company Angus Kennedy F-32-24-P at 10508 ft. Well defined tan-grey nodules with dark grey matrix material surrounding. (CM scale on right)
- 6.M Florida Exploration Federal 34-1 at 10486 ft. Horizontal and subvertical microstylolites in nodular skeletal wackestone facies (facies 3). Note the concentration of crinoid ossicles within the swarms. (CM scale on right)
- 6.N Florida Exploration Federal 34-1 at 10489.5 ft. Microstylolite swarm in nodular skeletal packstone facies. (Red calcite dye)
- 6.O Amerada Hess State ND 1-11H at 9420.5 ft. Limited intercrystalline porosity associated with dolomitization along cracks. Locally 5% porosity, overall 1% porosity or less.
- 6.P EOG Resources N & D 1-05H at 9408.5 ft. Maximum porosity observed in the lower Lodgepole Formation. Patchy intercrystalline dolomitic porosity in nodular skeletal packstone facies (facies 4) - approximately 15%.
- 6.Q EOG Resources N & D 1-05H at 9408.5 ft. Dolomitic porosity from photo F at a larger scale. Note the patchy distribution of porosity. Carbonate mud is absent where porosity exists but is abundant elsewhere in thin section. Overall porosity at this interval is 3-5%.

6.R Florida Exploration Federal 34-1 at 10486 ft. Intercrystalline porosity associated with dolomite viewed with fluorescent light. (Blue fluorescent dye)

6.S Florida Exploration Federal 34-1 at 10489.5 ft. Moldic porosity resulting from the dissolution of skeletal material viewed with fluorescent light. (Blue fluorescent dye)

6.T Socony Vacum Oil Company Angus Kennedy F-32-24-P at 10493.1 ft. Pyrite replacing an entire skeletal grain (center) and smaller patches of pyrite that formed irrespective of grain or matrix.

6.U Pennzoil Spring Creek 27x-31 at 10779.0 ft. Pyrite replacement of the internal structure of crinoid ossicles.

6.V Maxus Exploration Carus Fee 21-19 at 11271.5 ft. Calcitic vein/concretion in massive carbonate mudstone (facies 1).

inherently occurred after glauconitization but coeval with some or all of the other diagenetic phases. The relationship of the pyrite to the other phases is also somewhat unresolvable but was likely being precipitated throughout the deposition and burial of the Lodgepole Formation so long as decomposable organic matter, dissolved sulfate, and reactive iron minerals were present in association with the pore waters moving through the Lodgepole Formation (Berner, 1984).

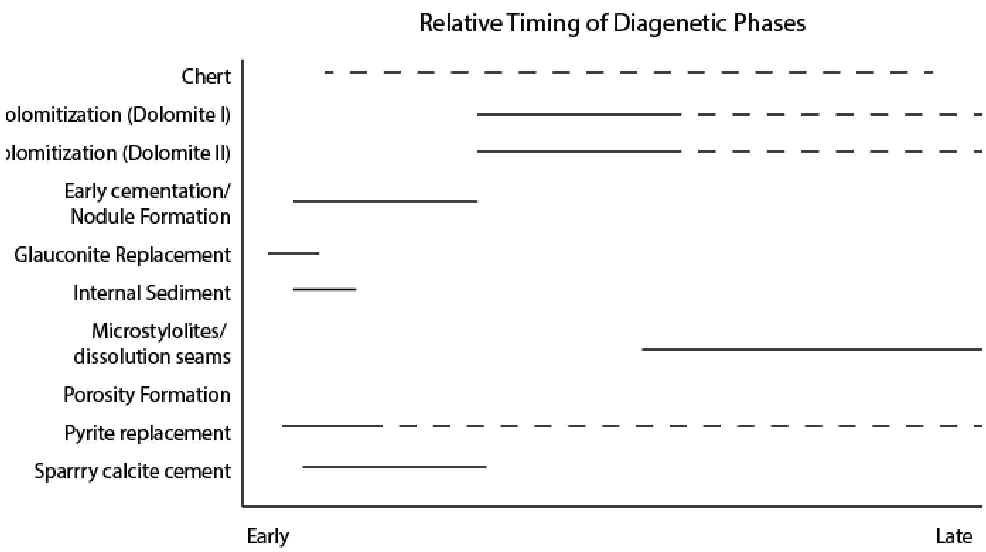

Figure 7. Relative timing of Diagenetic Phases

8. Discussion

8.1: False Bakken Deposition

The distribution and internal makeup of the False Bakken interval varies in character geographically across the Williston Basin (Fig. 8). Understanding the processes that control the stratigraphic expression and the aerial variations of the False Bakken are important to reconstruct the influence of sea-level variations on the deposition of this unit, and will allow predictions regarding the thickness, internal stacking and facies expression of this potential source rock and unconventional reservoir within the Lodgepole petroleum system. Depending on the location in the basin, the False Bakken can be represented by one, two, or three, black siliciclastic mudstone intervals and/or a glauconitic laminated skeletal packstone bed that in certain areas replaces the stratigraphically lowermost black mudstone bed. The character of each of the siliciclastic mudstone beds reflects a transgressive pulse with facies belts being moved outwards towards the basin margins. The facies of the glauconite horizon that is laterally equivalent to one or several of the mudstones also reflects condensed conditions characteristic for transgressions (e.g. Loutit et al., 1988).

The stratigraphic and aerial expression of the False Bakken interval with varying numbers of mudstone units and laterally equivalent glauconite beds may just be a function of the depositional site relative to siliciclastic sediment supply into the basin. Glauconite is overall more abundant in the northern to central part of the study area whereas the siliciclastic mudstones become more abundant towards the southern margin of the basin in southwestern North Dakota and eastern Montana (Fig. 8). This general pattern suggests that the siliciclastic input during False Bakken deposition must have preferentially come from the southern to southwestern basin margin. A sediment source in the southern portion of the study area would distribute silt- and clay-sized sediment preferentially in relative vicinity to its entry point. In such a scenario, the large relative distance of the glauconite-bearing sections to the presumed entry point of sediment reflect sediment-starved conditions during a transgression, but at the same time basin positions far enough away to be sheltered from the relatively higher siliciclastic input originating from the southern basin margin.

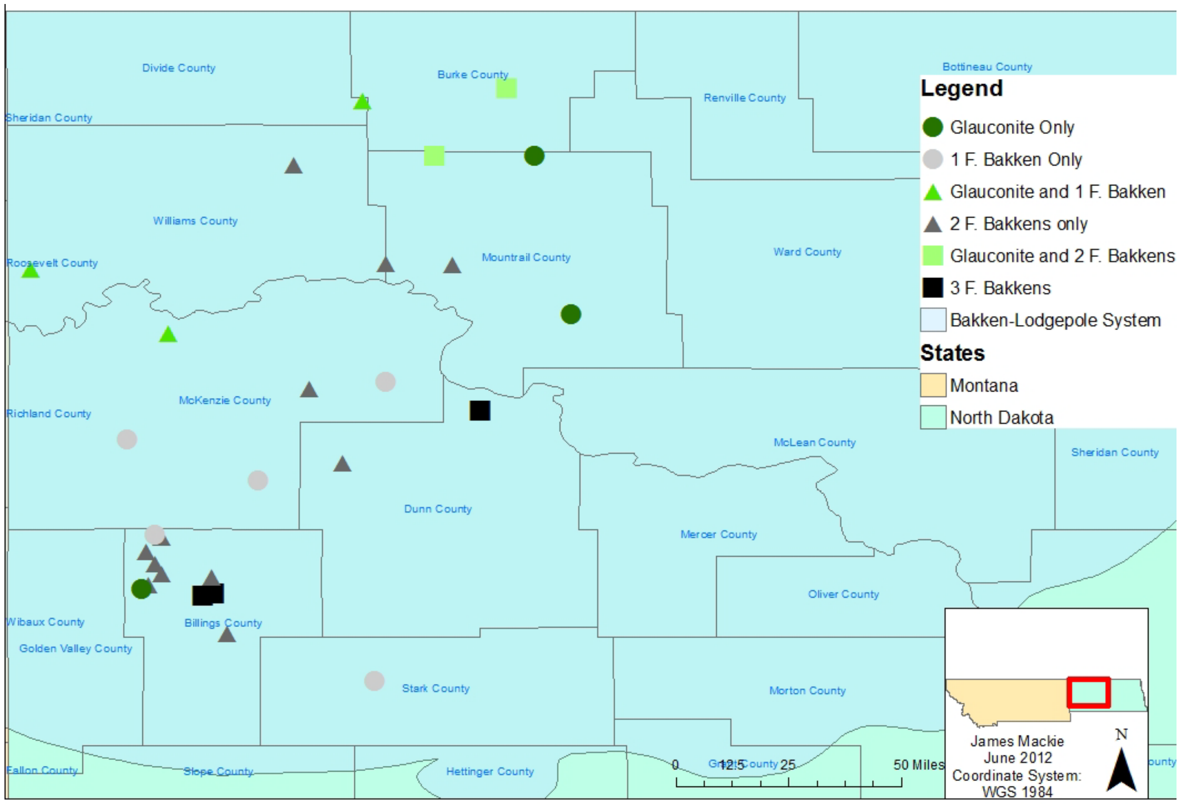

Figure 8. Distribution of False Bakken mudstone intervals and glauconite across the basin.

Another factor influencing depositional patterns in the Lodgepole depositional system are the large mound systems recognized in various parts of the basin (Cotter, 1965; Burke and Diehl, 1993). These mounds, likely located on structural highs, shed carbonate sediment, preferentially carbonate mud, into the adjacent basin areas. The mounds are thought to be located in mid-ramp settings, and in contrast to rimmed shallow-water carbonate platforms (Schlager et al., 1994) their sediment production capacity is not influenced by regular-scale third-order sea-level fluctuations when located below normal wave base (Schlager, 2003). It is therefore most likely that the cores that lack siliciclastic mudstone intervals but show one glauconite layer were supplied with carbonate mud during most of the transgressive False Bakken interval. Only during the most extreme sea-level rise, conditions must have also changed for the mounds themselves. They must have stopped shedding significant amounts of carbonate mud into the surrounding basinal areas, and thereby led to starved conditions within the distal parts of the Williston

Basin, allowing for glauconite deposition. The location of cores with glauconite must therefore have been far enough removed from the siliciclastic sediment source and/or sheltered from siliciclastic input through inner-basin highs thereby preventing detrital material to be delivered to the site of deposition.

The model proposed for glauconite versus siliciclastic mudstone distribution in the False Bakken interval also explains the observed one, two or even three siliciclastic and/or glauconite intercalations into the fine-grained carbonates. The maximum of three mudstones and glauconite units makes it most likely that the False Bakken interval does encompass three short-term trans- and regressions, probably of the parasequence-type. The diminished number of recognizable parasequences or "transgressive pulses" in the other sections are most likely caused by a dilution effect of the fine-grained siliciclastic material with carbonate mud from adjacent mounds: with increasing distance from the siliciclastic source and closer vicinity to one of the sources of carbonate mud the carbonate signal could have been entirely diluted by the carbonates shed into the basin during the same time. Furthermore, the high bioturbation rates present throughout the basin most probably would have helped obliterating the sedimentary signal by mixing the siliciclastic material with the surrounding carbonate mud.

From the three mudstone/glauconite intervals that occur in the False Bakken, the stratigraphically lowest one is generally the thickest and most distinct unit. It is therefore suggested here that this basal mudstone/glauconite interval is most likely the one that can be correlated laterally through the basin, whereas the overlying, less distinct mudstone and glauconite beds most likely correlate with some of the mud-rich carbonates directly overlying the False Bakken.

8.2: Distribution of Diagenetic Processes

Although they are significantly different in appearance in core samples, the more nodular skeletal wackestone and packstone facies (facies 3 and 4) were grouped together with the microstylitized wackestone and packstone facies as two facies rather than four separate ones. This was done because the amount of skeletal grains and matrix material as well as the position within the lower Lodgepole section is the same whether nodules or microstylolites are more prevalent.   Therefore it is assumed that within facies 3 and 4, both depositional processes and burrowing types are the same and do not warrant further subdivision. Nevertheless, it remains unclear what caused differential diagenetic evolution with the development of early cements and subsequent dolomite in some of the core localities while others do not show these diagenetic phases. Unraveling this phenomenon has important economic implications as significant porosity values within the lower Lodgepole interval are restricted to parts of the succession that have a nodular appearance.

The source of the calcite cement that allowed for the nodule formation may help to determine why the nodular texture formed in some places while it is absent in others. Based on observations on Early Paleozoic limestones in Scandinavia, Möller and Kvingan (1988) suggest that the calcite found in nodules generally stems from either pressure solution or the redistribution of carbonate from early dissolution of surface-near carbonate. In case of the Lodgepole Formation, if pressure solution was forming the source of the carbonate forming the nodules, this dissolution must have occurred in a unit other than the Lodgepole itself, most likely situated stratigraphically below. The reason is that the dissolution seams in the Lodgepole Formation most likely originated after the nodules formed and therewith could not have supplied calcium or carbonate ions to precipitate these carbonate concretions. If the calcite within the nodules indeed stems from units underlying the lower Lodgepole Formation it is most likely that the occurrence of calcite concretions is tied to pathways from stratigraphically lower units such as the middle Bakken member or underlying carbonate units such as the Three Forks and Duperow Formations. These pathways would be probably fracture zones, or large-scale faults. If this were true, then the occurrence of carbonate concretions would indicate the presence of fractures or faults within the succession. Alternatively, the source for the calcite that precipitated as cements in the Scallion interval nodules may be from early dissolution and subsequent precipitation around nucleation points in the shallow subsurface. This process is caused by acidic conditions in the reduction zone due to NH_4 and H_2S rich pore waters followed by burial into the oxidation zone (Gründel and Rösler 1963). This process would explain some of the geographic variability in the nodule formation if the thickness variations in the Scallion interval are in fact depositional as higher sedimentation rates and thickness would yield a slightly greater source for this early dissolved calcite possibly causing the observed variable amount of cementation laterally.

Since microstylolites are found in varying levels of abundance in nearly every core, it is difficult to make a binary distinction between nodular Scallion intervals and microstylitized Scallion intervals. This makes determining a geographic relationship between the two variations challenging. One would suspect that the intense pressure dissolution and the associated microstylolites would result in a thinner Scallion interval. As can be seen in Fig. 9, the Scallion interval is slightly thinner in the southern portion of the basin than in the northern area of the basin where the porosity is found. This may be because early cementation was slightly more intense here, making it more resistant to later pressure dissolution and allowing it to retain more thickness than areas further to the south. Alternatively, these areas might have seen higher levels of sedimentation and were therefore thicker prior to burial. This may have been due to the distribution of Waulsortian-type mounds, which were more abundant in the southern portion of the basin, as is discussed in the previous section (Burke and Diehl, 1993). A precise quantitative study based on the number and amplitude of the microstylolites may yield more insight on this possible variation pressure dissolution/microstylitization and associated volume loss and help to predict its geographic distribution.

There are several possible sources for the presence of dolomite within the lower Lodgepole Formation. Pressure solution has been attributed as a source for dolomite during limestone burial (Wanless, 1979, Mattes and Montjoy, 1980). Due to the abundance of microstylolites in the lower Lodgepole Formation, this may be considered as a factor in the formation of the dolomite in the nodular facies at first glance. Wanless (1983) states that dolomite rhombs formed during pressure dissolution are usually larger than 0.03mm and show strong zonation and are typically closely associated with the microstylolites. This does not coincide with the dolomite observed in the lower Lodgepole Formation, which is mostly smaller than 0.02mm and shows no zonation within individual dolomite rhombs. Also, dolomite in the Lodgepole Formation is rarely in direct proximity to the microstylolites. It is however possible that formation fluids capable of forming dolomite resulting from pressure dissolution migrated laterally into the more resistant nodular areas from the microstylitized areas where the insoluble material in the microstylolites served as a barrier to fluid flow.

The other applicable model for how dolomite formed in the Scallion interval is the burial compaction model. As a thick shale unit compacts, Mg^{2+} rich pore water is expelled, supplying the necessary ions for dolomitization (Morrow, 1987). In the case of the Lodgepole Formation, the underlying Upper Bakken (and maybe even the Lower Bakken) would serve as the source for the magnesium ions. One of the constraints on this model is the amount of shale required to supply enough magnesium for dolomitization. Assuming the pore water has the composition of sea water, it would take 32 cm^3 of shale to make 1cm^3 of dolomite (Morrow, 1987). Since the dolomite in the Lodgepole does not make up a huge percentage of the volume of the Scallion interval (around 15% on average) and is not even found everywhere in the basin, there is likely enough shale in nearby intervals to have provided sufficient magnesium to source the dolomite. Since a shale source is present throughout the basin, this explanation for the origin of the magnesium ions fails to explain the patchy distribution of the dolomite. It may be possible that more fractured areas had increased communication with the upper Bakken Formation causing the influx of shale related magnesium to vary geographically.

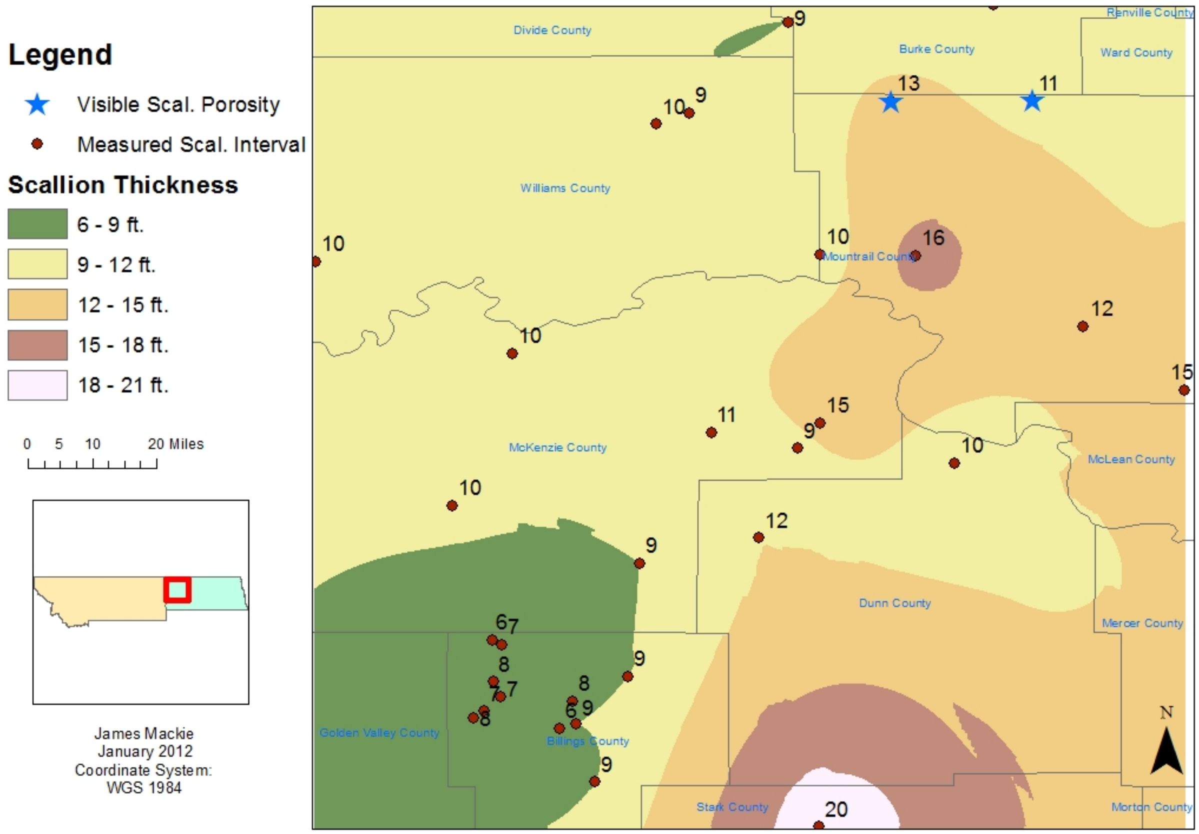

Figure 9. Isopach of the Scallion Interval

The source for the ionic constituents, in this case carbonate, is also an important factor in determining if dolomitization will create porosity. If the carbonate is locally sourced, then dolomitization is much more likely to create porosity than if it comes from an external source (Moore, 2001). If the carbonate ion of the dolomite is not derived from the calcite material it replaces, then it must have originated from another dissolution event that occurred throughout the basin (Moore, 2001). Moore (2001) listed exposure and meteoric phreatic dissolution as a method for this to occur but evidence for this is completely absent from the observed portion of the Lodgepole. Pressure-solution could be a possible source for ex situ CO_3 ions but microstylolites are generally absent in the tan nodular portion of the Lodgepole where dolomite is found suggesting that this was not the source. Also formation of the nodules where the dolomite is found likely occurred before the Lodgepole was buried enough for pressure solution to occur. This suggests that instead the dolomitization used the calcite from in situ microcrystalline calcite cement as well as the surrounding micrite within the Lodgepole Formation to form, which allowed significant porosity to develop. On a similar note, where micrite is still present in the interstitial spaces between dolomite rhombs and carbonate grains, porosity is not found suggesting that more complete dolomitization of the micrite matrix has to occur in order for dolomitic porosity to exist. Murray (1960) suggests that the concentration of dolomite has to be at least 50% of the total volume in order for the dolomite to create porosity and this seems to be the case although the number seems to be slightly lower within the Lodgepole at about 40%.

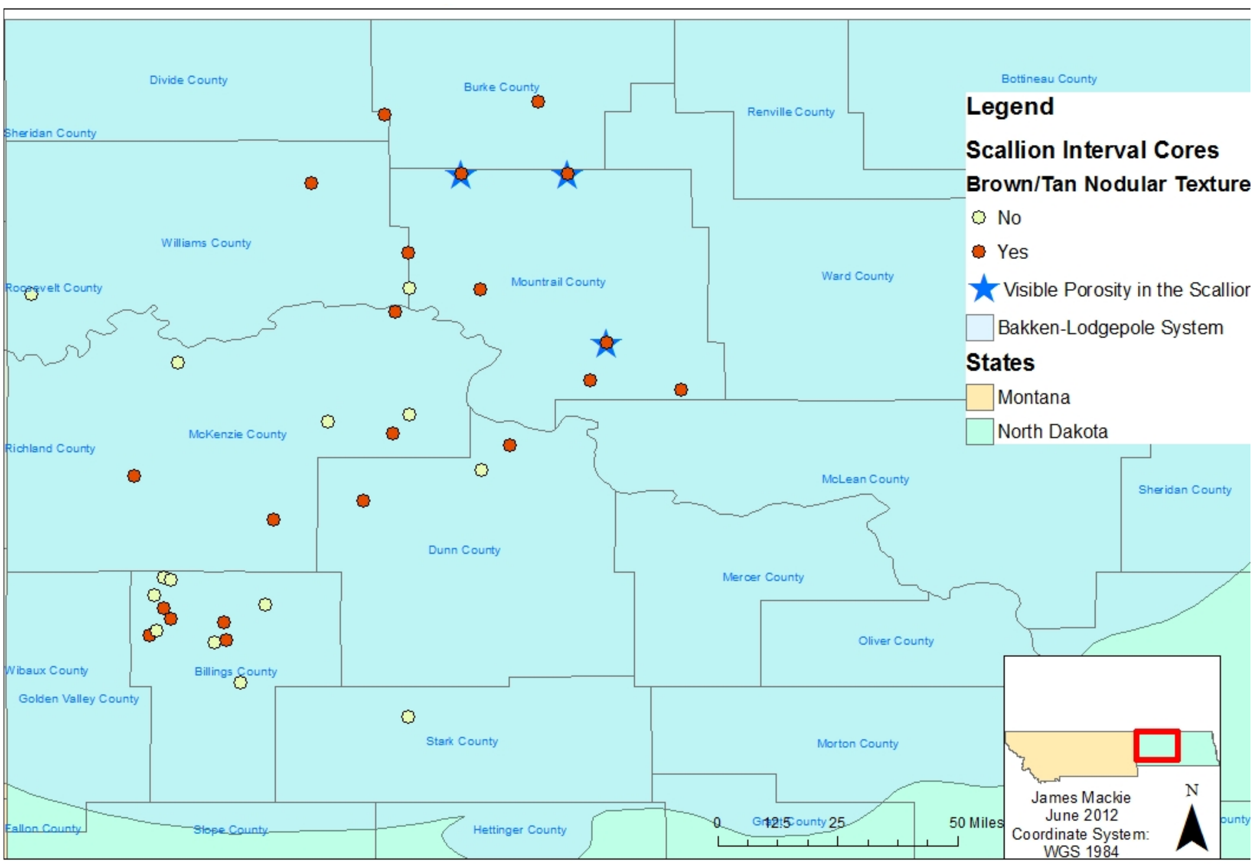

Figure 10. Distribution of dolomite and porosity across the study area.

When dolomite is mapped across the basin using a brown/tan Scallion interval as the indicator of its presence, there is a general trend showing that dolomite is more prevalent to the northern part of the study area, while pure grey calcitic nodules (indicating less dolomitization) are more common to the south. Along with this, it is also important to note that of the three cores that showed porosity with standard thin sections, all occurred in the northern side of the study area (Fig. 10). This coincides with the generally greater thickness of the Scallion interval across the same area (Fig. 9). The microcrystalline calcite cement associated with nodule formation may serve, at least partially, as the material that the dolomite replaces. If, in fact more intense cementation does result in a thicker Scallion Interval, then thickness can be used as a proxy for where dolomitization might be more common. Where there was more of this nodule-forming fine calcite cement, the amount of dolomite replacement can be higher creating the potential for more porosity. It is important that the geographic trend of the dolomite be considered cautiously. The well control from core is sparse in the northern part of the study area (Mountrail, Burke, Divide, and Williams County) so it may just be coincidental that all wells in this area contain dolomite.

9: Outlook

There were several questions addressed in this study that could be answered in greater detail after further study. Since many of the cores were taken to observe the underlying Bakken Formation, they often do not allow for a complete observation of the False Bakken interval or the overlying carbonate mudstone. A remedy for this issue would be to integrate petrophysical data and compare this to the facies observed in core. This would also enable a more detailed study of the variations in thickness in the Scallion interval as well as the distribution of the False Bakken mudstones. The spatial variation of the dolomite remains an important unanswered question. Since its presence would probably be difficult to discern on petrophysical logs, it would also be helpful to take a thin section sample of the Scallion Interval in every core to try to get a better picture of where dolomite is found throughout the basin.

10: Conclusions

This study recognized and described seven facies in the lowermost Lodgepole Formation.   There are five carbonate facies, massive carbonate mudstone, a bioturbated carbonate mudstone, a nodular skeletal wackestones, a nodular skeletal packstone and a laminated skeletal packstone, and two siliciclastic mudstone facies, a massive black siliciclastic mudstone and a black siliciclastic shell-rich mudstone. The "Scallion" Interval directly overlying the upper Bakken Shale consists of nodular skeletal wackestones and nodular skeletal packstones with intercalated beds of laminated skeletal packstones. These facies represent a depositional environment characterized by carbonate mud deposition that was hospitable to benthic filter feeding and burrowing organisms. This environment was impacted by intermittent storms bringing in and concentrating skeletal carbonate grains in distinct centimeter scale beds. Overlying the Scallion interval are the black siliciclastic mudstones and interbedded carbonate mudstones of the "False Bakken" interval. These facies represent quiet water deposition isolated from a carbonate mud source under dysoxic conditions. Higher energy events occasionally deposited thin beds of shell material during the time of False Bakken deposition.   Up to three separate pulses of False Bakken deposition were observed and in places the lowermost pulse of siliciclastic mud deposition is replaced by a glauconite-rich carbonate interval. Overlying the False Bakken is a thick succession of massive and burrowed carbonate mudstones representing the return to carbonate dominated sedimentation albeit at a greater depth isolated from the deposition of skeletal material.

All of these facies represent depositional environments located on a low-inclined ramp system with the nodular skeletal wackestone, nodular skeletal packstone, and laminated skeletal packstones reflecting deposition in a mid-ramp environment, whereas all the massive and bioturbated mudstone carbonate facies record a distal ramp setting. The two siliciclastic mudstones are interpreted as being deposited in a basinal environment in this study.

The lower Lodgepole succession consists of the basal Scallion interval characterized by an overall slight fining-upward trend, the False Bakken unit showing up to three distinct mudstone beds or equivalent glauconite-rich strata, and overlying massive monotonous carbonate mudstones. The Scallion interval is interpreted as representing a Lowstand Systems Tract (LST) because relatively coarse facies are found throughout the basin at this interval. The up to three mudstones of the False Bakken and equivalent glauconite bed most likely represent individual transgressive pulses forming the Transgressive Systems Tract (TST). The sediment starvation indicated by glauconitization and lack of any significant carbonate deposition suggests that sedimentation in the Williston Basin at this time was pushed significantly marginward by sea level rise. The monotonous mudstones marking the top of the investigated succession show the lower part of the overlying Highstand Systems Tract (HST). The return of carbonate deposition in this interval suggests that distal carbonate ramp facies were able to prograde over the rocks of the TST as sea level rise ceased.

Eight major diagenetic phases altered the original depositional fabric of the Lodgepole Formation. Porosity in the lower Lodgepole Formation is almost exclusively secondary and is directly related to the presence of dolomite. Although visible porosity can be as high as 20% in small localized areas, overall porosity does not exceed 5-6% and is usually closer to 0%. The distribution of dolomite is patchy both geographically and in individual samples. The dolomite occurs in two forms, cloudy sucrosic dolomite (dolomite I) and coarser, clear dolomite (dolomite II). These dolomite phases replace nodule forming microcrystalline calcite cement and coarser sparry calcite cement respectively. Pressure dissolution structures in the form of microstylolites are another abundant diagenetic feature in the Lodgepole and their presence is directly controlled by the amount of dolomite; where dolomite is abundant, microstylites become less common. The irregular distribution of dolomite and the restricted associated porosity limit the potential for lower Lodgepole formation as a hydrocarbon reservoir despite its position next to a world class source rock in the Bakken Formation. In addition, pyrite, chert nodules, calcitic internal sediments, and glauconitization occurred in varying amounts.

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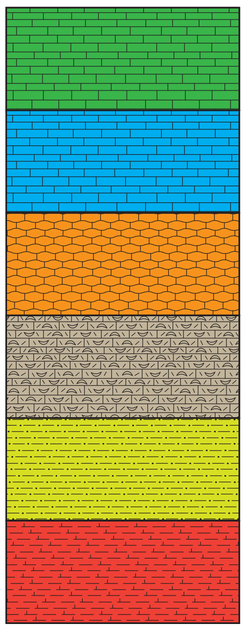
Appendix 1: Measured Sections

Sample #	Operator	Name	Lat	Long	County	Loc.	Pg. #
8251	Jerry Chambers	USA #1-24	47.1839266	-103.5481397	Billings	NDGS	59
12873	Maxus Exploration Co	Rausch Shapiro Fee	47.134897	-103.611171	Billings	NDGS	60
12072	Meridian Oil Co	MOI Elkhorn #33-11	47.216223	-103.566714	Billings	NDGS	61
12886	Shell Western E & P	Connell 24-27H	47.2567	-103.597082	Billings	NDGS	62
15716	Stephens Energy Company LLC	BR 12-29	47.17309315	-103.3856688	Billings	NDGS	63
7887	Tenneco Oil Co.	Mee USA 3-17	47.120931	-103.379412	Billings	NDGS	64-66
10803	Florida Exploration	Federal 34-1	46.990218	-103.335058	Billings	NDGS	67-68
18502	Whiting Oil and Gas	Teddy 44-13TFH	47.1116417	-103.4153847	Billings	NDGS	69-70
8638	Clarion Resources Inc.	Slater 1-24	48.751046	-102.433563	Burke	NDGS	71
13167	Conoco Inc.	SKARPHOL "D" #5	48.708913	-102.898789	Divide	NDGS	72
12785	Maxus Exploration Co	Carus Fee 21-19	47.542727	-102.963685	Dunn	NDGS	73
18355	Simray GP, LLC	Roberts Trust 1-13H	47.63474778	-102.6072548	Dunn	NDGS	74
607	Socony Vacuum Oil Company, Inc.	Angus Kennedy F-32-24-P	47.711593	-102.522114	Dunn	NDGS	75
12772	American Hunter Exploration LTD	Ahel et al Grassy Butte	47.485595	-103.234115	Mckenzie	NDGS	76
14947	Astral Oil Compnay, LLC	Astral Stenehjem 43-27	47.780575	-103.071758	Mckenzie	NDGS	77-78
9793	Exeter Exploration Co.	Schmitz 8-30	47.960366	-103.523677	Mckenzie	NDGS	79
17067	Headington Oil Company LLC	Sakakawea Federal 12x-35	48.11512996	-102.8687514	Mckenzie	NDGS	80
16652	Helis Oil and Gas Company, LLC	Levang 3-22H	47.80306811	-102.8260918	Mckenzie	NDGS	81
16689	Helis Oil and Gas Company, LLC	Linseth 4-8H	47.74549339	-102.8757536	Mckenzie	NDGS	82
12983	Pennzoil E and P Co.	Spring Creek 27X-31	47.615417	-103.658421	Mckenzie	NDGS	83-84
15889	Amerada Hess Corporation	Sara G. Barstad 6-44H	48.18393253	-102.8258589	Mountrail	NDGS	85
15986	Amerada Hess Corporation	J. Horst 1-11H	48.18138581	-102.6103593	Mountrail	NDGS	86
16160	Amerada Hess Corporation	State ND 1-11H	48.53077511	-102.6663559	Mountrail	NDGS	87
17676	EOG Resources, Inc.	Sidonia 1-06H	48.53303243	-102.3443921	Mountrail	NDGS	88-89
18101	EOG Resources, Inc.	Liberty 2-11H	47.90653945	-102.2797244	Mountrail	NDGS	90
16532	EOG Resources, Inc.	N & D 1-05H	48.02185641	-102.229529	Mountrail	NDGS	91
17043	Hess Corporation	St Andes-151-89-2413H-1	47.87729922	-102.001518	Mountrail	NDGS	92
13598	Conoco Inc.	Dickinson State A 83	46.888727	-102.82887	Stark	NDGS	93-94
9800	Arco Exploration	No. 1 Simpson	48.47947229	-103.197669	Williams	NDGS	95
18257	EOG Resources, Inc.	Round Prairie 1-17H	48.16786178	-103.9685497	Williams	NDGS	96
17015	Headington Oil Company LLC	Nesson State 42x-36	48.29136544	-102.8284633	Williams	NDGS	97
16405	Pogo Producing Co	Pegasus 2-17H	48.5046546	-103.1221075	Williams	NDGS	98
E358	Florida Exploration	11-4 Federal	47.31096	-103.56845	Billings	USGS	99
E383	Florida Exploration	12-1 Federal	47.30137	-103.54544	Billings	USGS	100
E349	Texaco Inc	5-1 Thompson Unit	47.229268	-103.26013	Billings	USGS	101
R658	Whiting Oil and Gas	31-3 Short Fee	47.149989	-103.588055	Billings	USGS	102-103
E967	Duncan Raymond T	1-24 Patterson	46.838244	-102.86002	Stark	USGS	104-108

Facies Key



Massive Carbonate Mudstone (facies 1)

Carbonate Mudstone With Burrows (facies 2)

Nodular Skeletal Wackestone/Nodular Skeletal Packstone (facies 3 and 4)

Laminated Skeletal Packstone (facies 5)

Massive Black Siliciclastic Mudstone (facies 6)

Black Siliciclastic Shell Rich Mudstone (facies 7)

Symbol Key

Rugosan

Crinoid

Stylolite

Microstylolite Laminae

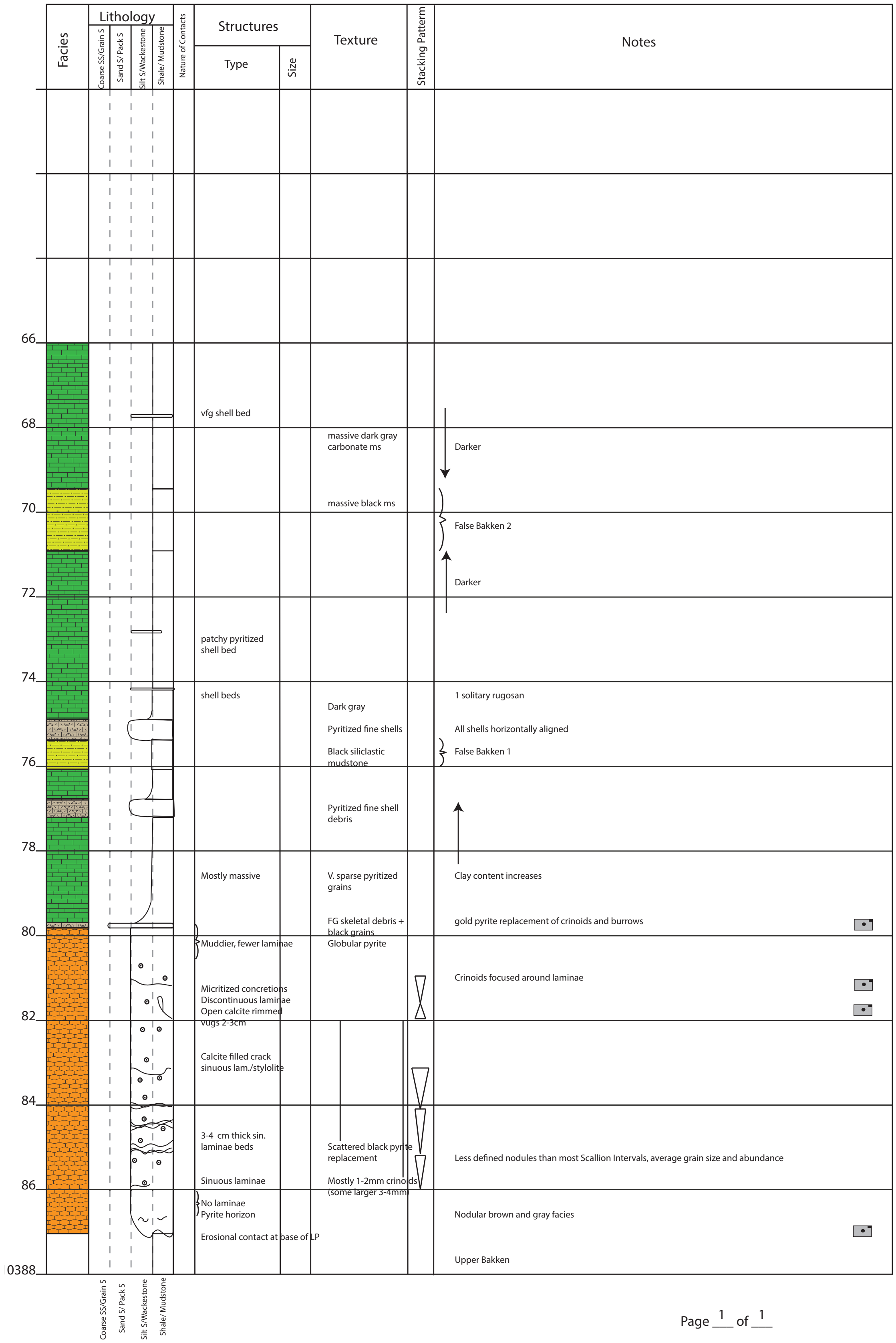
Core Photo

Burrow

Fining/Coarsening Upward

Well Jerry Chambers USA 1-24 County Billings State ND

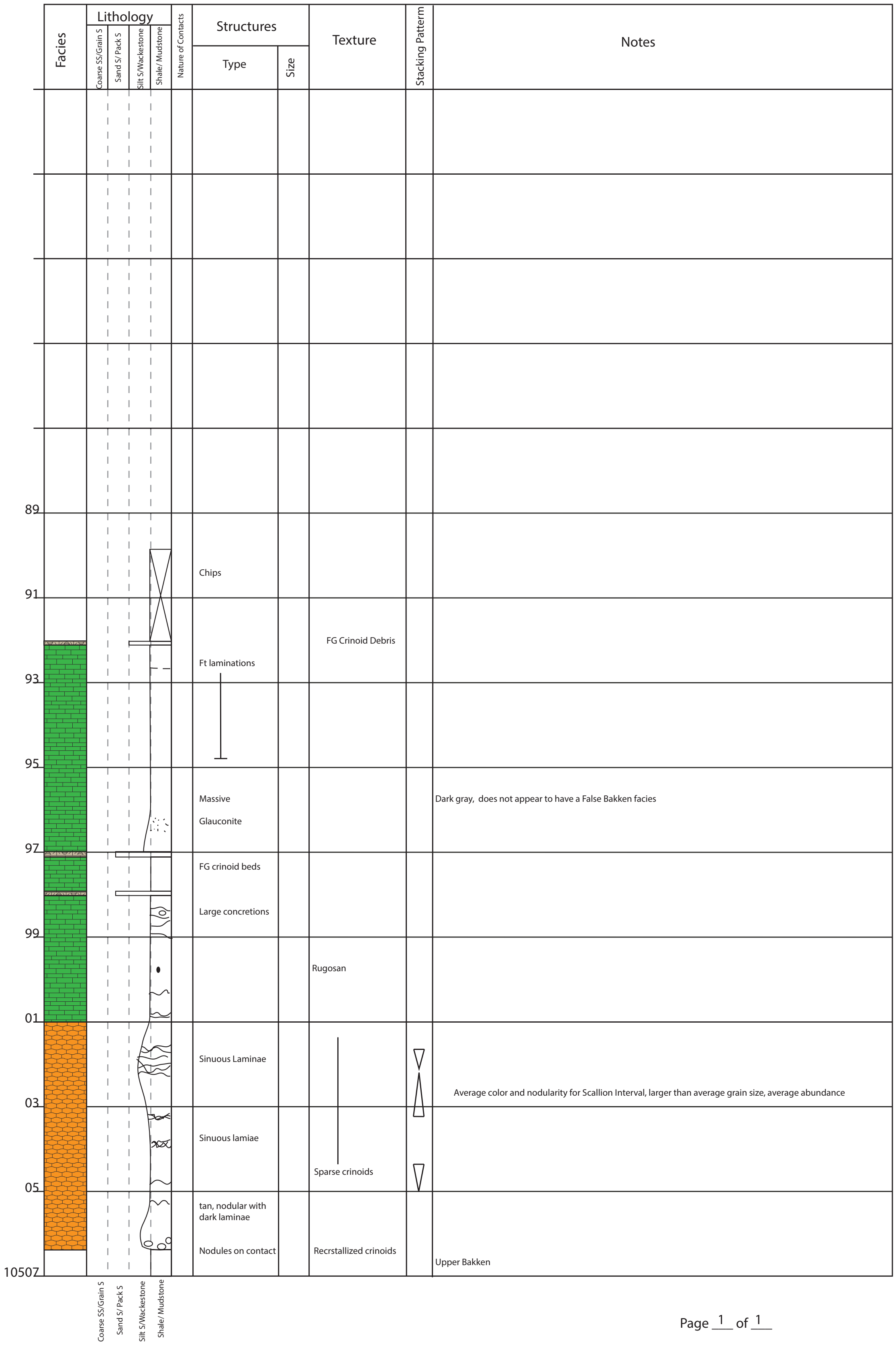
Stratigraphic Interval 10366-10388 Logged by JM Date 11/18/11



Page 1 of 1

Well Maxus Exploration Shapiro Fee #32-9 County Billings State ND

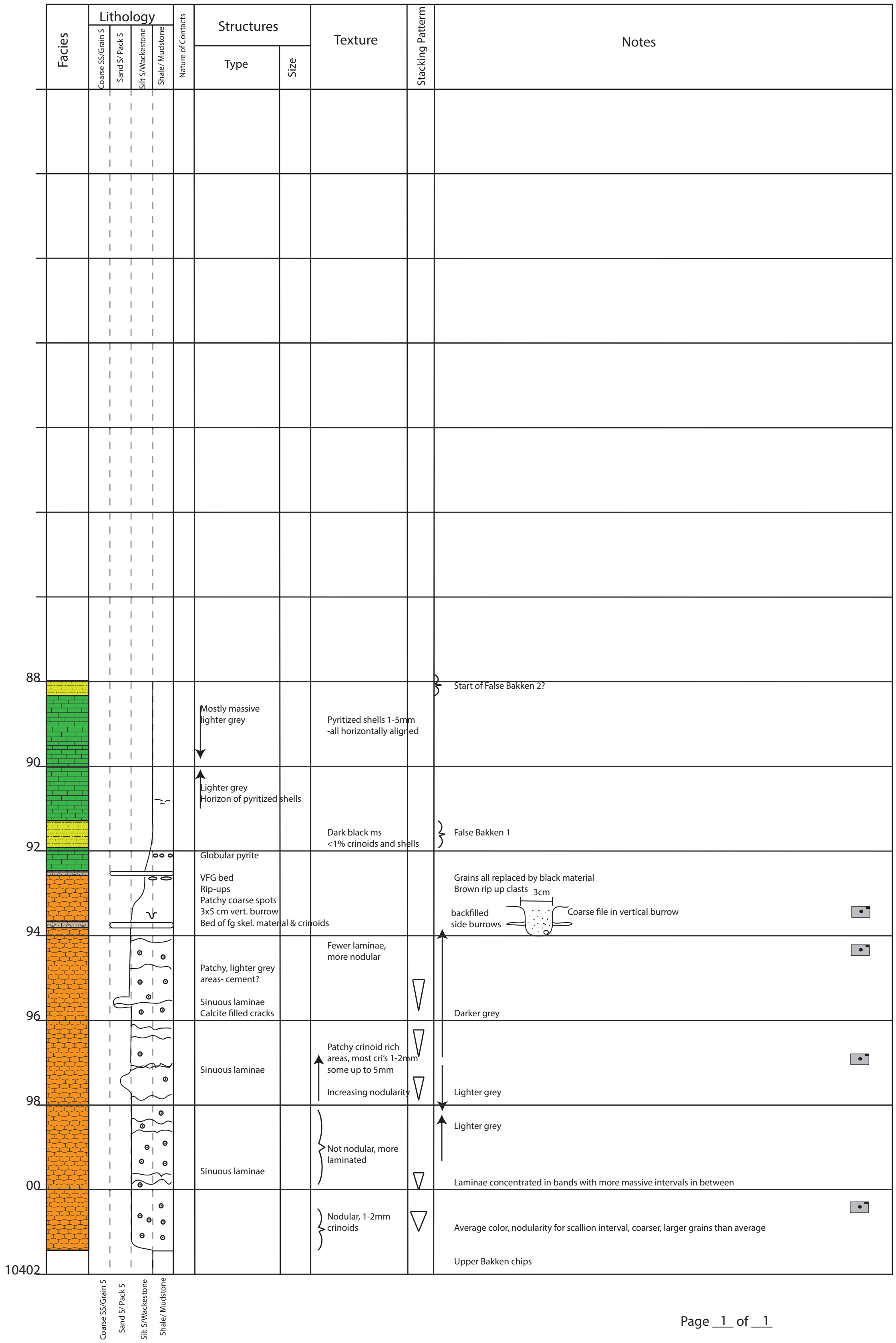
Stratigraphic Interval 104490-10509 Logged by JM Date 3/14/11



Page 1 of 1

Well Meridian MOI Elkhorn 33-11 County Billings State ND

Stratigraphic Interval 10388-10401 Logged by JM Date 11/20/11



Page 1 of 1

Well Shell Western Connell 24-27 County Billings State ND

Stratigraphic Interval 10488-10516 Logged by JM Date 11/19/11

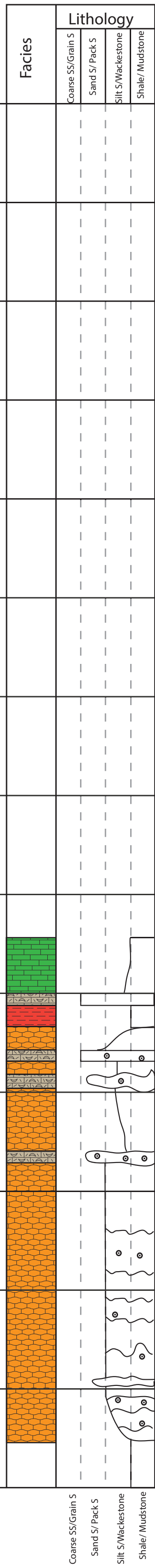
Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
88				Dissolution laminae- not sinuous				Same facies continues to 10480 w/ increased *Chondrites* burrows
90				Dissolution laminae				
92				Massive				
94				Ft bedding 3-4mm thick		Gray carbonate ms		
96								
98				Ft calicte filled horizontal cracks				
0				Ft lt and dk grey alternating beds Silt bed 2-4mm thick				
2								Lighter grey
4								False Bakken 2
6				Mostly massive		v. sparse brach. shells up to 5-8mm some vfg skeletal material		
8				faint bedding vfg shell bed w/ rip-up clasts		v. sparse recrystallized shells up to 5mm		False Bakken 1
10				Mostly massive FG skeletal debris bed w/ dark laminae Calcite filled vertical cracks		Dark grey carb. mud		
12								Missing section
14				Stylolitic sinuous laminae		lt grey slightly nodular facies 1-3mm crinoids		Crinoids scattered throughout, more concentrated in laminae, No contact with Upper Bakken
10516								

Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 1

Well Stephens Energy BR 21-29 County Billings State ND

Stratigraphic Interval 10660-10671 Logged by JM Date 11/19/11



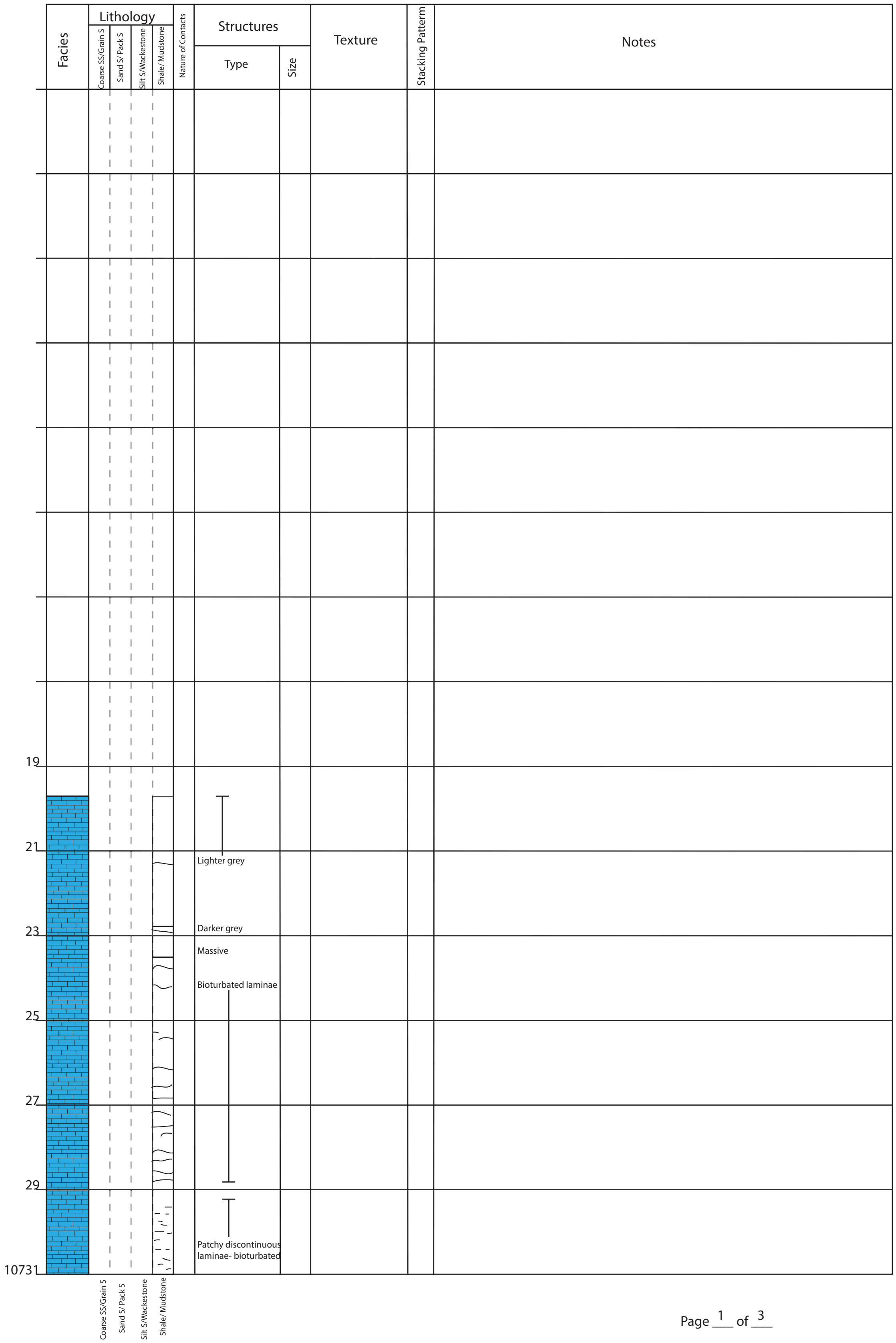
Depth	Structures: Type	Size	Texture	Stacking Pattern	Notes
61			Sparse thin shells		Start of FB 2? Darker Darker
63	Massive black ms Globular pyrite		Sparse pyritized brach shells		FB 1 Darker
65	High shell conc. in laminae bed Horiz. filled cracks		v. sparse crinoids crinoid and brach frags		
67	Few grains Darker, more laminae Scatter sinuous lam.		Some larger crinoids +brach frags up to 1.5cm		Crinoids focused in laminae
69	Calcite filled horiz. cracks Globular pyrite				Medium gray-brown Slightly less nodular for Scallion Interval, avg grain size and abundance
10671	Abundant pyrite in cracks along base of LP -dewatering of Bakken Concretions in top of U Bakken		crinoids 1-2mm Nodular texture		Upper Bakken

Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 1

Well Tenneco Oil Mee USA 3-17 County Billings State ND

Stratigraphic Interval 10719-10731 Logged by JM Date 3/13/11



Page 1 of 3

Well Tenneco Oil Mee USA 3-17 County Billings State ND

Stratigraphic Interval 10731-10759 Logged by JM Date 3/13/11

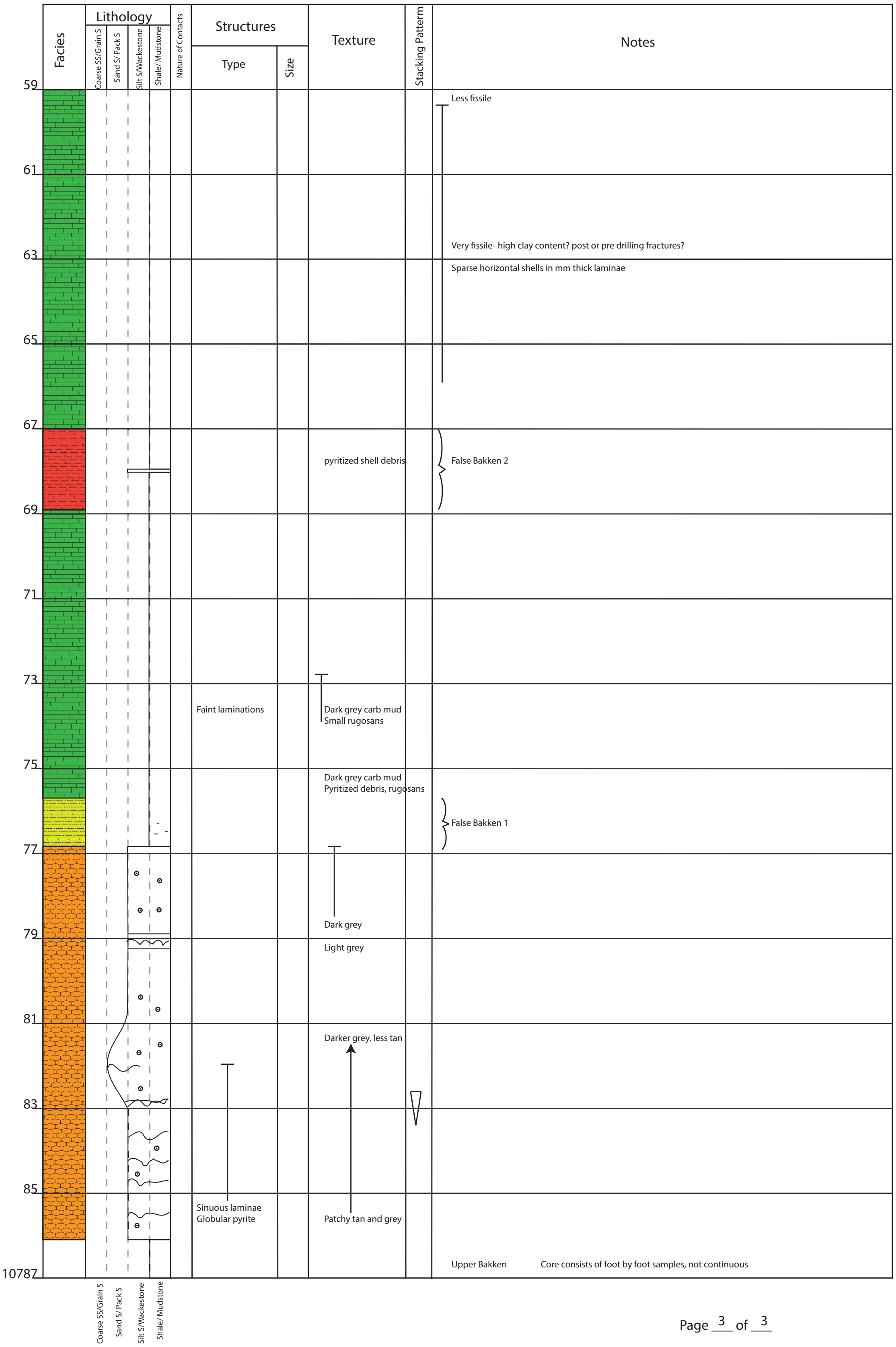
Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
31								
33								
35								
37				Patches of bioturbated laminae				
39				Sub parallel laminae		Dark grey		
41				Laminae set		lighter grey		
				laminae sets		lighter grey		
43				Laminae sets				
45				Slightly sinuous laminae		Light grey		
						Dark grey		
47				Faint laminae-bioturbated		Scare crinoids/ shell debris		
						Lightest grey		
						Lighter grey		
49						Dark grey-black vf shell debris, crinoids		False Bakken 3?
51						Lightest grey		
53						Lighter grey		
55				Ft sinuous laminae		Brown-dark grey		
57				Faint laminations				
				Massive		Dark grey		
10759								

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Page 2 of 3

Well Tenneco Oil Mee USA 3-17 County Billings State ND

Stratigraphic Interval 10759-10787 Logged by JM Date 3/13/11



Page 3 of 3

Well Florida Exploration Federal 34-1 County Mountrail State ND

Stratigraphic Interval 10457-10464 Logged by JM Date 11/17/11

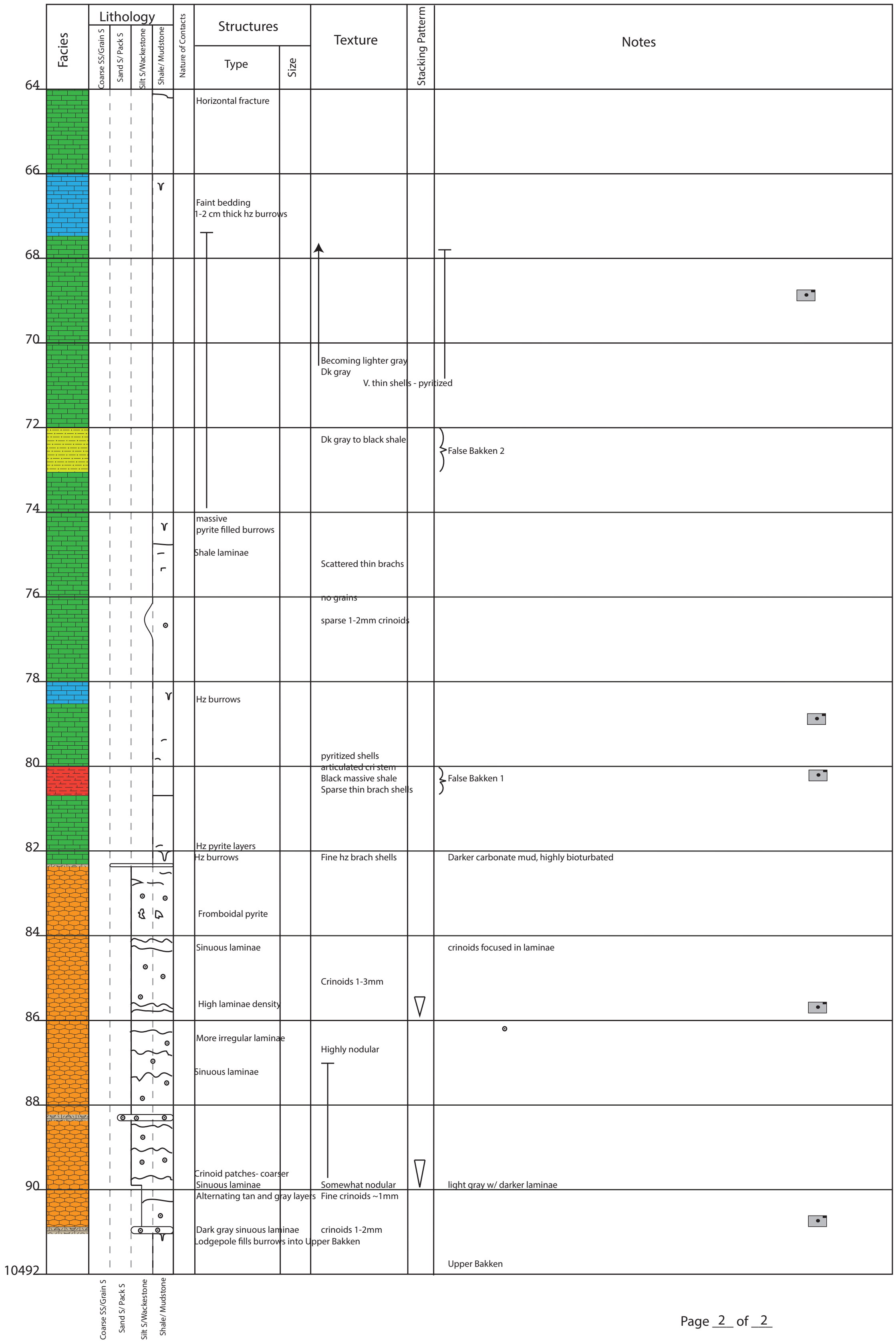
Facies	Lithology (Coarse SS/Grain S, Sand S/Pack S, Silt S/Wackestone, Shale/Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Pattern	Notes
56							
58							
60							
62							
10464			Mostly massive				Hz calcite filled cracks every 5-15 cm

Coarse SS/Grain S, Sand S/Pack S, Silt S/Wackestone, Shale/Mudstone

Page 1 of 2

Well Florida Exploration Federal 34-1 County Mountrail State ND

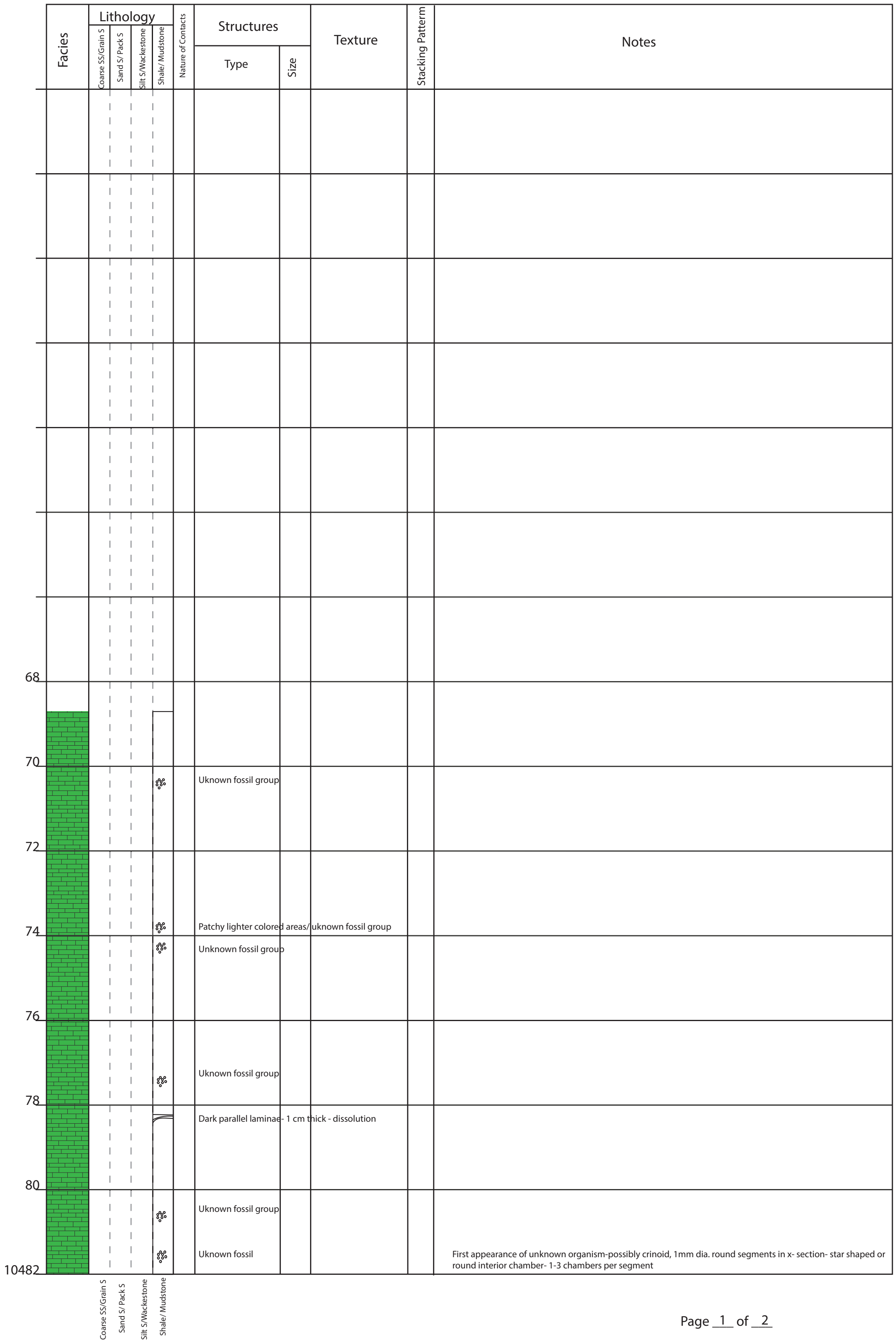
Stratigraphic Interval 10464-10490 Logged by JM Date 11/17/11



Page 2 of 2

Well Whiting Teddy 44-13 TFH County Billings State ND

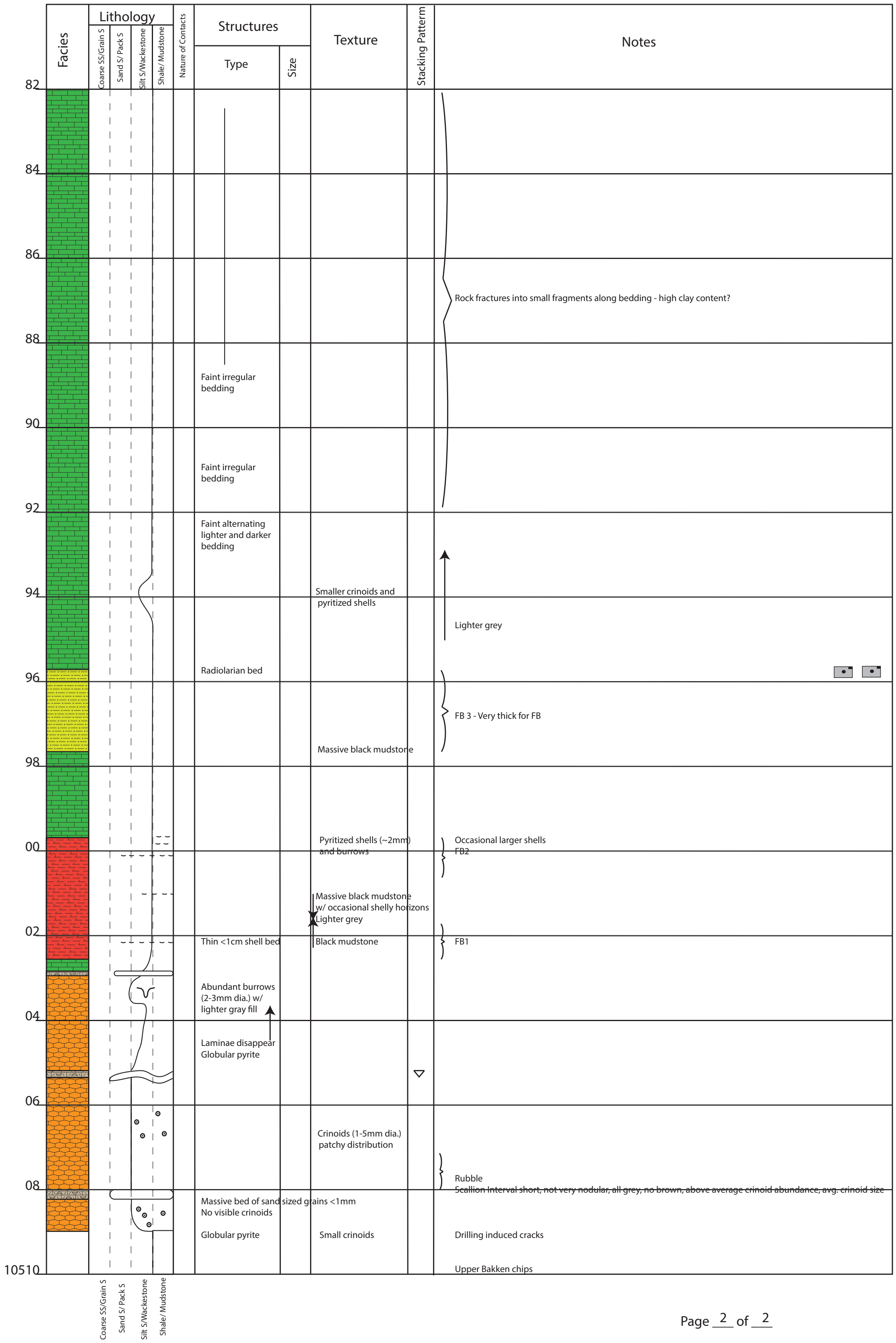
Stratigraphic Interval 10468-10482 Logged by JM Date 11/20/11



Page 1 of 2

Well Whiting Teddy 44-13 TFH County Billings State ND

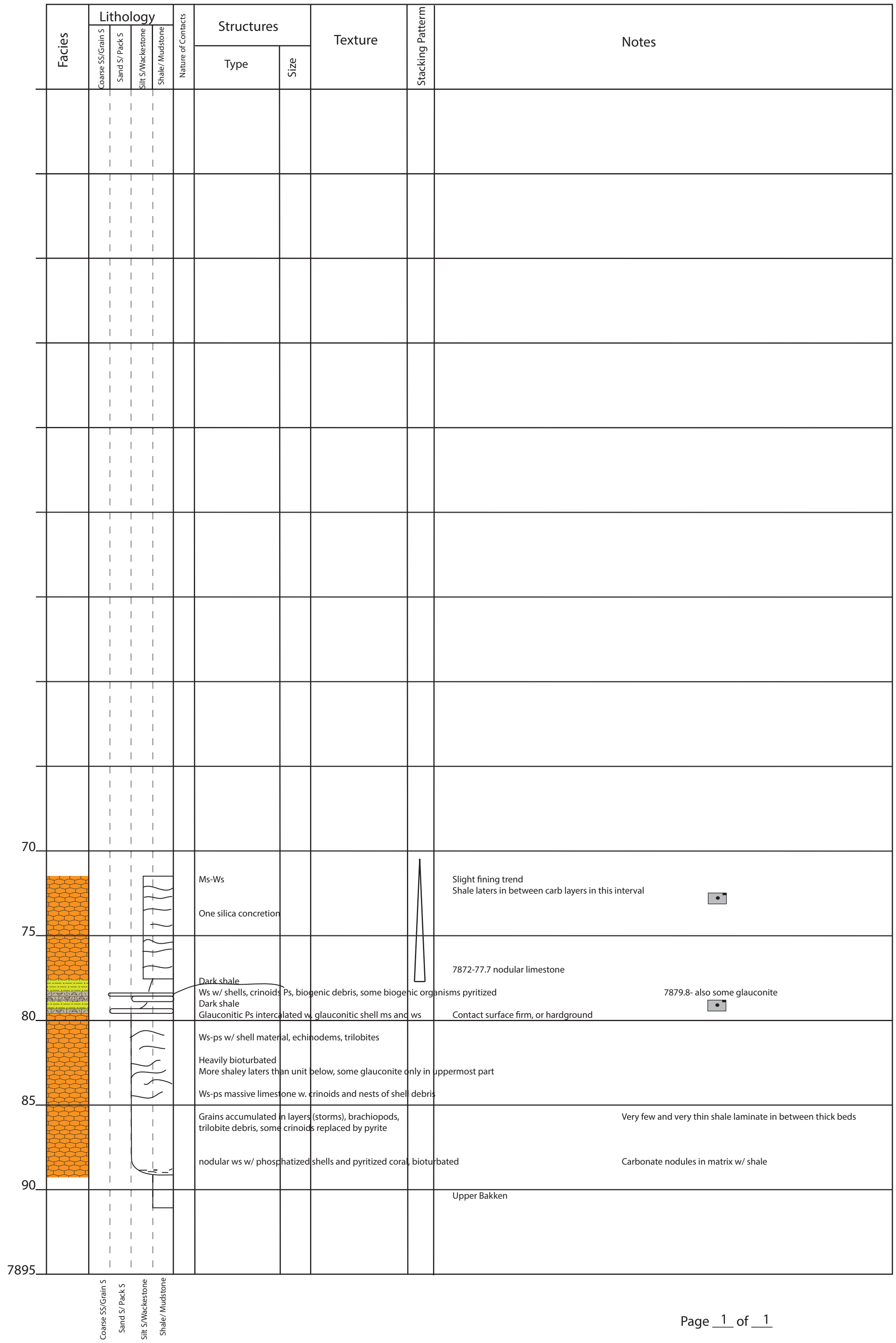
Stratigraphic Interval 10482-10510 Logged by JM Date 11/20/11



Page 2 of 2

Well Clarion Resources Slate 1-24 County Burke State North Dakota

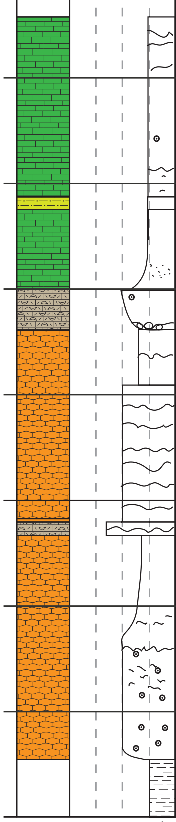
Stratigraphic Interval 7872-7891 Logged by SE Date 3/13/2011



Page 1 of 1

Well Conoco Inc. Skarphol D#5 Well County Divide State ND

Stratigraphic Interval 8905-8920 Logged by JM Date 3/14/11



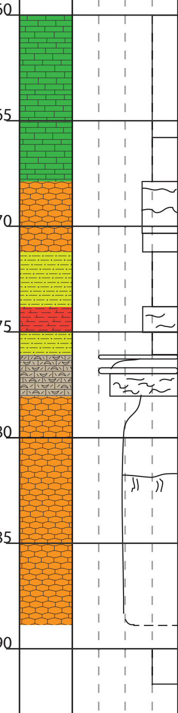
Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
04				Darker gray	Most			
06				Light gray nodules thin laminae	fewest	Sparse large crinoids		
08				Dark gray shale Most glauconite				False Bakken 1
10				Start of gluaconite Laminae around nodules		1-2mm crinoids Coarse skeletal material		
12								
14				Laminae less discontinuous		Lt gray Dark brown Horizontal brachs		
16				Dark patches BT or laminae?		Lt gray		
18				Irregular contact		Small cri's, brachs Dark gray-brown Globular pyrite		Upper Bakken
8920								

Coarse SS/Grain S
Sand S/ Pack S
Silt S/Wackestone
Shale/ Mudstone

Page 1 of 1

Well Maxus Exp. Carus Fee 21-19 County Dunn State ND

Stratigraphic Interval 11260-11292 Logged by SE Date 03/13/2011



Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
60				Nodular limestone, MS w/ peculiar structures within nodules				
65				Nerites More massive, MS Noduar limestone, M				
70				MS, structureless/massive w/a abundant shell debris Largely massive, some faint laminations (not laterally continuous) shale w/ shell debris and laminations		Transition between the two-calcite filled bioturbation (diagenetic effect)		70.9 -71.7: bioturbated and shells 71.7-73.8: black shale 73.8-75: shale w/ shell debris
75				Black shale xcm thick shell accumulations PS w/ shell debris WS-PS nodular carbonate, shell debris and many sub mm particles w more shale interlayers than below				75-76.5: black shale Top: slight fining
80				highly bioturbated WS-PS nodular carbonate: crinoids, shell debris and sub mm particles Highly bioturbated				
85				Contact in pieces, destroyed during coring process?				
90								Upper Bakken
11295								

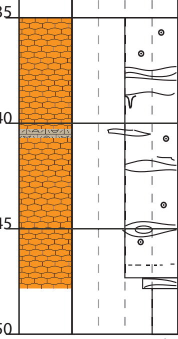
Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 1

Well Simray GP Roberts 1-13H County Dunn State ND

Stratigraphic Interval 110635-10648 Logged by SE Date 3/15/2011

Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
35			Crinoids, shells, some corals				Random orientation of shells/grains because of intense bioturbation
			Zone of more shale "dissolution" laminae				
40			Shell bed 1 cm thick		Crinoids, shells		
			Nodular ls but relatively compact				
45					Crinoids, shell frags (brachiopods), trilotbites		
					Crinoids, shell frags, trilobite debris, randomly oriented-BT		
			Dark vaguely laminated mudstone with carbonate concretions				
10650							Upper Bakken

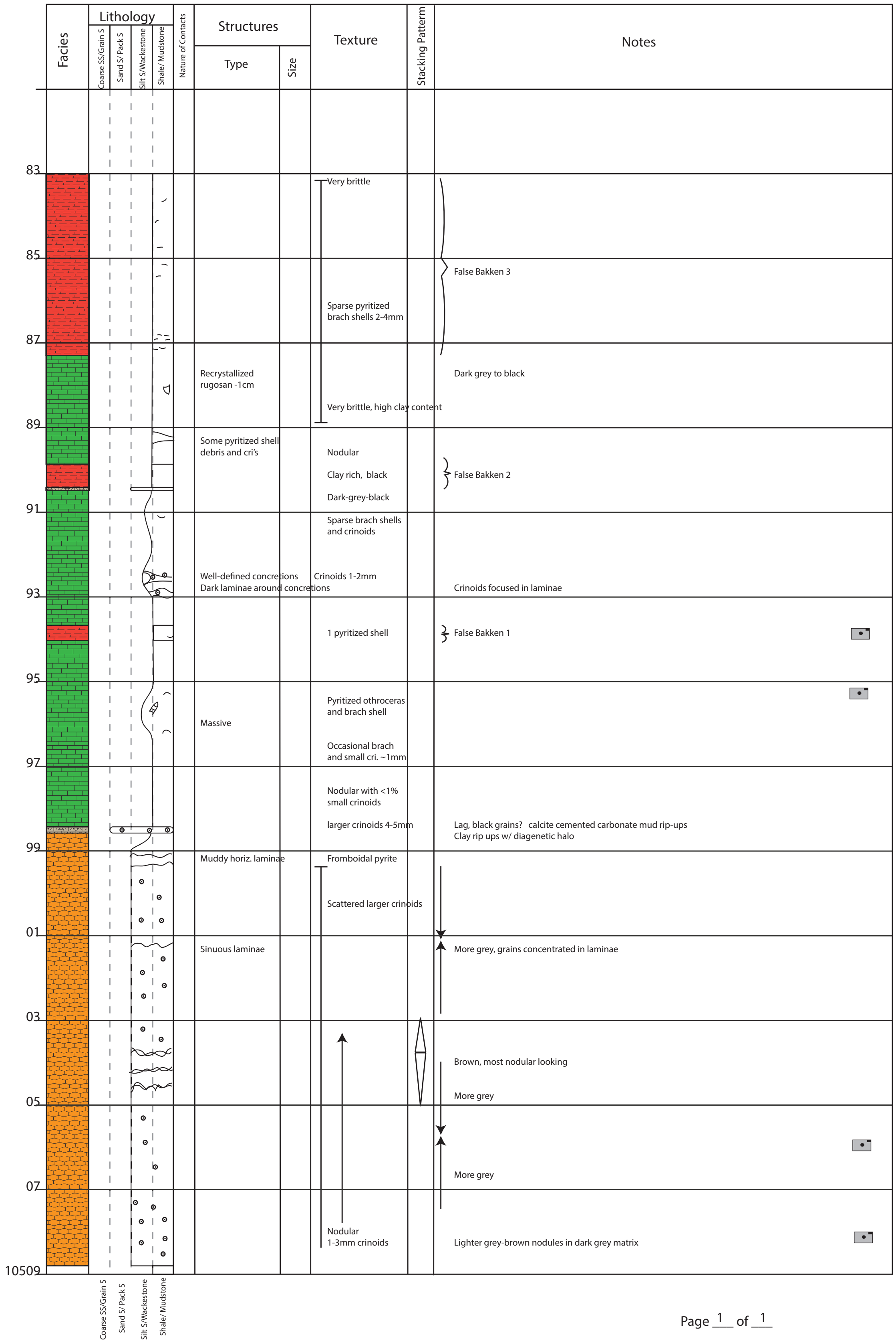


Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 1

Well Socony Vacum Angus Kennedy County Dunn State ND

Stratigraphic Interval 10483-10509 Logged by JM Date 11/17/11



Page 1 of 1

Well Am. Hunter Ahel et al Grassy Butte   County McKenzie   State ND

Stratigraphic Interval 11214-11242   Logged by JM   Date 11/18/11

Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
14–16				Laminae more sinuous				
16–18				Dk hz burrows w/ lighter rim Short vertical burrows		Recrystallized cri - 5mm		
18–20				Short vertical burrows - *Chondrites*				Alternating light/dark layers
20–22				Lenses of BT Hz burrows w/ dark fill Mostly massive				Medium gray carbonate mud
22–24				Sinuous laminae				Scattered small crinoids <1mm focused in laminae
24–26				Synsedimentary cracks into carbonate mud -hard ground? Sinous laminae band 2-3cm thick Black replaced solitary rugosan				
26–28				Vertical burrow Ft horizontal cracks w/ white fill Massive				Very brittle/clay rich, massive
28–30				Thin lag or shell bed				False Bakken 1
30–32				Mostly massive Bands of dark sinuous laminae		Vf recrystallized brach and crinoid fragments Crinoids and vf (<1mm) black grains		
32–34				Sinuous laminae Bioturbated mud Small vertical burrows		Crinoids and brach frags 1-2mm No nodular texture		Burrows focused in mud, grains focused in sinuous laminae
34–36				Burrow traces in lighter gray mud Sinuous laminae Dark grains -phosphate or dead oil?				Scattered replacement pyrite
36–38				Sinous laminae		Larger crinoid grains up to 2cm		
38–40				Bands of dark sinuous laminae		Gastropod 2-3 cm long		Noticeably high crinoid abundance for Scallion interval
40–11242				Sharp but irregular contact		Nodular-medium-dk gray and brown Abundant crinoids 1-2mm Pyritized grains 1-2mm		Upper Bakken

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Page 1 of 1

Well Astral Stenehjem 43-27 County McKenzie State ND

Stratigraphic Interval 10845-10872 Logged by JM Date 3/11/11

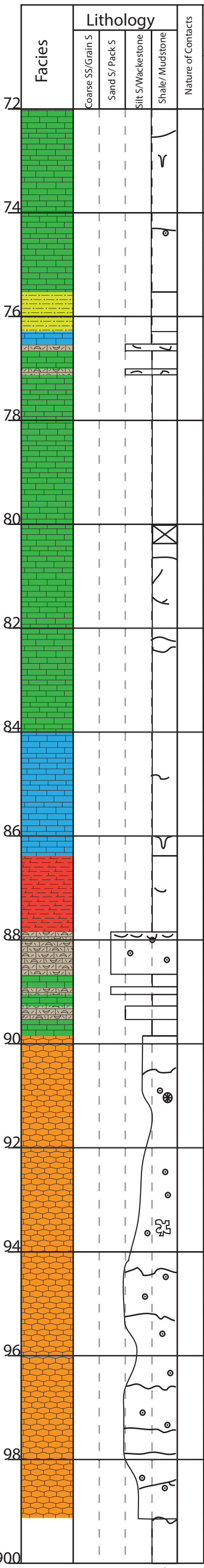
Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
44								Dark gray
46								Alternating light and dark gray layers
						Tiny crinoids		Brown
48				Dark laminae				Light gray
50				Light gray storm bed Biotubated layer Gray storm bed				
52				Light gray storm bed Light gray storm bed				
54				Calcite filled vertical crack Light gray storm bed Parallel laminae				
56				Sinuous laminae				
58								
60								Dark gray
62				Fractures Planar laminae				
64				Planar laminae Bioturbated bed Ft sinuous laminae				Draped ripple
66				Massive				Light gray
68								
70				Alternating light gray dark gray storm beds				
10872								

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Page 1 of 2

Well Astral Stenehjem 43-27 County McKenzie State ND

Stratigraphic Interval 10872-10900 Logged by JM Date 3/11/11



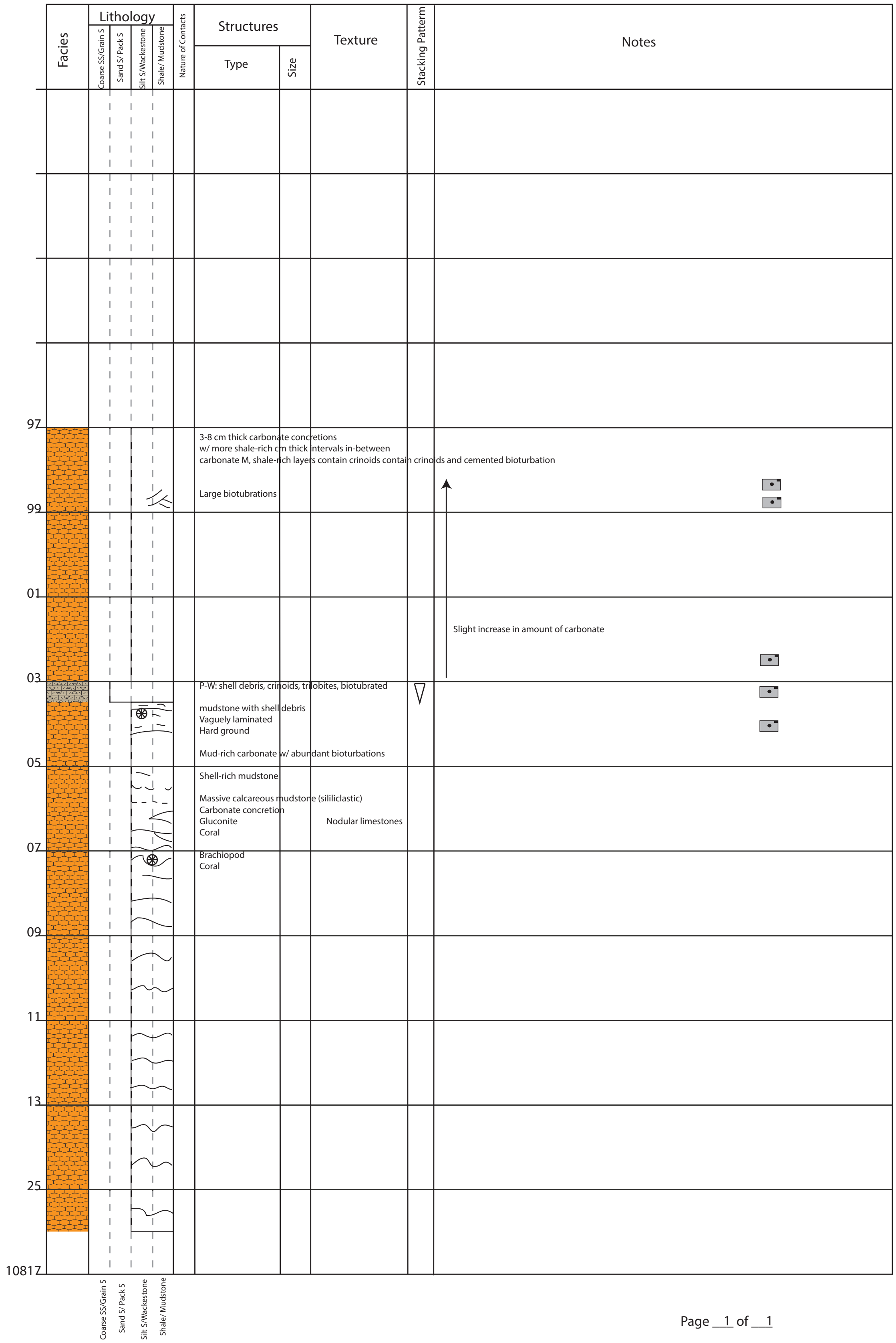
Depth	Structures: Type	Size	Texture	Stacking Patterm	Notes
72	Ripple Sinuous laminae Vertical BTs				
74	Some faint laminae		Sparse crinoids Gray Black		False Bakken 2
76					
78	Massive				Gray
80	Faint laminae Vertical fracture Subhorizontal fracture				
82	Nodule/laminae				Gray
84	Sub hz fractures Massive		V sparse brachs Gray-brown		Brown here - diagenetic? drilling mud?
86	Burrows? BT Horizontal shell beds Less BT		Gray Dark shale, calcareous		False Bakken 1
88			V. small crinoids		
90	Laminae in nodule		Rugosan		
92	Dark laminae Branching nodule				
94			Some larger crinoids		Crinoids focused in laminae
96	Dark sinuous laminae				Dark gray carbonate mud
98	Sub hz fractures Irregular contact		Small crinoids-1mm		Upper Bakken
10900					

Coarse SS/Grain S
Sand S/ Pack S
Silt S/Wackestone
Shale/ Mudstone

Page 2 of 2

Well Exter Exploration Schmitz 8-30 County McKenzie State ND

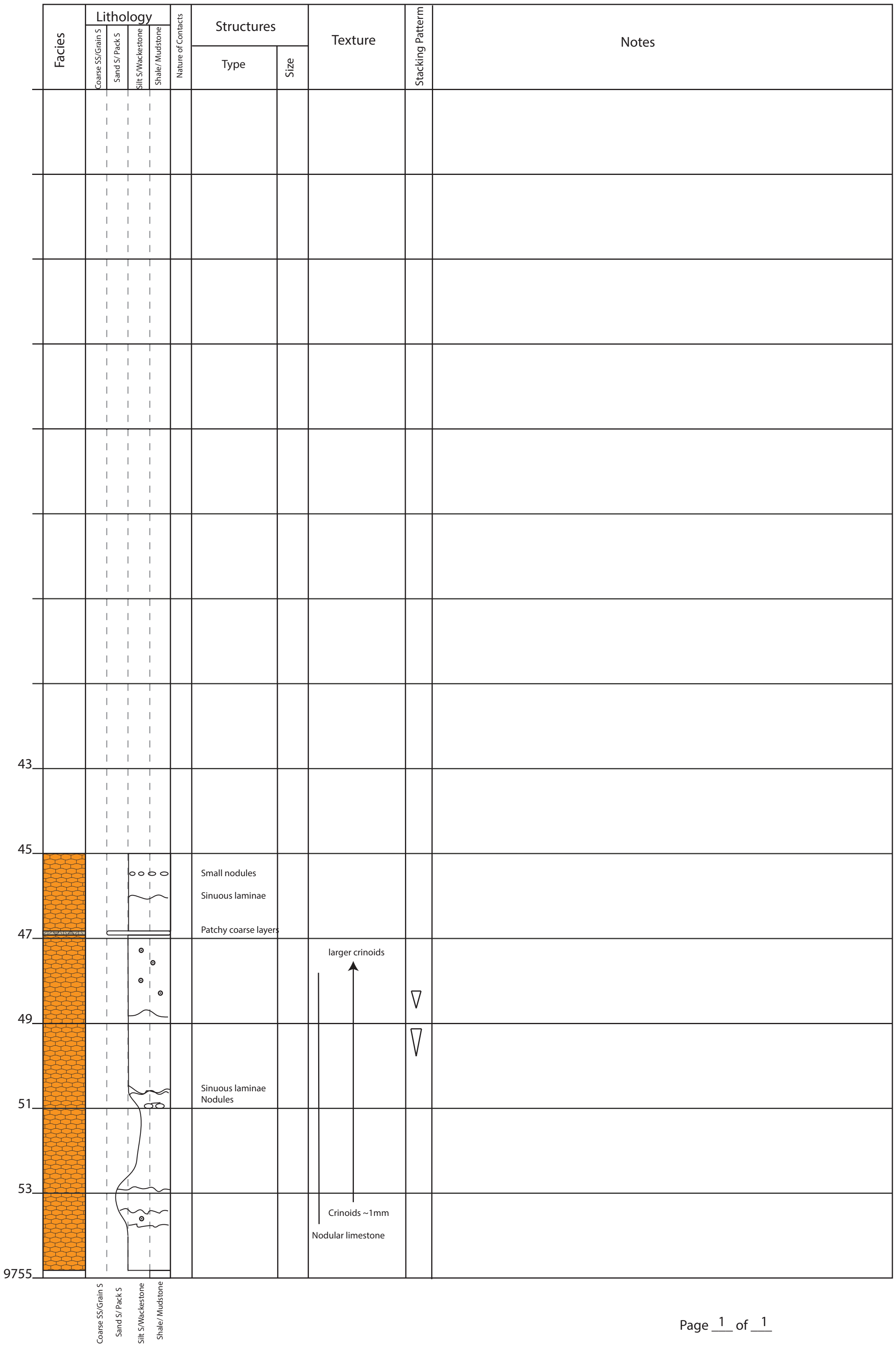
Stratigraphic Interval 10797-10815 Logged by SE Date 03/14/11



Page 1 of 1

Well Headington Oil Sak Fed. 13x-35 County McKenzie State ND

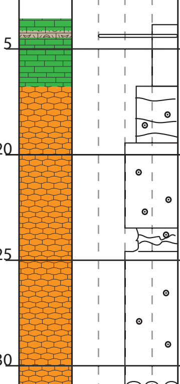
Stratigraphic Interval 9743-9755 Logged by JM Date 3/12/11



Page 1 of 1

Well Helis Levang 3-22H　　County McKenzie　　State ND

Stratigraphic Interval 10614-10633　　Logged by SE　　Date 3/12/2011



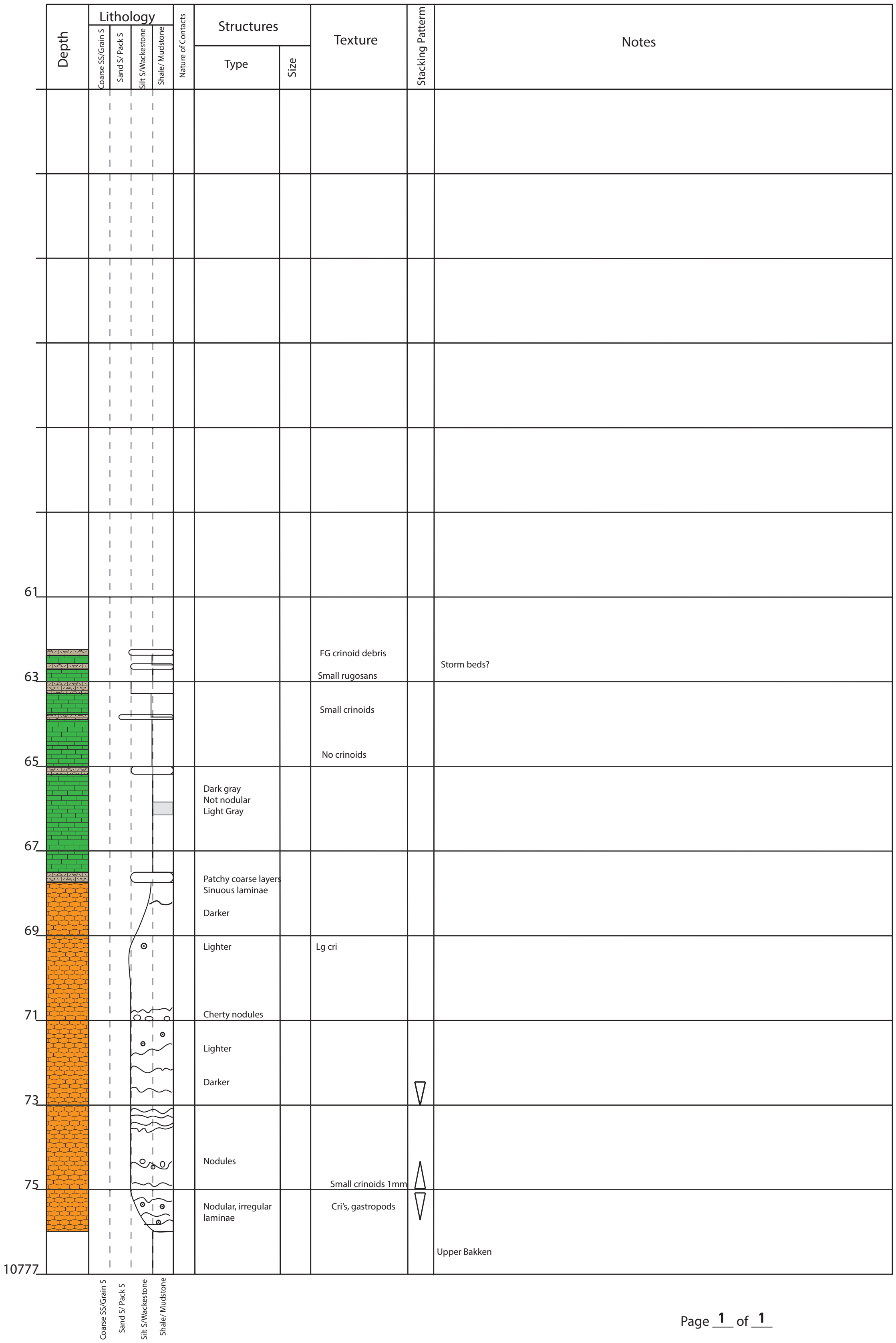
Depth	Facies / Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Size	Texture	Stacking Patterm	Notes
10							
			Lamina w/ crinoid particles				
15			Slightly greenish shale rich carbonate In places vaguely hz laminated				Some elongate components -Tasmanites?
			More carbonate rich, more shale rich intervals		Crinoids corals		Small phosphate grains?
			6-10 cm thick carbonate layers w/ dark shale (dissolution seams) in between				
20			Corals, echinoderms, phosphate clasts (small)				
			Shale/ dissolution seams every 2-5 cm		Crinoids -typical lower Lodgepole facies		Lots of crinoids, small shells
25			Relatively massive, few distinct facies variations				
30					Crinoids		
10635							

Coarse SS/Grain S　Sand S/ Pack S　Silt S/Wackestone　Shale/ Mudstone

Page 1 of 1

Well Helis Oil and Gas Linseth 4-8H County McKenzie State ND

Stratigraphic Interval 10761-10777 Logged by JM Date 3/12/11



Page 1 of 1

Well Pennzoil Spring Creek 27x-31BN County McKenzie State ND

Stratigraphic Interval 10752-10760 Logged by JM Date 11/18/11

Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
52				Calcite and phospate? filled crack				
54				Well defined nodules/ concretions				
56				Thick dark laminae layer, lots of globular and replacement pyrite		Highly nodular		
58				Sub horizontal dark layers Dark horizontal layers		Very sparse shells up to 2 cm- phosphatized or replaced by dead oil>		
10760								

Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 2

Well Pennzoil Spring Creek 27x-31BN County McKenzie State ND

Stratigraphic Interval 10760-10788 Logged by JM Date 11/18/11

Depth	Structures (Type)	Texture	Notes
60	Vertical burrow w/ pyritized fill	Tan and grey nodular texture w/no grains	
62	Concretion of gray carbonate mud w/ differential compaction around it Pyritized shell frags up to 10mm		
64	Burrow horizon Darker bands Dense horizontal burrow patches		
66	Rimmed burrows Abundant horizontal burrows	Dk hz laminae zones 1-2 cm thick	Lighter gray Bands close to regularly spaced laminae bands may be just be darker depositional lithology
68	Mostly massive Dark sub-hz layer Dk hz thin laminae	No grains Small shell frags in laminae (<1mm)	
70	Dk sinuous laminae Faint bedding/laminations	V sparse small brach frags	Fine bioclasts in laminae
72	Massive	Med gray carb ms no grains	
74	Fine hz filled cracks	More carbonate, less clay Clay-rich, very dk gray mudstone -no grains	Darker gray False Bakken 1
76	Lighter gray filled burrows 3-5mm Dark gray sinuous laminae interval	Scattered hz shells	Darker
78	Pyrite horizon Vertical cracks calcite and black fill -dead oil or phospate repalced grains	Patchy crinoids Scattered lg crinoids 1+cm	Darker gray
80	Sinuous laminae around micrite clasts Massive Sinuous laminae	Bioturbated <1% crinoids	
82	Thick laminae- micrite clasts in laminae High # of laminae	Highly nodular	Scattered pyrite replacement Crinoids concentrated in dissolution laminae
84	Patchy concentrations of crinoids Thicker sinuous laminae 2-4mm thick	Crinoids 1-4mm	
86	Sinuous15+cm vertical burrow	Gray-gray-brown nodular texture Crinoids 1-2mm	Possibly some dead oil filling voids at base of Scallion Upper Bakken chips
10788			

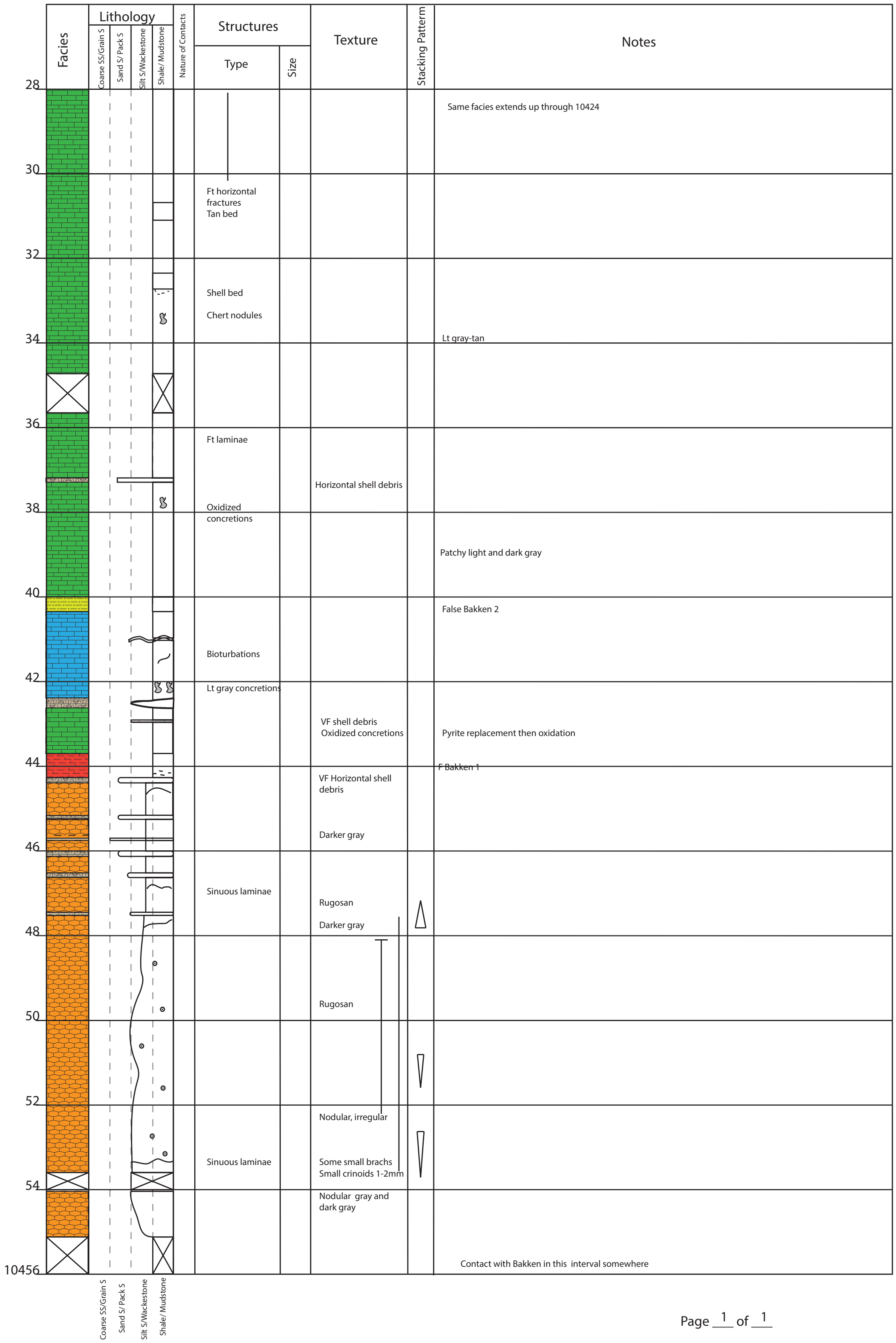
Column headings: Facies; Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone); Nature of Contacts; Structures (Type, Size); Texture; Stacking Patterm; Notes

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Page 2 of 2

Well Amerada Hess Sara G Barstad County Mountrail State ND

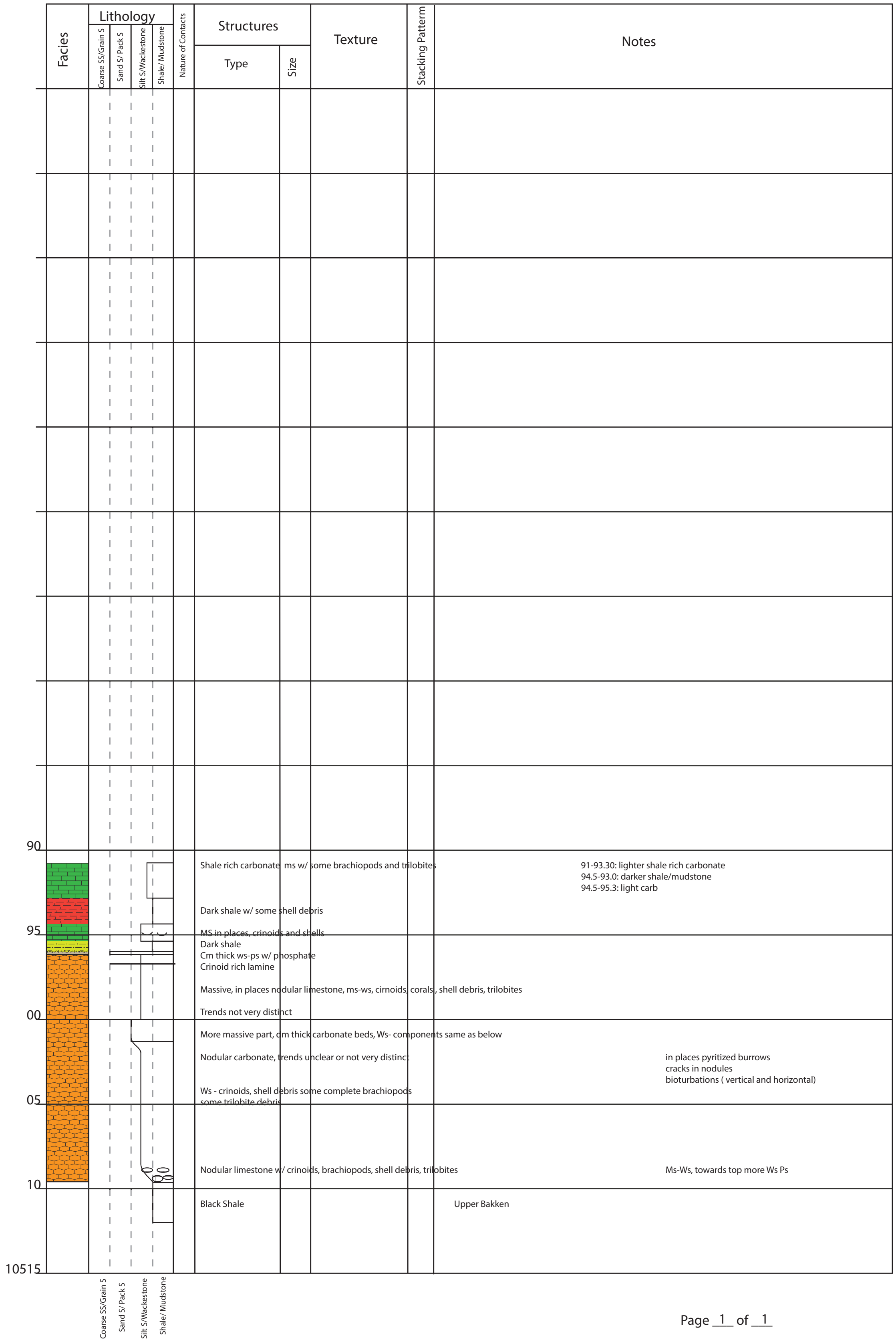
Stratigraphic Interval 10428-10456 Logged by JM Date 3/13/11



Page 1 of 1

Well Amerada Hess J Horst 1-11H County Mountrail State ND

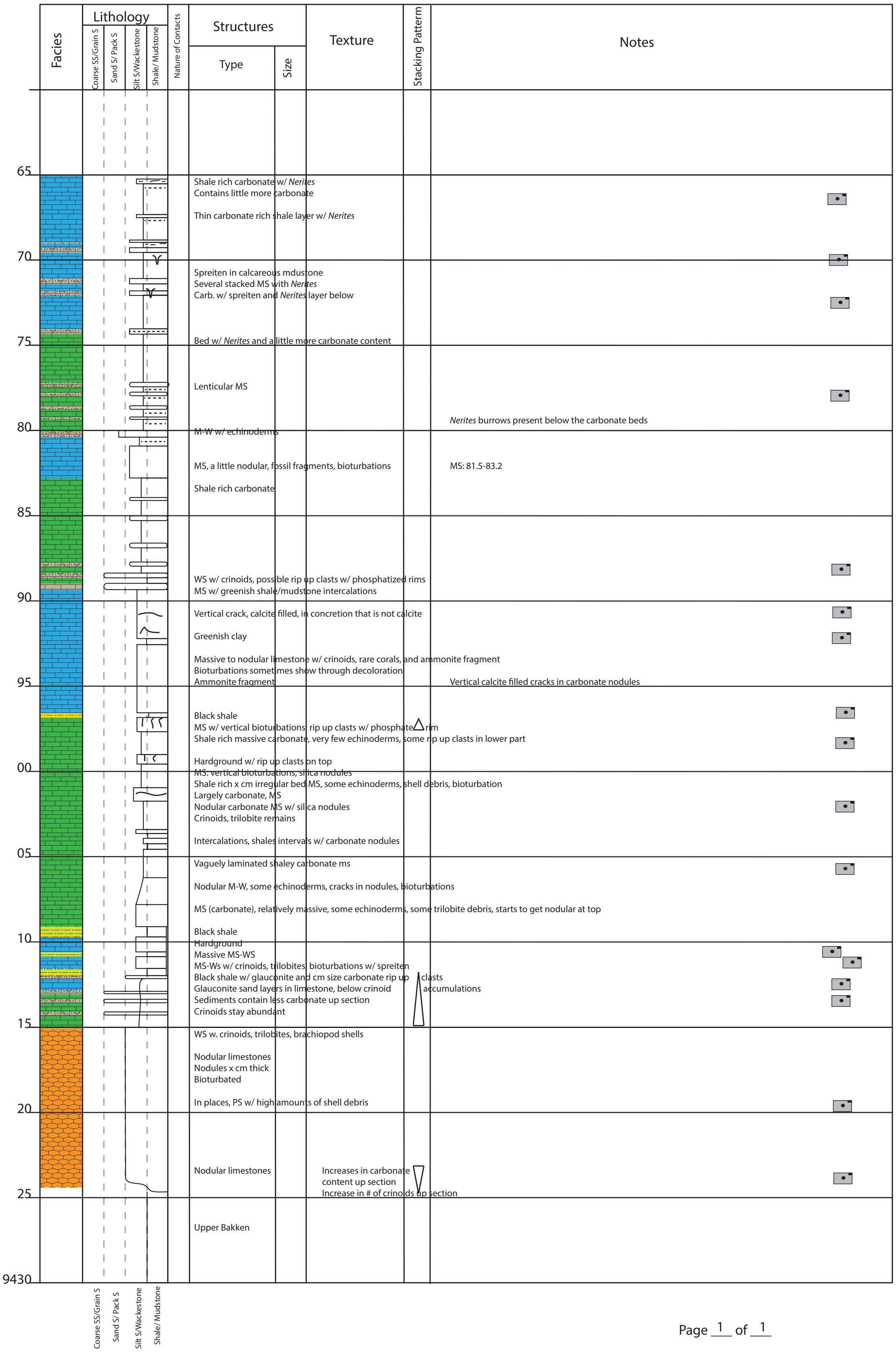
Stratigraphic Interval 10491-10512 Logged by SE Date 3/12/2011



Page 1 of 1

Well Amerada Hess State ND 1-11H County Dunn State ND

Stratigraphic Interval 9365-9425 Logged by SE Date 3/11/2012



Page 1 of 1

Well EOG Resources Sidonia 1-06H County Mountrail State ND

Stratigraphic Interval 8663-8691 Logged by JM Date 3/12/11

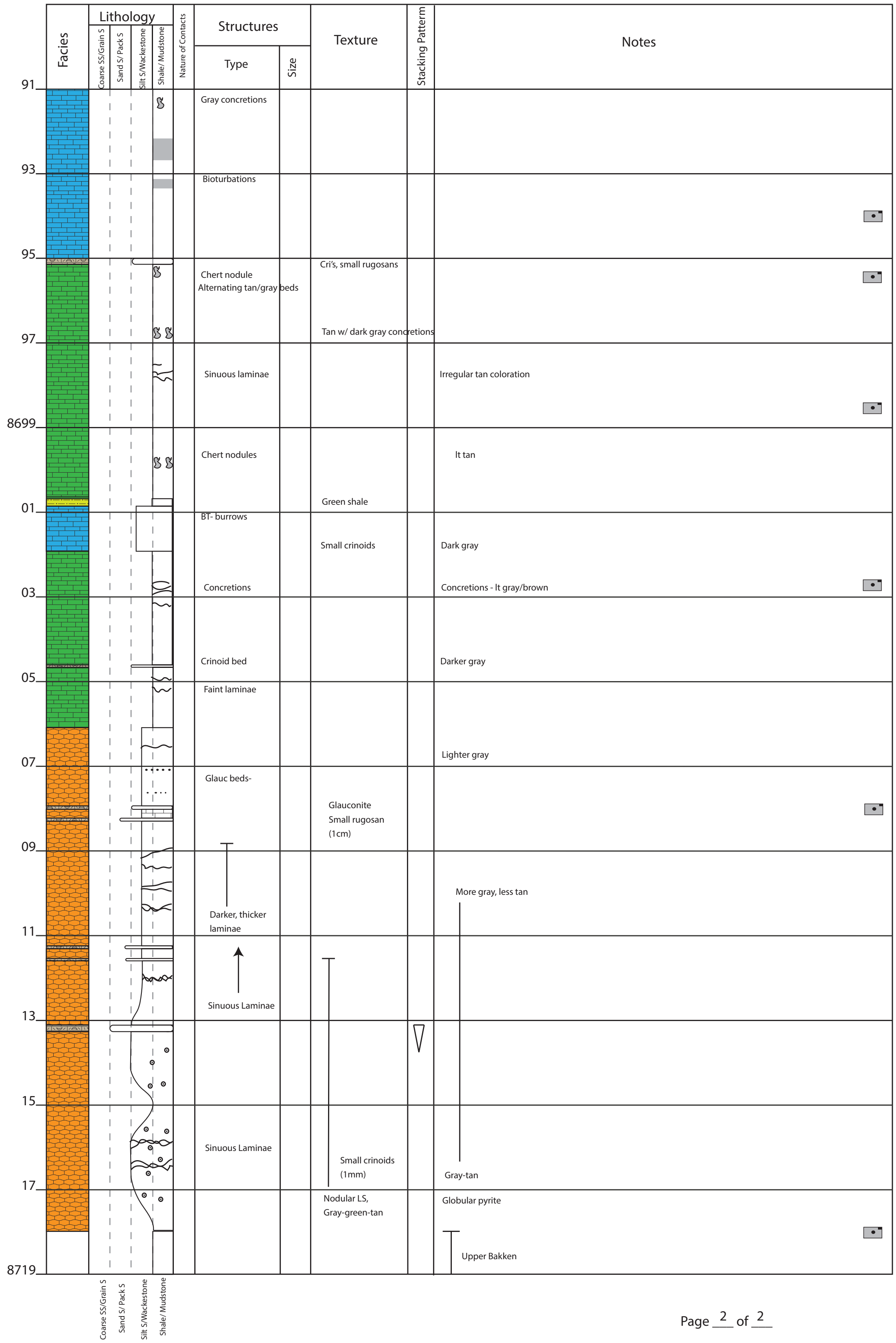
Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/Pack S, Silt S/Wackestone, Shale/Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
63				Concretion Concretion				
65				Conc. Conc. Conc.				
67				Dark laminae Conc. Small cherty nodule layer				
69				White layers Concretions White layer Conc. lt gray				Concretions not calcite- chert?
71				Laminae Bioturbations		Dk gray Lt gray		
73				Bioturbations Debris layer Laminae		Dk gray Crinoids, rip ups		
75				Chert layer on top of white layer				
77				White layer Parallel laminae		crinoids		White layers, do not fizz, ash beds?
79				Calcite nodules		Darker gray		
81				Conc. Vertical burrow				
83				Lt gray concretion				
85				Small gray-white nodules Gray laminae w/ tan in between		Burrows		
87				Laminations Back filled burrow				
89				Laminae Chert Tan nodule Vertical burrow Laminae				
8691								

Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 2

Well EOG Resources Sidonia 1-06H County Mountrail State ND

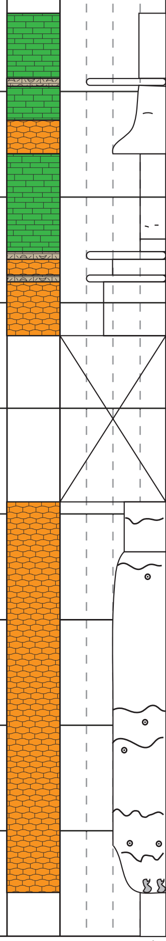
Stratigraphic Interval 8691-8719 Logged by JM Date 3/12/11



Page 2 of 2

Well EOG Resources Liberty 2-11H County Mountrail State ND

Stratigraphic Interval 9575-9592 Logged by JM Date 3/12/11



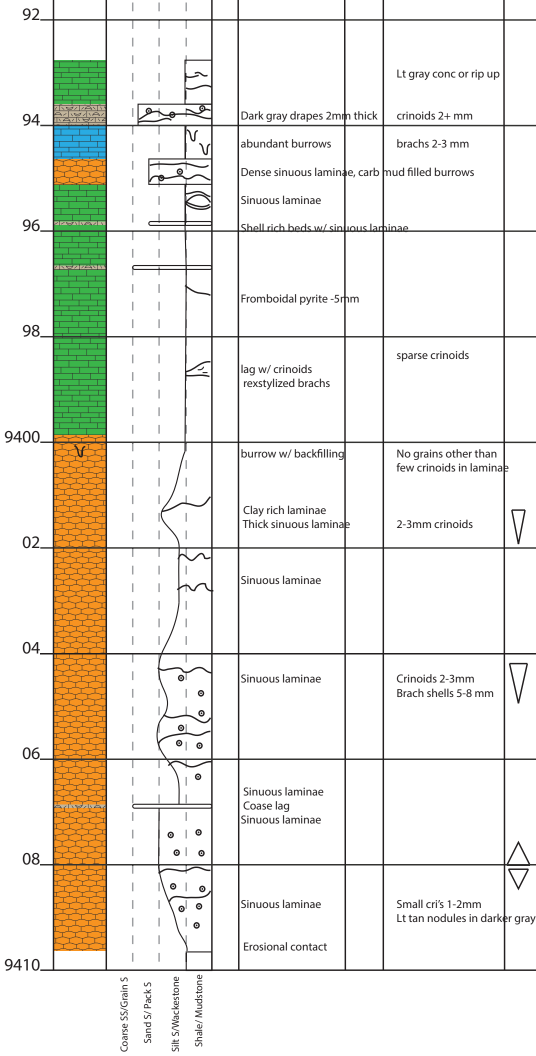
Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures Type	Structures Size	Texture	Stacking Patterm	Notes
74				Black-dark grey				
76				Dark grey		Brachs, cris Brachs, cris		
78				Dk grey Lt grey Dk grey Lt grey		Scattered shell frags Vfg skeletal debris		Darkest facies
80								
82								
84				Sinuous laminae rip up clasts		Sparse crinoids		light grey
86								
88				light brown laminations				
90				Globular pyrite Nodules at contact BT		Crinoids		Patchy grey and tan Upper Bakken
9592								

Coarse SS/Grain S | Sand S/ Pack S | Silt S/Wackestone | Shale/ Mudstone

Page 1 of 1

Well EOG N & D 1-05 H County Mountrail State ND

Stratigraphic Interval 9393-9410 Logged by JM Date 11/17/11



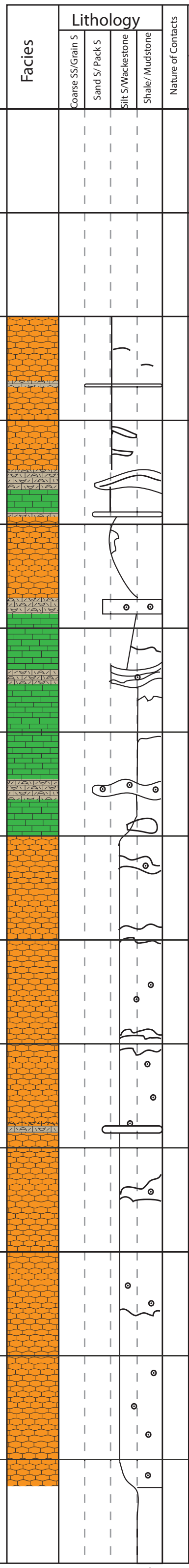
Depth	Structures: Type	Size	Texture	Stacking Patterm	Notes
92			Lt gray conc or rip up		
94	Dark gray drapes 2mm thick		crinoids 2+ mm		calcite filled hz cracks, scattered vf glauc grains, pyrite filled burrows
	abundant burrows		brachs 2-3 mm		tan
	Dense sinuous laminae, carb mud filled burrows				
	Sinuous laminae				
96	Shell rich beds w/ sinuous laminae				Iron staining
	Fromboidal pyrite -5mm				
98	lag w/ crinoids rexstylized brachs		sparse crinoids		vf glauconite grains -scattered
9400	burrow w/ backfilling		No grains other than few crinoids in laminae		
	Clay rich laminae Thick sinuous laminae		2-3mm crinoids		Crinoids concentrated around laminae
02	Sinuous laminae				
04	Sinuous laminae		Crinoids 2-3mm Brach shells 5-8 mm		Glauconite replacement of small (1mm) shells- glauconite horizon?
					Nodular facies lighter tan more color variation than other cores
06	Sinuous laminae Coase lag Sinuous laminae				
08	Sinuous laminae		Small cri's 1-2mm Lt tan nodules in darker gray matrix		
	Erosional contact				Upper Bakken
9410					

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Page 1 of 1

Well Hess St Andes 2413H-1 County Mountrail State ND

Stratigraphic Interval 9040-9064 Logged by JM Date 11/19/11



Depth	Structures: Type	Size	Texture	Stacking Pattern	Notes
40					
42	Horizontal burrows		Scattered fg rexstylized skeletal debris		Darker gray
44	Medium gray concretion 3-4 cm across		Coarse material surrounding concretion		
46	Filled cracks Laminae rich coarse beds Hz burrow traces		Concretionary texture w/ scattered crinoids		Several scattered small iron rimmed concretions or grains 4-5mm
48	Sinuous laminae bed w/ vfg skel material				
50	Concretions become increasingly large up to 8-10 cm Bands of sinuous laminae		crinoid grains 2-3 mm focused in laminae surrounding concretions Concretion rich facies		Lt tan matrix mud included in concretions Grains focused in laminae
52	Bands of sinuous laminae		Nodular- more grey than tan		
54	Irregular beds of fg skeletal debris		Nodular		
56	Lt gray sinuous laminae				Nodularity decreses Scattered glauc replacement
58	Dissoultion laminae increase				
60	Possible horizontal burrows		Sparse crinoids 1-5mm Highly nodular		Lt tan and dark grey - high contrast, nodularity, nodules considerably lighter tan than most cores
62	Micrite nodules at contact w/ U Bakken				Low crinoid abundance Upper Bakken - immature here
9064					

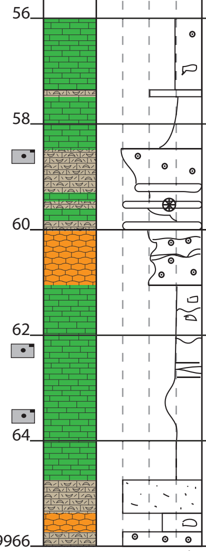
Coarse SS/Grain S
Sand S/ Pack S
Silt S/Wackestone
Shale/ Mudstone

Page 1 of 1

Well Conoco Dickinson State A #83 County Stark State ND

Stratigraphic Interval 9956-9966 Logged by JM Date 3/15/11

Depth	Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures Type	Size	Texture	Stacking Pattern	Notes
56				Well defined chert nodules		Sparse lg crinoids lighter gray micrite		
58						Frags of cylindrical unknown fossils Cri's and rugosans		
60				Sinuously laminated Cherty nodules Cherty nodules		Cri frags		
62				Dark laminae Laminations in cherty layer				
64				Cherty nodules		Sandy grains w/ no skeletal debris Cri frags		
9966								

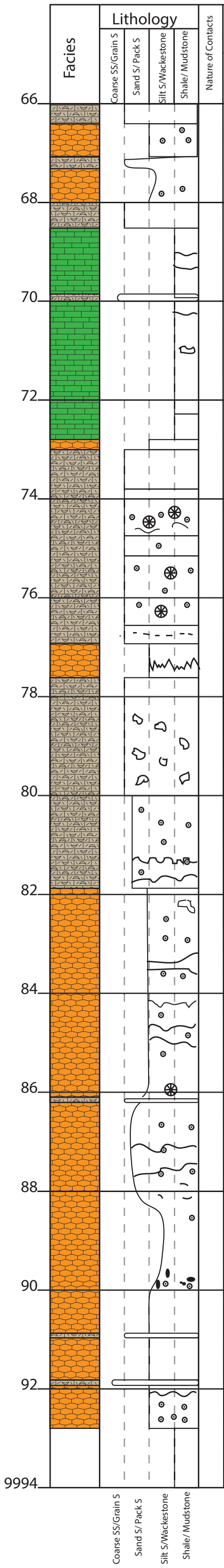


Coarse SS/Grain S
Sand S/ Pack S
Silt S/Wackestone
Shale/ Mudstone

Page 1 of 2

Well Conoco Dickinson State A #83 County Stark State ND

Stratigraphic Interval 9966-9994 Logged by JM Date 3/15/11

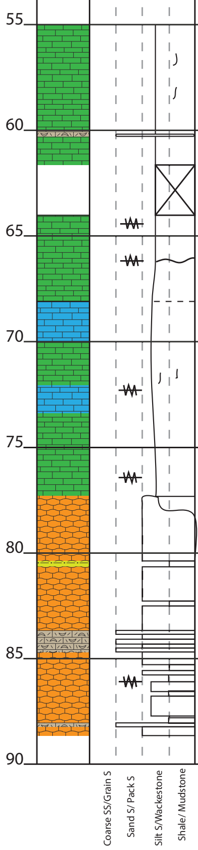


Depth	Structures: Type	Size	Texture	Stacking Patterm	Notes
66–68			crinoids carbonate sand grains crinoids		
68–70	Cherty layers/nodules				
70–72	Cherty nodules		Carbonate sand grains		
72–74	White shale/ash bed		unsorted scattered cri grains sand sized carbonate grains, no skeletal debris		
74–76	Microbial laminations		carb sand grains, lg rugosans crinoids fine sand sized grains		Mound sheddings 9974-9982
76–78	Brach bed Stylolite		Med- fine skeletal debris w/ lg rugosans Vfg debris- brachs and cris Some crinoid grains		
78–80			Sand sized grains w/ microbial laminations		
80–82	Diagenetic chert		Sand sized grains Sand grains and cri frags		
82–84	Diagenetic chert Chert				
84–86	Sinuous laminae Chert nodule Chert bed Chert nodules		Rugosans		
86–88	Sinuous laminae				
88–90	Unsorted, massive Globular pyrite Chert nodule layer		Rexstlyzed brachs and cris		
90–92	No laminae		Black skeletal debris		
92–9994	Sinuous laminae Pyrite filled vertical cracks at contact		Gray-brown patchy coloration		Upper Bakken

Well ARCO No. 1 Simpson County Williams State ND

Stratigraphic Interval 9755-9790 Logged by SE Date 5/25/2011

Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes



Verticaly filled cracks, not compacted, 2 generations of cement inside

Thick calcite filled crack @59 in MS and surrounding drark material

Irregular cm thick PS shell layer (bioturbated)
Star like calcite crack

Core broken up, same as above and below

Bioturbated siltstone event beds and *Chondrites*

Dark WS regularly laminated w/ echinoderms
Black fine-grained material overlying limestone (stylolite)

Lenses of pyritized carbonate siltstones
Chondrites

Chondrites

Healed vertical fractures in carbonate MS

Chondrites

Fractures in carbonate MS-WS, straight (=late_

Intercalations of MS-WS w/ shell fragments and *Chondrites* (light) w/ dark vaguely laminated carb. siltstone

Folded fracture

Scouring of dark carbonate siltstone into laminated and bioturbated light carbonate siltstone-MS w/ rip-up clasts

MS-WS, PS patches or thin layers (cm-scale) w/ shell fragments (no echinoderms)

Chondrites abundant
WS/ patches of PS
Some laminated siltstones- HCS?

MS-WS and micritized dark fracture
Planar laminated (irregular) darker MS w/ higher clay content- this is the material in between nodules
MS-WS w/ PS shell debris lenses and layers — 9781.5: photo possible carbonate siltsone w/ HCS
X cm thck (3-4 cm) shell debris w/ sharp base — This is where Brigham sampled (shell unit)
WS w/ PS lenses (shell debris)

MS w/ substantial crack filled w/ calcite? also triangular cracks w/ calcite? fil
MS nodules, in places surround more clay rich mudstones, vaguely laminated
MS, homogenous

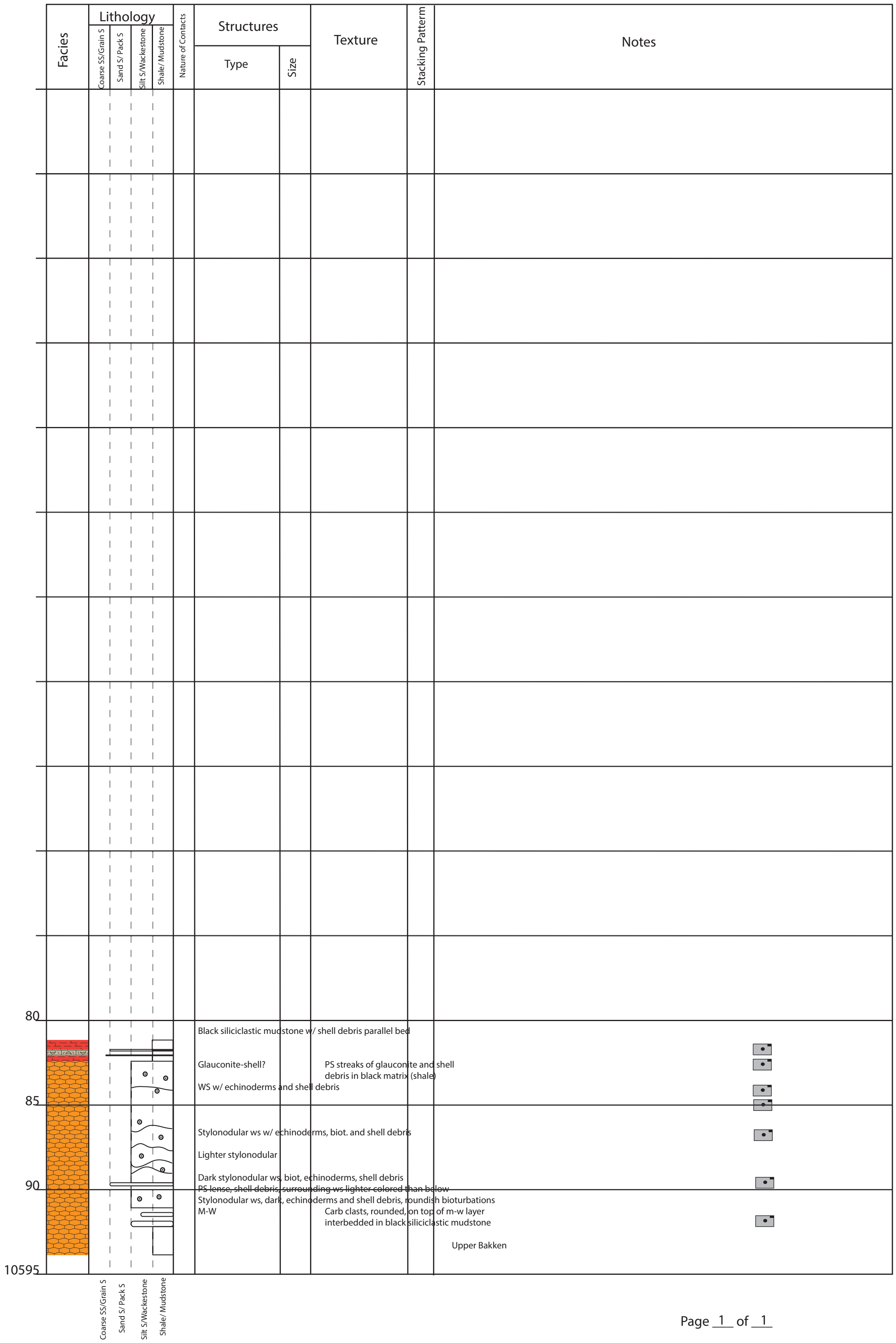
MS homogenous, w/ vertical cracks, some faint laminations and biotubations
WS w/ PS lenses and layers, x mm thick -shell debris and some echinoderms
PS-WS

Lenticular siltstone laminae, irregular; ripples probably also some shell debris on top

Page 1 of 1

Well EOG Resources Round Prairie 1-17H County Williams State ND

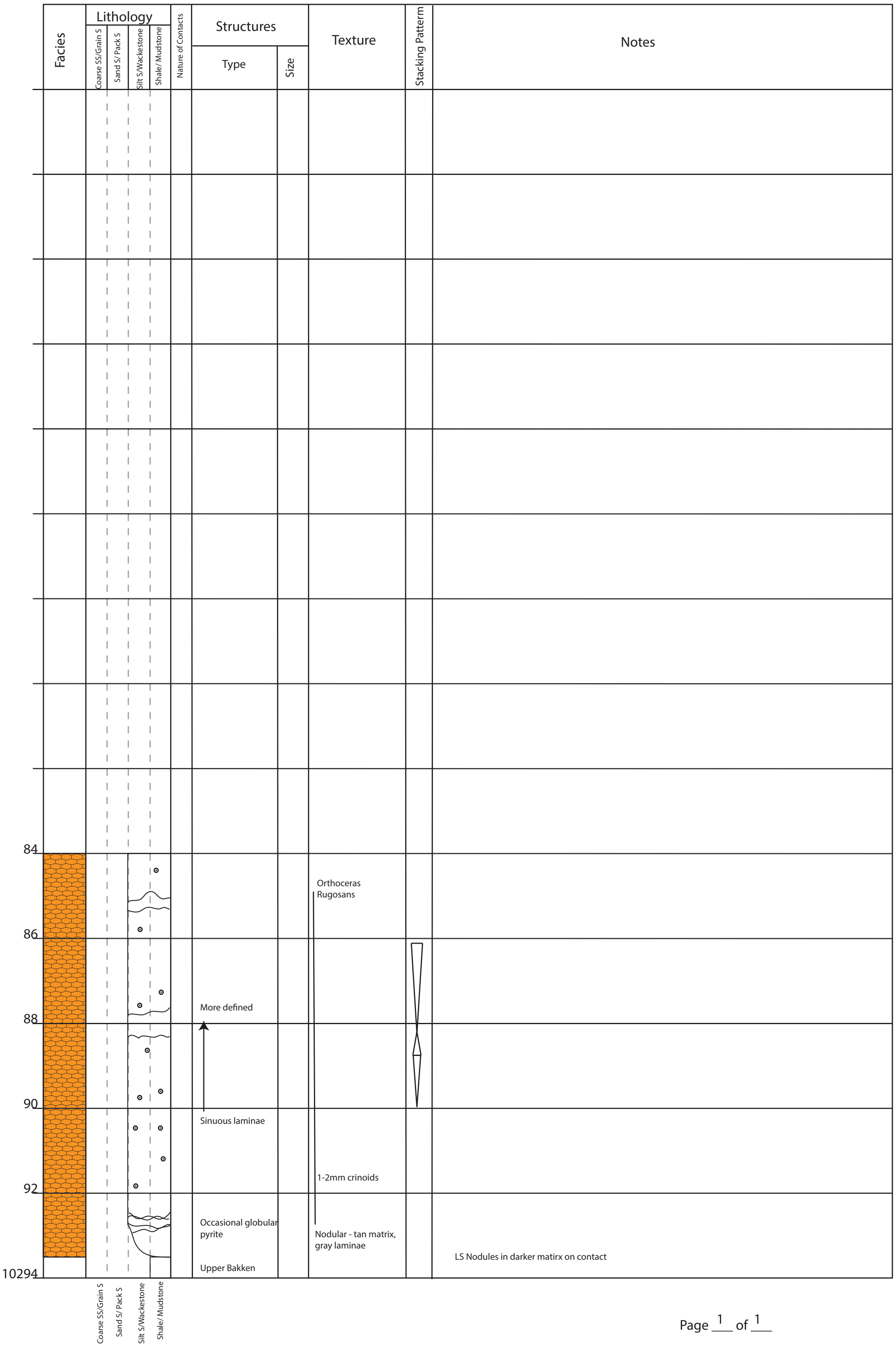
Stratigraphic Interval 10582-10594 Logged by SE Date 05/25/2011



Page 1 of 1

Well Headington Oil Nesson State 42x-36 County Williams State ND

Stratigraphic Interval 10284-10294 Logged by JM Date 3/13/11

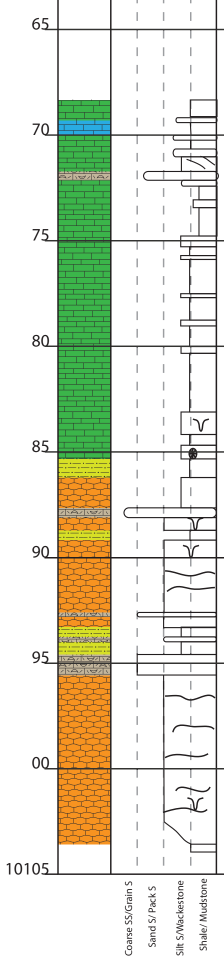


Page 1 of 1

Well Pogo Producing CO Pegasus 2-17H County Williams State ND

Stratigraphic Interval 10065-10105 Logged by SE Date 5/24/2011

Facies	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes



Massive dark gray MS

Massive dark gray MS w/ distinct bioturbations
Planar laminated carbonate siltstones
Another slump??
Sharp unit ~ 5cm thick max; above and below-laminated dark gray MS

Massive dark gray clay-rich mudstone
w/ xcm thick light carbonate MS intercalations

Light carbonate MS, bioturbated

Massive dark grey clay rich mudstone (carbonate-calcite)

Massive light MS w/ vertical burrows and black rimmed nodules
Massive dark clay rich MS
MS-WS - 1 coral, small shale fragments, irrefular patchy black rimmed nodues, highly bioturbated
MS, clay rich and black, mm- 1cm lenses of silt (very fine) in massive mudstone

Nodular MS-WS, some fluoresence of some moldic porosity
Burrows or intraclasts w/ echinoderms and shell material
Vertical burrowing in M-W
Irregularly laminated dark siltstones and mudstone laminae (nodular again on top)
Vertical burrows

Nodular MS-WS: shell debris, echinoderms, bioturbated

Irregularly laminated siltsontes
PS

Bioturbated siliciclastic mudstone
Glauconite W-P, bioturbated, echinoderms, coral,
black moldic (or filled) biogenic components (echinoderms and shell fragments)

WS: echinoderms and shell fragments

WS bioturbated, nodular w/ echinoderms and mm sized shell fragments
WS shell fragments and echinoderms
Mud filled burrows, dark
Increase in carbonate content , echinoderm size and #
Echinoderms randomly distributed - matrix is biotrubated

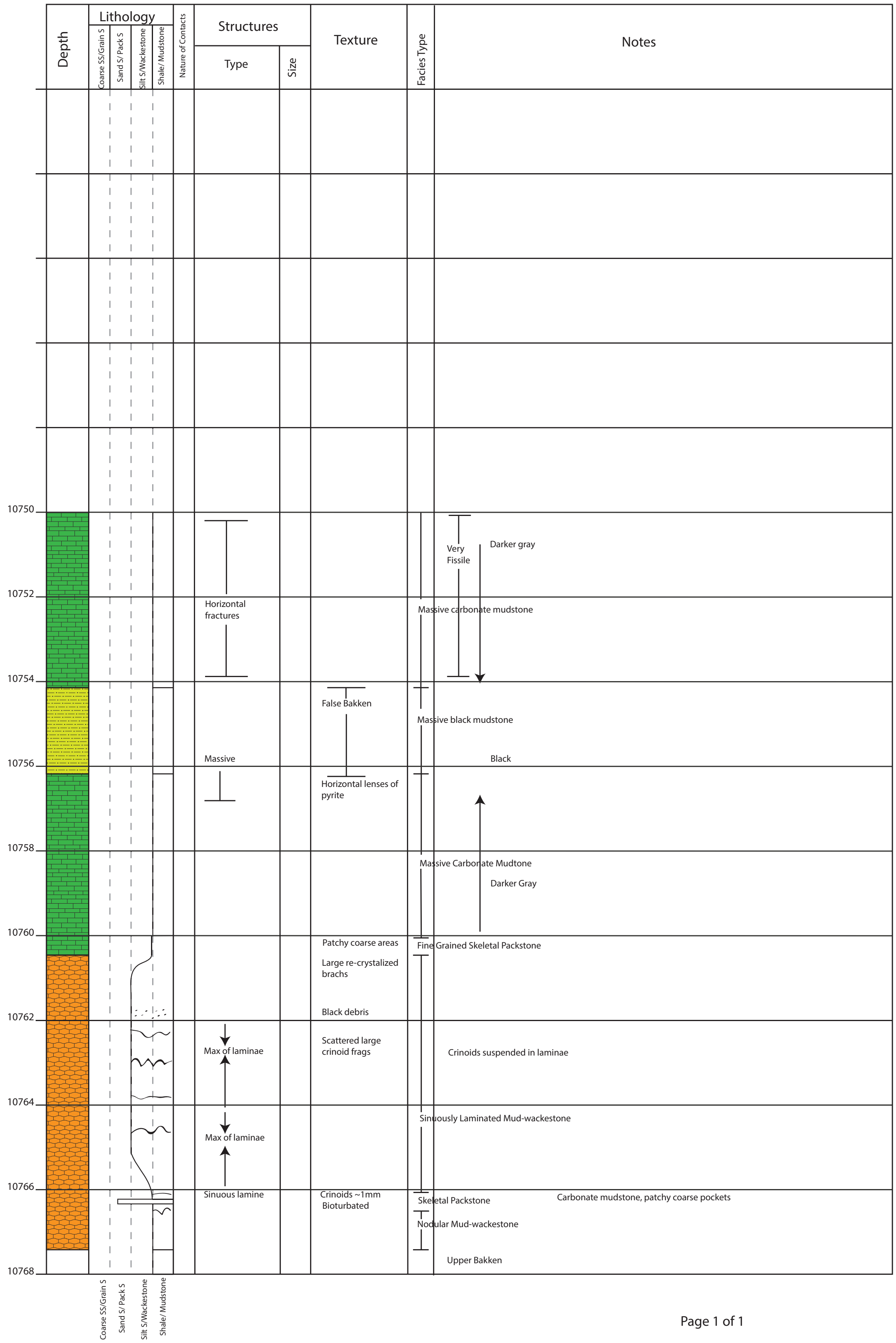
10100: moldic porosity and a little matrix porosity fluorescing

Upper Bakken

Page 1 of 1

Well: Florida Exploration11-4 Federal | County: Billings | State: North Dakota

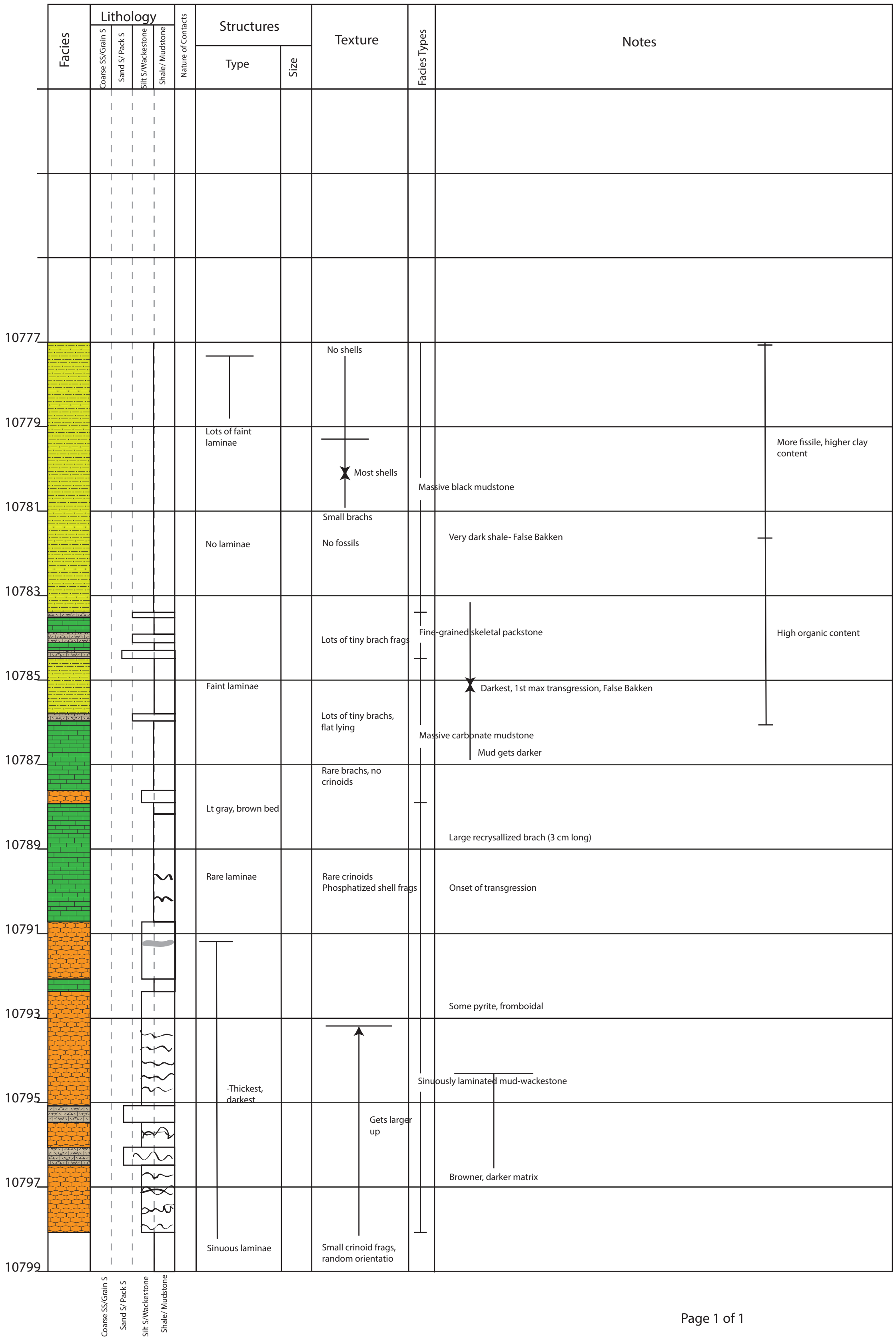
Stratigraphic Interval: 10750-10767 | Logged by: James Mackie | Date: 2/15/11, 2/22/11



Page 1 of 1

Well: Florida Exploration 12-1 Federal
County: Billings
State: North Dakota

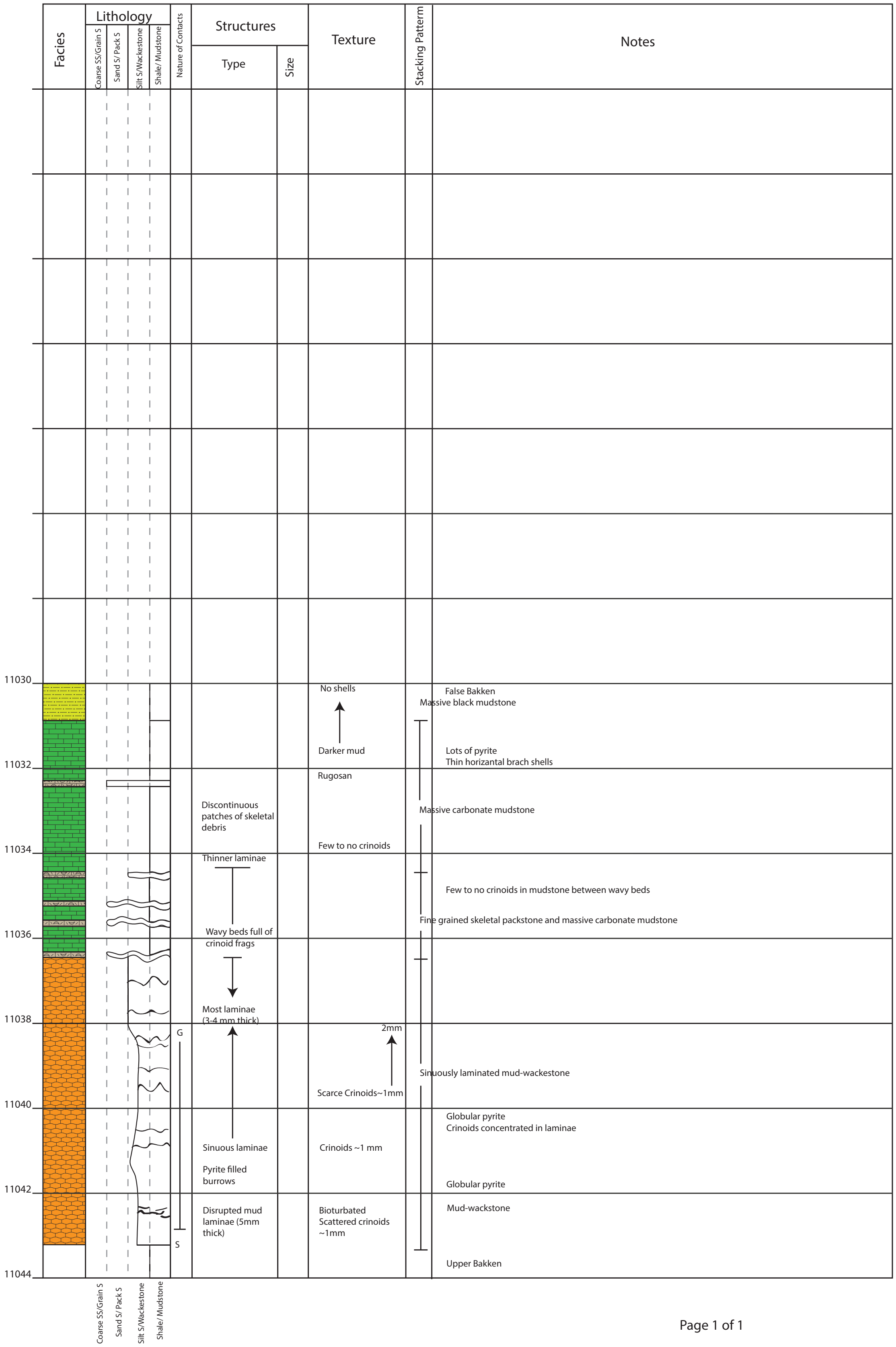
Stratigraphic Interval; 10799-10777 ft.
Logged by: James Mackie
Date: 11/10/10, 2/9/11



Page 1 of 1

Well: Texaco Inc. 5-1 Thompson
County: Billings
State: North Dakota

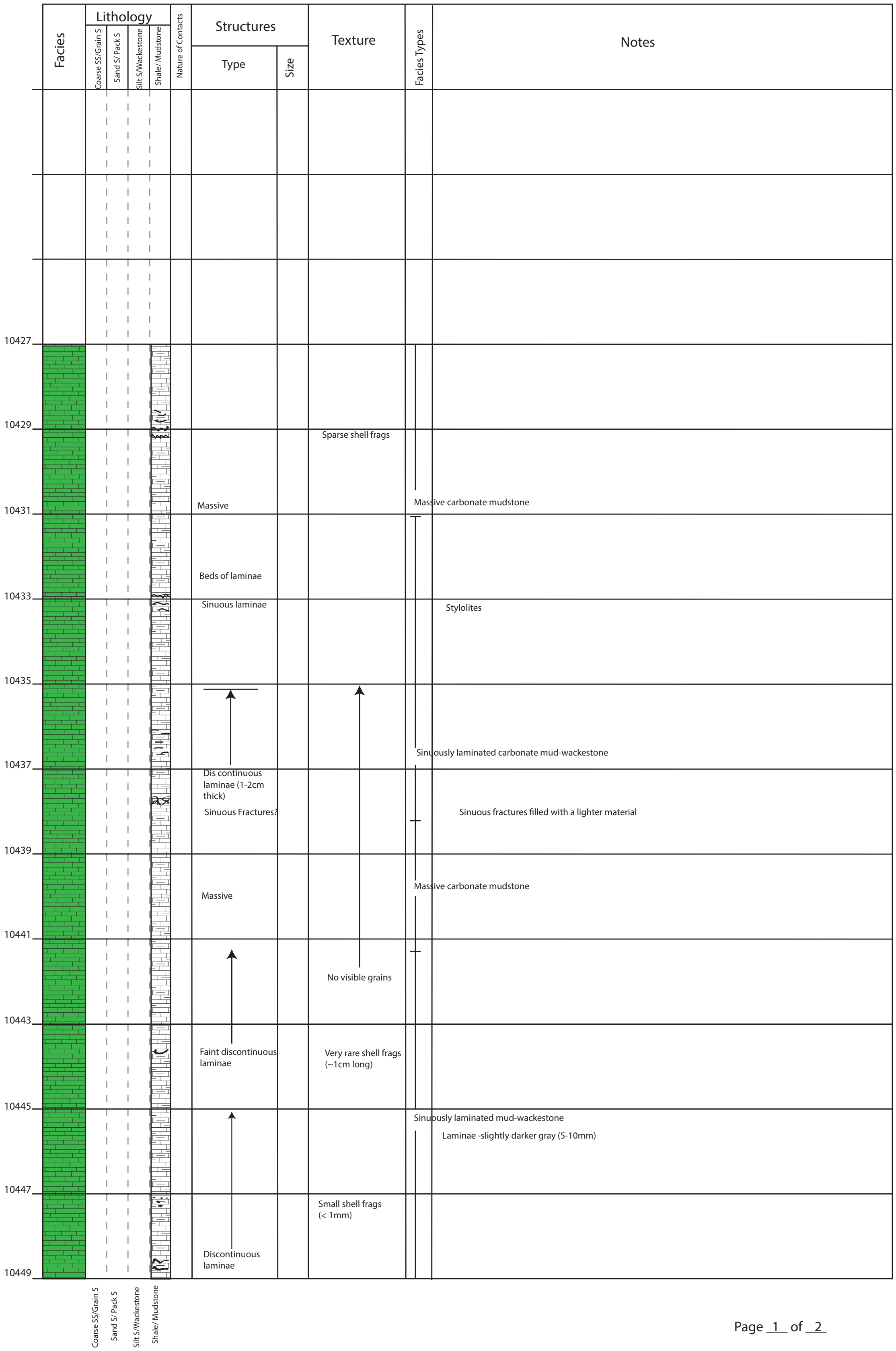
Stratigraphic Interval: 11030-11040
Logged by: James Mackie
Date: 2/15/11, 2/22/11



Page 1 of 1

Well : Whiting Oil and Gas 31-3 Short Fee   County: Billings   State: North Dakota

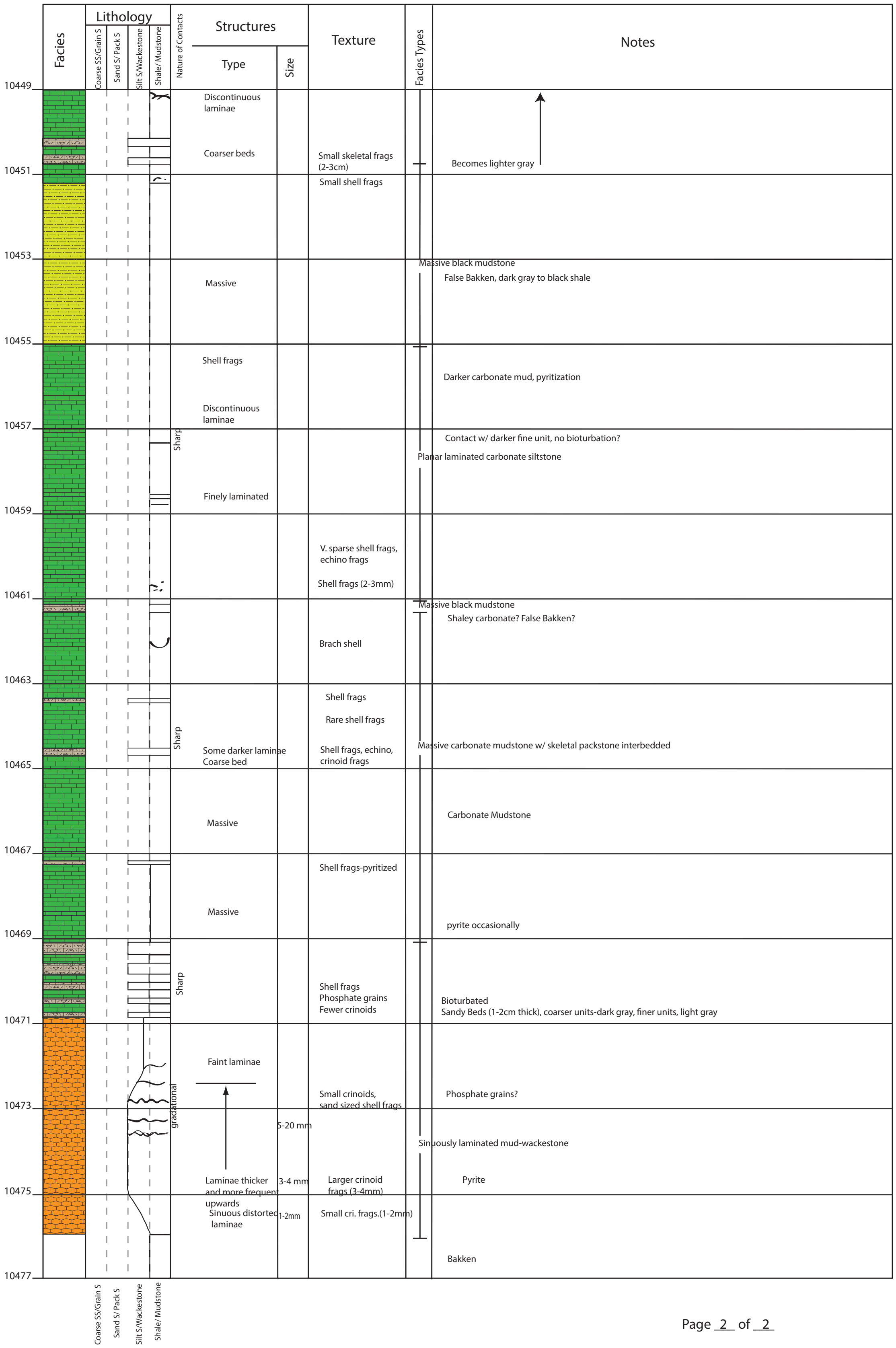
Stratigraphic Interval: 10449-10427   Logged by : James Mackie   Date: 10/13/10, 1/24/11



Page 1 of 2

Well : Whiting Oil and Gas 31-3 Short Fee   County: Billings   State: North Dakota

Stratigraphic Interval: 10477-10449   Logged by : James Mackie   Date: 10/13/10, 1/24/11



Page 2 of 2

Well: Duncan Raymond T 1-24 Patterson   County: Stark   State: North Dakota

Stratigraphic Interval: 9798-9770   Logged by: James Mackie   Date: 11/5, 2/8/11

Depth	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures Type	Structures Size	Texture	Stacking Patterm	Notes
9750			Planar laminae				Sparse small crinoids
9752			Bioturbation				
9754					Some small shell frags		Shallowing
9756			Planar laminae Mudstone nodules				
9758			Small gray nodules				
9760							
9762							
9764			Sinuous laminae				
9766							
9768			No laminae		Scattered brach and crinoid frags Faint nodules		
9770							

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Well: Duncan Raymond T 1-24 Patterson County: Stark State: North Dakota

Stratigraphic Interval: 9798-9770 Logged by: James Mackie Date: 11/5, 2/8/11

Depth	Lithology: Coarse SS/Grain S	Sand S/ Pack S	Silt S/Wackestone	Shale/ Mudstone	Nature of Contacts	Structures: Type	Size	Texture	Stacking Patterm	Notes
9770						No laminae				
9772						No laminae		1 crinoid ossicle		
9774						Small nodules (1cm dia.)				
9776										
9778										
9780						Lt gray nodules				Black biogenic debris
9782						Sinuous laminae				
9784						Sinuous laminae				
9786						Irregular fractures		Few crinoids		Crystalline carbonate nodule with pyrite lining Carbonate mudstone
9788						No laminae				Darker gray
9790										
9792								Crinoid and brach frags		
9794										
9796						Faint discontinuous laminae		Lighter gray		Occasional small crinoids
9798										

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Page 2 of 5

Well: Duncan Raymond T 1-24 Patterson County: Stark State: North Dakota

Stratigraphic Interval: 9826-9798 Logged by: James Mackie Date: 11/5, 1/27/11

Depth	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
9798							Dark brown, gets lighter in color up
9800							
9802			Faint Laminae				
9804					Orthoceras		Dark shale-false bakken?
9806							
9808			Stylolites, fractures		Much smaller crinoids		Crystal filled veins, scattered crinoids, voids Stromatactis
9810			Stylolites		Large brachs and crinoids		Transitions to mudstone
9812					Gastropod More sand sized grains here		
9814					Crinoids (<1cm) Brachs (4-5cm) Rugosans (2-3cm)		Calcite crystals in open pores Mostly Rugosans
9816					Fewer crinoids		
9818			Random orientation		Large crinoid and brach frags		Darker mud matrix
9820					Large crinoid frags, more mud, less sand		
9822					Carbonate ss Muddy, small shell frags, and large brachs Carbonate ss		
9824		Sharp	Nodular mud		Some crinoid frags Sand sized grains Large brach frags		No mud, high porosity Randomly oriented grains
9826							

Coarse SS/Grain S Sand S/ Pack S Silt S/Wackestone Shale/ Mudstone

Well: Duncan Raymond T 1-24 Patterson | County: Stark | State: North Dakota

Stratigraphic Interval: 9945-9826 | Logged by: James Mackie | Date: 10/28/10, 1/26/11

Depth	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Pattern	Notes
9826–9828					Brachs, few to no crinoids		High porosity, random orientation of shells
9828–9830					Intact brach shells		
9830–9832			-Most				
9832–9834			Vugs		Crinoids, rugosans		
9834–9836							
9836–9838			Nodules		Large calcite crystals		Darker mud
9838–9840			Vugs		Scattered crinoids No shells		
9840–9842			Discontinuous mud layers		Crinoids, 1 brach		Nodules Vugs reappear
9842–9844			No vugs Vugs		Small crinoids (1-2mm), carbonate sand Sand sized grains		Carbonate sandstone, vugs with crystal lined walls- size and frequency increase upwards until 9841'
9844–9937							9937-9844 missing
9937–9939		Sharp			Crinoids, more brachs		Lots of vugs start to appear
9939–9941		Sharp	Stylolites		Crinoids, brach frags		Stylolites seem focused around coarser beds
9941–9943		Gradational	Stylolites		Crinoids Rugosan		
9943–9945					Crinoid, brach frags		

Coarse SS/Grain S
Sand S/ Pack S
Silt S/Wackestone
Shale/ Mudstone

Well: Duncan Raymond T 1-24 Patterson   County: Stark   State: North Dakota

Stratigraphic Interval: 9976-9945   Logged by: James Mackie   Date: 10/28/10, 1/25/11

Depth	Lithology (Coarse SS/Grain S, Sand S/ Pack S, Silt S/Wackestone, Shale/ Mudstone)	Nature of Contacts	Structures: Type	Structures: Size	Texture	Stacking Patterm	Notes
9945–9947							
9947–9949					5-10mm		
9949–9951		Sharp					
9951–9953			Sinuous laminae Lt gray masses (anhydrite?)		Crinoid ossicles		
9953–9955			Irreuglar layer		Brach, crinoid frags		V. light gray- anhydrite?
9955–9957			Inclined laminae Lt gray concretions No laminae		Fossil frags (1cm long) Crinoid frags		Brachs, rugosan Start of mound flanks 9960-9957 missing
9960–9962			Crinoid ossicles dominate, brach frags				Appears Porous, very light gray in color
9962–9964					Smaller crinoids (1mm) Sparse larger crinoids		Sheddings
9964–9966			Laminae every 2-3 cm (2mm thick Lt gray concretions (2-5cm)				
9966–9968			Sinuous laminae Lt gray concretions		Very few fossils		
9968–9970			Sinuous dark laminae #increases up		Sparse crinoid ossicles		Diagenetic pyrite
9970–9972			Sinuous laminae		Number of crinoids decreases up		More mud/fewer crinoids Patches continue Mud/grains are in patches
9972–9974		Sharp Fines up	Well defined laminae/fractures		No mud		Crinoids fractured 25-30 degree inclined mud layer, fine grained mud-rich laminae are rich in organic material
9974–9976		Sharp			Small cri ossicles Size increases up Black shale		Pyrite just above contact Bakken

Coarse SS/Grain S   Sand S/ Pack S   Silt S/Wackestone   Shale/ Mudstone