

LATERAL VARIABILITY IN FACIES AND FACIES ASSOCIATIONS OF THE CODELL
SANDSTONE, WATTENBERG FIELD AND NORTHEASTERN COLORADO

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ABSTRACT

In recent years, the Niobrara Formation and the Codell Sandstone of the Carlile Shale Formation have been targets of oil and gas production in the Wattenberg Field of the Denver-Julesburg Basin. Horizontal drilling of these units has become more popular since 2010, with Niobrara wells extending to northeastern Colorado and Codell wells remaining within Wattenberg. It is likely that exploration in the Codell will follow the same trend of the Niobrara; therefore it is important that lateral facies variability within the Codell is determined as facies can be applied to reservoir potential. I described and logged five cores along a northeast-southwest transect through Wattenberg to northeastern Weld County for grain size, lithology, bioturbation, sedimentary structures, and sorting. Six facies were found between the five cores and represent a regressive marine shelf environment. A basic vertical sequence was found in all five cores and represented environments at the storm wave base up to the fair weather-lower shoreface transition. Two different facies were found in the northeast core, including a purely shoreface sand. This shoreface sand facies is of particular importance because it is pure sand consisting of preserved sedimentary structures with no bioturbation. Porosity and permeability within this unit are likely higher than the bioturbated facies because silt and mud have not been worked into the pores of the shoreface sand. The presence of the two different facies show evidence of lateral variability in the Codell to the northeast, and the shoreface sand could mean better reservoir potential to the northeast.

INTRODUCTION

Colorado has been a large producer of oil and gas since the 1950s, with most of the production in eastern Colorado coming from the Wattenberg Field are of the Denver-Julesburg (DJ) Basin (Figure 1). As unconventional reservoirs have become a viable source of oil and gas, DJ exploration has been focused on developing horizontal wells primarily in the Cretaceous Niobrara Formation, and to a lesser extent in underlying the Codell Sandstone of the Carlile Shale Formation (Milne and Cumella, 2014). In recent years, the unconventional exploration in the Niobrara has expanded to the northeast, well beyond the historical reach of the Wattenberg Field (Figure 2). However, as of 2014, horizontal wells within the Codell are still concentrated in Wattenberg Field, with few following the Niobrara expansion to the northeast (Figure 3) (Milne and Cumella, 2014). If unconventional reservoirs remain economically viable, it is likely that the Codell exploration will follow the Niobrara trend into northeastern Colorado.

Expansion of drilling to the northeast raises the question of lateral facies variability and its potential impact on reservoir quality in the Codell. Facies are can be defined by a number of qualifiers including, but not limited to grain size, bioturbation, lithology, cementation, and sedimentary structures. Variability in any or all of these attributes can affect porosity and permeability, and thus the production potential of a unit. Within the Wattenburg area, Codell facies and petroleum production are tightly linked, with Weimer and Sonnenberg (1983a) describing two main facies with distinctly different production summaries. The purpose of this study is to address the question of lateral Codell facies heterogeneity to the northeast of Wattenberg Field by studying five cores from the Codell on a northeast-southwest trending line through Wattenberg to the northeast corner of Weld County, Colorado (Figure 4).

GEOLOGIC FRAMEWORK

The Carlile Formation was deposited in different types of open marine environments within the Cretaceous Western Interior Seaway. The formation includes, from bottom to top, the Fairport Chalky Shale, Blue Hill Shale, and Codell Sandstone (Sabina 1993). The Juana Lopez member is an additional unit that overlies the Codell in northern New Mexico, southern Colorado, and western Kansas, but it is absent in northern Colorado (Galperin 1993). In the Wattenberg Field and northeastern Colorado, the Codell shares an unconformable contact with the overlying Fort Hayes Limestone member of the Niobrara Formation. The unconformity is marked by an erosional contact and missing time represented by missing faunal groups (Weimer and Sonnenberg, 1983a) In Colorado, the Codell ranges in thickness from a wedge edge to roughly 100 ft, with the average being 20 ft (Figure 5) (Weimer and Sonnenberg, 1983a). Kauffman (1969) and McLane (1982) interpreted the Codell member to have been deposited during the final regressive phase of the Greenhorn Cyclothem. That is, it formed due to a relative sea-level fall in the Western Interior Seaway that brought sands into the study area from the east. The Codell is predominantly a very fine to fine grained sand, is often heavily bioturbated, and is rich in clay (Henningsgaard 1986, McLane 1982). The top of the unit has also been described as a calcareous sandstone, as calcite cement begins to appear stratigraphically upward in several Codell cores (Henningsgaard, 1986). Regionally, the Codell has been observed and described mostly along a north-south trend, from northern New Mexico to southern Wyoming.

STUDY AREA AND METHODS OF INVESTIGATION

The Codell was studied on a northeast-southwest transect, beginning from Spindle Field in Adams County and extending to Tumbleweed Field in Weld County (Figure 4). Five cores along that transect were observed and described at the US Geological Survey's core repository. From the southwest to northeast, these five cores were from the Tudex Petroleum, #12-9 Barker (sec. 12, T1S-R68W), Pan Canadian, #34-4 Narco Barnes (sec. 4, T2N R67W), Rock Oil & Gas, #1 Ronald (sec. 27, T5N R63W), Andrau Enterprises, #13 Owl Creek (sec. 29, T7N R64W), and Magic Oil, #1 Schroeder (sec. 26, T12N R57W) wells. The cores were described for grain size, color, sorting, bioturbation, and sedimentary structures (Figure 6, 7, and 8). All cores were logged at a scale of 1ft of core to 0.5 in on the core log. The Magic Oil #1 Schroeder core was logged twice, once at the scale of the other cores and once at 1ft to the inch. The smaller scale was done to describe in more detail the sedimentary structures and was done for the top half of the Codell within that core. Trace fossils in all cores were identified by comparison to published images of marine traces.

Once each core was described, the core logs were analyzed to differentiate facies. Facies were designated based on similarities between grain size, types of burrows and trace fossils, bioturbation intensity, and sedimentary structures. Facies associations and interpreted depositional processes were assessed with the help of past studies of the Codell Sandstone (Henningsgaard 1986, Weimer and Sonnenburg 1983b, McLane 1982, Sablina 1993, Galperin 1993, Reisser 1976, Busch 1976, Krutak 1970, Wallace 1975) and published work on modern and ancient facies analogs for marine shelves (Plint 2010, Nichols 2009).

RESULTS

Facies Descriptions

Six different facies, labeled A through F, were identified in the five described cores. They are described below in order in when they appear stratigraphically in all cores, with Facies A being the stratigraphically lowest. However, not all facies are present in each core, but if present, then its occurrence is in the same sequence as described above. Table 1 shows the thickness of each facies per core.

Facies A. Facies A is a poorly sorted, dark gray, upper-fine to coarse grained sand. It contains a few long vertical burrows and rare horizontal burrows (Figure 9). This facies is mostly structureless when burrows are not present, but contorted bedding was seen. It occurs only at the bottom of the Tudex Petroleum #12-9 Barker well where it is approximately 1 ft thick, although similar facies occur towards the tops of other cores. Facies A has a gradational contact with Facies B in the #12-9 Barker well. Facies A coarsens upward from a fine to lower coarse sand within 12 cm and fines upward from the lower coarse sand to lower fine sand over the rest of its thickness, 25 cm. This unit is almost entirely sand, with a very low percentage of silt or mud (<10%).

Facies B. Facies B is a heavily bioturbated, moderately sorted, very fine to lower fine grained, gray to dark gray, silty sandstone (Figure 10). Horizontal burrows are more abundant than vertical burrows, but vertical burrows become more common upward. In the #34-4 Narco Barnes and #1 Schroeder cores, this facies displays almost exclusively horizontal burrows. Physical sedimentary structures are mostly destroyed by the extensive bioturbation, but remnants of the

original structures (possible current ripple structures) were occasional, seen in sandy lenses. Contorted bedding and irregular bedding can be seen when the sediment has not been completely bioturbated. Facies B contains a large percentage of silt, with sandy siltstones appearing at the base of this facies in #34-4 Narco Barnes. Sand and silt laminations are present, but most such alterations have been reworked by bioturbation. In the darker gray areas, the sand and silt are homogenized. Thin shale layers, less than 5 cm thick, are uncommon and appear only in the #1 Schroeder, #34-4 Narco Barnes, and #1 Ronald wells. In #34-4 Narco Barnes and #12-9 Barker wells, thin (<3 cm) intact layers of sand reveal parallel and low angle planar laminations. Within this facies, *Palaeophycus*, *Diplocraterion*, and *Skolithos* may be seen. It has a gradational contact with Facies C. The thickness of this unit ranges from 2.5 ft (#1 Ronald) to 13 ft (#34-4 Narco Barnes).

Facies C. Facies C is similar to Facies B, but differs in its abundance of vertical burrows and percentage of sand versus silt. Facies C is a moderately to heavily bioturbated, gray, very fine to upper-fine grained sandstone (Figure 11). Thin shale beds are still present in the #1 Schroeder, #34-4 Narco Barnes, and #1 Ronald cores. Burrowing destroyed most primary structures, yet there are more remnant structures preserved than in Facies B. Intact structures include planar cross laminations and parallel laminations. Contorted and irregular laminations are also present. Horizontal burrows are still abundant, but the presence of vertical burrows is increased relative to Facies B and the vertical burrows in Facie C become more common towards the top of the unit. The more common trace fossils present are *Thalassinoides*, *Teichichnus*, and *Asterosoma*; *Palaeophycus*, *Diplocraterion*, and *Skolithos* are also present. The thickness of this unit ranges

from approximately 2 ft (#1 Ronald) to 10 ft (#1 Schroeder). This facies has a sharp contact with Facies D when D is present, but a gradational contact with Facies E when Facies D is absent.

Facies D. This facies is a black shale that contains approximately 1 mm thick laminations of very fine grained, well sorted sand. Those sand laminations have a typical spacing of 0.5 to 2 cm. Bioturbation is present in the shale, but is minor and only horizontal burrows are present. The burrows increase in size towards the top of the facies. This unit is approximately 2.3 ft thick and is found only in the #1 Schroeder core where it is bound above and below by facies B. Due to its sharp contact with Facies B and its greater shale content relative to Facies B, it is considered a separate facies.

Facies E. Facies E is a very well sorted, light gray, very fine to lower fine grained sandstone. There is no bioturbation present in this unit and its silt content decreases upward over the basal 4.4 ft until there is no silt. Sedimentary structures are present throughout the unit and include parallel bedding, low angle planar cross bedding, planar cross bedding, and hummocky and swaley cross bedding (Figure 12). There is also evidence of a possible climbing ripple structure (Figure 13). Individual bed sets vary from 4 cm to 10 cm thick, indicating most structures relate to subaqueous dunes (Figure 14). This unit is only found in the #1 Schroeder core and is the only Codell facies described in which bioturbation is completely absent and sedimentary structures are completely unaltered. The unit is approximately 4.4 ft thick and shares its lower and upper contact with facies B.

Facies F. Facies F is a moderately to heavily bioturbated, well sorted, fine to coarse grained sandstone (Figure 15). Independent of grain size or specific core, this unit shows a gradual coarsening upward from Facies C. In some cores, like #12-9 Barker, the grains coarsen from lower very fine sand to lower fine sand. In other cores, like #1 Ronald, the grains coarsen from a fine sand to lower coarse sand. Structures in this unit have been destroyed or reworked by heavy horizontal and moderate vertical burrowing, with the vertical burrows becoming less common towards the top of the unit. Some irregular bedding can be seen, but no original sedimentary structures are preserved in this unit. Burrow types that may be present include *Skolithos* and *Palaeophycus* throughout, with *Teichichnus* towards the bottom of the facies. Thicknesses range from 2.75 ft in #12-9 Barker and about 5 ft in #13 Owl Creek. This facies terminates at the top of the Codell Sandstone.

Vertical Facies Sequences

Vertical facies sequences are associations of facies that occur in a particular order. They are the key to environmental interpretations as it is the sequence that is characteristic of lateral facies tracts via Walther's Law, not the individual facies.

The three Wattenberg cores (Figure 4) display a consistent vertical facies sequence of Facies B to, C and to F. The Tudex Petroleum #12-9 Barker, which lies just southwest of the Wattenberg cores, the amorously coarse grained, one-foot thick Facies A occurs below Facies B to C to F vertical sequence (Figure 9). Collectively these four cores suggest an ideal vertical facies sequence of A to B to C to F throughout the greater Wattenberg area.

To the northeast, the Magic Oil #1 Schroeder contains a different vertical facies sequence. That sequence, from bottom to top, consists of intercalated Facies B and D to E to C

to F. The presence of Facies D and particularly Facies E distinguish this vertical sequence from the sequence in the Wattenberg cores.

INTERPRETED DEPOSITIONAL ENVIRONMENTS

Settings Indicated by Trace Fossils Assemblages

Interpretation of depositional environment is generally facilitated by the combinations of lithology, grain-size trends, physical sedimentary structures, trace fossils, and body fossils. In the Codell, physical sedimentary structures are generally absent (destroyed by bioturbation) and body fossils are absent. Lithology and ichnofabrics thus become the most important variables.

The ichnofabrics observed consist of horizontal and vertical bioturbation traces, with the relative abundance of vertical traces increasing upwards through the Codell. All traces are interpreted to represent a complex assemblage of feeding, dwelling, and locomotion traces. Many, including most horizontal traces, could not be associated with a particular ichnogenus. The traces identified in this study were *Palaeophycus*, *Diplocraterion*, and *Skolithos* in Facies B; *Thalassinoides*, *Teichichnus*, *Asterosoma*, *Diplocraterion*, and *Skolithos* in Facies C; and *Teichichnus*, *Palaeophycus*, and *Skolithos* in Facies F. Trace fossils in the Codell were also identified by Sablina (1993), Galperin (1993), Wallace (1975), Henningsgaard (1986), and McLane (1982). *Ophiomorpha*, *Teichichnus*, *Thalassinoides*, *Plantolites*, *Asterosoma*, *Skolithos*, and *Chondrites* were described by Galperin (1993), Wallace (1975), Henningsgaard (1986). Sablina (1993) and McLane (1982) also reported *Diplocraterion* and *Zoophycus*. All of these are shallow marine traces (Basan 1978) formed after sediment deposition.

The diversity, abundance, and co-occurrence of all traces argues for a dominantly *Cruziana* ichno assemblage formed below normal wave base in a subtidal shelf setting rather than lagoon, tidal flat, or shoreline (Basan 1978, Nichols 2009). Figure 18 shows the positions of different ichnogenera in the shallow marine environment. Their presence together with horizontal traces suggests most deposition on the shallow shelf from a lower shoreface to more seaward positions. Where unidentified horizontal traces prevail, a *Zoophycus* ichnofacies is interpreted to prevail, which represents deposition in slightly deeper waters than the *Cruziana* ichnofacies.

All prior workers have also concluded a *Cruziana* ichnofacies is present, with Sablina (1993) and Wallace (1975) also arguing for a *Zoophycus* ichnofacies. A *Skolithos* ichnofacies was also interpreted as present by Sablina (1993), Galperin (1993), Wallace (1975), Henningsgaard (1986), and McLane (1982). The *Skolithos* ichnofacies, however, is characterized by a low diversity of abundant vertical dwelling and feeding burrows (*Skolithos*, *Diplocraterion* and *Arenicolites*) and it generally indicates deposition above normal wave base in settings characterized by shifting sands, such as shorefaces and intertidal sand flats *Skolithos* ichnofacies thus are associated with cross-laminated sands. Although *Skolithos* and *Diplocraterion* were observed in this study, those traces were never found alone nor did the host sediments still exhibit physical sedimentary structures. A separate *Skolithos* ichnofacies is thus not considered present. Rather when present, *Diplocraterion* and *Skolithos* are interpreted to be part of the *Cruziana* ichnofacies, but indicating deposition at the landward limit of that ichnofacies, namely at the approximate position of normal wave base. Their presence together with horizontal traces suggests most deposition on the shallow shelf from a lower shoreface to seaward position.

Depositional Environments – Wattenberg Area

The coarsening upward vertical facies sequence observed in the greater Wattenberg area, Facies A to B to C to F is interpreted to represent the generalized regressive sequence of a marine shelf environment (Figure 17). Facies A, which is not ubiquitous, is interpreted to be a coarse grained lag formed at the onset of the regression. Facies A fines upward over its one-foot thickness, is mostly structureless, but contains rare, long vertical burrows. Coarse sand grains with a fining upward sequence are characteristic of storm deposits, also called tempestites (Plint 2010, Nichols 2009). Tempestites often display massive bedding, which is bedding that displays no internal sedimentary structures, at the base of the bedset (Plint 2010). In an idealized tempestite, the massive bedding would grade into hummocky and swaley bedding and then into planar laminations (Plint 2010, Nichols 2009). However, sedimentary structures at the top of the tempestite are often destroyed by bioturbation, and the bioturbation marks the transition from storm deposit to normal offshore deposit (Plint 2010). A tempestite could explain the lack of sedimentary structures at the base of Facies A as well as the upward fining sequence. The massive bedding in Facies A transitions into the heavily bioturbated, siltier and finer grained sand of Facies B. Facies A was deposited in the offshore shelf, likely between the transition of the Blue Hill Shale and Facies B.

Facies A was also identified by Sablina (1993) who interpreted the coarsening and fining sequence as smaller order regression and transgression. Sablina (1993) suggests that the coarse sand was deposited by streams that were now able to reach the exposed shelf. It is possible that some of the coarser sediment was able to survive the subsequent transgression (which deposited Facies B) because of the presence of shelf valleys in the area and this could be why it is not seen in every core (Sablina, 1993). These arguments are rejected herein because the occurrence of a

one-foot thick transgression-regression sequence found in one core is unlikely. In order for streams to deposit on top of the Blue Hill Shale, an offshore deposit, the sea level would have had to have dropped considerably throughout the Cretaceous Interior Seaway and would be recorded as an unconformity across the Codell (Nichols 2009). This has not been observed or documented in any Codell study, and many studies recognize a regional gradational contact between the Blue Hill Shale and Codell (McLane 1982, Henningsgaard 1986).

Facies B represents deposition below storm wave base to the storm wave base-fair weather wave base transition. Below the storm wave base in the offshore zone, mud, silt, and very fine sand are found due to the low energy environment and settling of particles. This area is associated with the *Cruziana* ichnofacies, horizontal burrowers like *Teichichmus* and *Thalassinoides* are common and rework the sediment. The bioturbation can mix the sand and mud so much that original sedimentary structures cannot be seen. If structures are preserved, they are current ripple laminations. Facies B contains almost entirely horizontal *Cruziana* burrows and contains the most silt and mud of any of the sandstone facies. Structures are rare in Facies B but can be seen in Figure 10 as ripple laminations. Facies B coarsens upward while the silt and mud percentage decrease relative to sand. Vertical *Skolithos* ichnofacies burrows become more common towards the top of Facies B and show that the energy is increasing in this unit.

Facies C shows a transition from the storm wave base-fair weather wave base to an environment completely within the fair weather wave base. This is shown in how the burrows change from predominantly *Cruziana* ichnofacies to include members of the *Skolithos* ichnofacies upward, and how the sedimentary structures are more abundant and intact than those in Facie B. Sedimentary structures found in this facies include planar cross laminations and parallel laminations. These sedimentary structures are formed from storm deposits, which are

more common here than below the storm wave base. Vertical burrows begin to appear here, as they can survive during higher energy storm deposits by burrowing down into the sand and creating relatively permanent homes (Basan 1978). This facies still contains mostly horizontal burrows of the *Cruziana* ichnofacies, thus helping to distinguish this environment from that of the shoreface, where the *Skolithos* assemblage would be in greater abundance and more sedimentary structures would be preserved (Nichols 2009, Plint 2010).

Facies F can be interpreted as the transition from fair weather wave base to lower shoreface depositional environment because of its presence of coarser grains, and mix of *Cruziana* and *Skolithos* ichnofacies, and remnant sedimentary structures. In a purely lower shoreface depositional environment, more unaltered sedimentary structures and *Skolithos* assemblage burrows would be seen (Nichols 2009). This facies instead shows a transition in which there is high enough energy to deposit moderately to well sorted coarser grained sands, characteristic of shoreface, but not enough energy to preserve any original structures. Most of the structures have been reworked or destroyed and the abundance of horizontal *Cruziana* assemblage burrows do not allow this environment to enter completely into the shoreface. It is the higher percentage of sand versus silt and coarser grains that puts this facies at the top of the fair weather wave base, transitioning to lower shoreface.

Depositional Environments – Northeast Colorado

The Magic Oil #1 Schroeder well in northeast portion of the study area and was the only core in the northeast where the Codell was greater than 20 ft thick. It also has a unique vertical facies sequence of Facies B and D to E to C to F. Facies B, C, and F are still interpreted to have formed in progressively shallower subtidal shelf settings as argued above. Facies D and E

represent the variations on the theme and their depositional settings are constrained by their unique attributes and association with Facies B, C and F.

Facies D is a black shale with 1 mm thick sand laminations sharply bound by Facies B. Shale is characteristic of a low energy environment, a lagoon or offshore deposit. As this facies is bound by Facies B and dominated by a diverse assemblage of undifferentiated horizontal burrows (*Cruziana* ichnofacies), an offshore depositional setting is more likely. The dominance of shale over sand suggests either deposition below storm wave base (Plint 2010) or a position on the shelf that was temporarily farther removed from the source of sands to the shelf.

Facies E is the most noteworthy facies of this study as it is a relatively thick accumulation of cross laminated and cross bedded sand containing absolutely no bioturbation. This facies includes parallel bedding, low angle planar cross bedding, planar cross bedding, and hummocky and swaley cross beds. A similar facies was described in southwestern Colorado by McLane (1982). It included the same structures but also contained minor amounts of bioturbation. McLane (1982) interpreted this facies as a barrier bar deposited somewhere in the shoreface to foreshore region (McLane 1982). However, bioturbation is common in barrier bars and Facies E does not have any trace of bioturbation. Due to the lack of bioturbation, Facies E is interpreted herein to represent a shoreface deposit. The hummocky and swaley laminations at the base of Facies E could be evidence of storm generated combined flow that affects the lower to middle shoreface (Nichols 2009). The overlying low angle planar and planar cross beds indicate dunes of the middle shoreface to upper shoreface. These areas are constantly being reworked by waves and would preserve this type of cross bedding. The planar cross beds are very fine to fine grained sand and are placed on the upper shoreface because of their grain size. Plint (2010) argues that

finer grained sediment that creates these structures must be located on the upper shoreface because it is more protected from waves that could entrain the finer grains.

DISCUSSION

Implications of Lateral Facies Variability in Northeastern Colorado

Facies B, C, and F were found in sequence in all of the five cores studied and define a basic vertical facies template that is ubiquitous throughout the study area. They represent normal subtidal marine sedimentation. The presence of Facies A towards the southeast and Facies D and E towards the northeast shows that the Codell sandstone contains lateral variability in facies and facies associations on the northeast-southwest transect. The most significant of these is the occurrence of Facies E as it is different from any other facies that has been described in the Codell in that it completely lacks bioturbation and all the sedimentary structures have been preserved. Pure sandstones with preserved primary sedimentary structures typically represent better reservoir facies than bioturbated sands as bioturbation introduces fine-grained muds that clog pores and pore throats (Weimer & Sonnenberg 1983a). This facies suggests that northeastern Colorado could contain Codell targets that have better reservoir potential than the plays within Wattenberg, especially considering that much of the Codell in Wattenberg has high amounts of authigenic clay that lowers the porosity of the Codell (Birmingham 2001).

Regional Variability in Codell Facies and Environments

Within northeastern Colorado, the Codell has been studied by many authors, often relating to its petroleum potential. Studies of the Codell in Kansas (Wallace 1975), Wyoming (Weimer and Sonnenberg 1983a), and southern Colorado (McLane, 1982) have also offered insight into the facies present outside northeastern Colorado and have thus contributed to understanding depositional environments of the Codell as a whole.

Facies distinctions vary in number and detail per author, ranging from two facies (Sablina 1993) to six facies (Henningsgaard 1986, McLane 1982). However, the Facies B to C to F motif identified herein is distinguished in some form. The basal facies of the Codell is described as a moderately to heavily bioturbated, very fine to fine grained sandstone and siltstone that can contain shale laminations (Henningsgaard 1986, Weimer and Sonnenburg 1983b, McLane 1982, Sablina 1993, Galperin 1993, Reisser 1976, Busch 1976, Krutak 1970). Traces in the basal member are typically assigned to the *Cruziana* ichnofacies and the sand, silt and mud laminations are assumed to have been mixed (homogenized) by those traces. The middle facies or sets of facies is heavily bioturbated, fine to medium grained sandstone that contains less silt than in the basal facies and can contain planar cross bedding, low angle planar cross bedding, and ripple laminations (Henningsgaard 1986, Weimer and Sonnenburg 1983b, McLane 1982, Sablina 1993, Galperin 1993, Reisser 1976, Busch 1976, Krutak 1970). The uppermost facies is determined by a slight decrease in bioturbation and overall a coarsening of grains within the unit (Henningsgaard 1986, Weimer and Sonnenburg 1983b, McLane 1982, Sablina 1993, Galperin 1993, Reisser 1976, Busch 1976, Krutak 1970).

The corresponding interpretations of depositional environment are far more varied than those presented herein, but that is to be expected when a larger region (southern Colorado to

Wyoming and eastward into Kansas) is considered. All prior workers agree that the Codell was deposited in a shallow water marine environment, and the base of the Codell has uniformly been interpreted to have formed either on the marine shelf below the storm wave base or at the transition of the fair-weather and storm wave base (Sablina 1998, Galperin 1998, McLane 1982). However, only Sablina (1993) argued that the depositional environment of the Codell in its entirety was below the fair weather wave base and partially below the storm wave base.

The middle of the Codell is slightly coarser grained, and therefore uniformly interpreted as higher energy deposit than the base. This facies or facies association has been interpreted primarily as a shoreface depositional environment (Henningsgaard 1986, Weimer and Sonnenberg 1983b, Krutak, Reisser 1976, Busch 1976, Galperin 1993, McLane 1982, Wallace 1975, Krutak 1970). The shoreface is separated into two distinct units, upper and lower shoreface. The lower shoreface is above the fair-weather wave base and ripple laminations and mix of *Cruziana* and *Skolithos* ichnofacies are found here as it is a transition from offshore (basal facies) to shoreface. The upper shoreface is below sea level at low tide and is characterized by parallel laminations and *Skolithos* ichnofacies. The upward trend of middle to upper shoreface is distinguished by the upward change from ripple laminations to parallel or planar laminations. The bioturbation in this unit represents both the *Cruziana* and *Skolithos* ichnofacies and they often destroy sedimentary structures, but laminations can be seen in some cases.

McLane (1982), Galperin (1993), and Wallace (1975) have interpreted separate facies within the middle Codell to be from shoreline bar and shoreface to delta front environments. These interpretations are based on the coarser grains, increase in high energy sedimentary structures, and increase in *Skolithos* ichnofacies burrows. The grain size can reach a maximum of medium sized sand in this facies and begins to show planar bedding and cross bedding. The

presence of *Skolithos* assemblage, along with grain size and bedding, characterize a higher energy environment than what was previously seen in the Codell. McLane (1982) and Galperin (1993) also suggested that this facies has characteristics of barrier bars, where bioturbation is less common and more higher energy sedimentary structures, such as planar and parallel cross beds, are preserved due to rapid deposition. As already argued, this study found shoreface deposits to only be present in the Magic Oil #1 Schroeder well; they are considered to be lacking in the Wattenberg area, which highlights the regional facies variability that must occur in the middle of the Codell sandstone.

The upper Codell is usually interpreted to be either lag deposits or tidal-channel deposits (Galperin 1993, Wallace 1975, McLane 1982). Tidal channels help explain the coarser grains above heavily bioturbated finer grains and the planar cross bedding often found at the top of the Codell (McLane 1982). The *Skolithos* ichnofacies is found in these higher energy deposits (Sablina 1993). This unit could also represent a lagoon environment that has coarse grains due to influence of streams and waves during higher tides or storms (Galperin 1993). Some authors have found that this unit has the most amount of clay and that reworking of the sediment from bioturbation and deposition of coarse grains from tidal channels could produce the mix of clay and coarser sediment that is present in this unit (Wallace 1975, Galperin 1993).

CONCLUSIONS

The Codell Sandstone is a shallow marine sandstone that was deposited in the Cretaceous Western Interior Seaway. The Codell coarsens gradually upward, from a very fine grained silty sandstone or sandy siltstone to an upper fine to coarse grained sandstone, depending on the

location. The Codell represents a change in depositional environment from offshore to lower shoreface. This is a regressive sequence and the Codell is known to be the final regressive phase of the Greenhorn Cyclothem.

The Codell is generally a gray to dark gray, very fine to fine grained, heavily bioturbated sandstone. It has a basic vertical sequence of Facies B to C to F which can be seen in all of the cores. The sequence represents normal subtidal marine sedimentation. The three Wattenberg cores display this basic vertical sequence without any deviation. This shows that there is no lateral variability in facies or facies associations within Wattenberg Field. The Magic Oil core contains two facies not found in the other cores, Facies D and E. Facies D is a black shale representative of an offshore setting whereas Facies E, characterized by undisturbed sedimentary structures and completely lacking in bioturbation, was deposited on the shoreface. Together, they show that lateral variability in facies exists to the northeast of Wattenberg.

The shoreface deposits of Facies E are of most interest because of their reservoir potential. They are the only facies in which the lithology is almost entirely sand and it is completely unaltered by bioturbation. This is significant because bioturbation in the Codell reworks and homogenizes sediment, mixing sand and mud and decreasing the porosity of the sand. Facies E most likely has greater porosity and permeability than the bioturbated facies because there is no mud or smaller sediments to fill up the pore spaces in the sand. Since porosity and permeability are generally greater in a more pure sand, this facies has the potential to be a better reservoir than the Codell in Wattenberg Field.

Figure 1: Map of north-central Colorado showing the extent of Wattenberg Field (gray) and the general area of horizontal drilling in the Niobrara Formation (red box). From Milne and Cumella (2014).

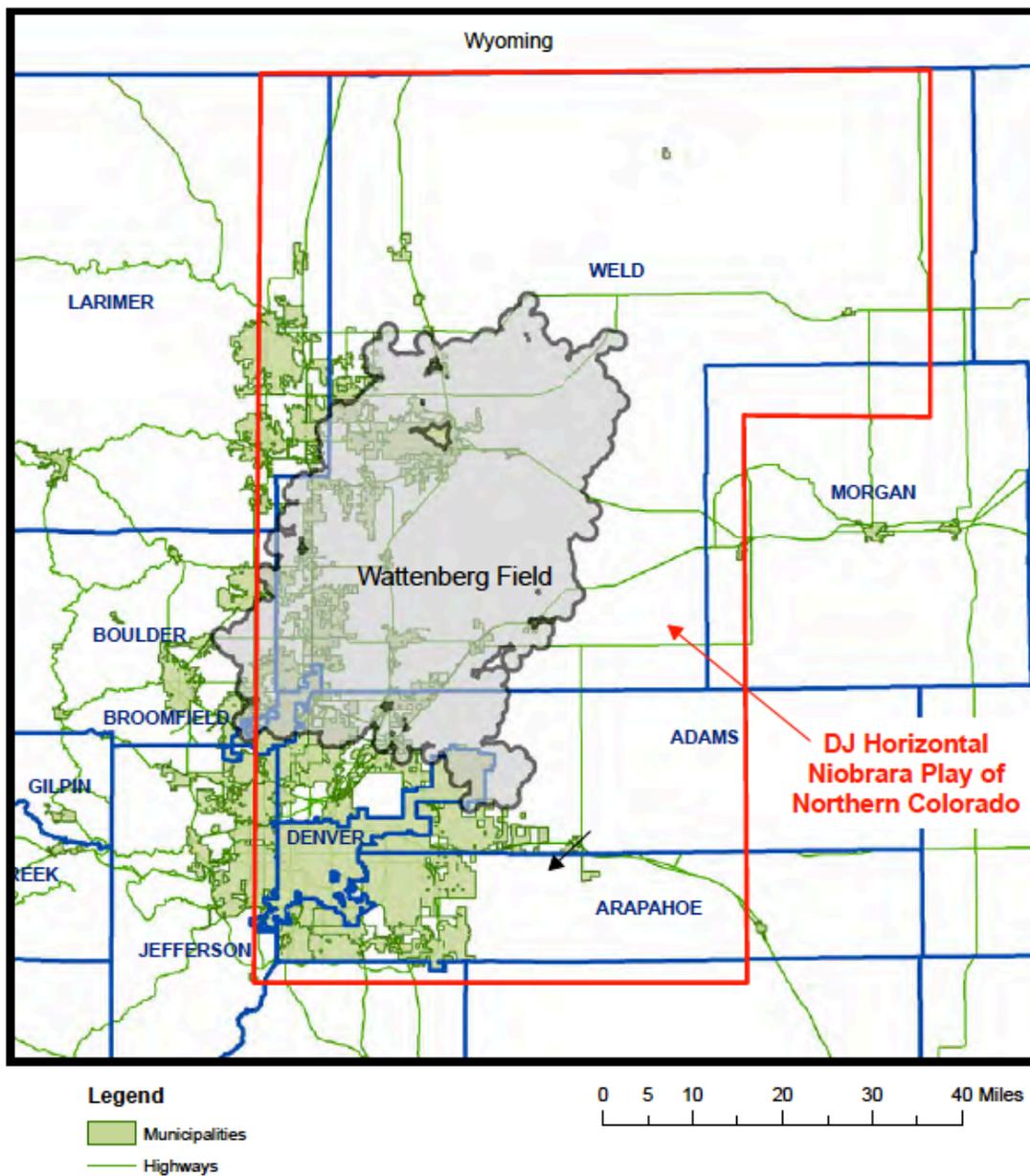


Figure 2: Series of maps showing the history of drilling into the Niobrara Formation in the Denver Basin (from Milne and Cumella, 2014). Blue represents vertical wells, red represents horizontal wells; modern extent of Wattenberg Field is shown in light yellow.

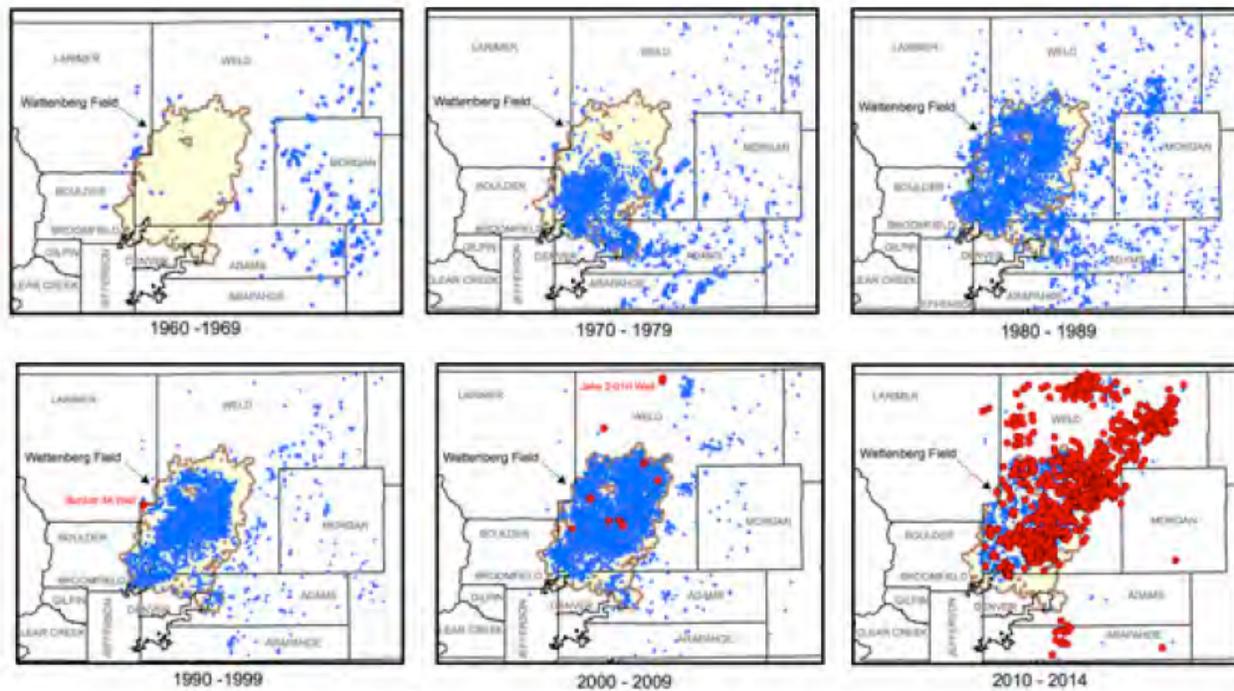


Figure 3: Left - Map comparing the extent of pre-2010 Niobrara production (orange) and new (2010-2014) horizontal wells (red). Right - Map comparing the extent of pre-2010 Codell production (green) and new (2010-2014) horizontal wells (red). Both maps from Milne and Cumella (2014).

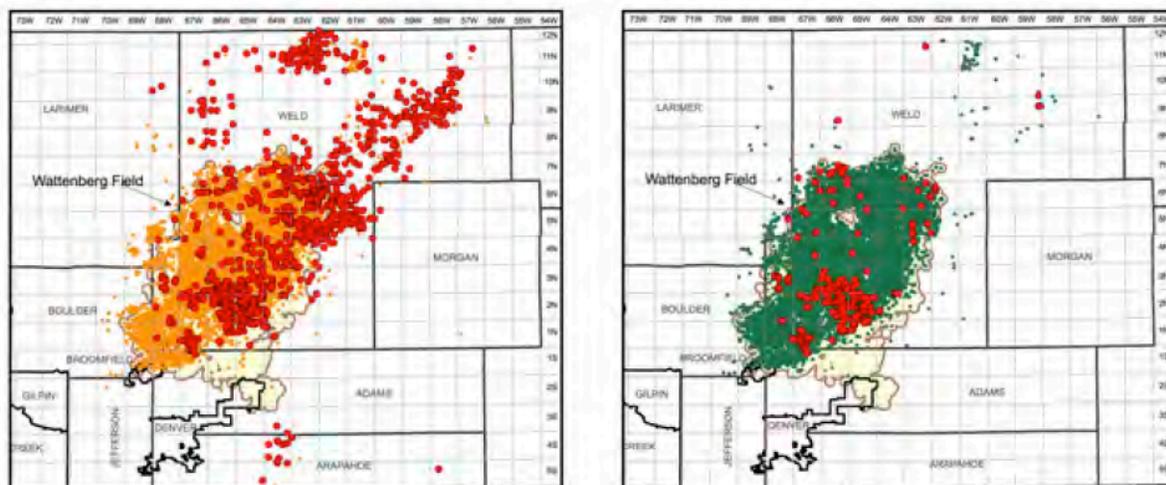


Figure 4: Map of the study area showing location of the five cored wells used in this study.

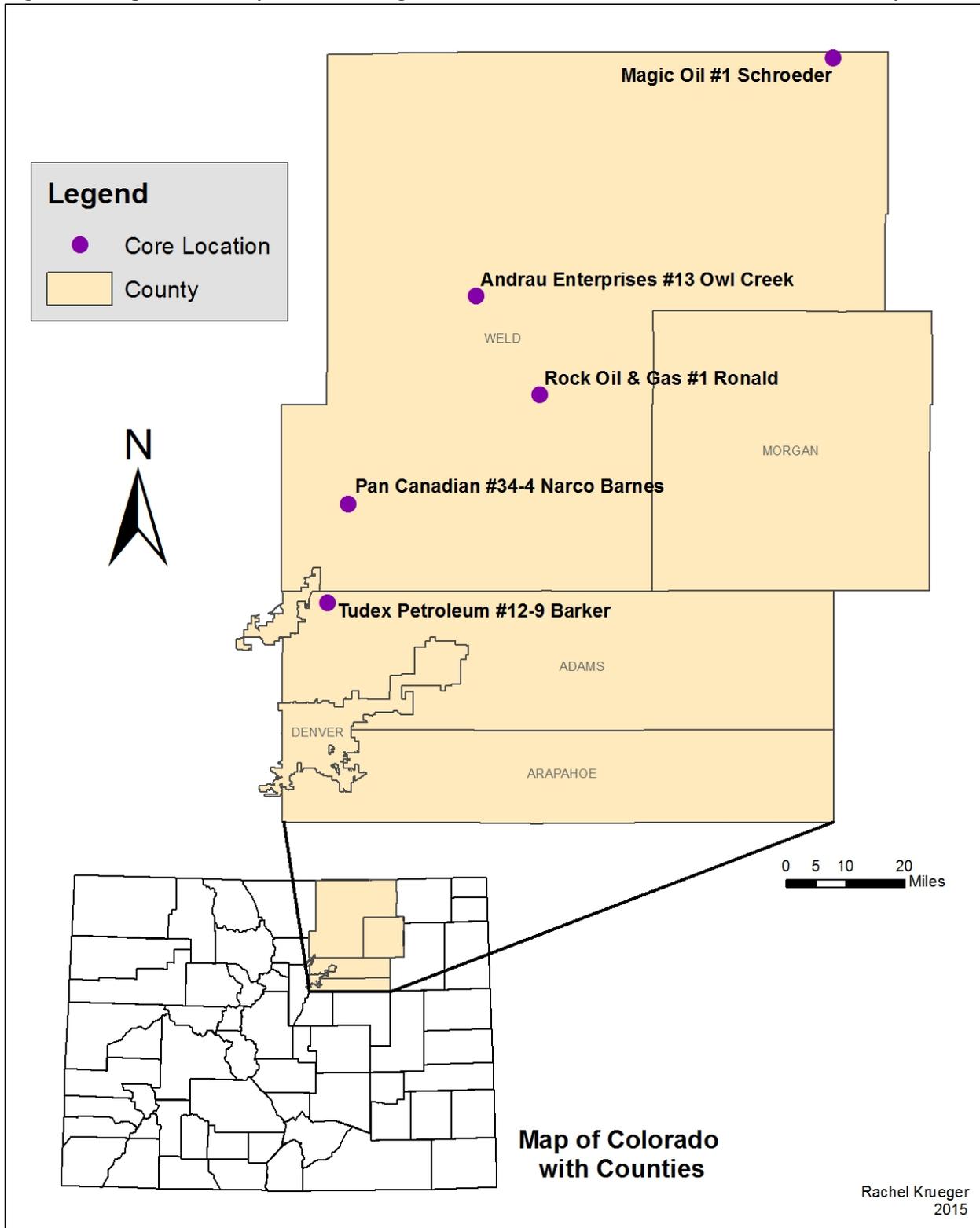


Figure 5: Isopach map of the Codell sandstone across northern Colorado, eastern Wyoming, and southwest Nebraska (from Weimer and Sonnenberg 1983a).

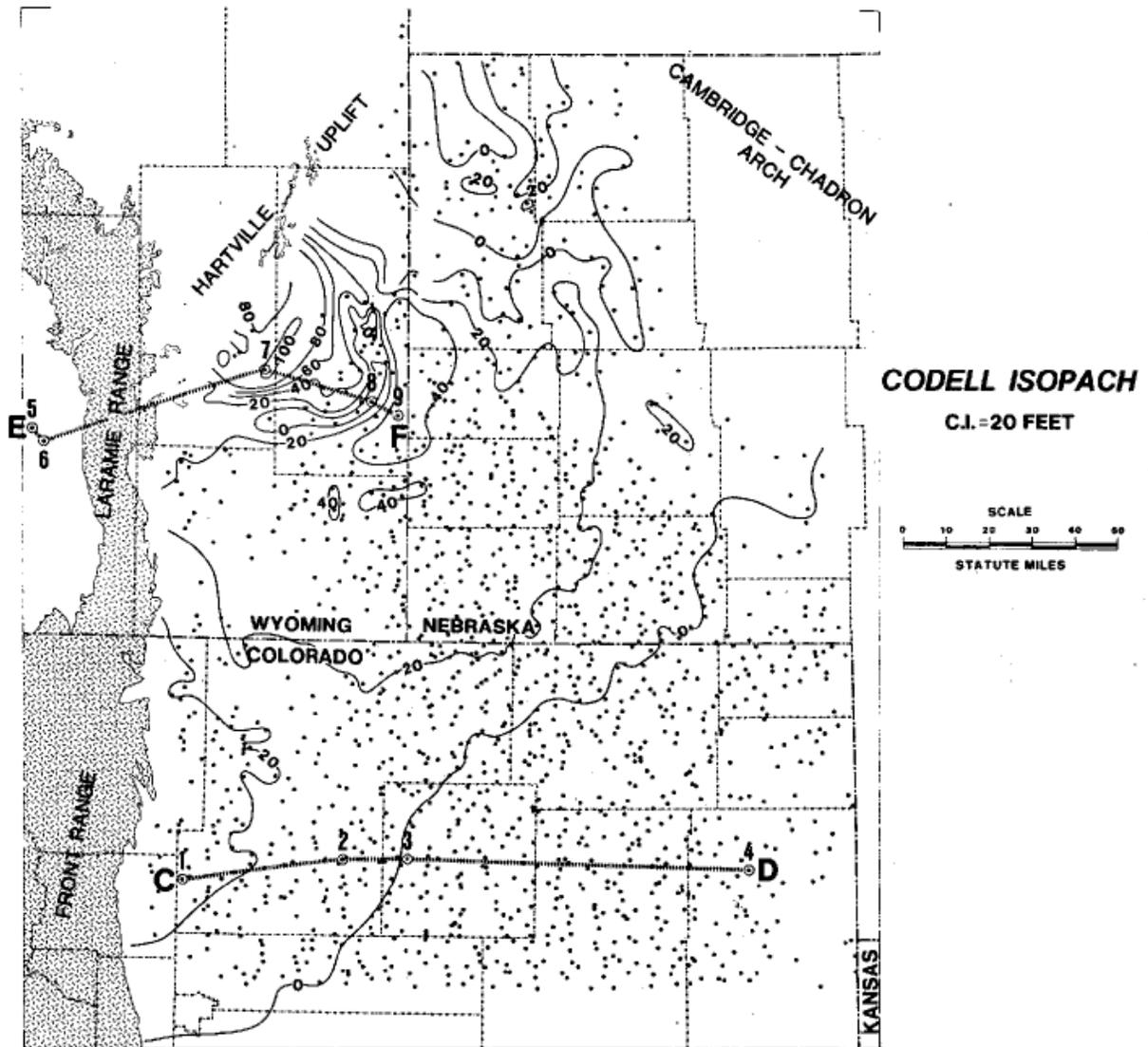


Figure 7: Core log of Magic Oil #1 Schroeder. Page 1 showing the top of the core. Facies are separated with red lines and labeled.

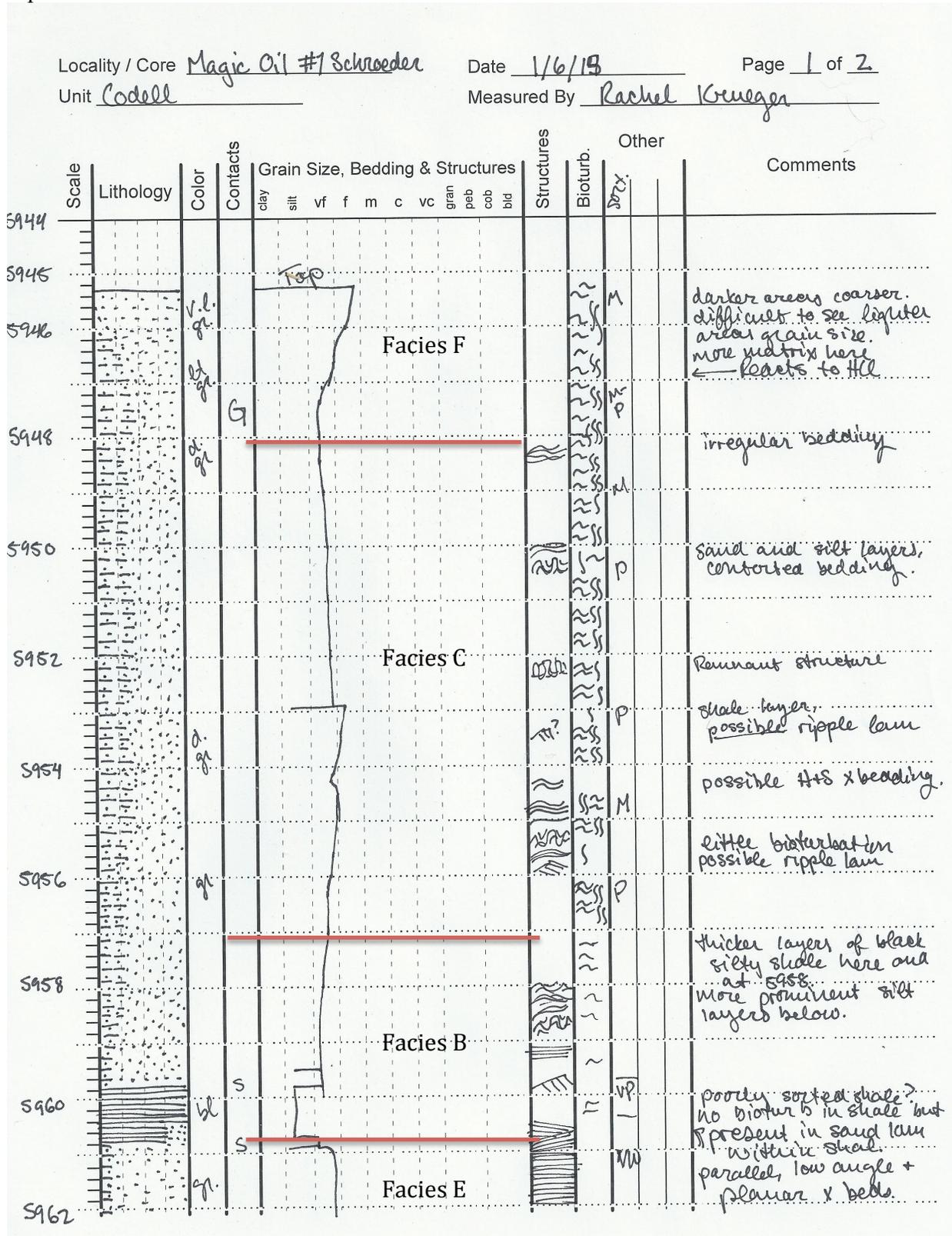


Figure 9: Photographs of typical Facies A (right) and B (left). Images from the Tudex Petroleum #12-9 Barker well. Light gray material is sandstone, dark gray is silty sandstone. For scale, core slabs are approximately 4 inches wide.

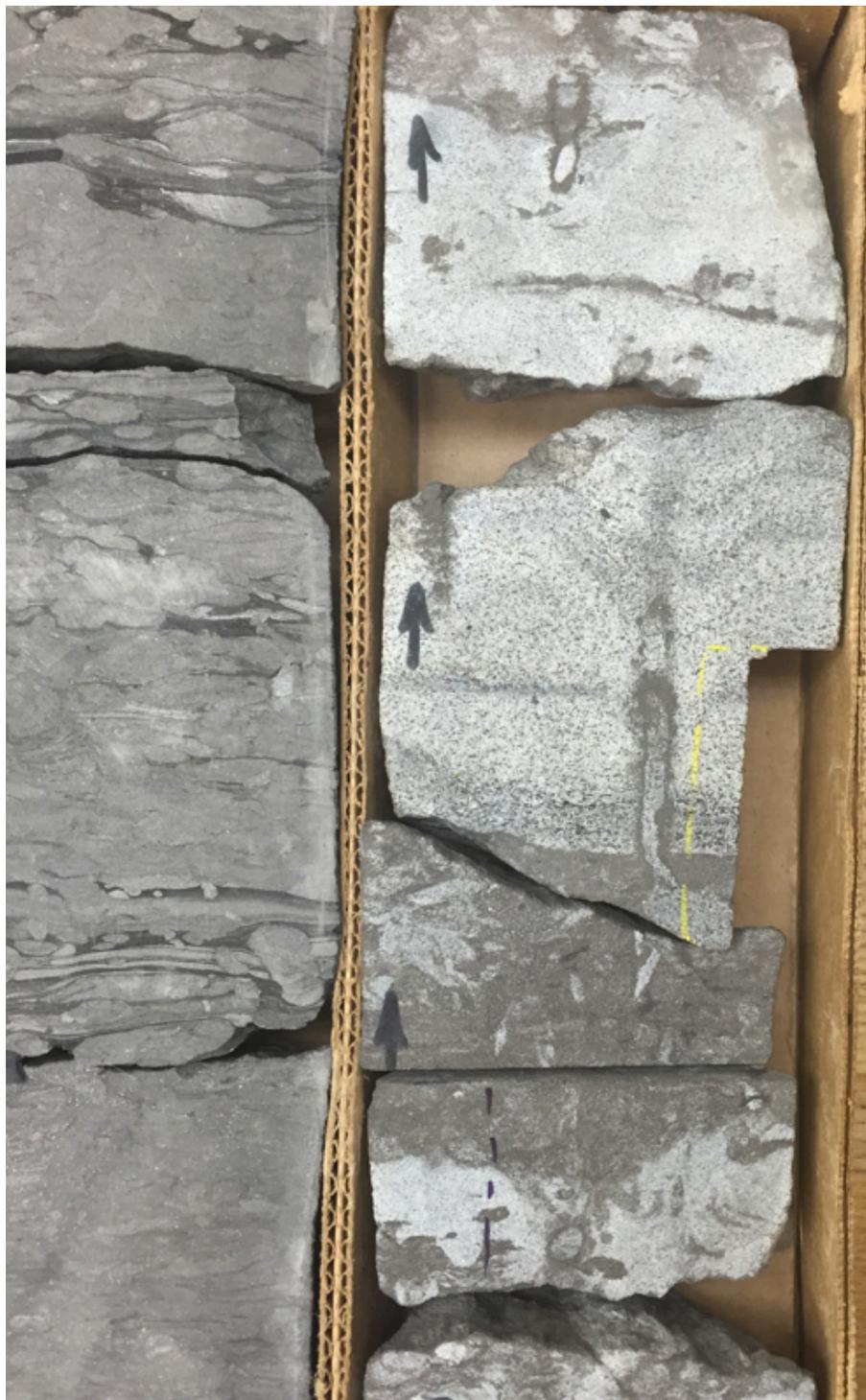


Figure 10: Photographs of Facies B from the Tudex Petroleum #12-9 Barker core. Light gray material is sandstone, dark gray is a silty sandstone or sandy siltstone. Black arrows point to examples of *Paleophycus*; red arrow points to an examples of a remnant structure, most likely parallel laminations. For scale, core slabs are approximately 4 inches wide.

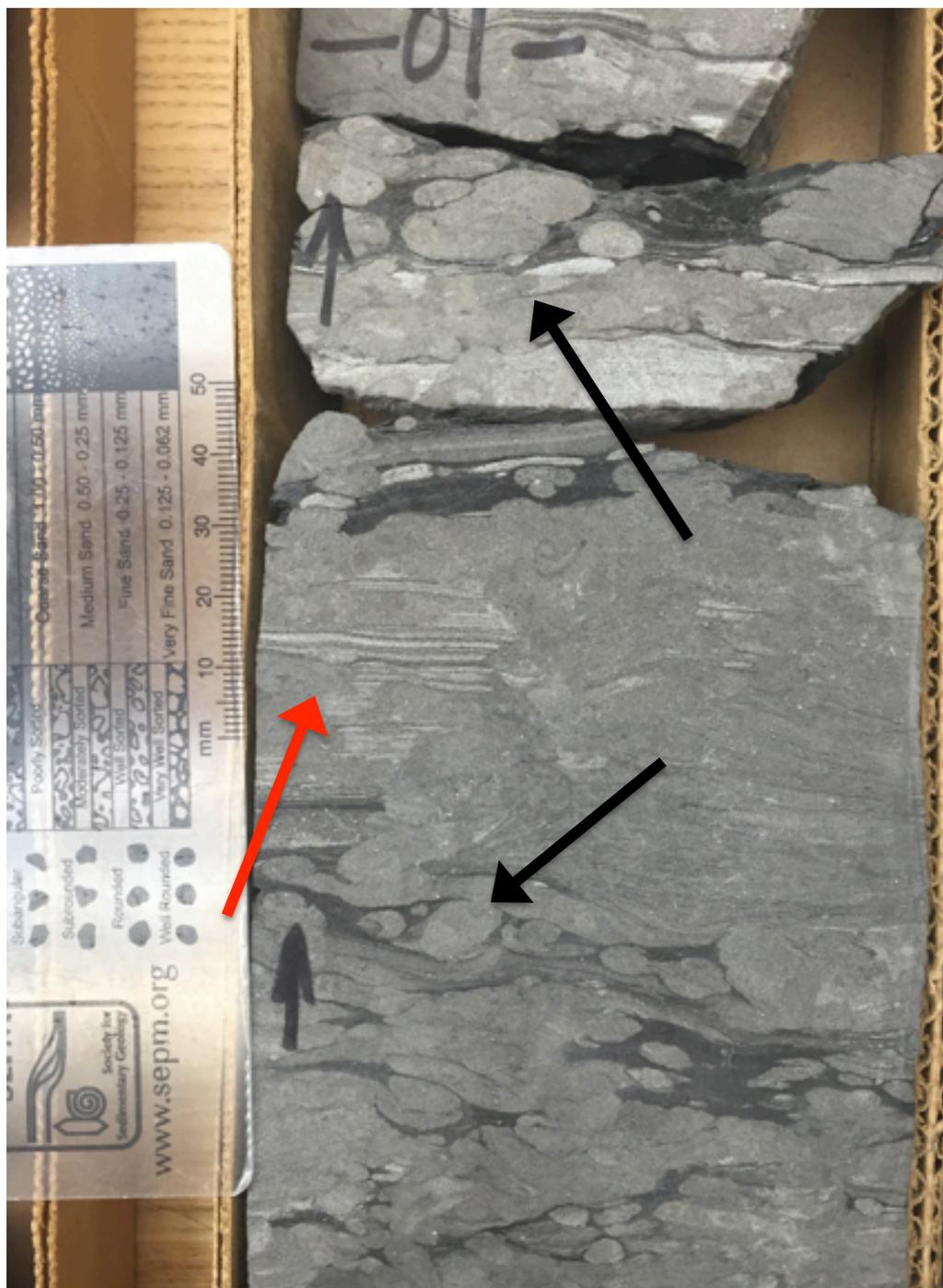


Figure 11: Photograph of Facies C in the Rock Oil & Gas #1 Ronald core. Light gray material is sandstone, dark gray is a silty sandstone. Black arrows point to examples of *Teichichnus*; and red arrows point to examples of remnant structures, likely parallel laminations. For scale, core slabs are approximately 4 inches wide.



Figure 12: Example of hummocky and swaley cross lamination (red box) and low-angle planar laminations (blue box) in Facies E, Magic Oil #1 Schroeder core. For scale, core slabs are approximately 4 inches wide.

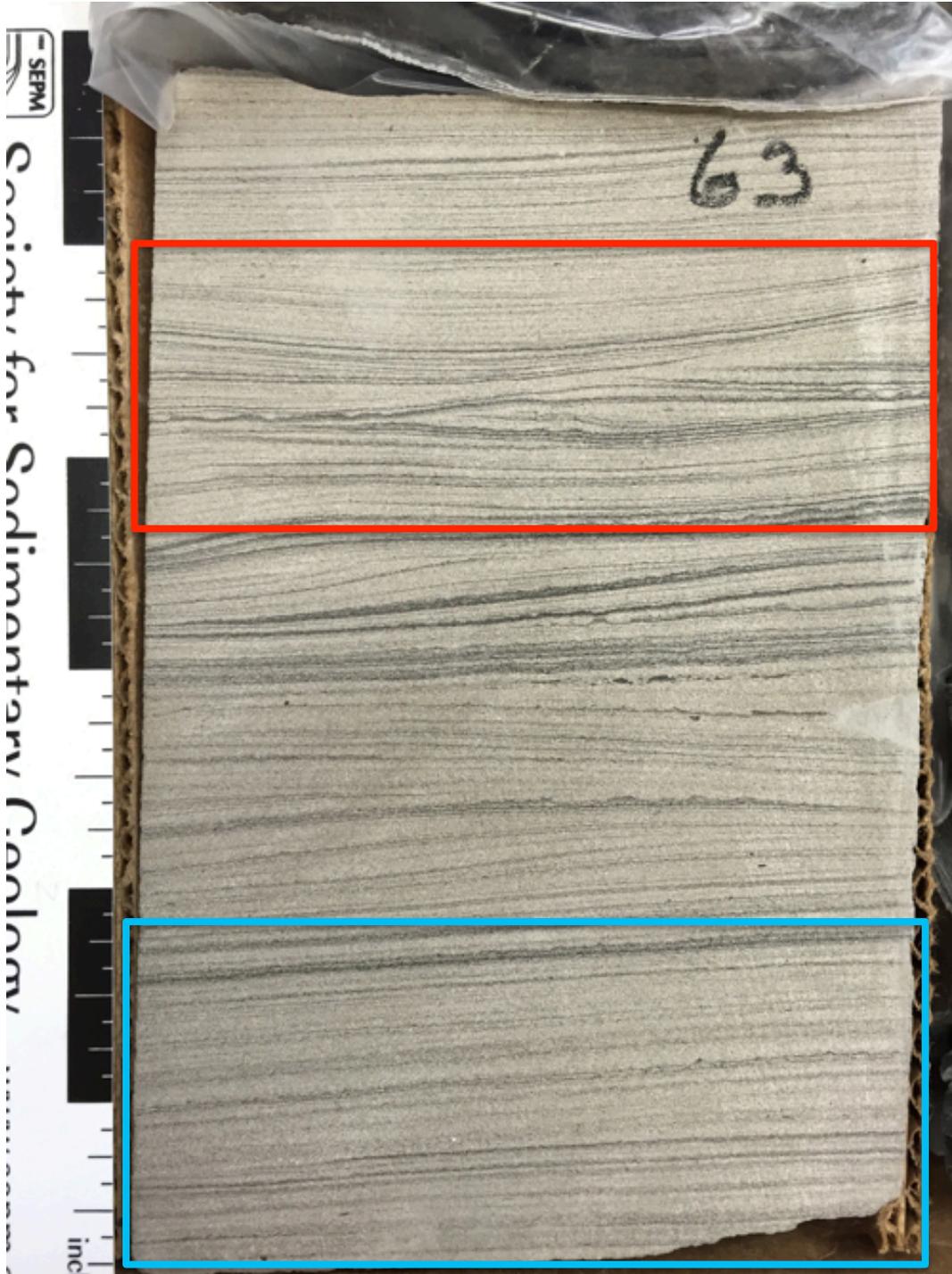


Figure 13: Example of planar cross bedding in Facies E, Magic Oil #1 Schroeder. For scale, core slabs are approximately 4 inches wide.

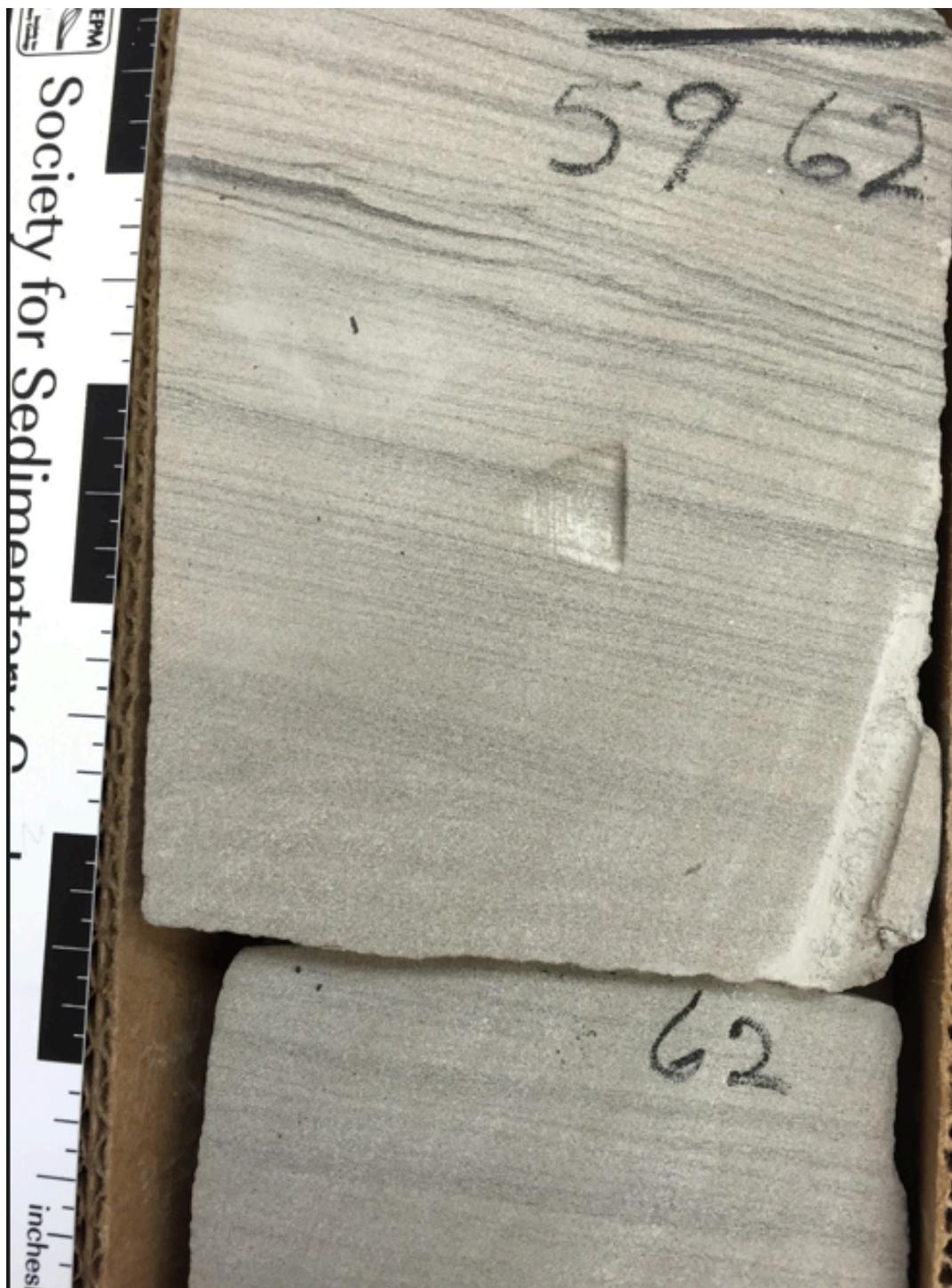


Figure 14: Examples of parallel and low-angle cross bedding in Facies E, Magic Oil #1 Schroeder. For scale, core slabs are approximately 4 inches wide.

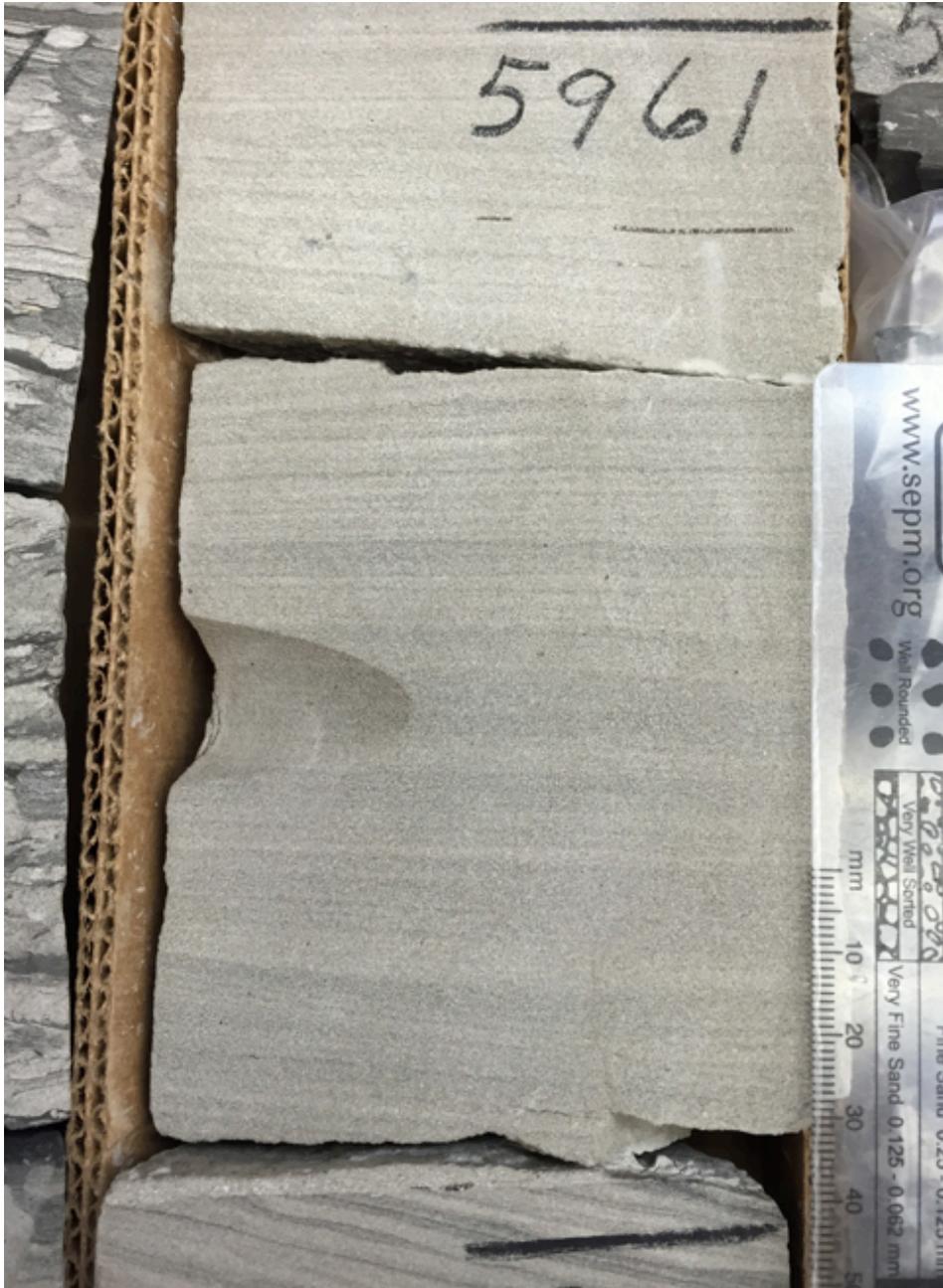


Figure 16: Photograph of Facies F in the Rock Oil & Gas #1 Ronald core. Light gray material is sandstone. Dark area has been wetted. Black arrow points to an example of possible *Diplochraterion*, but could be *Teichichnus*. For scale, core slabs are approximately 4 inches wide.

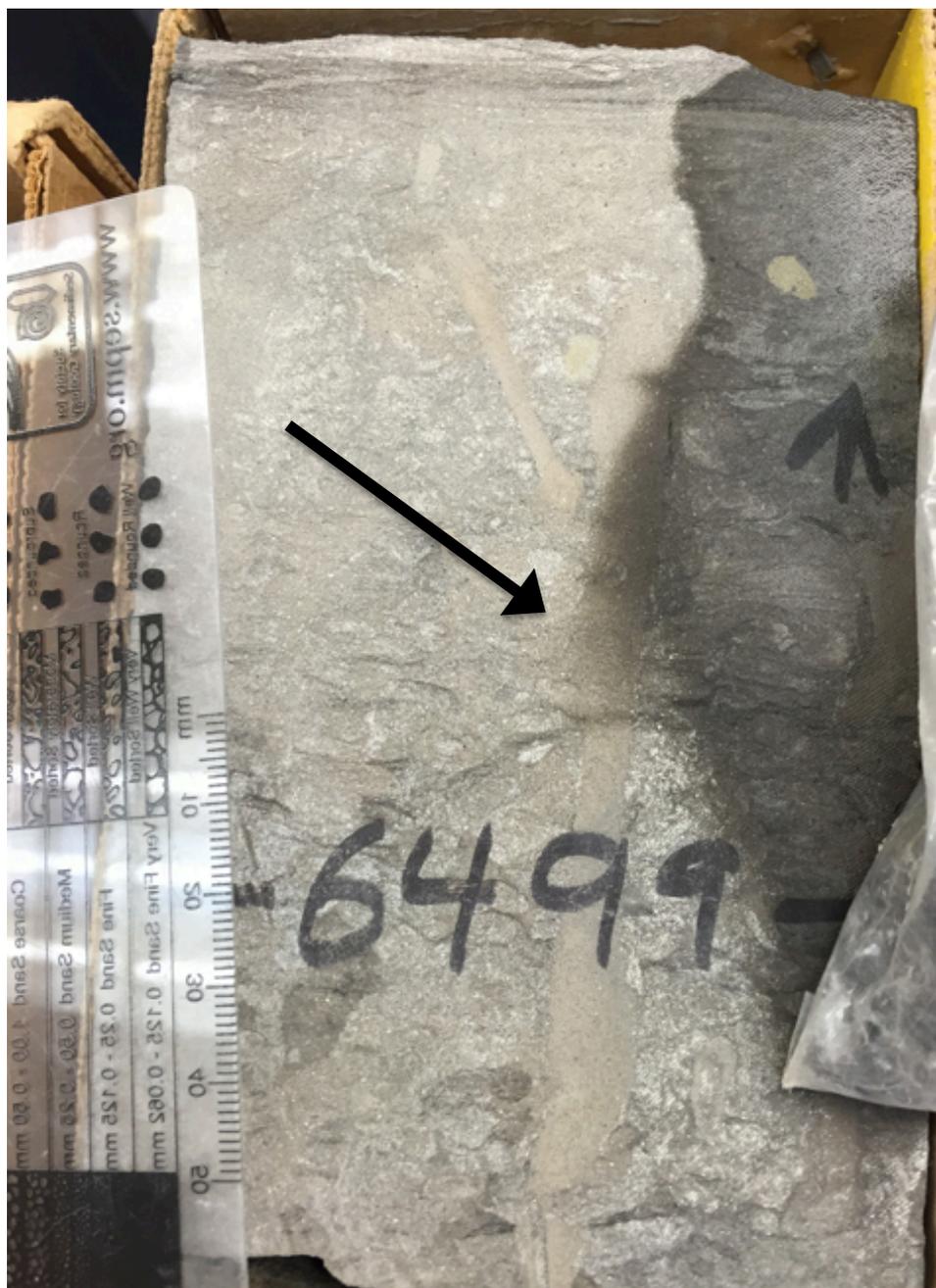


Figure 17: Cross section of shallow marine environment, with the neritic zone (marine shelf) expanded. The shelf is divided into which different processes are constrained. From Nichols (2009).

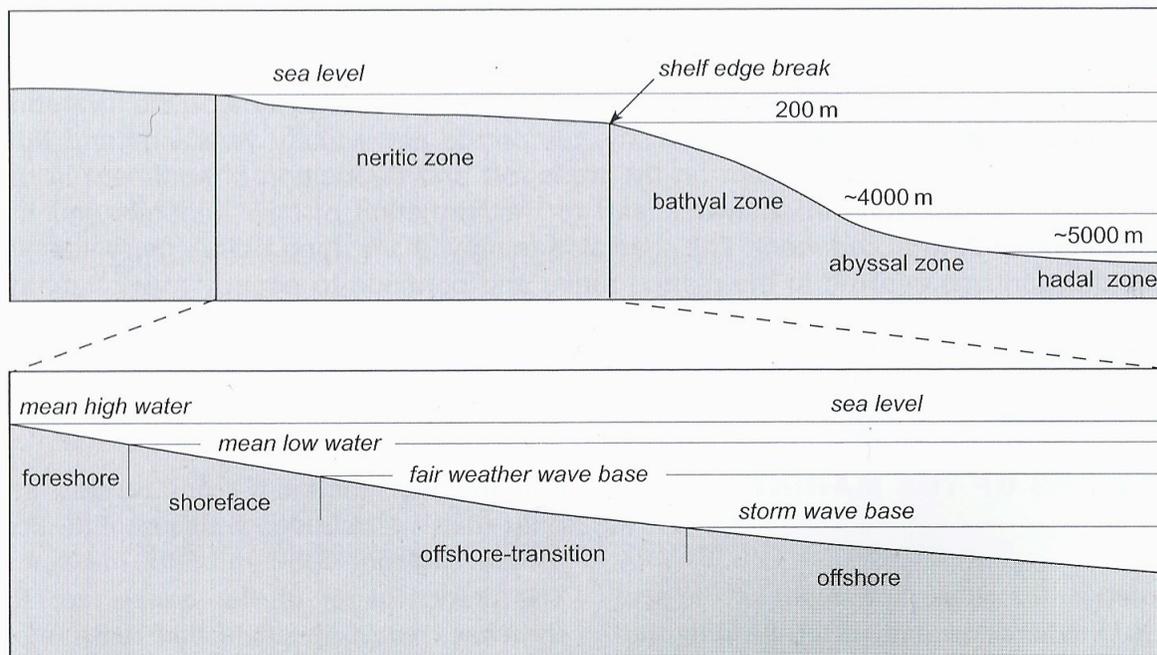
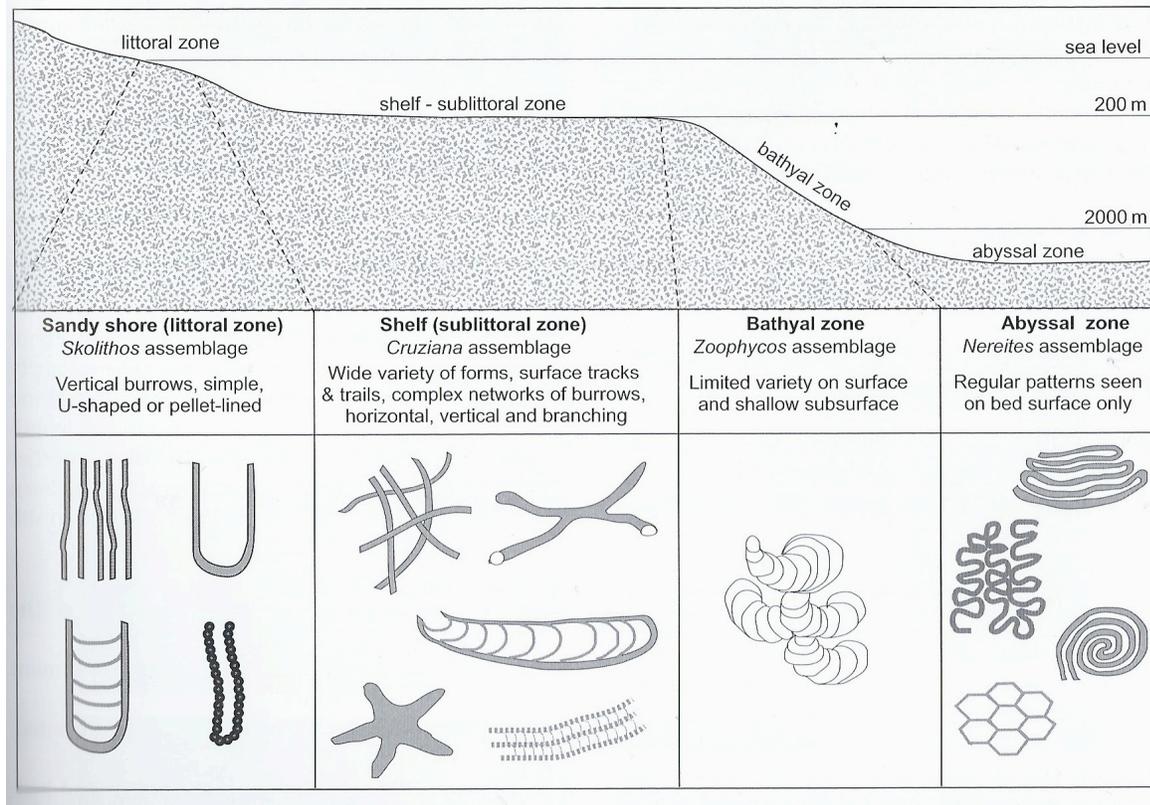


Figure 18: Position of ichnofacies in the shallow marine environment. From Nichols (2009).



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