Spring 2016

Reservoir Study and Facies Analysis of the Big Clifty Sandstone in South Central Kentucky

Tyler S. Bodine
Western Kentucky University, tyler.bodine040@topper.wku.edu

RESERVOIR STUDY AND FACIES ANALYSIS OF THE BIG CLIFTY SANDSTONE IN SOUTH CENTRAL KENTUCKY

A Thesis
Presented to
The Faculty of the Department of Geography and Geology
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By
Tyler S. Bodine

May 2016

RESERVOIR STUDY AND FACIES ANALYSIS OF THE BIG CLIFTY SANDSTONE IN SOUTH CENTRAL KENTUCKY

Date Recommended April 20, 2016

Dr. Michael May, Director of Thesis

Dr. Patricia Kambesis

Dr. Fred Siewers

Dean, Graduate School Date 4/25/16

Acknowledgements

I appreciate all who provided encouragement and support for this project. Special thanks to Dr. Michael May, my advisor, and my committee members Dr. Aaron Celestian, Dr. Patricia Kambesis, and Dr. Fred Siewers. I would also like to thank the Kentucky Geological Survey for maintaining the online oil and gas repository and allowing access to the dataset. Additional thanks to Mr. Bill McKenzie and Mr. Dave Mallory of Calgary, Canada, and the workers at the Stampede Mine in Logan County, Kentucky. I greatly appreciate access to the Stampede Mine.

I am very appreciative of the kindness and generosity of Mr. Andrew Reeder who worked with me as a consulting geologist at the Stampede Mine and who is a GIS genius. Thanks to my wife Laurel Coffey-Bodine and my son Atha Lee Bodine who inspired me to pursue this degree. I would also like to thank my mother, father, and grandmother for always having encouraged me to work hard and pursue what interests me. I hope this work helps the people of South Central Kentucky better understand the mineral resources of their region.

Table of Contents

List of Figures

List of Tables

RESERVOIR STUDY AND FACIES ANALYSIS OF THE BIG CLIFTY SANDSTONE, SOUTH CENTRAL KENTUCKY

Tyler Bodine May 2016 156 pages

Directed by: Michael T. May, Patricia Kambesis, Fredrick D. Siewers

Department of Geography and Geology Western Kentucky University

The Big Clifty (Jackson) Sandstone Member of the Golconda Formation is the most important of the Mississippian (Chesterian) heavy-oil reservoirs in the southeastern Illinois Basin. Heavy oil reservoirs, or asphalt rock deposits, have been studied extensively in south central and western Kentucky, and ~2 billion barrels of original oil in place (OOIP) have been proposed to occur in the Big Clifty Sandstone. Despite high OOIP estimates, heterogeneities in the reservoir negatively impact the production of heavy oil deposits. Heterogeneities related to depositional facies changes are poorly understood in the Big Clifty Sandstone of Kentucky, where it has been mostly described as a 60-120 feet thick sandstone unit. In some locations, the Big Clifty occurs as two distinct sand bodies with intercalated mud-rich units and, most typically, with the greatest clay- and silt-rich units present between sandstone bodies. Questions exist as to how such muddy facies occur in the reservoir.

This study couples sedimentary facies analysis with sequence stratigraphy to assess how lithological factors affect the occurrence of petroleum in Big Clifty reservoirs. Multiple datasets were integrated to develop a depositional model for lithologic facies observed in this study. Datasets include core, exposure descriptions, petrographic analysis, bitumen concentrations, electrical resistivity tomography (ERT), and borehole geophysical analysis. This study occurred in Logan, Warren, and Butler counties, with emphasis on an active asphalt-rock mine

in Logan County. Surface geophysical methods aided in demarcating Chesterian limestones, sandstone bodies and, in particular, highly resistive heavy-oil laden Big Clifty channel bodies.

In Warren County, located E-NE of the Stampede Mine, the Big Clifty coalesces into a single amalgamated sandstone channel or a series of superimposed stacked channels as observed in outcrop along Indian Creek at McChesney Field Station and at Jackson's Orchard. In these locations, the tidal influence is subtle with large-scale trough cross bedding dominating, and the contact on the Beech Creek Limestone is sharp. Facies changes related to the environment of deposition greatly impact the quality of heavy-oil reservoirs and must be taken into consideration during exploration and siting of asphalt rock mines.

Chapter 1: Introduction

The Big Clifty Sandstone is both a heavy-oil (low API gravity) and conventional (high API gravity) petroleum reservoir that occurs in the subsurface and outcrop belt in the Illinois Basin of Western Kentucky. Despite multiple studies attempting to quantify Big Clifty heavy oil resources (Jillson, 1926; Noger, 1987; Bowersox, 2014), no facies analysis studies have been done relating depositional facies to reservoir properties. No specific depositional model, furthermore, has been suggested for the Big Clifty Sandstone in South Central Kentucky. Such an understanding could aid in exploration of heavy-oil reservoirs, as well as determine the potential of Big Clifty Sandstone for wastewater disposal wells in the subsurface of Butler and Warren Counties.

1.1: Problem Statement

The economics of surface mining and processing heavy-oil reservoirs are negatively impacted by the occurrence of fine sediments and fluctuating heavy oil concentrations. Such heterogeneities in Big Clifty Sandstone reservoirs have impeded current attempts to develop heavy oil deposits in Logan County and made prospecting for new reserves challenging. Furthermore, sedimentary features such as grain size, composition, and shape are significant considerations needed to optimize processing heavy oil ore using ionic solution settling tanks. Such processes utilize electric pumps and piping prone to degradation as the result of the shape and strength of the materials they process. Additionally, solution-settling processes often do not work well with fine-grained materials.

Physical and reservoir properties such as grain size and porosity are largely controlled by facies in depositional systems (Pryor et al., 1990). Multiple types of depositional systems have been observed in Chester siliciclastic reservoirs such as deltaic, nearshore and marine embayments, incised valley systems, and estuarine systems (Webb and Grigsby, 2015). During Chesterian time, the Illinois Basin was a shallow ramp that rarely achieved depths below wave base (Treworgy, 1990). These shallow conditions further complicate interpreting facies, as systems were often reworked. Core and outcrop-based facies models provide a framework for the sedimentology and stratigraphy of Big Clifty heavy oil sandstones, which control reservoir properties. Currently no such model exists for heavy oil reservoirs in northeast Logan County.

1.2: Objectives

The main objectives for this study are the following: 1) develop a facies model for the Big Clifty Sandstone, and 2) relate this model to the exploration and production of heavy oil reservoirs in South Central Kentucky and, particularly, northeast Logan County. To accomplish these objectives a study was conducted incorporating sedimentological, petrographic, geophysical, and organic geochemical analysis of the study area. Core, surface exposures, Electrical Resistivity Tomography (ERT), petrographic, and laboratory datasets were integrated to develop the facies model.

Chapter 2: Geological Framework

2.1: Overview

The Illinois Basin is an intracratonic basin encompassing the majority of Illinois, Southwestern Indiana, and Western Kentucky (Figure 2.1). This sedimentary and structural basin is positioned near the New Madrid Rift Complex, and is bound on all sides (Figure 2.2) by positive structural features. The strata mostly consist of Cambrian through Pennsylvanian rocks that dip gently basinward from surrounding margins (Buschbach and Kolata, 1990). The geometry of the basin has been changing since faulting along the New Madrid Rift system occurred during the late Precambrian. Since the Precambrian, episodic subsidence occurring along normal faults has accommodated sedimentation and punctuated sedimentary sequences (Kolata, 1990).

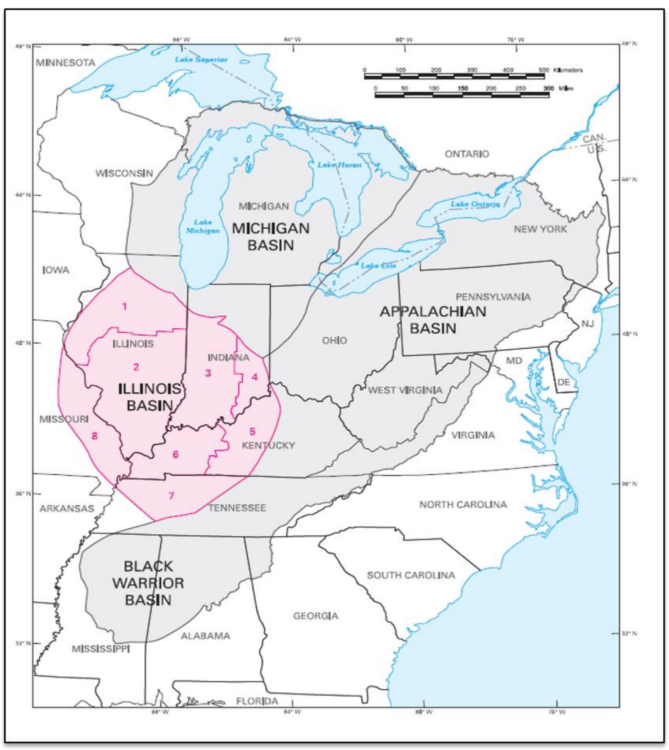


Figure 2.1. Map Showing the Illinois Basin, Appalachian Basin, Michigan Basin, and Black Warrior Basin. Source: Swezey (2009).

The Illinois Basin during much of the Paleozoic was connected to the open ocean to the south through the current day Pascola Arch (Figure 2.2). Fluctuating sea level caused major depositional sequences to develop, with each sequence representing a major regressive-transgressive cycle. Six primary sequences spanning the Phanerozoic are present in the Illinois Basin. From oldest to youngest they are the Sauk, the Tippecanoe, the Kaskaskia, the Absaroka, the Zuni, and the Tejas (Sloss, 1963; Kolata, 1990).

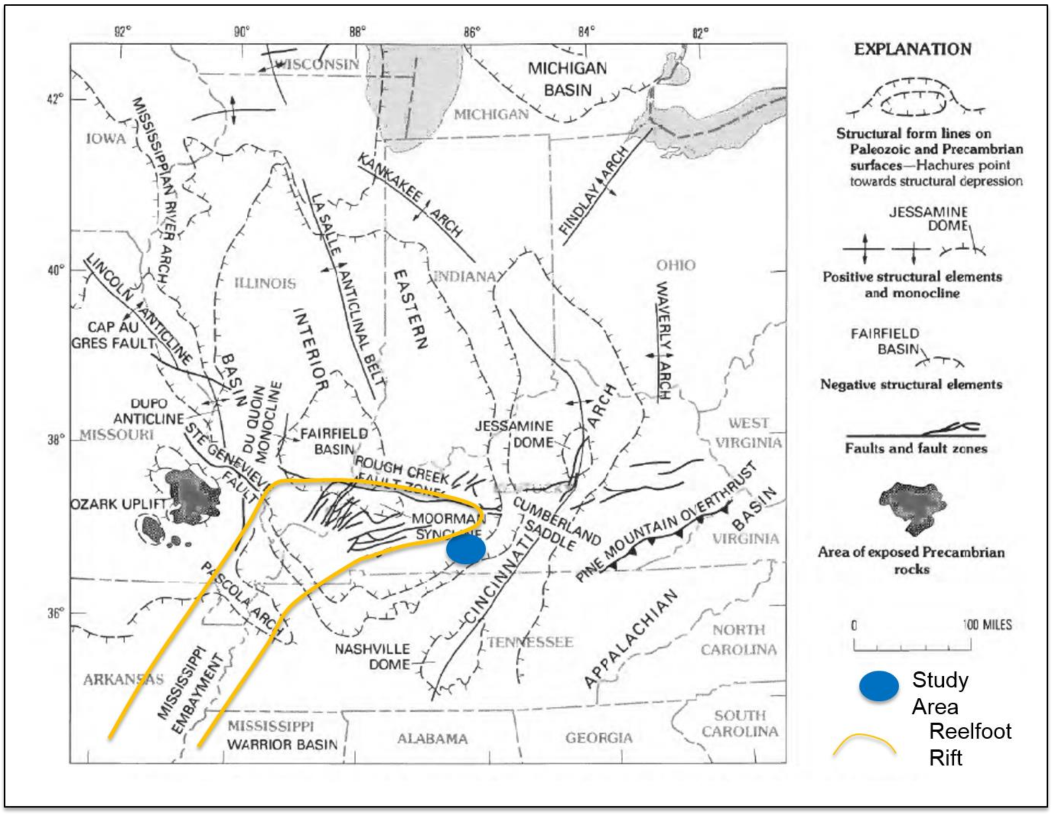


Figure 2.2. Map showing Study area in relation to structural features. The outline of the Reelfoot rift and Rough Creek graben fault zones are outlined in green. Notice the Pascola arch which was emplaced after the deposition of the Big Clifty Sandstone in the Illinois Basin. Source: Sable and Dever (1990).

2.2: Structural Framework

The New Madrid Rift Complex is the primary control on sediment accumulation rates and depositional environments in the Illinois Basin (Figure 2.2) (Kolata and Nelson, 1990). Siesmic-reflection data combined with gravity and magnetic anomalies have led to new understandings regarding the extent and geometry of the Reelfoot Rift Complex (Figure 2.2). The eastern arm of the rift complex consists of the Rough Creek Graben, which extends into Western Kentucky. The Rough Creek Graben possesses an east-west trend and is bound to the south by an unnamed fault system, which traverses the study area in Logan County and turns northward before reaching Warren County to combine with the Pennyrile Fault System. These faults occur as high-angle normal faults that, combined, have less than 3300 feet of displacement (Kolata, 1990; Nelson, 1990). The entire Rough Creek Fault System narrows to the east and widens to the west and southwest where it combines with the Reelfoot Rift. The Rough Creek Graben formed during the Precambrian; however, reactivation along existing faults occurred at least twice during the Paleozoic. During the Pennsylvanian, reverse faulting occurred from convergence related to the Alleghenian Orogeny. During this time many petroleum accumulating positive relief structures formed throughout the basin. During the Jurassic, extensional forces from the breakup of Pangaea caused dip slip reactivation (Nelson, 1990).

No specific work has been conducted that describes the structural geology of the unnamed fault system in Southwestern Kentucky. It has been suggested that the structural styles of this fault zone are quite similar to the Pennyrile Fault Zone to the north, which formed in response to extensional forces with the breakup of Pangaea (Kolata and Nelson, 1990). It is within the southern unnamed fault zone that Big Clifty Sandstone heavy oil deposits occur in Logan County (Figure 2.3).

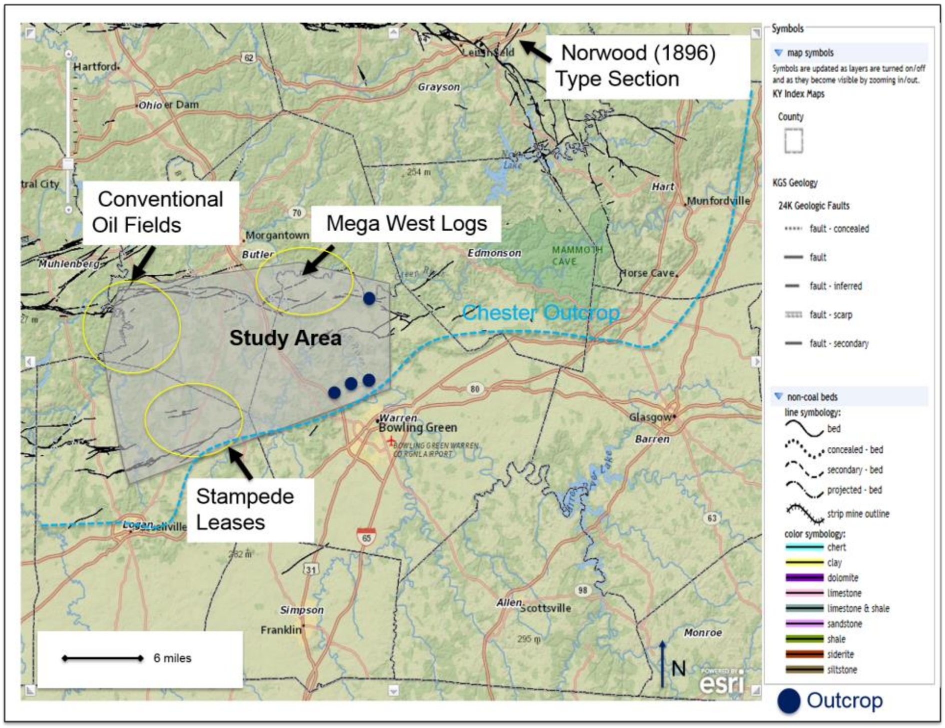


Figure 2.3. Map showing study area. Dashed purple line shows the approximate boundary between the outcrop belt of Big Clifty Sandstone and where it occurs in the subsurface. Black lines show mapped faults. Note the southern most fault zone that occurs in the study area. Type section from Norwood (1876) also displayed. Source: Modified from KGS maps: http://www.uky.edu/KGS/

2.3: Stratigraphy

The oldest rocks in the Illinois basin consist of 1,420 to 1,500 Ma granite and rhyolite, which are overlain by sedimentary rocks ranging from Paleozoic to Mesozoic (Swezey, 2009). The Paleozoic stratigraphic section in the Illinois Basin consists largely of carbonates punctuated by siliciclastics sourced by tectonic activity (Kolata and Nelson, 1990; Swezey, 2009). Three main periods of influx of siliciclastics into midcontinent basins are the result of the three orogenic revolutions that ultimately formed Pangaea (Pashin, 1993; Swezey, 2009). The last of these orogenies, the Alleghenian, occurred during the late Mississippian through Permian time and sourced the siliciclastics occurring between carbonates of the Chester Series in the Illinois Basin.

The Chester stratigraphic (Figure 2.4) section in the study area marks a transition from dominantly carbonate deposition during the early to middle Mississippian (Valmeyeran) to dominantly siliciclastic deposition during the Pennsylvanian (Treworgy, 1990). The Illinois Basin during this time was within 5° south of the equator and existed as a low-angle ramp covered by a shallow epeiric sea that shoaled south of the Rough Creek Fault zone. The Chester Series composes cyclical or rhythmic deposits of sandstone, shale, and limestone, with clastic sediments comprising 25 to 50 percent of the Series (Dana and Scobey, 1941; Sable and Dever, 1990). Sandstones commonly occur as fine to coarse-grained quartzarenite, which contrast the largely sublitharenites occurring in Kinderhookian and Osagean units.

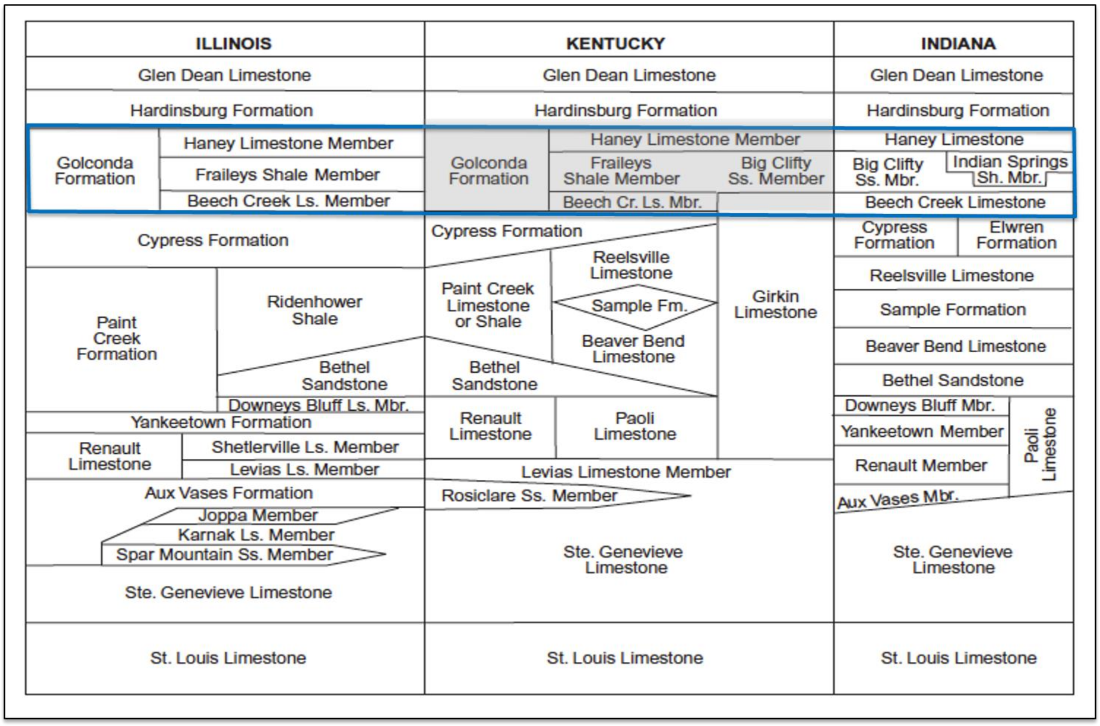


Figure 2.4. Stratigraphic column. In South Central Kentucky the Beech Creek Limestone member of the Golconda Formation thins into the Girkin Limestone along the basin margin. The Beech Creek is often overlain by fossiliferous shale. Source: Modified by the author from Nelson et al. (2002).

2.4: South Central Kentucky

The Chester Series occurs both in the outcrop belt and in the subsurface in South Central Kentucky, where it thickens over the Mormon Syncline and Rough Creek Graben. The Chester outcrop belt parallels the Cincinnati Arch north to south along I-65 until near Mammoth Cave, where it turns west/southwest (Figure 2.3). In this region of Kentucky, the Big Clifty Sandstone is typified as 60 to 120 feet of quartz sandstone (Sable, 1964; Sandberg and Bowles, 1965) that caps ridges, forming the Dripping Springs Escarpment. This sandstone cap enhanced the development of numerous caves occurring in underlying limestone. The bedrock dip in this region is to the west to southwest off the Cincinnati Arch and into the Illinois Basin.

Numerous conventional oil and gas fields occur in the subsurface of this region. Bowling Green Consolidated Field in Warren County is one of the largest, and developed rapidly creating an oil boom in the 1920s (McGrain and Sutton, 1973). Mississippian and Devonian-aged reservoirs are the primary producers. Sixty percent of the oil produced in the entire Illinois Basin is from Mississippian-aged reservoirs (Treworgy, 1990). The Big Clifty Sandstone is a conventional reservoir in Southwestern Butler County, where Chester stratigraphic units have produced the highest volumes of oil (Schwalb, 1975).

Unconventional hydrocarbons in the form of low API gravity oil and bitumen also occur extensively in Mississippian and Pennsylvanian rocks in this region. These deposits are not tar sands but rather are lithified sandstone containing <10 API hydrocarbons and are referred to as asphalt rock. Estimates ranging from three to six billion barrels of oil-equivalent asphalt rock occur in Mississippian and Pennsylvanian reservoirs in Kentucky. The majority of this oil is from the Big Clifty Sandstone (Noger, 1987; May and Kuehn, 2009; May, 2013).

Chapter 3: Literature Review

3.1: Chester Environments of Depositions (EODs)

Several excellent studies have been conducted that describe sandstone depositional patterns and characteristics during the Chester (Upper Mississippian) in the Illinois Basin (Siever, 1953; Potter et al., 1958; Potter, 1962; Swann, 1964; Droste and Keller, 1995; Smith and Read, 2001; Nelson et al., 2002; Webb and Grigsby, 2015)**.** Swann (1964) described the Chesterian as a rhythmic stacking of carbonates and sillicilastics occurring above the carbonate-dominant Valmeyeran and comprising 12 to 15 major regressive and transgressive cycles. Swann (1964) noted that exact boundaries of major cycles are difficult to determine as they commonly vary across the basin, which led to miscorrelation in early work. Compounding the problem, extreme lateral variation in lithology and thickness of siliciclastics occurs in the Chester Series. A sandstone body can shift laterally into shale over a distance of a mile or less (Siever, 1953).

According to Swann (1964), Chester siliciclastics entered the Illinois Basin from the northeast via the ancestral Michigan River and its associated deltaic system, which shifted laterally NW-SE some 200 miles (Figure 3.1). These delta lobe shifts led to geographic heterogeneities in the location of the sandstone across the basin both along strike (~200 miles) and down dip (~600 miles) as the paleoshoreline advanced and retreated.

Environments of deposition (EOD) for Chester Series siliciclastic intervals vary from fluvial to distal marine environments. Specific depositional environment classes have been suggested and include: shallow marine, deltaic, estuarine, and incised valley fill (Webb and Grigsby, 2015). Boundaries between classes are not always well defined and sedimentary units are commonly the result of multiple depositional classes. Facies analysis is a useful method for associating EOD based on lithology and sedimentary features. The term "facies" contains both a descriptive and interpretative component, which may be used to form a model describing sedimentary environments during deposition (Anderton, 1985). To address the complexities of the Chester Series and, more specifically, the Big Clifty Sandstone, this study combines the methods of facies analysis with sequence stratigraphy.

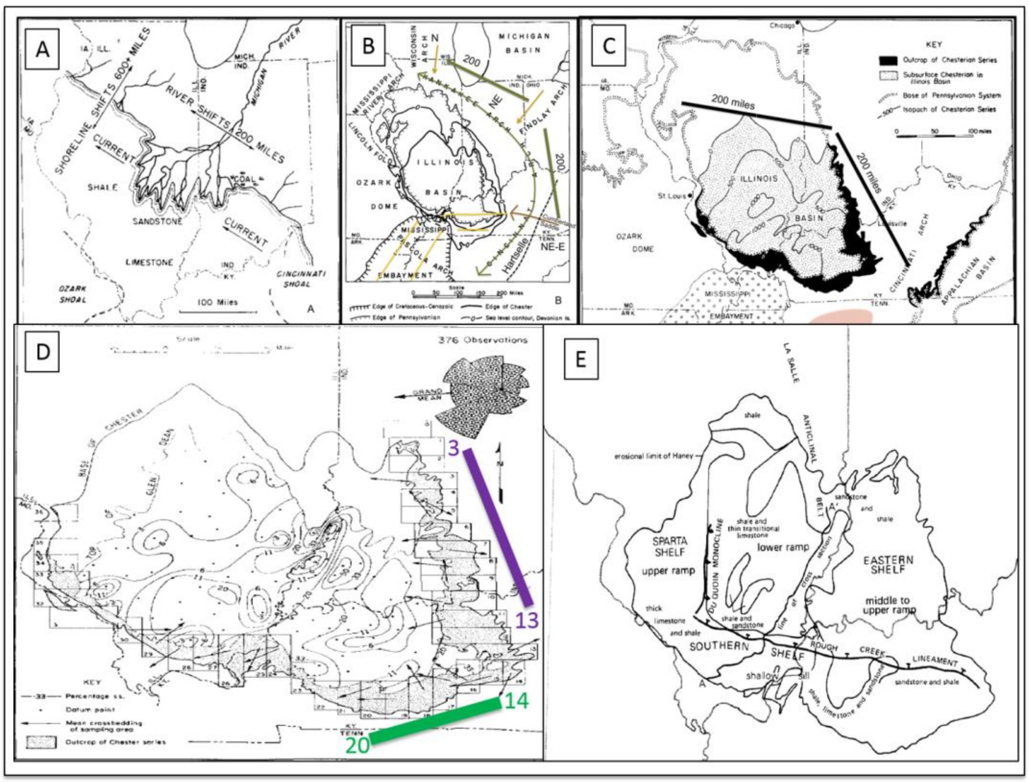


Figure 3.1. Compilation of maps from previous work. Source: A, B, and C are modified from Swann (1964) showing his Michigan River Delta system. The black bars in C are 200 miles, which is the range of the delta switching according to Swann (1964). D is modified from Potter et al. (1958) showing sample sections 3 through 13 (purple) and 14 through 20 (green). The grand mean is shown in the upper right corner. E is a map from Treworgy (1988) showing her subdivisions of the basin during Golconda time

3.2: Sequence Stratigraphy

Sequence stratigraphy is a branch of stratigraphy that uses genetically related packages of sediments bounded by unconformities to correlate chronostratigraphically related but lithologically varying facies types. Sequences are composed of parasequences and parasequence sets and are organized into system tracts (Sloss, 1963; Wagoner et al., 1988; Embry, 2009). Despite the wide usage of sequence stratigraphy in basin analysis, it has been infrequently applied to intracratonic basins (Leetaru, 2000). Nonetheless, some excellent sequence stratigraphic studies of Chesterian units exist for the Illinois Basin (Leetaru, 2000; Smith and Read, 2001; Nelson et al., 2002)

A study by Nelson et al. (2002) identified incised-valley fill (IVF) facies in the Big Clifty Sandstone in the Cub Run and Constantine quadrangles of Kentucky. These thick (60-120 feet) sandstone deposits fill scoured valleys. The grains are coarser than sandstones and interpreted to be tidal bars. Coals and carbonaceous shales have also been described in the upper portion of the unit in this area. Evidence for exposure is well documented in the Big Clifty Sandstone in the form of red and green mudstones and paleosols (Treworgy, 1988; Smith and Read, 2001; Nelson et al., 2002). Coals, however, have only been described in IVF deposits, which are fluvial in nature and likely formed during lowstand conditions (Nelson et al 2002).

Treworgy (1988) studied the Golconda Group across the Illinois Basin and described the basin as a shallow ramp during deposition of the Golconda Group. In her model, the basin was subdivided into three shelves (Figure 3.1, Part E) and separated by moderately deep areas, but never achieved depths below wave base.

Part E of Figure 3.1 shows the southern shelf, which occurred as a shallow sill with accommodation increasing westward. She divided the ramp into lower, middle, and upper sections and placed the boundaries between sections along structural "hinge lines." Lower ramp settings contain the conodont *Gnathodus* that occurs in the Beech Creek Limestone (Treworgy, 1988). The Frailey's Shale of Illinois and Western Kentucky formed under middle to lower ramp conditions while the Big Clifty Sandstone formed under middle to upper ramp conditions, and thickens to the east (Treworgy, 1988). Later work suggests that the Big Clifty Sandstone formed as a single regressive-transgressive unit spanning two sequences, accommodated by differential subsidence along existing structures (Smith and Read, 2001). The lower unit of Big Clifty Sandstone prograded into the Illinois Basin during high-stand conditions and the upper unit was deposited above a basin-wide exposure surface during the ensuing marine transgression (Nelson et al., 2002).

3.3: Big Clifty Sandstone

The Big Clifty Sandstone occurs as a fine-to-medium grained quartz arenite with framework grains consisting of mono and poly-crystalline quartz with minor feldspar and micaceous grains (May, 2013). The unit consists largely of sandstone in Western Kentucky, but also contains variable amounts of shale, siltstone, and limestone (Williams et al., 1982). Sandstone units are thin (e.g., 0.5-2 ft.) to massive bedded and exhibit cross bedding, ripple bedding, and flaser bedding (Noger, 1987).

No detailed facies analysis exists for the unit south of the Rough Creek Fault Zone, despite several studies having been completed on the heavy-oil deposits occurring in the Big Clifty Sandstone. Two facies studies of the Big Clifty Formation were conducted near Sulphur, Indiana (Visher, 1980; Specht, 1985). Results from these studies support interpretations in several major sequence stratigraphic studies (Treworgy, 1988; Nelson et al., 2002; Smith and Read, 2001). These researchers have described the Big Clifty Sandstone in Indiana as tidally influenced bar sands and tidal sand ridges that formed in a tidally influenced delta system. Baker (1980) studied the Big Clifty in the Wheatonville consolidated field in Gibson County, Indiana, and identified two sandstone lenses in the subsurface ~1 mile (1.6 km) apart. These sandstone lenses are approximately 0.75 miles (0.75 km) across and 5 miles (8.1) long and range in thickness from 20 to 64 feet (6.1 to 19.0 meters). Baker (1980) described the lower contact of the Big Clifty with the underlying Beech Creek or Girkin Limestone as sharp with sand bodies containing cross laminations and fine-grained clastics. These interpretations are consistent with a tidally influenced, near shore to shallow marine environments of deposition. Upper delta plain or fluvial deposits have not been described in Indiana.

Potter et al. (1958) conducted a basin-wide paleocurrent study of Chester sandstones and concluded that the Big Clifty Sandstone is a notable exception to the general Chester trends in both paleocurrent direction and location in the basin. The Big Clifty Sandstone occurs in the outcrop belt of Indiana and Western Kentucky along a north to south trend where it is well developed in the subsurface and becomes less developed westward in Illinois (Potter et al., 1958). Part D of Figure 3.1 shows the grand mean for paleocurrent data for both the Hardinsburg and Big Clifty sandstones in the lllinois Basin. Researchers note that cross bedding in the Big Clifty Sandstone is poorly developed in sections 3 to 13 of the outcrop and best developed in sections 14 to 20 (Figure 3.1 part D) where the sandstone has a dominantly westerly paleocurrent direction (Potter et al., 1958). Several interpretations were offered by the authors to explain the atypical nature of the Big Clifty Sandstone in the eastern Illinois Basin including a localized easterly sediment source, depositional strike elements from longshore currents, and relief from the Cincinnati Arch (Potter et al., 1958). Later work emphasized an easterly cratonic source during Big Clifty time as indicated by correlating the Big Clifty Sandstone to the Hartselle Sandstone of the Appalachian Basin of Kentucky and Tennessee (Sable and Dever, 1990). This work suggests that the northwest to west paleocurrent direction in the Big Clifty Sandstone in South Central Kentucky, results from sediments entering the basin across the Cumberland Saddle (Figure 3.3, Part B). Other researchers correlated the Big Clifty Sandstone to the Hartselle Sandstone of the Black Warrior Basin of Alabama noting a similar cratonic source for both the Hartselle and Big Clifty (Stapor and Cleaves, 1992). This interpretation has met challenges. Thomas and Macke (1982) suggested an Ouachita orogenic source for the Hartselle in the Black Warrior Basin. Compelling similarities exist in facies between the Hartselle and Big Clifty as both units consist of tidally influenced bar sandstones and both units are heavy oil reservoirs. These two siliciclastic units represent a dramatic shift in the siliciclastic- generating source region and could record the transition from Taconic to Alleghenian tectonic styles (Stapor and Cleaves, 1992).

3.4: Reservoir Studies

3.4.1: Asphalt Rock Reservoirs

Asphalt rock has been mined for over 100 years in Kentucky (Noger, 1987). Since the 19th century, geologists have studied these resources in an attempt to quantify them. The first asphalt mine in Kentucky was located in Logan County in 1891. The asphalt was used locally as a paving material (May, 2013). Kentucky Asphalt Rock Company mined the basal Pennsylvanian Caseyville Sandstone in Edmonson County in the first half of the 20th century with much success. The material was loaded into barges and shipped along the Green River and sold globally (May, 2013). A study by Jillson (1926) was one of the earliest attempts to quantify asphalt rock reserves in South Central Kentucky. This comprehensive report documented asphalt rock mining and reserves across the region by providing reservoir geometry and bitumen concentrations. Several mines northeast of Russellville in Logan County were examined. Jillson (1926) noted an average bitumen concentration of 7.36% in these locations with deposits ranging from 10 to 39 feet thick, with one 350 to 400 acre tract in Logan County estimated to contain ~1,500,000 tons of recoverable asphalt rock.

3.4.2: Previous Studies

During the 1960s and 1970s, the United States Geological Survey (USGS), in cooperation with the Kentucky Geological Survey (KGS), conducted a statewide geological mapping program on a 1:24,000 scale (Noger, 1987). This work provided maps to the public showing the location of asphalt rock mines for the first time and greatly enhanced efforts to quantify heavy oil reserves. The most comprehensive study to date of asphaltic sandstone resources in Kentucky was conducted in the early 1980s in a joint study between the KGS and Interstate Oil Compact Commission (Noger, 1987). Figure 3.2 shows the locations of asphaltic sandstone measured in this study. In the Cooperstown-Gasper area of Logan County, 43,000 acres were assessed and 390 million barrels of heavy oil were estimated to occur in the Big Clifty Sandstone (Noger, 1987).

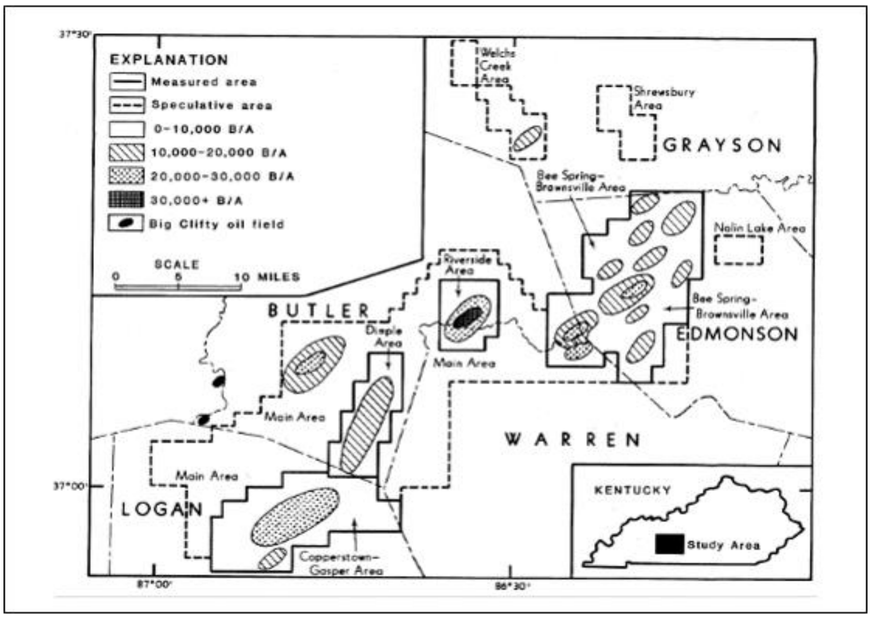


Figure 3.2. Map showing the location of asphaltic sandstone deposits across the study area. In the Cooperstown and Gasper area of Logan County, Noger (1987) reports approximately 20 to 30 K barrels per acre. Source: Noger (1987).

An estimated 2.1 billion barrels of heavy oil were calculated for all Big Clifty heavy oil reservoirs in South Central Kentucky. This estimation has been refined over the years, most recently by Bowersox (2014) who calculated an average volume of 6,300 barrels of heavy oil per acre for the Big Clifty Sandstone. In this study Bowersox (2014) noted approximately 389,000 acres of Big Clifty Sandstone resources (Figure 3.3).

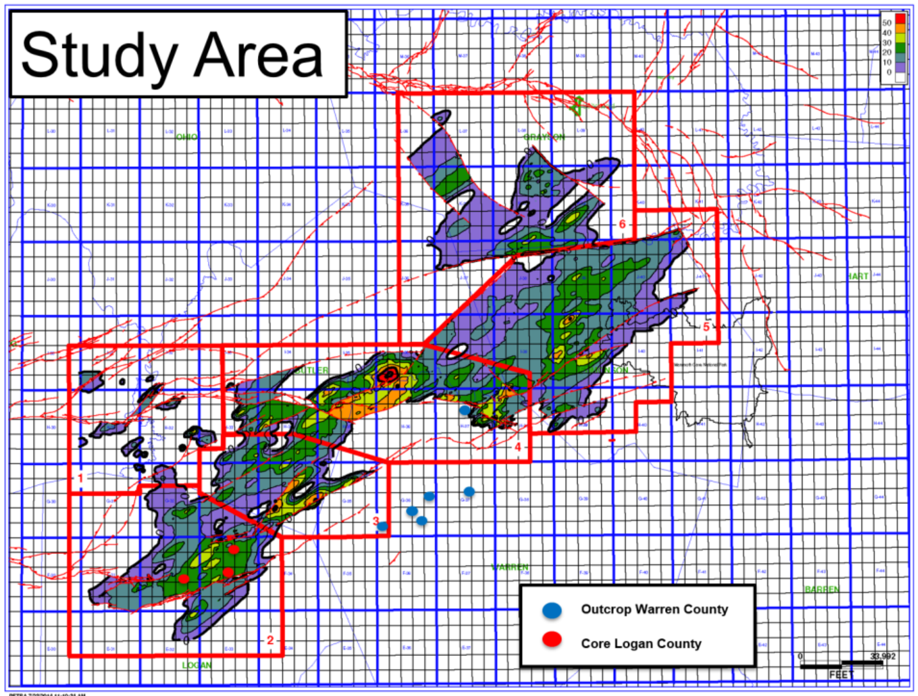


Figure 3.3. Net asphalt rock map of the Big Clifty Sandstone. Sandstone thickness values range from 0 to 50 feet and are shown on carter coordinate grid. Note the high values shown in the riverside area of Warren County where the Mega West project occurred. Outcrop and core data locations are shown with blue and red circles. Source: Created by Bowersox (2014) and used with permission.

3.4.3: Logan County

Much of the surface mining of asphalt rock has occurred in areas where heavy-oil reservoirs are at or near the surface, such as in Logan County. Overburden is a considerable expense for asphalt rock-mining operations. Perhaps the most successful asphalt-rock mining operation in Logan County to date was the Tarco pilot project operated by Larry Hastings and DOW Chemical in the 1980s. The Big Clifty Sandstone at the former plant site occurs close to the surface with an overburden of 4-10 feet (Groves and Hastings, 1983). The Tarco operation was located near Homer, Kentucky, approximately four miles from the current Stampede Mine site. The largest impediment to the economics of developing asphalt rock for crude oil is processing the ore. Heterogeneities in the reservoir greatly impact attempts to process asphalt ore through solution processes. The Big Clifty Sandstone in the vicinity of the Tarco site consists of approximately 40 feet of sandstone with bitumen content of between 6 to 8% (Groves and Hastings, 1983). No reservoir characterization or facies analysis data were published or made publically available from the Tarco operation.

3.4.4: Butler County

The Big Clifty Sandstone is a reservoir in Butler County. Schwalb (1975) published a report on the petroleum geology of Butler County and noted that the Big Clifty Sandstone occurs as a shallow conventional oil reservoir primarily in the northern and western portions of the county. The Big Clifty has also produced gas in the Huntsville field (Figure 3.4) with initial production of one well at 325 MCF (thousand cubic feet) per day (Schwalb, 1975).

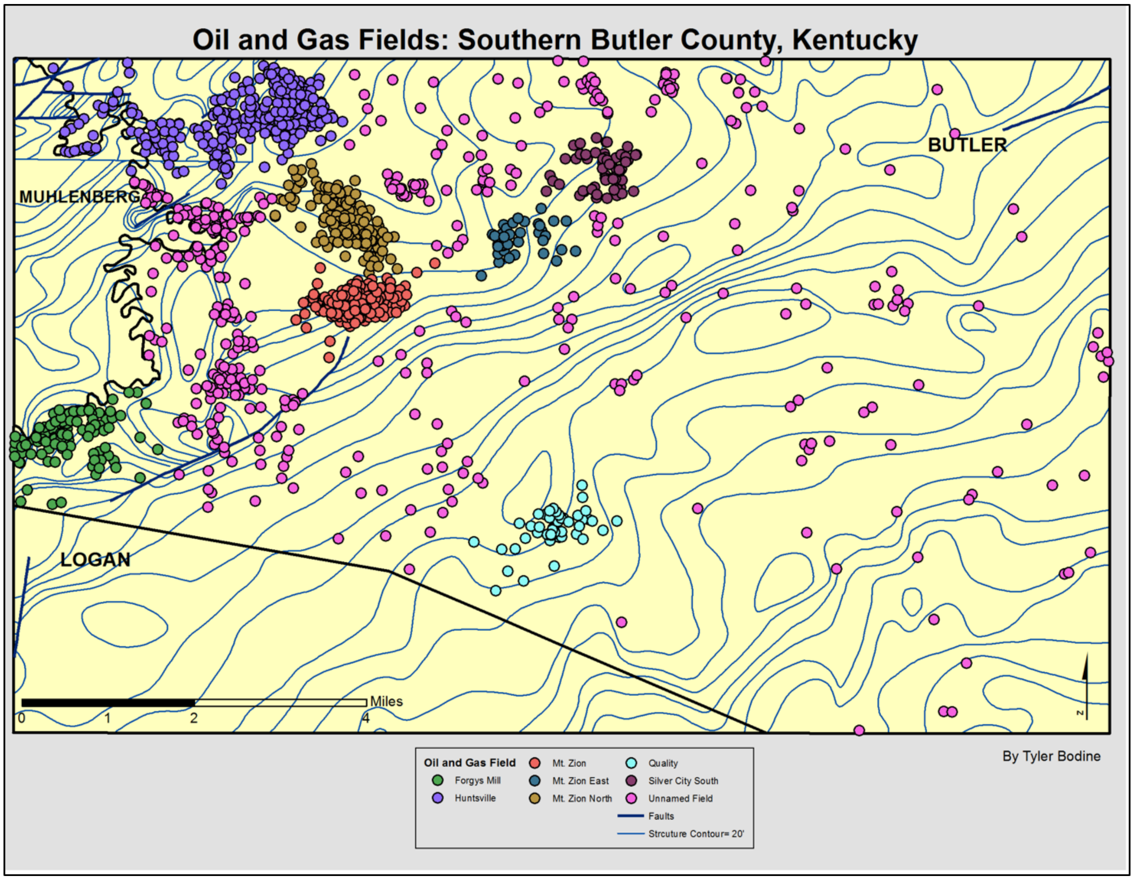


Figure 3.4. Map showing oil fields in south western Butler County. The purple circles represent the Huntsville field. The structure is on the Glen Dean Limestone in the west and the Big Clifty Sandstone in the east. Source: Created by author with data from the Kentucky Geological Survey (KGS, 2015) online at: http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp

In this report, Schwalb (1975) suggested that the term "shelf" does not describe the paleogeography of Butler County during Chester deposition and prefers instead the term "verge" to describe the shallowly dipping basin. He noted that no major change in degree of dip angle or sedimentation occurs north to south across the Pennyrile Fault System but, instead, suggested that the verge in this area begins at the Pennyrile Fault System and terminates toward the Tennessee border (Schwalb, 1975). This interpretation may conflict with Treworgy's (1988) classification of lower, middle, and upper shelf or shelves that transition over structural hinge lines. Schwalb (1975) suggested that Big Clifty Sandstone petroleum traps result from variation in sandstone thickness and sandstone quality rather than structural closure, although combination traps likely exist. Pryor et al. (1991) also described stratigraphic traps in Chesterian units and, according to their study, the distributions of reservoirs are controlled by "synsedimentary topography." They suggested regenerative feedback mechanisms caused by preexisting structures and/or syndepositional topography controlling both where reservoirs and seals occur in Chester units (Pryor et al., 1991). Marine shale is the primary seal for Chester sandstone where it encases the Sandstone body on all sides. These mechanisms exert a strong control on patterns of deposition and eogenetic diagenesis (Pryor et al., 1991).

3.4.5: Warren County

Several Pennsylvanian asphalt-rock deposits occur along the Green River in Warren County. No large-scale mining, however, has been attempted. Steam-flood and fire-flood processes have been attempted in Big Clifty reservoirs of Warren County with poor results (McGrain, 1976). From 2008 to 2011, Megawest Energy Corporation attempted a steam-flood design, targeting multiple Chester sandstone units (Big Clifty, Hardinsburg, and Tar Springs) in Edmonson, Butler, and Warren counties (May, 2013). No mining or enhanced oil recovery projects are currently active in Warren County.

Chapter 4: Methods of Investigation

4.1: Overview

This study is primarily based on cores taken from the Stampede Mine and surrounding areas in Logan County, Kentucky. Other data sets were collected from this site including Electrical Resistivity Tomography (ERT), and detailed measurements of surface exposures created from the mining pit. These data are compared to surface exposures along an approximately 30-mile (45-50km) traverse across Northeast Logan and Northern Warren counties. Subsurface data from Southwest Butler County and western Warren County are also examined and correlated to facies analysis (Figure 4.1). Thirty thin sections prepared from billets cut from core in Logan County were examined for facies type and porosity. Core plus surface exposure (Mine pit A) samples were collected and analyzed for bitumen concentration. Reservoir parameters, including porosity, permeability, and liquids saturation, are also determined through core analysis. Oilfield Research Inc. of Evansville, Indiana, conducted this analysis. Two cores from Logan County were analyzed in 2012 and 2013. These data, along with three core analysis studies from nearby Southern Butler County, are referenced. The resulting lithofacies model is used to interpret a type log from a conventional Big Clifty oil and gas field in Southwest Butler County.

The following describes the datasets utilized in this study. These data have been integrated and correlated to develop a depositional model as related to the emplacement of petroleum reservoirs both in and around the study area.

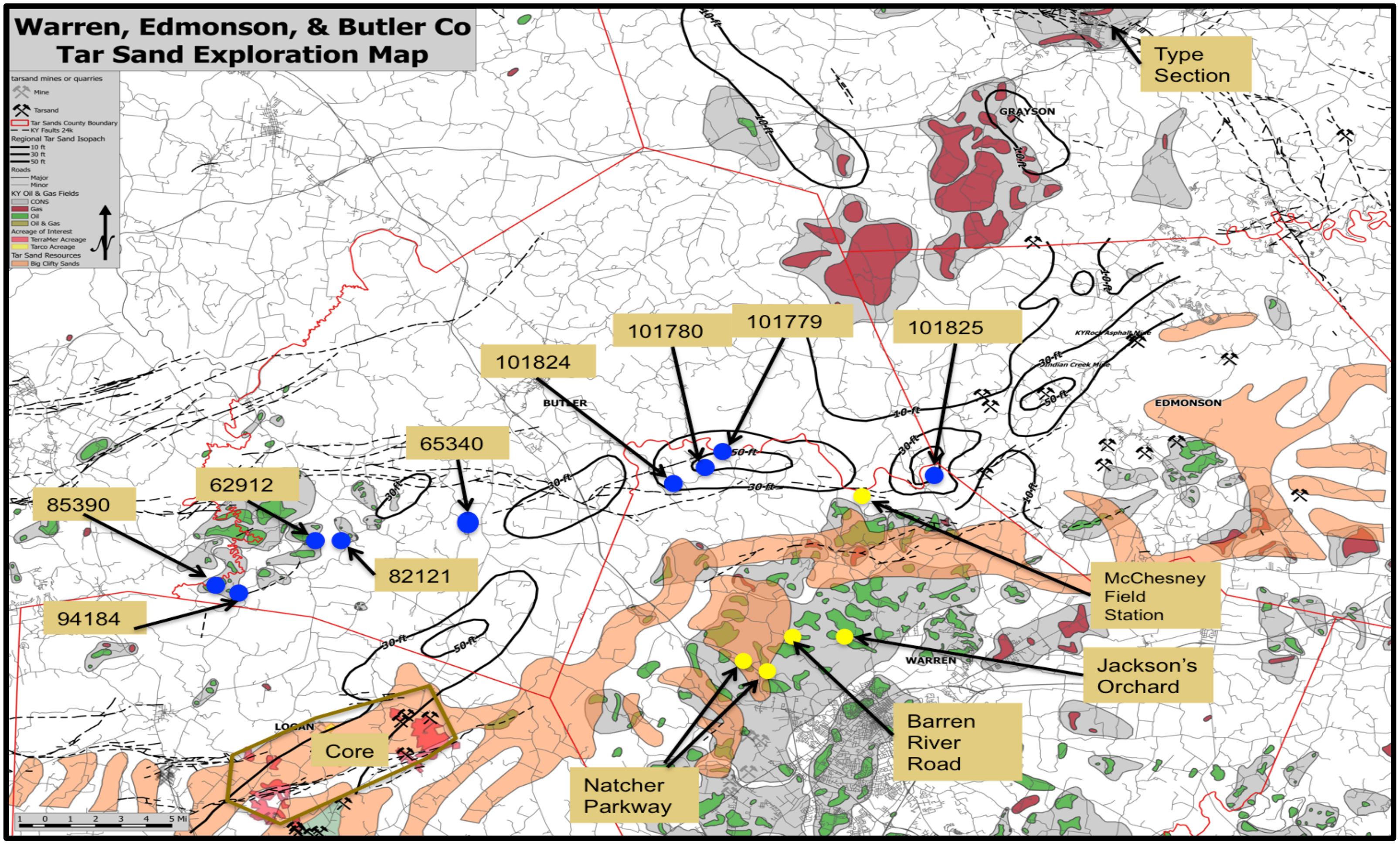


Figure 4.1. Location of the data used in this study. Logan County cores are shown as a Green polygon. Geophysical logs are shown with blue circles with KGS permit #. Surface exposures are shown with yellow circles.
Source: Created by Andrew Reeder and modified by the author with permission.

4.2: Study Area

This study takes place over Logan, Warren, and Butler Counties spanning the subsurface, shallow subsurface, and outcrop belt in South Central Kentucky. The datasets from the three counties are shown in Table 4.1 and Figure 4.1.

Location	Dataset
Logan County • Stampede Mine, ~11 miles NE of Russellville on highway 79 • Wells from Stampede Acreage (Figure)	*24 cores, 30 thin sections, Mining Exposures, Bitumen Concentration Analysis, ERT*
Warren County • Natcher Parkway and Glen Lilly Road (two locations) • Barren River Road, 2-3 miles north of Scott Quarry • Jackson's Orchard, Off of Slim Island Road • McChesney Field Station, along Indian Creek	*Road cuts, surface exposures*
Butler County • Multiple Oil Fields (Figure 3.4) • Type Log from 11-H-32	*800 Records examined: Drillers logs, core analysis, geophysical logs,*

Table 4.1: Showing the Datasets Utilized in this Study, along with Source Location.

4.3: Core Analysis

A total of 24 cores were pulled from drilled boreholes from the vicinity of Homer, Kentucky, in Carter Coordinate (CC) F-32 and F-33. Of these 24 cores, 20 were retrieved from the Stampede Mine property. Three cores were obtained from other leases referred to as Morgan Farm (MA, MAA, MBB, MCC) and one was taken from the Looper Farm property (LFA), shown in Figure 4.2. Three rounds of coring occurred at the Stampede Mine. However, only two rounds are included in this

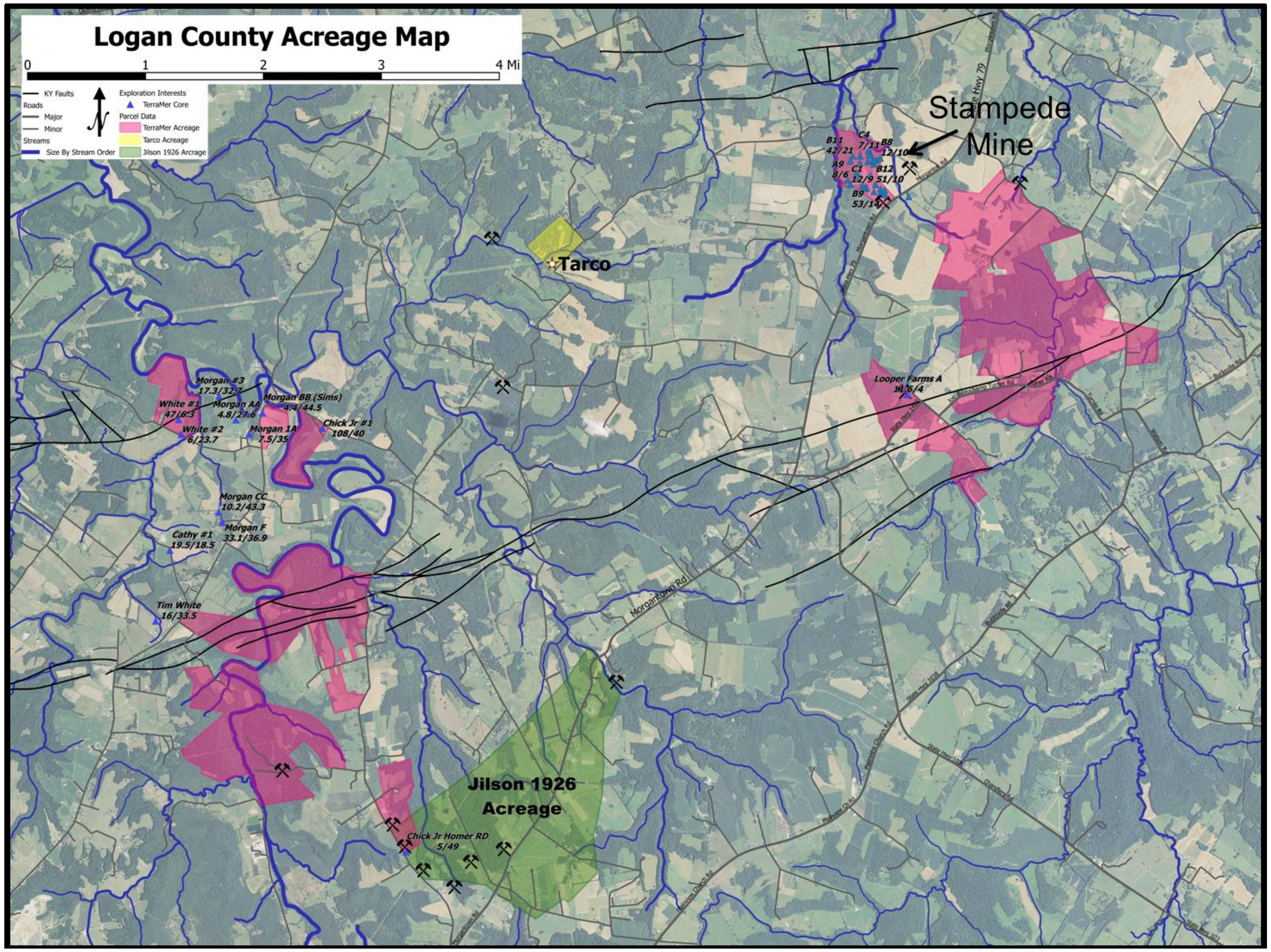


Figure 4.2. Map of Stampede acreage position in Logan County. Cores used in this study are also labeled. Tarco site is also shown along with the property examined in Jillson (1926) report. Source: Created by Andrew Reeder and used with permission.

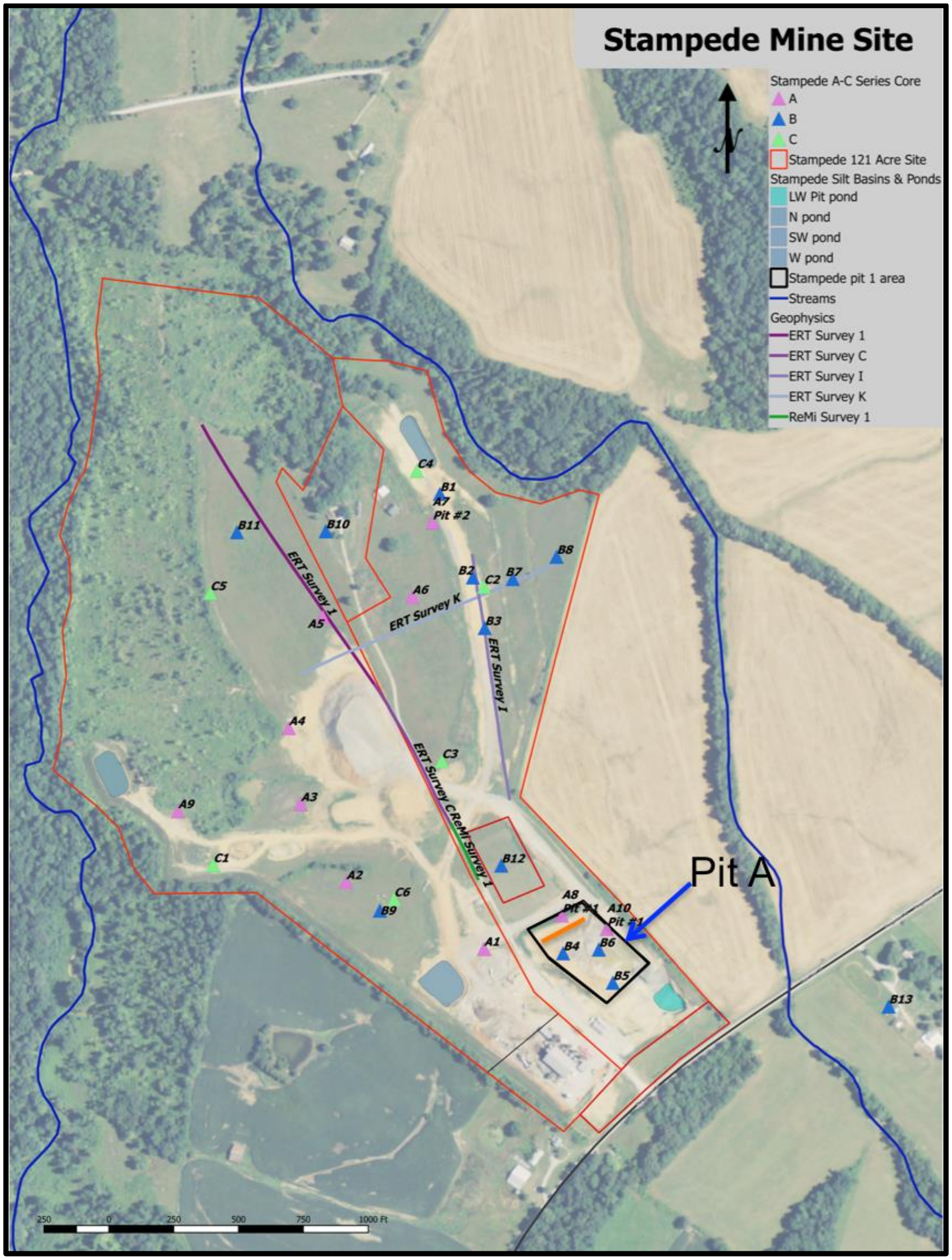


Figure 4.3. Map showing Stampede Mine site with core locations and ERT transects labeled. Outline of Pit A also shown on map.
Source: Created by Andrew Reeder and used with permission.

study because of failure to maintain a legitimate chain of custody of the core. Core from the Stampede Mine occur as the "A" series and the "B" series as designated in this study (Figure 4.3). The B series consist of thirteen cores; however, only ten contain a complete Big Clifty section. This coring operation occurred over two months in the Fall of 2014. One of these cores was retrieved across Highway 79 from the Stampede Mine on an adjacent property. The A series cores were obtained in Spring, 2015 (Figure 4.3). The A series consists of ten cores that span the entire Big Clifty section. Locations are shown in Figure 4.3. All cores were logged at the well site by either an engineer or a geologist and then brought to WKU for examination. Cores were cleaned, slabbed, logged, and photographed by the author. Core logging was done on a 1:10 scale in tenths of feet. All cores were examined for mineral composition, grain size, sedimentary structures, stratigraphic continuities and discontinuities, ichnofacies, and color using a Munsell chart. Sedimentary features were identified with the aid of the Indiana Geological Survey guidebook titled *Corebook of Pennsylvanian Rocks in the Illinois Basin* (Barnhill and Zhou, 1996). Example flow-charts illustrating the identification of lithology, primary, and secondary sedimentary structures are located in Appendix 7. All descriptions from cores are both hand annotated and digitized using the program Sedlog 3.1. Those logs are in Appendix VII as well. Ichnofacies descriptions and interpretations are in the style of Basan (1977) and MacEachern et al. (2007).

4.4: Outcrop Descriptions

Outcrop, roadcut, and surface exposure descriptions were made in Logan and Warren counties (Figure 4.1). Descriptions from Pit A at the Stampede Mine were compiled as surface mining progressed over approximately one year. Stratigraphic sections were measured and descriptions include mineral composition, grain size, sedimentary structures, and gross geometry or dimensions. Five surface exposures were measured in Warren County and those logs are included in Appendix B. These surface exposures were chosen based on the extent of given exposure of the Big Clifty section although no exposure contains a complete section.

4.5: Petrographic Analysis

Thirty oriented thin sections were examined for mineral composition, grain size, porosity, and sedimentary structures. Thin sections are described according to the methods outlined by Scholle, (1978; 1979). Thin sections were taken from billets during the logging process. Thin sections were cut with the assistance of National Petrographic Services Incorporated in Houston, Texas. Thin sections are a standard 30 microns and were stained with “Alizarin Red S” to identify carbonate. Petrographic analysis was conducted using a standard transmitted light petrographic microscope. Although diagenetic features were not the focus of petrographic analysis in this study, another study currently underway by May and Butler (2014) on the Big Clifty Sandstone in Warren and Butler Counties shows that occlusion from calcite cements is related to diagenetic alteration.

Carbonate rock thin sections were classified based on Dunham’s (1962) system. These thin sections were only used for facies interpretation. Limestone stringers or thin beds were observed in Big Clifty Sandstone reservoirs. Thin sections of the limestone were examined to better understand the origin of the limestone. Carbonate depositional environments are not the focus of this thesis and thus will not be discussed in detail. Limestone facies are important to note for exploratory purposes. Multiple Chesterian-heavy oil sandstone reservoirs occur that look quite similar and, sometimes, confusion occurs regarding which interval is being cored, particularly in fault zones. Limestone facies analysis alleviates some of this confusion, as limestone units are more distinctive based on variable carbonate skeletal and ooid grains.

4.6: Electrical Resistivity Tomography

Electrical Resistivity Tomography (ERT) is a technique that measures the resistance to electrical flow according to Ohm's Law. This technique was applied at the Stampede Mine by consulting geophysicists from Northern Kentucky University. This group collected and processed data during field excursions and presented their findings in two reports to the mine operators and geologists. Data from these reports were used in this study and constrained for interpretation by core and outcrop data. The collection of these datasets can be affected by many factors that must be taken into consideration during the interpretation process. A detailed analysis of these factors may be found in Reynolds (2011) and May and Brackman (2014). Four ERT transects were interpreted in this study, which are located in Appendix XII. The most important transect to this study was taken over Pit A directly on top of reservoir sandstone. The results from this transect serve as a control to interpret other ERT data from the mine site as the sandstone below was mined.

4.7: Bitumen Concentrations

Samples of reservoir sandstone from the Stampede Mine were collected during the logging process. Samples were gathered after cutting core using a rock saw. Sampling occurred at points of interest in the core. These samples were chosen based on appearance of heavy oil as shown in Appendix XVII. These samples were sent to Waypoint Analytical Inc. in Memphis, Tennessee and assayed for bitumen content using the methylene chloride extraction (9071 (MeCl2)) method.

4.8: Geophysical Logs

Geophysical logs from several Big Clifty Sandstone oil producing fields in southern Butler County were examined in this study (Figure 4.1). All data were taken from the KGS online data repository. Over 800 records were examined, however, only drillers logs, geophysical well logs, and wells with cores were used in this study, with a total of 56 wells (Appendix VIII). The location of wells with geophysical logs used in this study is shown in Figure 4.1, and the logs are located in Appendix VI. A type log is presented from section 11 of Carter Coordinate C H-32 that contains Gamma Ray and Density Porosity logs (Figure 6.6). This log was chosen because of the proximity to the mine site, and also because the Big Clifty interval was cored and core analysis was conducted at Oil Field Research Inc. of Evansville, Indiana.

Four geophysical logs are interpreted from Warren County and are listed in table 8 (Appendix VI) and shown on Figure 4.1. Core analysis was gathered along with geophysical logs for the wells in Warren County (Appendix VI) Mega West Energy collected these data while studying the potential of a gravity assisted steam-flood project. Geophysical logs include gamma ray, caliper, density porosity, neutron porosity, Shallow, medium, and deep resistivity, and PE. Density porosity is calculated on a sandstone matrix of 2.65 unless otherwise noted on the log.

4.9: Cross Sections and Isopach Maps

Cross sections across the Stampede Mine property are located in Appendix I. Structural cross-sections were flattened on 560' above mean sea level. Stratigraphic cross sections A and B are flattened on the top of the Beech Creek Limestone, while cross-section C is flattened on the top of facies 3. Structural dip is determined assessing true vertical depth sub-sea (TVDSS) of the top of the Beech Creek/Girkin/ Barlow limestone both in Logan County and in Butler and Warren counties. Structural dip on the Beech Creek Limestone is compared to a structural map prepared by Williams et al. (1982) shown in Appendix II.

Isopach and net isopach maps were constructed by the author and consulting geologists from the Stampede Mine. These maps are used with permission from the Stampede Mine and consulting geologist Andrew Reeder. Volumetric calculations are also included and used with permission from the Stampede Mine (Appendix II).

Chapter 5: Results

5.1: Overview

Lithofacies or facies analysis is the study of rocks or sediments based on characteristics such as lithology, grain size, biological activity, and primary sedimentary structures, which are the result of a process or several processes associated with specific environments of depositions (EOD). Much work has been conducted interpreting facies for EOD in Chesterian deposits in the Illinois Basin (Visher, 1980; Treworgy, 1988; Smith and Read, 2001; Nelson et. al, 2002). No studies, however, have focused on specifically documenting the lithofacies of the Big Clifty Sandstone as related to hydrocarbon emplacement and trapping in South Central Kentucky, particularly heavy-end oil.

Facies analysis was conducted using 24 core samples with an average length of 46 feet and ranging from 22 to 65 feet (6.7 to 19.8 meters). A complete representative core is shown in Figure 5.1.

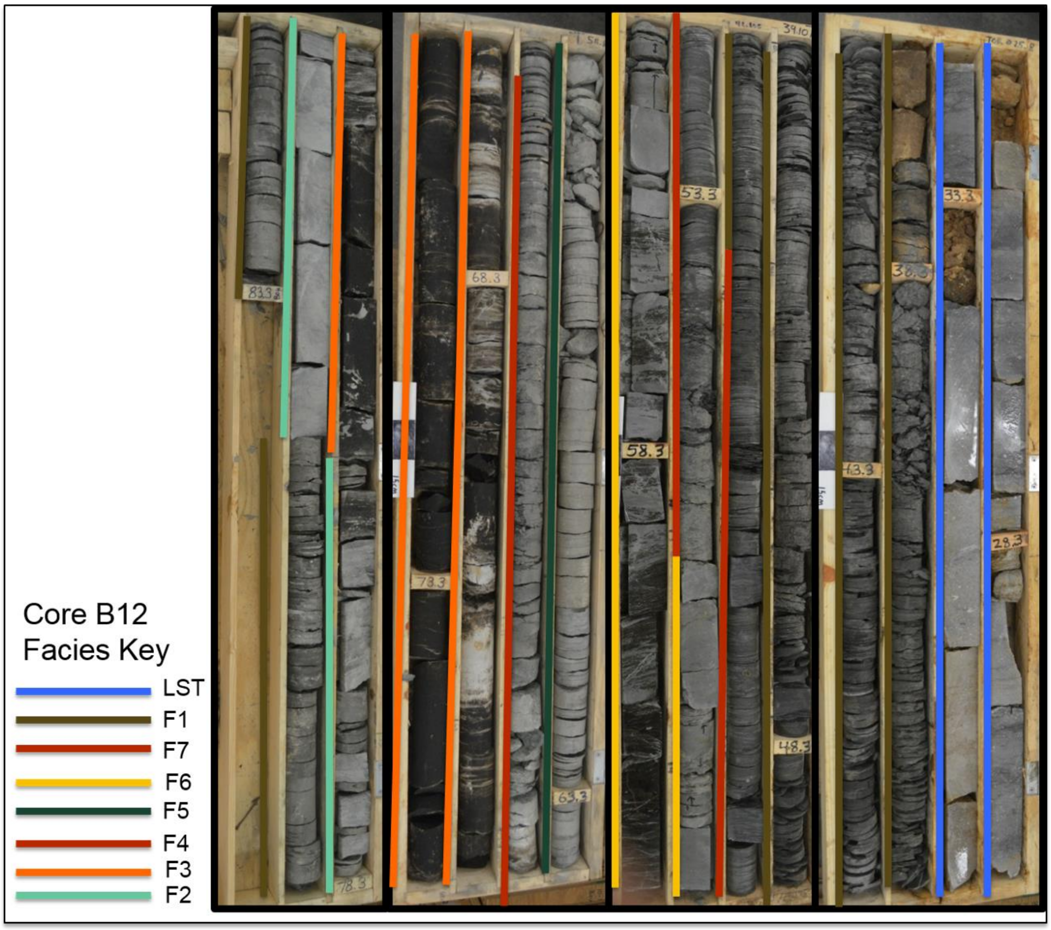


Figure 5.1. Complete core from the Stampede Mine showing facies identified in this study. Footage moves from top to bottom, right to left. This core is missing the Beech Creek Limestone which occurs below the Big Clifty Section. Facies 1, 4, 5, and 7 are mud-dominated facies. Source: Imaged by the author.

Cores were examined for lithology, grain size, sedimentary structures, bedding contacts, and ichnofacies. A total of ten distinct lithological units were noted in core including: sandstone, mud-rich rocks and limestone, which are not described in detail in this thesis. Limestone is, however, important for exploratory purposes and, although it will not be discussed in detail, photomicrographs may be referenced in Appendices XIV to XVII. Core descriptions from the Stampede Mine were supplemented with mining pit exposure descriptions. One outcrop adjacent to the mine property along Muddy Creek was also measured. These data were combined with petrographic thin-section descriptions and sieve grain-size analysis and recorded in Table 2.

Five surface exposures were measured for lithofacies in Warren County. Those logs are located in Appendix A. Lithofacies for these outcrops may be found in Table 2 with descriptions and photos of measured sections located in this chapter.

5.2: Lithofacies Analysis- Logan County

5.2.1: Facies 1: Fossiliferous Shale and Interbedded Limestone

Description: Facies 1 consists of laminated shale and interbedded limestone. This facies separates the Big Clifty Sandstone from the Beech Creek Limestone below and the Haney Limestone above. The shale is black to grey (N4-N5) and moderately fissile with convoluted white to light gray limestone lenses between 1-5 cm thick (Figure 5.2). Thin sections of limestone were examined under the petrographic microscope and it is possible that some of these lenses could be calcareously cemented sandstone (Appendix XV). No macrofossils were observed in the shale. The upper F1 unit has a maximum thickness of 14 feet while the lower unit has a maximum thickness of 18 feet. However, in places there is no shale. In such locations, the contact between the Big Clifty Sandstone and the Beech Creek Limestone is unconformable.

Lithofacies	F-1	F-2	F-3 (Reservoir)	F-4	F-5	F-6 (Reservoir)	F-7
Lithology	Shale	Siltstone, sandstone, shale,	Sandstone	Mudstone, paleosol	Shale, siltstone, sandstone, shale	Sandstone, caliche mudstone	Sandstone, siltstone, shale
Grain Size **Texture**	Very fine grained to clay size particles	Fine grained to very fine grained sandstone interlayered with shale	Medium grained to fine grained sandstone, well sorted Angular to subrounded, Low to moderate sphericity	Clay to fine grained	Clay to fined grained	Medium grained to fine grained to very fine grained to clay Angular to subrounded, low to moderate sphericity	Very fine grained to fine grained to clay
Sed. Structures/special character	Disturbed bedding	Possible disturbed bedding	Massive, laminated, cross laminated, and flaser bedded sandstone with Mud-intraclasts, fractures	Brecciation, slickensides,	Laminated shale, lenticular shale in places Massive black/organic mudstone	Mud drapes, abundant carbonate	Rhythmic bedding, hummocky bedding fluid escape structures
Rate of sedimentation **bioturbation**	Low	Low *Cruziana* (chondrites)	Moderate to high Rare bioturbation *Skolithos* at top Possible root structures	Low Represents period of subareal exposure	Low to moderate	Moderate to high The upper 2' of this facies is characterized by *ophiomorpha*-like structures in a glauconitic sandstone	Low to moderate mixed *Cruziana-Skolithos*
Reservoir Quality	N/A	N/A	Good porosity: 14 to 21% Permeability: 15 to 834 md See Table 4 and 5	N/A	N/A	Poor to moderate bioturbation negatively affects porosity and permeability in this reservoir.	N/A

Table 5.1: Facies 1-7 from Terramer Leases in Logan County, Kentucky. Source: Created by the author.

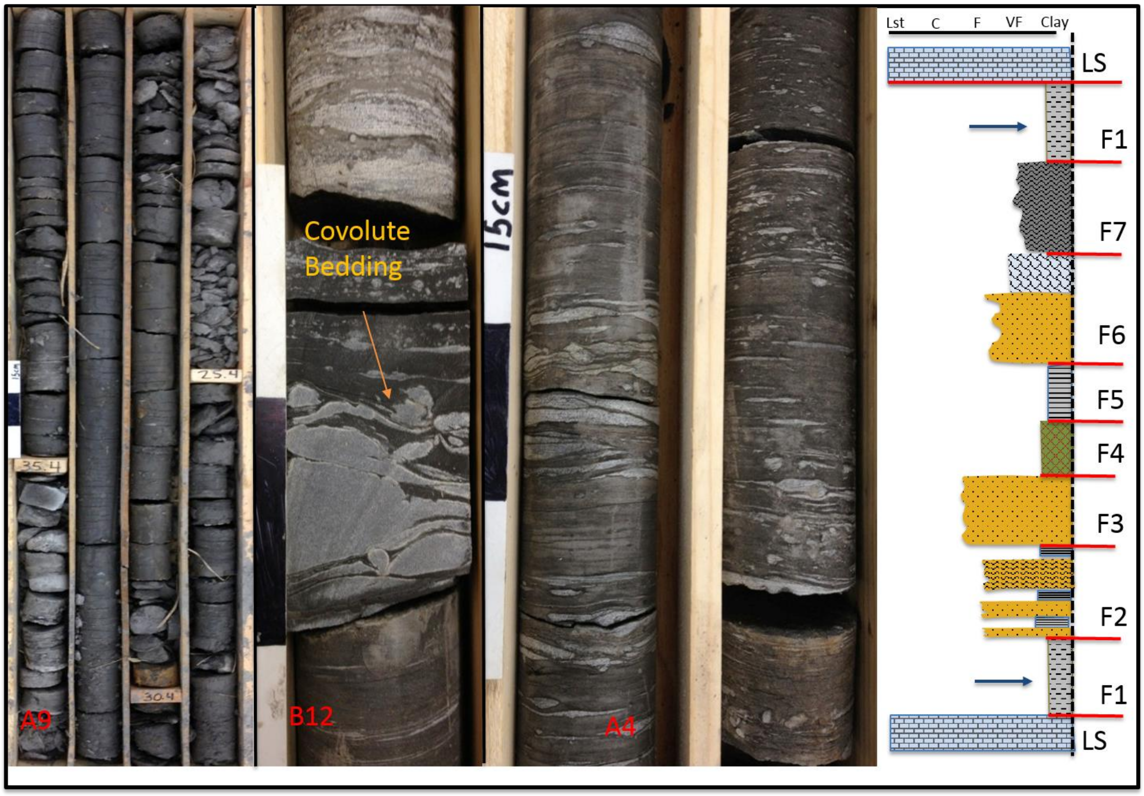


Figure 5.2. Facies 1 from the Stampede Mine. Note convolute bedding approximately 5 cm wide. Diagram on the right shows facies 1-7. Blue arrow is pointing to facies 1. The Limestone below F1 is the Beech Creek, while the limestone above is the Haney Limestone. Convolute lenses effervesce with HCl acid. Source: Imaged by the author.

Interpretation: This facies is entirely marine and represents a transition from carbonate to siliciclastic depositional systems (Smith and Read, 2001). The high clay content and lack of body fossils suggest a relatively deep environment. Examination of the convolute bedding in interbedded limestone to calcareous sandstone suggests a periodically unstable depositional environment. It is difficult to determine if the absence of the shale above the Beech Creek is always the result of scouring or non-deposition. Pryor et al. (1991) described the importance of antecedent syndepositional topography in determining the thickness and thinness of later deposited units. The study area, furthermore, is in a transitional zone between the

Illinois Basin proper and the Cincinnati Arch region where units are known to thin and pinch out. The Beech Creek represents a major marine flooding surface. Therefore, it is likely that missing shale above it represents scouring. Variation in facies 1 above the Big Clifty siliciclastic package probably represents a change of accommodation between syndepositional highs and lows. Convolute bedding (Figure 5.2) in this facies above the Beech Creek may be a characteristic of a distal environment and likely represents the transitional zone between Big Clifty siliciclastic wedge and below storm wave-base limestone. This unit thins and pinches out across northern Warren County in the direction of the Mormon Syncline. Visher (1980) observed a similar facies between the Big Clifty Formation and the Beech Creek Limestone. This shale was observed to thin and pinch out to the southeast of Crawford County, Indiana. Both units thin in the direction of the Rough Creek Fault zone.

5.2.2: Facies 2: Fine-to-Medium Grained Sandstone and Interbedded Mudstone and Siltstone

Description: Facies 2 consists of interbedded fine-grained sandstone, shale, and siltstone (Figure 5.3). This unit is extensively bioturbated, which mostly obscures primary bedding in the core. The unit ranges in thickness from one to seven feet (0.3 to 2 meters). Hummocky to wavy bedding is observable. The lower contact is gradational with facies 1, but the upper contact with facies 3 is sharp (Figure 5.3, Photo A).

This unit contains up to 50% clay minerals in places. However, some bitumen occurs in mud-free sandstone. Because of the completely reworked nature of the sediment in facies 2, ichnogenera are difficult to decipher, however *Chondrites*-like ichnofacies were identified (Figure 5. 3, Photo B).

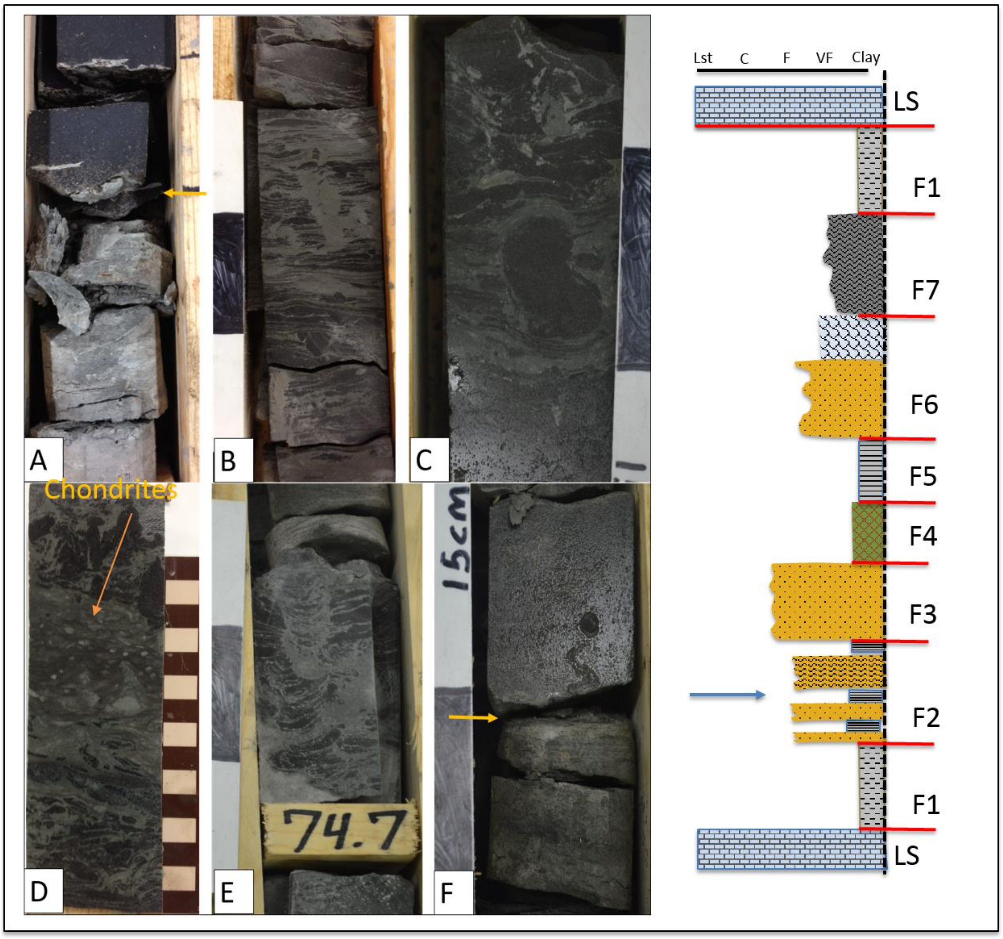


Figure 5.3. Facies 2 from the Stampede Mine. A shows the sharp upper contact with facies 3. B, C, D, and E show bioturbation including *Chondrites* (D), which occur in muddy interlayers. F shows the lower contact on facies 1. Light bitumen staining occurs in sandy zones and occurs as the dark coloration in C.
Source: Imaged by the author.

Interpretation: Facies 2 shows fluctuating energy conditions, which resulted in the interbedded lithologies observed. This unit likely represents the bottomsets of a prograding tidal sand bar complex. The moderate to high bioturbation suggests a low rate of sediment accumulation, which is punctuated by wavy to hummocky-bedded units. These punctuations could be the result of storm activity. Ichnofacies were difficult to positively identify but are thought to be *Cruziana*.

5.2.3: Facies 3: Fine-to-Medium Grained Quartz Sandstone and Siltstone

Description: Facies 3 consists of fine-to-medium grained cross-laminated quartz sandstone with minor mud or flaser beds (Figure 5.4 and Figure 5.7). In the Stampede Mine sample, this facies ranges in thickness from 0 to 13 feet. Framework grains are composed primarily of quartz, some with quartz overgrowths, and minor amounts of feldspar, chert, and detrital accessory muscovite (Figure 5.5).

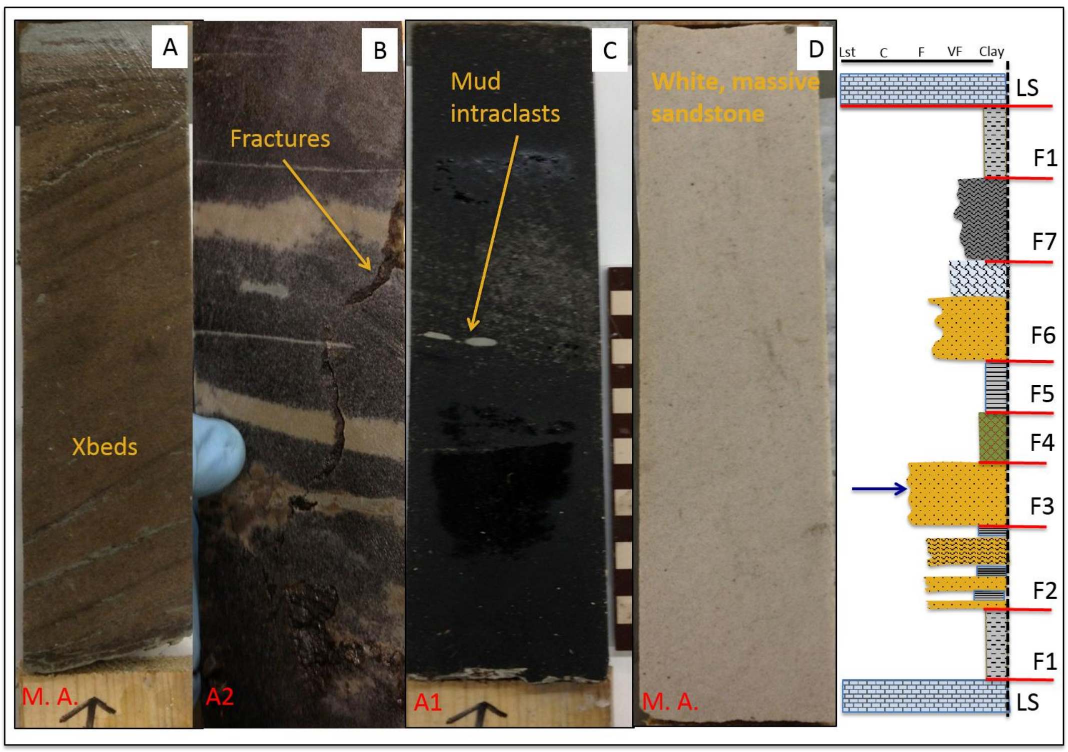


Figure 5.4. Facies 3 from the Stampede Mine (A series) and Morgan property (M.A.), showing some of the types of bedding observed in this facies. Red letters and numbers identify the core. A shows cross bedding with light bitumen staining. B shows horizontal laminated bedding cross cut by fracture. C shows cross bedding with mud intraclast along bedding plane and is moderately to heavily stained. D Shows massive white sandstone with no bitumen staining.
Source: Imaged by the author.

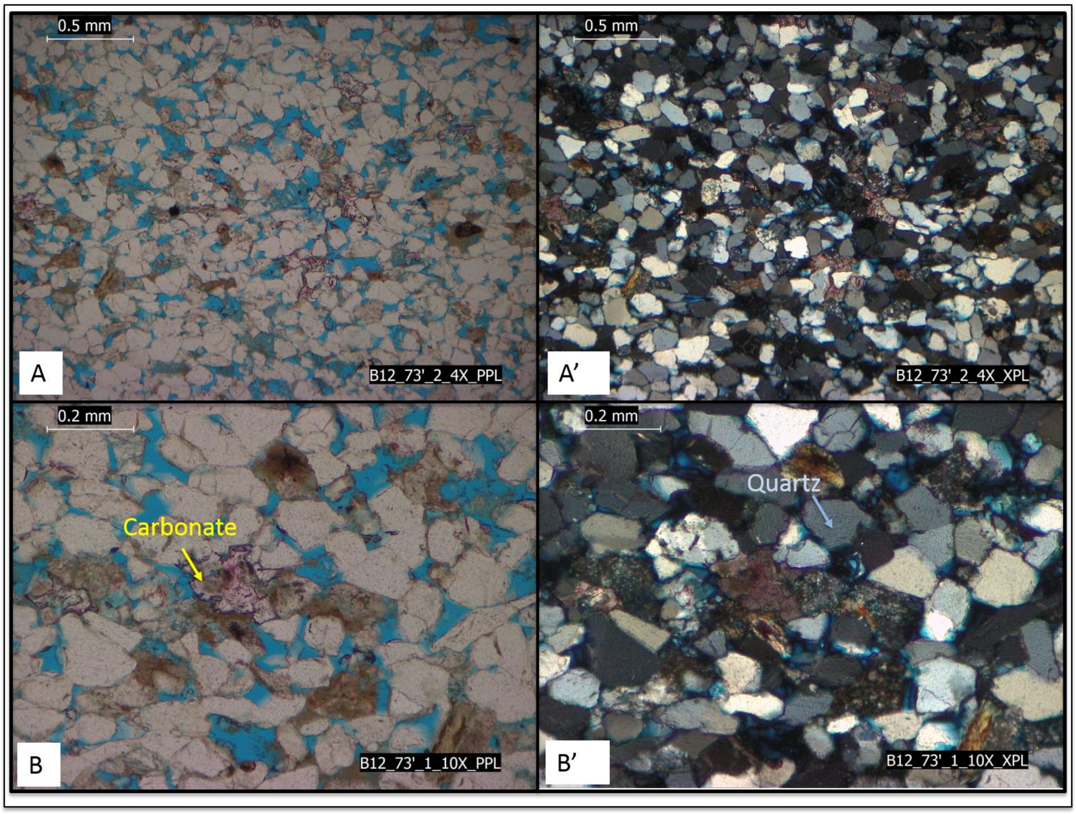


Figure 5.5. Photomicrographs showing Facies 3 from core B12. Blue staining fills intergranular porosity. A and B are taken in plane polarized light while A' and B' are taken in cross polarized light. A series are on a 0.5 mm scale while B series are on a 0.2 mm scale. Thin sections were stained with Alizarin red S to show carbonate as seen in photomicrograph B. Source: Imaged by the author.

Grain size ranges from 3 to 250 μ and are subangular to subrounded. Minor amounts of detrital carbonate were observed (Figure 5.6). The lower contact is sharp and mud chips were observed along the lower contact. Much of the primary bedding is obscured by the presence of heavy oil; however, flaser beds, massivebeds, and cross-laminated beds were observed (Figure 5.7). The upper one-to-three feet are mottled and contain vertical and horizontal bioturbation structures (Figure 5.8). Minor to heavy bitumen concentrations were observed throughout this unit. That information is presented in Table 4. Fractures were observed in the reservoir (Figure 5.9). Fractures are almost vertical and in one core a micro reverse fault was observed with millimeters of offset (Figure 5.9, Photo B).

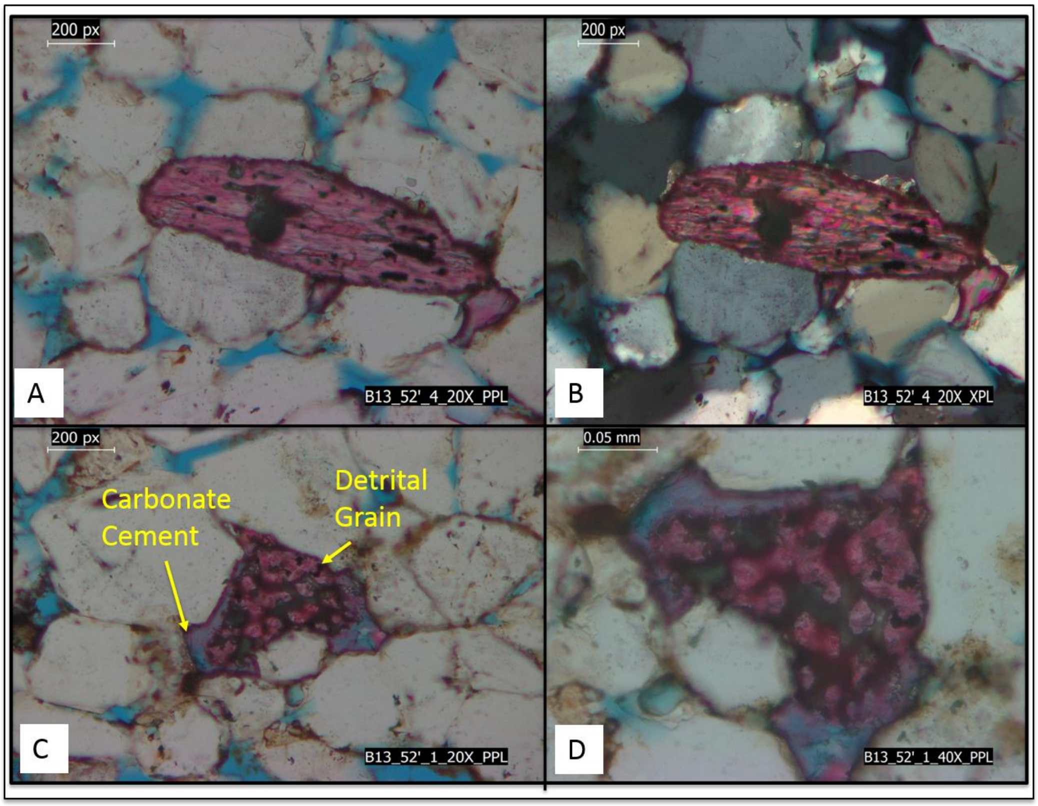


Figure 5.6. Photomicrographs showing detrital carbonate grains in facies 3. A and B show detrital carbonate grain in plane polarized (A) and cross polarized (B) light. Scale is 200 pixels for A, B, and C. C shows detrital carbonate grain. Note the calcite rhombs and calcite cement. D shows detrital carbonate grain on a scale of 0.05mm. Source: Imaged by the author.

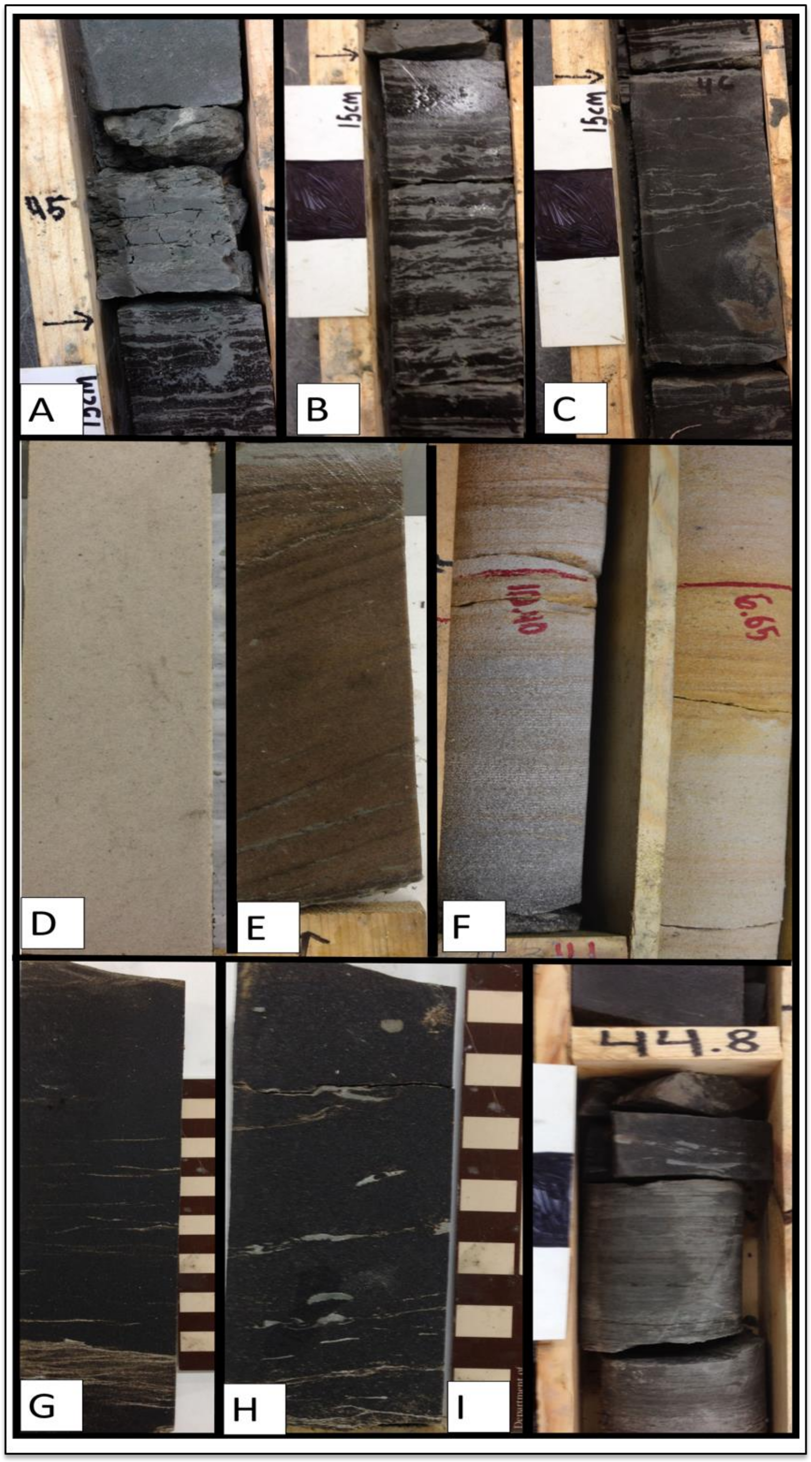


Figure 5.7. Types of bedding in facies 3. Views A,B, C show mottled bedding and vertical structures (A) at upper contact. D massive bedding. E cross bedding. F shows iron staining and light bitumen staining near the bottom. G and H show heavy bitumen staining and flaser bedding with mud intraclasts. I shows the sharp lower contact . Source: Imaged by the author.

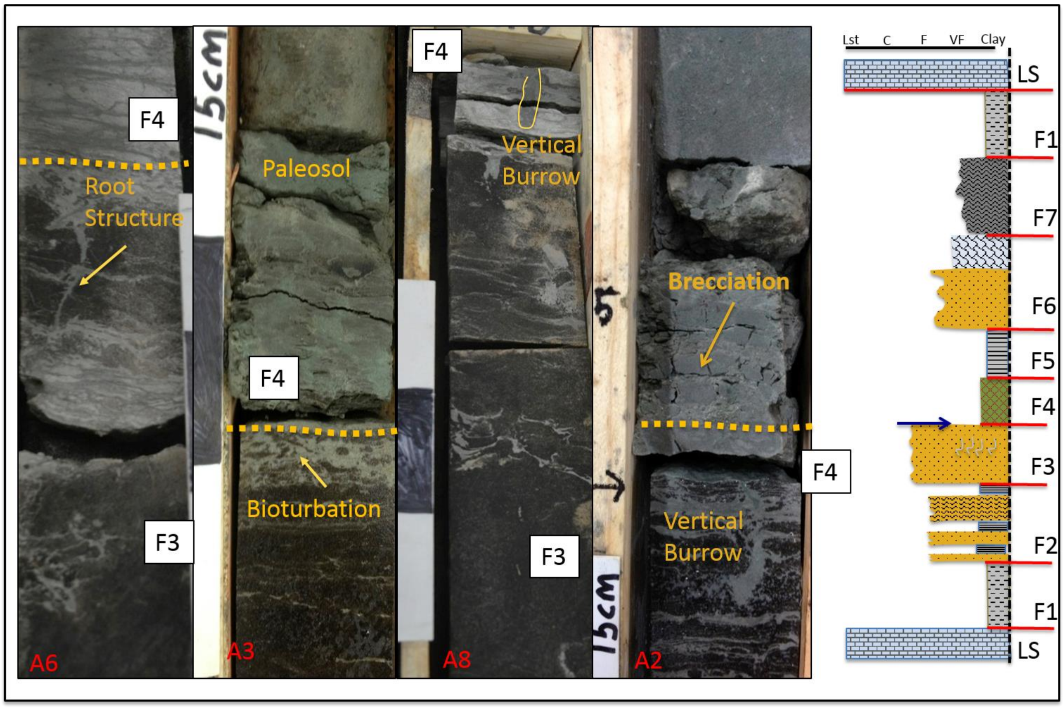


Figure 5.8. Photographs show the contact between facies 3 and facies 4. The contact is typified by vertical bioturbation, root structures, brecciation, and paleosols as shown above. Note the partitioning of reservoir sandstone by mud filled bioturbation as shown in A6, A3, A8, and A2. Bitumen is black to light brown. Source: Imaged by the author

Interpretation: Facies 3 contains characteristics of channel and bar sandstone deposits. The lower contact is sharp with mud intraclasts, suggestive of high-energy conditions. The unit is overlain by mudstone and a paleosol. Cross laminations suggest moderate- to high-energy conditions. No bimodal bedding was observed for this unit. No exposures of facies 3 were measured in Pit A. Miners did expose the top of the unit that was observed as undulatory. Thin (1 to 5 inch) (2.5 to 7.5 cm) coaly mudstone separate sand bodies which act as seals between reservoirs (Figure 5.10).

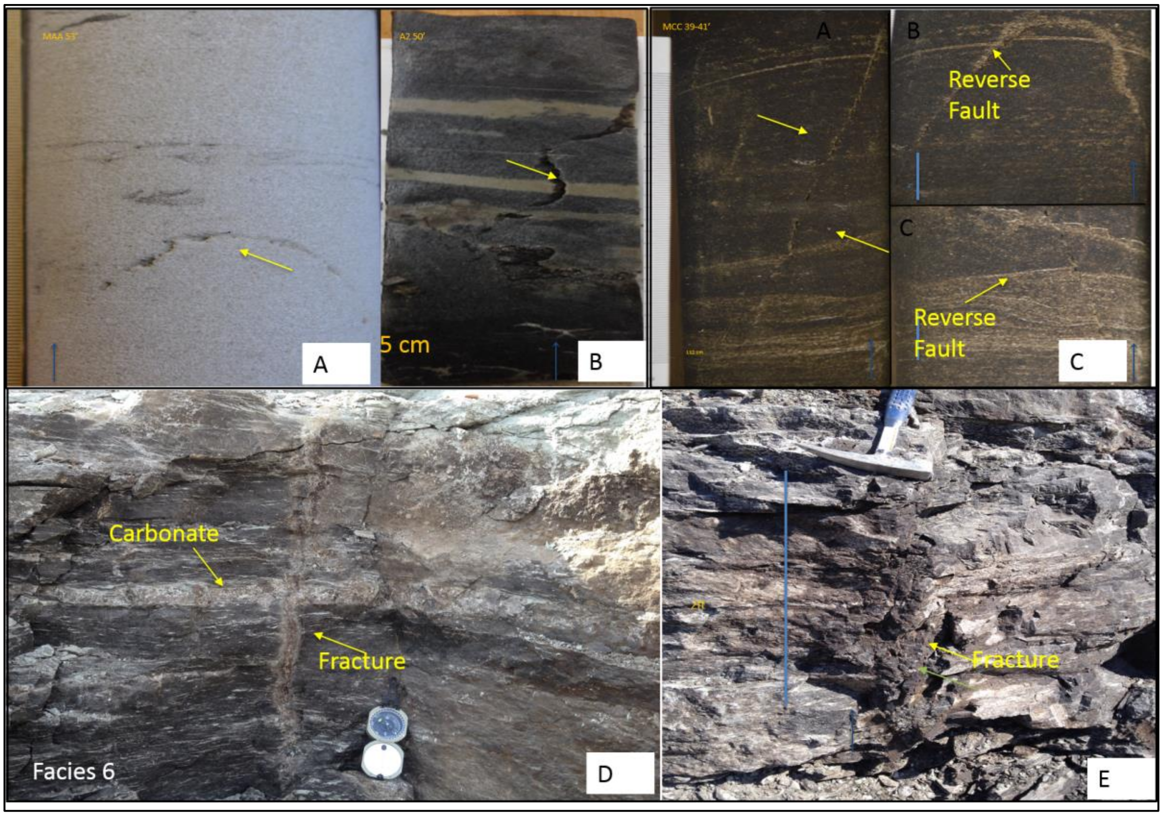


Figure 5.9. Fractures shown with yellow arrows observed in facies 3 (MAA, A2, MCC) and Facies 6 (Pit A). View A, B, and C show photos of cores. View B contains a reverse fault with millimeters of offset. View C shows two fractures observed in Pit A. Notice the carbonate lens cross cut by vertical fracture in D. Source: Imaged by the author.

Mottled bedding, mudcracks, and vertical structures in the upper one-to-three feet of the facies represent either a decrease in the rate of sedimentation or sediment stabilization under relatively shallow-water conditions. Root-like structures were noticed in the upper part of the sandstone, which is overlain by a paleosol and mudstone. Intergranular porosity varies but ranges from good to excellent. Meanwhile, detrital carbonate and clay occlusion occurs by cementation. Detrital carbonate grains observed in thin section were likely derived from incisement-up paleoslope into underlying limestone and transported via channel networks.

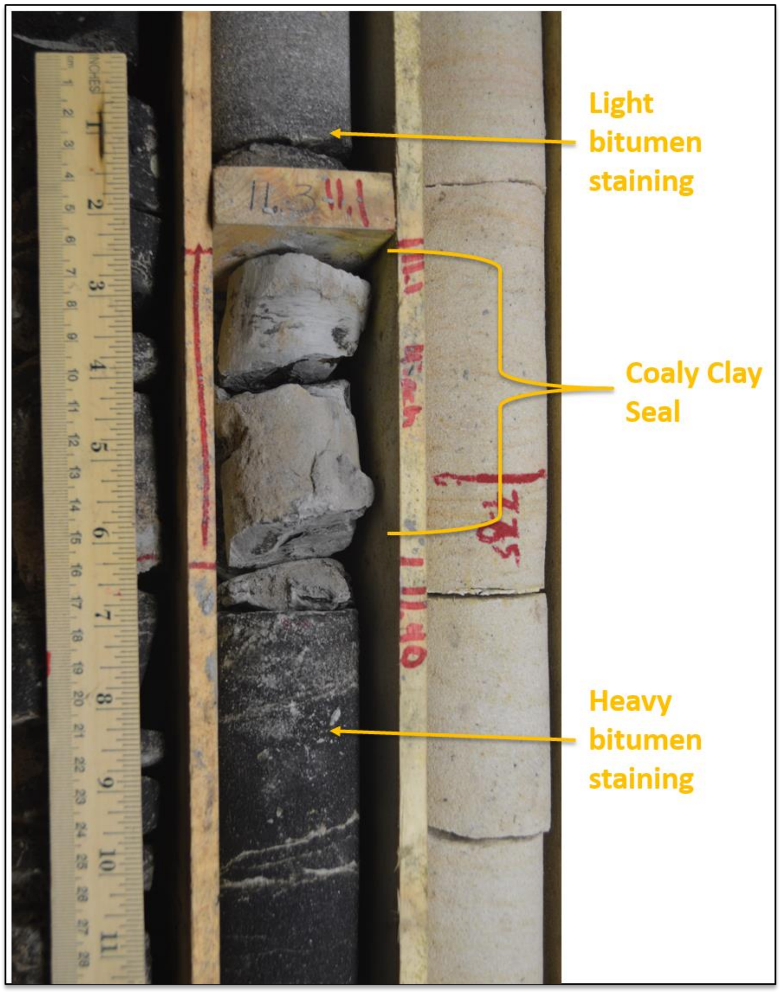


Figure 5.10. Coaly mudstone acts as a seal in Big Clifty reservoir in core LFA. Sandstone above the seal is light stained to void of bitumen, while sandstone below is heavily stained. Source: Imaged by the author.

5.2.4: Facies 4: Brecciated Mudstone and Paleosol

Description: Facies 4 is a massive to blocky mudstone and paleosol (red-green shales) (Figure 5.11) that contains slickensides (Figure 5.12) and is brecciated. This unit is up to four feet thick in places. Root casts and dolomitic nodules are observable. The lower contact contains vertical structures that protrude into Facies 3. The upper contact is gradational.

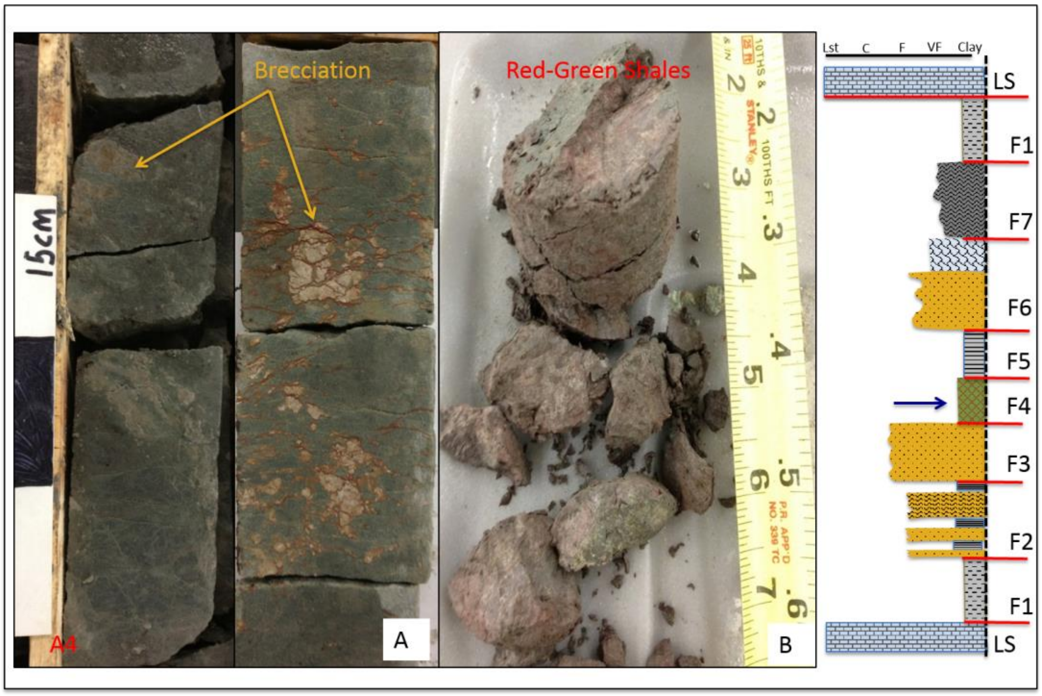


Figure 5.11. Facies 4 observed in cores from Stampede Mine and in MA property. Photo A shows brecciated mudstone. Photo B shows red green shales which are interpreted as a paleosol after Treworgy (1988), Smith and Read (2001), and Nelson et al. (2002). Paleosol occurs over facies 3. Source: Imaged by the author.

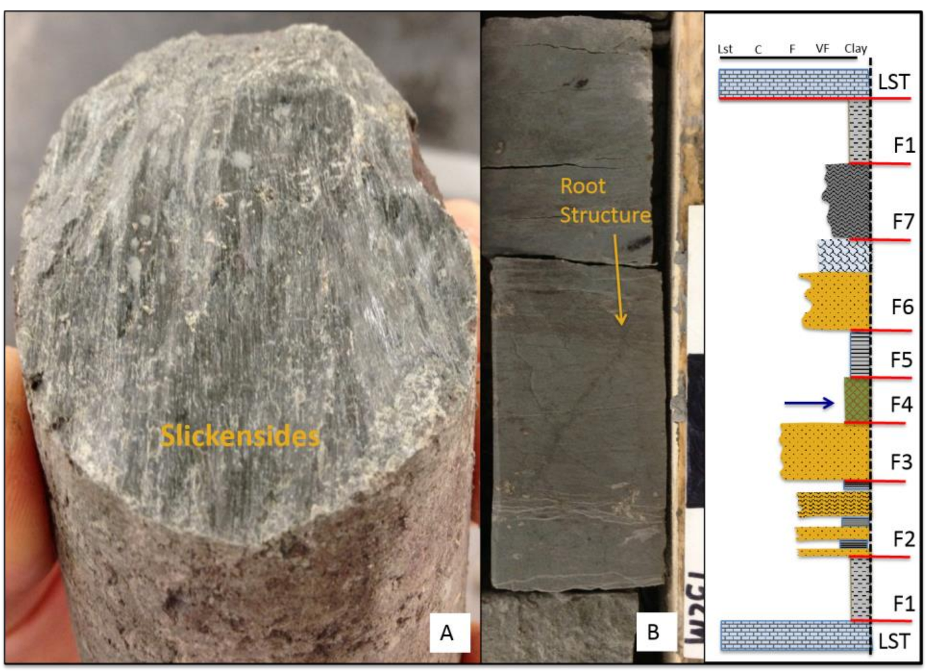


Figure 5.12. Photographs show slickensided paleosol from facies 4 (A). Carbonaceous branch structures occurring in facies 4 are interpreted as roots structures (B). Source: Imaged by the author.

Interpretation: The presence of red-green shales and a paleosol with root casts suggest parts of this unit were subareally exposed. Mud cracks occurring along the boundary between facies 3 and facies 4 support this interpretation. Treworgy (1988) and Nelson et al. (2002) described paleosol in the upper portion of the Big Clifty as occurring across the basin. This paleosol, and other exposure surfaces, represents maximum regression of sea level and, therefore, serves as a time marker between regressive and transgressive parasequences. This is important for allostratigraphic correlation of Big Clifty facies. Paleosols are correlated to the bottom of incised channel fill deposits described by Nelson et al. (2002).

5.2.5: Facies 5: Non-fossiliferous, Laminated Shale and Lenticular Shale

Description: Facies 5 consist of gray to light gray (N6 to N3) non-calcareous laminated shale and lenticular shale (Figure 5.13). The lower contact is gradational, while the upper contact is sharp. The unit ranges in thickness from two to thirteen feet. Minor amounts of sandstone are present as interbeds in laminated shale.

Interpretation: Higher shale relative to sandstone in this facies suggests it formed in low-to-moderate energy conditions. No macrofossils were observed in this unit. Unlike facies 1, no effervescing was observed with the application of HCl (non-calcareous). The upper portion is sharply overlain by tidal sandstone in facies 6. In context to facies 3 and 4, facies 5 likely represents a back-barrier or marginal-marine environment with low-to-moderate energy flux (Smith and Read, 2001).

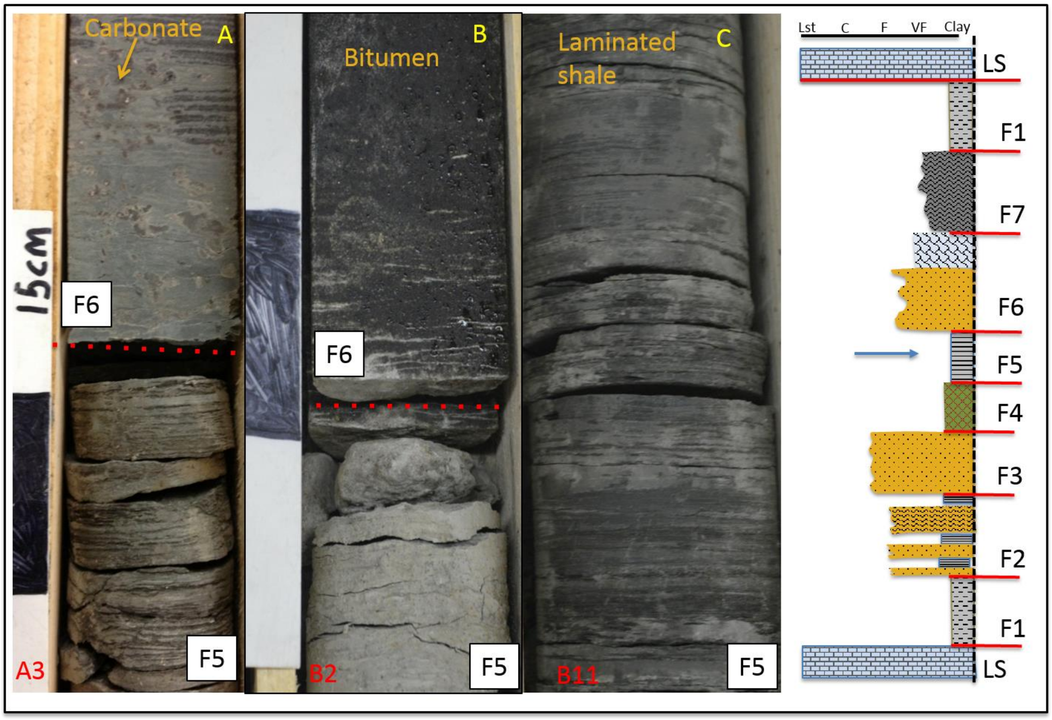


Figure 5.13. Photos of facies 5 showing laminated shale overlain by facies 6 (A and B). Photograph C shows laminated shale. Source: Imaged by the author.

5.2.6: Facies 6: Fine-to-Medium Grained Sandstone and Rhythmic Mudstone

Description: Rhythmic sandstone and clinoformal mud drapes and minor carbonate comprise Facies 6 (Figure 5.14). Grains are subangular to subrounded. Grain size ranges from silt to medium sand with 95% of the sieved sample occurring as 180 μ. Intergranular porosity is commonly occluded by clays (Figure 5.15). Sets of mud drapes range in length from a few inches to one foot, and are bound by reactivation surfaces (Figure 5.16). One to two millimeter mud drape tidal bundles were measured. Carbonate caliche occur (Figure 5.17) along bedding planes and can be up to two feet (60 cm) long and four inches (8cm) thick with vuggy pores that have been occluded by calcite (Figure 5.17).

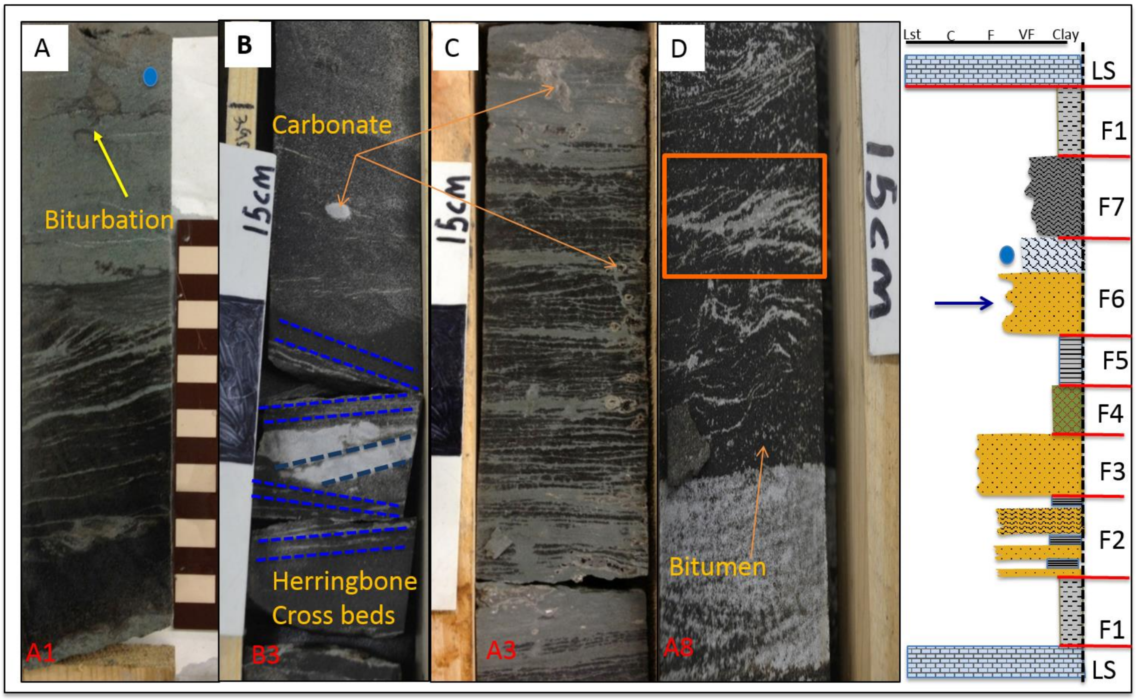


Figure 5.14. Facies 6 observed at the Stampede Mine. View A shows the upper portion of the facies that includes bioturbated sandstone (blue dot on stratigraphy column). void of bitumen. Herringbone cross bedding was observed (B), along with rhythmic bedding and carbonate grains (B and C). Clinoformal mud-drapes are also shown (D). Note the partitioning of heavy oil by fine mud drapes and carbonate. Source: Imaged by the author.

Biomodal paleocurrent indicators in the form of herringbone crossbeds are observable in exposures. In places, the upper two feet is intensely bioturbated occurring with reduction halos and desiccation cracks (Figure 5.18). Bioturbated sandstone acts as a permeability barrier and is void of bitumen (Figure 5.18, Picture D). Two to five feet vertical fractures occur in exposure and may be correlated to fractures observed in core. Asphalt concentrations appear to be more concentrated along fractures (Figure 5.9, Picture D) in exposure. Additional photos of facies 6 may be found in Appendix VII

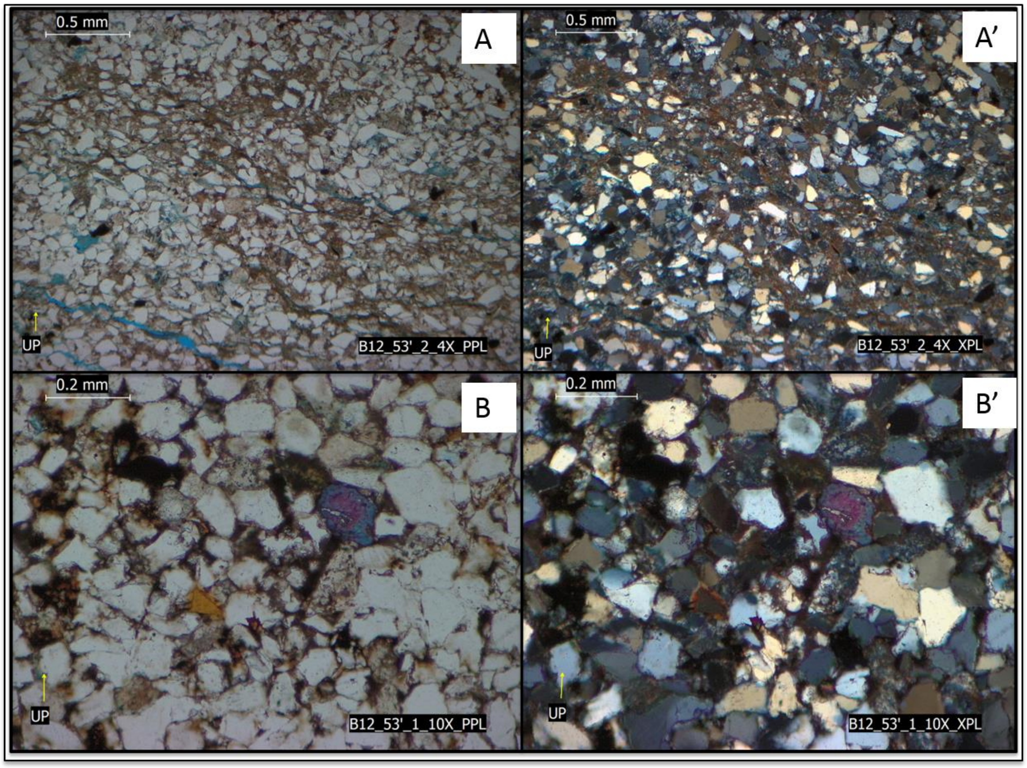


Figure 5.15. Photomicrographs showing facies 6 observed at the Stampede Mine. Both A and B are in plane polarized light and A’ and B’ are in cross polarized light. All photomicrographs are oriented with the up direction shown with the arrow. Notice the silt to fine grain size. Porosity (blue staining) is occluded by fine grained mate material. Source: Imaged by the author.

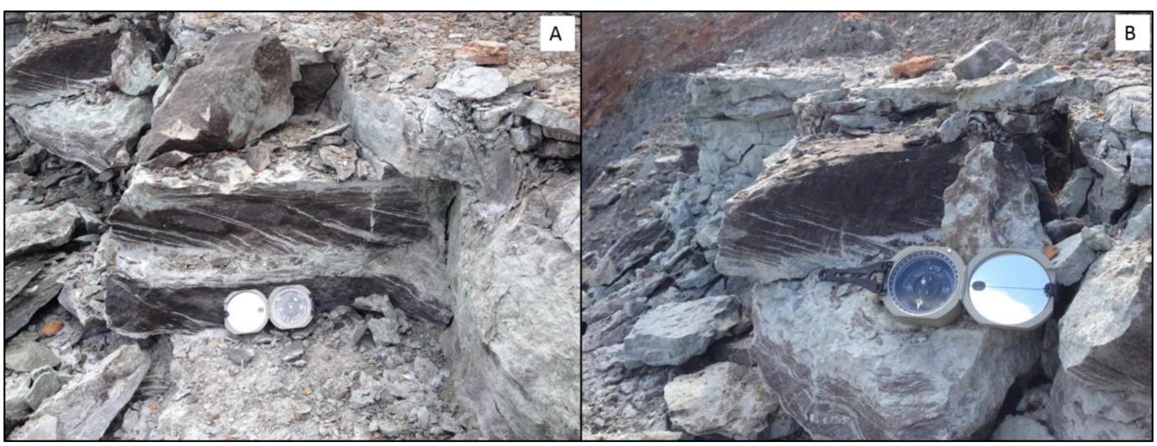


Figure 5.16. Photos A and B show mud drapes and reactivation surfaces. Cross laminated bedding is dipping to the south west. Both images are oriented approximately south east. Notice the light gray mudstone that partitions the reservoir which is charged with heavy oil (black staining). Photos are from Pit A at the Stampede Mine and this material is representative of the ore processed by the mine. Brunton for scale. Source: Images by the author.

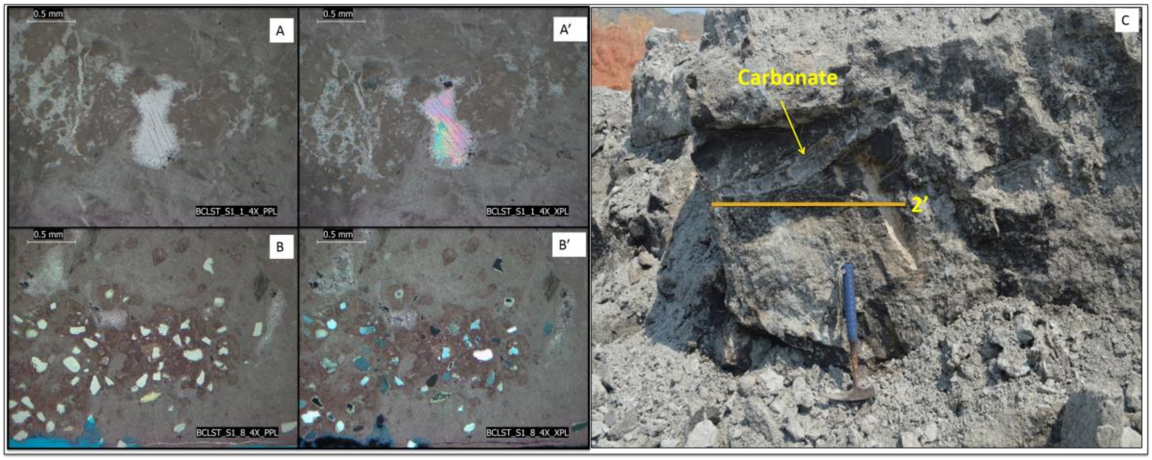


Figure 5.17. Photomicrographs and photo of limestone observed in reservoir facies 6. A and B are photos in plan polarized light showing caliche carbonate with spar-filled vuggy inclusions (A), and silt-sized quartz grains. Photo C shows carbonate observed in tidal-channel sandstone from Pit A. Carbonate is deposited along bedding plains and is likely derived from supratidal mudflats where it was eroded and transported before being deposited along bedding planes of tidal- channel sandstone. Carbonate lenses are anomalous and partition the reservoir which is impregnated with heavy oil (black staining) as shown in C. Source: Imaged by the author.

Figure 5.18. Photos from facies 6 showing *ophiomorpha* bioturbation (A and C), desiccation cracks (B), and bioturbated sandstone acting as a permeability barrier on top of petroleum-charged sandstone. Source: Images by the author, with all photos taken from pit A at the Stampede Mine.

Interpretation: Facies 6 represents intertidal sand flats. Evidence for this includes herringbone cross bedding, rhythmically bedded mud drapes, reactivation surfaces, and syneresis cracks (Figure 5.18). Other workers have described meso-to-macro tidal conditions in the Illinois Basin in the Pennsylvanian (Kvale and Archer, 1991). Unlike facies 3 where the tidal influence is subtle, facies 6 is a tide-dominated system as shown by slack water mud drapes and herringbone cross bedding. Intergranular porosity varies, with total occlusion from caliche, authigenic carbonate and clay minerals being common. Bedform geometry consists of a complex stacking of migrating tidal sand dunes that are declined to the southwest, which is the inferred ebb-tide direction (Figure 5.16). Interchannel mudstone partitions reservoir bodies and are noticed in exposures, mining excavation, and indirectly using ERT. *Ophiomorpha* and *Skolithos* ichnofacies occur in tidal channels in the overall intertidal channel complex (Figures 5.28 and 5.23). This sandstone contains ample oxidized iron-filled burrows, which range from one to five centimeters. Perhaps this diagenetic alteration of bioturbated sandstone, which sits directly on top of bitumen bearing sandstone, is the reason it is not charged with hydrocarbons (Figure 5.19). This subfacies does not occur in all cores but where it does occur, it contrasts sharply with overlying facies that contain marine *Cruziana* ichnofacies.

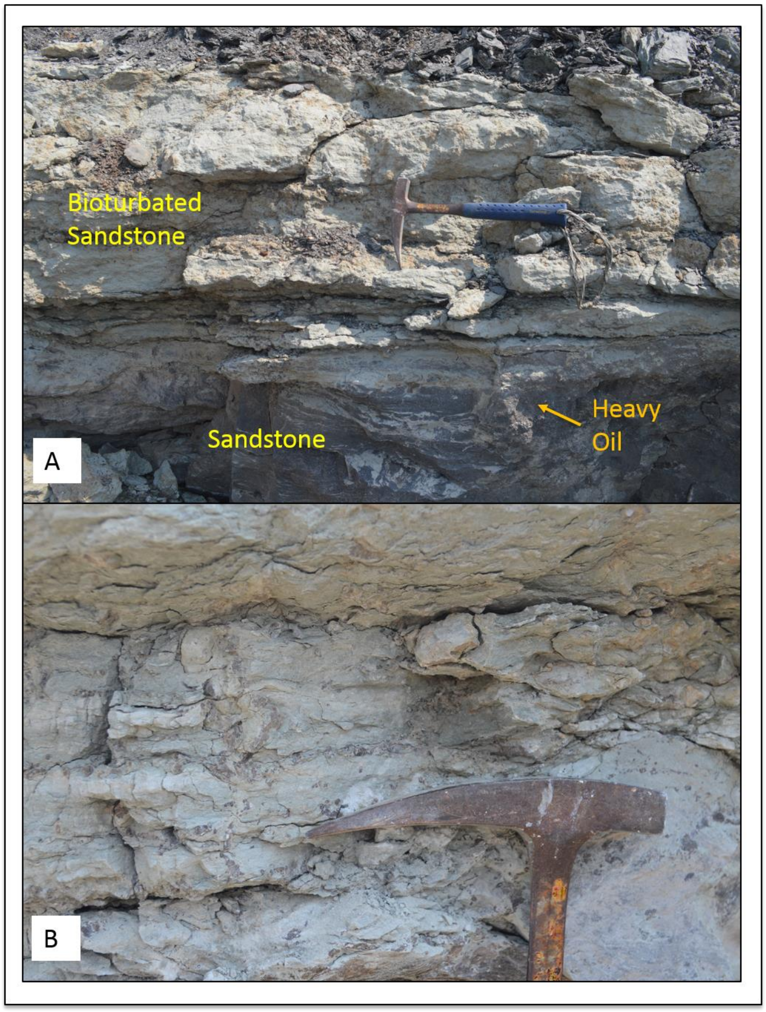


Figure 5.19. Close up view of the partitioning of facies 6 by *ophiomorpha*-like bioturbation (A). Oxidized iron-bearing minerals occur in bioturbated sandstone. Rock hammer approximately 7 inches for scale. Source: Images by the author.

5.2.7: Facies 7: Heterolithic Sandstone and Shale

Description: Facies 7 consists of lenticular to rhythmically bedded interlaminated sandstone and shale (Figure 5.20). Hummocky bedding and overturned cross laminations disrupt rhythmic bedding (Figure 5.21). Unit thickness ranges from two to twelve feet (0.6 to 3.6 meters) and averages five feet (1.5 meters). Grain size ranges from clay to very fine sand. Bioturbation can be seen in exposures and in core, which include *Rhizocorrallium*-like structures (Figures

5.22 and 5.23). The upper contact is gradational and the lower contact is sharp with extensive bioturbation in the first foot of section.

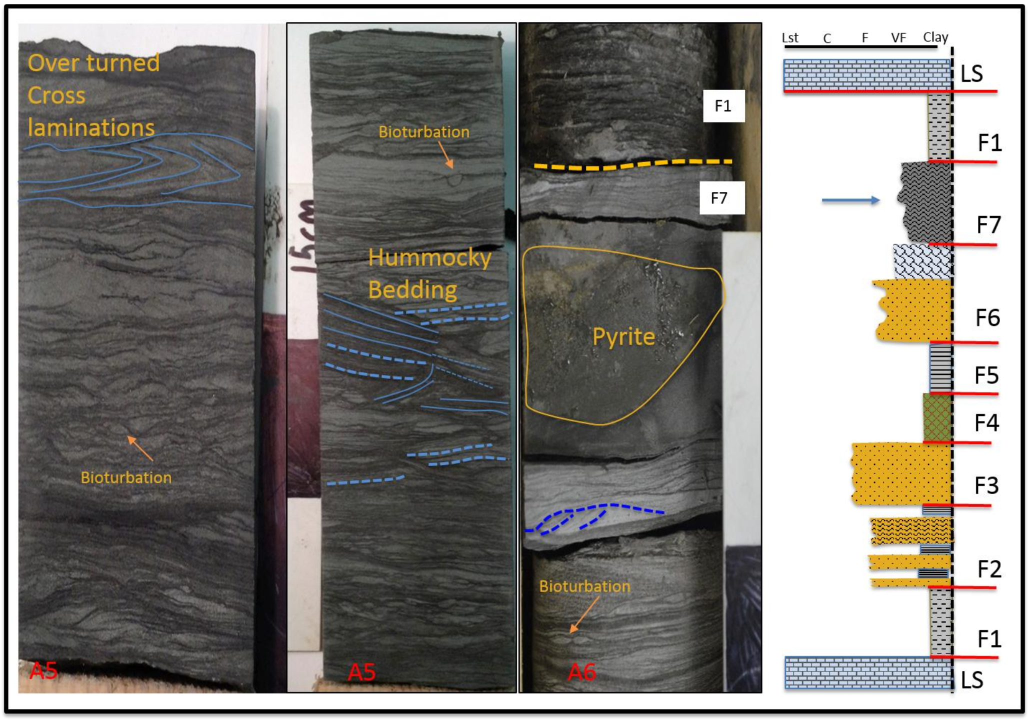


Figure 5.20. Photos of Core from facies 7. Note rhythmic and hummocky bedding is disrupted by bioturbation and overturned cross laminations. Pyrite was observed at the contact between facies 7 and facies 1 shown in core A6. Heterolithic deposits of facies 7 are moderately to heavily bioturbated. Source: Imaged by the author.

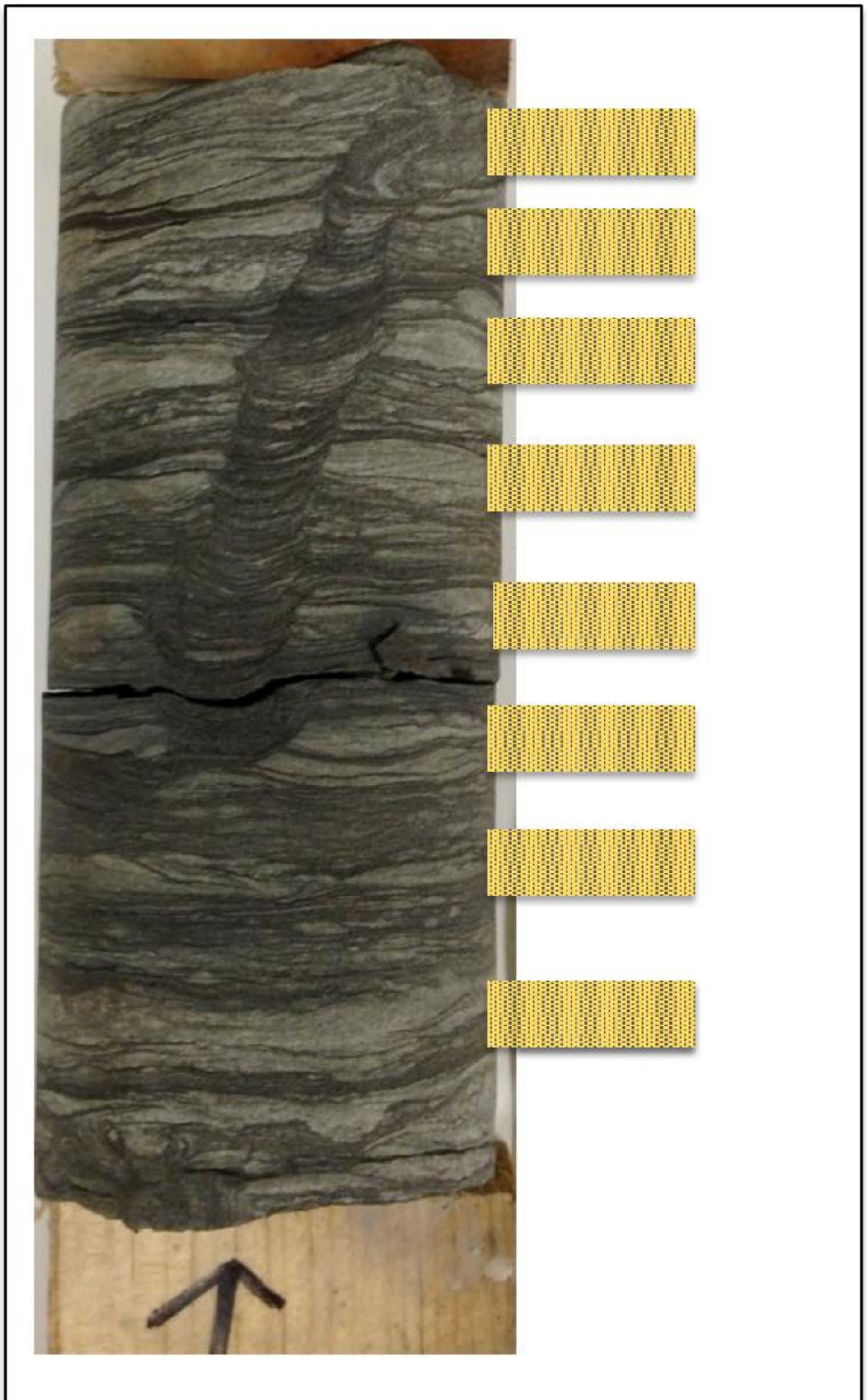


Figure 5.21. Core from facies 7. Yellow bars show rhythmic bedding which is cross cut by *Rhizocorrallium*- like bioturbation. Core is ~6.5 inches.
Source: Imaged by the author.

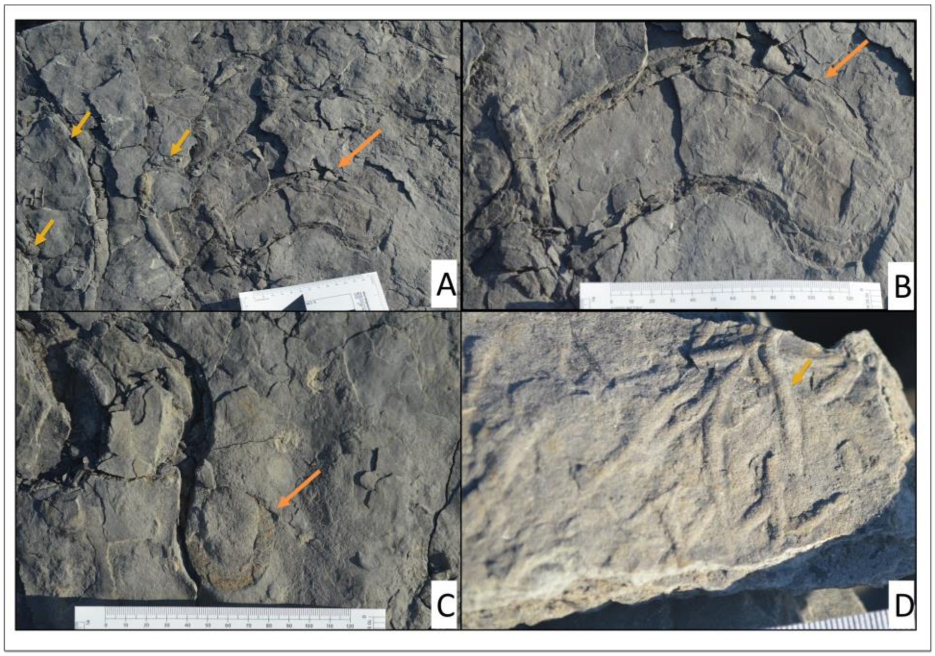


Figure 5.22. Facies 7 exposure surfaces from Pit A at the Stampede Mine showing *Rhizocorrallium*- like bioturbation (A, B, and C). View is perpendicular to bedding. Note the dark laminae and miniscae which is typical of *Rhizocorralium*. View D shows *Chondrites*-like bioturbation. Cruziana ichnogenera sharply contrast the glauconitic upper sandstone of facies 6. Source: Imaged by the author.

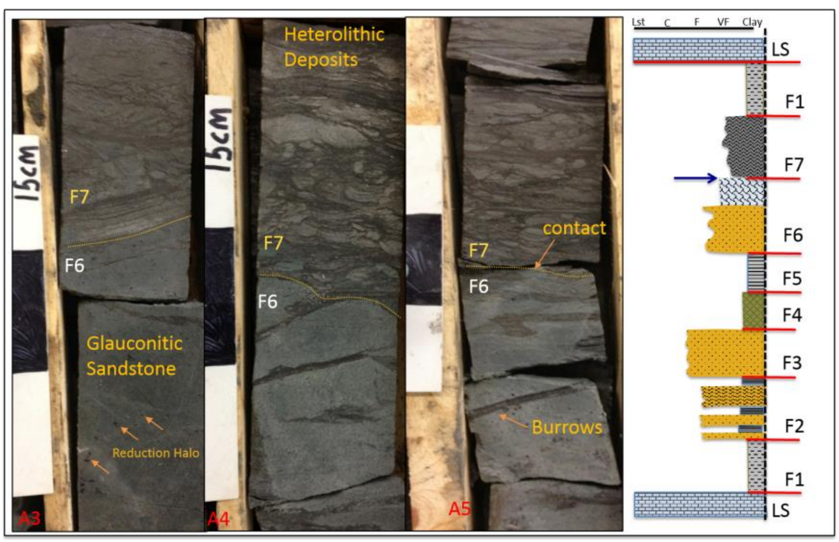


Figure 5.23. Anomalous glauconitic and burrowed sandstone occurs in the upper portion of facies 6. This sandstone is void of hydrocarbon and contains *Ophiomorpha*-like bioturbation. A sharp transition occurs above Facies 6 into heterolithic deposits (facies 7). Disturbed bedding and bioturbation is present at the contact as shown above. *Cruziana* ichnogenera occur above the contact such as *Rhizocorralium* and *Chondrites.* This transition is part of a transgressive parasequence and represents a shoreward shift in sea level.
Source: Imaged by the author.

Interpretation: Facies 7 represents a transition zone from tidal flat to subtidal. The first two feet (0.6 meters) of facies 7 are bioturbated with *Cruziana*-like ichnofacies that overlie burrowing structures in facies 6 (Figure 5.23). Structures are similar to those of *Rhizocorrallium* and *Chondrites*. This is a sharp contrast to the desiccation cracks and *Ophiomorpha*-like structures that dominate bioturbation of facies 6. This sharp contrast suggests a flooding surface. The upper contact grades into a marine shale (facies 1), which represents a distal environment from the shore.

5.2.8: Summary

Facies 1-3 reveal characteristics commonly found in bar-sand and tidal-sand ridge complexes, as described by Dalrymple and Choi (2007). This vertical stacking pattern prograded basinward on top of a distal marine shale (facies 1). These facies formed as ribbon sands that coalesced into large belts in which lateral variations occur. Examples of variations are found in facies 3 where thickness ranges from 0 to >50 feet (0 to 15 meters) of sandstone. Facies 4 caps the progradational package and represents a basin-wide exposure surface. This surface is well documented elsewhere in the basin (Treworgy, 1988) and was observed in numerous cores at the Stampede Mine and in a core approximately six miles away. Facies 5-6 consist of heterolithic facies deposited on top of the progradational sequence. These facies formed as mixed tidal flats and estuarine facies filled in on top of the previously deposited progradational unit. Core, field measurements, and thin-section analysis confirms that this unit contains more fine-grained material than in sequence 1-3. This fact has great economic implications for heavy oil development, which will be discussed in Chapter 6. One of the most distinguishing features is the identification of facies 4, which acts as a sequence boundary according to Treworgy (1988) and Nelson et al. (2002). This facies forms a surface on which parasequences may be distinguished.

5.3: Lithofacies Analysis-Warren County

Lithofacies analysis was also conducted at five Big Clifty Sandstone outcrops oriented roughly east west across northern Warren County, Kentucky. The following four facies were identified: 1) Fossiliferous shale, 2A) Ripple-bedded shale, siltstone, and sandstone, 2B) Ripple bedded sandstone, and 3) Cross-laminated sandstone. An overall upward coarsening sequence was observed in Warren County, except at McChesney Field Station and Jackson's Orchard where the entire Big Clifty section consists of cross-laminated sandstone. Facies descriptions are shown in Table 3.

5.3.1: Facies 1: Fossilerous Shale

Description: Facies 1 consists of a light gray to black fossiliferous shale (Figure 5.24). This shale effervesces from HCl and is fissile in the outcrop. Thickness ranges from eight to ten feet along the Natcher Parkway and Glen Lilly Road. The lower contact with the Beech Creek Limestone is exposed by a road cut along the Natcher Parkway and is gradational. The upper contact with facies 1 is sharp (Figure 5.24).

Interpretation: This shale is equivalent to facies 1 from the Stampede Mine site and other core in Logan County. It formed in deep water conditions as previously described for facies 1.

Lithofacies	1	2 A &B	3
Lithology	Shale	Sandstone, Siltstone, mudstone	Sandstone
Grain Size	Clay size particles	Very fine to medium grained sandstone interlayered with siltstone and clay-sized grains	Fine to medium grained sandstone, sandstone, well sorted
Sed. Structures/special character	Moderately fissile	Ripple bedded	Ripple bedded, massive, laminated, cross laminated, and flaser bedded sandstone mud intraclasts fractures structures
Rate of sedimentation **bioturbation**	Low NA	Low NA	Moderate to High NA
Reservoir Quality	Not Assessed	Not Assessed	Not Assessed

Table 5.2: Facies 1-3 Observed in Warren County, Kentucky. Source: Created by the author.

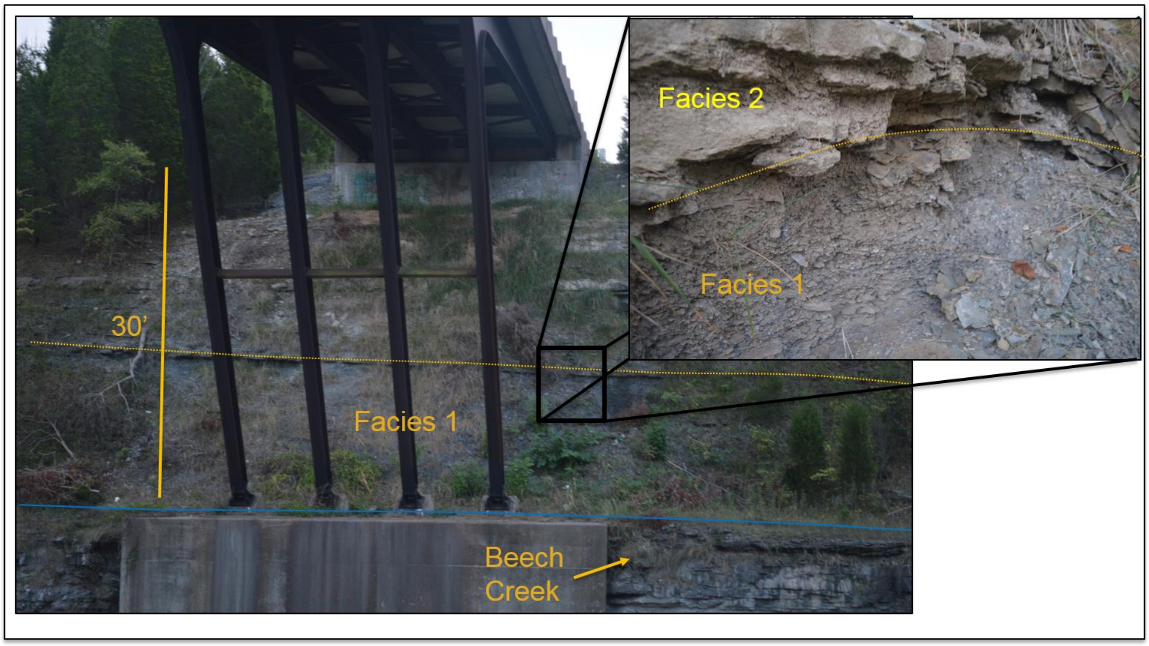


Figure 5.24. Photograph showing facies 1 and 2 along Natcher Parkway and Barren River Rd. in Warren County, Kentucky. Call out box shows the contact between facies 1 and 2 observed at the road cut. Source: Images by the author.

5.3.2: Facies 2A: Ripple-Bedded Sandstone and Interbedded Siltstone

Description: Facies 2A consists of alternating and interlaminated ripple bedded sandstone and siltstone. Ripple bedding ranges from a few millimeters to fifteen inches thick (Figure 5.25). Sandstone bed sets range from 2 inches to 8.25 inches thick. Interbedded shale thickness bedsets range from a few millimeters to a few inches in thickness. Neither macrofossils nor bioturbations are present in outcrop for this facies.

Interpretation: Alternating siltstone and sandstone interbeds suggest fluctuating energy conditions during the time of deposition. It is not clear if energy flux is related to tidal processes or is the result of changes in sediment input or a mixture of the two. It is also possible that these deposits may represent interchannel areas, which contain muddy sand and silt with splay-like geometries.

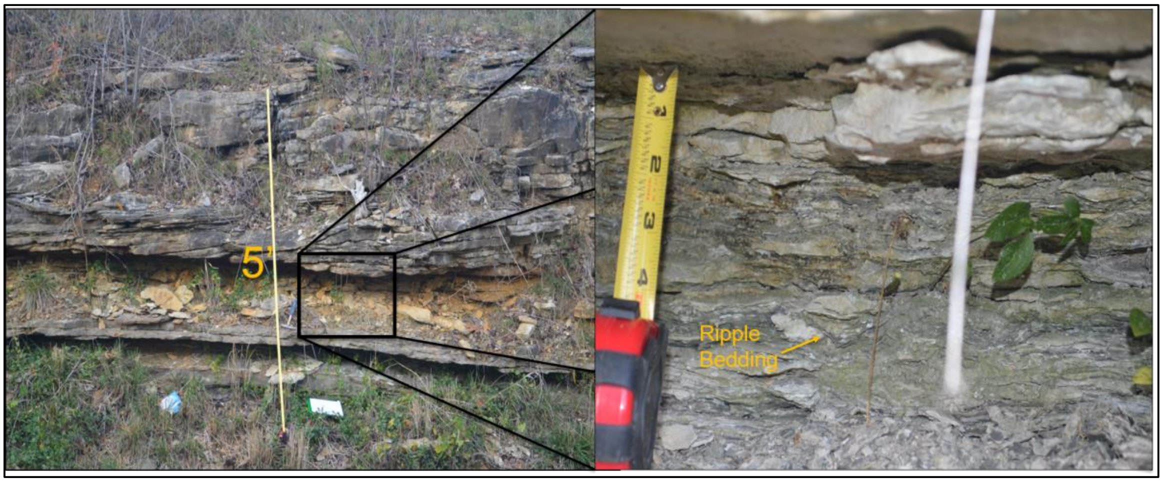


Figure 5.25. Photos of facies 2 from road cut along Barren River Rd. in Warren County, Kentucky. Note the interbedded and ripple bedded sandstone and muddy deposits. Muddy deposits differentially weather in outcrop compared to coarser sandstone. Source: Images by the author.

5.3.2: Facies 2B: Ripple-Bedded Sandstone

Description: Facies 2B consists of ripple-bedded sandstone (Figure 5.26). This facies is similar in character to facies 2A at the Stampede Mine but is void of shale. It ranges from two to five feet in thickness. The dominant sedimentary structure is ripple bedding. Bedding is wedge shaped and forms a shallowly (<15°) inclined surface. The upper contact is scoured and filled with facies 3.

Interpretation: The absence of shale interbeds differentiates this facies from facies 2 from the Stampede Mine. This could be caused by either an increase in current energy or a basinward shift in deposition. Moving up section from facies 2 to 3 shows an increase in sand to shale ratio (shale is ~0). The exposure is coarsening upwards. This interpretation is also supported by a scoured upper contact.

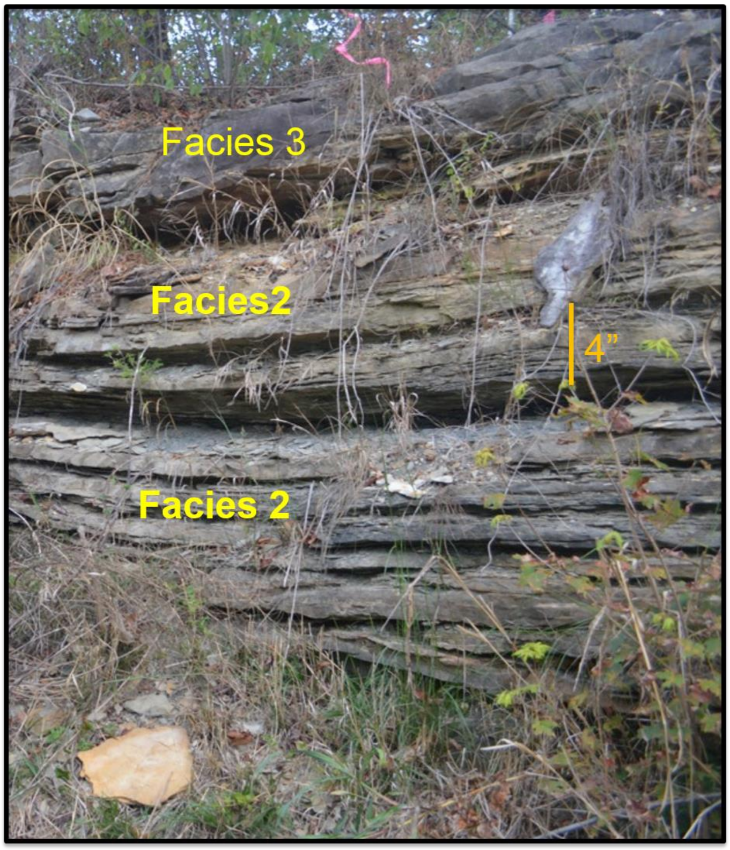


Figure 5.26. Road cut exposure showing facies 2, 3, and 4 along Barren River Rd. Exposure is coarsening upwards. Source: Image by the author.

5.3.3: Facies 3: Cross-Laminated Sandstone

Description: Facies 3 consists of cross-laminated quartz sandstone. This sandstone is trough cross-bedded to tabular cross-bedded and contains iron-oxide intraclasts and liesegang banding. The color ranges from white to dark brown. Bedding thickness ranges from an inch to eight inches (2.54 to 20.3 cm) with bedsets averaging eight feet thick to ~30 feet (2.5 to 9 meters thick) across the study area (Figure 5.27). The exposure at Barren River Road strikes approximately northwest. Two strike and dip readings from an inclined bedding plane strike and average of N28°W with a dip of 19° SW. Cross sets become tangential at the lower boundary. No biogenic or trace fossils occur in the field. The lower contact is sharp on facies 2, however at Jackson's Orchard and McChesney field station, the Big Clifty occurs entirely as facies 3. The upper contact was not observed at any outcrop due to ground cover.

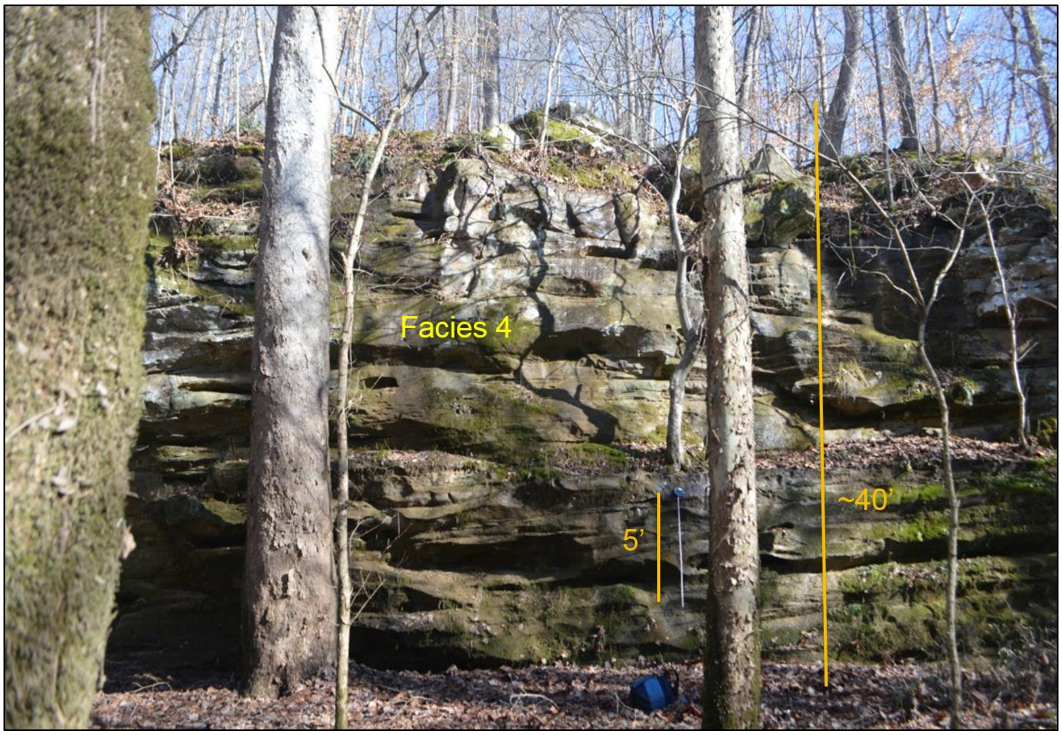


Figure 5.27. Approximately 40' of trough and planar cross bedded Big Clifty Sandstone exposed along Indian Creek at the McChesney Field Station. No fine shale or mudstone are observed at this exposure. Source: Image by the author

Figure 5.28. Road cut along Barren River Rd. showing facies 3. Facies 3 exhibits planar bedding that is filled with trough cross-bedded sandstone.
Source: Image by the author.

Interpretation: Facies 3 at the Natcher Parkway and at Barren River Road outcrop is coarsening upwards. At Jackson's Orchard and McChesney Field Station, the entire Big Clifty outcrops consists of 25-40 feet (7.6 to 12.1 meters) of cross-bedded sandstone. At Jackson's Orchard the lower contact is sharp onto the Beech Creek Limestone/Girkin formation Figure. Cross bedding likely formed as migrating megaripples or subaqueous dunes.

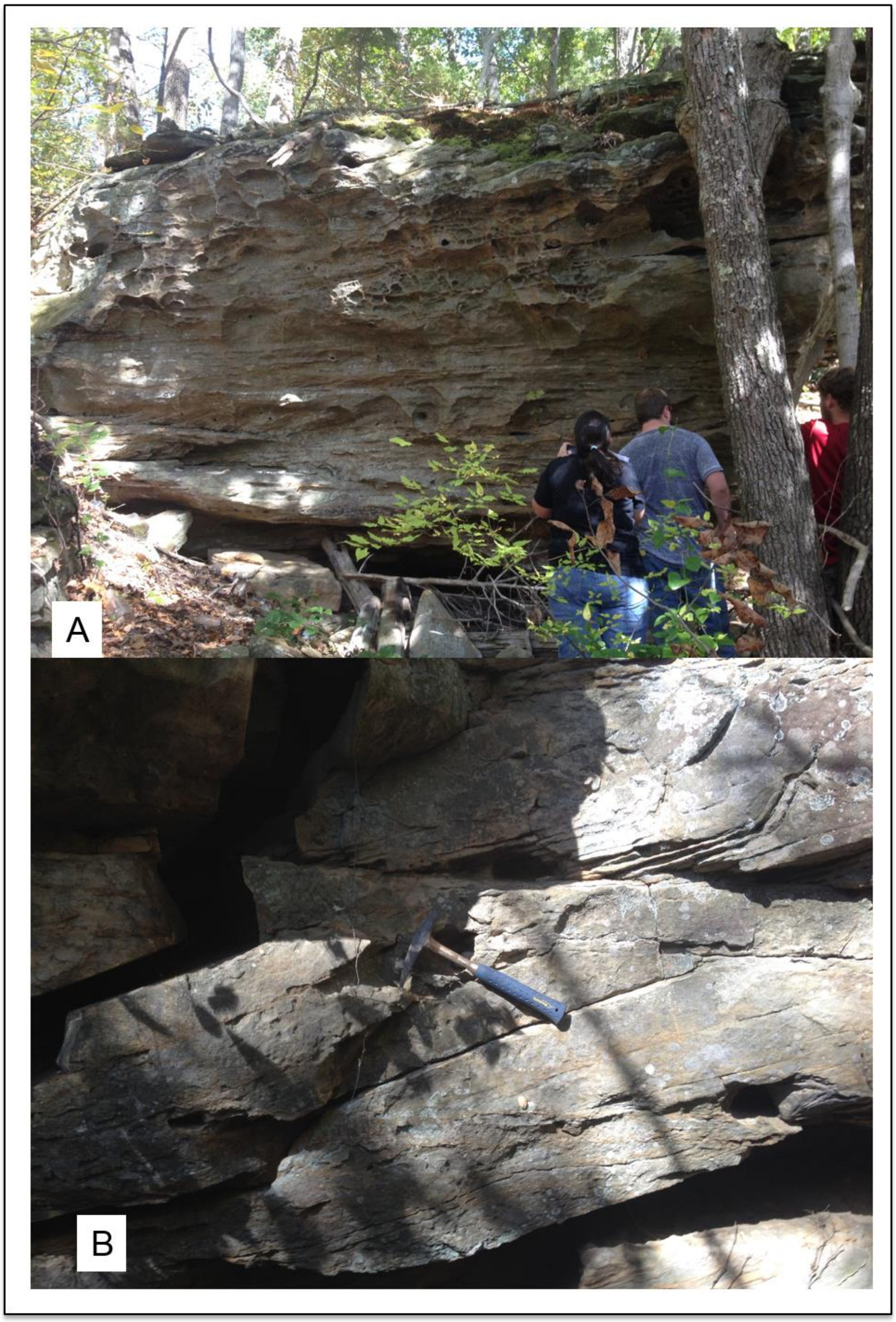


Figure 5.29. Outcrop photos of Big Clifty Sandstone at Jackson's Orchard. Note Large scale (1-3 feet) cross bedding (B). Honey comb weathering in outcrop (A). Source: Image by the author.

5.3.4: Summary

Two types of Big Clifty Sandstone sequences were observed in Warren County. Along the Natcher Parkway and at Barren River Road, coarsening upwards was observed. At Jackson's Orchard and McChesney Field Station the entire unit consists of crosslaminated sandstone with a sharp lower contact on the Beech Creek/Girkin Formation. The gross thickness of the unit from Logan County to northern Warren County remains approximately 40 feet (13 meters). Along this 30-mile transect, however, the net sandstone thickness varies dramatically. The change in depositional style was observed over ~4 miles (~6.4 km) from Natcher Parkway to Jackson's Orchard.

5.4: Cross Section and Map Construction

5.4.1: Structural Cross Sections

Structural dip was determined on the top of the Beech Creek/Girkin/Barlow limestone across the asphalt rock play utilizing three wells that penetrated the limestone. The Beech Creek Limestone is an excellent stratigraphic marker (Treworgy, 1988). Few wells, however, from this study penetrate the Beech Creek. Of those wells that did, TVDSS of the Beech Creek is shown in Appendix VIII and the rate of dip (50' per mile) is similar to the rate calculated by Williams and others (1982). The rate of dip from LFA core to A2 core is 48 feet per mile, within two units of the reported average. The Beech Creek and/or Girkin Limestone are present in geophysical logs from both Warren and Butler Counties at the tops are located in Appendix VIII

5.4.2: Stratigraphic Cross Sections

Cross sections over the Stampede Mine reveal complex and channel like geometries of sandstone reservoirs. Cross sections run both parallel and perpendicular to SW-NE trend identified in previous studies (Specht, 1985; Visher, 1980; Williams et al., 1982). Cross section C (Appendix I) is flattened on the top of facies 3. The channel-like geometry of facies 3 is shown in this cross section. Facies 6 is thin to absent in cores A5 and A9. This is also illustrated in Cross section A and B (Appendix II). While facies 3 thickens and thins across the mine property, facies 6 is sheet like. Thickness variation is observed in other facies, especially in facies 1. Facies 1 in well B13 is completely absent. This facies is also absent in MCC and presumably MAA, MBB, and MA; however, coring ceased before hitting the Beech Creek Limestone.

Two regional cross sections trending NE-SW were prepared using exposure descriptions, core logs, and geophysical logs, and are located in Appendix I. Cross sections document a transition in vertical stacking patterns in the Big Clifty Sandstone as shown in cross section A and B. In both cross sections the Big Clifty Sandstone transitions from a single, amalgamated sandstone in the northeast to two sandstone units to the southwest across the study area.

5.5: Petrographic Study

5.5.1: Sandstone

The Big Clifty Sandstone is a quartz arenite to sublitharenite ranging from very fine-to-medium grained, and is angular to subangular with low-to-moderate sphericity. Detailed petrographic analysis of the Big Clifty Sandstone is currently being completed based on prior research (May and Butler, 2014), and is not addressed in this thesis. Porosity estimates range from totally occluded to greater than 20% and is entirely intergranular. Petrographic thin sections are an important way to correlate facies and understand changes in porosity across reservoir facies (F3 and F6).

5.5.2: Limestone

Petrographic analysis of limestone from facies 6 reveals caliche and spar-filled vuggy intergrowths (Figure 5.17). Facies 6 formed in a tidal flat environment where allochthonous caliche and lime-mud from adjacent mud flats were transported then deposited parallel to bedding. No bioclastic carbonate was observed in facies 6. Photomicrographs of the Haney and Beech Creek Limestone are shown in Appendix

5.5.3: Siltstone

Silt-sized grains occur in both facies 6 and facies 3. Silt sized material is abundant in facies 6, which is interpreted as tidal-flat sandstone.

5.6: Oil Analysis

Laboratory analysis was conducted to gather bitumen concentration information for reservoir facies examined in this study at the Stampede Mine. The logs in Appendix A list bitumen concentrations along with the footage at which they were sampled. Bitumen concentrations range from 0 to ~6.5 %, with an average concentration of ~3% for both upper and lower sandstone reservoirs. These data are listed in Table 4. Petrographic parameters, determined by Oil Field Research Inc., are listed in Table 5. These data were compared to records from the Kentucky

Geological Survey online oil and gas database. Three core analysis reports containing average porosity, average permeability, and liquid saturation information are found in Table 6. All three records were completed by Oilfield Research Inc. based in Evansville, Indiana.

Facies	Facies 6	Facies 3
Number of samples	28	53
Min	1.03%	1.14%
Max	5.21%	6.53%
Mode	3.65%	2.63%
Average	3.30%	3.27%

Table 5.3: Statistical Analysis of Bitumen Concentrations from the Stampede Mine. Source: Created by the author.

5.7: Electrical Resistivity Tomography

Electrical Resistivity Tomography was conducted along four transects at the Stampede Mine. Few studies exist that utilize this technique in the exploration and development of shallow heavy oil or asphalt-rock deposits (May and Brackman, 2013). To better interpret the data, a control transect was run in Pit A. This line was run directly on top of facies 6 (Figure 5.30 and Figure 5.31).

Date	Horizontal Permeability Millidarcies (md)	Porosity % 	Bulk Wet Density gm./cc	Residual Oil %	Residual Water %
12/20/2012	75	19.4	2.26	40.3	19.7
1/8/2013	131	19.4	2.23	36.7	10.7

Table 5.4 Core Analysis of Big Clifty Sandstone. Location is Logan County. (No specific location was provided by company.) Source: Created by the author.

Source	Carter Coordinate	Date	Feet Core Analyzed	Average Permeability Millidarcies md	Average Porosity %	Average Oil Saturation %	Average Water Saturation %
KGS Well #62912	11-H-32	6/25/1984	7.0’	15	14.0	16.9	42.0
KGS Well# 54759	19-H-32	6/18/1983	2 samples	834	21.0	3.6	55
KGS Well# 62391	9-H-33	6/13/1984	5 samples	81	15.5	0.0	45

Table 5.5. Showing Core Analysis from the Big Clifty Sandstone in Butler County. Source Created by the author.

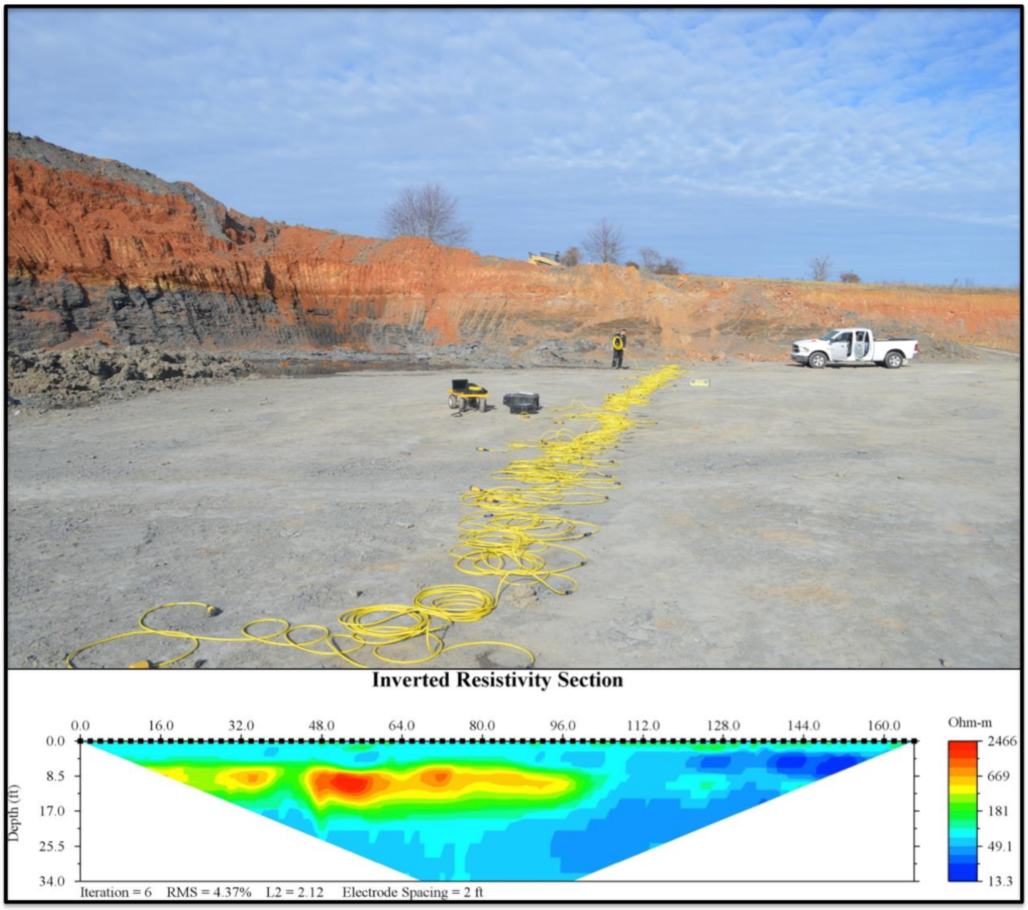


Figure 5.30. Photo from Pit A at the Stampede Mine. This transect was run as a control. After ERT data was collected the area was mined and measured (next figure) which allowed for excellent constraint of geophysical dataset.
Source: Image by the author.

Results show channel like geometries (Appendix V). After the data were collected in Pit A, this location was mined. As mining progressed, the lithology was observed, which allowed for direct control on ERT data. Warm colors are thus interpreted as sandstone, with cool colors occurring as shales in pseudo sections. Bright red colors indicate highly resistive material such as bitumen-impregnated sandstone.

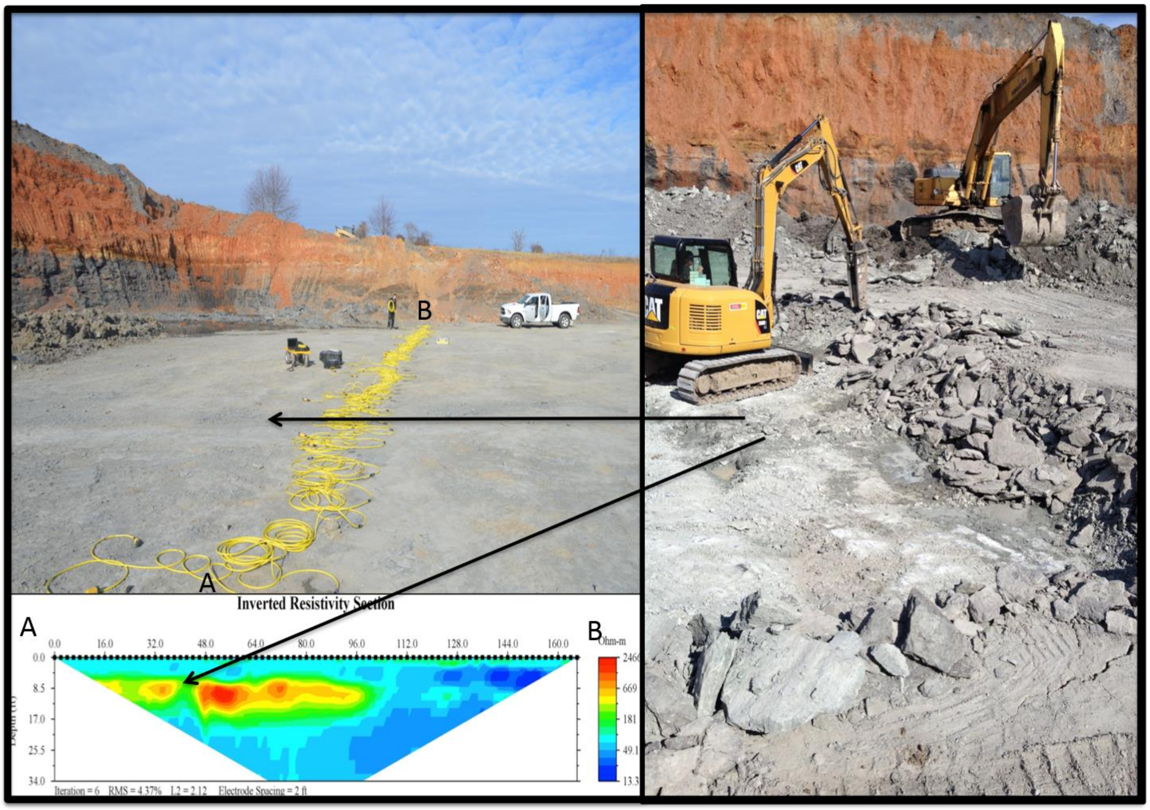


Figure 5.31. Mining over ERT transect allows for anomalous features in geophysical dataset to be constrained by direct observation of facies 6. Arrow shows a mudfilled interchannel area between facies 6 reservoirs. Note lenticular nature of ERT data reflects lenticular sandstone observed in Pit A. This ERT transect serves as a control to interpret other transects across the mine site. Source: Images by the author.

Chapter 6: Discussion

6.1: Core Analysis

Facies analysis documents a channel sandstone complex with interchannel mudstone, siltstone, and limestone. Channel sandstone geometries are observed in ERT pseudo sections (Figure 5.31 and Appendix V) and through cross sections (Appendix I). Interpretations of the Big Clifty Sandstone EODs in south central Kentucky include shallow marine environments, but detailed definitive studies of sub-environments are lacking (Williams et al., 1982). Two sedimentary packages of Big Clifty exposures are observed in the outcrop belt of south central Kentucky, 1) amalgamated channel sandstone, 2) lower and upper sandstone bodies separated by mudstone (Table 7).

Sedimentary Packages	**1**	**2**
Sandstone	*Entire unit consists of 35-45 feet of amalgamated channel sandstone, underlain by limestone of facies 1*	*Unit contains two distinct sand bodies referred to as lower and upper Jackson Sandstone, underlain by limestone of facies 1*
Facies	*1,2,3*	*1,2,3,4,5,6,7*
Upper contact	*Not observed*	*facies 1 to Haney Ls*
Lower Contact	*Sharp on limestone or facies 1*	*Sharp on limestone or facies 1*
Location	*Natcher Parkway, Jackson's Orchard, McChesney Field Station* *Warren County Well Logs*	*Stampede Mine* *Butler County well logs*

Table 6: Summary of vertical stacking patterns observed in study.
Source: Created by the author

None of these characteristics, however, are conclusive of a particular EOD. Unimodal and large-scale crossbedding as observed at Jackson's Orchard is suggestive of high current energy such as in deltaic or fluvial environments. Marine fossils (May 2013) and bimodal cross bedding, however, are suggestive of tidal to marine influence. The grain size of Big Clifty Sandstone as observed in the field exposures, core, and thin section is fine-to medium-grained and has been shown to contain ample clay and bioclastic carbonate (facies 6). Sandstone bodies in Warren County are vertically stacked and amalgamated both in surface exposure and in the subsurface. Across northern Warren County, the Big Clifty occurs almost entirely as sandstone. Facies 1 occurs thinly in the Megawest cores shown on cross section A. In Butler and Logan County, where facies 2 and 3 are thin thick mudstone, tidal-flat sandstone, and heterolithic deposits occur (cross section A and B). Tidally influenced deltaic systems have been suggested for the Big Clifty Formation of Indiana (Visher, 1980; Specht, 1985), and provide the EOD framework for various lithologies and sedimentary features observed in this study. Tidally influenced deltaic systems are discussed in the following section.

6.2: Tidally Influenced Deltaic Systems

The goal of this section is to combine datasets described in the previous chapter into a working depositional model that can best explain facies associations observable in core and surface exposures. This effort is aided by the work of two studies written on the Big Clifty Formation at Indiana University in the 1980s. Visher (1980) and Specht (1985) both purport that the Big Clifty Formation of Indiana is the product of a tidally influenced deltaic system. Specht (1985) provides a thorough review of tidally influenced deltaic systems, as also described in Coleman and Prior (1982). A thorough examination of tidal deltas, also referred to as bay head deltas or incised valley-fill deposits, may be found in Brown (1979), Gupta and Johnson (2002), Porębski and Steel (2006), Dalrymple and Choi (2007), and Maynard et al. (2010). Specht (1985) based the argument on the fact that the Big Clifty formed in a system such as the following: 1) the ancestral Michigan River of Swann (1964) shifted to the southeast margin of the basin over the current Cincinnati Arch during the deposition of the Big Clifty Formation; 2) paleocurrents measured by Potter et al. (1958) and Visher (1980) are both unimodal and polymodal (Visher (1980) found that bimodal deposits constitute approximately 30% of fluvio-tidal facies); and 3) major similarities exist in sedimentary characteristics between modern, tidally influenced deltaic systems and the facies observed in his work and by Visher (1980) and Baker (1980). The following section examines some of the facies associations of tidally influenced deltaic systems and compares them to the facies identified in this study.

Wright and Coleman (1975) described a typical progradational sequence for a tide-dominated delta system from the Orb Delta in Australia. In ascending order, the sequence consists of: 1) Shelf and prodelta mud; 2) Distal bar; 3) Tidal ridges and channel fill; 4) Over-bank splays, and subtidal mud flats, and mangrove deposits; 5) Tidal channel deposits; 6) Intertidal flats; and 7) Supratidal evaporite flats. Specht (1985) compared this Orb Delta sequence to the Big Clifty Formation and concluded they contain “striking” similarities. When this sequence is compared to the facies in Logan and Warren counties, similarities are also observable (Figure 6.1).

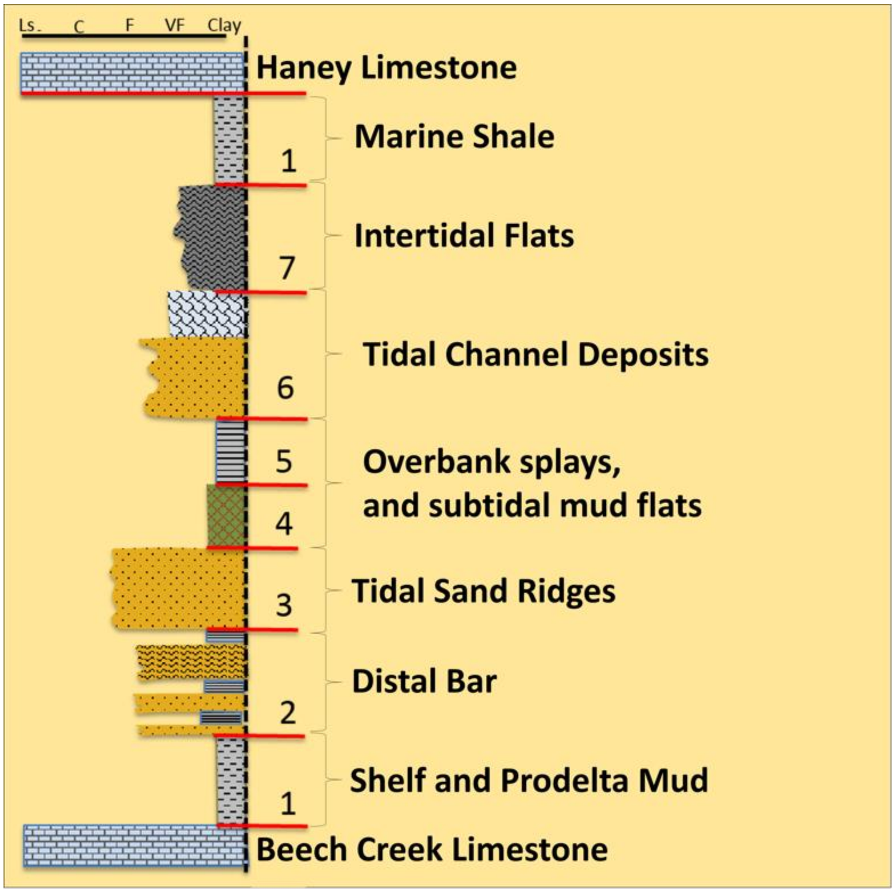


Figure 6.1. A comparison of the depositional model described by Wright and Coleman (1975) and the facies identified at the Stampede Mine. Source: Strat column created by the author; interpretation from Wright and Coleman (1975).

Figure 6.1 shows the facies from the Stampede Mine, along with the progradational sequence described by Wright and Coleman (1975). Using this interpretation, 6 of the 7 units match the vertical stacking patterns from the mine site. When this process is applied to the facies from Warren County, similarities are also observable.

Nelson et al. (2002) described the Big Clifty forming as a result of regressional and transgressional parasequences; thus, some of the units similar to the Orb Delta model could have been reworked. Tidally influenced deltaic systems are complex (Dalrymple and Choi, 2007). These systems result from the interactions of multiple processes, and individual tidally influenced deltaic systems contain differences in wave and fluvial energy, tidal range, climate, and structural regime. Because of these differences and others, no system is exactly like another and thus no one tidally influenced delta system necessarily serves as a model for any other (Specht, 1985). The transition from open-marine shelf to fluvial environments represents a profound spatial change in depositional conditions. Factors that control the nature of deposits include: 1) baythmetry and geomorphology; 2) type of current energy (tidal, wave, river, longshore); 3) rate and direction of sediment movement; and 4) salinity of the water (Dalrymple and Choi, 2007). A delta's location on the shelf is another consideration when interpreting facies in tidally-influenced delta systems, as described in Porębski and Steel (2006). A transition in energy systems occurs as sea level changes from fluvio-tidal to tidal wave (Figure 6.2). Again, with the notion that no tidally deltaic system is necessarily comparable to another, Figure 6.2 provides only a framework for understanding deltaic deposits in the Illinois Basin, which has been described as a ramp by Treworgy (1988) rather than a shelf. Nonetheless, the transition in energy regime from inter-tidal channel sandstone to subtidal, heterolithic mixed-flat facies observed in this study represents a shoreward shift in sea level trangression. This interpretation is also supported by a transition ichnofacies from *Ophiomorpha* in facies 6 to *Cruziana* in facies 7.

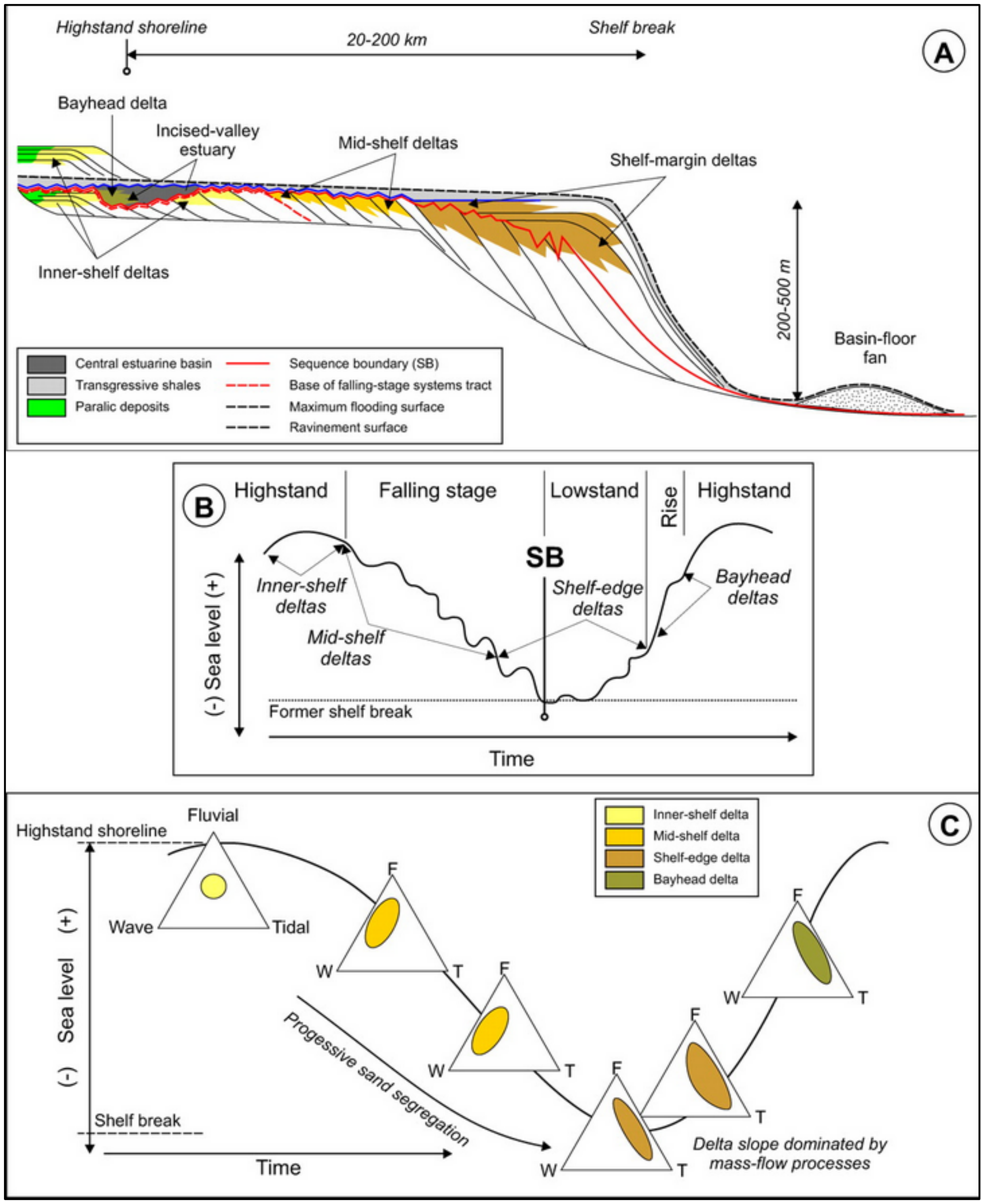


Figure 6.2. Location on the shelf and delta type (A), illustrating Big Clifty Sandstone formed in tidally influenced deltas dominated by flubio-tidal energy.
Source: Model from Porębski and Steel (2006).

Another important consideration for the identification of EOD in Chester sandstones is the geometry of tidally influenced sand bodies. Potter (1962) provided four idealized sand geometries for Chester sandstones, which include pods, ribbons, dendroids, and belts (Figure 6.2). Big Clifty reservoirs as described by Specht (1985) occur as ribbon bar sands that may coalesce to form wide belts.

Longitudinal changes in sand thickness relative to shore strongly influence the nature of the bars that develop (Dalrymple and Choi, 2007). Distributaries of tidally dominated delta systems are funnel shaped (Figure 6.3). At the seaward end of these systems elongated tidal bars or tidal sand ridges occur in relatively straight and wide channels (Dalrymple and Choi, 2007). Tidal ridges are commonly parallel to tidal currents and perpendicular to the shoreline, as well as being separated by scour channels. The dimensions of these ridges may vary greatly, but it is these ridges that form the foundation on which the tide-dominated delta progrades (Specht, 1985). A generalized vertical profile of a tidal bar is shown in Figure 6.4, where the tidal bar is composed of bottom sets, bar slope, and bar crest. This deposition is coarsening upwards. Facies 1 to 3 from this study fit the characteristics of tidal bar deposit (Figure 6.4).

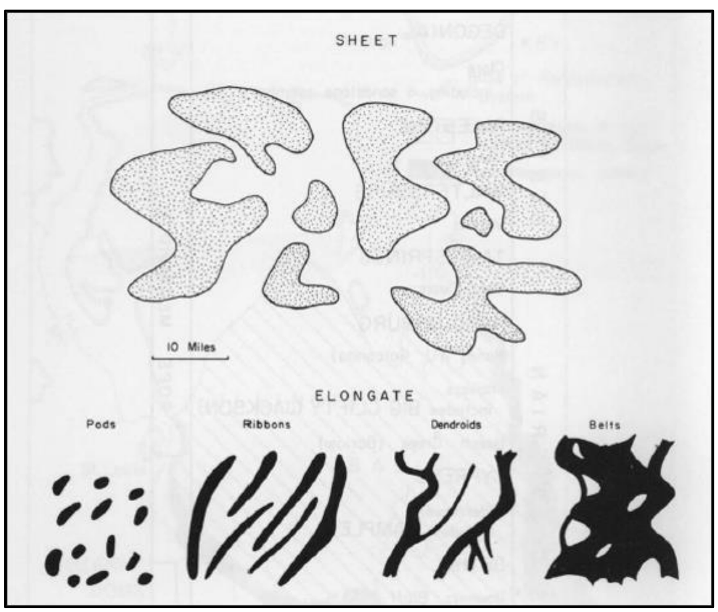


Figure 6.3. Geometries of Chesterian sand bodies. Source: After Potter (1962).

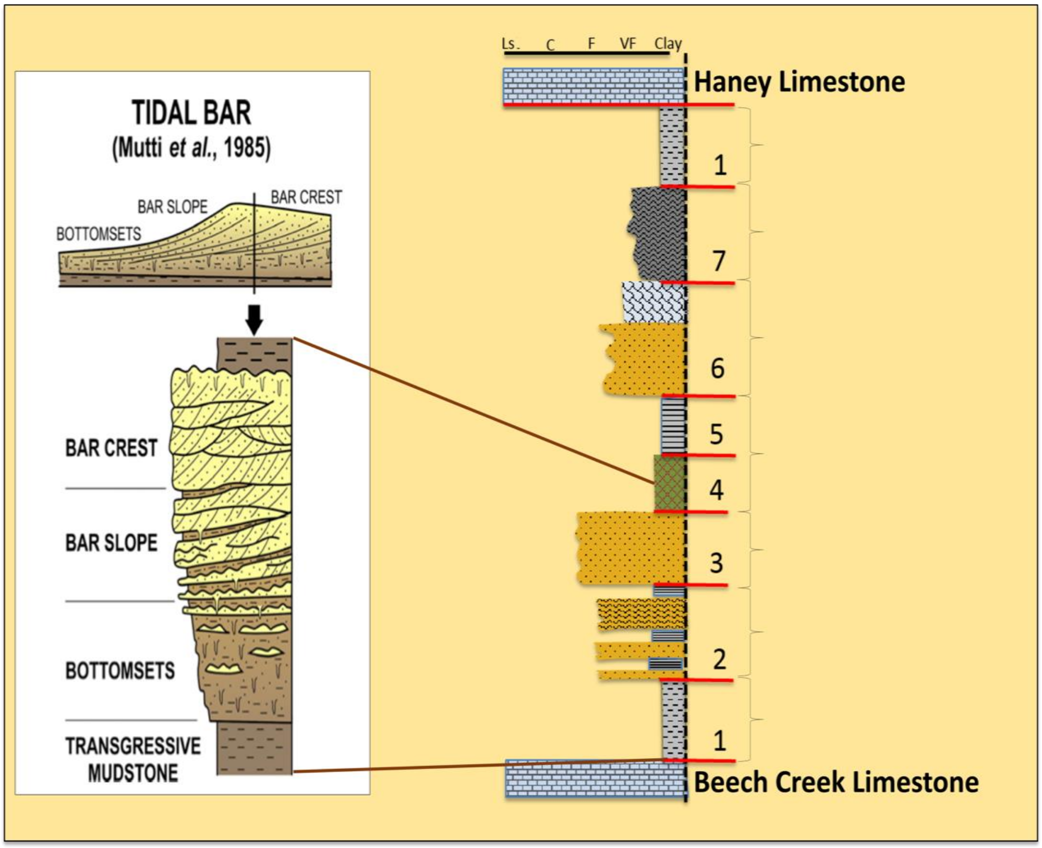


Figure 6.4 Tidal Bar model compared to facies 1, 2, and 3 from Logan County, Kentucky. Source: Modified from Dalrymple and Choi (2007).

During Big Clifty time, a tide-dominated delta occurred outside of the current margins of the Illinois Basin. Sediments from this delta system were transported in multiple distributary channels that commonly coalesced to form large belts. In turn, tidal bar complexes formed at the mouths of these channels. Accommodation in general increased along structural hinge lines (Treworgy, 1988) and is marked by a noticeable increase in suspended sediment deposition. Tidal currents aligned tidal sand ridges into northeast-southwest trending ribbons and belts that become sandier toward the head of the tidally influenced delta system. General grain size distribution may be seen in Figure 6.3 (e.g., mud vs. sand). The diagram in Part C of Figure 6.5 shows how flux in the amount of fines is controlled by EOD. It is known that, in the southeastern portion of the basin, Big Clifty sand bodies prograded further south and east than anywhere else in the basin during this time (Specht 1985). It is, therefore, likely that multiple sedimentary deposits controlled by varying energy regimes, as described in Porębski and Steel (2006), are preserved in this area.

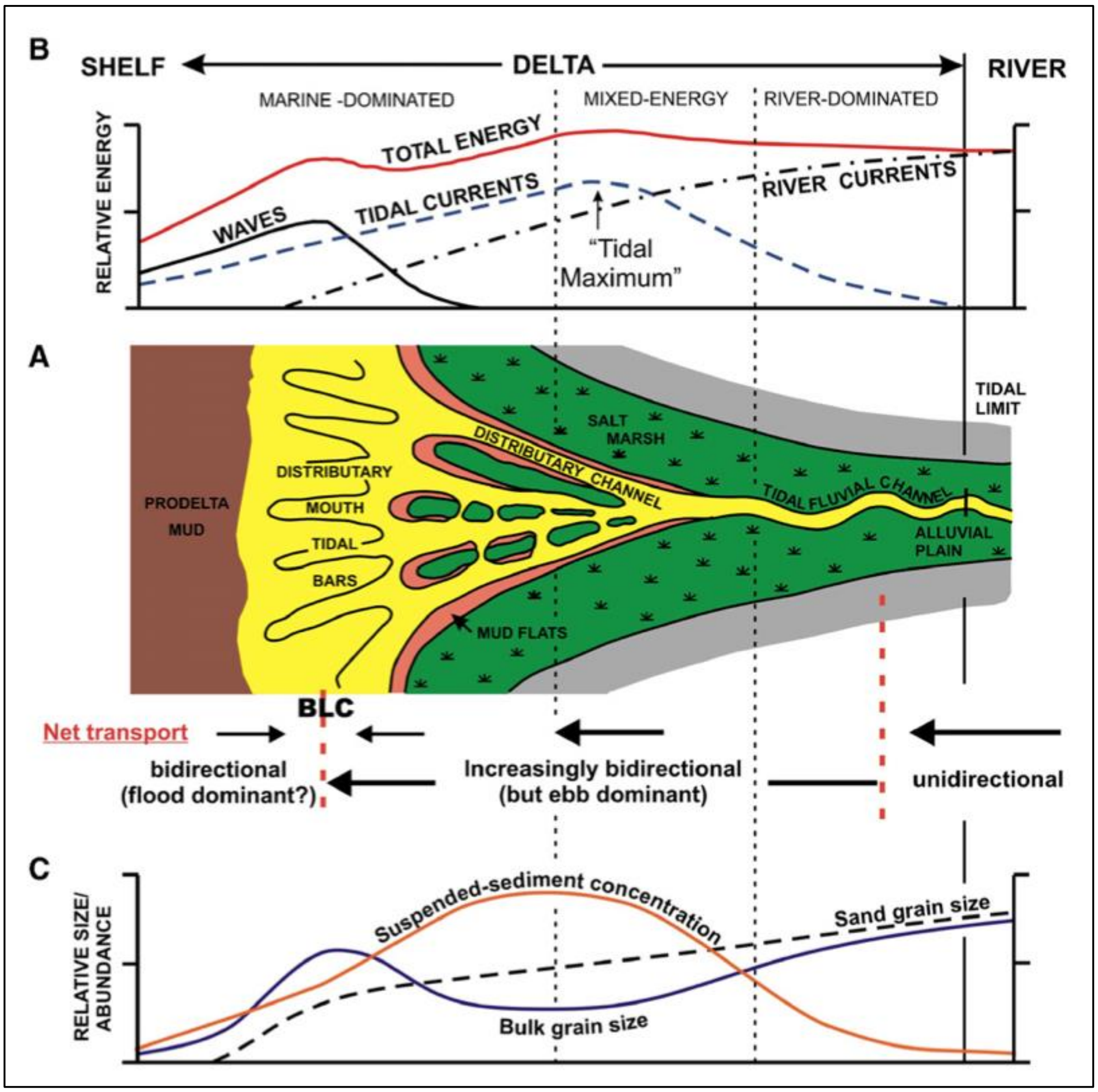


Figure 6.5. Model of bay head delta. Note the relationship between grain size (C), and mixed-energy systems (B). Source: After Dalrymple and Choi (2007).

USGS 7.5 minute quadrangle maps show that the thick sand belt trend increases northward into the Constantine and Cub Run quadrangles (Sable, 1964; Sandberg and Bowles, 1965) where coals and incised-valley fill (IVF) deposits are observed. It is important to keep in mind that, in addition to longitudinal facies changes in a tidally influenced delta system, it has been suggested that sea level also fluctuated during the deposition of Big Clifty siliciclastics (Nelson et al., 2002). Such fluctuations caused a basinward movement of facies across time and space (i.e., they are diachronous).

Sediment package 1 (Table 7), observed in north Warren County (Cross sections A and B) (and described in Edmonson, Hart, and Hardin counties) show fluvial-tidal influence and are part of the regressive parasequence. The sequence boundary is either placed on the top of sandstone, or at the bottom of IVF deposits. Whereas sediment package 2 deposits, positioned basinward of Warren County, suggest more tidal-to-wave energy conditions, and contain regressive tidal bar sands and transgressive heterolithic tidal flat deposits (facies 1, 2, 3, 4, 5, 6, and 7), the sequence boundary is on the top of facies 3 as observed at the Stampede Mine.

6.3: Petroleum Occurrence

The Stampede Mine provides an excellent case study to understand heavy-end oil development of Big Clifty reservoirs using surface-mining techniques. An extensive sampling program was conducted during this study to measure bitumen concentrations at the Stampede Mine. As shown in previous sections, two reservoir sand bodies occur over the mine property. Reservoirs are referred to as the lower reservoir (facies 3) and upper reservoir (facies 6) for convenience. Twenty-eight samples were retrieved in the upper reservoir and fifty-three were collected from the lower reservoir. These 81 samples were analyzed for bitumen content and are shown in Table 5.3. The average bitumen concentration is approximately 3.3% for both reservoirs analyzed. The maximum value for the lower reservoir is slightly higher at 6.5 % versus the upper, which is 5.21%. Out of fifty-three samples from the lower reservoir only five had lab results higher than 5% bitumen. The mode for the lower reservoir is 2.6% bitumen. Both average concentration values are below the 7.36% average reported in the Jillson (1926) reports. No attempts were made to calculate Original Oil in Place (OOIP) or reserve estimates in this thesis. Volume of rock based on calculations from net isopach maps shown in Appendices IX and X may be multiplied by average percent to yield approximate acre feet for the Stampede Mine. Doing so yields ~14,187,327 ft^3 with an average of 3% bitumen for the upper reservoir, and ~23,984,082 ft^3 at 3% bitumen for the lower reservoir. How much oil is actually recovered from Big Clifty Sandstone asphaltic reservoirs largely depends on the method. A successful method for extracting bitumen from tidally influenced sandstone reservoirs using surface mining must address the following: 1) angular to sub-angular grains, 2) fine the very fine grain size, and 3) vertical stacking patterns of sandstone in sequence stratigraphic context.

Facies analysis has great implications for low (10-12) API gravity oil processing and exploration activities. This study has shown two reservoir facies that have been interpreted to form in different EODs, with the result of differing amounts of fine sediments throughout the reservoir. The amount of fines negatively affects the quality of the “ore.” The angularity of grains is another important consideration.

Subangular grains can quickly wear out hoses and piping, observed at the Stampede Mine, as the material is pumped through multiple settling tanks. Although average bitumen concentration is ~3% for both reservoirs, the lower reservoir is a better target because it contains less fines. Detailed facies mapping through coring operations is an important component of any proposed surface mining program, and should be done before siting a mine. Mining strategies must address the lenticular geometry of the reservoirs, which are separated commonly by mud-filled interchannels as observed through ERT, exposure, and core. This point is especially relevant for a state that may import miners and mining techniques from the coal industry. Treating the sand body like a laterally continuous coal seam is costly and inefficient, as observed at the Stampede Mine.

Fractures were observed both in exposure and in core (Figure 5.). The extent to which fractures serve as a conduit to increase permeability and charging of reservoirs is not well understood for Big Clifty systems. The heavy oil play in Logan County occurs parallel to a known fault system, and faulting is a postulated charging conduit in the Illinois Basin (May, 2013). A relative increase in bitumen staining was observed along two vertical fractures in Pit A (Figure 5.9); however, no laboratory analysis was conducted to substantiate this observation. A reverse fault with millimeters of offset, along with other observed vertical fractures, agrees with the interpreted tensional and vertical principal stress of the region. Thus, movement in such a stress regime along deep-rooted east-west fault blocks related to Iapetan rifting resulted in normal/left lateral displacement (Nelson, 1990). Structural complexities related to faulting in and around the southernmost fault zone in Logan

County are not well known. According to the KGS (2016) online oil and gas database, only 729 oil and gas wells have been drilled in Logan County as of February, 2016. Of these wells, only 99 have been drilled equal to or deeper than 1500' and only 24 have been drilled equal to or deeper than 2000'. The quantity of wells with geophysical logs is even less. Poor well control and lack of geophysical data mean that structures related to faulting around Logan County's heavy oil and deeper reservoir targets are poorly understood. Extensive heavy oil deposits confirm the existence of migration pathways and trapping mechanisms, and suggest potential for future exploration.

6.4: Subsurface to Outcrop

Facies models may be used to inform well log analysis of Big Clifty Sandstone reservoirs in the subsurface. Figure 6.6 shows a representative log of the Big Clifty Sandstone from section 11 of Carter Coordinate H-32 in Butler County.

The type log was chosen for five reasons: 1) it spans the Golconda interval; 2) the drillers log mentions heavy oil shows; 3) the well is relatively close (9.7 miles NW) from the Stampede Mine property; 4) the Big Clifty interval was cored and measured for porosity, permeability, and water and oil saturation; and 5) it may be examined for lithology (gamma ray) and porosity (density porosity). Density porosity for this log is calculated using a limestone matrix of 2.72 g/cc. Results from core analysis are shown in Table 5.5. A study of this type log reveals a gross thickness of 78'. Net thickness using a gamma ray cut off of 60 API yields 17' for combined lower and upper reservoirs. The lower sandstone contains approximately 14' of net sandstone. The upper sandstone contains approximately 15', however, compared to the lower sand, the upper contains shale breaks that partition sandstone bodies (Figure 6.6).

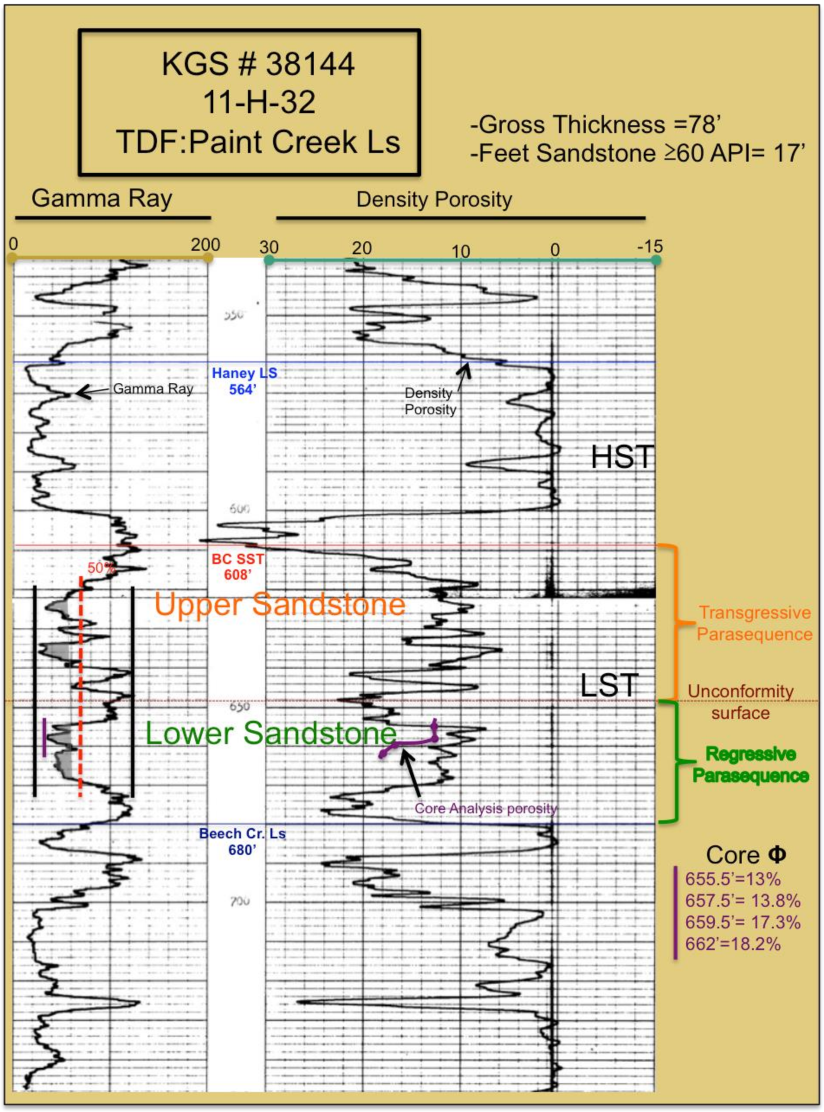


Figure 6.6. Type log of Big Clifty from Butler County, Kentucky. Density porosity was calculated on a limestone matrix. Source: Constructed by author using KGS (2015; 2016) well permit# 38144: http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp.

Applying facies analysis, an unconformity surface is identified that separates regressive and transgressive parasequences (Figure 6.6). The lower sandstone is interpreted as a tidal-bar complex with porosity decreasing in the upper five feet

(1.524 meters) from 18% to 13% (Figure 6.6). The overall shape of the gamma ray log for the lower sandstone is coarsening upwards (facies 1, 2, and 3). The upper sandstone represents a combination of tidal flat and mixed (heterolithic) tidal flat (facies 6 and 7) facies. The porosity from core analysis is higher than the density porosity for a given footage (Figure 6.6).

The two vertical stacking patterns of Big Clifty Sandstones are observable in geophysical well logs. In Butler County, it is common for drillers' logs to refer to the upper and lower Jackson sandstone. In the four logs from Warren County, the Big Clifty section occurs entirely as sandstone as described in group 1 facies, averaging 54 feet thick (Table 7). The change in vertical stacking patterns is seen in cross sections A and B, where the variation occurs along a NE-SW trend.

6.5: Integrated Model

Tidally influenced deltas provide the EOD framework for facies observed at the Stampede Mine and in exposure. Although highly complex, modern tidal deltas may be used to model ancient analogs, such as the Big Clifty Sandstone. The benefits of facies analysis are many and relevant for heavy oil exploration programs, mine siting, and interpretation of conventional targets, as described in this chapter.

Chapter 7: Summary/ Conclusions

The Big Clifty of South Central Kentucky was formed during a regressive-transgressive cycle in a tidally influenced deltaic system that shifted along paleoslope as sea level flucuated. Lithofacies identified in core and outcrop, and correlated to the subsurface with geophysical logs, support this interpretation. A typical Big Clifty regressive-transgressive cycle consists of the following: 1) the cycle begins with the progradation of a siliciclastic package onto a shallow limestone shelf (facies 1, 2, and 3); 2) Maximum regression is marked by a basin-wide exposure surface consisting of mudstone and paleosol (facies 4) and, less commonly, incised valley fill (Nelson et al., 2002); 3) A transgressive parasequence consisting of intertidal tidal flat sandstone and subtidal heterolithic flat deposits (facies 5, 6, and 7) resides on top of the sequence boundary; and 4) the cycle is capped by marine shale and the Haney Limestone. Variations of this general cycle are observed, particularly in the form of the entire unit occurring as a single sandstone body, such as in much of Warren County. In northern Warren County, the Big Clifty forms a large sandstone bluff, which is important for the extensive cave development in the region. Thick bodies of sandstone are also recorded in USGS geological maps in Hart, Hardin, and Grayson counties where the Big Clifty type section occurs near the town of Big Clifty. The results from this study suggest that the Big Clifty Sandstone in this area consists of a single regressive unit. Basinward of these locations in southwest Butler and Logan counties, the Big Clifty commonly consists of two distinct Sandstone bodies separated by four to ten feet (1.2 to 3 meters) of mudstone and paleosol (facies 4 and 5). The resulting facies model from this study allows for a sequence boundary to be placed between sand bodies in geophysical logs. The shift in EOD related to the sequence boundary resulted in increased amounts of fine-grained material in the sand body above the sequence boundary rather than below it. This has great implications for both conventional and asphalt rock reservoirs. A decrease in porosity was observed in well logs containing two sandstone bodies. How fine-grained material affects conventional reservoirs, however, was not addressed in this study. ERT analysis reveals complex channel geometries separated by mud-filled interchannels. Fractures and faults are observed in asphalt rock reservoirs and suggest faulting as a conduit for petroleum charging.

Specific conclusions include:

- Facies analysis studies are a crucial component of exploring for and developing asphalt rock reservoirs;
- Differences in reservoir quality are observed between upper and lower sand bodies, which may be explained by a variation in EOD in a sequence stratigraphic context and regional variable shelfal setting;
- Although the Big Clifty generally contains porosities ranging from 13-21%, variable concentrations of fine-grained material and diagenetic partitioning throughout the reservoir are observed (at least at the periphery of the basin);
- Although gross isopach maps are helpful for realizing regional trends in sandstone belts, this study has shown that variability in fine-grained material occurs in Big Clifty Sandstone along with complexities of multistoried sand bodies, which are crucial considerations in surface mining operations. This

work also has implications for enhanced oil recovery methods such as steam and fire floods or waste water disposal wells; and

- Despite the large estimated OOIP of Big Clifty Asphaltic reservoirs (Bowersox, 2014), recoverable amounts using surface mining and ionic solution processing are far less than anticipated due to complications in processing related to fine-grained material and heterogeneities in the reservoir.

References Cited

Anderton, R., 1985. Clastic facies models and facies analysis: *Geological Society London, Special Publications* 18(1), 31–47.

Baker, R. J., 1980. Geology of the Big Clifty formation in the Wheatonville consolidated oil field in Gibson County. Master's Thesis in Geology, Ball State University, Muncie, IN.

Barnhill, M. L., Zhou, H., 1996. *Corebook of Pennsylvanian rocks in the Illinois Basin*. Illinois Basin Consortium, Illinois Basin Study 3.

Basan, P.B. (ed.), 1977. *Trace Fossil Concepts: SEPM Short Course 5*. Oklahoma City, OK: Society of Economic Paleontologists and Mineralogists, 119-166.

Bowersox, J.R., 2014. Evaluation of western Kentucky's heavy oil and bitumen resources [28 slides]: Lexington, Kentucky, 2014: Eastern Unconventional Oil & Gas Symposium (EUOGS), *www.euogs.org/proceedings/2014/034-bowersox-euogs2014ppt.pdf,* accessed November 3, 2015.

Brown, L.F., 1979. Deltaic Sandstone Facies of the Mid-Continent, In: N.J. Hyne, Pennsylvanian Sandstones of the Mid –Continent. *Tulsa Geological Society Special Publication* 1, p. 35-63.

Buschbach, T.C., Kolata, D.R., 1990. Regional Setting of Illinois Basin. In Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J., (eds.), *Interior Cratonic Basins* American Association of Petroleum Geologists Memoir 51, 29–55.

Coleman, J.M., Prior, D.B., 1982. Deltaic Environments. In Scholle, P.A., Spearing, D.R., (eds.), *Sandstone Depositional Environments*, American Association of Petroleum Geologists Memoir 31, 139-178.

Dalrymple, R.W., Choi, K., 2007. Morphologic and facies trends through the fluvial–marine transition in tide-dominated depositional systems: A schematic framework for environmental and sequence-stratigraphic interpretation, *Earth-Science Reviews* 81(34), 135–174.

Dana, P. L., Scobey, E.H., 1941. Cross Section of Chester of Illinois Basin. *American Association of Petroleum Geologists Bulletin* 25(5), 871–882.

Droste, J.B., Keller, S.J., 1995. Subsurface Stratigraphy and Distribution of Oil Fields of the Stephensport Group (Mississippian) in Indiana. *Indiana Geological Survey Bulletin* 64.

Dunham, R.J., 1962. Classification of Carbonate Rocks According to Depositional Textures. In Ham, W.E., (ed.), Classification of Carbonate Rocks. *American Association of Petroleum Geologists Memoir* 1, 108-121.

Embry, A.F., 2009. *Practical Sequence Stratigraphy*. Calgary, Canada: Canadian Society of Petroleum Geologists. Available online at www.cspg.org.

Groves, K., Hastings L., 1983. The Tarco Process: For the Surface Extraction of Tar Sands. Symposium 3 on Synthetic Fuels From Oil Shale And Tar Sands. Louisville, Kentucky: Institute of Gas Technology, 579–595. Available online at: http://ds.heavyoil.utah.edu/dspace/handle/123456789/8533

Gupta, R., Johnson, H.D., 2002. High-resolution Facies Architecture of Heterolithic Tidal Deposits: An Integrated Outcrop and Electrofacies Analysis of a Complex Reservoir. In Lovell, M., Parkinson, N., (eds.), *Geological Applications of Well Logs: AAPG Methods in Exploration No. 13*, 161–184.

Jillson, W.R., 1926. New Oil Pools of Kentucky; an Indexed collection of twelve separate papers on oil and gas, Kentucky's mineral resources, progress of topographic mapping, and Geological survey administration in 1922 and 1923 (1st edn.). Frankfort, KY: Kentucky Geological Survey, Series 6, Volume 59.

KGS (Kentucky Geological Survey), 2015. Oil and gas well records. Lexington, KY: KGS. Available online at: http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp

KGS (Kentucky Geological Survey), 2016. Oil and gas well records. Lexington, KY: KGS. Available online at: http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp

Kolata, D.R., 1990. Illinois Basin Geometry: Interior Cratonic Basins. In Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J., (eds.), *Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51*, 197.

Kolata, D.R., Nelson, W.J., 1990. Basin-forming Mechanisms of the Illinois Basin: Interior Cratonic Basins. In Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J., (eds.), *Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51*, 287–292.

Kvale, E.P, Archer, A.W., 1991. Characteristics of Two, Pennsylvanian-age, semidiurnal tidal deposits in the Illinois Basin, U.S.A. *Canadian Society of Petroleum Geologists Memoir 16*, 179-188.

Leetaru, H. E., 2000. Sequence Stratigraphy of the Aux Vases Sandstone: A Major Oil Producer in the Illinois Basin: *American Association of Petroleum Geologists Bulletin* 84(3), 399–422.

MacEachern, J.A., Bann K.L., Pemberton, S.G., Gingras, M.K., 2007. The Ichnofacies Paradigm: High-Resolution Paleoenvironmental Interpretation of the Rock Record. In MacEachern, J.A., Bann K.L., Gingras, M.K., Pemberton, S.G., (eds.), *Applied Ichnology: SEPM Short Course Notes No. 52*. Tulsa, OK: SEPM (Society for Sedimentary Geology), 27-64.

May, M.T., 2013. Oil-saturated Mississippian–Pennsylvanian Sandstones of South-central Kentucky. In Hein, F.J., Leckie, D., Larter, S., Suter, J.R., (eds.), Heavy-oil and oil-sand petroleum systems in Alberta and beyond. *American Association of Petroleum Geologists Studies in Geology* 64, 373–405.

May, M.T., Butler, K., 2014. *Diagenetic Partitioning in Near-surface Unconventional Oil Trends in South Central Kentucky*. Paper presented at the Eastern Unconventional Oil and Gas Symposium, Lexington, KY, November 5-7, Abstract 35.

May, M.T., Brackman, T.B., 2014. Geophysical characterization of karst landscapes in Kentucky as modern analogs for paleokarst reservoirs. *Interpretation* 2(3), 51-63.

May, M.T., Kuehn, K.W., 2009. Renewed interest in heavy oils and rock asphalt in South Central Kentucky. *World Oil* 230(8), 65–69.

Maynard, J.R., Feldman, H.R., and Always, R., 2010. From Bars to Valleys: The Sedimentology and Seismic Geomorphology of Fluvial to Estuarine Incised-Valley Fills of the Grand Rapids Formation (Lower Cretaceous), Iron River Field, Alberta, Canada. *Journal of Sedimentary Research* 80(7), 611–638.

McGrain, P., 1976. Tar Sands (rock asphalt) of Kentucky: A Review. *Kentucky Geological Survey Report of Investigations 19*, Series 10, 1-16.

McGrain, P., Sutton, D.G., 1973. *Economic Geology of Warren County, Kentucky*. Lexington, KY: Kentucky Geological Survey, series 10, County report 6.

Nelson, W.J., 1990. Structural Styles of the Illinois Basin: Interior Cratonic Basins. In Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J., (eds.), *Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51*, 209-243.

Nelson, W.J., Smith, L.B., Treworgy, J.D., 2002. *Sequence stratigraphy of the lower Chesterian (Mississippian) strata of the Illinois Basin*. Springfield, IL: Illinois Geological Survey Bulletin 107.

Noger, M.C., 1987. Tar-Sand Exploration in Kentucky. In Meyer, R.F., (ed.), Exploration for heavy crude oil and natural bitumen. *American Association of Petroleum Geologists Studies in Geology* 25, 521–536.

Norwood, C.J., 1876. *Report on the Geology of the region adjacent to the Louisville Paducah, and Southwestern Railroad to the Ohio River*. Lexington, KY: Kentucky Geological Survey Report of Progress, new series, 4, 357-448.

Pashin, J.C., 1993. Tectonics, paleoceanography, and paleoclimate of the Kaskaskia sequence in the Black Warrior basin of Alabama. In Pashin, J.C., (ed.), *New Perspectives on the Mississippian System of Alabama.* Alabama Geological Society 30th Annual Field Trip Guidebook, 1-28.

Porębski, S.J., Steel, R.J., 2006. Deltas and Sea-Level Change. *Journal of Sedimentary Research* 76(3), 390–403.

Potter, P.E., 1962. *Late Mississippian sandstones of Illinois*. Springfield, IL: Illinois State Geological Survey Circular 340.

Potter, P.E., Nosow, E., Smith, N.M., Swann, D.H., Walker, F.H., 1958. Chester Cross-Bedding and Sandstone Trends in Illinois Basin. *American Association of Petroleum Geologists Bulletin* 42(5), 1013–1046.

Pryor, W.A., Lamborg, A.D., Roberts, M.J., Tharp, T.C., Wilsey, W.L.M., 1991. Geologic Controls on Porosity in Mississippian Limestone and Sandstone Reservoirs in the Illinois Basin. In Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J., (eds.), *Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51*, 329–359.

Reynolds, J.M., 2011. *An Introduction to Applied and Environmental Geophysics*. Hoboken, NJ: John Wiley & Sons.

Sable, E.G., 1964. *Geology of the Constantine quadrangle, Kentucky.* Alexandria, VA: USGS Numbered Series, U.S. Geological Survey Geological Quadrangle Map GQ-302.

Sable, E.G., Dever, G.R., 1990. *Mississippian rocks in Kentucky*. Alexandria, VA: U.S. Geological Survey Geological Report 1503.

Sandberg, C.A., Bowles, C.G., 1965. *Geology of the Cub Run quadrangle, Kentucky*. Alexandria, VA: USGS Numbered Series, U.S. Geological Survey Geological Quadrangle Map GQ-386.

Scholle, P.A, 1978. A Color Illustrated Guide to Carbonate Rock Constituents, Textures, Cements, and Porosities. *American Association of Petroleum Geologists Memoir 27*, IV-XIII.

Scholle, P.A., 1979. A color Illustrated Guide to Constituents, Textures, and Porosities of Sandstones and Associated Rocks. *American Association of Petroleum Geologists Memoir 28*, IV-X.

Schwalb, H.R., 1975. *Oil and gas in Butler County, Kentucky*. Lexington, KY: University of Kentucky, Report of Investigations, Kentucky Geological Survey Series X, 16.

Siever, R., 1953. Petrology and Sedimentation of Upper Chester Sandstones. *Journal of Sedimentary Research* 23(4), 207-219.

Sloss, L.L., 1963. Sequences in the Cratonic Interior of North America. *Geological Society of America Bulletin* 74(2), 93–114.

Smith, L.B., Read, J.F., 2001. Discrimination of Local and Global Effects on Upper Mississippian Stratigraphy, Illinois Basin, U.S.A. *Journal of Sedimentary Research* 71(6), 985–1002.

Specht, T.H., 1985. *Subsurface study of the Big Clifty Formation in southwestern Indiana*. M.S. Thesis in Geology, Indiana University, Bloomington, IN.

Stapor F.W., Cleaves, A.W., 1992. Mississippian (Chesterian) sequence stratigraphy in the Black Warrior basin: Pride Mountain Formation (lowstand wedge) and Hartselle Sandstone (transgressive systems tract). *Gulf Coast Association of Geological Societies Transactions* 42, 683-696.

Swann, D.H., 1964. Late Mississippian rhythmic sediments of Mississippi valley. *American Association of Petroleum Geologists Bulletin* 48(5), 637–658.

Swezey, C., 2009. *Regional Stratigraphy and Petroleum Systems of the Illinois Basin, U.S.A*. Alexandria, VA: U.S. Geological Survey Scientific Investigations Map 3068, 1 sheet. (Also available at http://pubs.usgs.gov/sim/3068/.)

Thomas, W.A., Mack, G.A., 1982. Paleogeographic relationship of a Mississippian barrier-island and shelf bar system (Hartselle Sandstone) in Alabama to the Appalachian- Ouachita orogenic belt. *Geological Society of America Bulletin* 93, 6-19.

Treworgy, J.D., 1990. Kaskaskia Sequence, Mississippian Valmeyeran and Chesterian Series. In Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J., (eds.), *Interior cratonic basins: American Association of Petroleum Geologists Memoir* 51, 125–142.

Treworgy, J.D., 1988. *The Illinois Basin: a tidally and tectonically influenced ramp during mid-Chesterian time*. Springfield, IL: Illinois Geological Survey Circular 544.

Visher, P.M., 1980. *Sedimentology and three-dimensional facies relations within a tidally-influenced Carboniferous delta: the Big Clifty Formation, Sulfur, Indiana*. M.S. Thesis in Geology, Indiana University, Bloomington, IN.

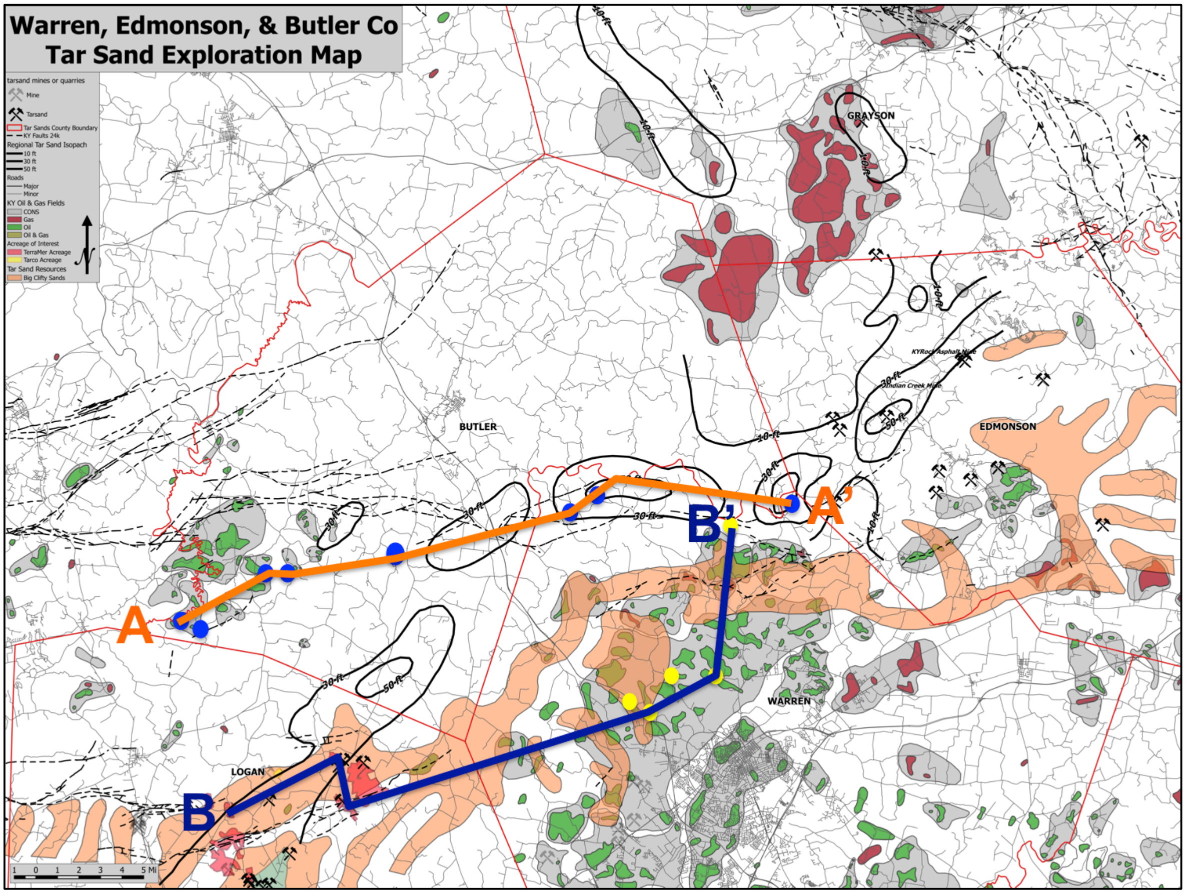
Wagoner, J. C. Posamentier, H.W., Mitchum, R.M., Vail, P.R, Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In Wilgus, C.K., Hastings, B.S., Kendall, C.G. St C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C., (eds.), *Sea-level changes: An Integrated Approach*. SEPM Special Publications 42, 39–45.

Webb, N.D., Grigsby, N.P., 2015. *Geological characterization and modeling of the Cypress Sandstone at Noble Field, southeastern Illinois*. Paper presented at the Eastern Section AAPG Meeting, Indianapolis, IN, September 21,

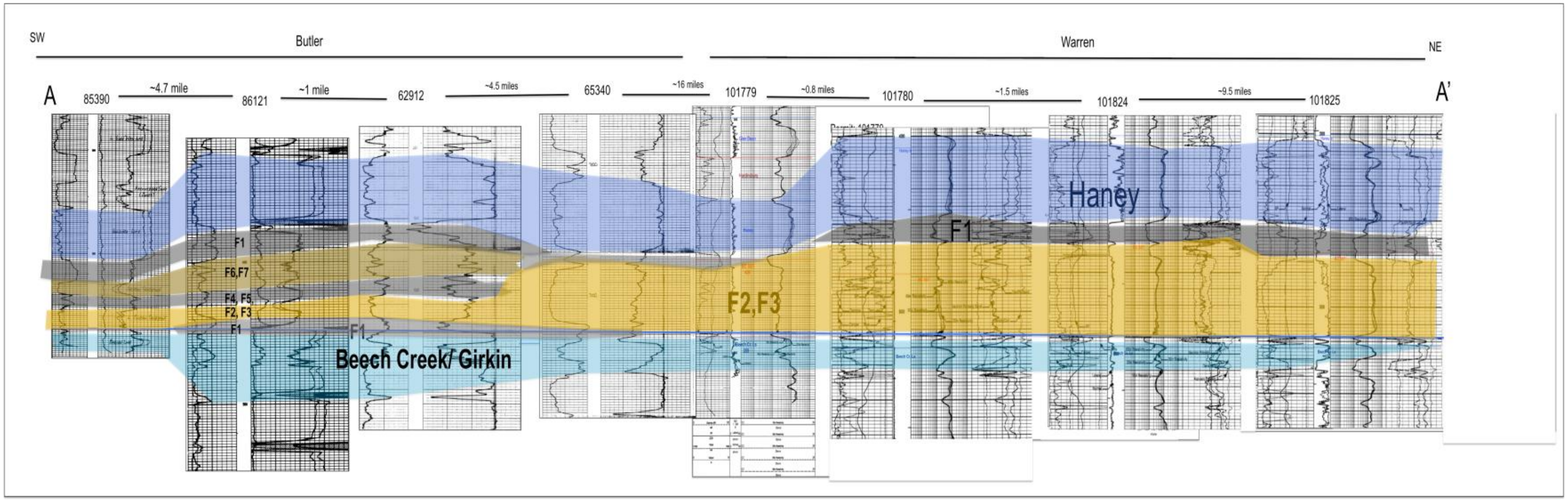
Williams, D.A., Noger, M.C., Gooding, P.J., 1982. *Investigation of subsurface tar-sand deposits in Western Kentucky: a preliminary study of the Big Clifty Sandstone Member of the Golconda Formation (Mississippian) in Butler County and parts of Edmonson, Grayson, Logan, and Warren Counties*. Lexington, KY: Kentucky Geological Survey, Series 11, Information Circular 7.

Wright, L.D., Coleman, J.M., 1975, Sediment transport and deposition in a macrotidal river channel, Orb River, Western Australia. In Cronin, L.E., (ed.), *Estuarine Research,* Vol. 2. New York: Academic Press, 309-322.

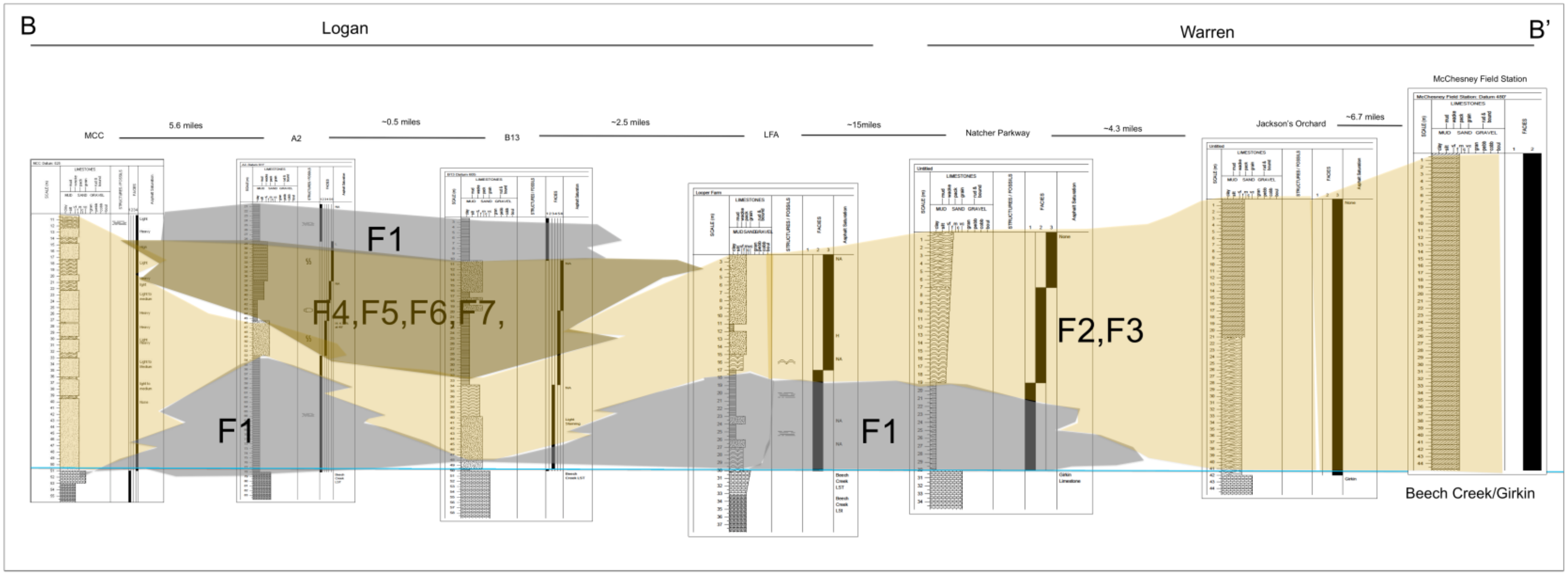
Appendix I: Cross Sections with index maps



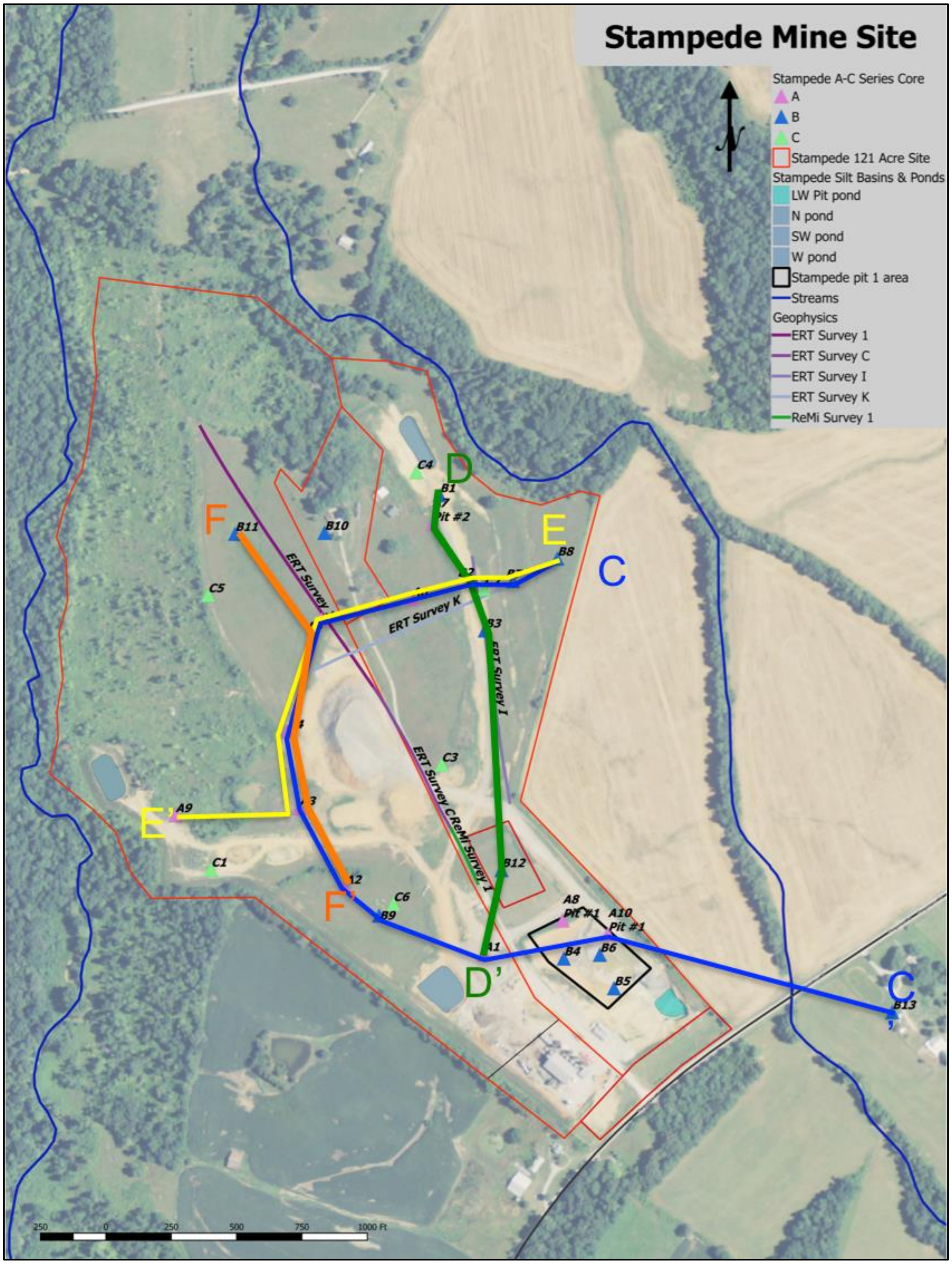
Index map for cross section A and B. Map constructed by Andrew Reeder and modified by the author with permission.



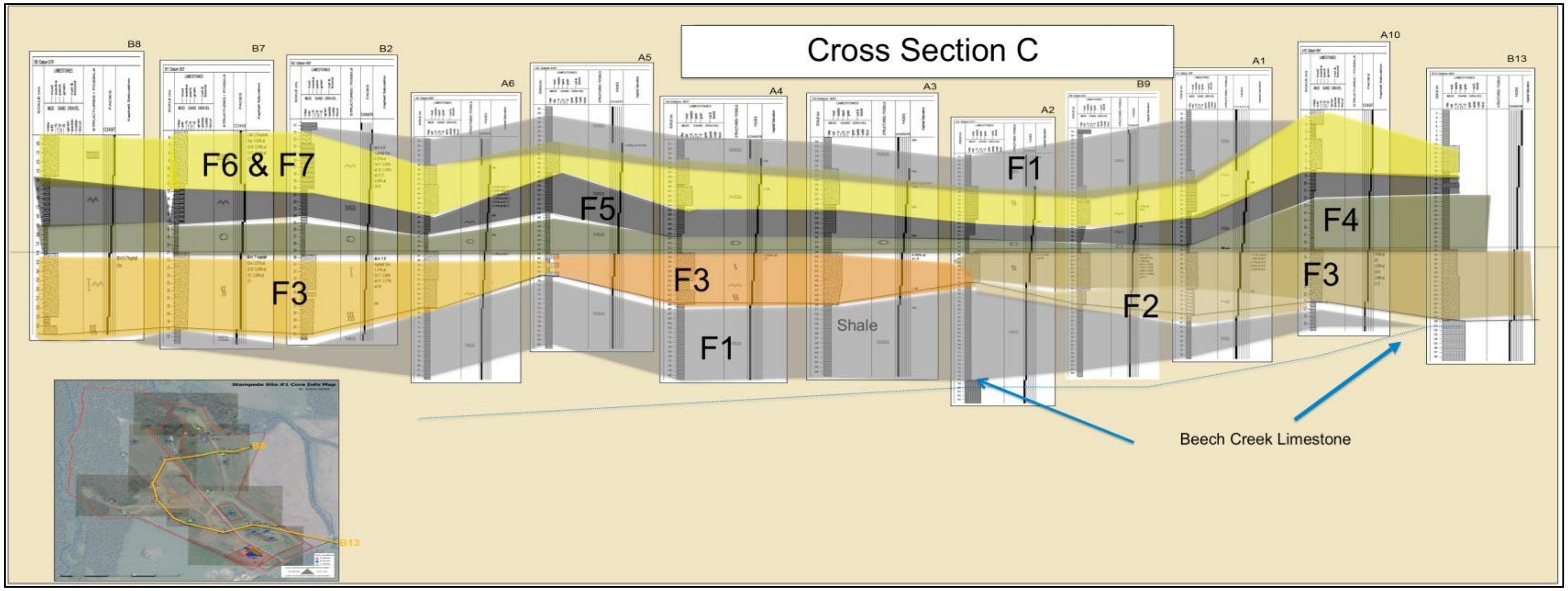
Stratigraphic cross section A flattened on the top of the Beech Creek runs from near Warren County, near the borders of Edmonson and Butler Counties, to southwestern Butler County. Note that along the cross section the Big Clifty Sandstone transitions from entirely sandstone to two sandstone units with a mudstone to shale interburden. Distances between core locations are shown in cross section. Source: Well logs were accessed from the KGS online data repository (kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp). Author constructed cross section.



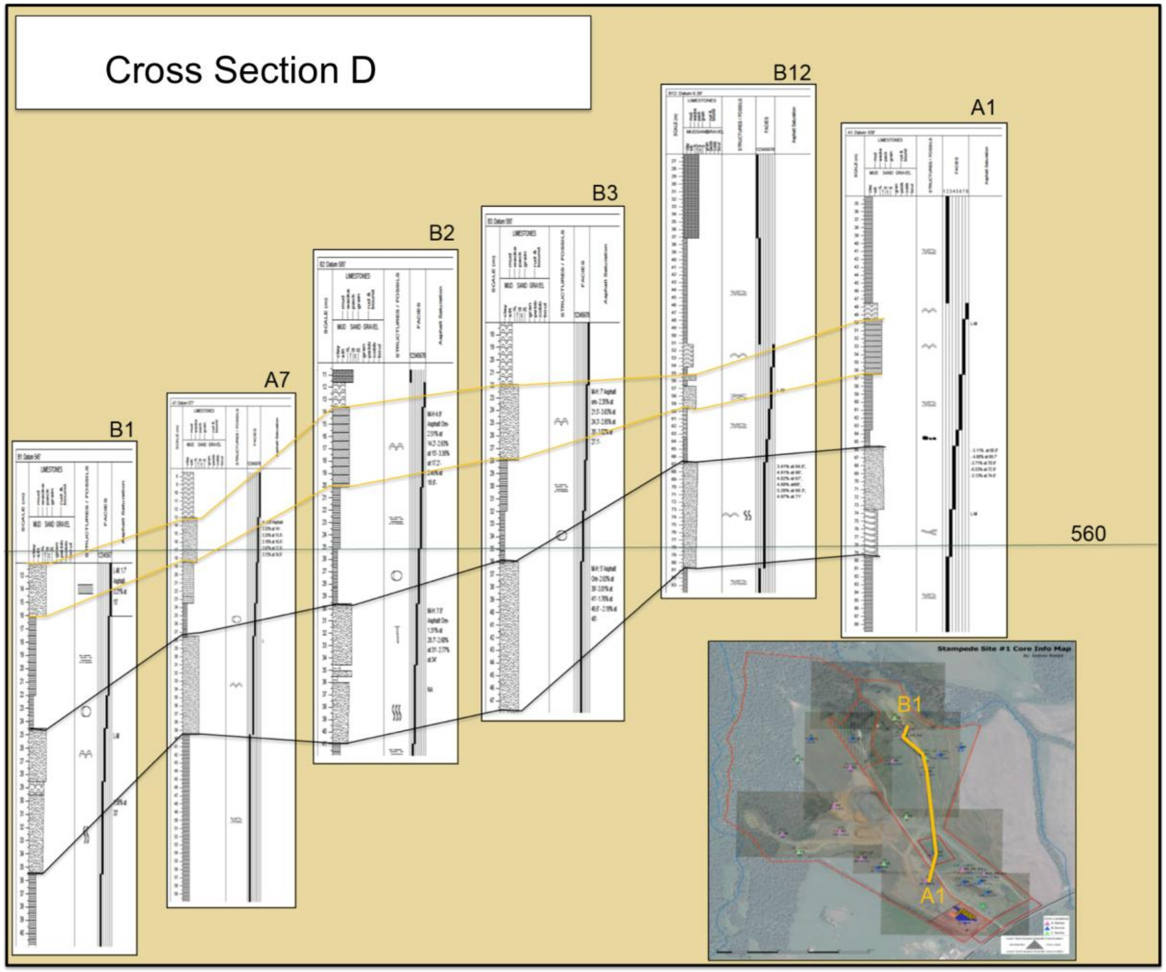
Stratigraphic cross Section B flattened on the top of the Beech Creek covers the outcrop belt of Warren County into the study area in Logan County. Note the transition from a single sandstone unit to two sandstone units separated by mudstone interburden, also observed in the subsurface (cross section A). Source: Author



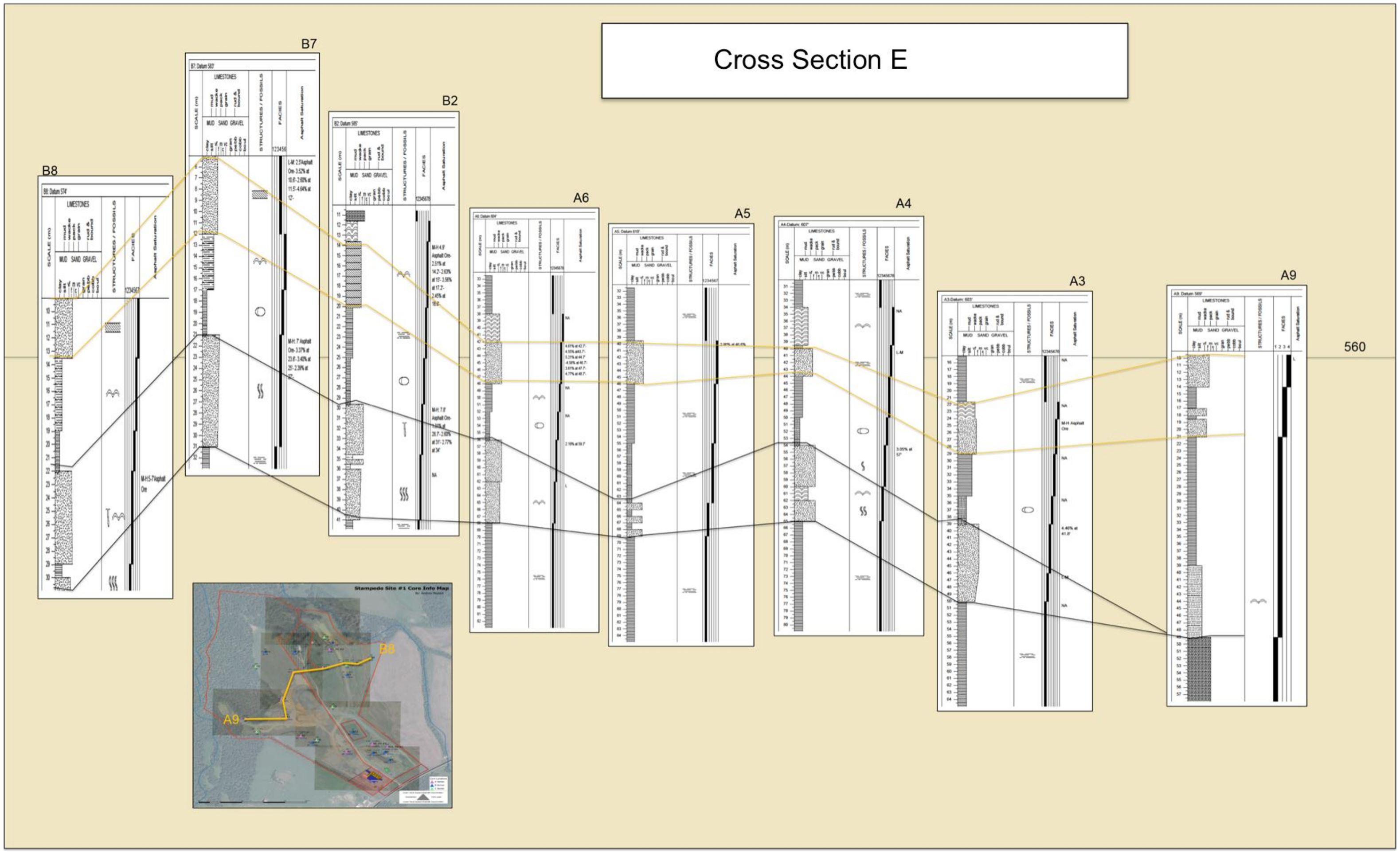
Index map for cross sections C, D, E, and F at the Stampede Mine. Source: Map constructed by Andrew Reeder and modified with permission.



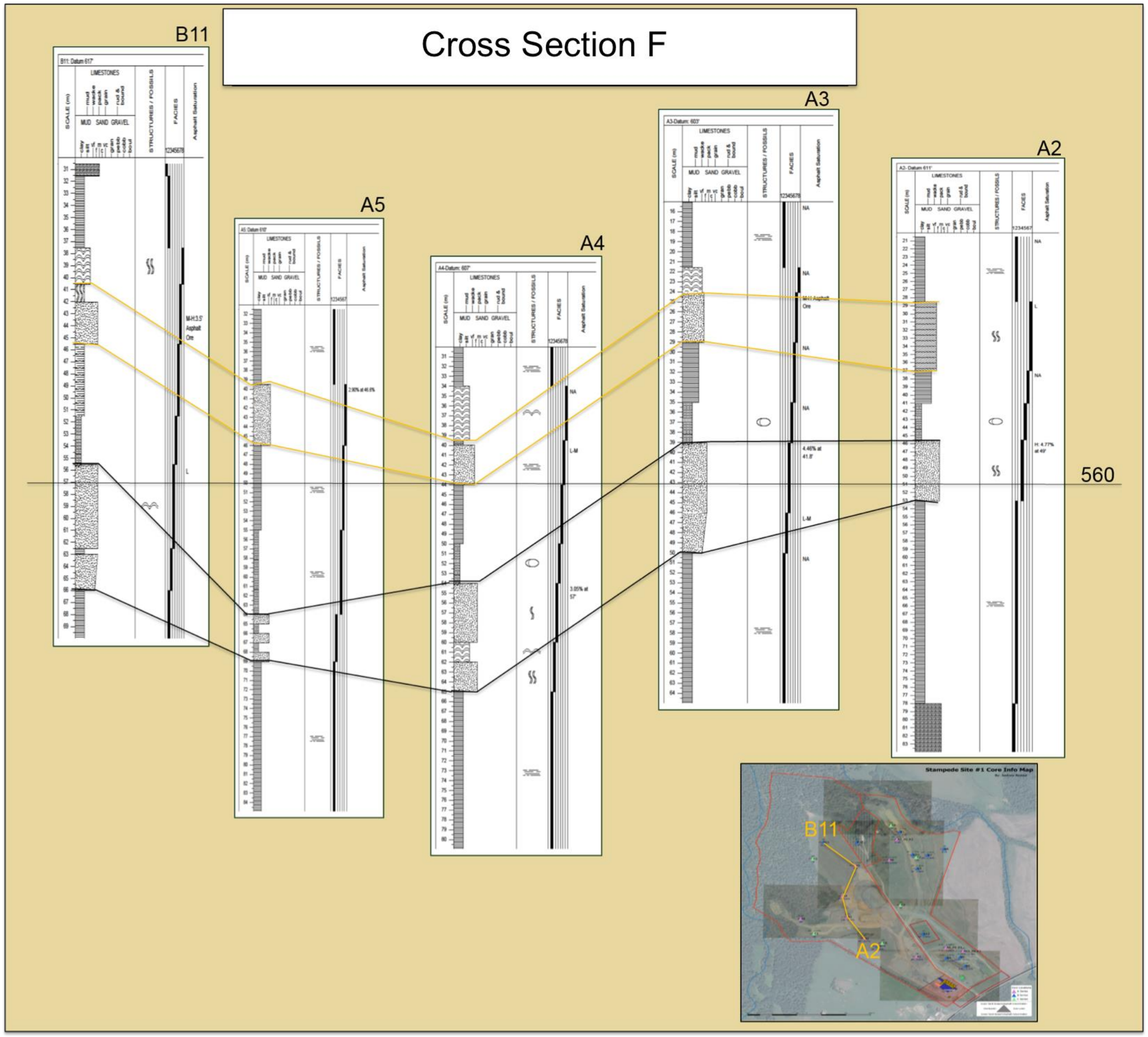
Stratigraphic cross section C flattened in the top of facies 3 runs across the Stampede Mine from core B13 to Core B8. Note the thinning of facies 3 in core A5, and facies 1 is completely absent in core B13. Source: Author



Structural cross section D hung on 560' elevation shows that the Big Clifty Sandstone section dips to the north from A1 to B1. Source: Author

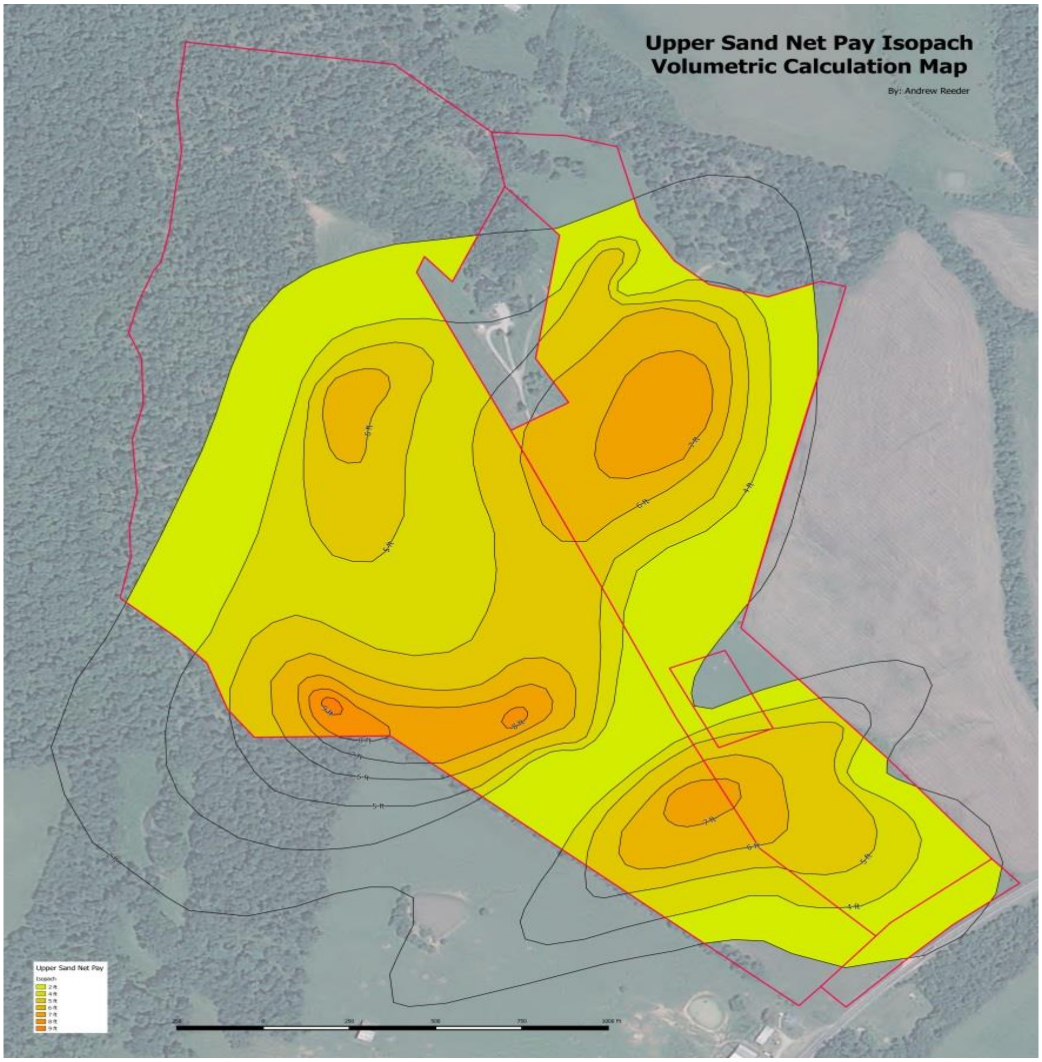


Structural cross section E hung on 560' elevation runs east west across the mine site. Note that facies 3 is completely absent in core A9. Only a few core from the Stampede Mine penetrated the Beech Creek. In future coring operations completely coring the interval until hitting limestone is recommended such that accurate structural information may be calculated. Source: Author

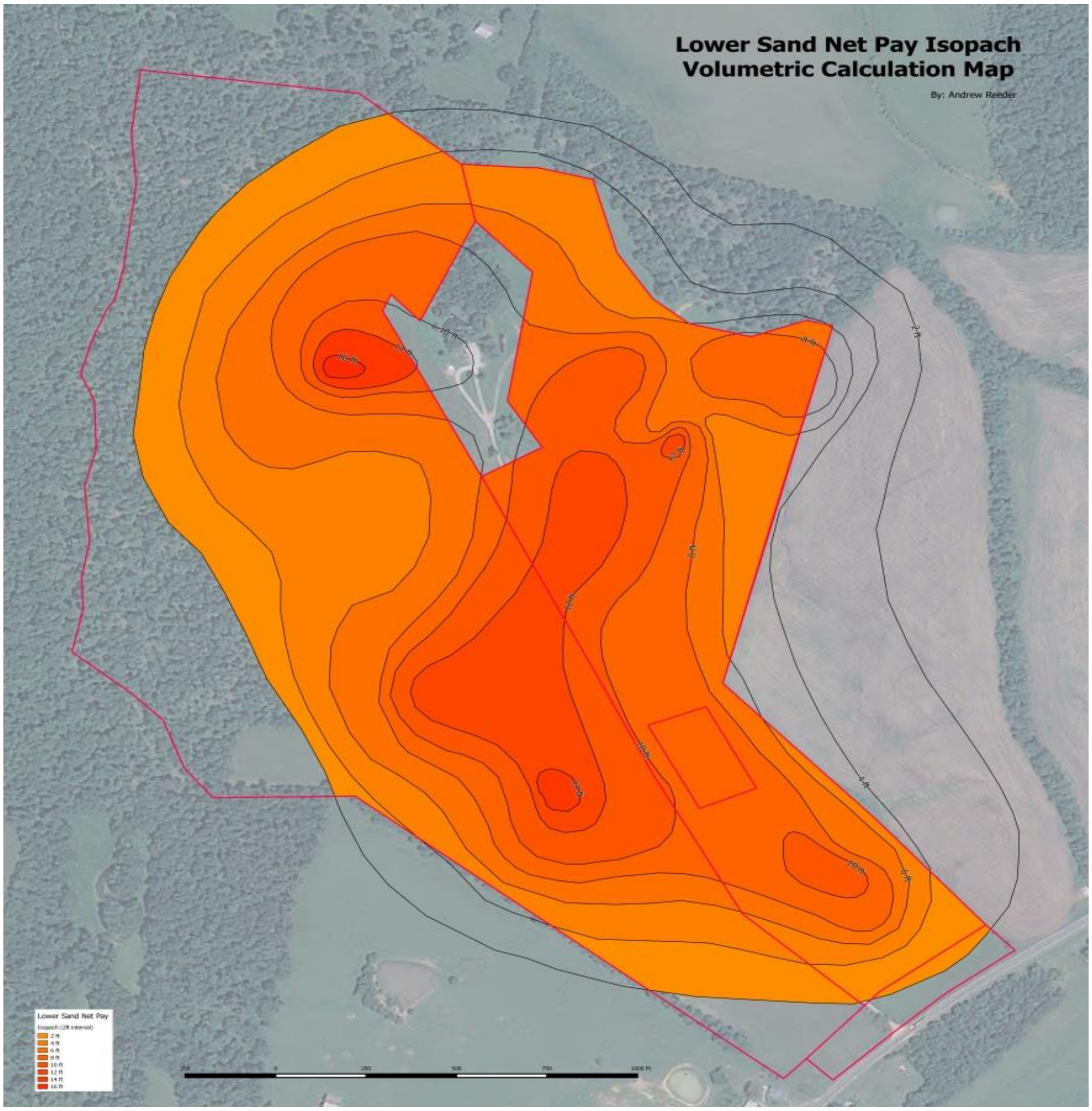


Structural cross section hung on 560’ elevation moving south to north across the mine site. Note the thinning of facies 3 in core A5. Source: Author

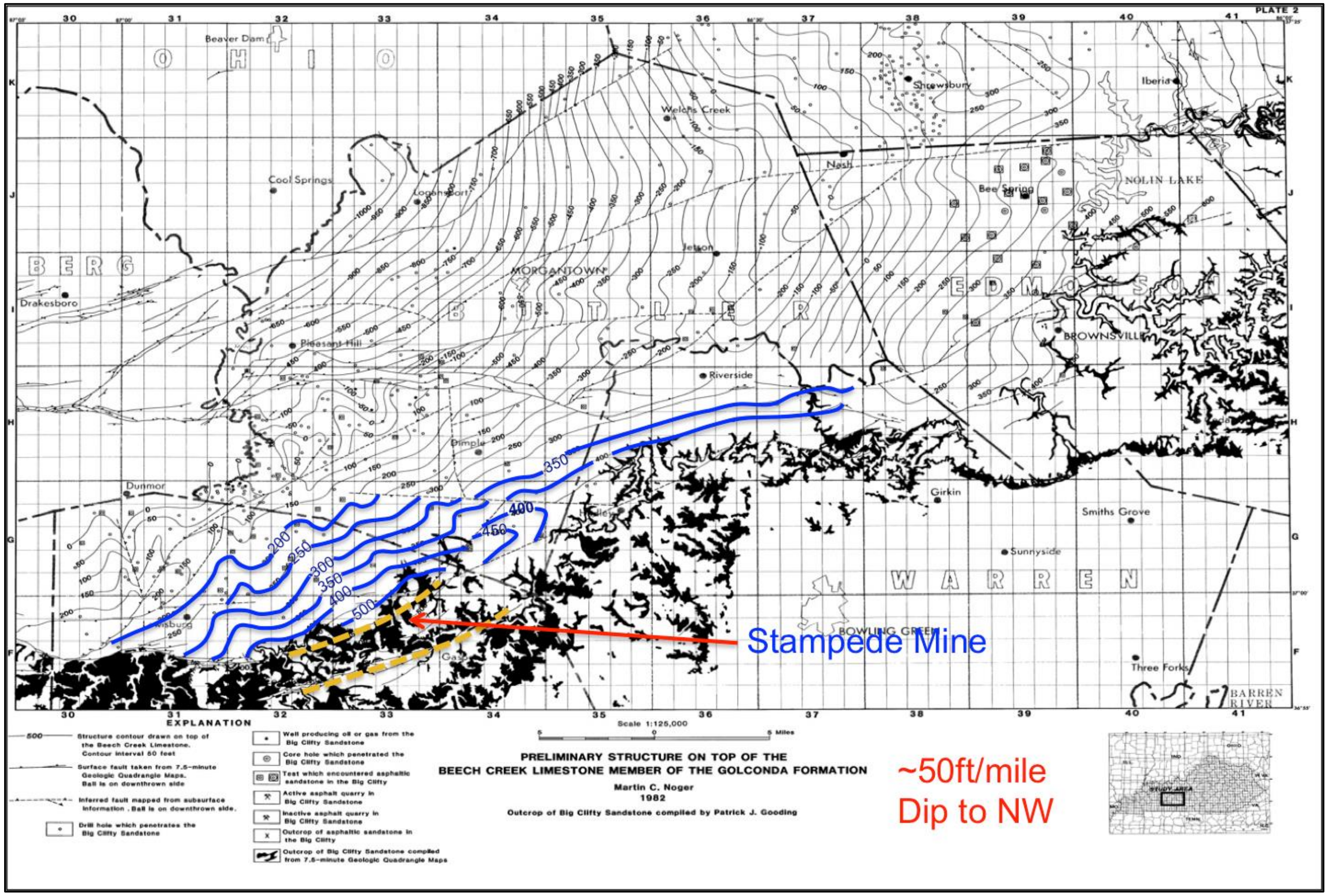
Appendix II: Additional Maps



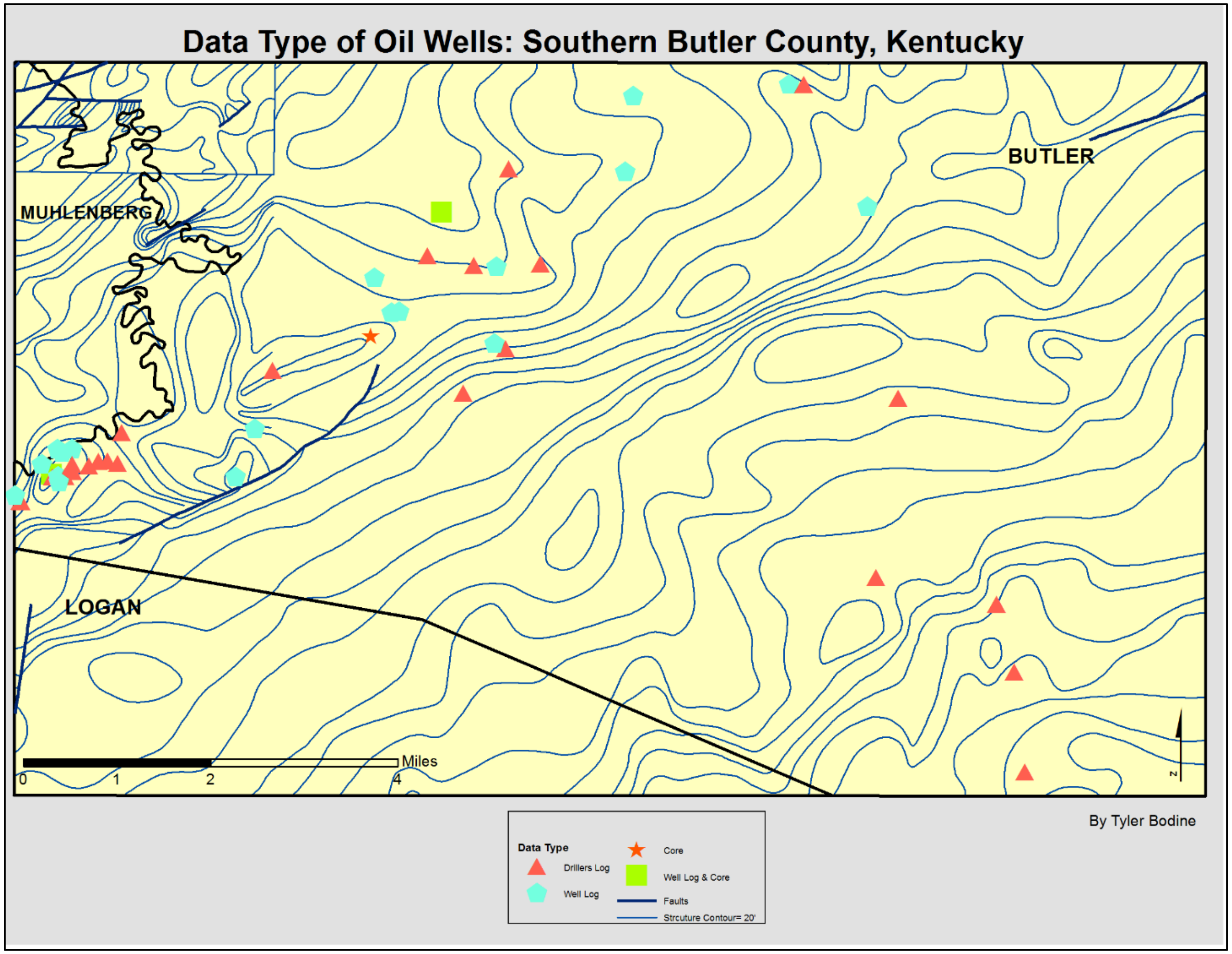
Map showing upper sand Net Pay. Cutoffs were determined through semi-qualitative and quantitative factors including bitumen concentration and physical appearance. Map was made by Andrew Reader with data from this study and used by author with permission.



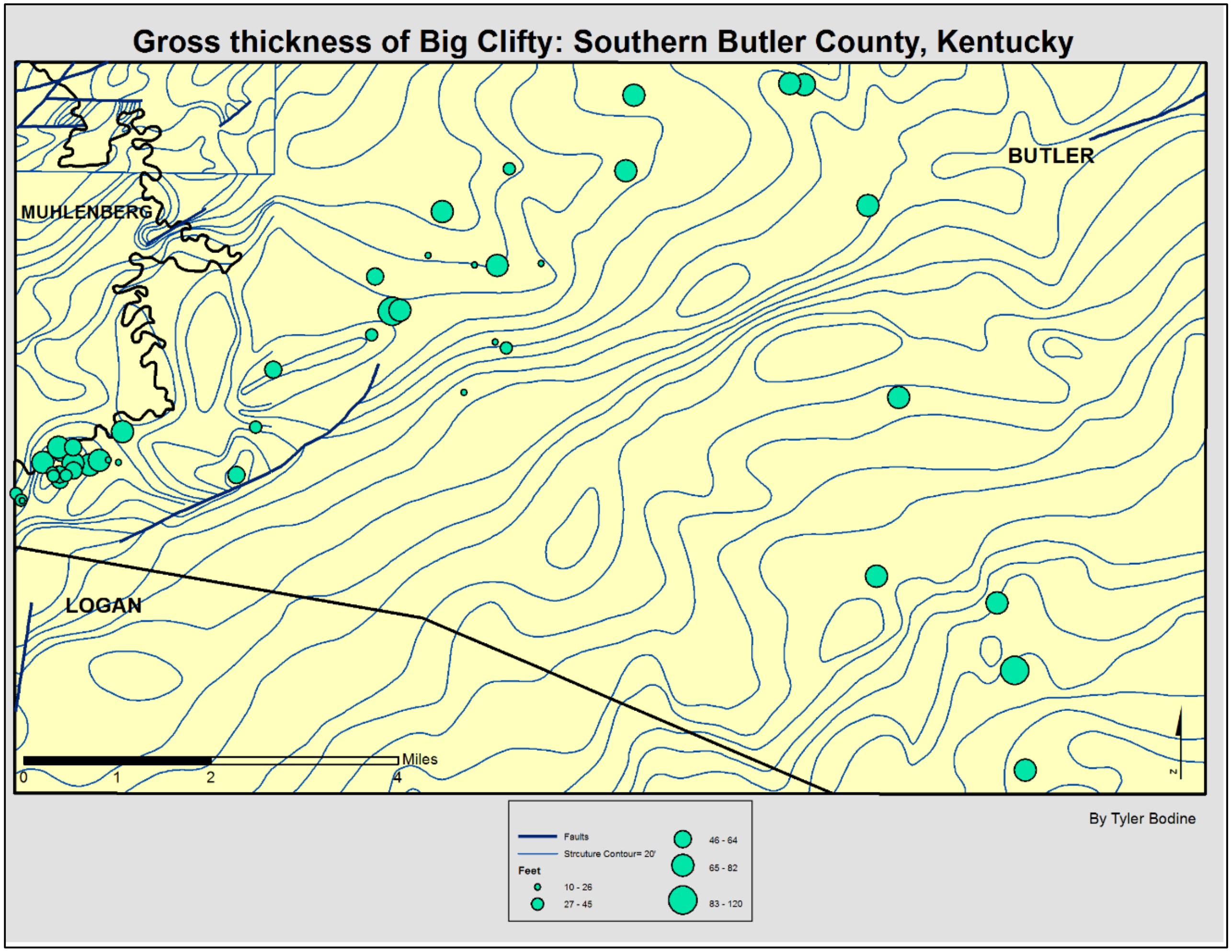
Net Pay cut off isopach for the lower sandstone at the Stampede Mine. Map was made by Andrew Reader with data from this study and used by author with permission.



Structure map on the top of the Beech Creek Limestone from Williams et al. (1982). Asphalt-rock play is shown with gold-dashed lines. Regional dip of 50' per mile was also calculated in this study. Source: Modified from Williams et al., 1982

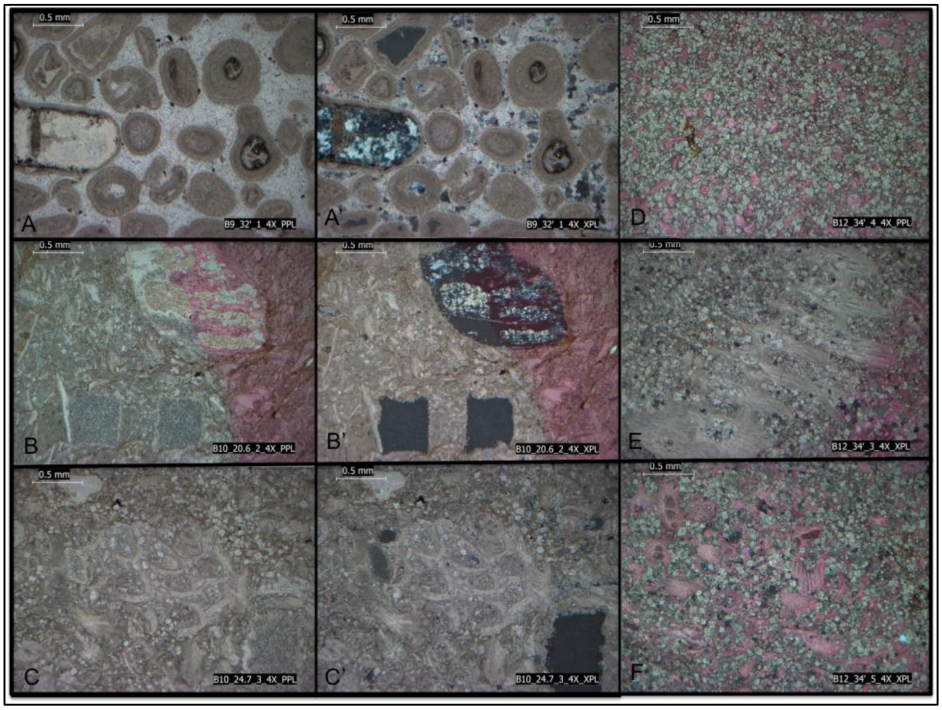


Map showing wells with types of data utilized in study of Big Clifty in subsurface of Butler County, Kentucky. Wells with geophysical logs are shown with blue circles. Source: Map constructed by author with data from the KGS online data repository (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

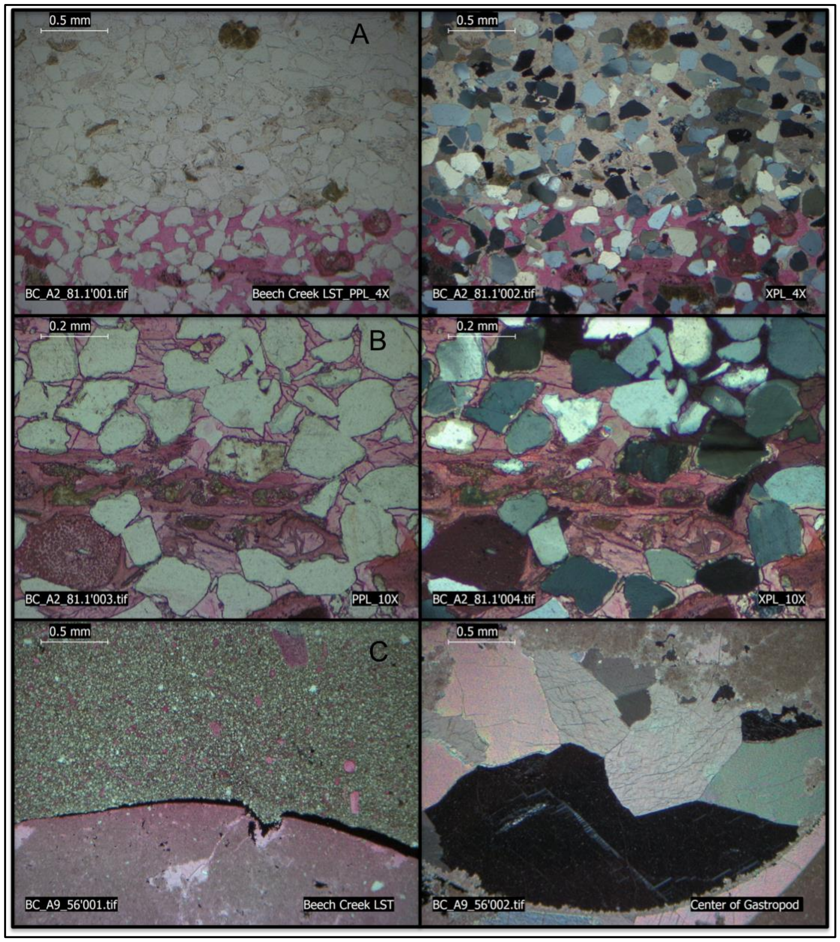


Map of gross thickness values of the Big Clifty Sandstone interval in the subsurface of Butler County. Map constructed by author with data from the KGS online data repository (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

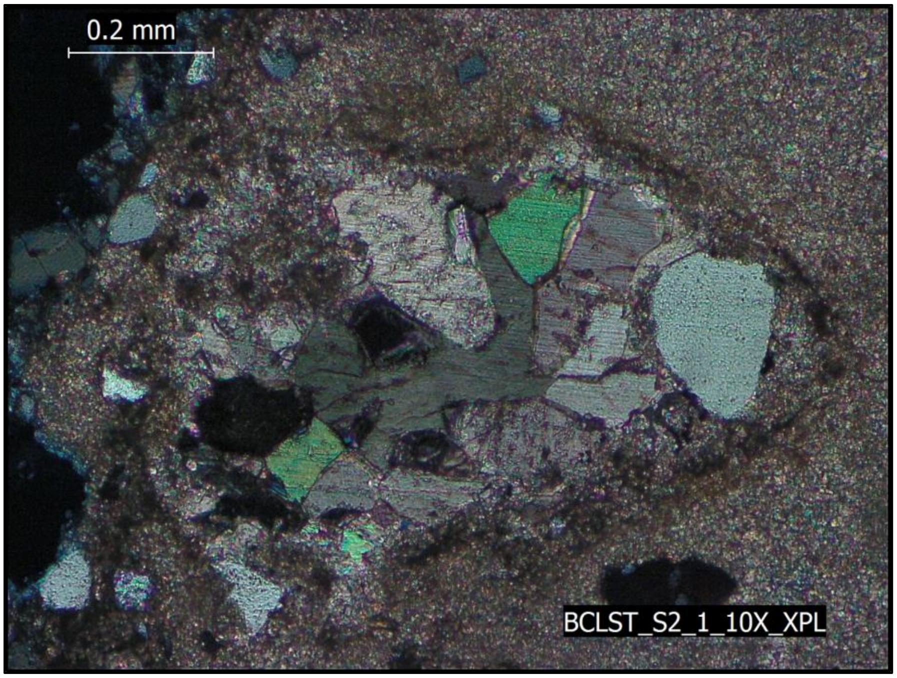
Appendix III: Photomicrographs



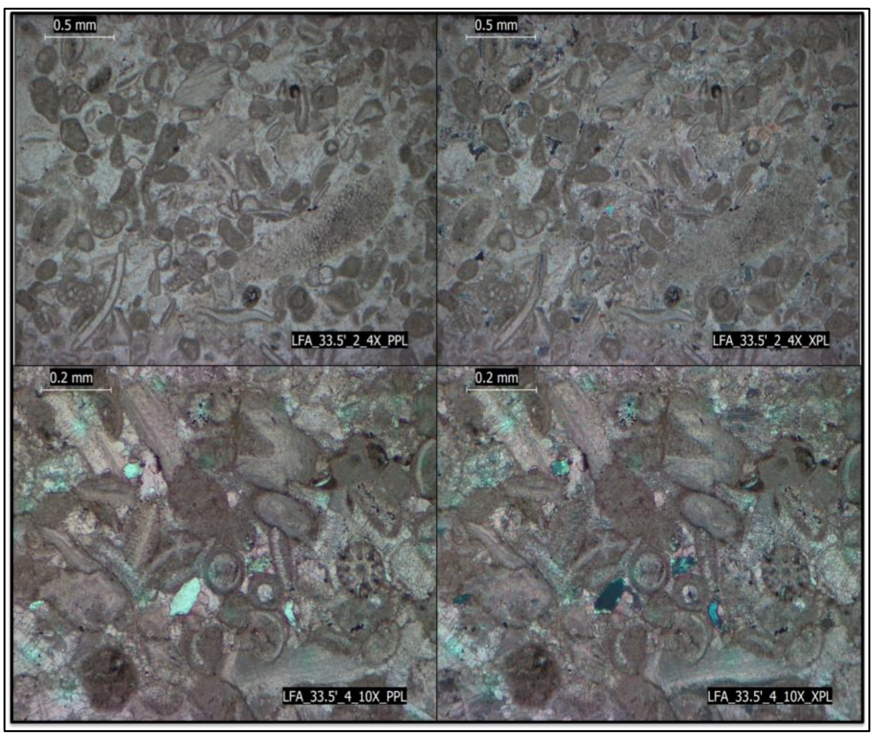
Photomicrograph of the Haney Limestone cored at the Stampede Mine. A, B, C, and D are in plane polarized light, while A', B', C', and E are in cross-polarized light. A and A' show oolites. Note biogenic material in B and C. Thin sections are stained with Alizarin S to identify carbonate. Note sucrosic dolomite in D. Source: Author



Photomicrograph of Beech Creek Limestone encountered in core A2, and A9. Note biogenic material and carbonate cement intermixed with quartz grains (A and B). The left view is in plane polarized light, while the right view is cross-polarized light. C shows the contact between a brachiopod shell and sucrosic dolomite. Source: Author

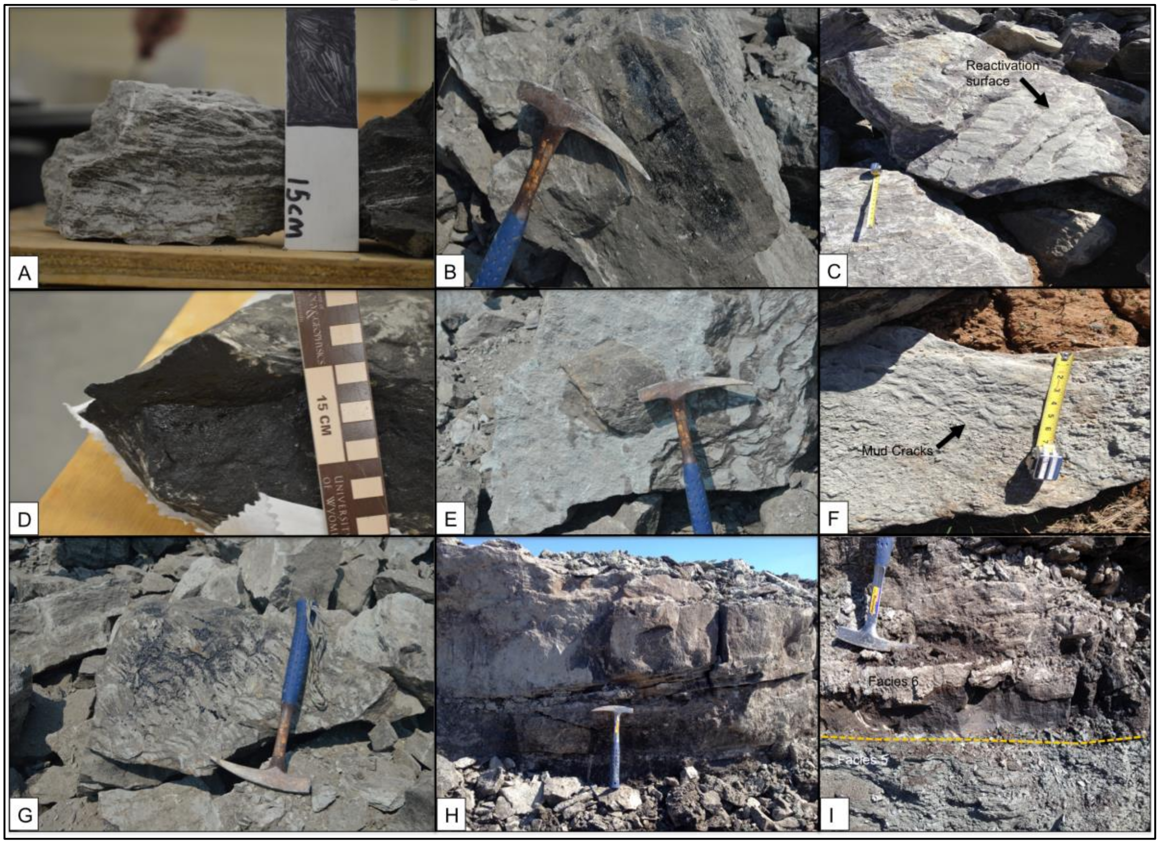


Photomicrograph of quartz grains encrusted with caliche from facies 6 of the Big Clifty Sandstone at the Stampede Mine



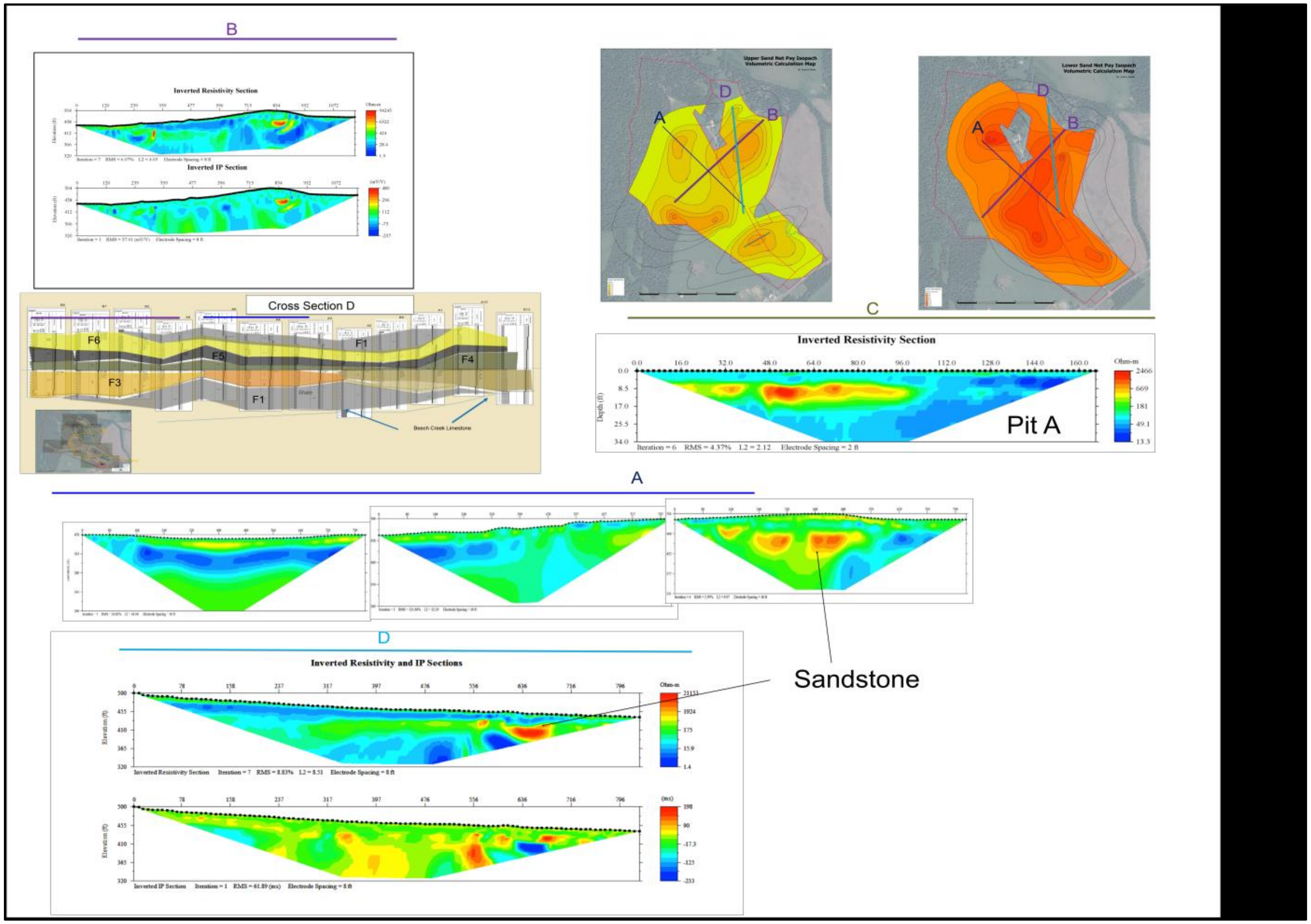
Photomicrograph of limestone encountered at TD of core LFA. Whether this is Beech Creek or Haney Limestone has been contested. It is currently interpreted as Beech Creek Limestone. Understanding limestone facies is important in exploring for Chesterian asphaltic sandstones in the Illinois Basin. Future work could conduct facies analysis on the limestone encountered in this study.

Appendix IV: Photos of "ore"



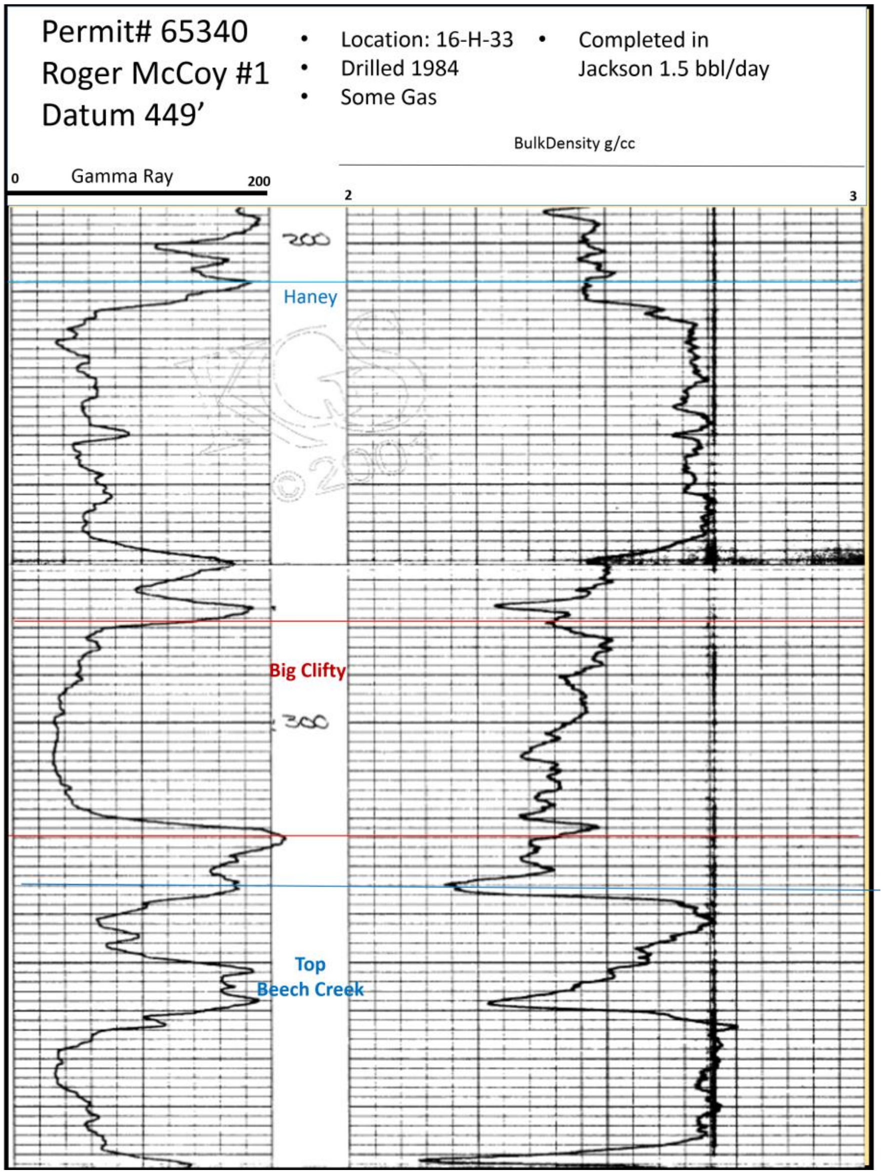
Photos of asphalt rock from Pit A at the Stampede Mine showing the variable concentrations of bitumen (A, B, C, D, E, F, G, H, I). Heavy concentration shown in photo D. Partitioning of "ore" shown by clay sized grains in A, B, C, E, and G. I shows contact between facies 6 and facies 5 in Pit A. Dessication cracks shown in F, and ripple-bedding shown in C. Source: Author

Appendix V: ERT Transects

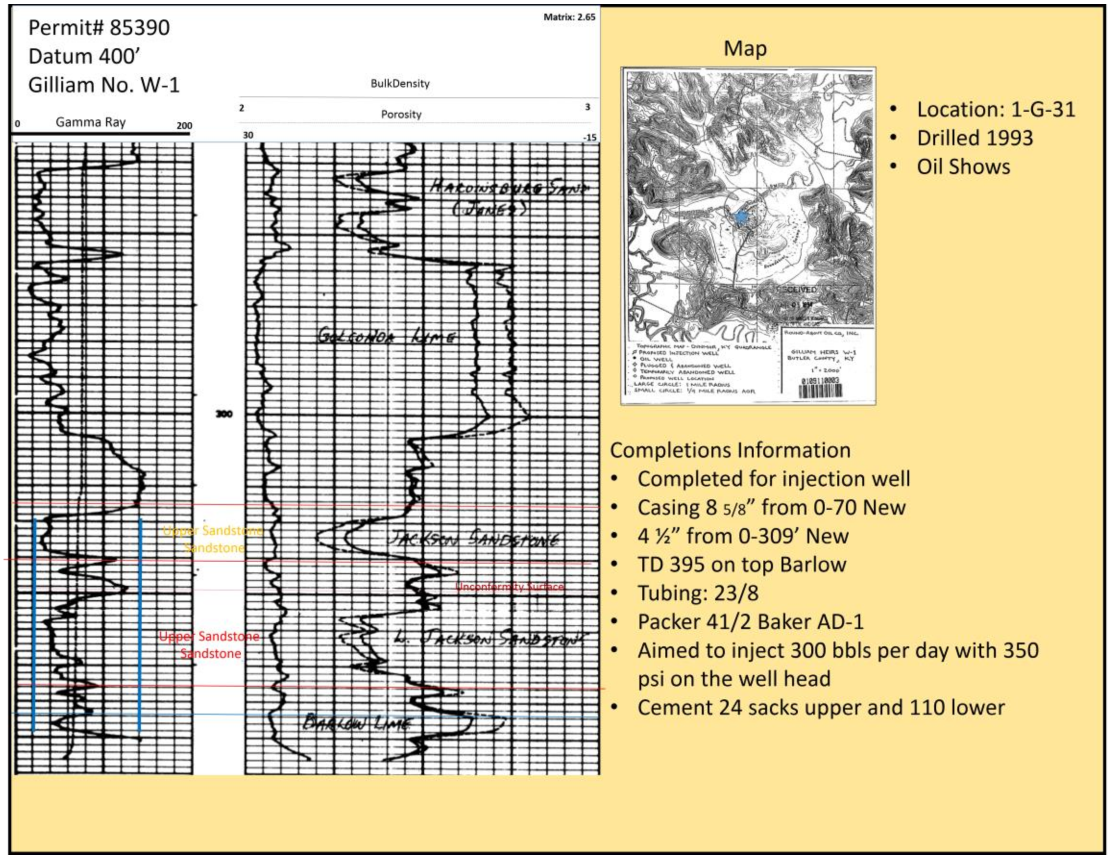


ERT lines from the stampede mine. Note the lenticular geometry of sandstone bodies. Warm colors signify high resistivity, usually related to bitumen concentration. Source: Author and Stampede Mine.

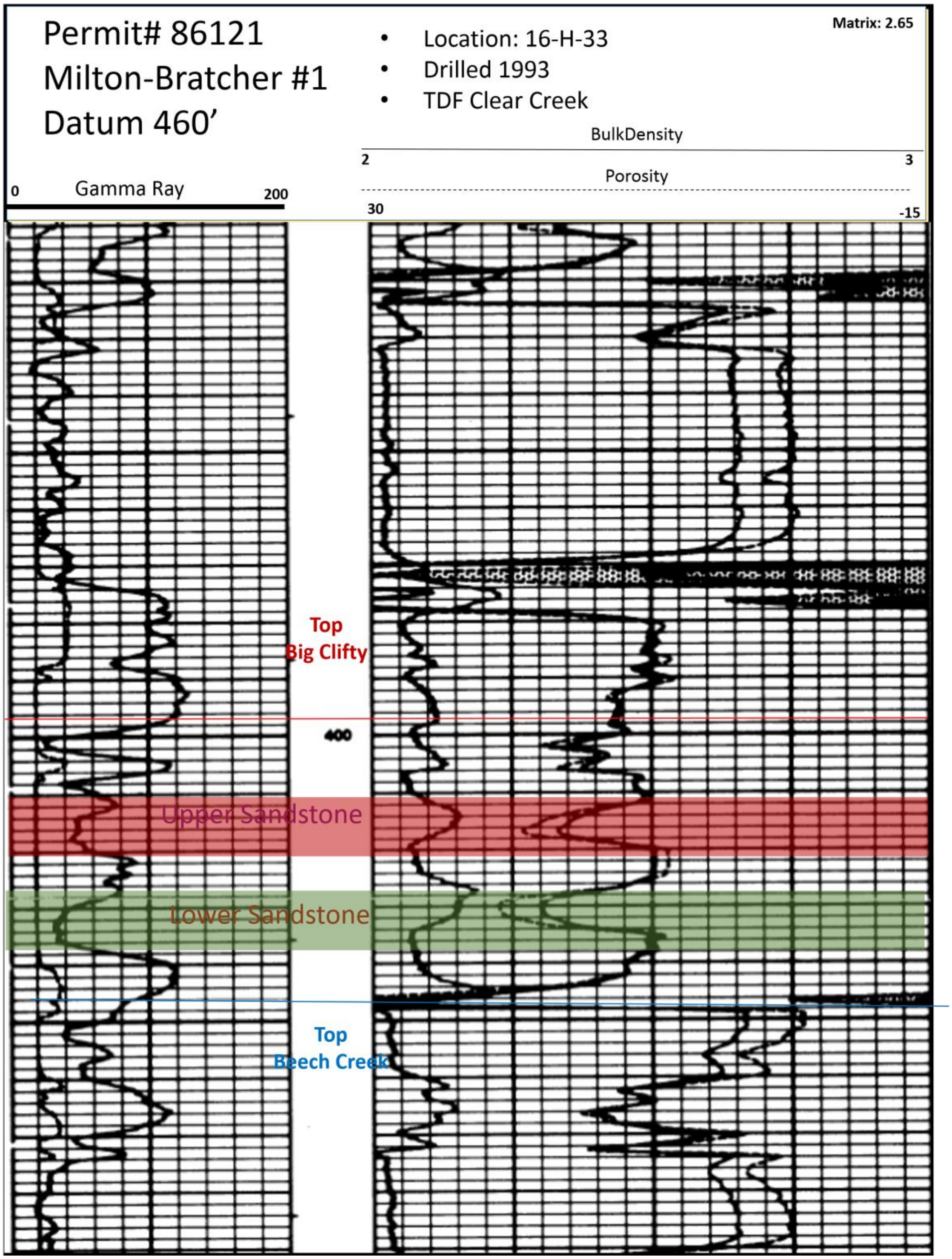
Appendix VI: Geophysical Logs



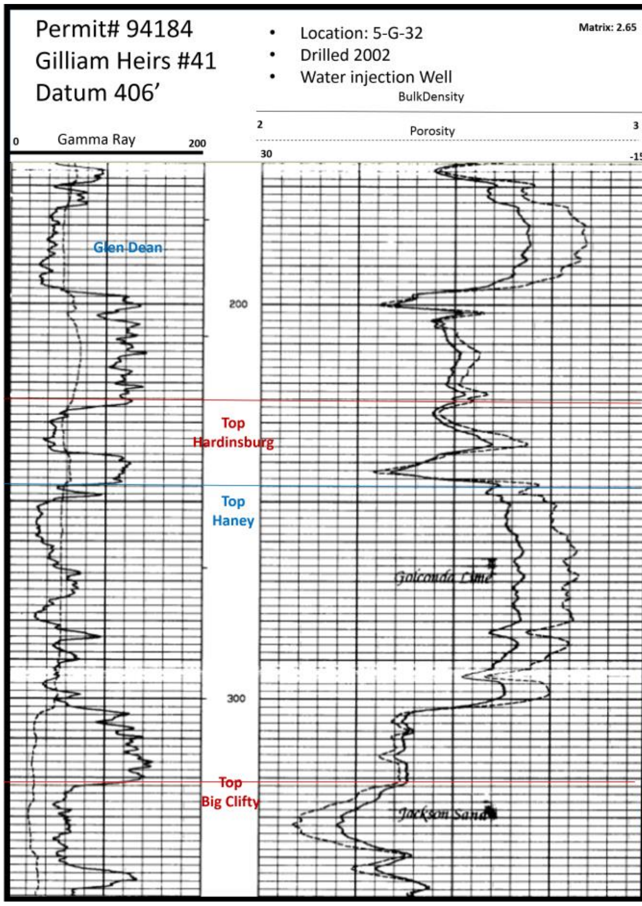
Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)



Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)



Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

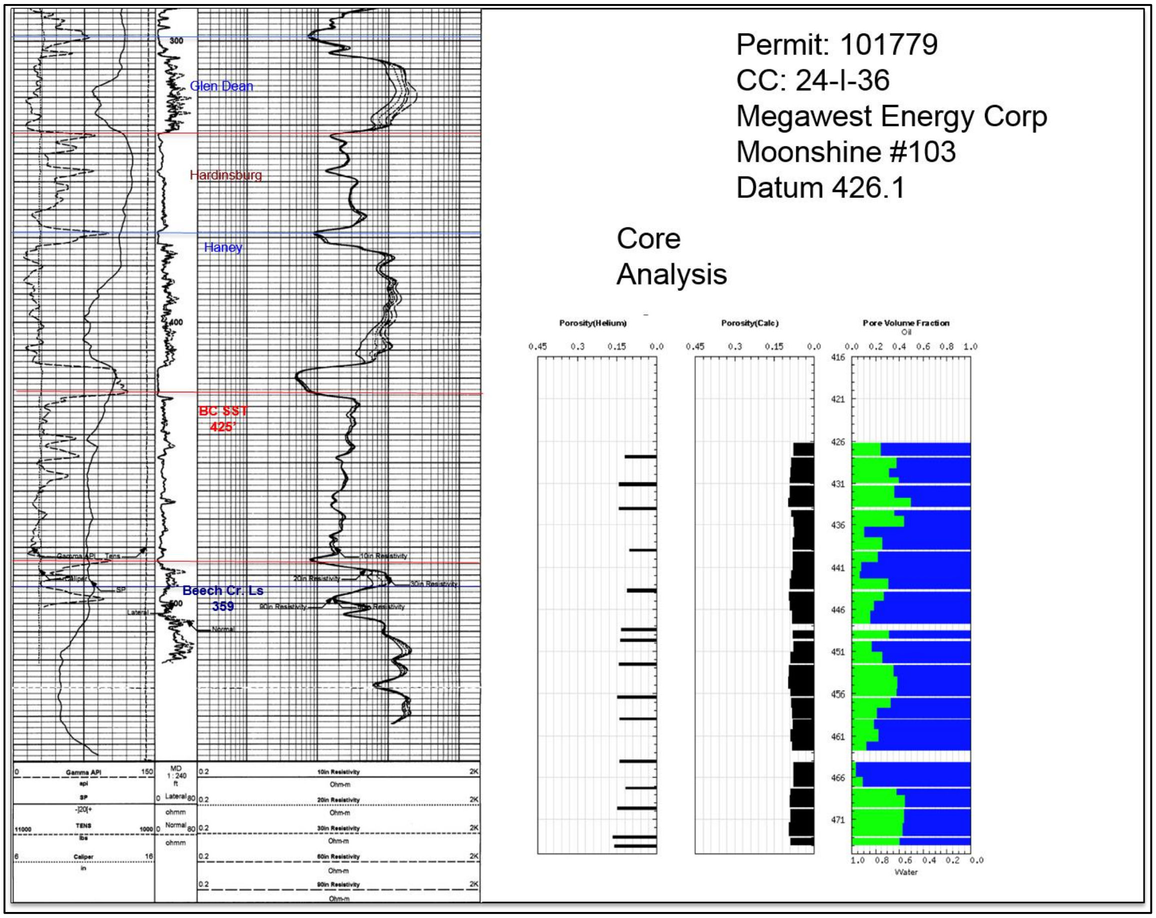


- Missing 21 feet on log- Upper and Lower sand described in drillers Logs
- Completed as water injection well

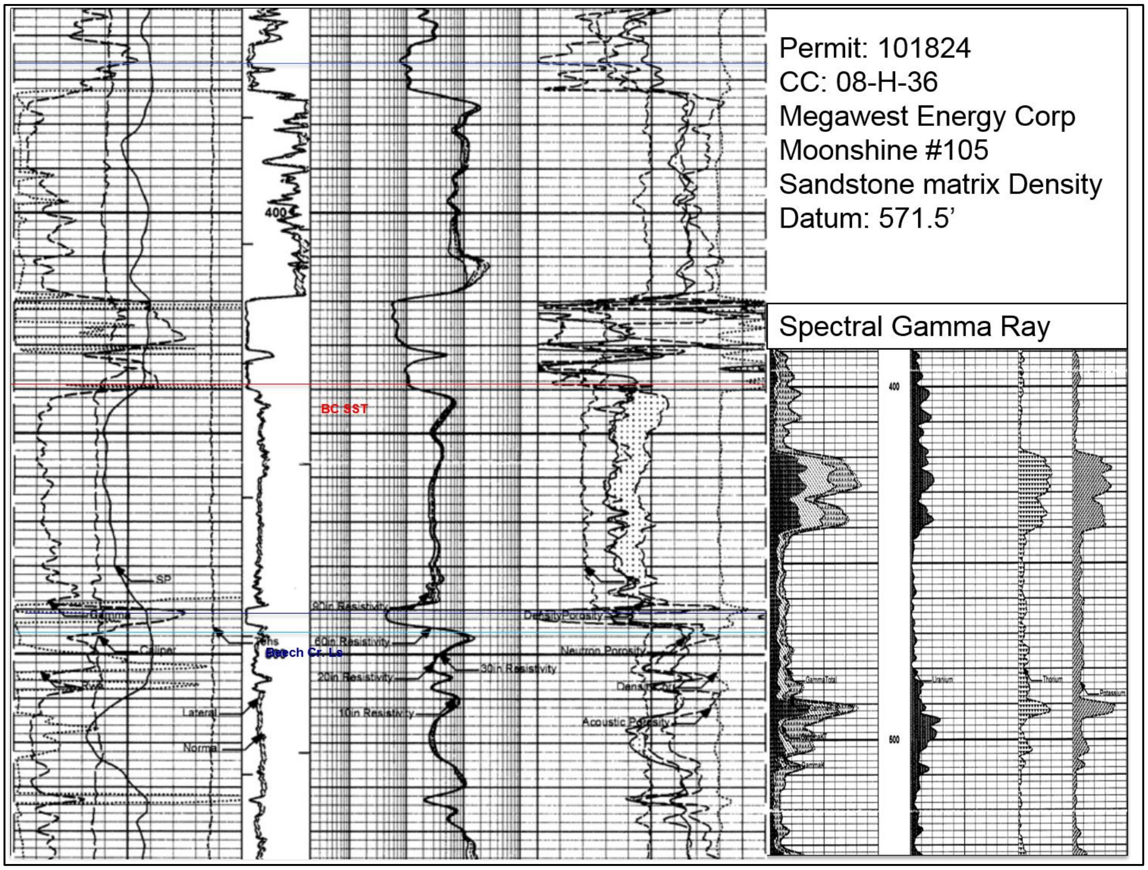
FROM	TO	ROCK TYPE (DESCRIBE ROCK TYPES AND OTHER MATERIALS PENETRATED AND RECORD OCCURRENCES OF OIL, GAS AND WATER FROM SURFACE TO TOTAL DEPTH)
0	12'	Clay
12	20'	Sgale
20	22	Lime
22	30	Shale W/Limy streaks
30	59	Shale
59	72'	Lime (Vienna)
72	79'	Shale
79	86'	Sandy Shale
86	105'	Shale
105	131'	Sand (Tar Springs) s.s.0.
131	140	Shale
140	151'	Lime (Upper Glen Dean)
151	163'	Shale, Limy
163	195'	Lime (Lower Glen Dean)
195	202'	Shale
202	208'	Lime
208	227'	Red Rock and Shale
227	246'	Sand (Hardingburg) s.o.
246	305'	Lime (Golconda)
305	323'	Shale
323	344'	Sand (Upper Jackson) s.o.
344	350'	Sh,ale Sandy
350	357'	Sand (lower Jackson)
357	366'	Sand Water
366	371'	Shale
371'	TD	Top of lime

Missing

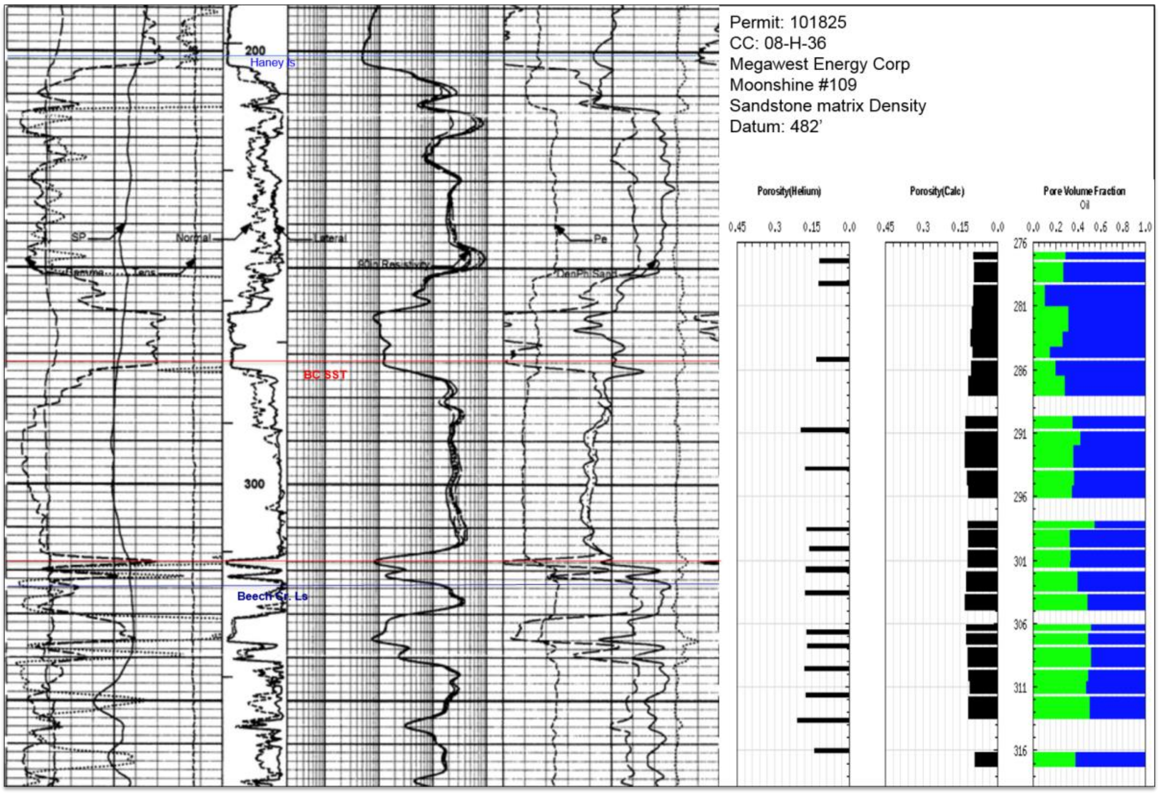
Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)



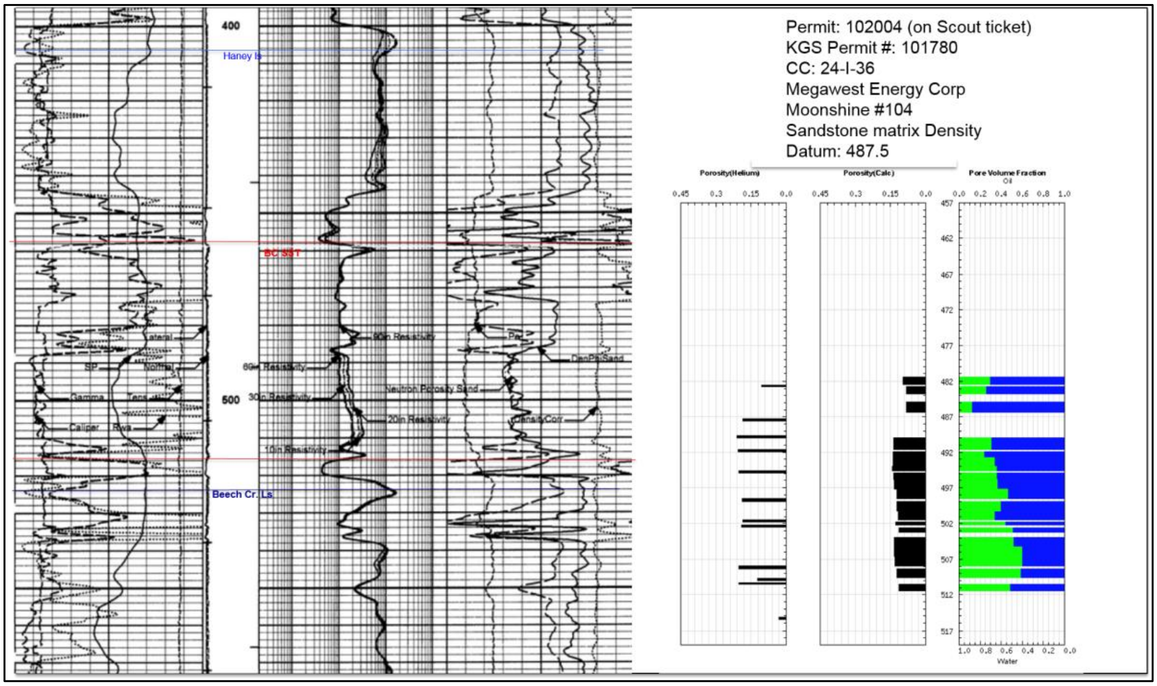
Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)



Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

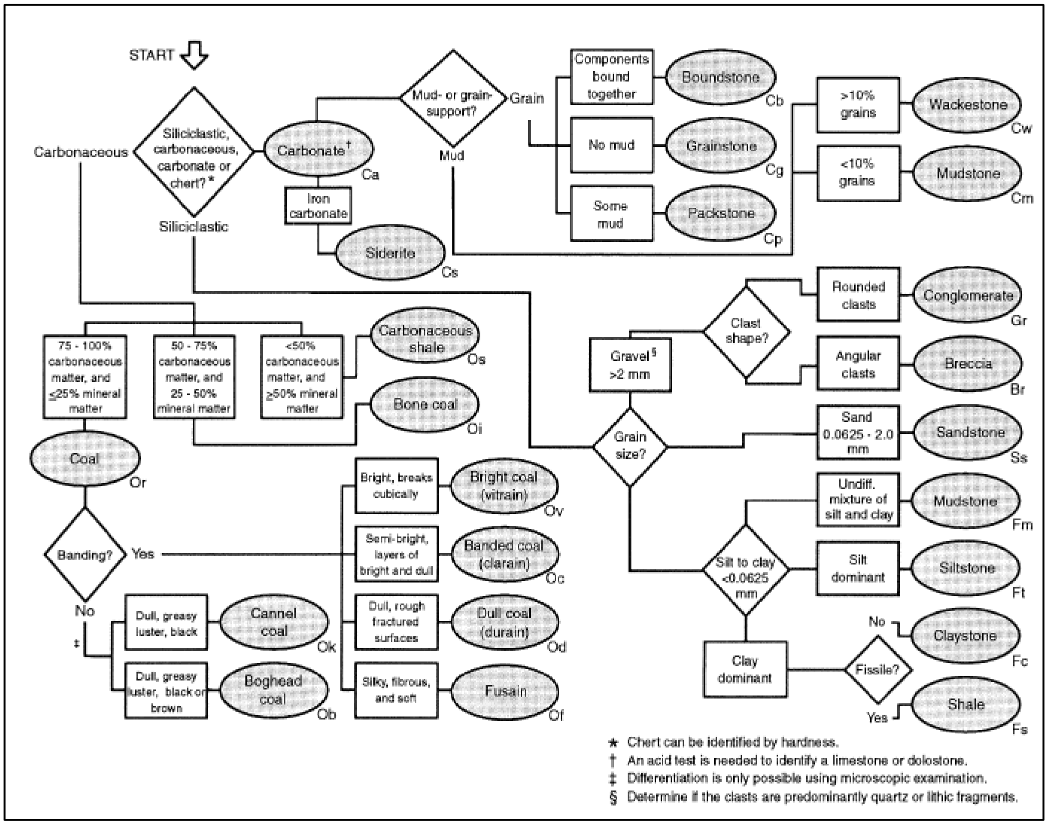


Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

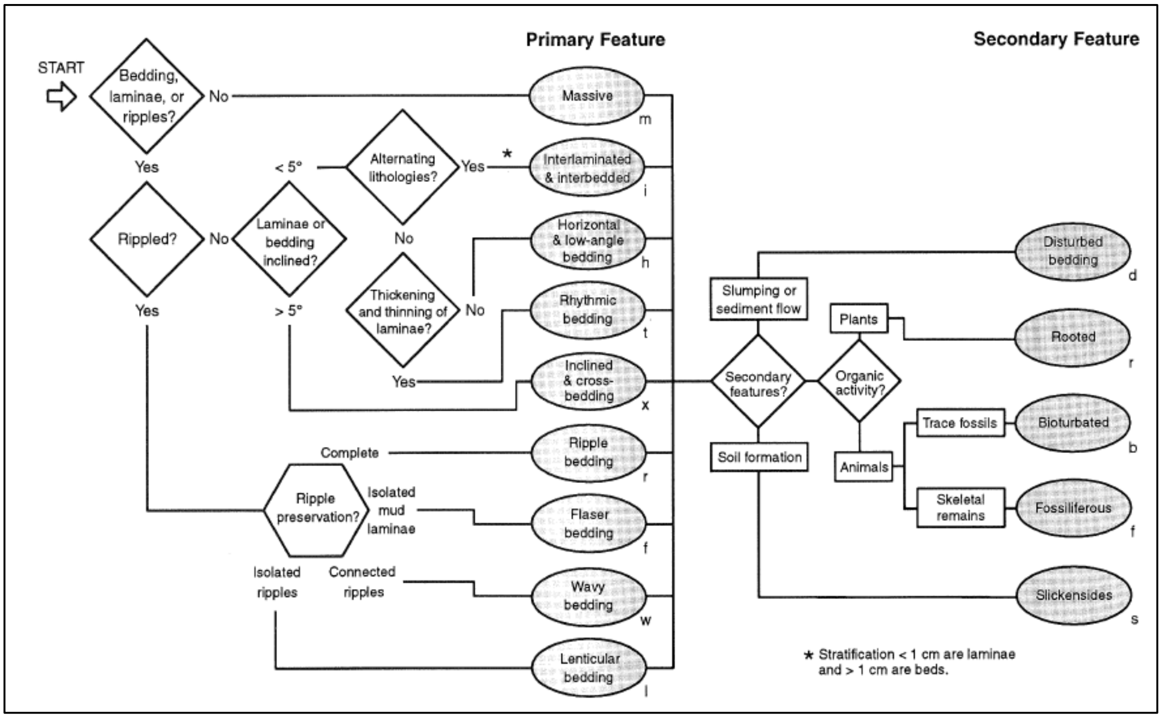


Well logs from KGS online data repository and modified by author (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

Appendix VII: Core and Exposure Logs

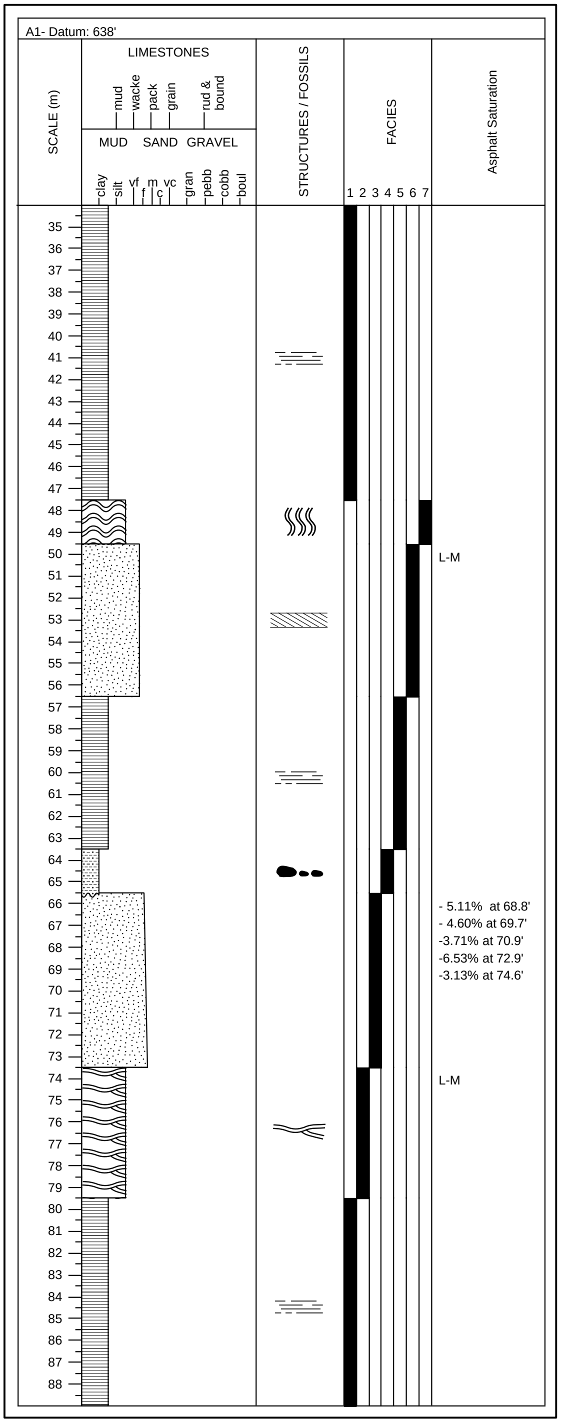


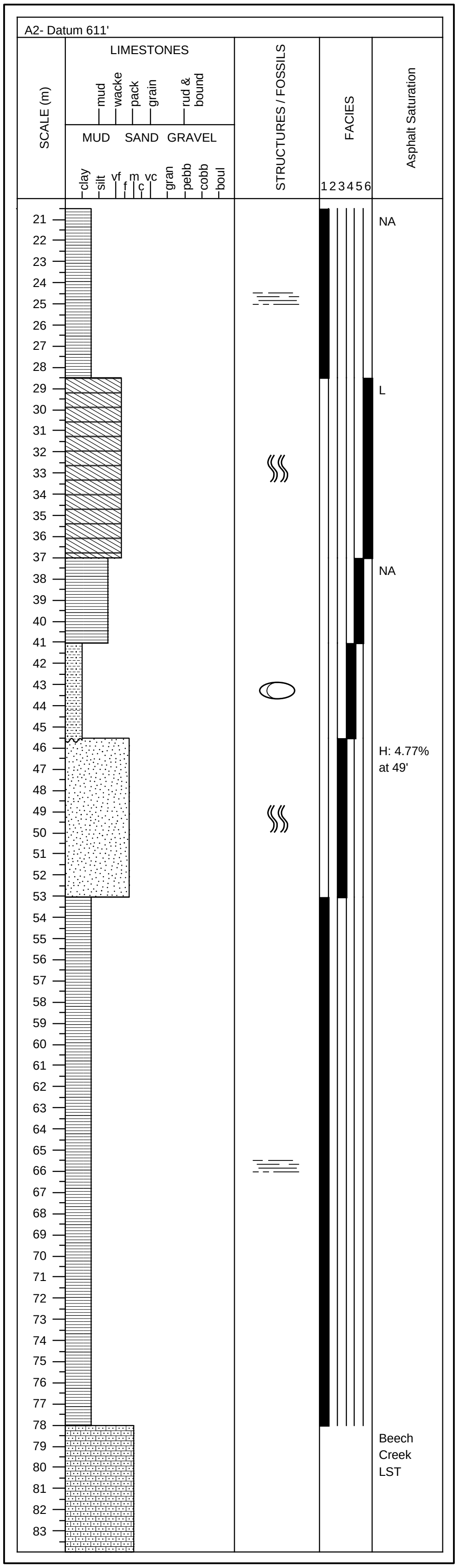
Flow chart used to determine the lithology of the rocks observed in core. Source: Barnhill and Zhou, 1996

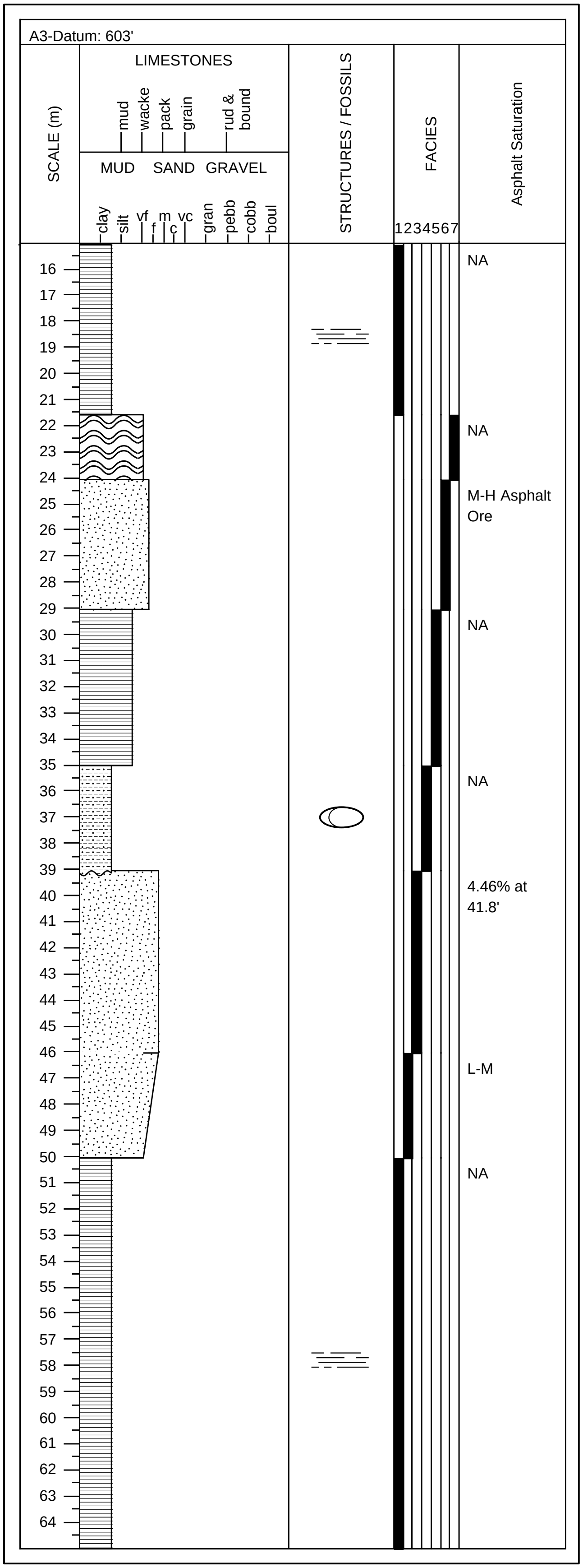


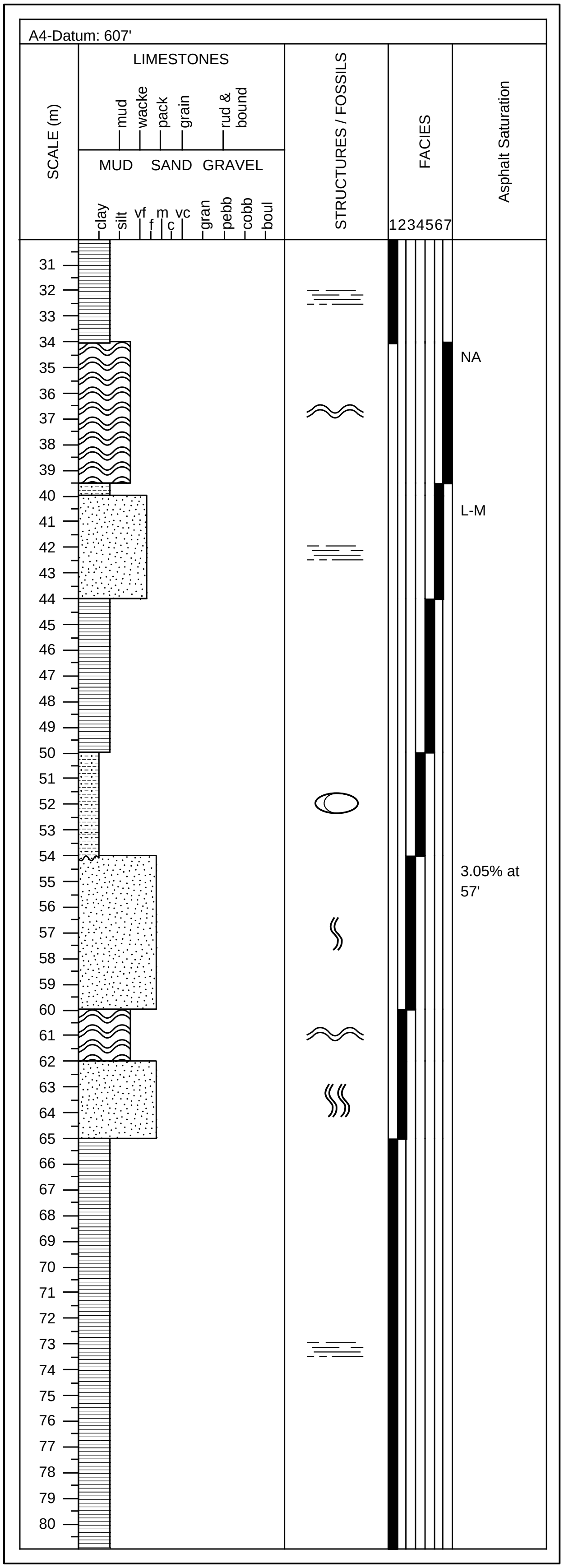
Flow chart used to identify sedimentary features observed in this study. Source: Barnhill and Zhou, 1996

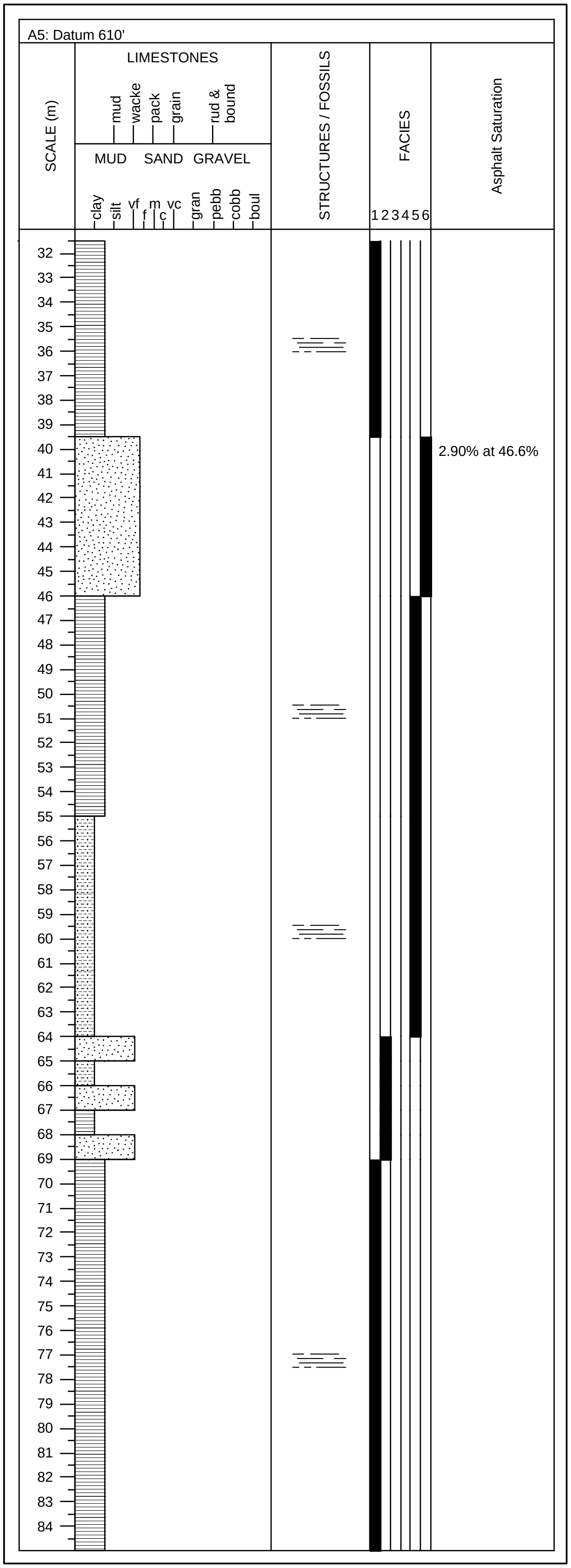
The author, using Sedlog 3.1, constructed the following logs. Note: The scale is in tenths of feet.

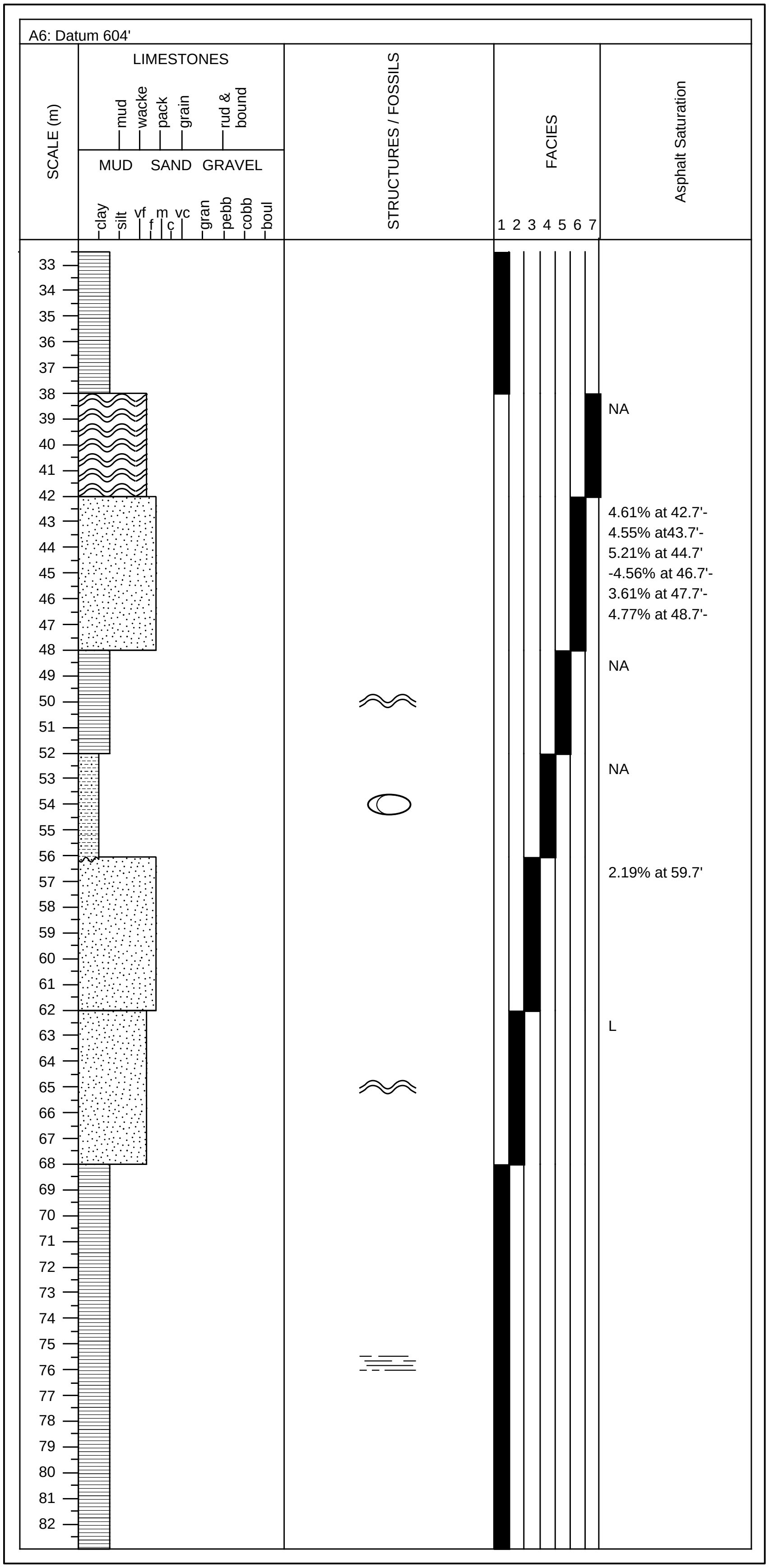


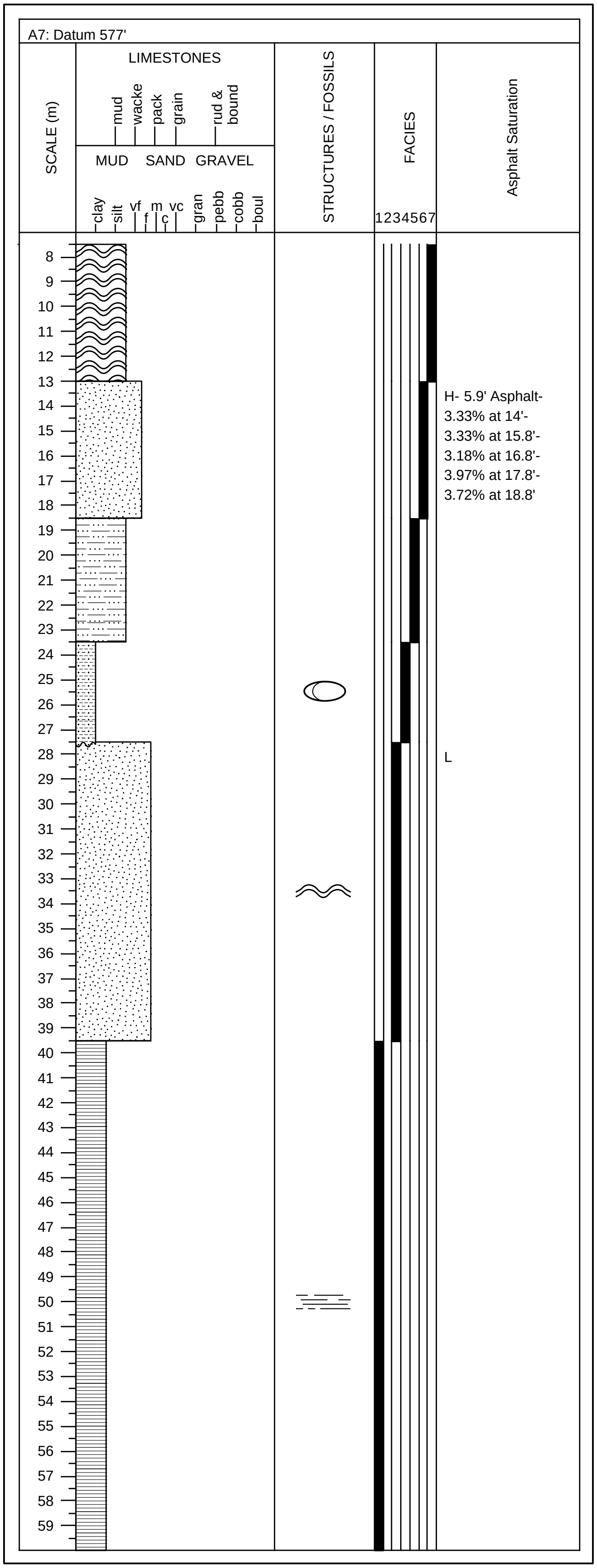

A2- Datum 611'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
NA
L
NA
H: 4.77% at 49'
Beech Creek LST

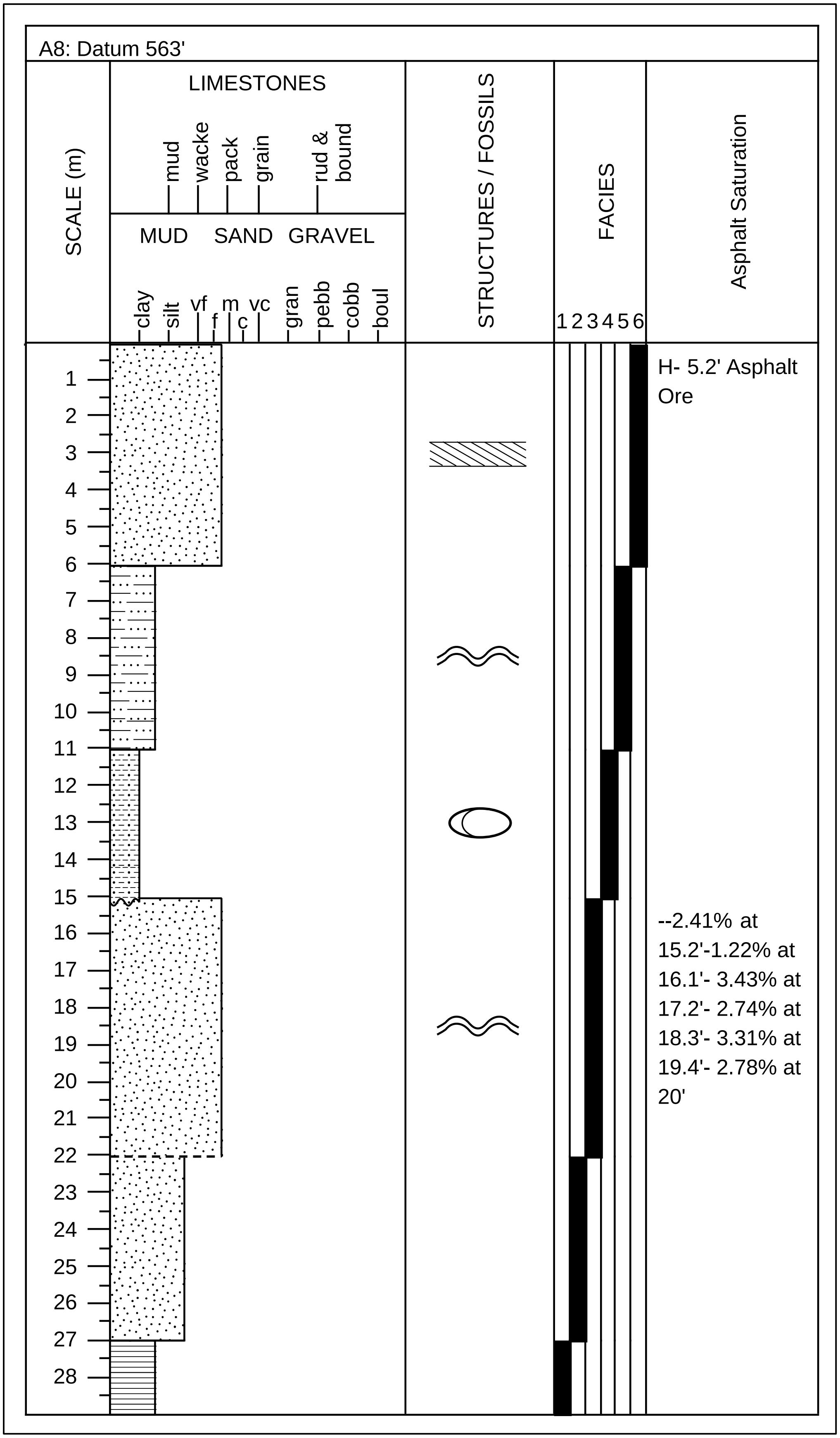

A3-Datum: 603'
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
NA
NA
M-H Asphalt Ore
NA
NA
4.46% at 41.8'
L-M
NA

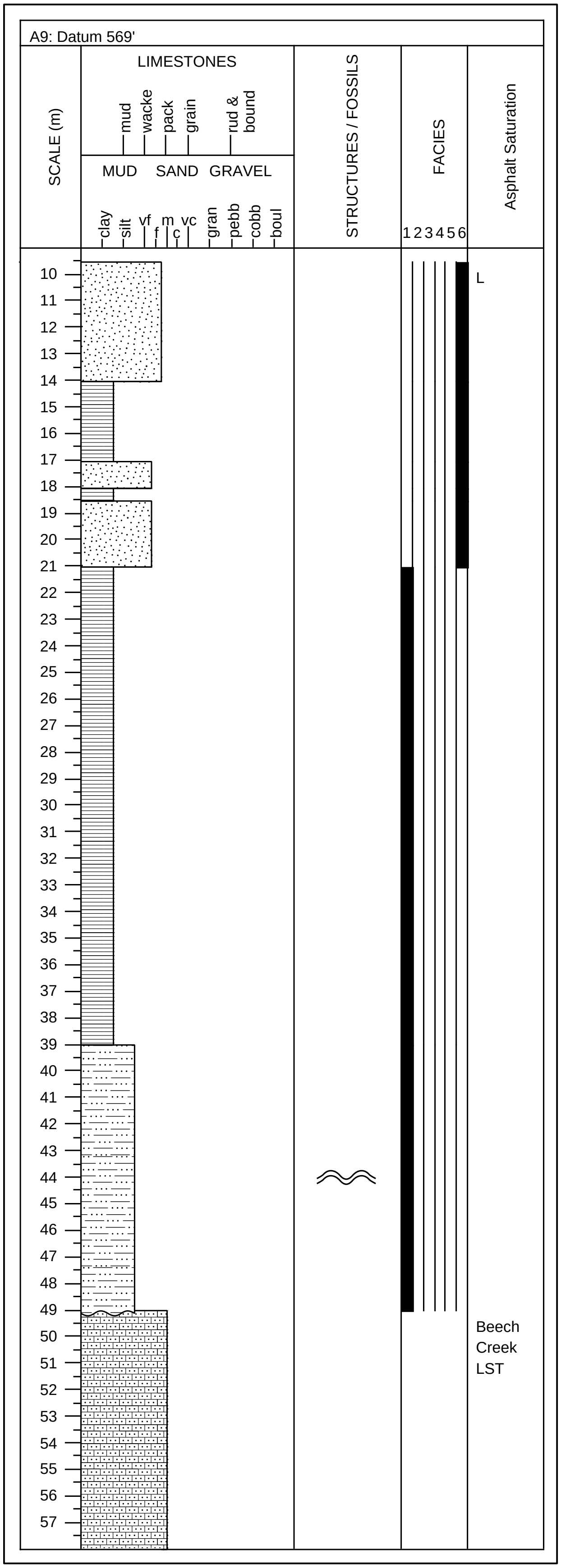

A4-Datum: 607'
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
NA
L-M
3.05% at 57'
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80


A5: Datum 610'
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
2.90% at 46.6%
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84

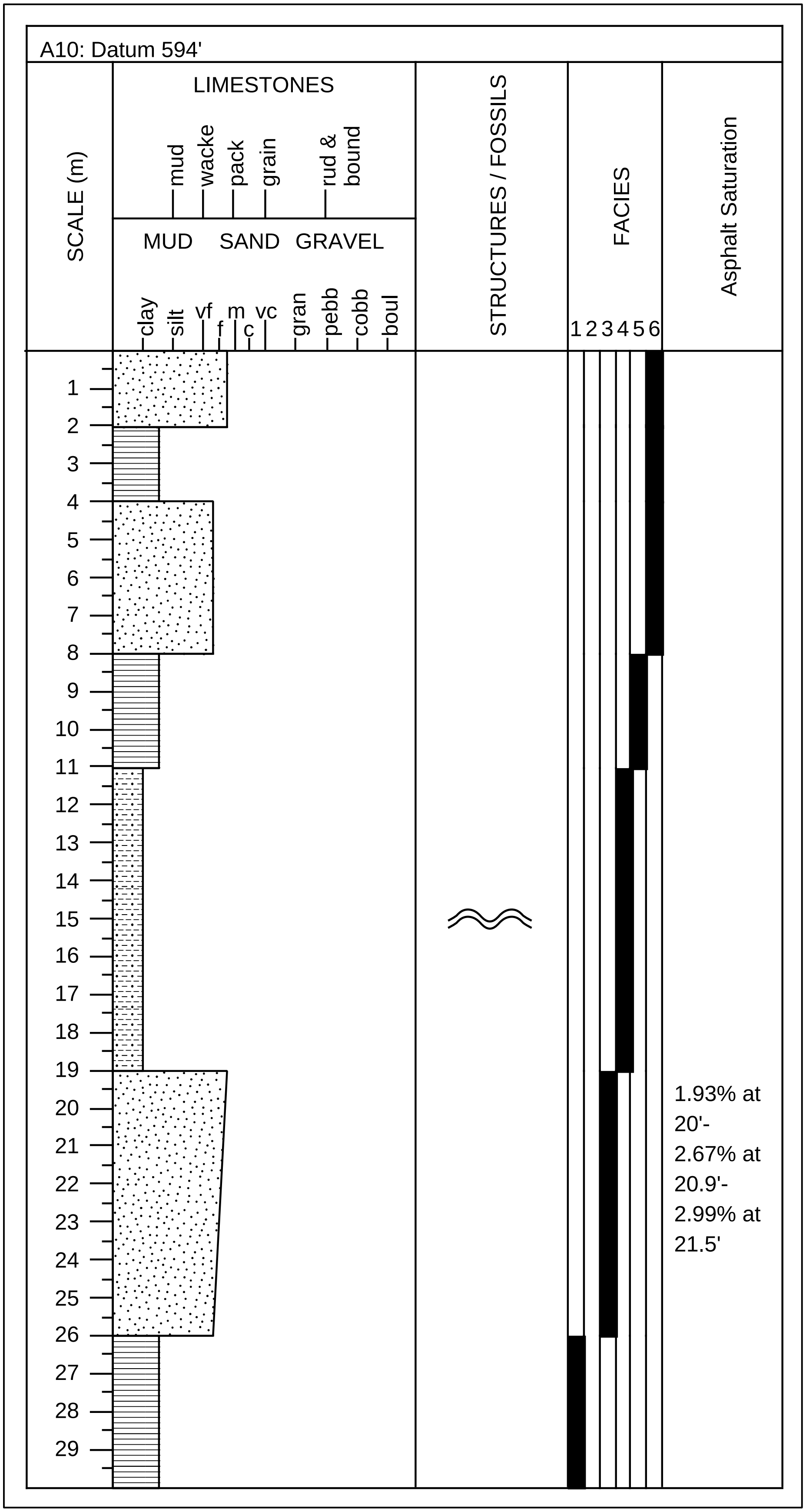

A6: Datum 604'
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6 7
Asphalt Saturation
NA
4.61% at 42.7'-
4.55% at43.7'-
5.21% at 44.7'
-4.56% at 46.7'-
3.61% at 47.7'-
4.77% at 48.7'-
NA
NA
2.19% at 59.7'
L

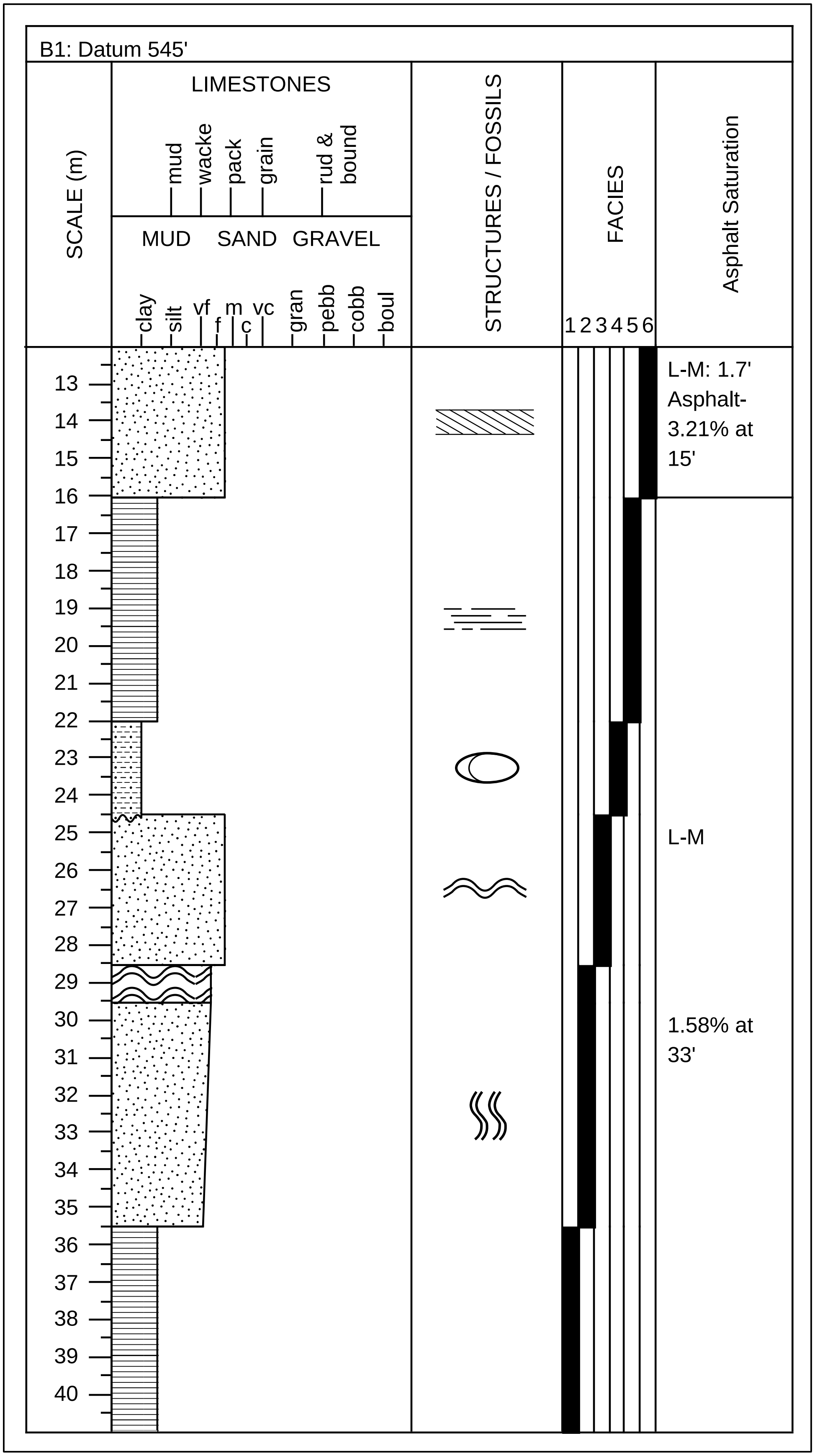

A7: Datum 577'
LIMESTONES
mud wacke pack grain rud & bound
MUD SAND GRAVEL
clay silt vf f m c vc gran pebb cobb boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
H- 5.9' Asphalt-
3.33% at 14'-
3.33% at 15.8'-
3.18% at 16.8'-
3.97% at 17.8'-
3.72% at 18.8'
L


A8: Datum 563'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud &
bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
H- 5.2' Asphalt Ore
--2.41% at 15.2'-1.22% at 16.1'- 3.43% at 17.2'- 2.74% at 18.3'- 3.31% at 19.4'- 2.78% at 20'

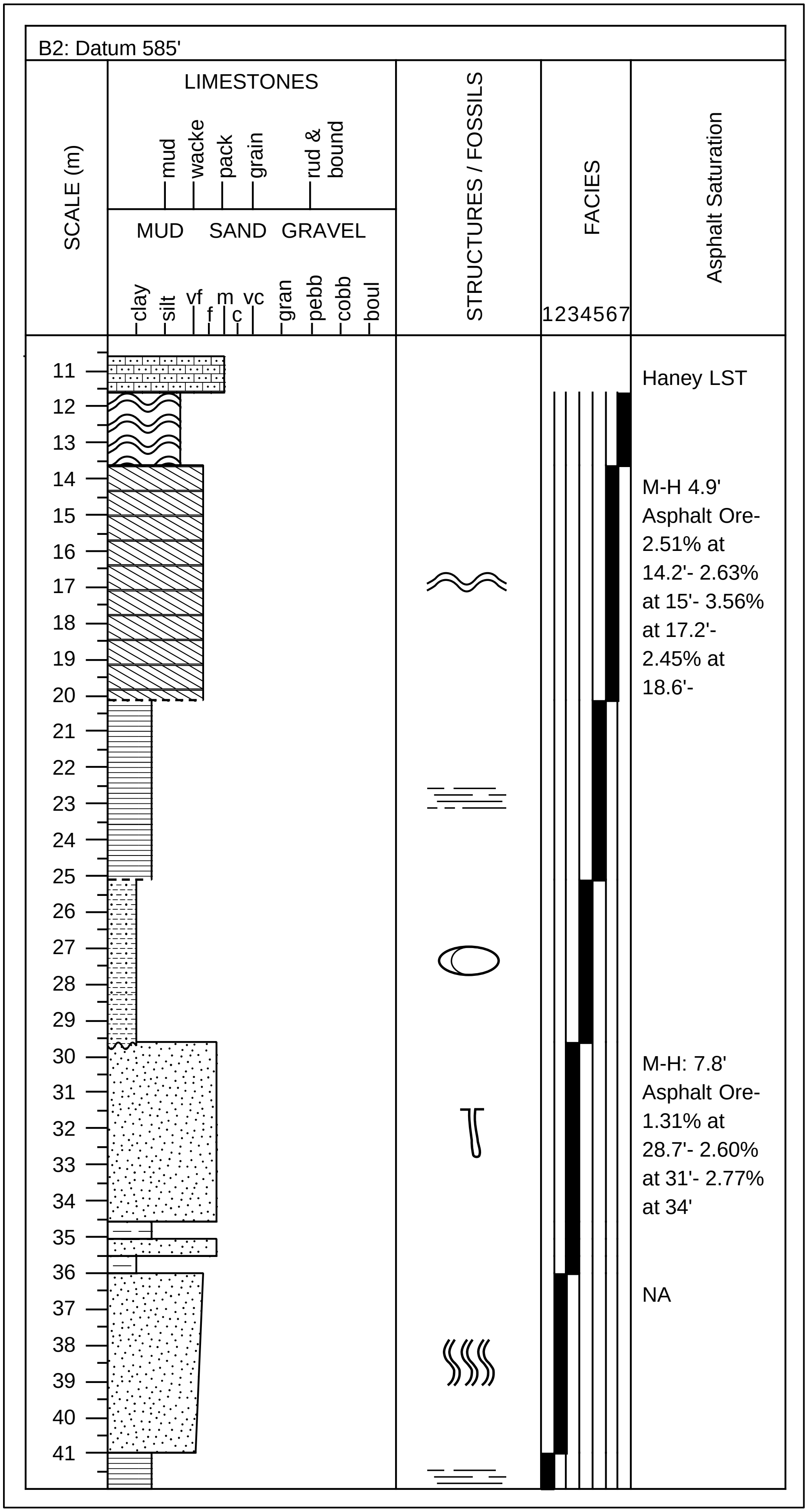


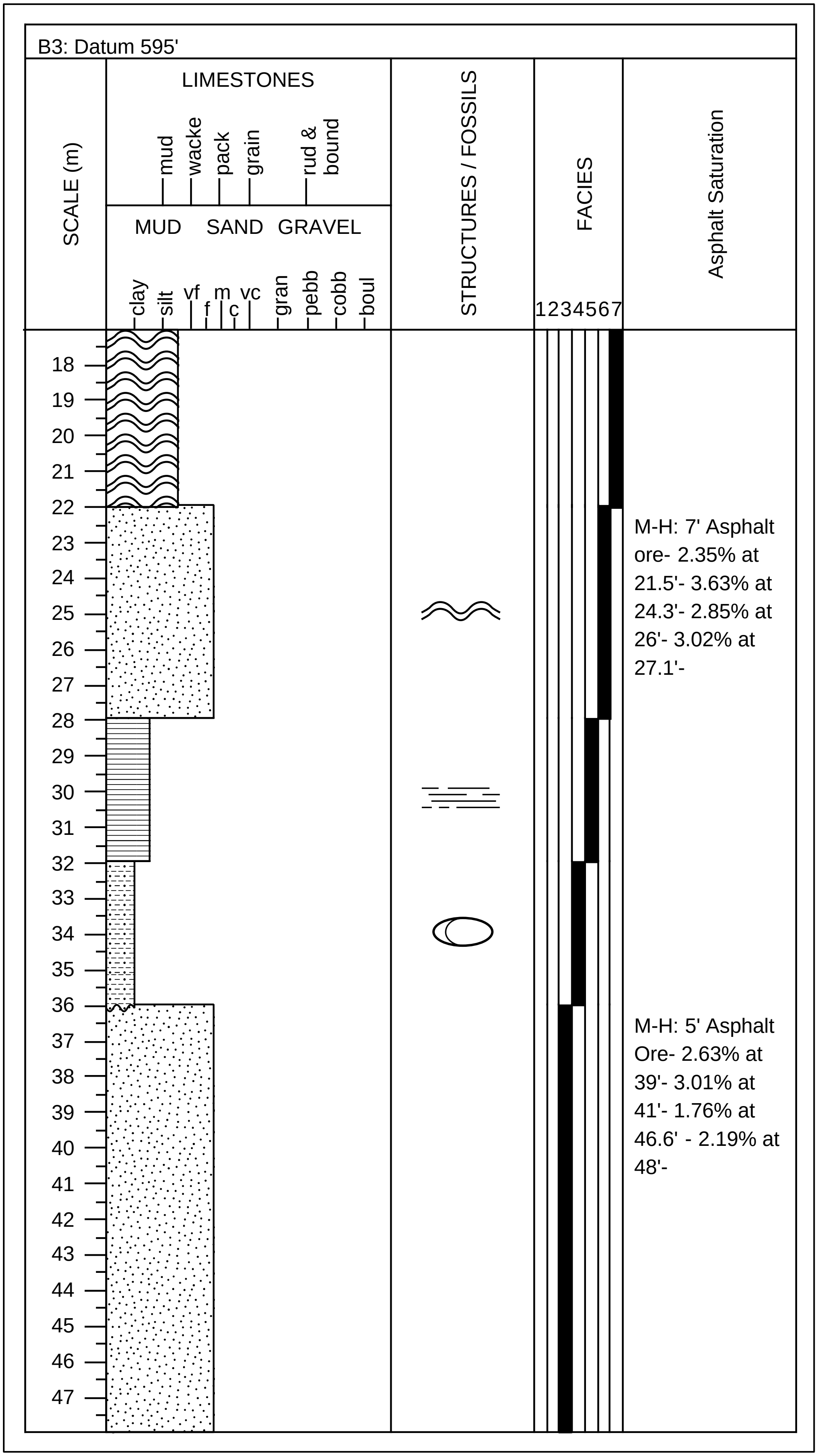
A9: Datum 569'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
L
Beech Creek LST
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57

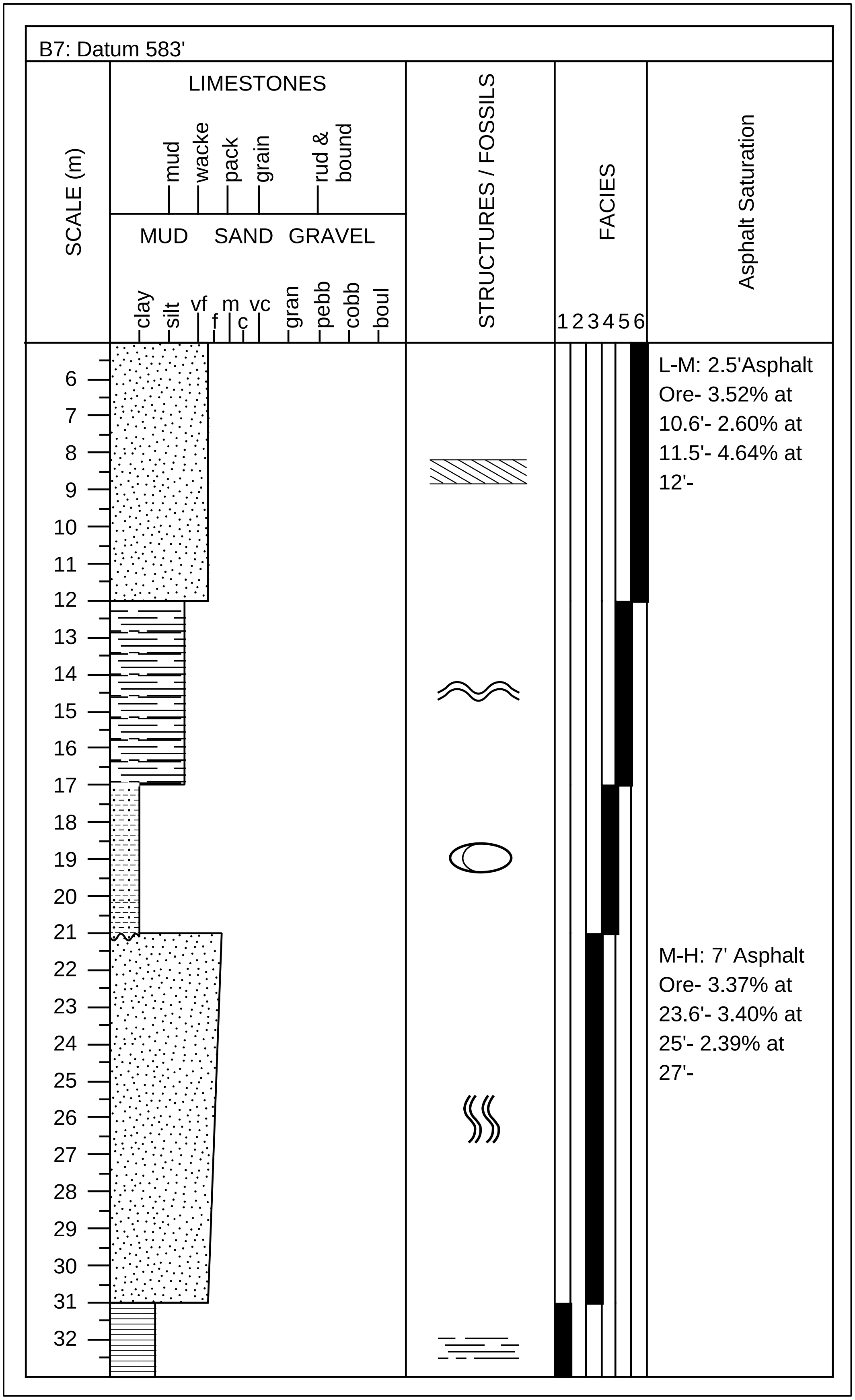

A10: Datum 594'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
1.93% at 20'-
2.67% at 20.9'-
2.99% at 21.5'

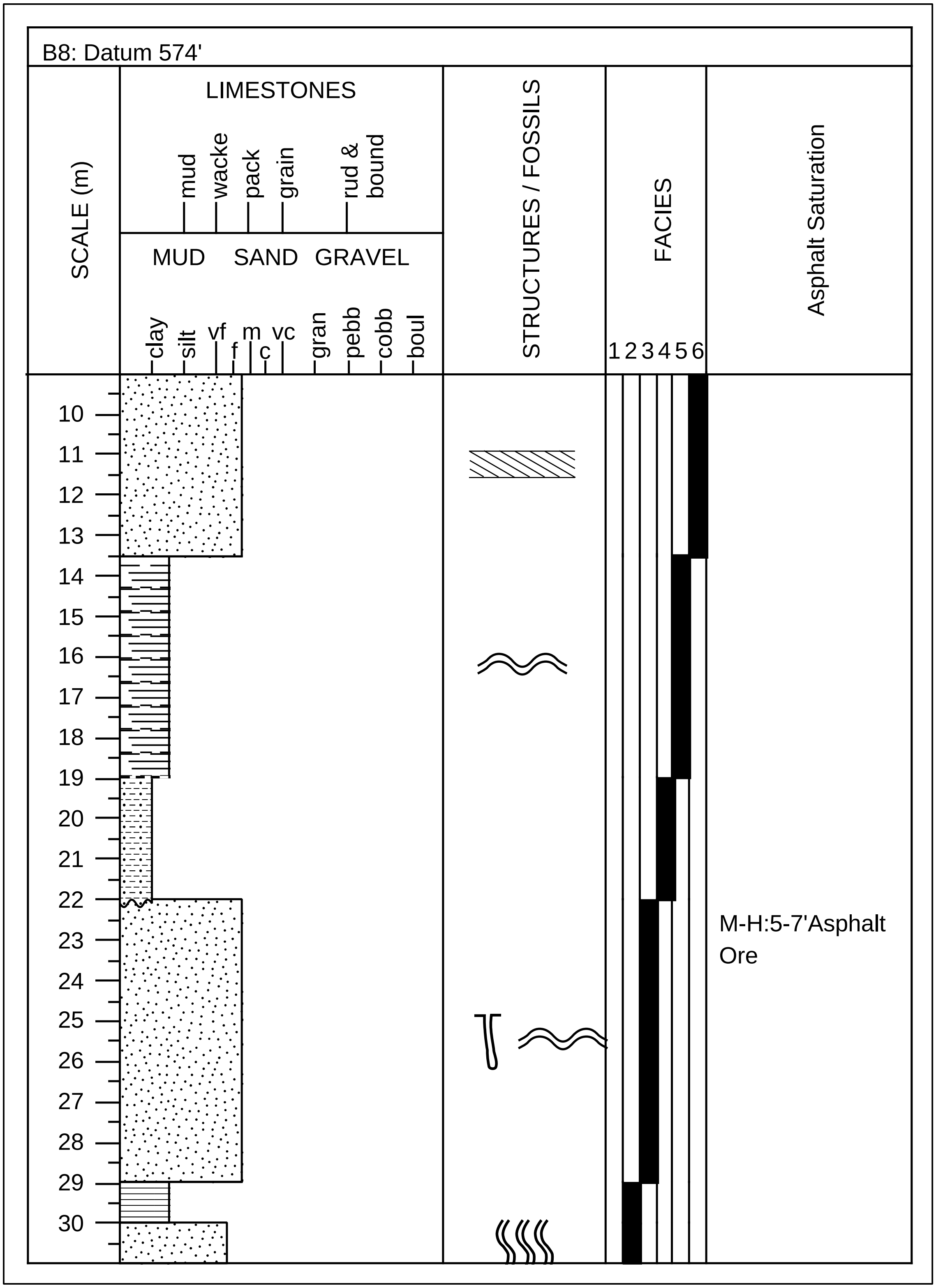


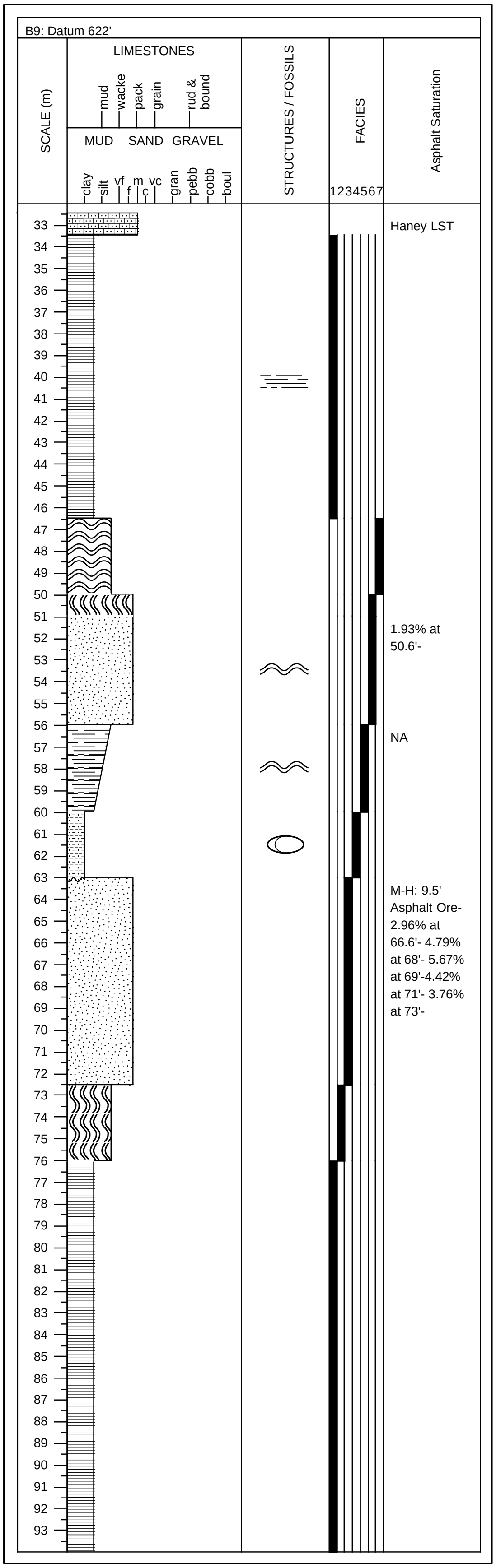
B1: Datum 545'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
L-M: 1.7' Asphalt- 3.21% at 15'
L-M
1.58% at 33'

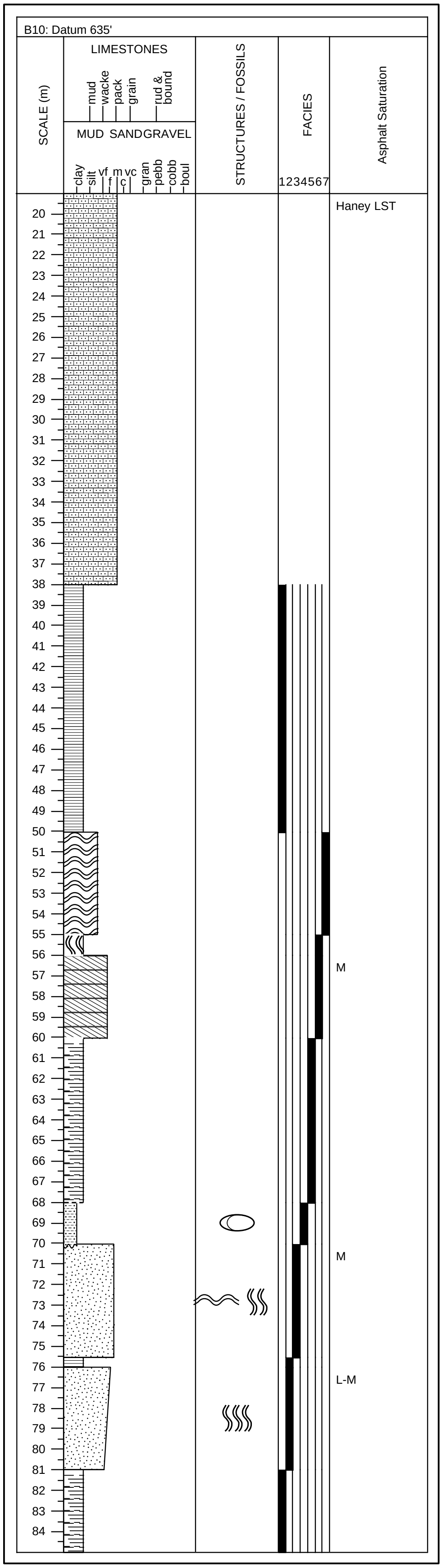

B2: Datum 585'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
Haney LST
M-H 4.9' Asphalt Ore- 2.51% at 14.2'- 2.63% at 15'- 3.56% at 17.2'- 2.45% at 18.6'-
M-H: 7.8' Asphalt Ore- 1.31% at 28.7'- 2.60% at 31'- 2.77% at 34'
NA

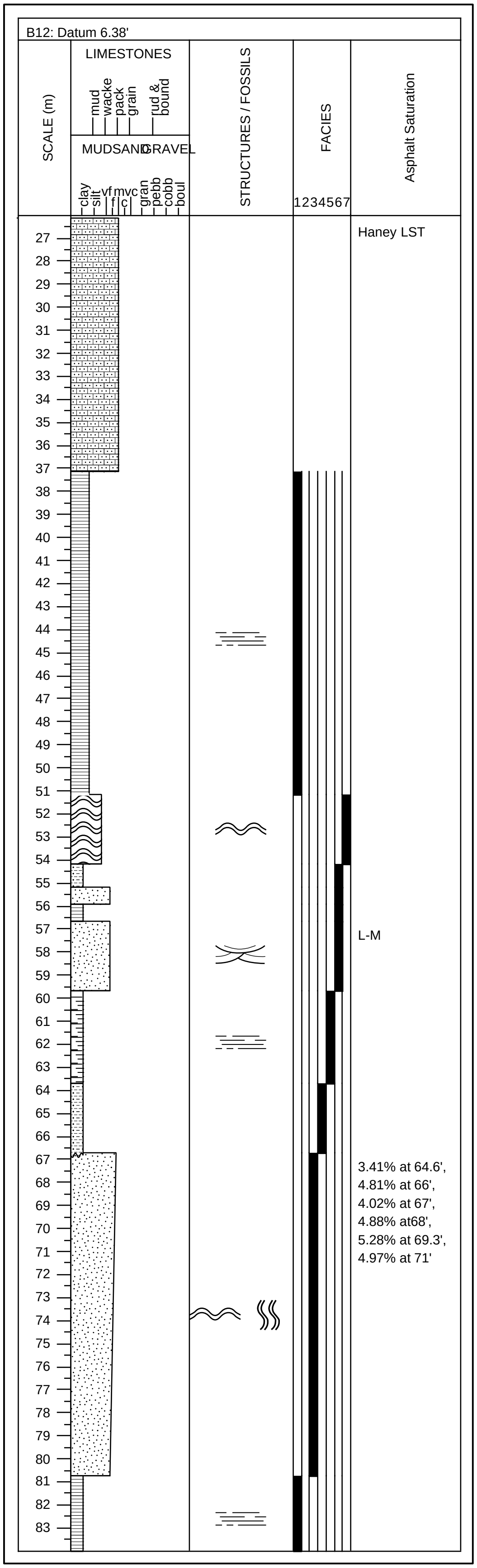

B3: Datum 595'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
M-H: 7' Asphalt ore- 2.35% at 21.5'- 3.63% at 24.3'- 2.85% at 26'- 3.02% at 27.1'-
M-H: 5' Asphalt Ore- 2.63% at 39'- 3.01% at 41'- 1.76% at 46.6' - 2.19% at 48'-

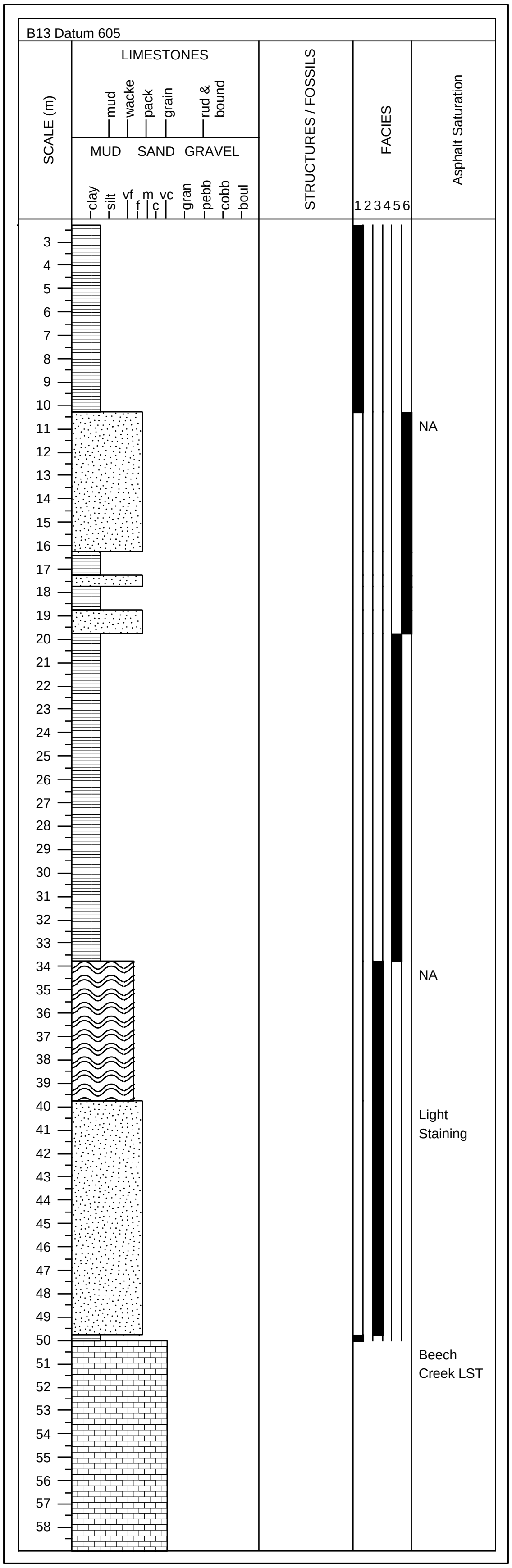

B7: Datum 583'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
L-M: 2.5'Asphalt Ore- 3.52% at 10.6'- 2.60% at 11.5'- 4.64% at 12'-
M-H: 7' Asphalt Ore- 3.37% at 23.6'- 3.40% at 25'- 2.39% at 27'-


B8: Datum 574'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
M-H:5-7'Asphalt Ore

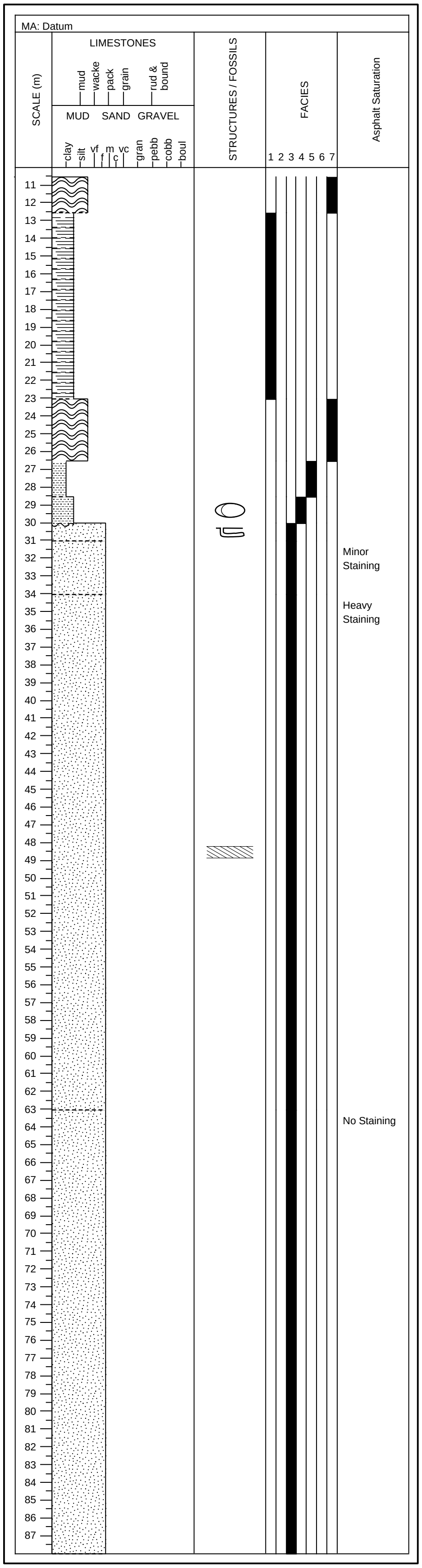

B9: Datum 622'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93
Haney LST
1.93% at 50.6'-
NA
M-H: 9.5' Asphalt Ore- 2.96% at 66.6'- 4.79% at 68'- 5.67% at 69'-4.42% at 71'- 3.76% at 73'-

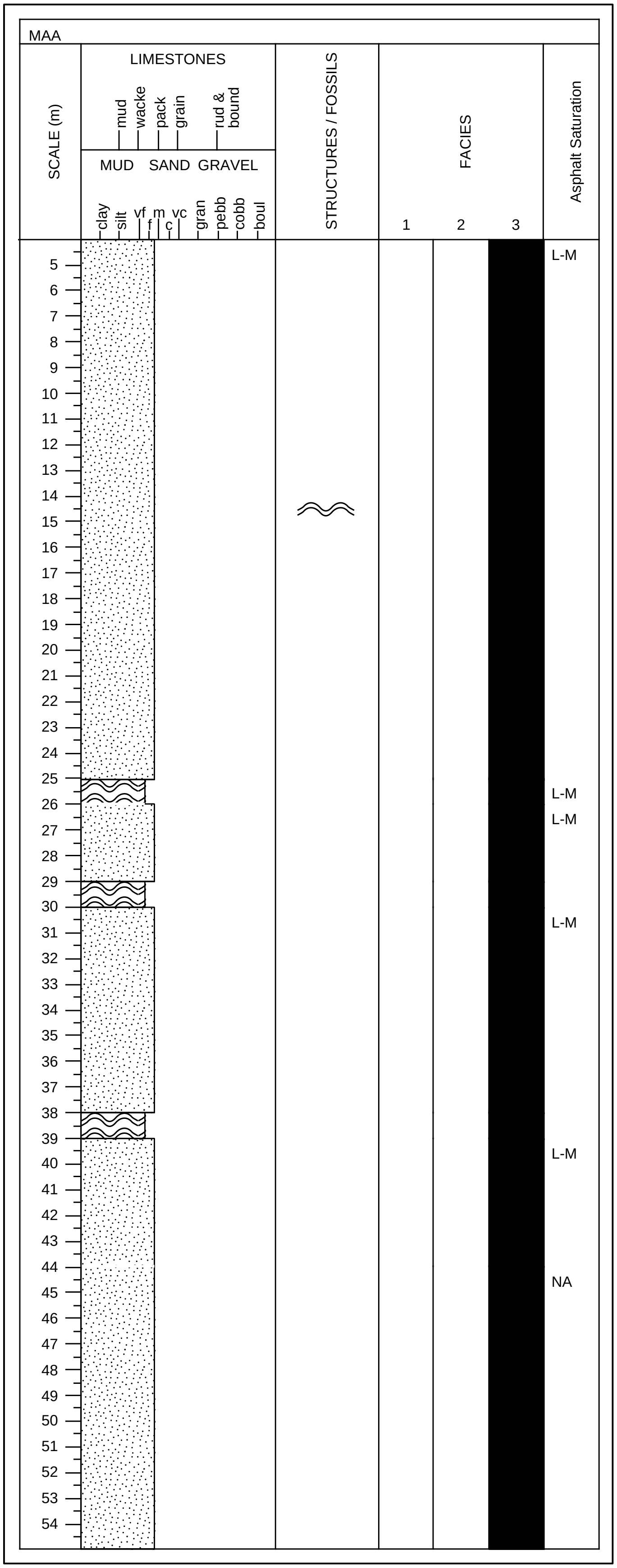

B10: Datum 635'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SANDGRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
Haney LST
M
M
L-M

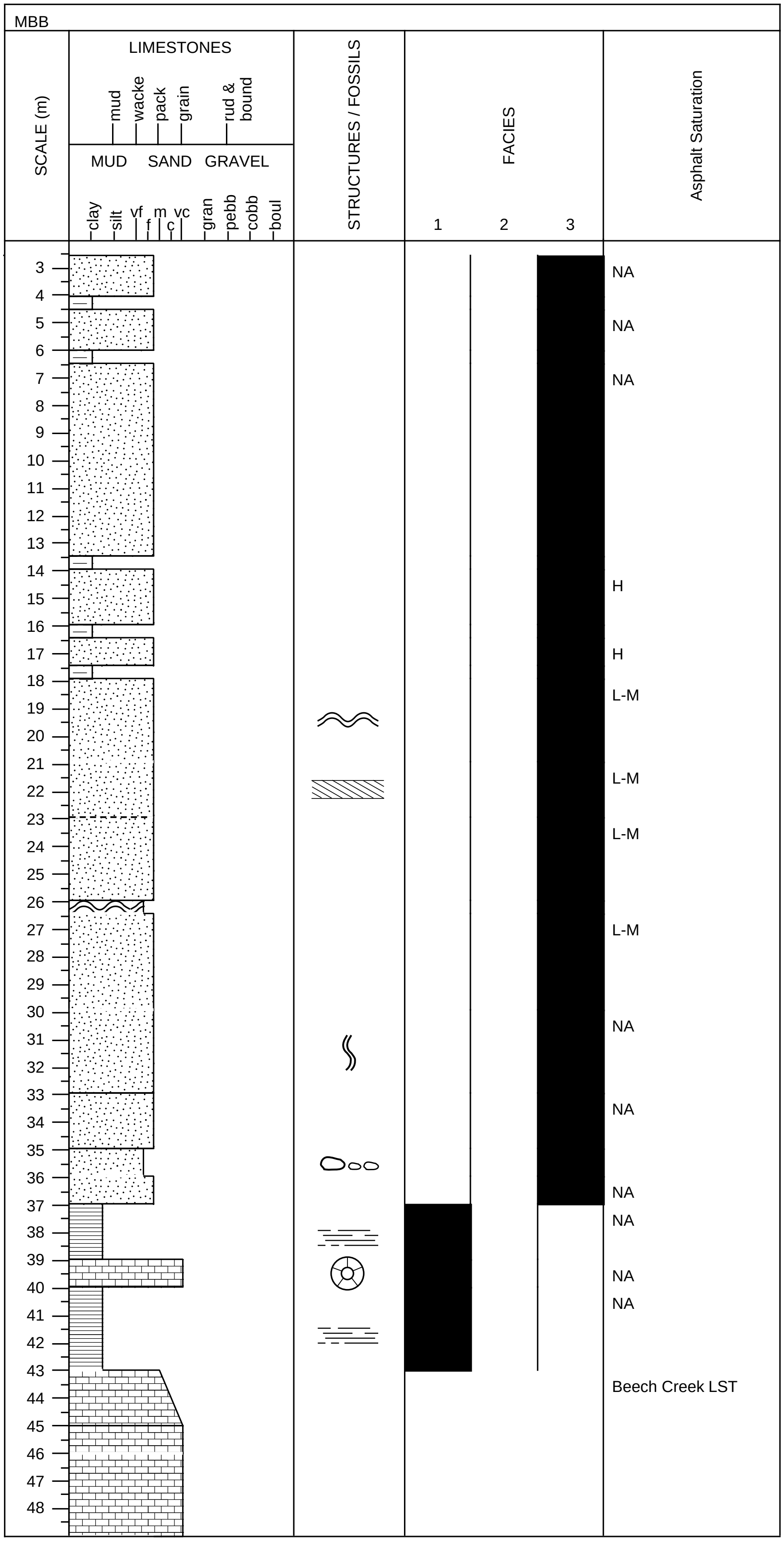

B12: Datum 6.38'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUDSAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1234567
Asphalt Saturation
Haney LST
L-M
3.41% at 64.6',
4.81% at 66',
4.02% at 67',
4.88% at68',
5.28% at 69.3',
4.97% at 71'

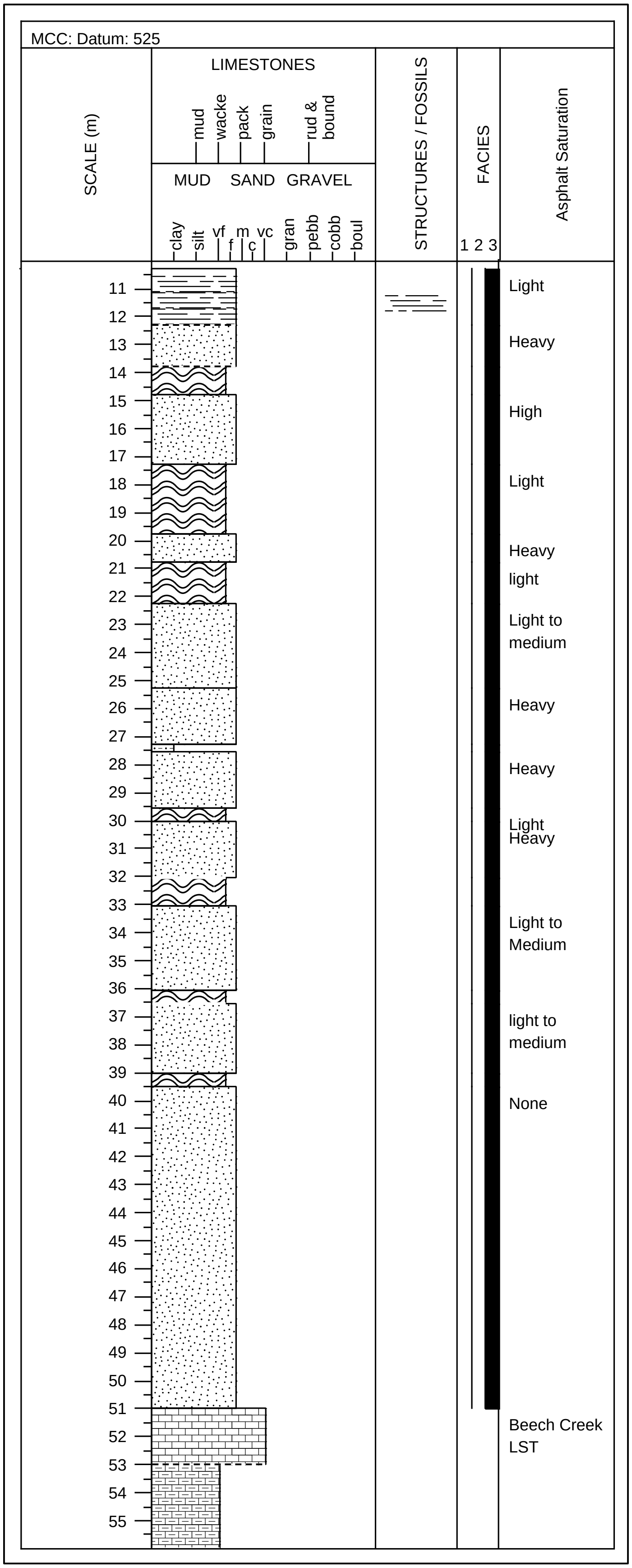


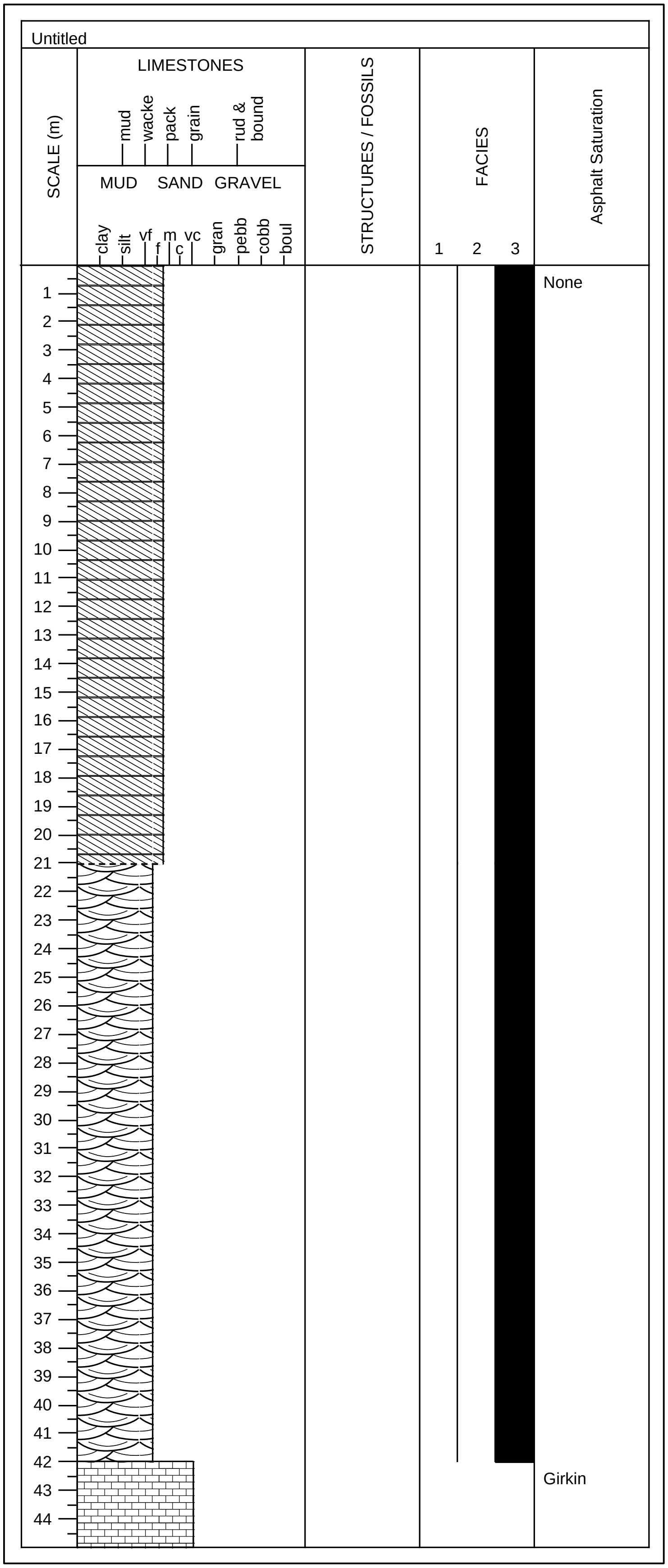
B13 Datum 605
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6
Asphalt Saturation
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
NA
NA
Light Staining
Beech Creek LST

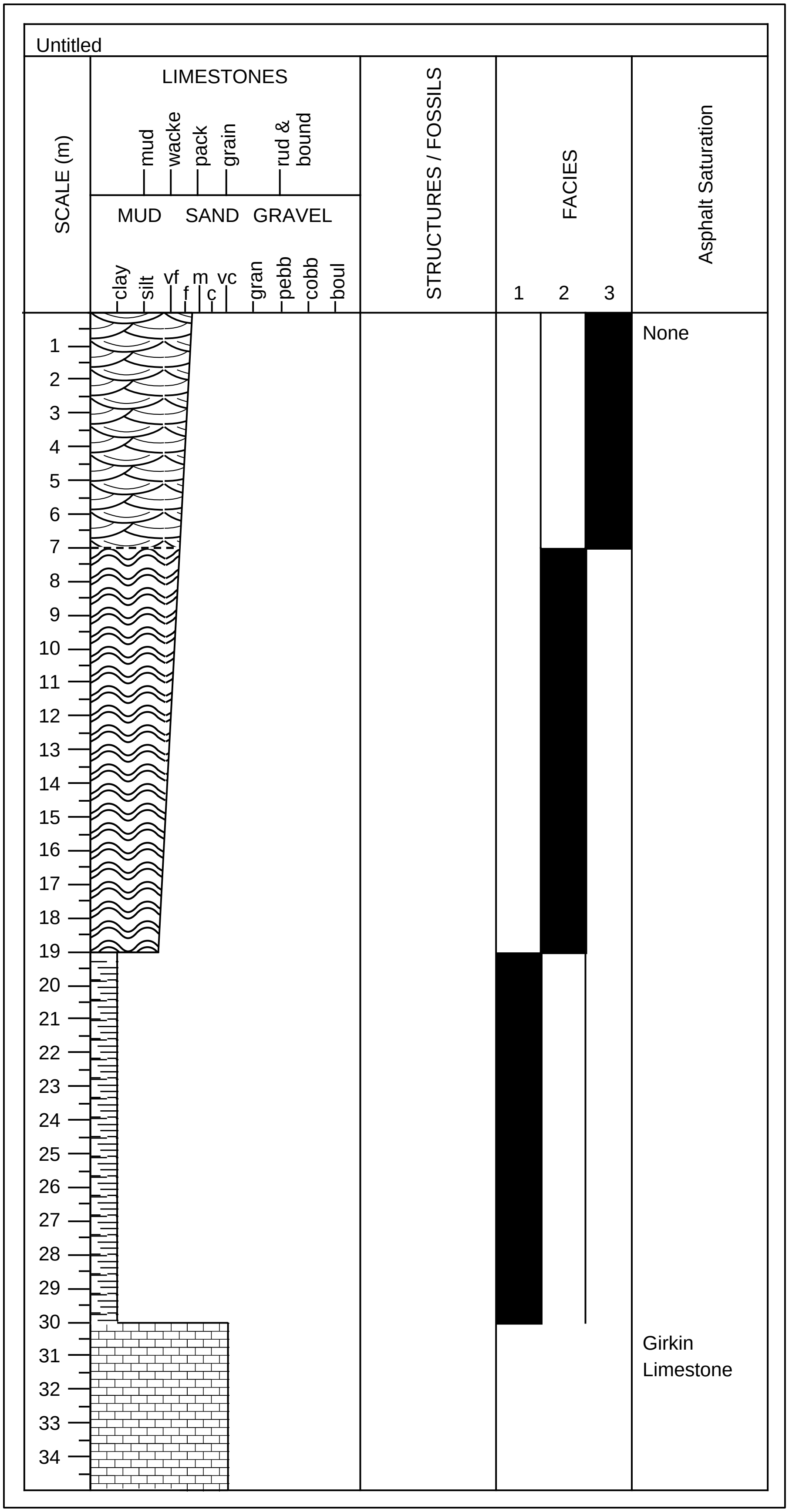

MA: Datum
LIMESTONES
mud
wacke
pack
grain
rud & bound
SCALE (m)
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3 4 5 6 7
Asphalt Saturation
Minor Staining
Heavy Staining
No Staining


MAA
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1
2
3
Asphalt Saturation
L-M
L-M
L-M
L-M
L-M
NA
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54

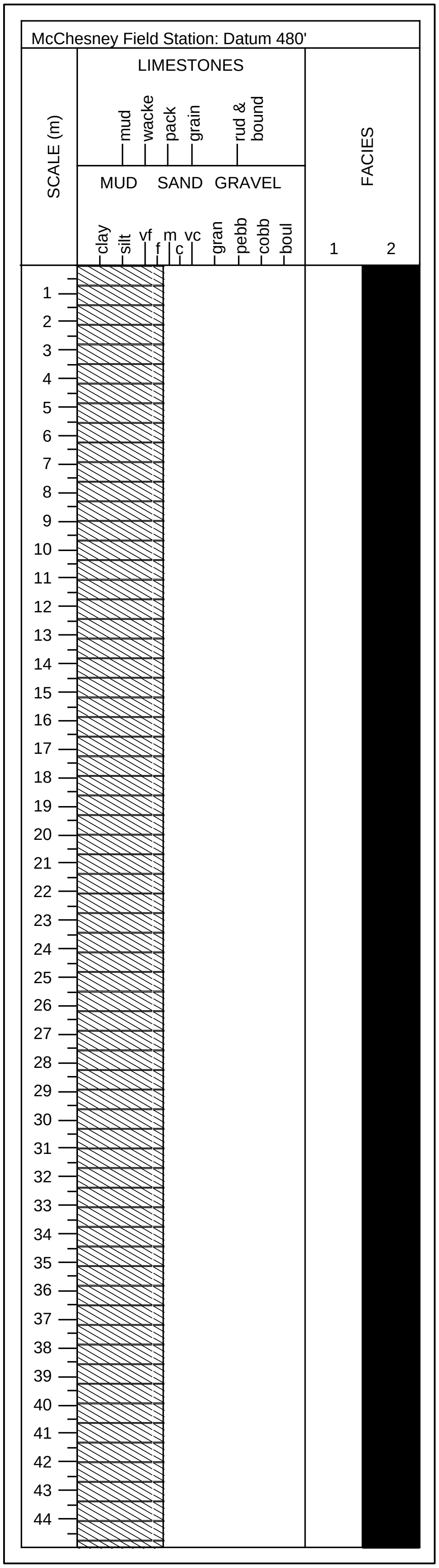

MBB
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1 2 3
Asphalt Saturation
NA
NA
NA
H
H
L-M
L-M
L-M
L-M
NA
NA
NA
NA
NA
NA
Beech Creek LST

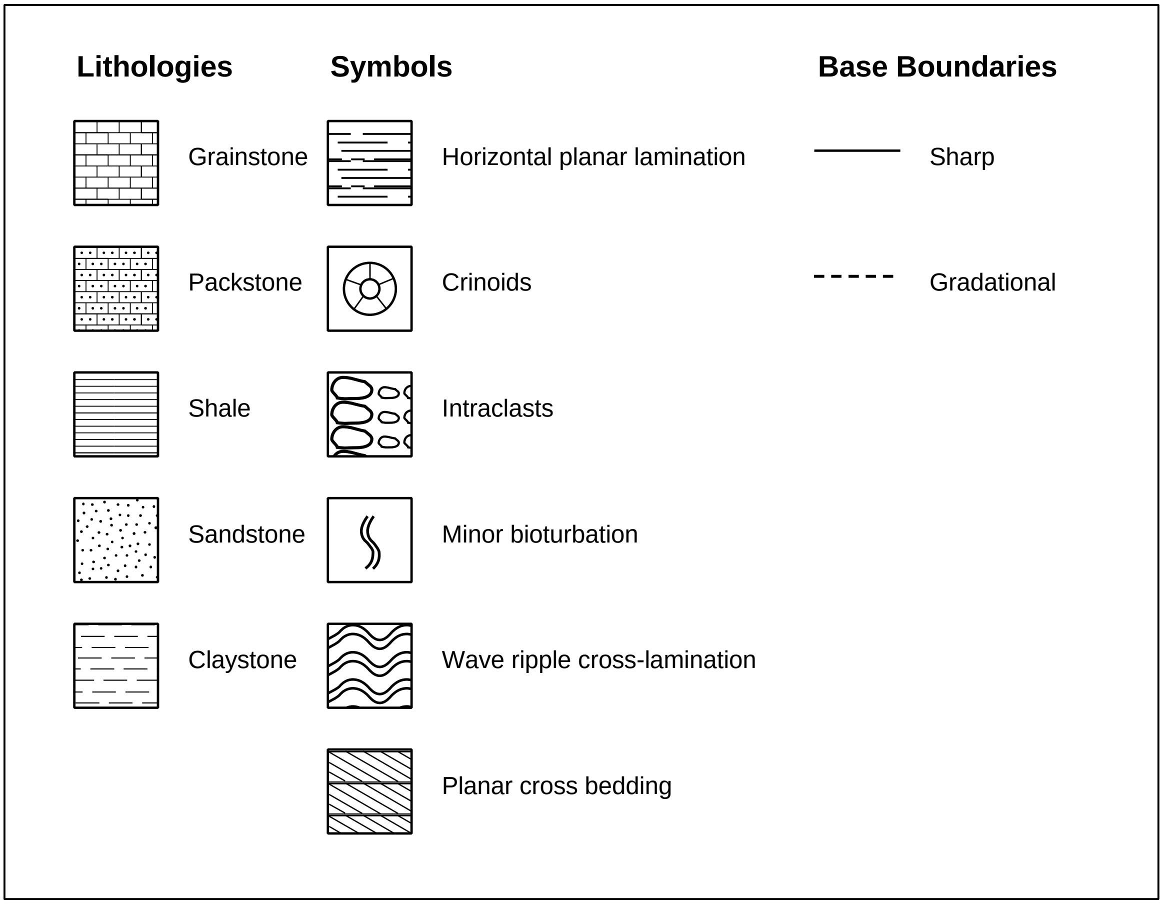

MCC: Datum: 525
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3
Asphalt Saturation
11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55
Light
Heavy
High
Light
Heavy
light
Light to medium
Heavy
Heavy
Light
Heavy
Light to Medium
light to medium
None
Beech Creek LST


Untitled
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
SCALE (m)
STRUCTURES / FOSSILS
FACIES
1 2 3
Asphalt Saturation
None
Girkin
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44



Untitled
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
FACIES
1 2 3
Asphalt Saturation
None
Girkin Limestone
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34


McChesney Field Station: Datum 480'
SCALE (m)
LIMESTONES
mud
wacke
pack
grain
rud &
bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
FACIES
1
2
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44



Key for core logs from Sed. Log 3.1 created by author.

Appendix VIII: Data Reference Tables

All tables were created by author using data collected during this study.

Permit #	Carter Coordinate	County	Datum	Big Clifty Top TVDSS Upper	Big Clifty Bottom TVDSS Upper	Gross Sandstone Upper	BC Top TVDSS Lower	BC Bottom TVDSS Lower	Gross Sandstone Lower	Combined Gross Sandstone	# Reservoir Type	Top Beech Creek TVDSS	Big Clifty Gross
101824	08-H-36	Warren	571.5	132.5	80.5	52	NA	NA	NA	52	1	75.5 ƫ	57
101779	24-I-36	Warren	426.1	1	-59	60	NA	NA	NA	60	1	-62	63
101825	8-H-36	Warren	482	210	164	46	NA	NA	NA	46	1	157	53
101780	24-I-36	Warren	487.5	29.5	-28.5	58	NA	NA	NA	58	1	-36.5	66
85390	1-G-31	Butler	400	75	60	15	350	379	29	44	2	6	69
86121	16-H-33	Butler	460	61	39	22	32	20	12	34	2	12	49
94184	5-G-32	Butler	406	84	60	24	56	49	7	31	2	35	49
65340	16-H-33	Butler	449	170	125	45	NA	NA	NA	45	1	111	59
62912	11-H-32	Butler	690	76	43	33	36	20	16	49	2	10	66
A1	Stampede Mine	Logan	638	588.5	581.5	7	572.5	564.5	8	15	2	NA ƫ	41.5
A2	Stampede Mine	Logan	611	582.5	574	8.5	565.5	558	7.5	16	2	533	49.5
A3	Stampede Mine	Logan	603	581.5	574	7.5	564	557	7	14.5	2	NA	43.5
A4	Stampede Mine	Logan	607	567	563	4	553	547	6	10	2	NA	47
A5	Stampede Mine	Logan	610	570.5	564	6.5	NA	NA	NA	6.5	1	NA	45.5
A6	Stampede Mine	Logan	604	566	556	10	548	542	6	16	2	NA	45

Permit #	**Carter Coordinate**	**County**	**Datum**	**Big Clifty Top TVDSS Upper**	**Big Clifty Bottom TVDSS Upper**	**Gross Sandstone Upper**	**BC Top TVDSS Lower**	**BC Bottom TVDSS Lower**	**Gross Sandstone Lower**	**Combined Gross Sandstone**	**# Reservoir Type**	**Top Beech Creek TVDSS**	**Big Clifty Gross**
A7	Stampede Mine	Logan	577	564	558.5	5.5	549.5	537.5	12	17.5	2	NA	52.5
A9	Stampede Mine	Logan	563	563	557	6	548	541	7	13	2	NA	NA
A10	Stampede Mine	Logan	594	594	586	6*	575	568	7	13	2	NA	NA
B1	Stampede Mine	Logan	545	545	541	4	520.5	516.5	4	8	2	NA	NA
B2	Stampede Mine	Logan	585	571.5	565	6.5	555.5	550.5	5	11.5	2	NA	NA
B3	Stampede Mine	Logan	595	573	567	6	559	547	12	18	2	NA	NA
B7	Stampede Mine	Logan	583	578	571	7	562	552	10	17	2	NA	NA
B8	Stampede Mine	Logan	574	565	560.5	4.5	552	545	7	11.5	2	NA	NA
B9	Stampede Mine	Logan	622	571	566	5	559	549.5	9.5	14.5	2	NA	47.5
B10	Stampede Mine	Logan	635	579	575	4	565	559.5	5.5	9.5	2	NA	NA
B11	Stampede Mine	Logan	617	575	571.5	3.5	561.5	554.5	7	10.5	2	NA	NA
B12	Stampede Mine	Logan	638	581.5	578.5	3	571	557.5	14	17	2	NA	NA
B13	KY Single Zone (north,east): 3519189.132777618, 4621246.11350958	Logan	605	595	589	6	571	555	16	22	2	555	40
MA	KY Single Zone (north,east): 3508768.8556053303, 4591494.482935033	Logan	475	452	448.5	3.5	445	387	58	61.5	2	NA	77.5

Permit #	**Carter Coordinate**	**County**	**Datum**	**Big Clifty Top TVDSS Upper**	**Big Clifty Bottom TVDSS Upper**	**Gross Sandstone Upper**	**BC Top TVDSS Lower**	**BC Bottom TVDSS Lower**	**Gross Sandstone Lower**	**Combined Gross Sandstone**	**# Reservoir Type**	**Top Beech Creek TVDSS**	**Big Clifty Gross**
MAA	KY Single Zone (north,east): 3509127.283296904, 4591285.61334307	Logan	470	466	415	51	NA	NA	NA	51	1	NA	51
MBB		Logan	460	**457.5**	**423**	34.5	NA	NA	NA	34.5	1		40.5
MCC		Logan	525	514.5	474	40.5	NA	NA	NA	40.5	1	474	NA
LFA		Logan	650	618	633	15	NA	NA	NA	15		620	NA
McChesney Field	Indian Creek	Warren		460		40				40			
Natcher Parkway										21			
Jackson's Orchard										45			
Barren Rvr. Road										25			
Average All Wells						19.5			9.75	27			
Average Stampede Mine						5.8			8	13.2			
Average Warren										54			
Average Butler										48.3			

Type 1 Reservoir – Big Clifty Sandstone occurs as single-bodied sandstone.
Type 2 Reservoir- Big Clifty Sandstone occurs as multistoried sandstone. Lower sandstone is better reservoir for asphalt rock.
TVDSS- True Vertical Depth Sub sea
ł- Gross interval thickness is measure from top of Big Cifty Sandstone to top of Beech Creek.
ţ- Gross interval is top of facies 7 to top of facies 1
**- Two feet of mudstone interbedded*

Table created by author. Well log data was accessed from KGS online data repository (http://kgs.uky.edu/kgsweb/DataSearching/oilsearch.asp)

ID	KGS_ Recno	Permit #	Top MD	Bottom MD	Gross Isopach	Data Type	Series	County
1	21404	54759	361.5	401	39.5	cored	1	Butler
2	62391	62391	290	363	73	cored	1	Butler
3	21406	48730	390	461	71	well log	1	Butler
4	46556	65340	266	340	74	well log	1	Butler
5	47601	65785	320	402	82	well log	1	Butler
6	89791	78118	302	378	76	well log	1	Butler
7	2003156	12836	364	446	82	well log	1	Butler
8	2003161	5662	310	390	80	drillers log	1	Butler
9	2003164	6234	251	293	42	drillers logs	1	Butler
10	110421	86121	374	448	74	well log	1	Butler
11	112229	87024	340	398	58	well log	1	Butler
12	89809	N3325	297	365	68	drillers	1	Butler
13	2003161	5662	328	409	81	cored	1	Butler
14	2003164	6234	251	293	42	drillers logs	1	Butler
15	2006219	5836-wf	586	626	40	drillers	1	Butler
16	59139	69362	530	540	10	well log	1	Butler
17	38144	62912	602	676	74	Well log core	1	Butler
18	32163	58930	428	506	78	Well Log	1	Butler
19	32162	56292	304	420	116	well Log	1	Butler
20	21404	54759	361.5	401	39.5	cored	1	Butler
21	2594	39165	338	349	11	drillers logs	1	Butler
22	2613	37539	384	404	20	drillers	1	Butler
23	54831	21412	405	450	45	drillers	1	Butler
24	55546	10852	627	649	22	drillers	1	Butler
25	55547	10710	432	450	18	drillers	1	Butler
26	54059	9938	536	572	36	drillers	1	Butler
27	36052	1964	468	515	47	drillers	1	Butler
28	20156	5401	306	370	64	Well Log	1	Butler
29	92870	25916	350	392	42	well_ core	1	Butler
30	92873	7732	390	431	41	drillers log	1	Butler
31	105549	4988	358	381	23	drillers Logs	1	Butler
32	105551	23537	375	401	26	drillers logs	1	Butler
33	105553	6325	344	379	35	drillers	1	Butler
34	105555	8665	400	415	15	drillers	1	Butler

35	106775	25917	301	373	72	drillers	1	Butler
36	109110	85390	308	384	76	well log	1	Butler
37	121656	91587	338	388	50	well log	1	Butler
38	127520	96217	304	384	80	Well Log	1	Butler
39	2002732	23823	325	391	66	drillers log	1	Butler
40	2002735	4962	302	377	75	well log	1	Butler
41	2002743	6828	305	381	76	drillers logs	1	Butler
42	2002745	8902	352	382	30	Drillers logs	1	Butler
43	2002747	25918	317	380	63	drillers logs	1	Butler
44	2002748	25919	248	300	52	welllog	1	Butler
45	2002802	5100	360	400	40	well log	1	Butler
46	2003368	4906	327	399	72	drillers log	1	Butler
47	2557	52220	296	348	52	well log	1	Butler
48	55981		541	595	54	drillers logs	1	Butler
49	88621	77386	390	420	30	well log	1	Butler
50	26539	16573	350	430	80	drillers log	1	Butler
51	28416		150	245	95	drillers log	1	Butler
52	28420		157	238	81	drillers log	1	Butler
53	28427		160	230	70	Drillers log	1	Butler
54	53312		265	340	75	drillers	1	Butler
55	53316		58	135	77	drillers	1	Butler
56	53778		199	256	57	drillers	1	Butler