PS An Analysis of a Near-Surface Big Clifty (Jackson) Sandstone Reservoir in Logan County, Kentucky*

Tyler S. Bodine[1] and Michael T. May[1]

Search and Discovery Article #51372 (2017)**
Posted April 24, 2017

*Adapted from poster presentation given at AAPG Eastern Section Meeting, Lexington, Kentucky, September 25-27, 2016

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Abstract

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) is proposed to occur in the Big Clifty. Heterogeneities related to depositional facies changes are poorly understood in Kentucky, where the Big Clifty has been mostly described as a 60-120 feet thick sandstone unit. In some locations, in contrast, such as at the Stampede Mine in Logan County, the Big Clifty occurs as two distinct sandstone bodies with intercalated mud-rich units. Currently no predictable depositional model exists to explain abrupt facies changes observed during open pit mining conducted over the last couple of years.

This study integrates sedimentological, stratigraphic, and geophysical datasets to characterize the lithological changes occurring in Big Clifty reservoirs and may be used as a model down dip into the basin where conventional-oil Jackson reservoirs are targeted. Datasets used in this study include over 30 cores retrieved from across Stampede Mine's acreage, surface-mine exposures, Electrical Resistivity Tomography (ERT) surveys, and bitumen concentration values.

The Big Clifty Sandstone formed in a tidally influenced deltaic system occurring on a low-angle dipping ramp. Shallow marine ichnofacies occur in rhythmically bedded deposits. A brecciated mudstone and red-green shale occurs above the lower sandstone reservoir. This muddy facies represents an exposure surface that separates regressive and transgressive parasequences. Sedimentary features and bitumen concentration vary across the exposure surface making bitumen concentration trends difficult to ascertain without close subsurface control. The extent of channelized sandstone bodies and bitumen-rich units however can be generally documented.

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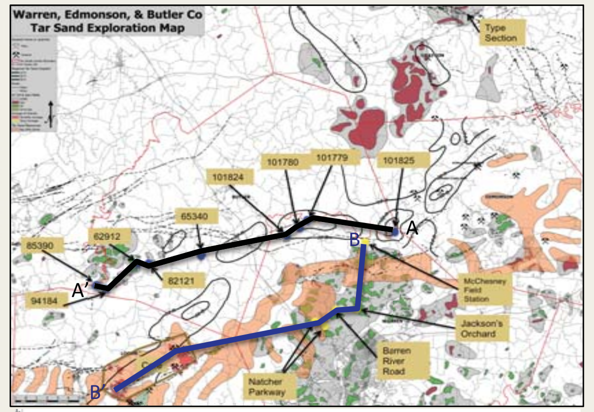
Abstract

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) has 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.

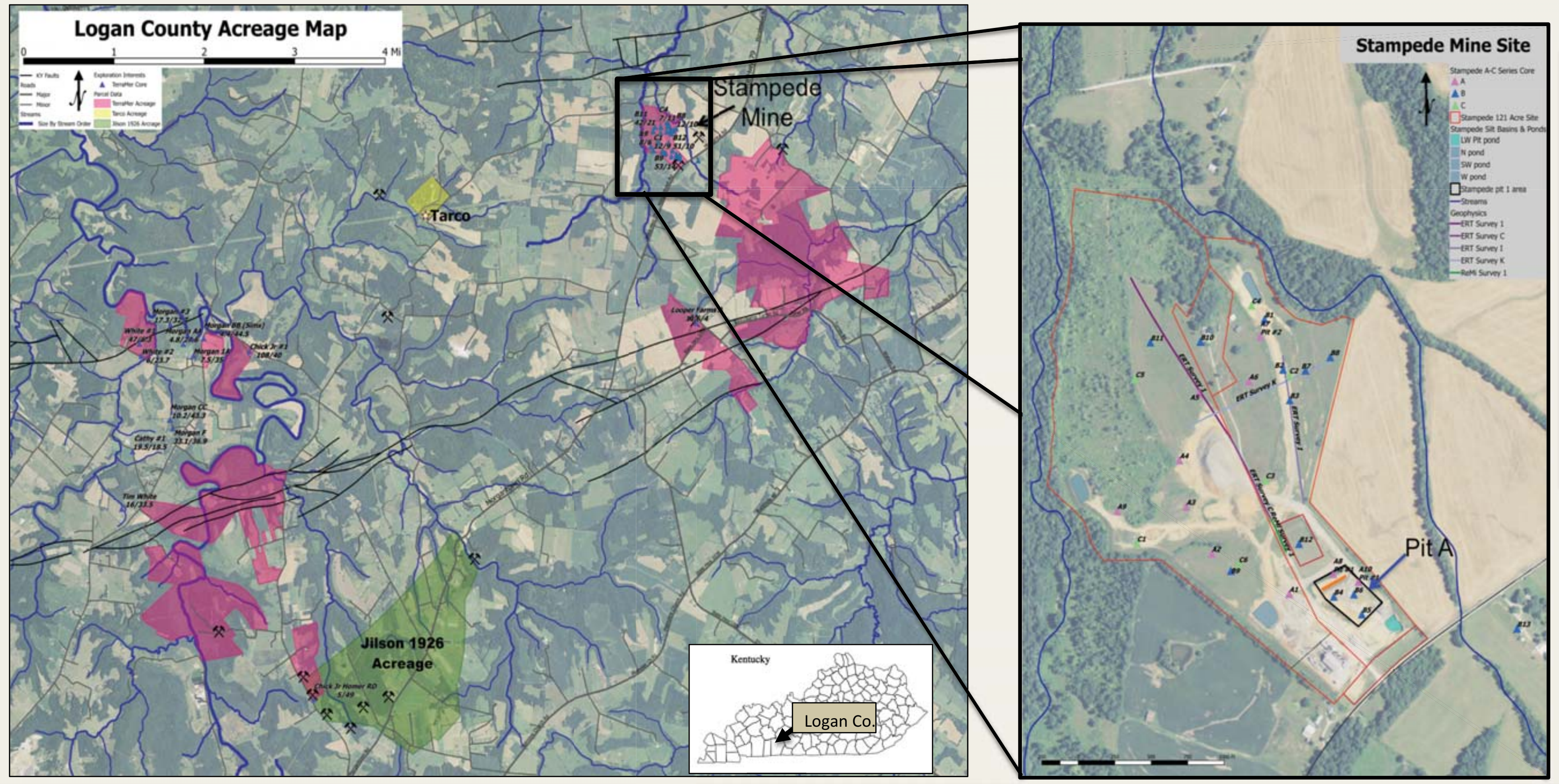
This study couples sedimentary facies analysis with sequence stratigraphy to assess how lithological factors affect the occurrence of petroleum in Big Clifty reservoirs. Multiple datasets were integrated to develop a depositional model for lithologic facies observed in this study. Datasets include core, 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. At the Stampede Mine property in Logan County, ERT surveys were conducted and constrained by core and exposure studies from the surface mining pit. The ERT surveys provide both reconnaissance stratigraphic control as well as a detailed definition of depositional facies that is also bore out by the core and exposure studies. Such surface geophysical methods aided in demarcating Chesterian limestones, sandstone bodies and, in particular, highly resistive heavy-oil laden Big Clifty channel bodies.



Location	Dataset
Logan County • Stampede Mine, ~11 miles NE of Russellville on highway 79 • Wells from Stampede Acreage	*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 Bluegrass Materials Quarry • Jackson's Orchard, Off of Slim Island Road above Barren River • McChesney Field Station, along Indian Creek near Green River	*Road cuts, surface exposures*
Butler County • Multiple Oil Fields • Type Log from 11-H-32 Carter Coor.	*800 Records examined: Drillers logs, core analysis, geophysical logs,*

General Methodology

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 (45-50 km) traverse across northeast Logan and northern Warren counties. Subsurface data from southwest Butler County and western Warren County are also examined and correlated to outcrop and mine data for facies analysis. Thirty thin sections prepared 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 compared. The resulting lithofacies model is used to interpret a log that typifies a conventional Big Clifty oil and gas field in adjacent southwest Butler County.



Bitumen Values At Stampede Mine

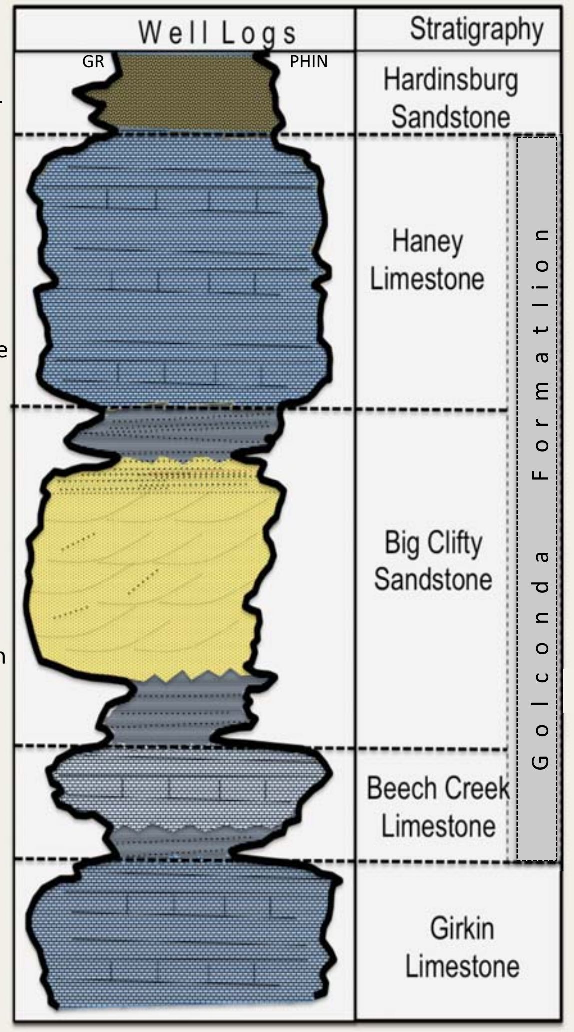
Facies	Facies 6	Facies 3
Number of samples	28	53
Min	1.03%	1.14%
Max	5.21%	6.53%
Mode	3.65%	2.63%
Average	3.30%	3.27%

Laboratory analysis was conducted to gather bitumen concentration information for reservoir facies examined in this study at the Stampede Mine. Bitumen concentrations range from 0 to ~6.5 %, with an average concentration of ~3% for both upper and lower sandstone reservoirs.

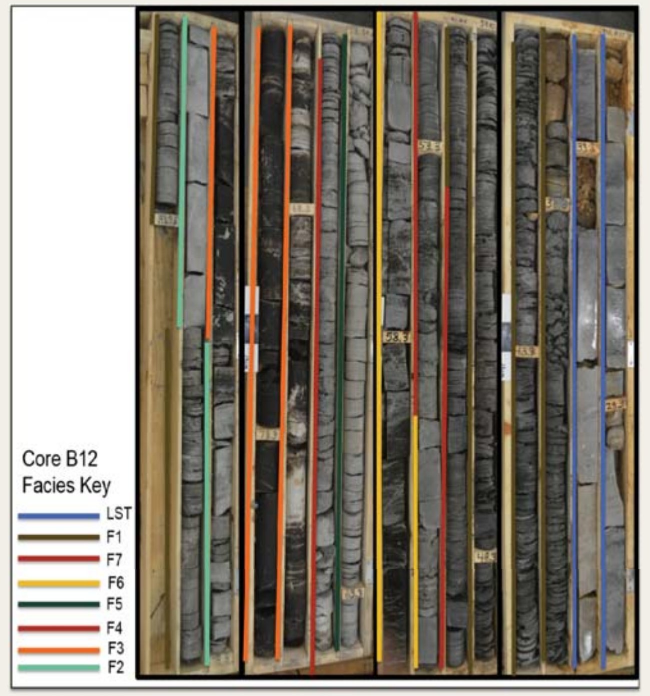
Stratigraphy - Big Clifty Sandstone

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. The unit consists largely of sandstone in western Kentucky, but also contains variable amounts of shale, siltstone, and limestone. Sandstone units are thin (e.g., 0.5-2 ft.) to massive bedded and exhibit cross bedding, ripple bedding, and flaser bedding.

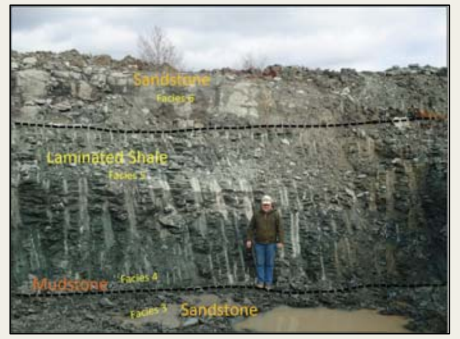
No detailed facies analysis exists for the unit south of the Rough Creek Fault Zone, despite several studies having been completed on the heavy-oil deposits occurring in the Big Clifty Sandstone. Two studies of the Big Clifty Formation facies were conducted near Sulphur, Indiana (Visher, 1980; Specht, 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 (1.2 km) across and 5 miles (8.1 km) long and range in thickness from 20 to 64 feet (6.1 to 19.0 meters). Baker (1980) describes 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 environment of deposition. Upper delta plain or fluvial deposits have not been described in Indiana.



Facies & Petrographic Database from Mine Pit and Coring



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 Ls. which occurs below the Big Clifty Section. Facies 1, 4, 5, and 7 are mud-dominated facies.



Photos showing core and the coring process along with surface exposures from the Stampede Mine. Two surface mining pits were developed at the Stampede Mine.
All cores were slabbed and logged, billets were prepared for thin sections and samples were collected for bitumen analysis. Photomicrographs generated via standard light microscopy methods.

Facies Evaluated in Stampede Mine Area

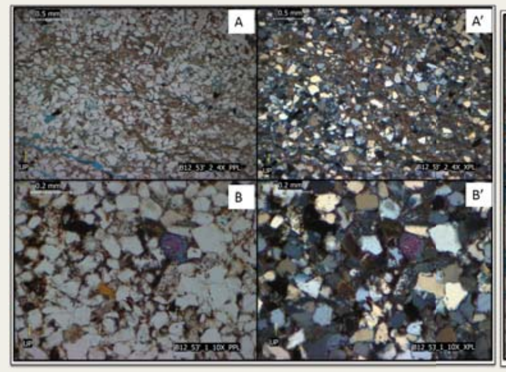
Lithofacies	F-1	F-2	F-3 (Reservoir)	F-4	F-5	F-6 (Reservoir)	F-7
Lithology	Shale	Siltstone, sandstone, shale.	Sandstone	Mudstone, paleosol	Shale, siltstone, sandstone, shale	Sandstone, caliche mudstone	Sandstone, siltstone, shale
Grain Size Texture	Very fine grained to clay size particles	Fine grained 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 Main Pay Zone	N/A	N/A	Poor to moderate bioturbation negatively affects porosity and permeability in this reservoir.	N/A

Facies Analysis Results & Select Reservoir Petrographic Characteristics

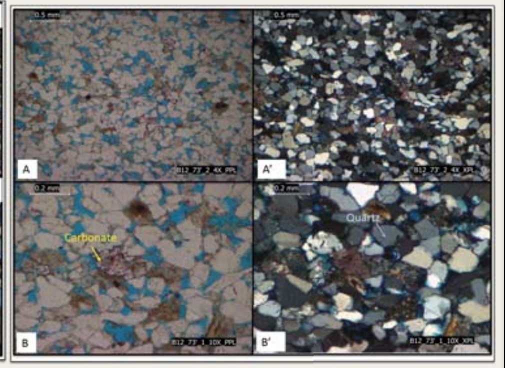
Facies Evaluated in Warren Co.

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

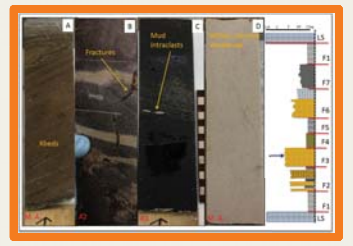
Facies 6 (Upper Reservoir)

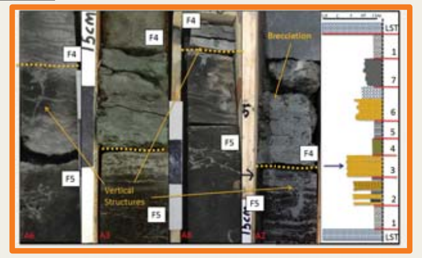


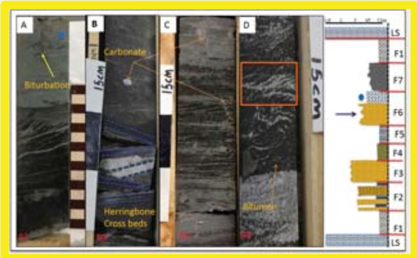
Facies 3 (Lower Reservoir)

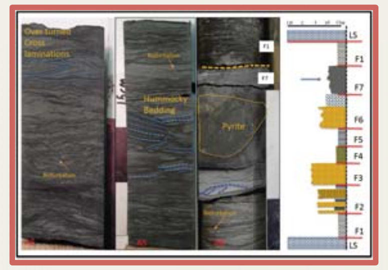


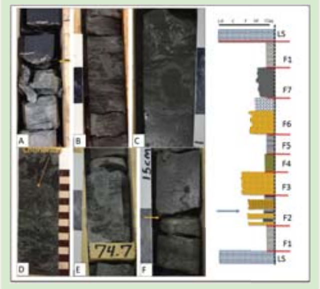
Photomicrographs showing reservoir facies 3 and facies 6 from the Stampede Mine. Thin sections were stained with alizarin red S for calcium carbonate and blue dye epoxy was used to highlight reservoir porosity porosity. The lower reservoir is of higher quality versus the upper reservoir as noted in the photomicrographs.

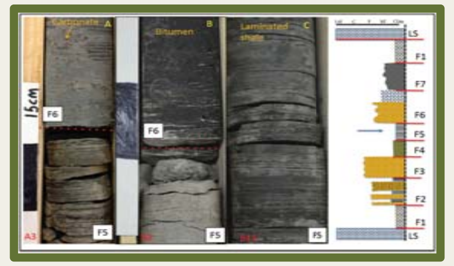


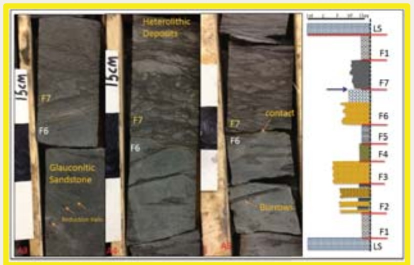


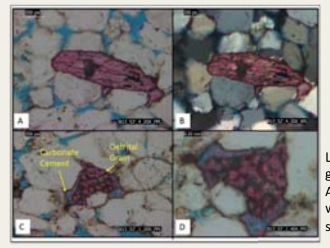






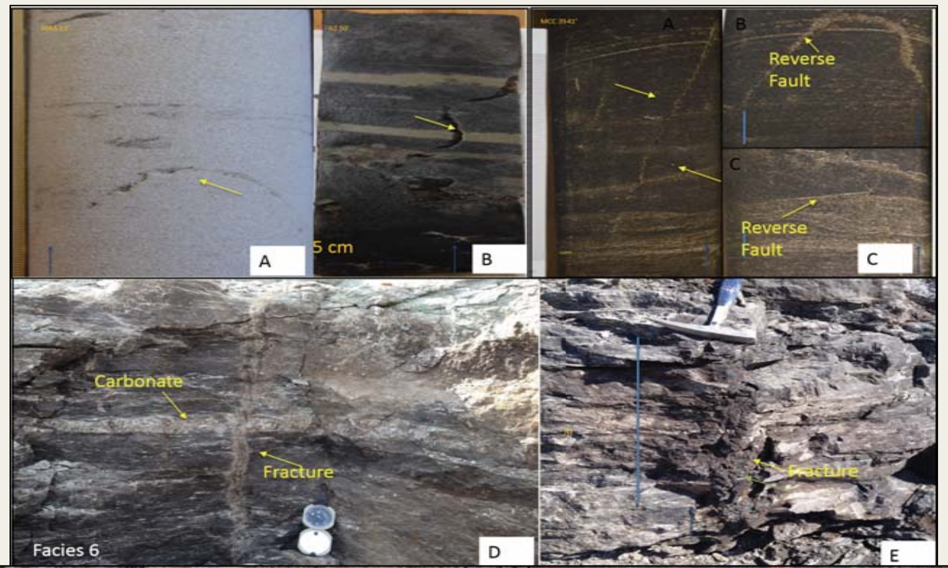


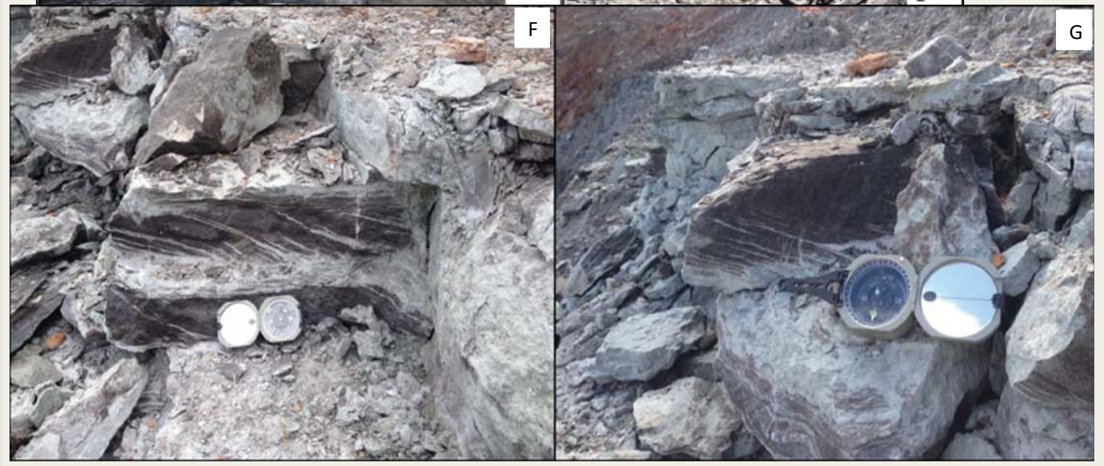


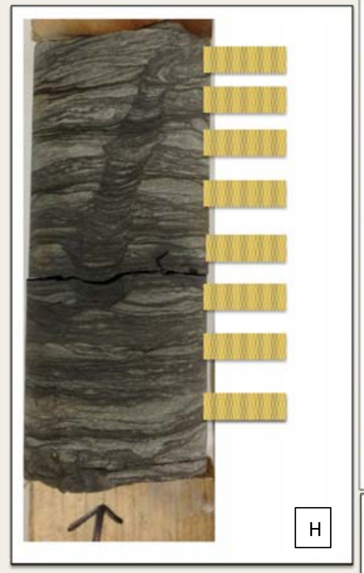


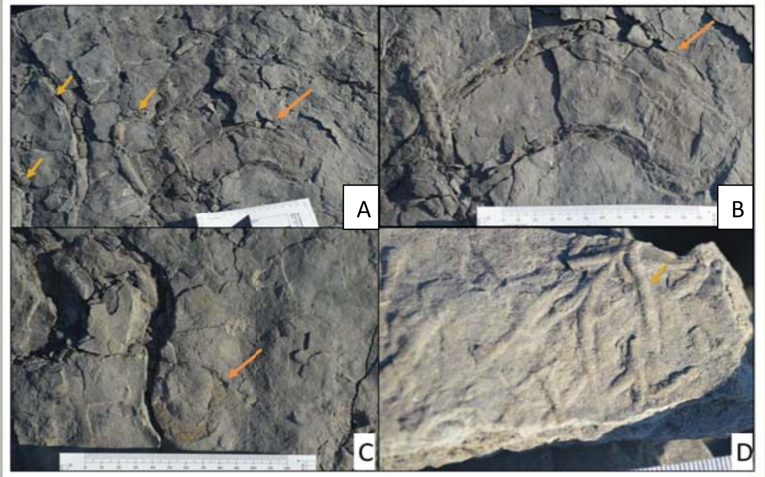
Left: Photomicrographs showing carbonate grains in resevoir facies 3.
Above: Clay seal separating reservoir sands with heavy bitumen staining from sandstone with light-to-no oil staining.

Select Reservoir Ichnological, Sedimentological & Fracture/Fault Characteristics In Stampede Mine Pit







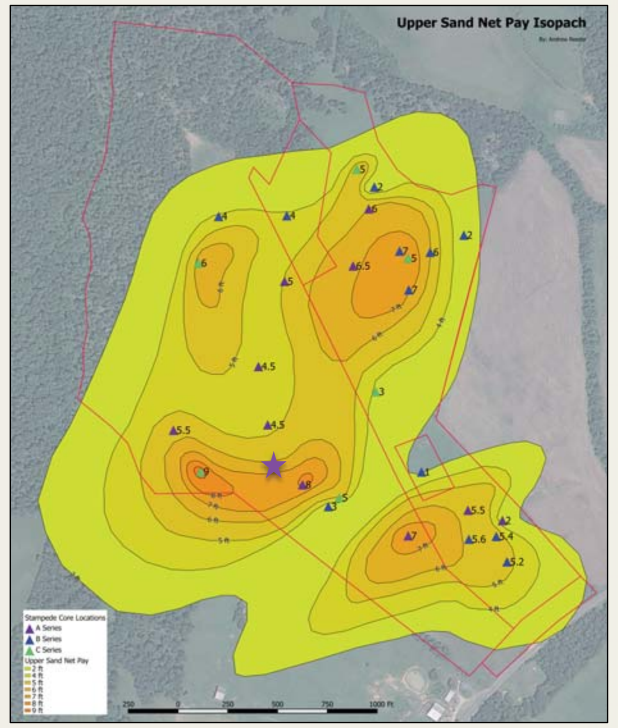


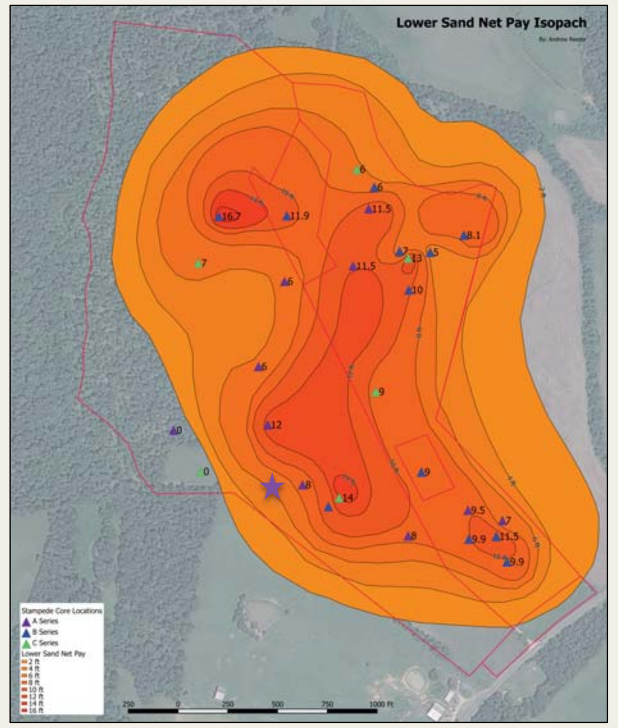
Fractures, small faults and carbonate layers were observed in exposure and in core (views A through E) and provide important clues to original petroleum migration. Crossbedded sandstone in reservoir facies 6 is shown above with reactivation surface (views F & G). Notice how mud drapes partition the reservoir.
Ichnofacies such as *Rhizocorrallium* from facies 7 shown above (view H), are important indicators of EOD. Above is a tidal rhythmite that is crosscut by *Rhizocorrallium*, which is also shown in outcrop (upper right A-D with white boxes). Bioturbation acts as a partition of reservoir facies 6 (lower right – views A-D – plain lettering), where burrowing-like traces occur.

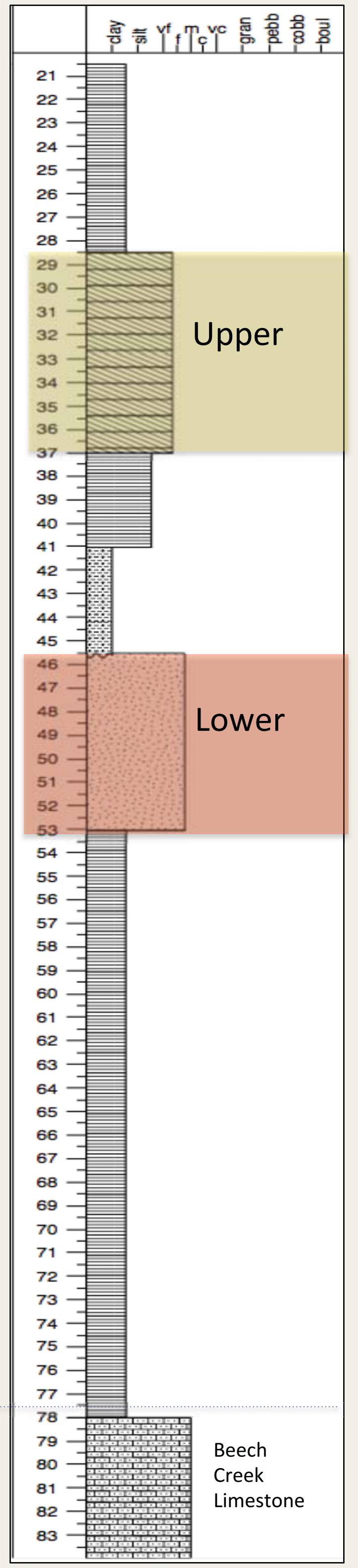
Exposure Surface & Pedogenic Horizon

Paleosols (A) and flooding surfaces (B) are key for the sequence stratigraphic interpretation of Big Clifty sandstone deposits. Paleosols consist of red and green mudstone that is commonly brecciated with slickensides. Paleosols occur atop channel sandstone deposits (facies 3).
A flooding surface occurs on top of reservoir facies 6, and can be traced laterally across the mine site. Below this surface, reservoir 6 sands lack bitumen,are bioturbated, and are glauconitic. These features along with desiccation features and absence of carbonate, suggest that facies 6 formed in an intertidal environment. Such features sharply contrast with the flooding surface shown here (B).

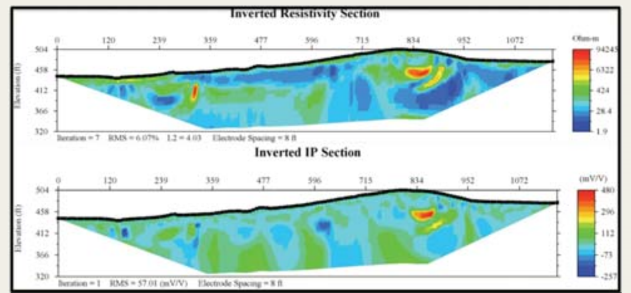
Net Sand Isopach Maps

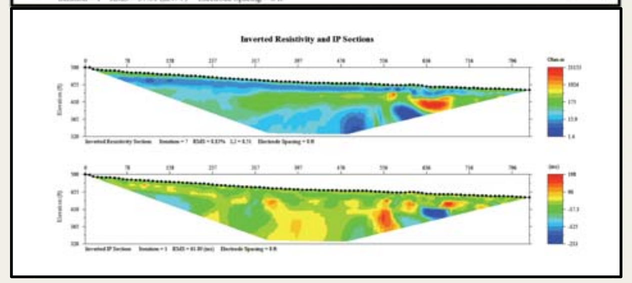




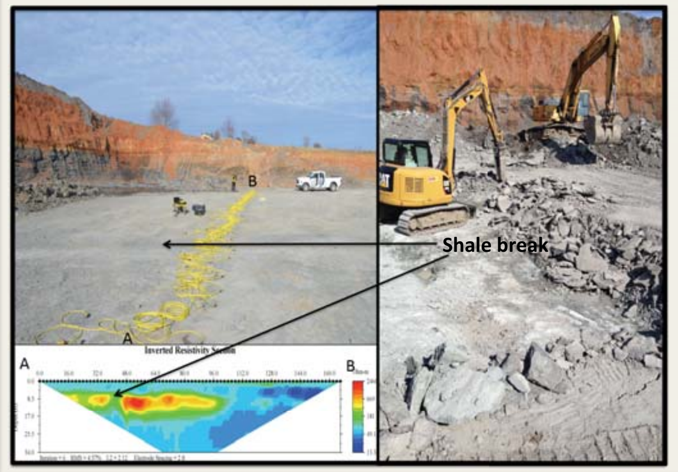


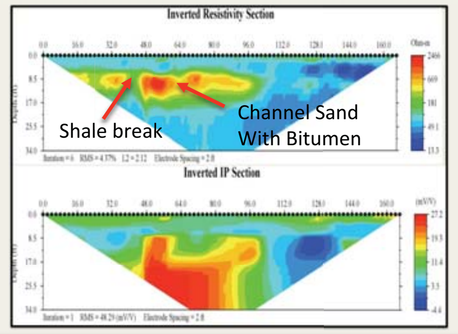
Geophysical Surveys – For Reconnaissance and Pit Mining





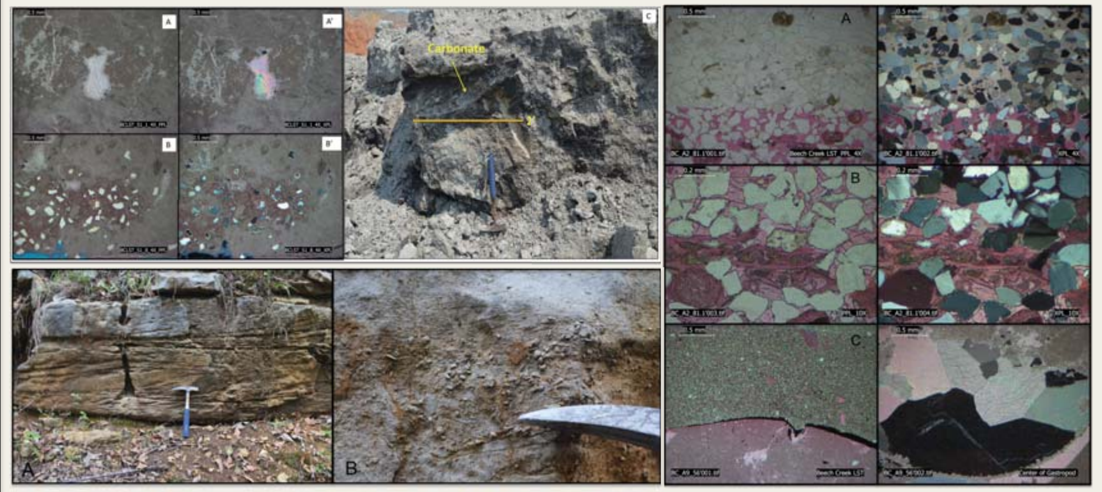
Electrical Resistivity Tomography (ERT) is a technique that measures the resistance to electrical flow according to Ohm's Law. This technique was applied at the Stampede Mine by consulting geophysicists from Northern Kentucky University. This group collected and processed data during field excursions and presented their findings in two reports to the mine operators and geologists. Data from these reports were used in this study and aided in constraining the stratigraphic context away from the mine pit and also aided in interpretation of core and outcrop data. The collection such 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 shown on site map in the first panel. The most important transect to this study was the one 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 that was mined.





Outcrops of Select Facies Away from Mine

Carbonate Partitions in Big Clifty

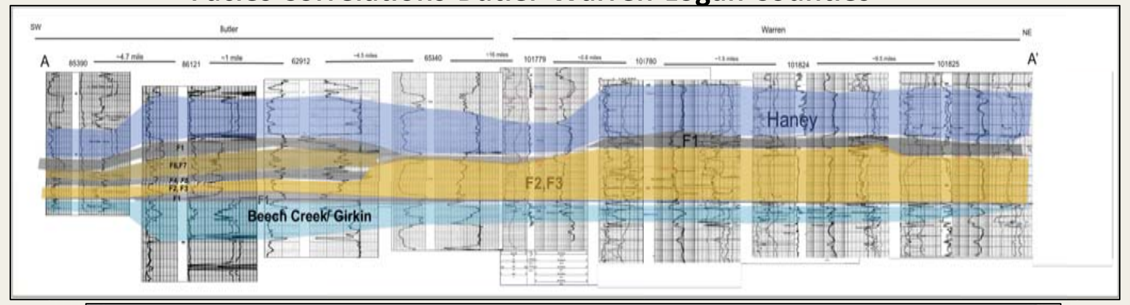


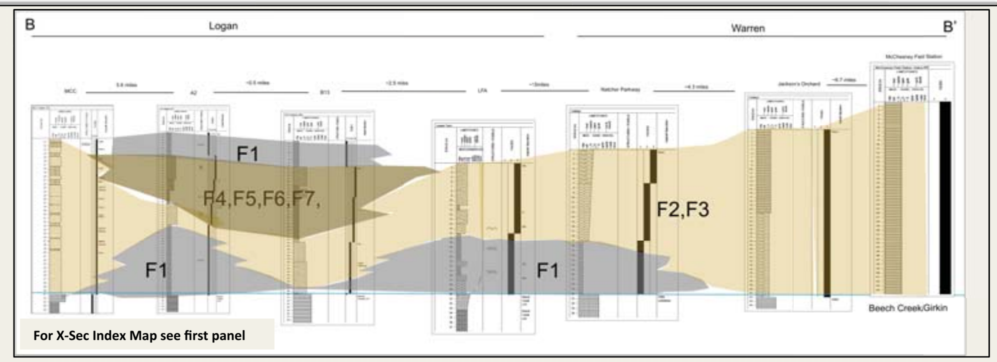
Limestone in the Big Clifty Sandstone occurs primarily in facies 6 (shown above), commonly along or intercalated with sand-unit bedding planes. Photomicrographs of Big Clifty carbonate units reveal carbonate mud, caliche, and silt-sized grains. Some quartz framework grains have even been partially replaced by calcite. During coring operations, Chesterian limestones become important stratigraphic markers, as stacked heavy-oil reservoirs make the positive identification in the field difficult.

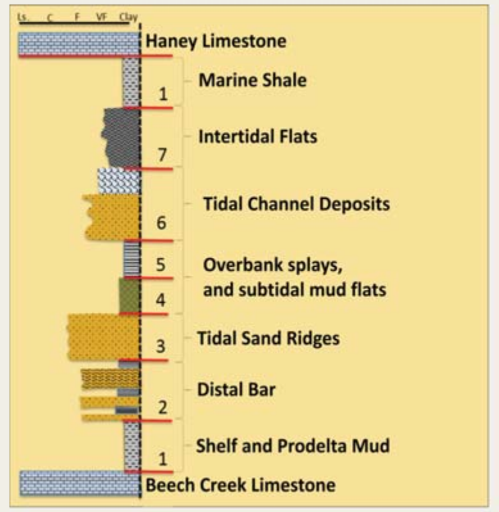
Acknowledgements

We would like to thank the Stampede Mine (TerraMer) for access to the mine. We are greatly appreciative of the help of Andrew Reeder of Bowling Green, Kentucky, Thomas Brackman and students at NKU, and Bill McKenzie of Calgary, Alberta.

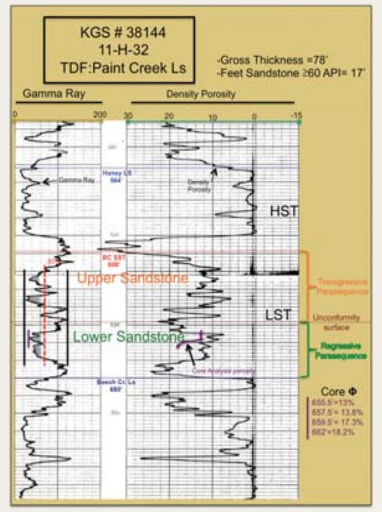
Facies Correlations-Butler-Warren-Logan Counties







Idealized Stacked Facies Model



Interpreted Sequence Stratigraphy

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 fluctuated. Lithofacies identified in core and outcrop/mining pit, 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. Such a thick sandstone characterizes the Big Clifty type section in Grayson County. The results from this study suggest that the Big Clifty Sandstone in the vicinity of the type section consists of a single regressive unit. Basinward of these locations in southwest Butler and northern 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 a paleosol (facies 4 and 5). The resulting facies model from this study suggests a sequence boundary positioned 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. Fine-grained material greatly reduces the economic viability of processing "ore" with ionic solutions and settling tanks, as observed at the Stampede Mine. A decrease in porosity is observable in well logs possessing 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.

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