Fluid Migration and Accumulation within the Mississippian: Why 2% Oil Cut Here, 15% Oil Cut One Mile Away*

W. Lynn Watney¹

Search and Discovery Article #50953 (2014)**
Posted May 12, 2014

*Adapted from oral presentation given at Mississippian Lime Play Forum, Oklahoma City, Oklahoma, February 20, 2014
**AAPG©2014 Serial rights given by author. For all other rights contact author directly.

¹Kansas Geological Survey, Lawrence, KS (lwatney@kgs.ku.edu)

Abstract

Water cut is a big factor in gauging the success of horizontal drilling in the Mississippi Lime Play (MLP). The contributing factors are related in part to the spectrum of producing lithofacies and reservoir quality encountered that varies laterally and vertically, sometimes dramatically. As the extent of the play has increased, so have the types of reservoirs including conventional tripolite, spiculite, and dolomite reservoirs that may or may not be affected by Pennsylvanian karst. Conventional reservoirs are typically in transition when sufficient oil column is not present to lead to irreducible water saturation, inherently leading to variable water cuts based on height about free water and types of pores that are present.

Unconventional reservoir such as tight, dark organic-bearing dolomitic and silty lithofacies of the “Cowley” are often interbedded the spiculitic and dolomitic conventional reservoirs. These rocks with sufficient oil prone organic matter and thermal maturity can locally become self-sourced reservoirs and possibly charge adjoining conventional reservoirs. Coupled with a thick thermally mature Woodford or Chattanooga Shale and fracturing, a hydrocarbon sweet spot is likely.

The structural history during and after the Mississippian with the development of the Arkoma and Anadarko basins and surrounding uplifts led to early thermal maturity of the Woodford Shale that goes back as far to the early Pennsylvanian. Evidence notable wrench faulting peaked in Atokan and Morrowan time in the Anadarko Basin extending well into Kansas. This dynamic setting lead to reactivation of basement weaknesses with both compressional strike-slip and transtensional faults that appear to closely tied to hydrocarbon migration fairways in the northern Midcontinent.
Fluid Migration and Accumulation within the Mississippian: Why 2% oil cut here, 15% oil cut one mile away

W. Lynn Watney
Kansas Geological Survey
Lawrence, KS 66006
Outline

• Mississippi Lime Play - definition
• Structural history of Arkoma and Anadarko Basin
• Source rocks
• Hydrocarbon migration
• Spectrum of lithofacies and quality reservoir rock
• Conventional reservoir
• Unconventional reservoir lithofacies
• Why variations in water cut?
• Conclusions
Mississippi Lime Play - Definition

Regional Structural Features-Horizontal Wells

Legend:
- Horizontal Oil/Gas Permian
- Horizontal Oil/Gas Missourian
- Horizontal Oil/Gas Desmoinesian
- Horizontal Oil/Gas Mississippian
- Horizontal Oil/Gas Woodford
- Arbuckle Oil/Gas
- Horizontal Oil/Gas Hunton

4,237 Horizontal Completions Thru Feb. 2012

Structure Map from H.G. Davis, 1988

Structure Map
Top of the Arbuckle Group (Cambro-Ordovician)
Contour Interval: 1000/5000 Feet

100 MILES
MLP in southern Kansas

Horizontal wells drilled since January 2011
Mississippian structure (450 ft C.I.) and notable faults
Structural history of Arkoma and Anadarko Basin

– Concurrent and post Mississippian structural setting
– Reactivation of basement weaknesses
– Major wrench fault systems and directed stress into craton
– Affecting maturation of organic matter, migration routes of oil migration, and contributed to trapping of hydrocarbon
– Inherited fractures contribute to well performance
Structures - Ancestral Rockies
Early Chesterian - Late Leonardian deformation

Intraplate fault reactivation is mainly dependent on orientation of (weak) fault zones relative to plate margin... deformation in interior can be represented by simple rheological models (van der Pluijm et al., 1997)

Changing/transient stress trajectories through time

Marshak, Karlstrom, and Timmons (2000)
Ages from Dickinson and Lawton (2003)
Peak Late Paleozoic Tectonism during Morrowan and Atokan

Top of the Early Middle Pennsylvanian (Atokan) Thirteen Finger Limestone
- View to the southeast
- Vertical exaggeration = 18x
- Faults from Rascoe and Adler (1971)
- Blue outline – Extent of Atokan Thirteen Finger Limestone

Evidence for left lateral offset (Budnik, 1986)
- Palinspastic restoration oblique slip (left reverse slip) on the uplift bounding faults (McConnell, 1989)

(Higley, 2011)
Proterozoic correlations – Magnetic Field and Phanerozoic Structures

Total Intensity of Magnetic Field Reduced to Pole overlain with configuration of Precambrian surface

- Correspondence of Phanerozoic structures to magnetic anomalies
- Local and subregional changes in strike and dip appear to closely correlate to magnetic map
- Major influence on lithofacies distribution and sequence characteristics

(Cole, 1976; Kruger, 1999)
Chester Isopach delimiting incised valley system (~100 miles long)

Rhombic horst blocks (reverse faults on south and west flanks)

Incised valley

(Damme, Pleasant Prairie, Eubank Field, Cutter Field, Shuck Field)

(Gerlach, Nicholson, DOE-CO2)
Mississippian-U. Orodovician Expansion
Chester incised valley & fracture set

Disrupted beds within the St. Louis interval that are suggestive of karst collapse.

Arbitrary Time Profile B-B', W - E
Pleasant Prairie structural block
Fault orientation-right lateral component along restraining bend

Arbitrary Profile A-A', SW – NE

Morrow to basement isochron

Inferred Karst

MRW
MER
ARBK
PC

2 mi

Hedke (DOE-CO2)
Strike-Slip Faults – flower structures & restraining bends

Flower Structures
Positive (Palm Tree) → Transpression
Right lateral

Modified from http://www4.uwsp.edu/geo/faculty/hefferan/geol320/strikeslip.html
Structural contour map, on top Precambrian surface

- Contours in Kansas and Nebraska modified from Burchett et al. (1981)
- Nemaha fault trace in Kansas adapted from Berendsen and Blair (1992).

Garber Uplift – restraining bend along Nemaha U.
Cluster of current earthquakes near Edmund OK
KGS-OGS Current #1, Pontotoc County, OK

Generalized fault framework of the area encompassing the Nemaha zone

- The Nemaha zone originated by strike-slip movements – right lateral
- Trace of the Nemaha fault adapted from Berendsen and Blair (1992).

Garber Uplift – restraining bend along Nemaha U.

Major NE-trending faults on the top of Mississippian overlying and on the flanks of the Nemaha Uplift

Approximate Meramec subcrop

• Fault zones as splays and resembling flower structures
• Faulting greatly diminished in the overlying Desmoinesian strata with flatter dip
Phanerozoic structures are largely derived by reactivation of basement weaknesses
-- MLP developed on southern rhyolite granite Proterozoic terrane
cross-cut by the Midcontinent Rift System

Magnetic – reduced to pole, overlain with configuration of Precambrian surface (Cole, 1976; Kruger, 1999)
Potential Fields in Sumner County, KS

Wellington Field

Bouguer anomaly values, gridded with a two-pass, 8-directional gridding algorithm & second-order polynomial surface.

Reduced to the pole using inclination of 65 degrees and declination of 7 degrees.

Sumner County Kansas
Gravity with oil and gas fields

http://www.kgs.ku.edu/PRS/PotenFld/County/rs/sumnerGravOg.html

Sumner County Kansas
Magnetics with oil and gas fields

http://www.kgs.ku.edu/PRS/PotenFld/County/rs/sumnerMagOg.html
Third-order structural residual
Top Mississippian
Sumner County, KS

Wellington Field
(NE-SW trending structural high)

Nemaha Uplift

3.6, 3.3, 3.1, 2.8 earthquakes since mid-December 2013
Sumner County
Magnetic field anomalies delineate discontinuities/faults in the basement

Total magnetic field intensity reduced to pole, 910 meters

Mississippian faults (green)

Wellington Field

Nemaha Uplift

3.6, 3.3, 3.1, 2.8 earthquakes since mid-December 2013

6 mi (9.6 km)

- Mississippian contour interval = 450 ft
- Surface lineaments -- Black lines
West side of cross section crosses major basement faults related to the Midcontinent Rift.

- Tilt angle total magnetic with top Mississippian structure.
- Rust-colored dots are horizontal wells drilled since Jan. 2011.
- Green circles – DOE digital type wells with correlated formation tops.
- Purple squares – Arbuckle commercial-scale CO₂ simulation sites.
- 3.6, 3.3, 3.1, 2.8 earthquakes since mid-December 2013.
Major basement fault represented by flexure and faulting in the overlying Phanerozoic strata

Proterozoic magnetic-rich Granite intrusive (as per R. VanSchmus)

Proterozoic Rift Fill (arkosic sandstone)

SW-NE Structural Cross Section
Lower Pennsylvanian to Arbuckle and Proterozoic sediment (MRS fill)

On-the-fly cross section tool from mapper

J. Victorine KGS
Source rocks

– Organic richness, maturity, timeframe of generation

“Cowley facies is likely a source rock”

4003.7 ft dark cored dolomite (x-nic)
Hydrocarbon migration

– Proximity of source rocks, timing and mechanism of HC migration
Elevated thermal maturation in NE Oklahoma and along the NE edge of the Anadarko Basin

Vitrinite isoreflectance map of Woodford Shale
- Left – Anadarko Basin
- Right --- Arkoma Basin
(from B. Cardott, 2012)
Elevated thermal maturation along NW flank of Anadarko Basin

Burial history curves for the Lone Star 1 Bertha Rogers (A) and Chesapeake 1-24 West Edmond SWD (B) wells in Anadarko Basin

- Generation from the Simpson Group Oil Creek Formation layer source rocks (light green) started about 340 Ma.
- Woodford Shale oil generation about 335 Ma.
- Thirteen Finger limestone (blue) about 300 Ma.

Higher gas-oil ratio in south-central and southwest Kansas
-- early oil migration followed by methane

Tilt Angle Bouguer gravity 2-5 mile filter with oil fields overlay western 2/3rd of Kansas

Strong delineation of inferred basement structure and distribution of oil fields
influence of basement derived fractures and faults

MRS rift axis defined by gravity positive (blue to white) flanked by gravity negative (red) sediment fill

Kansas

Central Kansas Uplift

Spivey-Grabs Field
Conventional reservoir – deposition, diagenesis, and structural setting, hydrocarbon accumulation controlled by capillary pressure (matrix), hydrocarbon column, relative permeability, fractures dictate water cut
  - Weathered chert breccia, tripolilitic chert, porous dolosparite, spiculite

Unconventional reservoir lithofacies –
  - Argillaceous dolomitic cherty argillaceous siltstones.
  - Tight rocks tight rocks interbedded with porous nodular chert and spiculite
  - Organic bearing and local source rock
Eastern Oklahoma
Basinal lithofacies in western Arkoma Basin and ramp & carbonate platform on Ozark and NE Anadarko Shelf

Wellington Field
Sumner Co, KS

Cherokee Co., KS

Mississippi Lime Play

Anadarko Basin

Arkoma Basin

Caney Shale gas

KSG-OGS Current #1 cored from Top Chester Caney Shale to Devonian Limestone

Northcutt and Campbell (1995)
Pittsburgh and Midway Coal Co. #12 Test Hole, Cherokee County
Southeast Kansas
Pennsylvanian to the top of Arbuckle
-- Western flank of Ozark Uplift near Tri-State Pb-Zn Mining District
Can we relate real data seismic amplitude and frequency to reservoir thickness as it has been suggested by the modeling?
Mississippian oil reservoir (top)
Cored Well, Berexco Wellington KGS #1-32

Top Miss. to Kinderhookian Northview Shale (410 ft)

- Siliceous intercrystalline dolomite (field pay)
- Nodular chert, argillaceous dolosilitite
- Argillaceous dolosilitite
- Spiculite - dolo-packstone
- Argillaceous siliceous dolosilitite (pico/nano darcy perm)
- Vuggy dolomitic spiculite (oil show)
- Tight dolosilitite

Freeware: http://www.kgs.ku.edu/stratigraphic/PROFILE/
KGS #1-32 Wellington: Estimation of permeability based on magnetic resonance imaging (MRIL™) using porosity and T2 center-of-gravity versus core Kmax, K90, and Kvert core permeabilities.

Permeability profile entire Mississippian

120 ft (37 m) low k, argillaceous dolosiltite
TOC ~2%
(caprock, seal)

Sw = 60%

Doveton & Fazelalavi, July 2012
Bottom porosity in dolomitic spiculite in lower Cowley facies with oil show near base of Mississippian KGS Wellington #1-32
Wellington 4029.73 ft (Cowley facies) deep-water, porous and permeable dolospiculite (oil bearing)
Oil column in typical conventional reservoirs requires ~75 ft to approach irreducible water saturation and zero water cut based on capillary pressure curves for common Mississippian reservoirs in MLP.

Mercury injection capillary pressure curves are calculated by TecLog™ using NMR data -- compared to Osage dolomite reservoir at Schaben Fld., Ness Co. from Dubois et al. (2003)

Approaching irreducible Sw
“High bound water saturations in the tripolitic chert have led to difficulty in estimating reserves and determining producible zones. This problem in water saturations is further complicated by difficulty in establishing free water level. While some fields exhibit apparent structural closure greater than 200 feet, the presence of nearly isolated blocks of production within these fields surrounded by nonproductive areas may indicate that there is not a continuous hydrocarbon column and that free water level is independently established for each block”. -- Watney, Guy, Byrnes (2001)
“Cowley facies”
Bercexco Wellington KGS #1-32 (left) & #1-28 (right) (3000 ft northeast of #1-32)

Cross Section Java Appet – J. Victorine, KGS, DOE-CO2
Correlations – regional team (Bittersweet), DOE-CO2
Pierson Ls. Member (Cowley facies) is *organic-bearing and thermally mature* and probably local source rock for MLP.

**TOTAL ORGANIC CARBON**

<table>
<thead>
<tr>
<th>Client ID</th>
<th>Well Name</th>
<th>State</th>
<th>County</th>
<th>Top depth (ft)</th>
<th>Formation</th>
<th>Sample Type</th>
<th>Prep</th>
<th>TOC, wt.%</th>
<th>Verified</th>
<th>Lab Id</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3605.40</td>
<td>Core</td>
<td>NOPR</td>
<td>0.10</td>
<td>3402822662</td>
<td>Penn sh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3738.25</td>
<td>Core</td>
<td>NOPR</td>
<td>0.39</td>
<td>3402822664</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3754.00</td>
<td>Core</td>
<td>NOPR</td>
<td>0.19</td>
<td>3402822666</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3784.50</td>
<td>Core</td>
<td>NOPR</td>
<td>1.87</td>
<td>3402822668</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3937.25</td>
<td>Core</td>
<td>NOPR</td>
<td>0.94</td>
<td>3402822670</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3968.75</td>
<td>Core</td>
<td>NOPR</td>
<td>1.28</td>
<td>3402822672</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>3982.00</td>
<td>Core</td>
<td>NOPR</td>
<td>0.60</td>
<td>3402822674</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>4024.00</td>
<td>Core</td>
<td>NOPR</td>
<td>0.21</td>
<td>3402822676</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>4048.50</td>
<td>Core</td>
<td>NOPR</td>
<td>1.11</td>
<td>3402822678</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>4059.75</td>
<td>Core</td>
<td>NOPR</td>
<td>0.69</td>
<td>3402822680</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berexco LLC Wellington KGS No. 1-32</td>
<td>4065.50</td>
<td>Core</td>
<td>NOPR</td>
<td>1.59</td>
<td>3402822682</td>
<td>MSSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Compilation of Hydrocarbon Source-Rock Analyses for Wells in East-Central and Northeastern Kansas, and adjacent areas in Missouri and Nebraska**

by K. David Newell (Kansas Geological Survey, University of Kansas, Lawrence, KS, 66046-3738), August, 2013
Local HC maturation in Woodford Shale and “Cowley facies”

- Potential for charging along fractures
- Displace water
- Increasing oil cut
- Locally, continuous HC column???
Prototype index map of type logs & Index for SW to NE Cross Section in south-central Kansas

Type wells = deep wells with digitized modern logging suites

Wellington Field

~25 mi

KS-OK Line

75 miles

J. Victorine, KGS
Boggs SW Field
Barber Co. (gas, P&A)

SWD well
Harper Co.

D&A
Sumner Co.

Wellington KGS #1-28
Sumner Co.

Gas, P&A

75’SOCM & GO

Pierson? 

Compton & Northview

“Cowley facies”

200 ft

Mississippian

Complex lithologic changes in Mississippian Reservoir

Datum = sealevel
Total length of section ~75 mi
No horizontal scale

Index map on previous page

Cross section Java applet, J. Victorine, DOE-CO2
UNGER FIELD HORIZONTAL FRACTURE SETS WITH WATER
Horizontal Well
American Energies Corporation
Slocombe-Rood #1-19
Unger Field
Marion County, Kansas
Thickness of uppermost H3 layer (color fill) with structure top of pay zone (contours)

**NW-SE trending horizontal well - east flank of NW-SE trending structure**

Approximate location of lateral

Max. 12 ft of H3
Horizontal well, nearly depleted **water-drive** Hunton Gp. oil field with untapped oil

--- **Drill-pipe conveyed triple-combo log and cuttings**

<table>
<thead>
<tr>
<th>Depth</th>
<th>3880 ft</th>
<th>4080 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res.</td>
<td>GR, CAL, AHT30, N &amp; DØ Pe</td>
<td></td>
</tr>
<tr>
<td>Lithology</td>
<td>Cluster Groups</td>
<td></td>
</tr>
<tr>
<td><strong>Hunton Pay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Sw</td>
<td>Finely crystalline sucrosic, intercrystalline Ø, poor light brown spotty stain, trace free oil, good fluorescence, cut, odor</td>
<td></td>
</tr>
<tr>
<td>High Sw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sucrosic, fine intercrystalline Ø, light brown spotty stain, free oil, fluorescence, cut, odor</td>
<td>Logs – high Ø &amp; high resistivity</td>
<td></td>
</tr>
<tr>
<td>Finely crystalline, cherty dolomite, no visible porosity, no to poor show, no free oil, fair fluorescence, cut, odor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Water Saturation and Conductive (Open) Fractures from triple combo and microresistivity imaging log

- Fractures trending E-NE intersecting the lateral
- Slotted liner isolate fracs
- Natural completion, ave. 11 BOPD since 2011

Hunton Pay – in interval with fewer fractures and low water saturation

Nearby vertical wells have depleted reservoir due to proximal fracture sets leaving adjoining areas of reservoir untapped.

- Oil on flank of structure may reflect updip truncation of the pay
- Placing lateral oriented NE-SW along less fractured fairway?
Core to Characterization and Modeling of the Mississippian, North Alva Area, Woods and Alfalfa Counties, Oklahoma

Dan Costello1, Martin Dubois2, and Ryan Dayton1

1 Chesapeake Energy Corporation
2 Improved Hydrocarbon Recovery, LLC
Reservoir lithofacies and phi-k relationships

Core to Characterization and Modeling of the Mississippian, North Alva Area, Woods and Alfalfa Counties, Oklahoma

Dan Costello1, Martin Dubois2, and Ryan Dayton1
1 Chesapeake Energy Corporation
2 Improved Hydrocarbon Recovery, LLC
Factors in water cut?

- Prograding and downlapping Osage and Meramec strata along ramp
- Variable pore types along the lateral
- Not simple oil:water contact
- ~135 ft of oil column
- Reservoir pressure, drive?
- Locally charged with thermally mature, underlying Woodford Shale or “Cowley facies”? 
- Fractures? Water or oil?
- How was well completed?
Conclusions

• Mississippi Lime Play - definition
• Structural history of Arkoma and Anadarko Basin
• Source rocks
• Hydrocarbon migration
• Spectrum of lithofacies and quality reservoir rock
• Conventional reservoir
• Unconventional reservoir lithofacies
• Why variations in water cut?
• Conclusions