Review of Hydrocarbon Production from the Stonewall and lower Interlake Formations: Western North Dakota – Williston Basin

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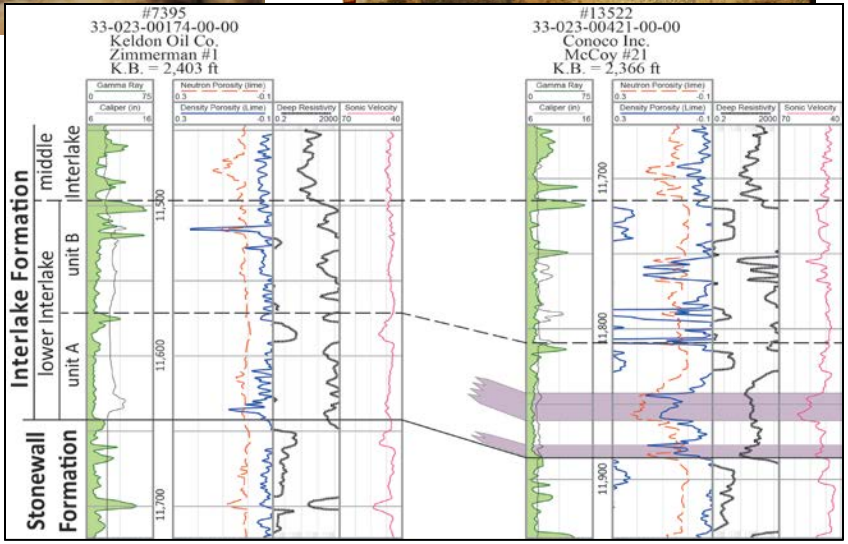
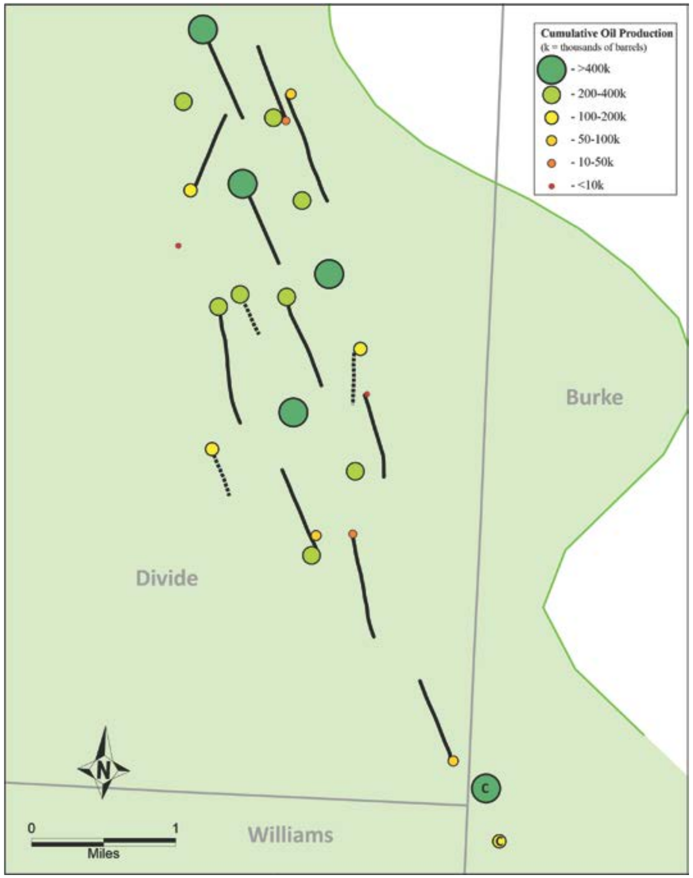
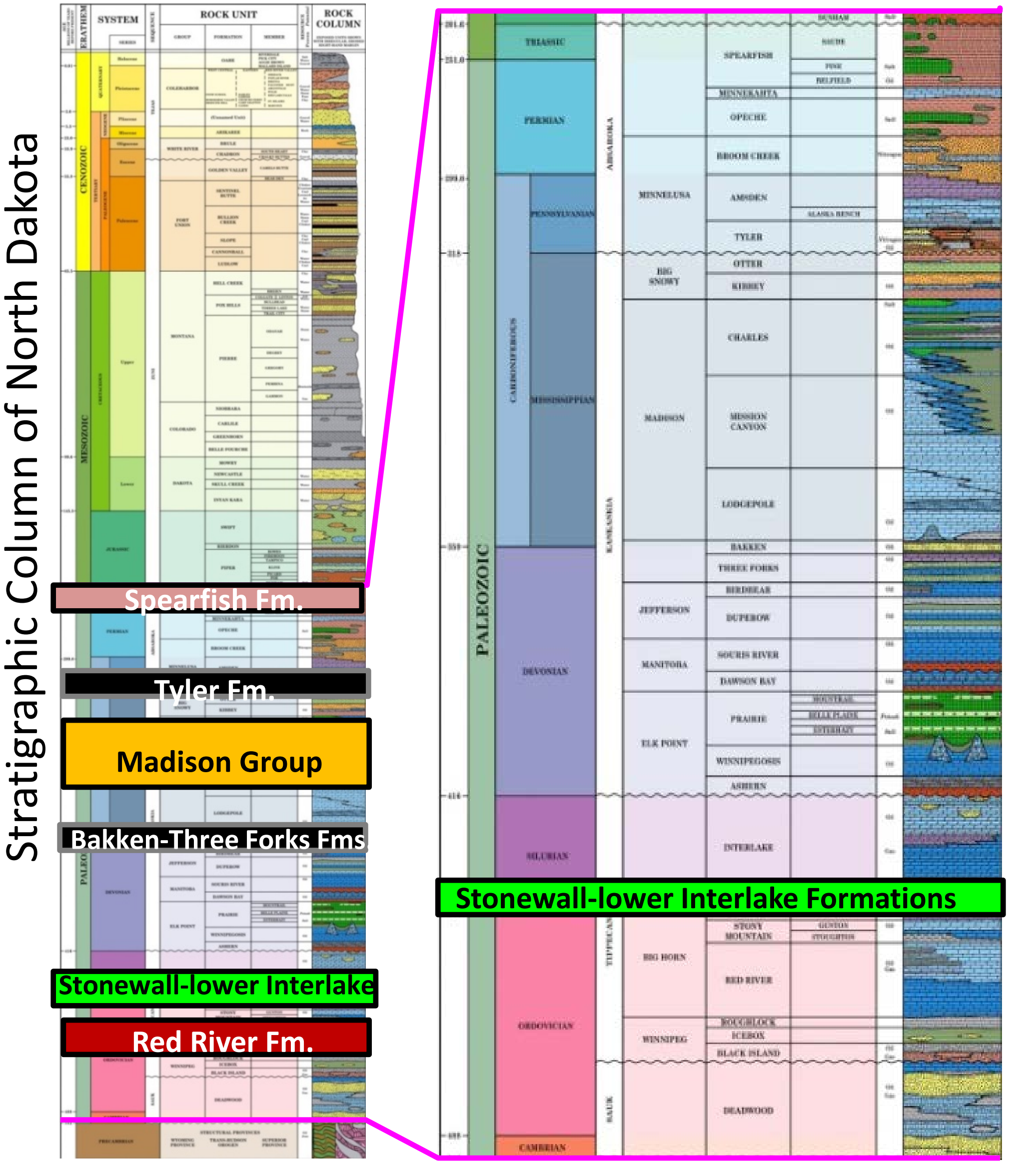
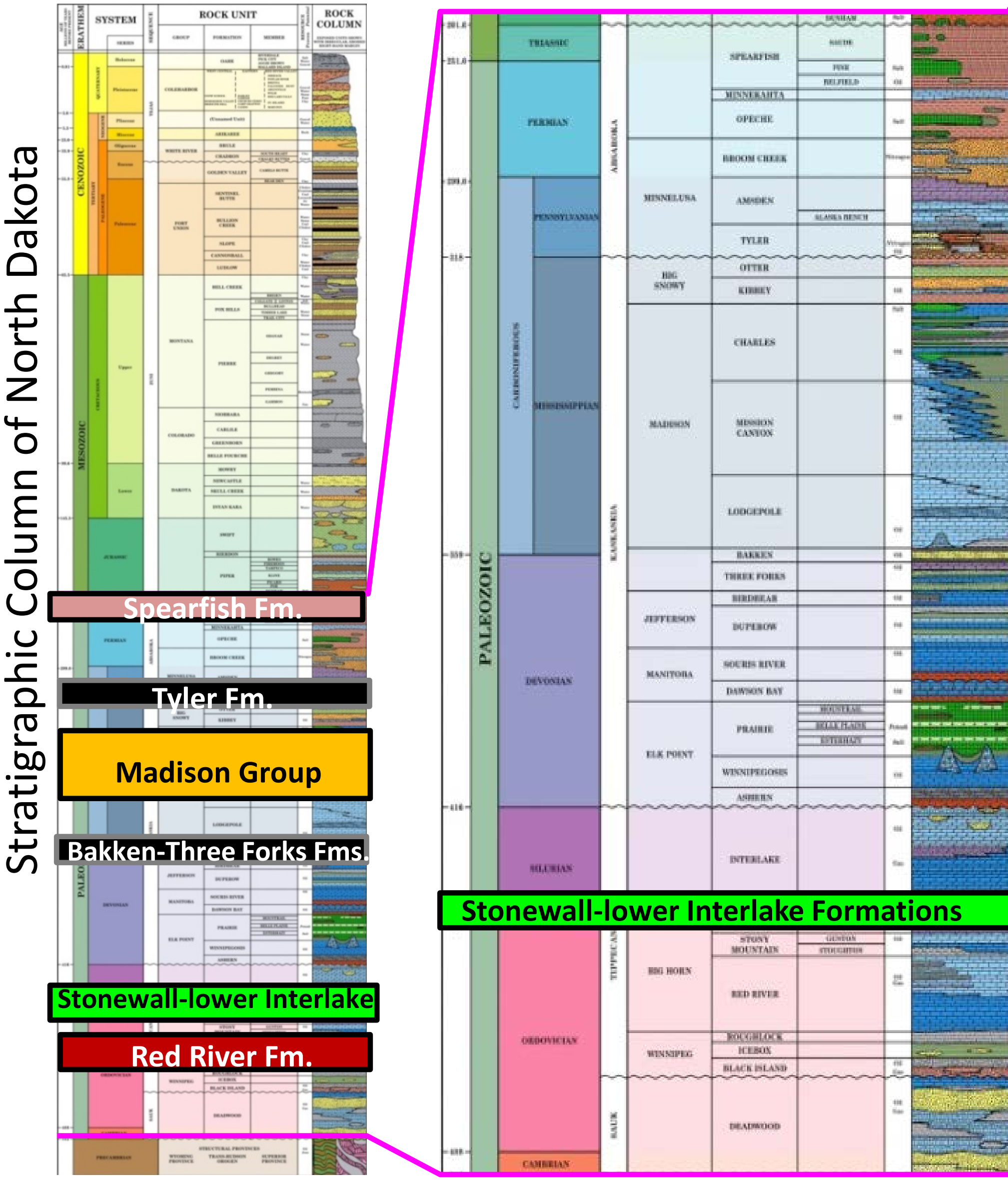




Williston Basin Stratigraphy



Stonewall Hydrocarbon Production



Cumulative North Dakota Oil Production by Formation

5) 86 MMBO - Tyler

2) **1,018 MMBO – Madison***

7) 61 MMBO - Lodgepole

1) **1,952 MMBO – Bakken/TF**

8) 21 MMBO - Birdbear

4) 156 MMBO - Duperow

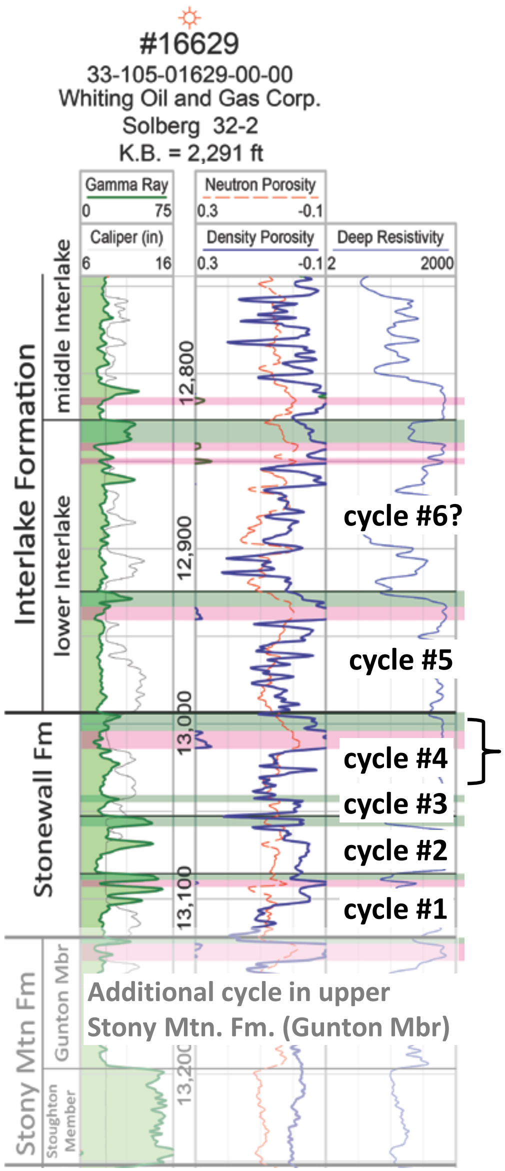
10) 10 MMBO - Winnipegosis

6) 65 MMBO - upper Interlake

9) 17 MMBO – lower Interlake/Stonewall

3) **316 MMBO – Red River**

Stratigraphy

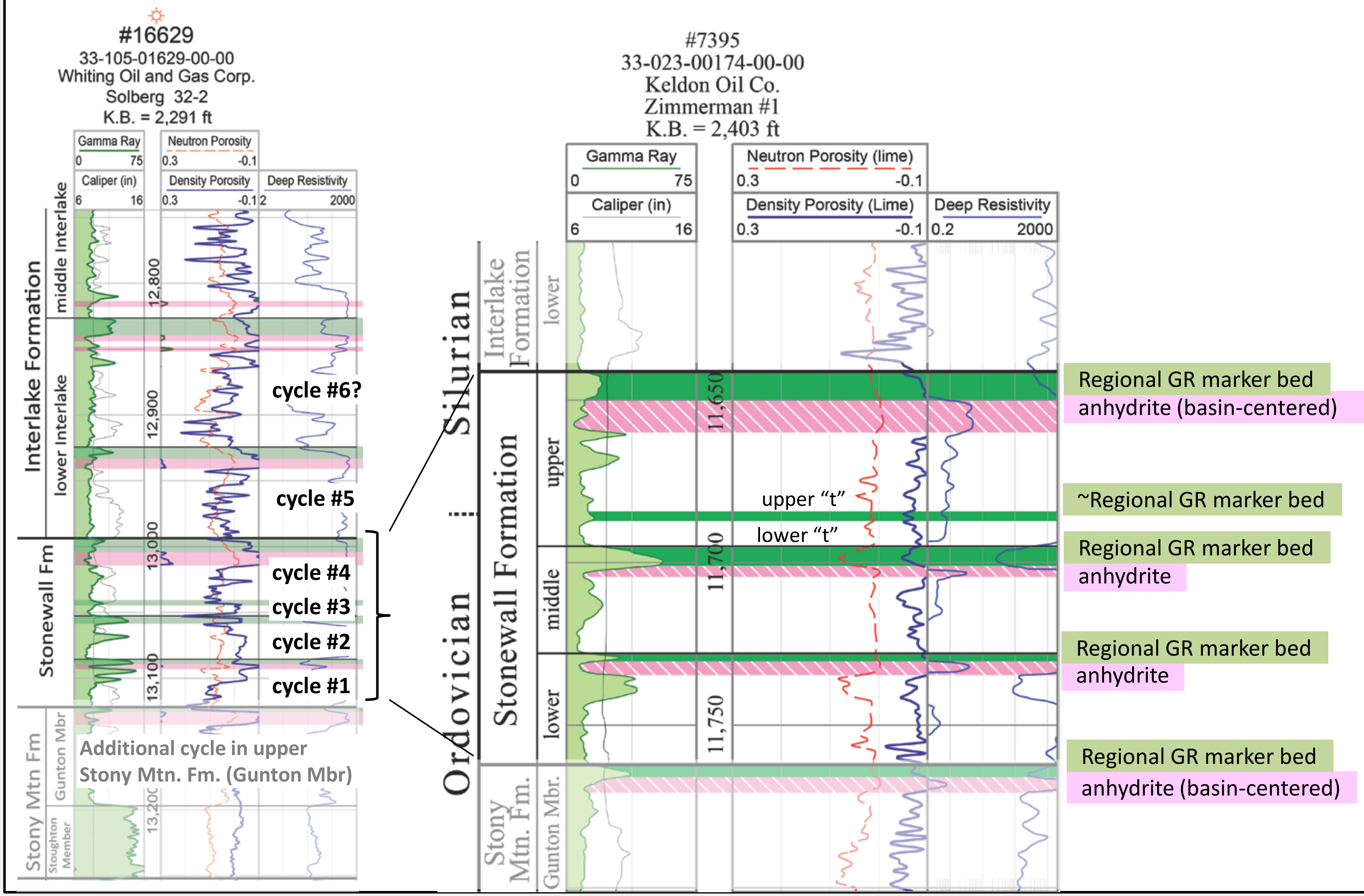


upper Stonewall cycle

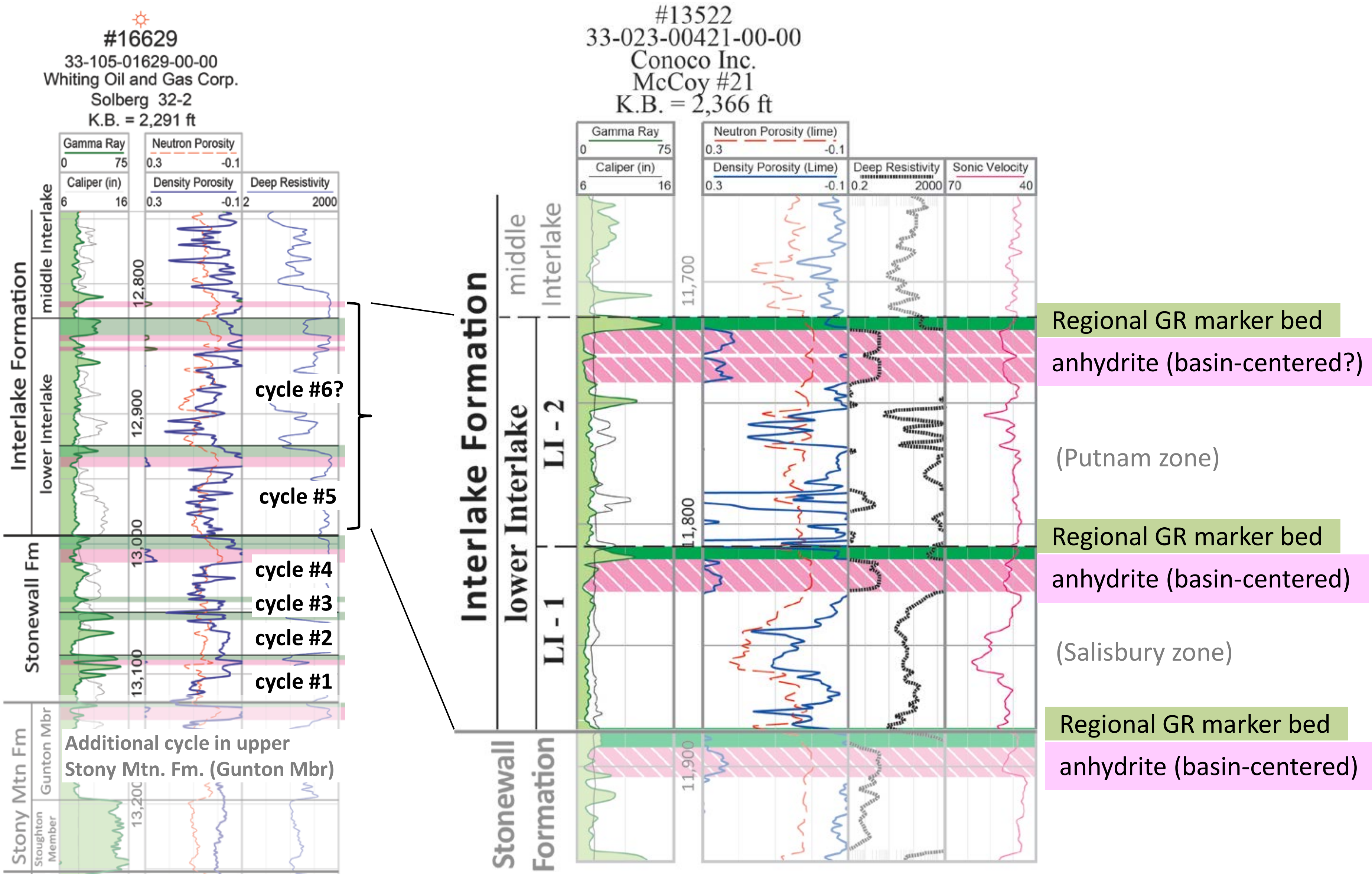
Varies from sandy argillaceous dolomitic mudstone to dolomitic claystone

- Each cycle is composed mostly of carbonate rock capped by nodular to bedded anhydrite and/or silty to sandy argillaceous dolomitic "marker" beds (e.g., upper and lower "t" marker beds).
- However, while all the sedimentation cycles share some commonalities, they also display significant variations from one another both vertically and laterally.

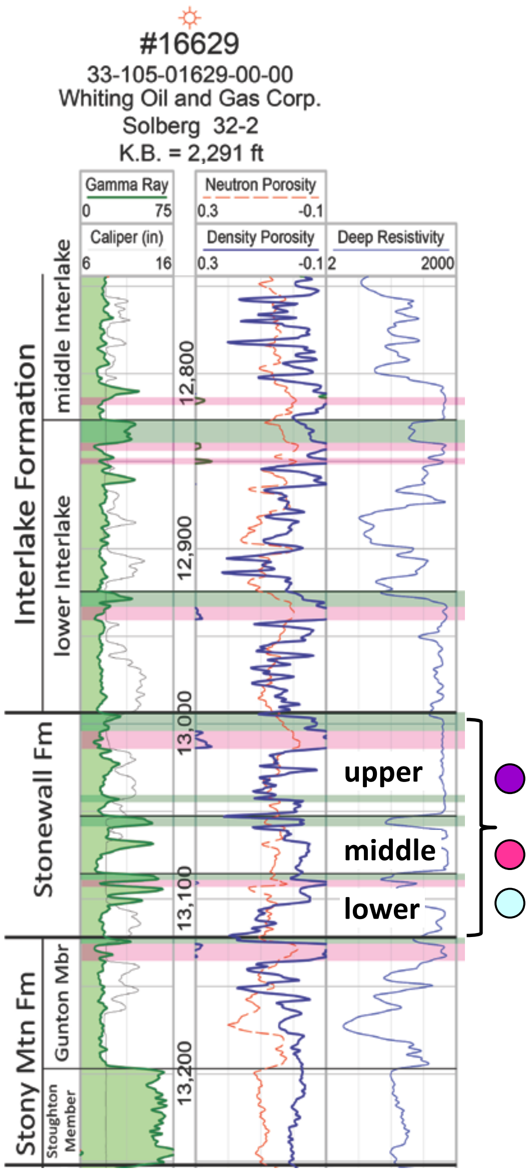
Stratigraphy – Stonewall Formation

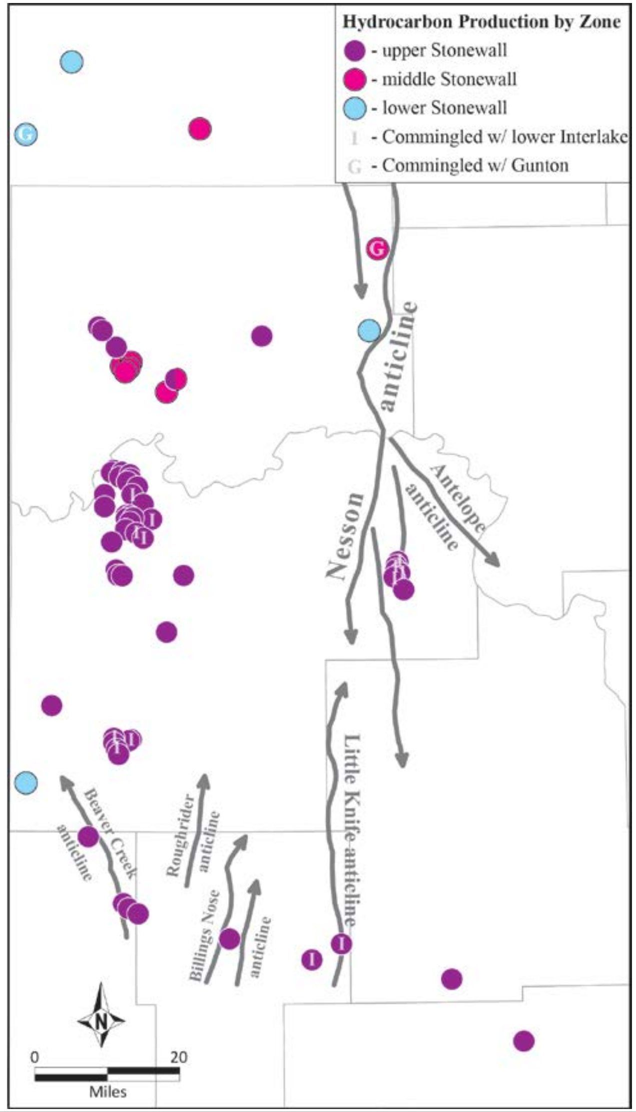


Stratigraphy – lower Interlake

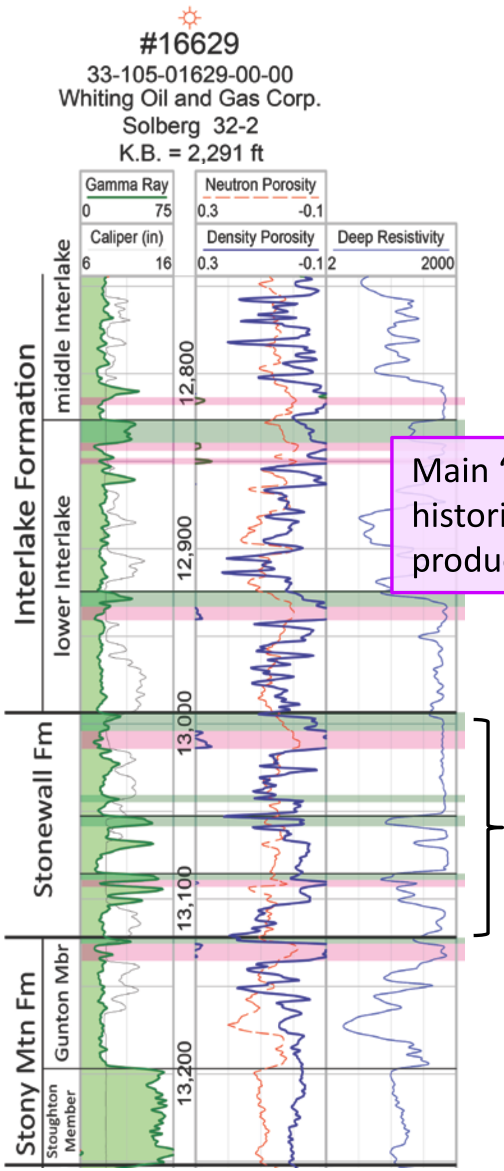


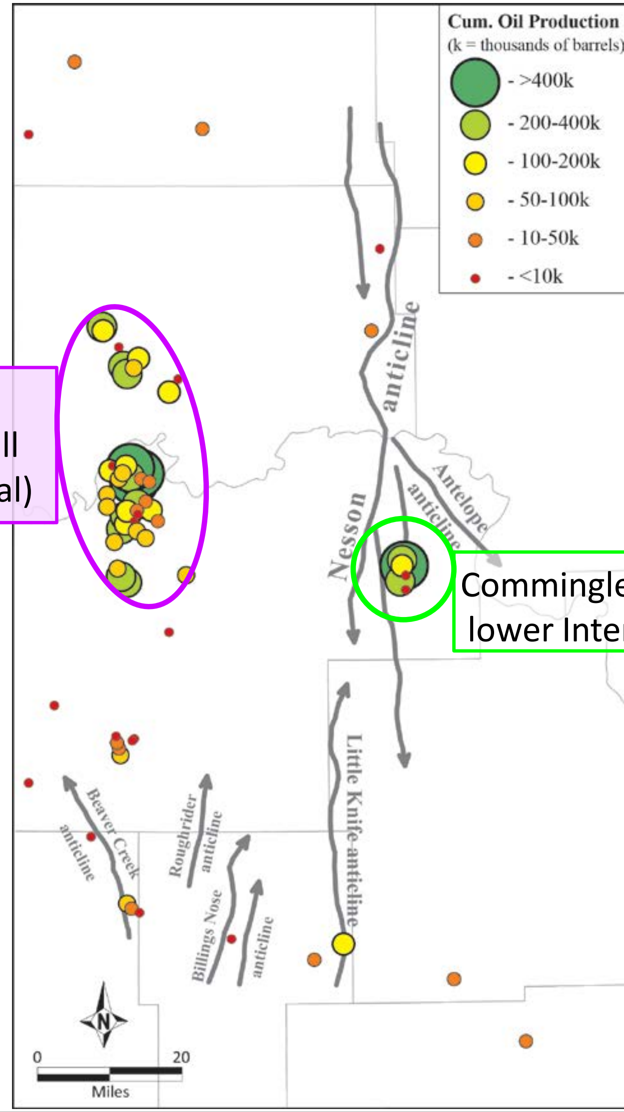
Historical Production Trends: Stonewall Formation





Historical Production Trends: Stonewall Formation

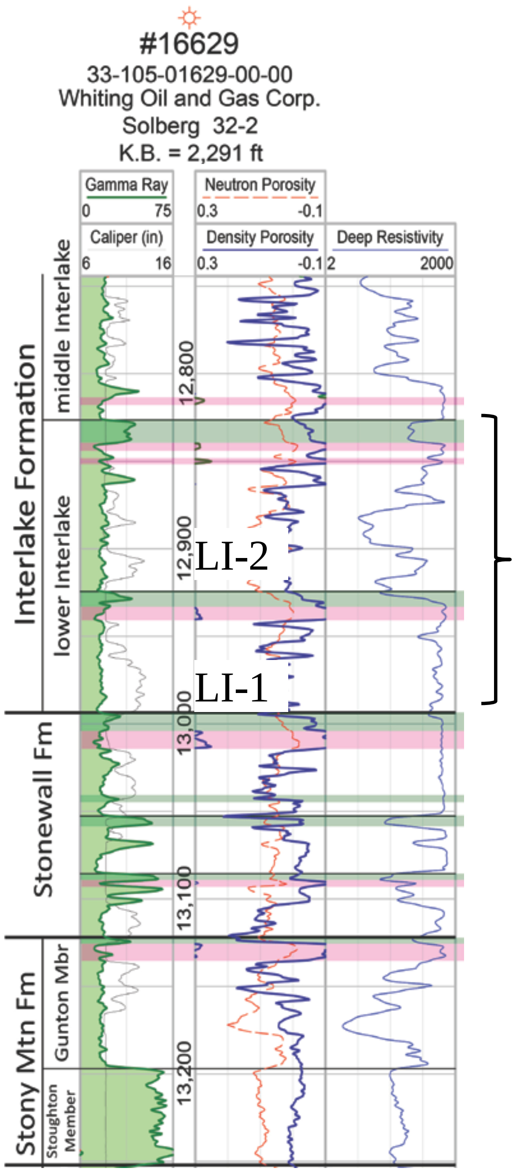


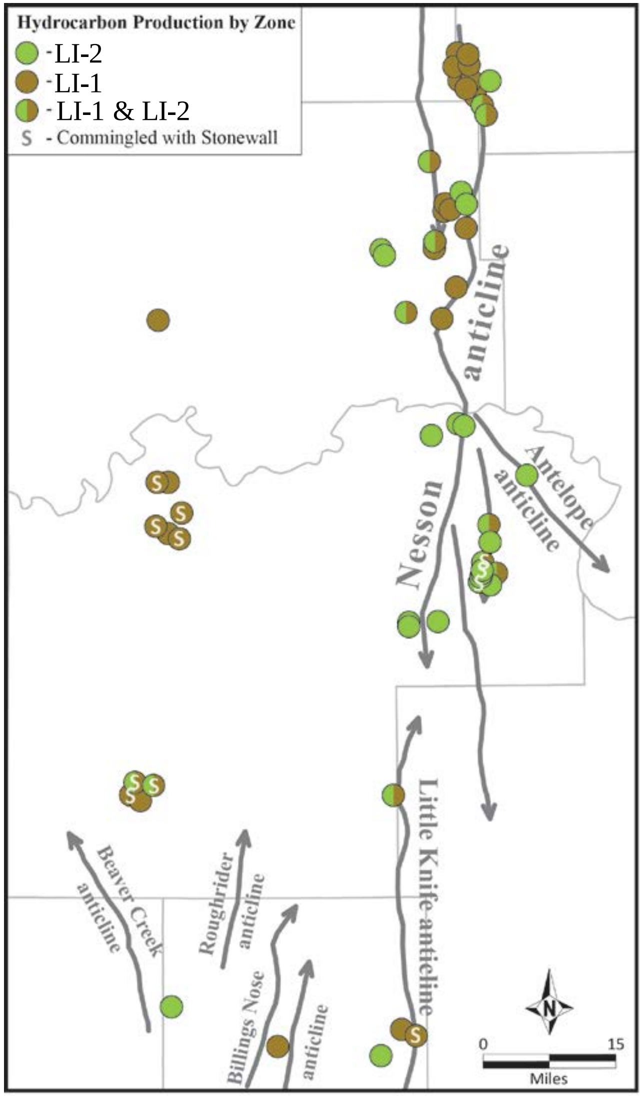


Main "fairway" of historical Stonewall production (vertical)

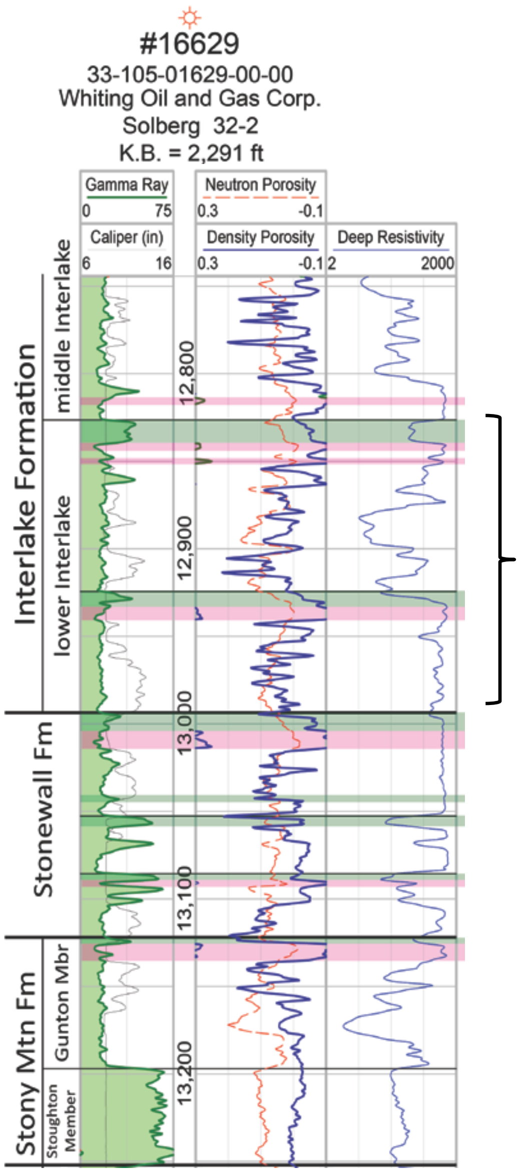
Commingled w/ lower Interlake

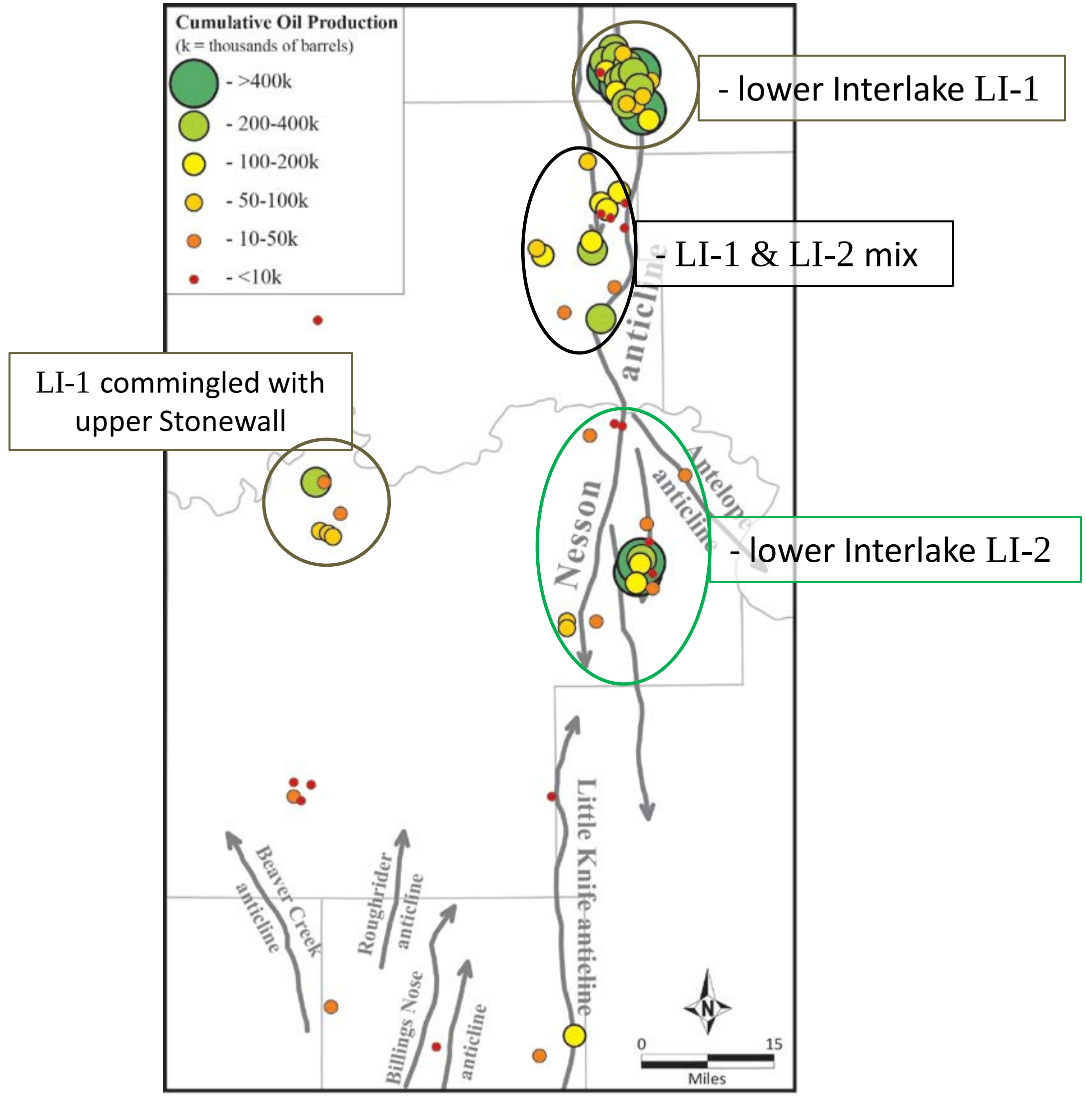
Historical Production Trends: lower Interlake Formation



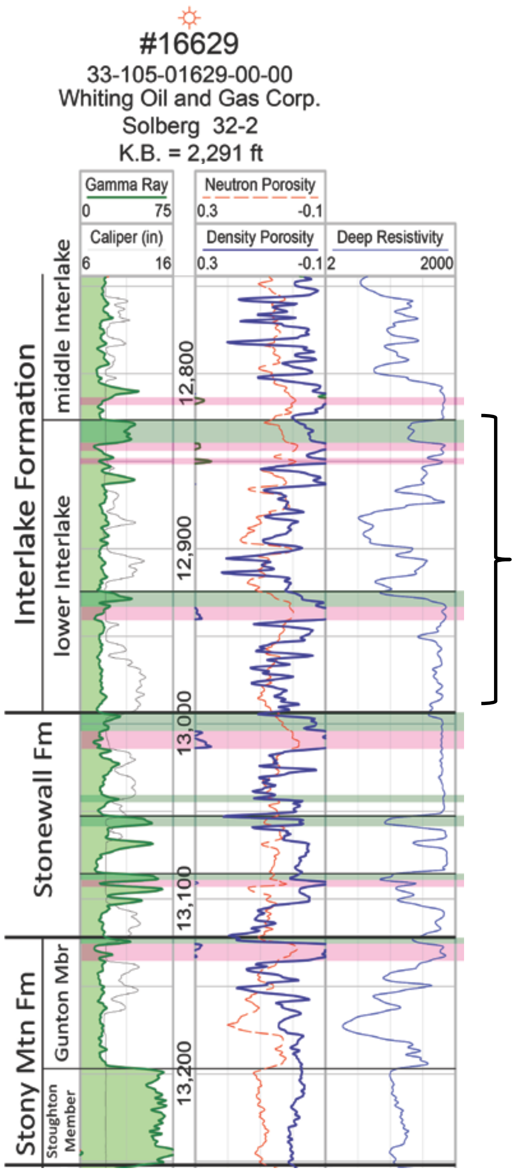


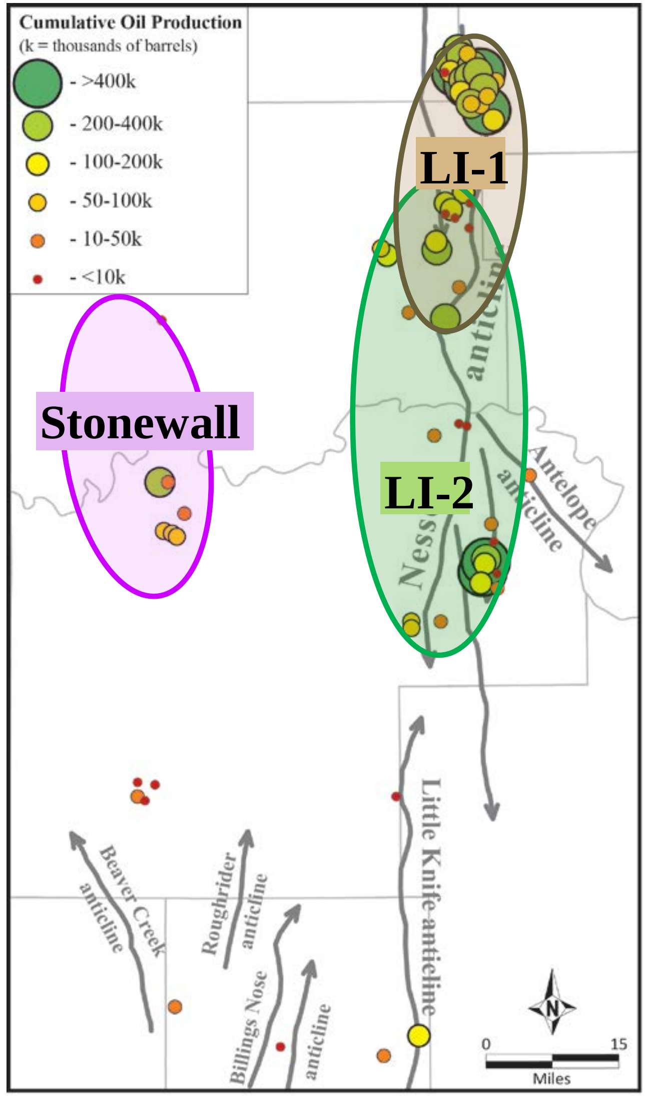
Historical Production Trends: lower Interlake Formation



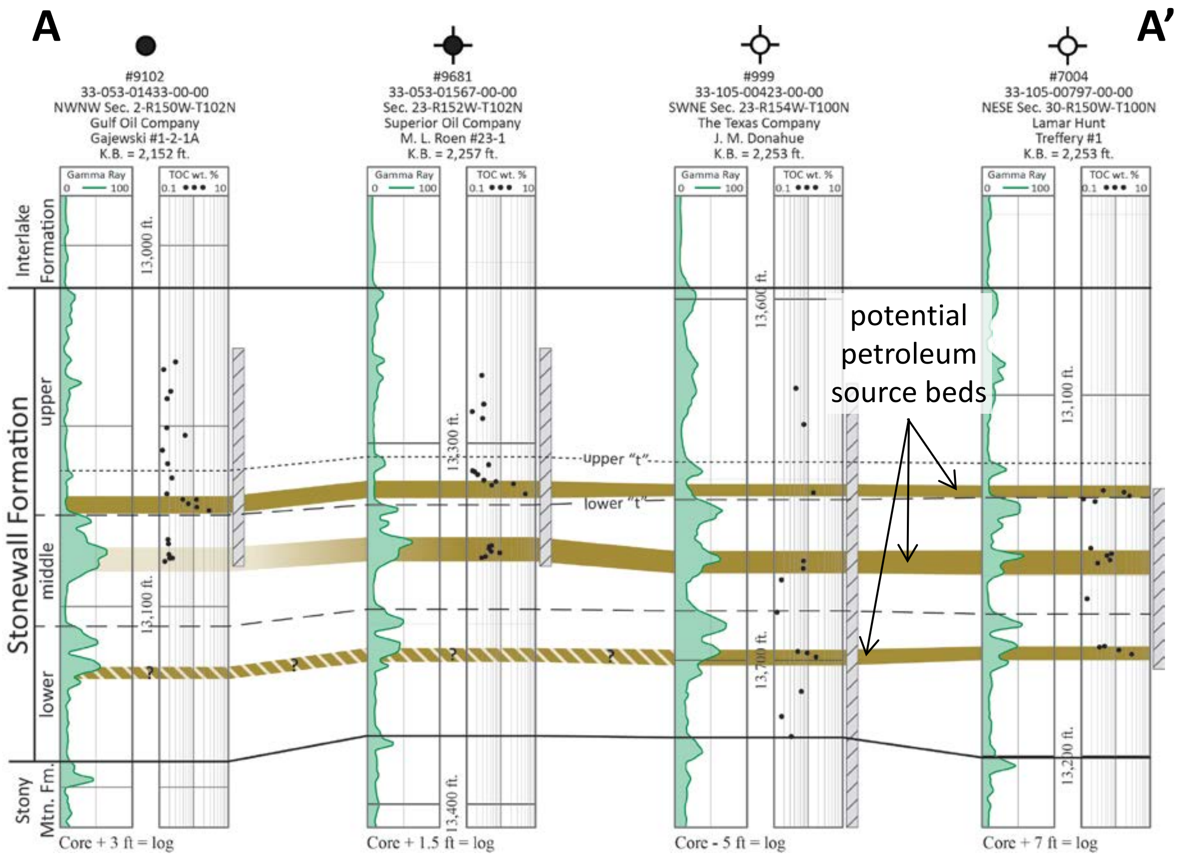


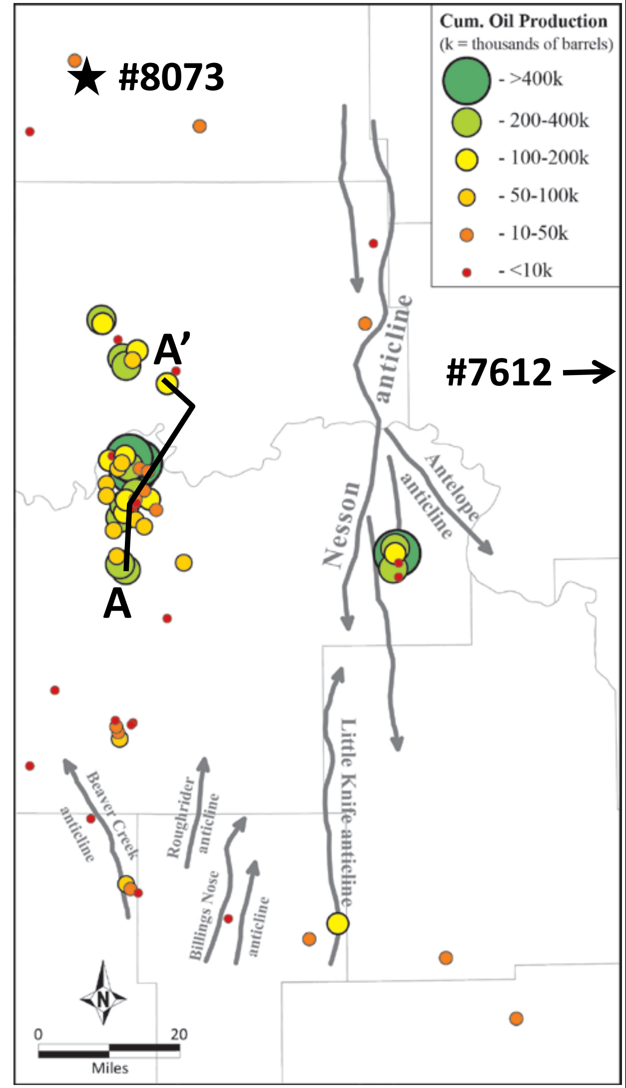
Historical Production Trends: lower Interlake Formation





Petroleum Source Beds - Stonewall Formation



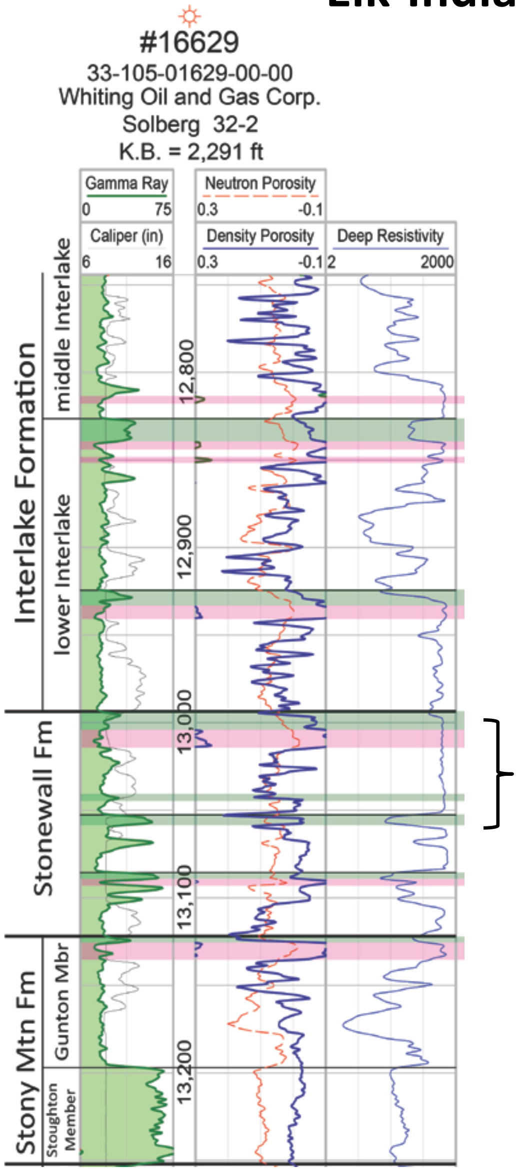


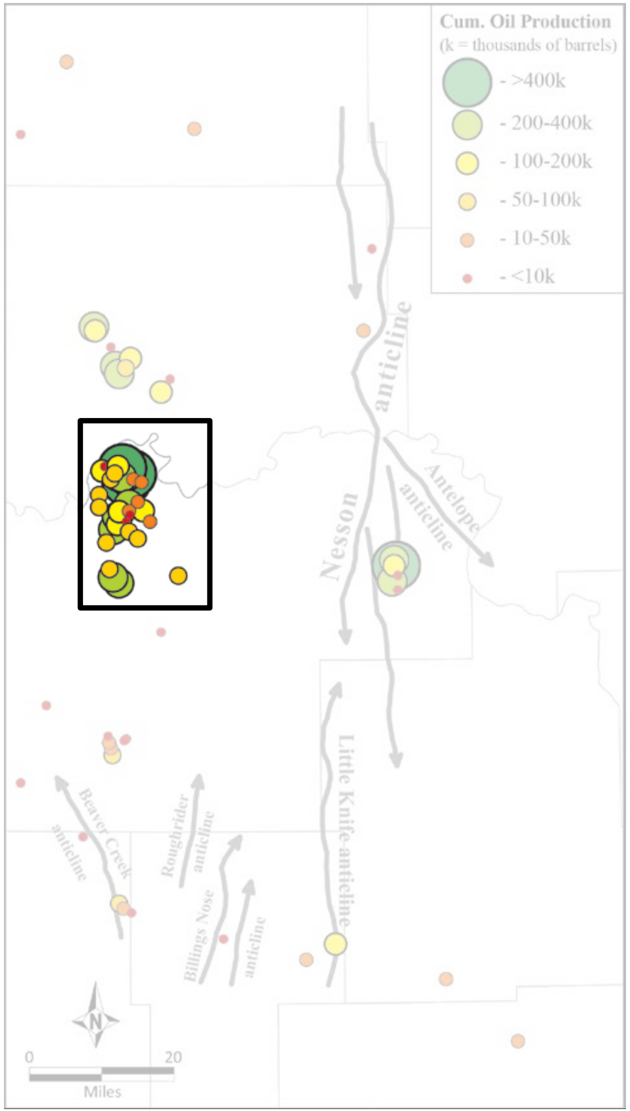
- Organic-rich (0.5-5.2% TOC*) carbonate mudstone
- Commonly present at up to three stratigraphic intervals
- Source rock net thickness = ~6-8 ft.
- Tmax values 455-460° (late mature oil generation window) with HI values <150 mg HC/g TOC

*TOC values may be significantly depleted due to thermal maturation slide #13

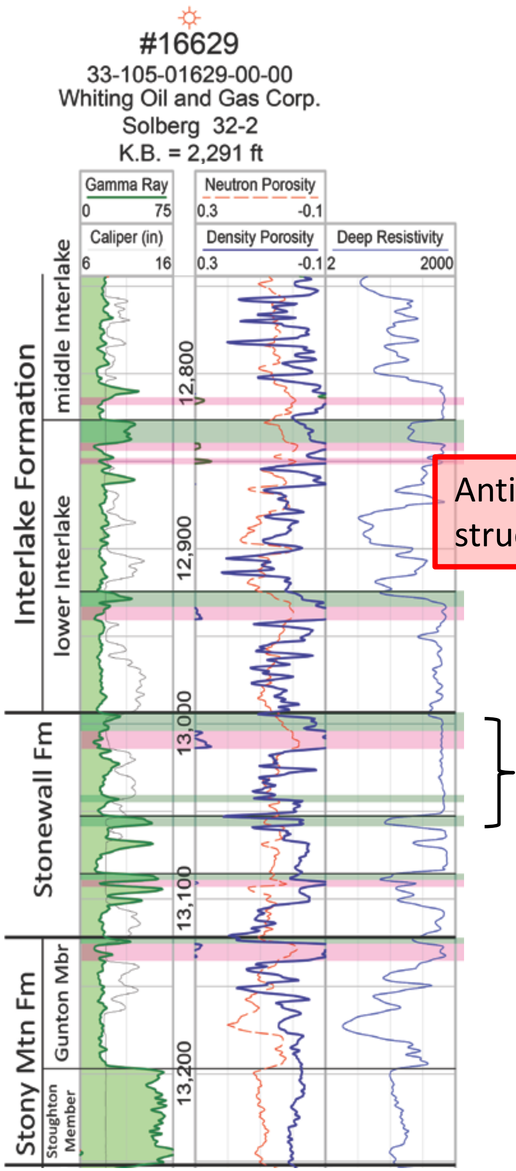
Case Study for Stonewall Formation Production:

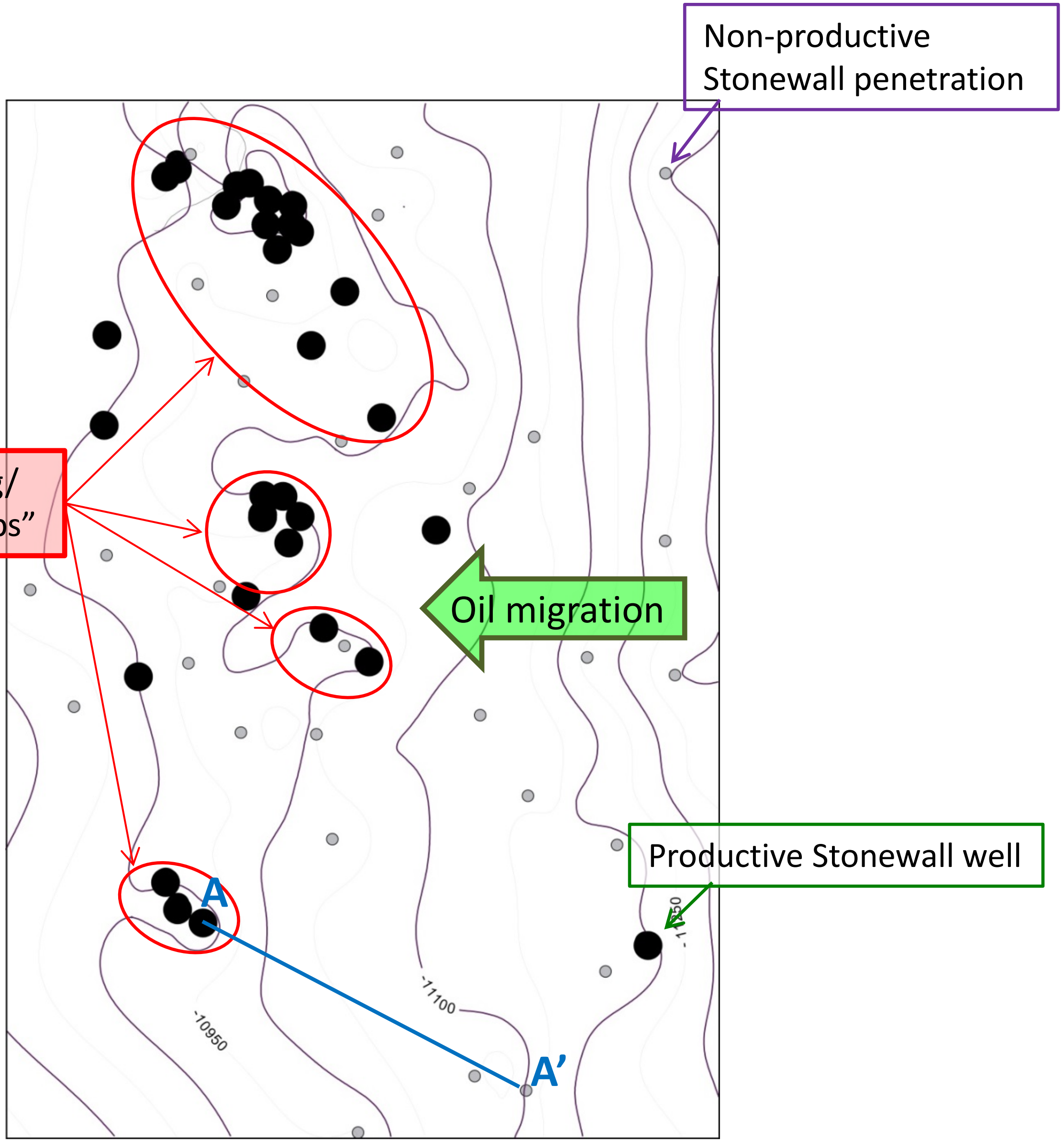
Elk-Indian Hills Field Area – Northern McKenzie County



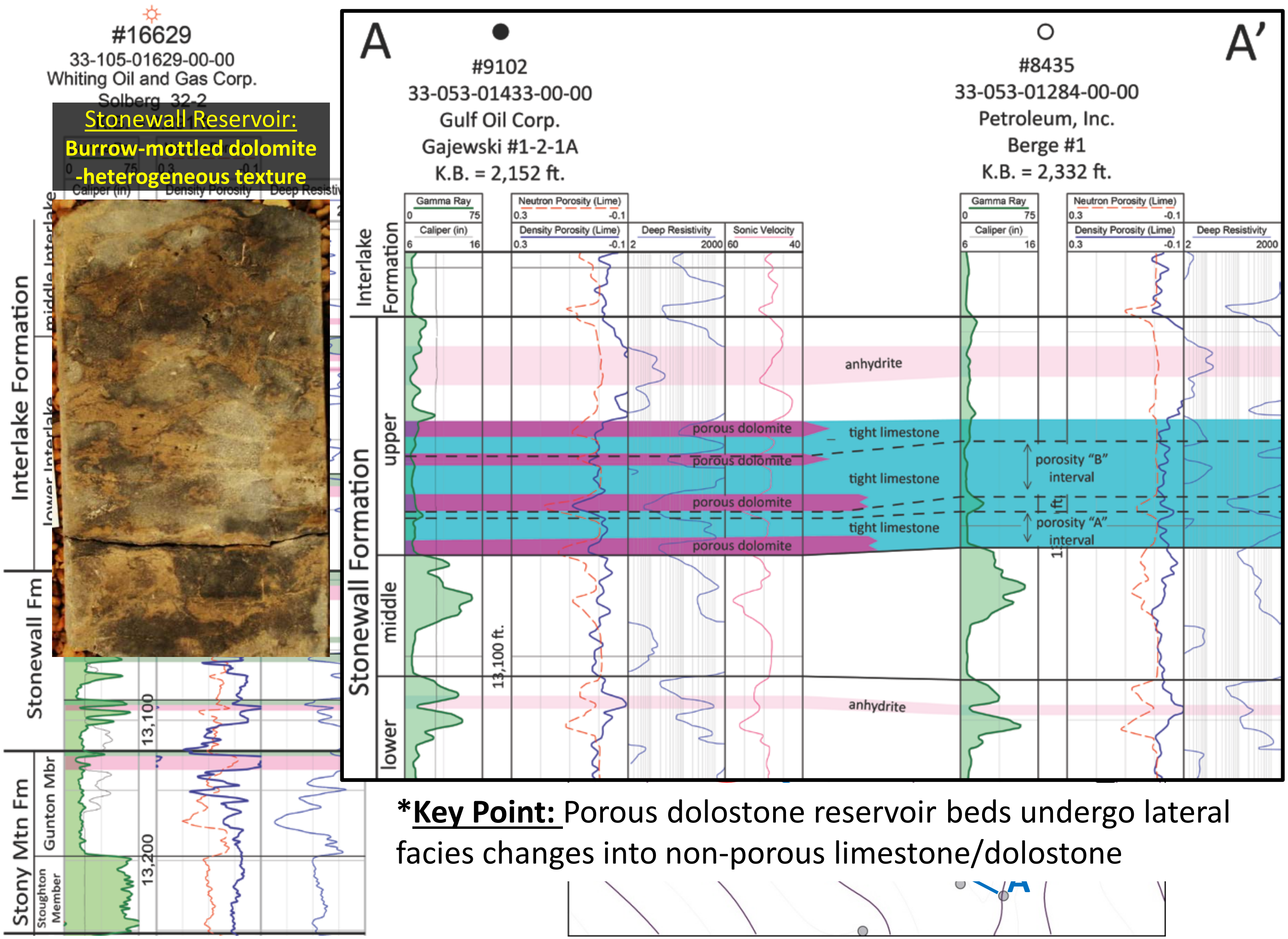


Elk-Indian Hills Field Area: upper Stonewall Production



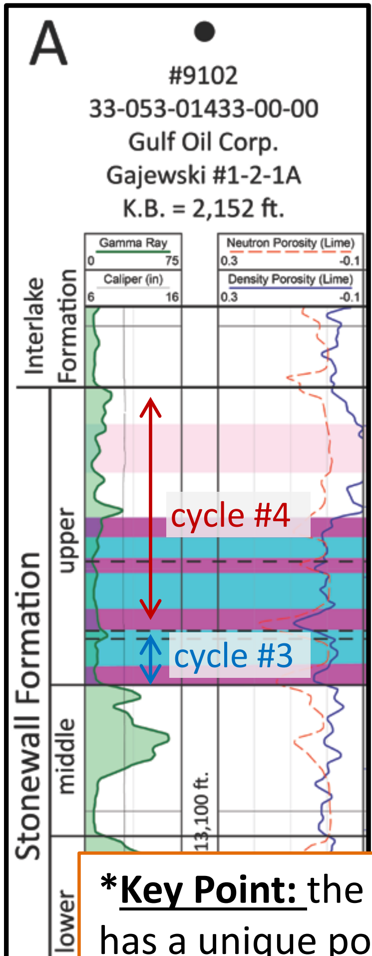


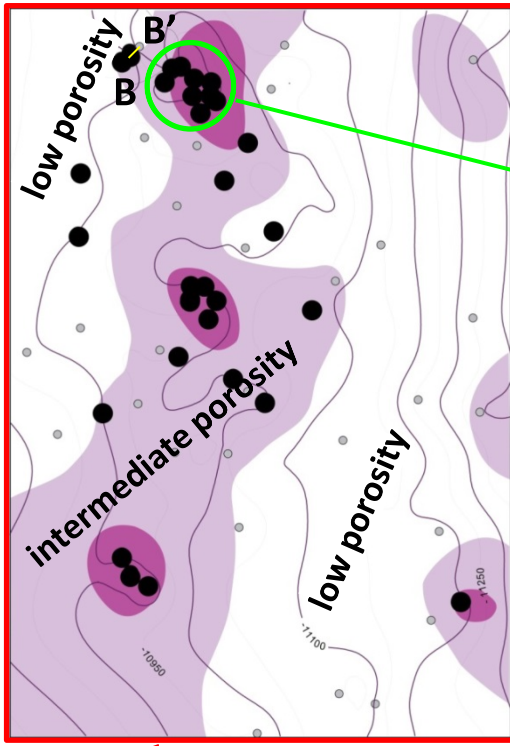
Elk-Indian Hills Field Area: upper Stonewall Production



*__Key Point:__ Porous dolostone reservoir beds undergo lateral facies changes into non-porous limestone/dolostone

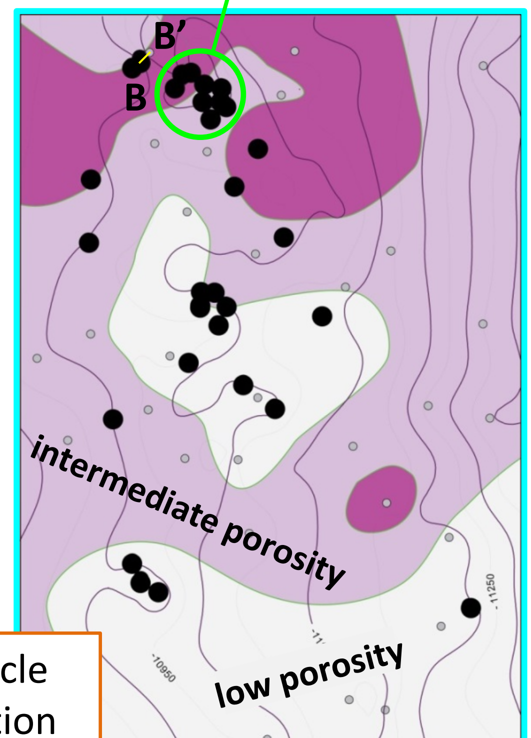
Elk-Indian Hills Field Area: upper Stonewall Production





Best overall vertical well production

- Both reservoir horizons are moderately to highly porous
- Positioned along anticlinal crest



***Key Point:** the reservoir of each sedimentation cycle has a unique porosity development trend/distribution

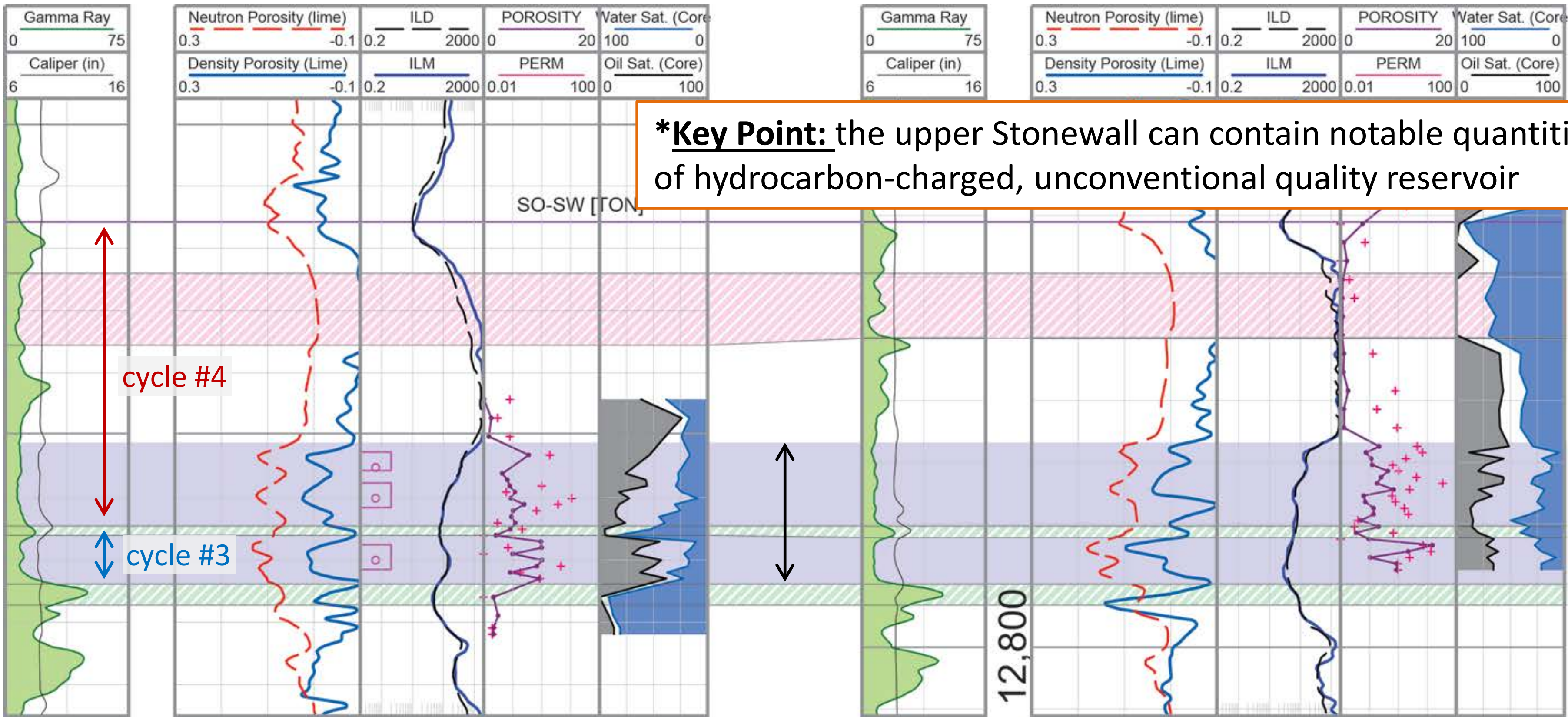
Horizontal ("Unconventional") Potential

B

#10407
33-053-01751-00-00
Columbian Oil Develop. Corp.
Page #30-1
K.B. = 1,941 ft.

#10431
33-053-01755-00-00
Columbian Oil Develop. Corp.
Deer Pass #20-1
K.B. = 1,879 ft.

B'

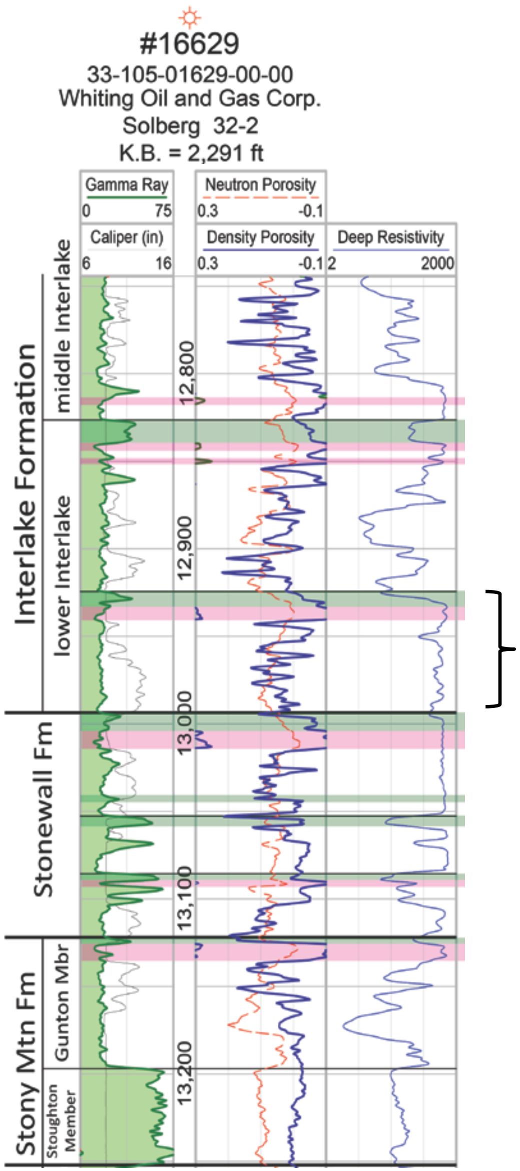


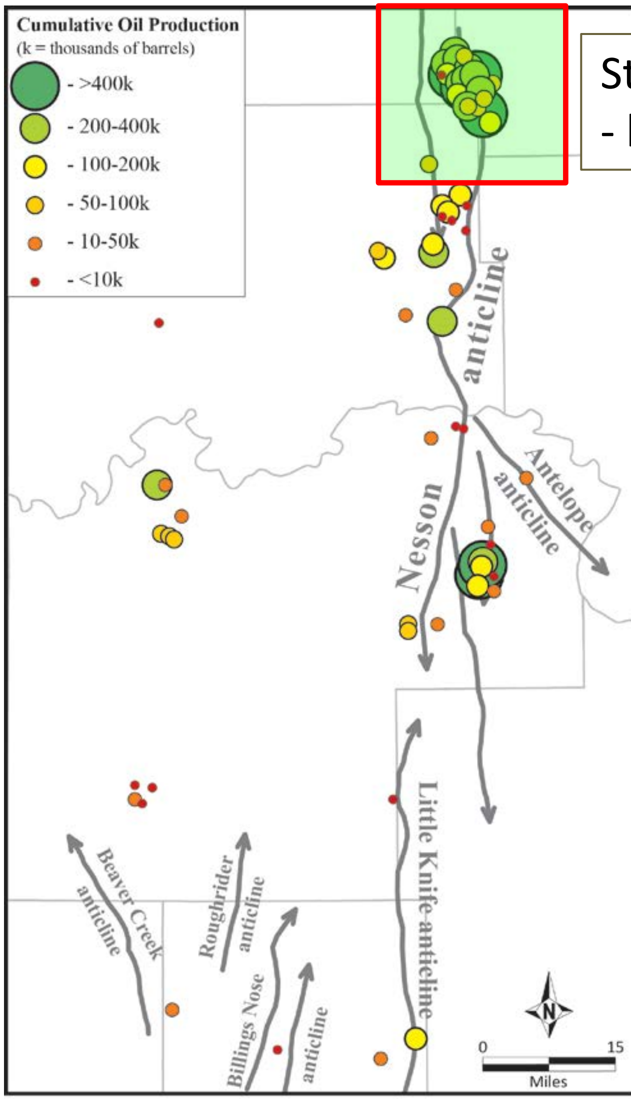
***Key Point:** the upper Stonewall can contain notable quantities of hydrocarbon-charged, unconventional quality reservoir

- ~23 ft. net thickness
- Porosity: ~4-10% - w/ Permeability: 0.1<10.0 md
- Core plug saturations: 20-50% oil with <25% water
- **OOIP: 4-6 MMBO/640 acres (8-12 MMBO/1280 acres)**

*#10407 vertical well perforations cumulatively produced 53.7 MBO & 70.6 MMCF gas with ~6% water cut from a fractured reservoir

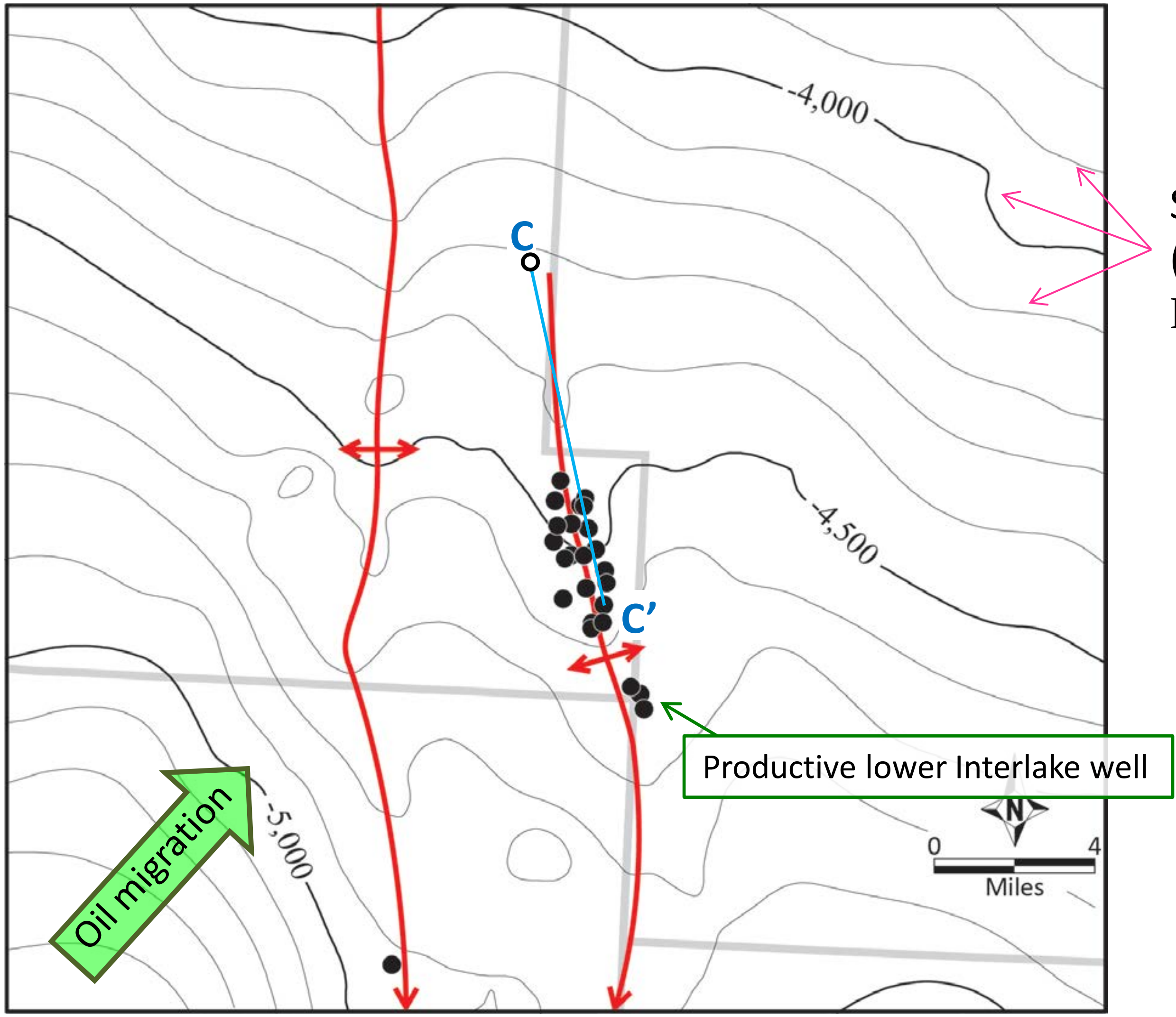
Hydrocarbon Accumulations: lower Interlake Formation





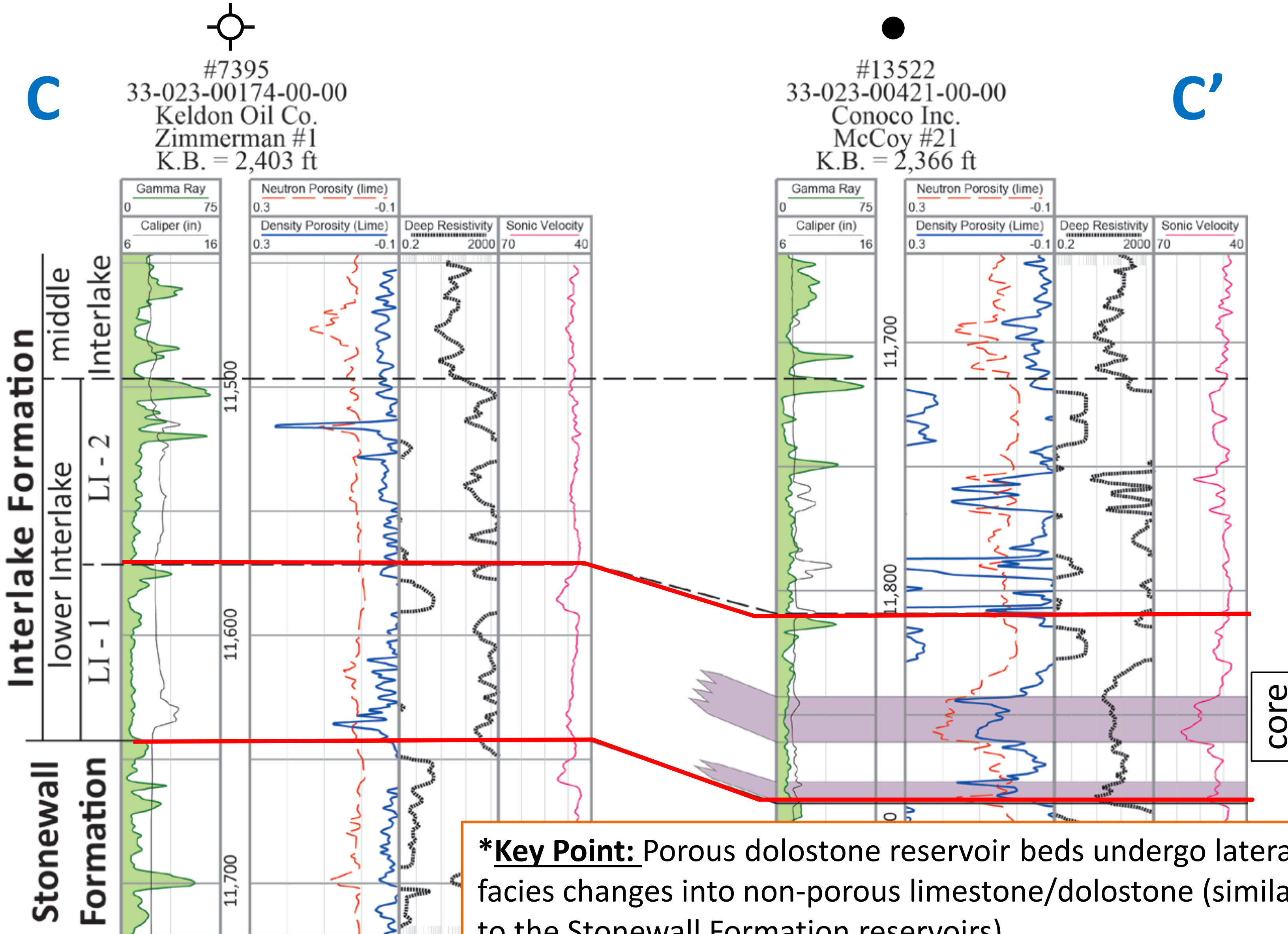
Stoneview Field area:
- lower Interlake **LI-1**

Stoneview Field Area: lower Interlake Production



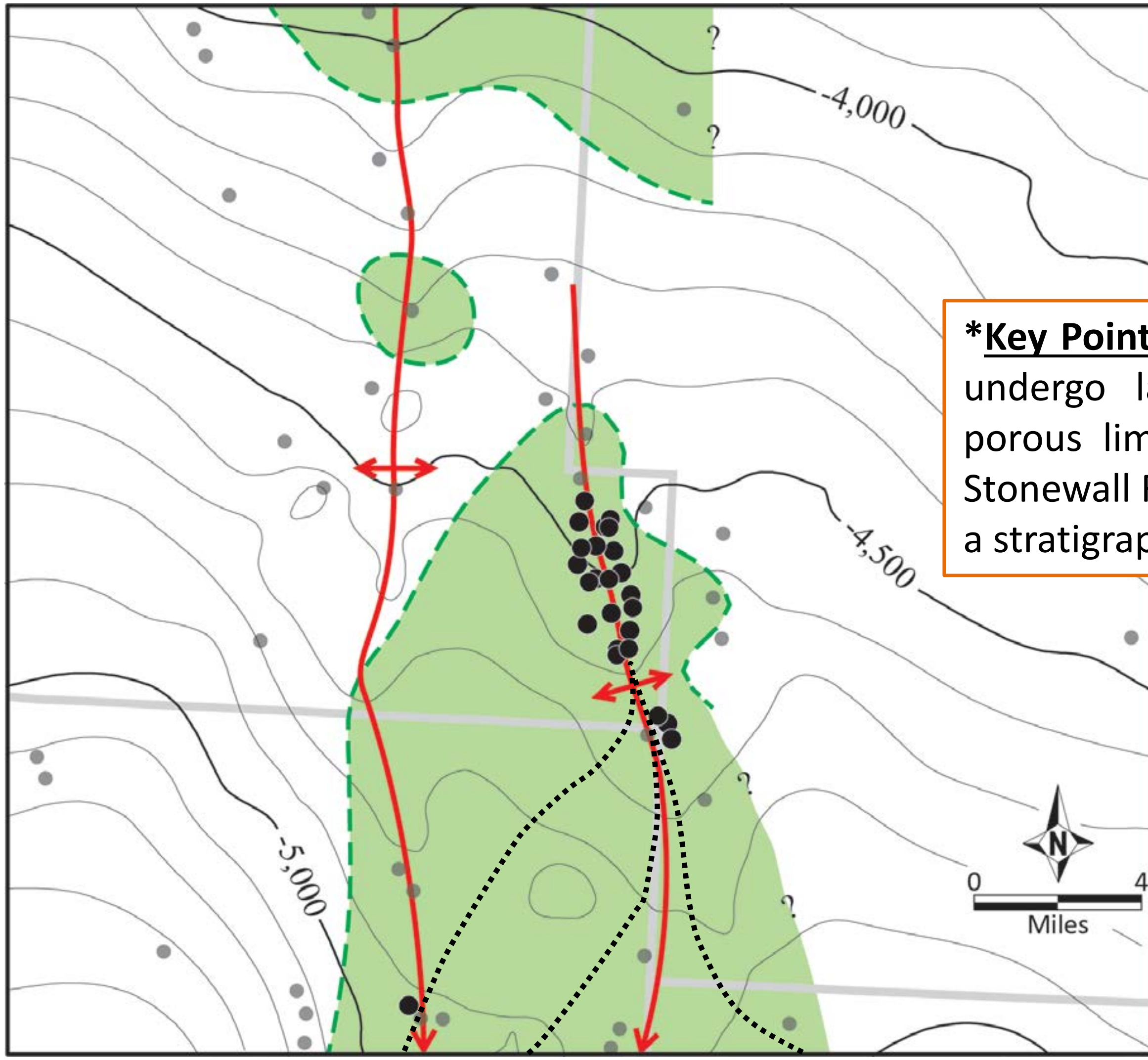
Structure Contours (feet below sea level): LI-1 top

Stoneview Field Area: lower Interlake Production



*<u>**Key Point:**</u> Porous dolostone reservoir beds undergo lateral facies changes into non-porous limestone/dolostone (similar to the Stonewall Formation reservoirs)

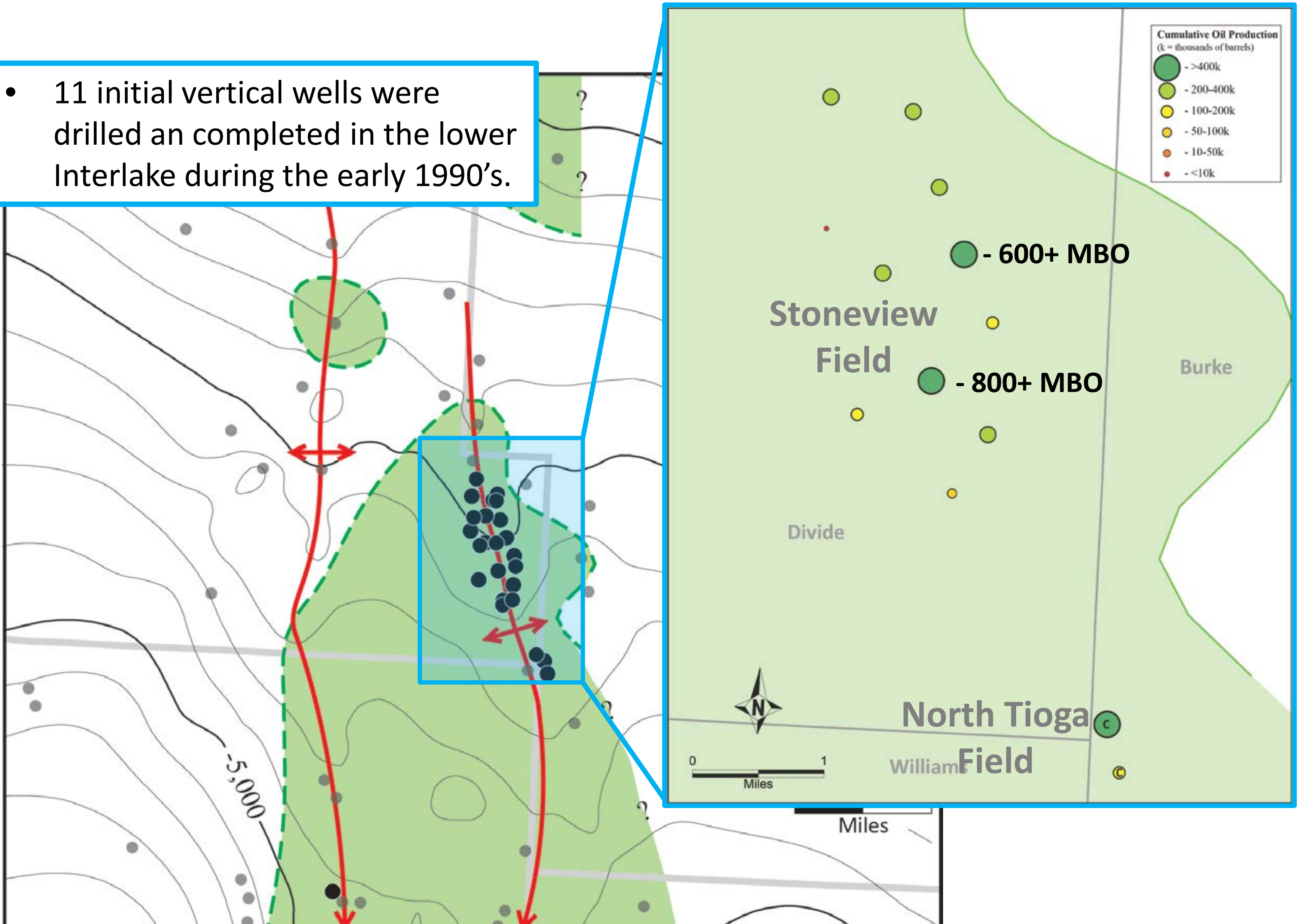
Stoneview Field Area: lower Interlake Production



Key Point: Porous dolostone reservoir beds undergo lateral facies changes into non-porous limestone/dolostone (similar to the Stonewall Formation reservoirs), which forms a stratigraphic trap overlying structure.

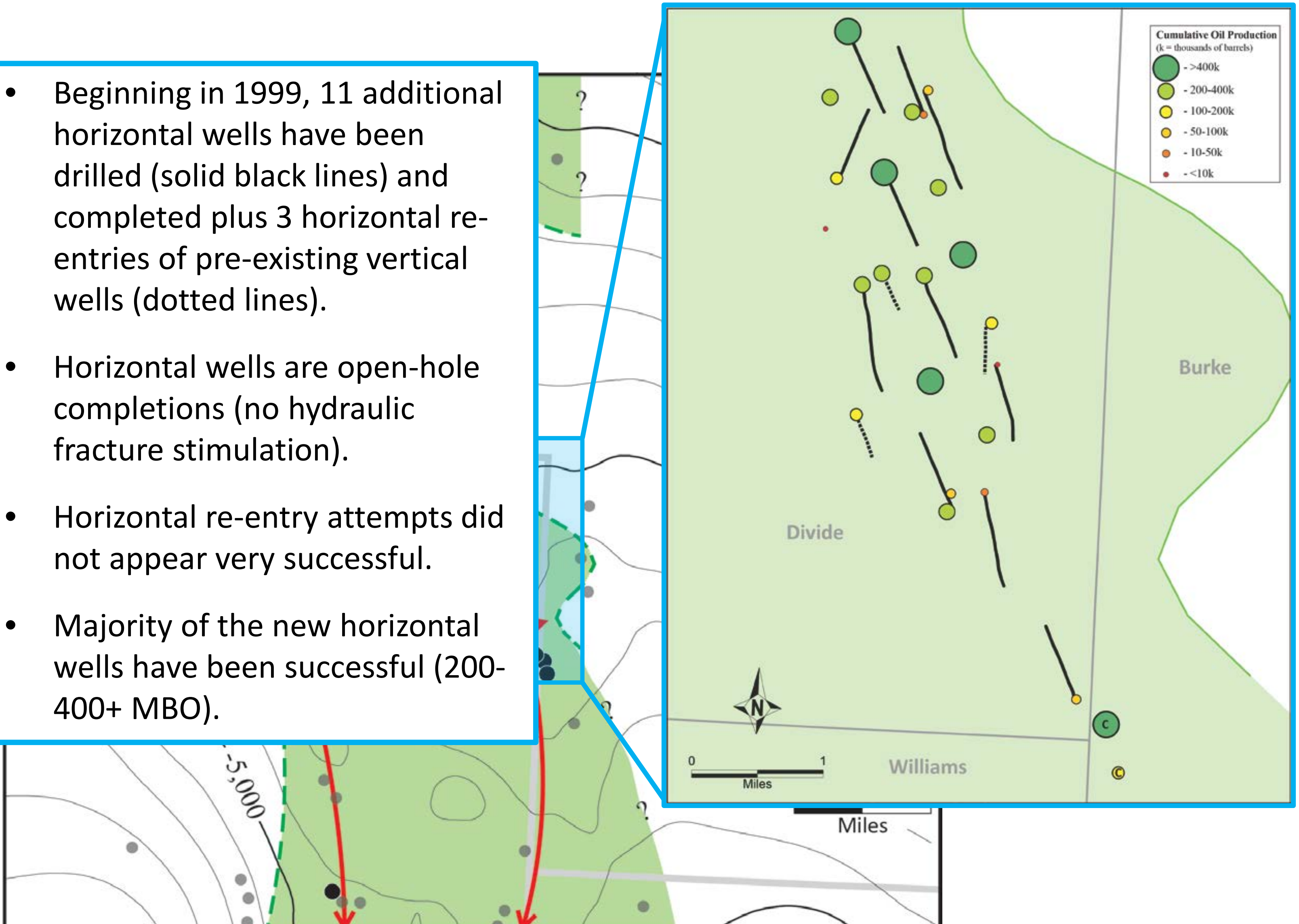
Stoneview Field Area: lower Interlake Production

- 11 initial vertical wells were drilled an completed in the lower Interlake during the early 1990's.

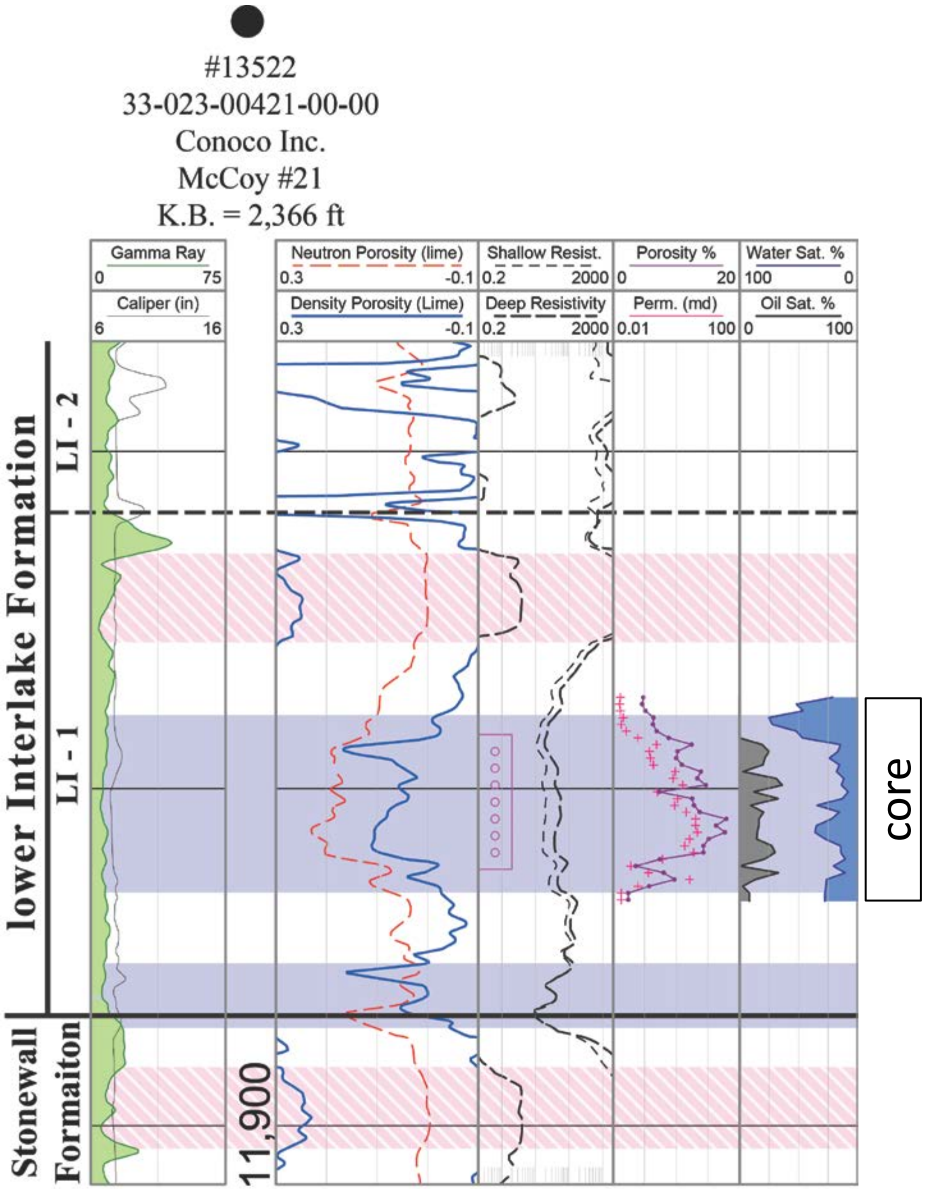


Stoneview Field Area: lower Interlake Production

- Beginning in 1999, 11 additional horizontal wells have been drilled (solid black lines) and completed plus 3 horizontal re-entries of pre-existing vertical wells (dotted lines).
- Horizontal wells are open-hole completions (no hydraulic fracture stimulation).
- Horizontal re-entry attempts did not appear very successful.
- Majority of the new horizontal wells have been successful (200-400+ MBO).



Stoneview Field Area: lower Interlake – Reservoir Facies



Relatively homogeneous reservoir that can respond positively to water flooding

Concluding Remarks:

- Six cycles of sedimentation comprise the Stonewall and lower Interlake Formations
- Each cycle contains discontinuous hydrocarbon reservoir beds each with unique porosity trends
- Stonewall-lower Interlake hydrocarbon production appears to be primarily a function of stratigraphic trapping of hydrocarbons due to discontinuous reservoir quality (facies change)
- Structural features along stratigraphic/porosity pinch-outs may further enhance production potential
- Reservoir facies varies between the two units: Stonewall = burrow-mottled dolostone (heterogeneous = hydraulic fracture candidate?), lower Interlake = massive to laminated dolostone

Slide Notes:

(GI-210 publication material was original presented at the 2018 Willison Basin Petroleum Conference)

Slide #1

Timothy Nesheim – North Dakota Geological Survey – lower Interlake and Stonewall Formations

The three main components of the presentation include: 1) an overview the Stonewall-lower Interlake stratigraphy, 2) examine the historical production trends of the various subintervals that comprise these units, and 3) review two case studies of field areas with notable production, one for the Stonewall and another for the lower Interlake.

Slide #2

Looking at a stratigraphic column for North Dakota, with the state's 40+ geological formations arranged from the shallowest-youngest formations at the top to the deepest-oldest formations at the base, the Stonewall and lower Interlake Formations are positioned towards the base of the Williston Basin, below the prolific Madison Group and Bakken-Three Forks Formations, yet above the Red River. Together, these two units straddle the Silurian-Ordovician boundary (Murphy et al., 2009).

Slide #3

For regulatory purposes, the lower Interlake and Stonewall have been pooled together into the Stonewall Pool. Therefore, a well that has produced from the Stonewall pool may have produced from the lower Interlake and/or Stonewall Formations. In terms of cumulative production, the Stonewall Pool has produced over 17 million barrels of oil to date. This may be a blip in the radar currently to the Bakken-Three Forks, which has cumulatively produced over 2 billion barrels, but it compares to the cumulative production totals of the Birdbear and Winnipegosis Formations, two units which have received much more attention from industry in the past.

Slide #4

These upper Ordovician-lower Silurian units record repeated cycles of carbonate-evaporite deposition (Fuller, 1961), where burrow-mottled to massive to laminated limestone-dolostone beds are capped by generally basin-centered, nodular to bedded anhydrite. Also, these cycles all contain 1-2 foot thick silty-sandy argillaceous marker beds, which are green to grey in core and yield elevated gamma-ray wireline log signatures. These marker beds can typically be correlated in the subsurface from basin-center to the outer basin margins (Fuller, 1961; Carlson and Eastwood, 1962; Kendall, 1976).

Slide #5

The Stonewall is composed of 4 cycles of carbonate-evaporite sedimentation. The lower two of these cycles comprise the lower and middle Stonewall members. The third sedimentation cycle is relatively thin and does not have a pronounced anhydrite bed. The third cycle also appears lithologically comparible to the overlying fourth Stonewall cycle, and therefore I combine these two upper cycles into the upper Stonewall member.

The upper and lower "t" marker beds are notable in part because they have been correlated from outcrop in Manitoba, through the subsurface extending through southern Saskatchewan and western North Dakota (Kendall, 1976; Bezys and Conley, 1998). Also, paleontological studies in Saskatchewan have placed the Silurian-Ordovician contact in proximity to the upper "t" bed, a very significant geologic boundary (Haidl, 1991; Jin et al., 1999).

Slide #6

Moving up in section, the lower Interlake appears to contain at least two more cycles of sedimentation. While the lower Interlake is still comprised of carbonate (mostly dolostone) and anhydrite beds, I would like to note that in core samples there are some stark differences geologically between the lower Interlake and Stonewall. Industry has referred to these units informally as the "Salisbury" and "Putnam" zones in western North Dakota, nomenclature that has not been formally endorsed. For this presentation, these lower Interlake subunits are referred to as LI-1 and LI-2.

Slide #7

Stonewall productive oil and gas wells have included perforations in all three informal members. Most Stonewall wells have produced from the upper member. Being pooled together with the lower Interlake, a number of Stonewall wells have been commingled with lower Interlake reservoirs. Interestingly, only one Stonewall well has commigled production between reservoirs spanning at least two of the separate Stonewall members. Only vertical wells have produced from the Stonewall Formation to date.

Slide #8

Looking at cumulative oil production, a number of the vertical Stonewall wells have produced several hundred thousand barrels of oil. The majority of these wells are located in northern McKenzie and southern Williams counties. The better producing Stonewall wells along the Nesson anticline are commingled with the lower Interlake and are believed to have produced the majority of their oil from lower Interlake reservoirs. Therefore, one can identify a historic "fairway" for Stonewall production in northern McKenzie and southern Williams counties, an area with the highest Stonewall well density and best corresponding production results.

Slide #9

The majority of lower Interlake productive wells (color coated based on which subinterval/s the well produced from) extend along the Nesson anticline. Historical production from LI-1 mostly occurs along the central to northern portions of the Nesson, while LI-2 production has largely been from the central to southern margins of the anticline. The handful of lower Interlake producers located beyond the Nesson anticline are commonly, but not always, commingled with the Stonewall Formation (upper member).

Slide #10

Cumulative production from lower Interlake reservoirs includes dozens of wells that have produced 100,000's of barrels of oil, as well as a number of intermediate to marginal wells. The best producing lower Interlake wells are positioned along the Nesson Anticline.

Slide #11

Even though the Stonewall and lower Interlake Formations are pooled together, share geological similarities, and have commingled production within a number of wells, their main production trends vary spatially from one another. These production trend differences are likely related to variations in the depositional distribution of reservoir, seal, and potentially source rock facies, which probably changed between each Stonewall-lower Interlake sedimentation cycle.

Slide #12

Through the examination and analysis of core samples, the Stonewall Formation appears to contain approximately three distinct stratigraphic intervals that display potential petroleum source bed characteristics. Within the central portions of the basin, these three prospective source beds contain up to 5% TOC (by weight), have a combined net thickness of approximately 6-8 ft., and have reached the late mature stages of oil generation base on Tmax and HI values (Nesheim, 2015). The high level of thermal maturity may have significantly depleted the amount of original TOC. Marginally mature to immature Stonewall core samples have been found to contain up to 22% TOC with hydrogen index values of 400-700+ mg HC/g TOC (Nesheim, 2015).

Slide #13

The first case study examines upper Stonewall production from the Elk-Indian Hills field area located in northern McKenzie County, where there has been the highest concentration of productive Stonewall oil and gas wells.

Slide #14

The majority of the productive Stonewall wells are located along positive structural relief, either along one of the smaller structural bumps in the central to southern parts of the map or along the moderate sized anticline to the north, indicating a structural component to the play. However, several productive wells are located without any positive structural relief, suggesting another important component may at least partially control Stonewall production.

Slide #15

The two-well cross-section includes the Gajewski #1-2-1A (left), which contains both a log and core of Stonewall productive reservoir, and the non-productive Berge #1 (right). The upper Stonewall in the Gajewski contains several porous, burrow-mottled dolostone beds interbedded with tight, non-porous limestone. This reservoir is very heterogenous in texture as well as porosity and permeablility. Meanwhile, the upper Stonewall in the Berge #1 appears to be entirerly comprised of tight, non-porous limestone and thus does not contain any viable reservoir to trap or produce hydrocarbons from. Therefore, hydrocarbon reservoir presence and distribution also appears to play a role in controlling production from the Stonewall.

Slide #16

These maps display upper Stonewall reservoir distribution using the available well control. The lower and middle portions of the upper Stonewall display varying reservoir distribution, likely because these intervals were deposited during different cycles of sedimentation. The highest concentration of Stonewall producing wells are located along positive structural relief and where both reservoir intervals are moderately to highly porous. Therefore, a combination of structure and stratigraphic trapping has controlled most of the Stonewall production for this area. However, some of the outlying producing wells appear to be primarily a result of stratigraphic trapping.

Slide #17

While additional vertical well exploration and development opportunities likely exist for the Stonewall, unconventional-style completions (horizontal drilling and multi-stage hydraulic fracturing) may also play a future role as well. Two cores located about a mile apart demonstrate the upper Stonewall can contain a significant amount (23 ft. net thickness) of moderately porous and oil-charged rock with variable but overall low permeability. Note the poor correlation between porosity and permeability, which may be due to the heterogenous texture (burrow-mottled) of the reservoir. Original oil in place (OOIP) calculations indicate the upper Stonewall contains approximately 4-6 million barrels of oil (MMBO) per section (640 acres) which is 8-12 MMBO per 1280 acre spacing. These overall reservoir characteristics and OOIP is comparable with other unconventional reservoirs of the Williston Basin (e.g. Middle Bakken, upper Three Forks). The Page #30-1 also produced vertically from the upper Stonewall, producing ~54,000 barrels of oil with only a 6% water cut and ~71 MCF gas from an interpreted naturally fractured reservoir. The porous reservoir in the upper Stonewall is discontinuous, but in locations where the upper Stonewall contains reservoir similar to the Page and Deer Pass cores, it may be condusive to unconventional-style completions.

Slide #18

The second case study examines lower Interlake production from the LI-1 subinterval within the Stoneview Field of southeastern Divide County, northern Nesson anticline (red outlined area).

Slide #19

Two distinct north-south oriented anticlinal crests can be recognized from the structure contours (generated using well control), which make up the greater Nesson anticline. The lower Interlake productive wells are clustered primarily along the eastern crest. Similar to the Stonewall production reviewed to the southwest, well positioning indicates lower Interlake production is related to positive structural relief. However, there does not appear to be up-dip structural closure for these producing wells. Also, there is minimal production along the western anticlinal crest. If production was strictly structurally controlled, there would potentially be more production towards the west.

Slide #20

The displayed two-well cross-section includes wireline logs for both productive (McCoy #21 – right) and non-productive (Zimmerman #1) lower Interlake well penetrations. The productive well contains porous dolostone interbedded with non-porous dolostone while the non-productive well only contains non-porous dolostone spanning most of the LI-1 subinterval. Simliar to the Stonewall, the lower Interlake also contains discontinuous reservoir, where porous dolostone beds laterally undergo facies changes into non-porous carbonate (dolostone) beds.

Slide #21

The next map shows where LI-1 contains several feet or more of porous dolostone (green) (typically 15-40 net feet) versus where it contains essentially negliglble reservoir rock. The production from the Stoneview Field occurs where LI-1 porous dolostone truncates northwards along the up-dip side of a north-south trending anticlinal crest. The lower Interlake Stoneview Field is essentially a combination structure-stratigraphic trap.

Slide #22

Development of the LI-1 reservoir in the Stoneview Field began during the early 1990's with the completion of 11 productive oil and gas wells. Most of these wells have produced 100,000's of barrels of oil, which is excellent for vertical wells. There have even been two rather prolific lower Interlake vertical wells in the field that have produced over 600,000 and 800,000 barrels of oil to date.

Slide #23

Developmental drilling transitioned to horizontal wells beginning in 1999. Since then, 11 additional horizontal wells and 3 horizontal re-entries of pre-existing verticals have been completed. All of these horizontal wells targeted LI-1 and were completed as open-hole wells. While the horizontal re-entry attempts did not appear very successful (the preceeding vertical well production rates exceeded those of the following horizontal well completions), many of the new horizontal wells have been successful with cumulative production commonly exceeding 200,000 barrels of oil per well.

Slide #24

The LI-1 resevoir rock appears to consist of massive to faintly laminated dolostone, which is relatively homogenous in textural consistency. Porosity and permeability of this reservoir facies trend positively together (unlike the burrow-mottled Stonewall reservoir facies). Preliminary water flooding attempts of this reservoir appear have to bolstered oil production rates.

Slide #25

In review, the Stonewall and lower Interlake Formations together are comprised of six cycles of carbonate-evaporite sedimentation. Each cyles contains discontinuous hydrocarbon reservoirs with unique porosity development trends that appears to vary between cycles. Hydrocarbon production from these units appear to be combination structure-stratigraphic traps, although some of the Stonewall productive wells may be strictly stratigraphic trapping (no positive structural relief). Also, the reservoir facies appears to vary between the lower Interlake and Stonewall, varying from heterogeneous burrow-mottled dolostone (Stonewall) to relatively homogenous massive to faintly laminated dolostone (lower Interlake).

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