[PS]Diagenesis and Isotopic Evidence of Porosity Evolution in Reef Reservoir-Analog Facies in Outcrops of the St. Joe Group (Kinderhookian to Basal Osagean) in SW Missouri and NW Arkansas*

Beau Morris[1], Sal Mazzullo[2], and Brian White[3]

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[1]Outlaw Exploration, LLC, Wichita, KS (morrisgeo@me.com)
[2]Mazzullo Exploration, LLC, Wichita, KS (sjmazzullo@gmail.com)
[3]Woolsey Corp., Wichita, KS (bwilhite@woolseyco.com)

Abstract

Fenestrate bryozoan-crinoid bafflestone, mud-dominated reefs and associated crinoid grainstones are present in the Kinderhookian Compton and basal Osagean Pierson formations (St. Joe Group) in SW Missouri and NW Arkansas. These are analogs of actual and potential petroleum reservoirs in subsurface Kansas and northern Oklahoma. The reefs likely were deposited in low-energy environments at or below wave-base, and commonly overlain by shallow-water crinoidal sands. Early diagenesis in the reef deposits primarily involved occlusion of the limited primary porosity present by marine cements, notably by former high-magnesium calcite, radiaxial-fibrous cement. The oxygen-carbon isotopic composition of this cement (means: $\delta^{18}O$ -2.5 °/oo, $\delta^{13}C$ +4.7 °/oo) is the proxy for seawater isotopic composition at that time. Despite the muddy nature of the sediments and their marine cementation, post-depositional subaerial exposure resulted in significant secondary porosity and the formation of vugs. In outcrops, most of these vugs were occluded by coarse calcite cement and internal vadose sediment or presumed meteoric origin. This interpretation is supported by the depleted composition of the coarse calcite cements relative to the marine seawater proxy. These reefs maintain enough porosity to be stained by oil. In contrast, the indications of high-porosity reefs in the subsurface suggest that, unlike the outcrops, they likely have preserved high secondary porosity and can be potential petroleum reservoirs.

DIAGENESIS AND ISOTOPIC EVIDENCE OF POROSITY EVOLUTION IN REEF RESERVOIR-ANALOG FACIES IN OUTCROPS OF THE ST. JOE GROUP (KINDERHOOKIAN TO BASAL OSAGEAN) IN SW MISSOURI AND NW ARKANSAS

Beau T. Morris, Outlaw Exploration, LLC, Wichita, KS 67226
S.J. Mazzullo, Mazzullo Exploration, LLC, Wichita, KS 67226
Brian W. Wilhite, Woolsey Energy Corp., LLC, Wichita, KS 67202

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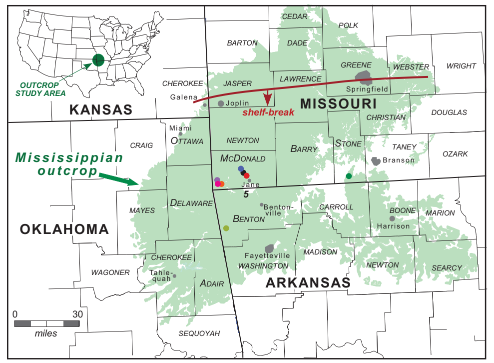
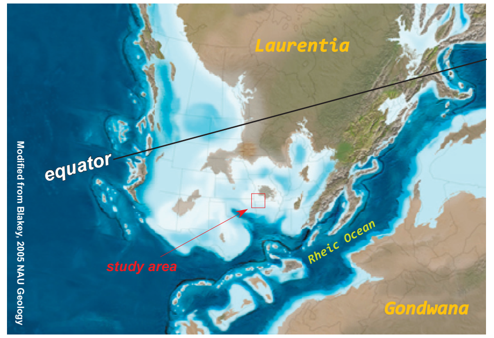
MEASURED REEF LOCATIONS DESIGNATED WITHIN THIS STUDY



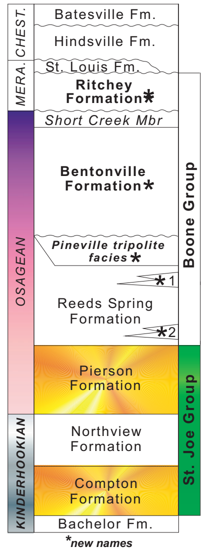


The above diagram shows a paleogeographic representation of the field study area. Highlighting the study area's location in reference to the paleo-equator, Ozark Dome (landmass to the northeast of boxed study area), and convergent boundary of the North and South American plates. During late Kinderhookian and early Osagean times the collision of these two plates (Ouachita tectonism) resulted in syndepositional tectonics overprinting the lithostratigraphic architecture of the Compton and Pierson formations.

Reefs within the Compton and Pierson formations develop in belts as swarms or coalesced buildups.

REFERENCE NAME / LAT. LONG COORDINATES	COUNTY, STATE / SEC.-TWN.-RNG. (SPOT)
JANE (BEAU'S REEF)	**McDonald Co., Missouri**
N 36⁰ 32' 47.00" W 940 19' 34.96"	18-21N-31W (NW NW SE)
JANE REEFS (3 reefs)	**McDonald Co., Missouri**
N 36⁰ 32' 47.00" W 940 19' 34.96"	18-21N-31W (NW NW SE)
JANE SOUTH (2 reefs)	**McDonald Co., Missouri**
N 36⁰ 32' 43.47" W 940 19' 24.03"	18-21N-31W (NE NW SE)
JANE NORTH (4 reefs)	**McDonald Co., Missouri**
N 360 33' 26.74" W 940 20' 11.18"	12-21N-32W (NW NE SE)
NOEL, HIGHWAY DD REEF	**McDonald Co., Missouri**
N 36⁰ 34' 4.38" W 940 30' 10.98"	9-21N-33W (SE SW NE)
NOEL, HIGHWAY DD NORTH REEF	**McDonald Co., Missouri**
N 36⁰ 34' 9.59" W 940 30' 11.54"	9-21N-33W (E2 SW NE)
HIGHWAY 59 & 90 JUNCTION, REEF (reef is inaccessible)	**McDonald Co., Missouri**
N 36⁰ 32' 54.37" W 940 29' 41.12"	15-21N-33W (SE NW SW)
HIGHWAY 86 REEF	**Stone Co., Missouri**
N 36⁰ 31' 50.44" W 930 27' 50.32"	18-21N-23W (NE NW NE)
HIGHWAY 412 REEFS (4 reefs)	**Benton Co., Arkansas**
N 36⁰ 10' 17.12" W 940 23' 22.51"	9-17N-32W (NE NE NE)

MISSISSIPPIAN OUTCROP AND SUBSURFACE STRATIGRAPHIC TERMINOLOGY



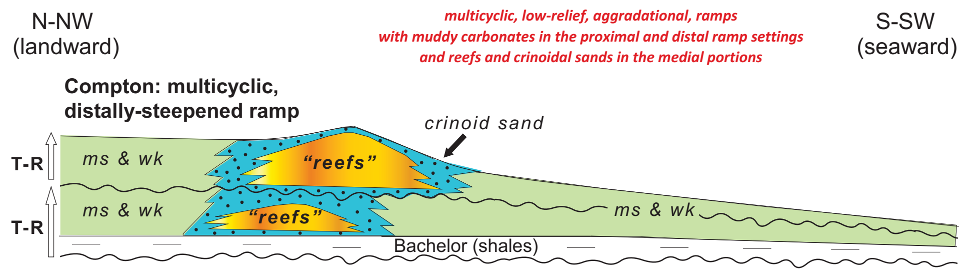
*new names
1 - White River tripolite facies
2 - Buffalo River tripolite facies

Mazzullo et. al., (2013)

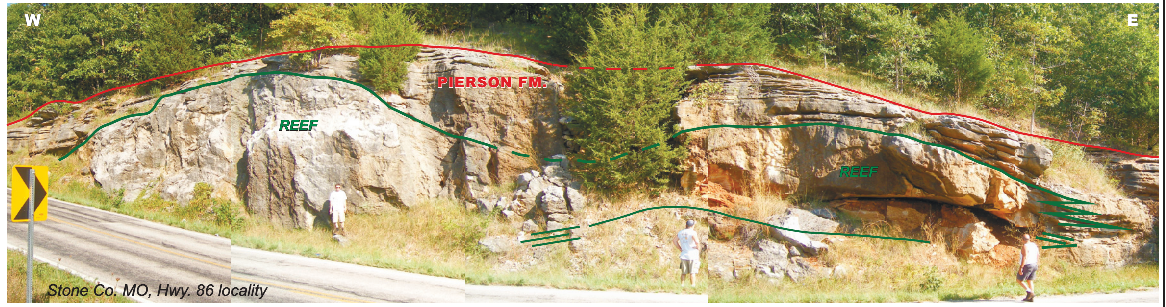
COMPTON REEFS WAULSORTIAN-LIKE & NON-WAULSORTIAN TYPES

Tabular - Flat Bottom Convex Top Shapes
between 5 ft - 30 ft thick on outcrop

DEPOSITIONAL ARCHITECTURE OF COMPTON REEFS

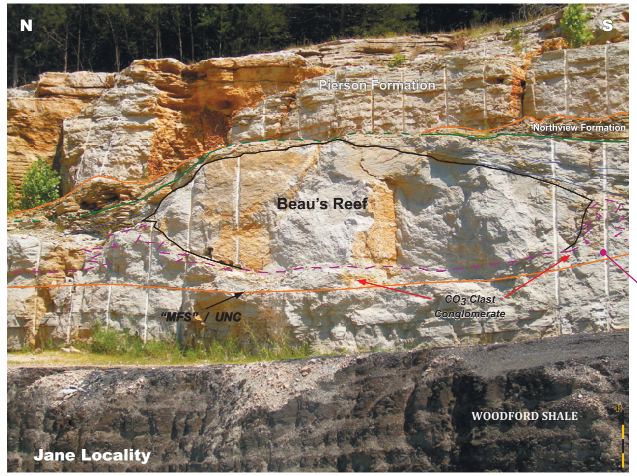


WAULSORTIAN-LIKE REEF



Stone Co. MO, Hwy. 86 locality

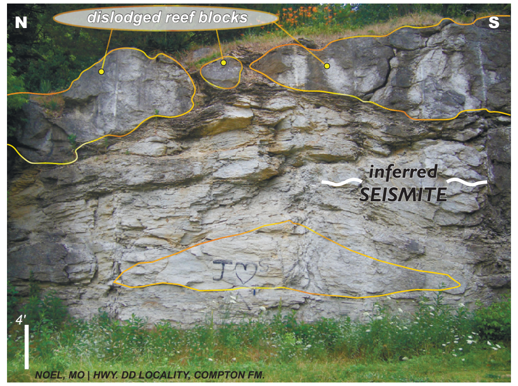
BRYOZOAN - CRINOID MUDDY BAFFLESTONE REEFS



Beau's Reef, along the east side of Highway 71 north of Jane, Missouri. Large tabular reef blocks at this location are sandwiched between T-R cycles of the upper and lower Compton Formation, and display pronounced evidence of syndepositional tectonism and subaerial exposure. For example, Beau's reef has locally bulldozed up underlying sediment with its northward displacement, and its associated facies prograde northward opposite of regional dip and basin direction.

Carbonate clast conglomerate represents bulldozed sediment during reef displacement and marking a regional disconformity throughout the field area and traceable into the subsurface westward.

Dislodged reef blocks within the Compton Formation along the eastern side of Highway DD near Noel, Missouri have an apparent tapered and pinched or torn appearance resulting from syndepositional tectonism. Furthermore, these reefs, overlie seismite beds or beds of chaotic nature with no explicit bedding and attributed to earthquake.



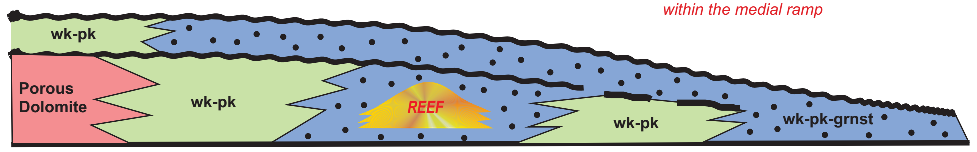
NOEL, MO | HWY. DD LOCALITY, COMPTON FM.

PIERSON REEFS NON-WAULSORTIAN TYPE

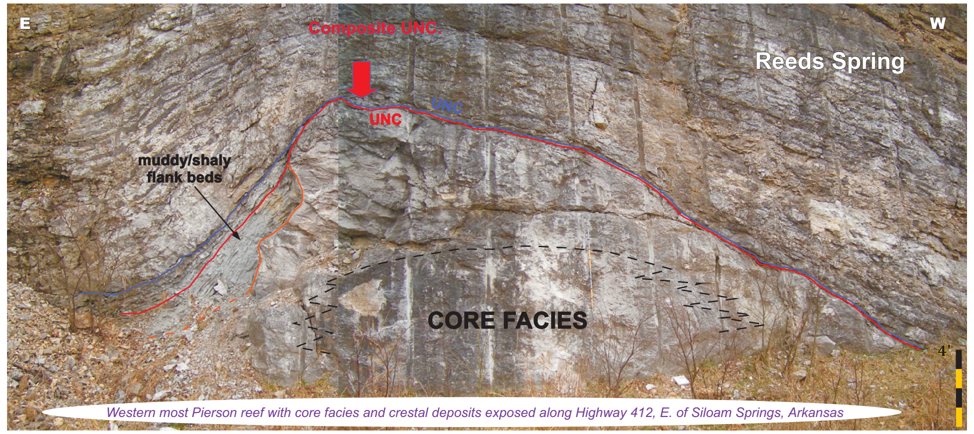
Flat Bottom Convex Top Shapes
up to 16 ft thick on outcrop

DEPOSITIONAL ARCHITECTURE OF PIERSON REEFS

progradational ramps with shallower-water, higher-energy environments than Compton reefs (i.e. coarser carbonates in the proximal and distal ramp settings and reefs within the medial ramp

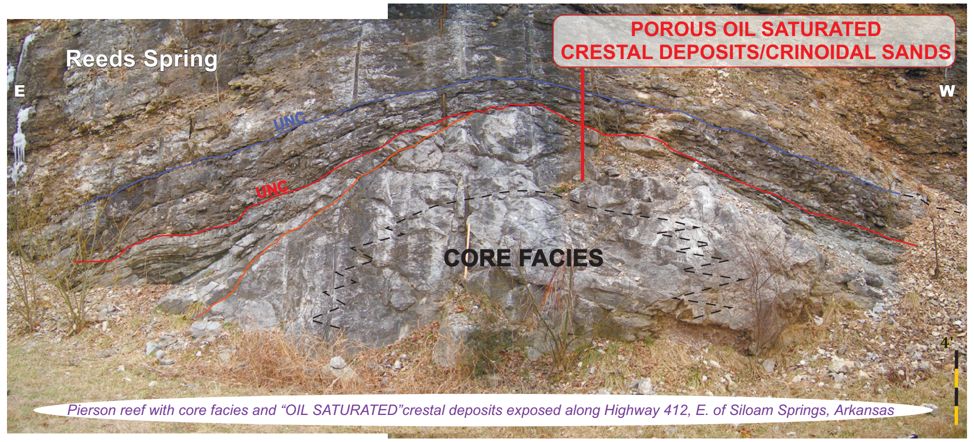


LAYERED BRYOZOAN - CRINOID BAFFLESTONE REEFS



Western most Pierson reef with core facies and crestal deposits exposed along Highway 412, E. of Siloam Springs, Arkansas

Reefs within the Pierson Formation exposed along south side of Highway 412, east of Siloam Springs, Arkansas. These reefs (pictured above and below) contain a layered bryozoan - crinoid bafflestone framework. They are porous and oil saturated along the outcrop, and contain multiple Pierson age unconformities along their tops. One unconformity for example, pictured above and highlighted orange has eroded the entire eastern side of the exposed reef and another (not pictured here) has formed a buried hill within the Pierson at the eastern end of this outcrop. These reefs are not inferred to be out of place or dislodged.



Pierson reef with core facies and "OIL SATURATED" crestal deposits exposed along Highway 412, E. of Siloam Springs, Arkansas

DIAGENESIS OF COMPTON REEFS

WAULSORTIAN - LIKE

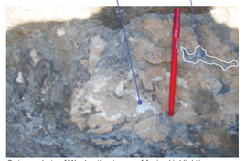
Hand sample photograph of Waulsortian-like reef facies highlighting stromatactis cavity filled with RFC marine cements and dissolutional vugs within those cavities filled with coarse PFC. black scale bar = 1"

STROMATACTIS CAVITY

Photomicrograph of RFC and fascicular-optic marine cements (multi-generational) within a stromatactis type cavity. 20x magnification, cross polars

example of coarse pore-filling calcite (PFC) filling a dissolution vug of meteoric origin

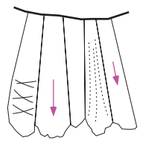
example of radiaxial fibrous calcite (RFC) filling a stromatactis cavity



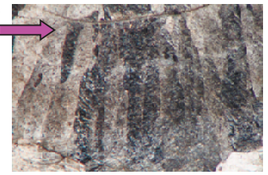
Outcrop photo of Waulsortian type reef facies highlighting dissolutional vugs (meteoric origin), some filled with internal vadose crystal silt and others occluded by coarse PFC. pen for scale

POTENTIAL SUBSURFACE POROSITY

RADIAXIAL FIBROUS CALCITE "MARINE CEMENTS"



after Kendall (1985)



Photomicrograph of RFC marine cements "stromatactis". 20x magnification cross polars

Waulsortian-like reefs contain abundant networks of stromatactis or stromatactoid cavities occluded with RFC marine cements, and meteoric dissolution vugs occluded with coarse PFC or cements of meteoric origin on outcrop. ***The combination of stromatactis and dissolution vugs within these reefs displays tremendous potential for POROSITY to be present in reefs of the subsurface.***

Similarly, ***non-Waulsortian type reefs display tremendous potential for the presence of POROSITY.*** *However, their potential is derived primarily from the presence of meteoric dissolution vugs.*

NON-WAULSORTIAN TYPE

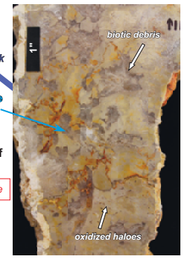
POTENTIAL SUBSURFACE POROSITY

example of a dissolution vug filled with internal vadose crystal silt and coarse PFC

Outcrop photo of reef core facies showing a large incised channel and abundant meteoric dissolution vugs filled with internal vadose crystal silt (some dolomitized) and coarse PFC. hammer for scale

Bryozoan Rich Internal Framework

Large Calcite Occluded Vugs



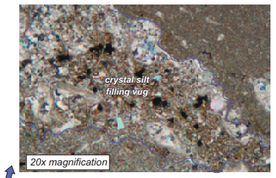
Hand-sample photo with abundant meteoric dissolutional vugs filled with biotic debris, crystal silt, and PFC. black scale bar = 1"

Meteoric Dissolution Vugs of

tubular fenestrae
laminoid fenestrae
irregular fenestrae

shape

Grover and Read, 1978

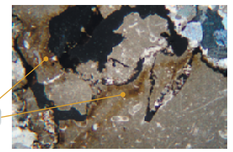


Photomicrograph of internal vadose crystal silt filling a vug, later occluded by coarse pore filling calcite. cross polars

internal vadose crystal silt:
eroded marine cements & biotic particles forming "crystal silt" Dunham, 1969

Photomicrograph of a dissolutional vug truncating a bryozoan. Vug later occluded with coarse PFC. magnification 20x cross polars

oil staining



Photomicrograph of dissolutional porosity within reef core facies (note brown oil staining along stylolite and vugs). magnification 20x cross polars

EVOLUTION OF REEF POROSITY

REEFS WITHIN THE COMPTON AND PIERSON FORMATIONS EXHIBIT A RECOGNIZABLE DIAGENETIC SEQUENCE; HOWEVER, WITH MILD DIFFERENCES AND SUBTLE COMPLEXITIES, RESULTING IN AN OVERALL HIGH POTENTIAL FOR THESE REEFS TO BE POROUS AND OF RESERVOIR CALIBER WITHIN THE SUBSURFACE.

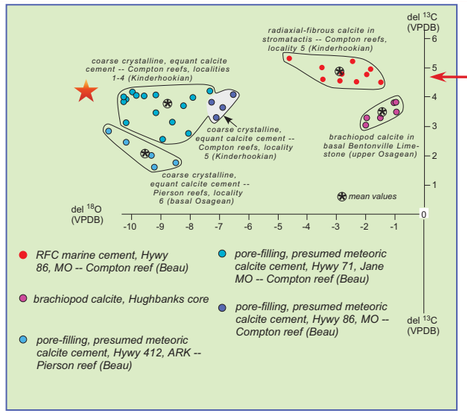
DIAGENETIC HISTORIES OF REEFS WITHIN THE COMPTON AND PIERSON FORMATIONS

- *reef growth and formation of primary porosity (i.e. stromatactis; interparticle; intraparticle; fenestral)*
- *precipitation of syndepositional marine cements (i.e. radiaxial fibrous calcite marine cement (RFC); former high magnesium calcite (HMC) bladed marine cements) during reef growth occluding the majority of primary porosity*
- *dissolution by meteoric fluids (via subaerial exposure or these reefs) creating vugs and fractures along with dissolving some RFC & HMC marine cements and skeletal particles, and stabilization of remaining RFC and HMC to their current mineralogy*
- *generation of internal vadose crystal silt (described by Dunham, 1969 as eroded or weathered residue of cements and bioclastic material forming crystal silt, and directly related to subaerial exposure) flooring vugs and shells often as geopetal features and filling fractures, occluding some secondary porosity*
- *precipitation and occlusion of much, but not all of the remaining secondary porosity by coarse pore-filling calcite (PFC)*
- *dolomitization and de-dolomitization (further, forming and occluding porosity) within internal vadose crystal silt*
- *formation of stylolites is the latest diagenetic event recognized (excluding the Pierson) accompanying moderate to deep burial of these rocks*
- *Pierson reefs include a partial dissolution and creation of secondary porosity that was then mostly filled with oil (potentially within the telogenetic environment)*

EVIDENCE OF UNCONFORMITY

- *oxidized haloes and reddish discoloration along fractures and some vugs*
- *dissolutional vugs and associated fractures*
- *abundant crinoid overgrowths*
- *clasts of reef matrix within vugs*
- *internal vadose crystal silt within vugs and fractures*

ISOTOPIC SEAWATER COMPOSITIONS DERIVED FROM CEMENTS



KINDERHOOKIAN SEAWATER PROXY

MEANS OF O - C COMPOSITIONS
delta 18O - 2.8 o/oo, delta 13C + 4.8 o/oo
(both the means and ranges are enriched

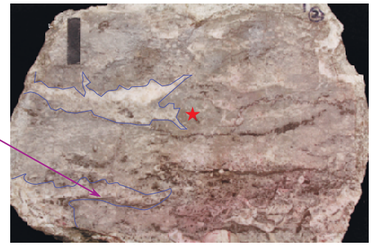
"HEAVIER"

compared to

DEPLETED "LIGHTER" mean composition
delta 18O - 8.7 o/oo, delta 13C + 3.7 o/oo
supporting the interpretation that cements occluding vugs and fractures are of meteoric origin

DIAGENESIS OF PIERSON REEFS

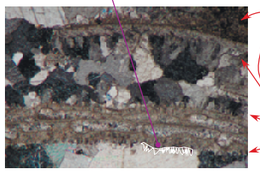
example of dissolution vug floored with internal sediment



Hand-sample photograph of reef core facies (layered bryozoan-crinoid bafflestone), with meteoric dissolution vugs, abundant marine cements, and coarse PFC. black scale bar = 1"

★ *example of a dissolution vug formed from subaerial meteoric exposure. Vugs are often filled with biotic debris, internal sediment, phreatic cements (in the forms of pendant and or isopachous rinds), and coarse PFC cements*

example of isopachous, bladed, former HMC marine cement lining a bryozoan



Photomicrograph of a vug within reef core facies, highlighting isopachous rinds of former HMC bladed marine cements and later occlusion of those vugs by coarse PFC. magnification 20x, cross polars.

isopachous rinds of marine cements

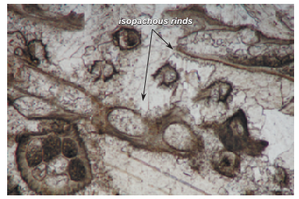
POTENTIAL SUBSURFACE POROSITY

NOTE
typical grainstones are of light color because of clear to opaque cements; however reef crest deposits along the outcrop are OIL SATURATED resulting in a dark matrix

Hand-sample of reef crestal deposits (crinoid grainstone) saturated with oil. yellow scale bar = 1"

Reefs within the Pierson Formation display much more primary porosity partly due to their internal framework (layered bafflestones) and shallower-water depositional environment than the Compton. Furthermore, these reefs contain abundant dissolution vugs of meteoric origin occluded with coarse PFC supporting a ***similar potential for high POROSITY to be present within these reefs in the subsurface.***

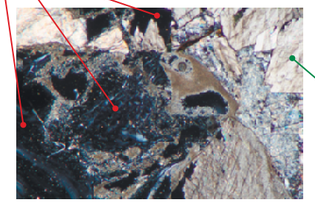
Likewise, these reefs further exhibit reservoir potential in thick overlying crestal deposits SATURATED WITH OIL on the outcrop. (similar reservoirs are present within the Illinois Basin producing between 30 & 90 MBO per well)



Photomicrograph within a vug, isopachous rinds of former high magnesium calcite bladed marine cements rimming bryozoans and later occlusion by coarse pore filling calcite. 20x magnification, plain light

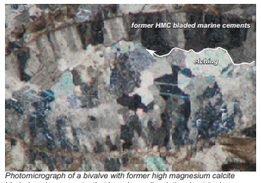
POTENTIAL SUBSURFACE POROSITY

porosity within vug



example of coarse pore-filling calcite PFC

Photomicrograph of reef core facies showing porosity (black areas) within vugs. magnification 20x, cross polars

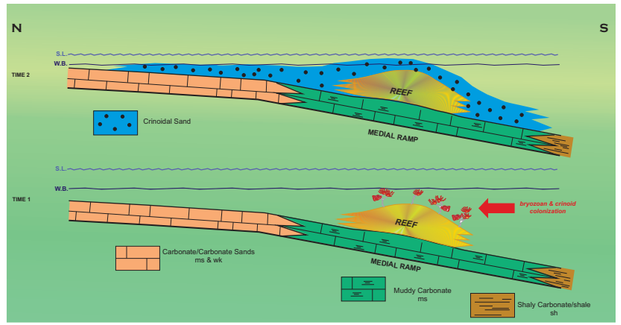


Photomicrograph of a bivalve with former high magnesium calcite bladed marine cements, that have been dissolutionaly etched. 20x magnification, cross polars

RECOGNITION OF REEFS WITHIN THE SUBSURFACE

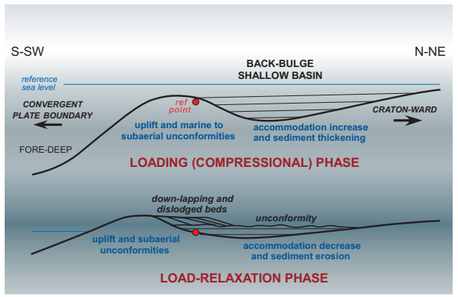
THE SEDIMENTARY ARCHITECTURE, DEPOSITIONAL AND DIAGENETIC HISTORY OF KINDERHOOKIAN AND LOWER OSAGEAN AGE REEFS HEREIN, PROVIDE A TEMPLATE FOR SUBSURFACE EXPLORATION IN KANSAS AND OKLAHOMA. MOREOVER, THE EVIDENCE OF POROSITY EVOLUTION AND THE RECOGNITION OF REEFS WITHIN THE SUBSURFACE ON WIRELINE LOGS, IN CUTTINGS AND CORES, AND AS PRODUCING RESERVOIRS WITHIN FIELDS PROVIDES A REAL AND TANGIBLE RESERVOIR TARGET YET TO BE EXPLOITED.

REEF-RESERVOIR ANALOG MODEL (OUTCROP TO SUBSURFACE)

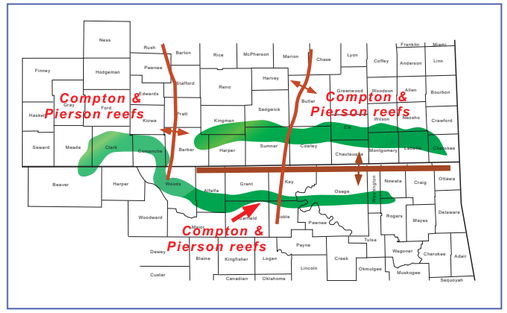


REEFS EXPOSED WITHIN THE MISSISSIPPIAN OUTCROP BELT DEVELOP IN THE MEDIAL PORTIONS OF AGGRADATIONAL AND PROGRADATIONAL RAMPS WITHIN THE COMPTON AND PIERSON FORMATIONS, RESPECTIVELY.

THE SUBSURFACE LIKELY CONTAINS BOTH IN-PLACE AND DISLODGED REEF BLOCKS; HOWEVER, IN-PLACE REEFS ARE THE MAIN RESERVOIR OBJECTIVES



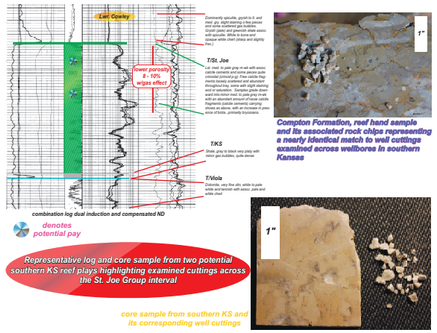
GENERALIZED MODEL VISUALIZING THE EFFECTS OF FORE-BULGE TECTONISM (I.E. DISLODGING REEFS; PROGRADATION NORTHWARD; SUBAERIAL EXPOSURE)



THE ABOVE MAP HIGHLIGHTS THE MAJOR TECTONIC-PHYSIOGRAPHIC FEATURES WITHIN THE PROSPECTIVE AREA OF REEF DEVELOPMENT IN THE SUBSURFACE. SUCH AREAS INCLUDE, ALONG AND FLANKING THE KANOKA RIDGE AND WITHIN ARCUATE BELTS IN MEDIAL RAMP POSITIONS IN LOCAL BASINS.

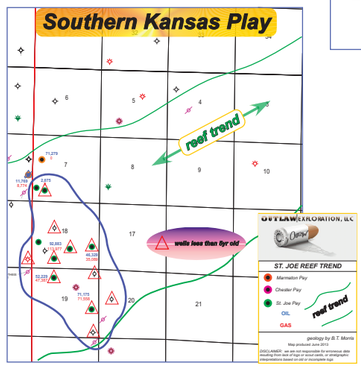
EVIDENCE OF SUBSURFACE REEF RESERVOIRS

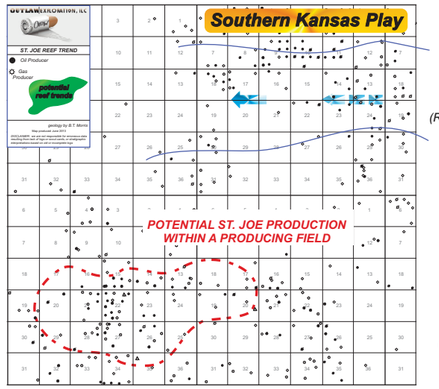
"sample identified reef & bypassed pay"



CUTTINGS AND CORE TEND TO OFFER THE BEST MEANS OF IDENTIFICATION OF REEFS WITHIN THE ST. JOE GROUP BECAUSE OF THEIR DISTINCT ROCK CHARACTERISTICS

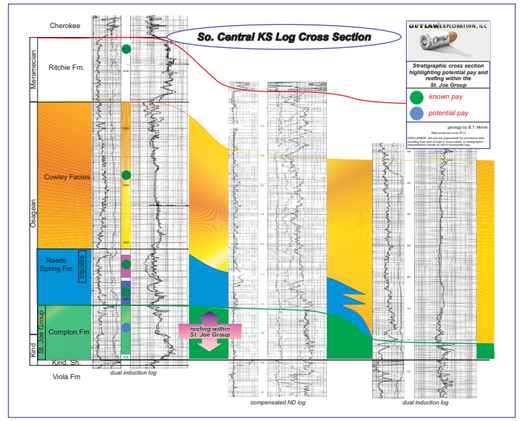
IDENTIFIED REEF TRENDS/PLAYS (VIA WIRELINE LOGS AND CUTTINGS. THE FIELD AT RIGHT (blue circle) HAS PRODUCED OVER 250,000 THOUSAND BARRELS OF OIL IN LESS THAN 5 YEARS FROM ROUGHLY 5 WELLS.





THICKENING WITHIN ST. JOE GROUP (REEFING) WITH POROSITY AND SHOWS

dramatic thickening and porosity development



WIRELINE LOG SIGNATURES REPRESENTATIVE OF SOUTHERN KANSAS SHOWING REEFING WITHIN THE ST. JOE GROUP IN STRATIGRAPHIC CROSS SECTIONS (AT LEFT AND BELOW) HUNG ON THE KINDERHOOK SHALE.

ACTUAL REEF TARGETS WITHIN THE ST. JOE GROUP PROVIDE AN OPPORTUNITY TO EXPAND ON AN ALREADY LARGE PRODUCING INTERVAL OF MISSISSIPPIAN AGE FORMATIONS WITH THE ADDITION OF THESE RESERVOIRS