Reservoir Characterization for the Application of ASP Flood Technology in the Bridgeport Sandstone in Lawrence Field, Illinois*

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Abstract

The lower Pennsylvanian Bridgeport Sandstone of Lawrence Field, a 400-million barrel mature-producing field in southeastern Illinois, is a candidate for enhanced oil recovery (EOR). Detailed reservoir characterization research, supported by a Department of Energy grant, has identified target zones for the alkali-surfactant-polymer (ASP) EOR method. Identification of flow units and knowledge of permeability barriers and potential thief zones are critical to the success of this EOR project.

Mapping efforts identified distinct flow units in the northern part of the field showing that the Bridgeport consists of a series of thick incised channel-fill sequences. The sandstones are about 75-150 ft thick and typically consist of medium-grained, poorly sorted fluvial to distributary channel deposits at the base. The sandstones become indistinctly bedded distributary channel deposits in the main part of the reservoir before fining upwards and becoming more tidally influenced near their top. These channel deposits have core permeabilities ranging from 20 md to well over 1000 md. The tidally influenced deposits are more compartmentalized compared to the thicker and more continuous basal fluvial deposits. Fine-grained sandstones that are laterally equivalent to the thicker channel-type deposits have permeabilities rarely reaching about 250 md.

Cores were described and potential permeability barriers were correlated using geophysical logs. Petrographic analyses were used to better understand porosity and permeability trends in the region and to characterize barriers and define flow units. Diagenetic alterations that impact porosity and permeability include development of quartz overgrowths, sutured quartz grains, dissolution of feldspar grains, formation of clay-mineral coatings on grains, and calcite cementation. Many of these alterations are controlled by facies.

Lawrence Field is unique in terms of the scale and the application of ASP flood technology and the success of the project would encourage similar EOR projects in comparable fields around the world.

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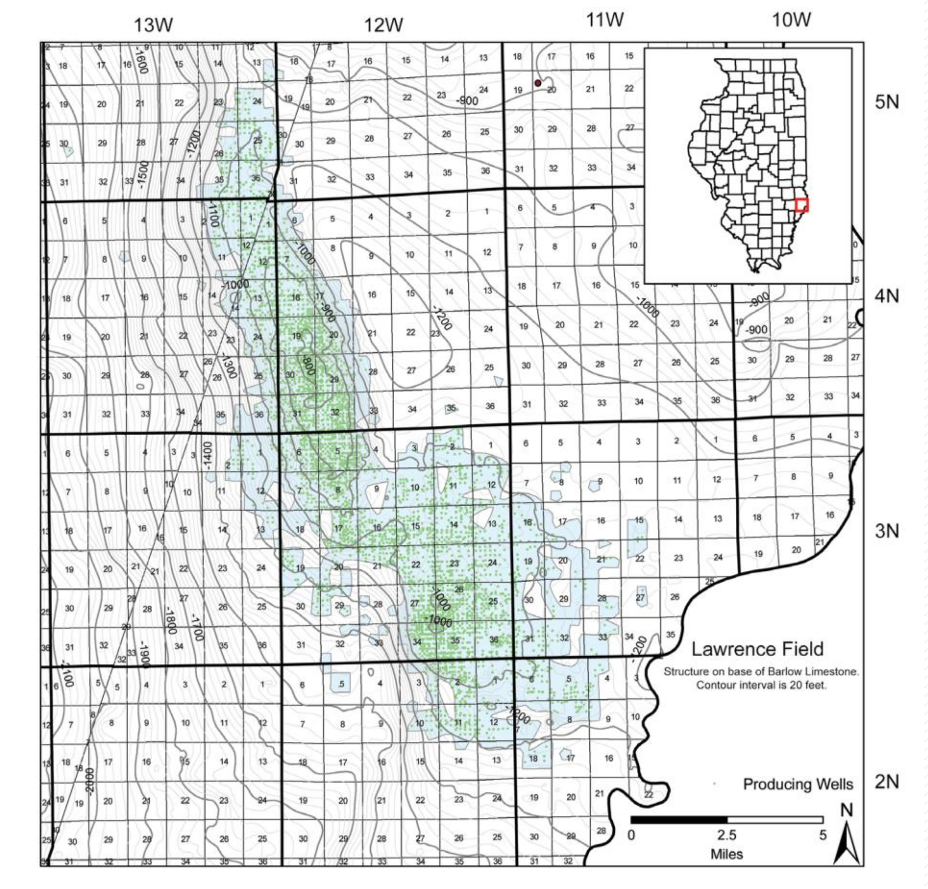
Lawrence Field

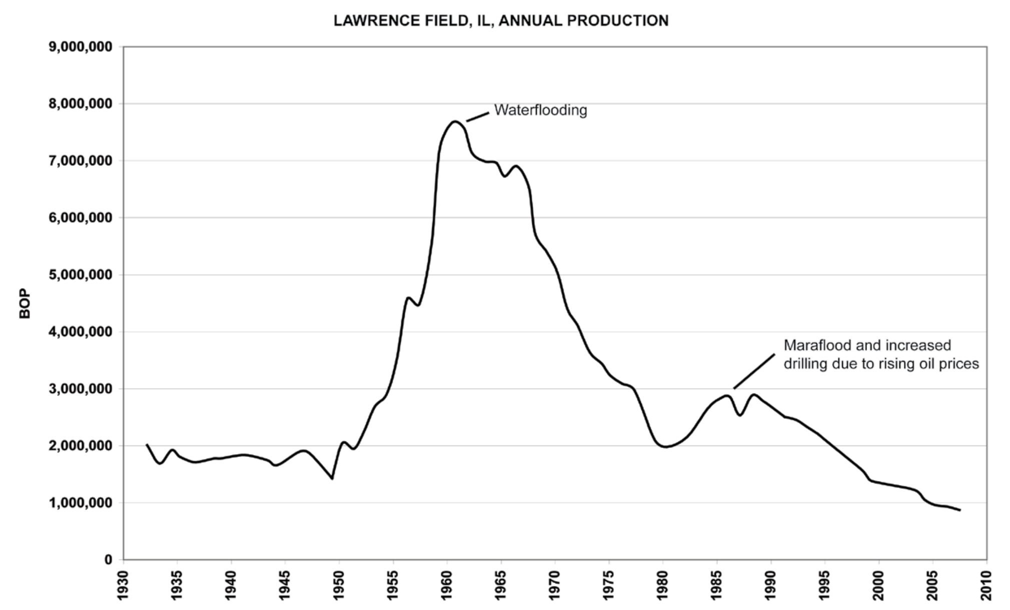


-Lawrence County, southeastern Illinois within the Illinois Basin

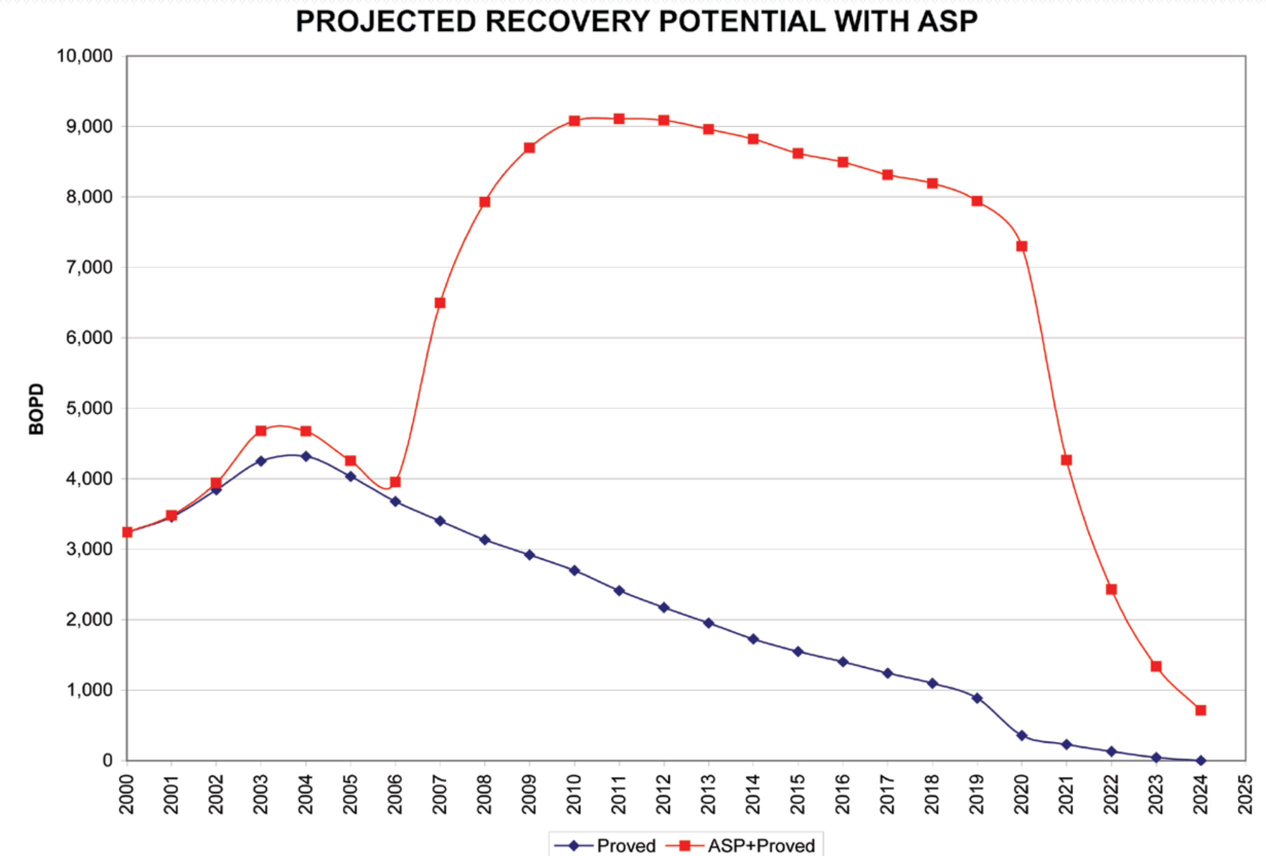
-Occupies the southern reaches of the La Salle Anticlinorium

-The area of interest for ASP application in Section 5 T3N, R12W and Section 32 T4N, R12W and is outlined in red.

Production History of Lawrence Field

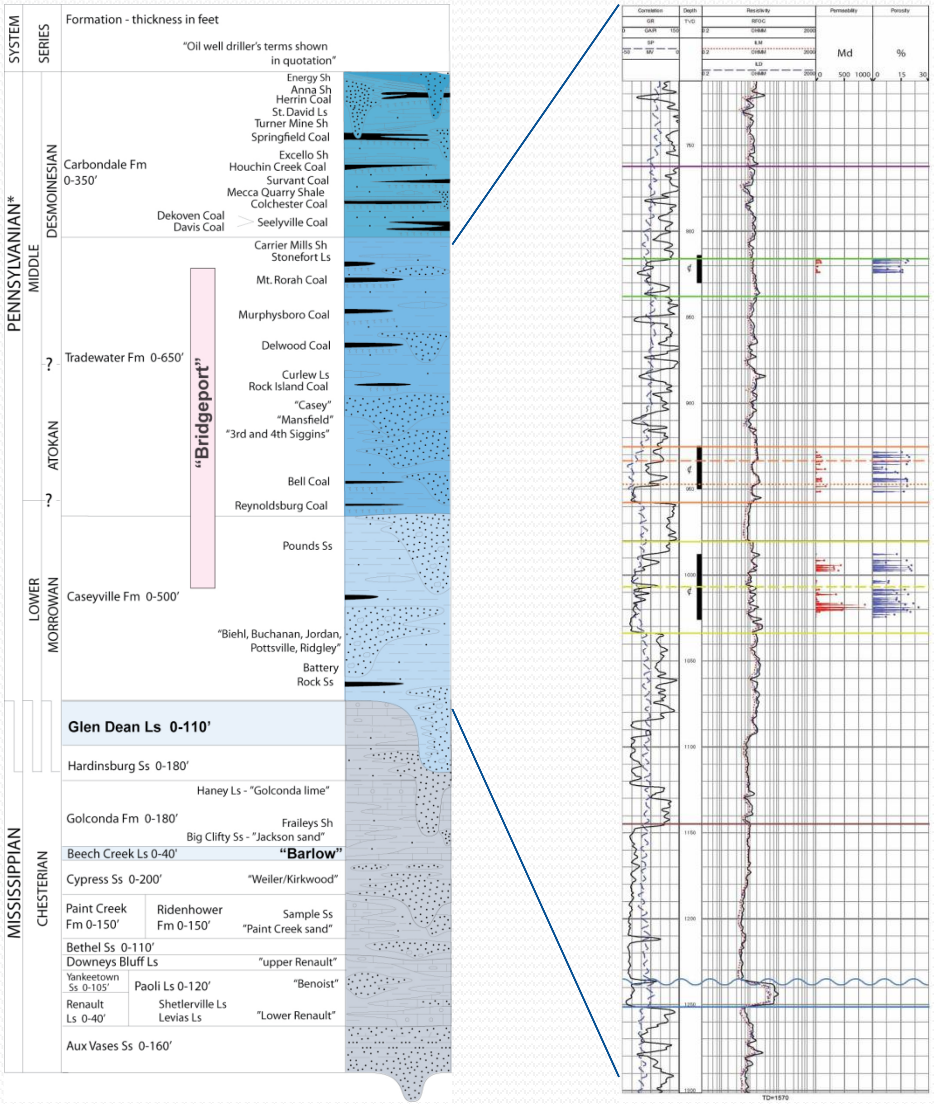


- Discovered in 1906
- Mature producer: in excess of 410 million bbl of oil produced primarily from Pennsylvanian Bridgeport and Mississippian Cypress sandstones.
- Current production is at a rate of <2% oil cut and it is estimated that recovery thus far is less than 40% of original oil in place.
- Historical success with waterflooding and polymer flooding (Maraflood)



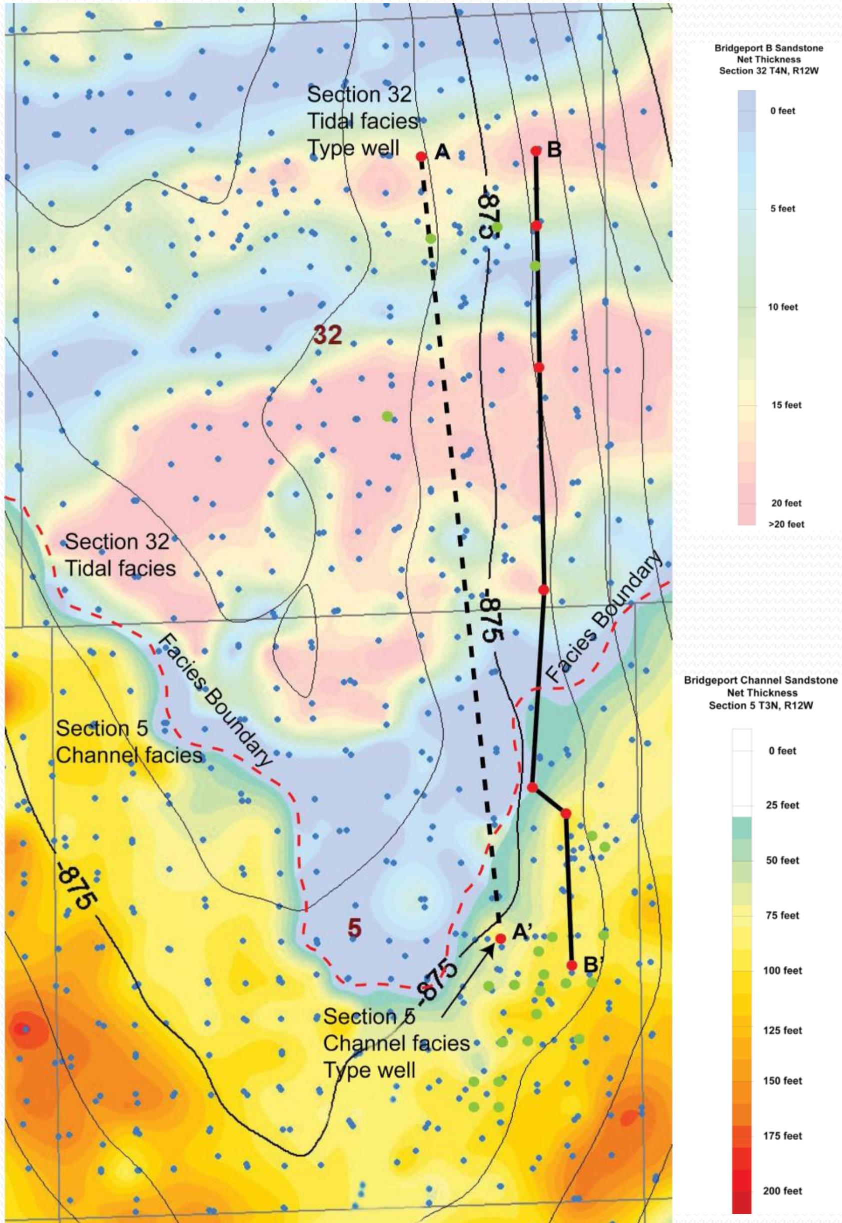
-Graph of projected field-wide recovery potential with the application of ASP. Estimates indicate that 10% of OOIP may be recovered or approximately 42 million bo by ASP flooding both the Cypress and Bridgeport reservoirs.

Southern Illinois Stratigraphy



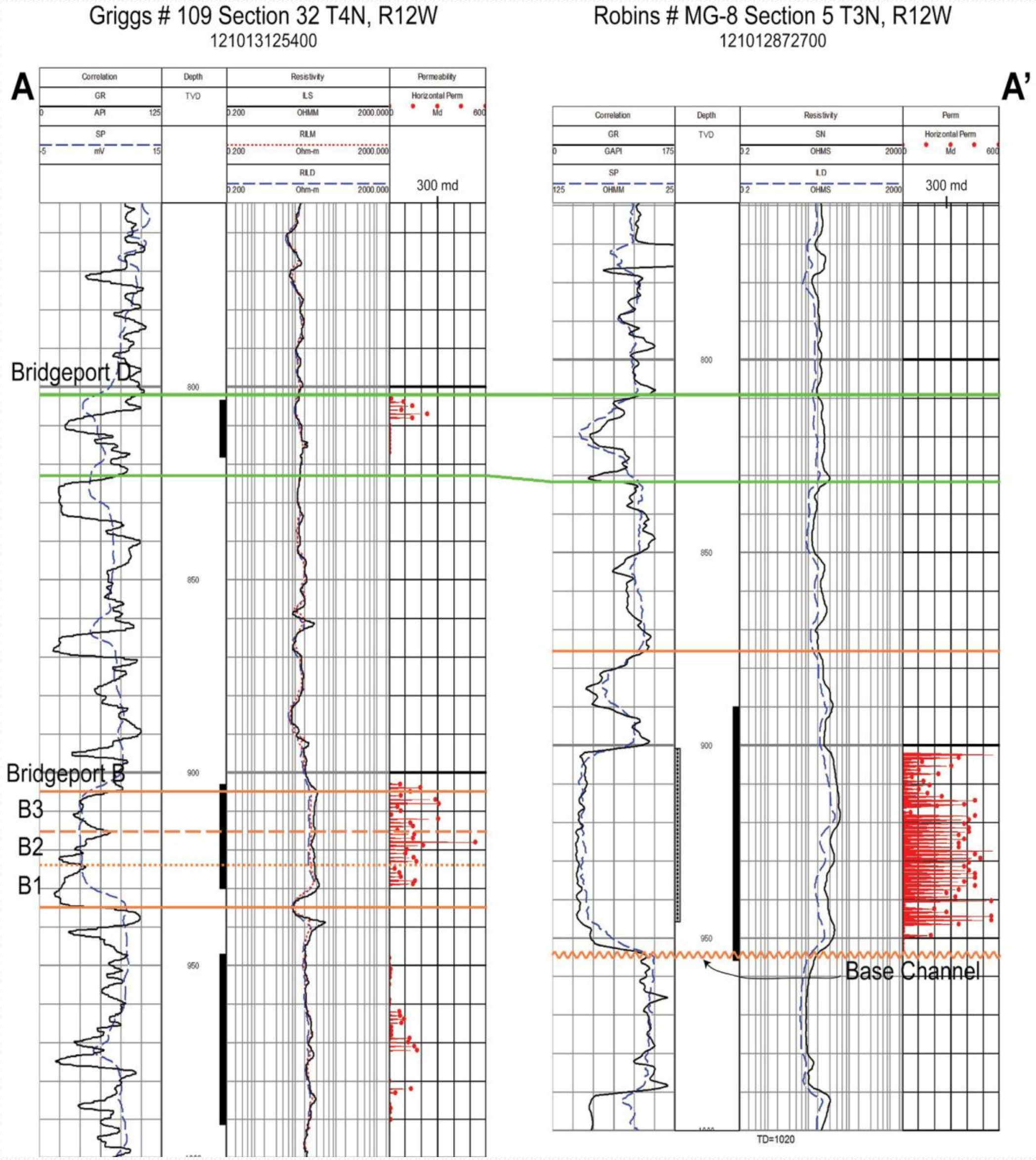
The Pennsylvanian Bridgeport sandstone reservoirs are located below the widespread continuous coals such as the Herrin, Springfield, Colchester and Seelyville of the Carbondale Formation.. These middle Pennsylvanian reservoirs can be highly productive and have historically been successfully waterflooded. The "Bridgeport B" sandstone is one of the most productive Pennsylvanian reservoirs in the field and has been a target reservoir for the current ASP project as well as Maraflood projects in the 1980's. A schematic of depositional models for several reservoirs is on the center panel. The resistivity, gamma ray, and spontaneous potential curves for the Griggs 107 well in Section 32 T4N, R12W and core-measured permeabilities (red) and porosities (blue) graphed in the right-most tracks

Area of Interest for ASP application



The contour lines on the map (25' C.I) show the structure on the base of the Barlow Limestone, a regionally extensive Chesterian thin limestone marker bed above which the Pennsylvanian Bridgeport sandstone reservoirs are found. The isopach map is a composite of two depositional facies showing 50% clean sandstone thickness with warmer colors indicating areas with thicker sandstone. In Section 32, Bridgeport B sandstones average ~25 feet thick and trend more or less east-west over the anticline. Note the locations of the two cross sections on the map (A-A' and B-B'). These cross sections are shown and annotated on the center panel to compare and contrast the differences in reservoir sandstone bodies between the two sections. Wells with Bridgeport core are highlighted with green dots.

Changes in Reservoir Character



- Above are two end point wells in the A-A' cross section from the map on Panel 1. The "Bridgeport D" sandstone unit is used as a stratigraphic datum as it is easily correlated in the area over a few square miles. Below the "D" is the "Bridgeport B" sandstone, which has been informally subdivided into three subunits: the B1, B2, and B3 in Section 32 T4N, R12W and the north-central portion of Section 5 T3N, R12W. The well on the left is the Griggs #109 in Section 32 and on the right is the Robins # MG-8 in Section 5. Bridgeport sandstones in Section 32 commonly show a stacking of up to three lenses while the sandstones in Section 5 are characteristically thick and blocky.

Changes in Reservoir Character (cont.)

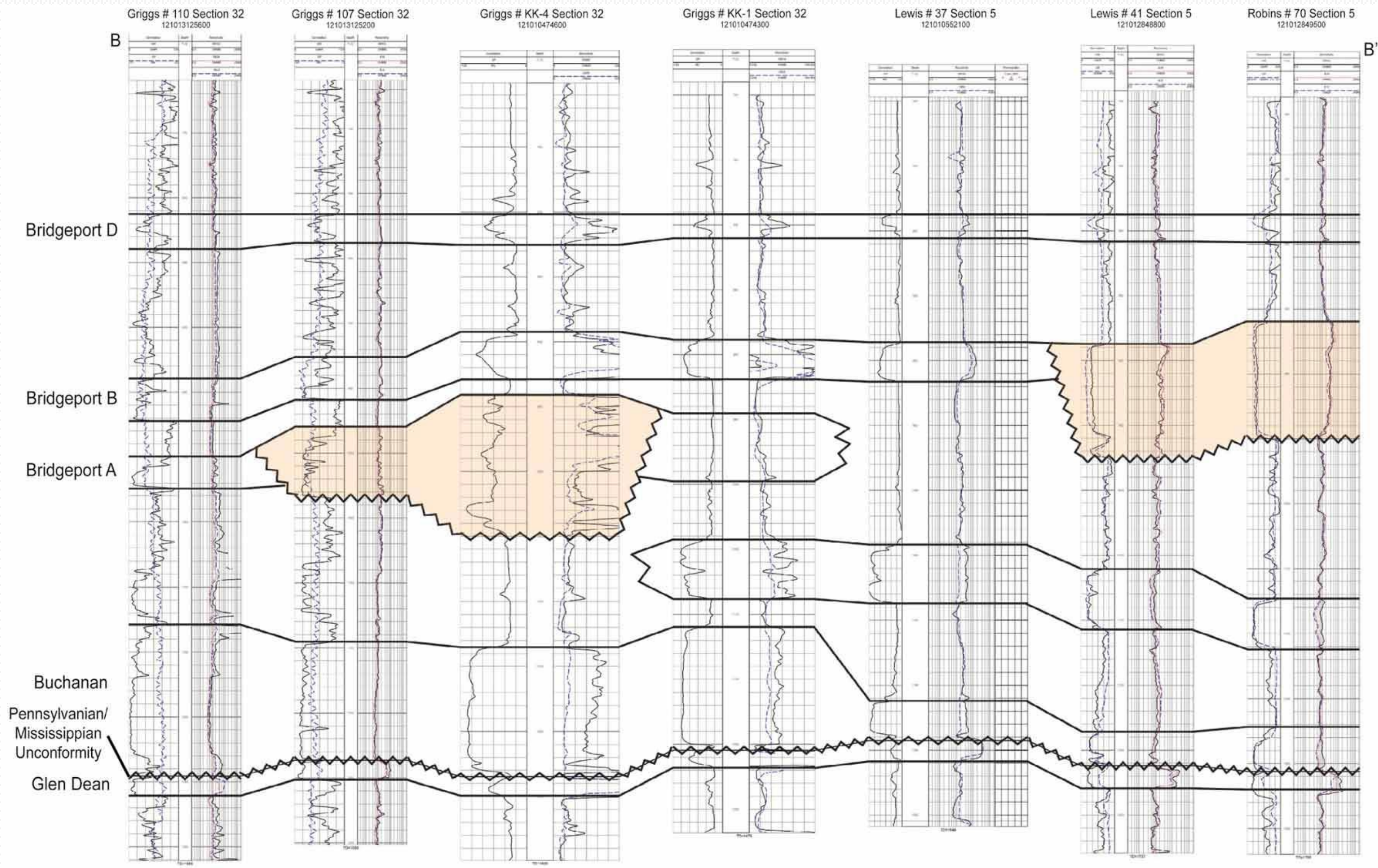
-Core-measured permeability is plotted in red on the right side of each log with a scale of 0-600 md. Average core-measured permeability in Section 5 sandstone is 63% higher (Average 113 vs. 314 md) compared to Section 32.

-Recognizing and understanding changes in permeability throughout the reservoir is important in delineating flow units, understanding flow channeling, and determining remaining recoverable oil

-Characteristics related to the environment of deposition and examination of the clay mineralogy as well as taking a close look at the petrography of the sandstone can go a long way towards explaining these pronounced differences in permeability.

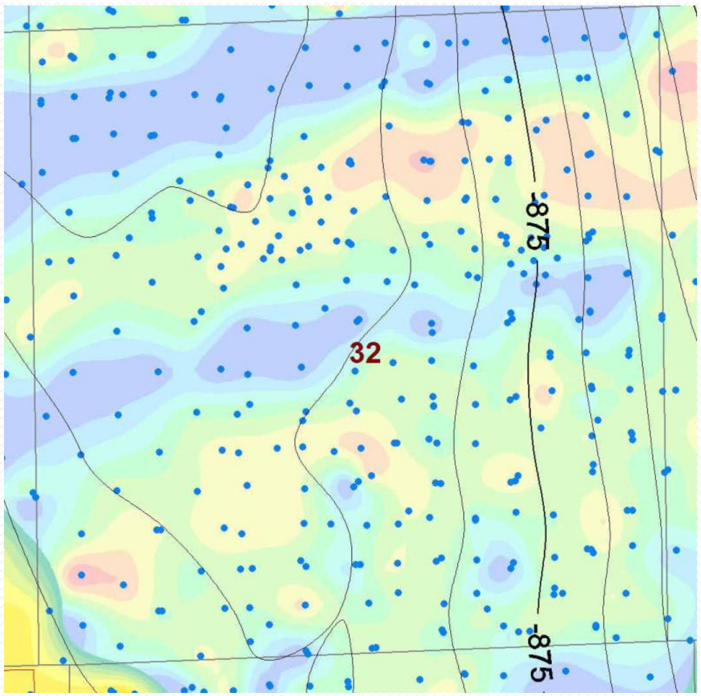
-These wells are about 1 ¼ mile apart but it is common to see this rapid change over only a few hundred feet. (See Cross Section B-B')

North-south cross section B-B' showing channel-fill sandstone and non-channel fill tidal sandstone deposits



This cross section connects the 1980s Maraflood pilot and a recently completed ASP pilot in the channel-fill sandstone in Section 5 with the tidally influenced sandstone deposit of the Bridgeport B in Section 32 where ASP flood development is presently in progress.

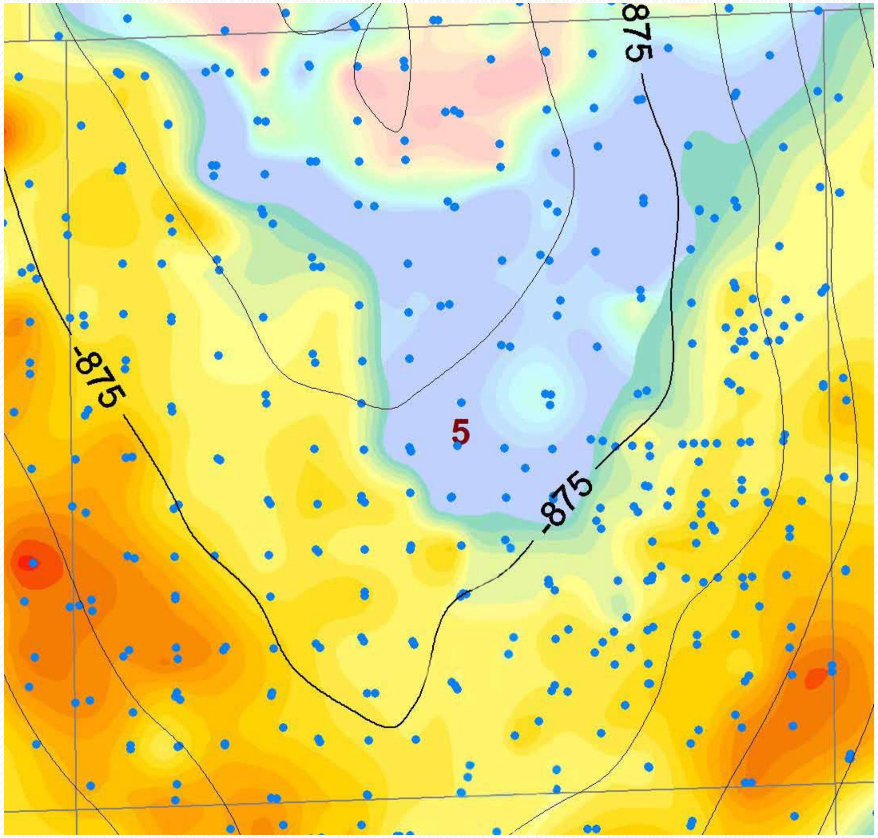
Mapping Compartmentalized Reservoirs



Bridgeport B1 net sandstone in Section 32

- Sandstone is mapped with a 2-foot contour interval with the warmer colors representing thicker sandstone.
- Reservoir sandstone in the northern half of Section 32 trends east-west whereas in the southern half of the section, the sandstone takes on a triangular shape and occupies the region between the two thick sandstone bodies that trend into Section 5 from the northeast and northwest and converge in the southern part of the section
- Bridgeport B1 and B2 sandstones develop predominantly in the same area. The B1 is thicker and better developed than the B2.
- Bridgeport B3 sandstone (not shown) is the thinnest and most poorly developed sandstone in the Bridgeport B interval in Section 32.

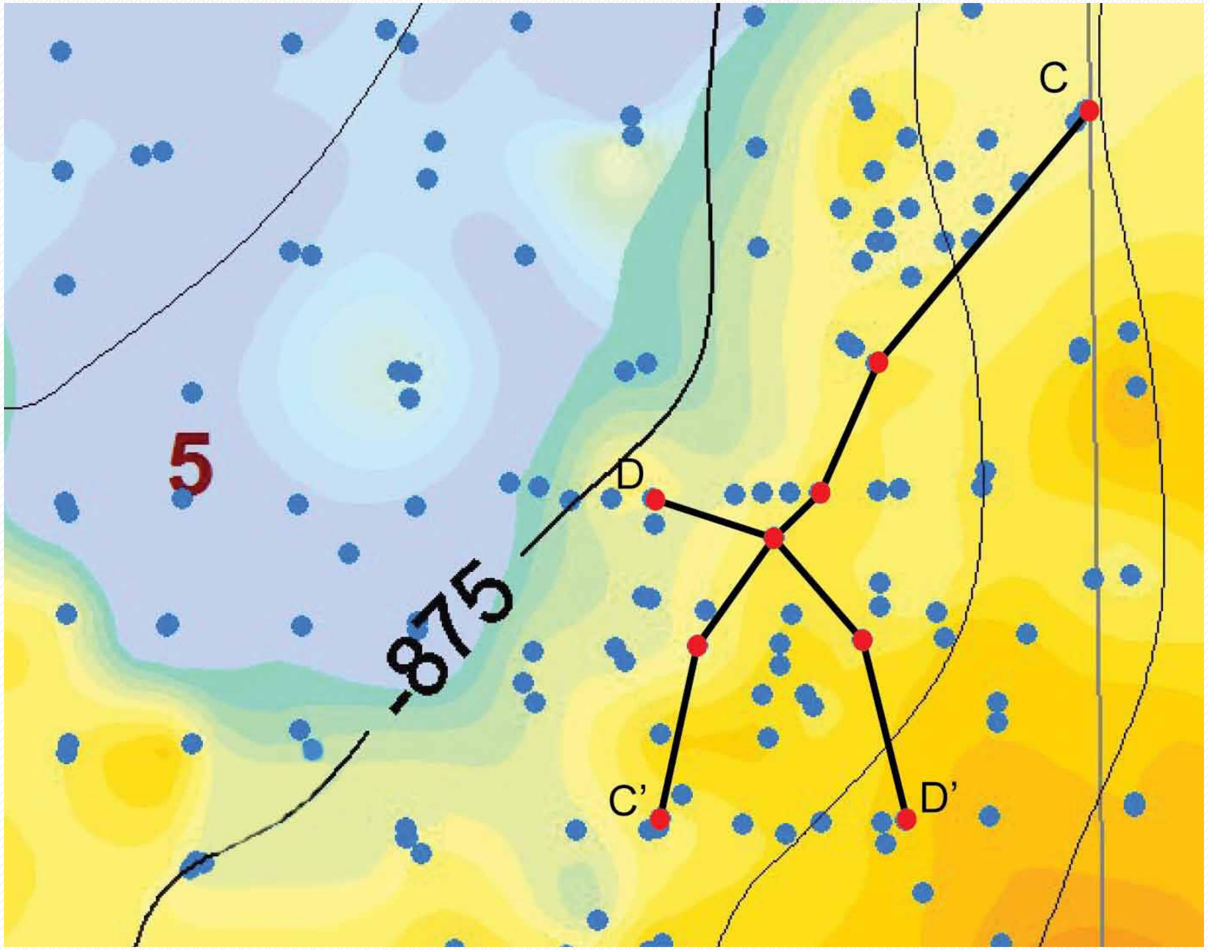
Mapping Compartmentalized Reservoirs



Bridgeport net sandstone in Section 5

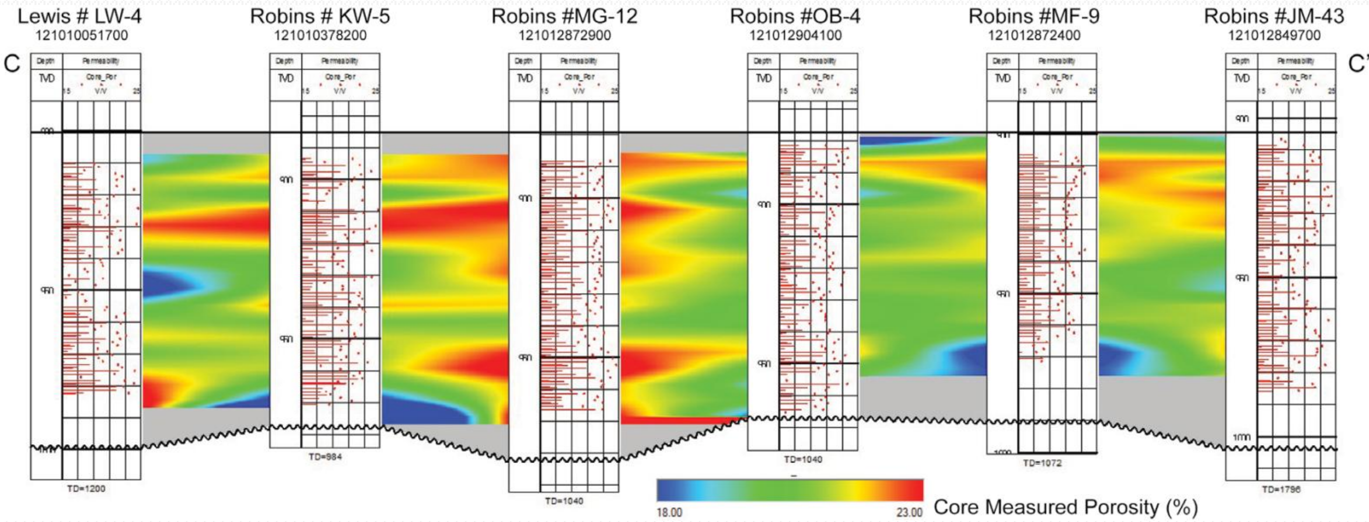
- Sandstone is mapped using a 10-foot contour interval with the warmer colors representing thicker sandstone.
- Reservoir sandstone in the eastern part of Section 5 trends northeast-southwest and tends to be blocky up to the western edge.
- Sandstones trend northwest-southeast in the western part of Section 5 and show multiple, stacked benches along the eastern edge, becoming blocky and thick to the west.
- Sandstone shows good vertical continuity in geophysical logs and cores.
Thickness of these blocky sandstones ranges up to ~170 feet.

Core Porosity and Permeability Cross Sections

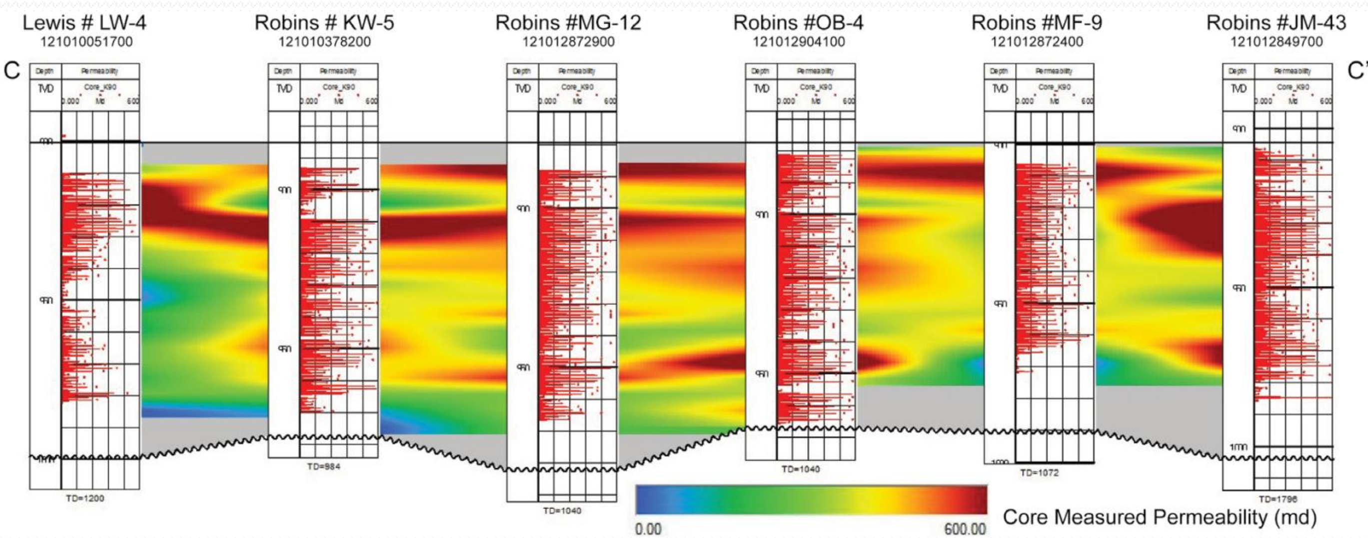


- Map showing cross section grid in the eastern part of Section 5 through wells with core-measured porosity and permeability values.
- The porosity and permeability values are from thick channel-fill sandstone.
- This is the same area as the 1980s Maraflood pilot and the recently completed ASP pilot.
- Cross sections below show porosity and permeability values interpolated between the wells.
- The cross sections indicate the presence of flow units in the sandstones which have higher permeability and porosity.

Core Porosity and Permeability Cross Sections

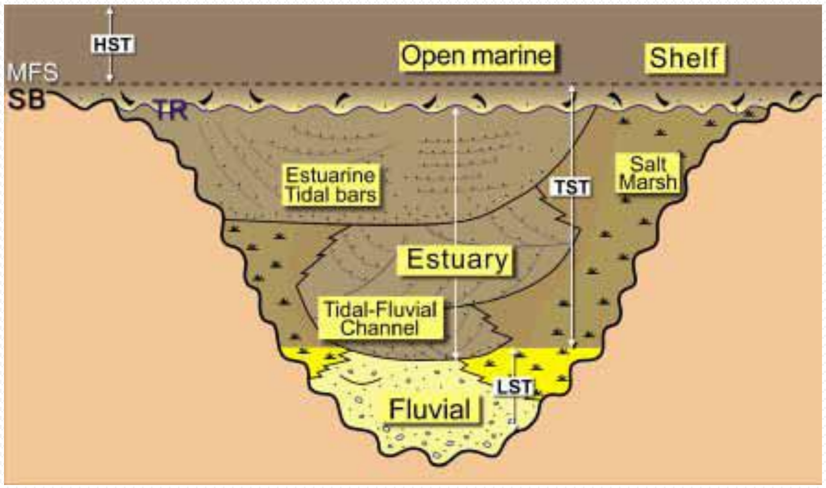


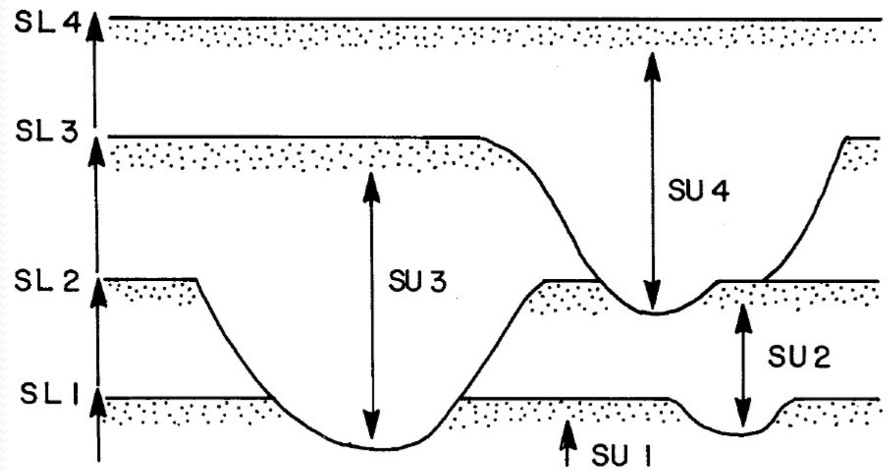
- Cross section C-C' showing core porosity. Warmer colors are areas of higher porosity (23%) and cool colors are areas of lower porosity (18%).



- Cross section C-C' showing core permeability. Warmer colors are areas of higher permeability (600 md) and cool colors are areas of lower permeability.

Depositional Environment for Bridgeport Reservoirs





Schematic diagram showing tide-dominated estuary located within an incised channel. Entire system is transgressive in character with the basal fluvial deposits overlain by estuarine deposits and capped with open-marine deposits of the succeeding progradation. This incised valley fill model is analogous to sedimentary structures observed in core in Section 5 3N, 12W. From Dalrymple and Choi, 2007.

Schematic diagram illustrating a typical estuarine-fill complex deposited under continuously rising sea level. The stillstand units are relatively tabular and extend from channels cut in the previous unit to the upper intertidal to supratidal. From Clifton, 1982.

EOR Targets in Section 32 4N, 12W and Section 5 3N, 12W

Section 5

- The large, unconstrained volume of the reservoir in Section 5 means it would likely require a large amount of chemicals that could be difficult to trace. Additionally, the high permeability of the reservoir sand means that it would take a great volume of fluid to flood effectively.

- It is difficult to correlate flow units within these reservoirs with standard mapping techniques using logs. However, doing a few things would increase the likelihood of achieving a successful flood. 1. Further petrographic study of the rock should reveal the factors controlling the change in permeability within a sandstone that, on a log, looks fairly uniform. 2. Computer modeling of the permeability should aid in the placement of a possible flood to most effectively sweep the reservoir.

- Oil saturations have been lowered due to the previous waterflooding and Maraflooding. However, it should be noted that high permeability/quality reservoirs are generally very good targets for EOR techniques.

- Also, the thick sandstones in Section 5 are somewhat off structure and thus, a portion of the sandstone is below the oil-water contact.

Section 32

- Because of the history of Lawrence field, the Bridgeport B sands in Section 32 are a better EOR target.

- The target reservoirs have smaller volumes and are more confined than that found in Section 5.

- Flow units are traceable, meaning we should have an idea where injected chemicals will be going.

- Permeability of the sandstone in Section 32 is also lower, meaning previous water flooding has probably been less effective and has left more oil in place.

Conclusions

- Implementation of Enhanced Oil Recovery Program in Mature Pennsylvanian and Chesterian sandstone reservoirs may have broad application in the Illinois Basin and elsewhere.

- The potential for channelized flow in highly permeable channel-fill intervals versus intervals with low permeability has added to the difficulty of implementing EOR techniques in these reservoirs. The highly permeable intervals have likely been depleted by successful waterflooding operations leaving more recoverable oil in the less porous and permeable intervals.

- Compartments can be most effectively drained where they are geologically well defined and reservoir management practices are coordinated through unified, compartment-wide, development programs.

- The overprint of diagenetic alteration has added to the high degree of variability in these reservoirs.

- Diagenetic alteration is also complex, taking place over a geologic time frame, resulting in areas of both enhanced porosity and permeability and diminished porosity and permeability.

- Lower overall porosity and permeability is caused by facies changes, resulting in introduction of very fine ductile grains

- X-ray diffraction and thin-section analysis has shown that the identified clay-mineral suite in reservoir intervals should be considered because they are primarily located in pores where interaction with existing or injected fluids is likely. These data are important for determining the suitability of various EOR techniques.

- Petrographic examination of thin sections shows that diagenetic alteration has resulted in additional compartmentalization. Cementation of reservoir quality sandstone intervals by ferroan calcite has caused major permeability barriers/obstacles in many cored wells.

- Compaction of ductile grains particularly in some ripple-bedded intervals has greatly reduced porosity and permeability, diminishing reservoir quality.

- Other facies, such as the mottled sandstone/obscurely bedded facies have increased porosity and permeability due to the lack of compaction in channel fill deposits.

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