PS Reservoir Characterization of Lower Pennsylvanian Sandstones for the Application of ASP Flood Technology in Lawrence Field, Illinois*

Nathan D. Webb[1], John P. Grube[1], Curt S. Blakley[1], Beverly Seyler[1], and Vineeth Madhavan[1]

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Abstract

The alkali-surfactant-polymer (ASP) enhanced oil recovery (EOR) method is currently being applied in the lower Pennsylvanian Bridgeport sandstone of Lawrence Field, a 400 million barrel, mature producing field in southeastern Illinois. Detailed reservoir characterization has delineated flow units and permeability barriers that identify target zones for the application of ASP flood technology.

Siliciclastic rock dominates lower Pennsylvanian strata in Lawrence Field. Deposition occurred unconformably over older Mississippian strata in an area of active uplift along the southern reaches of the LaSalle Anticlinorium. Contemporaneous tectonic influence in the area on both the deposition of the Bridgeport sandstones and reservoir characteristics is just beginning to be clearly understood. Detailed mapping of the subsurface geometry of Bridgeport sandstone reservoirs, as well as knowledge of their petrophysical characteristics, are critical to the success of an ASP type flood. Mapping with thousands of geophysical logs of various vintages has revealed that throughout the northern part of the field, a cyclical series of lenticular sandstone bodies, typically around 30 feet thick, interdigitate with non-reservoir siltstones and shales to create confined reservoirs ideal for the successful application of the ASP EOR technique. Those lenticular reservoirs are further subdivided into compartmentalized flow units that are bounded by thin shaley intervals that may or may not permit communication between compartments. Elsewhere, these more lenticular reservoirs appear to be eroded and replaced with younger, much thicker channel fill deposits of clean sandstone in some areas and low energy, fine-grained sediments in others.

Examination of nearly 4000 feet of core has revealed sedimentological features of both the lenticular sandstone bodies and the channel fill facies. Petrographic analysis further illuminates reservoir characteristics by showing the importance of the diagentic overprint and areas where high

permeabilities create potential thief zones. Finally, recasting the Bridgeport strata in a sequence stratigraphic framework by defining regionally extensive sequence boundaries is helping to clarify how the Bridgeport reservoirs relate to one another and in which environment they were deposited. Success of ASP flood technology in Lawrence Field would encourage similar EOR projects in comparable fields throughout the Illinois Basin and around the world.

Selected References

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Jacobson, R.J., 2000, Depositional history of the Pennsylvanian rocks in Illinois: GeoNote 2, Illinois State Geological Survey, Prairie Research Institute. Web accessed 7 June 2012. http://www.isgs.illinois.edu/maps-data-pub/publications/geonotes/geonote2.shtml

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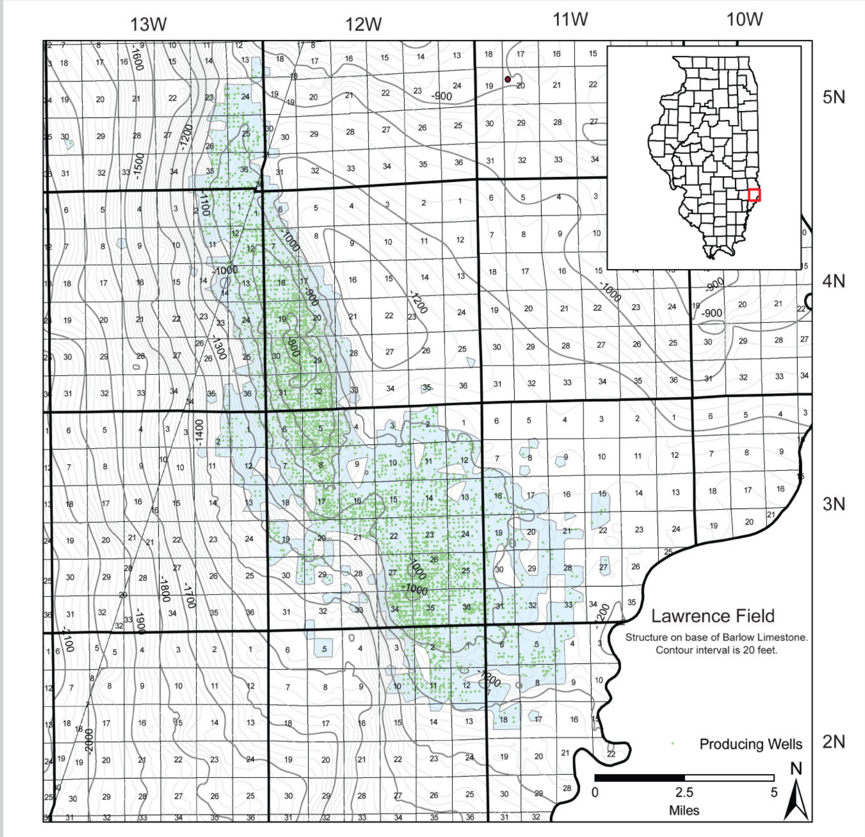
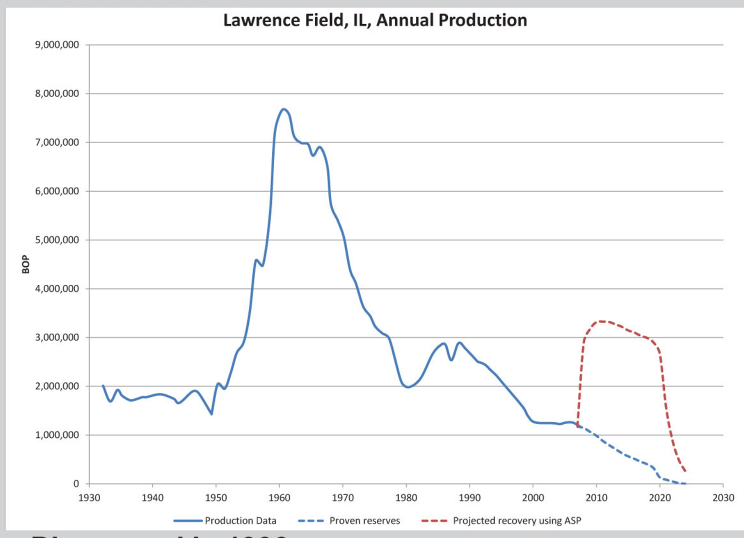
Examination of nearly 4000 feet of core has revealed sedimentological features of both the lenticular sandstone bodies and the channel fill facies. Petrographic analysis further illuminates reservoir characteristics by showing the importance of the diagenetic overprint and areas where high permeabilities create potential thief zones. Finally, recasting the Bridgeport strata in a sequence stratigraphic framework by defining regionally extensive sequence boundaries is helping to clarify how the Bridgeport reservoirs relate to one another and in which environment they were deposited. Success of ASP flood technology in Lawrence Field would encourage similar EOR projects in comparable fields throughout the Illinois Basin and around the world.

Lawrence Field



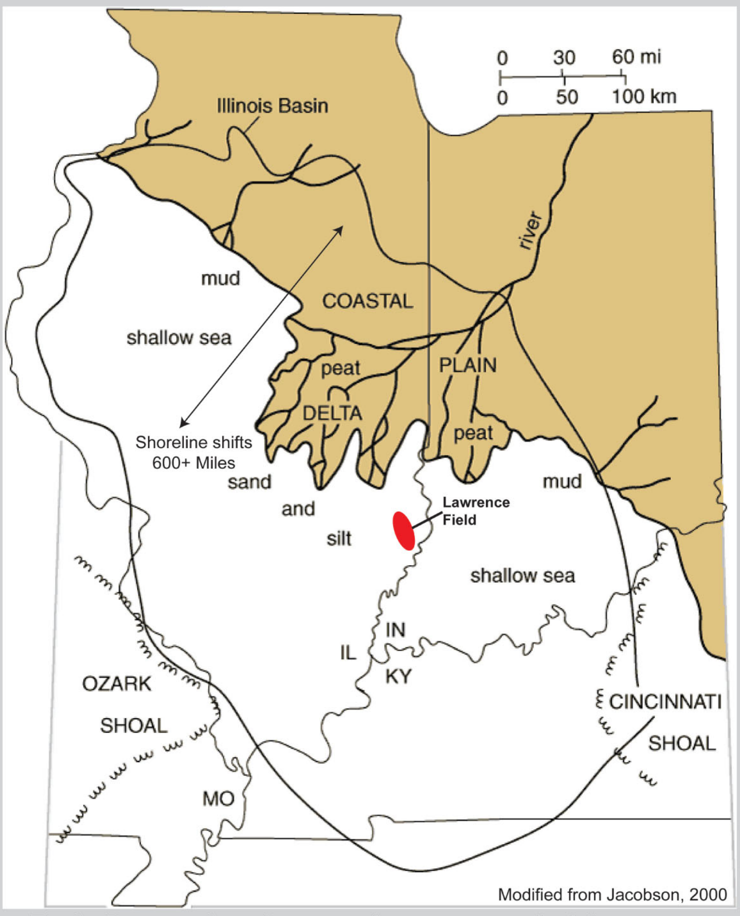
Right: Map of Lawrence Field in Lawrence County, SE Illinois. Structure map shows the southern reaches of the La Salle Anticlinorium.

Production



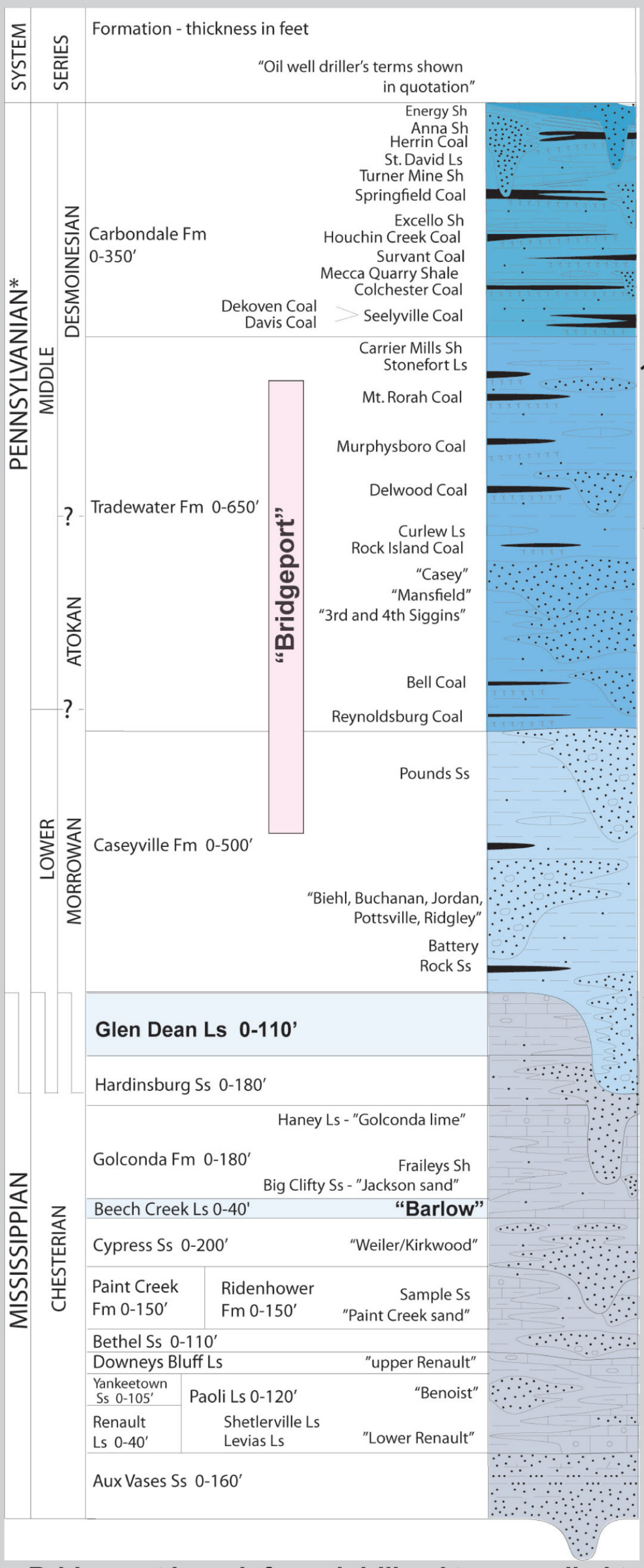
- Discovered in 1906
- Mature producer: >410 million bbl of oil produced
- Production primarily from Pennsylvanian Bridgeport Ss and Mississippian Cypress Ss
- Current production is at a rate of <2% oil cut
- Estimated recovery thus far ~<40% of OOIP
- Historical success with waterflooding and surfactant polymer flooding (Maraflood)
- Projected incremental recovery using ASP of at least 42 million bbl of oil, or 10% of produced oil (Plains Illinois, 2002)

Pennsylvanian Paleogeography

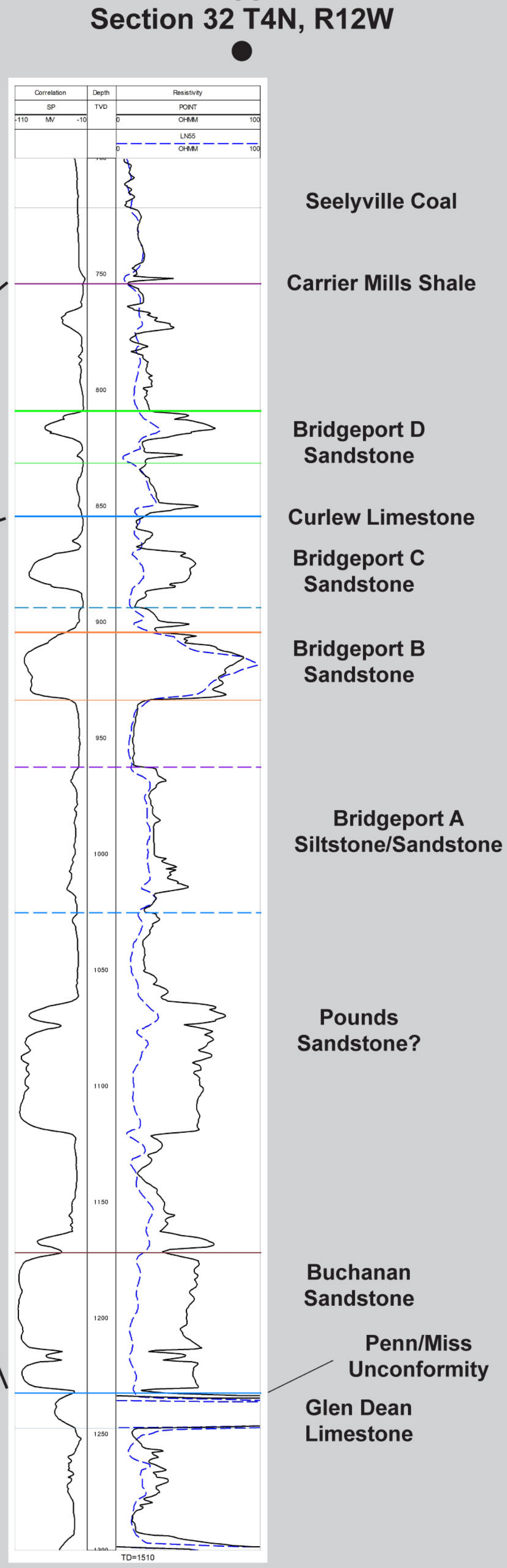


- Early Pennsylvanian erosion removed older strata as river systems scoured deep channels into the bedrock, creating a high-relief surface that affected early Pennsylvanian sedimentation.
- Pennsylvanian strata are characteristically cyclic owing to migration of delta systems and the shoreline through time.
- Shoreline shifts occurred partly because of eustatic sea level changes, but also because of variations in the amount of sediment influx and local changes in basin subsidence rates resulting in a predominant and complex sequence stratigraphic overprint.
- Lawrence Field occupies a location in the basin that was subject to sedimentation along a shifting shoreline, causing depositional conditions to alternate between marine and nonmarine, producing lithologic variety in the Pennsylvanian rocks.

Regional Stratigraphy

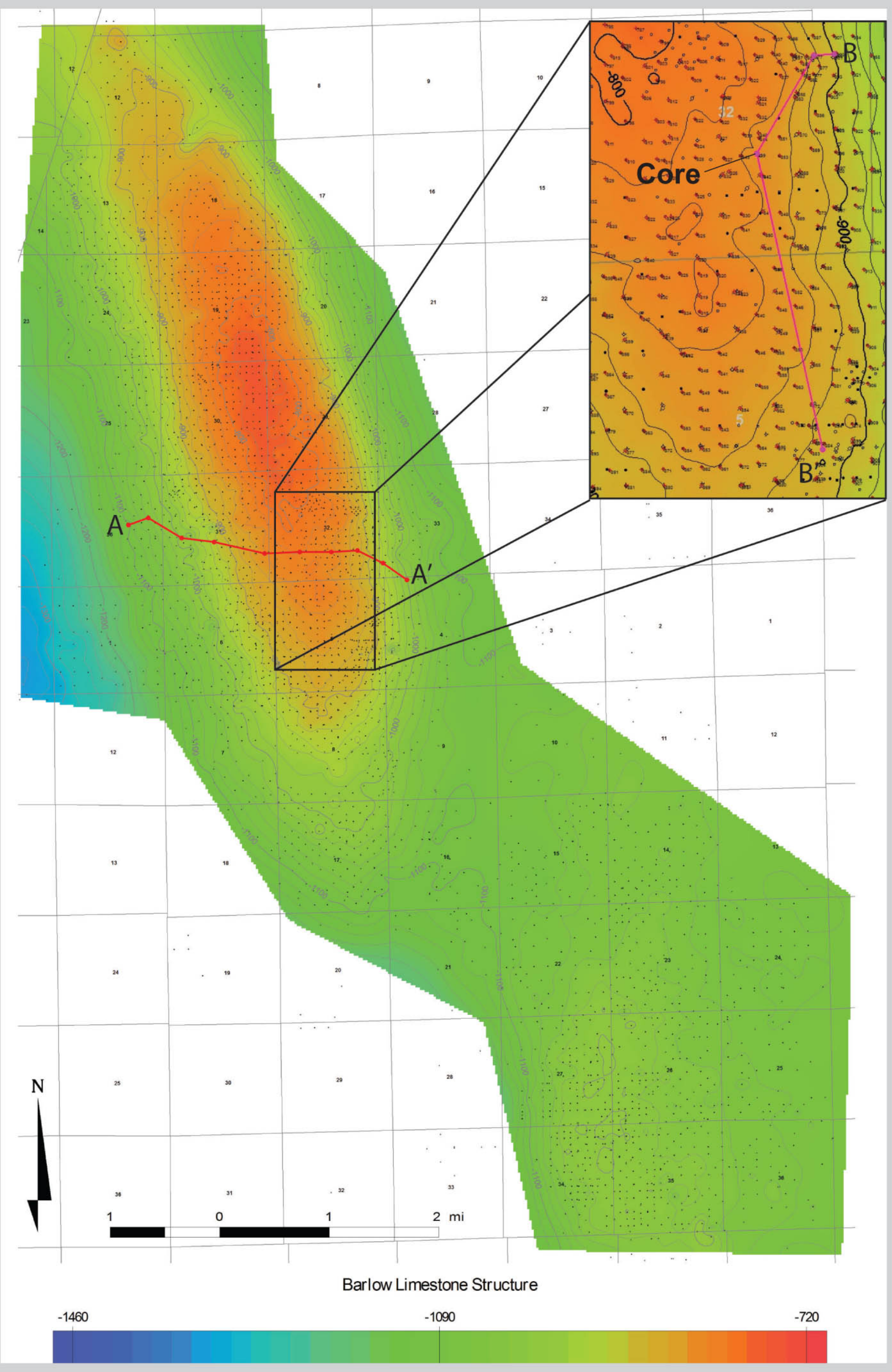


JT Griggs #60
Section 32 T4N, R12W



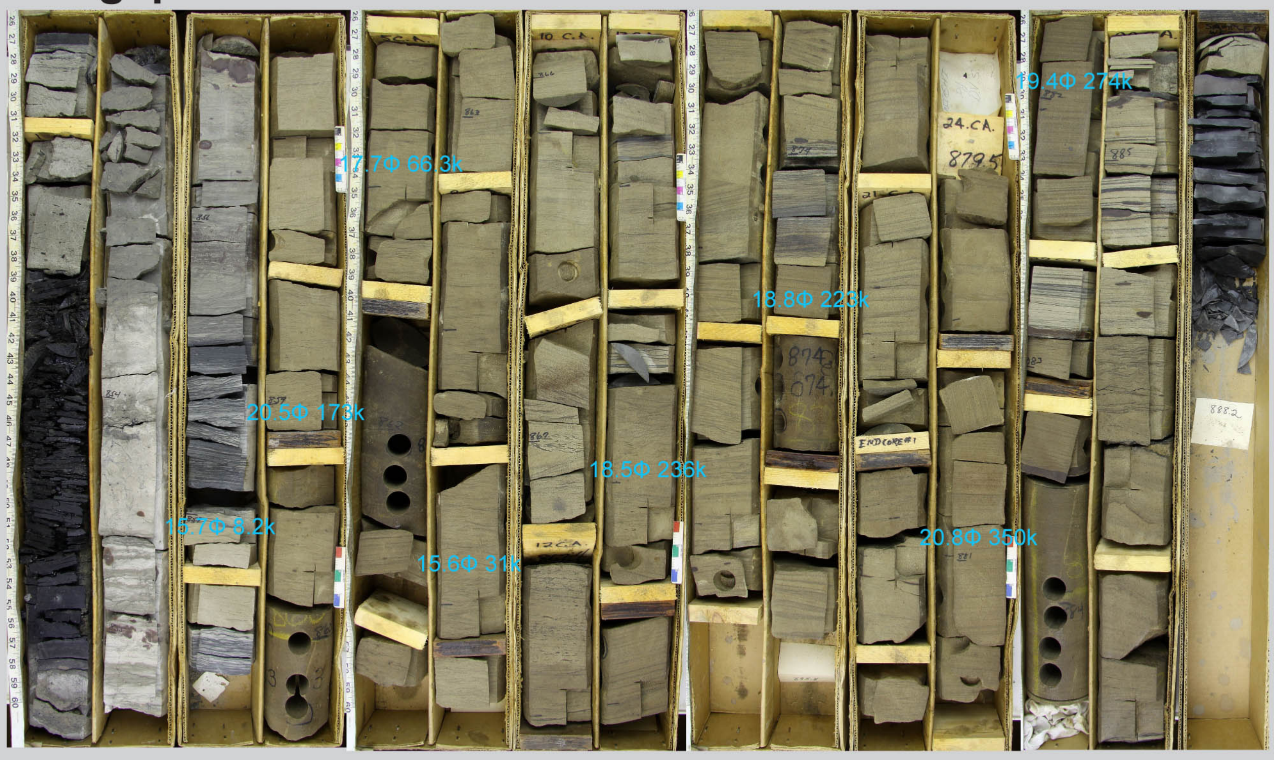
- Bridgeport is an informal drillers' term applied to Pennsylvanian aged sandstone bodies of the Tradewater and upper Caseyville Formations
- Bridgeport sandstone reservoirs are located below the basinwide coals such as the Herrin, Springfield, Colchester and Seelyville of the Carbondale Formation
- Caseyville and Tradewater Formations exhibit discontinuous, commonly stacked sandstone bodies juxtaposed against thick, valley-fill sandstones, thus making their widespread correlation problematic
- Four reservoir zones have been identified for potential ASP recovery: Bridgeport A, B, C, and D. Other Caseyville sandstone reservoirs also show EOR potential.
- The "Bridgeport B" sandstone is one of the more productive Pennsylvanian reservoirs in the field and is currently being ASP flooded with plans for expansion in the near future
- Field scale mapping of the target "Bridgeport B" reservoir is aided by the identification of sequence stratigraphic surfaces
- Bridgeport B sandstone is only present in areas where the underlying "Beta Shale" and an overlying coal are found
- Typical channel fill reservoirs are found in Section 5 T3N, R12W
- The JT Griggs #60 type log, above, shows the typical succession of Pennsylvanian rocks in the field

Mapping the Bridgeport B

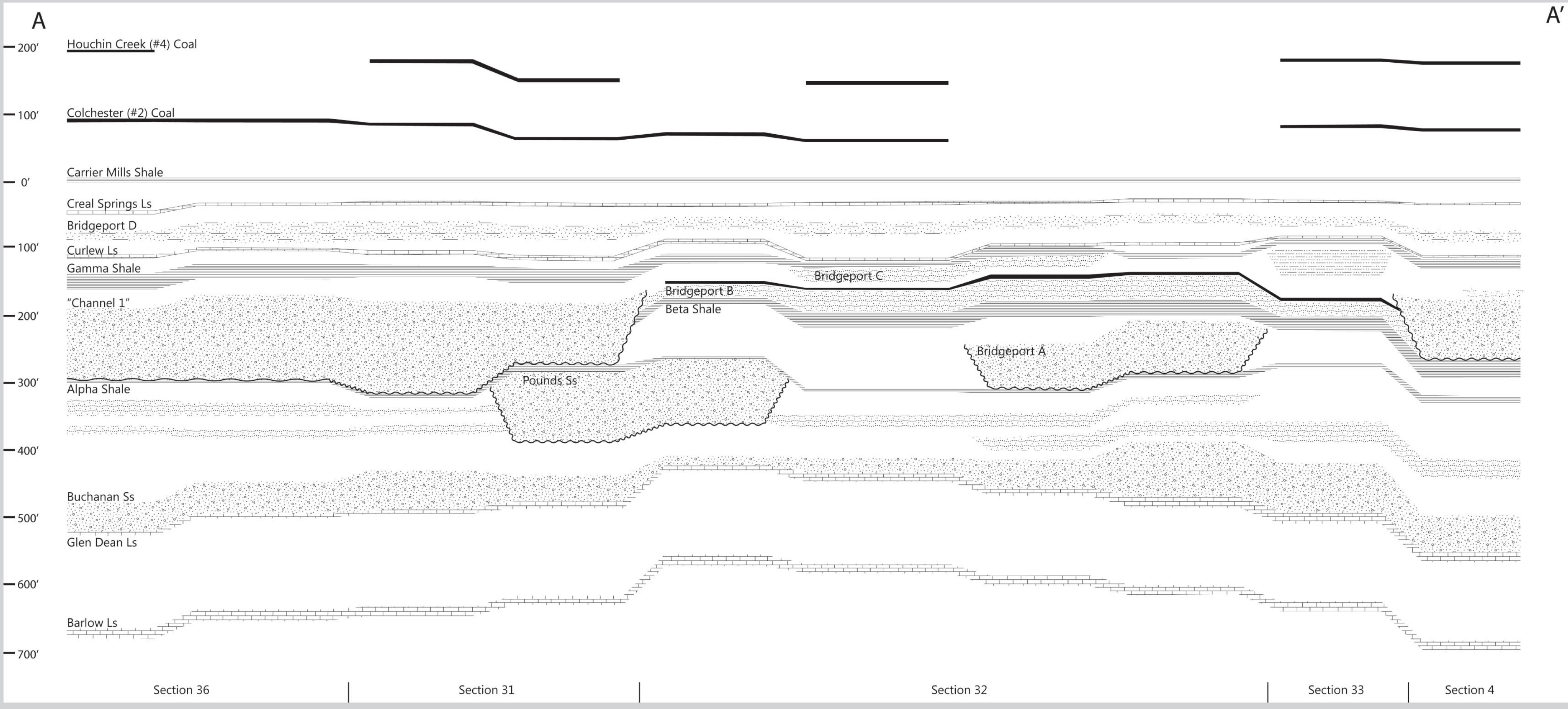


Left: Structure map of the base of the Barlow Limestone, a regionally extensive Chesterian age thin limestone marker bed above which the Pennsylvanian Bridgeport sandstone reservoirs are found in Lawrence Field. Contour interval is 20'. The northern part of the field features the NW-SE trending Bridgeport Anticline while the Lawrenceville Dome occupies the southern part. Both structures make up the southern extension of the La Salle Anticlinorium.

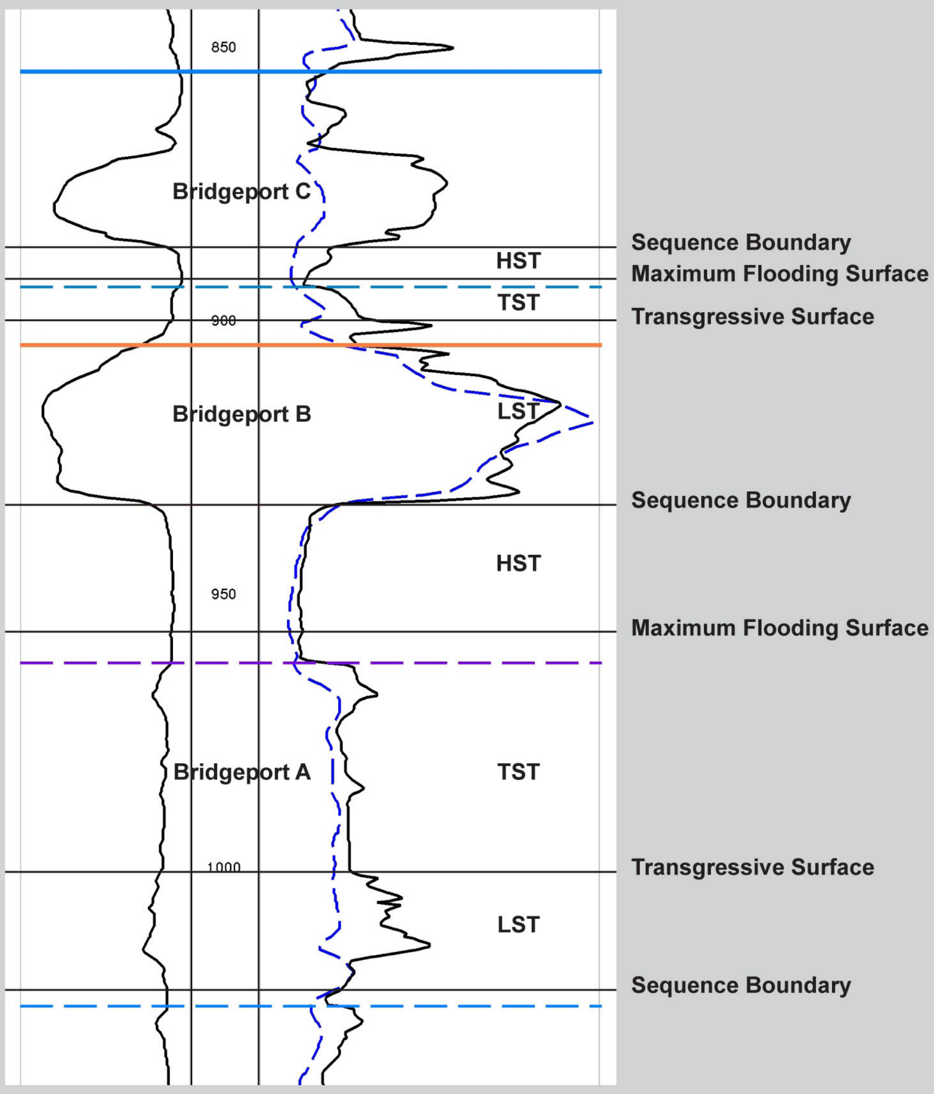
Bridgeport B Core



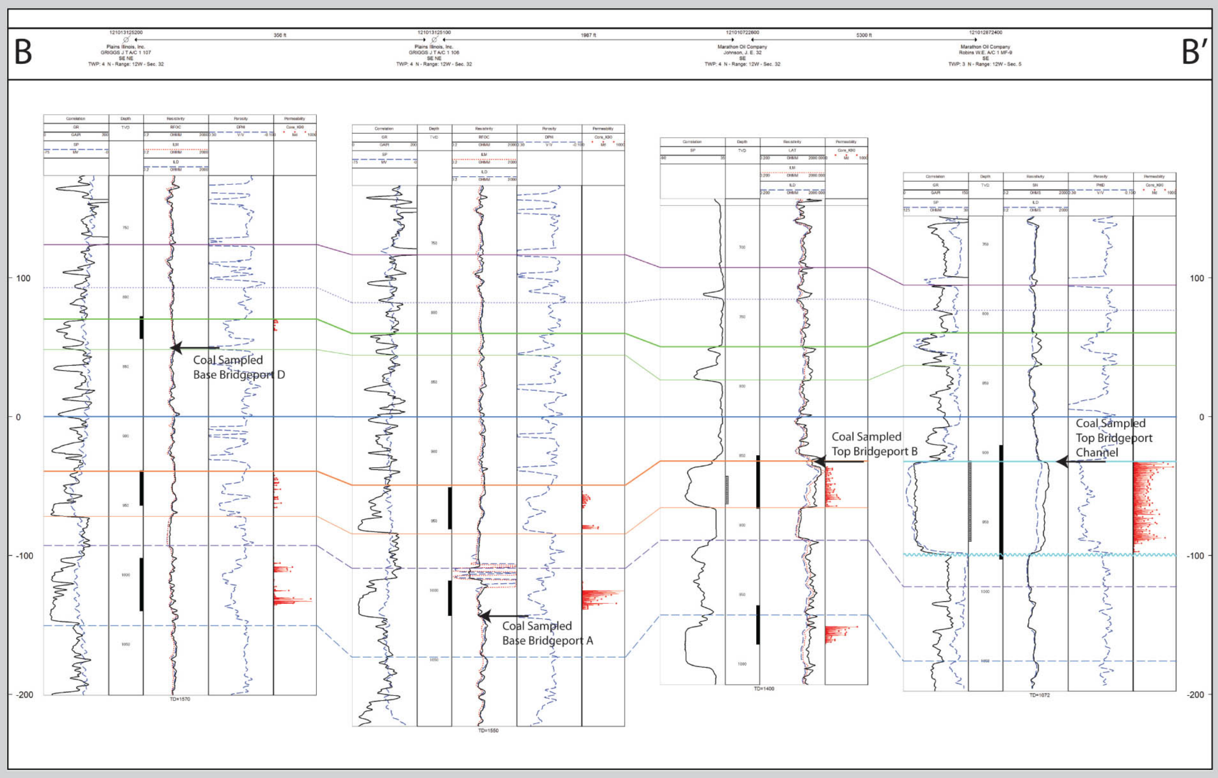
Bridgeport B core showing the typical succession of sediments and arrangement of facies in Section 32. The Bridgeport B is underlain by the widespread marine shale called the Beta Shale. The contact between the base of the Bridgeport B sandstone and the Beta Shale is erosional and constitutes a sequence boundary. The Bridgeport B sandstone averages roughly 30 feet thick, is medium to fine grained and fines upward. Tabular crossbedded to planar bedded sandstone (~20Φ 280k) generally makes up the lower portion of the Bridgeport B. The upper portion of the sandstone changes facies to wavy and ripple bedded (~17Φ 125k). A sharp contact at 857.5' marks another facies change into finer grained lenticular bedded sediments that cap the sandstone and as they transition into rooted sediments that supported the overlying coal. A few inches of dark grey shale on top of the coal indicates the next phase of transgression.



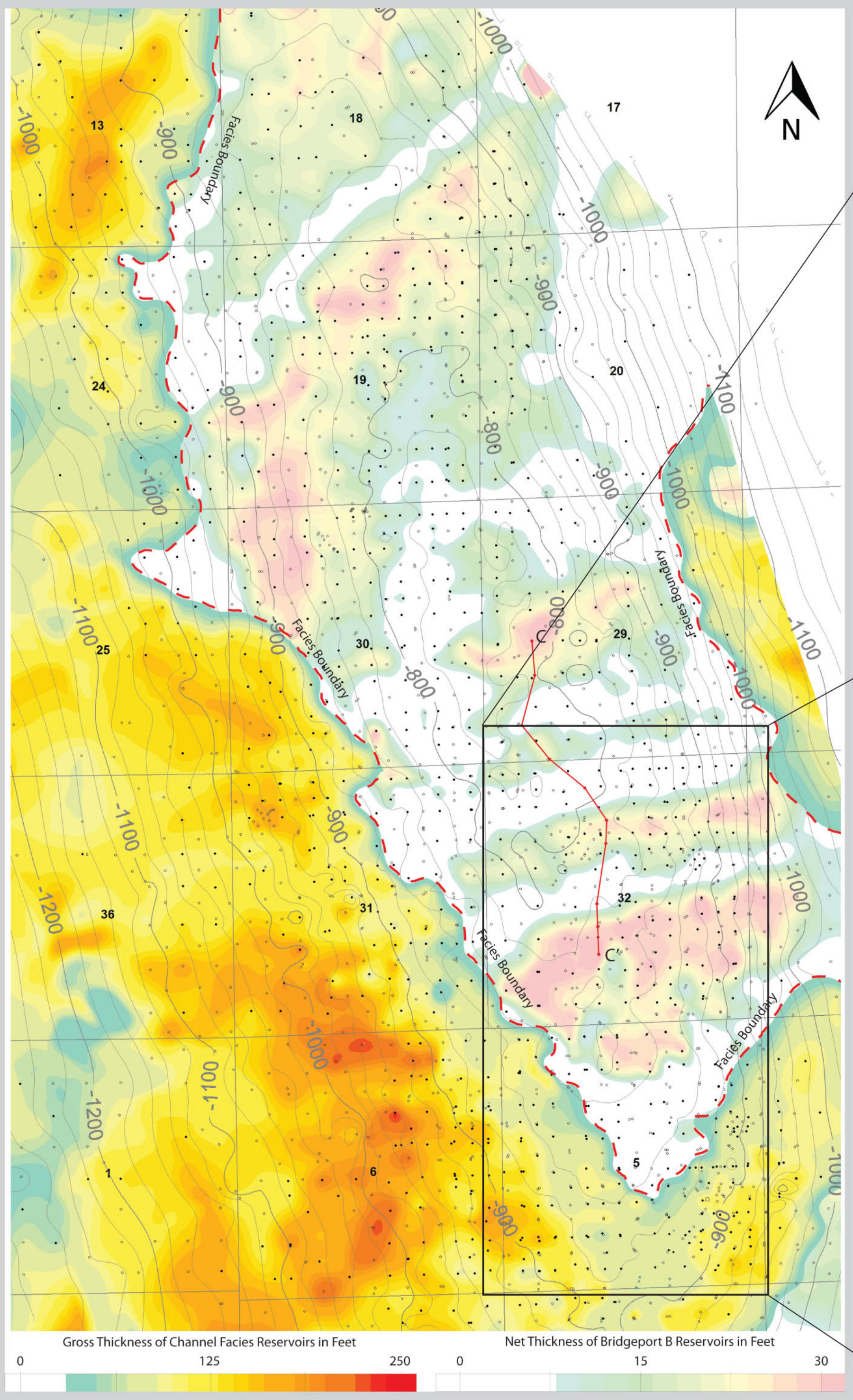
East-West cross section A-A' across the Bridgeport Anticline (see structure map above) in the Northern part of Lawrence Field showing the stratal arrangement of lower Pennsylvanian sediments. The Carrier Mills Shale is the datum. Here, the discontinuous nature of the Bridgeport A, B, and C can be seen. The Bridgeport B is widely traceable in part because of the consistent underlying Beta Shale and overlying coal. The Bridgeport B is truncated to both the East and the West by younger Pennsylvanian channel fill deposits, making its lateral correlation outside of the field tenuous.



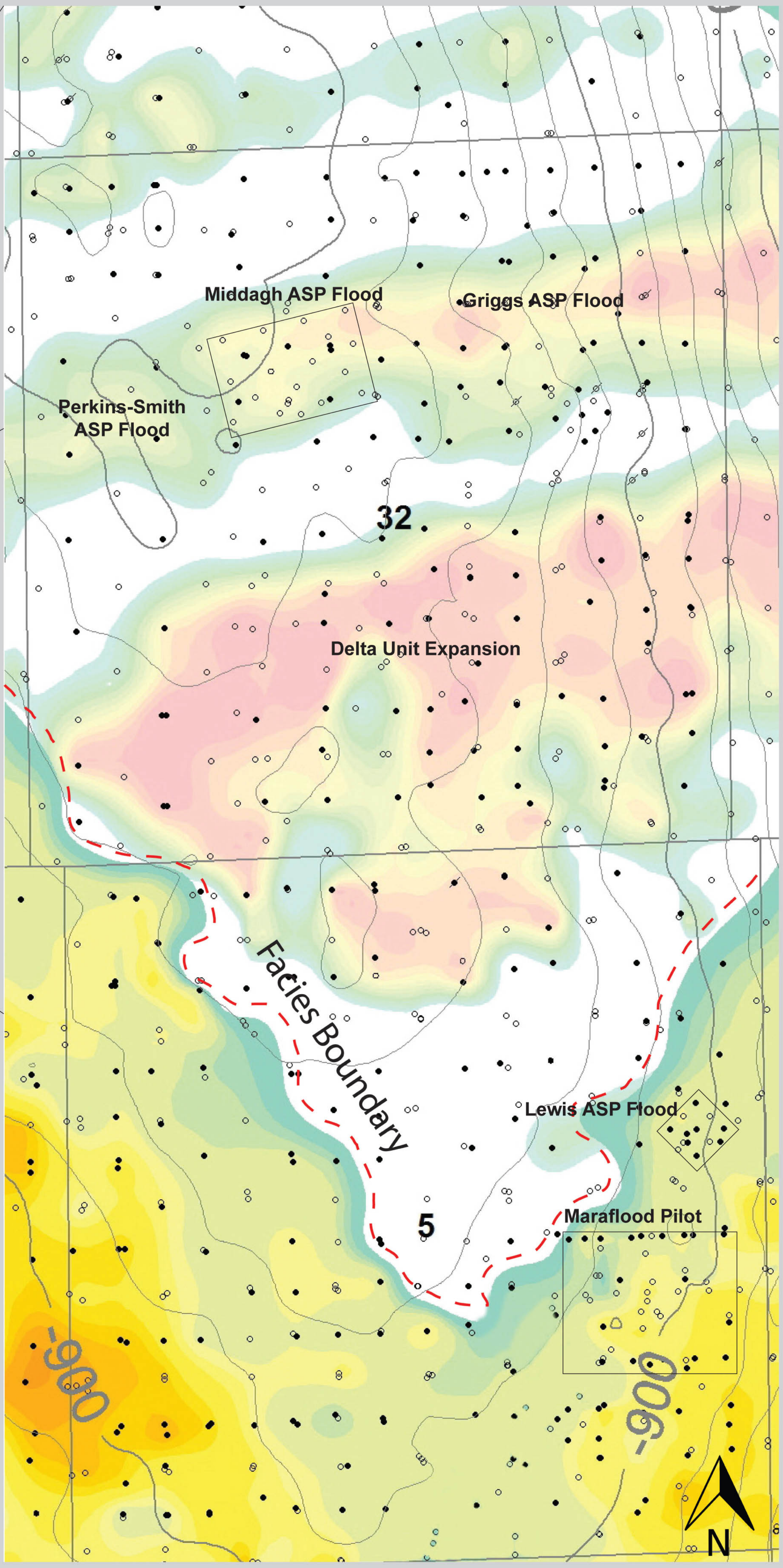
Sequence stratigraphic framework of the Bridgeport B. Note how systems tracts become thinner above the Bridgeport B. This is probably due to decreased accommodation space in the basin following the filling of early Pennsylvanian channel systems.



Cross section B-B' showing four wells where coals were sampled for palynological study. The Curlew Limestone is used as the datum. The difficulty of correctly correlating the Bridgeport B reservoir when channel fill sandstones occupy the same stratigraphic position is apparent. Core measured permeability is plotted in red on the right side of each log with a scale of 0-1000 md. Average core measured permeability in Section 5 sandstone is 63% higher (Average 113 vs. 314 md) compared to Section 32. 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. Coal palynology has clarified the correlation of reservoir sandstone bodies by providing evidence that thick channel fill deposits in the same stratigraphic position as the Bridgeport B are actually later events and have probably removed the Bridgeport B sediments.



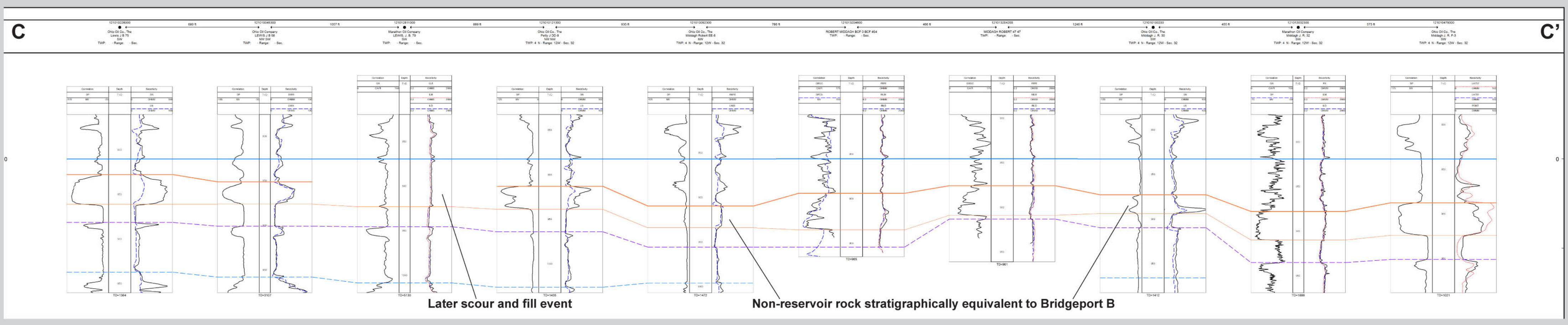
Isopach map showing the Bridgeport B sandstone on top of the Bridgeport Anticline in the northern part of Lawrence Field. Thick channel fill deposits truncate the Bridgeport B to the west and southeast. Data density drops off significantly to the east. Structure contours are on the Barlow Limestone. From this small scale overview of the northern part of Lawrence Field, we can see that the Bridgeport B is compartmentalized into discreet sandstone bodies that are separated from one another by stretches of non-reservoir rock.



ASP Targets

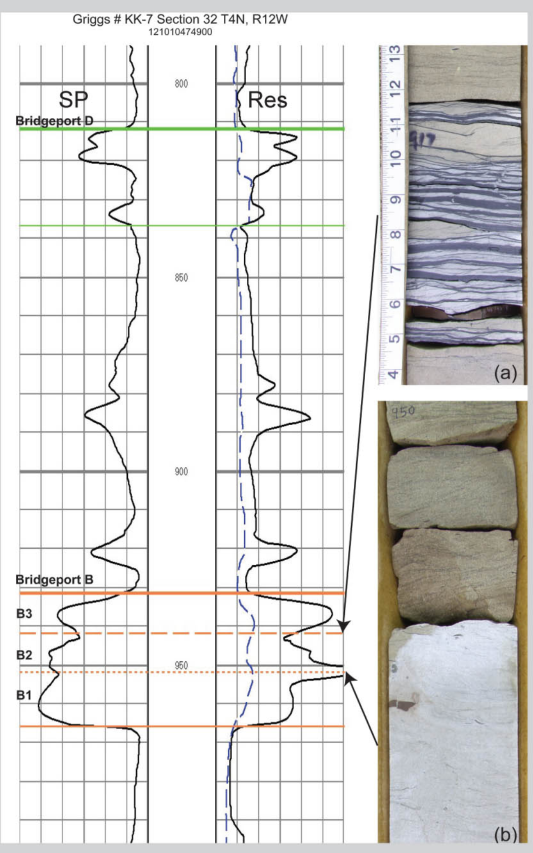
Right: Isopach map of the target area for ASP application in Section 32 T4N, R12W and Section 5 T3N, R12W. The map is a composite of two depositional facies showing 50% clean sandstone thickness of the Bridgeport B with warmer colors indicating areas with thicker sandstone. In Section 32, Bridgeport B sandstones average ~25 feet thick and trend more or less east-west over the anticline. Two channel fill sandstone bodies up to ~200' thick enter Section 5, one from the northeast and one from the northwest, straddling the anticline and converging southward.

Shown are the present and expansion ASP flood areas. The 15 acre Middagh flood was reaching peak production at the end of 2011. Pre-flood production was 16 BOPD; peak ASP flood production was 100+ BOPD. The Perkins-Smith 58 acre flood was initiated in late 2011. No results have been reported to date. The Delta unit 350 acre expansion is under development with flood initiation expected in mid-2013.

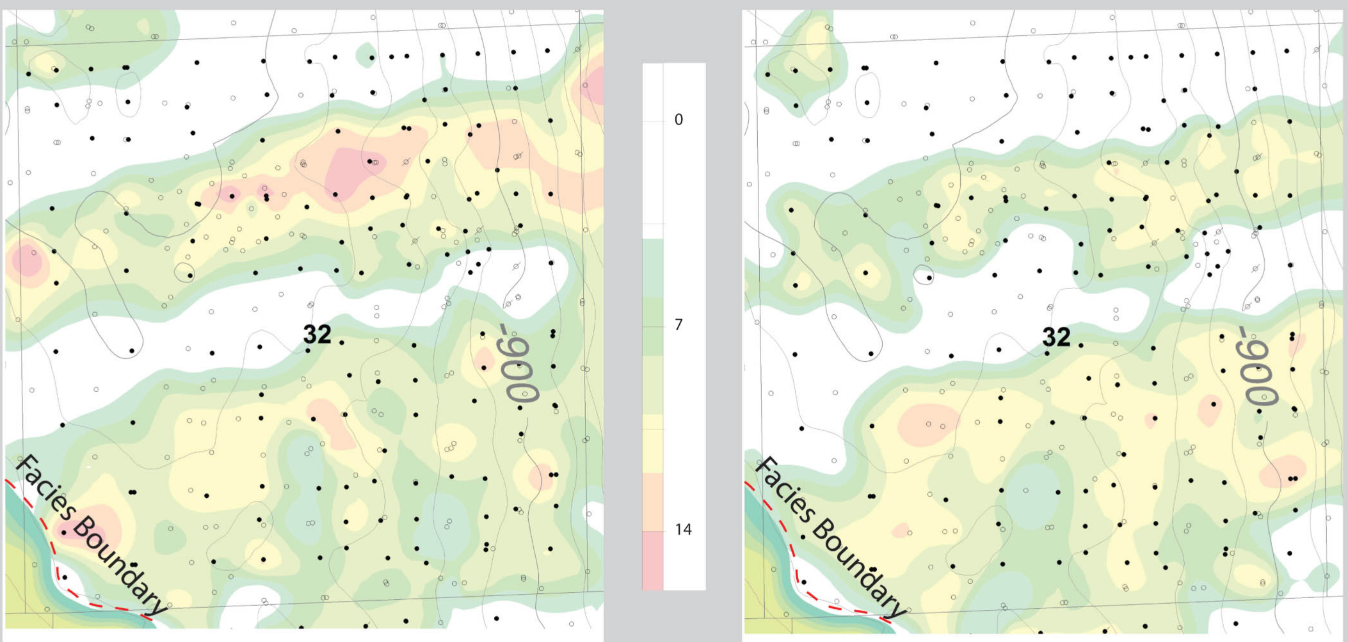


North-South cross section C-C' (see map above) showing small scale compartmentalization of the Bridgeport B reservoir. East-west trending sandstone bodies are bounded by non-reservoir siltstones. The question of the timing of the event that deposited the siltstone vs. the event that deposited the reservoir sandstone will require further research.

Compartmentalization

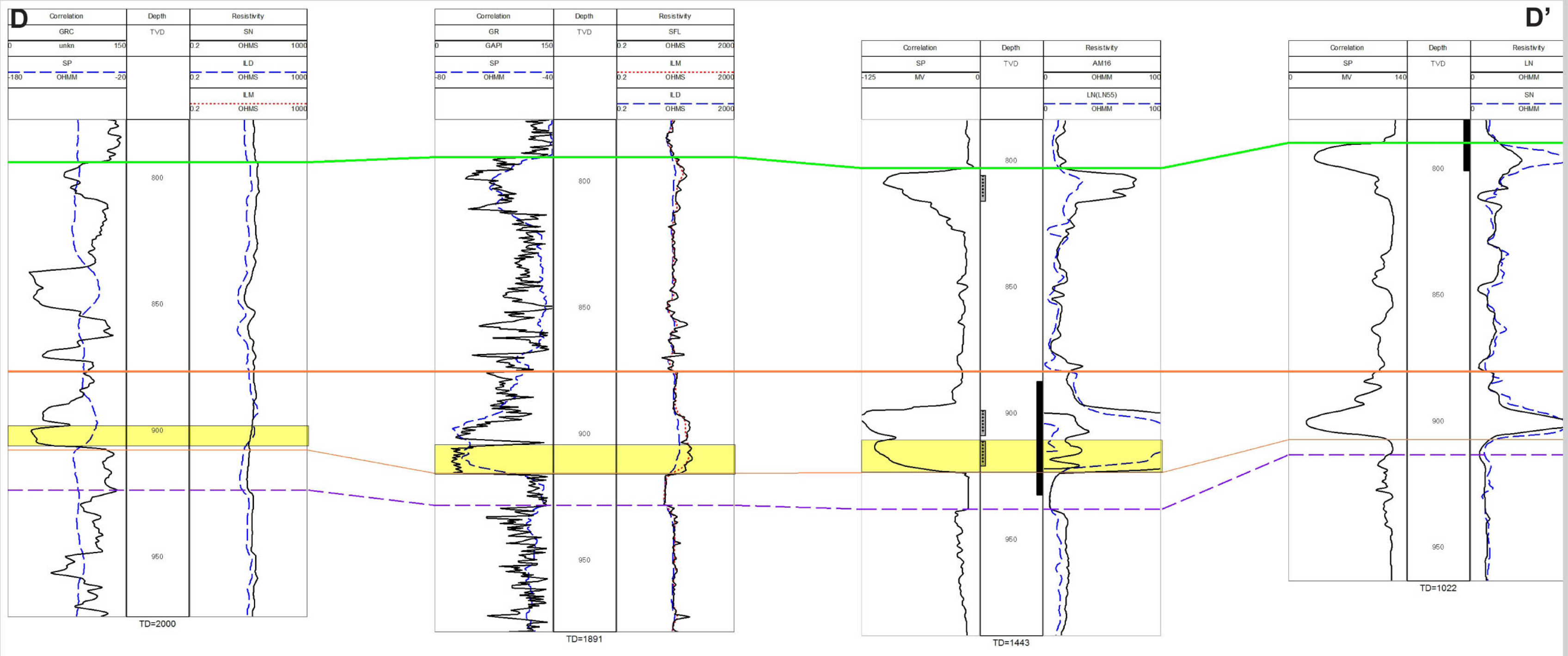


Typical log from Section 32 shows the Bridgeport D marker bed with the underlying Bridgeport B reservoir sandstone. Three stacked subunits, the B1, B2, and B3 are separated by baffles that are typically thin (usually 6"-1' thick) shaly intervals (a) or calcite cemented sandstone (b) that act to compartmentalize the reservoir. Tracing these features through the reservoir allows for the generation of flow unit maps.

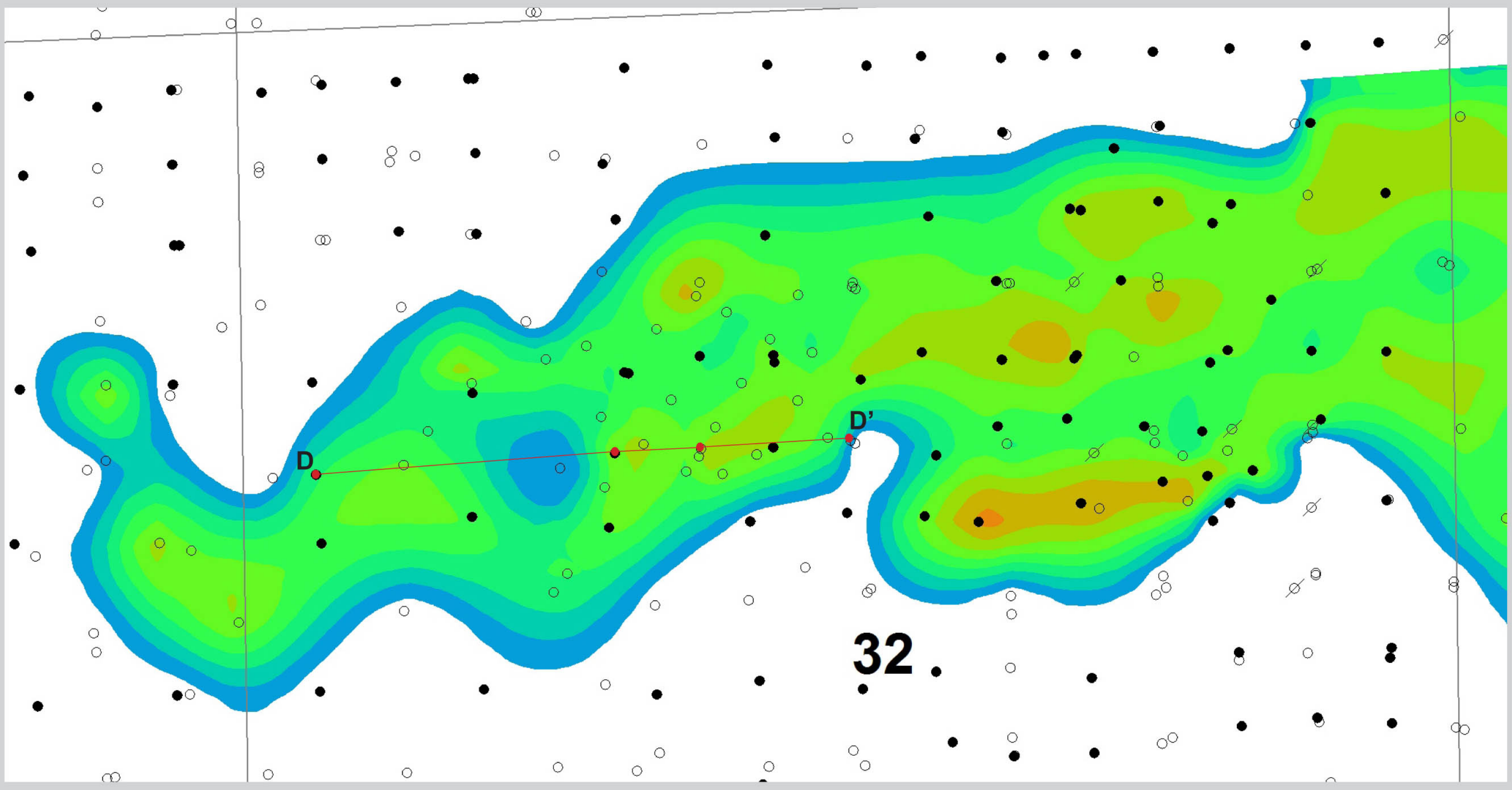


- Isopach flow unit maps of net sandstone of the Bridgeport B1 (left) and B2 (right) subunits in Section 32
- Sandstone is mapped with a 2' contour interval with the warmer colors representing thicker sandstone
- Reservoir sandstone in the northern half of Section 32 trends east-west whereas in the southern half of the section, the sandstone takes on a triangular shape and occupies the region between the two thick channel fill sandstone bodies that trend into Section 5 from the northeast and northwest
- 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.

Following Flow Zones



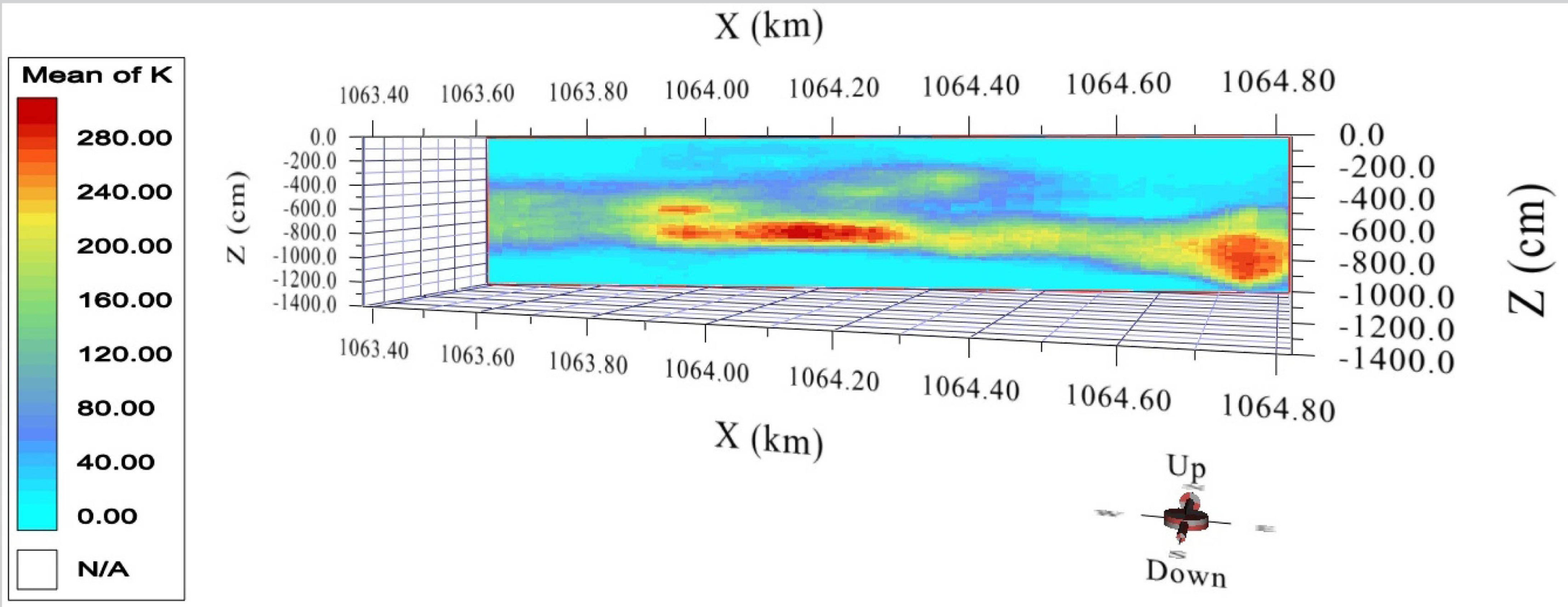
The Bridgeport B is subdivided into facies to better understand and to more easily trace flow units within the reservoir. The cross section to the left is an example where the cross bedded facies has been identified in the lower part of the Bridgeport B. Cross bedded facies sandstones are identified in cores by their fine-medium grained texture, presence of rip up clasts, and cross to subhorizontal bedding. This facies tends to manifest itself on logs by having a more blocky appearance.



Cross Bedded Facies Map

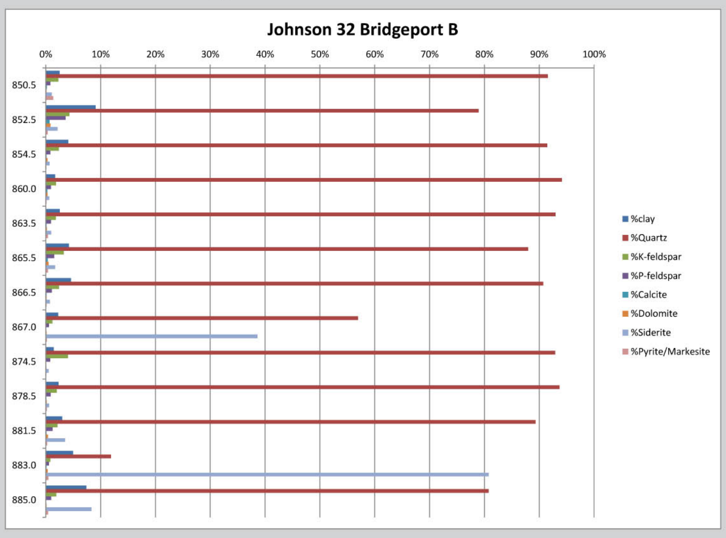
Isopach map showing the gross thickness of the cross bedded sandstone facies within the NE-SW trending Bridgeport B reservoir in the northern portion of Section 32. Bridgeport B sandstones are coastal deposits that occupy the lowstand systems tract. Sandstones can typically be broken into a lower cross bedded facies showing many scoured and reactivated surfaces, and an upper, more tidally influenced ripple bedded facies. Tidal indicators in the sandstone in Section 32 include ripple bedding, flaser and lenticular bedding, tidal rhythmites and tidal couplets. Many of these features are also observed in the upper most portions of the channel fill sequence in Section 5.

Geocellular Modeling

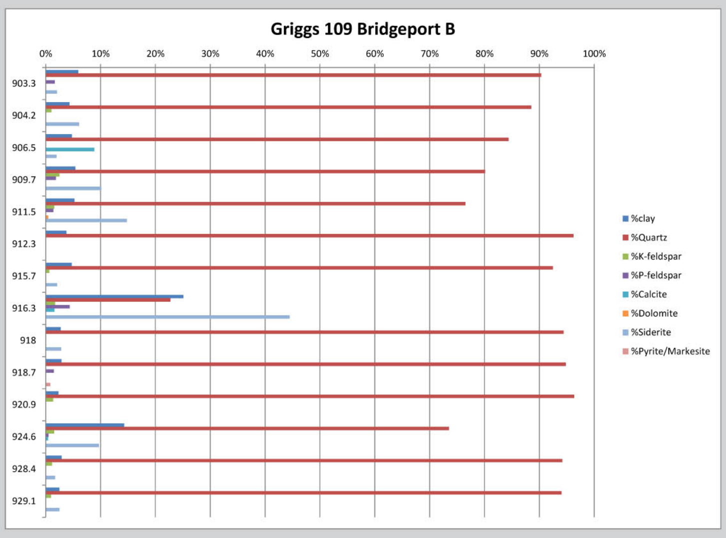


Above is a cross section slice through the Bridgeport B sandstone in the northern part of Section 32. The model was created using pre-waterflooding-vintage electric logs. SP curves were normalized and assigned permeability values based on core analysis data from Bridgeport B core in the immediate area. The resulting model indicates high permeability zones (warmer colors) within the Bridgeport B. When compared to the cross section at the top of this panel, the correlation can be seen between the lower cross bedded facies and the zones of high permeability. Geocellular modeling research was conducted by James Damico (ISGS) with John Grube.

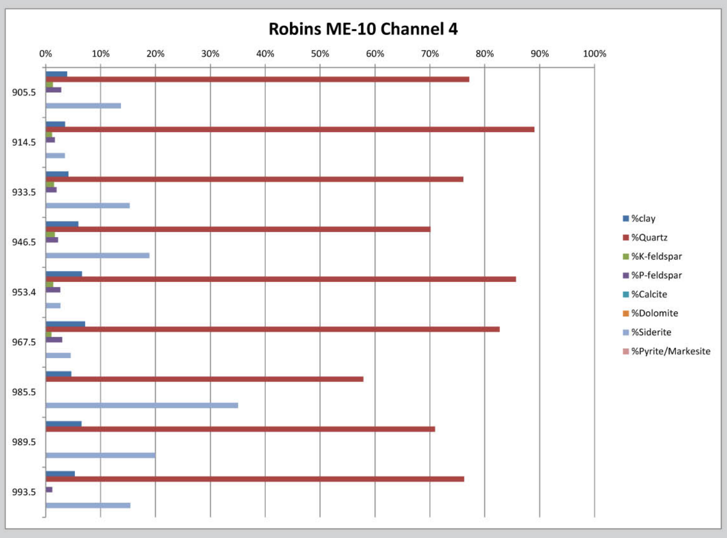
Mineralogy



X-ray diffraction analyses of bulk mineralogy from core samples show that quartz is the most abundant mineral comprising between 78-93% of most reservoir samples. Two samples at 867 ft. and 883 ft. contain very large amount of siderite. Siderite ($FeCO_3$) is a minor component in all other samples. Diagenetic clay minerals comprise 2-8% of samples. Although clay minerals are a minor component they play a major role in preserving porosity by coating many quartz grains, thereby limiting the development of quartz overgrowths. Potassium and plagioclase feldspar are minor components. The average porosity and permeability of these samples is also 19% and ~150 md respectively.



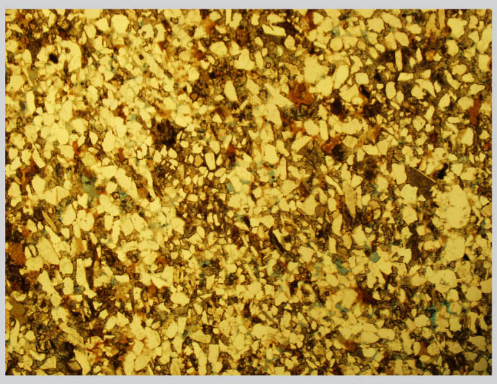
X-ray diffraction analyses of the bulk mineralogy of core samples from the Bridgeport B reservoir. The sandstone is fine to very fine grained has been interpreted as deltaic. The average porosity and permeability of the Bridgeport B in this well are 19% and ~150 md respectively. Quartz is the most abundant mineral and ranges between 75-95% in sandstone reservoir samples. Siderite and diagenetic clay minerals are the next most abundant minerals, siderite ranges between 2-15%, clay minerals range between 3-15%. Potassium and plagioclase feldspars are minor components in all samples. One sample at 906.5ft. has 8% calcite.



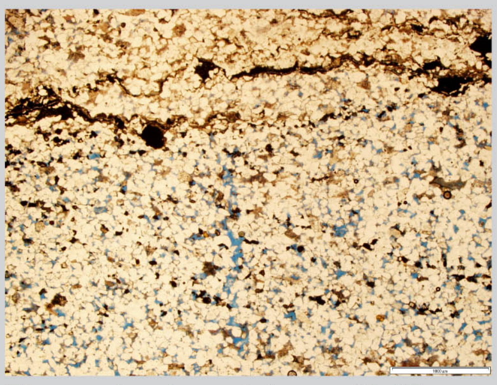
Graph shows that quartz sand is the major component of all analyzed core samples ranging from 58-88%. Siderite is the next most abundant mineral ranging from 2-35%, diagenetic clay minerals range from 3-7%, potassium and plagioclase feldspar are minor components. The average porosity and permeability of samples is much higher at 21% and 400 md respectively in these thick channel fill reservoirs than in the tidally influenced coastal reservoirs in the Griggs 109 and Johnson 32 wells.

Petrography

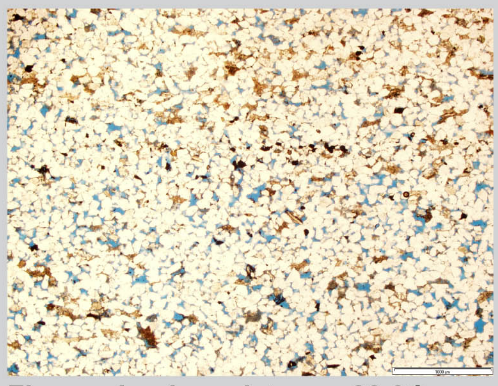
Thin sections from various cores showing diagenetic features. Bridgeport B - Section 32



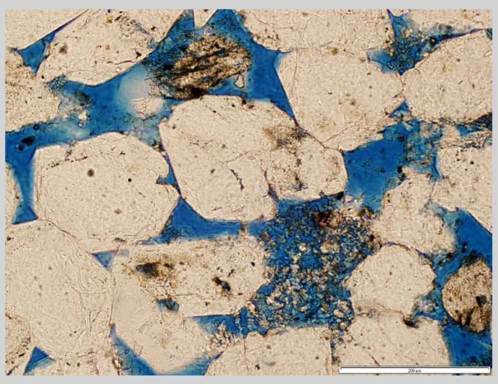
Fine grained sandstone. 17.7Φ, 95k. Much of the pore space has been filled with siderite cement, creating a permeability barrier.



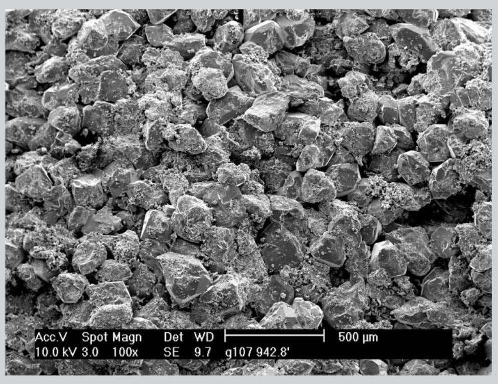
Fine grained sandstone. 19.1Φ, 66k. Fracturing of the sandstone is apparent. Much porosity is occluded by compaction.



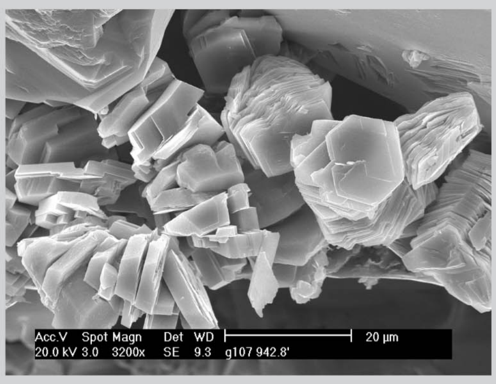
Fine grained sandstone. 20.3Φ, 171k. Moderate compaction & quartz cementation. Feldspar dissolution has enlarged some pores.



Fine grained sandstone. 20.1Φ, 206k. Close-up showing quartz overgrowths cementing grains. Degraded feldspar grains have been replaced with kaolinite.

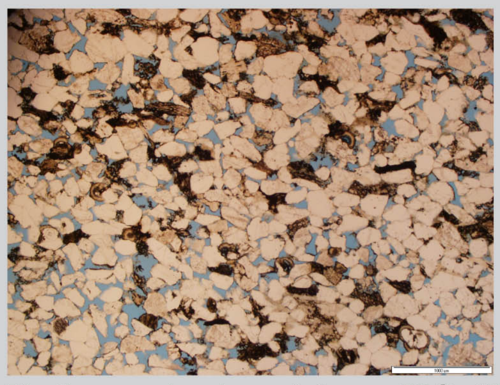


SEM micrograph shows quartz overgrowths, enlarged pores due to the dissolution of feldspar grains, and pore filling and bridging diagenetic clay minerals.

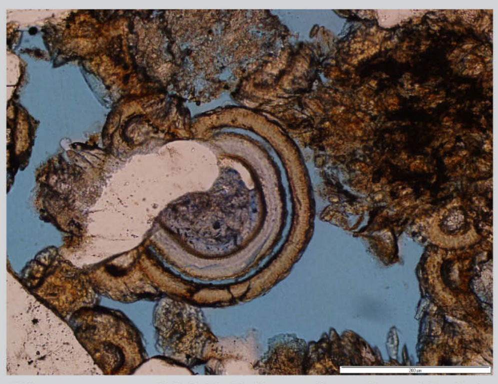


SEM micrograph shows booklets of the diagenetic clay mineral kaolinite.

Bridgeport Channel - Section 5



Medium grained sandstone. 23Φ, 1050k. Organic material and spores replaced by siderite are common. Little evidence of compaction.



Close-up of 985.5 feet depth. 19.3Φ, 39k. Well preserved spores replaced by siderite are common throughout the sandstone at this depth.

- Sandstone reservoirs in the Bridgeport B interval of Section 32 were deposited in a tidally influenced coastal environment. These sandstones are finer grained, lower energy sediments, and are therefore less porous and permeable than the channel fill reservoir sandstones in Section 5.
- Sandstone reservoirs in Section 5 were deposited in fluvial channels following sea level regression and scouring of the former shelf. These sandstones are coarser grained, higher energy sediments that show a more marine influence near the top. The sandstone is more porous and permeable than the Bridgeport B in Section 32.

Depositional Environments

- Prior to deposition of the Bridgeport B sandstone, the widespread marine Beta Shale marker bed was deposited through a period of sea level highstand.
- Tidally influenced coastal sediment prograded across the Lawrence Field region, filling available accommodation space as channels aggraded, leading to the vertically stacked and laterally discontinuous patterns found in the Bridgeport B (Figure 1).
- Depositional energies moderated as reflected in the B2 and B3 intervals where ripple bedded sandstones punctuated by several inch thick shaly, lenticular bedded intervals predominate. These shaly, lenticular bedded intervals act as vertical boundaries to fluid flow, effectively compartmentalizing the Bridgeport B reservoirs.
- Eventually a sea level still stand took place and the surface of the sand was scoured. E-W trending channels were cut across Section 32 and were filled with very fine grained sandstone to siltstone of non-reservoir quality.
- Coal swamp capped the succession in the area as indicated by the thin bedded coal at the top of the Bridgeport B. A significant transgression marks the end of the Bridgeport B cycle and the emplacement of another marine shale as the next cycle of sedimentation begins for the Bridgeport C interval.
- Channel fill episodes are observed in Bridgeport units in the area of interest; especially in Section 5 where channel fill sandstones are found (Figure 2)
- Tectonics appear to have influenced the deposition of Bridgeport B sediments. Although subsidence of the Illinois Basin continued throughout the Pennsylvanian, subtle uplift along the La Salle Anticlinorium appears to have resulted in low accommodation space and thin successions of sediment along the crest of the anticline.
- The complexity of this depositional system illustrates the need for detailed mapping of individual sandstone reservoirs and also explains the high degree of variability in reservoir characteristics and geometries over a small area. Understanding this complexity is necessary for successful EOR development.

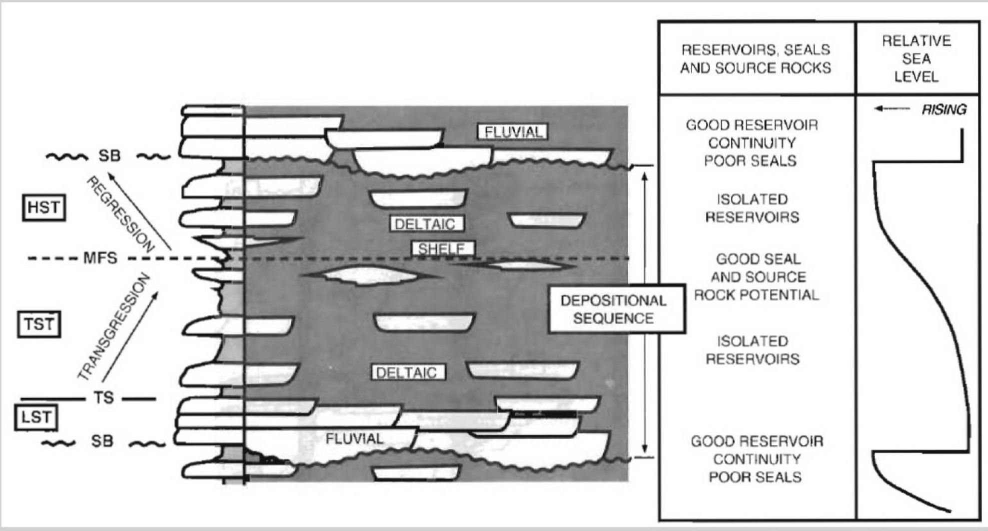


Figure 1 - Schematic of the vertical facies patterns, depositional environments, sand continuity, and relative sea-level change in a sequence deposited in a proximal shelf setting. In the Bridgeport B, portions of this sequence may be truncated due to limited accommodation space. Posarnentier & Allen, 1999.

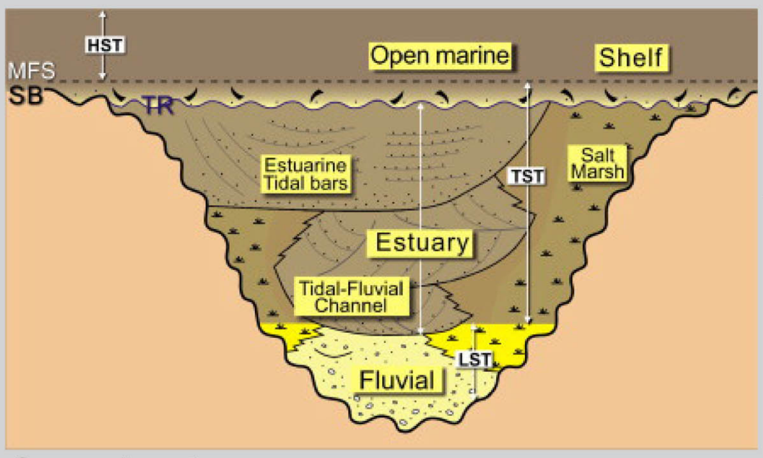


Figure 2 - Schematic illustrating a typical estuarine fill complex deposited under continuously rising sea level. From Clifton, 1982. This model may represent the complex cycles seen in the Bridgeport interval off the flanks of the Bridgeport Anticline.

EOR Targets

- The Bridgeport B sandstones in Section 32 may be a better EOR target than the channel fill facies reservoirs in Section 5
- The Bridgeport B reservoirs in this area have not been as effectively developed as the channel facies reservoirs in Section 5 because of their more compartmentalized characteristics
- Yet because these target reservoirs are more confined, flow units and their geometries tend to be more mappable and therefore the chemical flood can be designed and implemented for the greatest recovery potential. A better understanding of reservoir characteristics allows for better cost control which increases the economic feasibility of EOR projects
- The thick sandstones in eastern Section 5 are along the flank of the structure with a portion of the sandstone dropping below the original oil-water contact. Loss of expensive EOR chemicals into the water zone becomes a factor.
- Oil saturations have been lowered due to primary and secondary production and implementation of the Maraflood Project. While highly porous and permeable reservoirs are generally very good targets for EOR application, there is less remaining oil to recover using ASP technology
- It is difficult to correlate preferential flow units within the channel facies reservoirs with standard mapping techniques using the older style SP- electric logs that are principally available throughout Lawrence Field. Recent porosity logs and core information have greatly enhanced the ability to delineate reservoir characteristics that are necessary to increase the likelihood for successful ASP- EOR applications.

Conclusions

- Reservoir characterization is important for implementation of Enhanced Oil Recovery programs because the economic success of an EOR project is dependent on the design and implementation of the project being aligned with the unique geologic characteristics of each reservoir
- Successful implementation of EOR programs in mature Pennsylvanian reservoirs will have broad application in the Illinois Basin and elsewhere
- The potential for channelized flow in the more permeable portions of the channel fill facies in Section 5 and the more marine influenced facies in Section 32 versus intervals with low permeability has added to the difficulty of implementing EOR techniques in these reservoirs. The more permeable intervals have less residual oil as primary production and secondary waterflooding have selectively recovered more oil from these intervals while leaving more recoverable oil in the less porous and permeable intervals. Thus, techniques to reduce channelized flow must be designed and implemented.
- 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 taking place over a geologic time frame resulting in areas of both enhanced and diminished porosity and permeability.
- Compaction of grains, particularly in some ripple-bedded intervals has greatly reduced porosity and permeability, diminishing reservoir quality.
- Other facies, such as the cross bedded facies have increased porosity and permeability due to the lack of compaction in channel fill deposits
- Thin section and X-ray diffraction analysis shows 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.
- Depositional environments of the Pennsylvanian Bridgeport sandstone reservoirs are complex and are characterized by sea level drop regressive incisement, followed by transgressive infill packages that commonly show tidal influence in the upper sediments of the cycle. Understanding the depositional setting is necessary to unravel the complexity of the reservoir facies and their individual characteristics that are fundamental components for the design and implementation of successful ASP-EOR projects

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