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Technical Progress Report

Quarterly Report

Alkaline-Surfactant-Polymer Flooding And Reservoir Characterization of the Bridgeport and Cypress Reservoirs Of the Lawrence Field

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Abstract

Feasibility of alkaline-surfactant-polymer flood for the Lawrence Field in Lawrence County, Illinois is being studied. Two injected formulations are being designed; one for the Bridgeport A and Bridgeport B reservoirs and one for Cypress and Paint Creek reservoirs. Fluid-fluid and coreflood evaluations have developed a chemical solution that produces incremental oil in the laboratory from the Cypress and Paint Creek reservoirs. A chemical formulation for the Bridgeport A and Bridgeport B reservoirs is being developed.

A reservoir characterization study is being done on the Bridgeport A, B, & D sandstones, and on the Cypress sandstone. The study covers the pilot flood area and the Lawrence Field.

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Introduction

The alkaline-surfactant-polymer technology has produced incremental oil recovery in multiple field projects.[1,2,3] Alkaline-surfactant-polymer floods are planned for the Bridgeport B and Bridgeport A reservoirs, and for the Cypress and Paint Creek reservoirs.

Laboratory Evaluation

The objective is to formulate two alkaline-surfactant-polymer solutions to be injected into the Bridgeport A and Bridgeport B, and the Cypress and Paint Creek. Fluid-fluid studies (interfacial tension and phase behavior measurements) and corefloods (linear and radial) will be used to develop chemical combinations and to compare oil recovery efficiency. Bridgeport A and Bridgeport B reservoirs alkaline-surfactant-polymer formulation will be the same as will the Cypress and Paint Creek alkaline-surfactant-polymer formulation. Ideally, the two pairs of reservoirs formulations will use the same chemicals.

Numerical Simulation

Once formulations have been developed, numerical simulation will be used to forecast alkaline-surfactant-polymer flood performance. Alkaline, surfactant, and polymer facilities design will be finalized and construction will begin at this time as well.

Executive Summary

Laboratory Evaluation

The Bridgeport A and Bridgeport B crude oil samples from well J.T. Griggs 80 were cross contaminated and, therefore, not usable for future work. J.T. Griggs 79 Bridgeport B oil API gravity was higher than the sample previously used. Oil viscosity was approximately one third the original value. Bridgeport D oil API gravity and viscosity was similar to the prior values. New samples of Bridgeport A and Bridgeport B oil will be collected next quarter to define oil characteristics. Once oil characteristics are defined, future work will develop an alkaline-surfactant-polymer combination that recovers incremental oil in both the Bridgeport A and Bridgeport B. Interfacial tension, phase behavior, and radial coreflood evaluations will be performed.

The geologic model for the numerical simulation of the Bridgeport A and B, and the Cypress and Paint Creek began during the fourth quarter of 2001. Top of structure, porosity, net thickness, and wells' location and definition were input into the model. Cypress and Paint Creek crude oil PVT definition was developed. Crude oil PVT will be developed once oil characteristics for the Bridgeport B are determined.

Reservoir Characterization

Preliminary computer mapping using Landmark Graphics Software has been completed for the Pennsylvanian Bridgeport A, B, and D Sandstones and for Cypress Sandstones in the pilot area and area immediately surrounding the pilot area. The Bridgeport A, B, and D Sandstones and the Cypress Sandstone in the pilot area in Lawrence Field have been subdivided for mapping purposes. The Bridgeport A, B, and D Sandstones and the Cypress Sandstone in the pilot area in Lawrence Field have been subdivided for mapping purposes. The Bridgeport D Sandstone has been subdivided into 2 units. The Bridgeport B has been subdivided into 3 units and the Bridgeport A has been subdivided into 3 units. The Cypress Sandstone has been subdivided into 5 units. The shale separating the Bridgeport A and B Sandstones has been used as a marker horizon for the purpose of correlations in the Pennsylvanian because this section lacks other widespread marker horizons. The Barlow Limestone, immediately overlying the Cypress Formation, is a widespread marker horizon used extensively for correlation and structure mapping in the Lower Chesterian. Thicknesses of reservoir quality, fifty percent clean, sandstones have been calculated for all subdivisions in the Bridgeport and Cypress Sandstones for all logged wells in the pilot area and a buffer area surrounding the pilot area. Each log has been tied to a reference set of cross sections to ensure that subdivision of sandstones within the Bridgeport and Cypress Formations is consistent within the pilot area. Fifty percent clean sandstone thickness of each unit has been mapped using Landmark Graphics Software. Sandstone thickness maps of each unit in the Bridgeport shows a general east-west orientation of sandstone bodies with thicknesses varying from 0 to 3 meters (9 feet). Cypress sandstone units tend to show the same east-west

orientation and vary from 0 to5 meters (15 feet). The Bridgeport D is the least widespread of the Bridgeport Sandstones. The upper unit in the Bridgeport D is more continuous than the lower Bridgeport D unit. The Bridgeport D appears to have greater reservoir potential in the upper, more widespread unit. The Bridgeport B is the most widespread and homogeneous of the Bridgeport Sandstones. It was consistently mapped based on its relationship to the marine shale separating the Bridgeport A from the Bridgeport B sandstones. The Bridgeport A shows the greatest amount of heterogeneity of the Bridgeport sandstones. While all Bridgeport Sandstones exhibit a large degree of heterogeneity, units within each Bridgeport interval within or surrounding the pilot area show reservoir development with potential for chemical flood recovery. However, many of the reservoir sandstones are compartmentalized and of limited aerial extent, therefore limiting the effectiveness of flood recovery. Some of the Cypress sandstone units are the most consistent and widespread of the sandstones being considered for flood recovery in the pilot area. This study demonstrates that units within the Bridgeport and Cypress intervals can be consistently selected and mapped based on comparison of similar log character predominantly on gamma ray and Spontaneous Potential traces supported by characteristics on the porosity and resistivity traces. Modern log suites were compared with more vintage log suites to ensure that the Bridgeport and Cypress Sandstones and subdivisions within each formation were selected on a consistent basis. This permitted the use of all available geophysical log data. Preference for correlation was given to the gamma ray/porosity log where modern log suites were available.

Experimental

Laboratory Evaluation

Crude oil viscosities were measured at 21°C (70°F) with a Brookfield viscometer equipped with a UL adaptor. API gravity was determined using ASTM D1217.

Numerical Simulation

Numerical simulation for waterflood and chemical flooding will be performed using GCOMP, a state of the art reservoir simulator with a chemical flood option.[3,4] The black oil option includes capabilities for incorporating chemical flooding properties such as interfacial tension reduction, effect of reservoir water on interfacial tension reduction, capillary number and relative permeability effects due to interfacial tension reduction, polymer effect on solution viscosity and residual resistance factor, chemical consumption, and chemical partitioning.

Reservoir Characterization

Preliminary computer mapping using Landmark Graphics Software has been completed for the Pennsylvanian Bridgeport A, B, and D Sandstones and for Cypress Sandstones in the pilot area and area immediately surrounding the pilot area. The Bridgeport A, B, and D Sandstones and the Cypress Sandstone in the pilot area in Lawrence Field have been subdivided for mapping purposes. The Bridgeport A, B, and D Sandstones and the Cypress Sandstone in the pilot area in Lawrence Field have been subdivided for mapping purposes. The Bridgeport D Sandstone has been subdivided into 2 units. The Bridgeport B has been subdivided into 3 units and the Bridgeport A has been subdivided into 3 units. The Cypress Sandstone has been subdivided into 5 units. The shale separating the Bridgeport A and B Sandstones has been used as a marker horizon for the purpose of correlations in the Pennsylvanian because this section lacks other widespread marker horizons. The Barlow Limestone, immediately overlying the Cypress Formation, is a widespread marker horizon used extensively for correlation and structure mapping in the Lower Chesterian. Thicknesses of reservoir quality, fifty percent clean, sandstones have been calculated for all subdivisions in the Bridgeport and Cypress Sandstones for all logged wells in the pilot area and a buffer area surrounding the pilot area. Each log has been tied to a reference set of cross sections to ensure that subdivision of sandstones within the Bridgeport and Cypress Formations is consistent within the pilot area. Fifty percent clean sandstone thickness of each unit has been mapped using Landmark Graphics Software. Sandstone thickness maps of each unit in the Bridgeport shows a general east-west orientation of sandstone bodies with thicknesses varying from 0 to 3 meters (9 feet). Cypress sandstone units tend to show the same east-west orientation and vary from 0 to5 meters (15 feet). The Bridgeport D is the least widespread of the Bridgeport Sandstones. The upper unit in the Bridgeport D is more continuous than the lower Bridgeport D unit. The Bridgeport D appears to have greater reservoir potential in the upper, more widespread unit. The Bridgeport B is the most widespread and

homogeneous of the Bridgeport Sandstones. It was consistently mapped based on its relationship to the marine shale separating the Bridgeport A from the Bridgeport B sandstones. The Bridgeport A shows the greatest amount of heterogeneity of the Bridgeport sandstones. While all Bridgeport Sandstones exhibit a large degree of heterogeneity, units within each Bridgeport interval within or surrounding the pilot area show reservoir development with potential for chemical flood recovery. However, many of the reservoir sandstones are compartmentalized and of limited aerial extent, therefore limiting the effectiveness of flood recovery. Some of the Cypress sandstone units are the most consistent and widespread of the sandstones being considered for flood recovery in the pilot area. This study demonstrates that units within the Bridgeport and Cypress intervals can be consistently selected and mapped based on comparison of similar log character predominantly on gamma ray and Spontaneous Potential traces supported by characteristics on the porosity and resistivity traces. Modern log suites were compared with more vintage log suites to ensure that the Bridgeport and Cypress Sandstones and subdivisions within each formation were selected on a consistent basis. This permitted the use of all available geophysical log data. Preference for correlation was given to the gamma ray/porosity log where modern log suites were available.

Results and Discussion

Laboratory Evaluation

Bridgeport A, B, and D oil API gravity and viscosity of the different samples are

Well	Formation	API gravity (deg)	Viscosity (cp)
Johnson J.E. 30*	Bridgeport A	34.7	8.2
J.T. Griggs 80	Bridgeport A	32.4	9.4
J.T. Griggs 53*	Bridgeport B	28.3	28.0
J.T. Griggs 79	Bridgeport B	32.6	9.8
J.T. Griggs 80	Bridgeport B	31.1	7.9
J.T. Griggs 100*	Bridgeport D	36.1	9.7
J.T. Griggs 79	Bridgeport D	32.2	10.3

* - February 2000 samples

The J.T. Griggs 80 Bridgeport A and Bridgeport B were cross contaminated.

Numerical Simulation

Two geologic models for the numerical simulation of the Bridgeport A and B, and the Cypress and Paint Creek are being developed. Top of structure, porosity, net thickness, and wells' location and definition were input into each model. Cypress and Paint Creek PVT crude oil definition was developed. Crude oil PVT will be developed once oil characteristics for the Bridgeport B are decided.

Reservoir Characterization

Preliminary computer maps completed using Landmark Graphics Software are shown below. The Bridgeport D Sandstone has been subdivided into 2 units. The Bridgeport B has been subdivided into 3 units and the Bridgeport A has been subdivided into 3 units. The Cypress Sandstone has been subdivided into 5 units. The shale separating the Bridgeport A and B Sandstones has been used as a marker horizon for the purpose of correlations in the Pennsylvanian because this section lacks other widespread marker horizons. The Barlow Limestone, immediately overlying the Cypress Formation, is a widespread marker horizon used extensively for correlation and structure mapping in the Lower Chesterian. Thicknesses of reservoir quality, fifty percent clean, sandstones have been calculated for all subdivisions in the Bridgeport and Cypress Sandstones for all logged wells in the pilot area and a buffer area surrounding the pilot area.. Sandstone thickness maps of each unit in the Bridgeport shows a general east-west orientation of sandstone bodies with thicknesses varying from 0 to 3 meters (9 feet). Cypress sandstone

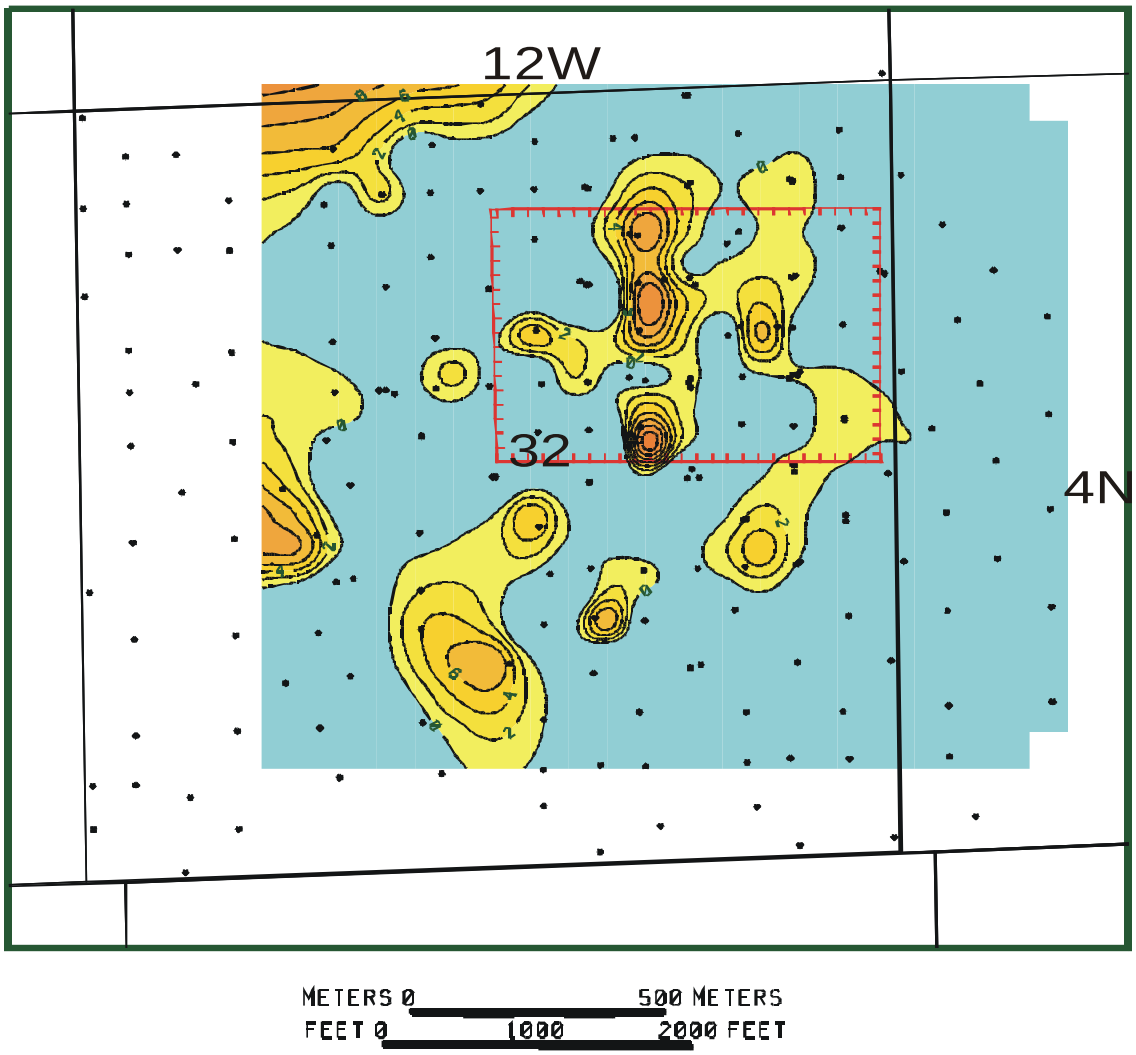
units tend to show the same east-west orientation and vary from 0 to5 meters (15 feet). The Bridgeport D is the least widespread of the Bridgeport Sandstones. The upper unit in the Bridgeport D is more continuous than the lower Bridgeport D unit. The Bridgeport D appears to have greater reservoir potential in the upper, more widespread unit. The Bridgeport B is the most widespread and homogeneous of the Bridgeport Sandstones. It was consistently mapped based on its relationship to the marine shale separating the Bridgeport A from the Bridgeport B sandstones. The Bridgeport A shows the greatest amount of heterogeneity of the Bridgeport sandstones. While all Bridgeport Sandstones exhibit a large degree of heterogeneity, units within each Bridgeport interval within or surrounding the pilot area show reservoir development with potential for chemical flood recovery. However, many of the reservoir sandstones are compartmentalized and of limited aerial extent, therefore limiting the effectiveness of flood recovery. Some of the Cypress sandstone units are the most consistent and widespread of the sandstones being considered for flood recovery in the pilot area. This study demonstrates that units within the Bridgeport and Cypress intervals can be consistently selected and mapped based on comparison of similar log character predominantly on gamma ray and Spontaneous Potential traces supported by characteristics on the porosity and resistivity traces. Modern log suites were compared with more vintage log suites to ensure that the Bridgeport and Cypress Sandstones and subdivisions within each formation were selected on a consistent basis. This permitted the use of all available geophysical log data. Preference for correlation was given to the gamma ray/porosity log where modern log suites were available.

Bridgeport D

The Bridgeport D reservoirs are the shallowest of the Pennsylvanian sandstones characterized in this project. The Bridgeport D was subdivided into two units for mapping in the pilot area (figures 1 & 2). Geophysical log characteristics for the Bridgeport D were keyed to regional cross sections and consistently correlated throughout the pilot area. The Spontaneous Potential and gamma ray logs are commonly rounded when the 50 percent clean sandstone thickness is 3.3 meters (10 feet) or greater and pointed where the beds are thin. The entire D interval is typically made up of two thin stacked clean sandstone benches separated by a thin interval of shale. The entire Bridgeport D interval is commonly the thinnest of the three Bridgeport intervals in the project area. The upper unit in the Bridgeport D contains thicker and more widespread sandstone than the lower unit. Maximum thickness of the upper unit is 4.5 meters (14 feet). Preliminary mapping shows no distinct orientation of reservoir sandstones in the upper Bridgeport D. Zones containing no Bridgeport D reservoir sandstone occur in the pilot area in both the lower and upper units. Bridgeport D reservoir sandstones are best developed outside the pilot area in the upper unit. Deposition of clean sandstone in the lower Bridgeport unit was very sporadic. There is no clean sandstone in many wells in the lower Bridgeport D interval in most of the pilot area. Most of the sandstone accumulation in the lower unit occurs in a single sandstone body that has an apparent north-south orientation with a maximum thickness of 4.5 meters (14 feet) and is 2 km long and .3 km wide. This sandstone body stands alone and is surround by an area of zero sandstone deposition.

Much of the Bridgeport D interval studied in core in the pilot area is fine-to very fine grained sandstone with mostly subparallel to horizontal laminated bedding. Good oil staining is observed in beds of reservoir quality sandstone that are usually less than 15 cm (6") thick. Occasional herringbone, ripple cross bedding was observed in some of the core such as at 814 ft in the Griggs 108 well. Other fine-grained sandstone in the upper Bridgeport D contains slumped and disrupted bedding such as that observed from 248.1 - 248.8 m (814 - 816 feet) in the Griggs 110 well. Sandstone conglomerates containing large rounded sedimentary clasts occur at 810 feet in the Griggs 109. Subaerial exposure features were observed at 251.5 meters (825 feet) in the Griggs 107. The fine-grained horizontal laminated sandstones are commonly interbedded with gray to dark gray shales and are distinctly cyclical in nature. The presence of tidal couplets such as those observed at 251.5 meters (825 ft) in the Griggs 107, place deposition of the fine grained facies in a low energy tidal environment. Other cores also contain intervals that are interpreted as tidal rhythmites. Reservoir development and quality in the Bridgeport D is diminished by numerous intervals of interbedded shale and very fine-grained sandstone. Cyclic deposition of very fine-grained siliciclastics is observed in all core from the Bridgeport D. A coal bed, 15 cm (6") thick, is observed at 253 meters (830 ft) at the base of the Bridgeport D in the Griggs 107 well. The coal is overlain by fine-grained sandstone which is overlain by interlaminated and interbedded shale and fine-grained sandstone deposited by tidal processes or possibly small channel splays that encroached on a coastal, brackish coal marsh. These cyclical tidal deposits contain only minor traces of horizontal burrows. Sandstones with good reservoir qualities are sandwiched between finer grained, cyclical, tidal deposits that form reservoir seals, creating a considerable amount of compartmentalization within the Bridgeport D reservoirs. Thick well developed clean sandstones were not observed in core from the pilot area.

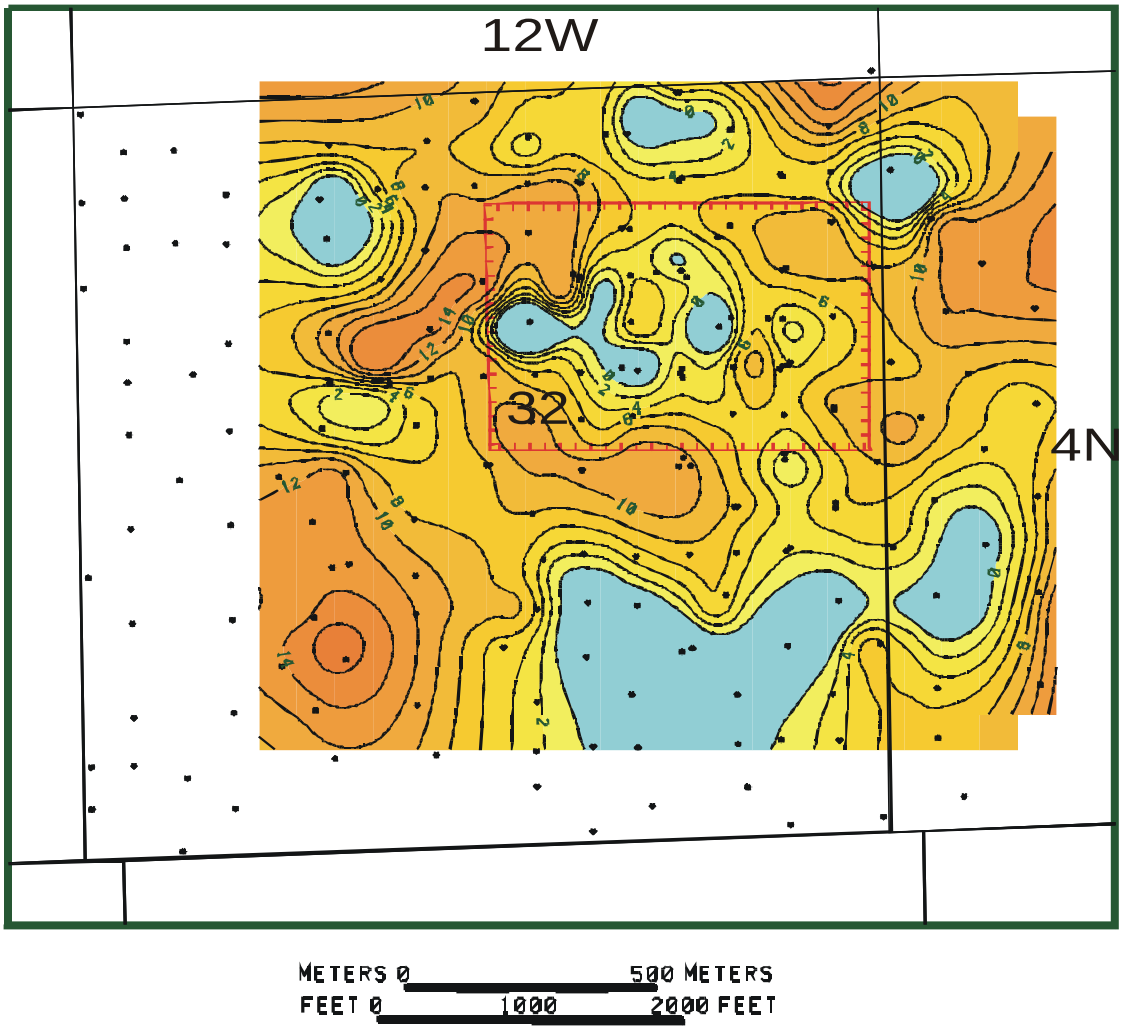
Permeability in Bridgeport D Sandstone in the Griggs 107 well ranges from 40 to 80 millidarcies in a 2 meter (6 foot) interval in the upper Bridgeport D sandstone. Measured permeabilities from Bridgeport D units in other wells were similarly low. These are the lowest reservoir permeabilities measured in the pilot area.



CI = .66 meters (2 feet)

Pennsylvanian Bridgeport D Sandstone subunit 1. Lowermost unit of the Bridgeport D Sandstone. Pilot area is outlined in red.

Figure 1



Pennsylvanian Bridgeport D Sandstone subunit 2. Top unit of the Bridgeport D Sandstone. Pilot area is outlined in red.

Figure 2

Bridgeport B

The Bridgeport B has been divided into three intervals for mapping (figures 3, 4, & 5). Fifty percent clean sandstones in the Bridgeport B most commonly have a rounded Spontaneous Potential or gamma ray log signature. Mapping of the fifty percent clean sandstone thickness shows that the Bridgeport B is the most consistent and widespread of the Pennsylvanian Bridgeport Sandstones. The lower Bridgeport B sandstone unit is more consistent, widespread, and thicker than the upper two sandstones in the Bridgeport B. Accumulation of the Bridgeport B Sandstone shows an overall fining upward character. The lowest unit in the Bridgeport B has the thickest and most widespread 50 percent clean sandstone. It has a maximum thickness of 6.75 meters (20 feet). Preliminary computer mapping of the lower unit shows an elongate reservoir sandstone body oriented approximately east - west. This sandstone body is interpreted as tidal channel deposits based on geometry, orientation and sedimentary structures observed in core.

Computer mapping of the 50 percent clean sandstone thickness of the middle unit in the Bridgeport B shows a thinner, less widespread sandstone body oriented east-west across the study area with a maximum thickness of 3.6 meters (12 feet). This sandstone body is isolated and is surrounded by wells containing no reservoir sandstone.

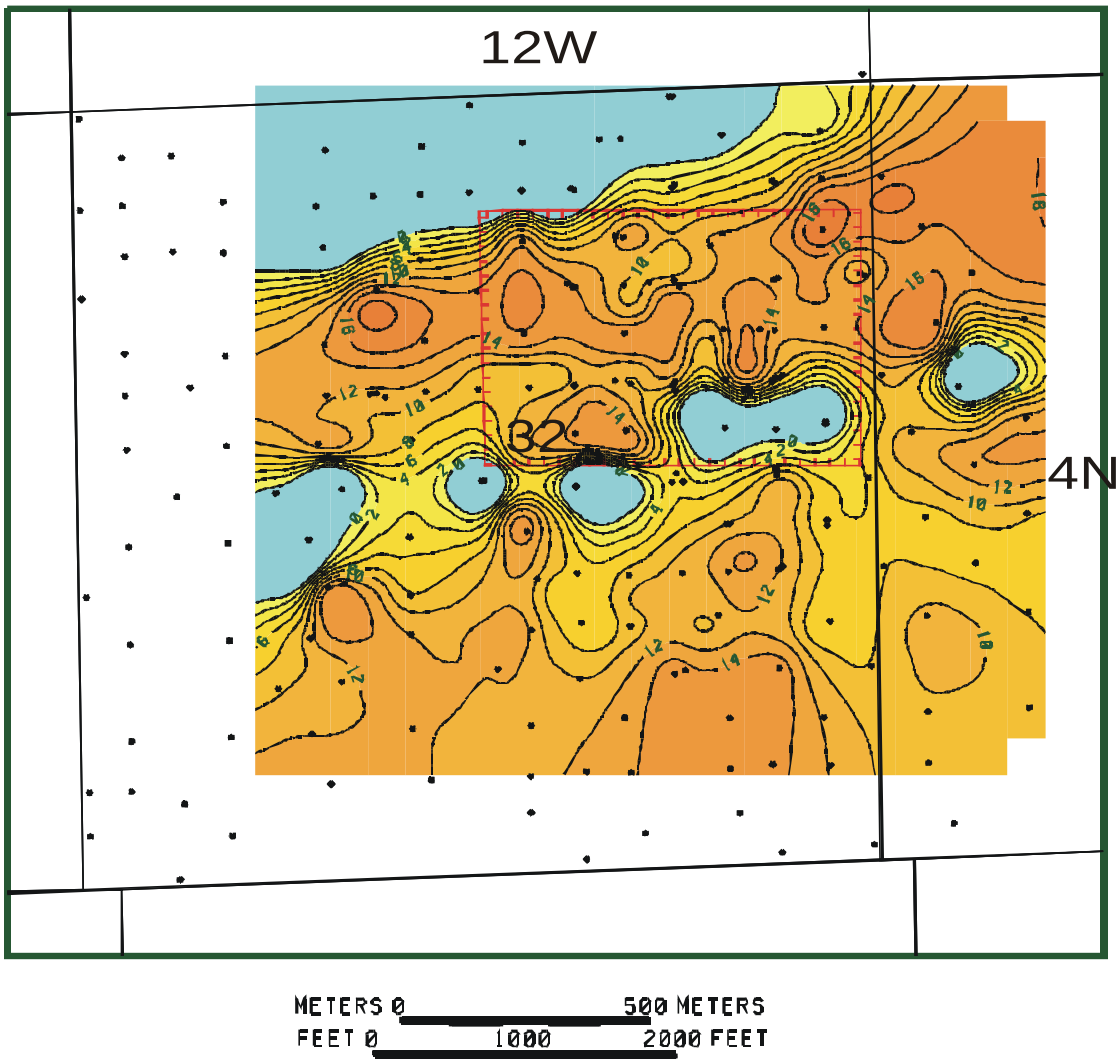
The upper unit in the Bridgeport B contains little 50 percent clean sandstone with most wells containing no reservoir sandstone. There is a small east- west oriented sandstone in the northeast portion of the pilot area. The thickness of this elongate sandstone reaches 2 meters (6 feet) in the pilot area. The orientation and geometry of sandstone bodies in the lower, middle, and upper Bridgeport B units are similar, the dimensions of individual sandstone bodies decreases for the base of the Bridge B to the top of the Bridgeport B.

The dominant facies observed in the Bridgeport B core include the bioturbated, interbedded shale and fine-to very fine grained sandstone facies and a ripple laminated sandstone facies. Horizontal burrowing is common within the interbedded shale and fine-to very fine grained sandstone facies. This is a non-reservoir facies and is common in the upper portion of the Bridgeport B. Rhythmic and cyclic deposition is evident in this facies. Only slight to moderate bioturbation is observed in these beds. Much of the reservoir sandstone in the Bridgeport B is composed of fine- grained, ripple-bedded sandstone. Low to medium angled planar cross bedding occurs in the lower Bridgeport B unit at 287.2 meters (942 feet) in the Griggs 107 well. Calcite cemented sandstone is also present in the Griggs 107 well at 296.5 meters (949 feet).

The base of the Bridgeport B shows a sharp contact with the underlying shale unit that separates the Bridgeport A from the Bridgeport B. A minor amount of erosion may have occurred at this contact. The sedimentary structures and the widespread nature of this shale indicate that this is a an open marine shale.. The shale grades upward from a tidally influenced interbedded shale and sandstone with tidal couplets to a dark gray, fissile, marine shale. The thickest, most consistent sandstones occur in the lowest

Bridgeport B interval. This interval appears to be the better of the Bridgeport reservoirs with respect to thickness and flow unit development. Detailed mapping shows a large degree of compartmentalization in all Bridgeport Sandstones. Compartmentalization is caused by a wide variety of episodic conditions that lead to deposition of reservoir sandstones and non-reservoir sediments in fluvial, deltaic and tidally influenced environments. However while compartmentalization is evident in nearly all sandstones, sandstones commonly exhibit a directional orientation that must be considered in reservoir development for the most effective recovery of petroleum.

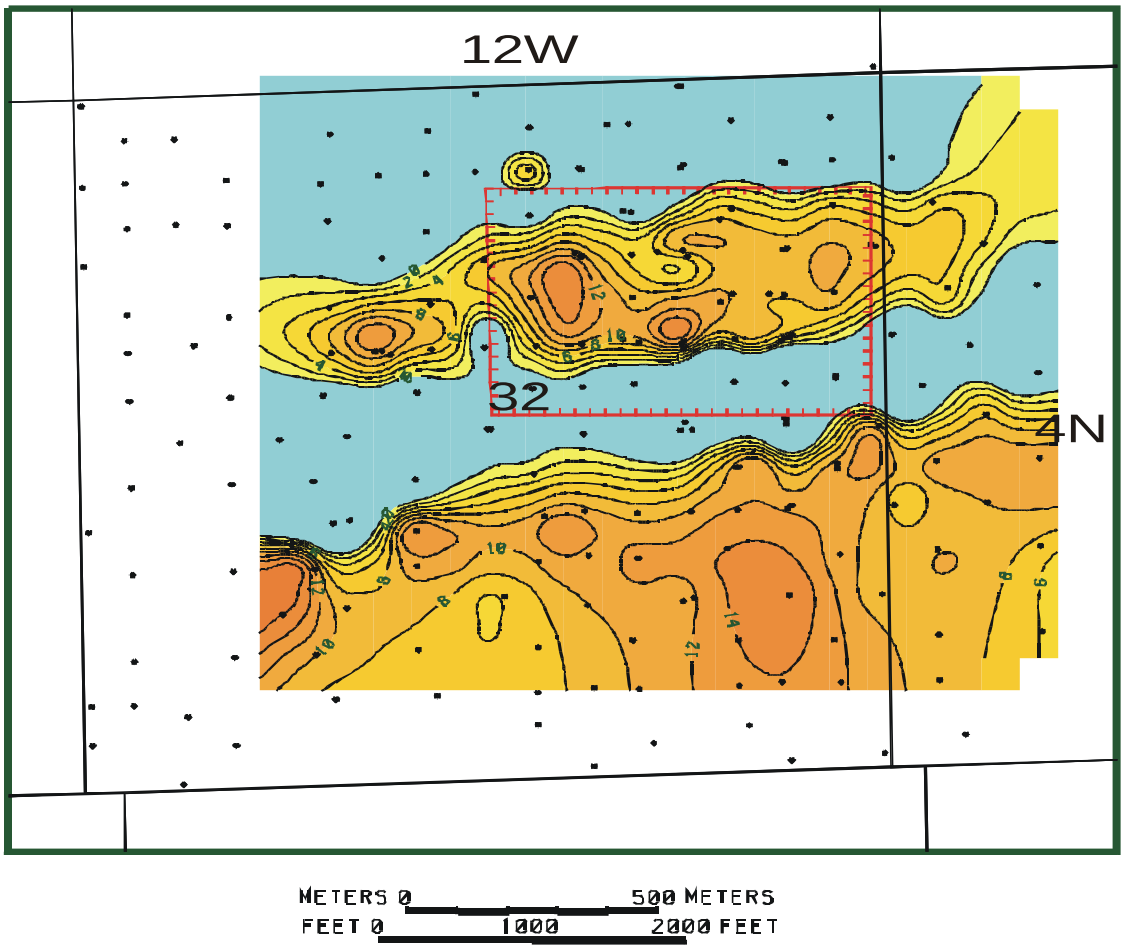
The Bridgeport B in the Griggs 107 contains well developed, 50 percent clean sandstones in the lower two intervals. The upper interval contains no sandstone. Each clean sandstone is separated by interbedded shale and very fine-grained sandstone. The permeability graph shows that there are two permeable sandstones, the upper sandstone is 2 meters (6 feet) thick with permeabilities ranging between 50 and 150 millidarcies. The lower sandstone is 1.5 meters (~5 feet) thick with permeabilities ranging between 75 and 200 millidarcies. High angle, tabular cross-bedding is present core of the Bridgeport B Sandstones. Sandstones are is fine to very-fine grained and well sorted.



CI = .66 meters (2 feet)

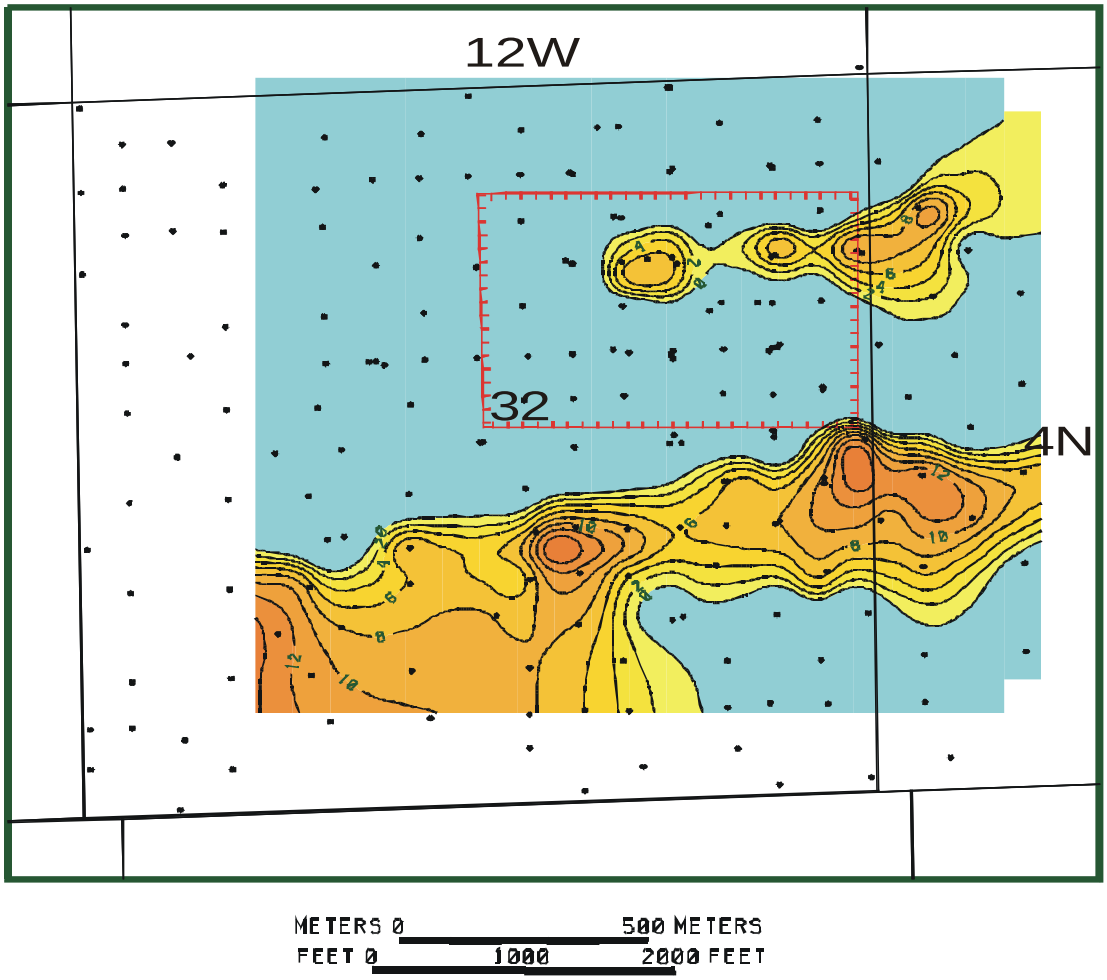
Pennsylvanian Bridgeport B Sandstone subunit 1. Lowermost unit of the Bridgeport B Sandstone. Pilot area is outlined in red.

Figure 3



Pennsylvanian Bridgeport B Sandstone subunit 2. Second from basal unit of the Bridgeport BSandstone. Pilot area is outlined in red.

Figure 4



CI = .66 meters (2 feet)

Pennsylvanian Bridgeport B Sandstone subunit 3. Top unit of the Bridgeport B Sandstone. Pilot area outlined in red.

Figure 5

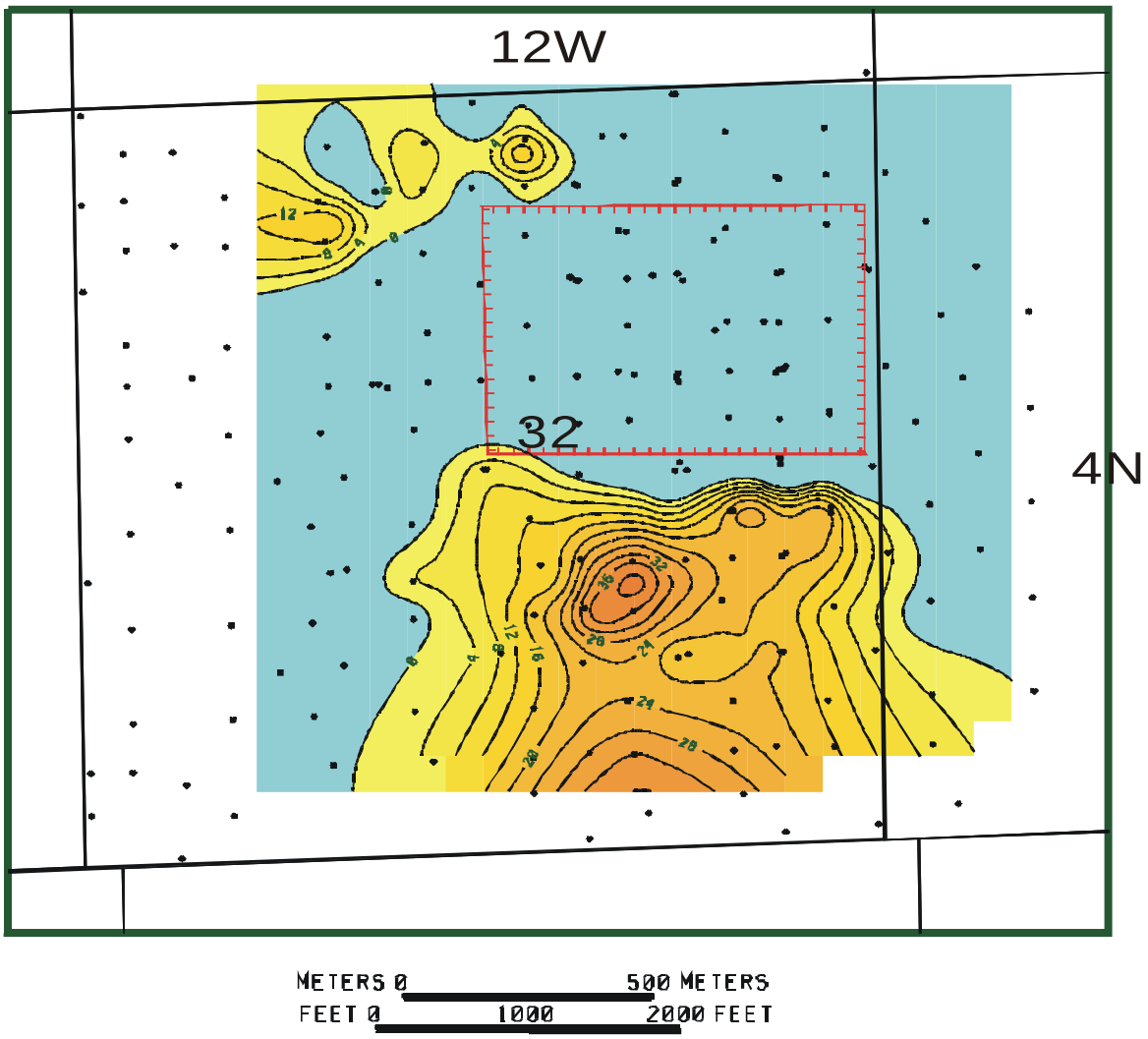
Bridgeport A

The Bridgeport A was correlated across the pilot area and divided into three intervals based on detailed analysis of electric log characteristics (figures 6, 7, & 8). The shale separating the Bridgeport A from the overlying Bridgeport B is a key marker horizon. The base of the A sandstones, where they are well-developed, commonly shows a blocky Spontaneous Potential or gamma ray character and can develop with up to three benches. The base of the blocky sandstones are abrupt, however the portion above the blocky sandstones shows a fining upward character and may be serrated or spiked. Where all three intervals develop, the overall Bridgeport A is thicker than the overall Bridgeport B or D. Each of the three mapped intervals exhibits rapid vertical and lateral variations in thickness and log or facies character. The upper two intervals of the Bridgeport A contain more widespread reservoir sandstones than the lower interval with respect to the pilot area. Reservoir sandstone is not developed in the lower interval in the pilot area. The log of the Griggs 107 shows sandstone in the middle and upper intervals of the Bridgeport A but not in the lower interval. Maximum thickness in the upper Bridgeport A sandstone is 8 meters (24 feet). Maximum thickness of the middle Bridgeport A is 13 meters (39 feet).

The upper portion of each of the three intervals is commonly composed of fine-grained siliciclastics consisting of interbedded very fine-to fine grained sandstone and shale. The interbedded very fine-grained sandstone and shale facies is cyclic and can contain minor horizontal burrows. The facies becomes interlaminated in some cored intervals such as 288.7-292 meters (947 - 958 feet) in the Griggs 109 where tidal couplets are present. Fifty percent clean sandstones found in the lower, blocky portions of the intervals in of the Bridgeport A are fine grained with some medium and minor coarse grains in the higher energy deposits. Medium to high angle tabular cross-bedding is common and beds with angular shale clasts are interspersed. The cross bedded facies is the most common reservoir facies observed in Bridgeport A units. A slumped and disrupted bedding facies is less common in the Bridgeport A and occurs at 306.4-306.8 meters (1005 - 1006 feet) in the Griggs 107 well. Intervals containing large amounts of angular, shattered appearing shale clasts are also found in the Bridgeport A such as that at 302.4 meters (992 feet) in the Griggs 107 well. Some shale clasts appear to be flat rip-up clasts while most clasts appear to be channel bank slump material that has not been transported and rounded.. Pyrite cement is very common in the Bridgeport A sandstones and occurs as banding in cross beds and nodules as seen at 311.2 - 312.2 meters (1021-1024 feet) in the Griggs 107 well. These sandstones contain large amounts of pyrite cement that fill intergranular pore space and spread outward from fractures. This cement reduces permeability and interferes with fluid flow on both a horizontal and vertical basis. Pyrite cement is common in the basal cross bedded intervals of the Bridgeport A sandstone. Calcite cement is also common though less prevalent than pyrite. Pyrite, other than traces, was not observed in the other Bridgeport B and D sandstones or the Cypress sandstones. The sedimentary structures observed and geometries of the fifty percent clean sandstones in the lower units of the Bridgeport A are characteristic of fluvial to distributary channel deposits in a tidally influenced deltaic environment. Within the pilot area, channel deposits appear to be more widespread in the middle Bridgeport A interval

than in the upper interval. The lower Bridgeport A interval shows no reservoir sandstone development within pilot area.

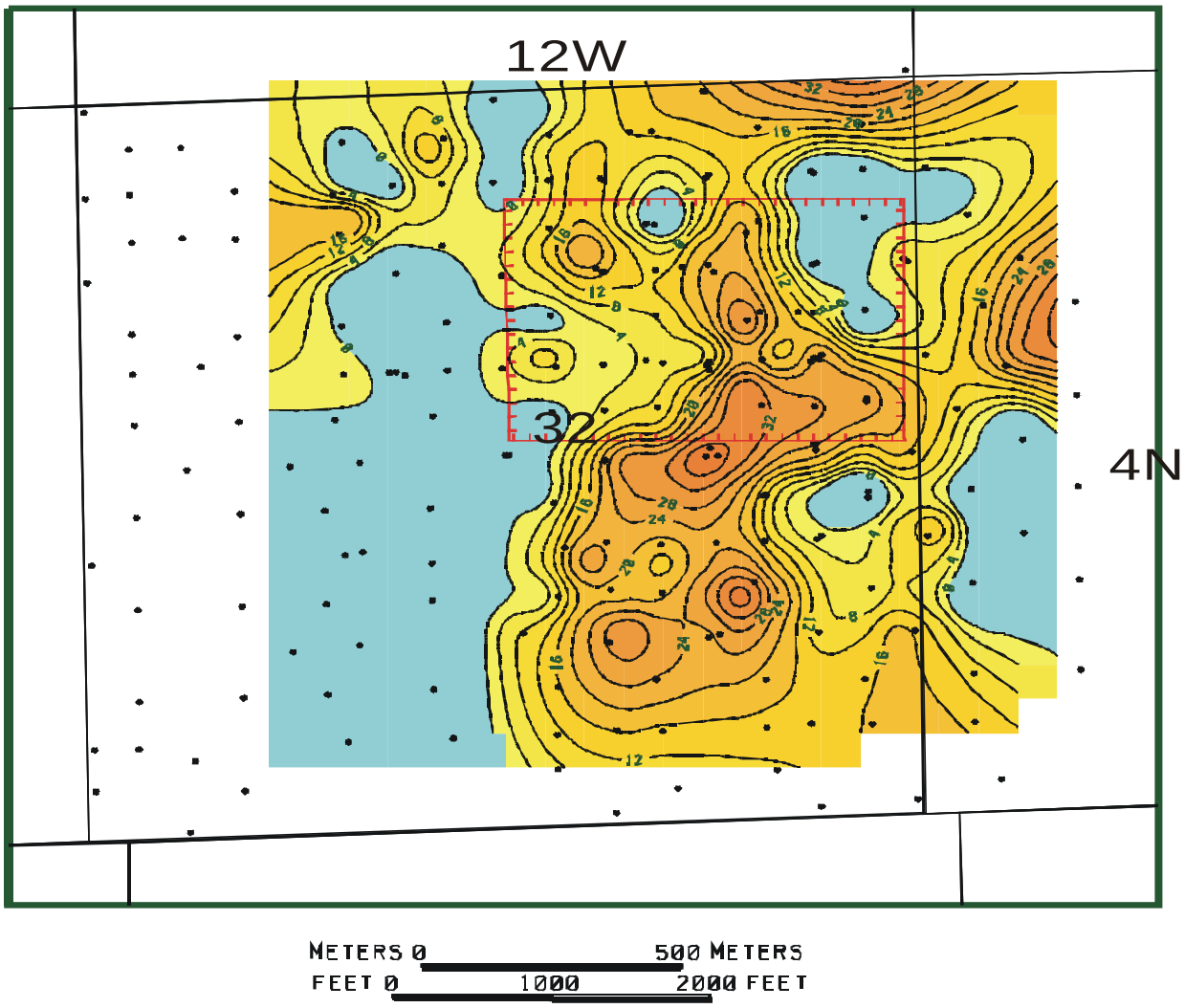
A graph of permeability of the Bridgeport A Sandstone in the Griggs 107 well shows two well developed intervals of high permeability in the upper and middle intervals of the Bridgeport A. The upper, high permeability interval contains 1.5 meters (5 feet) of sandstone with permeability exceeding 200 millidarcies. The middle interval is also 1.5 meters (5 feet) thick with permeability exceeding 1.8 darcies. The middle sandstone interval is the most permeable sandstone in the Griggs 107 well and has the highest permeability measured from the core studied for this project. High permeability sandstones are separated by interbedded shale and very fine-grained sandstone containing flaser and lenticular bedding as well as tidal couplets. Stacked channel deposits are separated vertically by slack water, tidally influenced, abandon channel deposits and horizontally by channel margin overbank, splay, and interdistributary deposits. These shaly deposits and pyrite cements form permeability barriers and compartmentalize the highly permeable channel sandstone in the Bridgeport A.



CI = 1.1 (4 feet)

Pennsylvanian Bridgeport A subunit 1. Lowermost unit of the Bridgeport A Sandstone.

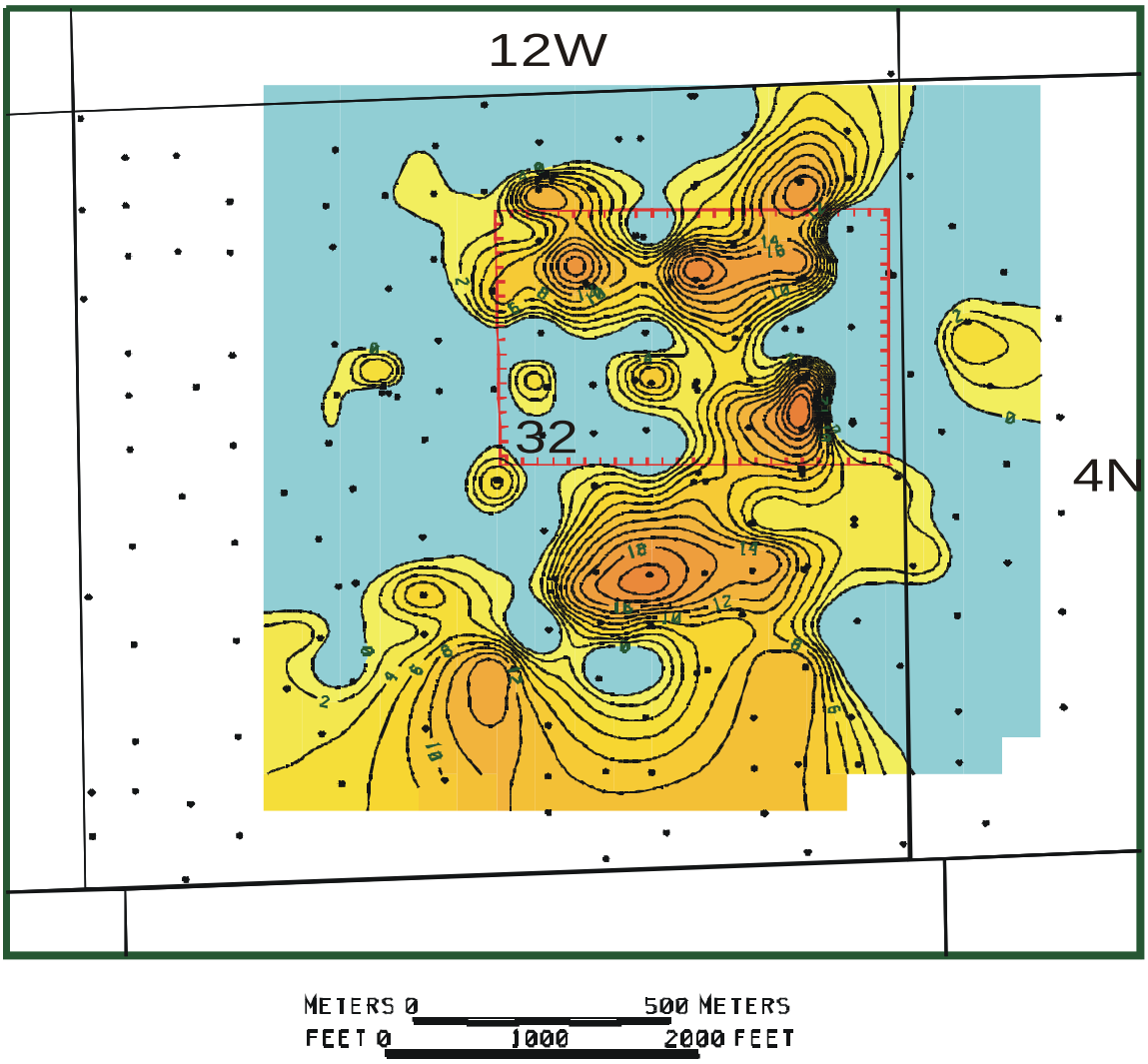
Figure 6



CI = 1.1meters (4 feet)

Pennsylvanian Bridgeport A subunit 2. Second from base unit of the Bridgeport A Sandstone. Pilot area is outlined in red.

Figure 7



CI = .66 meters (2 feet)

Pennsylvanian Bridgeport A subunit 3. Top unit of the Bridgeport A Sandstone. Pilot area is outlined in red.

Figure 8

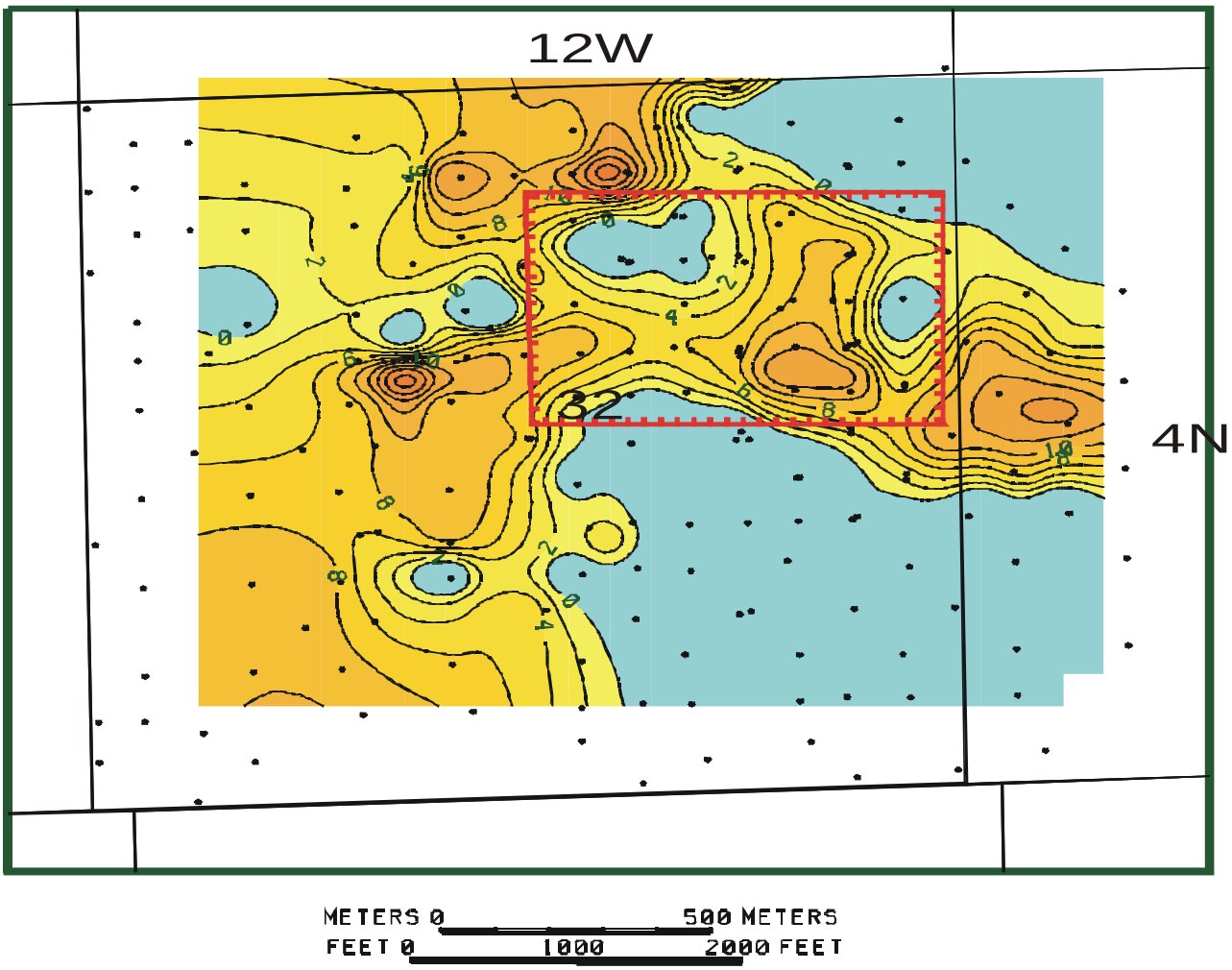
Cypress Sandstone

The Cypress Sandstone, a Middle Mississippian lower Chesterian unit, was divided into five units based on detailed analysis of geophysical log characteristics (figures 9, 10, 11, 12, &, 13). These five divisions are correlative to those mapped in the middle Cypress in a previous study in Sections 19 and 30, T4N-R12W in Lawrence County, Illinois. Mapping of the middle Cypress as a single massive sandstone would provide erroneous information on reservoir compartments and may lead to an ineffective design for flooding of the pilot area. Detailed analysis of geophysical log characteristics of the middle Cypress permits correlation of five units across the pilot area to the previously mapped study area in Sections 19 and 30, T4N-R12W. Carefully contoured maps from the previous study show elongate northeast-southwest oriented sandstone bodies. Preliminary computer generated thickness maps of the 5 units in the pilot area show a less distinctive orientation of sandstone bodies. This may be an artifact of the computer mapping algorithm used in the Zmap plus module of the Landmark Graphics software used to generate these maps. The series of 50 percent clean sandstone maps for the Middle Cypress shows that sandstone accumulation is least widespread and thinnest in the lowermost and uppermost units. Sandstone accumulation began in the lowermost unit and increased through the second, third and fourth units and thinned again in the uppermost fifth unit. The middle Cypress is comprised of a series of stacked, depositionally similar units. Well developed 50 percent clean sandstones in each of the units is separated from the other units by impermeable intervals composed of shaly sandstones, thinnly interbedded shale and sandstone, and in some cases, shale beds. Sandstone accumulation in the lowermost unit is oriented east-west through the pilot area and is sporadic. Maximum thickness is 4.5 meters (14 feet) and many wells have no reservoir sandstone. The second Middle Cypress unit is more widespread than the first and has a maximum thickness of 5 meters (16 feet). The third unit is also widespread with a maximum thickness of 5.5 meters (17 feet). The forth unit is less widespread than the third unit and has a maximum thickness of 5.1 meters (16 feet). Sandstone accumulation in the fifth unit is much less than that found in the second through fourth units, maximum thickness is 4 meters (12 feet) and many wells contain no reservoir sandstone.

Two different reservoir facies were observed in core of the middle Cypress Sandstone in the pilot area. A homogeneous, mottled, obscurely bedded facies composed of fine-grained sandstone with scattered iron stained round speckles and scattered, randomly oriented small shale flecks was observed in the fourth interval from the base of the middle Cypress in the Griggs 107 well. The speckled, possibly highly bioturbated facies contains the highest porosity and permeability measured in Cypress core in the pilot area. Samples from 3.65 meters (12 feet) of this fourth unit have permeability values greater than100 millidarcies. Permeability of up to 500 millidarcies was measured in these samples. The most common reservoir facies is composed of ripple bedded, fine-grained sandstone with wispy shale laminations. Herringbone micro cross-bedding such as that observed in the Griggs 106 well at 431.7 meters (1416 feet) is also associated with the ripple-bedded facies. Flaser and lenticular bedding along with cycles of rippled bedding and herringbone bedding are indicators of tidal deposition. The third, second and first units from the base of the Cypress in the Griggs 107 well are composed of the

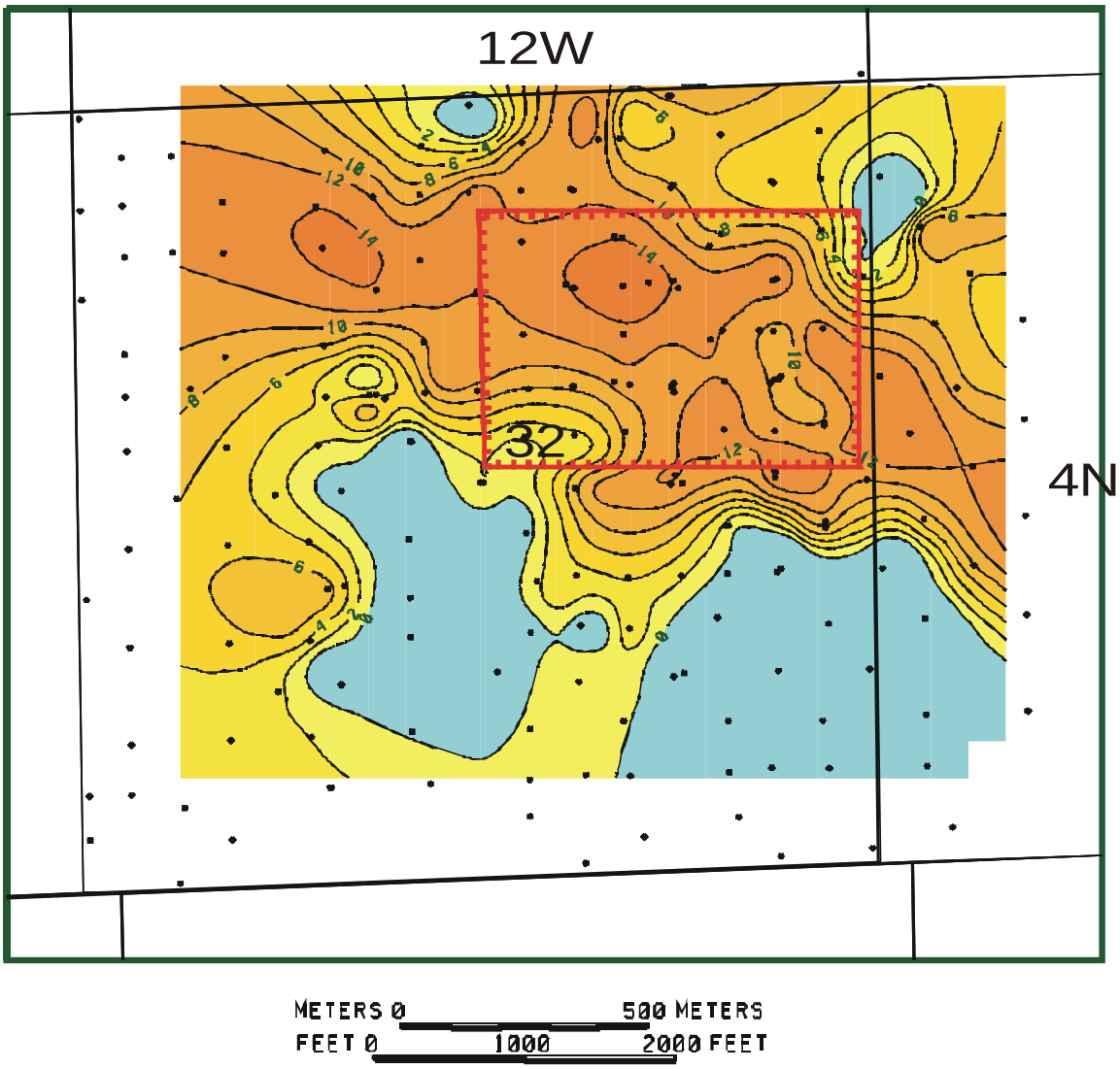
ripple bedded facies. Permeabilities range from 50 to 200 millidarcies in the ripple bedded facies with most samples measuring less than 100 millidarcies. Tidal couplets observed in the non-reservoir facies of these units are additional diagnostic characteristics of tidal deposition. Sandstones units with similar sedimentary features to those in the pilot area and directly correlative to the Cypress units in the pilot area have been tentatively interpreted as linear tidal shoals from the earlier study in sections 19 and 30 of the same township.

Reservoirs in the middle Cypress are vertically compartmentalized and show limited aerial extent in the horizontal plane. Effective implementation of flooding in the pilot area should take into account compartment orientation that is dictated by depositional trends and type and location of permeability barriers.



Middle Cypress subunit 1. Lowermost unit of the Middle Cypress Sandstone

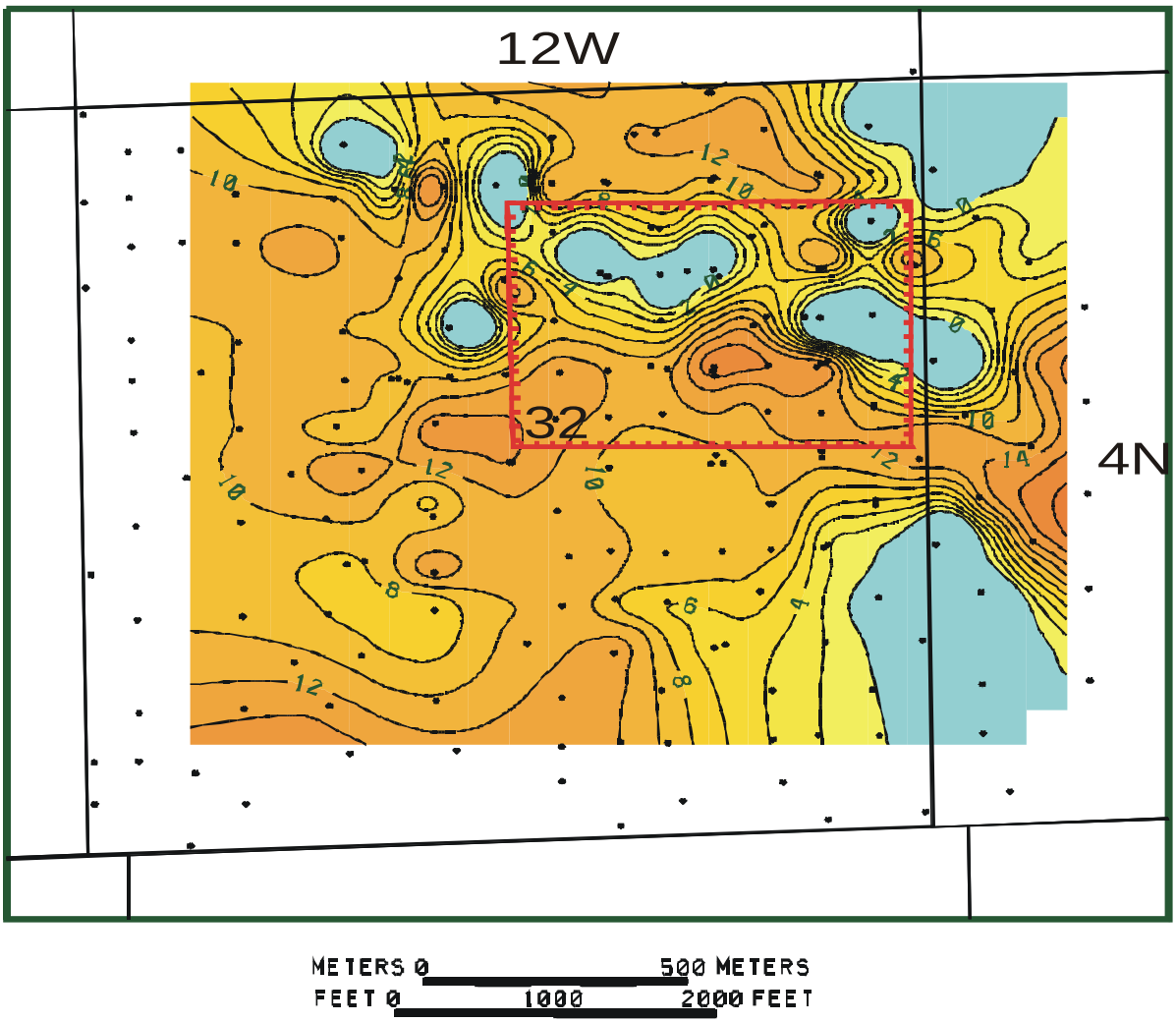
Figure 9



CI = .66 meters (2 feet)

Middle Cypress subunit 2.Second lowest unit of the Middle Cypress Sandstone.

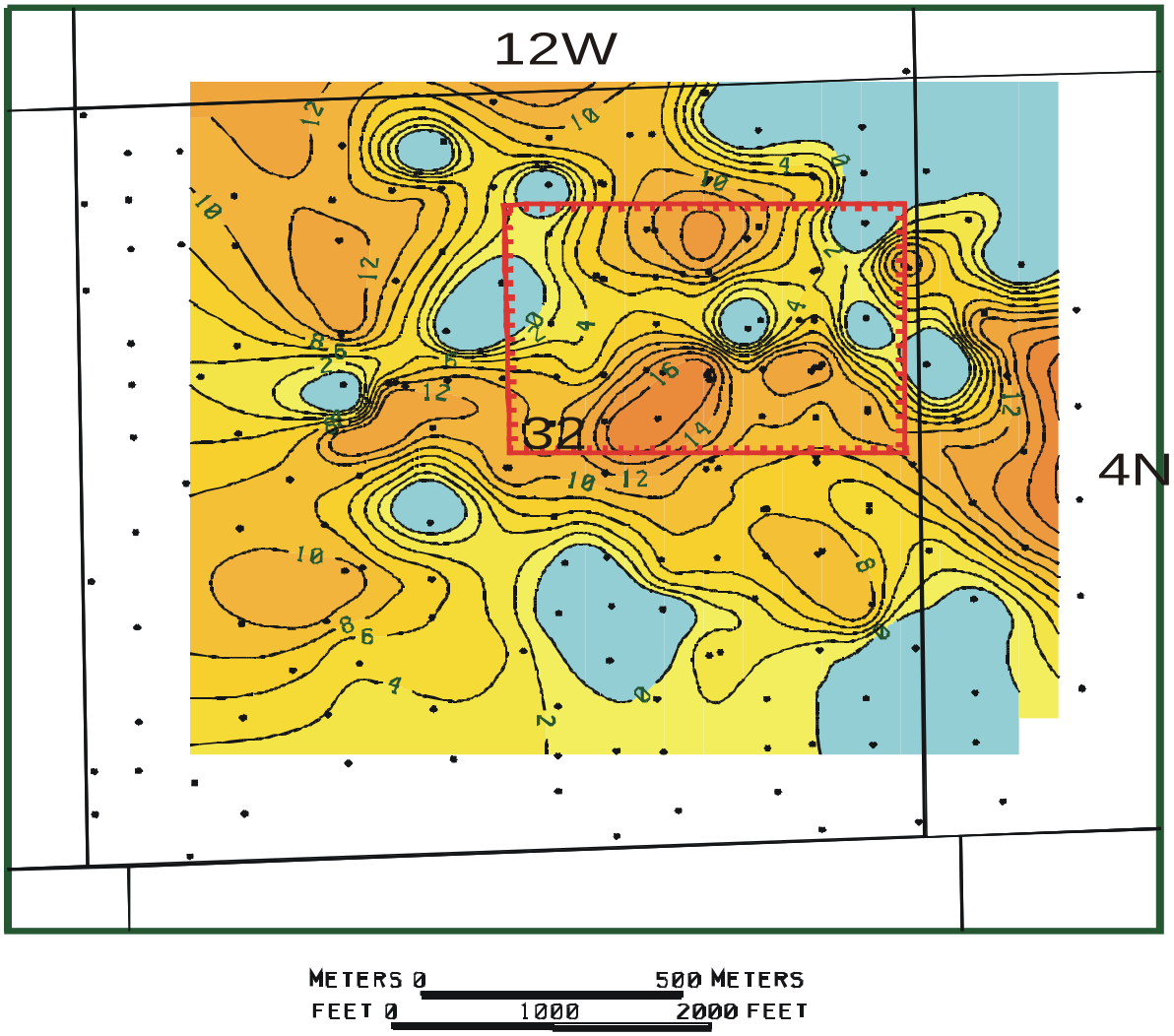
Figure 10



CI = .66 meters (2 feet)

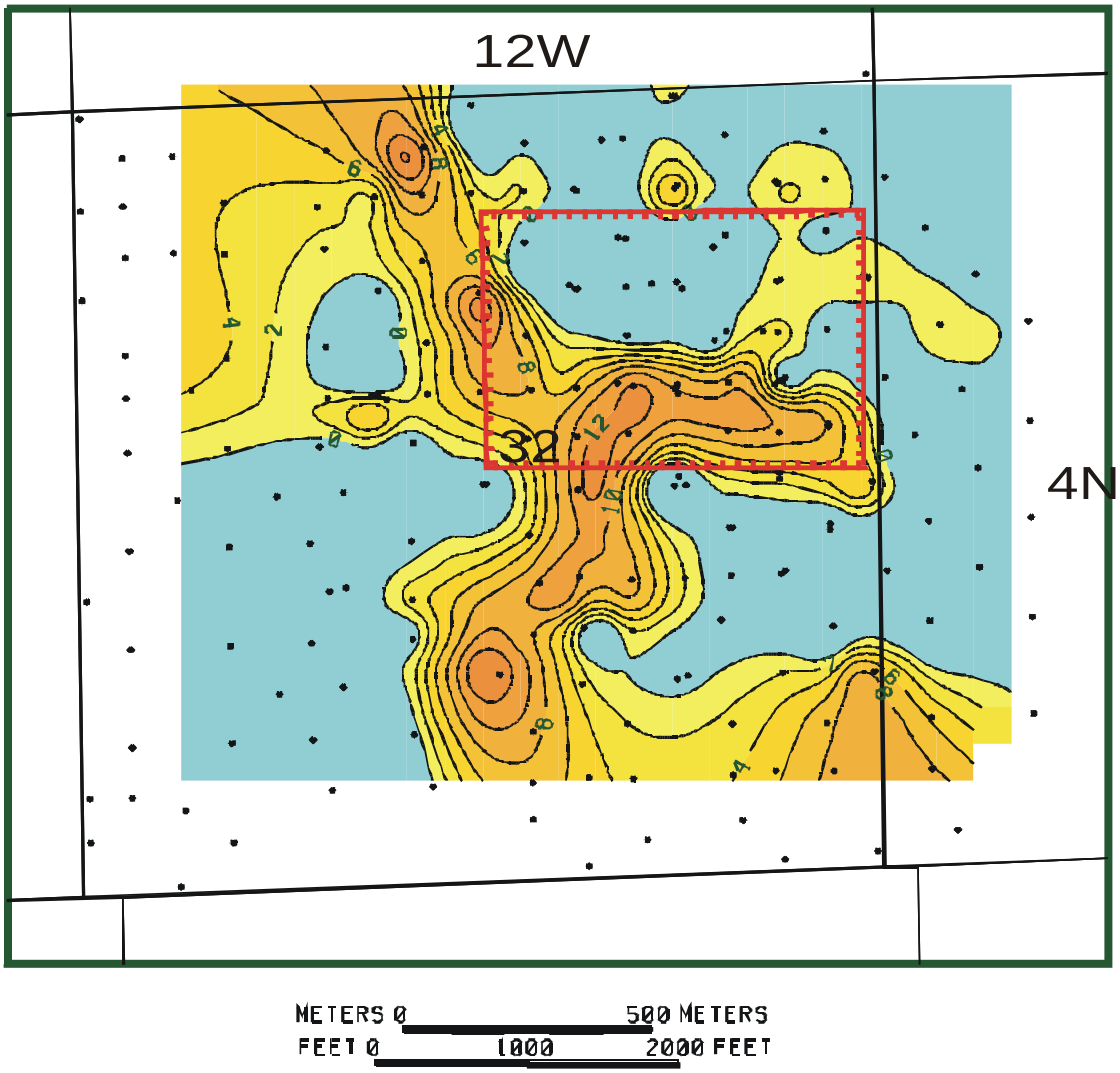
Middle Cypress subunit 3. Third subunit from base of the Middle Cypress Sandstone.

Figure 11



Middle Cypress subunit 4. Fourth unit of the Middle Cypress Sandstone.

Figure 12



CI = .66 meters (2 feet)

Middle Cypress subunit 5. The fifth and top unit of the Middle Cypress Sandstone.

Figure 13

INSERT FIG 9, 10, 11, 12, 13

Conclusion

Laboratory Evaluation

Future work will be to develop an alkaline-surfactant-polymer combination that recovers incremental oil in both the Bridgeport A and Bridgeport B. Interfacial tension, phase behavior, and radial coreflood evaluations will be performed. Numerical simulation of the Bridgeport A and B, and the Cypress and Paint Creek will begin next quarter.

Numerical Simulation

Two geologic models for the numerical simulation of the Bridgeport A and B, and the Cypress and Paint Creek are being developed.

Reservoir Characterization

Analysis of geophysical log characteristics in the Pennsylvanian Bridgeport A, B, and D sandstones and the Middle Mississippian Cypress Sandstone permitted subdivision of each of these sandstone reservoirs. Preliminary mapping of clean 50 percent sandstones using Landmark Graphics Zmap Plus software of subunits within each of these sandstones shows a high degree of compartmentalization in all reservoirs.

The Bridgeport D is the least widespread of the Bridgeport Sandstones. The upper unit in the Bridgeport D is more continuous than the lower Bridgeport D unit. The Bridgeport D appears to have greater reservoir potential in the upper, more widespread unit. The Bridgeport B is the most widespread and homogeneous of the Bridgeport Sandstones. It was consistently mapped based on its relationship to the marine shale separating the Bridgeport A from the Bridgeport B sandstones. The Bridgeport A shows the greatest amount of heterogeneity of the Bridgeport sandstones. While all Bridgeport Sandstones exhibit a large degree of heterogeneity, units within each Bridgeport interval within or surrounding the pilot area show reservoir development with potential for chemical flood recovery. However, many of the reservoir sandstones are compartmentalized and of limited aerial extent, therefore limiting the effectiveness of flood recovery. Some of the Cypress sandstone units are the most consistent and widespread of the sandstones being considered for flood recovery in the pilot area. This study demonstrates that units within the Bridgeport and Cypress intervals can be consistently selected and mapped based on comparison of similar log character predominantly on gamma ray and Spontaneous Potential traces supported by characteristics on the porosity and resistivity traces. Modern log suites were compared with more vintage log suites to ensure that the Bridgeport and Cypress Sandstones and subdivisions within each formation were selected on a consistent basis.

General

The work done to date continues to suggest a successful project and that the process will be applicable to other areas of the Lawrence Field and to other fields with similar sand types and characteristics.

References

1 Meyers, J.J., Pitts, M.J., and Wyatt, K.: "Alkaline-Surfactant-Polymer Flood of the West Kiehl, Minnelusa Unit", SPE 24144, presented at the Eight Symposium on Enhances Oil Recovery in Tulsa, Oklahoma, April 1992.

2 Gao, S., Li, H., Yang, Z., Pitts, M.J., Surkalo, H., and Wyatt, K.: "Alkaline-Surfactant-Polymer Pilot Performance of the West Central Saertu, Daqing Oil Field", SPE 35383, presented at the Tenth Symposium on Improved Oil Recovery in Tulsa, Oklahoma, Apirl 1996, SPE Reservoir Engineering, Volume 11 number 3, August 1996, pages 181-188.

3 Vargo, Jay, Turner, Jim, Vergnani, Bob, Pitts, Malcolm J., Wyatt, Kon, Surkalo, Harry, and Patterson, David: "Alkaline-Surfactant-Polymer Flooding of the Cambridge Minnelusa Field, " SPE Reservoir Evaluation and Engineering, vol 3 number 6, December 2000, pages 552-558.

4 Pitts, Malcolm J.: "Detailed Evaluation of the West Kiehl Alkaline-Surfactant-Polymer Field Project and Its Application to Mature Minnelusa Waterfloods," Department of Energy Report number DOE/BC/14860-9, Bartlesville Project Office, March 1995.