

Contract No. G-015-028

Final Report submitted to:

The North Dakota Industrial Commission

## Hydraulic Fracturing and Microseismic Monitoring Project

Submitted by:

Headington Oil Company LLC and XTO Energy Inc

On behalf of the Bakken Research Consortium:

Brigham Exploration

Continental Resources

Encore Operating

Hess Corporation

Petro-Hunt LLC

Whiting Petroleum

Schlumberger Oilfield Services

MicroSeismic, Inc.

Terrascience

DOE National Energy Technology Laboratory

Lawrence Berkeley National Laboratory

15 Dec 2008

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## Section 1. Introduction

On behalf of the Bakken Research Consortium, Headington Oil Company LLC and XTO Energy Inc. are providing this final report to the North Dakota Industrial Commission regarding the status of its Hydraulic Fracturing and Microseismic Monitoring project in Williams County, North Dakota. The final group of participants in this project includes: Brigham Exploration, Continental Resources, Encore Operating, Headington Oil Company LLC (and XTO Energy, Inc as a result of its acquisition of Headington's Williston Basin assets), Hess Corporation, Petro-Hunt LLC, and Whiting Petroleum as Working Interest Participants; and Schlumberger Oilfield Services, MicroSeismic Inc., Terrascience Systems Ltd, and the DOE National Energy Technology Laboratory in conjunction with the Lawrence Berkeley National Laboratory as Technical Participants.

### 1.1 Project Concept

The Bakken Consortium was conceived as an opportunity to deploy the most advanced available technology to investigate opportunities to optimize the drilling, completion and production of horizontal Williston Basin Bakken formation wells. Of special significance was the implementation of microseismic technology to monitor fracture initiation and growth. In an effort to maximize the potential for successful microseismic monitoring, it was decided three parallel horizontal wellbores would be drilled within a 640 acre unit. Two of the wellbores would be completed using methods common to the Williston Basin. The middle wellbore would be used initially to deploy geophones horizontally in the Bakken target zone to allow for microseismic monitoring of hydraulic fracture stimulation. Completion of the monitoring well would be considered at some future date. It was determined a pilot hole would be drilled and a core taken in one well and all three laterals would be logged. Further, advanced LWD and MWD techniques would be used in the drilling of the second two wells.

### 1.2 Project Area

The project area is located in Section 36-T156N-R95W in eastern Williams County, North Dakota, on the eastern flank of the Nesson Anticline (Figure 1). Surface locations for the three wells are in the eastern part of Section 36, and the parallel horizontal wellbores were drilled from east-to-west (Figures 2 and 3). The northern and southern horizontal wellbores have been completed, fracture stimulated and are currently producing. The central well was used to deploy geophones for the microseismic monitoring of the stimulation of the two producing wells. Two other buried microseismic arrays and one surface array were also employed in the monitoring phase of the project.

### 1.3 Project Status

The primary operational phase of the project has been completed. All three wells have been drilled; both producers have been completed and stimulated and are currently producing. All data have been collected, analyzed and presented to Consortium members. The project has been completed as outlined in the NDOGRC application.

Pertinent aspects of the drilling and completion phase are summarized in the sections to follow. The status of key events related to this phase of the project is as follows:

- All three wells have been drilled.
- Downhole geophones were successfully deployed in the monitoring well.
- Two buried and one surface array were successfully deployed to monitor stimulation.
- Both producing wells have been fracture stimulated.
- Primary fracture stimulation has been monitored by four microseismic arrays.
- All microseismic data has been processed.
- \$12.98 million in drilling and completion costs have been incurred to date.
- 3D Seismic has been completed and \$0.5 million in 3D-seismic related costs have been incurred to date.

All information pertaining to this project will remain confidential through 31 December 2008 as required by the contractual arrangement with the North Dakota Industrial Commission.

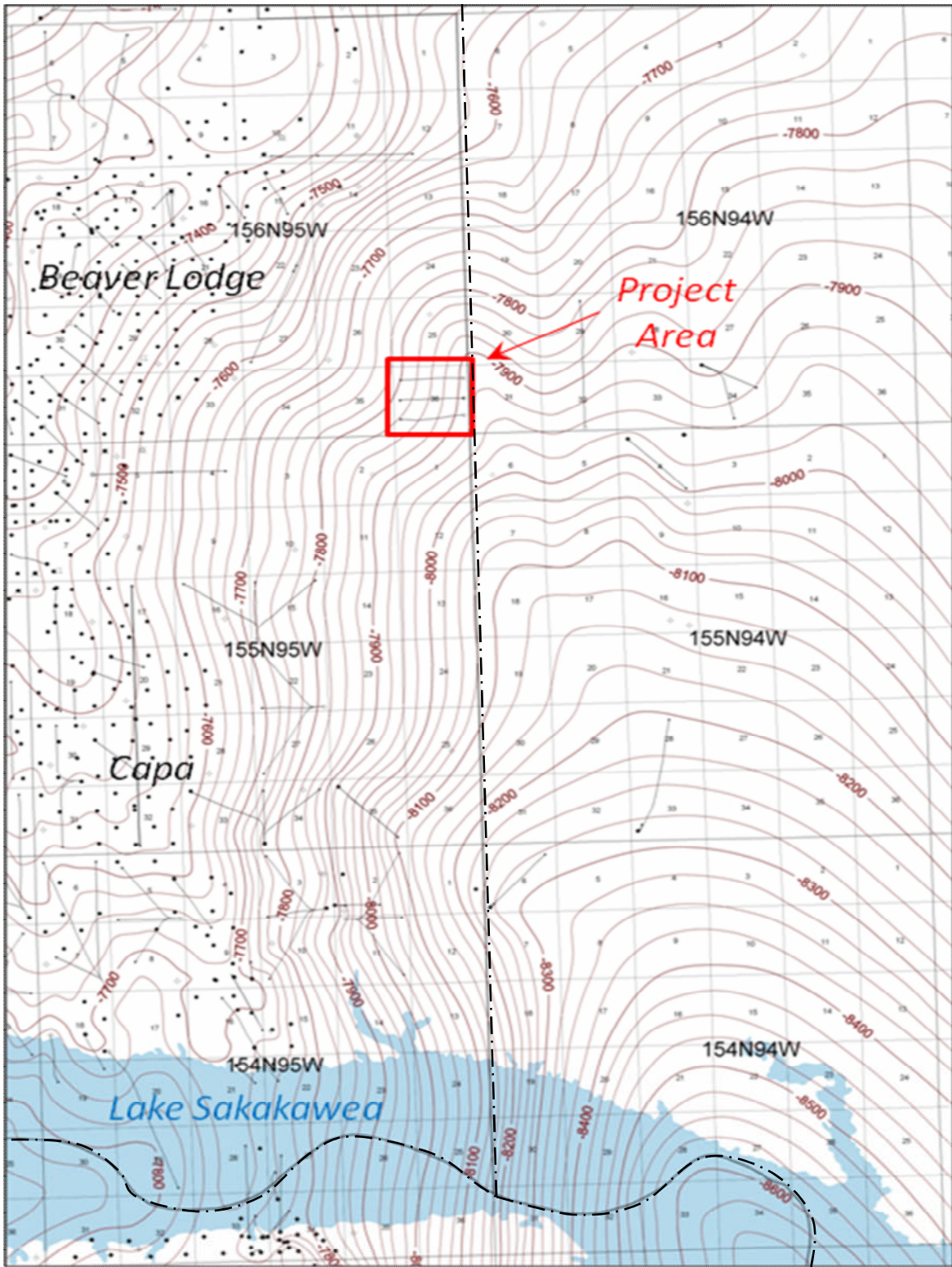


Figure 1. Project Area location in Eastern Williams County, ND Structure contours are on the top of the Bakken Formation (25' contour interval)

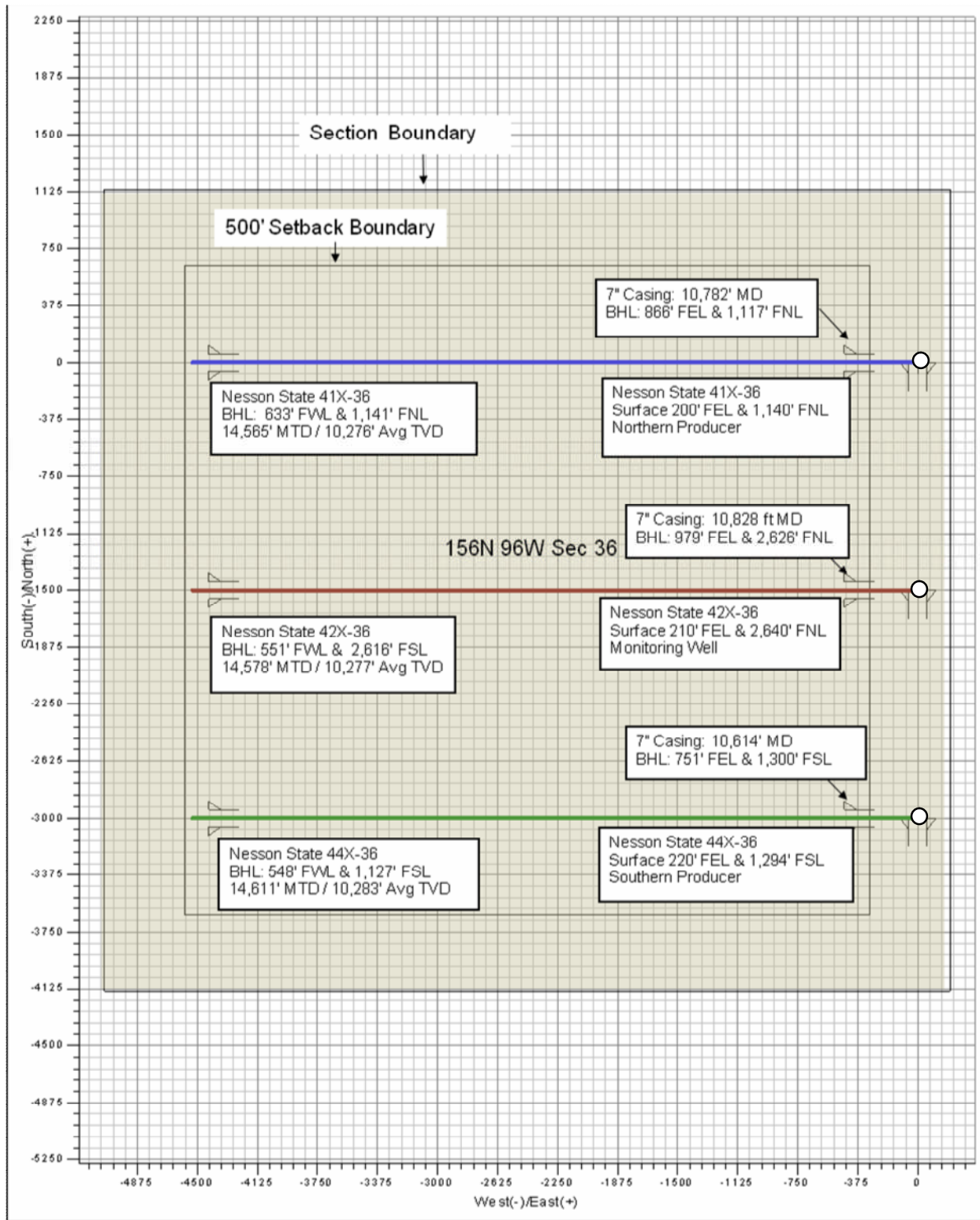


Figure 2. Surface and bottom hole locations for the three horizontal wellbores in Section 36



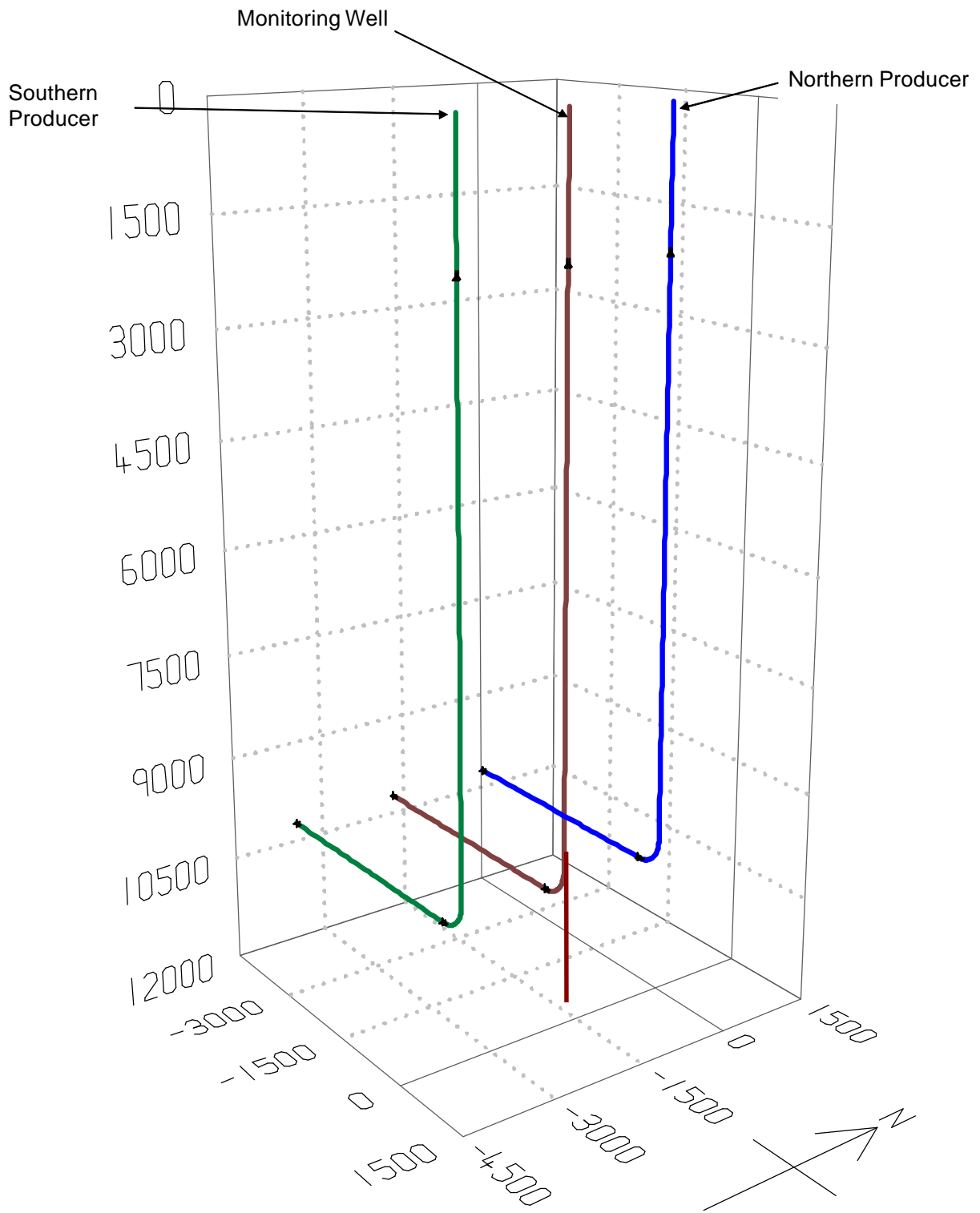


Figure 3. Spatial relationships of the three horizontal wellbores in Section 36

## Section 2. Geologic Setting

The Bakken Research Consortium study area is located in the central portion of the Williston Basin in eastern Williams County, ND and targets data acquisition from the Bakken formation. The Bakken formation (Bakken) lies at the boundary of the Mississippian & Devonian systems and consists of three members – an upper organic shale up to 25' thick, a middle silty carbonate and dolomitic/calcareous siltstone/sandstone up to 78' thick and a lower organic shale up to 58' thick. The upper and lower Bakken shales are among richest source rocks in the world and, in the Consortium area, are thermally mature and overpressured (probably related to oil and gas generation). The geology of the Bakken in the Consortium area is consistent with regional mapping of the Bakken in the east Nesson area.

The Bakken unconformably overlies impermeable Devonian Three Forks shales and dolomites and the younger Bakken members progressively overlap the older members outward from the center of the basin. The Bakken is conformably overlain by non-porous and non-permeable carbonates of the lower Mississippian Lodgepole formation.

Structurally, the study area is located along the northeastern margin of the Nesson Anticline. This large structure acts as both a focusing mechanism for hydrocarbon migration and as a mechanism of fracturing within the Bakken. Salt solution in the deeper Middle Devonian Prairie evaporite section may also contribute to local fracture intensity.

## Section 3. Drilling and Logging Program

The three wells included in the Consortium project were drilled from the east to the west. The northern and southern most wells were completed using different, but common Williston Basin completion designs. The middle well (the Nesson State 42X-36) was reserved as a monitoring well. All three wells included approximately 60 feet of 16 inch conductor pipe. The wells were drilled vertically to 50 feet below the base of the Fox Hills formation where 9 5/8 inch surface pipe was set. The wells were then drilled with a diesel- water inverted mud system to a kickoff point determined by the estimated depth of the target. A 14 degree/100 feet build rate was used to achieve an inclination of 90 degrees. Approximately 50 feet beyond the end of the build section, 7 inch casing was set with cement lifted above the top of the Dakota Silt. A 6 inch bit was used to drill the remainder of the lateral, with each lateral terminating short of the 500 foot setback boundary imposed by state regulations. Liners were run specific to the function of each well. Those functions and the final liner programs are discussed below.

An advanced logging program was developed to gather the most comprehensive geologic data set possible. All three laterals were logged using the following tools: FMI (Formation Micro Imager), Sonic Scanner, ECS (Elemental Capture Spectroscopy) and RST (Reservoir Saturation Tool). In addition, the vertical section of the Nesson State 42X-36, including the pilot hole, was logged with the following tools: PEx (Platform Express), ECS, CMR (Combined Magnetic Resonance), Sonic Scanner. A thorough description of each of these tools is included in Appendix #1. Copies of all logs have been sent to the NDIC as required.

### 3.1 Nesson State 41X-36

The Nesson State 41X-36 was drilled from a surface location 200' FEL and 1140' FNL. 9 5/8" conductor pipe was set at 1,924.' The well was kicked off at 9,870' using conventional directional tools (MWD, Bent housing motors). 7" intermediate casing was set at 10,782'. The well was drilled to a total measured depth of 14,565' with a bottom-hole location at approximately 1141' FNL and 633' FWL. After logging, a 5" pre-perforated, un-cemented liner was set in the lateral section. Included in figure 4 is the as completed construction diagram for this well. Figure 5 is a wellsite geology plot. Figure 6 is a composite log section for the lateral. Appendix 2 is an end of well review submitted by Schlumberger. Appendix 3 is a geologic report submitted at the end of drilling operations.

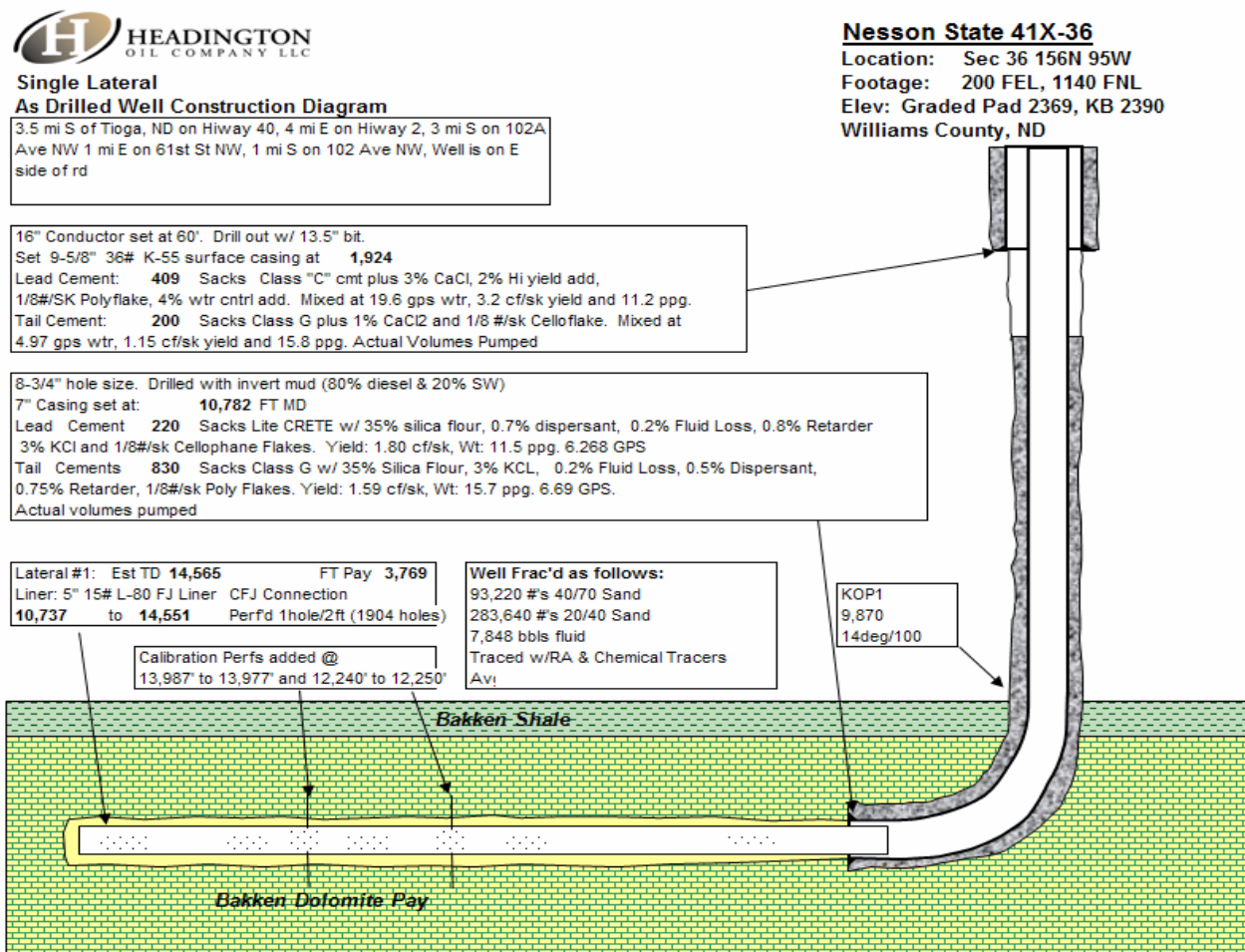


Figure 4. Nesson State 41X-36 completed wellbore configuration

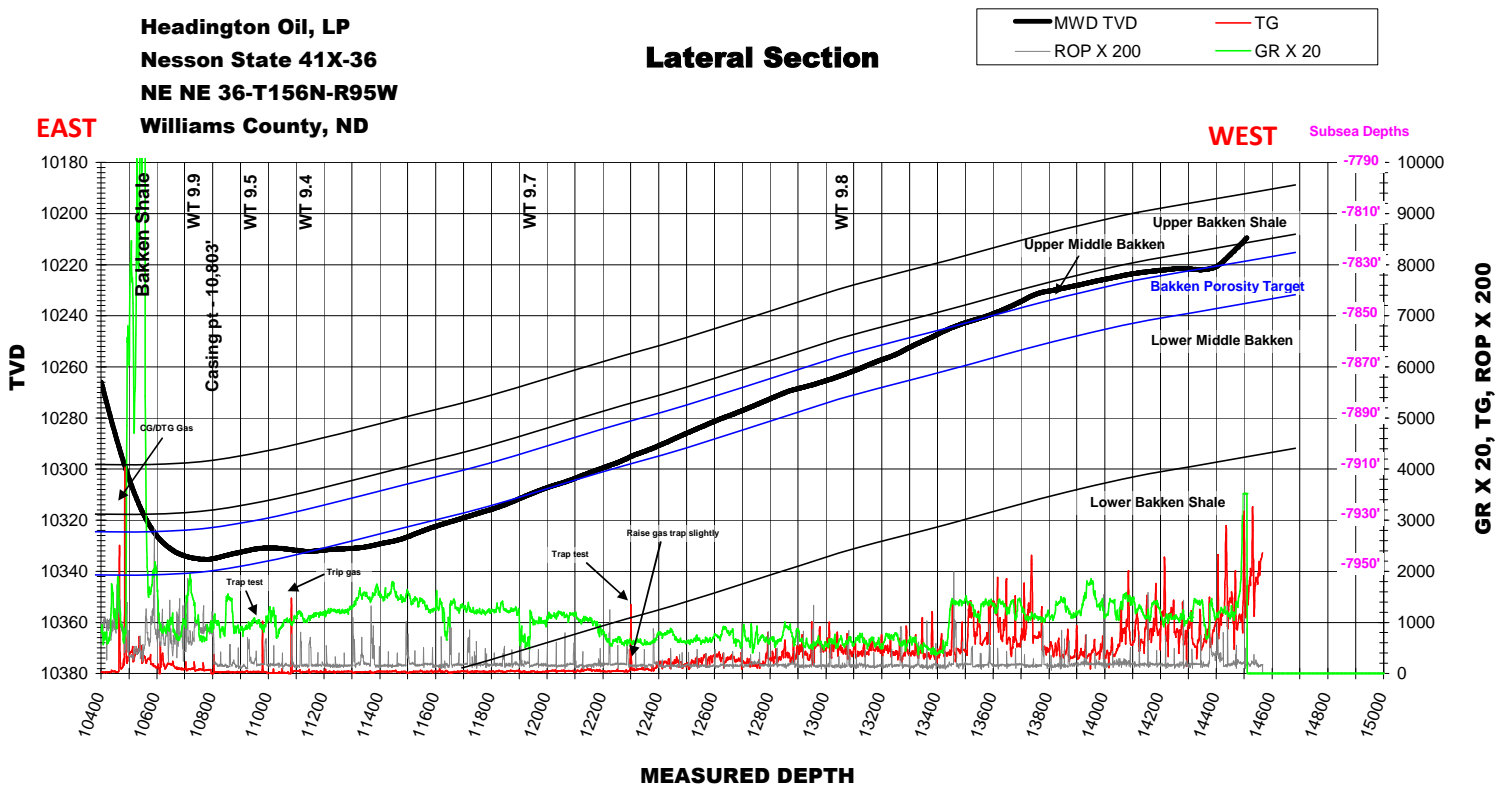


Figure 5. Nesson State 41X-36 Wellsite Geology Plot

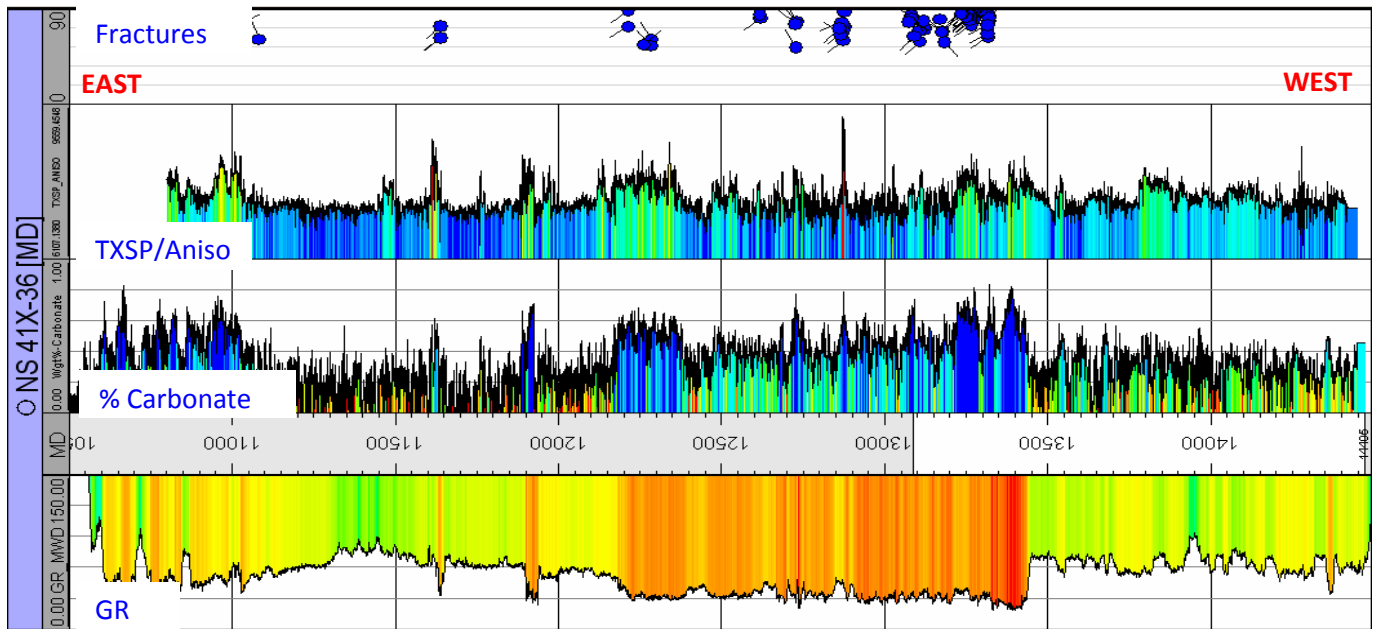


Figure 6. Nesson State 41X-36 combined horizontal logging data

### 3.2 Nesson State 42X-36

The Nesson State 42X-36 was drilled from a surface location 210' FEL and 2,640' FNL. 9 5/8" conductor casing was set at 1,950'. A vertical hole was drilled to 10,588', approximately 100' into the Three Forks. Approximately 180' of core were taken and electric logs were run in the vertical pilot hole. The well was then plugged back and a lateral drilled in the Middle Bakken. The build section and lateral were drilled with Schlumberger's Periscope and MP3 drilling optimization tools. The total depth of the well was 14,578'. The bottom hole location was approximately 2616' FSL and 551' FWL. A 5" liner was subsequently cemented in the lateral section. Included in figure 7 is the as completed construction diagram for this well. Figure 8 is a wellsite geology plot. Figure 9 is an end of well placement plot. Appendix 4 is an end of well review submitted by Schlumberger. Appendix 5 is a geologic report submitted at the end of drilling operations. Appendix 6 is a well placement report submitted by Schlumberger.

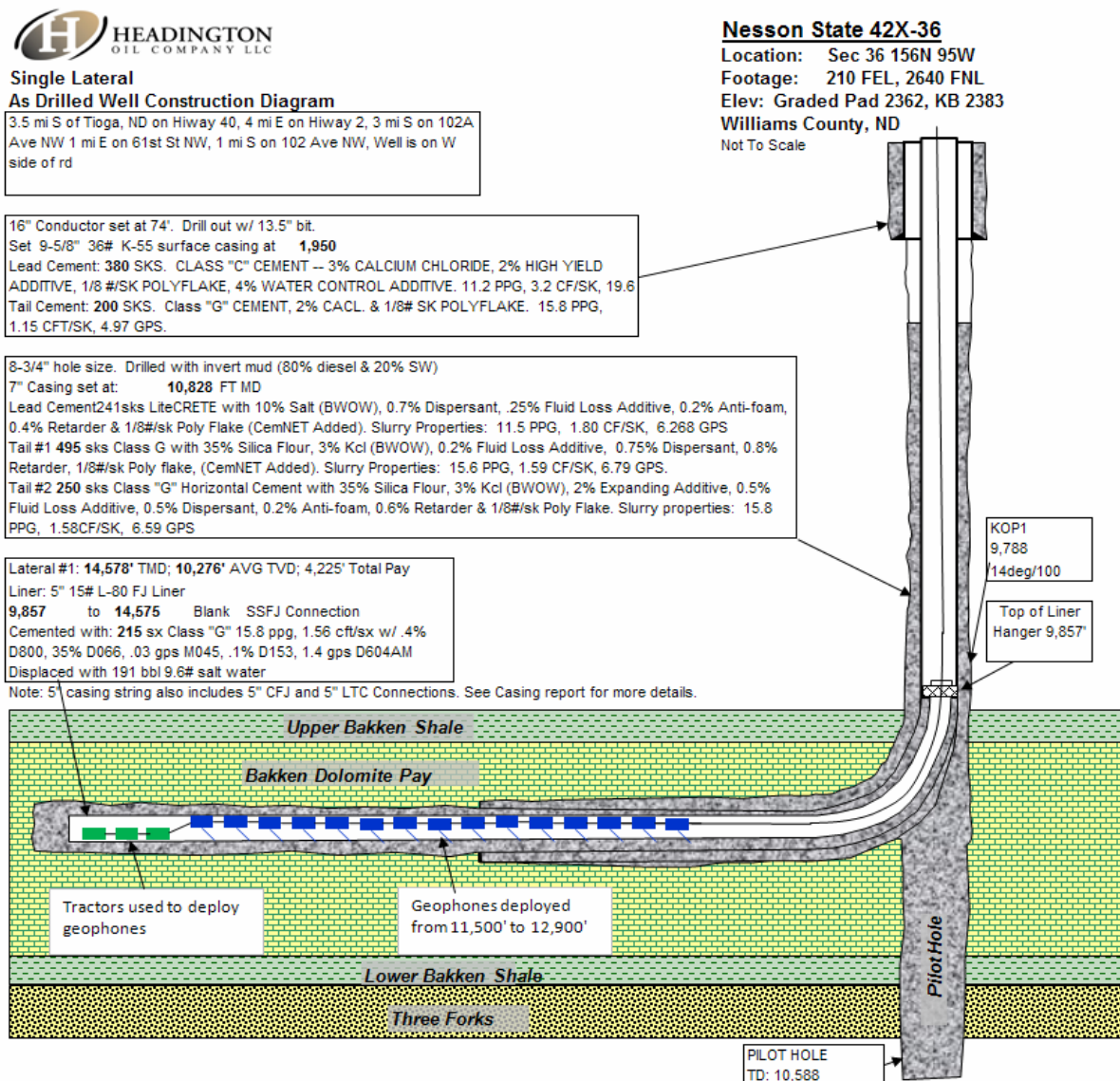


Figure 7. Nesson State 42X-36 monitoring configuration

Headington Oil, LP  
 Nesson State 42X-36  
 SE NE 36-T156N-R95W  
 Williams County, ND

**Lateral Section**

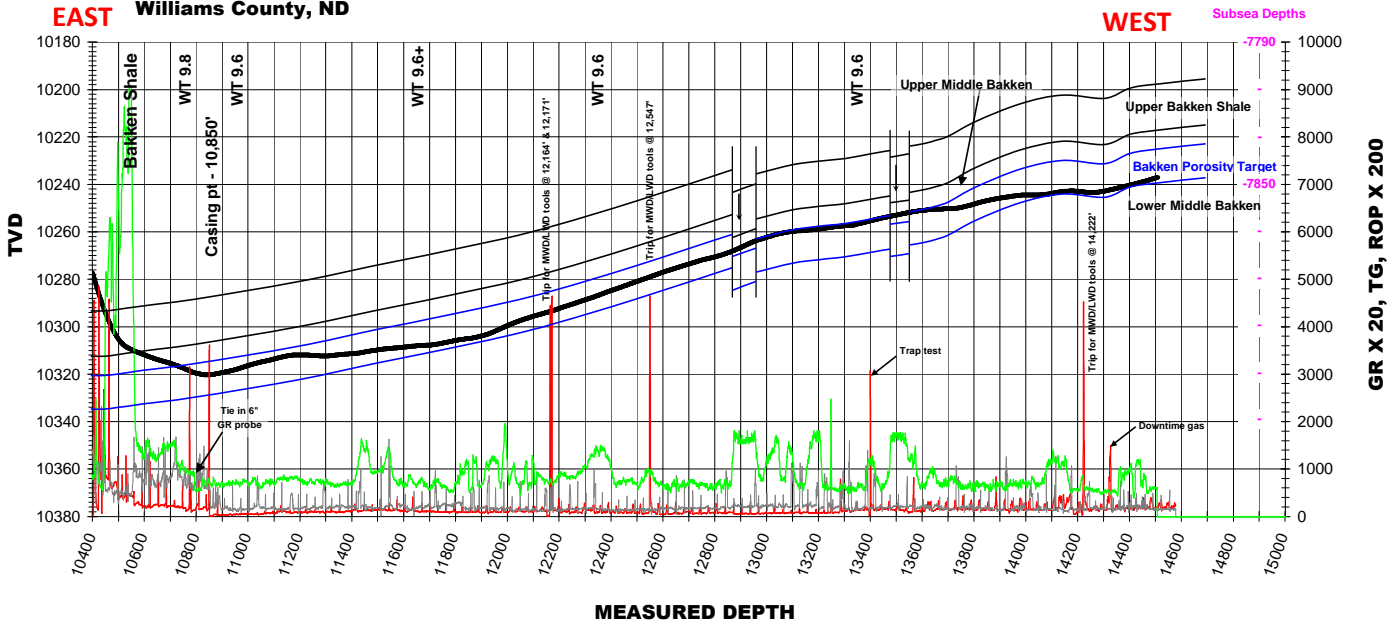


Figure 8. Nesson State 42X-36 Wellsite Geology Plot

**PeriScope Inversion - Zoomed**

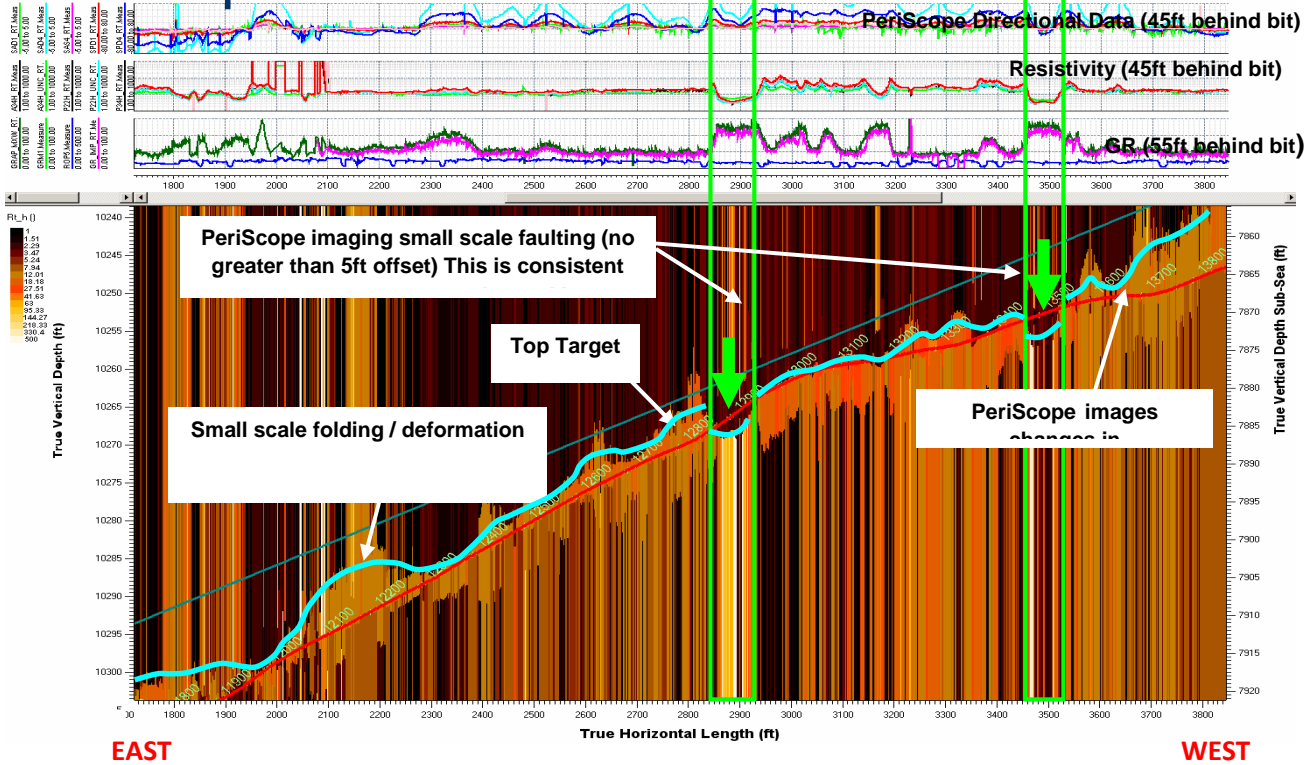


Figure 9. Nesson State 42X-36 Well Placement Plot

Section 3.3 Nesson State 44X-36

The Nesson State 44X-36 was drilled from a surface location 200' FEL and 4,140' FNL. 9 5/8" conductor pipe was set at 1,962'. The well was kicked off at 9,910'. The build section and lateral were drilled with Schlumberger's Periscope drilling optimization tool. The total measured depth of the well was 14,611' with a bottom-hole location at approximately 1,127' FSL and 548' FWL. An un-perforated liner configured with external casing packers was subsequently set in the lateral section (actual location of swell packers included in Figure 10 below). Figure 11 is a wellsite geology plot. Figure 12 is a composite log section for the lateral. Appendix 7 is an end of well review submitted by Schlumberger. Appendix 8 is a geologic report submitted at the end of drilling operations. Appendix 9 is a well placement report submitted by Schlumberger at TD.

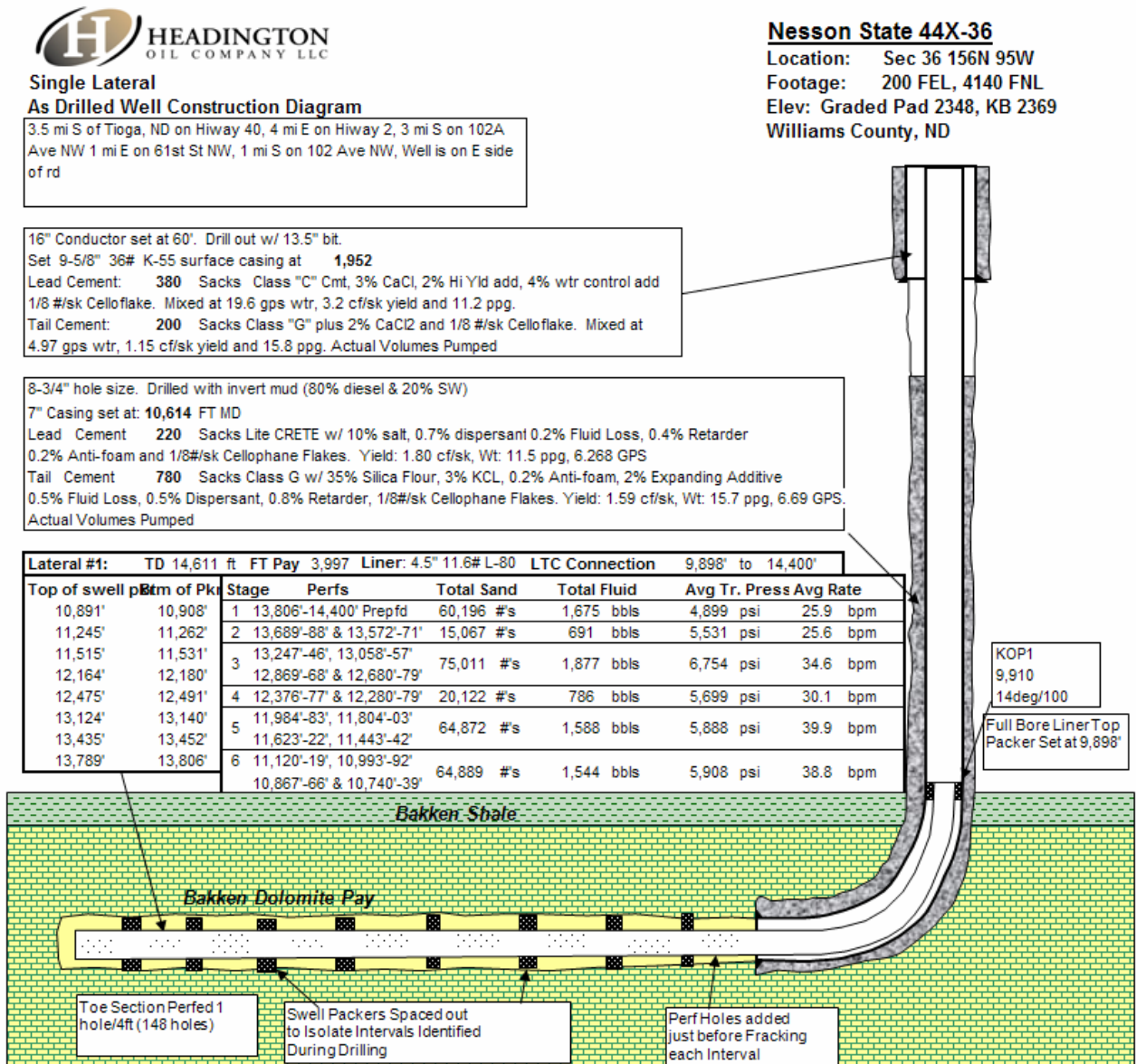


Figure 10. Nesson State 44X-36 completed wellbore configuration

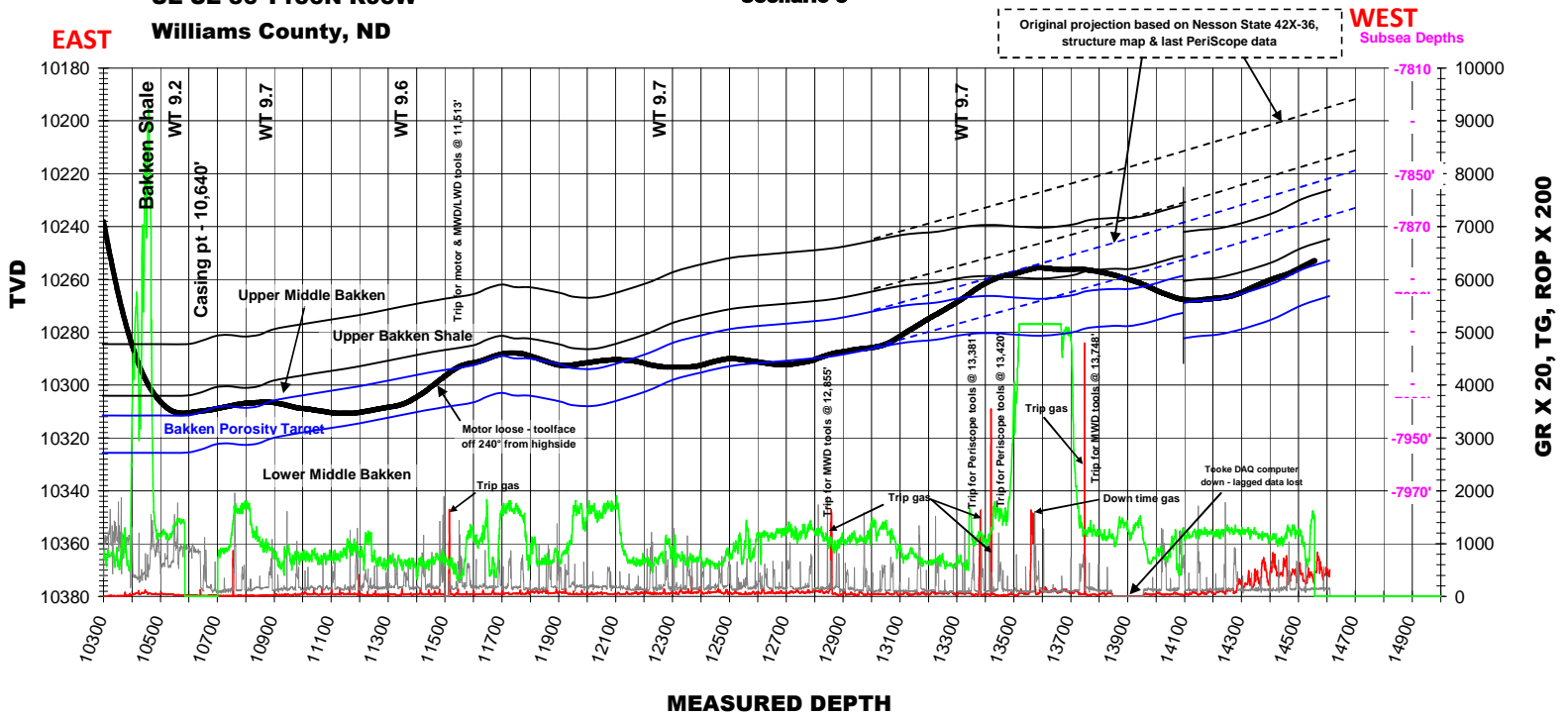


Figure 11. Nesson State 44X-36 Wellsite Geology Plot

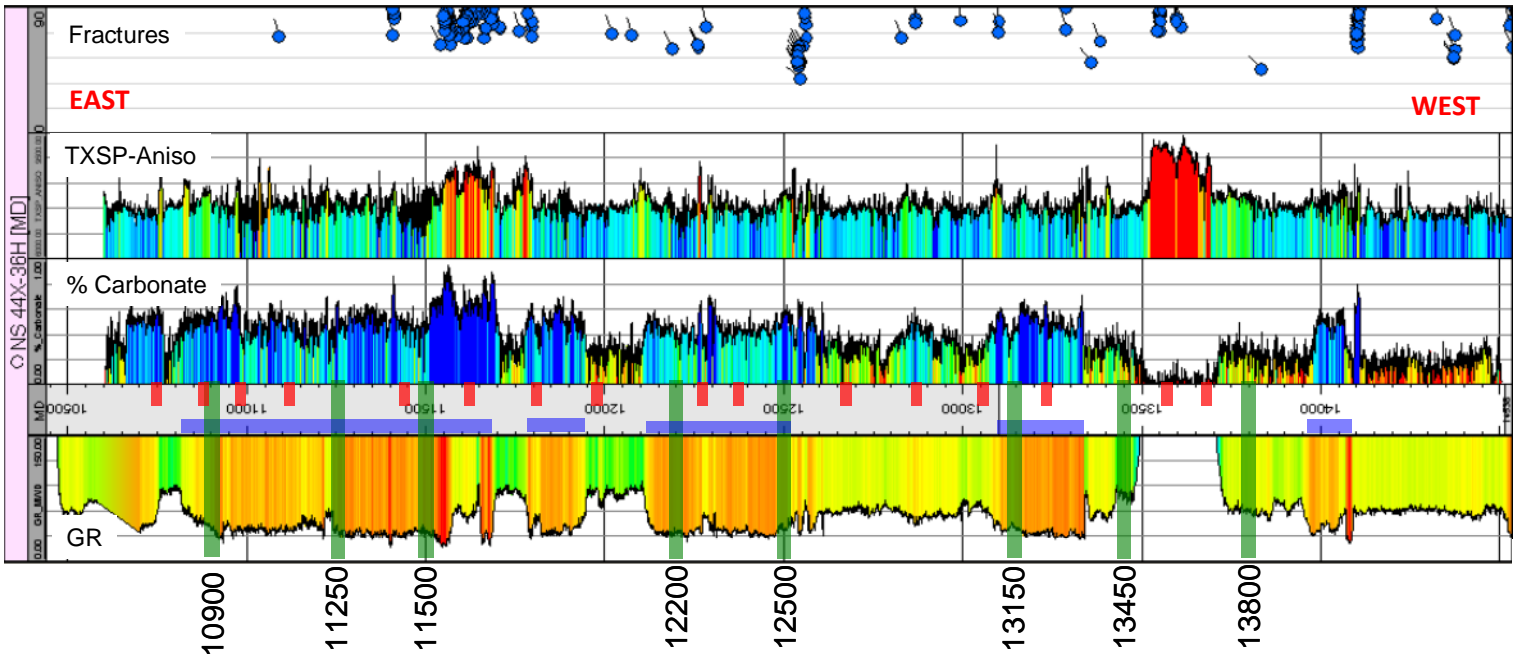


Figure 12. Nesson State 44X-36 Combined horizontal logging data



#### Section 4. Reservoir Parameters

In an effort to characterize the reservoir in the Consortium wells, two ninety foot cores were taken by Reed Hycalog Coring Service covering the interval of 10,284 feet to 10,466 feet (from the base of the Lodgepole formation into the Upper Three Forks formation) in the Nesson 42x-36 well; 182' of core were recovered. An attempt was made to orient these cores while drilling, but this was only partially successful. The core was analyzed by TerraTek in Salt Lake City. A Spectral Gamma Ray, TerraTek's Tight Rock Analyses, and detailed rock mechanics tests were conducted on the core. Several thin sections were made, and SEM, and X-ray Diffraction analyses were done.

Porosity ranges for the various formations and members cored were as follows: Lodgepole (1.3-1.8 %), Upper Bakken Shale (3.8-5.9 %), Bakken Middle member (1.5-8.2 %), Lower Bakken Shale (1-7.1 %), and Three Forks (4.4-7.6 %). Permeabilities for the same intervals range as shown: Lodgepole (.00006-.00008 md), Upper Bakken Shale (.00008-.00018 md), Bakken Middle member (.00017-.00373 md), Lower Bakken Shale (.00008-.00026 md), and Three Forks (.00005-.00012 md).

Natural fractures are thought to be a primary source of both porosity and permeability within the Bakken and the FMI and other logs run in the Nesson State wells confirmed the presence of fractures in this area. These natural fractures appeared to be enhanced in specific lithofacies and by structural bending, but were limited in quantity and were of very small aperture.

Shows encountered while drilling the Middle Member of the Bakken were relatively poor in all three wells and probably reflect tight reservoir. Production to-date also seems to confirm this.

Figure 13 is the component gamma ray log of the core study. Figure 14 is a description from the Nesson State 42X-36 core. Figure 15 is a representation of permeability as calculated in core studies. Figure 16 represents measured core porosity.

Detailed analyses, descriptions, correlations between core and logs (by Schlumberger), and core photos are included in this report and/or in the appendices. The core is currently located in the North Dakota Core Repository in Grand Forks, ND, and logs and geologic reports are on file with the State of North Dakota.

**TerraTek**  
 A Schlumberger company  
 Pioneer Business Park  
 1936 S. Fremont Dr.  
 Salt Lake City, UT 84104  
 (801) 584-2400

0.0	<b>Total Counts</b>	1,500.0
	GR CPM	

## Component Core Gamma Log

Headington Oil, LP  
 Nesson State 42X-36

**Bakken**  
 February 19, 2008

TerraTek No: 810439

0.0	<b>Potassium</b>	3.0	0.0	<b>Uranium</b>	24.0	0.0	<b>Thorium</b>	56.0
	%			ppm			ppm	

Depth

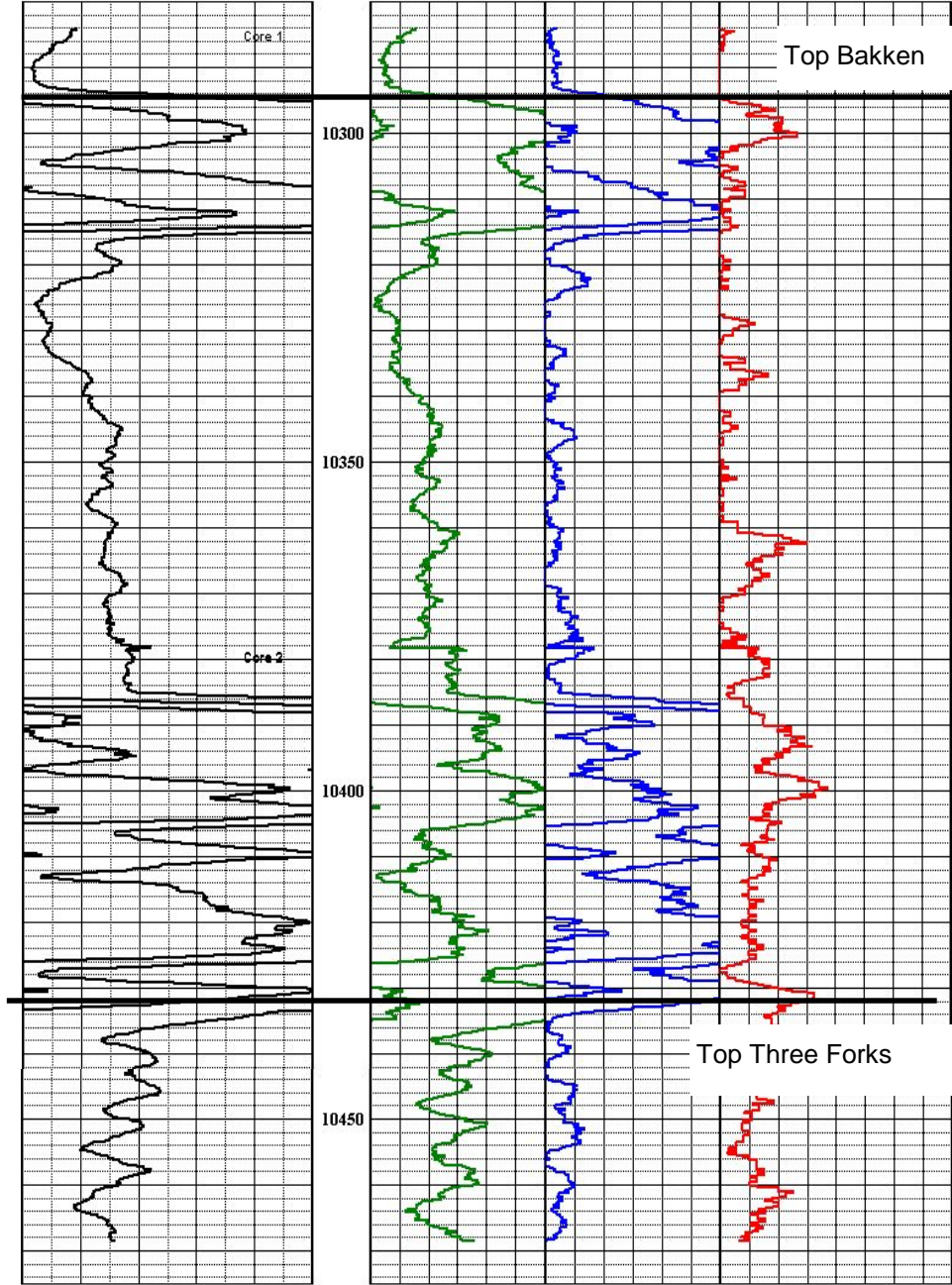


Figure 13. Nesson State 42X-36 Core Component Gamma Log

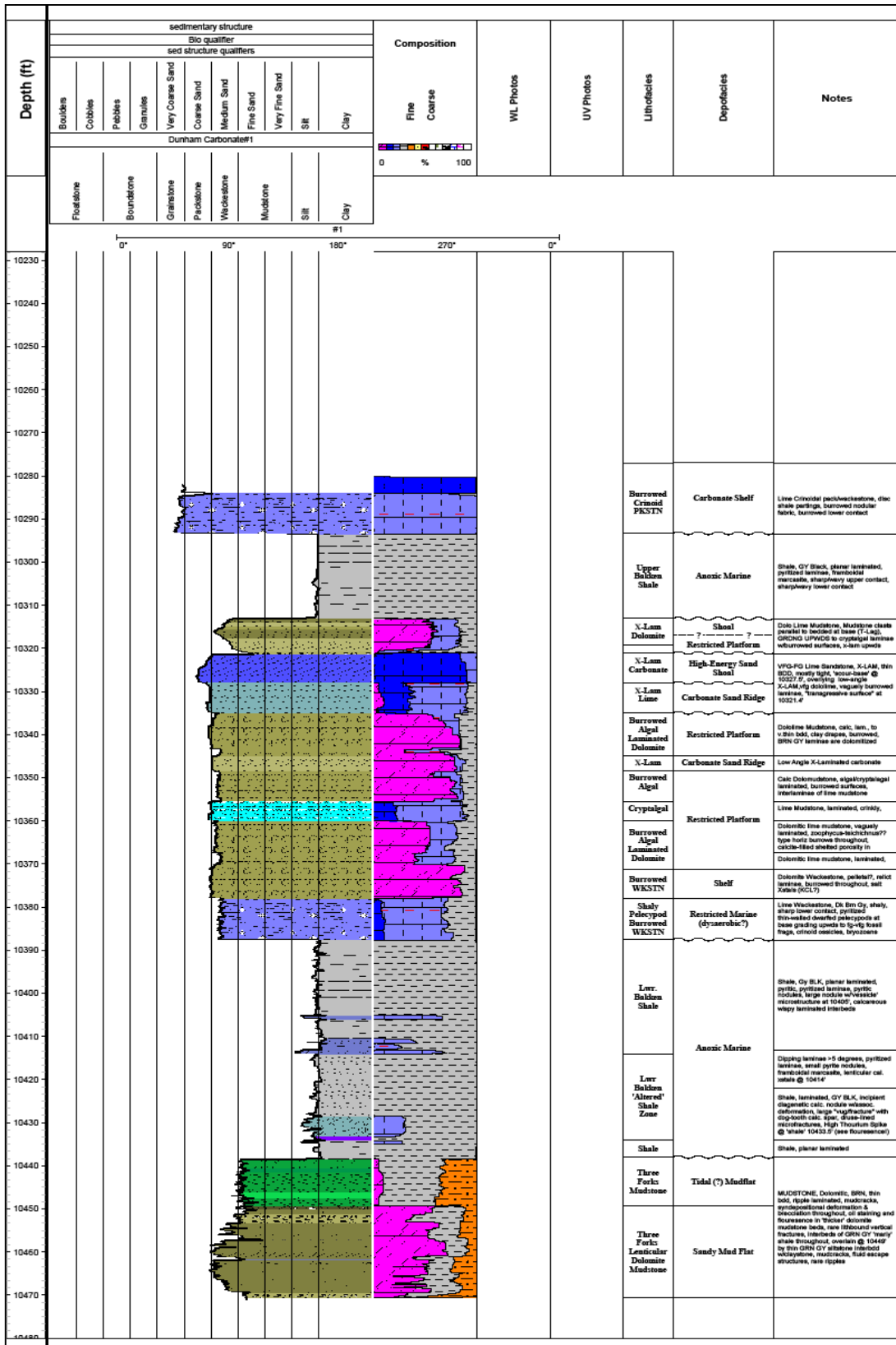


Figure 14. Nesson State 42X-36 Core Description

Permeability

K, md

0.0000000  
 0.0005000  
 0.0010000  
 0.0015000  
 0.0020000  
 0.0025000  
 0.0030000  
 0.0035000  
 0.0040000

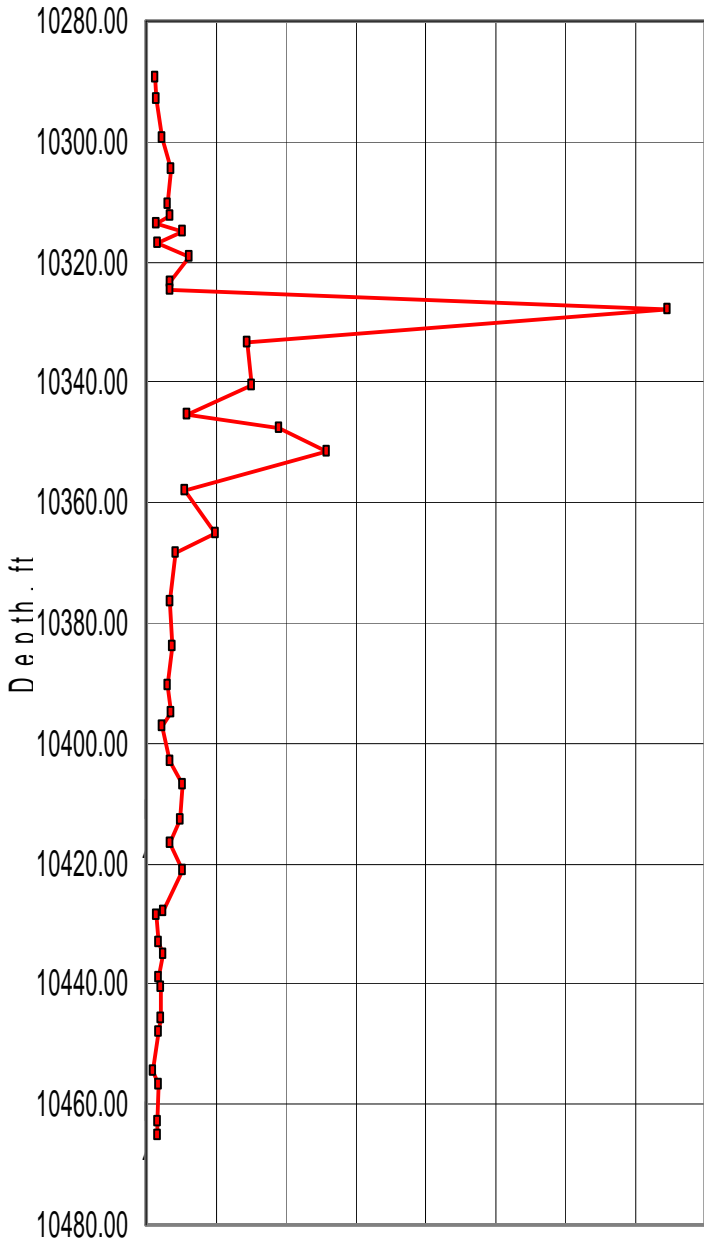


Figure 15. Nesson State 42X-36 Core Permeability Log

Porosity, %

0.00 2.00 4.00 6.00 8.00 10.00

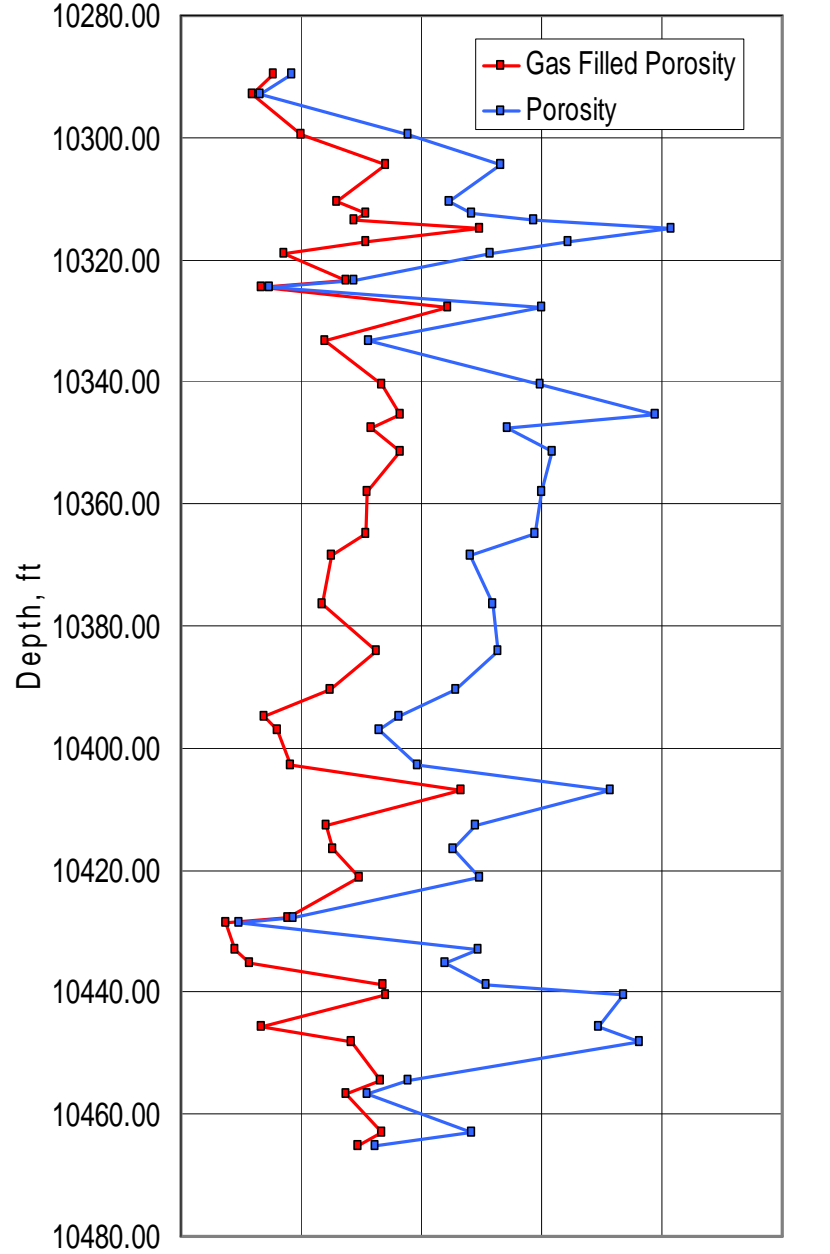


Figure 16. Nesson State 42X-36 Core Porosity Log

## Section 5. Fracture Stimulation Results

(Note: Appendix 24 is Schlumberger's review of the fracture stimulation of both wells.)

### 5.1 Nesson State 41X-36 Fracture Stimulation Treatment

The Nesson State 41X-36 was completed with an pre-perforated 5" liner. This allowed the well to be produced before fracture stimulation. The well was placed on rod pump for 55 days before stimulation, yielding 70 bbls of oil and 542 bbls water, all associated gas was flared. Before stimulation, two perforation shots were fired in the horizontal section (13,987'-77' and 12,240'-50'). These shots were designed to allow calibration of the microseismic monitoring equipment. The well was fracture stimulated in one stage on 5/19/08 with 376,680 lbs of sand and 7,848 bbls of fluid. Average treating pressure was 4,622 psi, average pump rate was 66.2 bbl/min. The stimulation was traced with granular radioactive tracers and non-reactive chemical tracers dissolved in the frac fluid. The post completion wellbore construction is summarized in Figure 4 above. The pump schedule for the fracture stimulation is summarized below in Figure 17. Appendix 10 contains the radioactive and chemical tracer data. The full fracture stimulation report for the Nesson State 41X-36 is included in Appendix 11.

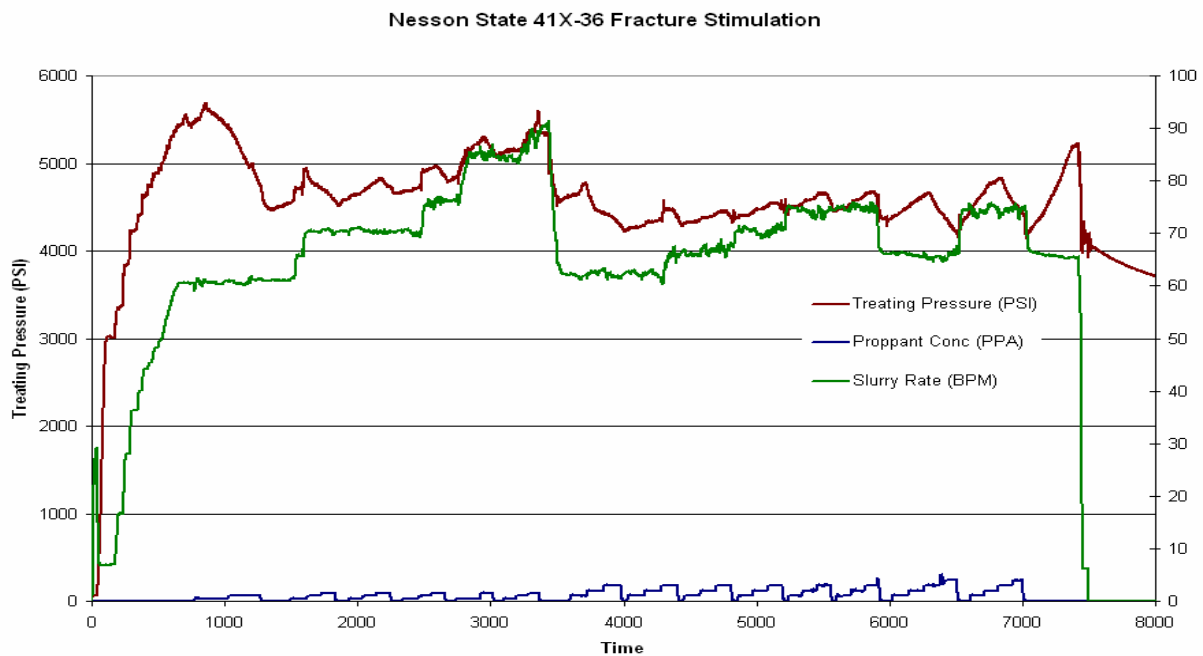


Figure 17. Nesson State 41X-36 Fracture Stimulation Pump Plot

## 5.2 Nesson State 44X-36 Fracture Stimulation Treatment

The Nesson State 44X-36 was completed with 4.5" liner. External casing packers were placed for annular isolation. The well was fracture stimulated in six stages beginning on 5/19/08 with a total of 300,157 lbs of sand, 8,161 bbls of fluid, average treating pressure was 5,708 psi and average rate was 32.5 bpm. The stimulation was traced with granular radioactive tracers and non-reactive chemical tracers dissolved in the frac fluid. The post completion wellbore construction is summarized in Figure 10 above. The pump schedule for the fracture stimulation is summarized below in Figure 18. Appendix 12 contains the radioactive and chemical tracer data. Appendices 13a – 13f contain the complete fracture stimulation report.

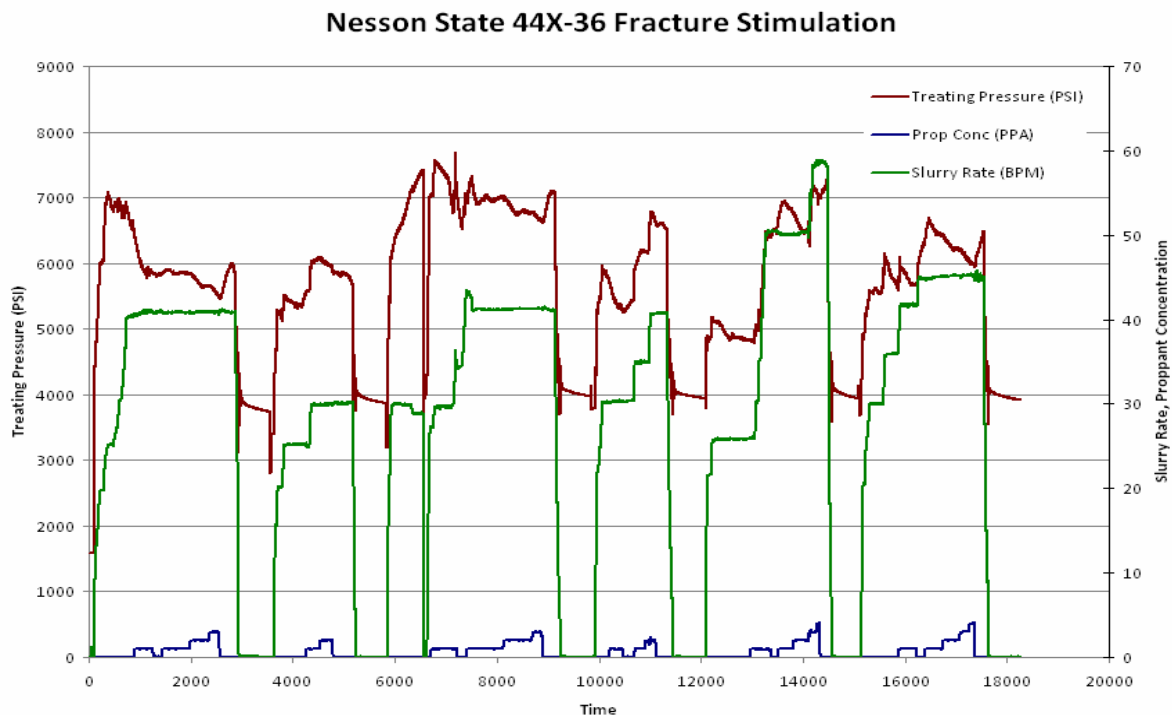


Figure 18. Nesson State 44X-36 Fracture Stimulation Pump Plot

## Section 6. Production Results

Combined, the Consortium producing wells (Nesson State 41X-36 and Nesson State 44X-36) have made 13,964 barrels of oil as of November 24, 2008. The Nesson State 41X-36 has produced 7,186 bbls while the Nesson State 44X-36 has made 6,777 bbls. To date, all gas has been flared as a gas flowline is currently being installed. Current estimates indicate the Nesson State 41X-36 has a gas to oil ratio (GOR) of 1.5 MCF/BO and the Nesson State 44X-36 has a GOR of 1.66 MCF/BO. The Nesson State 41X-36 has produced 5,599 bbls of water to date. Of this total, it is estimated 4,495 bbls was load water. This represents 57% of frac load pumped. The Nesson State 44X-36 has produced 5,553 bbls of water to date. It is estimated that of the water produced to date 2,425 was load water, this is a 30% load water recovery. Figure 19 below is a graph of the daily production data for the Nesson State 41X-36. Figure 20 represents the production data for the Nesson State 44X-36. Figure 21 is the combined oil production for the two wells.

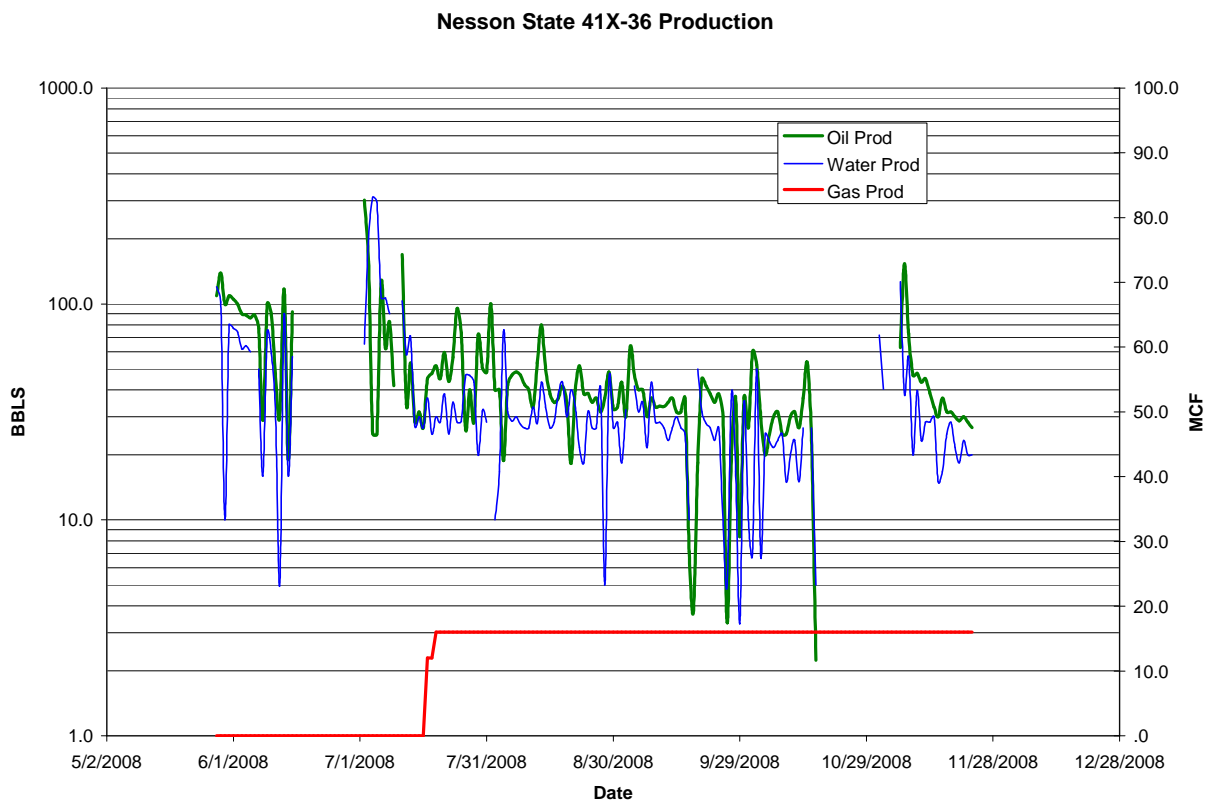


Figure 19. Nesson State 41X-36 Production Plot

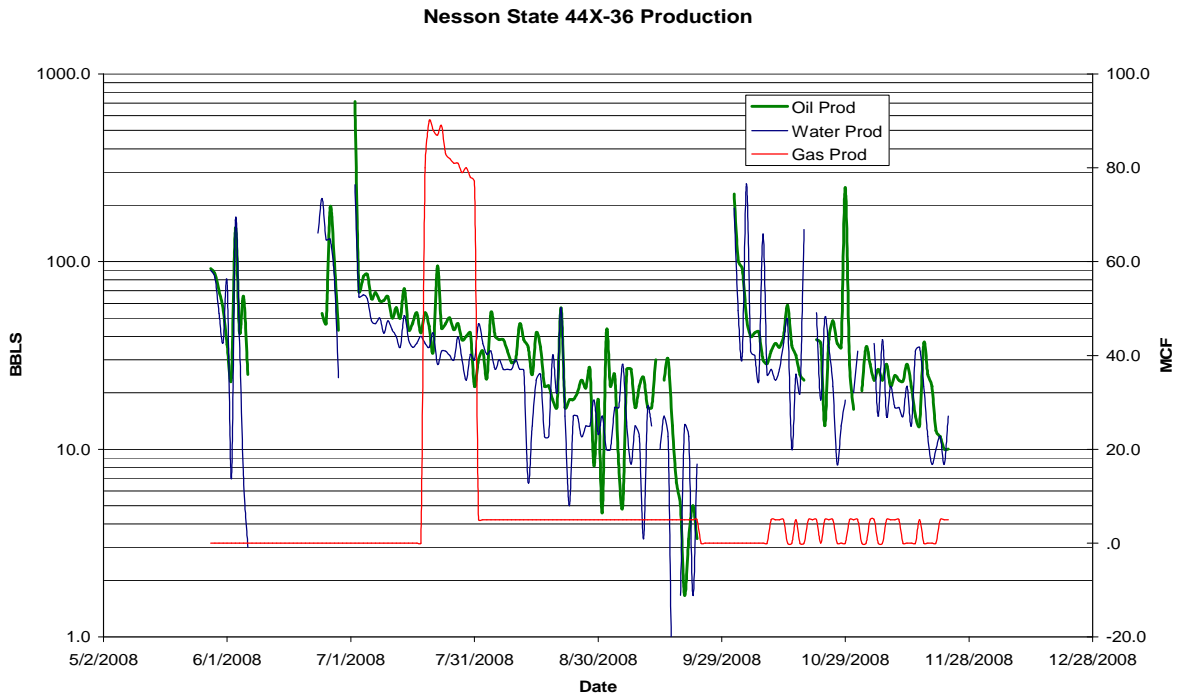


Figure 20. Nesson State 44X-36 Production Plot

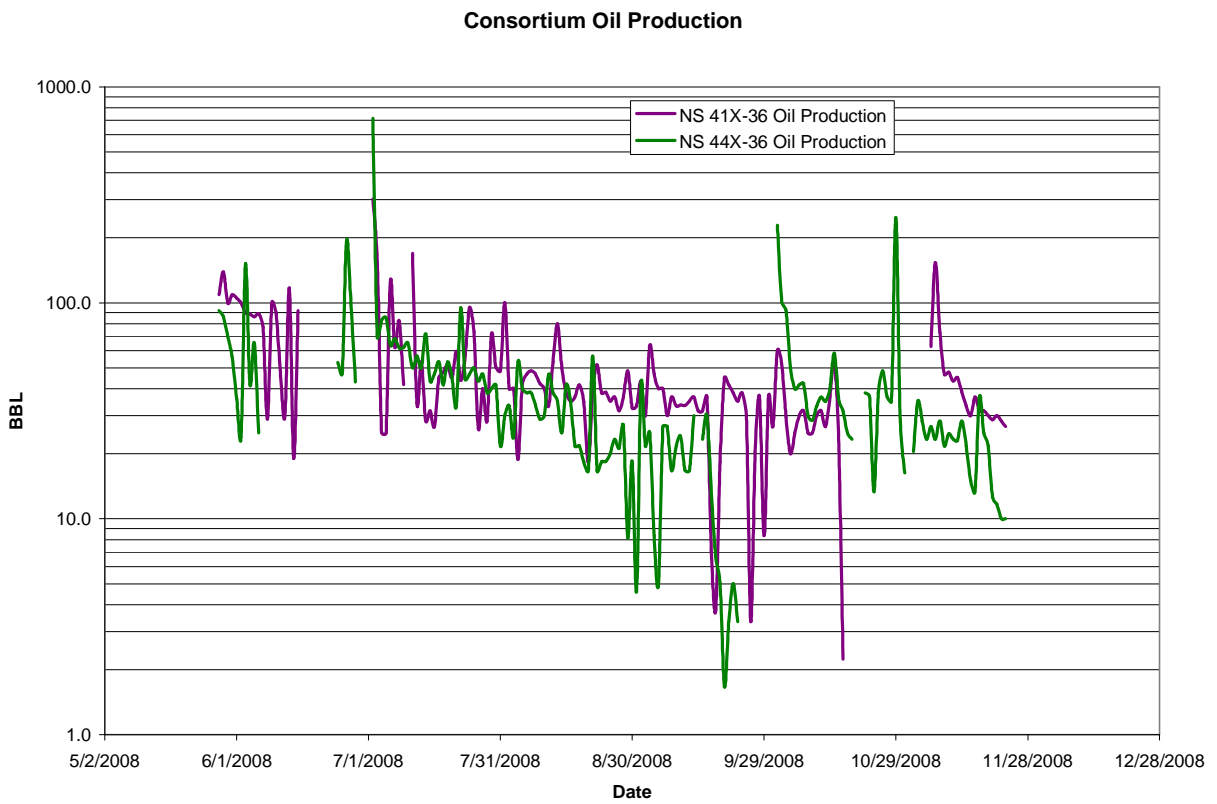


Figure 21. Combined Oil Production Plot



## Section 7. Consortium 3D Seismic Program

Headington Oil Company LLC/XTO Energy acquired 3D seismic data over a 9 section area surrounding section 36 T156N R95W. The parameters used for this survey are listed below and the location map is shown in Figure 22. These data were provided to Consortium members for their internal use in analyzing and correlating with other data acquired through the Consortium project area.

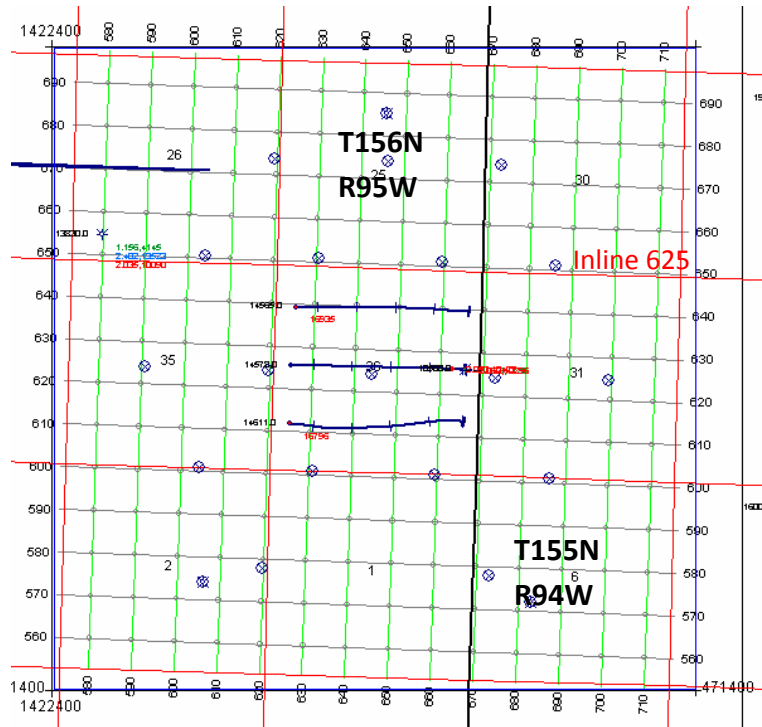


Figure 22. Consortium 3D Base Map Showing Line 625

### 3D Data Acquisition Parameters

Project Size(s): 126.80 square miles  
 Receiver Spacing: 220 ft.  
 Receiver Line Spacing: 1,100 ft.  
 Total Receivers: 14,649  
 Receiver Density per Square Mile:  
 115.5  
 Source Spacing: 220 ft.  
 Source Line Spacing: 1,760 ft.  
 Total Source Points: 9.268  
 Source Density per Square Mile:  
 73.1  
 Energy Source(s): Dynamite /  
 Vibroseis  
*Dynamite Details*

Drill Hole Depth: 60 ft  
 Explosives: 10 pounds gel  
 Number of Detonators: 1  
*Vibroseis Details*  
 Number of Sweeps: 8  
 Sweep Length: 12 seconds  
 Record Time: 5 seconds  
 Sample Rate: 2 ms  
 Recording Patch Size: 20 x 96 =  
 1,920  
 Roll On/Off: Y  
 Geophones: 10 Hz. (6 Geophones  
 per group)

The 3D seismic data resulting from this program show the Consortium area to be on the east flank of the Nesson Anticline and gently dipping to the east at approximately 1 ½ degrees as shown in the Bakken Time Structure map (Figure 23). There appears to be no significant structure associated with this area other than some minor faults and low relief structural noses that affect the Bakken, primarily outside of the Consortium section.

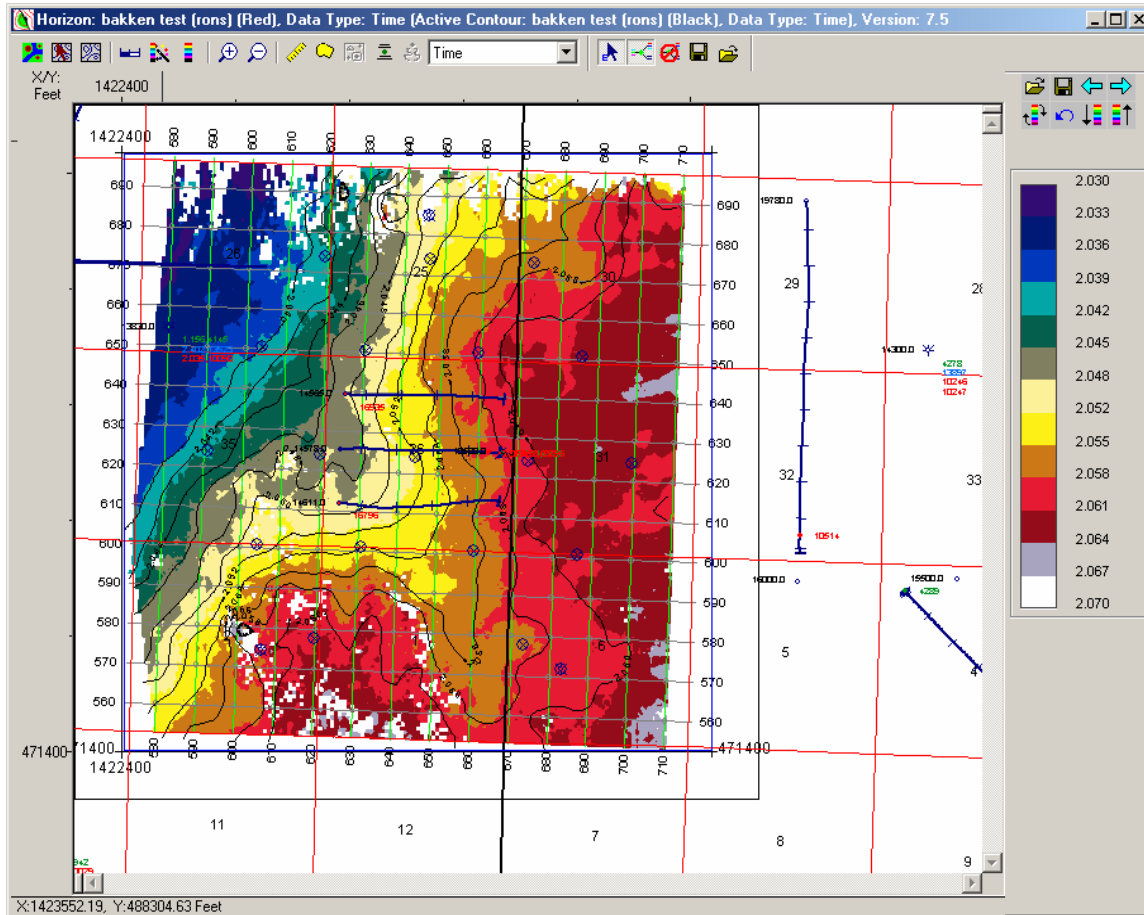


Figure 23. Bakken Time Structure Map

The data does show a minor NW-SE trending structural nose coming off the east side of the Nesson Anticline through the Consortium Section. This nose may be the result of salt velocity anomaly in the overlying Dunham salt section as there is a good aerial correlation of the nose with that of the Dunham thickness, or may possibly be due to salt dissolution thickening associated with the Prairie Salt. There is an excellent well tie here with the Nesson State 42X-36 vertical pilot hole through the Three Forks section. This tie is shown on Figure 24 which depicts inline 625 with the synthetic overlain for detail.

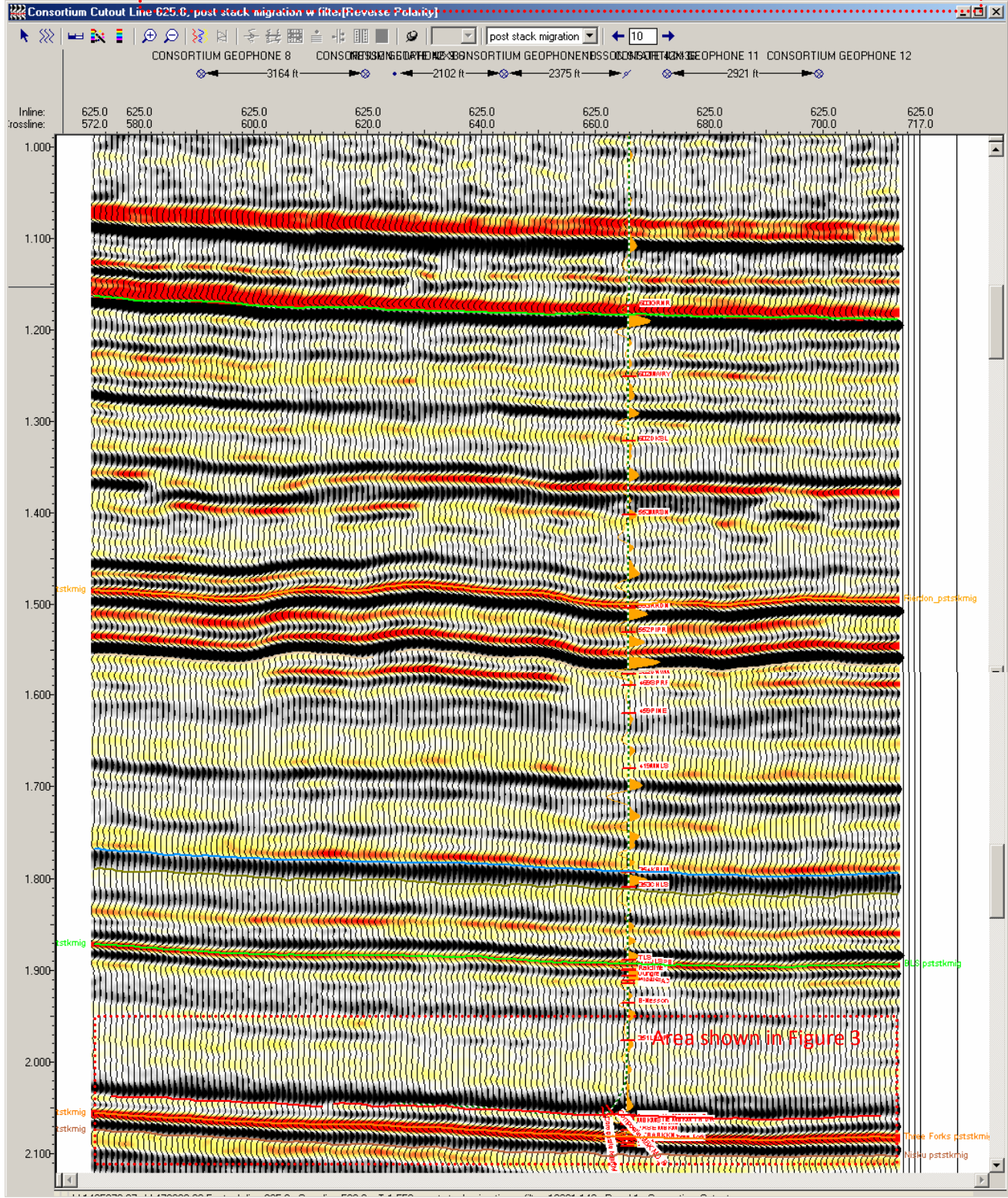


Figure 24. Well Seismic Tie Nesson State 42X-36



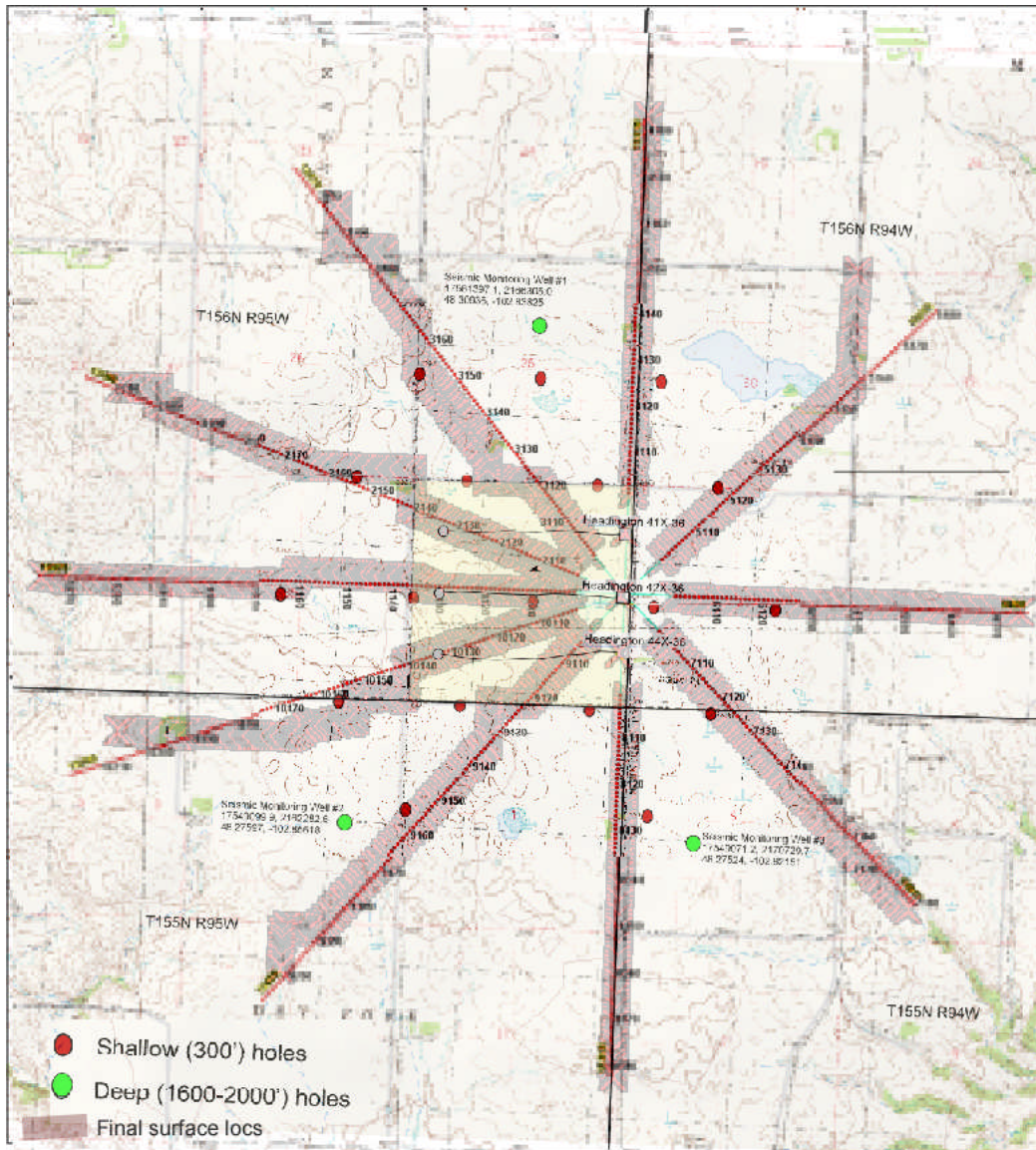


Figure 26. Final Deployment of Microseismic Arrays

### 8.1 Downhole Array (Schlumberger)

Schlumberger performed microseismic monitoring (*StimMAP*)\* on the two (2) treated wells in the Bakken Research Consortium Project. The wells are the:

- Nesson State 41X-36 (BHL NENE Sec 36 T156N R95W) treated on May 19, 2008
- Nesson State 44X-36 (BHL NESE Sec 36 T156N R95W) treated on May 19 – 21, 2008

During the data analysis, the arrival time of the P-wave and S-wave of the seismograms for each tri-axial level was determined and a hodogram analysis of the spatially oriented tri-axial geophone packages was also obtained. Many events were detected during the treatment of both wells. Most of these events appeared to be background noise. Only a small percentage of the detected events were considered to be related to the hydraulic fracturing. Events were deemed valid only if they provided a clear P-wave and S-wave arrival, from which an accurate arrival time could be measured for the calculation of an event location. A velocity model was

\* mark of Schlumberger

constructed from processing the *SonicScanner*\* anisotropy log that was recorded in the vertical pilot section of the monitoring well. The velocity model, coupled with careful P-wave and S-wave arrival times, allowed for the most accurate locations of the microseismic events generated by the propagation of the hydraulic fracturing.

In addition to using the *SonicScanner* data for developing a velocity model, Schlumberger deployed a unique down-hole tool that is capable of recording the time of a perforation ignition at an accuracy of microseconds. The precise timing of multiple perforation ignitions was used to calculate the well-to-well velocities for the P-wave and S-wave arrivals generated by the perforation ignitions. Additionally, Schlumberger deployed a new uphole recorder that detects the ignition of a perforation from the perforation control hardware at ground surface. This new uphole recorder was compared to the down-hole tool. The outcome is that the new uphole recorder displays no measurable time delays within an accuracy of a half millisecond. This unique precision allowed for a direct and very accurate measurement of well-to-well velocities.

### 8.1.1 Nesson State 41X-36

The monitoring well, Nesson State 42X-36 (BHL SESE Sec 36 T156N R95W), is located 1499 ft to the south and 55 ft to the west of the Nesson State 41X-36. During the treatment, an array of 15 triaxial geophones, with 100 feet between each sensor set, monitored the microseismic activity. This linear array of triaxial geophones was positioned in the horizontal leg of the monitoring well, within the Middle Bakken.

The Nesson State 41X-36 hydraulic fracture program was designed by Schlumberger and consisted of a single treatment of SlickWater frac fluid and 40/70 Jordan proppant. The treatment proceeded according to design with all of the proppant and fluid being pumped away. A total of 1660 events were recorded. Of these forty (40) microseismic events were considered to be valid and were successfully located during the treatment.

### 8.1.2 Nesson State 44X-36

The monitor well, Nesson State 42X-36, is located 1304 feet to the north and 49 feet to the east of the Nesson State 44X-36. The same geophone array was used as for the Nesson State 41X-36.

The Nesson State 44X-36 hydraulic fracture programs was designed by Schlumberger and consisted of six (6) separate SlickWater based. treatments that are outlined in the table below: The treatment proceeded according to design with all of the proppant and fluid being pumped away.

<b>Description</b>	<b>Stage 1</b>	<b>Stage 2</b>	<b>Stage 3</b>	<b>Stage 4</b>	<b>Stage 5</b>	<b>Stage 6</b>
Average Injection Rate (bbl/min)	25.9	25.6	34.6	30.1	39.9	38.8
Average Surface Pressure (psi)	4,899	5,531	6,754	5,699	5,888	5,908
Fluid Volume (gal)	140,710	58,031	157,635	66,040	130,883	129,706
Proppant Volume (lb)	60,196	15,067	75,011	20,122	64,872	64,998
Max BH Proppant Con (ppa)	3.1	2.1	3.1	2.4	4.1	4.1

Number of microseismic events	6	5	25	9	13	5
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A total of 2150 events were recorded. Of these sixty three (63) microseismic events were considered to be valid and were successfully located during the treatment.

### 8.1.3 Conclusions:

The main conclusions from the microseismic monitoring of these two wells are:

- There are indications of both longitudinal and transverse fracture initiation.
- Fracture extension is in the NE-SW orientation.
- Fractures growth is biased more in the NE direction.
- High rate SlickWater yield more multiple fractures than X-linked fluid systems.
- Fairly strong correlation between perforation placement and stress in fracture initiation.
- Much less height growth with SlickWater in both wells.
- Swell packers communicated when longitudinal fracture initiation was present. This seemed to happen in several stages on the Nesson State 44X-36 well according to the radioactive (RA) tag analysis.
- Three (3) factors effect fracture initiation.
  - Horizontal stress
  - Perforation location and orientation
  - Natural fractures
- Horizontal wellbores at a low angle to maximum stress require longer stage spacing.
- Transverse fractures require higher near wellbore conductivity and are more prone to near wellbore problems.
- Wellbores normal to maximum stress more prone to transverse fracturing
  - Perforation orientation can influence fracture initiation orientation
- SlickWater enables multiple fracture initiation and is contained in the Middle Bakken, at least in this area.
- Viscosified (X-linked) fluids inhibit multiple fracture propagation and are more likely to grow out of the Bakken.
- Current conductivity fractures are sub-optimal.
- Stress profiles are key to designing completions that drain both the Middle Bakken and Three Forks.
- Fracture communication with the Three Forks in this area is still uncertain.

Schlumberger's final analysis of the results of the microseismic monitoring as well as the integration of those results with available rock and fracture stimulation data can be found in appendices 16 through 20.

### 8.2 Buried Arrays (Terrascience, Weir Jones Inc, DOE NETL and LBL)

In May 2008 under the sponsorship of the North Dakota Oil and Gas Research Council a Consortium of operators led by Headington Oil Co LLC, now XTO Energy Inc., initiated an induced microseismicity data monitoring program in the Bakken formation. The work was carried out at a site in north western North Dakota, approximately 30 miles east of the town of Williston. The objective of the investigation was to determine (a) if a significant number of acoustic events were induced in the reservoir formation during hydraulic fracturing operations, and (b) if these events could be detected by highly sensitive near-surface geophone arrays with

sufficient reliability to locate the events within the fractured reservoir. A total of ninety geophones were deployed in the near surface arrays by Terrascience Systems Ltd.

The results from these near surface geophone arrays located in boreholes at depths between 250 ft and 1,500 ft, together with data from an array deployed in a lateral hole located at the reservoir horizon, were recorded continuously during the perforation and fracturing operations. The near surface arrays continued to be monitored for a further two months. The data were subsequently analyzed by Weir-Jones Engineering Consultants Ltd., the Department of Geophysics of University of BC, Lawrence Berkeley Laboratories, WesternGeco, and Schlumberger. The results and conclusions were as follows:

1. There is no doubt that the near surface geophone stations, both DOE and SW (Terrascience), were working as designed and producing very high resolution data. All these stations recorded the Schlumberger Vibroseis data very clearly. As anticipated the peak particle velocities at the deepest and most distant DOE stations were the lowest, while the peak velocity at the SW station closest to the Vibroseis truck were almost 200 times higher.
2. Hydraulic injection in the formation results in the release of very little elastic / acoustic energy.
3. Injection may cause the delamination of existing bedding planes within the formation and the horizontal migration of injection fluids.
4. Delamination does not appear to be associated with extensive brittle failure and the attendant energy release.
5. The energy arrivals which were detected by the near-surface arrays during the calibration and perforation shots, the injection, and the subsequent production were ambiguous. Despite excellent coupling and a comparatively quiet environment at the DOE and Terrascience subsurface array locations, we are unwilling to categorize any of the hundreds of acoustic “events” we detected during calibration, frac’ing and production, as being unambiguously microseismic in origin. This was because either:
  - a. These “events” were not synchronised with  $t_0$  of the calibration/string shots. Furthermore, events were accepted if, and only if, they were detected in Schlumberger array. MSI did not use such a criterion;
  - b. These “events” were uncorrelated across the DOE and Terrascience arrays;
6. The data collected from the multi-sensor array deployed in the lateral indicates that there is strong acoustic attenuation in and around the reservoir.
7. The absence of perforation shot multiples in the data collected by the Schlumberger lateral array indicates high energy attenuation in and around the reservoir.
8. There are indications of high attenuation in the upper 2000 ft of the stratigraphic column.

Final reports from both the Department of Energy and Wier Jones can be found in appendices 22 and 23.



### 8.3 Surface Array (MicroSeismic, Inc.)

Using Passive Seismic Emission Tomography (PSET<sup>®</sup>) technology, MicroSeismic, Inc. (MSI) performed surface monitoring of microseismicity during the hydraulic fracture stimulation treatment (frac) conducted during May 19-20, 2008, in the Nesson State 41X-36 and 44X-36 wells. MSI utilized a surface seismometer array designed to minimize noise and optimize signal from microseismic events induced by the frac. A velocity model was constructed using interval velocities provided. Processing parameters were selected and seismic processing was utilized to reduce noise and enhance signal. PSET<sup>®</sup> result analysis was conducted utilizing a set of spatial and temporal filtering tools developed specifically to eliminate noise events and enhance the microseismicity associated with the fracture stimulation treatment. An interpretation was then made of fracture geometry.

Surface passive seismic monitoring of the hydraulic fracture stimulation treatment in the Nesson State 41X-36 and 44X-36 wells was successful in providing information about the complexities of the geology and stress fields within the rock surrounding the well. PSET<sup>®</sup> imaging of the string shot and calibration shot has demonstrated that small amplitude events from known locations can be accurately located to depths up to 10,300 feet in this area of North Dakota. Observations made of microseismic activity during fracture stimulation treatment are as follow:

- Primary azimuth of microseismic zones is 60 degrees with secondary microseismic zones having an azimuth of 130 degrees.
- Zone half-lengths in general are approximately 750 feet for perforated zones and approximately 1000 feet for the “open hole” completion.
- It appears fracture development during the open hole completion generates fewer and lower amplitude microseismicity.
- Complexity of microseismic zones most likely represents the complexity of the fracture network.
- Both the “open hole” completion and the perforated zones treat the entire length of the horizontal.
- Microseismicity observed during treatment of the perforated zones tends to be skewed to the north of the well possibly influenced by the treatment of the 41X-36 which was run between stages 1 and 2 of the 44X-36.
- The count of microseismic events detected and used for interpretation are as follow:
  - 41X-36 – 271 Events
  - 44X-36 Stage 1 – 115 Events
  - 44X-36 Stage 2 – 85 Events
  - 44X-36 Stage 3 – 160 Events
  - 44X-36 Stage 4 – 77 Events
  - 44X-36 Stage 5 – 126 Events
  - 44X-36 Stage 6 – 119 Events

Microseismic Incorporated’s final report can be found in appendix 23.

## Section 9. Impact on Operations & Future Plans

### 9.1 Impact on Operations.

All participants in the Consortium have had the opportunity to review the data gathered and draw their own conclusions. While the impact on each operator's program will be unique, XTO has identified several conclusions which will affect our program.

- Due to data gathered through the Consortium project XTO has proposed a multi-well program of coring and pilot holes to study frac barriers and reservoir dynamics.
- There appears to be a correlation between perforations and fracture initiation. XTO is investigating the opportunity to perforate previously completed wells before refracs to better distribute stimulation treatments.
- Given the apparent correlation between perforation and fracture initiation, XTO believes the "plug and perf" method of staged completions is a more effective means of stimulating the wellbore.
- The magnitude of maximum stress is close enough to that of minimum stress that XTO believes in most cases wellbore orientation has little impact on induced fracture orientation.
- The microseismic data from each of the four data sets appears to be in conflict to a significant degree.
- Due to the apparent disagreement in the microseismic data as well as the cost and operational complexities associated with microseismic investigation, it is unlikely XTO will pursue further microseismic investigations independent of the Consortium.
- The signal to noise ratio in the Bakken is low enough that if future microseismic operations occur, care will need to be taken to maximize signal strength.
- Based on data gathered during logging of the three wells and supported by microseismic data, XTO believes that most induced fractures will grow at some angle oblique to the wellbore. Given this assumption, XTO believes wells completed using staged completions (i.e. external casing packers) will be as productive with fewer zones (5 to 6) as with more zones (15 to 20). XTO recognizes not all participants in the Consortium agree with this conclusion.
- While XTO recognizes the need to maximize the amount of wellbore in the target zone, XTO does not believe the data gathered by advanced LWD/geo-steering techniques offsets the cost or operational problems associated with the technology.
- Based on frac modeling done on gathered data, it is likely fracs are growing into the Three Forks but may not be effectively propped open.

## 9.2 Future Plans

On October 9<sup>th</sup> 2008 all participants in the Bakken Consortium met in Denver, Colorado to discuss results and future plans. While no plans were definitively set the following ideas were discussed:

- Refracs
- Drilling a Three Forks test on the Consortium Section
- Re-deploying microseismic monitoring during fracture stimulation of a possible Three Forks test and/or refracs
- Simultaneously refrac'ing each existing producer to understand the impact of Barnett style "simulfracs".

No plans were finalized at this meeting. However, there was agreement among the Consortium members to reconvene in early 2009 to consider future plans.