ENHANCED OIL RECOVERY
BY
HORIZONTAL WATERFLOODING

Final Report

September 6, 2002 – September 30, 2005

By

Scott Robinowitz
Dwight Dauben
June Schmeling

May 2006

Work Performed Under Contract No. DE-FG26-02NT15452

Grand Resources Inc.
2448 East 81st Street, Suite 4040
Tulsa, OK 74137

DISCLAIMER

ABSTRACT

This report summarizes the final results of a project conducted by Grand Resources, Inc. entitled “Enhanced Oil Recovery by Horizontal Waterflooding”. This work was conducted over a three-year period beginning in September 2002.

The objective of the project was to conduct a field test of a horizontal waterflooding process for the recovery of additional oil from a low permeability shallow Bartlesville sandstone reservoir in northeast Oklahoma. Recovery from conventional primary and secondary recovery operations has been low, leaving a considerable resource available for an improved oil recovery process.

The horizontal waterflooding process as originally envisioned consists of a central horizontal injection well and two adjacent and parallel horizontal producing wells. The basic concept is that a large amount of water can be injected into the horizontal injector at pressures that are below the fracture-parting pressure. The oil will then be recovered in the horizontal producing wells.

The original plan to implement the project in the Woolaroc Field, Osage County, Oklahoma was terminated due to a lower-than-expected permeability of the rock matrix as determined from core analyses. The project was thereafter moved to the nearby Wolco Field with the concurrence of the DOE.

A three-horizontal well project was implemented in the Wolco Field, with operations commencing on December 30, 2003. Oil production from the pilot was disappointing. The major contributing factors were lower-than-expected oil saturation and channeling between the horizontal injection well and one of the horizontal producing wells.

The Wolco pilot was modified in 2004 by drilling the laterals into the opposite direction and utilizing the injection from an existing vertical disposal well. These modifications in effect moved the project into a portion of the field where an underlying high permeability zone exists. It appears that the injected water is moving principally through the high permeability lower zone and pushing oil upward into the horizontal laterals. Oil production has stabilized at approximately 15 BOPD. An estimated 6,000 stock tank barrels (stb) has been recovered from the project to-date. This response has been considered a technical and economic success.

The horizontal well technology has been successfully expanded into adjacent acreage in the Avant Field. The combined production from the Wolco and Avant projects is currently approximated at 50 BOPD.

Grand has conducted an ambitious technology transfer program to the oil industry. The industry response has been outstanding. The seed money provided by the DOE is expected to pay large dividends as the technology is accepted and applied to other areas within the United States.

TABLE OF CONTENTS

FIGURES AND TABLES

FIGURES

TABLES

ACKNOWLEDGEMENT

The field-testing of horizontal waterflooding described in this report has been supported by the U.S. Department of Energy, National Energy Technology Laboratory under contract DE-FG26-02NT15452.

Appreciation is extended to the DOE for its support of this project. The seed money provided by the DOE has allowed Grand to assume the risk needed to mobilize the required equipment, personnel, and funds to evaluate and improve horizontal well technology for use in waterflooding. Without such funding, it would not have been practical for Grand to develop the technology to the same degree that it has. The field demonstration has been successful. As a result, it is expected that the technology will be applied in similar reservoir settings to improve oil recovery throughout the United States.

Special appreciation is extended to Virginia Weyland who has served as the contracting officer for the DOE. She has provided effective guidance of the project and many helpful suggestions.

Credit is also extended to the management of Grand Resources, Inc., for being willing to take risks and to expend its own funds well beyond the original budget in order to accomplish the goals of the project. Particularly noteworthy is the willingness of management to proceed beyond the original Wolco pilot, even with results that appeared to be quite discouraging at the time.

INTRODUCTION

Grand Resources, Inc. (Grand) has been an independent oil producer for many years in northeast Oklahoma. The company has been successful in producing oil from the prolific Bartlesville sandstone formation utilizing conventional technology. However, recovery has been low, consistent with the experience of other operators in the area. Grand management has held a long-term view that horizontal well technology should be applicable in Bartlesville sandstone reservoirs. However, it was not clear initially how the technology could best be applied because of the complexities of the reservoir and the many difficulties encountered by operators in waterflooding the formation.

The Bartlesville sandstone formation has been described in various studies that have been conducted previously. Ye[1] reports that 1.5 billion barrels of oil have been produced from the Bartlesville sandstone through the 1960s. The Bartlesville remains an important producing horizon even though it is considered to be in a mature stage of depletion. Although the total oil recovery has been impressive, the actual oil recovery as a percent of the initial oil-in-place has been low. A major portion of the low oil recovery is attributed to the complexities of the reservoir. Ye[1] and the Oklahoma Geological Survey's FDD project report[2] indicate that the reservoir was deposited in a fluvial-dominated deltaic environment. These reservoirs tend to contain natural, pressure-sensitive fractures that can be correlated with surface lineaments[3]. The Bartlesville has low permeability, is extremely heterogeneous and produces from a solution gas drive mechanism, which is inherently an inefficient process for the recovery of oil during primary recovery operations.

Grand began its venture into horizontal waterflooding by bringing together a combination of personnel and the necessary equipment. Grand acquired the tools and the rights to use the rotary-steerable horizontal drilling equipment developed by Amoco Production Company. An experienced team consisting of a geologist, drilling engineer, and reservoir engineer were also assembled to provide the needed technical expertise. Finally, the DOE provided the needed seed money to begin the development of the technology for application in Bartlesville sandstone reservoirs.

The horizontal waterflood, as originally conceived, consists of one or more horizontal injection wells and adjacent, parallel horizontal producing wells. The concept of horizontal waterflooding was introduced by Taber[4] in 1992 as a method for improving the performance of conventional waterfloods. The rationale for this geometry is that water can theoretically be injected at much higher rates and lower pressures in horizontal wells than in vertical wells, allowing oil to be recovered quicker. This process is similar to one proposed earlier by Kelkar[5] for application in the Glen Pool Field. It is also consistent with the publications of Joshi [6,7] in the application of horizontal wells.

This final report discusses the results of the successful DOE sponsored program for the use of horizontal wells to improve oil recovery.

EXECUTIVE SUMMARY

This final report summarizes the results and conclusions of a project conducted by Grand Resources, Inc. (Grand) entitled “Enhanced Oil Recovery by Horizontal Waterflooding”. This work was conducted with the support of the U. S. Department of Energy under Contract No. DE-FG26-02NT15452.

The objective of the project was to evaluate horizontal waterflooding for the recovery of oil from a low permeability, shallow Bartlesville sandstone reservoir in northeast Oklahoma. Primary oil recovery from this reservoir has been low due to the low reservoir pressure, a low permeability matrix, and an inefficient solution gas drive mechanism. Conventional waterflooding has yielded only modest recovery because of the inability to inject water at sufficiently high rates below the fracture-parting pressure. Operating above the fracture-parting pressure often leads to the rapid breakthrough of water and poor recovery. Oil recovery from combined primary and secondary recovery is often in the range of 15% OOIP or less. This leaves a huge resource of oil available for an improved oil recovery process.

The horizontal waterflooding process as originally envisioned for this project consists of a horizontal injection well and two adjacent, parallel horizontal producing wells. The basic concept is that a large volume of water can be injected below the fracture-parting pressure. The horizontal producing wells can then produce the mobilized oil. This process thereby has the potential for accelerating and increasing the total recovery from the field.

A three horizontal well waterflood project was designed for application in the Woolaroc Field, located in Osage County, Oklahoma. It was determined that this site was not suitable after collecting and analyzing cores from a newly drilled well in the area. Low matrix permeability was the major factor. With the approval of the DOE, Grand elected to move the project to the nearby Wolco Field, which has a thicker and more permeable sand.

Grand successfully drilled the three horizontal wells in the Wolco Field close to the original plan. The project was put on production on December 30, 2003. The project performed as expected on the basis of injection and withdrawal rates. However, production was disappointing based upon low oil rates and high water cuts. Diagnostic testing revealed much of the injected water was leaving at the heel of the injection well and communicating directly with one of the horizontal producing wells. Also, the oil saturation in the pilot area was much lower than had been expected based upon the evaluation of vertical well logs that had been run in the past.

Grand modified the original Wolco pilot because of the disappointing oil producing rates. This was accomplished by the plugging back and re-drilling of the horizontal laterals from the existing vertical wellbores in the opposite direction of the original pilot. These laterals were drilled in the top 10 ft of the Bartlesville to take advantage of the higher oil saturation within the zone. The original horizontal injection

well was shut-in and an existing vertical water disposal well is being used to provide the needed pressure support. The re-drilling of laterals moved the pilot into a portion of the field where an underlying high permeability zone exists.

The modified pilot, consisting of a vertical injection well and two adjacent horizontal producing wells, has been a success. It appears that the injected water is flowing primarily through the underlying high permeability zone and pushing oil upward to be captured by the horizontal producers. Oil production has stabilized at approximately 15 BOPD.

Based upon the success of the modified Wolco pilot, the project has been successfully expanded outside the scope of the DOE project into nearby acreage. The combined production from the two areas is approximately 50 BOPD. Cumulative oil recovery to-date has been approximately 15,000 stb. The combined projects are considered to be a major technical and economic success.

Grand has made major technological advancements during the course of implementing the program. Refinements have been made in the technology by using low-cost rotary-steerable tools for the drilling and the logging of short radius horizontal laterals. Major advancements have also been made in the understanding of the reservoir conditions where the technology is applicable and in the design of suitable projects.

Grand has shared the technology developments with the industry. A highly ambitious technology transfer program has been implemented with outstanding industry response. The support from the DOE provided the needed seed money that has allowed the development of the technology. Four additional projects have already been initiated and are in various stages of implementation. The full impact from the DOE support has yet to be realized.

The following graph shows the timing of the major activities of the project.

<table>
<tr><th>2002</th><th>2003</th><th>2004</th><th>2005</th><th>2006</th></tr>
<tr><td colspan="5">-- Contract initiation
-- Woolaroc evaluation
-- Evaluation of new location in the Wolco Field
-- Drilling and logging of 4A injector
-- Drilling and logging of 6A producer
-- Installation of surface facilities
-- Drilling and logging of 5A producer
-- Start-up of pilot
-- Diagnostic tests
------- Redrilling of horizontal producers
Production from modified Wolco pilot ---------------------------------------
Final report ---</td></tr>
</table>

DISCUSSION

Table 1 provides a historical listing of the major activities that occurred during the execution of the project. Ultimately it has been successful; however, the project evolved over a period of time to deal with various issues. The major steps during the project included:

- Evaluation of a pilot area in the Woolaroc Field, as discussed in Grand's original proposal to the DOE.
- Movement of the project to an alternative location in the nearby Wolco Field after determining that the Woolaroc site was unsuitable.
- Modification of the Wolco pilot design after encountering unexpectedly low oil saturations and channeling between the injector and one of the producers.

The project, designed to be completed within two years, began in September 2002. A one year no-cost extension was granted to Grand because of the unexpected problems that had been encountered. This final report concludes the activities of the project.

Mr. Scott Robinowitz has served as the Project Manager. He has supervised the project activities and has been the official contact with the DOE. Mr Marvin Robinowitz, President of Grand, has encouraged technical innovation and provided strong company support for the successful execution of the project. Mr. Bob Westermark has been involved in all phases of the project including the direct supervision of drilling and completion of wells, operations, and technology transfer. Ms. June Schmeling has provided geological support. Dr. Leonid Germanovich of Georgia Tech has provided assistance as a consultant on rock mechanics issues related to borehole stability and well completions. Dr. Dwight Dauben has provided assistance in reservoir engineering and simulation.

This following discussion provides a chronological description of the major activities of the project. It discusses the technological advances made during the course of the project and describes the various technology transfer activities that have taken place. Table 2 provides an overview of a very active technology transfer program, including the publication of several technical articles [8-11].

Description of the Bartlesville Sandstone

A brief description of the Bartlesville sandstone reservoir is provided because of the importance of understanding how it impacted the results of the horizontal waterflooding project. The Bartlesville has been the subject of numerous studies because of its importance within the oil industry in Oklahoma.

Ye[1] characterizes the Bartlesville sandstone as "mainly a fluvial incised valley fill deposited in a transgressive manner from a low braided fluvial to an upper tidal-influenced meandering fluvial deposition system". A portion of the Bartlesville was deposited in a lowstand system tract (LST), dominated by high-energy braided fluvial deposits. Most of the deposition occurred in a transgressive system tract (TST), dominated by meandering fluvial deposits and crevasse splay deposits. The porosity and permeability tend to be low in the TST and reservoirs producing from these deposits tend to have low productivity and recovery. Areas that produce from LST deposits tend to have higher porosity, higher permeability, higher productivity and better oil recovery. The locally used terms for the different zones within the Bartlesville are the "C" zone for the TST sands with porosity of 15-20% and the "D" zone for the high-energy LST environment with porosity of greater than 20%. LST deposition predominated in the Woolaroc Field whereas a combination of LST and TST deposition occurred in the Wolco Field.

Woolaroc Field

Work on the program began with the Bartlesville sandstone in the Woolaroc Field. This reservoir was initially considered to be a suitable site for the proposed horizontal waterflood pilot based upon production data and the characteristics of the formation as determined by existing well logs and production data. Well logs indicated that the formation was relatively uniform laterally and vertically. Deposition occurred along a north-south axis, with sand thickness in the range of 20-30 ft in the middle of the channel. Simulation studies indicated that the reservoir should be suitable based upon the anticipated rock and fluid properties. Figure 1 is a map showing the location of the Woolaroc Field and the Wolco Field (where the pilot was ultimately conducted).

Figure 2 is an isopachous map of the Bartlesville sandstone in the Woolaroc Field showing the planned configuration of wells for the pilot. As shown, the plan was to use a central horizontal injection well to permit the injection of a large amount of water below the fracture-parting pressure. Two adjacent, horizontal producing wells would then capture the mobilized oil. The plan was to drill the wells on a toe-to-heel orientation to maximize the sweep efficiency between wells. Industry experience indicates that there is a tendency of injected fluids to flow from the heel of the horizontal injector toward the heel of the horizontal producing wells [12-15]. The toe-to-heel orientation thereby helps to compensate for the preferred flow tendencies and improve oil recovery by sweep improvement.

A vertical well was initially drilled in the proposed pilot area for the purpose of collecting basic data to confirm the suitability of the field for conducting the pilot. The following procedure was followed:

- Drill a vertical well in the pilot area through the Bartlesville sandstone
- Evaluate the suitability of the formation by the use of cores and well logs. The major properties of interest were the permeability, porosity, fluid saturation, and the presence and orientation of natural fractures.
- Utilize the reservoir simulator with updated rock and fluid properties to help confirm the suitability of the pilot area.

- If reservoir properties proved suitable, plug back the well and drill the horizontal lateral parallel to the orientation of the natural fractures.

Drilling of Woolaroc 85-22 began on December 2, 2002. The location of this vertical well is shown as the triangle in Figure 2. The Bartlesville sandstone was encountered at 1672-1725 ft. A 30 ft core was collected from the interval 1695-1725 ft. This core was visually examined and sent to Core Laboratories for routine core analysis.

Grand personnel set and cemented a 5 ½” inch string of casing to 1630 ft in anticipation of drilling a horizontal lateral into the Bartlesville sandstone. The plan was to drill the horizontal lateral parallel to the dominant fracture orientation as determined from the acoustic borehole televiewer. The borehole televiewer was not run as planned due to hole conditions.

Dr. Leonid Germanovich visually examined the cores to evaluate the lithology and texture of the rock and to determine the presence of micro-fractures. Cores were noted to be very uniform in appearance with few shale laminations and no obvious fractures. The visual examination indicated that borehole stability was not likely to be a major problem and a lateral could be completed open hole.

Table 3 is a summary of the routine core analysis results. As shown, the average porosity was reported to be 13.9% pore volume and the average permeability to air was 1.1 md. The cores were described as very fine grained and shaly. The porosity was somewhat lower than expected and the permeability was much lower than expected. Previous reservoir simulations were based upon higher permeability values using relationships that were developed from nearby Bartlesville sandstone cores.

Simulations were conducted to evaluate the performance that can be expected for a three-well pattern (shown in Figure 2) using the reservoir rock properties that were determined from the core analysis. The model assumed horizontal well lengths of 1000 ft and spacing of 500 ft. The porosity was specified to be 15% pore volume and the permeability was 1 md. These simulations indicated extremely low injectivity, delayed and minimal oil response. The project would obviously not be economic.

A decision was reached to discontinue the pilot in the Woolaroc Field due to negative results indicated from the simulation studies. A recommendation was made to move the pilot to the Wolco Field, as shown in Figure 1. Ms Ginny Weyland, the DOE Contract Officer, was informed and concurred with the decision.

Original Wolco Pilot Project

The horizontal waterflooding project was implemented in the Wolco Field. The project has proved to be technically and economically successful. However, the technology has evolved with time to adapt to a reservoir environment that was quite different than originally perceived. The following discussion describes how the project was implemented in the Wolco Field.

Reservoir Description

Figure 3 is a structure map showing the location of the horizontal waterflooding pilot and other wells of interest. Blake 2A and 3A are temporarily abandoned vertical wells in the area. Blake 1A is a water disposal well, and WS-1 is a water supply well. These vertical wells were used to characterize the reservoir for the purpose of selecting a suitable site for the pilot and for evaluating the optimum length and spacing of the horizontal laterals. Wolco 4A is shown as a horizontal injection well and Wolco 5A and 6A are parallel horizontal producing wells. The horizontal wells are depicted to be 1000 ft in length with spacing of 500 ft. The horizontal wells are oriented in a northeast-southwest direction to correspond with the predominate orientation of the natural fractures that occur within the field. The structure map shows that the top of the Bartlesville slopes upward toward the northeast at approximately 30 ft per 1000 ft (1.44°)

The Blake 2A is characterized by a density log shown in Figure 4 and by an induction log shown in Figure 5. These logs indicate clean sandstone with good vertical communication and no major shale breaks. The thickness is approximately 80 ft.

The Blake 3A is characterized by a density log as shown in Figure 6 and by an induction log shown in Figure 7. These logs also indicate clean sandstone with good vertical communication. Properties from this well were used in reservoir simulation studies. These include an average porosity of approximately 18%, an average permeability of 30 md, and an oil saturation of 45%.

The Blake 1A is characterized by a density log as shown in Figure 8 and by an induction log shown in Figure 9. As indicated in Figure 8, the bottom of the Bartlesville has a high porosity interval. As explained earlier, this lower high energy zone is known locally as the “D”. The overlying lower permeability zone is referred to as the “C” zone.

Figure 10 shows a cross section of Blake 1A, 2A, and 3A. This figure shows that Blake 2A and 3A have similar properties, whereas Blake 1A contains the higher energy lower zone.

The horizontal well pattern was designed on the assumption that the high energy channel located in the area around Blake 1A would not significantly affect pilot performance. The heel of the horizontal injection well was also positioned away from the high energy channel with the knowledge that fluids preferentially leave the lateral near the heel.

The reservoir pressure in the area was approximately 100 psi prior to the initiation of the project. This pressure level is not sufficiently high to sustain significant production by itself without the pressure support provided by injection of fluids into the reservoir.

Reservoir Simulation

Simulations studies were conducted using the conditions represented by the Blake 3A. The simulations were conducted for several purposes:

- Confirm suitability of the Wolco Field for conducting the horizontal waterflooding pilot.
- Determine the optimum configuration of wells, especially the placement of the laterals within the vertical intervals.
- Determine water injection rate and pressure requirements needed for the design of surface facilities.

Simulations were performed which indicated that the horizontal waterflooding process will be effective in the recovery of oil from the pilot area chosen. In particular, there should be no problem in achieving an adequate level of injectivity, as had been the limiting factor for the proposed Woolaroc pilot. The higher injectivity and productivity anticipated in the horizontal laterals in the Wolco pilot area is attributed to the thicker sand and the higher permeability.

A number of simulations were performed to evaluate the optimum placement of laterals within the vertical interval. These simulations showed that the preferred vertical placement of the horizontal producing wells is near the top of the zone. In contrast, the preferred vertical location of the horizontal injection well is toward the bottom. These positions are preferred because of (1) the saturation differences within the vertical interval that favor the production of oil from the top and the injection of water near the bottom, and (2) gravity differences between oil and water that promote the upward movement of oil.

Table 4, together with Figures 11 and 12, summarize the results of the simulation studies. Table 4 lists the reservoir properties used in the model, the initial layer saturations, and the recovery projections over a period of time. Figure 11 shows the predicted producing rates, and Figure 12 shows the predicted cumulative recovery. A portion of the hydrocarbon saturation in the top two layers was assumed to be gas, as shown in the table. The horizontal injection well was placed 20 ft from the bottom and the horizontal producing wells were placed 20 ft from the top. Injectivity was constrained by placing limits on surface injection pressure and by total injection rate.

Several conclusions were reached from the simulation studies:

1. The Wolco Field appeared to be a suitable location for a horizontal waterflooding project.

2. Projections for oil recovery are favorable.

3. A large amount of water is associated with the recovery of the oil.

Drilling

Grand uses a low-cost, rotary-steerable system to drill short radius curves. This system was developed and licensed by Amoco Production Company (now BP). The usual procedure is for an outside contractor to drill the vertical hole to a specified depth. The vertical well is then cased and cemented. Grand then uses its own equipment and personnel to drill the curve and the horizontal lateral. In some cases, the vertical well is initially drilled through the formation of interest for the purpose of collecting data about the formation. The well is then plugged back and the curve and lateral drilled.

Two drilling assemblies are used to drill the horizontal well: the curve drilling assembly (CDA) and the lateral drilling assembly. A gyroscopic surveying tool is utilized to orient the CDA which drills a reliable curve based upon the tool configuration. The turning radius is typically 70 ft. This means that the well goes from vertical to horizontal in 70 ft of true vertical depth (TVD) and approximately 110 ft of total length. The curve is typically drilled with water or mud. The CDA is pulled from the hole after the curve has been completed.

A modified air hammer is used to drill the horizontal lateral to the desired length. An air/foam mixture is used for circulation to permit underbalanced drilling, thereby minimizing formation damage. Precautions are taken to avoid the use of surfactants that tend to emulsify with the oil, which can also cause formation damage. Surveys are run frequently to confirm that the wellbore direction and inclination are within plan. Grand has drilled laterals up to 1000 ft with this system.

A geologist is on site during the drilling of the well. He analyzes the cuttings from the well and provides an interpretation of the lithology, sand quality, and the presence of oil. Observations of fluids circulated to the pit also provide valuable information on the contents of the reservoir being drilled. Attention is given to the first fluids to the surface after a survey, which acts as a mini drill stem test (DST) as the reservoir has had approximately one hour to fill the wellbore with natural fluids.

Drilling and Logging of Injection Well Wolco 4A

A well plan was initially generated for the drilling of the Wolco 4A horizontal injection well. The major specifications included:

- Orientation: 35° east of north
- Placement within zone: 20 ft from bottom
- Trajectory: 70 ft turning radius; 85° at end of curve; build at 4° per 100 ft to follow the dip of the formation
- Lateral Length: 1000 ft

The drilling of Wolco 4A began on April 8, 2003 and continued with various interruptions until June 4, 2003. The location of this well is shown in Figure 3.

The vertical portion of the hole was drilled by an outside contractor to a depth of 1627 ft measured depth (MD). Century Geophysical ran open hole logs (gamma, induction, and borehole televiewer) on April 10, 2003 in the hole above the Bartlesville to confirm the geology and to identify the presence and orientation of natural fractures. No major fractures were identified during the logging run. Five and one-half inch casing was set in the hole and cemented to surface on April 11, 2003.

The curve was subsequently drilled from 1635 ft to 1733 ft, corresponding to a TVD of 1703 ft. The curve held direction and ended as planned at an inclination of 85°. The curve was drilled with fluid as the circulating medium.

The horizontal lateral was drilled using air/foam as the circulating fluid. The lateral was drilled to a length of 2732 ft MD, which corresponds to a lateral length of 999 ft. The planned length had been 1000 ft. Figure 13 shows that the well was drilled very close to the plan in regard to the direction, inclination, and total length.

A couple of operational problems were encountered during the drilling and logging of the well. (1) Loss circulation occurred during the drilling of the curve, indicating the presence of fractures; (2) A joint of composite pipe was parted in the curve on one occasion as the lateral was being drilled. The parted pipe was successfully recovered and drilling operations continued.

Century Geophysical ran openhole logs through the lateral portion of the wellbore on June 5-6, 2003. Grand has developed a method to log horizontal wells through short radius curves by deploying logging tools via sucker rods. The logs included gamma ray, density, induction and borehole televiewer. The logging tools were conveyed to a distance of approximately 500 ft from the vertical wellbore. The logging tools could not be pushed beyond that distance due to the friction and flexibility of the sucker rods. The well logs indicated:

- The acoustic borehole televiewer showed very few fractures

- The density log indicated porosities in the range of 15-19%, with an average of approximately 16%. The density log is shown in Figure 14.

- The induction log indicated resistivity in the range of 1-3 ohms, corresponding to high water saturation. This had been expected since the plan was to drill the horizontal injection well low within the sand. The induction log is shown in Figure 15.

Overall, the Wolco 4A horizontal injection well was successfully drilled and completed as planned.

Drilling and Logging of Producing Well Wolco 6A

A well plan was initially generated for the drilling of the Wolco 6A horizontal producing well. The basic plan was to (1) drill and cement a vertical hole to a point above the Bartlesville sandstone, (2) core and log a vertical hole through the Bartlesville, (3) plug back, and (4) drill the horizontal lateral into the Bartlesville sandstone.

Drilling of Wolco 6A began on June 23, 2003 and continued with various interruptions through September 10, 2003. The location of this well is shown in Figure 3.

The vertical portion of the well was drilled to 1664 ft MD, completed with 5 ½" casing, and cemented with returns to the surface. Mechanical problems prevented the collection of cores. The well was subsequently drilled to a depth of 1862 ft MD and Century Geophysical ran density and induction logs on August 11, 2003 through the Bartlesville sandstone. A cement plug was set and dressed off to the desired kick off point located at 1678 ft MD.

The density log, shown in Figure 16, shows porosity values in the range of 13-16%, with an average of 16%. The top of the clean Bartlesville sandstone is at 1728 ft.

The induction log, shown in Figure 17, indicates resistivity values in the range of 3-23 ohms, with an average of 5 ohms.

The curve and lateral sections were drilled from August 20 - September 10, 2003 with the following plan:

- Orientation: 215° toward the southwest
- Placement within zone: 20 ft from top
- Trajectory: 70 ft turning radius; 88° at end of curve
- Lateral Length: 1000 ft

The curve was successfully drilled with fluid as the circulating medium according to plan.

The lateral was drilled with air/foam with periodic surveys taken to determine the rate of build. The survey taken at 1964 ft MD showed a build angle out of range. Two steel drill pipe failures occurred during the process of correcting the trajectory of the hole. Recovery of the parted pipe was successful. Drilling operations ceased after drilling of 827 ft of the lateral. Figure 18 shows a comparison of actual and planned well programs. This figure shows the problems that were encountered in maintaining the proper build rate and in achieving the planned length of the lateral.

Figure 19 is a combination gamma, density, and induction log run by Century Geophysical in March 2004 for the horizontal lateral portion of Wolco 6A. The density log indicates an average porosity of approximately 18%. The resistivity ranges from 4-10 ohms, and averages approximately 5 ohms.

The drilling of Wolco 6A was considered to be a success in spite of the modest differences between the plan and the actual drilling.

Drilling and Logging of Producing Well Wolco 5A

A well plan was initially generated for the drilling of the Wolco 5A horizontal producing well. The basic plan was to (1) drill and cement a vertical hole to a point above the Bartlesville sandstone, (2) drill and log a vertical hole through the Bartlesville, (3) plug back, and (4) drill the horizontal lateral into the Bartlesville sandstone.

Drilling of Wolco 5A began on June 24, 2003. The location of this well is shown in Figure 3.

The vertical portion of the well was drilled to 1627 ft MD, completed with 5 ½" casing, and cemented with returns to the surface. The well was deepened to 1844 ft MD. Century Geophysical ran density and induction logs through the vertical openhole section of the Bartlesville on September 24, 2003. A cement plug was set and dressed off to the desired kick-off point at 1656 ft MD.

The density log, shown in Figure 20, indicates porosities in the range of 12-19%, with an average of approximately 16%. The top of the clean Bartlesville sandstone was indicated to be at 1698 ft. The induction log, shown in Figure 21, indicates resistivity values in the range of 3-11 ohms.

The curve and lateral were drilled during September and October 2003 with the following plan:

- Orientation: 215° toward the northeast
- Placement with zone: 20 ft from top
- Trajectory: 70 ft turning radius, 88.5° at end of curve; dipping downward at 3° to follow the structure of the formation.
- Lateral Length: 1000 ft

The curve was drilled from 1656 ft to 1754 ft MD, corresponding to a TVD of 1725 ft. The curve was drilled with fluid as the circulating medium. The curve was surveyed and found to be oriented at 256°, which was 41° off the plan. A correction run was made on November 19, 2003.

Drilling of the lateral continued to a total measured depth of 2655 ft, This corresponds to a lateral length of 901 ft, compared to the target length of 1000 ft.

Figure 22 is a comparison of the planned and actual directions of the lateral and clearly shows the deviation and correction.

Century Geophysical ran openhole logs through the lateral portion of the wellbore on March 24-25, 2004. The density log, shown in Figure 23, indicates an average porosity of approximately 18%. Two tighter intervals were encountered, indicating the presence of compartments in the reservoir. The induction log, shown in Figure 24, indicates resistivity ranging from 4-10 ohms, with an average of approximately 5 ohms.

Drilling of Wolco 5A was considered to be successful. The ability to survey and to correct direction during the drilling of the lateral is a positive aspect of the rotary-steerable drilling system being used.

Permitting

Grand dealt with several permitting issues related to the supply, injection, and disposal of water. These included:

- Reactivation of the Arbuckle Water Supply Well, WS #1
- Injection of water into the Wolco 4A injection well
- Disposal of produced water into Blake 1A

These wells are shown in Figure 3. Water from the Arbuckle WS #1 was initially injected into the Wolco 4A injection well at a rate of 2000 BWPD. All produced water from Wolco 5A and 6A was disposed of into Blake 1A. As the horizontal waterflood began to respond, the produced water volumes increased. The plan was to begin to re-inject the produced water into Wolco 4A and eventually shut in WS #1.

Water Supply Well, WS#1

Grand worked with the Osage Nation to reinstate WS #1 as a water supply well. Historical information indicated that it would have more than enough capacity to supply the 2000 BWPD needed for injection into Wolco 4A.

WS #1 was drilled as a water supply well in 1983. In 1986 it was converted to a disposal well and used intermittently to dispose approximately 75 BWPD. Grand secured the necessary permit to reinstate WS #1 as a water supply well.

Wolco 4A Injection Well

Grand worked with the Environmental Protection Agency (EPA) in Region 6 to secure a permit for the injection of 2000 BWPD into the Wolco 4A horizontal well. The EPA had concerns that the requested 2000 BWPD injection rate would lead to pressures in nearby vertical holes that would potentially pollute the ground water supply. These concerns were based upon experiences in vertical wells where the high rate injection of water would lead to a significant build up of the reservoir pressure.

Dr. Dwight Dauben performed a number of reservoir simulations to predict the distribution of reservoir pressure with respect to location away from the injection well. The most critical points were old vertical wells located close to the point of injection. The simulations all indicated that reservoir pressures would remain low in the surrounding areas because the geometry of the horizontal lateral would permit a large volume of water to be injected at low injection pressures. The adjacent, horizontal producing wells also help to keep reservoir pressures low because of their large capability to capture the mobilized fluids in the reservoir. The EPA gave approval for Grand to inject up to 2000 BWPD into Wolco 4A at zero surface pressure.

The work performed by Grand helped to establish a methodology that the EPA uses in the permitting of horizontal water injection wells. It paved the way for other permits that will be needed in nearby horizontal injection wells in the future.

Vertical Disposal Well, Blake 1A

All produced waters from Wolco 5A and 6A were to be injected into the Blake 1A. The Blake 1A was originally drilled as a producer in 1980, but converted to a disposal well in 1986. The injection permit was still considered valid upon review by the EPA, but subjected to new operating pressures.

Additional simulation studies were performed to consider the combined effects of the horizontal injection and producing wells and the disposal into Blake 1A. These simulations continued to indicate that reservoir pressures would remain low and not create any threat of contamination to ground water supplies. Reservoir pressures were predicted to remain low around the vertical Blake 1A well because of the high permeability, high energy channel that exists around the well.

The EPA granted a permit to allow up to 1000 BWPD to be injected into Blake 1A at zero surface pressure.

Infrastructure Upgrades

The original pilot area in the Woolaroc Field already had sufficient surface facilities in place to support the planned project. However, almost no infrastructure was in place in the Wolco area where the project was transferred. As a result, a considerable amount of additional equipment and expense was required to implement the project in the new pilot area.

Grand personnel initially met with the affected land landowners in Wolco regarding well locations, location of roads, and the installation of surface facilities and flow lines. The goal was to minimize the impact on the surface of the land. The major installed items included:

- Pumping units, tubing, and rods for the two horizontal producing wells

- Submersible pump capable of pumping 2000 BWPD from the water supply well
- Supply of electricity to the producing and injection wells, water supply well, and to the tank battery
- Installation of tank battery to handle the produced fluids
- Surface flow lines
- Upgrading of roads

Figure 25 shows the surface layout of facilities in the pilot area.

Field Operations

The horizontal waterflood became fully operational on December 30, 2003. Approximately 2000 BWPD was being pumped from the water supply well directly into Wolco 4A at zero surface pressure. The initial producing rates were:

	Oil Rate BOPD	Water Rate BWPD
Wolco 5A	6	250
Wolco 6A	2	350
Total	8	600

Each well was equipped with similar sized pumping units, 2 $^{7}/_{8}$" tubing and a 1 ½" rod pump. Both wells were producing at maximum rates and reached a pumped off condition after two weeks from field startup. All produced fluid was pumped to the tank battery. The produced water was separated out and gravity fed into the Blake 1A disposal well at zero surface pressure.

The oil production from Wolco 6A reduced to zero on January 29, 2004 and the fluid level rose by 224 ft. Water injection into the Wolco 4A was shut off on January 29, 2004 to observe the overall field response. Fluid levels taken in Wolco 6A on January 31, 2004 showed that the well returned to a pumped off condition in the absence of water injection into Wolco 4A.

The initial production was obviously a disappointment, due to the low oil rate and the high water cut. Our analysis at the time indicated that:

- Injection and withdrawal rates were close to the numbers that had been forecast
- The oil rate and oil cut were much below original expectations, partly due to the higher-than-expected water saturations in the matrix.
- The strong interaction between the Wolco 4A injector and Wolco 6A producer indicated fracture communication.

Because of the disappointing early results, some diagnostic tests were performed to better understand the causes.

Step-Rate Testing

Wolco 4A

A step-rate test was conducted in the Wolco 4A injection well on February 12, 2004 to help determine the cause for the rapid and direct communication with the Wolco 6A producing well. It had been presumed that the well was injecting below the fracture-parting pressure since 2000 BWPD was being injected at zero surface pressure.

The step-rate test was set-up to monitor the rate and pressure as water was being injected at a constant rate into the well. Pressure measurements were made with a downhole sensor. The well was initially shut-in and a series of increasing constant rate injections then took place while recording the downhole pressure. Sufficient time was allowed for the pressure to stabilize before proceeding with the next rate. Figure 26 shows the resulting relationship of injection rate and bottom hole pressure. As shown, a slope change occurred at a bottom hole pressure of 573 psi, which is interpreted to be the fracture-parting pressure. This would indicate a fracture-parting pressure gradient of approximately 0.34 psi/ft, which is well below the hydrostatic head of water. By contrast, the fracture-parting pressure in many reservoirs is in the range of 0.70 psi/ft.

The step rate test indicated that the fracture-parting pressure was being exceeded when injecting 2000 BWPD at zero surface pressure. To stay below the fracture parting pressure, it would be necessary to stay below the 1745 BWPD where the fracture-parting was indicated.

The following are some of the conclusions that were reached from the step-rate testing:

- A zero surface pressure does not guarantee that water is being injected below the fracture-parting pressure.

- In the absence of continuous bottom hole pressure measurement, a limit needs to be made on the maximum allowed injection rate. In the case of Wolco 4A, it was suggested that the rate not exceed 1500 BWPD while injecting at zero surface pressure.

- Step-rate tests should be periodically run during the course of a waterflood since the fracture-parting pressure changes as the pressure within the reservoir increases.

The determination that the fracture-parting pressure was being exceeded does not in itself prove the cause for the observed channeling problem. Our experiences with the Bartlesville sandstone indicate a complex depositional environment that produces rapid changes in porosity, permeability, and strong evidence of compartments. Natural fractures are abundant and sensitive to pressure.

Blake 1A

A step-rate test was also conducted on the Blake 1A disposal well. As previously indicated, this well is completed in a portion of the reservoir containing a high-energy, high-permeability lower “D” zone. The test was conducted using bottom hole pressure measurements. Figure 27 shows the relationship of injection rate and bottom hole pressure.

As shown, there were no indications of fracture-parting as rates were sequentially increased up to 3000 BWPD. The surface pressure remained at zero pressure during the entire period of injection. The slope change occurring at 410 psi may indicate an increasing contribution of the upper, lower permeability “C’ zone to the total flow.

It was concluded that the fracture-parting pressure was not exceeded at the rates and pressures that prevailed during the step-rate test of Wolco 4A. That meant that water could be injected at rates of up to 3000 BWPD without concern of fracture-parting.

Spinner Survey

A spinner survey was run in April 2004 in Wolco 4A to determine the distribution of flow away from the horizontal lateral. The purpose of the test was to collect additional information that might be helpful in understanding the direct communication occurring between Wolco 4A and Wolco 6A. The spinner tool was conveyed on sucker rods and depth measurements were based upon the rod tally.

Figure 28 indicates that all of the injected fluid left the lateral within the curve with injection rates ranging from 1000-2800 BWPD. This interval of injection corresponds with the loss of circulation that occurred while drilling the curve. The presumption is that this area contains natural fractures that may have been opened up while drilling with water in the curve portion of the well.

Industry experience indicates a tendency for injected fluids to preferentially leave the lateral close to the vertical wellbore. However, this tendency is not pronounced in situations like Wolco where the matrix permeability is low. In such case, the flow capacity of the lateral greatly exceeds the flow capacity of the matrix.

The conclusion from the spinner survey is that almost all of the injected fluids are leaving the lateral within the curve. The most likely cause is the presence of pressure-sensitive fractures around the wellbore.

Project Evaluation

The produced volumes of oil over the first six months were disappointing. The oil rate was low and the water-cut was very high. Wolco 4A was shut-in because of the previously discussed communication problem. Based upon the negative results, a decision was reached to modify the pilot operation in an attempt to get better results.

Modifed Wolco Pilot Project

Grand personnel made a thorough review of the original pilot project to determine the best possible course of action. It was recognized that the existing project was not economical and the prospects for improvement were not evident. A motivating force to re-drill the laterals was the observation that most of the oil saturation was located in the top 10 ft of the sand. Figure 29 shows the distribution of oil saturations that were calculated from the well log that was run in the initial vertical hole drilled in Wolco 6A. As shown, the oil saturation within the top 10 ft averages approximately 60%. By contrast, the original Wolco 6A well was completed lower in the zone where the oil saturation was approximately 40%.

A plan ultimately emerged after continued review and evaluation of performance. This plan consisted of the following:

1. The Wolco 5A and 6A horizontal producing wells should be drilled in the top portion of the Bartlesville sandstone in the opposite (180°) direction. Drilling in the very top of the sand will allow access to the highest possible oil saturation.

2. The Blake 1A vertical disposal well would be used as an injector to displace oil toward the two horizontal producers.

3. The resulting pilot is located in a portion of the reservoir containing the higher permeability “D” zone at the bottom of the sand.

The original pilot was based upon the concept that a horizontal injection well could inject large volumes of water below the fracture-parting pressure into a low-permeability sand to displace oil. The mobilized oil can then be captured by the two adjacent and parallel horizontal producing wells. This process is still considered valid. However, it appears that it was difficult to control the flow distribution within the horizontal injection well. Additionally, the laterals in the producing well were drilled lower within the zone than currently considered optimal.

The modified pilot is based upon the concept that water injected into a reservoir containing a high permeability lower zone can effectively displace oil toward horizontal producing wells completed in the very top of the zone where the oil saturation is the highest. The injected water is predicted to flow principally in the underlying high-permeability zone and push oil upward toward the horizontal producing wells.

Figure 30 shows the configuration of the original and modified Wolco pilots.

Re-Drilling of Wolco 6A

The sidetracking plan for the original Wolco 6A well was to plug back with cement into the casing. Sidetracking of the well would be accomplished by dressing off the cement to the kick off point (KOP). The curve drilling assembly would be picked up, oriented and the curve drilled. An air hammer would then be used to drill the horizontal lateral while air/foam was being circulated. The plan was to re-drill the well in the top 10 ft of the sand to take advantage of the higher oil saturation. After two failed attempts (Wolco 6A-2 and 6A-3), Wolco 6A-4 was successfully drilled with a lateral located 180° from the original direction.

Very little oil was encountered during the drilling of the first 84 ft of the lateral. Thereafter, oil was clearly visible in the pit and when making connections. An increasing amount of oil was observed with the continued drilling of the lateral. An advantage of drilling with an air-foam mixture is that each connection serves as a mini drill stem test. The lateral continued to build with distance until it approached the top of the zone. The length of the Wolco 6A-4 lateral is 202 ft. The rapid changes of oil saturation encountered by the horizontal lateral provide additional evidence of compartmentalization.

Figure 31 presents the section and plan views of Wolco 6A-4, while section and plan views of both Wolco 6A and 6A-4 are shown together in Figure 32. A combination gamma ray, density, and guard log was run in the Wolco 6A-4 lateral and is shown in Figure 33. The original Wolco 6A had an average of 17% porosity in the lateral with less than 5 ohms of resistivity while Wolco 6A-4 well has porosity of approximately 16% and average resistivity of 15 ohms.

The initial producing rates were encouraging, making 13 BOPD and 100 BWPD. This compares with production of 2 BOPD and 350 BWPD in the original well.

Re-Drilling of Wolco 5A

The plan for the re-drilling of Wolco 5A was similar to that of Wolco 6A. The re-drilling began in September 2004. After two failed attempts, Wolco 5A-4 was successfully drilled in late December of 2004. Figure 34 presents the section and plan views of Wolco 5A-4 and Figure 35 presents section and plan views of Wolco 5A and 5A-4 together. The Wolco 5A-4 lateral had a length of approximately 625 ft and was drilled in the top 10 ft of the sand in the opposite direction of the original Wolco 5A well.

Production Operations

A total of 5718 stb has been produced from the horizontal waterflooding project over a 16-month period. This corresponds to an average rate of approximately 12 BOPD. The oil rate has been stable over the life of the project and has actually increased during the later stages of the reporting process to approximately 15 BOPD. The wells are producing at a water cut of approximately 92%.

Production from this pilot has been co-mingled with fluids from another project for the past eight months, making it difficult to quantify the amount of production that can be allocated to the Wolco pilot. The best estimate is that production is remaining stable at approximately 15 BOPD.

The project has been considered a technical and economic success. Although the economic return has not been spectacular, it is considered quite remarkable to achieve this level of production response from a reservoir that had been essentially abandoned.

Revised Simulations

Figure 36 shows some predictions to evaluate the performance of the final resulting pilot consisting of the vertical injection well, Blake 1A, and the two new horizontal producing wells, Wolco 6A-4 and Wolco 5A-4. The produced water is injected into Blake 1A which in turn provides pressure support for the pilot. Blake 1A is located in a portion of the reservoir containing the high-energy, high-permeability zone in the lower portion of the Bartlesville. The two horizontal producing wells were drilled and completed in a thin oil column that exists in the top 10 ft of sand. Reservoir properties were adjusted to match the early 15 BOPD production observed in the modified pilots, as well as the amount of water being produced. The simulations indicate that most of the injected water flows initially through the underlying high permeability channel and exerts enough upward pressure to allow oil to be produced from the two horizontal producing wells. The comparative case assumes that the horizontal wells are replaced by vertical wells completed only in the upper 10 ft of the reservoir. The simulations indicate that the horizontal wells will recover a significantly higher oil recovery, as shown in the following table.

Time (years)	Cumulative Oil for Horizontal wells (stb)	Cumulative Oil for Vertical Wells (stb)
1	5,116	954
5	17,548	4,008
10	28,570	6,927

All of the reservoir simulations to date indicate that the most important part of the process is to place the horizontal producing wells close to the top of the sand where the highest oil saturations exist. It is important to provide pressure support to maintain the producing rates and to achieve maximum recovery. In contrast to the original concept, it now appears less critical to use a parallel horizontal injection well. Part of the needed support comes from the existing pressure (125 psi) within the reservoir. In the case of the Wolco pilot, it appears that the injection of water into a higher permeability lower zone can provide the needed pressure support to achieve economic oil recovery.

Project Expansion

Based upon the success of the DOE sponsored project, Grand applied similar technology to the nearby Avant Field, which is also producing from the Bartlesville sandstone. This has been highly successful, as discussed in a paper that was presented by R.V. Westermark[11] at the 2006 SPE/DOE IOR Symposium. The combined production from this and the Wolco project is approximately 50 BOPD. This is outside of the scope of the DOE sponsored project; however, it does demonstrate that the technology developed with the support of the DOE is now being utilized in other locations.

Figure 37 shows the combined production from the Wolco and Avant projects. Production from the adjacent acreages is produced into a common tank battery. The first 16 months principally reflect the contribution of the Wolco project. The last 8 months reflect the production from both projects combined. Approximately 15 BOPD is being produced from Wolco and the remaining 35 BOPD is coming from the adjacent Avant operation.

TECHNOLOGY TRANSFER

Grand has had a very active technology transfer program to advise the oil industry of the developments of the DOE sponsored project. These have greatly exceeded the commitments made in the original proposal to the DOE. The major technology transfer activities are listed in Table 2. Some of the major activities include:

1. Creation of a website located at: www.grandoil.com. Contact with Scott Robinowitz is needed for authorized personnel to gain access to budget items, status reports, and daily operational data.

2. Periodic briefings to the Osage Tribe and to the Petroleum Technology Transfer Council (PTTC).

3. Preparation of technical publications, including:

    - Three technical papers for the Society of Petroleum Engineers (SPE)
      SPE 89373: "Enhanced Oil Recovery with Horizontal Waterflooding, Osage County, Oklahoma", April 2004
      SPE 94094: "Increased Production Results from Pilot Horizontal Waterflood in Osage County, Oklahoma, April 2005
      SPE 99668: "Application of Horizontal Waterflooding to Improve Oil Recovery from Old Oil Fields", April 2006
    - *World Oil* , March 2004
    - *American Oil and Gas Reporter*, September 2004

4. Booth at three of the Osage Nation's Annual Oil and Gas Summits.

5. Presentation of SPE 89373 at the SPE/DOE IOR, Tulsa, OK, April 2004

6. Presentation at Osage Producers Association.

7. Presentation at the Eastern Kansas Oil and Gas Association, Chanute, KS.

8. Presentation at Osage Nations' 3rd Annual Oil and Gas Summit.

9. Presentation of SPE 94094 at the SPE POS, Oklahoma City, OK, April 2005

10. Presentations at PTTC sponsored workshops, Norman, OK and Chanute, KS.

11. SPE Mid-Continent Section meeting, Tulsa

12. Presentation at four workshops held by the Marginal Well Oil and Gas Commission, Ardmore, Pawhuska, Tulsa, and Oklahoma City, OK.

13. Presentation of SPE 94094 at the SPE IOR, Tulsa, OK, April 2006

14. Presentation to SPE students at dinner meeting in Lawrence, KS, March 2006

15. Presentation to the Kansas Geological Society, May 2006

CONCLUSIONS

1. The originally proposed horizontal waterflooding project in the Woolaroc Field proved not to be suitable since core analyses indicated a lower-than-expected permeability.

2. Grand’s initial data collection program has proven to be quite valuable in making technical and economic decisions. This procedure consists of (1) drilling a vertical hole to collect and analyze data from core and log analysis, (2) plugging back with cement, and (3) kicking off from the vertical well to drill the horizontal lateral in the optimum orientation. This initial data collection in Woolaroc allowed Grand to make informed decisions before committing major financial resources.

3. The decision to move the project to the nearby Wolco Field proved to be a correct one. This reservoir in this field has greater sand thickness, higher matrix permeability, and a higher potential for expansion into nearby fields.

4. Disappointing performance was obtained from the original horizontal waterflooding project in Wolco. This was attributed to the lower-than-expected oil saturation and to the direct communication between the horizontal injection well and one of the horizontal producing wells. It appears that oil may have migrated out of the area over a period of years due to regional pressure gradients. Fractures may have been the cause for the observed channeling problem.

5. The DOE project failed to demonstrate the viability of the horizontal waterflooding process as originally envisioned. The basic concept in this process is that a large amount of water can be injected at low pressure through a horizontal injection well into a low-permeability reservoir. The mobilized oil in turn is recovered by adjacent, parallel horizontal producing wells. The concepts are still considered valid. Much better performance would have been expected in the Wolco project if adequate oil saturated had existed and if the inadvertent channeling had not occurred.

6. The modified Wolco pilot demonstrated the viability of horizontal waterflooding in reservoirs containing an underlying high permeability zone. In this case, water is injected into a vertical well while oil is recovered from adjacent horizontal producing wells drilled at the top of the zone. The injected water flows principally through the high permeability lower zone and pushes oil upward toward the horizontal producing wells.

7. The modified Wolco pilot has proven to be a technical and economic success in-spite of a limited amount of oil in place. Most of the oil is contained within the top 10 ft of the reservoir.

8. Reservoir simulation studies have played a key role in assessing the suitability of a particular project and in optimizing the design. Numerous simulations indicate that:

   - Horizontal waterflooding patterns should be aligned parallel to the natural fracture orientation to maximize the amount of oil that can be moved through the matrix.
   - Horizontal producing wells should be placed as high as possible within the reservoir to contact the maximum amount of oil saturation.
   - Pressure support is needed to sustain the production from a horizontal producing well.
     - Vertical injection wells can be effectively used if sufficient injectivity can be developed.
     - Horizontal injection wells of shorter length can be used if greater injectivity than can be provided by a vertical injection well is required.
   - Horizontal injection wells should be drilled in a toe-to-heel orientation with horizontal producing wells to counter the tendency of injected fluids to flow from the heel of the injector toward the heel of the producer. Vertical or shorter length horizontal injectors should be located toward the toe of the horizontal producer.

9. Grand has worked with the Environmental Protection Agency to help establish the guidelines for the permitting of horizontal injection wells.

10. Grand's rotary-steerable system has proven to be an effective way to drill short-radius horizontal laterals at low cost. The experiences gained in Wolco have helped to refine the drilling techniques. The short-turning radius permits the use of conventional rods and pumps in the vertical portion of the well.

11. An ineffective lateral can be easily replaced by plugging back and drilling a new lateral from the vertical wellbore.

12. Grand has developed cost-effective procedures for the logging of short radius horizontal laterals.

13. Grand has conducted a comprehensive technology transfer program to advise the industry of the results of the project. The response from the industry has been outstanding.

ABBREVIATIONS

BOPD	barrels of oil per day
BWPD	barrels of water per day
CDA	curve drilling assembly
DOE	Department of Energy
DST	drill stem test
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
FDD	Fluvial-Dominated Deltaic
IOR	Improved Oil Recovery
KOP	kick off point
MD	measured depth
md	millidarcy
Ώ	ohms
OOIP	original oil in place
POS	Production and Operations Symposium
psi	pounds per square inch
PTTC	Petroleum Technology Transfer Council
pv	pore volume
ss	subsea
stb	stock tank barrel
TVD	true vertical depth
WS	Water Supply

REFERENCES

1. Ye, Liangmiao; Kerr, Dennis: "Sequence Stratigraphy of the Middle Pennsylvanian Bartlesville Sandstone, Northeastern Oklahoma: A Case of an Underfilled Incised Valley", AAPG Bulletin, Vol 84, No. 8, August 2000, pp 1185-1204.

2. Andrews, Richard D.; Campbell, J. A.; Northcuff, R. A.: "Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Bartlesville Play", Oklahoma Geological Survey, Special Publication 97-6, 1997.

3. Guo, Genliang and Carroll, Herbert B.: "A New Methodology for Oil and Gas Exploration Using Remote Sensing Data and Surface Fracture Analysis", Performed Under DOE Contract Number DE- AC22-94PC91008, February 1999.

4. Taber, J. J.; Seright, R. H.: "Horizontal Injection and Production Wells for EOR or Waterflooding", SPE 23952, presented at the 1992 SPE Permian Basin Oil and Gas Recovery Conference, Midland, Texas, March 18-20, 1992.

5. Kelkar, M. C.; Liner, C.; Kerr, D.: "Integrated Approach Towards the Application of Horizontal Wells to Improve Waterflooding Performance", Final Report, DOE/BC/14951-16, October 1999.

6. Joshi, S. D.: "*Horizontal Well Technology*", published by PennWell, Tulsa, OK, 1991.

7. Joshi, S. D.: "Cost/Benefits of Horizontal Wells", SPE 83621, presented at the SPE Western Regional/AAPG Pacific Section Joint Meeting held in Long Beach, California, May 19-24, 2003.

8. Westermark, R. V.; Robinowitz, S.; Weyland, H. V.: "Horizontal Waterflooding Increases Injectivity and Accelerates Recovery", *World Oil* V 225, No 3, pp 81-82, March 2004.

9. Westermark, R. V.; Dauben, D.; Robinowitz, S.: "Enhanced Oil Recovery with Horizontal Waterflooding, Osage County, Oklahoma", SPE 89373, presented at the 2004 SPE/DOE Fourteenth Symposium on Improved Oil Recovery, Tulsa, OK, April 17-21, 2004.

10. Westermark, R. V.; Schmeling, J.; Dauben, D.; Robinowitz, S.; Weyland H. V.: "Increased Production Results From Pilot Horizontal Waterflood in Osage County, Oklahoma", SPE 94094. presented at the 2005 SPE Production and Operations Symposium, Oklahoma City, Oklahoma, April 17-19, 2005.

11. Westermark, R. V.; Schmeling, J.; Dauben, D. L.; Robinowitz, S.; Weyland, H. V.: "Application of Horizontal Waterflooding to Improve Oil Recovery from Old Oil

Fields", SPE 99668, presented at the 2006 SPE/DOE Symposium on Improved Oil Recovery, Tulsa, OK, April 22-26, 2006.

12. Vicente, R.; Sarica, C.; Ertekin, T.: "A Numerical Model Coupling Reservoir and Horizontal Well Flow Dynamics: Transient Behavior of Single-Phase Liquid and Gas Flow", SPE/CIM 65508, presented at the 2000 SPE/CIM International Conference on Horizontal Well Technology, Calgary, Alberta, Canada November 6-8, November 2000.

13. Popa, C. G.; Chipea, M.: "Improved Waterflooding Efficiency by Horizontal Wells", SPE 50400, presented at the 1998 SPE International Conference on Horizontal Well Technology, Calgary, Alberta, Canada, November 1-4, 1998.

14. Popa, Constantin; Turta, Alex T: "Waterflooding by Horizontal Injectors and Producers", SPE 78989, presented at the 2002 SPE International Thermal Operations and Heavy Oil Symposium and International and Horizontal Well Technology Conference, Calgary, Alberta, November 4-7, 2002.

15. Zhao, Litong; Turta, Alex: "Toe-To-Heel Waterflooding: Field Scale Numerical Simulation Study", SPE 89380, presented at the 2004 SPE/DOE Fourteen Symposium on Improved Oil Recovery, Tulsa, Oklahoma, April 17-21, 2004.

Figure 1:
Location of the Woolaroc and Wolco Fields

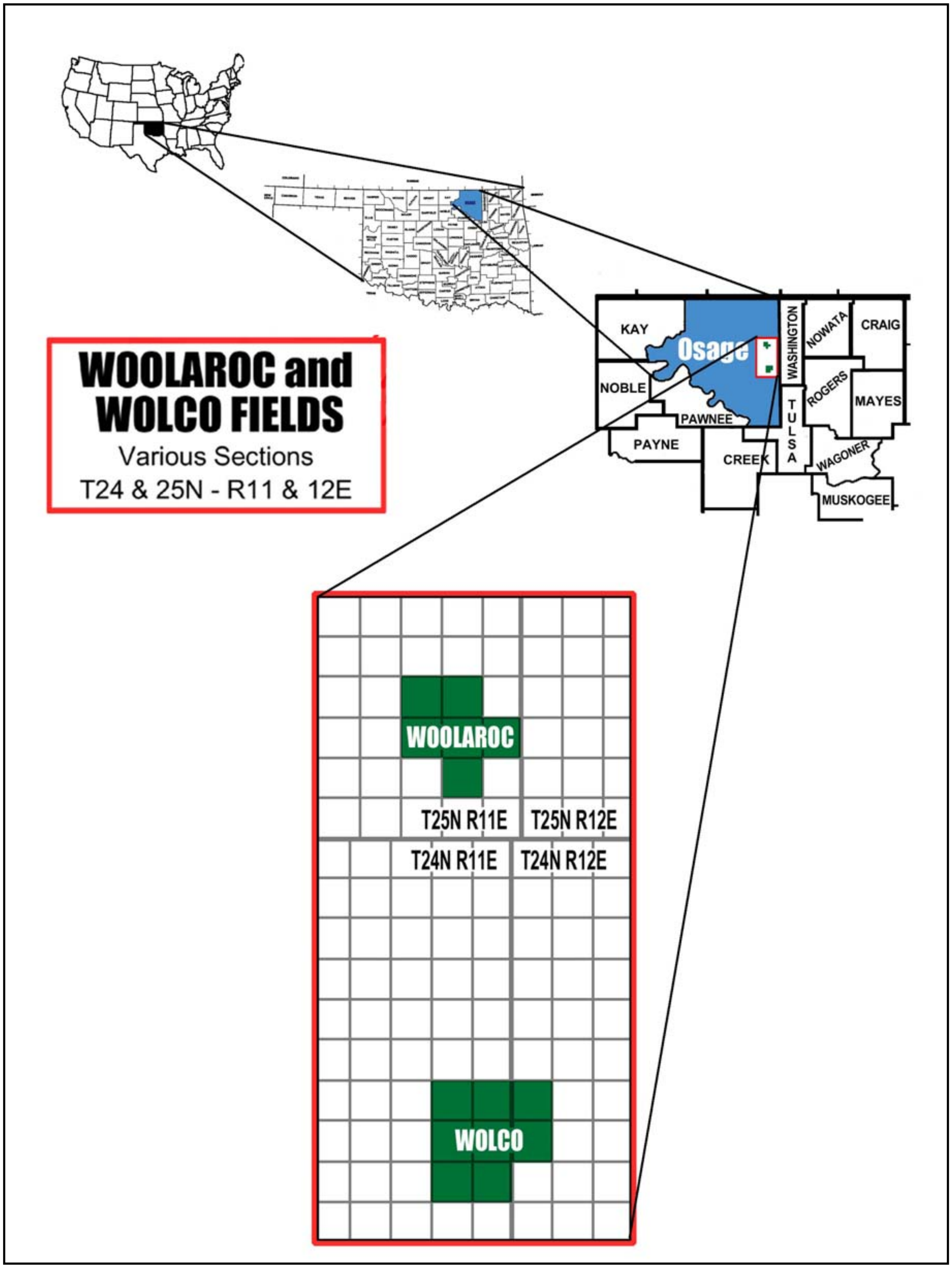


Figure 2:
Isopachous Map of the Bartlesville Sandstone in the Woolaroc Field Showing the Location of Proposed Horizontal Waterflood Pilot and Woolaroc 85-22

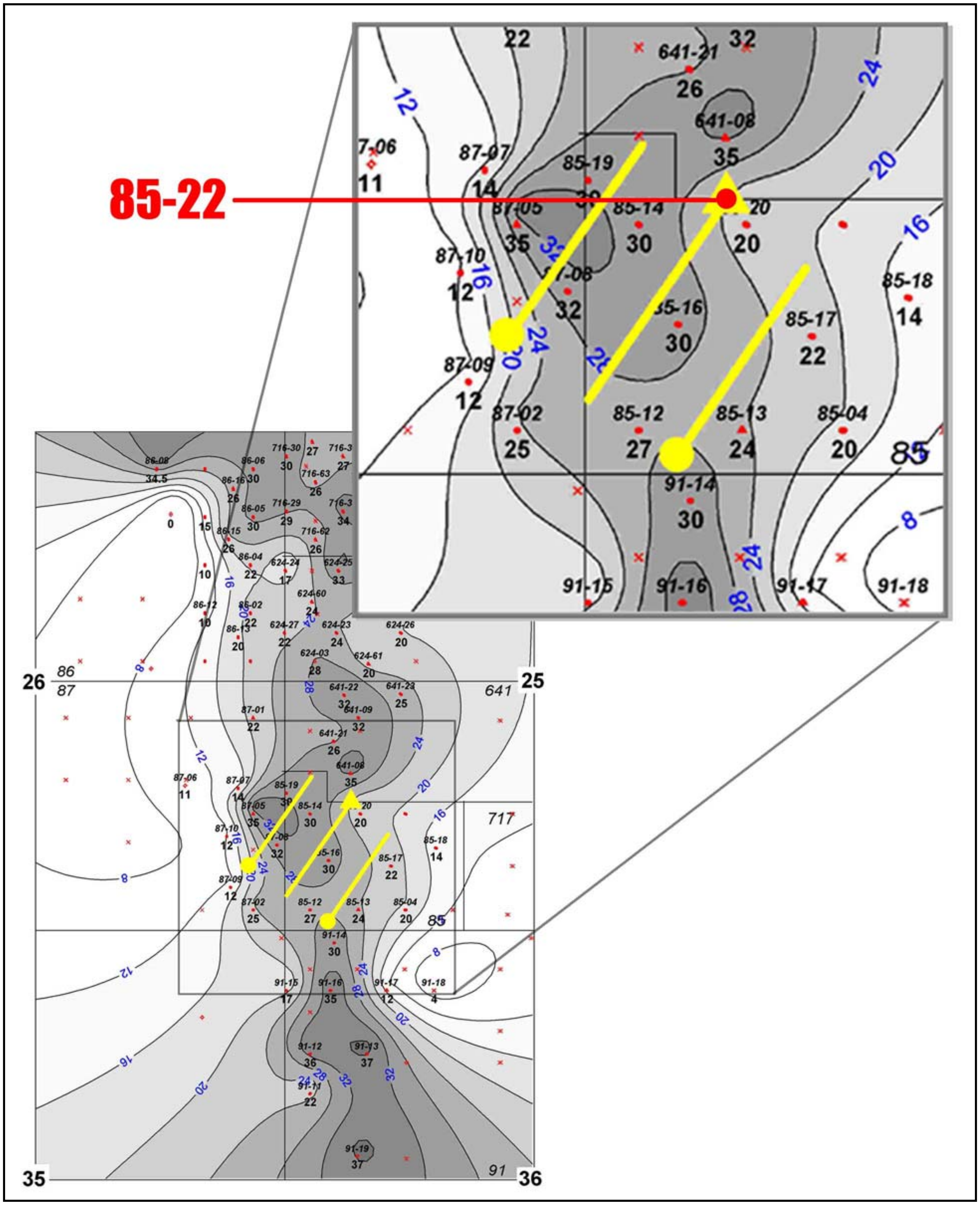


Figure 3:
Structure Map: Top of Clean Bartlesville Sand and Cross Section Location

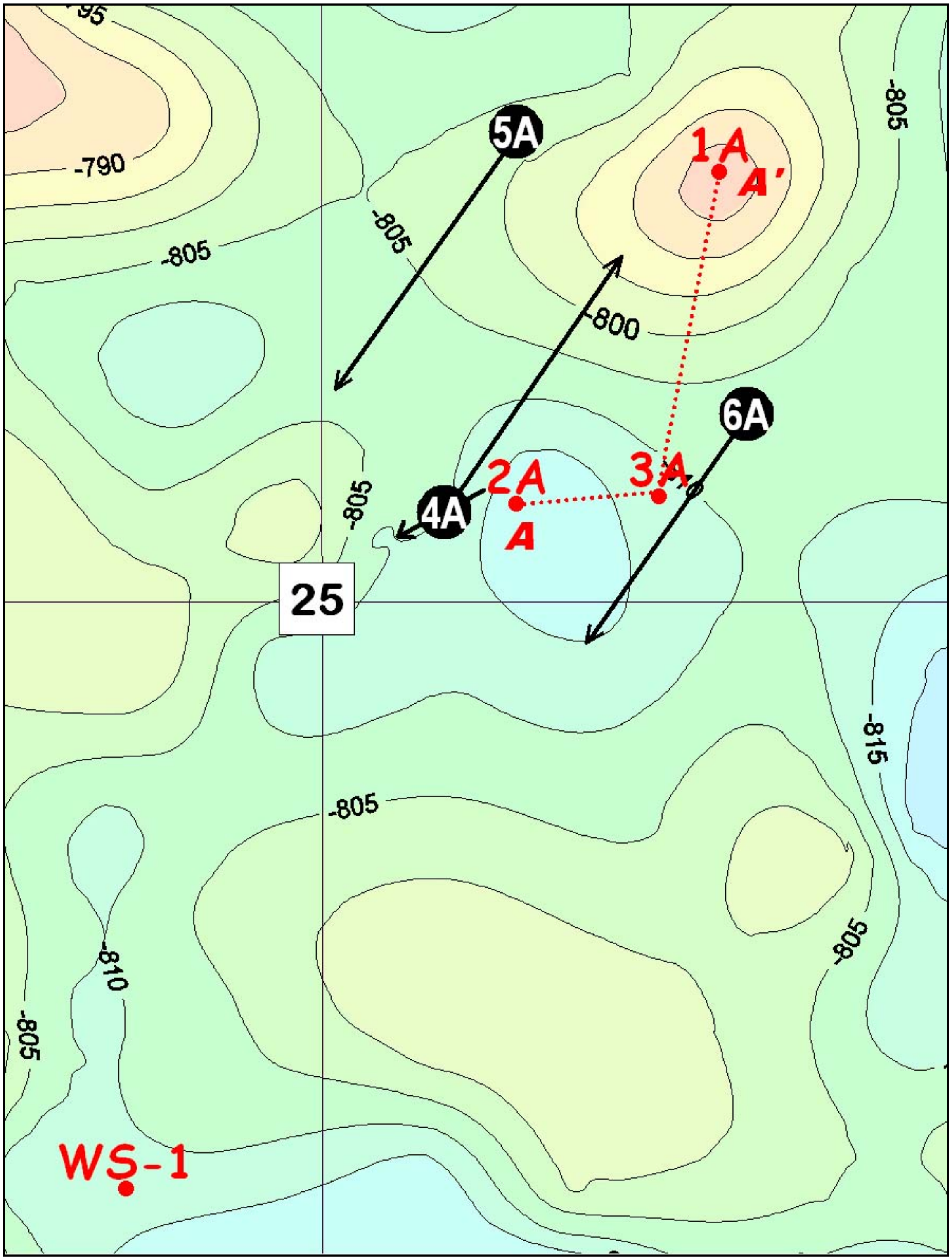


Figure 4:
Blake 2A Density Log

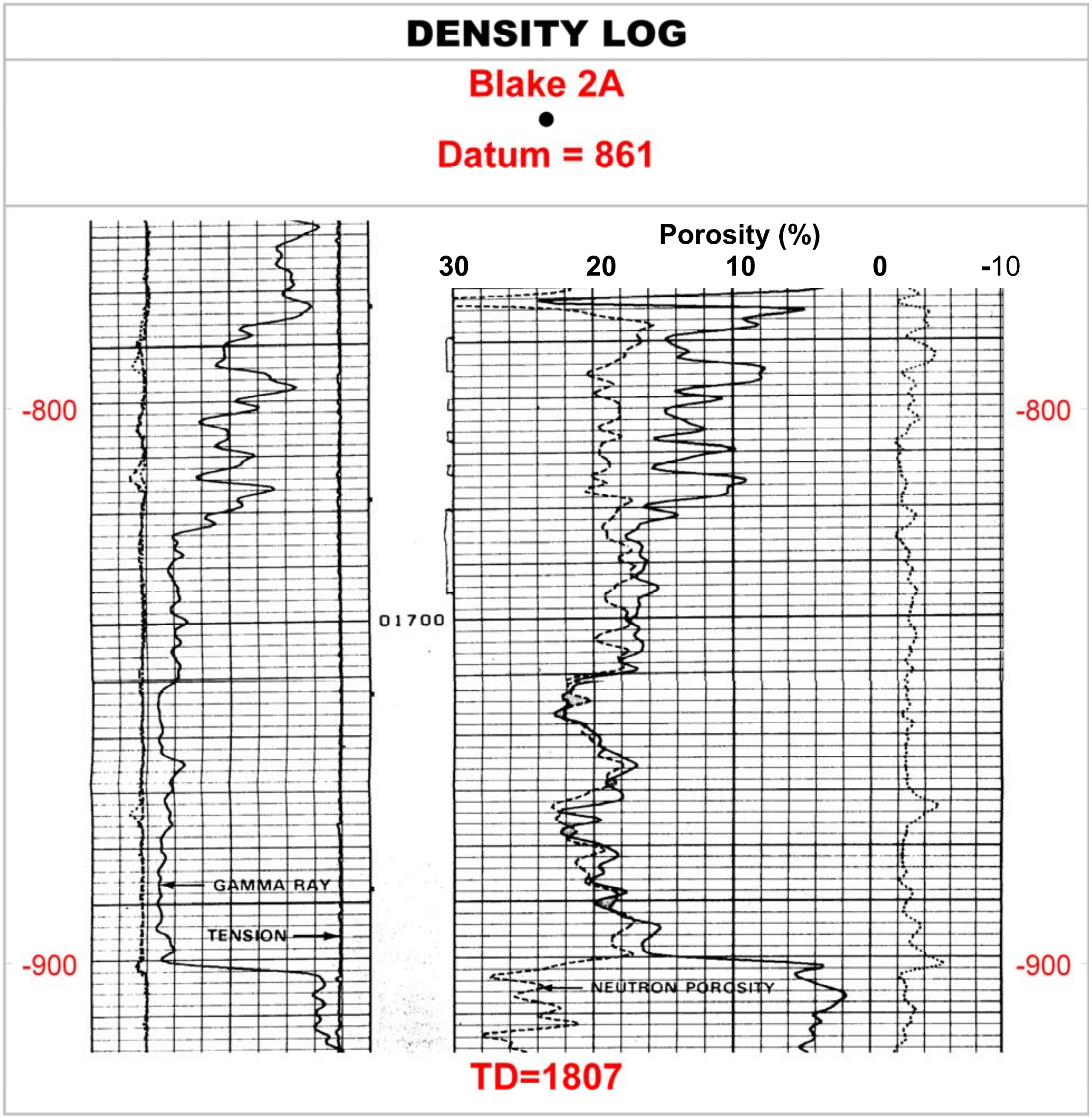


Figure 5:
Blake 2A Induction Log

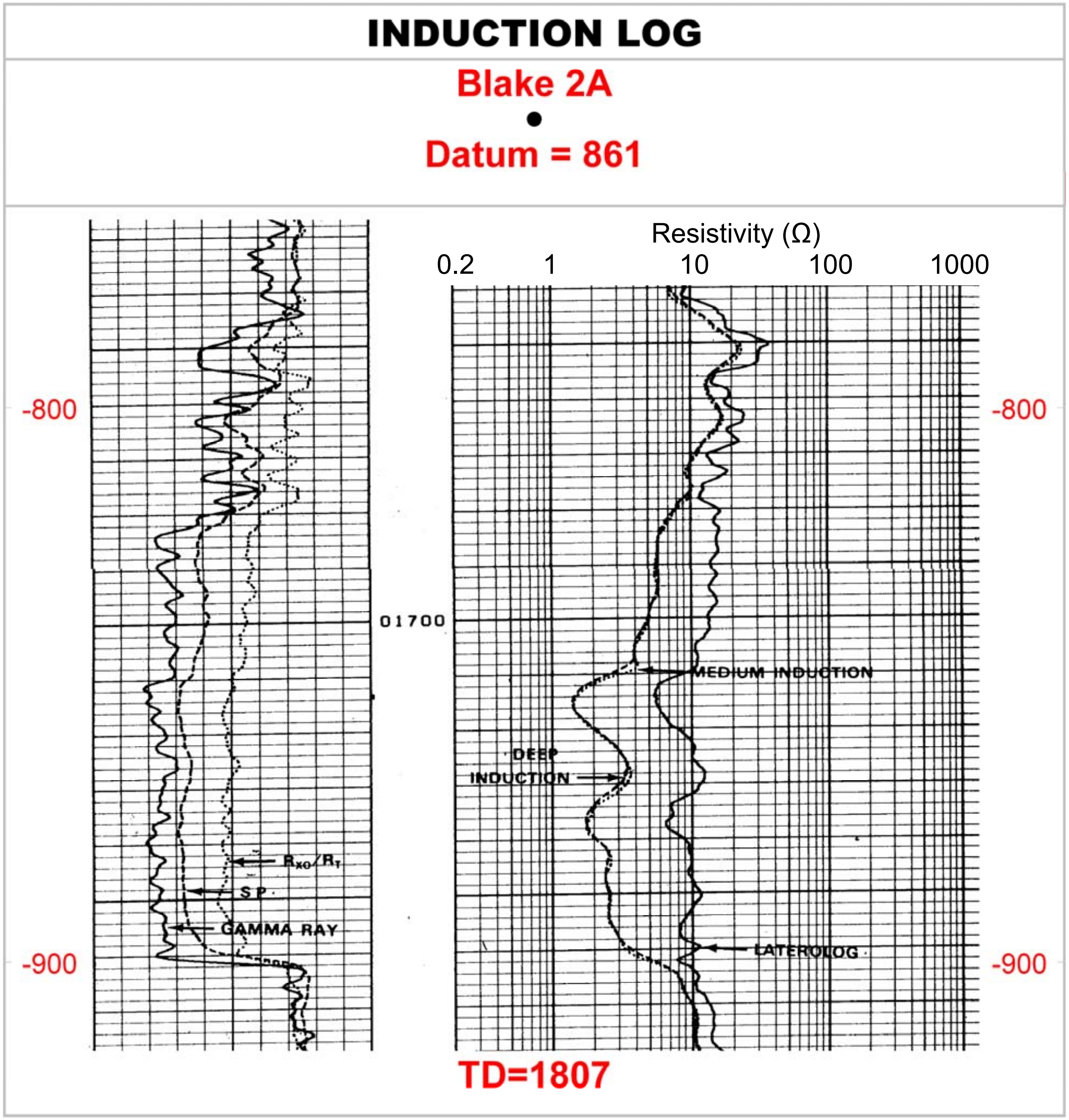


Figure 6:
Blake 3A Density Log

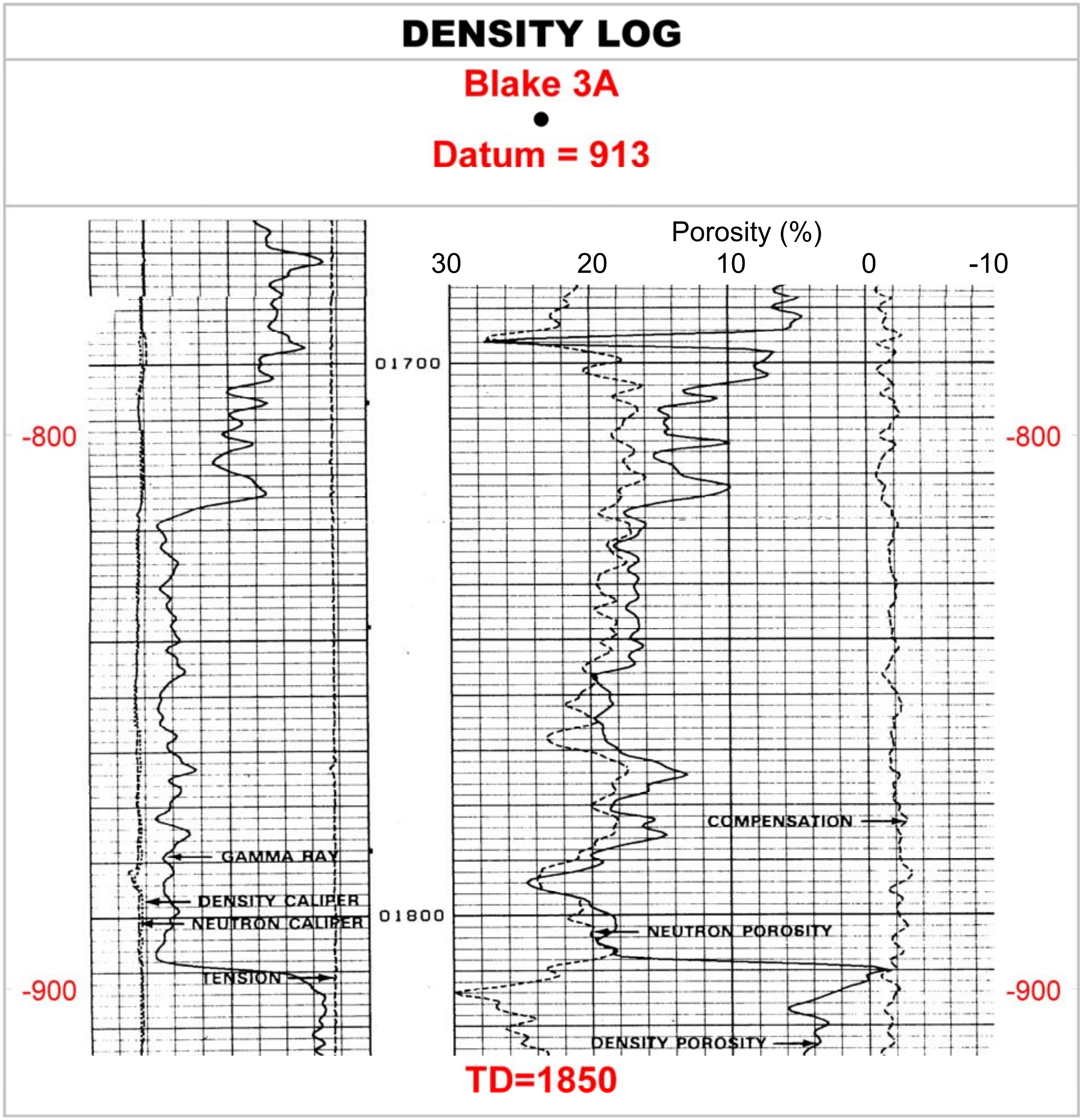


Figure 7:
Blake 3A Induction Log

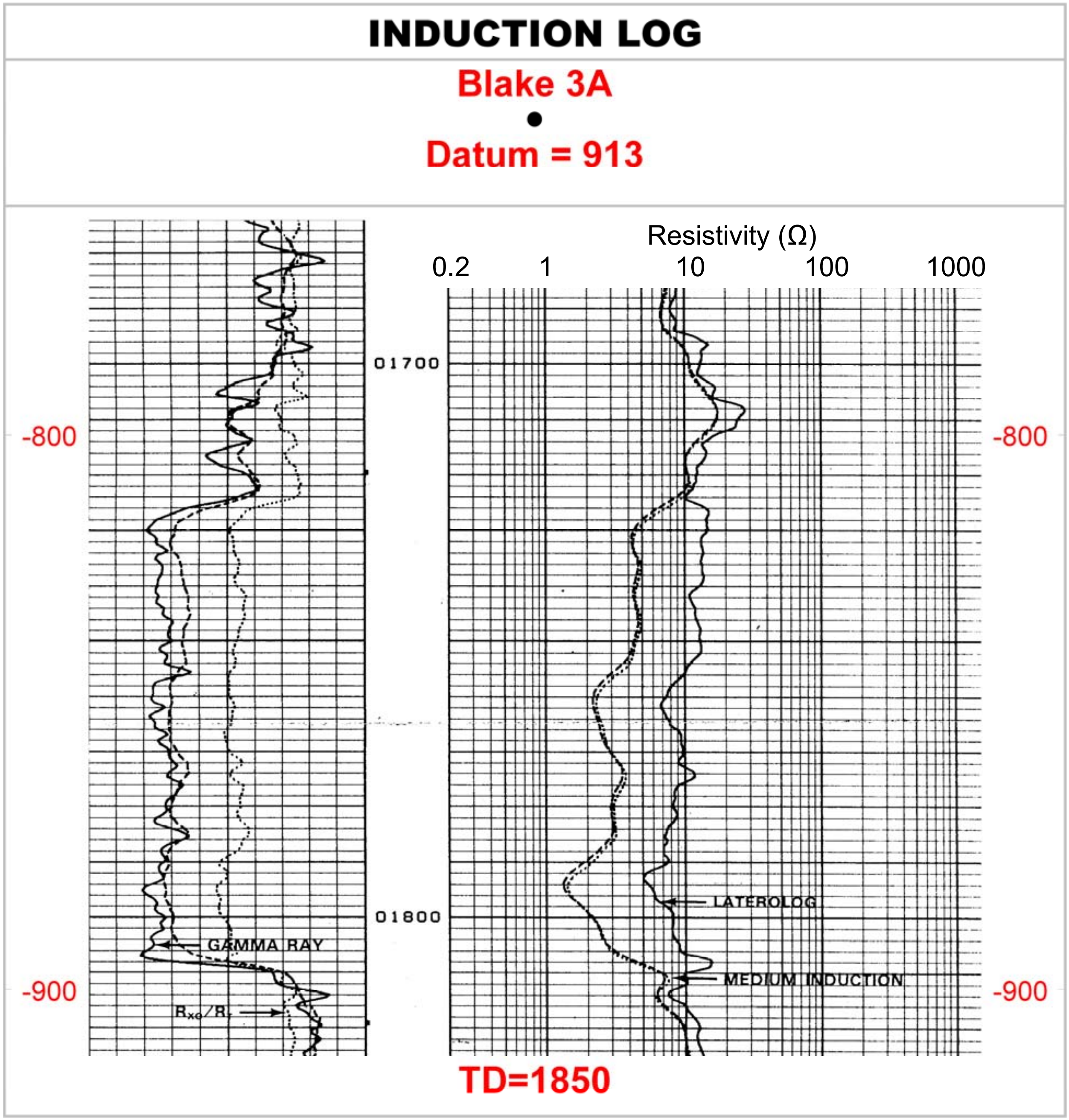


Figure 8:
Blake 1A Density Log

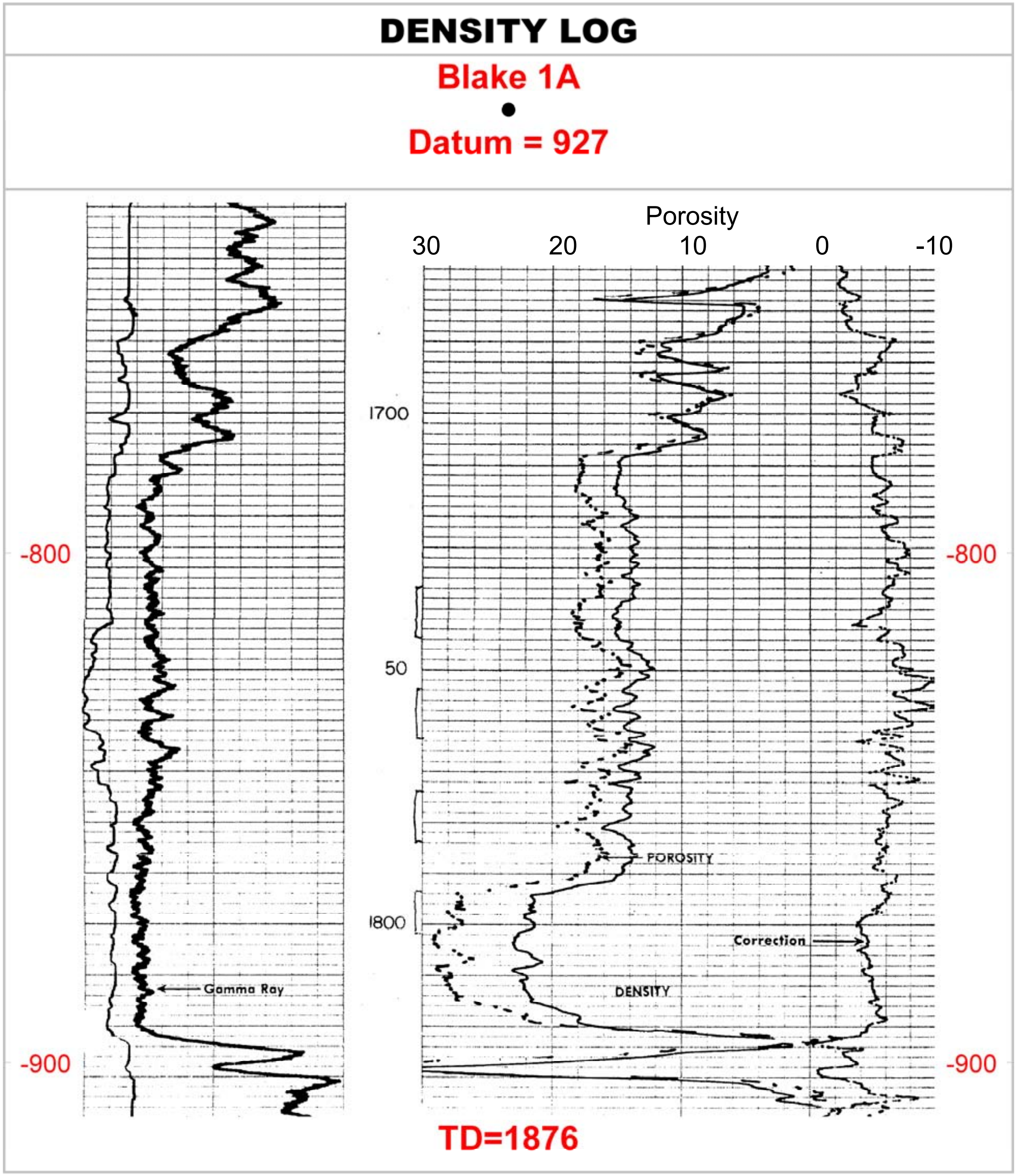


Figure 9:
Blake 1A Induction Log

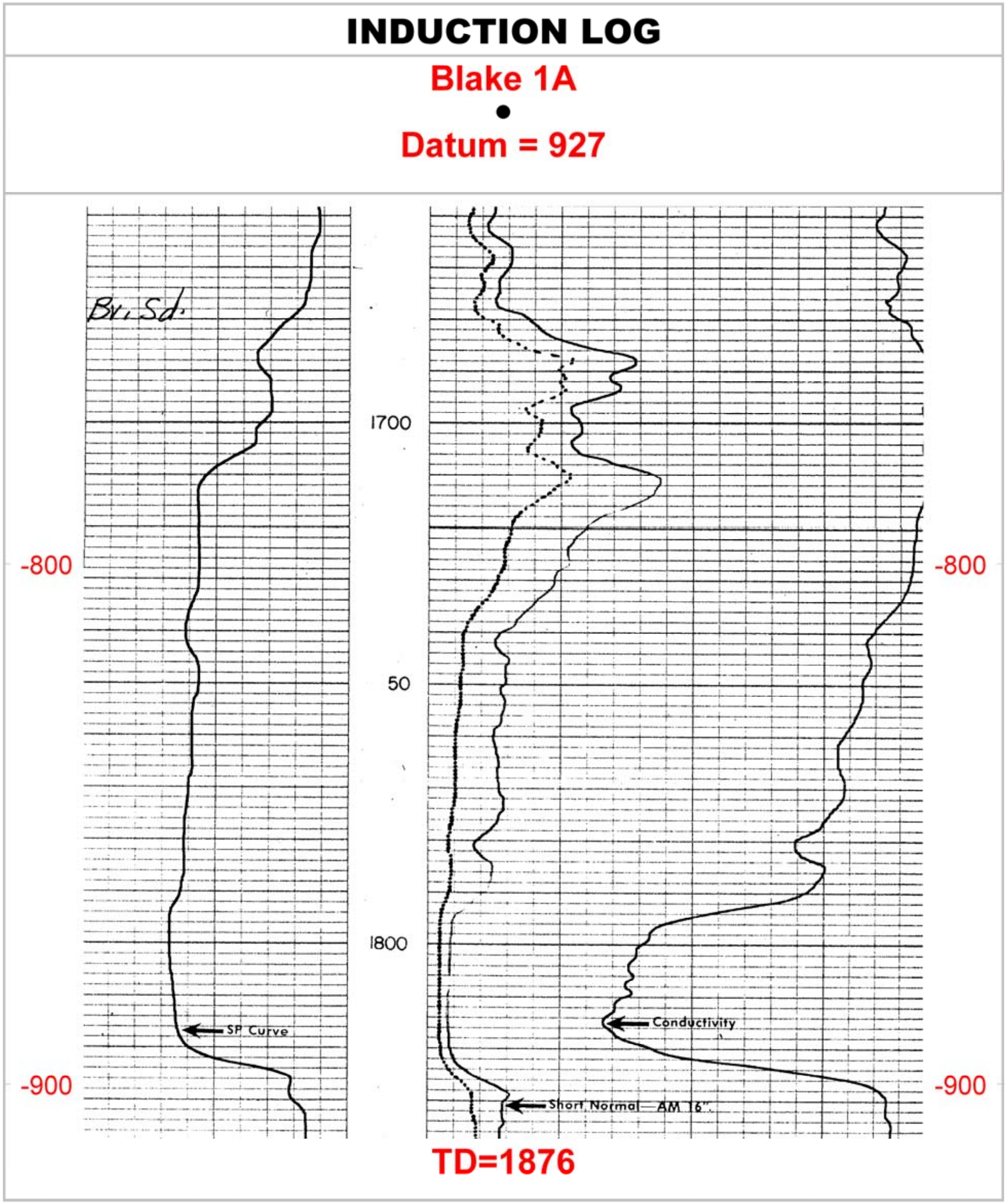


Figure 10:
A-A′ Cross Section Across Pilot Area

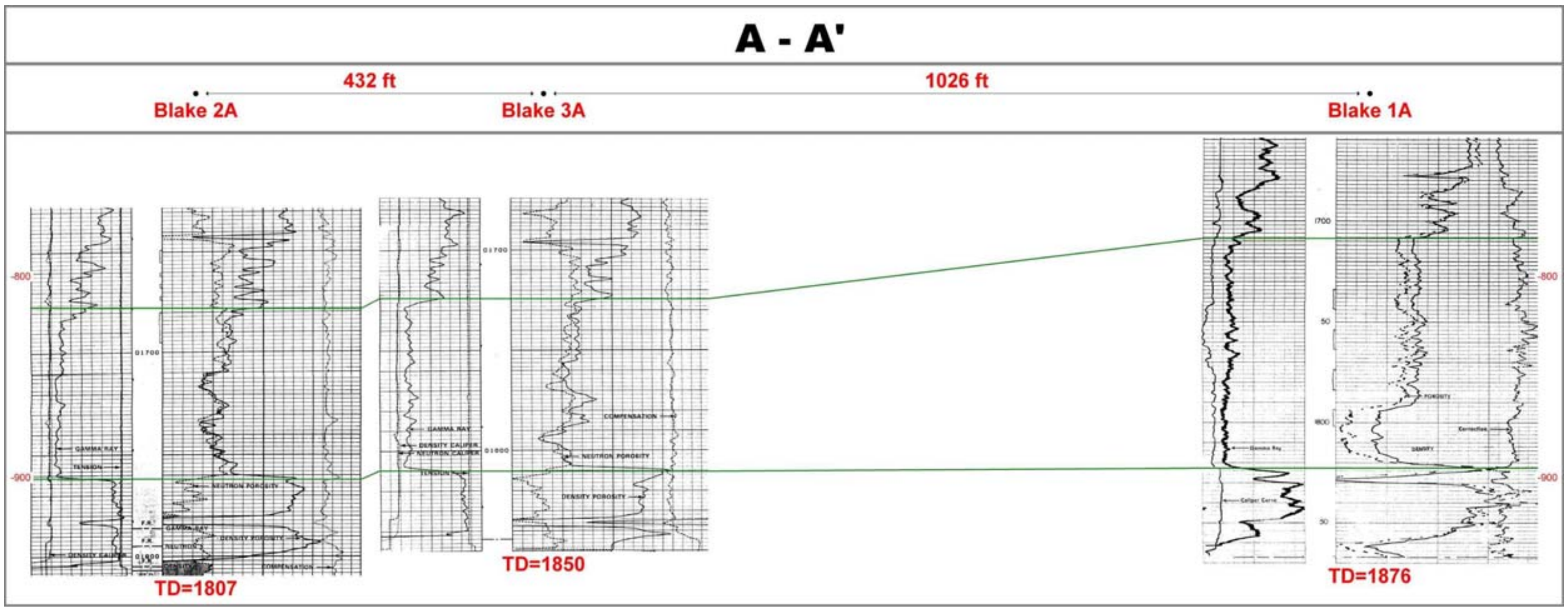


Figure 11:
Predicted Producing Rates from a Horizontal Waterflooding Project in the Wolco Field

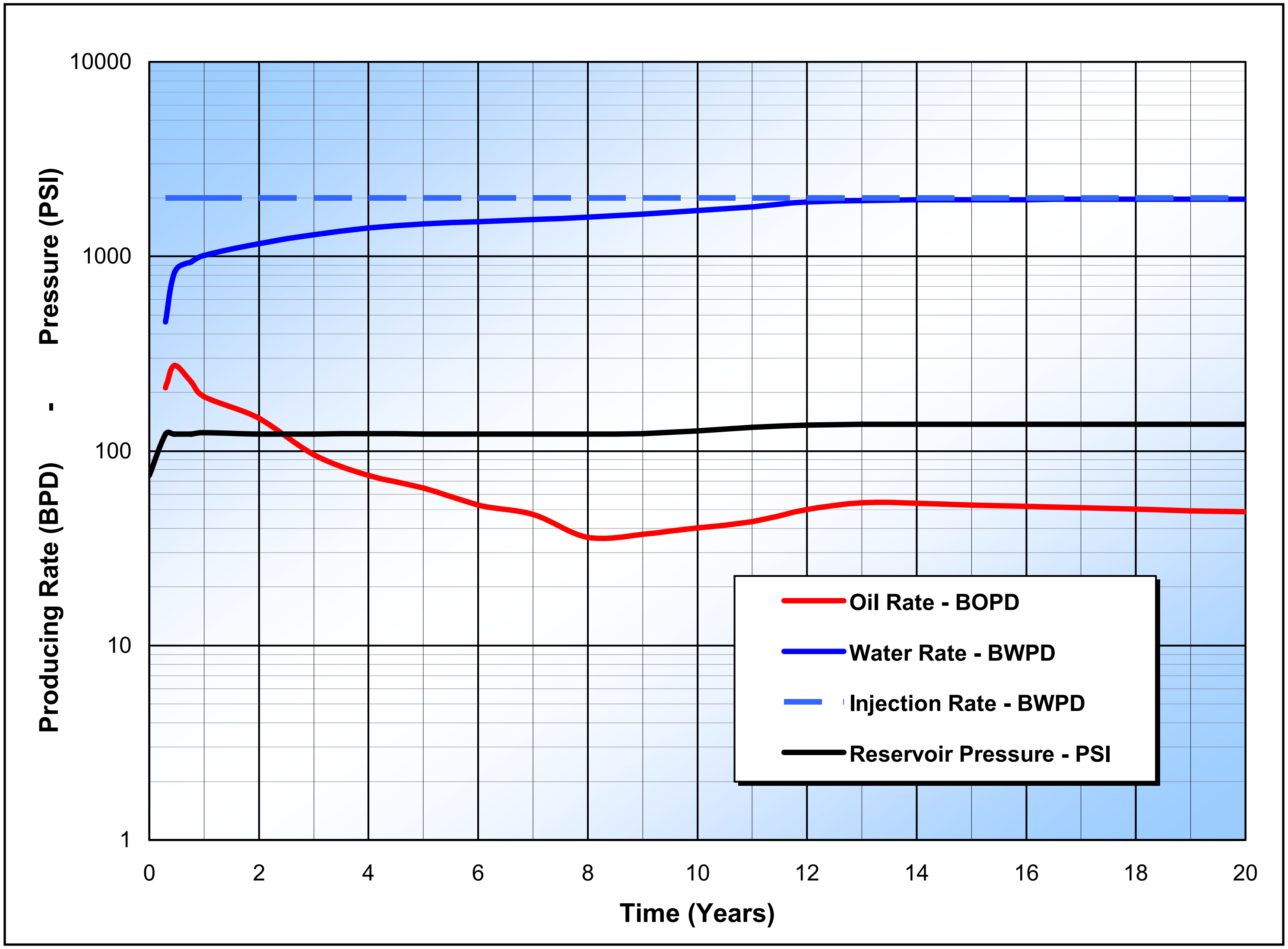


Figure 12:
Predicted Cumulative Production from a Horizontal Waterflooding Project in the Wolco Field

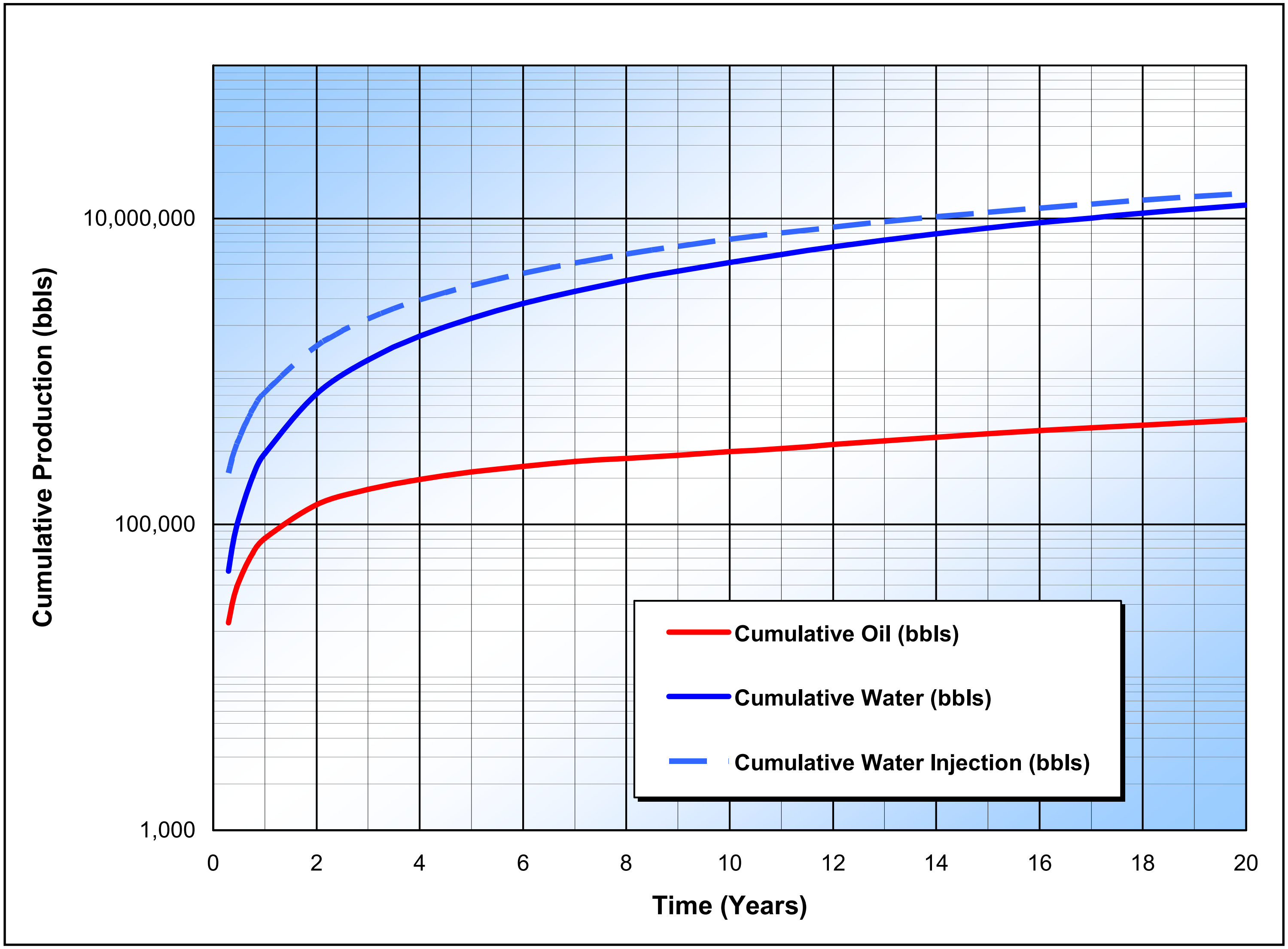


Figure 13:
Section and Plan Views: Wolco 4A

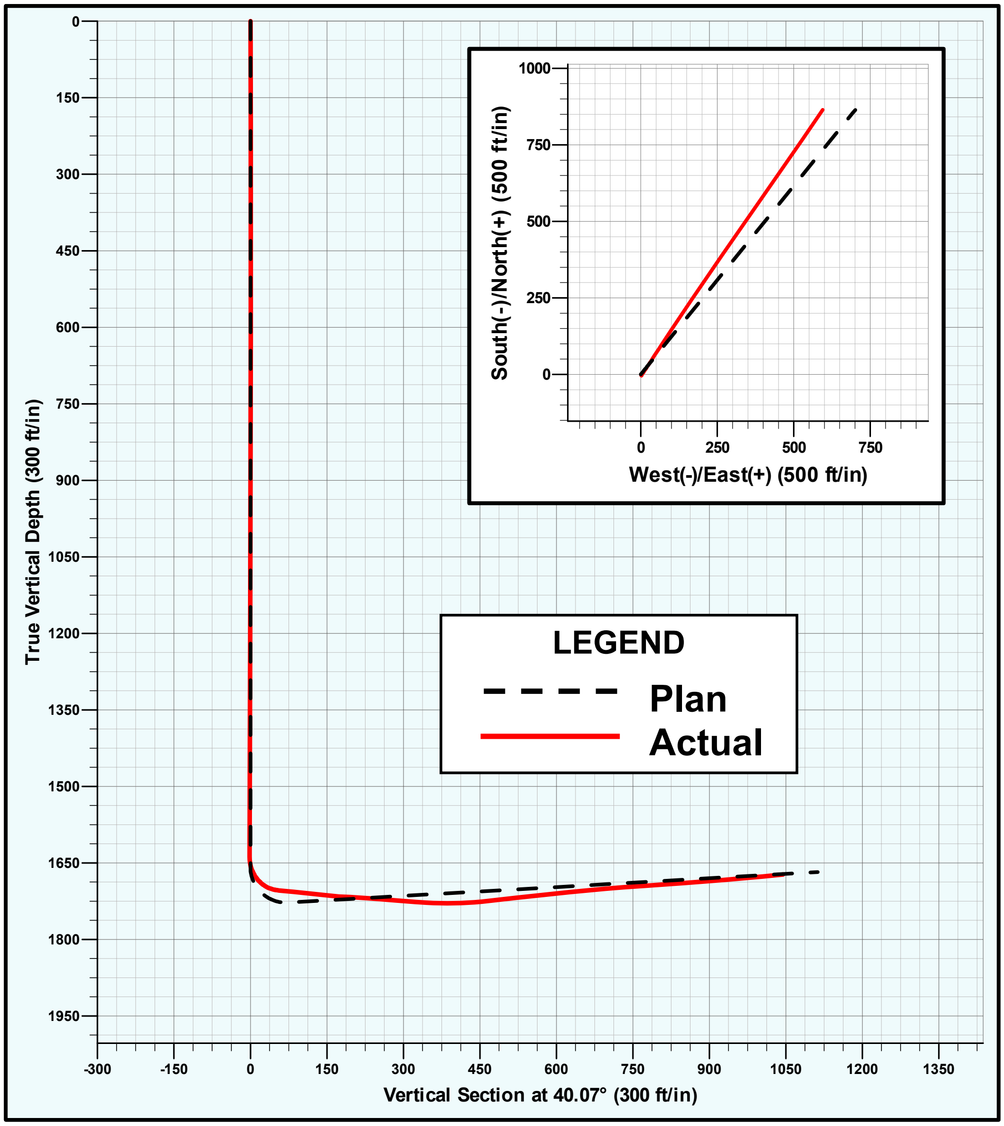


Figure 14:
Wolco 4A Density Log

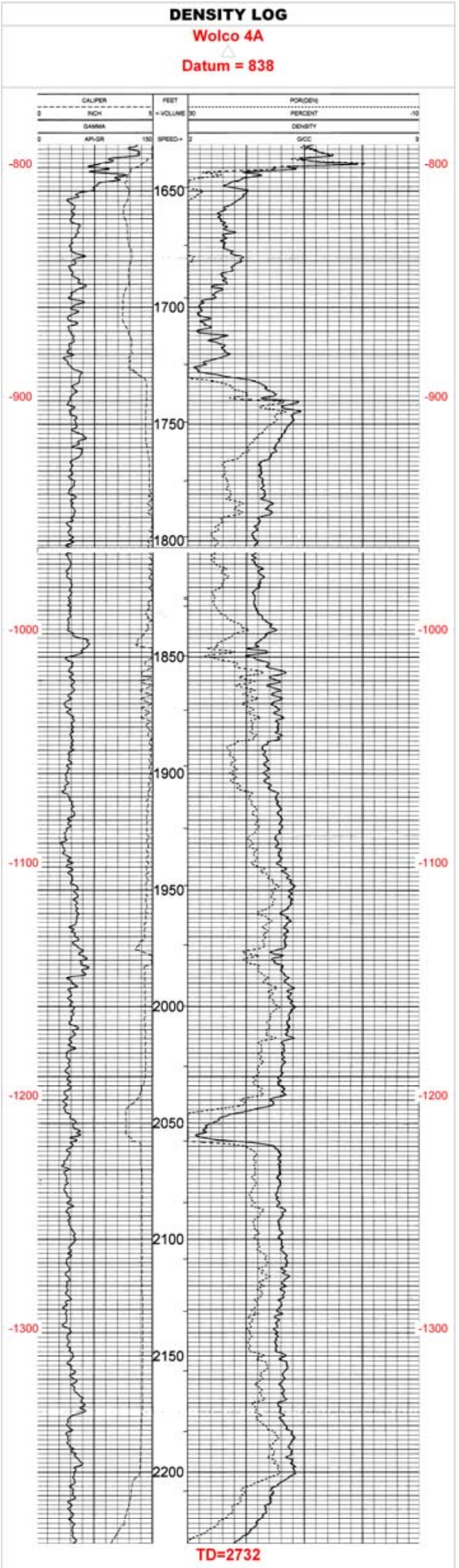


Figure 15:
Wolco 4A Induction Log

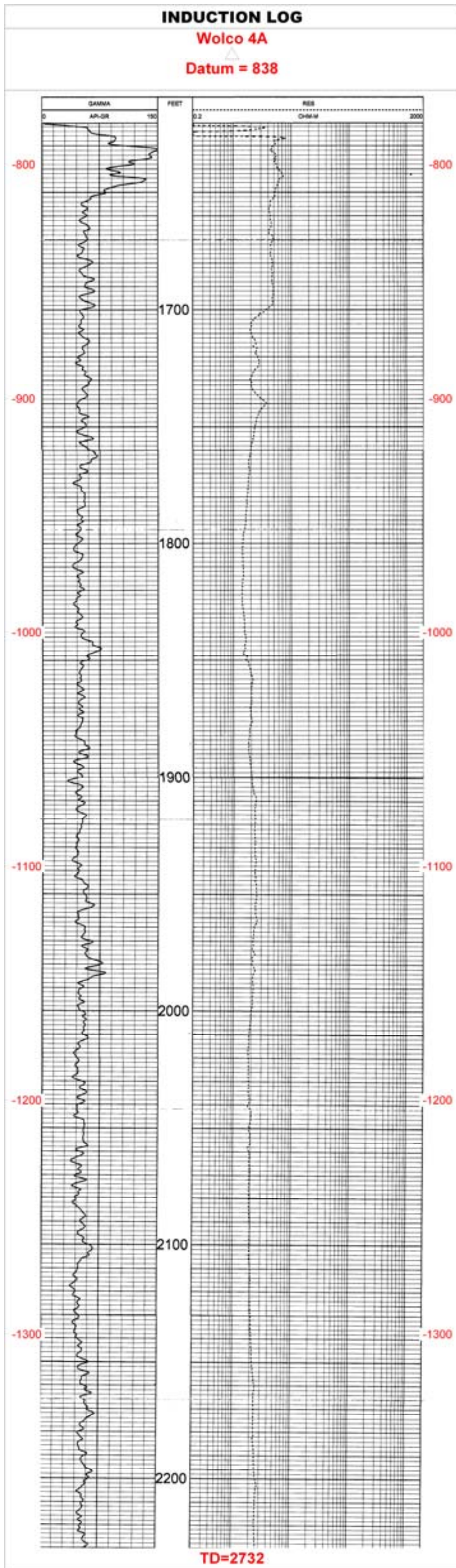


Figure 16:
Wolco 6A Density Log

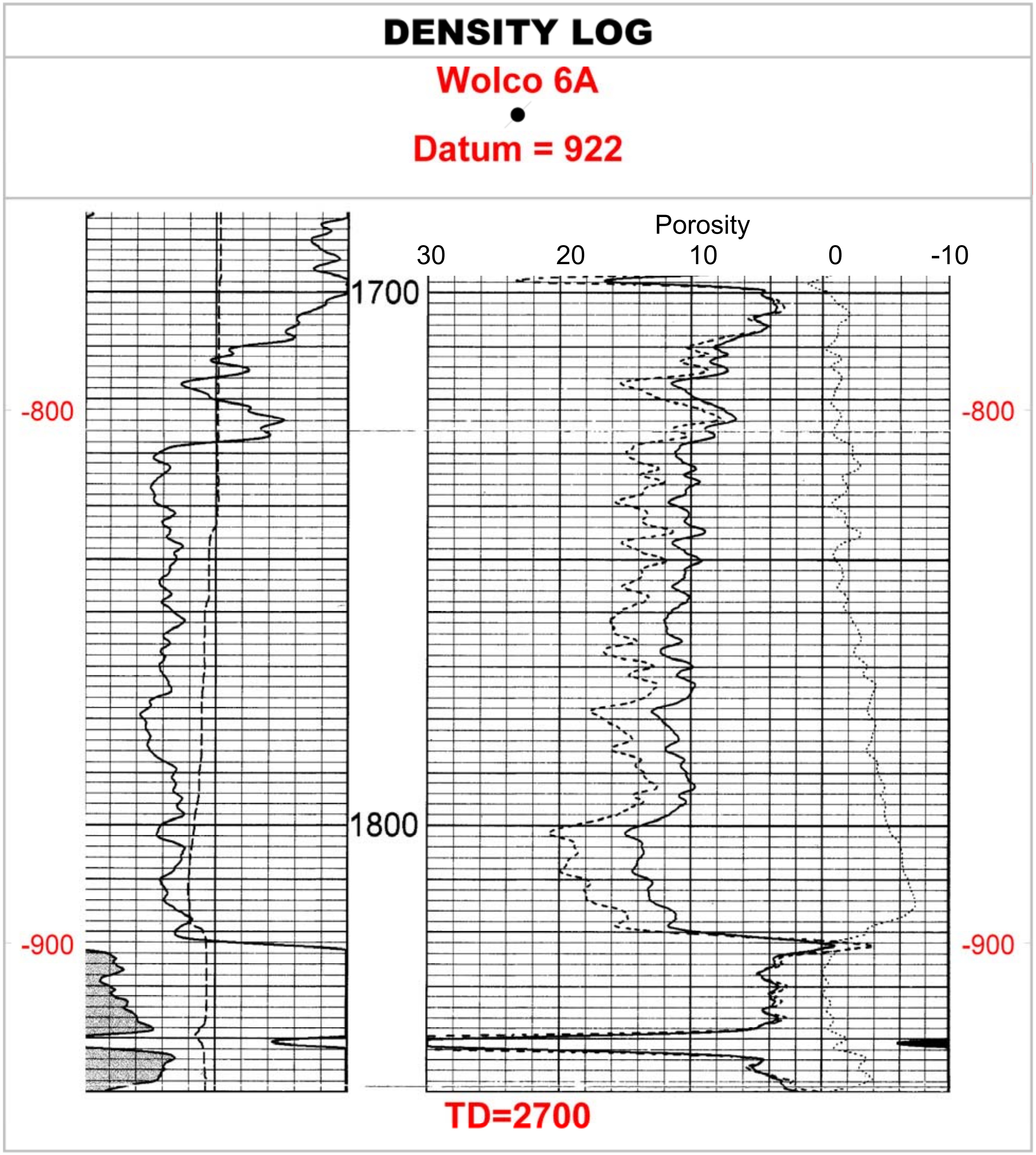


Figure 17:
Wolco 6A Induction Log

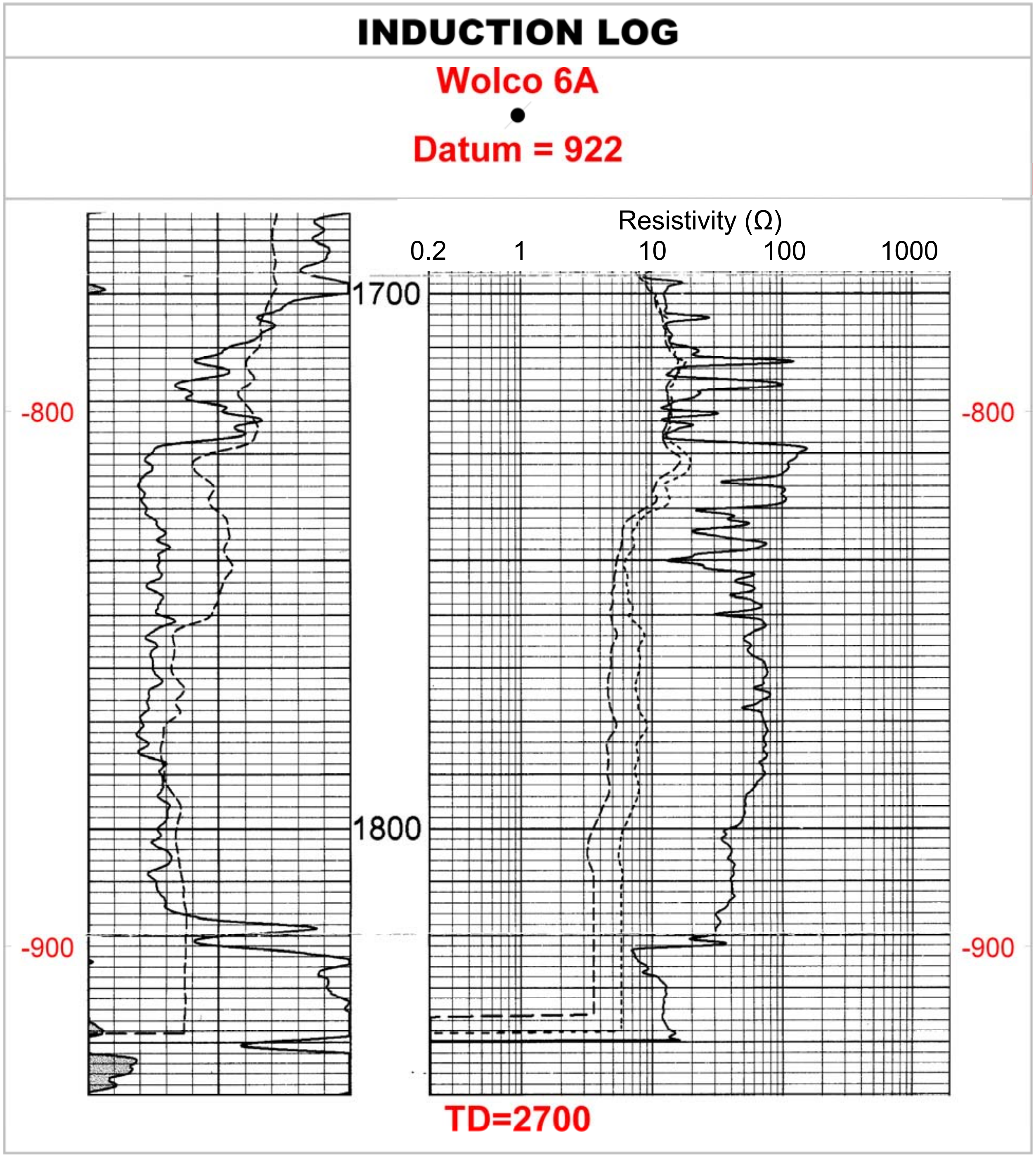


Figure 18:
Section and Plan Views: Wolco 6A

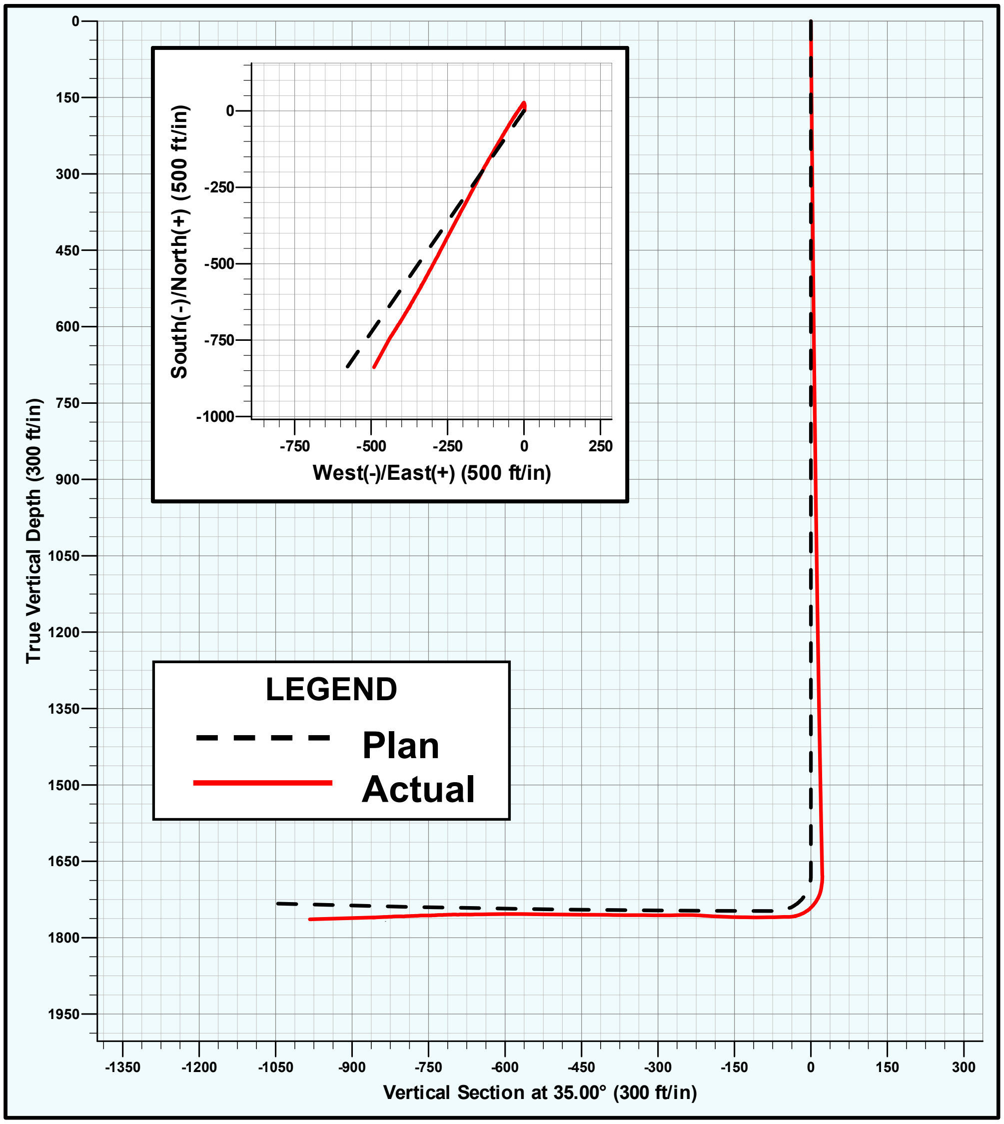


Figure 19:
Wolco 6A Density and Induction Log

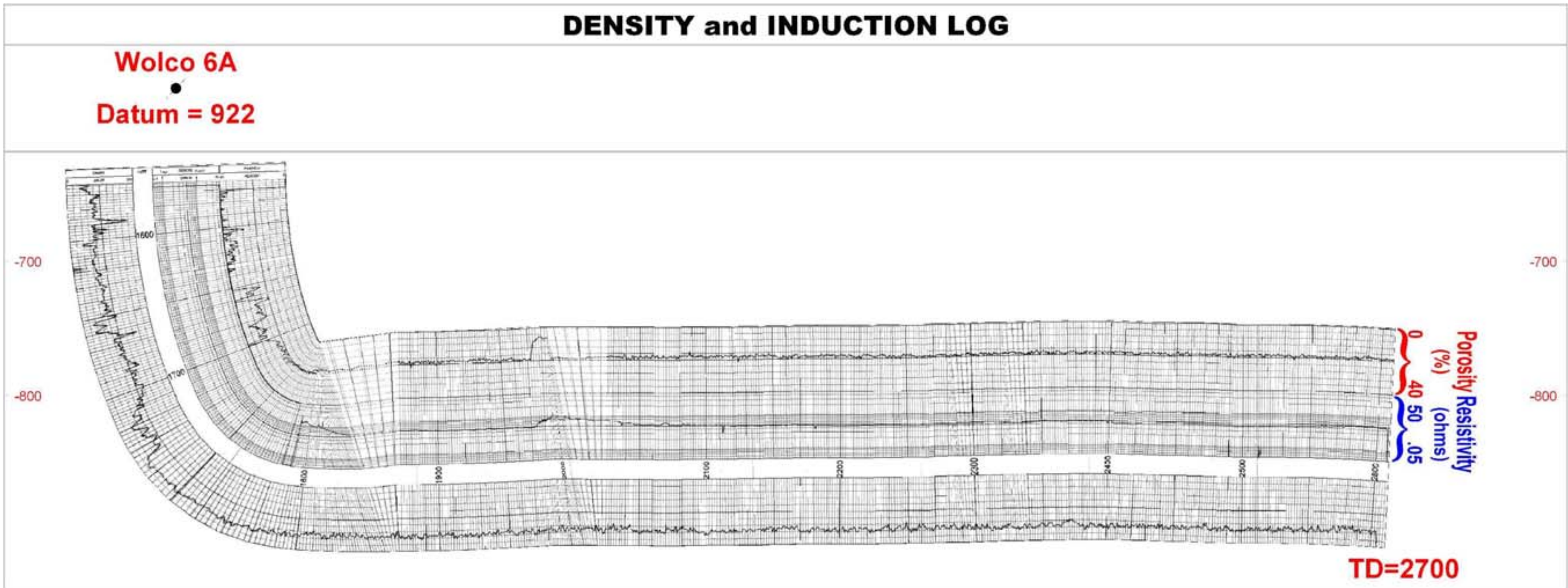


Figure 20:
Wolco 5A Density Log

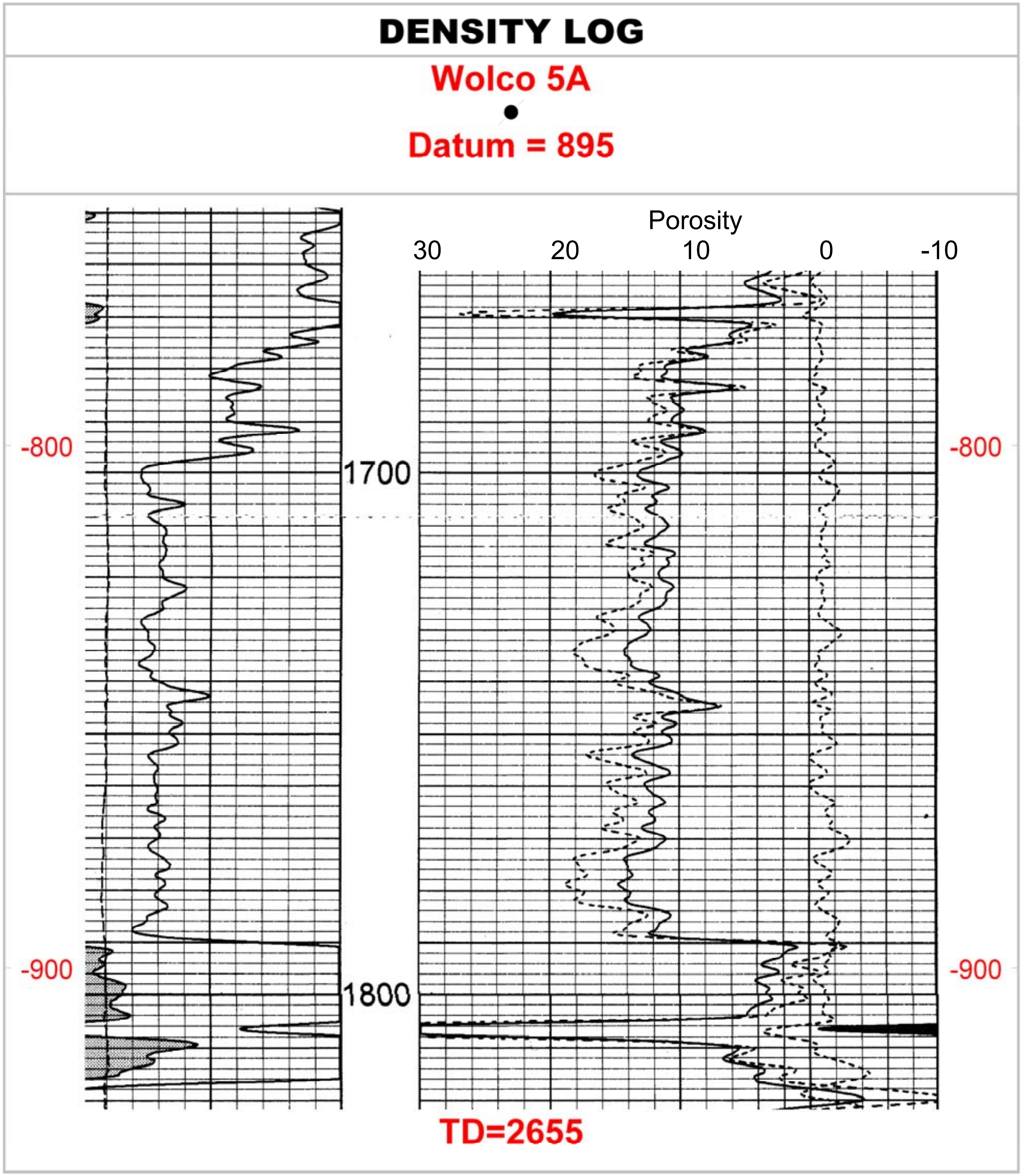


Figure 21:
Wolco 5A Induction Log

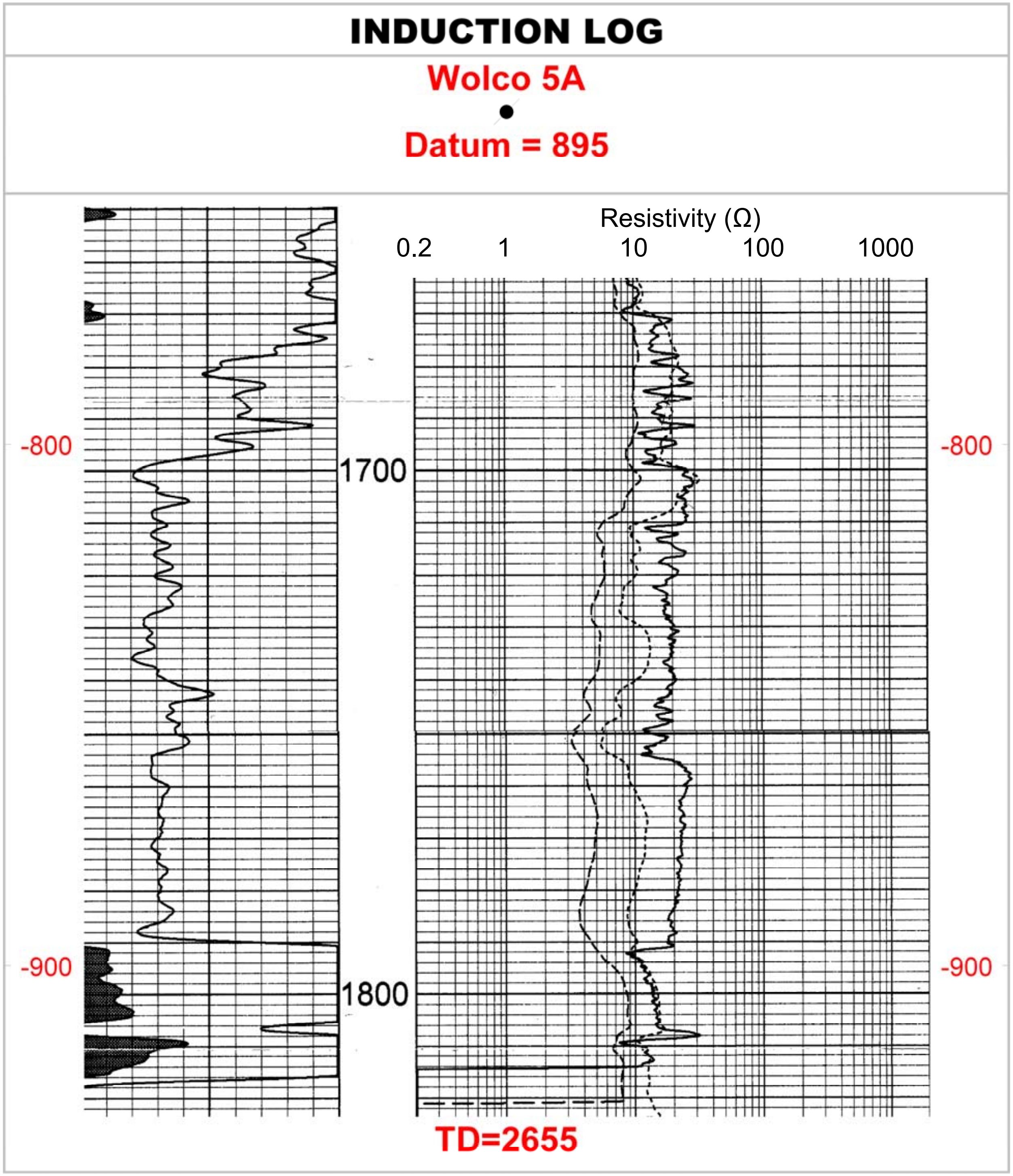


Figure 22:
Section and Plan Views: Wolco 5A

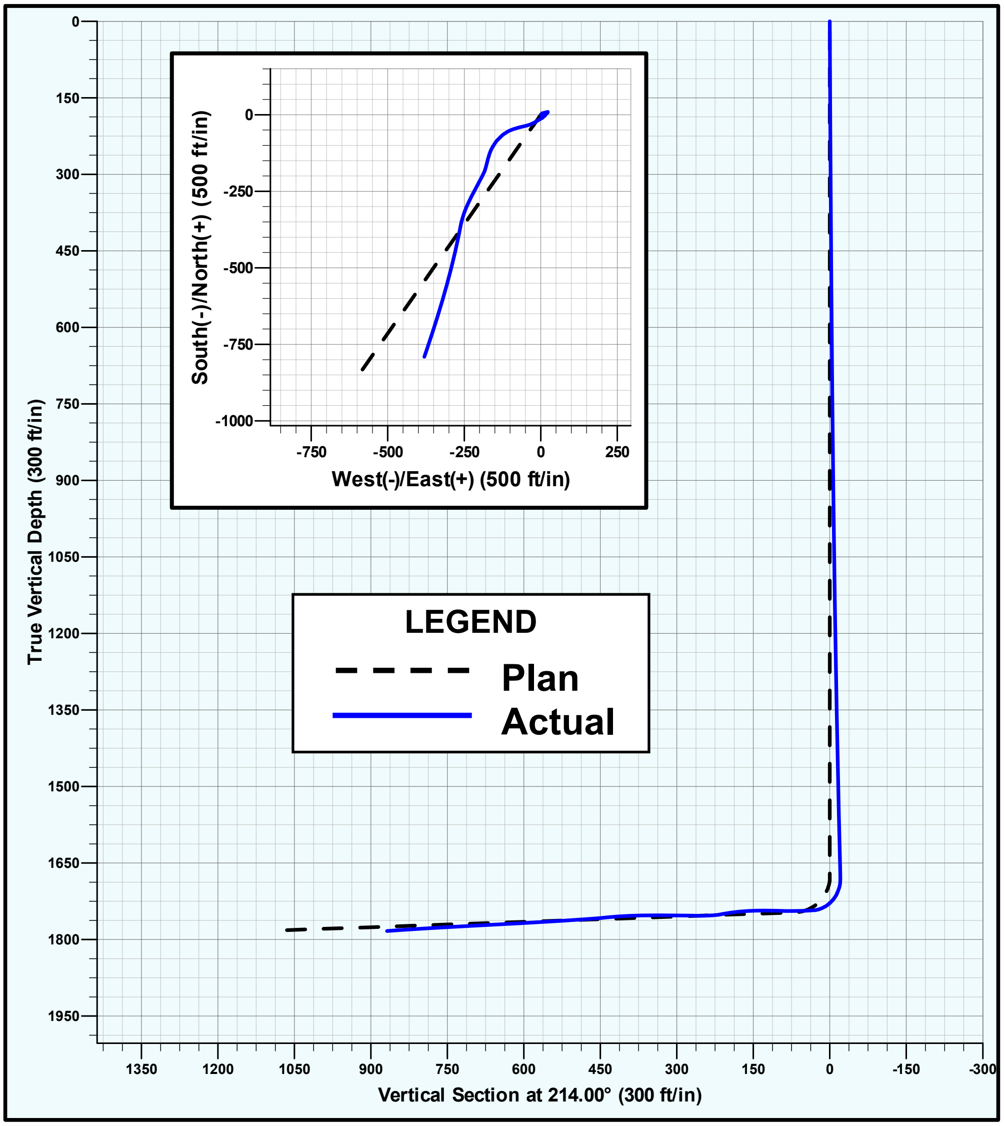


Figure 23:
Wolco 5A Density Log of Lateral Wellbore

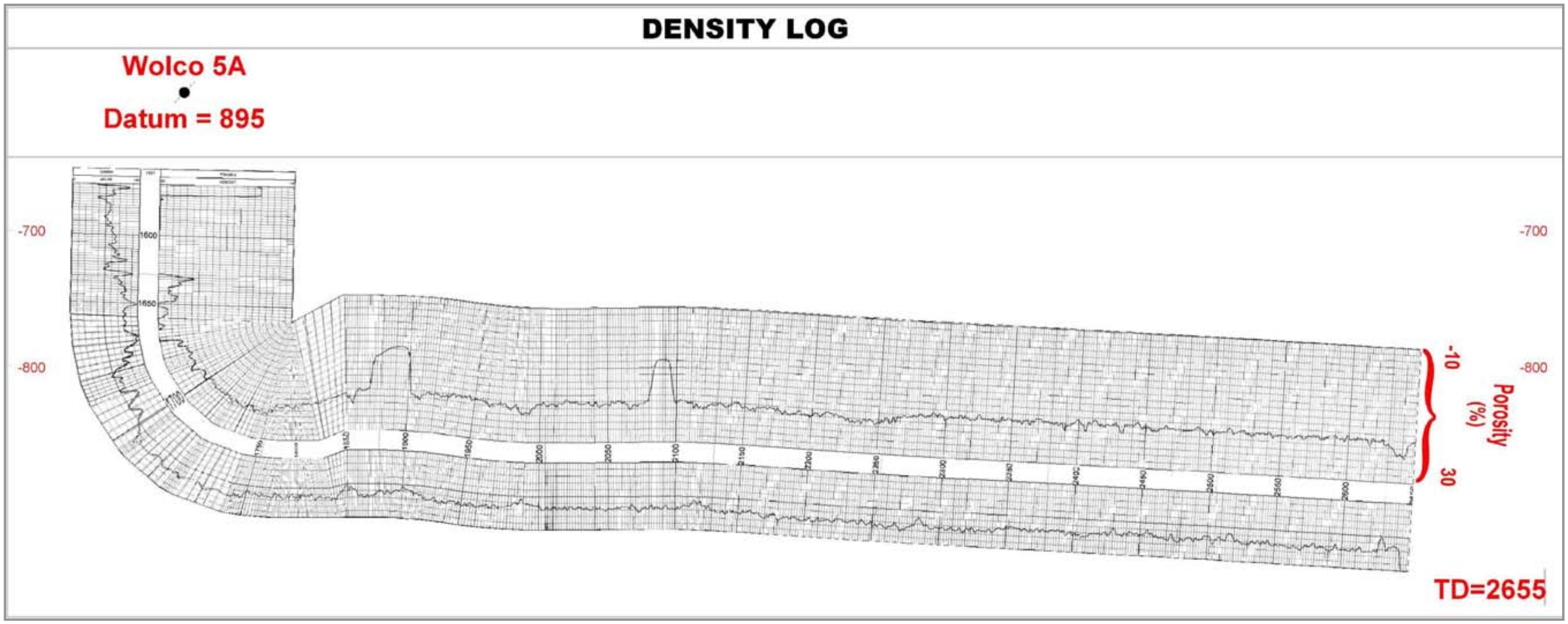


Figure 24:
Wolco 5A Induction Log of Lateral Wellbore

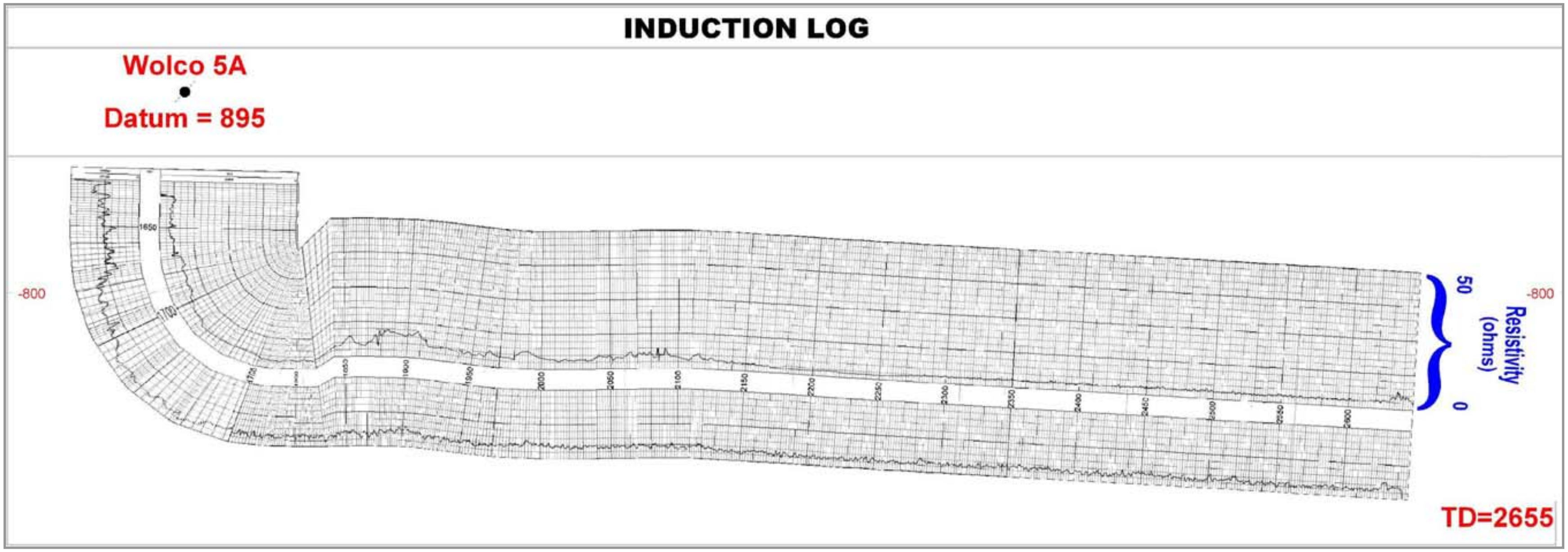


Figure 25:
Wolco Surface Use Map

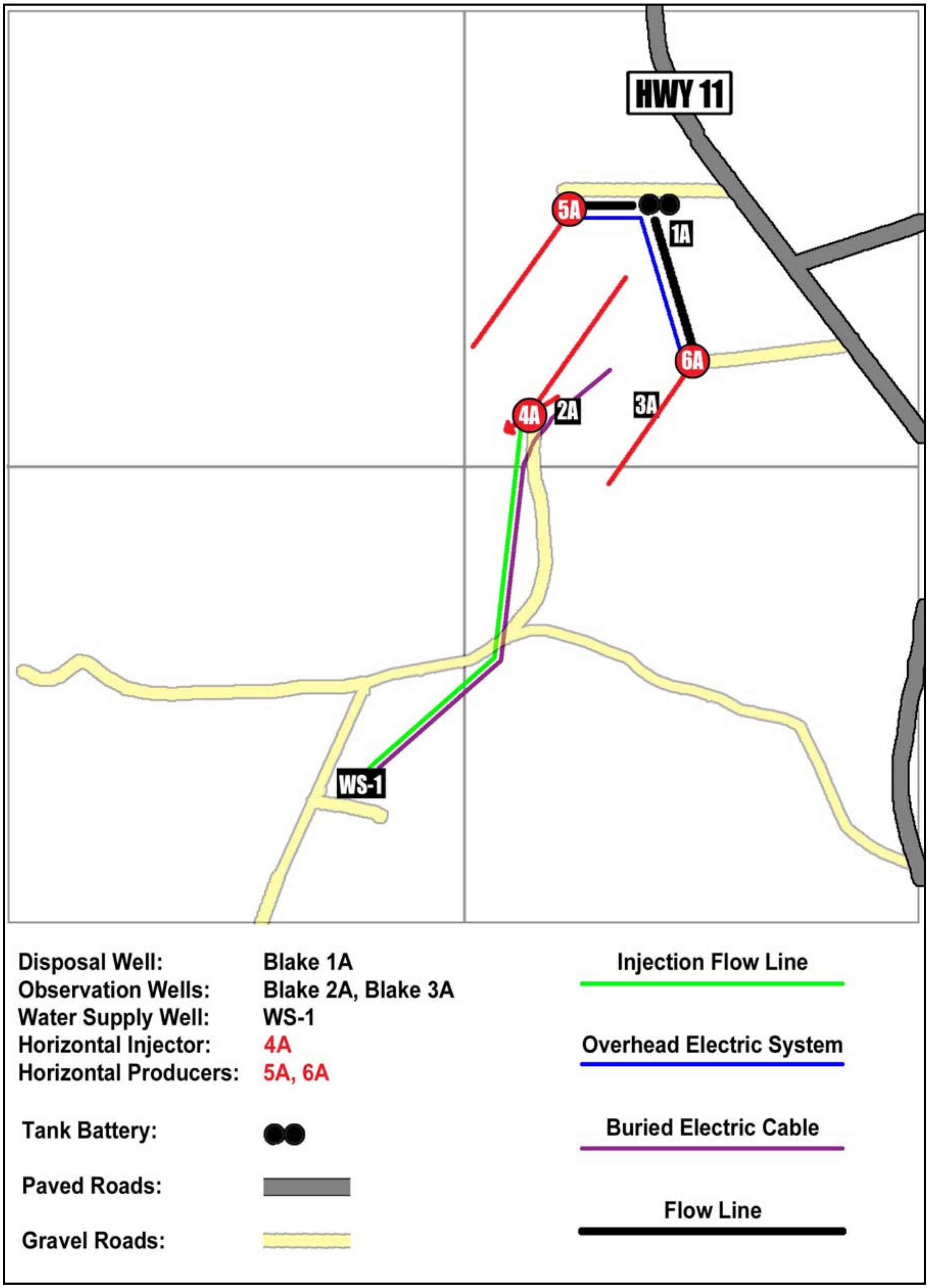


Figure 26:
Step-Rate Test: Wolco 4A

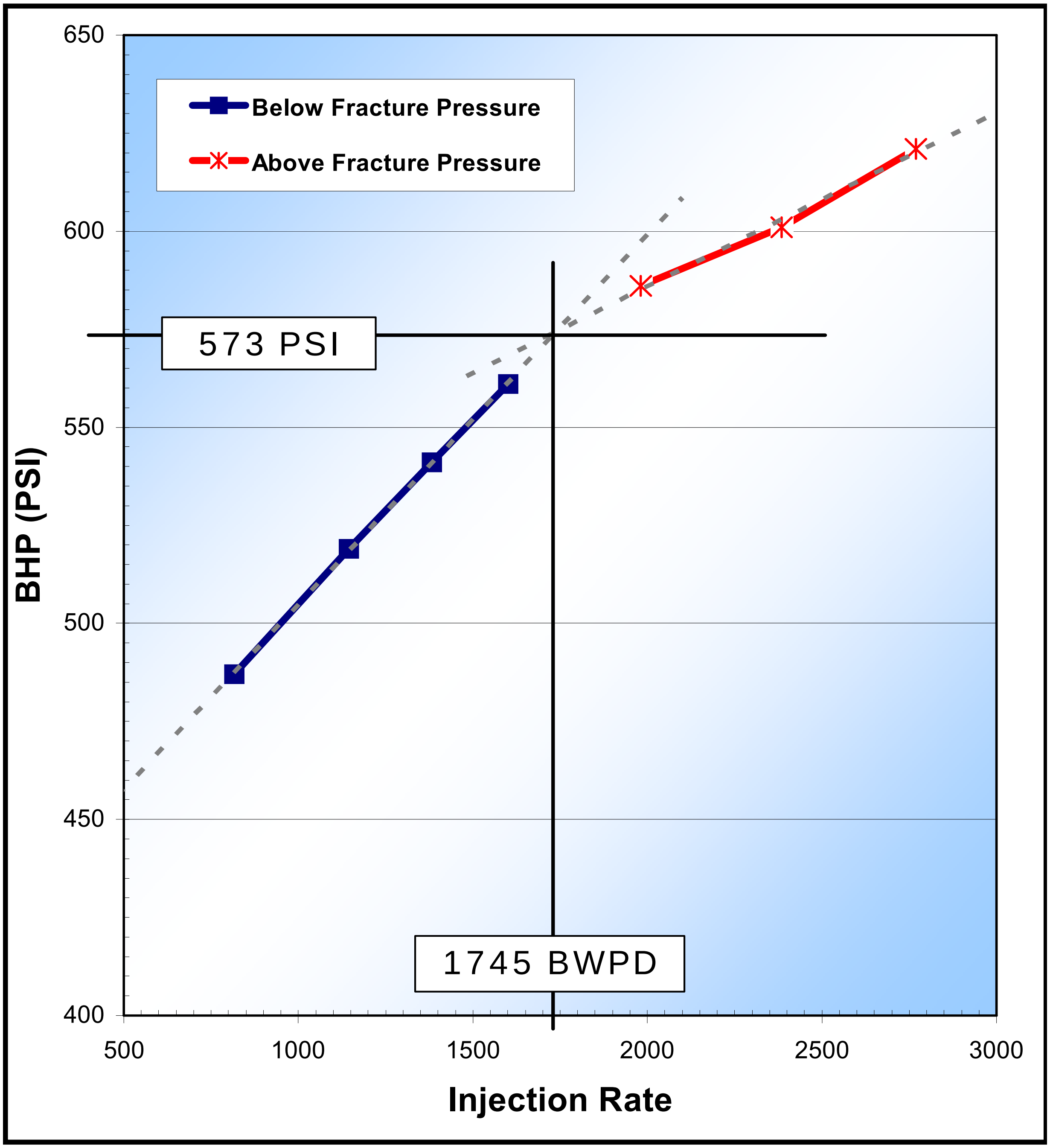


Figure 27:
Step-Rate Test: Blake 1A

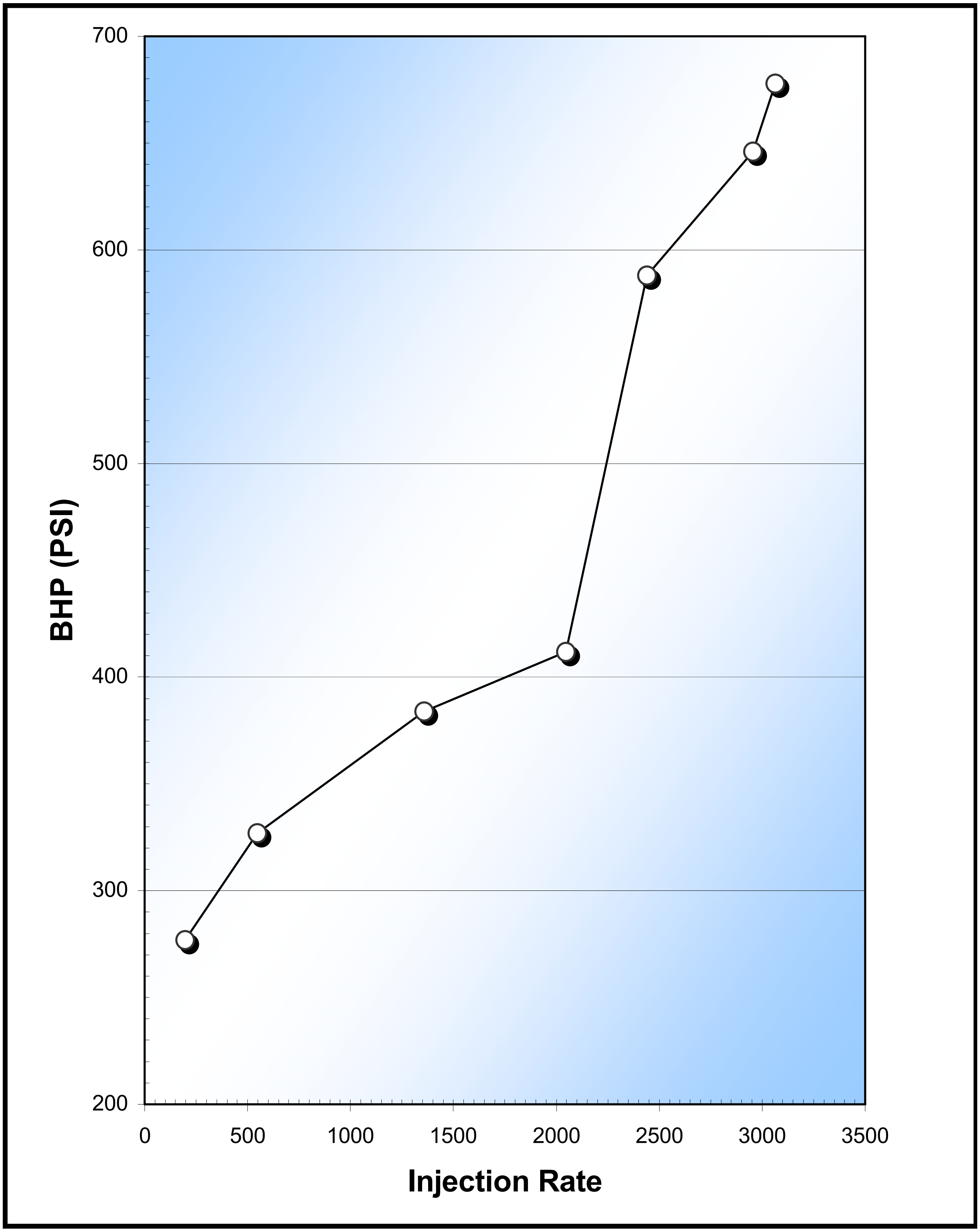
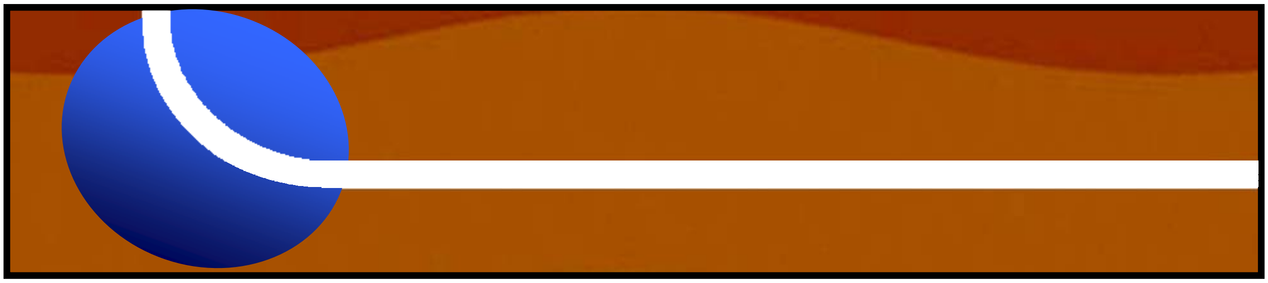


Figure 28:
Spinner Survey: Wolco 4A



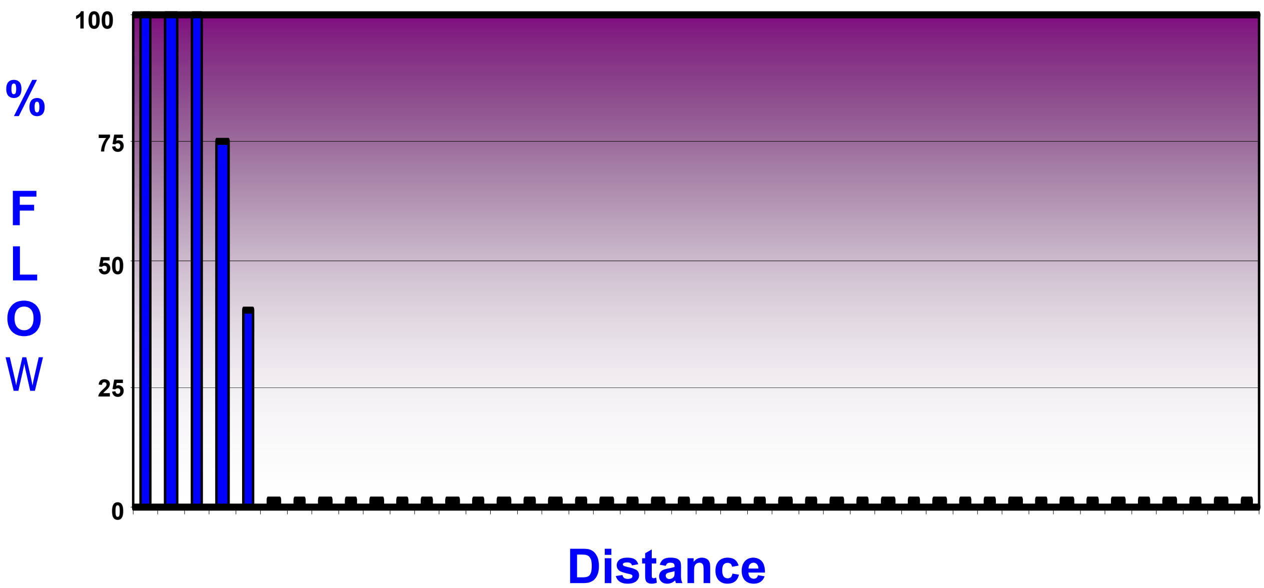


Figure 29:
Wolco 6A Oil Saturations

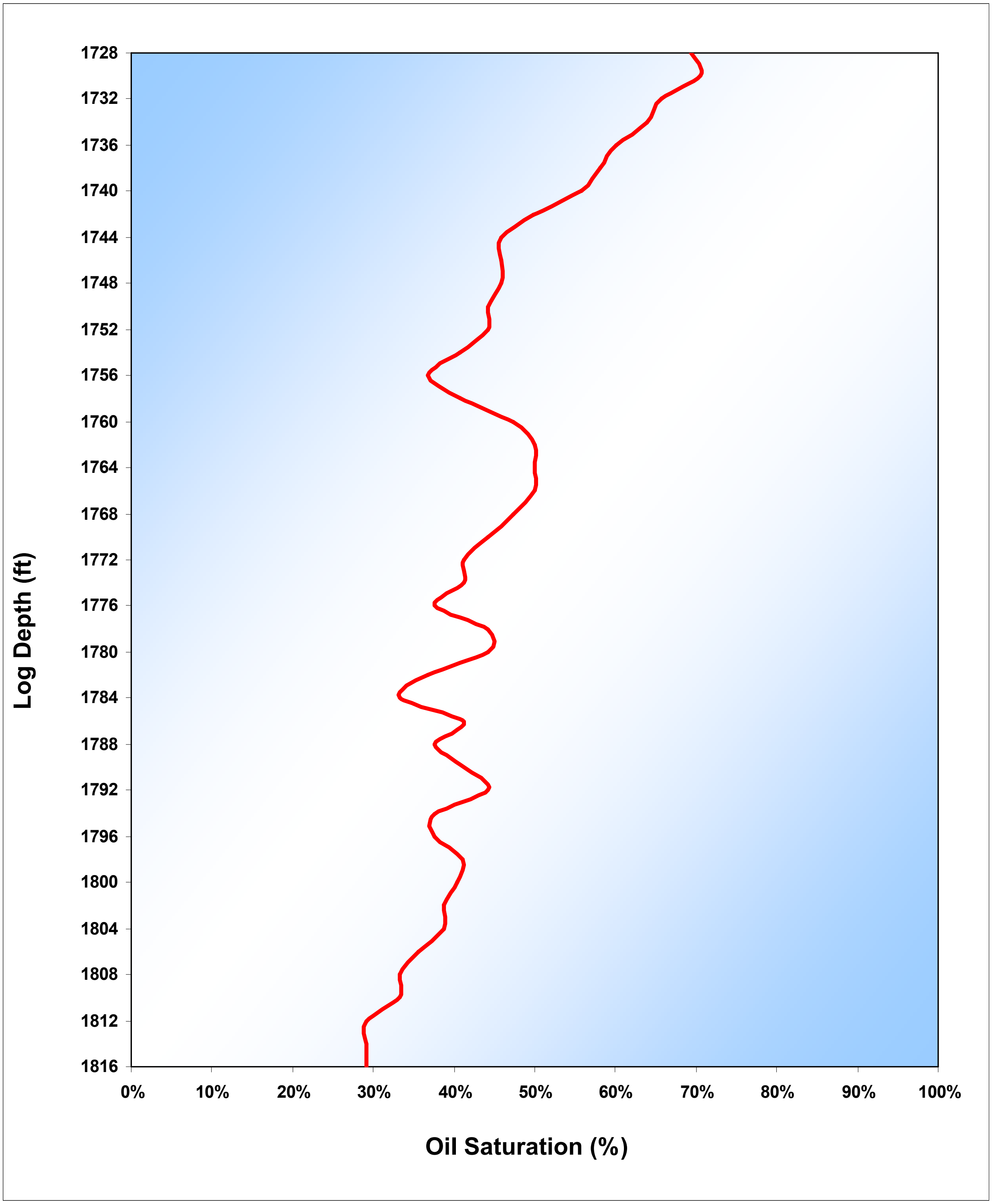


Figure 30:
Configuration of the Original and Modified Wolco Pilots

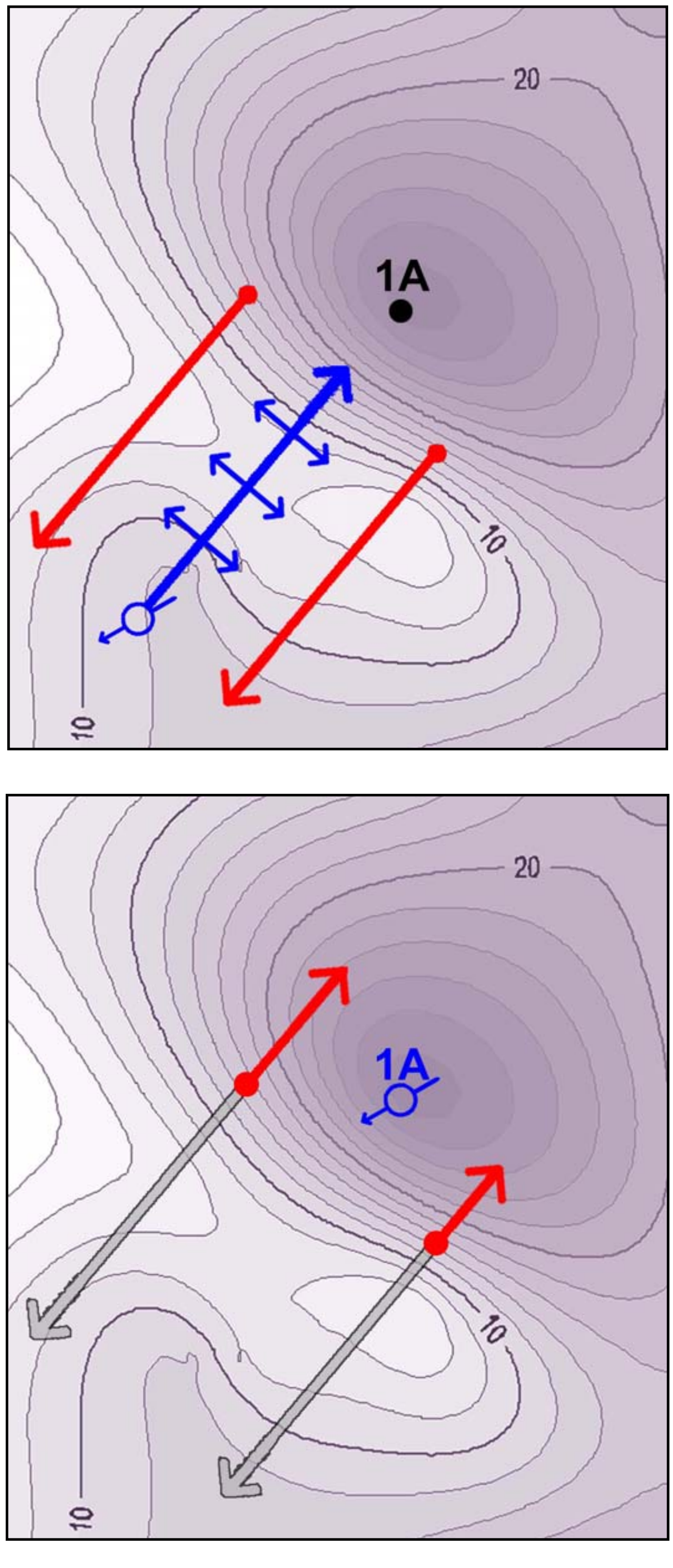


Figure 31:
Section and Plan Views: Wolco 6A-4

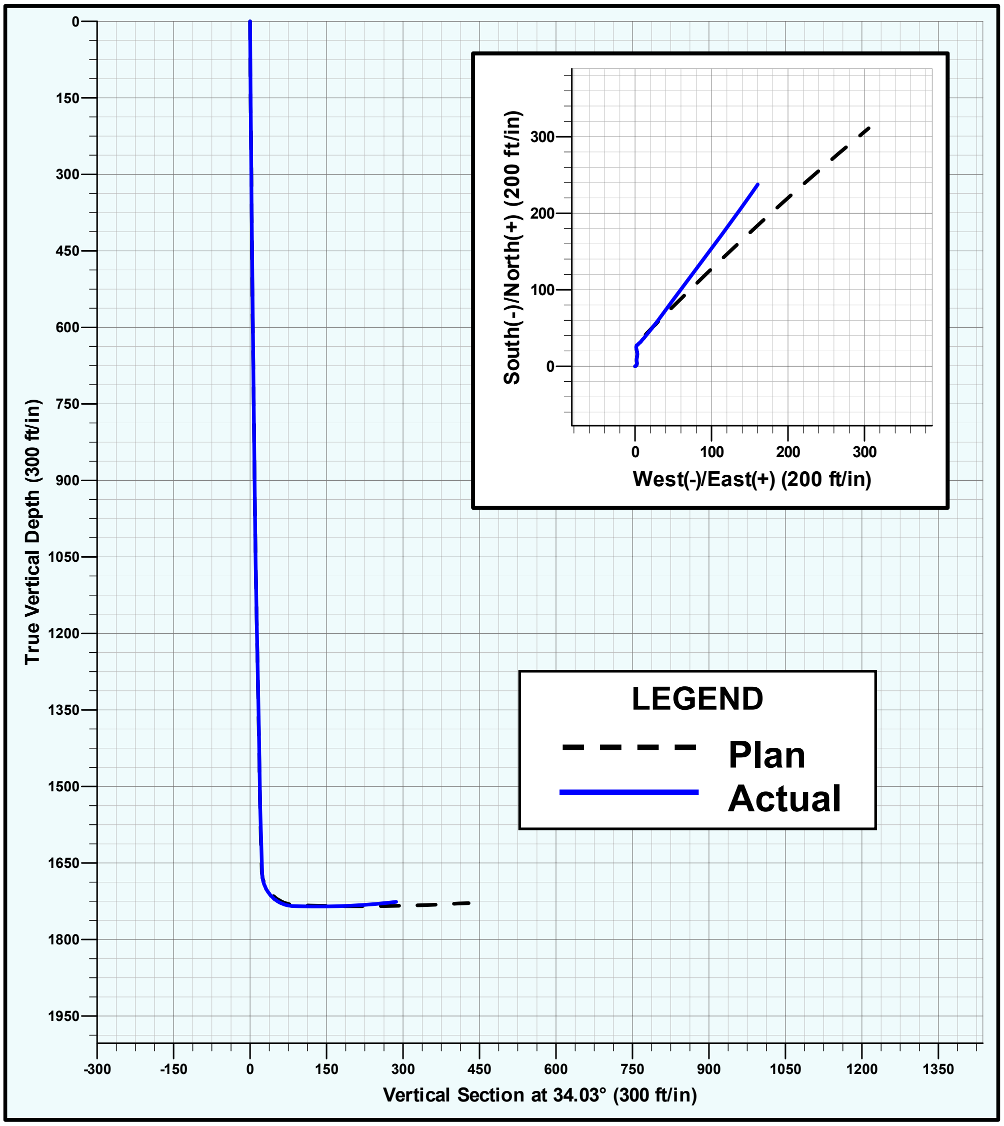


Figure 32:
Section and Plan Views: Wolco 6A and 6A-4

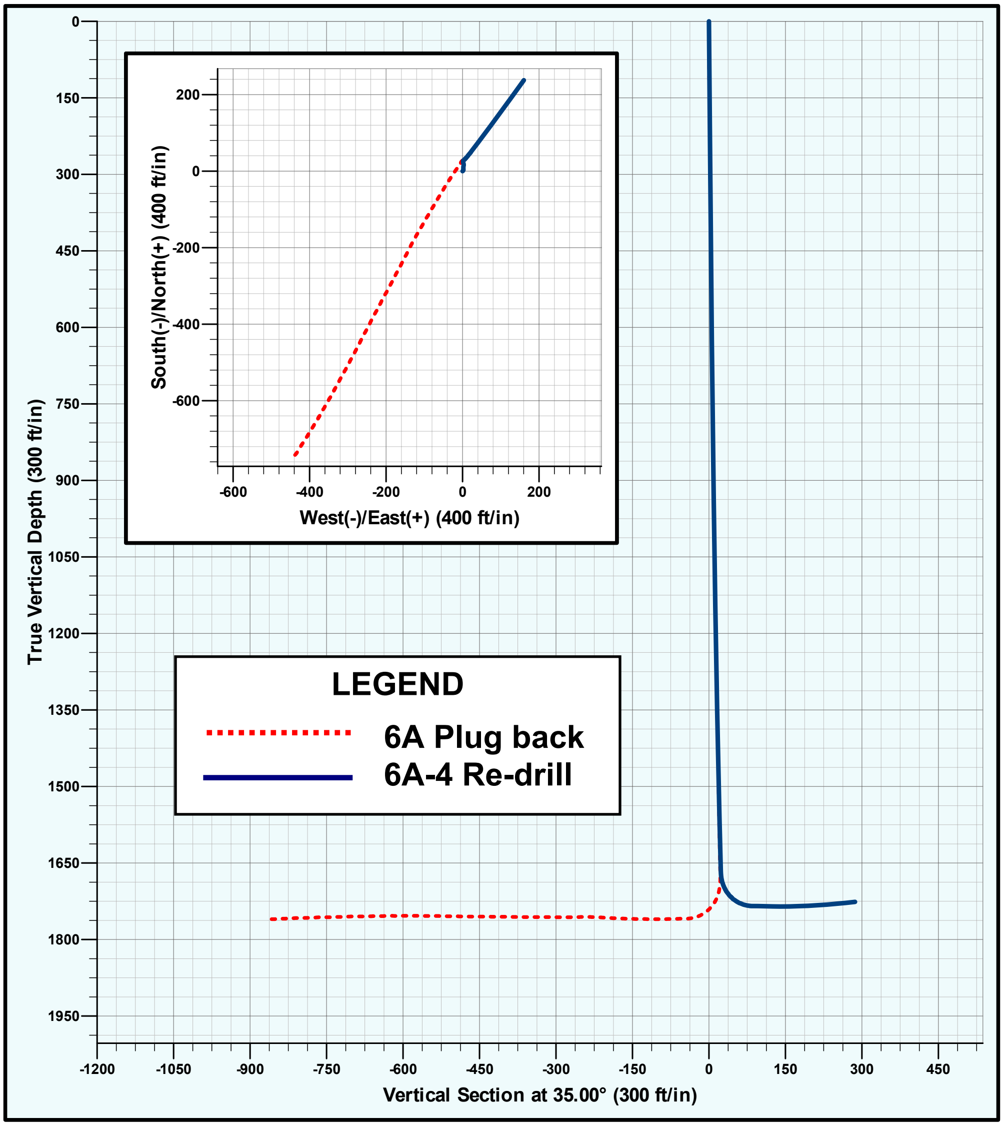


Figure 33:
Wolco 6A-4, Gamma/Density/Guard Log

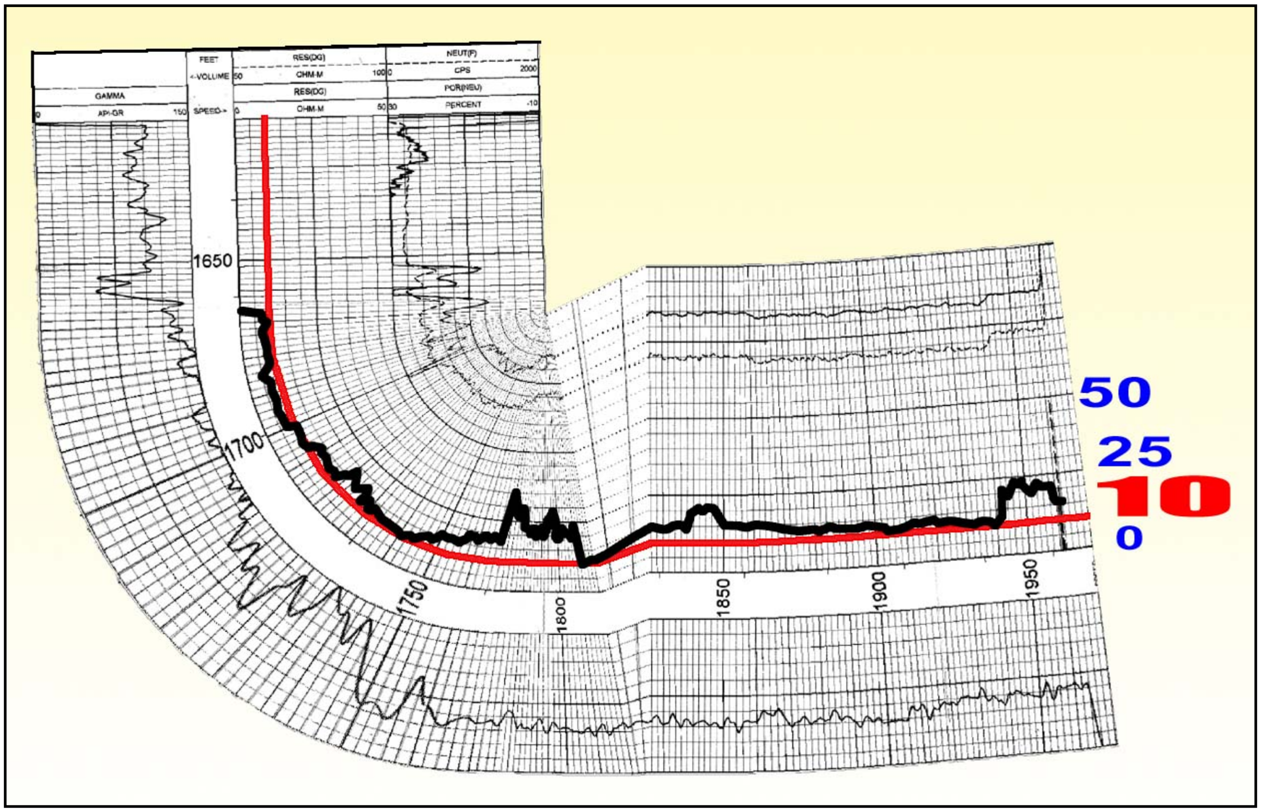


Figure 34:
Section and Plan Views: Wolco 5A-4

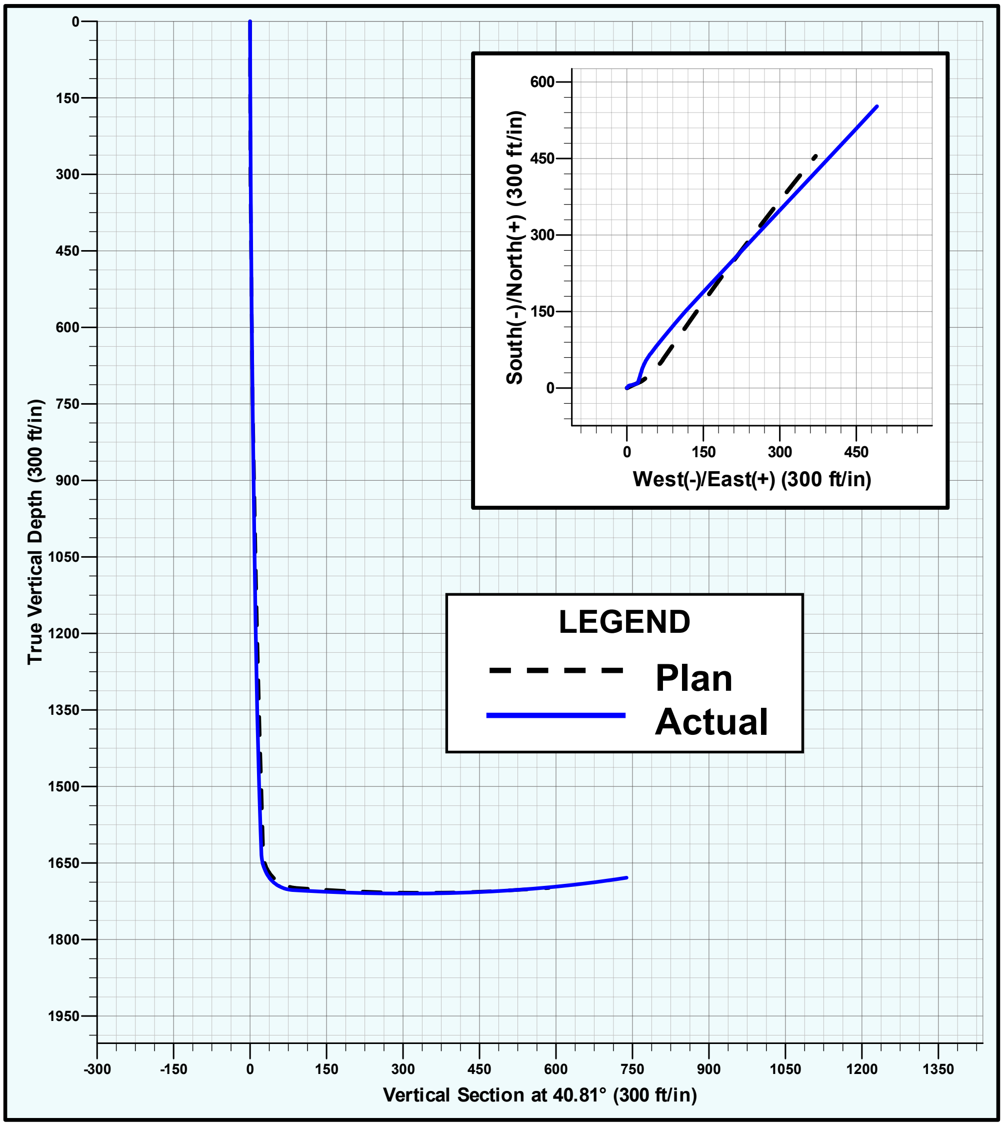


Figure 35:
Section and Plan Views: Wolco 5A and 5A-4

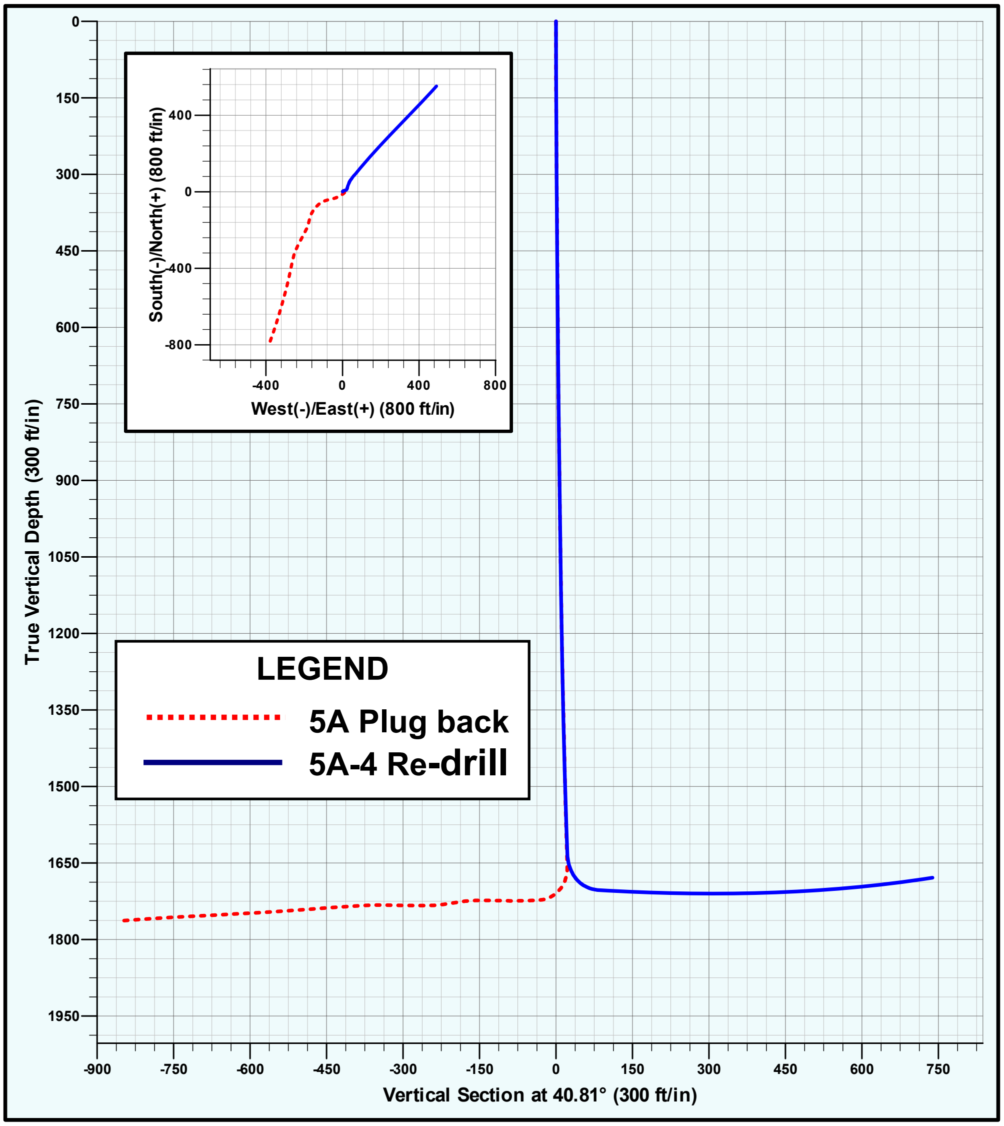


Figure 36:
Updated Simulation Results

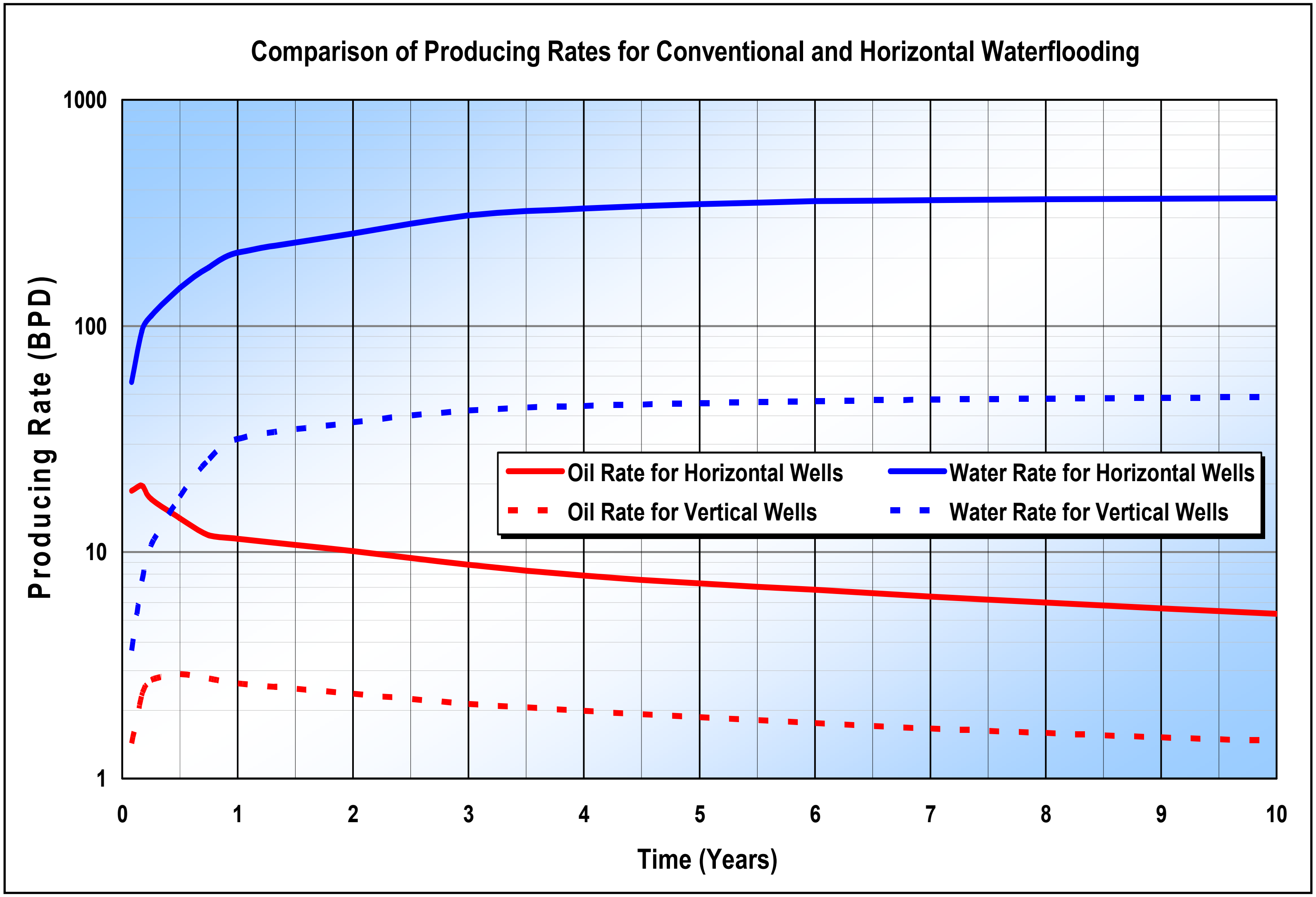


Figure 37:
Production from the Wolco and Avant Pilots

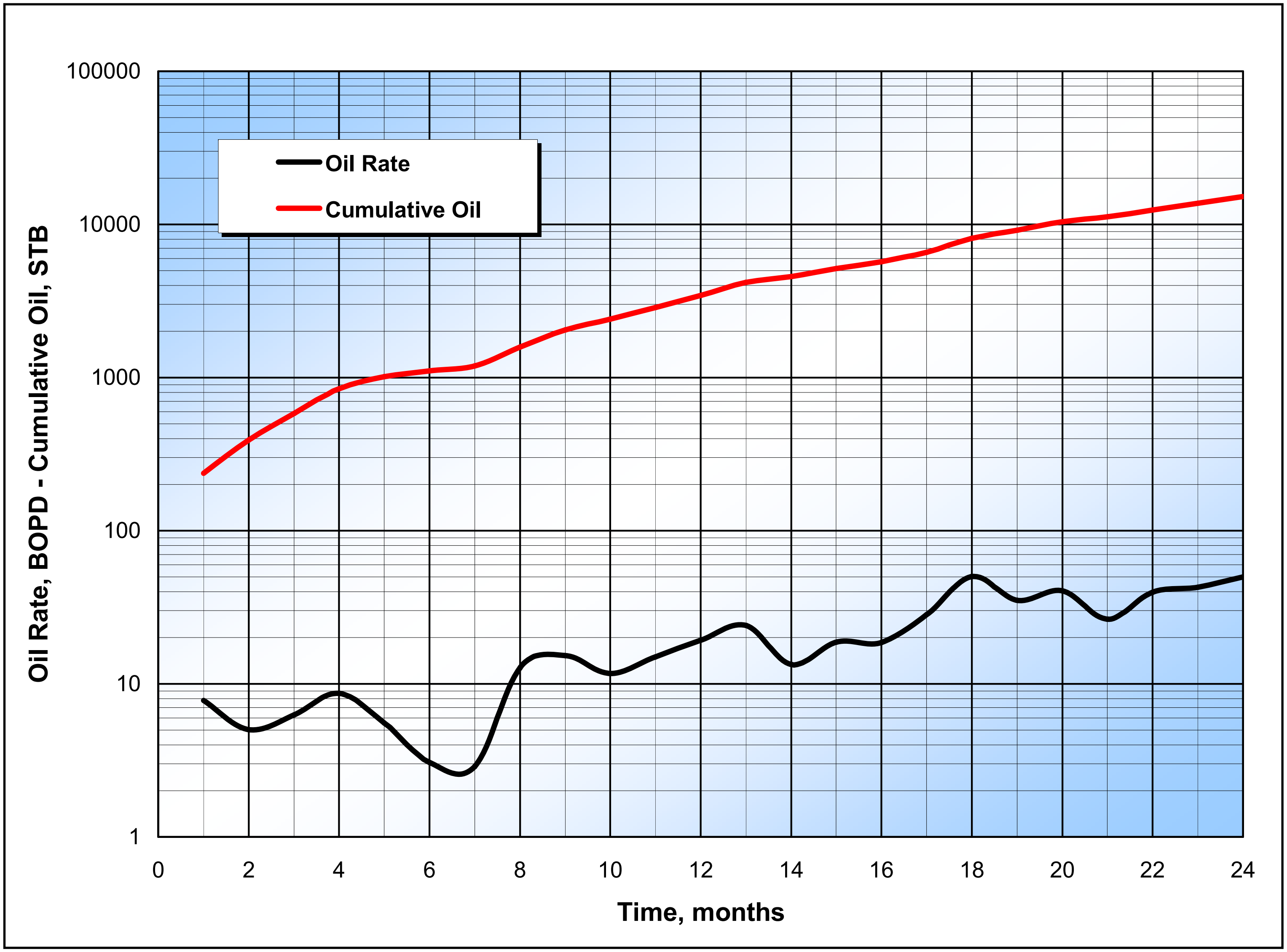


Table 1:
Time Line of Major Events

Date	Event
September 2002	Signing of contract with DOE
October-November 2002	Evaluation of pilot area in the Woolaroc Field, including coring of vertical well
March 2003	Woolaroc considered unsuitable; move to alternative location in the nearby Wolco Field
March-April 2003	Evaluation of new pilot area in the Wolco Field
April-June 2003	Drilling, logging, and completion of horizontal injection well, Wolco 4A
August 2003	Drilling, logging, and completion of horizontal producing well, Wolco 6A
August 2003	Work with the EPA in the permitting of the horizontal 4A injection well and disposal of water into the vertical 1A well
August 2003	Work with the Osage Nation In the reactivation of Water Supply Well #1
September-October 2003	Drilling, logging, and completion of horizontal producing well, Wolco 5A
September-December 2003	Installation of surface facilities
December 29, 2003	Horizontal waterflooding pilot initiated
February 2004	Step-rate test conducted in horizontal injection well 4A
April 2004	Spinner survey conducted in horizontal injection well 4A; 4A shut-in
July-August 2004	Re-drilling and logging of horizontal producer 6A
August 2004	One-year no cost extension received from DOE
September-October 2004	Re-drilling and logging of horizontal producer 5A
January 1, 2004 to present	Production from Wolco’s original and modified pilot
May 2006	Completion of final report

Table 2
Summary of Technology Transfer Activities

Date	Event	Activity
Periodic	Creation and updating of website Contacts with Joe Hughlett of the Osage Tribe Contacts with Lance Cole of PTTC	Update of DOE sponsored project
September 2002	Booth at Osage Nation's 1st Annual Oil & Gas Summit, Tulsa	Contacts with independent operators about horizontal waterflooding
May 8, 2003	Marginal Oil and Gas Well Commission Technology Trade Fair, Oklahoma City	Contacts with independent operators about horizontal waterflooding
September 2003	Booth at Osage Nation's 2nd Annual Oil & Gas Summit, Tulsa	Contacts with independent operators about horizontal waterflooding
February 2004	Osage Producers Association Meeting, Pawhuska	Presentation of horizontal waterflooding activities
March 2004	Article in World Oil	Discussion of DOE sponsored project
April 17-21, 2004	SPE Paper 89373 at IOR Conference, "Enhanced Oil Recovery with Horizontal Waterflooding, Osage County, Oklahoma", Tulsa	Presentation results from DOE sponsored project
September 2004	Article in the *American Oil and Gas Reporter*	Project progress update
September 2004	Eastern Kansas Oil and Gas Association, Chanute, Kansas	Presentation of horizontal waterflooding activities
September 2004	Booth at Osage Nation's 3rd Annual Oil & Gas Summit, Tulsa	Contacts with independent operators about horizontal waterflooding
April 17-19, 2005	SPE Paper 94094, "Increased Production Results From Pilot Horizontal Waterflood in Osage County, Oklahoma", Oklahoma City	Presentation of results from DOE sponsored project
May 2005	Marginal Oil and Gas Well Commission Technology Trade Fair, Oklahoma City	Contacts with independent operators about horizontal waterflooding
October 2005	Osage Nation's 4th Annual Oil & Gas Summit, Tulsa	Presentation of horizontal waterflooding activities
November 2005	SPE Mid-Continent Section meeting, Tulsa	Presentation of horizontal waterflooding activities
March 17-20, 2006	Four workshops held by Marginal Oil and Gas Well Commission, Ardmore, Pawhuska, Oklahoma City, Tulsa	Presentation to independent operators on horizontal waterflooding
March 29, 2006	SPE students dinner meeting in Lawrence, Kansas	Presentation of horizontal waterflooding activities
April 24-26, 2006	SPE 99668 at IOR Conference, "Application of Horizontal Waterflooding to Improve Oil Recovery from Old Oil Fields", Tulsa Vendor update Independents day at IOR Conference	Presentation of horizontal waterflooding experiences Presentation to a small group Presentation to independents
May 2006	Kansas Geological Society, Wichita	Presentation of horizontal waterflooding activities

Table 3
Routine Core Analysis on Woolaroc 85-22

Sample Number	Depth (ft)	Net Confining Pressure (psi)	Porosity (%)	Air Permeability (md)	Grain Density (g/cm^3)
1	1695.11	800	13.27	0.855	2.691
2	1696.50	800	13.66	1.41	2.639
3	1696.59	800	16.34	3.35	2.676
4	1698.55	800	16.48	<0.001	2.671
5	1699.00	800	13.90	0.751	2.683
6	1700.38	800	15.14	1.69	2.675
7	1701.59	800	15.14	1.27	2.674
8	1702.75	800	12.81	0.197	2.664
9	1703.57	800	15.11	0.783	2.693
10	1704.71	800	6.56	0.012	2.795
11	1705.50	800	6,34	0.018	2.763
12	1706.81	800	16.40	1.39	2.806
13	1707.76	800	17.05	1.88	2.874
14	1708.80	800	17.41	2.85	2.948
15	1709.84	800	16.75	1.17	2.824
16	1710.76	800	14.56	0.551	2.736
17	1711.85	800	14.24	0.784	2.680
18	1712.80	800	15.06	1.14	2.667
19	1713.68	800	15.97	2.38	2.673
20	1714.68	800	13.46	0.692	2.670
21	1715.56	800	15.17	1.54	2.671
22	1716.25	800	15.20	2.01	2.667
23	1717.09	800	13.03	0.232	2.679
24	1718.65	800	15.68	1.73	2.677
25	1719.50	800	15..62	1.79	2.679
26	1720.40	800	15.11	2.00	2.681
27	1722.55	800	8.06	0.359	2.839
28	1723.28	800	11.62	0.134	2.713
29	1724.31	800	11.03	0.134	2.711
30	1725.04	800	11.83	0.180	2.707
Average			**13.89**	**1.14**	

Table 4
Reservoir Simulations Performed for Wolco

Reservoir Properties

Reservoir	Bartlesville
Depth to top of reservoir, ft	1730
Connate water, % pore volume	34
Residual oil saturation, % pore volume	26
Estimated initial pressure, psi	75
Producing well pressure, psi	50
Pattern size, acres	23
Drainage area, acres	640
Horizontal well dimensions Length, ft Spacing, ft	 1000 500
Completion details Location of central injection well Location of producing wells	 20 ft from bottom of zone 20 ft from top of zone
Model constraints Surface injection pressure constraint, psi Injection rate constraint, bpd	 100 2000

Initial Layer Saturations

Layer	Thickness (ft)	Porosity (% pv)	Permeability (md)	S_g (% pv)	S_o (% pv)	S_w (%pv)
1	10	18	31	9	45	46
2	20	19	50	6	44	50
3	28	19	50	0	43	57
4	10	20.5	100	0	32	68
5	16	20.5	100	0	26	74

Recovery Projections

Time (years)	Oil Recovery (stb)	Water Cut (% pv)
1	80,700	84
5	220,000	96
10	298,000	97
15	391,000	97
20	482,000	98