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INCREASING WATERFLOOD RESERVES IN THE WILMINGTON OIL FIELD THROUGH IMPROVED RESERVOIR CHARACTERIZATION AND RESERVOIR MANAGEMENT

Annual Report 1996

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August 1997

Performed Under Contract No. DE-FC22-95BC14934

City of Long Beach
Long Beach, California

National Petroleum Technology Office
U. S. DEPARTMENT OF ENERGY
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Prepared for
BDM-Oklahoma/
U.S. Department of Energy
Assistant Secretary for Fossil Energy

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DISCLAIMER

Foreword

This project is intended to increase recoverable waterflood reserves in slope and basin reservoirs through improved reservoir characterization and reservoir management. The particular application of this project is in portions of Fault Blocks IV and V of the Wilmington Oil Field, in Long Beach, California, but the approach is widely applicable in slope and basin reservoirs. Transferring technology so that it can be applied in other sections of the Wilmington Field and by operators in other slope and basin reservoirs is a primary component of the project.

Abstract

This project uses advanced reservoir characterization tools, including the pulsed acoustic cased-hole logging tool, geologic three-dimensional (3-D) modeling software, and commercially available reservoir management software to identify sands with remaining high oil saturation following waterflood. Production from the identified high oil saturation sands will be stimulated by recompleting existing production and injection wells in these sands using conventional means as well as short radius and ultra-short radius laterals.

Although these reservoirs have been waterflooded over 40 years, researchers have found areas of remaining oil saturation. Areas such as the top sand in the Upper Terminal Zone Fault Block V, the western fault slivers of Upper Terminal Zone Fault Block V, the bottom sands of the Tar Zone Fault Block V, and the eastern edge of Fault Block IV in both the Upper Terminal and Lower Terminal Zones all show significant remaining oil saturation. Each area of interest was uncovered emphasizing a different type of reservoir characterization technique or practice. This was not the original strategy but was necessitated by the different levels of progress in each of the project activities.

Executive Summary

Waterflood oil recovery in the Wilmington Field has historically been inefficient due to a variety of factors, including reservoir heterogeneity, poor sweep efficiency, high water cut, and poor injection profiles. Sands with high remaining oil saturation are still present despite extensive waterflooding, but locating these sands has been difficult.

Reservoir management software has identified areas of potentially high remaining oil saturation in both the Upper Terminal Zone and the Lower Terminal Zone of Fault Block IV. A pulsed acoustic cased-hole logging tool was run in potential recompletion candidates and recovered compressional wave data from which porosities were calculated. Unfortunately, shear wave data were not recovered therefore acoustically derived saturations cannot be predicted for the Fault Block IV wells. A standard remedial recompletion will be completed in each zone to validate the conclusions reached utilizing the reservoir management software.

Examination of recent electric logs (E-logs) revealed sands with remaining high oil saturation in the Tar Zone and Upper Terminal Zone of Fault Block V. A deterministic 3-D model was built around the Upper Terminal Zone recompletion candidate Well J-120. Well J-120 was recompleted and is undergoing steam consolidation as of this report date. A deterministic 3-D model was also built around the Tar Zone recompletion candidate Well J-15. Well J-15 was also recompleted and is undergoing steam consolidation as of this report date.

Initial results from the first four recompletions will be available for the next quarterly report.

Introduction

This project uses advanced reservoir characterization tools, including the pulsed acoustic cased-hole logging tool, geologic (3-D) modeling software, and commercially available reservoir management software to identify sands with remaining high oil saturation following waterflood. Production from the identified high oil saturation sands will be stimulated by recompleting existing production and injection wells in these sands using conventional means as well as short radius and ultra-short radius laterals.

Discussion

- **Reservoir Characterization**

Theoretical relationships, confirmed by laboratory and field data, suggest that hydrocarbon-bearing rocks in situ can be differentiated from rocks containing brines using sonic velocity measurements. Rock-log and fluid-log models are needed to calibrate, interpret, and understand the acoustic log data[1].

Because hydrocarbons in situ generally have much lower bulk moduli and densities than brines, replacing water with hydrocarbons lowers the compressional velocity and increases slightly the shear wave velocity. Williams[2] presented convincing evidence that hydrocarbons could be detected from the difference between measured Vp/Vs and that predicted for a water saturated rock from shear wave velocity. Because the water delineation line is similar for clean and clay-bearing sands, virtually the same relationship can be used to detect hydrocarbons in both, eliminating the need for an independent lithology indicator. However, because of the lack of quantitative physical models to predict the effect, this technique has been applied with caution and a limited degree of success.

Researchers have developed a rock model which relates frame moduli to porosity in unconsolidated sands found in the Wilmington Field and other slope and basin reservoirs. However, this developed model assumes a uniform saturation in the pore space. Research is continuing to determine the effect on acoustic properties.

Monopole and dipole shear sonic logs can provide accurate compressional and shear wave velocities in cased holes, even in shallow, unconsolidated sands such as in the Wilmington Field. Porosity can be determined from shear wave velocity, provided an appropriate transform is used. Qualitatively, acoustic logs can be used to locate bypassed oil.

In practice, researchers have only been able to detect the shear wave in wells 167-W and M-499 out of six wells logged. Tube wave interference remains a formidable obstacle to overcome. An attempt to filter the wave with an absorber showed promise in a test well but failed in actual Wilmington well trials. The acoustic logging tool is being modified to overcome the tube wave interference.

- **Reservoir Engineering**

Injection and production data are still being input into the computer and quality controlled. This is an enormous task that we did not initially recognize. The input strategy has been altered and researchers are now concentrating on completing individual zones rather than the entire fault block at once.

The first zone completed was the Upper Terminal Zone of Fault Block IV. Injection and production data have been input, quality controlled, transformed into a database, and exported to Production Analyst reservoir management computer software. Researchers generated cumulative production bubble maps, cumulative injection bubble maps, daily production maps, and isocut maps. These maps revealed an area on the east side of the fault block that appeared to have low cumulative oil recovery against the Harbor Entrance Fault. Idle well Y-63 penetrates the low recovery area and will be selectively recompleted in the Upper Terminal Zone across from the "Hx", "J", "Y", and "K" sands.

In zones where data input is not completed, researchers scanned the log files for newer electric logs which would indicate bypassed oil. Another technique employed to find bypassed oil was to identify anomalous production well characteristics such as lower than average water cuts, high oil production rates, and high water production rates. These techniques generated the X-32, J-15, and J-120 recompletion proposals.

Idle Well X-32 penetrates the Lower Terminal Zone of Fault Block IV and will be selectively recompleted across from the "AB", "AC", and "AD" sands. This prospect was generated from a well which was redrilled to a deeper production horizon and showed significant resistivities across the "AB", "AC", and "AD" sands. Surrounding Lower Terminal production wells produce with higher than field average oil cuts with good productivity. Also, X-32 penetrates the zone close to the Harbor Entrance Fault and could produce any oil that might be banked under and against the fault.

Fault Block V recompletion prospect J-15 was also generated from recent electric logs that passed through the Tar Zone and anomalous neighboring Tar Zone production wells. The "F_1" & "F_o" sands in this area of the Tar Zone in Fault Block V have not been completely drained. Electric logs from wells Z1-24, J-66, FJ-73, and J-46 show the resistivities have changed very little in the "F_1" sand and only moderately in the "F_o" sand from the 1960's until 1983. These wells reflect the saturations across a 1100 ft linear interval crossing just north of J-15. The 1982 E-log from nearby Well J-66, located 160 ft away, showed remaining oil saturation resistivities of 7 ohms in the "F_1" & "F_o" sands. The original J-15 resistivities of these same sands were 6 ohms in the "F_1" sand and 27 ohms in the "F_o" sand back in 1947.

Currently, there are two wells near J-15 that are selectively completed in the "F_1" & "F_o" sands, Z1-7 and J-7. Well Z1-7 is located 680 ft north of J-15 while J-7 is located 600 ft south of J-7. Z1-7 produces 76 b/d gross and 13 b/d net for an 82.9% water cut with 16 ft of fluid over the pump (FOP). J-7 produces 422 b/d gross and 11 b/d net for a 97.4% water cut with 1080 ft of FOP. J-7 hasn't produced up to expectations most likely due to the high FOP and resultant low pressure drawdown on the reservoir.

The proposed work for J-15 included extreme overbalanced perforating the 8-5/8" casing from 2310 ft ("F_1"+8 ft) to 2345 ft ("F_o"+25 ft) and consolidating the reservoir sand with one cycle of steam injection. Overbalanced perforating has been developed by Oryx Energy Company as a method to reduce skin damage. Sand consolidation with steam has been developed by Union Pacific Resources in the Wilmington Field. As of this report date, J-15 is undergoing the cyclic steam consolidation.

Fault Block V recompletion prospect J-120 was generated from recent electric logs that passed through the Upper Terminal. The "Hx_1" sand in this area of the Upper Terminal Zone has not been adequately drained. Electric logs from recently redrilled wells J-120, J-17, and J-46 show the resistivity has changed little from the 1960's until 1983. A 1983 E-log from J-120 showed remaining oil saturation resistivity at 7-8 ohms versus 12 ohms in 1961. The resistivity of the "Hx_1" sand in nearby Well J-17 has remained virtually the same at 9 ohms from 1964 until 1983. Only a few wells in the Upper Terminal Zone have been open to production in the subject sand. Currently, Well A-52 is the only well able to produce from this sand. A-52 is almost 1000 ft away from J-120 and located on the other side of the structure. Also, there has been little or no water injection into this sand east of the Maine Avenue Fault. On the east side of the Maine Avenue Fault, the "Hx_1" varies from 20 ft to 30 ft in gross thickness and is well developed with good remaining oil saturation. Areally, this covers about one half of the Upper Terminal Zone in Fault Block V. The "Hx_1" sand is wet and not as well developed on the west side of the Maine Avenue Fault. The original "Hx_1" oil-water contact is located far to the south of J-120.

The proposed work for J-120 included extreme overbalanced perforating the 7" casing from 2993 ft ("Hx_1"-3 ft) to 3009 ft ("Hx_1"+19 ft) and consolidating the sand with one cycle of steam injection. As of this report date, J-120 is undergoing the cyclic steam consolidation.

- **Deterministic 3-D Geologic Modeling**

Researchers also changed strategy on the geologic 3-D modeling to focus on specific areas within a zone and fault block for directional survey data input, fault picks, and sand marker picks. Midway through the data input a serious problem was uncovered with the NEWILMA program code and database used to build the deterministic geologic 3-D model. The problem involved the subsidence correction when NEWILMA calculates the vertical subsea depth (VSS) from the well directional survey. Depths are supposed to be increased by adding the subsidence components.

There are three parts to the subsidence correction. The first part is a correction to the surface site to the elevation of the ground level when the well was drilled. The second part is to correct the marker (based on the X, Y location) by adding the subsidence that occurred between the time the well was drilled and the present. The third part subtracts the compression due to fluid withdrawal from the oil sands. The original subsidence correction subroutine had calculated an incorrect value for the subsidence from when the well was drilled to the present, did not correct for the surface change between 1937 and when the well was drilled, and did not address the compression of the sands. The subsidence subroutine was successfully altered and the program recompiled.

Earth Vision software has generated structural contour maps of the Upper Terminal Zone in Fault Block V at the "Hx_1, Hx_o, Hx_2, and Hx" sand markers. All penetrating wells had their electric log examined and had these sands markers identified and entered into the Earth Vision NEWILMA database. Researchers are now working on isopach maps for these same horizons as part of the deterministic geologic model. The first version of the deterministic geologic model for the J-120 recompletion prospect is shown in Figure 1.

A deterministic geologic model has also been generated for the Upper Terminal Zone Fault Block IV prospect at the "Hx" sand marker (Fig. 2). It shows recompletion candidate Y-63 penetrates the Upper Terminal Zone just to the west of the Harbor Entrance Fault. Researchers theorize oil is banked up against the Harbor Entrance Fault and can be captured by Y-63.

- **Pulsed Acoustic Logging**

Well M-499 was drilled in 1993 as an infill well to produce the Upper Terminal Zone of Fault Block IV. It was logged both open hole and cased hole with a comprehensive log suite[3]. Excellent open hole sonic data were obtained. Cased hole compressional and shear logs from the MPI (XACT) tool were similar to open hole results. Cased-hole shear data required filtering to remove a strong tube wave arrival prior to processing the data. The XACT tool used in this well had an early version of the receivers without calibration and acceleration correction, and with downhole (analog-domain) summing/differencing to enhance monopole or dipole energy, respectively. The XACT source was an old version with a center frequency in P of about 3 kHz and in S of 1.2 kHz.

The casing bond tool (CBT) revealed excellent bond in the zone of interest. There was little casing arrival, and a well developed formation arrival could be seen throughout much of the hole. The Ultra-Sonic Imager (USI) showed moderately good cement bond but some fluid behind the casing.

Recompletion candidate well FY-67 was logged with the MPI tool and the Schlumberger tool. A dogleg in the well at 1560 ft made passage of the MPI tool difficult, and the centralizers on the tool were removed and replaced with wraps of duct tape. Compressional waveforms recorded by the Dipole Shear Imager (DSI) and the XACT agree quite well except were low amplitudes confuse the analysis. DSI Lower Dipole data are better than Upper Dipole data, but no reliable shear velocities could be determined in either case. The XACT tool did not provide shear velocities either.

The USI tool revealed fairly poor bonds, lots of water behind casing, above 3000 ft. Below the 3000 ft mark average bond appears to be better than in well M-499 with relatively few intervals in which fluid is predicted behind casing. There was a distinct difference in bond quality between the upper and lower sides of the hole, with the low side having better bond. Throughout the well there were indications of gas behind casing, but in amounts less than indicated in well M-499.

Inspection of the Schlumberger monopole data reveals a significant early casing arrival throughout much of the hole, although a good formation arrival can be seen later in the wave train. The change at 3000 ft is also clear on the waveforms; below that depth the casing arrival is less distinct. If this can be compared directly to the CBT results in well M-499, it suggests a much worse bond in well FY-67, in contrast to the USI data which indicated a slightly better bond.

An attempt to re-log the well with a modified MPI XACT tool was terminated when the tool could not pass through the known dogleg at 1560 ft.

Well 167-W was originally drilled in 1983 with a deviation of 28-32 degrees. Steel casing extends down to 4032 ft, below which a slotted fiberglass liner was installed for sand control and corrosion protection. It was logged twice with the MPI XACT tool and once with the Schlumberger DSI tool along with a USI for cement bond evaluation. Compressional waveforms recorded by the DSI and XACT show similar variations downhole. Velocities determined from the monopole data of both tools agree quite well except where low amplitudes confuse the analysis. DSI Lower Dipole data are better than Upper Dipole, but no reliable shear velocities could be determined in either case. The XACT data did not provide shear velocities either. DSI data provided compressional and probable shear velocities in the fiberglass section of the hole.

The USI reveals quite variable casing bond in well 167-W. Bond is similar to that of well M-499. Unlike well FY-67, there is no clear difference in bond quality between the upper and lower sides of the wellbore.

Recompletion candidate well X-32 was logged with the MPI XACT tool. This well was originally drilled in 1946. No shear wave data were obtained, but reasonable compressional wave velocities were determined from the monopole data.

Recompletion candidate well Y-63 was logged on two separate occasions with the XACT tool. Neither compressional nor shear wave velocities could be determined from the first logging sequence. A return visit with a modified XACT tool and tube wave absorber also did not yield acceptable data. Fourteen different combinations of receivers, sources, spacers, and attenuaters were tried and did not reproduce the data from the first logging sequence.

The XACT tool has been undergoing a number of design modifications since the initial logs were recorded in well M-499 in 1993. The original tool had four "receivers", each of which consisted of 4 crystals mounted at 90° intervals. To record monopole data the signals from crystals mounted 180° apart in line with the source are summed downhole. To record dipole data the crystals from receivers mounted 180° apart in-line with the source are differenced downhole. The receivers are not calibrated, so the sums and differences do not perfectly discriminate the appropriate phases. The source is a pulse of fluid which acts across a membrane on the wellbore fluid, in such a way that it is in phase across the tool in monopole mode and out of phase across the tool in dipole mode. The source was not perfectly "balanced", so some monopole energy is generated in dipole mode, and some dipole energy is generated in monopole mode. In compressional mode the center frequency is about 3 kHz. In dipole mode the center frequency is about 1.2 kHz.

A number of design changes were made to the XACT tool prior to logging the first wells in this project. First a new receiver section was developed, in which the crystals were remounted to cancel accelerations imparted to the body of the tool by the fluid in the borehole. Also, the receivers were calibrated to improve the summing and differencing to enhance mode discrimination. Finally, the receivers were configured so that summing or differencing could be achieved uphole (A and C mode) or downhole (A+C mode; A-C mode). A new source (XMTR) was developed which was more carefully balanced to produce pure monopole or pure dipole energy. This source also generated significantly more energy in each pulse. And, it was modified to generate a dipole mode with a center frequency of about 800 Hz. This tool was run during August 1995 in holes OB2-3, 167-W, FY-67, X-32 and Y-63. In several of these holes the original transmitter was also run for comparison.

In general, data from the original transmitter appears to be better because it excites less low frequency (~600 Hz) tube wave energy.

A tube-wave absorber was developed to attenuate fluid-borne energy. This section was re-run in FY-67 (it didn't get past the dogleg) and Y-63 in December 1995. Based on data recorded at 350 ft in a test well at Stanford, the maximum amplitude reduction using one absorber is about 3x (10dB), with little attenuation outside the stop band (250-1750 Hz).

Schlumberger's DSI tool records on 8 receivers up- and down-going dipole data from two different sources, mounted 90° to each other, and monopole (higher-frequency) data from a third source. All three data sets are analyzed independently using STC processing. Log quality control consists of color displays of the coherence as a function of slowness with picks, and the filtered waveforms as a function of time.

Receiver data are differenced or summed downhole, thereby making it difficult to unambiguously determine the mode type where dipole and tube/Stonely waves interfere.

- **Technology Transfer**

Technical transfer activities included a field trip to the Wilmington Field for the American Association of Petroleum Geologists (AAPG) in association with their 1996 national meeting in San Diego. An article was also placed in the AAPG guidebook for the national meeting (APPENDIX 1).

Researchers are also planning the Stanford Rock and Borehole Geophysics Project Annual Meeting. Papers written and presented will include:

"Viscoelasticity and Dispersion in Unconsolidated Reservoir Rocks from the Wilmington Field, California" (APPENDIX 2)

"A Comparison of Dynamic and Static Moduli in Unconsolidated Reservoir Rocks from the Wilmington Field, California" (APPENDIX 3)

"Hydrocarbon Saturation Determination from Sonic Log Data" (APPENDIX 4)

"Identifying Patchy Saturation from Well Logs" (APPENDIX 5)

Tidelands Oil and USC are developing a CD-ROM multimedia presentation on the history of this project. This historical record will be updated continuously and available to other operators and the public in general. Periodically, CD's would be produced and distributed to other organizations as part of our technical transfer commitment. In addition, Stanford has placed a "home page" of the SPE paper and the DOE project on the World Wide Web.

Chris Phillips, Chief Geologist with Tidelands, made a presentation on the 3-D deterministic geologic model entitled "Application of Advanced Reservoir Characterization to Increase the Efficiency of a Thermal Steam Drive in the Wilmington Oil Field, California" at the 1995 AAPG Pacific Section Meeting in San Francisco, CA. on May 3-5, 1995. Don Clarke and Mike Henry of the City of Long Beach were co-authors.

Dan Moos of Stanford was in New Orleans on May 18, 1995 speaking at the Society of Professional Well Log Analysts (SPWLA).

Several articles were published in trade journals and newspapers about this DOE project. Articles were published in the October 10, 1994 edition of the Long Beach Press - Telegram newspaper, in the October, 1994 issue of the SPE Los Angeles Basin Section Newsletter, in the December, 1994 issue of World Oil magazine, and in the March, 1995 issue of Petroleum Engineer International magazine.

Tidelands, the City of Long Beach, and USC held a technical transfer meeting of DOE Class III participants on May 15, 1995 in Valencia, CA to discuss their desire to have specific joint activities, such as the 1996 AAPG National Meeting, the 1997 SPE Western Regional Meeting, and the 1998 Joint SPE Western Regional/AAPG Pacific Basin Section Meeting. Tidelands and City of Long Beach personnel have already begun work on these meetings to promote technical sessions on slope and basin clastic reservoirs, advanced reservoir characterization, and enhanced oil recovery.

Scott Hara of Tidelands sent out a letter to California Coastal members of AAPG on January 10, 1995 announcing our DOE projects and to contact him to be placed on a mailing list of future technical transfer activities.

References

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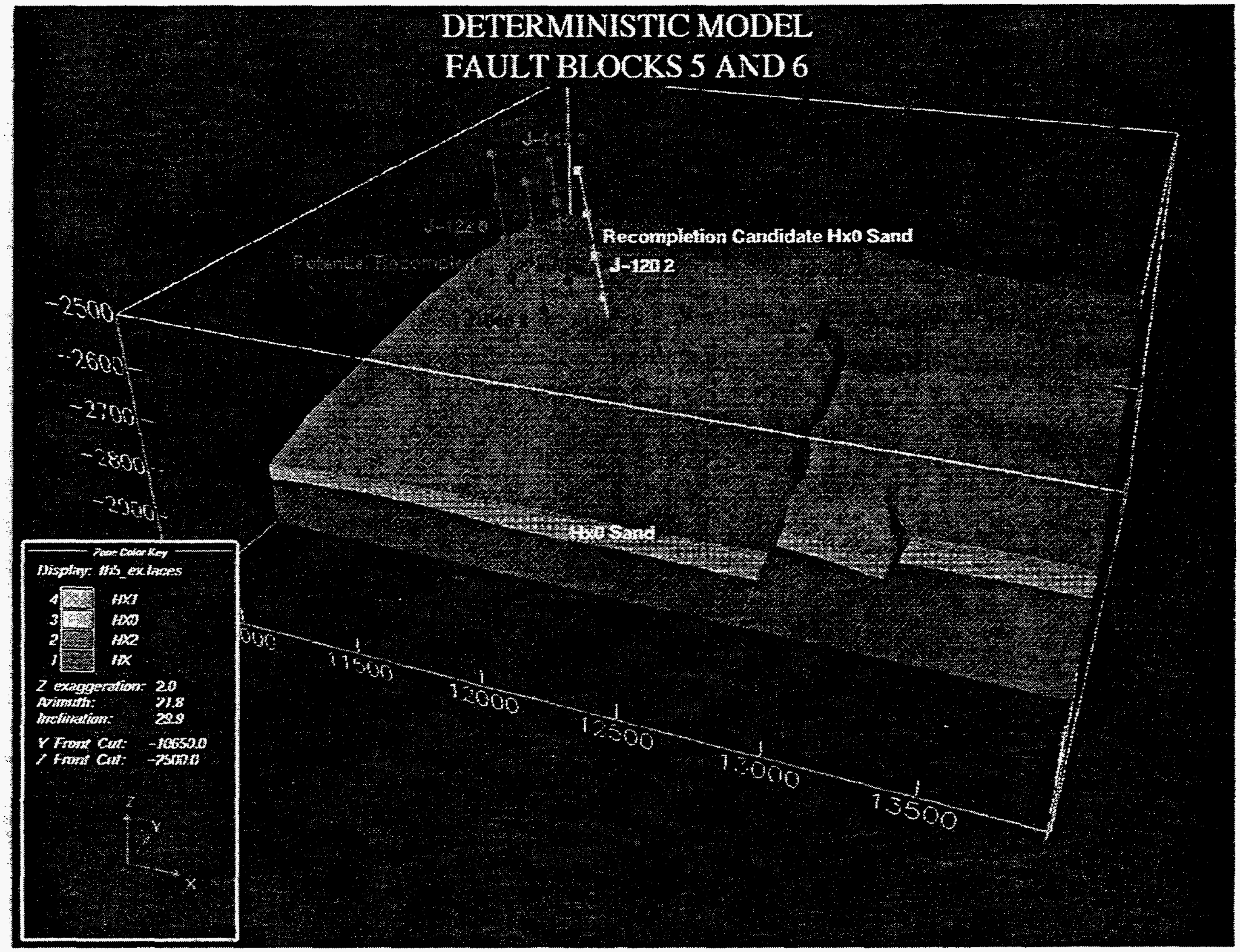
2. D. Williams, *The Acoustic Log Hydrocarbon Indicator,* paper W for Society of Proffesional Well Log Analysts 31st Annual Logging Symposium, June 1990.

3. D. Moos, S. Hara, C. Phillips, A. Hooks, K. Tagbor, *Field Test of Acoustic Logs for Measuring Porosity and Oil Saturation in a Mature Waterflood in the Wilmington Field, CA*, paper SPE 29655 presented at the Society of Petroleum Engineers Western Regional Meeting, Bakersfield, CA, March 1995.



DETERMINISTIC MODEL
FAULT BLOCKS 5 AND 6
Recompletion Candidate Hx0 Sand
J-120 2
-2500
-2600
-2700
-2800
Hx0 Sand
Zone Color Key
4 HX1
3 HX0
2 HX2
1 HX
Z exaggeration: 2.0
Inclination: 29.9
11500
12000
12500
13000
13500

FIGURE 1

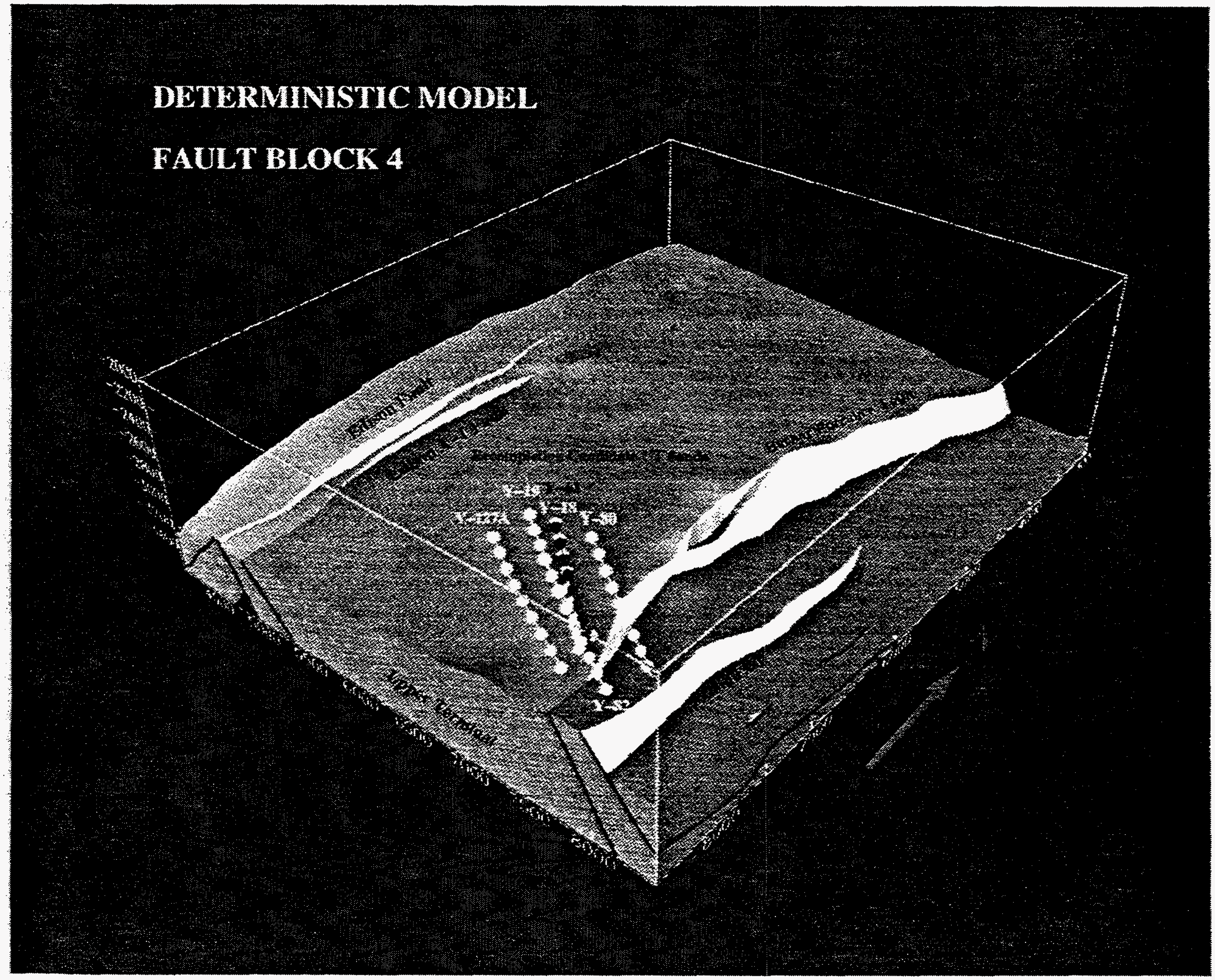


FIGURE 2

Sonic Logging to Detect Bypassed Hydrocarbons in the Wilmington Field, CA

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INTRODUCTION

Theoretical relationships, confirmed by laboratory and field data, suggest that hydrocarbon-bearing rocks in situ can be differentiated from rocks containing brines using sonic velocity measurements. A project to test this technique has been undertaken in the Wilmington Field, California, with co-funding from the Department of Energy (DOE cooperative agreement no. DE-FC22-95BC14934). Models, using values of fluid and formation properties typical of the Miocene-age turbidites within the target interval, confirmed that it should be possible to differentiate between hydrocarbon and non-hydrocarbon bearing sands in this field using compressional and shear wave sonic velocity logs. To date six wells (ranging in age up to 50 years) have been logged through casing with a multipole sonic logging sonde. Velocities measured in the open hole agreed with those measured after casing was installed in the most recently drilled well. Although compressional velocities have been determined in all but one case, shear-wave velocities have been obtained in only two of the six wells. Predictions of oil saturation are in qualitative agreement with models and prior measurements. However, one surprising result is that porosity can be determined from shear-wave velocity logs through casing. This may prove to be important in the future when through-casing resistivity logs become commercially available.

The Wilmington Field

The Wilmington field is located within a NW-SE trending faulted anticline beneath and immediately offshore of Long Beach, CA (Figure 1). The first successful well was drilled in 1932. As of 1994, more than 2.5 billion bbls of oil and 1.2 billion Mcf of gas had been produced, and it was believed that more than 1.8 billion bbls of oil still remained. Initial production was enhanced by a waterflood started in the 1950's primarily to mitigate surface subsidence which had reached more than 29 feet in the center of the bowl directly overlying the region of greatest production (Colazas and Strehle, 1995). Injection wells and production wells are located throughout the field, and production primaily continues from the center.

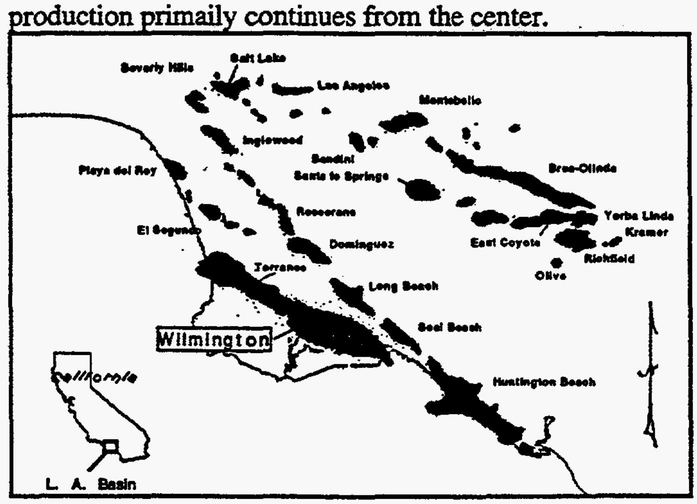

Figure 1: Location map, showing the Wilmington Field and other oil fields within the Los Angeles Basin (after Mayuga, 1968).

Production at Wilmington is from a thick sequence of clastic basin and slope sediments (unconsolidated, low maturity, turbiditic arenites and clean arenites with porosities exceeding 25% and permeabilities of 100's to 1000's of millidarcys, interlayered with sandy clays (wackes) containing 50%

Insufficient information to CONF

or more detrital smectite (Henderson, 1987 and Norton and Otott, 1996)). The producing horizons lie between depths of 2250 and about 10000 feet. The hydrocarbons produced at Wilmington range from 12° API gravity (Tar zone) to 18°-19° API gravity (Ranger and Upper Terminal Zones) to 27° API gravity (Lower Terminal). API gravities as high as 30 are produced from deeper sections of the field (the Union Pacific, Ford, and 237 zones).

Theoretical Basis of the Sonic Detection Technique

Generally, when a rock is loaded under an increment of compression, such as from a passing seismic wave, an increment of pore pressure change is induced, which resists the compression and therefore stiffens the rock. The low-frequency Gassmann (1951) - Biot (1956) theory predicts the resulting increase in effective bulk modulus, K_{sat}, of the saturated rock:

$$\frac{K_{sat}}{K_0 - K_{sat}} = \frac{K_{dry}}{K_0 - K_{dry}} + \frac{K_f}{\phi(K_0 - K_f)} \quad (1)$$

where ϕ is the porosity and K_0, K_f, and K_{dry} are the bulk moduli of the mineral material, the pore fluid, and the dry rock, respectively. Gassmann predicted no change for the isotropic shear modulus with saturation, $\mu_{sat} = \mu_{dry}$. The bulk and shear moduli are related to the compressional wave velocity, V_P, shear wave velocity, V_S, and density, ρ, through the familiar equations:

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \qquad V_S = \sqrt{\frac{\mu}{\rho}} \quad (2)$$

Equation (1) assumes a homogeneous mineral modulus and statistical isotropy of the pore space, but is free of assumptions about the pore geometry. Most importantly, it is valid only at sufficiently low frequencies such that the induced pore pressures are equilibrated throughout the pore space (i.e., that there is sufficient time for the pore fluid to flow and eliminate wave-induced pore pressure gradients).

These theoretical predictions have been confirmed qualitatively by a number of field studies. For example, seismic detection of free gas exploits this fluid effect because the abrupt increase in fluid compliance due to the gas generates a very large P-wave impedance contrast, producing a "bright spot" on a reflection seismic record. More recently, bright spots have also been observed to occur at oil/water interfaces(Clark, 1990). Using sonic P- and S-wave velocity logs, Williams (1990) demonstrated an Acoustic Log Hydrocarbon Indicator (ALHI) which was based on the difference between measured V_P/V_S and that predicted for a water-saturated rock from the shear-wave velocity. More recent results indicate that elastic properties may vary systematically with saturation (Hornby and others, 1992).

Predictions for Wilmington

The ability to detect hydrocarbons using elastic waves depends both on the amount by which their properties differ from those of brines and the degree to which those properties control the velocities of the saturated rock. Several factors influence the properties of the fluids at reservoir conditions. In general, density, bulk modulus and viscosity all decrease with increasing API number (decreasing density) and temperature and increase slightly with increasing pressure. Gas in solution has a large effect, even in comparison to that of temperature, in reducing density and bulk modulus. Using equations presented in Batzle and Wang (1992), it is straightforward to determine the properties of reservoir fluids.

These can then be applied, using the Biot-Gassmann relations, to predict the elastic-wave velocities as a function of depth. Figure 2 shows the predicted shear and compressional velocities and the velocity ratios as a function of depth and pore fluid for an assumed porosity of 30%. These results suggest that, for basin clastics such as those found at Wilmington, seismic velocities are quite sensitive to the properties of the pore fluids. And, for the expected properties of the actual pore fluids, the sonic detection technique should be quite successful at differentiating between sands with high saturations and those in which the hydrocarbons have largely been replaced with water.

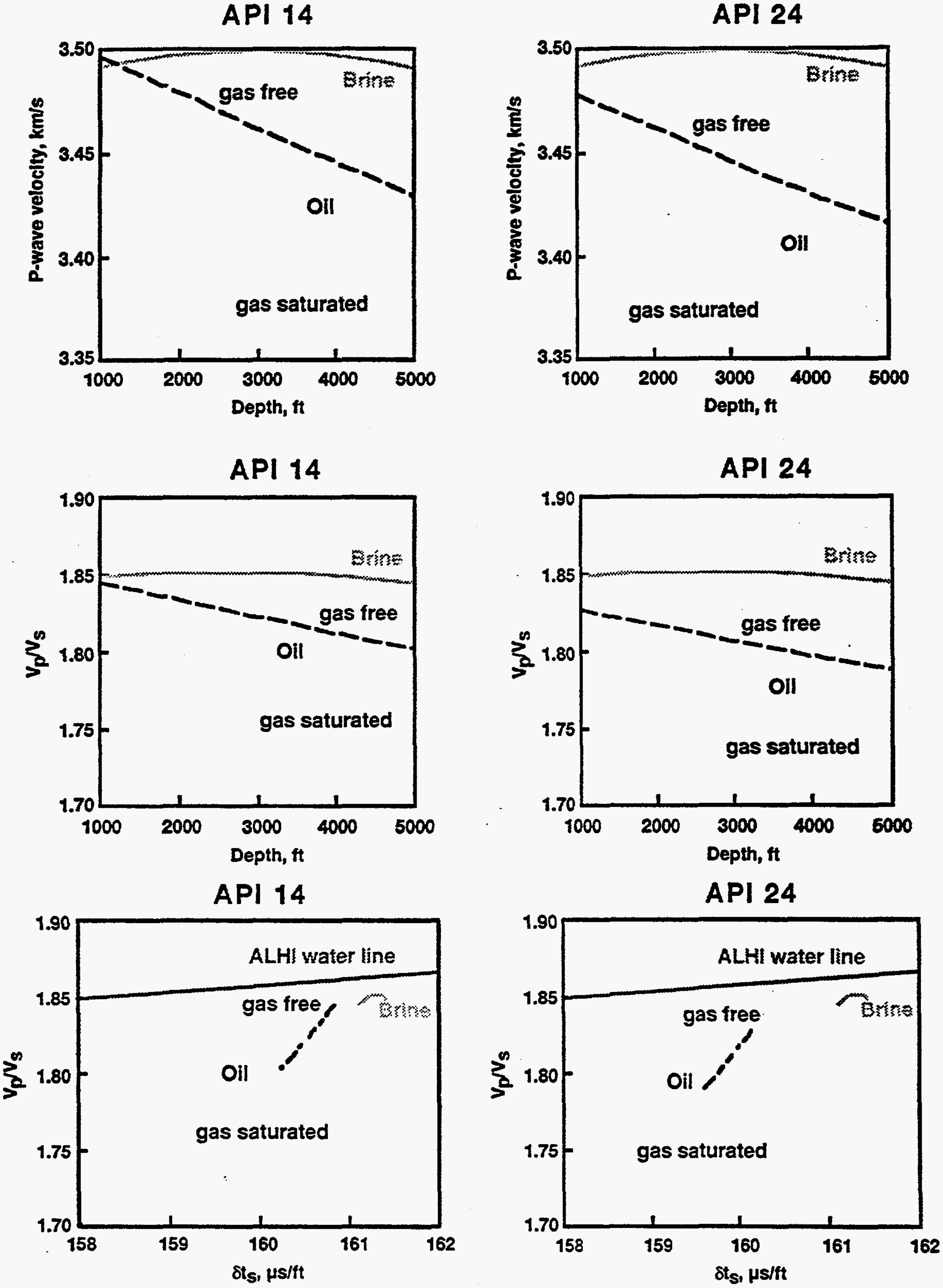

Figure 2: Elastic-wave velocities predicted for a 30% porosity Wilmington sand saturated with various pore fluids (after Moos, and others, 1995). Also shown are cross plots of V_p/V_s vs. dt_S, including the Williams (1990) ALHI water line for comparison.

Results in M-499

Well M-499 was completed in the Upper Terminal Zone of Fault Block IV in an area previously considered to be watered out. To evaluate the production potential from a selective recompletion of an existing well, M-499 was perforated only in sands with oil saturations above 40%, based on the analysis of open-hole well logs. New high power, low frequency (1.2-2.5 kHz) monopole and dipole sonic logs (Chen and Eriksen, 1991) were recorded to evaluate their ability to measure formation porosity and oil saturation through casing as a guide in carrying out selective recompletions in existing wells. Compressional-wave velocities were determined from analysis of monopole waveforms. Shear-wave velocities were determined through analysis of the dipole waveforms.

The very high energy and low center frequency of the source results in a depth of investigation which is more than ten times that of typical sonic logs (up to two meters), allowing data to be recorded in both open and cased holes. By exciting dipole modes in the wellbore, shear-wave velocities can be determined even in "slow" formations (that is, with shear-wave velocity below 1.5 km/s or shear-wave slowness (dt_S) above 200 μs/ft). In addition, by separately recording the waves on opposite sides of the tool, one can differentiate between true dipole modes, which provide information on the shear-wave velocity, and tube waves, which can interfere with the dipole mode in cased holes.

Sonic data were recorded in M-499 both before and after the installation of casing (Moos, and others, 1995). The velocity data presented here were determined from the cased-hole measurements. A comprehensive suite of open-hole logs was also recorded in the well to guide in completion decisions and for comparison to analyses of porosity and saturation using the sonic data.

Porosity

It is generally accepted that in hard rocks conventional (compressional-wave) sonic logs can be used to determine porosity through the use of the Wyllie time-average equation or Raymer's relationship. However, experience has demonstrated that these techniques cannot be used to determine porosity in fields such as Wilmington. This is largely because of the unconsolidated nature of the rocks in these fields (Moos, and others, in press). Furthermore, dt_P is affected both by porosity and by other factors such as fluid properties. Because the shear wave is (theoretically) relatively unaffected by the fluid, it should be possible to derive a porosity log from dt_S, provided an appropriate model is used to relate porosity to velocity.

A further benefit of using shear-wave velocity to determine porosity is that such logs can be run through casing. In most instances. Sonic logs have a much greater radius of investigation than nuclear logs (Westaway, et al., 1981), making the result from shear-wave analysis a more reliable predictor of formation properties away from the near-wellbore zone.

Figure 3 shows porosity derived from shear-wave velocity using techniques described in Moos and othres (in press) for the entire logged interval in M-499. Also shown are porosities derived from empirical relationships (Moos, and others, 1995) and from the density log. There is excellent agreement throughout most of the logged interval between the different porosity measures, with the exception of washed-out sections within which the density log reads anomalously small values leading to overly large porosity estimates.

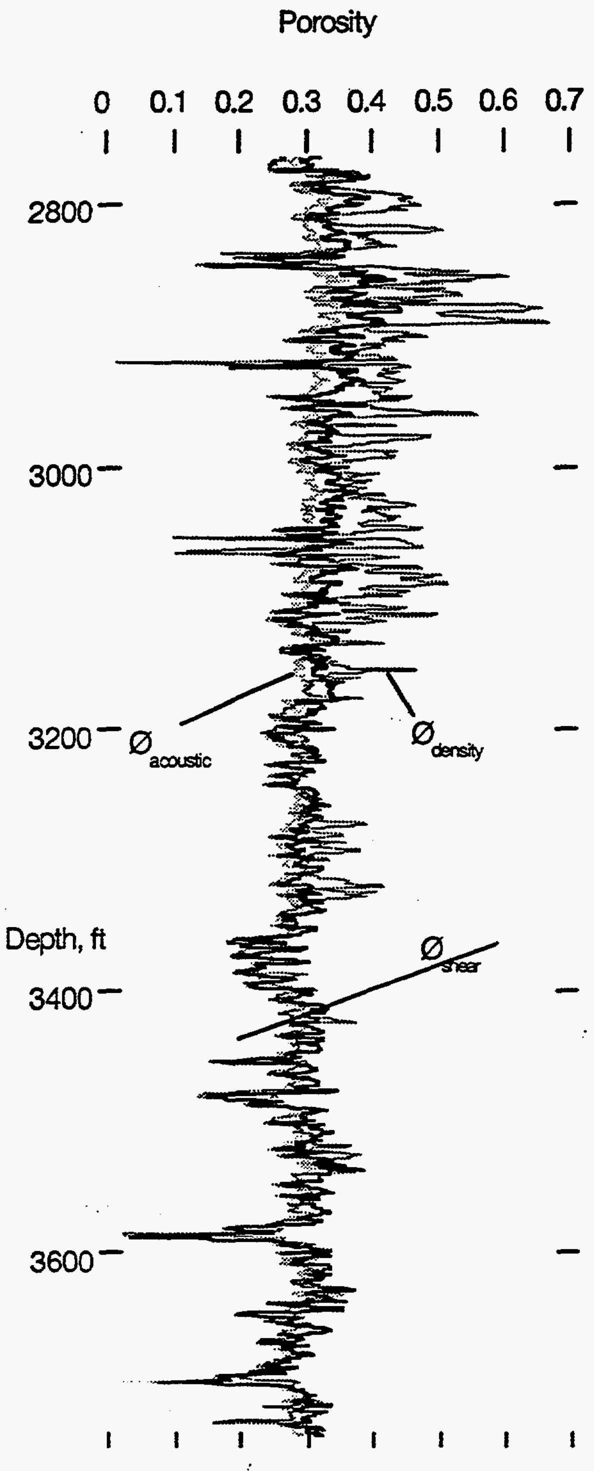

Figure 3: Porosity determined from a density log ($Ø_{density}$), from an empirical relationship developed using other data ($Ø_{acoustic}$) (Moos, and others, 1995), and from the theoretical relationship described in Moos et al. (in press); ($Ø_{shear}$). In general, there is excellent agreement between the two sonic porosity measures, whereas the density porosity is generally slightly greater, likely due in shallow sections to poor pad contact in the rugose hole.

Saturation

Figure 4 compares the ALHI water lines of Williams (1990) to data from the Upper Terminal section of M-499. Based on William's analysis and Biot-Gassmann, oil-bearing units are predicted to lie below the water lines. As can be seen, a significant percentage of the depth interval logged is predicted to be oil-bearing.

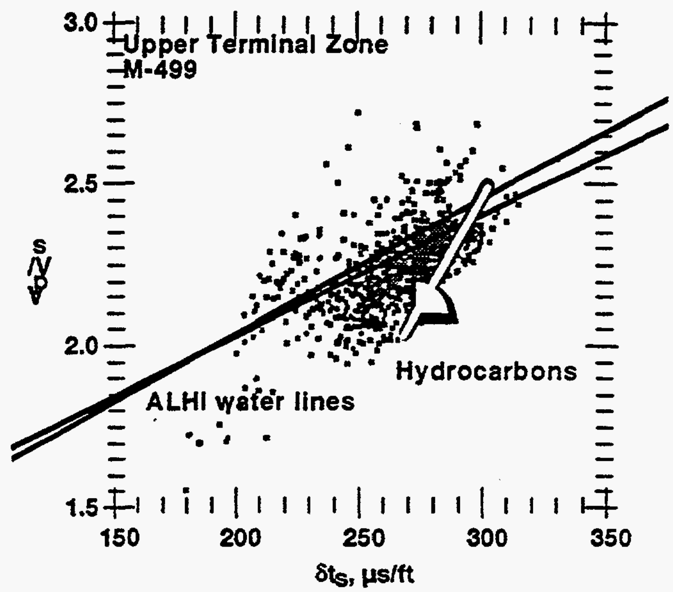

Figure 4. Crossplot of V_p/V_s vs. dt_S showing the ALHI water lines of Williams, compared to data from the Upper Terminal of well M-499.

In Figure 5 the normalized distance from the water line is compared to saturation determined using Archie's Law for the Upper Terminal Zone. There is qualitative agreement between the two curves, with the exception of some intervals which are predicted to have high oil saturations based on the sonic data, but which do not appear to have high oil saturation based on the conventional log analysis. These zones can largely be eliminated from consideration for recompletion using geological constraints, data from recent offset wells, and production experience. Of more importance is the observation that the intervals chosen for completion based on the conventional analysis are also predicted to have high oil saturation based on the sonic results.

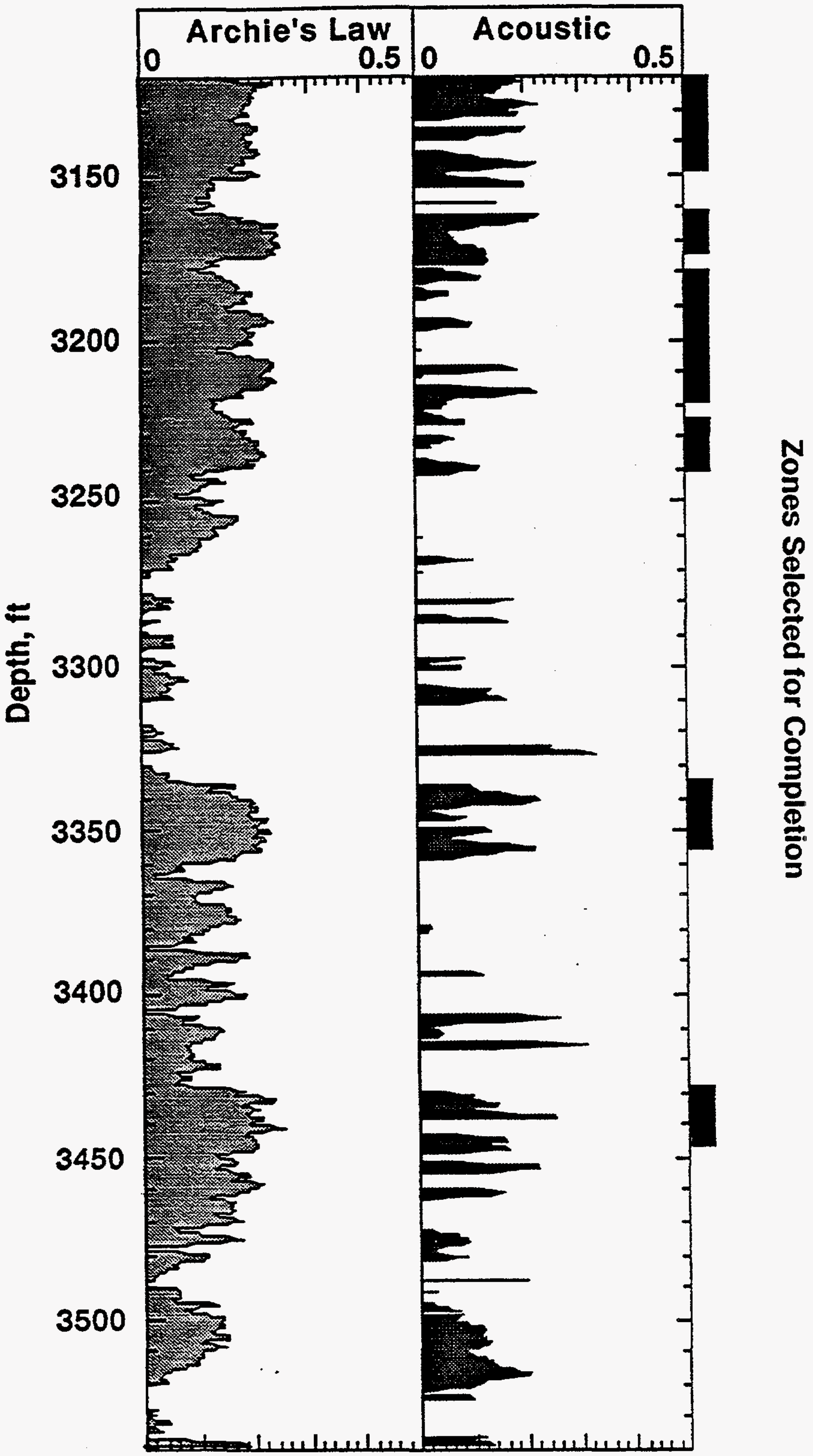

Figure 5. Saturation predictions based on Archie's Law and on the sonic data. Also shown are the intervals chosen for completion based on the Archie's Law analyses.

Results in Other Wells

Although the results from M-499 are promising, it is necessary to demonstrate first that it is possible to routinely obtain the sonic data necessary for this analysis, and second that the sonic technique can accurately differentiate between watered-out and potentially productive zones. To accomplish this the sonic logs were run in five more holes as summarized in Table I. Prior to running these additional logs the tool was modified to improve receiver characteristics and to allow independent recording of wave arrivals on opposite sides of the tool.

Table I: Summary of hole characteristics.

Well	Depth Interval, kft	Deviation	Year Drilled	Well Type
M-499	2.8-3.7	43°	1993	Prospect
167-W	2.5-4.5	30°	1983	Water flood
FY-67	1.6-3.7	17°	1948	Water flood
Y-63	1.6-3.2	17°	1948	Prospect
X-32	3.0-5.6	17°	1946	Prospect
J-15	1.2-2.9	vertical	1942	Prospect

Compressional-wave velocities were determined in all of these wells except in Y-63. In contrast, shear-wave velocities could be determined only in M-499 and in the uppermost few hundred and lowermost several hundred feet of well 167-W. In the intermediate depth range within 167-W (from about 2900 to 3300 feet) the shear wave arrived at the same time and was characterized by the same frequency content as the interfering tube wave. In 167-W, the ability to record independently the wave arrivals on opposite sides of the tool was essential for differentiating between tube wave and the dipole mode.

Thus it appears that the critical determinants of the success of shear-wave logging are: (1) the age of the well, and (2) the shear-wave velocity. Deviation, leading to eccentering of the tool in the casing, and the casing in the hole, does not appear to be a problem in spite of the inevitable additional generation of tube-wave energy by the dipole source. Further study is needed to determine if factors such as the casing diameter and the cement thickness and bonding to the formation affect the quality of the dipole data.

Neither standard casing bond logs nor specialty logs which measure the azimuthal variation of bond using acoustic techniques provided clear predictions of the quality of the sonic logs.

CONCLUSIONS

Based on the results so far, three conclusions can be reached. First, porosity can be determined accurately using shear-wave velocity in reservoirs such as Wilmington, provided the appropriate model for their relationship is used. Second, cased-hole shear-wave logging in formations such as the Wilmington sands is extremely difficult, due both to wellbore conditions and to the similarity of the dipole mode moveout and that of the tube wave. Furthermore, discrimination between these two modes, even where their moveout is different, requires separate recording of arrivals on opposite sides of the tool to verify wave mode symmetry. However, it is clear that if the data can be recorded it is possible to discriminate between watered out and potentially productive zones. Additional analysis of the data so far recorded and of new data will help to refine these preliminary conclusions.

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