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

Quarterly Technical Progress Report
April 1, 1998-June 30, 1998

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Increasing Waterflood Reserves in the Wilmington Oil Field Through Improved Reservoir
Characterization and Reservoir Management

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

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Objectives

The objectives of this quarterly report are to summarize the work conducted under each task during the reporting period April - June 1998 and to report all technical data and findings as specified in the "Federal Assistance Reporting Checklist".

The main objective of this project is the transfer of technologies, methodologies, and findings developed and applied in this project to other operators of Slope and Basin Clastic Reservoirs. This project will study methods to identify sands with high remaining oil saturation and to recomplate existing wells using advanced completion technology.

The identification of the sands with high remaining oil saturation will be accomplished by developing a deterministic three dimensional (3-D) geologic model and by using a state of the art reservoir management computer software. The wells identified by the geologic and reservoir engineering work as having the best potential will be logged with cased-hole logging tools. The application of the logging tools will be optimized in the lab by developing a rock-log model. This rock-log model will allow us to translate measurements through casing into effective porosity and hydrocarbon saturation.

The wells that are shown to have the best oil production potential will be recompleted. The recompletions will be optimized by evaluating short radius lateral recompletions as well as other recompletion techniques such as the sand consolidation through steam injection.

Summary of Technical Progress

● Reservoir Characterization

Refining the Upper Terminal Zone Fault Block V structure maps based upon the data developed from the J-17 redrill. The saturation map was also refined and updated. These new maps were used in understanding and validating the horizontal log responses seen while drilling J-17. A paper titled "Determination and Application of Formation Anisotropy Using Multiple Frequency, Multiple Spacing Propagation Resistivity Tool from a Horizontal Well, Onshore California" was written using these data (Appendix 1).

● Reservoir Engineering

Researchers are evaluating candidate wells J-106 and J-79 which are completed in a deeper zone but pass through the Tar Zone, Fault Block 5, in the study area. Candidate well J-106 is likely to be a recompletion candidate in the "S" sand of the Tar Zone. Candidate well J-79 is likely to be a recompletion candidate in the "Fo" sand of the Tar Zone.

● Deterministic 3-D Geologic Modeling

The geologic model was updated with the refined structure and saturation maps discussed earlier.

● Cased Hole Logging

No cased hole logging took place.

● Recompletions

Budget period one horizontal redrill candidate J-17 was started in early March 1997. The liner was perforated with 0.74 cm (0.29") holes, alternately phased 150° and 210°, and spaced one (1) hole per ten (10) foot interval from 1001 m (3285') to 1189 m (3900'). A string of thermal insulated tubing with a thermal packer on bottom were installed. A total of 8,556 m³ (53,817 bbls) of cold water equivalent steam was injected into the well in order to consolidate the sand. It was not successful. Note - previous reports listed the phasing as 0° which was in error.

A rig moved on the well in April 1998 in order to remove the steam injection equipment and install the production equipment. Unfortunately, the well was found with sand in the liner. Although the well reached the empirically derived cumulative steam injection, it did so at a very low daily rate. J-17 was cleaned out and placed back on steam injection with a portable steam generator capable of higher injection pressures. J-17 should be done steaming during the third quarter of 1998.

● Technology Transfer

A paper was presented to the Society of Professional Well Log Analysts (SPWLA) 39th Annual Logging Symposium titled "Determination and Application of Formation Anisotropy using Multiple

Frequency, Multiple Spacing Propagation Resistivity Tool from a Horizontal Well, Onshore California" in Keystone, Colorado in May, 1998. (Appendix 1)

A paper was presented to the Stanford Rock Physics and Borehole Geophysics Project annual meeting titled "Acoustic Determination of Pore Fluid Properties Using a 2-Component Model" at Stanford, California in June, 1998. (Appendix 2)

Held a meeting May 14th with PanCanadian Petroleum engineers David Rushford and Jean Pierre Fossey and exchanged data concerning our recompletion techniques employed in our project.

References and Publications

None

APPENDIX 1

DETERMINATION AND APPLICATION OF FORMATION ANISOTROPY USING MULTIPLE FREQUENCY, MULTIPLE SPACING PROPAGATION RESISTIVITY TOOL FROM A HORIZONTAL WELL, ONSHORE CALIFORNIA.

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ABSTRACT

As part of a Department of Energy cost share program, a horizontal well was drilled in thin heterogenous Miocene age turbidite sands. The challenge was to economically drill and exploit remaining reserves in the 60 year old Wilmington Field (Long Beach, California). The solution was to use new technology and sidetrack an existing wellbore with a horizontal lateral to capture hydrocarbon reserves uneconomically recoverable with historically used conventional methods. The new technologies included detailed reservoir characterization, 3-D geologic modeling, geosteering in thin beds and modeling the Logging While Drilling (LWD) responses.

Propagation resistivity measurements can be affected by eccentricity, invasion, variations in dielectric permittivity and thin beds. In situations of high relative dip, adjacent beds and formation anisotropy become significant factors in the log response. The use of a multiple spacing, multiple frequency propagation resistivity tool enables the calculation of multiple independent sets of vertical and horizontal resistivities. In addition to identifying and quantifying anisotropy, this also helps to determine additional borehole and formation effects.

This case history demonstrates the application of forward modeling and inversion processing to enhance understanding of the horizontal log response and the reservoir structure of a complex horizontal well drilled onshore California.

Current geosteering techniques frequently use offset wireline or LWD data from vertical or low angle wells. These logs predominantly measure the horizontal resistivity of the formation. Vertical resistivity cannot be accurately determined, if at all, in these situations. At high relative dip angles (e.g. in horizontal wells), a model generated from horizontal

resistivity alone will not be representative of the actual log response.

Horizontal and vertical resistivities derived from the inversion processing and subsequent modeling were in excellent agreement with both the offset wireline data and the actual LWD log.

INTRODUCTION

This case history was generated to determine the location of formation boundaries relative to the borehole of a horizontal well that had previously been drilled. In this instance, the models were based on the interpretation of the structures and location of formation tops as indicated by the LWD data. This case history shows the limitations of short normal and deep induction data as curves from which to generate forward models for geosteering as well as the limitations of isotropic LWD forward modeling programs where the relative dip is high enough for anisotropy to be a significant effect on the recorded LWD data.

Anisotropic affects on LWD and wireline resistivity measurements have been well documented in the literature (Wu, et al, 1997, Bittar, et al, 1994, Meyer 1996, Wu, et al, 1996, Hagiwara 1996, Klein, et al, 1995, Frisch, et al, 1993, Graciet, et al, 1997). These effects, whether due to alternating beds of differing resistivity or variable fluid saturation within beds have the effect that the measured resistivity can be significantly greater than true formation resistivity.

Anisotropy becomes significant in formations with relative dip of 60 degrees or more to the borehole (Wu et al, 1996) and consequently comparison to data from offset wells drilled with low relative dip is not straightforward. The ability to extract the horizontal component (R_h) and the vertical component (R_v), from measured resistivity in anisotropic formations is critical. Prior knowledge of the local vertical to

horizontal resistivity ratios allows more comprehensive forward modeling of the resistivity prior to drilling a horizontal (or high relative dip) well. The success of geosteering any well will depend on the completeness of the model as well as the skill of the geosteering engineer.

The introduction of a dual frequency, multiple spacing propagation resistivity tool (MPR™) (Meyer, et al, 1994a, 1994b) gives the ability to directly measure formation anisotropy (Wu, 1997) with knowledge of relative dip. This tool makes 32 different raw phase and amplitude measurements using two frequencies (2MHz and 400kHz) and four transmitters (a long spaced array with a 35" spacing to the mid-point of the receiver pair and a short spaced array with a 23" spacing). From this configuration the 32 raw values can be processed to produce 8 fully compensated phase difference and attenuation resistivities or 4 fixed depth of investigation curves (10", 20", 35" and 60" radii of investigation), (Meyer, 1997).

In this paper horizontal resistivity, R_h , is the resistivity measured parallel to the bedding plane while vertical resistivity, R_v , is measured perpendicular to the bedding plane. In vertical wells where bedding planes are perpendicular to the borehole, induction and propagation resistivity devices will measure R_h , while laterolog devices will measure a component of both R_h and R_v . Relative dip is defined as the angle between the borehole axis and a line drawn normal to the formation bedding plane measured in their common plane (Bittar, 1994.) It reaches its maximum value of 90 degrees when the borehole axis is parallel to the bedding plane.

GEOLOGICAL SETTING AND PURPOSE OF WELL

The project is located in the Wilmington Oil Field, Long Beach, California, (Figure 1). The Wilmington structure is a doubly plunging, highly faulted, tilted anticline. The approximately 2000 feet of stratigraphic section consists of stacked, oil bearing, unconsolidated turbidite sands and shales of Pliocene and Miocene age. There are 7 defined production horizons segregated by major north-south trending faults. The target Hx0 sand sits conformably on top of the Upper Terminal Zone (the third major producing horizon).

The Hx0 sands are better developed and were included in the original completions for the Upper Terminal production to the east in Fault Block VI. They were not included in Fault Block V, (area studied), due to relatively low oil saturation and the fear that they would water out and limit production from the better oil sands below. The 1980's electrical logs from wells penetrating the Hx0 showed that oil saturation had not changed significantly from original values and that primary production was possible. With an average of 12 feet of net sand out of an average of 17 feet of interval, developing economical strategies for producing this section were quite a challenge.

The Hx0 sands of fault block V and VI were reviewed as part of a Department of Energy (DOE) short term project, (US Department of Energy, 1994). The project proposed using new reservoir characterization tools to locate bypassed oil. EarthVision™ software and Silicon Graphics (SGI™) workstations were the primary reservoir modeling tools used by the operator for this purpose. The geological data was organized and a saturation model was created. To make the project as economically attractive as possible and to expose the most sand face, a horizontal well course was laid out along the top of the structure, (Figure 2). Structural analysis showed that the formation dip in the area along the well path does not exceed 2½ degrees. At this low angle the difference between true vertical thickness (TVT) and true stratigraphic thickness (TST) is negligible.

The DOE's objectives are to increase domestic reserves. To that goal the operator tested the feasibility of using a production hoist with a hydraulic sub-base to drill a high dog-leg horizontal well from an idle production well. If the overall cost of drilling and completing is reduced then more reserves become economically available.

DRILLING HISTORY

The J-017 4, 6 1/8" hole section was started on 6th March 1997 using a steerable drilling assembly with a 4¾" LWD system. A fresh water, clay based mud system with 4% KCl to inhibit clay swelling and 10 - 15% crude oil to control water loss and increase lubricity was used. Polypropylene glycol lubricant was added to the mud system after oriented drilling became difficult. Mud resistivities varied from 0.19 to 0.22 ohm-m at bottom hole temperature. The well was successfully drilled to 4118 feet MD on the 19th March. Completions activity continued to 1 May when

tubing conveyed perforating guns were run. A total of 40 perforations were made between 3285 feet and 3900 feet MD. After equipping the well with a thermal packer and insulated tubing for steam stimulation, the rig was released on the 7th of May 1997.

ANALYSIS OF THE LWD DATA

One of the features of this propagation resistivity tool response is that, in anisotropic conditions, the curve order can look like conductive invasion with the short spaced data reading less than the long spaced at either frequency. However, comparison of the deeper reading attenuation measurements shows that they read less than the phase measurements for both frequencies, (Figure 3a and 3b). This anisotropic curve order has been noted by other authors (Meyer, et al, 1996, Wu, et al, 1996) and is a distinguishing characteristic. The anisotropic affect is seen throughout the log. If conductive invasion had occurred then the attenuation curves would be greater than the phase curves.

Invasion, another potentially significant borehole affect, is not seen nor are affects due to changes in the dielectric constant present. Dielectric affects cause the attenuation curves to read higher than the phase measurements which is not the curve order shown in this example. Variation in the relative dielectric constant at this formation resistivity has a minimal affect in any case.

The resistivity curves respond to the approach of the top of the Hx0 from the Hx1 formation, at a relative dip of 88 degrees, by showing an increase in the deeper reading 2MHz attenuation and a drop in the phase difference values at 3248 feet MD (2845 feet TVD sub sea). The bed boundary is crossed at 3313 feet MD (2848 feet TVDss), (Figure 3a). As the well traverses the Hx0, the separation between the attenuation and phase difference curves is relatively constant until they approach the basal shale member at 3426 feet MD (2853 feet TVDss). There is insufficient resistivity contrast at the interface to see horn development (Anderson, 1990) between the upper more sandy section of the Hx0 and the shale member. The well remained in the shale until it crossed a normal fault at 3480 feet MD (2854 feet TVDss) into the Hx0J. The shale is characterized by a reduced phase difference and attenuation curve separation compared to the turbiditic sands above and below it and a slightly higher gamma ray measurement, (Figure 3a).

The approach to the fault at 3480 feet MD is not detected by the deeper reading 2Mhz or 400kHz attenuation curves. This suggests that the incident angle of the borehole is close to perpendicular to that of the fault which explains the lack of response of the phase and attenuation curves immediately preceding the fault. The shallower reading phase difference curves respond immediately to the formation change after the fault (although the 400kHz to a lesser extent than the 2Mhz). The anisotropy displayed by the Hx0J remains relatively consistent until the well crosses back into the Hx0 basal shale, (Figure 3a). The well stays in the Hx0 until 3974 feet MD (2845 feet TVDss) where it is proposed that it drops back into the Hx0J. The Hx0J shows variation in resistivity response from the previous times the well entered this formation. This may be a function of changes in the properties of the formation as well as a change in relative dip (87 degrees from 89 degrees at 3450 feet, 2854 feet TVDss).

The deeper reading 2Mhz and 400kHz long and short spaced attenuation curves showed little separation and response to the change in lithology as the well traversed through the Hx0 into the Hx0J, compared to the phase difference curves. The 2Mhz phase curves were more responsive to the anisotropy than the deeper reading 400kHz phase difference curves. This frequency dependent response in thin bedded environments has been noted by other authors (Meyer, 1996, Bittar, et al, 1994).

With the log showing indications of possible structural changes, as well as lateral variation, the only way to help better determine the position of the formation tops, aside from more drilling, is to model the log response.

MODELING APPLICATIONS

Current LWD geosteering modeling involves gathering a set of offset well data (predominately wireline or LWD data), adjacent to the proposed borehole and structure maps of the targeted horizons and then modeling that data along the proposed well path. Selection of the LWD sensors to geosteer with will depend on the reservoir properties. Where there is sufficient resistivity contrast between the zone of interest and adjacent zones then propagation resistivity is the primary choice due to its depth of investigation.

Propagation resistivity models are based on the presence of certain physical effects that are generated by propagation resistivity devices at high relative dip angles. In situations with a moderately high contrast (at least 10:1) between the reservoir and adjacent shoulder beds or water zones, physical effects called polarisation horns (Anderson, 1990) can develop depending on the relative dip angle and the resistivity contrast. These horns appear within about 2 feet TVD of a suitable resistivity contrast. Approaching resistivity contrasts will also cause curve separation to occur, with the deeper reading curves responding earlier than the shallow reading curves to the approaching boundary (Wu, et al, 1991). This curve separation is not as dramatic an indicator of an approaching boundary but it occurs earlier than horn development. Steering with LWD propagation resistivity devices makes use of these effects as a guide to wellbore placement.

After the well has been drilled, the resistivity model is refined to help interpret the actual response. In this process a clearer picture of the structure around the well path can be obtained.

The pre-well process of creating a set of models can be summarized as follows:

1. Analysis of the structure map to determine formation dip and dip azimuth across the proposed well path.
2. Determination of the relative dip between formation and proposed borehole.
3. Selection of appropriate offset resistivity data to provide a resistivity profile to put into the dipping bed models.
4. Conversion of the resistivity data into a step like R_t profile in TST.
5. Input of the R_t profile into the dipping bed model and generation of TST based modeled data.
6. Conversion, using the proposed borehole survey data, of the TST based resistivity model to a measured depth presentation.

A variety of modeled scenarios are created to take into account different entry and exit angles into and from the target zone to give the geosteering engineer a tool kit of modeled responses for comparison with the actual data. Ideally the geosteering software will allow the geosteering engineer to rework his model at the rig site to account for changes in the structure (like changes in formation dip, presence of faulting,

thinning or thickening of formations, etc.). This makes decision making more timely and cost effective.

The effectiveness of the initial set of models depends very much on the input data from the offset wells. The most appropriate data comes from a pilot well drilled through the target zone with the LWD tool that will be subsequently used to sidetrack the well into the horizontal section. This will give the best immediate source for formation tops, thicknesses, resistivity profile, marker bed identification, etc. This ideal situation does not always occur, forcing the geosteering engineer to rely on adjacent offset well data. The availability and quality of data may vary considerably and this can be a significant limitation. The amount of production in an established field can induce subsidence as well as moving oil/gas/water contacts. Unless the amount of subsidence is known, the formations may not appear where anticipated causing problems when landing the well. The age of the data can also have an impact. Wireline resistivity data can range from older short normal through to array induction. The more recent wireline data will have better vertical resolution (depending on the processing) and more curves that will allow a better determination of true formation resistivity. Unfortunately, in slimhole/reentry applications in more mature fields this sort of information may not be available and engineers will have to resort to using data that may be considerably older and less representative of actual conditions. The effectiveness of forward modeling in these conditions is shown in this case history.

MODELING SOFTWARE

Three modeling programs were used in this study, two of which are described below. The third program, an isotropic dipping bed modeling program, (Wu, 1991) has the same limitations as the anisotropic dipping bed model program except that the input is R_t instead of R_v and R_h . The wireline data was modeled using the isotropic forward model and the LWD data was modeled with both the isotropic and anisotropic modeling programs.

ANISOTROPIC INVERSION MODEL

This program inverts a pair of resistivity curves (phase difference and attenuation) to calculate horizontal resistivity (R_h) and vertical resistivity (R_v). There are four possible sets of input data: 2MHz long or short spaced phase difference and attenuation and

400kHz long or short spaced phase difference and attenuation. These individual sets are obtained from the processed resistivity data derived from the 32 raw phase and amplitude curves stored in the LWD tool while drilling. One of the four pairs of phase difference and attenuation data is input into the program along with relative dip data. The product is a measured depth based calculation of Rh and Rv, Rv/Rh ratio and some quality control parameters. This program has the following assumptions: first, that the curve separation is entirely due to anisotropy and not other effects like invasion, eccentricity, dielectric constant variations and second, that the relative dip angle is known. In this instance there was insufficient resistivity contrast to produce eccentricity effects, invasion did not occur and the formation resistivity is low enough to make changes in the dielectric constant have a minimal impact. However, if these effects are present, they will cause an error in the Rv/Rh measurement. As a consequence, this program can help identify the presence of these other effects. Once the entire data set is processed, 4 Rv/Rh ratios and 4 sets of Rh and Rv curves are produced, based on the frequency and spacing of the measurements. Comparison can then be made between the data sets to determine whether anisotropy is the primary cause of curve separation or whether there is an additional affect occurring.

ANISOTROPIC DIPPING BED MODEL

This model is used in forward modeling anisotropic propagation resistivity log responses. This model assumes that the formations are infinitely parallel with respect to each other and that there are no borehole effects (that is, tool size, hole size, mud resistivity, eccentricity and invasion are not modeled). The model is applicable in this instance as these borehole effects are not present. The input data are either 2MHz or 400kHz derived Rh and Rv values with their associated true stratigraphic depths. The Rv and Rh data are usually squared off in a step like profile before being run through the program for speed of processing as well as defining bed boundary interfaces. The program can be run using either a constant relative dip or a file with changing relative dips and their associated depths. The outputs from the program are the modeled long and short spaced 2MHz or 400kHz resistivities referenced to true stratigraphic depth. This modeled data can then be input into a geosteering software package and combined with the measured depth profile of the

proposed well, the bed tops, dip and dip azimuths, to produce a geosteering model.

It is possible, therefore, to generate in conjunction with the anisotropic inversion program, four independently calculated forward models based on the Rv and Rh values calculated using the different spacings and frequencies.

ISOTROPIC MODELING USING WIRELINE DATA

In the absence of pilot hole resistivity data, the geosteering engineer will use offset wireline data to derive his model. There were a number of wells adjacent to the well path that gave good well control. The data varied in age from early 1950's to the mid 1980's. Figure 4 shows the resistivity data from adjacent wells to the horizontal well. Vertical resolution of the ILD and SN devices used to generate an Rt profile is relatively large at about 3 feet. Finer resolution is needed for effective modeling in thin beds. This limited resolution may restrict the creation of an accurate Rt profile on which the model is based.

Figure 5 shows the squared off Rt profile from Well J-017 3, and the modeled data based on that profile. This well was chosen to model as it was closest to the LWD entry point. Figure 10 shows the measured depth profile of the modeled log along with the memory data from the drilled well. The beds represented in Track 1 were defined by offset geological control. Various Rt profiles were examined to model the wireline data while remaining as true as possible to the lithological structure. As no pilot hole was drilled through to the Hx0B member the lower formation tops were not identified by the LWD tool. The horizontal well drilled down into the Hx0J member but did not progress any further in stratigraphic depth.

The model from the Rt profile in Figure 5 shows some artifacts that the wireline data does not show. Two horns are generated at the top of the Hx0 and Hx0B which occur as a response to the resistivity contrast. The overall curve shape of the LWD model response differs from the wireline data because of the better vertical resolution of the LWD tool.

The inclination of the J-017 3 well path through this section from 2800 feet TVDss to 2900 feet TVDss was 13°. Under these conditions the induction wireline data is responding only to the horizontal component of the resistivity. Without knowing the

vertical to horizontal resistivity ratio, it is impossible to predict what affect the vertical component would have on the LWD measurement when the relative dip is high enough that anisotropy effects becomes significant. Educated estimates can be made which can be input into an anisotropic model but as anisotropy is rarely uniform, this process would have limited benefit. As more wells are drilled and logged with this LWD tool, a better picture of the formation anisotropy will be obtained and at that point, observed ratios could be more reliably extrapolated. Figure 10 shows the measured depth profile of the revised model and the actual data.

Analysis of the model produced the following points:

1. Horn development is similar in magnitude and curve order on entry into the Hx0.
2. Modeled resistivities are approximately comparable.
3. Model curve order does not match the actual log.
4. The resistivity response to the presence of the fault is not mirrored by the model, (Figure 10).
5. Below 3642 feet MD the comparison is limited to the extent that the model shows the curves are separated
6. The model does not reflect the actual decrease in resistivity beyond 3900 feet MD.

With understanding of the limitations of the model and in particular that it is isotropic and has poor vertical resolution, the geosteering engineer would still be able to use it as a guide. It would not necessarily help him in modeling changes in local formation structure though, nor would it help to refine the location of the tops of the formation relative to the borehole.

ISOTROPIC MODELING USING LWD DATA

In this case, the isotropic Rt profile was picked from the horizontal LWD data and contains components of both Rv and Rh. The bed boundaries of this initial profile were based on the same bed boundaries used in the following anisotropic model.

Figure 6 shows the Rt profile with the formation bed boundaries in Track 1, the LWD data in Track 2 and the initial model in Track 3.

The modeled data compares to a limited extent to the LWD data. The Rt profile would have to be reworked to produce a model that would more closely fit the real data. Figure 7 shows a revised profile and

the model it generated. This is certainly a better match but the bed thickness and tops between the Rt profiles do not closely resemble each other. This is because the revised Rt profile is a composite fit between Rv and Rh in an attempt to produce an isotropic model of an anisotropic response. The revised profile could still be further improved to get a better fit. Figure 11 shows the measured depth profile of the revised model and the actual data.

Analysis of the model produced the following points:

1. There is a significant improvement over the model generated from the wireline data.
2. The curve order matches the actual data in that the attenuation values are lower than the phase values.
3. The anisotropic effect on the curve order is only partially represented in the model.
4. The response across the fault does not compare with the real data.
5. The model past 3650 feet MD resembles the actual log in the approximate resistivity values, the long spaced phase difference reads higher than the short spaced and the attenuation curves read less than the phase curves. However the order of the attenuation curves is not the same as that in the actual data.
6. The model does not show the gradual reduction in resistivity values past 3900 feet MD.

The isotropic model could be used to help geosteering the well but unless the Rt profile is further revised to account for the anisotropy, the model is not much use as an aid to explaining the actual response or to help verify the formation or structural model.

ANISOTROPIC MODELING USING LWD DATA

The anisotropic inversion model was run to produce four sets of Rv and Rh data based on the 2Mhz and 400kHz long and short spaced data. According to Wu, et al, 1997, the stability and uniqueness of the Rh and Rv calculation are significant problems associated with the nonlinear inversion process. This is apparent when the four sets of data are examined. The advantage in this particular process and using a tool that provides an extensive data set is that there are four sets of independently calculated Rv and Rh data that can be compared to determine whether the major effect causing the curve separation is anisotropy. Figure 8 shows the TVD based 2MHz long and short spaced Rv and Rh curves and with the LWD data while Figure 9 shows the same for the 400kHz data.

It is apparent that the 400kHz Rv and Rh curves are less stable in some parts when compared to the 2MHz data. Indeed, the non linearity plus some of the range limitations imposed in the program's processing has produced points where multiple solutions are apparent or has produced small gaps in the data. These artifacts are not apparent at the same depth on all four data sets which point to an inversion artifact rather than a data problem. Having this amount of data available for comparison will give a level of confidence as to whether a feature is a true response or an artifact. Comparison between all four sets of data is very close, indicating that anisotropy is the cause for the separation, (Figure 16).

Figure 12 shows the Rv/Rh ratio, the Rv and Rh curves and the Rt profile generated for the 2MHz Long spaced data. This profile was the first iteration. The Rv/Rh ratio across the log varies from between 2:1 to 4:1 except in the area of the horn at 2847 feet TVDss. The calculated ratio over the area of the horn can be disregarded as the values are being calculated from a physical effect and not a true formation effect. The Rv and Rh profiles for the other spacings and frequency show a similar comparison to the actual data.

The 2Mhz Rt profile was run through the dipping bed modeling routine and is shown in Figure 13. The comparison between it and the actual data in Track 3 is very good. Additional iterations to improve the Rv and Rh modeled response could be made with time. The measured depth profile is shown in Figure 14a and 14b.

Analysis of the model produced the following points:

1. Comparison of Rv and Rh curves from all 4 sets of data indicated that curve separation is caused by anisotropy.
2. Comparison of Rh with offset wireline data is very good, (Figure 15)
3. The modeled data reflects the curve order and magnitude of the actual data, (Figure 14a).
4. For both frequencies and spacings, Rh is less in value than the actual data while Rv is greater.
5. Rv/Rh ratio varies from 2.5:1 to 4:1 in the Hx0 and Hx0J sands and 2:1 to 2.5:1 in the lower Hx1 shale.

The response of the model fits very well to the actual data. This good fit continues to 3950 feet MD where the actual resistivities start to fall in value. This is not

mirrored in the model and is most likely due to lateral variation within the formation.

CONCLUSIONS

The results of the anisotropic inversion and dipping bed programs demonstrate that in high relative dip situations isotropic modeling does not provide a clear solution to post well analysis although it may provide an adequate enough model to geosteer with. Pre-well modeling is made less effective in situations where Rt profiles are generated from wireline data that have relatively poor vertical resolution. Independent calculations of multiple sets of Rv and Rh data based on differing frequencies and transmitter to receiver spacings gives a much higher degree of confidence than if just a single Rv and Rh curve were generated. Rh curves can be directly compared to offset wireline data for more effective well correlation. Post well modeling of the actual data using these models, allows for a more rigorous interpretation of the structure around the well bore. With the consequent refinement in the geological structure, placement of future wells will be made more effectively.

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Figure 1
Location map of the
Wilmington Field
California, USA.

Figure 2
Structure map of the
Hx0 Formation in
Fault Block V of the
Wilmington Field
showing the well path
of the J-017 4
horizontal well.
Adjacent offset well
control is shown as
dots on the map.

Figure 3a
J-017 4 LWD log
showing Gamma
Ray in Track 1,
2Mhz long and
short spaced
resistivities in Track
2 and 400kHz long
and short spaced
resistivities in Track
3.

Note that the curve
order is indicative
of anisotropy.

Figure 3b ->>
Lower section of
the J-017 4 LWD
log.

Figure 4 Adjacent well data (J-017 3 and J-121 0).

Figure 5 Rt profile from J-017 3 offset to the J-017 4 Hx0 formation top at 2847 TVDss.

Figure 6 Isotropic model based on the LWD data.

Figure 7 Revised isotropic Rt profile with the model it produced.

Figure 8 2Mhz long and short spaced Rv and Rh curves.

Figure 9 400kHz long and short spaced Rv and Rh curves.

Figure 10 ->
Measured Depth
profile generated
from the J-017 3 Rt
profile.

Figure 11 ->>
Measured Depth
profile generated
from the revised
isotropic LWD
model.

Note that due to
space limitations the
second sections of
Figures 10 and 11
have not been
shown.

Figure 12
2Mhz long spaced derived Rv and Rh data and the 'squared off' Rv and Rh profile created for input into the anisotropic forward modeling program.

Figure 13
TST profile of the anisotropic model created from the 2Mhz Long Spaced data.

< Figure 14a
Measured Depth profile of the LWD data and the anisotropic modeled data.

< Figure 14b. Measured Depth profile of the LWD data and the anisotropic modeled data.

Figure 15
2MHz Rv and Rh profile compared to adjacent well wireline resistivity data. The wireline data has been shifted to the J-017 4 Hx0 TST depth.

Figure 16.
Rv and Rh data for the 2MHz and 400kHz long and short spaced data. Note the excellent agreement between the frequencies and spacings.

APPENDIX 2

PAPER B2**ACOUSTIC DETERMINATION OF PORE FLUID PROPERTIES
USING A 2-COMPONENT MODEL****Daniel Moos***Stanford Borehole Geophysics Laboratory**and**GeoMechanics International***Gretchen Zwart***GeoMechanics International***ABSTRACT**

Previously, it has been shown that hydrocarbon-bearing rocks can be differentiated from those which are brine-saturated using compressional and shear-wave velocities. However, it has been impossible to quantify saturation using the Gassmann relations, because a single component model does not adequately describe the properties of the dry frame. Application of a two component mixing model (Berryman and Milton, 1991) provides improved quantitative values for the solid, the dry frame, and the pore compressibility. Using these results, the equations of Brown and Korrington (1975), can be applied without imposing arbitrary restrictions such as a fixed dry frame Poisson's ratio (Saxena, 1996). Although the current work does not do so, a simple extension of this model can account for the pressure-dependence of frame properties.

INTRODUCTION

An interactive forward modeling package was developed to investigate the ability of Berryman's (Berryman and Milton, 1991) rock physics model for two-component (composite) properties to predict measured P- and S- wave velocities. Berryman's approach extends Gassmann's (1951) relations using Brown and Korrington's (1975) formalism to allow construction of a composite containing two porous solid constituents. Relationships between porosity and frame moduli for each constituent can be specified independently. The resulting materials can be mixed using any reasonable mixing law, and saturated using Brown and Korrington's (1975) relationship.

First, we compute V_p and V_s from input log data by determining the effective compliance of the solid portion of the porous medium and assuming a variety of pore fluid compliances. A three component mixing model (two solids and the pore space) is used to determine the moduli of the porous frame. By using the frame properties which were determined by forward modeling, we can then determine fluid compliance using bulk density and measured V_p and V_s . The results of application of this approach to a variety of log data are briefly discussed in this paper.

Prior to deciding to use Berryman's approach, we considered a number of published models to evaluate their applicability to the problem of pore fluid compliance prediction from acoustic velocities. The approach proposed by Saxena (1996), although similar to Berryman's approach, was not sufficiently general to be widely applicable in practice, as it needlessly restricts the relationship between frame shear and bulk moduli. Effective medium theories, differential effective medium theories, and double embedding techniques (which can also be used to develop multi-component models) were rejected because these rely on mathematical models which restrict their applicability. For example, many models are only applicable for a restricted range of defect concentrations, or are based on very specific component geometries. Berryman's approach to using Brown and Korrington was chosen because (1) it allows the use of any mixing law, (2) it allows the use of any relationship between properties and porosity of the components, and (3) because it relies on measurable quantities in its application.

MODEL

In order to apply a two-component model, it is necessary to specify relationships for each component between porosity and modulus. Figure 1 shows schematically a number of published relationships between porosity and modulus. In this paper we choose to assume that a modified Hashin Shtrikman lower bound (Dvorkin and Nur, 1996) is appropriate to relate the properties of each component to its porosity. As we will apply our results to unconsolidated materials, this type of model is most appropriate. In practice, any model can be chosen, as mentioned above.

Figure 1: Relationships between porosity and modulus for a quartz sand. The modified Hashin-Shtrikman bound is shown in red. Relationships appropriate for cemented clastics include cementation models, critical porosity relations, and models such as the Wyllie time-average or Raymer/Hunt/Gardner. Using only one component, it is necessary to vary the endpoint properties to account for changes in volume of (for example) clay.

Figure 2 shows the input parameter window of an application developed to test this model. We allow either or both components to be porous, and use Hashin-Shtrikman bounds on the mixture, based on selection of the enclosing component. Fig. 2 shows an example in which porosity is the same in both constituents. Relationships between porosity and frame modulus for each component are assumed to follow a modified Hashin Shtrikman lower bound (Dvorkin and Nur, 1996b; Moos et al., 1997). The mixture law is a volumetric "Bounding Average" similar to that proposed by Marion et al. (1990).

Input Files		Modulus Constants	
Input file:	<input type="text" value="lithin.txt"/> Key: <input type="text" value="test"/>		
Density input file:	<input type="text" value="rho.in.txt"/>		
Parameter file:	<input type="text" value="Param.txt"/>		
Ksat output file:	<input type="text" value="Ksat.txt"/>		
Kf output file:	<input type="text" value="Kfluid.txt"/>		
Y output file:	<input type="text" value="Yout.txt"/>		
		clay	sand
		Critical bulk modulus:	<input type="text" value="5"/> <input type="text" value="6"/>
		Critical shear modulus:	<input type="text" value="0.9"/> <input type="text" value="1.6"/>
		Mineral bulk modulus:	<input type="text" value="40"/> <input type="text" value="36"/>
		Mineral shear modulus:	<input type="text" value="20.0"/> <input type="text" value="44"/>
		Critical porosity:	<input type="text" value="0.60"/> <input type="text" value="0.38"/>
		Model:	<input type="text" value="HSLB"/>
Mixture type		Selected Plots	
Porous component	Enclosing component		
☐ Clay	☐ Clay	☐ Kphi, etc. plot?	
☐ Sand	☐ Sand	☒ Sensitivity plot?	
☒ Both	☒ Both	☐ Endmember plot?	
<input type="text" value="Equal distri..."/>	<input type="text" value="Mix by volu..."/>	☐ Composite dry frame plot?	
		☐ Velocity plot?	
		☐ Ksat and G plot?	
		<input type="text" value="Run calculations"/>	

Figure 2: Front panel of the forward model, illustrating the range of options currently available. Input and output data files are entered using the dialogue in the upper left. The properties of each end member can be specified using entries in the upper right. The lower left box contains push buttons which allow selection of the porosity distribution and the mixing law. A number of plots can be selected to aid in diagnosing the model predictions and to show the results.

It is advantageous to use a bound-type model as this guarantees that the actual properties of the medium will always be limited by the prediction, either from above or below. By applying Berryman's mixing model twice, both upper and lower bounds on the rock properties can be calculated. If these bounds are close together it provides confidence that the results can be applied without knowing how the mixture is achieved in the real world. If they are not, geological insight must be used to select the appropriate component mixture law.

Figure 3: The sensitivity plot shown here illustrates the variation in bulk modulus with porosity and clay content which results from using the parameters shown in Figure 1a. Bulk modulus decreases with increasing porosity. However, the relationship between clay content and bulk modulus is more complicated as the properties of the individual components depend on porosity in different ways.

The model is applied in practice by first fitting a subset of the data. In some ways this is analogous to using a "training set", but in this approach the user can interact with the model to select the parameters. As we currently apply this approach, the training set must include compressional and shear-wave velocities, porosity, density, and a log which defines the relative volumes of the two constituents. In shaly sands a gamma-ray log is often available for this purpose. If one can assume an a priori model for the materials, it is possible to carry out a forward model with only the velocities and a constituent volume log. For example, one can use V_s to determine porosity. This approach, which has been applied with some success using Gassmann, is not explored further in this paper.

The most efficient method when using a training set is to match as closely as possible the shear-wave velocity in intervals which have the highest percentage of each end-member. These provide each single-component porosity / shear modulus relationship. The component porosity / modulus model and parameters, and the mixture model and parameters, are chosen by the user to minimize the misfit between the measured and predicted shear-wave velocity throughout the interval. The same process can be repeated with the bulk modulus.

RESULTS

Figures 4 and 5, respectively, allow comparison of results from the Wilmington field M499 well over the depth range 0.95 to 1.08 km using one and two component. Although the fit is quite good in both cases, the two-component velocity predictions are more consistent with the measured results. The measured compressional-wave velocities in general lie close to the predicted values for oil and brine, consistent with the fact that there is virtually no free gas in this field. The input parameters for the end members are shown in Table I.

Figure 4: Comparison of calculated V_p and V_s to log values assuming a single solid constituent for the porous frame. Bulk and shear moduli of the porous frame are calculated as a function of porosity using a Hashin-Shtrikman lower bound. P-wave velocities are calculated using a saturated bulk modulus assuming fluid compressibilities of 2.0, 1.62, and 1e-5 GPa for oil, water and gas, respectively. Logged velocities are plotted in blue. In general, an excellent fit is obtained for these data even using a single component. Using a single-component model, the shear-wave velocities in sands are systematically under-estimated in comparison to those in more clay-rich materials.

Figure 5: Comparison of calculated V_p and V_s to log values assuming two solid constituents for the porous frame. The fit to the data is better than using one component, and there is virtually no systematic error associated with changes in clay volume.

Table I: Parameters for Wilmington and Colombian sands and shales

Parameter	Wilmington	Wilmington Two Components		Columbia Two Components	
	One Component	“shale”	“sand”	“shale”	“sand”
K_{crit} GPa	4.20	1.50	7.00	18.00	5.00
G_{crit} GPa	1.10	0.90	2.20	2.9	4.60
K_m GPa	38.00	40.00	36.00	38.00	38.00
G_m GPa	32.00	20.00	44.00	20.00	44.00
Φ_{crit}	0.50	0.60	0.32	0.40	0.26

By comparison, Figure 6 shows data from a field in Colombia over the depth interval 0.7 to 1.0 km. The parameters which best fit this data using two components are also shown in Table I. In Figure 3 the slight over-prediction of V_s at shallow depths and under-prediction at greater depths may be an indication of the necessity to vary the parameters to account for the increase in effective confining pressure with depth within the modeled depth interval.

Figure 6: Fits to velocity data acquired in a Colombian oil field computed using a two-component model with parameters as shown in Table I. This data is not fit quite as well as the data from Wilmington, perhaps because the porosity - modulus relations for the components did not account for the presence of variable amounts of cementation, and because of a systematic increase in effective confining pressure with depth within the logged interval. However, the predicted compressional velocities are generally consistent with the data, and with the known presence of oil and brine throughout and the occasional presence of free gas.

Figure 7 shows histograms of differences between measured and predicted velocities using the data from Wilmington modeled in Figures 4 and 5. With a single component model, the scatter in the fit to the shear-wave velocity (Figure 7a) is slightly larger and the mean is not zero. Both models indicate that there is little or no gas in situ (the predicted P-wave velocity

Figure 7: Histogram of the differences between predicted and measured velocities; a-d are for a model using one solid component and e-h are for a model using two solid components.

assuming gas saturation is much too low). However, the two-component model does a better job placing the measured data between the predictions for water (too high) and oil (too low) than does the single-component model.

Figure 8 shows relationships for the Wilmington field data between saturation derived using Archie's Law and the predicted fluid compliance found by inverting the actual measured velocities. Although the scatter in compliance is larger than the trend with

saturation, as expected for the heavy oils found in Wilmington (API 24 or lower in this interval, for which the ratio of brine bulk modulus to oil bulk modulus is approximately 2), the scatter is smaller for the two-component model. The trend does roughly follow an expected volumetric average of the compliances. Similar results were presented by Hornby et al. (1992).

Figure 8: Comparison of one and two component mixing models to predict fluid compliance for data from the Wilmington field. The line illustrates the expected variation in fluid compliance if a volume average of the compliances is appropriate for fluid mixture properties.

SUMMARY

In summary, it is clear that a two-component model for the rock solid frame is more appropriate than one with only a single solid component. Such a model both improves the fit to field data and reduces the scatter in predictions of fluid compliance from which saturation can be determined. The analysis further showed that the pressure dependence of frame properties may be important.

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