AN ADVANCED INTERPRETATION TECHNIQUE INTEGRATES WELL LOG AND CORE DATA FOR THIN-BED RESERVOIR EVALUATION

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ABSTRACT

Integrating reservoir parameters derived from log and core data allows previously bypassed thin and productive zones to be identified. Recent advancements in enhanced data acquisition methods and well log interpretation techniques have reduced problems encountered with conventional thin-bed well logging and data analyses. Improved data acquisition methods record filter-free data at higher sample rates. Advanced log interpretation techniques utilize enhanced porosity, shaliness, and resistivity measurements to compute more realistic hydrocarbon saturation in thin beds. An advanced analysis program integrates reservoir parameters derived from core and well log data to provide an optimum reservoir description package for lithology, porosity, permeability, and probable production. These reservoir parameters are presented on a single, expanded-scale plot. Examples and computed key parameters using this technique are compared with the conventional log interpretation techniques.

INTRODUCTION

Quantitative analysis of thinly laminated sequences for improved estimates of pay thickness, porosity, and water saturation is one of the most challenging tasks in well log interpretation. This problem has been recognized for a considerable length of time and different qualitative rules of thumb for different fields have been developed to estimate the production potential of these thin-bed reservoirs (Allen, 1984). The source of the problem is the vertical resolution of the logging tools which is a function of the physical characteristics of the tool. Vertical resolution of the porosity and resistivity tools are 2 to 8 feet and measurements are strongly influenced by adjacent beds in thin-layer environments. Quantitative interpretation using conventional methods may yield high water saturation and lower porosity values, causing zones to be overlooked, especially in laminated shaly sand reservoirs.

Improvement of vertical resolution through modification of the tool design often results in decreases in the depth of investigation and adverse borehole rugosity effects. Until recently, due to their excellent vertical resolution (approximately 0.5 inches) and high sample rates (64 samples/foot), dipmeter logs were used exclusively to delineate thin beds (Quinn and Sinha, 1985). Using Diplog® data for a sand count presentation is shown in Figure 1. The ability of the dipmeter log to better define the bed boundaries compared to other conventional resistivity and porosity logs can be seen in this figure.

Recent advancements in the interpretation of these thin beds includes the use of additional high vertical resolution tools, better data acquisition methods, and enhanced log interpretation techniques. The computed results are integrated with the core data, and the log and

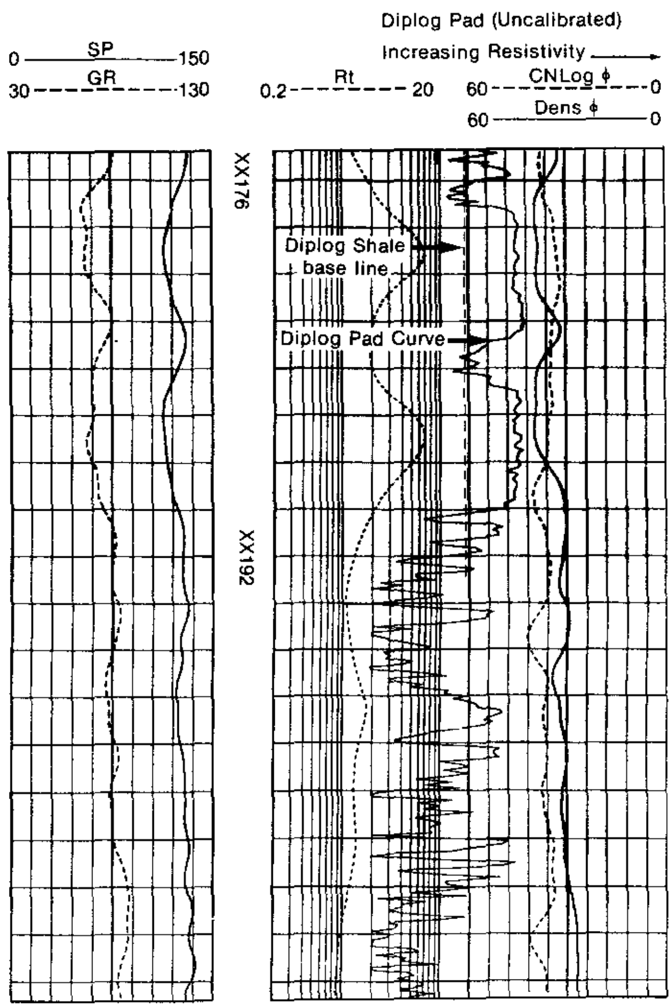

Figure 1. Sand count presentation.

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core-derived parameters of the reservoir are presented on a single, expanded scale plot. The technique for the quantitative interpretation of thin beds, as stated above, can be separated into three main components:

1) use of high vertical resolution tools,

2) better data acquisition methods, and

3) enhanced log interpretation techniques.

HIGH VERTICAL RESOLUTION TOOLS

A number of high resolution devices are now available to the industry to quantitatively evaluate thin beds. Devices include the Circumferential Borehole Imaging Log (CBIL), Deep Investigation Resistivity Tool (TBRt), Shallow-Reading Dielectric Log, Diplog, Microlaterolog, and Minilog®. The CBIL is an excellent tool for defining beds as thin as one-third inch and can be used in fresh, salt, or oil-base muds. The TBRt or the dielectric tool, depending on mud and formation water salinities, is recommended over other thin-bed resistivity devices. Combining the CBIL with the TBRt or dielectric logs provides valuable measurements for thin-bed resistivity and boundary definition. These three tools are described briefly below.

Circumferential Borehole Imaging Log

The CBIL, an advanced version of the borehole televiewer, utilizes a rotating transducer operating in a pulse-echo mode to scan the entire circumference of the borehole wall (Faraguna et al, 1989). Changes in the acoustic impedance of the rock (due to variations in lithology and physical rock features, such as fractures and laminations) cause variations in the amplitude of the received echo. The pulse-echo travel time is also measured and both the amplitude and travel time maps are displayed to provide 360 degree images of the borehole, showing lithological and geometrical variations.

The vertical resolution obtained with this tool is a function of the focused-beam spot size, transducer rotation rate, and logging speed. The CBIL transducer operates at 360 revolutions per minute and with a logging speed of 10 feet per minute, a complete scan is produced every one-third inch. This 0.33-inch vertical resolution can be improved further by reducing the logging speed. The vertical resolution of this tool is shown in Figure 2 in which a dipmeter-pad curve is also plotted for the comparison. The CBIL tool will operate in fresh, salt, or oil-base mud system with mud weight up to 15-16 lb/gal (depending on the borehole diameter).

Deep Laterolog for Thin Beds (TBRt)

The TBRt is a new deep laterolog instrument (Khokar and Johnson, 1989) based on the classical laterolog-3 concept, but with significant modifications that enhance vertical resolution and depth of investigation. The instrument body provides the long, equipotential electrodes to focus survey current from a small, pad-mounted center electrode, deep into the formation, producing a high resolution measurement. The backup pad provides either a conventional Minilog or microlaterolog measurement as a supplement to the TBRt measurement. The ability of the TBRt tool to delineate thin beds is shown in Figure 3 which also includes the medium and deep induction with the shallow focused log from the Dual Phase Induction tool.

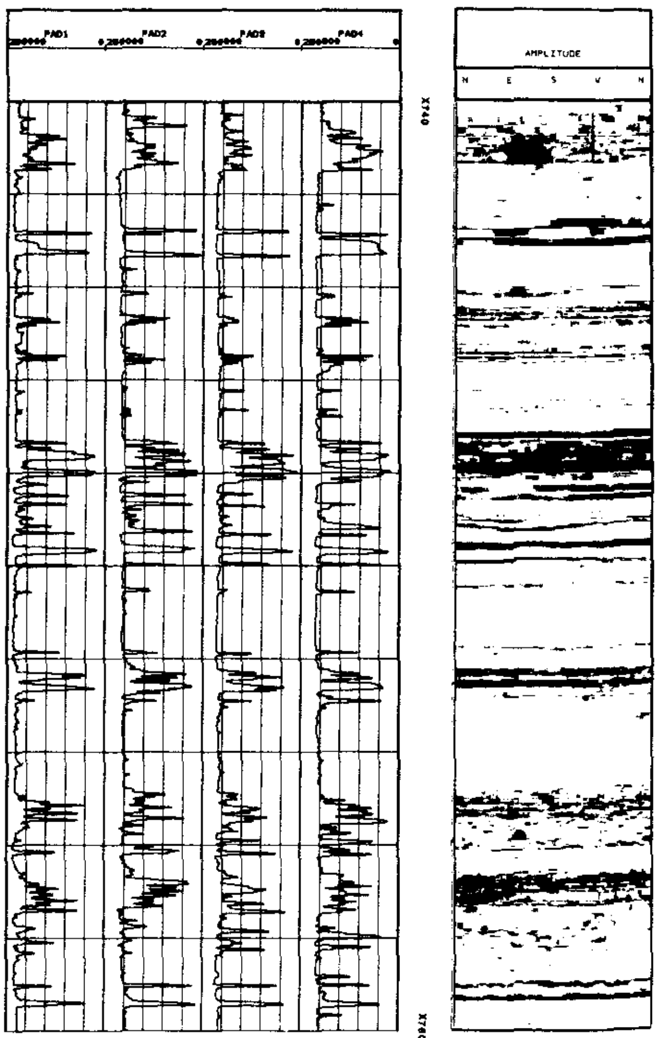

Figure 2. CBIL response for a typical thin-bed interval with pad curve from the dipmeter tool for comparison.

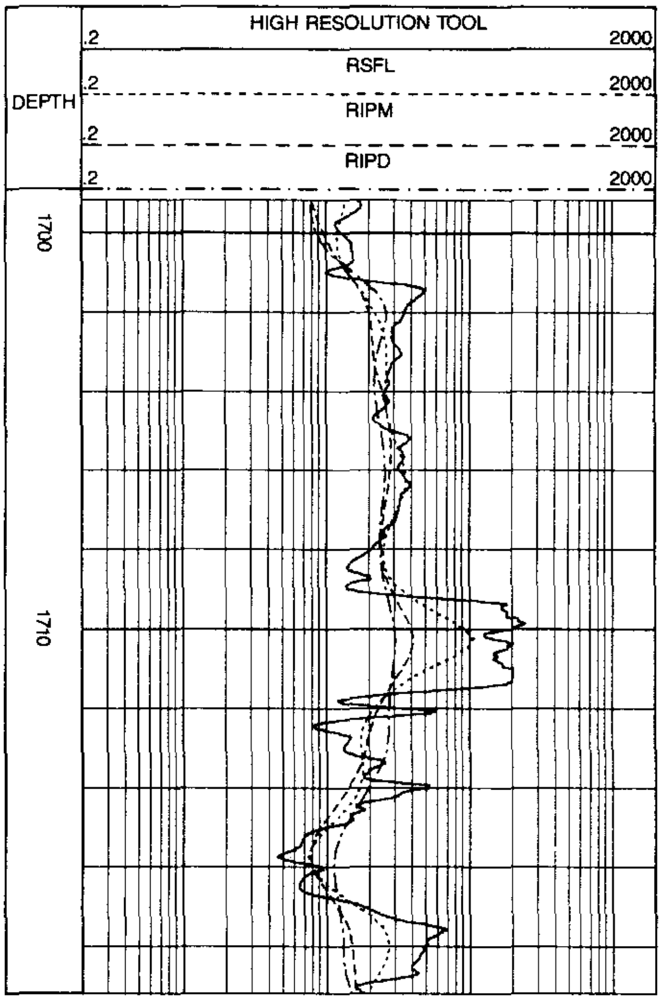

Figure 3. Thin-bed resolution of TBRt vs. Dual Phase Induction log.

Dielectric Log

The Dielectric Log is recommended in wells with oil-base or low salinity water-base muds (Lawrence and Fernandez, 1987). The dielectric logging instrument measures two propagation characteristics of an emitted electromagnetic wave:

1) the attenuation of the wave between two receivers, and

2) the phase shift (or propagation time) between two receivers.

The dielectric constant and the resistivity are calculated by entering these two measurements into a computer-generated model relating the dielectric constant and conductivity to the phase shift and attenuation. For thin-bed evaluation, the pad-type, high-frequency dielectric tool, such as the 200 MHz, is recommended and can delineate beds as thin as 3 inches. This tool has a relatively shallow depth of investigation but the calculated resistivity can be enhanced as discussed later to estimate true thin-bed resistivity. Figure 4 shows a typical log obtained using the 200 MHz dielectric tool.

DATA ACQUISITION METHODS

One of the most critical steps in thin-bed analysis involves choosing the proper data acquisition method. It is important that each measurement be made using the appropriate, optimum high sample rate. For instance, dipmeter data may need to be recorded at a sample rate of 64 samples/foot, while 8 samples/foot may be adequate for radioactive devices such as the density, neutron, and gamma ray log. In addition to recording data at higher sample rates, it is equally important that the data be obtained without using filtering methods common to conventional logs. Recording filter-free data ensures that all the information is preserved for possible future use and that no data will be destroyed. The data can always be filtered later, if desired, for conventional

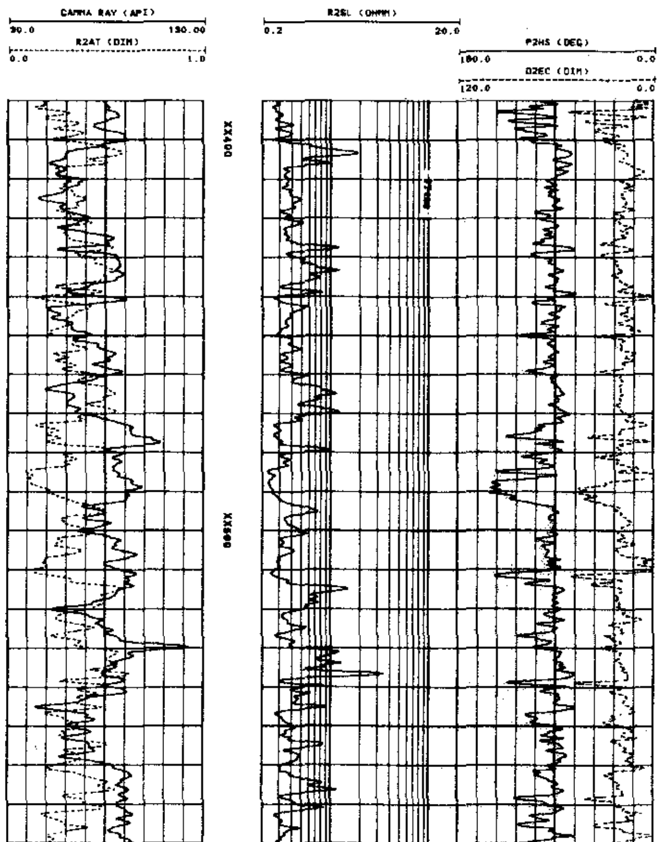

Figure 4. Typical presentation of logs obtained from the 200 MHz Dielectric tools.

log presentations. In the past, well logs were often filtered to reduce the appearance of "noise" even though in many cases, valid data may have been discarded in the process. The sophisticated digital equipment and data processing techniques in use today have greatly reduced the need for noise reduction compared to the past. A comparison of the conventional 4 samples per foot filtered data with 8 samples per foot unfiltered data is shown in Figure 5.

LOG INTERPRETATION TECHNIQUES

The four major steps in interpreting thin-bed reservoirs include determination of the following:

1) thin-bed porosity,

2) thin-bed resistivity,

3) thin-bed shaliness, and

4) thin-bed hydrocarbon saturation.

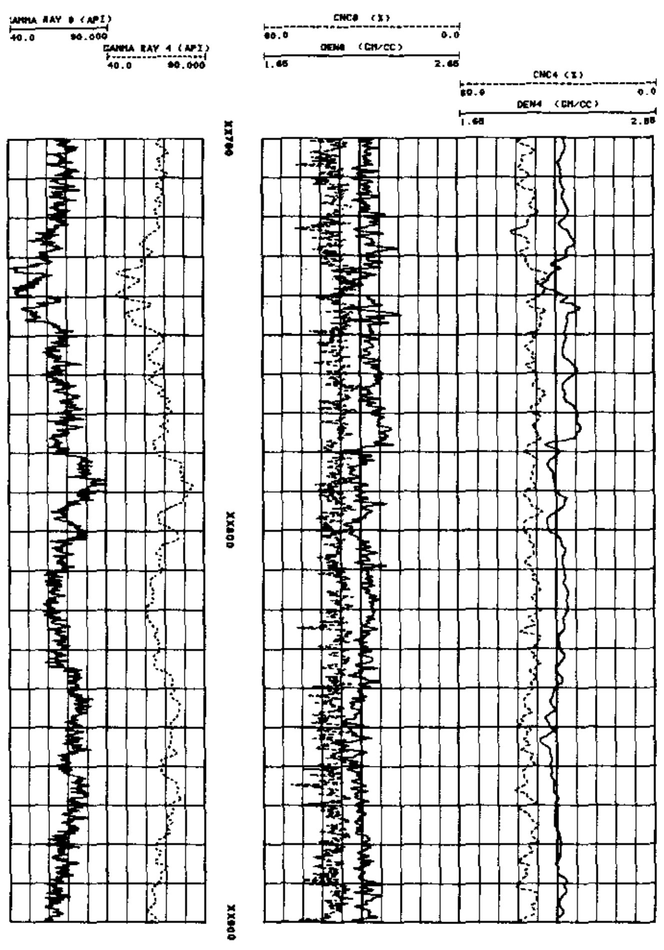

Figure 5. Comparison of conventional 4 samples/foot filtered data with new acquisition method of 8 samples/foot, unfiltered data.

High sample rate and filter-free data is then enhanced to obtain the above mentioned parameters.

Thin-Bed Porosity

Special processing techniques have been developed for obtaining the true porosity of thin beds from density, neutron, and acoustic logs. The conventional density, which relies primarily on the long-spaced detector, appears to average the true thin-bed density, depending on the thickness of the bed. The short-spaced density data, however, has a much better vertical resolution and therefore, shows sharper inflections at each bed boundary. Environmental effects such as mud cake or washouts may prevent the short-spaced detector from being used directly to generate a true density measurement. Determining the magnitude of the environmental effects and applying the compensation, however, permits the short-spaced, higher resolution measurements to be used as a more accurate representation of the true density.

This environmental compensation process can be accomplished by the following steps.

1) Filter the short-spaced measurement to have the same vertical resolution as the long-spaced measurement.

2) Calculate the environmental compensation as the difference between the conventional density and the filtered short-spaced density.

3) Apply the environmental compensation to the short-spaced measurement.

The resulting compensated thin-bed density will have the same vertical resolution as the short-spaced density but will be free of environmental effects. Figure 6 gives a graphical demonstration of this process to compensate the short-spaced density for environmental effects and thereby determine the true thin-bed density.

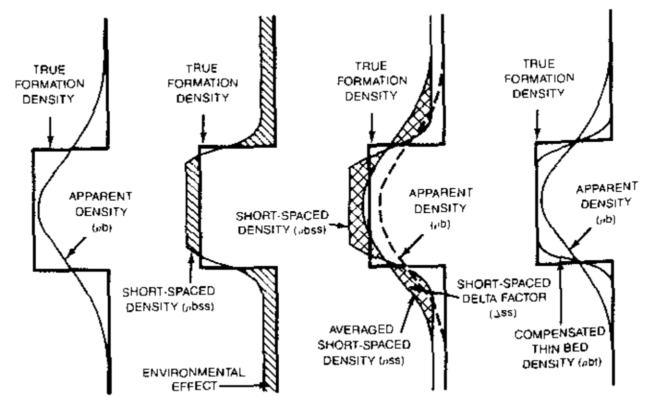

Figure 6. Graphical demonstration of the environmental compensation process for the density log.

The environmental compensation process can be described mathematically by the following simple equations:

$$\Delta_{ss} = DEN - DENSSF \qquad (1)$$

and

$$DENT = DENSS + \Delta_{ss} \qquad (2)$$

where

Δ_{ss} = short-spaced environmental compensation ("delta") factor

DEN = conventional bulk density in gm/cc

DENSS = short-spaced bulk density in gm/cc

DENSSF = filtered short-spaced bulk density in gm/cc

DENT = compensated thin-bed bulk density in gm/cc

Applying this processing to the short-spaced measurement assumes that the environmental effects are generally constant over the vertical distance of the long-spaced detector. Caution may be required in areas of extreme borehole conditions with erratic rugosity. For quality control, the resulting thin-bed density can be filtered and then compared to the original conventional density. These two curves should then overlay for high-quality data. Excellent results have been obtained using this technique (Fig. 7).

Neutron logs can be enhanced using this same technique in applying environmental compensation to the short-spaced neutron porosity. The resultant, enhanced thin-bed neutron porosity is compared with the conventional neutron porosity in Figure 8. Other conventional enhancement techniques, like deconvolution, can also be applied (Lyle and Williams, 1986). The noise level of logs and response functions are two factors (Looyesfijn, 1982) that determine the suitability of the deconvolution technique. Acoustic logs have proven to be better candidates for deconvolution. The response function is well defined and for good borehole conditions, the noise level is low enough to allow improvement in vertical resolution.

Thin-Bed Resistivity

Due to the fact that tools with higher vertical resolution usually give a shallower depth of investigation, most of the high vertical resolution tools discussed in the beginning of this paper give resistivity of the flushed zone. To estimate the true resistivity of the thin bed, the same "delta" processing method used on density logs has been found to work successfully with resistivity devices. By treating the deep induction or deep laterolog as a long-spaced device, the filter-free higher resolution resistivity devices can be environmentally compensated in the same manner as described for the short-spaced density.

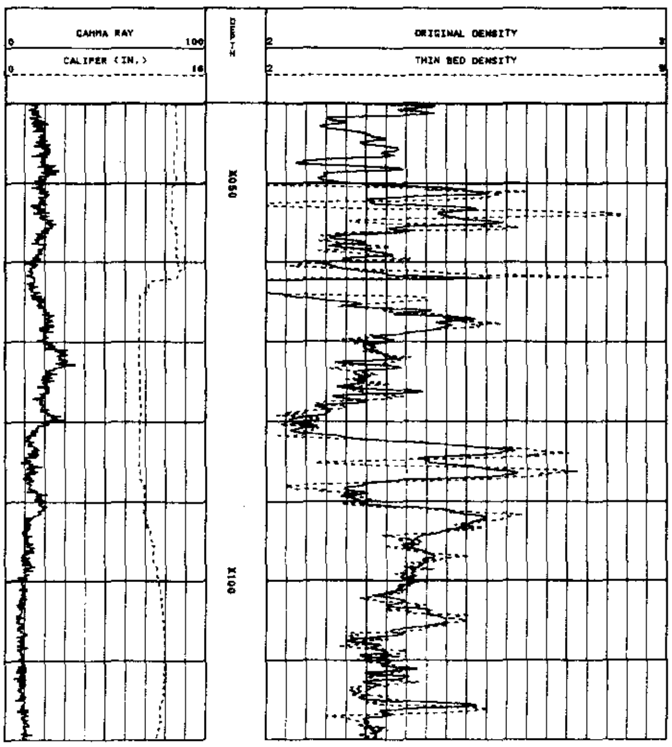

Figure 7. Enhanced thin-bed density log vs. conventional density log.

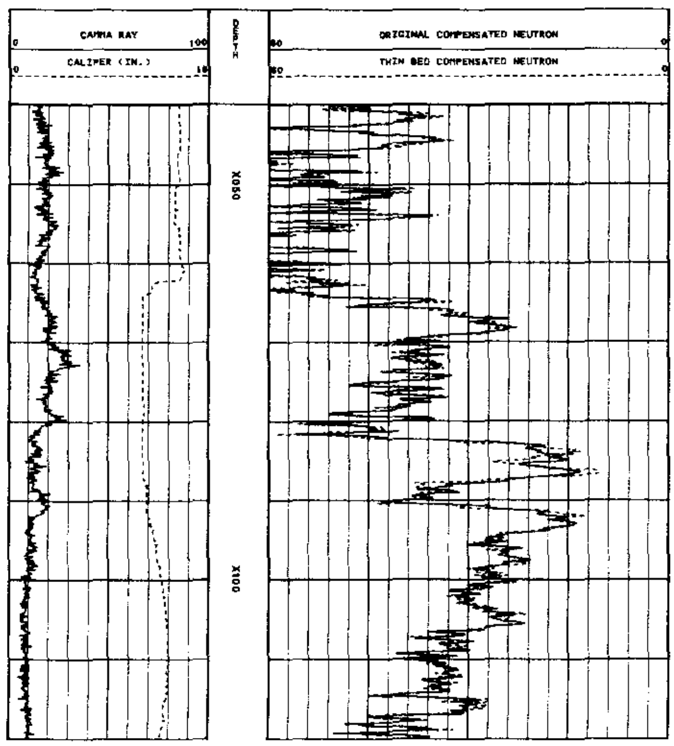

Figure 8. Enhanced thin-bed neutron log vs. conventional neutron log.

This method helps compensate the shallow-reading resistivity devices for the effects of invasion and borehole variability (Fig. 9). Of course, the deeper reading thin-bed device, TBRt, is recommended whenever possible to reduce the possibility of errors due to drastic environmental changes.

Thin-Bed Shaliness

Conventional shale indicator logs, like the gamma ray and the Spectralog®, can be used to find shale volume and bed boundaries if recorded at high sample rates, with slower logging speed. For example, a gamma ray recorded at 8 samples/foot without filtering will have better vertical resolution than the conventional gamma ray. Often, what appears to be noise on a gamma ray log actually is due to thinly laminated sections. Laminations can be verified by comparison to either a repeat section log or from other shale indicators. Several processing techniques have also been developed to enhance these logs in order to distinguish shale from sand and define bed boundaries. Deconvolution techniques may be used on the SP log for a better definition of beds. Blocking and layering programs are used to optimize the location of bed boundaries by evaluating one set of logs at a time. Figure 10 shows sand/shale boundaries identified by using a blocking technique. CBIL and TBRt tools have excellent vertical resolution for defining sand/shale zones as shown in Figure 11.

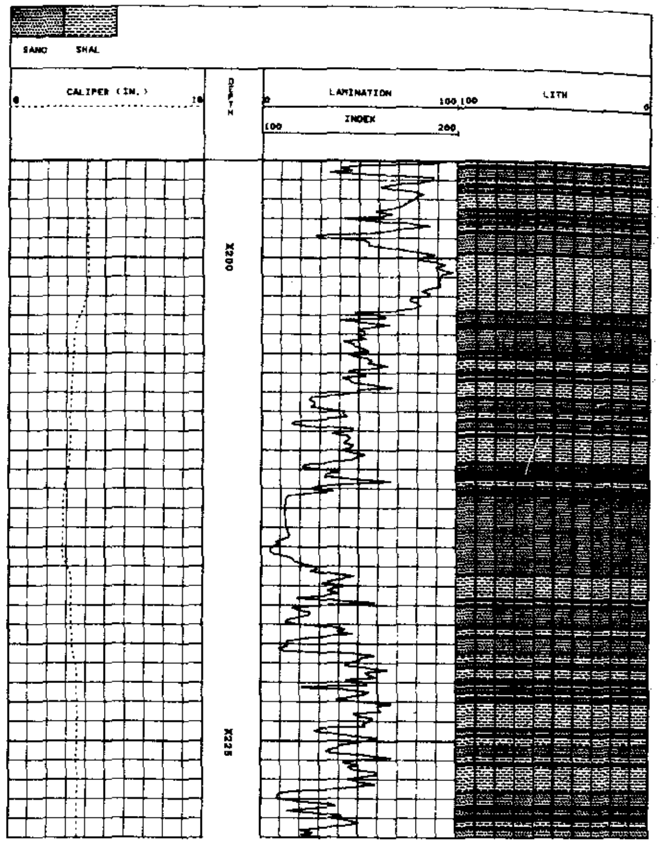

Figure 10. Sand/shale boundaries using blocking routine.

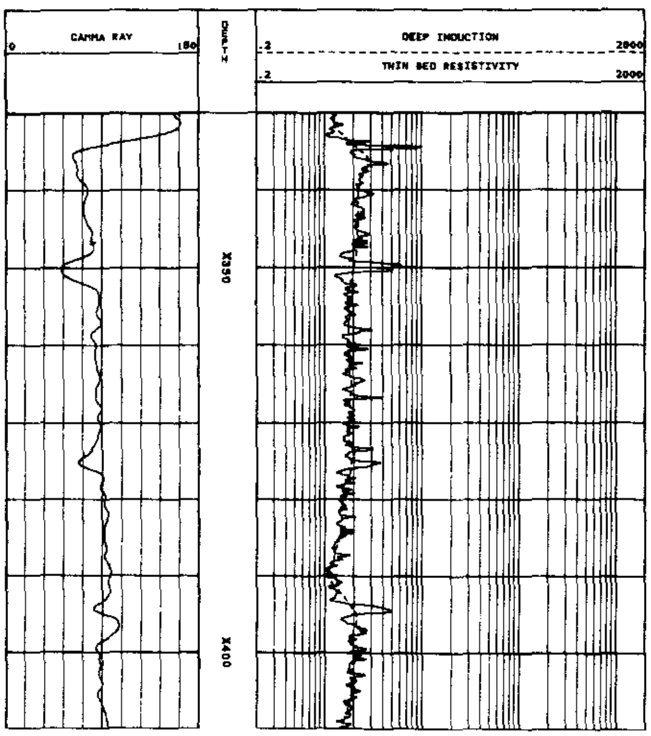

Figure 9. Enhanced thin-bed resistivity log vs. conventional resistivity log.

Thin-Bed Hydrocarbon Saturation

Combining the thin-bed porosity, resistivity, and shale volume information leads to the calculation of the thin-bed hydrocarbon saturation. Different water saturation models ranging from Archie's equation to Waxman Smits equation (Rukhovets and Fertl, 1981) are available to calculate the true water saturation of thin beds. The water saturation can first be calculated in the clean section and then compensated for the volume of shale to obtain effective hydrocarbon saturation. Net hydrocarbon volume can thus be obtained using the high resolution measurements.

DATA PRESENTATION

The final results of the thin-bed analysis can be presented in a variety of customized formats, e.g., by itself, including the raw data plus water saturation and porosity, or using both conventional and thin-bed analyses (Fig. 12). In tabular-type presentation, average and cumulative values of vital reservoir parameters can be presented using different sets of cutoffs. This presentation can be used to obtain the net thickness, porosity,

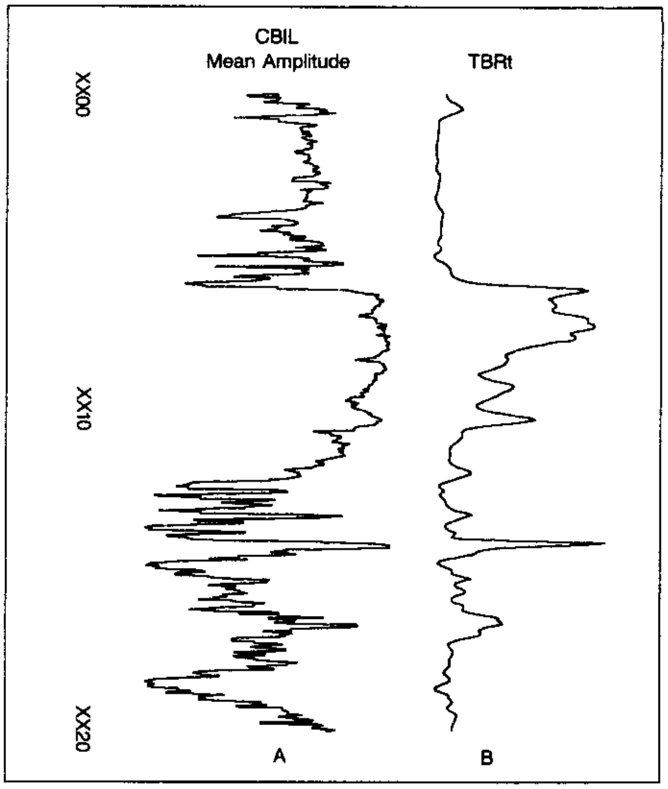

Figure 11. Comparison of bed definitions from CBIL and TBRt logs.

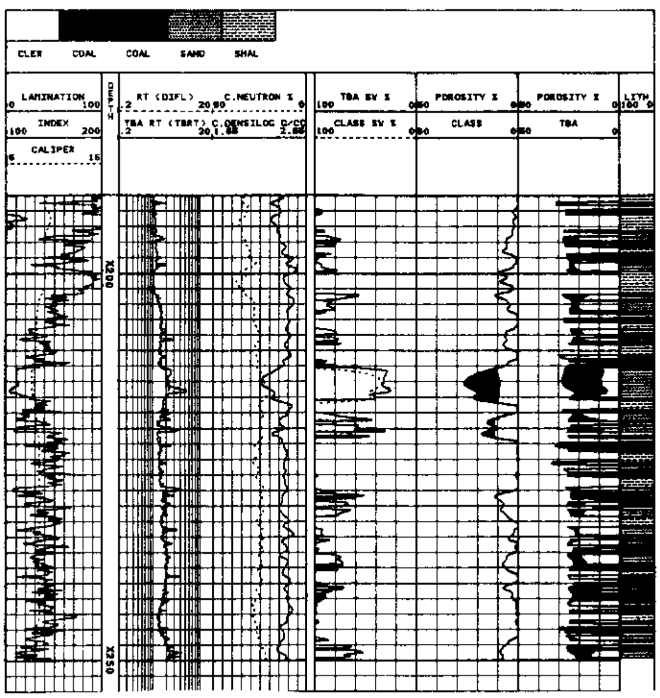

Figure 12. Thin-bed analysis results.

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DATA FILE NAME: W00003                                    DATE: 4/20/89       3:30p
***********************************************************************************
*      COMPANY :ALPHA OIL CO.               WELL: BETA-226                        *
*      FIELD:   ZETA OIL FIELD                                                    *
*                                                                                 *
*         ZONE :LOWER                   TOP=  10305.00  BOTTOM=  10608.00  FEET   *
*                                                                                 *
***********************************************************************************
* CUT-OFFS  *                                                                     *
***********************************************************************************
*   POROSITY     NONE     12.000   14.000   16.000   18.000   20.000   22.000     *
*   WAT-SAT      NONE     40.000   40.000   40.000   40.000   40.000   40.000     *
***********************************************************************************
*                                                                                 *
***********************************************************************************
* VARIABLES *                                                                     *
***********************************************************************************
*                                                                                 *
* THICKNESS *  303.000  170.500  169.625  164.875  158.625  145.375  109.625      *
*                                                                                 *
* POR-FEET  *   67.247   38.330   38.214   37.482   36.423   33.881   26.369      *
*                                                                                 *
* HYD-FEET  *   30.561   27.180   27.102   26.631   25.927   24.224   18.982      *
*                                                                                 *
***********************************************************************************
  THICKNESS  IN FEET        POR-FEET   IN FEET         HYD-FEET   IN FEET

LEVELS CONSIDERED
*****************
  POROSITY EQUAL TO OR GREATER THAN CUT-OFF
  WATER SATURATION EQUAL TO OR LESS THAN CUT-OFF

REMARKS
*******
  RESULTS FROM THIN BED ANALYSIS
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Figure 13. Summary of important reservoir parameters computed by conventional log analysis.

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DATA FILE NAME: W00003                                    DATE: 4/19/89    88  4:17p
***********************************************************************************
*      COMPANY :ALPHA OIL CO.               WELL: BETA-226                        *
*      FIELD   :ZETA OIL FIELD                                                    *
*                                                                                 *
*         ZONE :LOWER                   TOP=  10305.00  BOTTOM=  10608.00  FEET   *
*                                                                                 *
***********************************************************************************
* CUT-OFFS  *                                                                     *
***********************************************************************************
*   POROSITY     NONE     12.000   12.000   12.000   12.000   12.000   12.000     *
*   WAT-SAT      NONE     40.000   35.000   30.000   25.000   20.000   15.000     *
***********************************************************************************
*                                                                                 *
***********************************************************************************
* VARIABLES *                                                                     *
***********************************************************************************
*                                                                                 *
* THICKNESS *  303.000  106.625   71.875   46.000   25.000   11.000    6.250      *
*                                                                                 *
* POR-FEET  *   40.493   18.968   12.977    8.646    4.863    2.284    1.299      *
*                                                                                 *
* HYD-FEET  *   21.857   13.375    9.614    6.692    3.950    1.956    1.144      *
*                                                                                 *
***********************************************************************************
  THICKNESS  IN FEET        POR-FEET   IN FEET         HYD-FEET   IN FEET

LEVELS CONSIDERED
*****************
  POROSITY EQUAL TO OR GREATER THAN CUT-OFF
  WATER SATURATION EQUAL TO OR LESS THAN CUT-OFF

REMARKS
*******
  RESULTS FROM CONVENTIONAL LOG ANALYSIS (CLASS)
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Figure 14. Summary of important reservoir parameters computed by thin-bed analysis.

and hydrocarbon feet for the entire zone (Fig. 13). Figure 14 is a similar presentation obtained by using conventional log analysis techniques.

INTEGRATION OF WELL LOG AND CORE DATA

If the core data is available, the log-derived and core-derived parameters are depth matched and compared. The computed values can be calibrated (if desired) with the core-derived values for some parameters (e.g., porosity, permeability, A, M, and N). In the final form, all the raw, computed, and core data can be presented on a single, expanded scale plot (Fig. 15). This integrated presentation provides an optimum reservoir description package for lithology, porosity, permeability, and probable production.

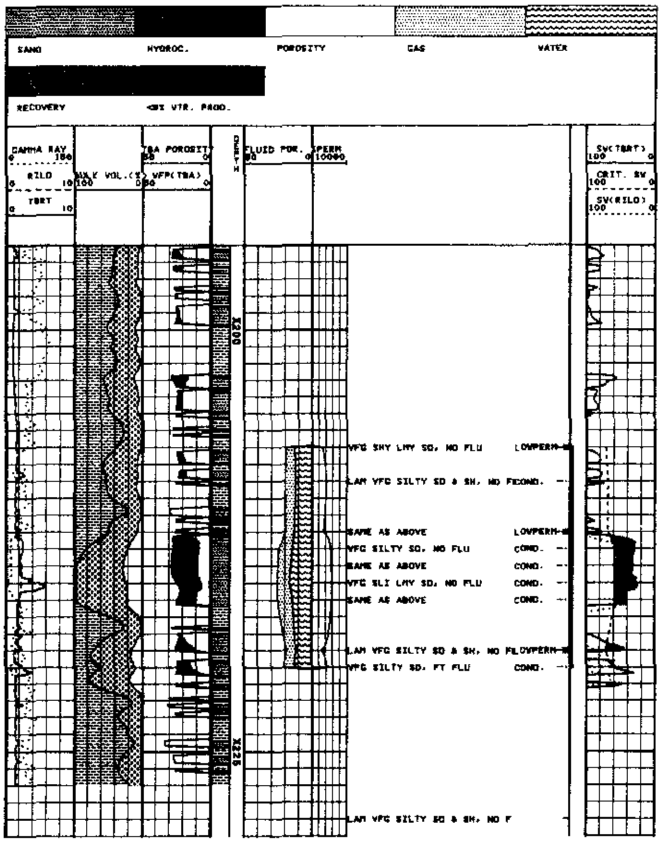

Figure 15. Combination of raw, computed, and core data in a single expanded plot.

CONCLUSIONS

1) Use of recently introduced, high vertical resolution logging tools gives more realistic sand/shale ratios and better definition of bed boundaries.

2) With the new available techniques, it is now possible to quantitatively evaluate thinly laminated sequences.

3) The thin-bed porosity, resistivity, shaliness, and water saturation are calculated more realistically by using the enhanced processing techniques.

4) Comparison of the core and the log-derived data adds confidence to the thin-bed analysis package.

5) Presentation of raw, computed, and core data (including core description) on a single expanded scale plot provides an excellent description of the laminated reservoir.

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