U.S. GULF COAST FIELD EXPERIENCE WITH THIN-BED WELL LOG ANALYSIS

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ABSTRACT

Thinly bedded reservoir sand sequences are encountered throughout the world, particularly as low-resistivity intervals in the U.S. Gulf Coast area. Despite apparent water saturation values ranging from 55 to 85%, as derived by conventional log interpretation techniques, such intervals can be important producers.

Recent technological advances in novel, high-resolution logging instrumentation, increased high-sampling rate data acquisition, advances in high-resolution signal processing (e.g., deconvolution) techniques, and newly developed thin-bed interpretation methods now allow an improved reservoir description of such sequences. Improvements include reliable net pay count; enhanced well-to-well correlation; better thin-bed correlation of well log, core, and test data; and thus provide a more accurate identification and quantitative evaluation of oil and gas-bearing stringers.

This paper presents several Gulf Coast field examples using well logging, coring, and well test information to illustratethese concepts.

INTRODUCTION

For years, the quantitative evaluation of thinly bedded geological sequences for realistic estimates of pay thickness, porosity, and water saturation has been one of the most challenging tasks for the well log industry. Because of inherent vertical resolution limitations of the conventional logging measurement system, the recorded logging curves present averaged values, which are a function of the vertical resolution of the specified logging device. In a laminated shale/sand environment, this may result in a pessimistic evaluation of hydrocarbon volume in place. Ideally, a logging instrument for a thin-bed evaluation must have a vertical resolution as thin as practical while maintaining a radial depth of investigation sufficiently deep to measure the unaltered formation. These requirements are somewhat mutually exclusive, as deeper investigation of most measured parameters is usually achieved by increasing sensor spacing at the expense of reduced vertical resolution.

However, recent technological advances in high-resolution logging instruments, data acquisition, processing, and interpretation of well log data have made it possible to accurately delineate the bed boundaries and evaluate thin beds for hydrocarbon potential.

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ADVANCEMENT IN LOGGING INSTRUMENTS

Until recently, Diplog®, Micro Laterolog, and Minilog® information were used exclusively to delineate thin beds (Quinn and Sinha, 1985). Several high-resolution instruments, discussed here, have since been developed and are now being used in thin-bed analysis for a reliable reservoir description.

Dielectric Tool

The pad-type, high-frequency (200-MHz) dielectric tool has been used recently in oil-base or low-salinity water base muds (Lawrence and Fernandez, 1987). The dielectric logging instrument measures the attenuation and the phase shift of the emitted electromagnetic wave between two receivers. Using these two measured parameters, formation resistivity and dielectric constants are calculated. While this tool has a relatively shallow depth of investigation, it can delineate beds as thin as 3 in. Furthermore, the measured resistivity can be enhanced to estimate true thin-bed resistivity.

TBRt Tool

The new thin-bed resistivity (TBRt™) pad type instrument, based on the classical laterolog-3 concepts, exhibits high vertical resolution and greater radial depth of investigation. Computer modelling and field-test data confirm the instrument can provide formation resistivity data for beds at least one inch thick while detecting beds less than 0.5 inch thick (Khokhar et al., 1989). In addition,TBRt measurements, unlike conventional deep resistivity measurements, are virtually unaffected by shoulder-bed effects. A schematic presentation of the TBRt instrument, which can be run in combination with most other openhole logging devices, is shown in Figure 1. A Micro

Laterolog or a Minilog can be recorded by using the backup arm as a supplement to the TBRt log. Figure 2 shows the predicted depth of investigation, defined as the radial distance measured from the borehole wall into the formation that produces 50% of the instrument response. As shown in Figure 2, it ranges from 13 to 21 in. for R_t/R_{xo} ratios from 0.1 to 50.

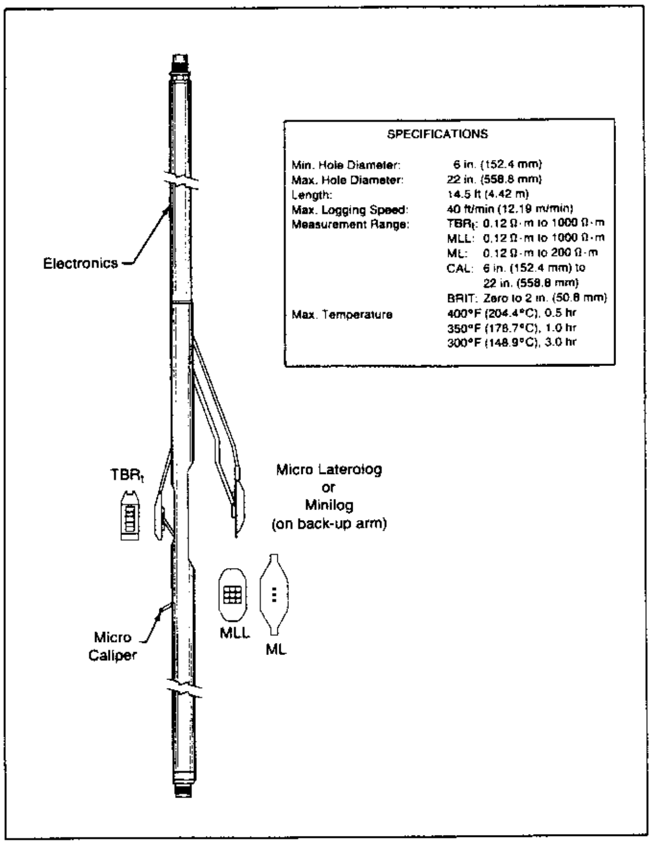

Figure 1. Schematics and specifications of TBRt tool.

The vertical resolution of the tool primarily depends on the height of the measurement electrode installed on the TBRt pad.

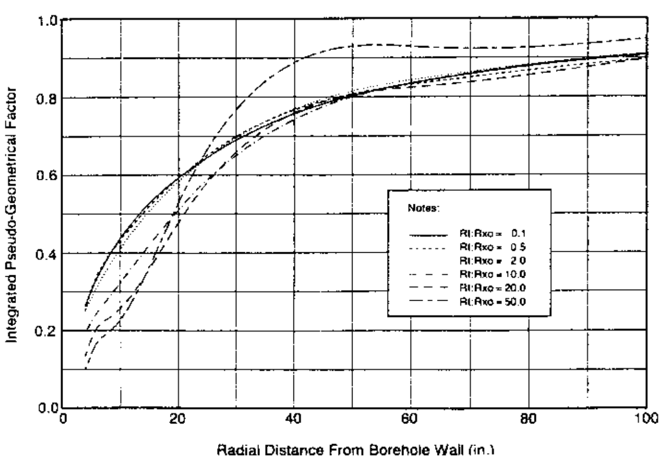

Figure 2. Predicted depth of investigation of TBRt tool for different R_t/R_{xo} ratios.

For beds less than 2 inch thick, a 1 inch TBRt pad is used instead of the standard 2 inch pad. The modelled response to thin beds corresponding to the standard 2 inch resolution TBRt pad is shown in Figure 3.

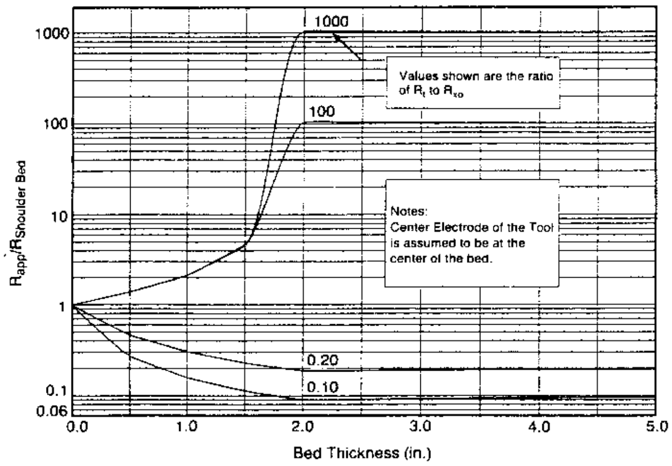

Figure 3. Thin-bed response of TBRt tool with standard 2 in. pad.

CBIL Tool

The Circumferential Borehole Imaging (CBIL[SM]) tool, an advanced version of the borehole televiewer, provides a detailed acoustic image of the entire circumference of the borehole wall from which thin beds can easily be delineated. In addition, the tool records acoustic caliper, tool orientation, and correlation curves (e.g., gamma ray). One of the two rotating transducers, one 1.5 in. dia. and the other 2.0 in. dia., mounted inside the tool emits focused bursts of acoustic energy (250 kHz) towards the borehole andmeasures the amplitude and travel time of the reflected wave. These transducers (only one of the two is selectively used during data acquisition) rotate at 360 rpm. At a logging speed of 10 ft/min, the CBIL tool provides a vertical resolution of 0.33 in. From reflectance amplitude images of the entire circumference of the borehole wall, up to 10 independent pad traces can be generated and displayed versus depth. These amplitude traces then can be used to:

(a) delineate thin beds
(b) determine bed thickness
(c) find the dip and azimuth of the dipping plane

Figure 4 shows a comparison of standard resistivity-type dipmeter pad data, CBIL amplitude-derived synthetic pad traces, and pad data from an experimental high-frequency acoustic dipmeter in a test well near Austin, Texas. Resolution of bedding features is comparable for all three types of logs. Since the CBIL provides one of the most accurate measurements of true bed thickness, this information can be used for bed thickness corrections applied to other tool responses. Table 1 lists the various logging devices and their corresponding applications and constraints for thin-bed analysis.

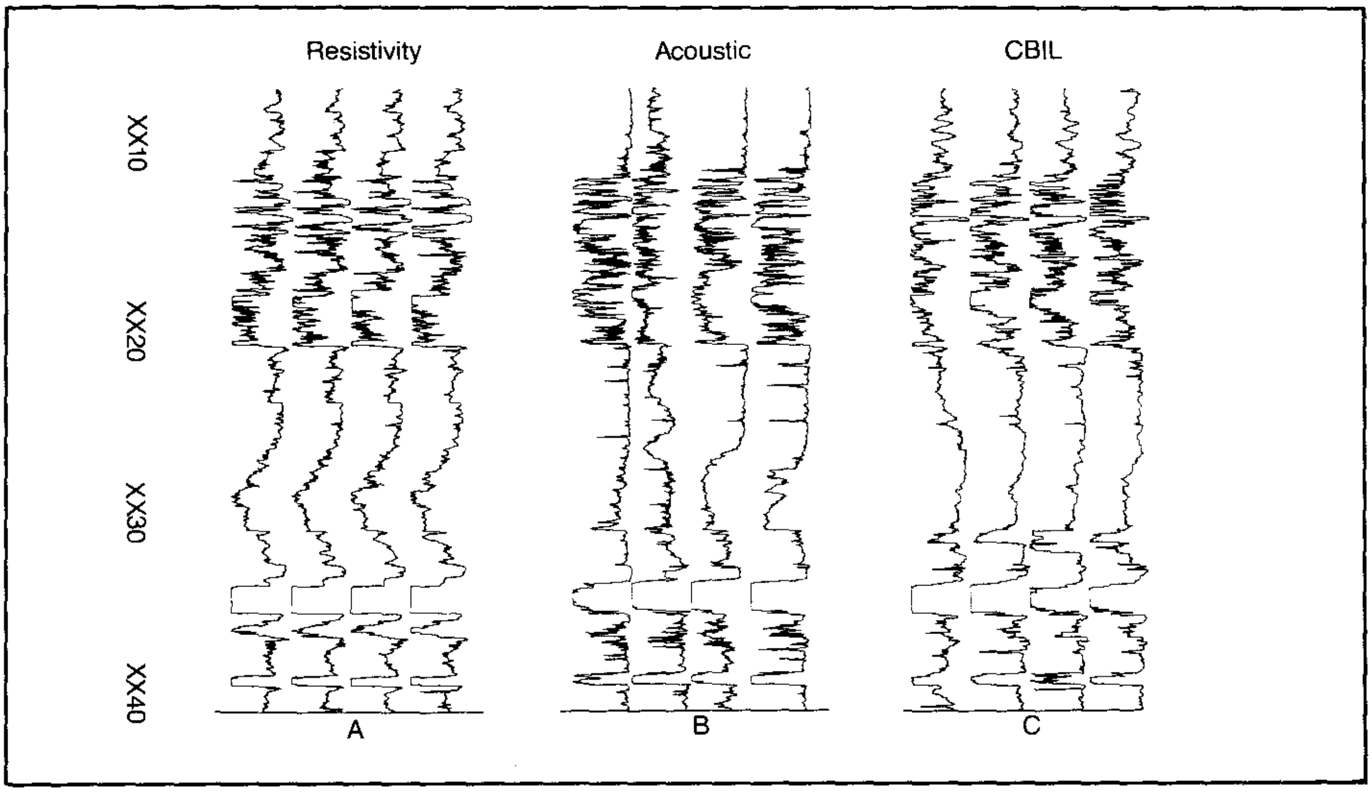

Figure 4. Comparison of resistivity dipmeter pad traces, acoustic dipmeter pad data, and CBIL amplitude-derived synthetic pad traces.

TABLE 1

TOOLS FOR THIN-BED ANALYSIS - APPLICATIONS AND CONSTRAINTS		
Instruments	Application	Constraints
SP	6-in. bed resolution with deconvolution	Noise on SP log oil-base mud
GR	6-in. bed resolution with enhancement	Statistical noise
Dielectric-200MHz	3-in. bed resolution	Depth of investigation
Dielectric-47MHz	8-in. bed resolution	Requires high R_t
Diplog	0.5-in. resolution	Depth of investigation
Deep Induction, Dual Phase & Deep Laterolog	After enhancement used in specific mud environment	Vertical resolution both need a high resolution tool for enhancement
TBRt	2-in. bed resolution R_t log	Oil- base mud
Micro Laterolog	2-in. bed resolution	Depth of investigation oil-base mud
Minilog	2-in. bed resolution	Depth of investigation oil-base mud
Comp.Density Log	4-in. bed resolution with enhancement	Borehole washout
Comp.Neutron Log	6-in. bed resolution with enhancement	Borehole washout
CBIL	1/3-in. resolution	Mud weight
Spectralog	6-in. bed resolution with enhancement	Statistical noise

ADVANCEMENTS IN DATA ACQUISITION

Improved data transmission from downhole instruments, coupled with more sophisticated electronic discrimination devices, has led to improvements in both quantity and quality of data acquired fromsubsurface well logging instruments. The data are recorded at much higher, optimum sample rates as compared to previous conventional measurements. Our experience suggests that dipmeter data can be recorded at 64 samples per foot, while 8 samples per foot is adequate for acoustic, TBRt, and radioactive devices (e.g. density, neutron and gamma ray). CBIL data are recorded at 250 samples per revolution.

It is also important to record raw data without using any filter. Heavy filtering may actually result in loss of some valid data.

ADVANCEMENT IN DATA PROCESSING

Because processing techniques depend on available log data, selecting the proper thin-bed logging services for the desired processing technique will ensure the best results. For example, a logging suite composed only of induction, acoustic, and gamma ray logs is limited to deconvolution processing. More detailed enhancement methods will require additional logs with better vertical resolution.

Deconvolution of Well Log Data

The feasibility of improving the vertical resolution of petrophysical logs by means of deconvolution techniques has been studied extensively (Looyestijn, 1982; Lyle and Williams, 1986; Meyer, 1987). Several methods for deconvolving well log data have been suggested, which require knowledge of the accurate tool response functions.

The HORIZON software of our Well Data System™ (WDS™) offers a similar approach. Bed layers and tool response equations are used to deconvolve the log data and determine an optimum constant value of the measurement for each layer. The deconvolved data are convolved again according to the tool response equation and compared to the actual measured log data. This digital technique utilizes an iteration process to minimize the difference between convolved and measured log data. The bed boundaries can be estimated by any of the high-resolution tools discussed earlier, or the software can find the bed boundaries by calculating slopes of the logs. Figure 5 shows a plot of raw and deconvolved (layered and squared) data obtained with this technique. The bed boundaries, or layers, picked by the digital method are shown on the left side of each track.

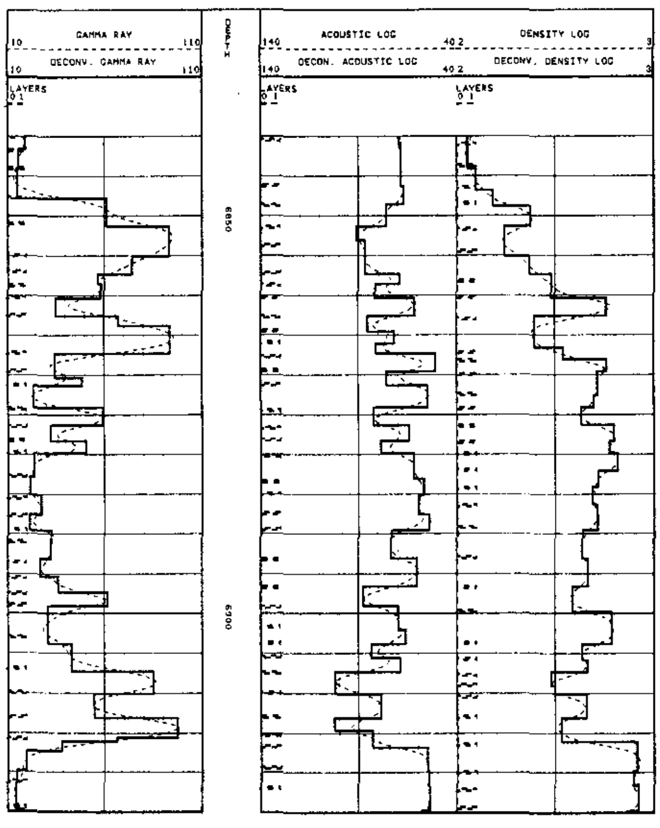

Figure 5. Raw log, bed boundaries, and deconvolved (layered and squared) logs.

Enhancement

Unfortunately, when deconvolution is applied to nuclear measurements, statistical uncertainties as well as meaningful signals are amplified. Recently, alternative approaches for data enhancement have been published (Dyos, 1987; Sinha et al., 1989). For example, data from density and neutron logs can be enhanced to estimate true porosity of thin beds. By using the higher vertical resolution of the short-spaced detector measurement and compensating for environmental effects, a more accurate density orneutron value is obtained. The short-spaced detector measurement is filtered to provide the same vertical resolution as the long- spaced measurement. The difference between conventional density and the filtered short-spaced detector measurement is considered the environmental compensation and is applied to the short-spaced detector measurement. The resulting high-resolution thin-bed measurement is more accurate (Sinha et al., 1989).

Another technique to enhance resistivity measurements has been proposed by Lawrence and Mezzatesta, 1989. Though this technique is similar in theory to the one just discussed, it uses a multiplicative environmental correction factor rather than an additive factor. The equation used for resistivity enhancement is:

$$R_{thr} = R_{tb} \, (R_d/R_{ftb})$$

where:
R_d = conventional deep resistivity in ohm-m,
R_{tb} = thin-bed resistivity in ohm-m
R_{ftb} = filtered thin-bed resistivity in ohm-m, and
R_{thr} = true high-resolution deep resistivity in ohm-m.

The conventional deep resistivity measurement can be taken from a deep induction or a deep laterolog device, whereas thin-bed resistivity values can be obtained from microlaterolog, dielectric, dipmeter, or, preferably, the new TBRt log. Medium induction log data can also be used if tools with high vertical resolution are not available. Enhancement of the deep induction log in this case will be limited by the vertical resolution of the medium curve, as shown in Figure 6.

ADVANCEMENTS IN THIN-BED INTERPRETATION

To evaluate a thin-bed reservoir, the three basic parameters of resistivity, porosity, and shaliness are needed. Combining these parameters allows the calculation of the thin-bed hydrocarbon volume. Different water saturation models, ranging from Archie to the Waxman-Smits equation, are available to calculate reliable water saturation. Recent advancements in interpretation modules allow the log analyst to combine all available information for a detailed reservoir description. For example, porosity from core analysis can be used for proper definition of matrix properties. Similarly, permeability from formation tester measurements or from other reliable sources can be integrated in the interpretation module to select a more reliable permeability equation.

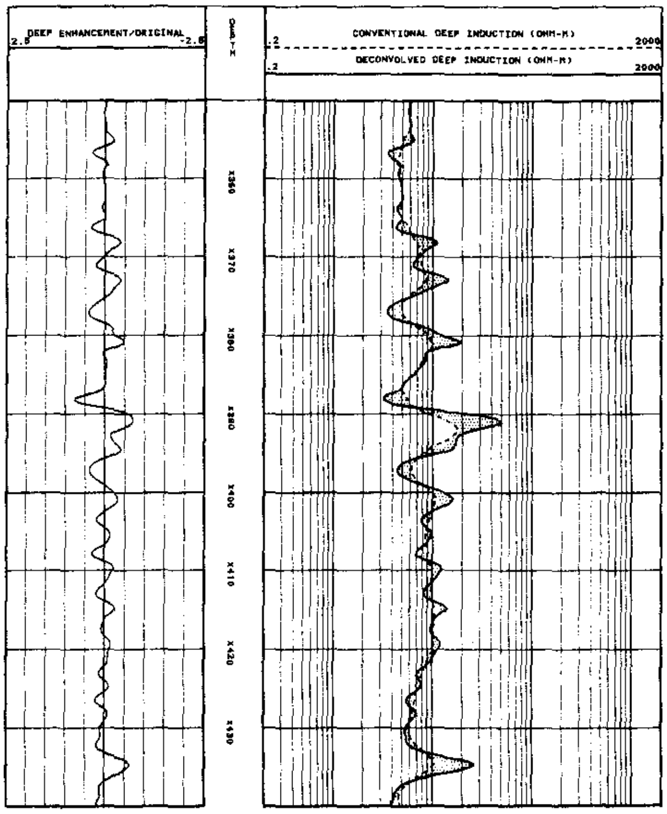

Figure 6. Deep induction log vs. deconvolved resistivity using medium induction log.

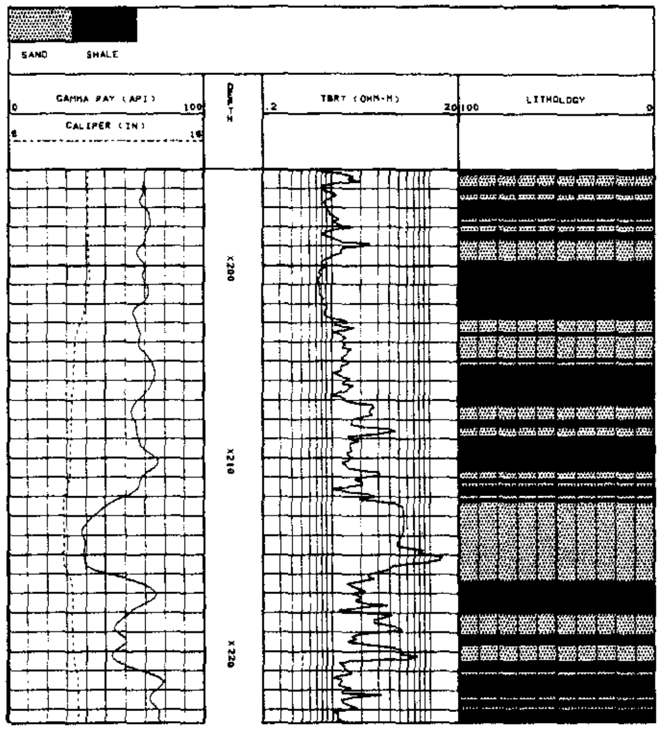

Figure 7. Example A: Improved sand count using TBRt log.

The final interpretation can be presented in various customized formats. The standard presentation of the thin-bed analysis combines raw logging data and computed results obtained both from conventional and thin-bed analysis (TBA) techniques. In another type of presentation, called Strata Logik®, raw and computed log data, core information, and well test and production data are combined into one comprehensive presentation.

FIELD EXAMPLES

Delineation of Thin Beds

Example A: Figure 7 shows improved net sand count and the sand/shale ratio of the highly laminated clastic sequence. Using TBRt log data and new processing techniques, sand/shale delineation is significantly improved. The conventional gamma ray curve and TBRt resistivity curve are shown with the lithology determination.

Example B: The use of high-resolution data to detect oil-water contacts more accurately is shown in Figure 8. The oil-water contact at X350.5 ft is clearly visible on the TBRt log and is verified by the core analysis. Also note the tight streak at X347.5 ft identified by the slight increase in resistivity and corresponding drastic decrease in core-derived permeability. The conventional deep resistivity log had completely missed these events.

Example C: An excellent example of TBRt data clearly delineating very thin lignite beds is shown in Figure 9. The interval from X907 to X909.4 ft contains two separate but thin coal streaks, rather than the single thicker coal seam indicated by the density and neutron logs. Since ultrathin lignite streaks frequently occur in this Tertiary interval, the TBRt resistivity data significantly enhance detailed stratigraphic well-to-well correlation.

Thin-Bed Analysis

Example D: Figure 10 shows a well with conventional core and test results. The thin-bed analysis was primarily based on enhanced dipmeter data. The core porosity is compared to the computed porosity and is shown in the first track. Water saturations computed using the CLASS® technique (Fertl et al., 1987) and the TBA method are plotted in the second track. The two water saturations compare well in thick zones, but the conventional CLASS technique missed some potential zones. The section from XX927 to XX945 ft was perforated and produced 900 BOPD water free.

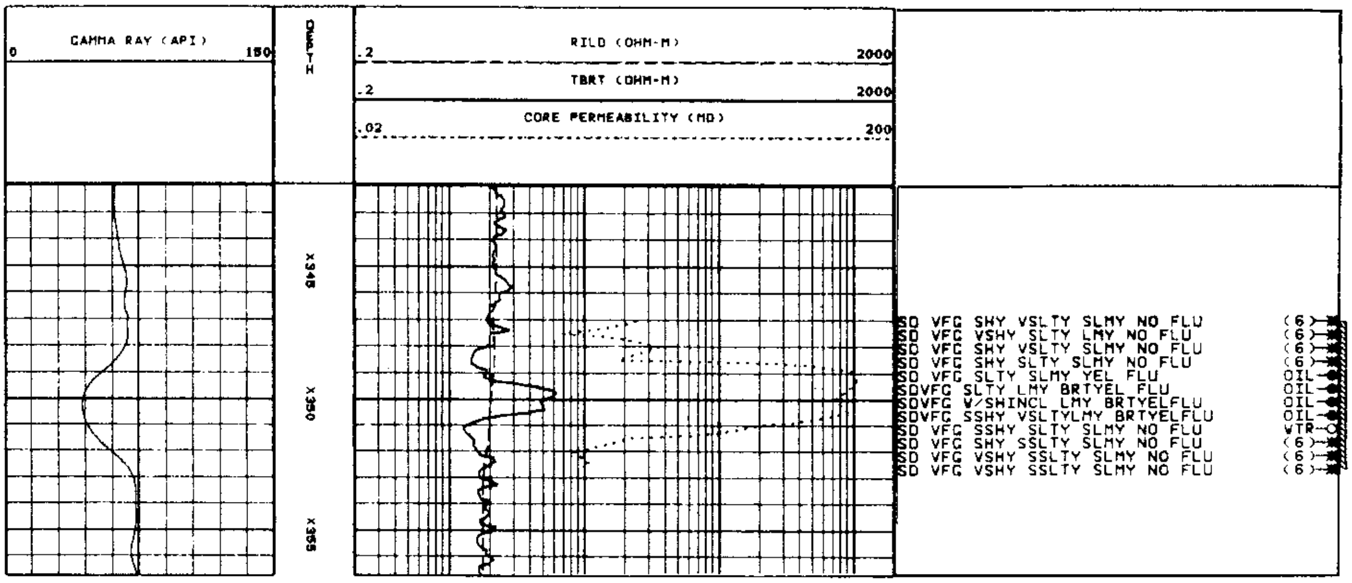

Figure 8. Example B: Accurately defining oil-water contact.

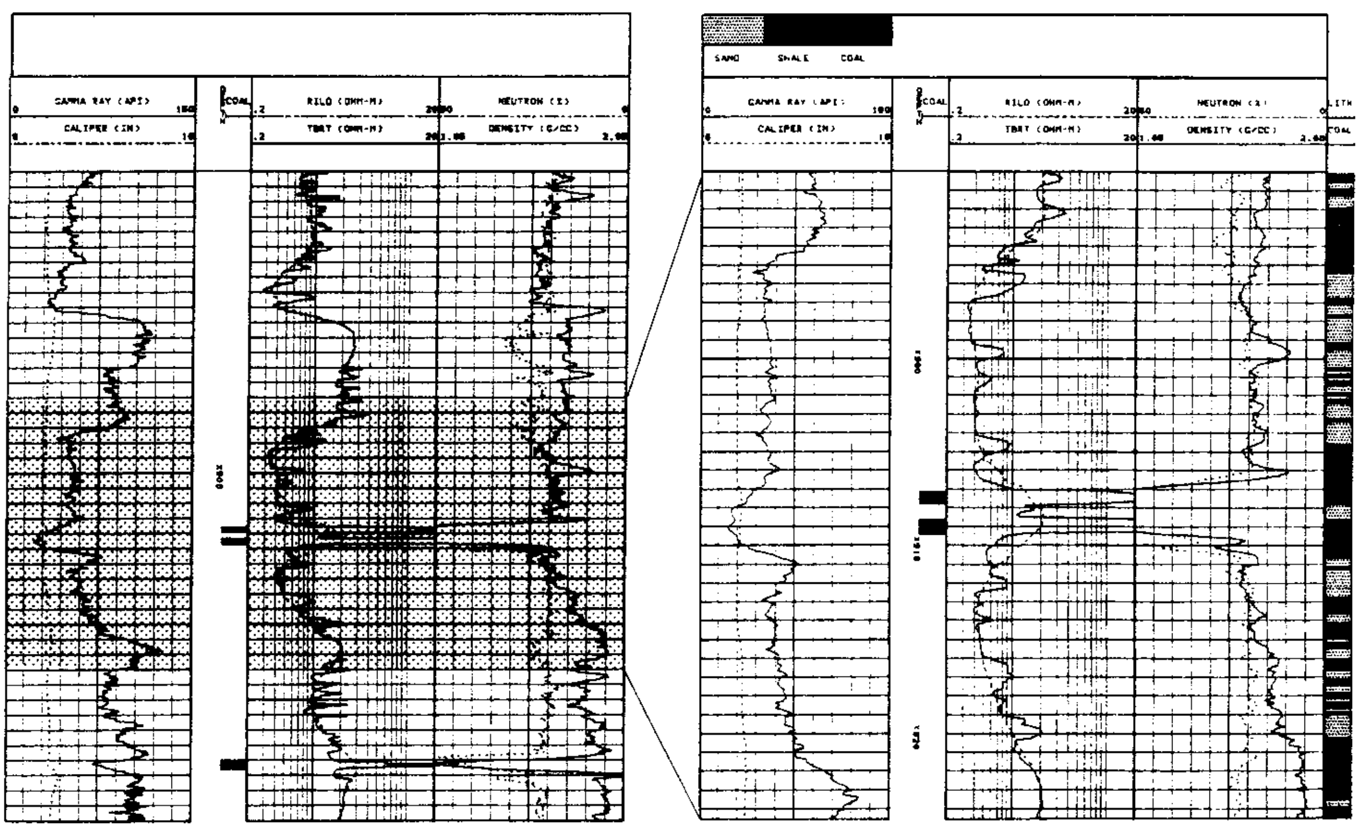

Figure 9. Example C: Delineation of thin lignite coal beds.

Example E: Figure 11 shows a standard presentation of thin-bed analysis in another well. Raw data are plotted with the computed data and lithology. In addition to the thin-bed water saturation, water saturation from the CLASS program is plotted for comparison. The better vertical resolution of TBRt tool is also shown.

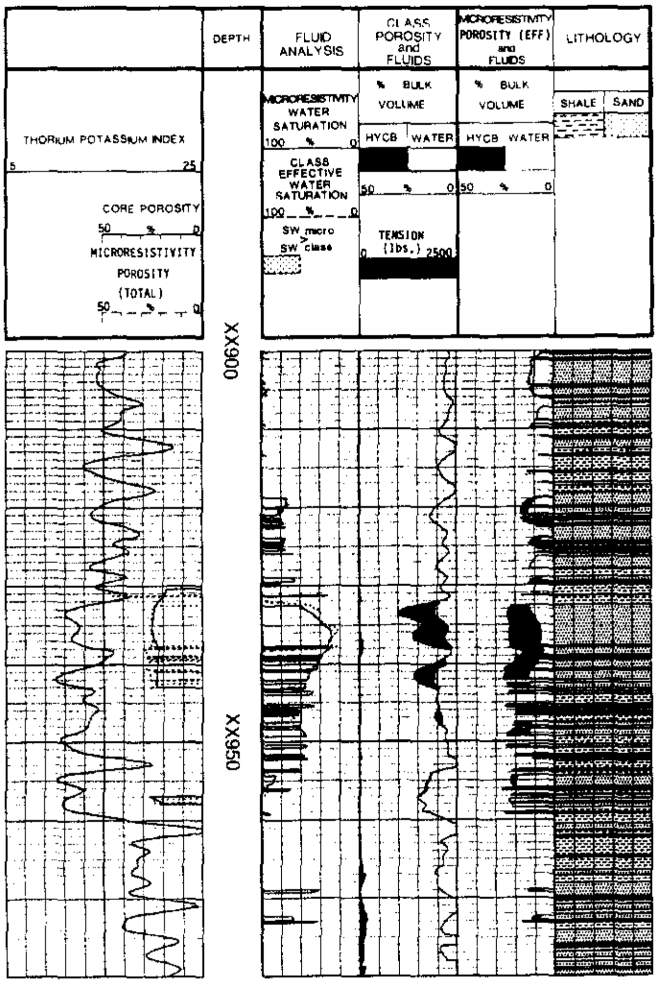

Figure 10. **Example D: Result of thin-bed analysis using Diplog data.**

Example F: Figure 12 illustrates the Strata Logik package, which integrates logging information, core, well test, and production data into one comprehensive presentation. The thin four-feet zone from X212 to X216 ft produced 1.7 MMcf/D of gas and 30 B/D of condensate without water.

Example G: Figure 13 shows the successful application of this technique as a movable hydrocarbon indicator in a well recently drilled offshore the U.S. Gulf Coast. TBRt and microlaterolog data are compared in an overlay and used to compute movable hydrocarbons. On test, this interval produced at rates exceeding 1000 BOPD.

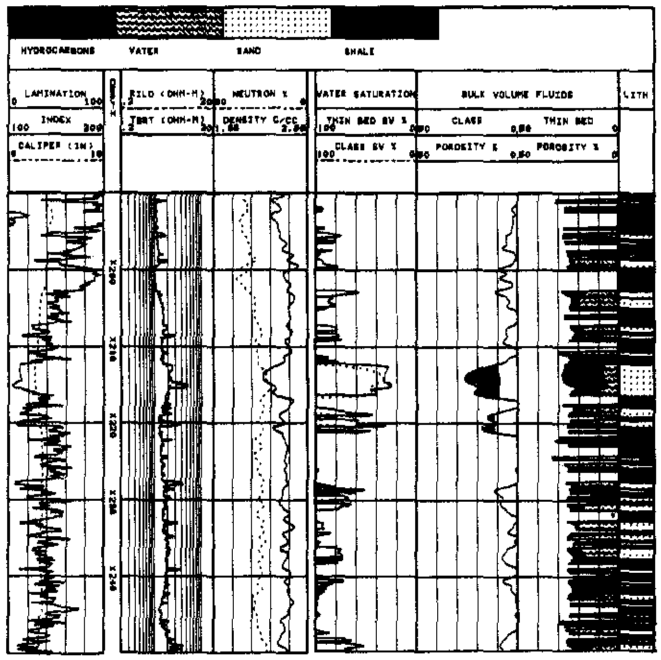

Figure 11. Example E: Result of thin-bed analysis stand presentation.

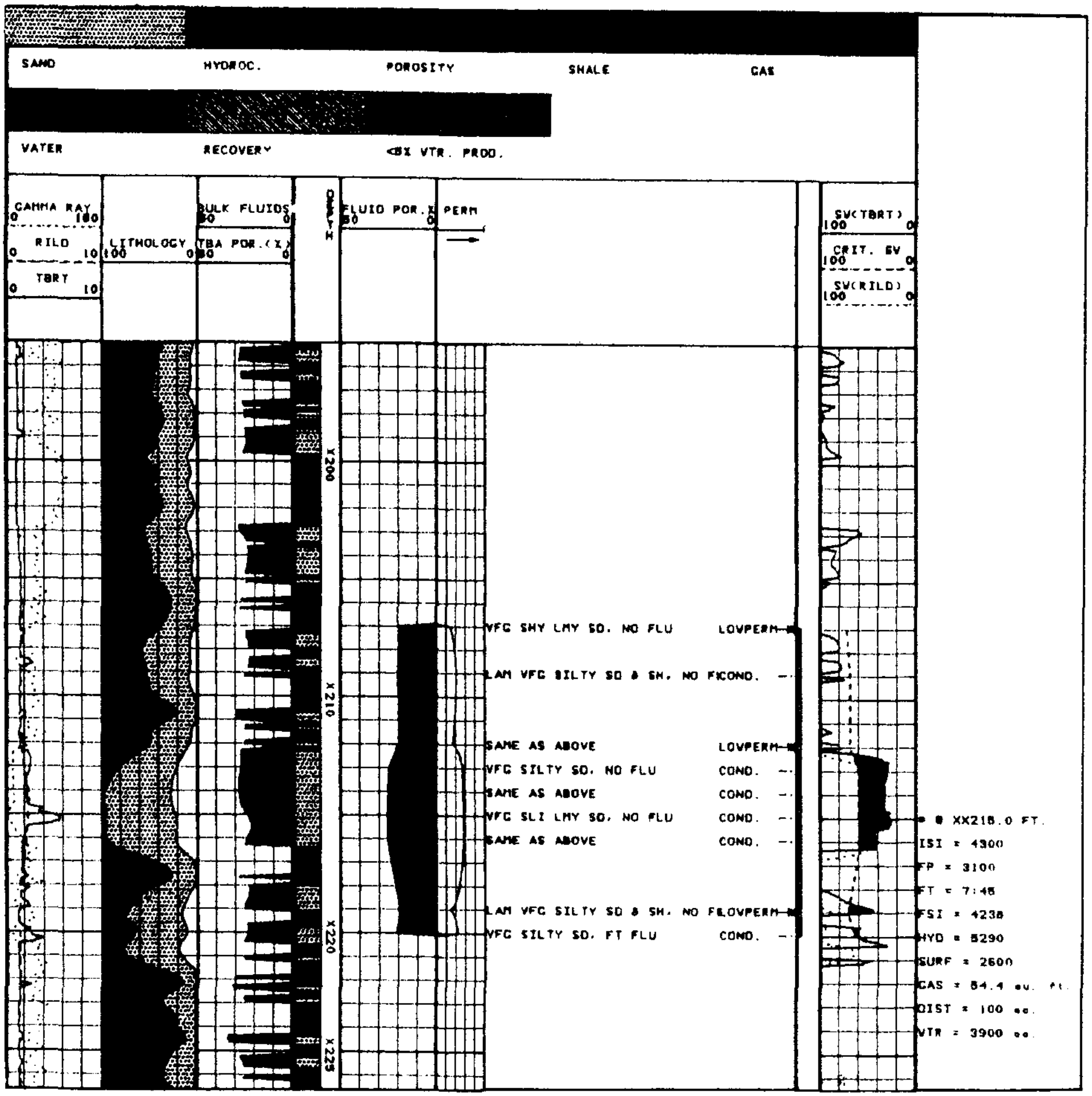

Figure 12. Example F: Integrated reservoir description, Strata Logik presentation.

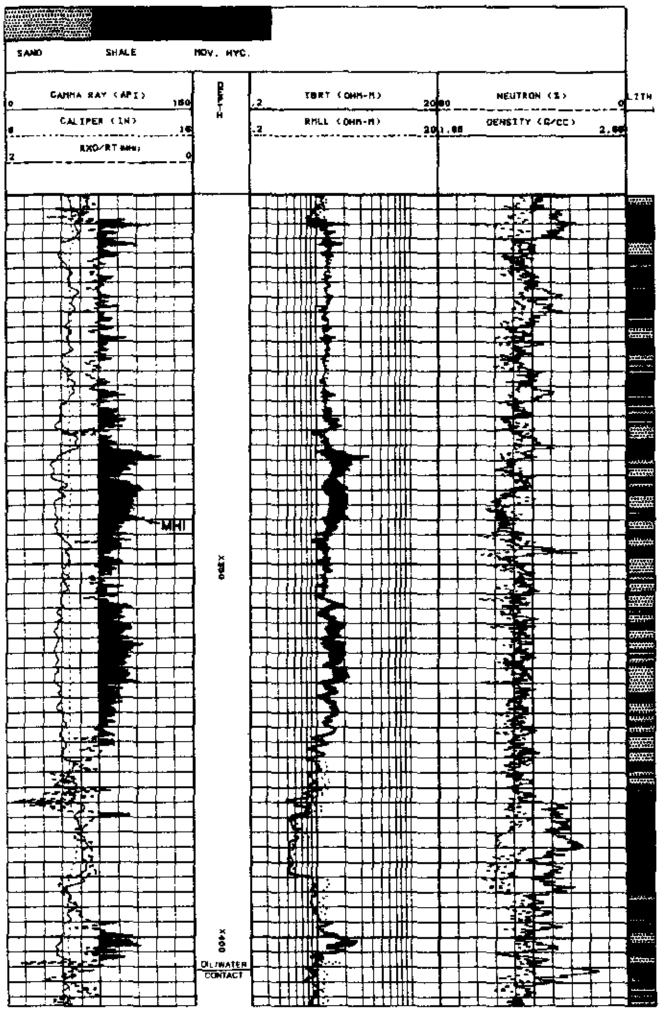

Figure 13. Example G: Application of TBRt and Microlaterolog data as indicator of movable hydrocarbons.

CONCLUSIONS

1. Use of high-resolution logging tools and better data acquisition methods facilitate:
   (a) delineation of thin beds
   (b) improved sand/shale counts and net pay determination
   (c) improved well-to-well correlation
   (d) thin-bed correlation of log and core data

2. Enhanced data processing techniques give more realistic parameters for thin-beds to help calculate improved hydrocarbon volume.

3. Interpretation modules integrating all available information give more realistic reservoir parameters.

4. Thin-bed well log analysis techniques provided an excellent description of liminated reservoirs, such as turbidites.

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