THIN-BED LOG ANALYSIS USING HIGH-RESOLUTION MEASUREMENTS

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ABSTRACT

Thinly bedded sand/shale geological sequences present problems for conventional well log analysis methods. Recent improvements in data acquisition and log interpretation methods provide solutions to these problems by using a systematic approach.

Acquisition methods are improved by recording data in thinly bedded sequences at higher sample rates while simultaneously removing conventional filters. Recording filter-free data preserves accuracy and allows flexibility in subsequent presentations.

Thin-bed log interpretation problems can be solved by enhancing values of porosity, shaliness and resistivity through optimum resolution and spacing measurements. Correcting the shorter spaced detector measurements for environmental effects yields better thin-bed definition.

Applying the environmental correction process to thin-bed resistivity logs yields the same quality of results as demonstrated with porosity devices and improves hydrocarbon detection in thinly bedded zones.

Through a sophisticated computerized process, high-resolution resistivity measurements, combined with enhanced porosity and shale indicators, predict effective hydrocarbon volumes in thinly layered depositional environments. Productive zones that previously might have been otherwise overlooked are now located precisely.

Examples are shown to illustrate this new technique for thin-bed analysis.

INTRODUCTION

For years, thinly bedded geological depositional environments have been difficult to analyze using conventional well log analysis techniques. Because of vertical resolution and data acquisition limitations inherent in early logging measurement systems, the log analyst historically has been forced to rely on detailed core information to evaluate thinly laminated reservoirs. However, recent technological advances in well log data acquisition and interpretation methods have made the task of thin-bed analysis more manageable. By combining high-resolution measurements of resistivity, porosity, and shaliness in a new computerized process, one can better predict hydrocarbon location and volume. Consequently, the production from a reservoir containing thin zones can be maximized because fewer productive intervals are overlooked. Thin-bed analyses can be used in many ways to improve reservoir descriptions:

- Enhance thin-bed resolution
- Improve sand/pay counts
- Distinguish sand/shale interbeds
- Assist in low-resistivity contrast interpretation
- Improve permeability estimations

- Provide thin-bed correlation of log and core data
- Improve well-to-well correlation
- Ensure more accurate estimation of hydrocarbon location and quantity.

The overall result of thin-bed analysis is, of course, a more detailed and accurate reservoir description that leads ultimately to economic benefits.

DATA ACQUISITION ADVANCES

New technology has led to improvements in both the quantity and quality of data acquired from subsurface well logging instruments. Increased quantity is a result of improved data transmission from the downhole instrument and larger data storage capacity. Better quality originates from improved instrument signal-to-noise ratios coupled with more sophisticated electronic discrimination devices (Minette et al., 1986).

It is now possible to record information at much higher sample rates, a result in part of increased data storage capacity. This higher rate is especially beneficial with new imaging devices such as the Circumferential Borehole Imaging Log (CBIL™) (Faraguna et al., 1989). Improved data quality eliminates or reduces the need for data filtering and allows meaningful high-resolution measurements to be recorded at higher sampling rates. This improved quality is particularly noticeable with radioactivity measurements such as density, neutron, and natural gamma ray spectral data. A new high-resolution thin-bed resistivity device, the TBRt™ (Khokhar et al., 1989), takes advantage of these and other improvements to provide resistivities of beds as thin as 1.2 cm (0.5 in.). Table 1 lists resistivity logging devices and their corresponding advantages and constraints for thin-bed analysis. Applications of porosity and lithology devices are shown in Table 2. Commonly used supplementary thin-bed logging instruments are listed in Table 3. The particular devices chosen for thin-bed analysis depend on several factors, including geological and borehole environment conditions. Selecting the proper thin-bed logging services helps determine which processing techniques will ensure the best results. For example, a logging suite composed only of induction, acoustic, and gamma ray logs is limited to deconvolution processing; auxiliary thin-bed resistivity and porosity devices permit more detailed enhancement methods.

DATA-PROCESSING IMPROVEMENTS

High-resolution measurements provide a mechanism for improved log interpretation—especially when incorporated into the new computerized data-processing algorithms. Additionally, with new computer technology, sophisticated enhanced resolution processing can be performed at the well site using the new Well Data System (WDS™) package (Ball et al., 1987).

Data can be enhanced by using deconvolution ("auto enhancement") techniques (Lyle and Williams, 1986) involving knowledge of instrument vertical responses or by using high-resolution measurements to enhance lower resolution measurements.

Enhancement

Data from high-resolution devices can be subjected to greater environmental effects than data from lower resolution, deeper investigating devices. The enhancement process accomplishes two things simultaneously. The high-resolution measurement enhances the lower resolution data while the lower resolution measurement environmentally compensates the high-resolution measurement (Fig. 1). For example, consider the case of porosity determination in thin-beds.

Density and neutron logs provide a means for obtaining the true porosity of thin-beds if the resolution of each tool is maximized. For instance, by using the better vertical resolution of the short-spaced detector measurement, one can enhance the delineation of thin-beds from density logs. By compensating the short-spaced detector measurement for environmental effects, a more accurate value of true density can be obtained in thin zones.

Conventional compensated density devices use measurements from the short-spaced detector to correct data from the long-spaced detector for environmental effects such as mudcake. Generally, this process is expressed very simply as:

$$DEN = DENLS + CORR \tag{1}$$

where

DEN = conventional compensated bulk density in g/cc,
DENLS = long-spaced detector bulk density in g/cc,
CORR = correction curve in g/cc.

Thus CORR is simply the correction to DENLS necessary to obtain true bulk density (Fig. 2A). The CORR value is determined from calibrations and a comparison of long-spaced versus the short-spaced bulk density, generally using a "spine and rib" algorithm (Dresser Atlas, 1984). For new enhancement techniques, however, use of the higher resolution short-spaced detector is emphasized for determination of density in thin-beds.

Special processing techniques provide an estimate of environmental effects on short-spaced measurements and allow subsequent compensation (Sinha et al., 1989). The conventional density measurement, which relies primarily on data from the long-spaced detector, is an average of the true thin-bed density and is a function of the bed thickness. The short-spaced density measurement has a much better vertical resolution and therefore has sharper inflections at each bed boundary. Environmental effects such as mudcake or washouts may prevent short-spaced detector data from being used directly as a true density measurement. However, determining the magnitude of environmental effects allows the high-resolution measurements from the short-spaced detector to be used. This environmental compensation process can be accomplished by the following steps:

1. Filter the short-spaced detector measurement to have the same vertical resolution as the long-spaced measurement. (The filter length is a function of the long-spaced vertical resolution.)

2. Calculate the environmental compensation as the difference between the conventional density and the filtered short-spaced detector measurements. (Use a resolution matched conventional density in this process.)

3. Apply the environmental compensation to the original short-spaced detector measurement.

The resulting high-resolution thin-bed density measurement has the same vertical resolution as the measurement from the short-spaced detector but is free of environmental effects.

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

$$\Delta ss = DEN - DENSSF \tag{2}$$

and

$$DENHR = DENSS + \Delta ss, \tag{3}$$

where

Δss = short-spaced detector environmental compensation "delta" factor,
DEN = conventional compensated bulk density in g/cc,
DENSS = short-spaced detector bulk density in g/cc,
DENSSF = filtered short-spaced detector bulk density in g/cc,
DENHR = high-resolution thin-bed bulk density in g/cc.

Figure 2B shows results obtained by applying this compensation technique to the higher resolution measurement from short-spaced detector.

When applying this processing to the short-spaced measurement, it is assumed that environmental effects are generally constant over the vertical distance of the long-spaced detector. Results may be less accurate in areas of extreme borehole conditions with erratic rugosity. For quality control, filter the resulting thin-bed density and compare it with the original conventional density. These two curves should overlay. Excellent results have been obtained using this technique, illustrated in the following examples.

Figure 3 is an example of a high-resolution density log compared to a conventional density log. The density quality index is equivalent to the delta factor, Δss.

Neutron logs can be enhanced using similar, yet distinct techniques of applying environmental compensations to the short-spaced neutron detector measurement (Fig. 4).

In this example, the quality index is computed as a function of the ratio of the filtered short-spaced count rate relative to the equivalent single-detector count rate from the compensated neutron device. Higher values indicate less environmental effect. Other conventional enhancement techniques are also available for neutron logs.

A new technique to enhance resistivity measurements has also been developed. Although similar in theory to the technique used for density enhancement, this new resistivity method uses a multiplicative environmental correction factor rather than an additive factor. The multiplicative factor has an advantage in that it yields identical results for both conductivity and resistivity units when reciprocated. The equation used for resistivity enhancement is:

$$RTHR = RTB\ (RDEEP/RTBF), \qquad (4)$$

where

RDEEP = conventional deep resistivity in ohm-m,
RTB = thin-bed resistivity in ohm-m,
RTBF = filtered thin-bed resistivity in ohm-m,
RTHR = 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.

The term RDEEP/RTBF is the multiplicative environmental correction factor that compensates thin-bed resistivity data for effects such as washouts, mudcake, and invasion. Whenever the ratio of RDEEP to RTBF is one, no environmental effects exist over a given vertical window length. This ratio is computed at each level to provide a dynamic environmental correction over the processed interval. The possibility for slight errors increases whenever the environmental conditions change rapidly over the length of the deep instrument's vertical resolution. The resultant high-resolution resistivity can be filtered and compared with the original deep resistivity as a further check of quality. The TBRt instrument has a much deeper depth of investigation than other thin-bed resistivity devices and its data can therefore be used as a direct resistivity measurement in many cases. However, in areas exhibiting deep mud filtrate invasion, this same environmental correction process can be useful for TBRt data. In most cases, excellent results have been achieved. Figure 5 illustrates a deep induction log that has been enhanced using this technique.

Medium induction log data can also be used to enhance deep induction data by using the medium induction instrument response characteristics (Fig. 6). This technique is limited by the vertical resolution of the medium curve [about 1 m (3 ft)], yet has an advantage in that no extra logging device is required. Research in this field continues to yield promising results.

Deconvolution (Auto Enhancement)

Log devices may not provide the true value of the formation properties at all depth levels because of the averaging effect of the vertical instrument response. Instrument measurements represent average formation properties over intervals that range from a few inches to several feet, depending on the characteristics of each device. There are several techniques to remove the averaging effect, and produce more representative values of true formation properties (Lyle and Williams, 1986). These techniques use as input both the measurements and the vertical instrument responses. The process of correcting the measurements from the averaging effect is called deconvolution (auto enhancement). Figure 7 shows the effect of deconvolving the conventional gamma ray and acoustic logs by applying the Lyle and Williams algorithm.

Thin-Bed Boundary Layers

The vertical resolution of gamma ray logs in sand/shale laminations can be improved by sampling at higher rates while simultaneously removing filters. The logging speed should be varied by a factor inversely proportional to the sampling rate. For example, if the sample rate is doubled, reduce the logging speed by one-half in order to maintain comparable statistical accuracy for radioactive measurements. What often appears to be noise on a gamma ray log is actually a response to thinly laminated sections. This can be verified by recording a repeat section or by comparing data to other shale indicators.

Several layering methods distinguish sand/shale and other lithological boundaries. These range from sophisticated second-derivative, parabolic and Gaussian filter techniques to a new simplified weighted moving average; each capable of using shale indicators other than the gamma ray, such as dipmeter and spectral gamma ray.

The HORIZON℠ statistical estimation package offered as a part of the WDS service includes a module containing four different layering options. One of these options utilizes a new dynamically weighted moving average method to help distinguish sands from shales. This method calculates a blocking factor (BF) based, for example, on the ratio of a gamma ray curve value (GR) to the moving average gamma ray (GRA).

$$BF = GR/GRA \qquad (5)$$

A dynamic blocking factor threshold, BFX, is computed at each level and compared with BF. If BF is less than BFX, then the interval is flagged as a sand. Otherwise, the zone is blocked as a shale. Figure 8 shows an example of this effective technique.

Incorporating the Circumferential Borehole Imaging Log (CBIL℠) has also yielded encouraging results for lithology delineation in thin beds.

Thin-Bed Measurement Values

After the initial bed-boundary ("layer") is determined, other programs assign constant values for each logging measurement over each layer. For instance, each thin bed should have a certain single resistivity value that corresponds to the true overall resistivity of that bed. The same concept can also be applied to other log measurements such as density, neutron porosity, and gamma ray. Since the vertical resolution for thin-bed resistivity is usually slightly better than it is for thin-bed porosity, statistical error minimization techniques "square" or block each curve using the response function of each device. Filtering these squared or blocked curves with each tool response filter yields curves that should match the original logs with a minimum of error. This process helps ensure that the true bed boundaries and bed measurement values are determined. Figure 9 shows this processing on a density log before and after enhancement.

DATA PRESENTATION

Enhanced thin-bed measurements are used to compute thin-bed porosity and hydrocarbon volume, and the final presentation can be displayed on customized formats. Figure 10 presents a standard thin-bed analysis (TBA). It displays the raw data and the calculated thin-bed results compared to conventional processing methods such as the CLASS® analysis program (Ruhovets et al., 1981).

Whenever core, formation test, drillstem test and/or production data are available, a StrataLogik® presentation offers additional advantages (Fig. 11). Any of these presentations and other customized formats can be performed using WDS. Color presentations provide additional visual enhancement.

CONCLUSIONS

Enhancing resistivity, porosity, and shaliness measurements helps to solve thin-bed log interpretation problems. Through a systematic approach, production can be maximized by minimizing the amount of bypassed hydrocarbons. By taking advantage of new hardware capabilities and software developments, more detailed and accurate reservoir descriptions, leading to economic benefits, can be achieved.

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ABOUT THE AUTHORS


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Tony D. Lawrence received a physics/mathematics degree from the University of Alabama. He has held various log interpretation, sales, and marketing positions since joining Atlas in 1975. Tony currently holds the title of staff petrophysicist in the Well Data System group in Houston. Tony is a member of SPWLA and SPE.

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TABLE 1
Thin-Bed Analysis: Resistivity Data Acquisition

INSTRUMENT	ADVANTAGES	CONSTRAINTS
Dual Induction	Deconvolved Rt	Vertical resolution
Dual Phase	Deconvolved Rt Less shoulder effects	Vertical resolution
Dual Laterolog	Measures Rt Salt-based mud	Oil-based mud
Dielectric (200 MHz, 47 MHz)	Oil-based mud 3 in. resolution (200 MHz) 8 in. resolution (47 MHz)	Depth of Investigation Requires higher Rt
TBRt	Measures Rt 2 in.-Bed resolution Companion minilog	Oil-based mud
Microlaterolog	2 in.-bed resolution	Depth of investigation
Minilog	2 in.-bed resolution	Depth of investigation

TABLE 2
Thin-Bed Analysis: Porosity/Lithology Data Acquisition

INSTRUMENT	APPLICATIONS
Compensated Densilog	Enhanced 4 in.-bed resolution
Compensated Z-Densilog	Enhanced 4 in.-bed resolution Pe, 2 in.-bed resolution
Compensated Neutron	Enhanced 6 in.-bed resolution
Compensated Acoustilog	Deconvolved traveltime
High-Resolution Gamma Ray	Enhanced 6 in.-bed resolution Thin-bed lithology

TABLE 3
Thin-Bed Analysis: Supplementary Data Acquisition

INSTRUMENT	APPLICATIONS
Spectralog	Enhanced 6 in.-bed resolution Thin-bed lithology (K, U, Th) Can be run in cased holes
PDK-100	Cased hole logging device High sample rate logging Thin-bed Sw through pipe
CBIL	Borehole imaging device Circumferential measurement ⅓ in.-bed resolution
CALog	Qualitative acoustic velocity Lithology indicator 1½ in.-bed resolution

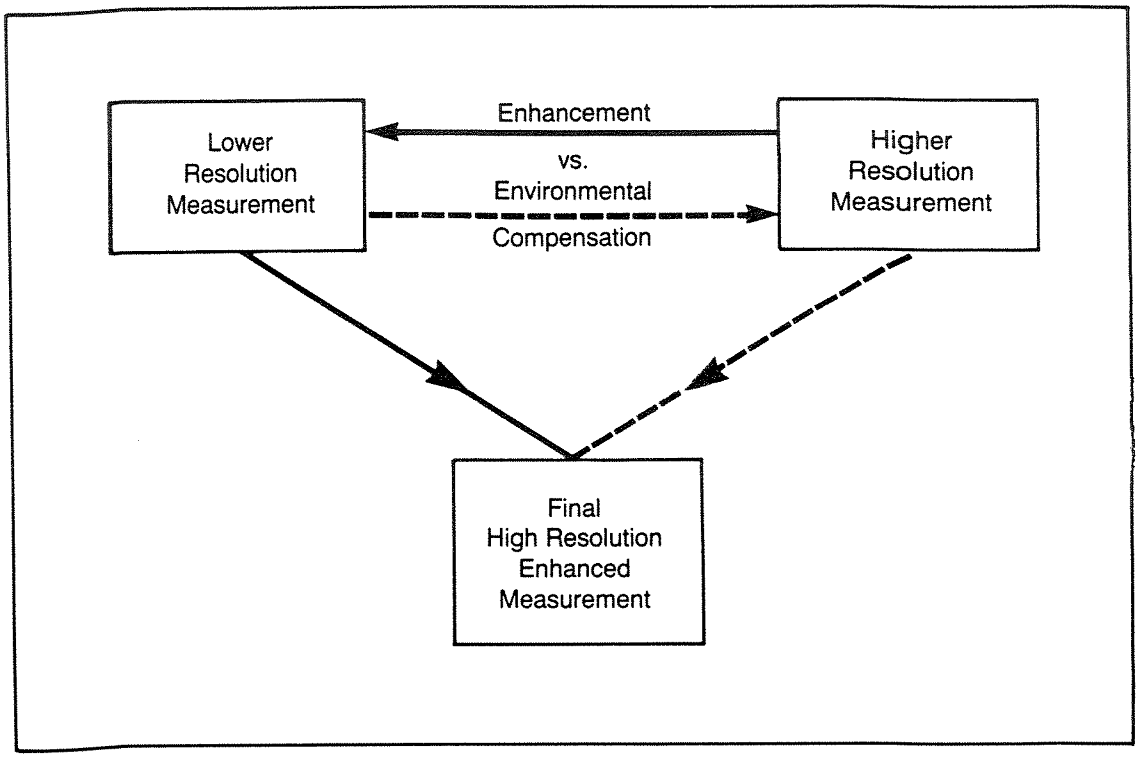

FIGURE 1
Comparison of enhancement vs. environmental compensation process

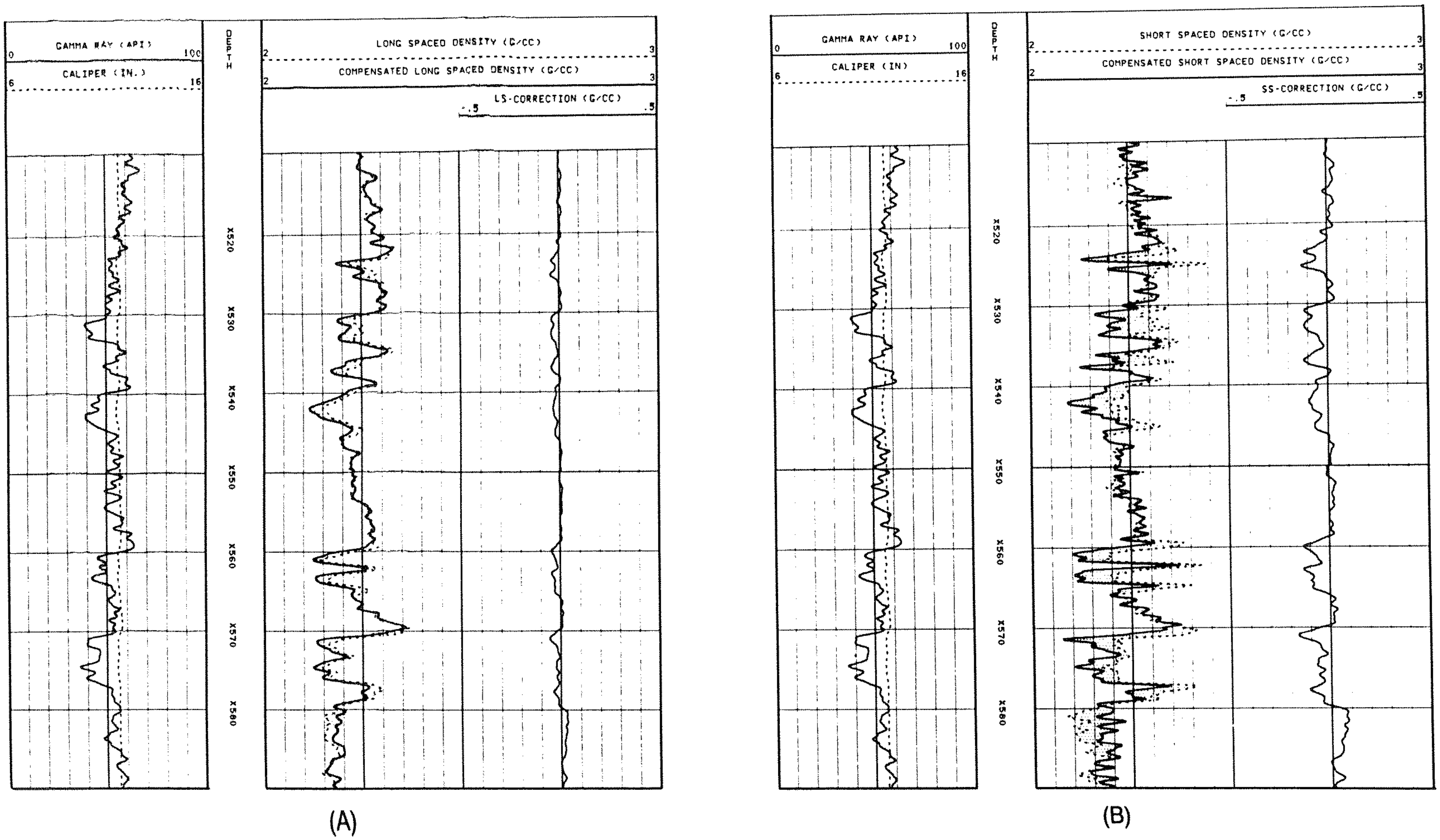

FIGURE 2
Conventional compensated long-spaced density (A), Compensated high-resolution short-spaced density (B).

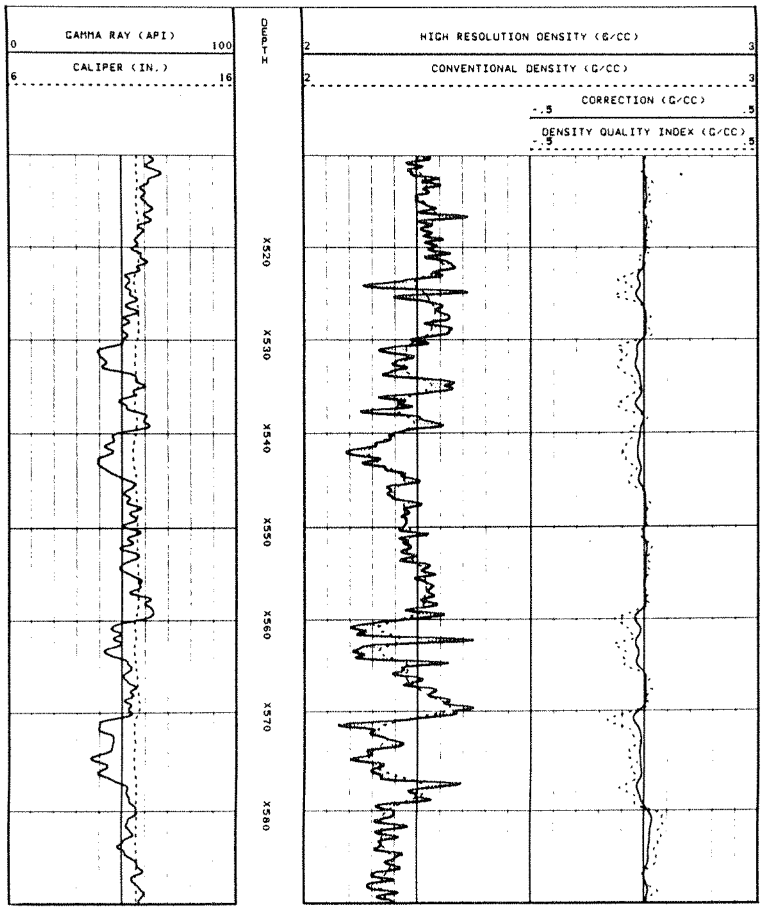

FIGURE 3
Comparison of enhanced high-resolution compensated density vs. conventional compensated density data

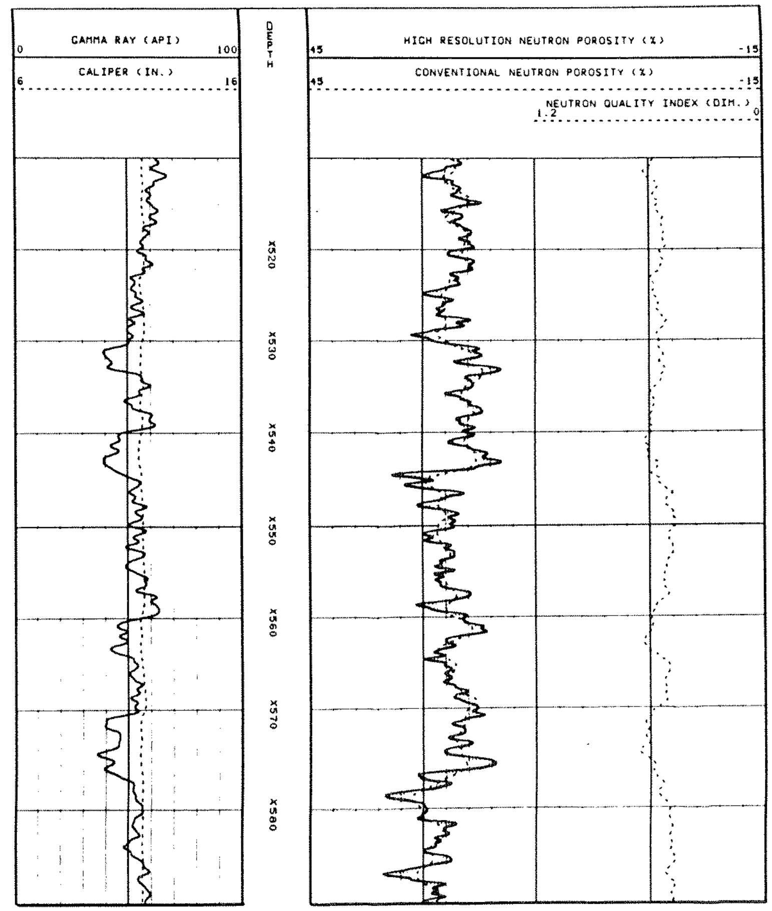

FIGURE 4
Comparison of enhanced high-resolution compensated neutron vs. conventional compensated neutron data

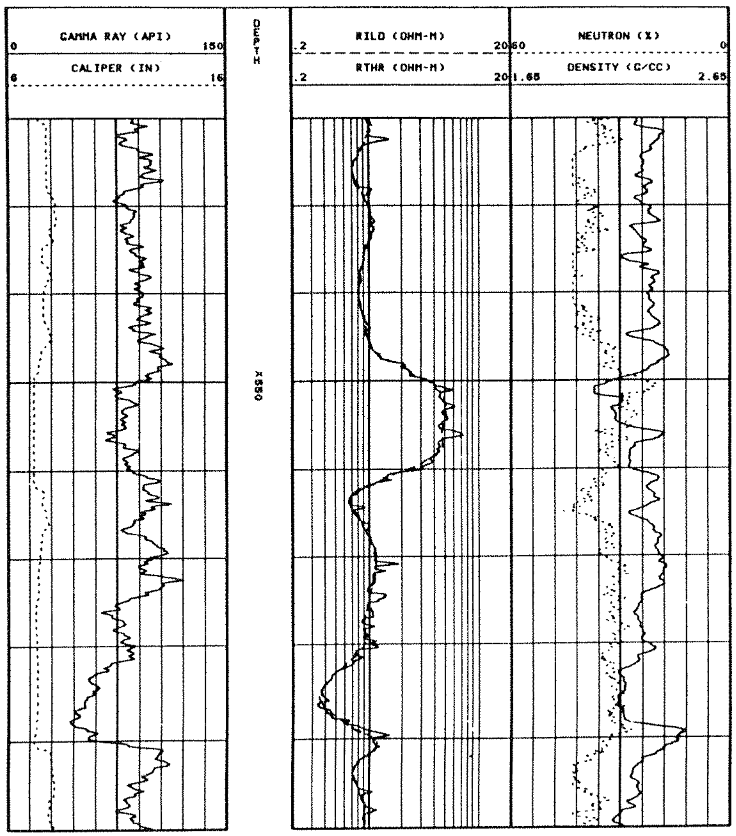

FIGURE 5
Deep induction log vs. enhanced resistivity using the TBRt data

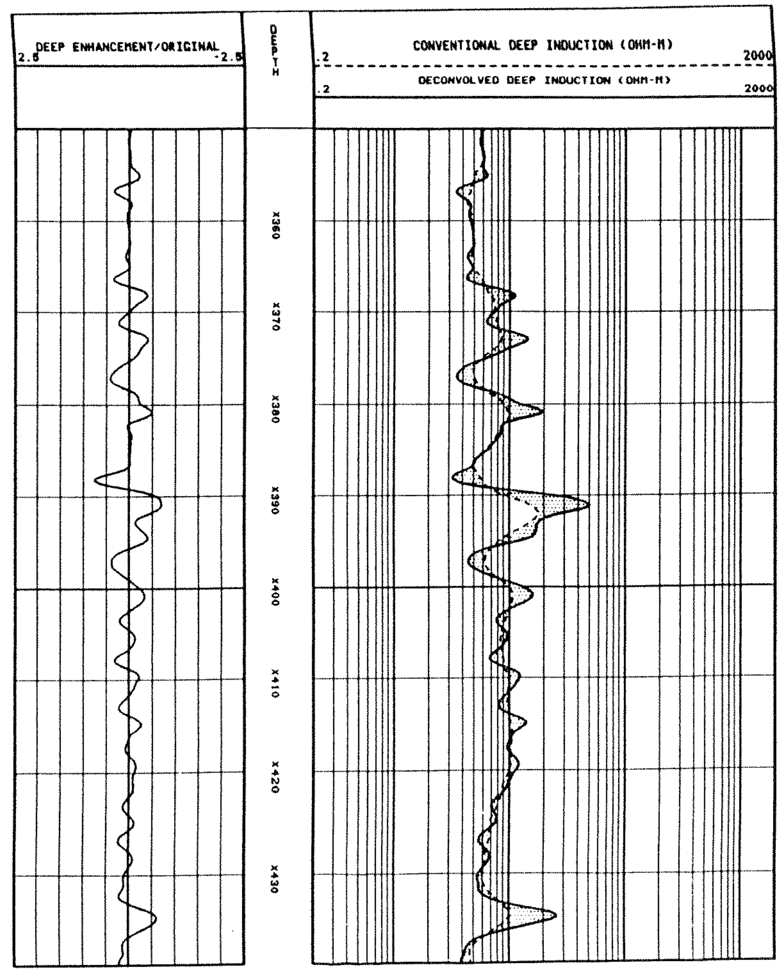

FIGURE 6
Deep induction log vs. deconvolved resistivity using the medium induction data

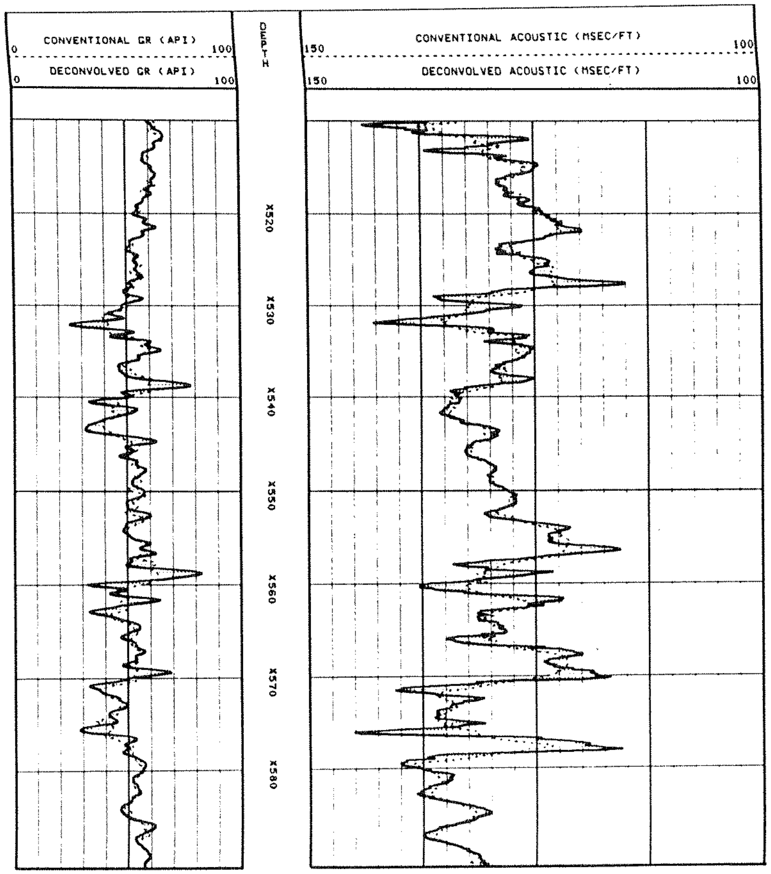

FIGURE 7
Conventional vs. deconvolved acoustic and gamma ray logs

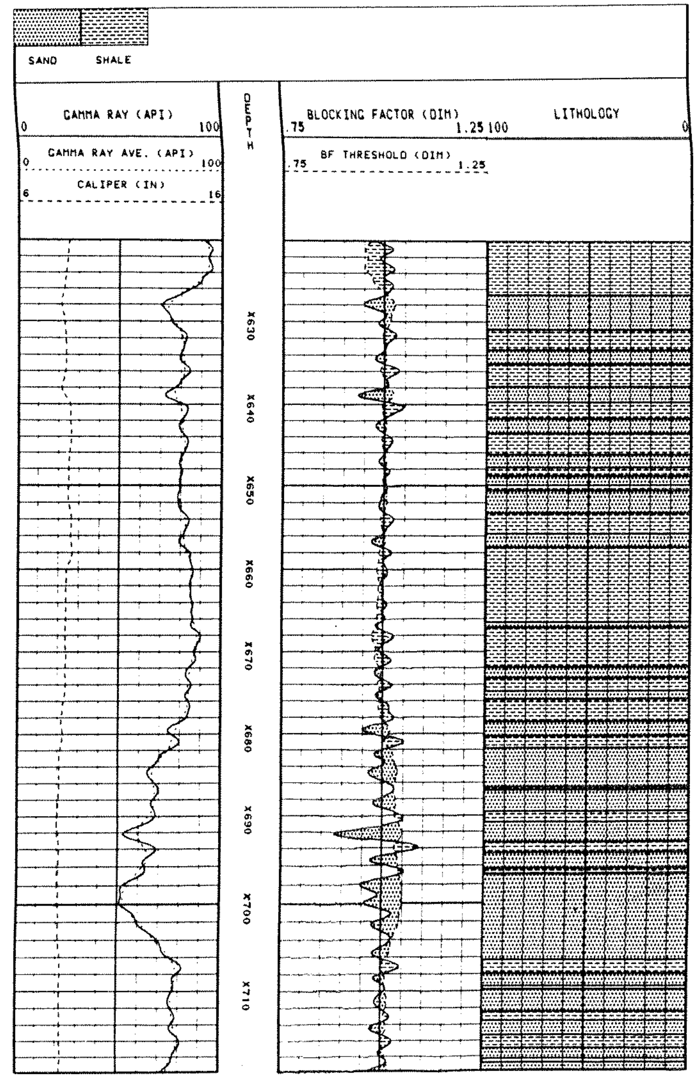

FIGURE 8
Dynamic weighted moving average blocking technique

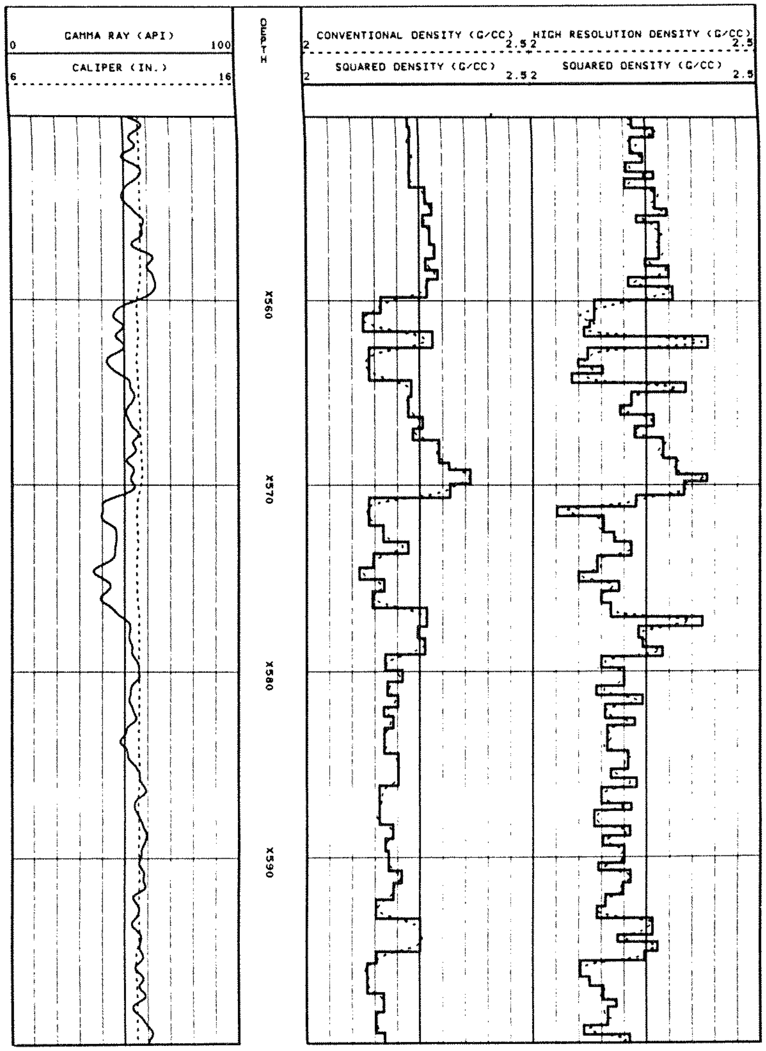

FIGURE 9
Conventional vs. high-resolution density layered and squared results

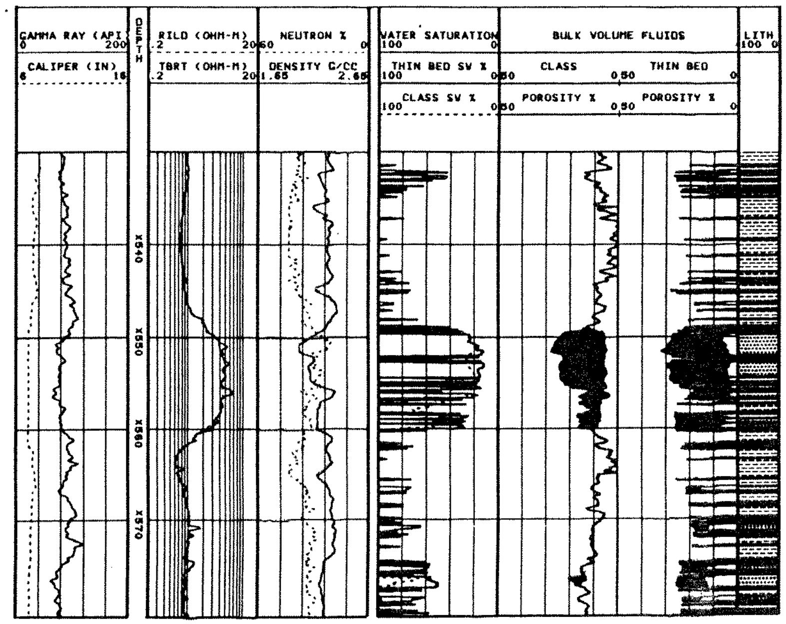

FIGURE 10
Standard thin-bed analysis (TBA) presentation

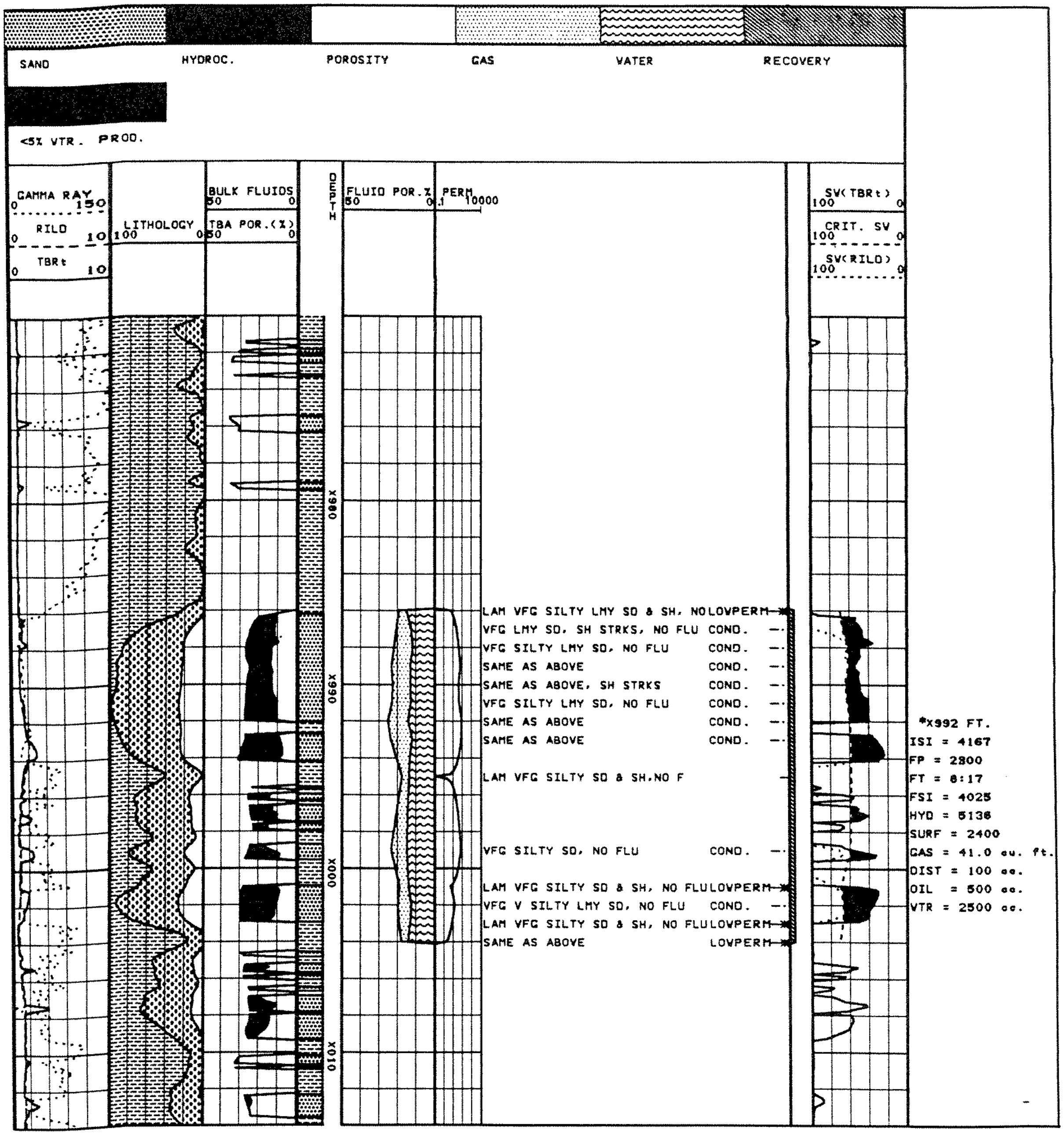

FIGURE 11
StrataLogik integrated data presentation