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A LOG ANALYSIS TECHNIQUE FOR EVALUATING. LAMINATED COMPLEX CARBONATE AND SANDSTONE RESERVOIRS

N. Ruhovets

Halliburton Logging Services
Houston, Texas

ABSTRACT. Existing high-resolution log interpretation techniques were primarily developed for evaluating thinly laminated shaly sand reservoirs, where effective porosity depends mainly on the volume and distribution mode of the clay. These techniques cannot be applied to complex carbonate and sandstone reservoirs where porosity also depends on lithology and degree of cementation, and so may change abruptly from one bed to another, even in clean formations.

A special high-resolution interpretation technique has been developed for complex reservoirs containing carbonates and highly cemented sandstones. Required input logs are induction (or other deep-investigating resistivity logs), density, neutron, gamma ray (or another standard shale indicator), an unfiltered P_e-index, and a high-resolution resistivity log such as a dipmeter or high-frequency dielectric.

Initially, shale volume and its mode of distribution (dispersed or laminated) are determined at the high-resolution level. Shale volume is then integrated to the medium-resolution level and used to conventionally compute effective and total porosities from density-neutron crossplots. The integrated shale volume is also used to calculate effective and total water saturations. Effective porosity at the high-resolution level is determined from a shallow investigating high-resolution resistivity log, using apparent mud filtrate resistivity computed continuously at the medium-resolution level. Water saturation in the thin beds is determined from linear relationships established at the medium- or low- resolution level between effective porosity and water-filled effective porosity. Lithological composition of laminated complex reservoirs is determined at the vertical resolution of the unfiltered P_e-index, assuming that in thin beds no more than two minerals are present.

The paper presents a discussion of the principles underlying this new interpretation technique. Applications to log interpretation in complex reservoirs are then illustrated using three field examples having different lithological compositions.

INTRODUCTION

Specific features of complex reservoirs in general, and particularly thinly laminated reservoirs, are their multilithological compositions and highly differentiated properties. Unlike thinly laminated shaly sand reservoirs which are always represented by interbedding of thin sand and shale laminae, the laminated complex reservoirs do not necessarily contain shale laminae (probably more often than not they do not). Thus, unlike shaly sands, the major problem is not the presence of laminated shale, but rather the abrupt changes in such reservoir properties as lithology, porosity, and water saturation from one bed to another. Accordingly, when dealing with thinly laminated complex reservoirs, the major goal should be the revelation of the properties of the individual thin beds, regardless of whether laminated shale is present, from the integrated properties measured by logs having insufficient vertical resolution to resolve the individual bedding features.

Shale volume and mode of distribution at the high-resolution level can be determined from a high-resolution log which is sensitive to variation in clay content. However, high-resolution shale indicators such as resistivities from dipmeters and micrologs, and resistivity and attenuation from high-frequency dielectric tools, are also sensitive to reservoir porosity. Therefore, their usage requires additional information from conventional shale indicators such as gamma ray (GR), spontaneous potential (SP), and others.

If shale is present in a complex reservoir, determination of shale distribution mode, porosity, and water saturation at the high-resolution level is done through the computation of two components of reservoir properties: a complex component (which includes the component properties of all carbonates and sandstones) and a shale component. Accordingly, individual beds are called either complex beds (whether clean or with dispersed clay) or shale beds. Computations are performed at three resolution levels in accordance with the vertical resolutions of the logs involved: high-resolution (dipmeter, high-frequency dielectric, micrologs, unfiltered P_e-index), medium-resolution (porosity logs, GR, High Resolution Induction (HRI)) and low-resolution (conventional induction, laterolog). The essence of the technique devised for determining high-resolution porosity, lithology, and water saturation consists of using the response from a high-resolution bedding indicator to transform to the high-resolution level the information obtained from a conventional interpretation of low-resolution logs.

Conventional porosity and integrated high-resolution resistivity values (recorded by calibrated dipmeters, micrologs or high frequency dielectric tools) are used to compute apparent mud filtrate resistivity, which in turn is used to compute high-resolution porosity from high-resolution resistivity. In this respect the high-resolution log is an instrument for converting information from a low- to a high-resolution level, and is not just a high-resolution shale indicator (often it is not this at all).

The only high-resolution log sensitive to lithology, but not fluid resistivity, is the unfiltered P_e-index. If one assumes that no more than two minerals can be present within any interval equal to the unfiltered P_e-index vertical resolution, then the lithology of laminated complex reservoirs can be determined to the resolution of the unfiltered P_e-index.

Linear relationships observed between porosity and water-filled porosity are assumed to be the same on both the low and high-resolution levels. Thus, these relationships determined at a low-resolution level, in combination with high-resolution porosity, can be used for computing high-resolution water saturation.

SHALE VOLUME AND MODE OF DISTRIBUTION

Shale Volume

Determining shale content in complex reservoirs is often a difficult problem. This is especially true in thinly laminated reservoirs. Only if the thickness of the beds in complex laminated reservoirs matches or exceeds the vertical resolutions of such standard shale indicators as GR or enhanced-resolution GR, can shale volume be determined conventionally.

High-resolution shale indicators such as resistivities from dipmeters, micrologs, and high-frequency dielectric tools are influenced by porosity changes at least as much as by shale-content variations; however, electromagnetic wave attenuation measured by high-frequency dielectric tools is usually influenced somewhat more by shale content than by porosity. In other words, these logs respond to both porosity and shale content. To use these logs as shale indicators, the components associated with porosity must be excluded. This can be accomplished with the help of other shale indicators which are only minimally sensitive to porosity. These porosity-insensitive shale indicators (such as GR and SP) have relatively low vertical resolutions, which necessitates a combinatorial solution.

If the thickness of the beds of a laminated reservoir is considerably less than the vertical resolution of conventional shale indicators, the following technique can be used to eliminate shale volume distortion caused by the high-resolution shale indicator component related to porosity. The technique, however, requires that high-resolution resistivities (or attenuations) in clean beds and shales be different. In clean beds flushed by fresh-mud filtrate, resistivities are almost always higher and attenuations lower than in shales. At least two shale indicators must be used: high-resolution and conventional. One possible combination is illustrated in Fig. 1 (dipmeter and GR).

The generic formula for computing shale volume from a resistivity log can be presented as follows:

$$V_{sh} = \frac{\dfrac{1}{R_{log}} - \dfrac{1}{R_{max}}}{\dfrac{1}{R_{min}} - \dfrac{1}{R_{max}}}$$

where R_{log}, R_{max}, and R_{min} are resistivity, maximum resistivity and minimum resistivity respectively.

Initially, a value defining the dipmeter response to clean reservoirs is derived conventionally from maximum dipmeter resistivities, and a shale value is defined from minimum resistivities (see vertical lines in Fig. 1). A similar procedure is utilized for the GR log.

Shale volume is computed from both shale indicators. High-resolution shale volume is integrated to the vertical resolution of the conventional shale indicator. Now the two shale volumes having the same vertical resolution can be

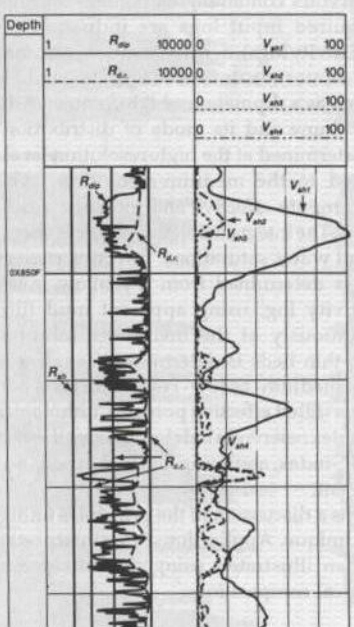

Figure 1: Determination of shale volume and mode of distribution in laminated complex reservoirs

R_{dip} - Dipmeter resistivity; $R_{d.r.}$ - Curve, connecting maximum dipmeter resistivities; $R_{c.r.}$ - clean-rock resistivity parameters (500 ohm-m, 50 ohm-m, 12 ohm-m); R_{sh} - shale resistivity parameter (6 ohm-m); V_{sh1} - shale volume computed from GR; V_{sh2}, V_{sh3}, V_{sh4} - Integrated shale volumes computed from dipmeter with $R_{c.r.}$ equal to 500 ohm-m, 50 ohm-m, 12 ohm-m, respectively.

compared to each other. If the integrated high-resolution shale volume is greater than the GR shale volume, a new clean-rock resistivity value is chosen closer to the shale value and the two shale volumes (high-resolution and integrated high-resolution) are recomputed. This process is repeated until the integrated high-resolution shale volume coincides in some zones with the conventionally determined shale volume, and has lower values in the rest of the laminated reservoir. These high-resolution and integrated high-resolution shale volumes are then used for further log interpretation at high- and medium-resolution levels.

In our example (Fig. 1), integrated shale volumes computed with the clean reservoir lines drawn through maximum resistivity (500 ohm-m) and resistivity equal 50 ohm-m exceed the shale volume from GR in three zones and one zone, respectively. Integrated shale volume computed with a 12-ohm-m clean line is less than or equal to GR shale volume. A significant volume of shale (about 15%) is calculated only in one narrow zone about 1 ft wide. The 12-ohm-m line defines the resistivity of clean beds having maximum porosities. If this line was chosen as the clean bed parameter, the error in the shale volume computation would be minimal since core data indicate that there is no shale present in this interval of the well. However, in cases like this, it could be difficult to obtain accurate shale volume without having information from core data since GR exhibits radioactivity which is basically not related to shale content.

Mode of Shale Distribution

If shale is present in a complex laminated reservoir, its distribution mode can be determined under certain conditions from a high-resolution shale indicator. A shale indicator measuring resistivity will be considered. Similar logic can be applied to other shale indicators such as dielectric attenuation.

The first condition for successfully determining the shale distribution mode is that the thickness of reservoir beds should match or exceed the vertical resolution of the shale indicator (i.e., boundary effects on the high-resolution resistivity measurements should be minimal). Second, there should be no significant distortion of the high-resolution resistivity by residual hydrocarbons in the flushed zone. Third, the resistivities of complex beds (clean or containing dispersed clay) and shale beds should be different. It is assumed that resistivities in complex beds are higher than in shale.

Under these conditions, a curve drawn through maximum dipmeter resistivities is the resistivity of the complex component (Fig. 1). Separation between this curve and the clean-bed parameter line (the former has lower resistivities than the latter) indicates the presence of dispersed clay in the complex beds. If these lines coincide, or if the clean-bed parameter line is moved to a lower resistivity than the complex-component resistivity, there is no dispersed clay in the complex beds, i.e., the entire computed volume of shale is represented

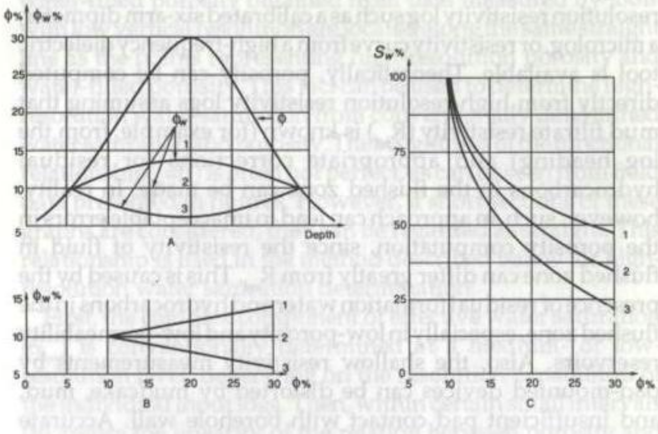

Figure 2: Modeling relations among porosity and three different water-filled porosities; and among porosity and corresponding water saturation.

A. Porosity and water-filled porosities versus depth
B. Porosity versus water-filled porosities
C. Porosity versus water saturation

by laminated shale. In this case, variations in the resistivity of the complex component are caused only by porosity changes.

Thus, as is shown in the table below, the total shale volume and its mode of distribution can be computed from the same formula (Eq. 1) by using corresponding parameters presented in Fig. 1.

	R_{max}	R_{min}	R_{log}
V_{sh}	$R_{c.r.}$	R_{sh}	R_{dip}
V_{shl}	$R_{d.r.}$	R_{sh}	R_{dip}
V_{cldc}	$R_{c.r.}$	R_{sh}	$R_{d.r.}$

$$V_{cld} = V_{sh} - V_{shl}$$

or (2)

$$V_{cld} = V_{cldc} * (1 - V_{shl})$$

In the case presented in Fig. 1, dispersed clay would be computed in several zones if a 500-ohm-m line was used as a clean-rock parameter line. Only laminated shale would be computed if 50-ohm-m or 12-ohm-m lines were used as the clean-rock line.

POROSITY

High-resolution porosity can be computed if a high-resolution resistivity log such as a calibrated six-arm dipmeter, a microlog, or resistivity curve from a high-frequency dielectric tool is available. Theoretically, porosity can be computed directly from high-resolution resistivity logs assuming that mud filtrate resistivity (R_{mf}) is known (for example, from the log heading) and appropriate corrections for residual hydrocarbons in the flushed zone can be made. In reality, however, such an approach can lead to unacceptable errors in the porosity computation, since the resistivity of fluid in flushed zone can differ greatly from R_{mf}. This is caused by the presence of residual formation water and hydrocarbons in the flushed zone, especially in low-porosity and low-permeability reservoirs. Also, the shallow resistivity measurements by pad-mounted devices can be distorted by mudcake, mud, and insufficient pad contact with borehole wall. Accurate corrections for all these factors are difficult to make.

On the other hand, all these disturbing factors can be compensated to a large degree by computing apparent mud filtrate resistivity (R_{mfa}) from porosity logs and from the shallow investigating resistivity integrated to the vertical resolution of the porosity logs. This apparent mud filtrate resistivity can then be used to compute high-resolution porosity from high-resolution resistivity. In these computations water saturation is assumed to be 100%. When a water saturation equation is involved in the computations here, and also in Water Saturation section which follows, all input and output variables are complex components which are computed according to the following generic formula:

$$X = X_c * (1 - V_{shl}) + V_{shl} * X_{shl}$$

where X is a property of complex reservoir,

X_c is a complex component of property X,

X_{shl} is a value of X in shale component.

This approach excludes laminated shale from water saturation equations, thereby simplifying them and facilitating transformation of computed data from the low-resolution level to the high.

Thus, the following procedure is used to compute high-resolution porosity:

1. The complex components of total porosity (ϕ_{tc}) and integrated high resolution conductivity (C_{ic}) are computed in accordance with Eq. 3.

2. Rmfa is computed from a chosen water saturation equation with inputs ϕ_{tc} and R_{ic}.

3. The complex component of high-resolution total porosity ($\phi_{tc\,h.r.}$) is computed from the same water saturation equation with input of R_{mfa} and the complex component of the high-resolution resistivity ($R_{c\,h.r.}$) substituted for R_{ic}.

4. The $\phi_{t\,h.r.}$ is computed from $\phi_{tc\,h.r.}$ in accordance with Eq. 3.

5. $\phi_{e\,h.r.}$ is computed as follows:

$$\phi_{e\,h.r.} = (\phi_{t\,c\,h.r.} - \phi_{sh} * V_{cldc\,h.r.}) * (1 - V_{shl\,h.r.})$$

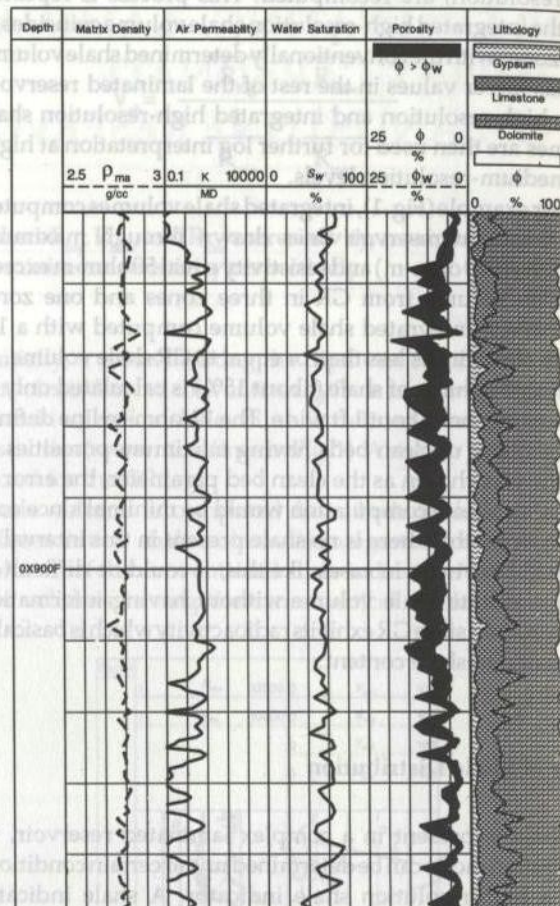

Figure 3: Well 1. Core Data

LITHOLOGY

The combination of density, neutron, and P_e-index logs allow computation of up to three-mineral lithologies at every depth. The P_e-index curve is filtered to the vertical resolution of density and neutron logs, i.e. lithological composition is determined with a resolution of approximately 2 ft. Consequently, if, for example, three-mineral lithology is determined at some depth, it represents three beds of different lithologies with minimum total thickness of 2 ft and with minimum bed thickness of the individual beds being proportional to the corresponding volumes of the determined minerals. If the vertical resolutions of density, neutron, and P_e-index logs could be improved by factors of 2 or more, the most likely result would be computation of only one or two mineral lithologies (one or two beds) at a given depth, which in this case, would include contributions from a smaller depth interval.

This logic is used to determine lithological composition to the vertical resolution of the unfiltered P_e-index. If a three-mineral lithological composition is determined from conventional log interpretation, only two minerals with the

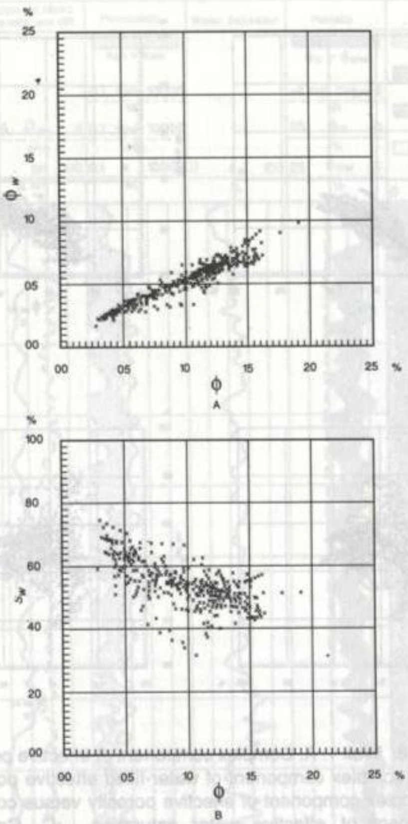

Figure 4: Well 1. Core data
A. Porosity versus water-filled porosity
B. Porosity versus water saturation

highest volumes are selected for further consideration. Their volumes are then recomputed in accordance with the value of unfiltered P_e-index and with assumption that their sum is equal to unity. If the unfiltered P_e-index does not lie between the P_e-indexes of the two selected minerals, the mineral with intermediate volume is replaced by the third mineral and volumes of the remaining two minerals are recomputed according to unfiltered P_e-index value. Similarly, if two minerals are determined by conventional log interpretation, their volumes are recomputed to match the unfiltered P_e-index.

WATER SATURATION

Many years ago it was discovered (Buckles, 1965) that in many reservoirs there are clearly indicated hyperbolic correlations between connate water saturations and porosity, such that $*S_w$=Constant. Actually, this is only one of three possible cases (Fig.2). $*S_w$ is currently called water-filled porosity. These three cases can be more clearly seen from relationship between porosity and water-filled porosity than between porosity and water saturation (Fig. 2, B and C). The former is represented by three types of slopes of straight lines: negative, zero, and positive; the latter is represented by three similar hyperbola type curves.

The straightness of the graphs representing the relationship between porosity and water-filled porosity is very important. In this case, the points representing integrated porosity and water-filled porosity obtained from data measured by tools with low vertical resolution are located along the same straight line as the points representing high-resolution porosity and water-filled porosity. This fact can be used to determine high-resolution water saturation from conventionally determined water saturation and porosity. The staightness of the functional relationship $_w$=f() is often not perfect, as can be seen from field data presented in figures. However, if short sections of these graphs are considered, they can be regarded as straight. This relationship is used in the method described below for high-resolution water saturation determination.

First, the complex component of effective water saturation (S_{wc}) is conventionally determined at a medium- or low-resolution level, depending on the resolution capabilities of the individual input logs. Then, within certain small intervals (to assure the linearity of the relation between porosity and water-filled porosity), maximum and minimum values of the complex component of effective porosity ($_{ec}$) and the corresponding components of water-filled porosity ($_{ewc}$) are found at each depth. These data are used to compute the slope and intercept of the straight line $_{ewc}$=f($_{ec}$). The same straight line, with the complex component of high-resolution effective porosity ($_{ec\,h.r.}$) substituted for $_{ec}$, is then used to determine the high-resolution complex component of water-filled effective porosity:

$$\phi_{ewc\,h.r.} = \phi_{ec\,h.r.} - \phi_{ec}) * \text{slope} + \phi_{ewc}$$

High-resolution water saturation ($S_{w\ h.r.}$) can then be determined from the complex component of the high-resolution effective water saturation ($S_{wc\,h.r.}$) using Eq. 3.

FIELD EXAMPLES

The field examples which follow illustrate high-resolution log interpretation in complex reservoirs in comparison with conventional interpretation. High-resolution interpretation was performed using the computer program CLARA (Complex Laminated Reservoir Analysis) based on the high-resolution interpretation technique described in this paper. Conventional interpretation has been done using CORAL - a complex reservoir analysis program (Ruhovets and Oliver, 1985).

Well 1

This well is located in the Permian Basin in West Texas. The reservoir is represented by the San Andres formation, Permian period. Whole core analyses were performed each foot in the illustrated interval. According to core data (Fig. 3) the reservoir formation is composed of dolomite and, to a lesser degree, limestone. Silt and gypsum (from 1% to 15%) are also present.

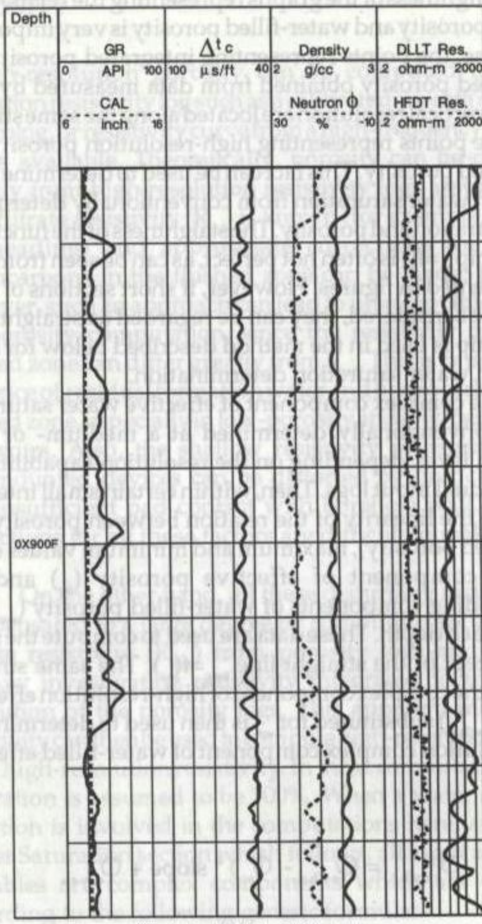

Figure 5: Well 1. Original logs

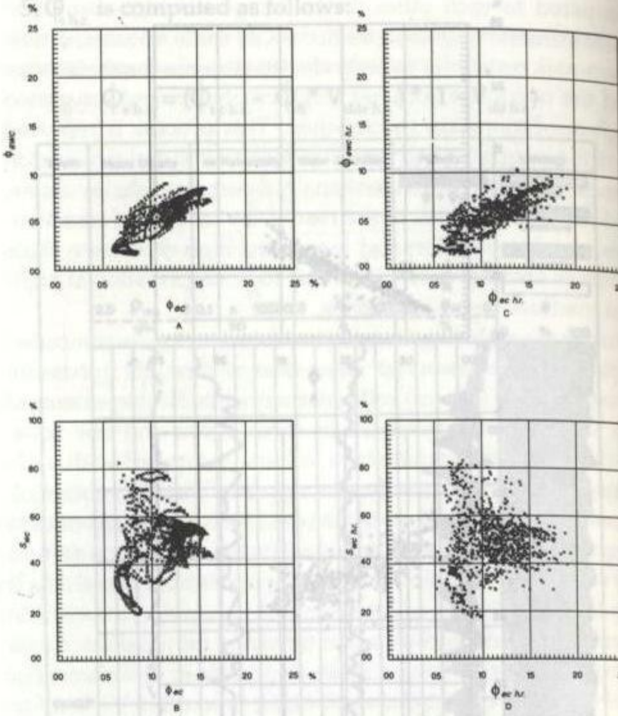

Figure 6: Well 1. A. Complex component of effective porosity versus complex component of water-filled effective porosity. B. Complex component of effective porosity versus complex component of effective water saturation. C. Complex component of high-resolution effective porosity versus complex component of high-resolution water-filled effective porosity. D. Complex component of high-resolution effective porosity versus complex component of high-resolution effective water saturation.

Porosity ranges from 3% to 19%, air permeability ranges from 1 md to 20 md, and S_w from 40% to 50%. No clay minerals were found. The well was drilled with salt mud (R_m=0.09 ohm-m at 100°F), which is advantageous for high-resolution log interpretation in a clean reservoir since porous beds are well delineated by low, flushed zone resistivities relative to the high resistivities in the tight beds. In shaly formations, saline mud filtrate can equalize shallow-investigating resistivities in porous beds and shale laminae.

The relationship between porosity and water-filled porosity from core data (Fig. 4A) exhibits a straight-line distribution with positive slope and relatively small dispersion of data points. These linear relationships have positive slopes in all three wells presented in this paper; water saturations are also relatively high (30% to 60%) in all three wells. Apparently, positive slopes are characteristic for reservoirs with relatively high water saturations. The relationship between porosity and water saturation (Fig. 4B) is basically hyperbolic in character, but veiled by a high dispersion of the data points.

Logs used for interpretation include (Fig. 5) DLLT deep resistivity, dielectric resistivity from the High Frequency Dielectric Tool (HFDT), density, neutron, acoustic, and GR. Conventional log interpretation results match closely core analysis in the determination of all basic reservoir properties, including porosity, lithology, water saturation, and even permeability (Figs. 3 and 7). One probable reason is that cores were analyzed every foot, which is close to the vertical resolution of the available logs (about 2 ft).

High-resolution interpretation (Fig. 8) exhibits considerably more details than conventional interpretation, except lithology, which was determined conventionally from density, neutron, and acoustic logs. Maximum porosity in thin beds increased from about 15% to 17% according to conventional interpretation to 17 to 19%. Both high-resolution interpretation and core data indicate the highest porosity (19%) at depth X868 ft.

High-resolution water saturation exhibits more fine variations, but basic features and values did not change significantly when compared to core data and conventional interpretation. Fig. 6 features relationships between the complex components of effective porosity and water-filled effective porosity, and effective porosity and effective water saturation computed at both medium- and high-resolution levels.

These data indicate that high-resolution variables extend to higher and lower values as compared to filtered variables, but basic features of corresponding relationships are similar at both resolution levels. This is an indication that the slopes of the functions $_w$=f(), and consequently water saturations, are determined correctly.

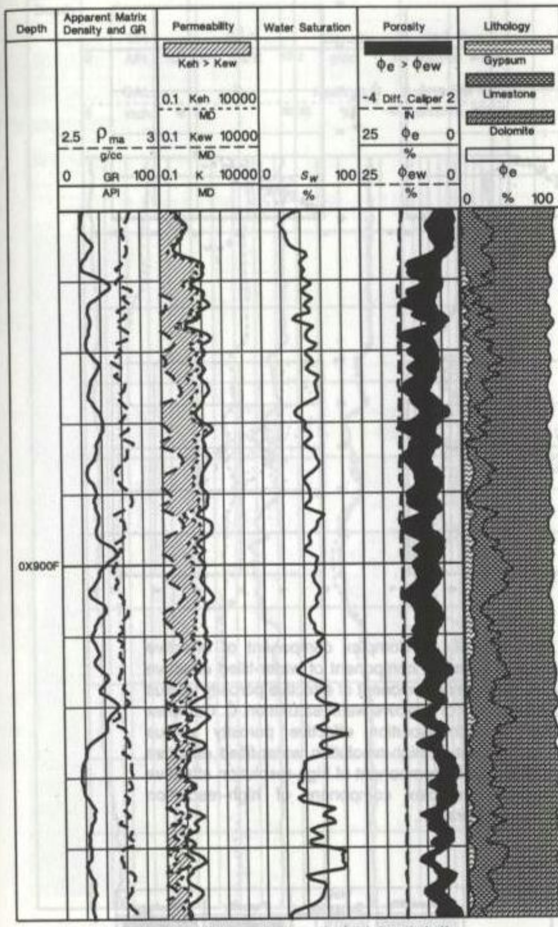

Figure 7: Well 1. Conventional Interpretation

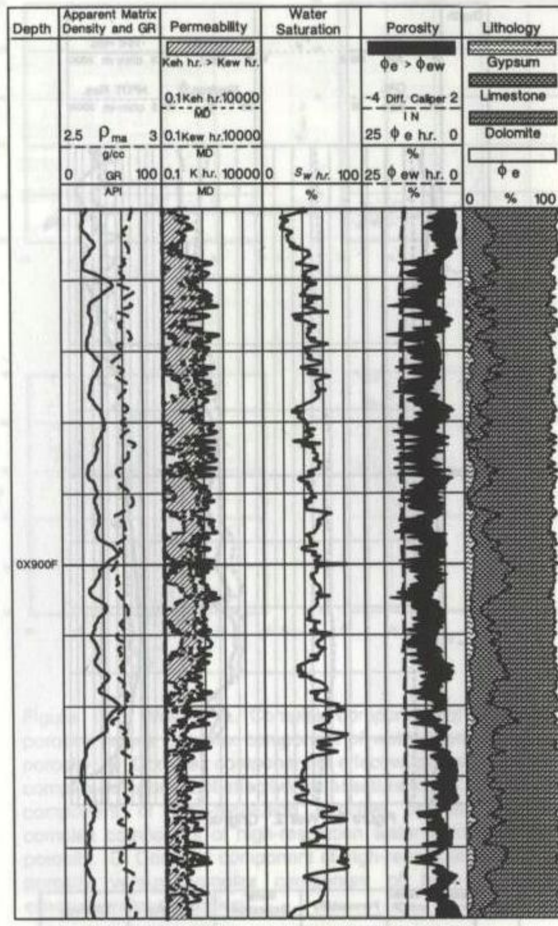

Figure 8: Well 1. High Resolution Interpretation

Well 2

The well is located in southeastern New Mexico. The reservoir is represented by the Fusselman formation, Silurian period. Logs used for interpretations include HRI deep resistivity, high-frequency dielectric resistivity, density, neutron, P_e-index and GR (Fig. 9). The well was drilled with fresh mud (R_m =1.8 ohm-m at 70°F).

According to conventional log interpretation (Fig.11), the reservoir in the illustrated interval is composed of sandstone and, to a lesser degree, dolomite. A minimal amount of shale is also computed (5% to 7%).

Maximum porosity reaches 26% to 27%, average water saturation is about 50%, permeability changes from 10 md to more than 100 md. Effective permeability to hydrocarbons is greater than effective permeability to water in intervals with water saturation less than 60%, indicating oil producing reservoirs.

High-resolution interpretation indicates the presence of several thin beds with higher porosities (by 4% to 5%) and lower water saturations (by 7% to 10%) than is observed in the corresponding high porosity zones indicated by conventional interpretation (Figs. 11 and 12). Some minor amounts (3% to 6%) of dispersed clay and laminated shale were indicated in several zones by the high-resolution interpretation.

Relationships between complex components of effective porosities and water-filled porosities are represented by virtually straight lines with positive slopes, which is characteristic of reservoirs with relatively high water saturation (Fig. 10, A and C). Some local zones, however, in this well (as well as in the other two field examples in this paper) have zero and negative slopes.

Hyperbolic relations are rarely seen in crossplots of $_{ec}$ vs. S_{wc} (Fig. 10, B and D) due to the high dispersion of data points. Still, it can be seen from these graphs that the minimum water saturations changed from about 50% (S_{wc}) to about 40% ($S_{wc\,h.r.}$) in zones with porosity ranging from 10% to 30%, and from about 50% (S_{wc}) to about 60% ($S_{wc\,h.r.}$) in zones with porosity ranging from 0% to 10%.

Well 3

This well is located in the Midland Basin in West Texas. The reservoir is represented by a Lower Devonian formation. The well was drilled with fresh mud (R_m=0.65 at 70°F). Logs used for interpretation include dual induction deep resistivity, calibrated six-arm dipmeter resistivity, density, neutron, acoustic, and GR (Fig. 13).

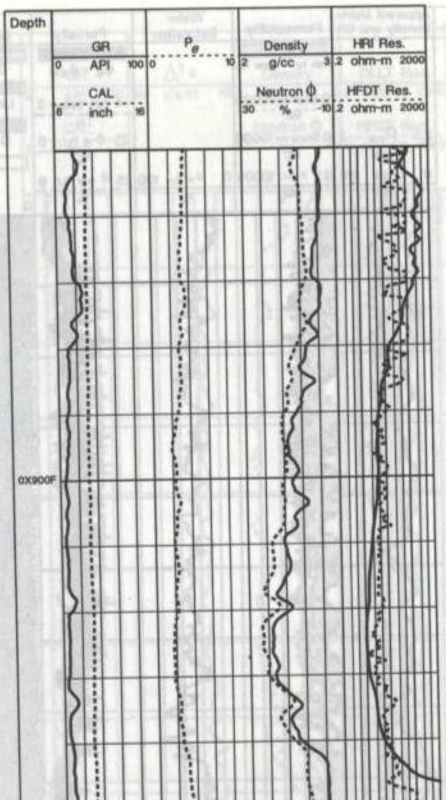

Figure 9: Well 2. Original logs

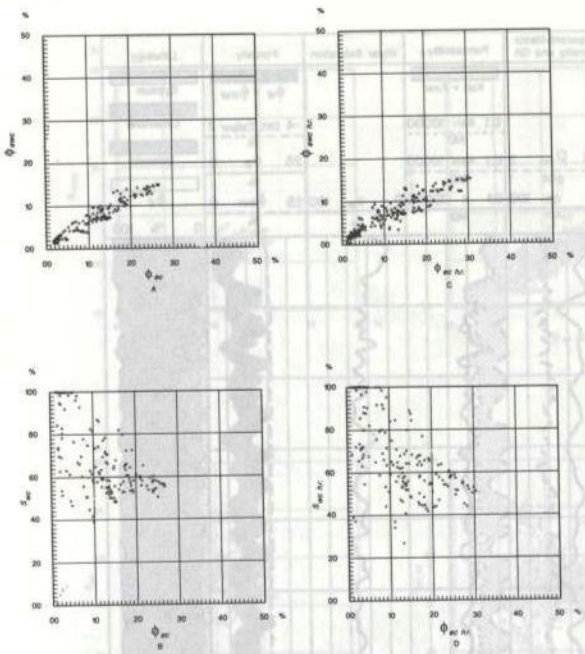

Figure 10: Well 2. A. Complex component of effective porosity versus complex component of water-filled effective porosity. B. Complex component of effective porosity versus complex component of effective water saturation. C. Complex component of high-resolution effective porosity versus complex component of high-resolution water-filled effective porosity. D. Complex component of high-resolution effective porosity versus complex component of high-resolution effective water saturation.

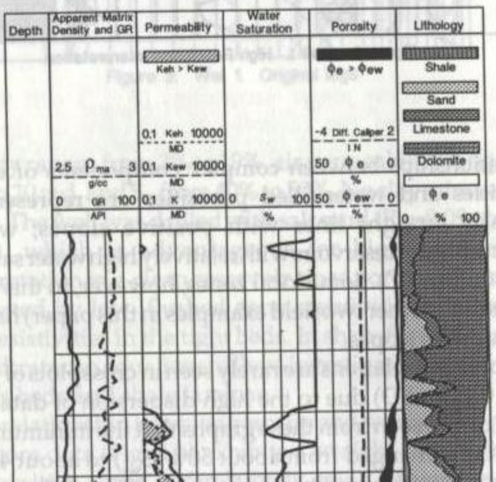

Figure 11: Well 2. Conventional interpretation

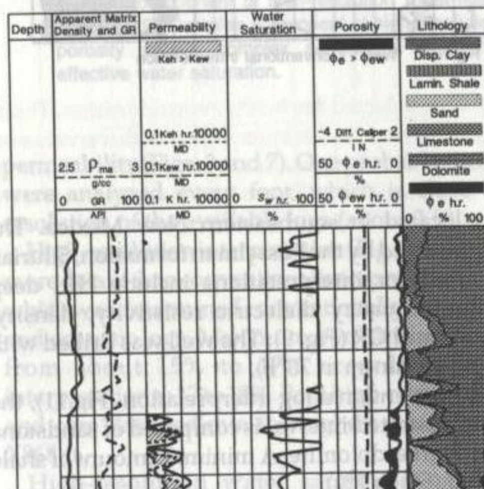

Figure 12: Well 2. High-resolution interpretation

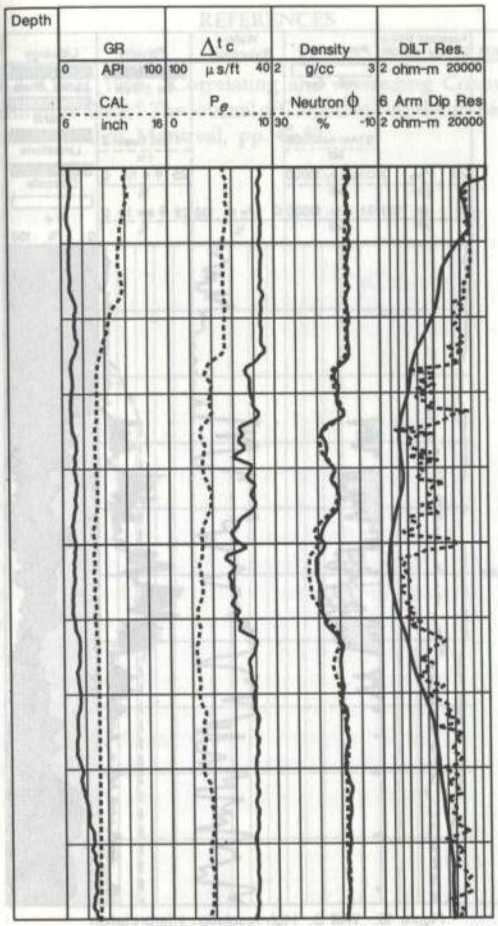

Figure 13: Well 3. Orginal logs

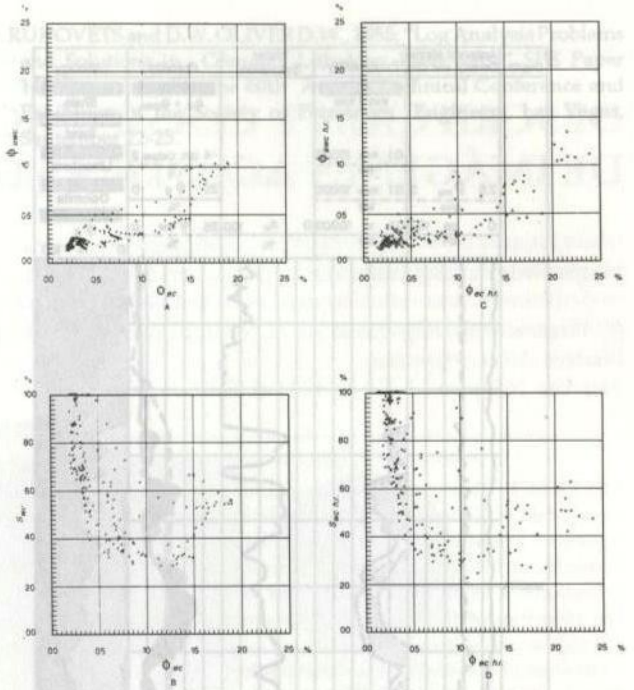

Figure 14: Well 3. A. Complex component of effective porosity versus complex component of water-filled effective porosity. B. Complex component of effective porosity versus complex component of effective water saturation. C. Complex component of high-resolution effective porosity versus complex component of high-resolution water-filled effective porosity. D. Complex component of high-resolution effective porosity versus complex component of high-resolution effective water saturation.

According to conventional log interpretation (Fig. 15), the reservoir is represented by limestone, sandstone and, to a lesser degree, by dolomite. Porosity changes from 3% to 18%, water saturation varies mostly between about 30% and 60%. Permeability ranges from 1 md to almost 100 md. Effective permeabilities to hydrocarbons are higher than effective permeabilities to water in zones with water saturations less than 60%.

The high-resolution interpretation (Fig. 16) reveals that there are many thin beds in this reservoir with porosities 4% to 5% higher and with water saturation mostly lower than indicated by conventional interpretation in the corresponding zones.

The slopes of the lines representing the functions $_{ewc}=f(_{ec})$ (Fig. 3, A and C) are generally positive, but there are many zones with negative and zero slopes, especially in lower-porosity intervals. The hyperbolic character of the relationship between $_{ec}$ and S_{wc} (Fig. 14, B and D) is better seen in this well than in the prior two examples.

CONCLUSION

A new log analysis technique has been developed for evaluating thinly laminated complex reservoirs. Shale content and its mode of distribution, porosity, water saturation, and permeability can be determined with a vertical resolution of 1 to 3 inches, in accordance with the vertical resolutions of shallow investigating resistivity and high-frequency dielectric tools. Lithological composition can be determined at the vertical resolution of the unfiltered P_e-index (4 to 5 inches). Only high-resolution shale volume and its mode of distribution are computed directly from a high-resolution resistivity or electromagnetic wave attenuation log. Conventional shale indicators are used only to assist in selecting computational parameters for the high-resolution shale indicator. High-resolution porosity, permeability, water saturation, and lithological composition are computed initially at a low-resolution level in a conventional way and then reconstructed to the high-resolution level using a high-resolution resistivity log or, in the case of lithology, an unfiltered P_e-index. The quality of high-resolution porosity and water saturation computations basically depends on the quality of the high-resolution measurements, which should be properly calibrated.

There are certain limitations regarding when this technique can be used. The most stringent limitation is on determining the mode of shale distribution: this can be performed only if boundary effects and residual hydrocarbon effects on resistivities in thin beds are minimal. The high-resolution shale volume computation requires that the resistivities in complex beds and shales be different. These limitations are frequently unimportant, since complex laminated reservoirs

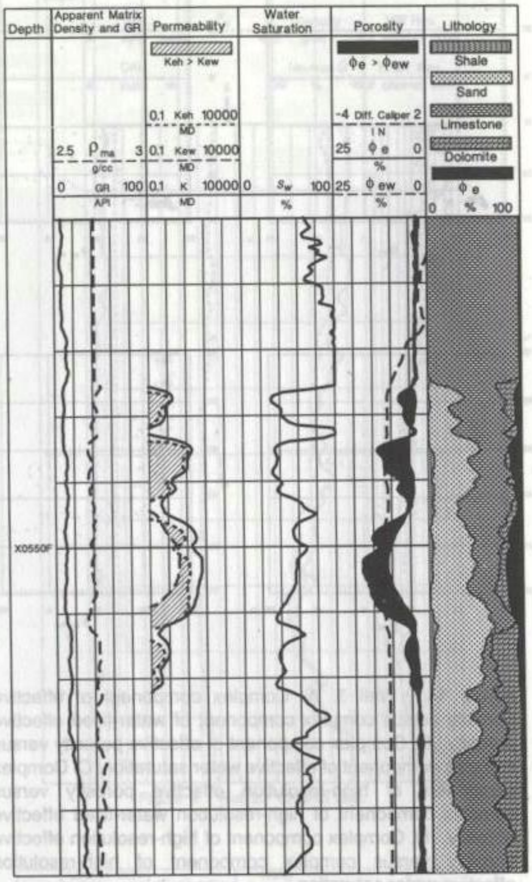

Figure 15: Well 3. Conventional interpretation

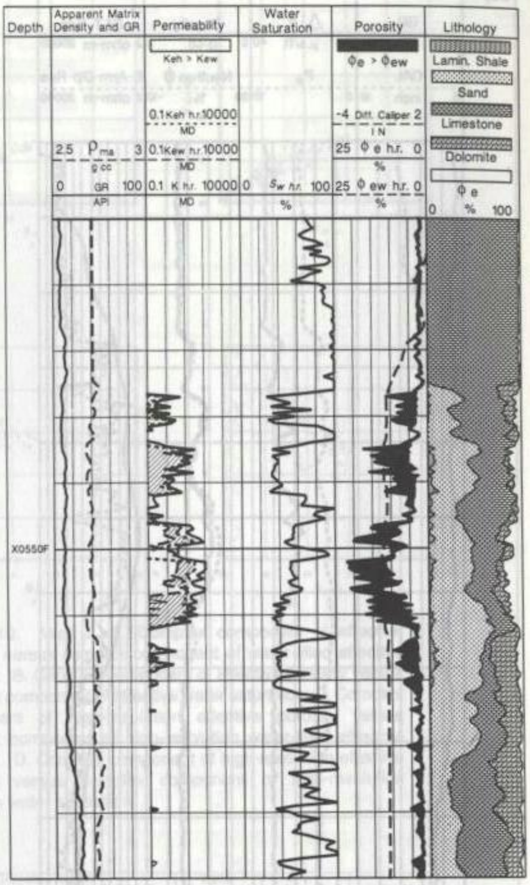

Figure 16: Well 3. High-resolution interpretation

are often clean or have only a minimal amount of shale. The technique was illustrated in three field examples having different geological conditions. In all cases the high-resolution interpretation provided more detailed evaluation of porosity, permeability, and water saturation.

NOMENCLATURE

C_{ic} -complex component of integrated high-resolution conductivity, mmho/m
R_c -complex component of high-resolution resistivity, ohm-m
$R_{c.r.}$ -resistivity of clean rock, ohm-m
$R_{d.r.}$ -resistivity of complex component, ohm-m
R_{ic} -complex component of integrated high-resolution resistivity, ohm-m
R_{mfa} -apparent mud filtrate resistivity, ohm-m
R_{sh} -shale resistivity, ohm-m
R_{dip} -dipmeter-measured resistivity, ohm-m
S_w -effective water saturation
S_{wc} -complex component of effective water saturation
V_{dd} -volume of dispersed clay
V_{ddc} -complex component of dispersed clay volume
V_{sh} -total volume of shale
V_{shl} -volume of laminated shale
-porosity (generic)
$_{e}$ -effective porosity
$_{ec}$ -complex component of effective porosity
$_{ew}$ -effective water-filled porosity
$_{ewc}$ -complex component of effective water-filled porosity
$_{sh}$ -shale porosity
-total porosity
$_{tc}$ -complex component of total porosity
$_{w}$ -water-filled porosity (generic)

Subscripts

h.r. -high-resolution

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