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A new approach of using resistivity index as separation of resistivity and porosity logs for the estimation of total organic carbon content in the Eagle Ford shale

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Abstract

The separation of resistivity and porosity logs in organic-rich intervals measured in terms of logarithmic resistivity cycle, called ΔlogR parameter, is generally used to calculate total organic carbon content TOC, with reference to the base lines established in a water bearing non-source rock of a given lithology. Application of the overlay method in organic rich Eagle Ford shale is prone to errors due to non-availability of reference water base lines in similar lithology.

An increase in porosity in terms of resistivity means an increase in volume of conducting water, resulting in a decrease in resistivity. These changes are proportional, so that if the porosity and resistivity are correctly modeled, the amount of increased porosity results in deflections of similar magnitude of both the resistivity and porosity curves. It means modeled resistivity of water filled resistivity curve generated with porosity, serves as base lined curves for both resistivity and porosity curves. Separation between resistivity and modeled water filled resistivity curves represents the so called properly scaled resistivity and porosity curves defined by usual ΔlogR technique. The use of ΔlogR calculated directly as logarithm of resistivity index dynamically generated through Archie's relation, is very robust for TOC calculation and also eliminates the requirement of establishment of water base lines of resistivity and porosity logs in conventional technique.

Logarithm of resistivity index alone has been used as ΔlogR for quantification of TOC with new approach. Apparent in-situ vales of cementation exponent 'm', most crucial parameter required for the generation of water filled resistivity has been derived by combining the resistivity log and bulk volume of water from core measurements, which takes care of effects of clays on conduction of electrical currents. Variation of 'm' in the range of 1.9-2.0, ensures the applicability of Archie's equation mainly due to very high salinity of bulk volume of water which also suppresses the effect of clay conductivity. Comparison of estimates for total porosity, total water saturation, and TOC obtained using new organic-shale evaluation method are corroborating with the respective values derived from core laboratory measurements.

Entire procedure is illustrated with examples of Eagle Ford shale gas formation where sufficiently large number of measurement on core samples are available for the calibrations of log derived values of porosity, bulk volume of gas/water and TOC. The technique organic-shale evaluation is very robust and can be extended for the evaluation of other fields of the world.

Introduction

Total Organic Carbon describes the organic richness of sedimentary rocks and is one of the most important indexes that indicate the abundance of organic matter (OM) in the formation. Quantifying the kerogen content, typically defined as TOC, is a necessary step in evaluating a shale gas. A number of log techniques has been developed and demonstrated the use of well logs in determining variations and absolute quantities of OM. Passey, et al. (1990), introduced and reintroduced in 2010, a practical method for the quantitative assessment of source rock based on separation of porosity and resistivity logs. The magnitude of the separation of the porosity and resistivity curves in a shale-rich

zone indicates organic richness. They presented an empirical method, the ΔlogR technique, to correlate the total organic carbon (TOC) with ΔlogR and the level of organic metamorphism (LOM), where ΔlogR is defined as the separation of resistivity and porosity logs under a fixed scale.

The separation of resistivity and porosity logs in organic-rich intervals measured in logarithmic resistivity cycles, called ΔlogR parameter, is generally used to calculate total organic carbon content TOC, with reference to the base lines established in a water bearing non-source rock of a given lithology. Application of such overlay method in organic rich Eagle Ford shale is prone to errors due to non-availability of reference water base lines in similar lithology. Separation between resistivity and modeled water filled resistivity curves represents the so called properly scaled resistivity and porosity curves defined by usual Δ log R technique. The use of ΔlogR calculated directly as logarithm of resistivity index dynamically generated through Archie's relation, is very robust for TOC calculation and also eliminates the requirement of establishment of water base lines of resistivity and porosity logs in conventional technique.

New approach presented in this paper, modeled resistivity of water filled resistivity curve dynamically generated with porosity logs has been used as reference line. ΔlogR parameter derived as logarithm of resistivity index has been used for TOC calculation using the same empirical equation suggested by Passey, et al., 1990. Core petrophysical porosity, grain density and bulk volume of gas/water data have been used to calibrate well log methods for determining TOC. Log data include sonic transit-time, density, resistivity, and neutron porosity. Rock matrix parameters are determined using core measurements. Calculated and measured TOC show good correspondence in wells with good borehole conditions and quality logs.

Geologic settings

The Eagle Ford shale play is one of the most interesting shale plays to be discovered in the United States for its all the three states of hydrocarbon i.e. gas, condensate and oil. The direction of phase change from liquid to gas in the Eagle Ford shale is from north to south and from shallow to deep, where oil is mainly present in the shallowest northern section (Figure-1). The Eagle Ford shale formation expands throughout a laterally extensive area from Maverick County in the west, all the way across the state to the eastern county of Burleson, and beyond. But the major productive part of this play extends from Maverick to Gonzales (Figure-1).

Eagle Ford shale reservoir is quite variable, ranging from siltstones to limestones to true shales. Eagle Ford mudstones vary from slightly to very silty, calcareous, phosphatic, pyritic, glauconitic, bentonitic and carbonaceous facies, ranging from massive to well-laminated and slightly to abundantly fossiliferous. Average mineral volumes and clay percentages from core measurements available in the study area of Eagle Ford Shale formations of South Texas are indicated in Figure-2.
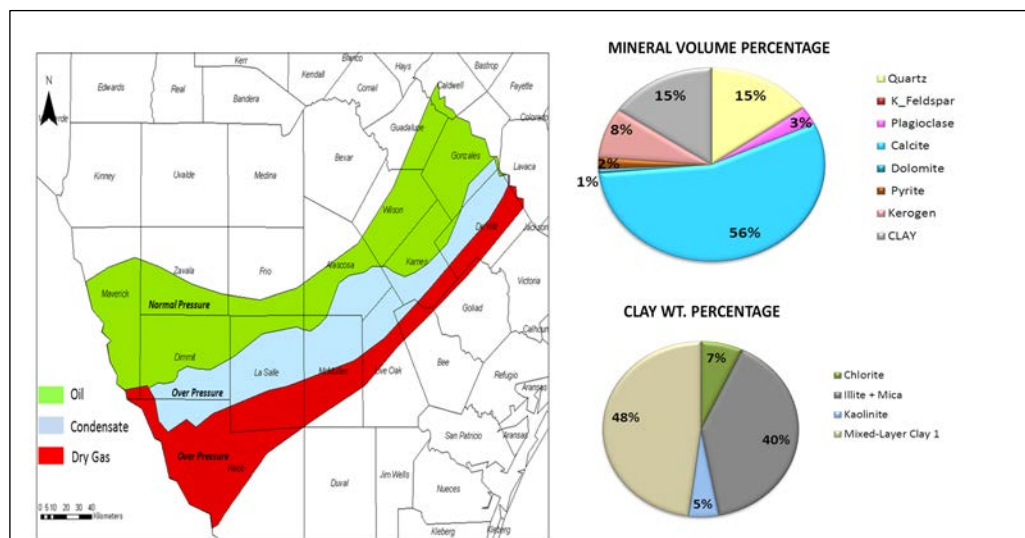

| *Figure-1 Eagle Ford Shale petroleum window interpretation map* | *Figure-2 Average minerals and clay volumes percentages in the study area of the Eagle Ford in south Texas* |

Porosity and Resistivity overlay technique and its base line limitations

Passey et al. (1990) introduced a technique for identification of source rocks and determination of the total organic carbon content. In this technique, the algebraic expressions for the calculated ΔlogR respectively from the sonic/resistivity, neutron/ resistivity and density/resistivity overlays are;

$$\Delta \log R_{Sonic} = \log_{10}(R/R_{baseline}) + 0.02 \times (\Delta t - \Delta t_{baseline})$$
$$\Delta \log R_{Neutron} = \log_{10}(R/R_{baseline}) + 4.0 \times (\varphi N - \varphi N_{baseline})$$
$$\Delta \log R_{Density} = \log_{10}(R/R_{baseline}) - 2.50 \times (\rho b - \rho b_{baseline})$$

Where, ΔlogR is the separation measured in logarithmic resistivity cycle. R is the resistivity measured in ohm-m by the logging tool, $R_{baseline}$ is the resistivity corresponding to the $\Delta t_{baseline}$, $\varphi N_{baseline}$ and $\rho b_{baseline}$ values at non-source, clay-rich rocks. Δt, φN and ρb are the sonic, neutron and density log readings. The constant values 0.02, 4.00 and 2.50 are based on the ratios of each of sonic, neutron and density logs per resistivity cycle, i.e. 1/50, 1/0.025 and 1/0.4 respectively. The ΔlogR separation is linearly related to the TOC content and is a function of maturity. The empirical equation for calculating TOC content in organic rich rocks from Δ log R is:

$$TOC = (\Delta \log R) \times 10 (2.297 - 0.1688 \times LOM)$$

Where TOC is the total organic carbon content (wt%) and LOM is the measured level of maturity. LOM is obtained from the vitrinite reflectance or thermal alteration index by using the maturation indicators of Hood et al. (1975).

With the baseline established, organic-rich intervals can be recognized by separation and non-parallelism of the two curves. The separation is designated as Δ log R and can be measured at each depth increment on the scale of the resistivity log.

A single base line generally cannot be defined for an entire well because of variable lithology and/or changes in formation water salinity. Generally a base line shift occurs at carbonate/clastic interfaces and where formation salinities change drastically. Also, gradual base line shifts are necessary to account for compaction with depth. In these cases, each unit must have separate baseline, and results integrated into the final well profile of calculated TOC values (Passey, et al, 1990).

New approach of dynamic base line with modelled water filled resistivity

Archie demonstrated Sw, the fraction of pore space filled with water, to be proportional to the nth root of the ratio of resistivity R_0 and R_t. Resistivity index I_r defined by Archie as ratio of R_t and R_0 is a measure of separation between porosity φ and resistivity R_t curves,

$$I_r = S_w^{-n} = R_t/R_0 = R_t/FR_w = \varphi^m R_t/aR_w$$

$$\begin{aligned} \text{Log } I_r &= \text{Log } R_t - \text{Log } R_0 \\ &= m \text{ Log } \varphi + \text{Log } R_t - \text{Log } aR_w \\ &= \Delta \log R \end{aligned}$$

Computation of ΔlogR through overlaying of a properly scaled porosity log on a resistivity curve, a widely-used source rock evaluation technique for quantifying total organic carbon by Passey, et al, 1990, is equivalent of logarithm of resistivity index.

The apparent decrease of R_0 is in proportionate to increase of porosity displayed in reverse scale to the resistivity to take care of immature source rock. What was true for water saturation and resistivity should also be true for the fraction of the rock matrix that is not TOC. TOC should be proportional to the nth root of the ratio of resistivities R_0 and R_t as in case of water saturation. This forms the basis of new approach, where calculation of $\Delta \log R = \log I_r = \log (R_t/R_0) = \log R_t - \log R_0$, takes care of both i.e. increase of resistivity related to mature source rock and the effect of increase porosity is inbuilt as apparent decrease of R_0 against the immature organic rich intervals. Both curves R_t and R_0 pull apart as in case of resistivity and porosity overlays where porosity is calibrated with resistivity in opposite scale. The technique becomes more robust when using the ΔlogR calculated from R_0 and R_t

directly, as it does not require any reference base line which may not be available in absence of water bearing non source rock of similar lithology.

Methodology

Computation of resistivity index first requires the determination of formation porosity, formation water resistivity, and cementation exponent 'm' which are then used to derive its value as $R_0 = F R_w = R_w /\varphi^m$. Resistivity index alone can only be used for quantification ΔlogR if formation water resistivity , matrix and fluid parameters and cementation exponent 'm' are precisely known and do not vary significantly over the interval of interest as in case of precise evaluation of porosity and water saturation in conventional reservoirs. New approach for the evaluation of TOC in Eagle Ford Shales based on Δ log R values equated with logarithm of resistivity index, $\text{Log } I_r = \log (R_t /R_0) = \log R_t - \log R_0$, is capitulated in following steps:

Porosity determination
Core measurement is extremely important to calibrate the porosity values derived from wireline measurements. Density, sonic and neutron porosity values are directly calibrated with available core data with a possible petrofacies discriminator. Log derived total porosity values have been calibrated with available core measured total porosity.

Estimation of Bulk Volume Water
Core measured bulk volume of gas (BVG) is supposed to be more consistent than conventional gas and water saturations (Sg and Sw) measurements as suggested by Passey, et. al., 2010 and has been used for derivation of bulk volume of water on BVG vs total porosity plot. Zero intercept of BVG on porosity axis is indicated as bulk volume of water (BVW). The value of BVW=0.02 can be used to derive values of Sg and Sw with core calibrated porosity.

Determination of Archie's exponent of bulk volume of water
Bulk volume of water are related with resistivity measurements through simplified Archie's relation, $BVW^X = R_w/R_t$, Where 'm' = 'n' = 'x' and $BVW = \phi S_w$. Value of 'x' = log (R_w/R_t)/ log(BVW) derived from this equation has also been used as an indicator of in-situ values of the parameters reflecting the nature of electrical conductance in shale formation. Conduction of electrical currents through surface conductance phenomenon associated with clays brings the values of these parameters considerably lower than their default value of 2.0 in clean sand/limestone Archie's reservoirs.

Average values of x (='m') against Eagle Ford shale estimated as 1.87, with very little variance as compared to its default value in case of clean Archie's reservoirs i.e. 'm' = 'm*' = 2.0, suggests the absence of conduction of electrical currents in the rock due to shaly sand mechanism i.e. cation exchange capacity. It indicates the conduction of electrical currents only through bulk volume of water and Archie's equation can be used for the computation of resistivity of water filled/saturated of rock (R_0)

Determination of Formation water Resistivity
Water samples from gas shales are very scarce because most gas shales are generally at irreducible water saturation. Therefore, calibration to core analysis commonly provides the best means to estimate formation water resistivity, R_w. Computation of $R_t = R_w /(BVW)^m$ can performed with most convergent values of a unique combination of Rw and 'm' through a least square fit in an iterative procedure.
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TOC Estimation Using Δ Log R derived from Logarithm of Resistivity Index
Depth wise TOC (wt%) content in organic rich rocks from ΔlogR is computed using the following empirical equation suggested by Passey et al (1990).

TOC = (ΔlogR) x 10 (2.297 – 0.1688 x LOM)

where ΔlogR separation is linearly related to the TOC content and is a function of level of maturity LOM. LOM is obtained from the vitrinite reflectance or thermal alteration index by using the maturation indicators of Hood et al. (1975). LOM derived from vitrinite reflectance on core samples are indicated

in Figure-3. ΔlogR diagram relating its value to TOC via maturity (LOM) are also shown in this figure. Values ΔlogR are derived with new approach using logarithm of resistivity index.
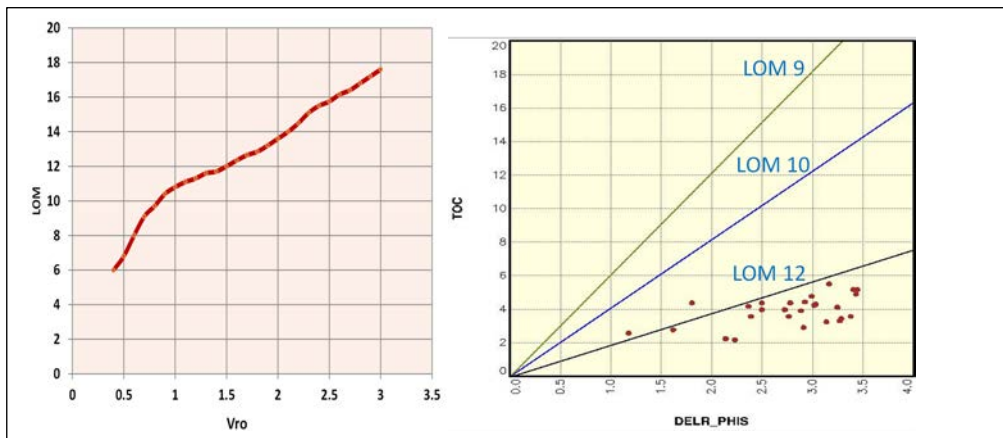

Figure-3 Level of Maturity LOM derived from Vitrinite Reflectance, Vro measurements on core samples and ii. ΔlogR diagram relating its value to TOC via maturity

Validation of TOC with core data

For many wells, log derived TOC values were compared with measured values from cores. In most cases the match is very good and has given us confidence to apply the technique in wells for which core data are available on TOC measurements. Quantitative correlation of log derived and core measured TOC values in a key example well using Neutron, sonic and density porosity logs are shown in two key wells (Figure-4 and 5).
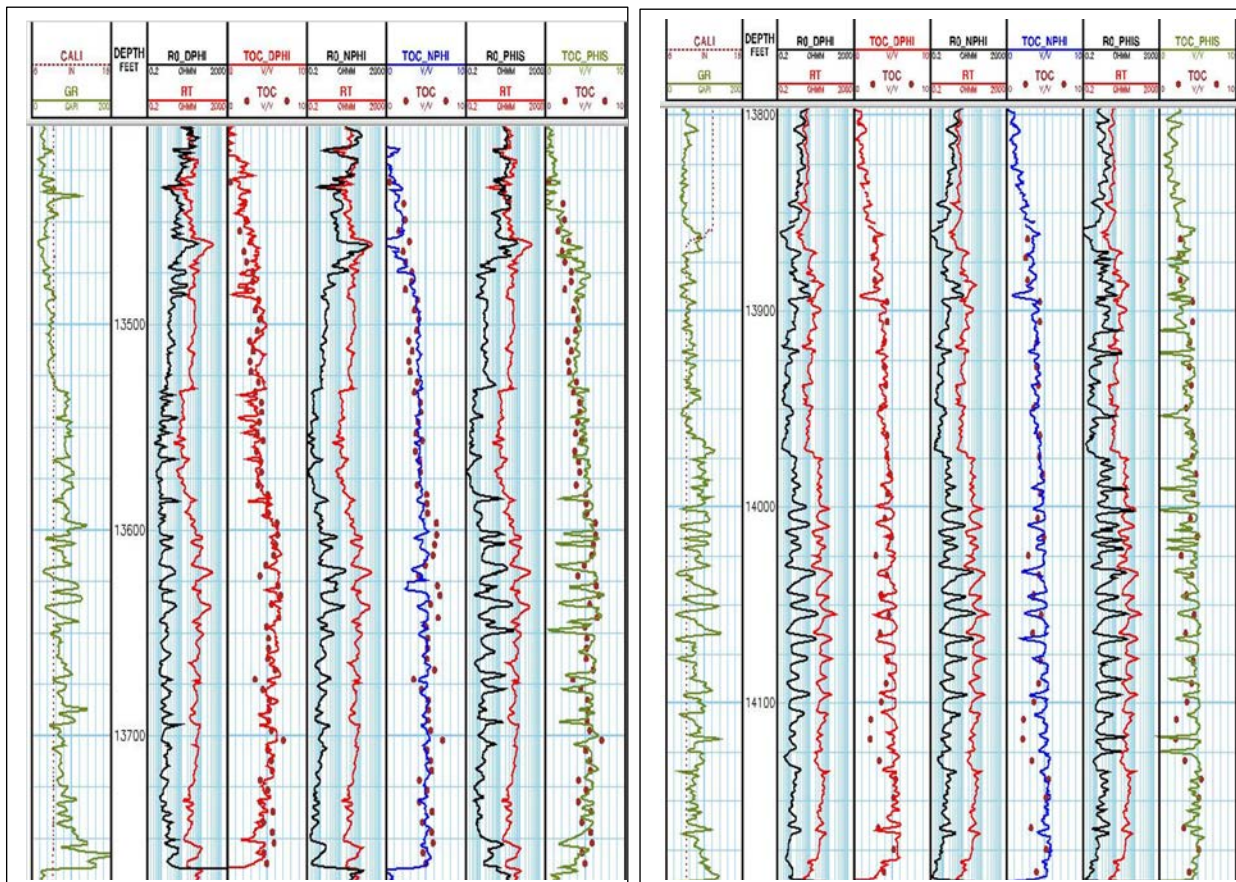

Figure-4 & 5 Comparison of core measured TOC values (Brown dots) with log derived values from density, neutron and sonic logs respectively indicated on track-III, V and VII. R_t and R_0 are indicated with red and black curves respectively on track-II and Gamma ray on track I.

Density, neutron and sonic logs are indicated on track-III, V and VII respectively. Rt and R0 are indicated with red and black curves respectively on second track. Gamma ray log is presented on first track.

Discussions and Conclusions

Many of the problems of interpretation occur in formations where the water is not too salty (< 20,000 ppm NaCl). In high salinity formation waters which water has high salinity, clays have less influence in formation resistivity. Therefore, in reservoirs with very salty formation water, to calculate saturation without correction for clay (Archie equation) would be closer to the real water saturation. Moreover, the amount of water filled porosity (i.e., bulk volume water or BVW) plays a role on the impact of clay conductivity, because with decreasing amount of conductive formation water (i.e., low porosity), the relative impact of clay conductivity to that of the formation water will increase (Passey, et al, 2010). In such case a conventional Archie method can be used for the water saturation estimation with apparent values of 'm' and 'n' at formation water salinity, which compensate for the excess conductivity associated with surface conductance due to clay.

Total organic content (TOC) values range from 2.1 to 7.5 wt.% (mean: 4.5 wt.%). Variations in organic-matter type and organic content are correlative with high-frequency stratigraphic fluctuations. Gas-prone organic material is characteristic of silt-rich, high stand, Eagle Ford intervals. In contrast, more oil- prone organic facies occur preferentially within transgressive Eagle Ford mudstones having excellent source and seal potential.

TOC varies laterally and stratigraphically throughout the study area. However, TOC is higher in the lower Eagle Ford compared to the upper Eagle Ford. The automated technique for calculating TOC shows reasonable results when compared to actual measurements, and can give an easy and quick look to define the petroleum potential of a prospect.

Acknowledgments

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