A New Approach of using Resistivity Index as Separation of Resistivity and Porosity Logs for the Total Organic Carbon in the Eagle Ford Shale

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Abstract

The separation of resistivity and porosity logs in organic rich intervals measured in term of logarithmic resistivity cycle called ΔlogR. This 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 error due to non-availability of reference water base lines in similar lithology.

As increase in porosity in term 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 result in deflection 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 represent the so-called properly scaled resistivity and porosity curves defined by usually ΔlogR technique. The ΔlogR is calculated directly as logarithm of resistivity index dynamically generated through Archie's relation, and is very robust for TOC calculation. It also eliminates the requirement of establishment of water base lines of resistivity and porosity logs in conventional techniques.

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 measurement.

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

Keywords: *- Total Organic Carbon (TOC), Organic Matter (OM), Hydrocarbon, Formation, Well Logging*

INTRODUCTION

Total Organic Carbon describe 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 kerogencontent, 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 variation 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 indicate organic richness. They presented empirical method, the ΔlogR technique, to correlate the total organic carbon (TOC) with ΔlogR and the level oforganic 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 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 unavailability of reference water base lines in similar lithology. Separation between the resistivity and modelled water filled resistivity curves represent 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 techniques.

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 logs methods for determining TOC. Log data include sonic transit- time, density, resistivity and neutron porosity. Rock matrix parameter are determined using core measurement. Calculated and measured TOC show good borehole conditions and quality logs.

GEOLOGIC SETTINGS

The Eagle Ford shale clay is one of the most interesting shale clays 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 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 of Maverick Country in the west, all the way across the state to the eastern country of Burleson, and beyond. But the major productive part of this clay extend from Maverick to Gonzales [Figure-1].

Eagle Ford shale reservoir is quite variable, ranging from siltstones to limestones to true shale.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 volume and clay percentage from core measurement available in the study area of Eagle Ford shale formations of South Texas are indicated in Figure-2

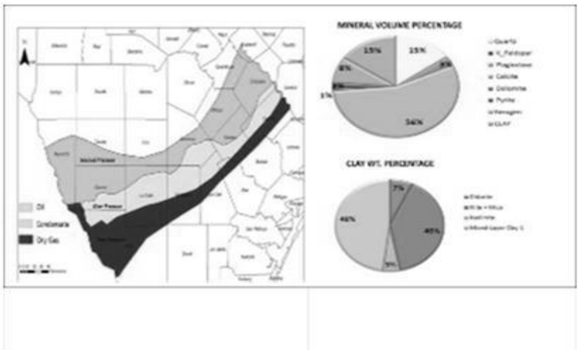


Figure-1 Eagle Ford Shale petroleum window interpretation map

Figure-2 Average minerals and clay volumes percentage in the study area of the Eagle Ford in south Texas

POROSITY AND RESISTIVITY OVERLAY TECHNIQUE AND ITS BASE LINE LIMITATION

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;

$$\Delta logRSonic = log10\left(\frac{R}{Rbaseline}\right) + 0.02 \times (\Delta t - \Delta tbaseline) \quad (1)$$

$$\Delta logRNeutron = log10\left(\frac{R}{Rbaseline}\right) + 4.0 \times (\varphi N - \varphi Nbaseline) \quad (2)$$

$$\Delta logRDensity = log10\left(\frac{R}{Rbaseline}\right) - 2.50 \times (\rho b - \rho bbaseline) \quad (3)$$

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 $\Delta t_{baseline}$, $\varphi_{Nbaseline}$ and $\rho_{bbaseline}$ values at non-source, clay-rich rocks. Δt, φ_N and ρ_b are the sonic, neutron and density log readings. The constant values 0.02, 4.00 and 2.50 are based on the ratio 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 ΔlogR is;

$$TOC = (\Delta logR) \times 10(2.297 - 0.1688 \times LOM) \quad (4)$$

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 ΔlogR and can be measured at each depth increment on the scale of resistivity logs. A single baseline generally cannot be defined for an entire well because of variable lithology and/or changed in formation water salinity. Generally a baseline shift occurs at carbonate/clastic interface and where formation salinities changes drastically. Also, gradual baseline shift are necessary to account for compaction with depth. In these cases, each unit must have separate baseline, and result integrated into the final well profile of calculated TOC values (Passey, et al.(1990)).

NEW APPROCH OF DYNAMIC BASELINE WITH MODELLED WATER FILLED RESISTIVITY

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

$$Ir = Sw\text{-}n = Rt / R_0 = Rt / FRw = \varphi mRt / aRw \quad (5)$$

$$\begin{aligned} Log\ Ir &= Log\ Rt - LogR_0 \\ &= m\ Log\varphi + LogRt - Log\ aRw \\ &= \Delta\ log\ R \quad (6) \end{aligned}$$

Computation of ΔlogR through overlying 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 always be true for the fraction of rock matrix that is not TOC. TOC should be proportional to the nth root of the resistivities R_0 and Rt as in case of water saturation. This forms the basic of new approach, where calculation of,

$$\Delta logR = logIr = log\ (R_t / R_0) = logR_t - logR_0 \quad (7)$$

Takes care of both i.e. increase of resistivity related to mature source rock and the effect of increase porosity is 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 became 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 roc 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 values asR_0 = F R_w = R_w / φ^mResistivity index alone can only be usedfor 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 approachfor the evaluation of TOC in Eagle Ford shales based on ΔlogR values equated with logarithm of resistivity index, LogIr = log(R_t /R_0) = logR_t -logR_0, is calculated in following steps;

I. Porosity determination

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

II. Estimation of Bulk Volume of water

Core measured bulk volumes of gas (BVG) is supposed to be more consistent than conventional gas and water saturations (S_g and S_w) measurement 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 S_g and S_w with core calibrated porosity.

III. Determination of Archie's Exponent of Bulk Volume of Water

Bulk volume of water are related with resistivity measurement through simplified Archie's relation, $BVW^x = R_w / R_t$, where 'm' = 'n' = 'x' and BVW = φS_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 current through surface conductance phenomena associated with clays bring the values of these parameters considerably lower than their default values 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 reservoir i.e. '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).

IV. 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 R_w and 'm' through a least square fit in an iterative procedure.

V. TOC Estimation Using ΔlogR 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).

$$TOC = (\Delta logR) \times 10(2.297 - 0.1688 \times LOM) \quad (8)$$

whereΔlogR 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,

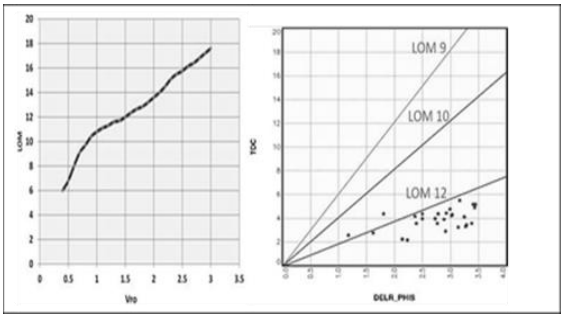
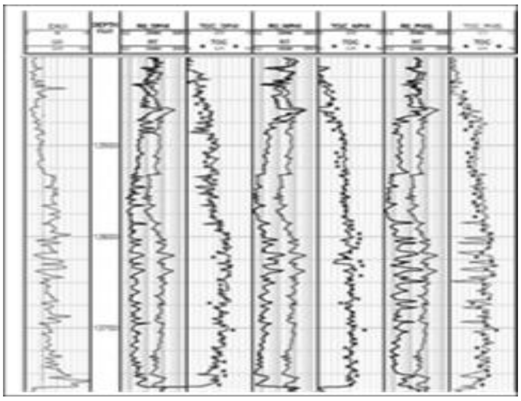


Figure-3 Level of Maturity LOM derived from Vitrinite Reflectance, Vro measurements on core samples and ii. ΔlogR diagram relating its value to TOC via maturity.



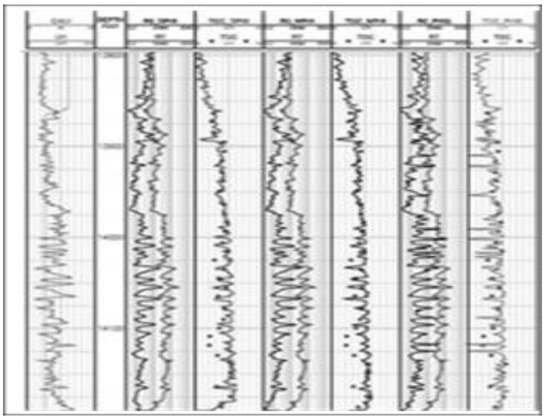


Figure-4 & 5 Comparison of core measured TOC values (Brown dots) with log derived values from density, neutron and sonic logs respectively indicated on track-III, V and VII. Rt and R0 are indicated with red and black curves respectively on track-II and Gamma ray on track I.

Density, neutron and sonic logs are indicated on track-III, V and VII respectively. R_t and R_0 are indicated with red and black curves respectively on second track. Gamma ray log is presented on first track.

DISCUSSION AND CONCLUSION

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, the 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.

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