A PROPOSED SOLUTION TO RESOLVE THE TOTAL AND EFFECTIVE POROSITY APPROACHES TO WATER SATURATION

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Summary

The merits of Total and Effective porosity approaches have always been a source of discussion within the Petrophysical community globally. In general, an operating company adopts a single approach (Total or Effective) in their modelling workflows and ignores the alternative method. This is normally to have a consistent approach across the company so that the end users know what they are receiving into their subsequent workflows.

In the proposed method, both Total and Effective Porosity Methods have been applied. The differences are then used to minimise and improve the resulting porosity and saturation calculations such that the results are mutually comparable. Total Porosity based water saturation equations are dependent on the 'shale/clay' volume and porosity to compensate for the 'shale/clay' bound water resistivity. Effective Porosity is based on water saturation equations on the shale volume and resistivity. The difference is that the Effective Porosity Water Saturation approach is not directly dependent on the 'shale/clay' porosity and can be used as a fitting parameter via the dry clay density (that doesn't exist in-situ) in addition to compensating for the invaded fluid volume.

Examples will be presented in a wider range of geological environments will be discussed.

Adjusted Dual Water Equation To Reconcile Total And Effective Porosity With Their Respective Water Saturations

Summary
In this paper, an adjustment to a common implementation of the Dual Water equation is proposed. Subsequently, the adjusted Dual Water equation is combined with modified Simandoux equation and automated log based parameter selection to populate the formation evaluation. The workflow outlined is then able to deliver well interpretation comparable with experts' manual evaluations by simultaneously solving for water saturation in total and effective porosity regimes. Our study demonstrated that this method has the potential to reduce the well interpretation processing time to only a few minutes per well. Firstly, the proposed adjusted Dual Water equation is presented. Secondly, the methodology of the workflow for automated well interpretation is illustrated, which was applied on a large dataset in the Gulf of Mexico in the clastic reservoir, overburden and underburden sections. Finally, the study results display the automated evaluations' quality, cost and time savings, along with potential application of the improved workflow. Additionally, proposed is the value of adapting this methodology to different types of fields, along with potential challenges and efficiency improvements.

Introduction
Petrophysicists across the energy industries typically evaluate wells and zones on an individually basis using their expert knowledge. The parameterisation of the zones, wells, fields and regions are often only available in specialist software user projects or reports. This expert knowledge is confined within these silos and frequently multiple practitioner subjectivity impacts the evaluation results. Combined with time pressures, limited calibration data and challenges of integrating multiple datasets leads to reduce quality and higher uncertainty in these evaluations. Our study demonstrated that our proposed method has the potential to reduce the well interpretation time to only a few minutes whilst simultaneously reducing subjectivity and uncertainty.

The paper details our study, firstly, the proposed adjusted Dual Water equation is presented. Secondly, the methodology of the workflow for automated well interpretation is illustrated, which was applied on a large dataset in the Gulf of Mexico in clastic reservoir, overburden and underburden sections. Finally, the study results display the automated evaluations' quality, cost and time savings, along with potential application of the improved workflow. Additionally presented is the value of adapting this methodology to different types of fields, along with potential challenges and efficiency improvements.

Proposed Dual Water Equation Modification
The Dual Water equation can be written as (Clavier et al. 1977 and 1984):

$$C_t = \frac{C_w S_{wt}^n}{F_o} + \frac{S_{wt}^{n-1}\left(\beta Q_v - \alpha v_Q Q_v C_w\right)}{F_o}$$

where C_t=Formation Resistivity, C_w=Formation Water Resistivity, S_{wt}=Formation Water Saturation, F_o=Formation Resistivity Factor (Φ_t^{-m}), Φ_t=Total Porosity, m=Archie's cementation exponent, n=Archie's saturation exponent, β=specific conductance of the Na+ compensating ions, Q_v=Cation exchange capacity per unit pore volume, v_q=clay water associated with 1 unit (meq) of clay counterions, α is a unitless factor of the expansion of the clay water layer at low salinities. At salinities greater than about 20kppm, where the thickness of the clay water layer at low salinities, the layer is diffuse and relates it to the Helmholtz thickness. Assuming $\alpha=1$, and substituting $\beta Q_v=v_Q Q_v C_{cw}$:

$$C_t = \frac{C_w S_{wt}^n}{F_o} + \frac{S_{wt}^{n-1} v_Q Q_v (C_{cw} - C_w)}{F_o}$$

A simplified form of the Dual Water equation was proposed by Best et al. (1978):

$$C_t = \frac{C_w S_{wt}^n}{F_o} + \frac{S_{wt}^{n-1} S_{bw}(C_{bw} - C_w)}{F_o}$$

which is often implemented using $S_{bw}=V_{sh}*\Phi_{tsh}/\Phi_t$ and $C_{bw}=C_{sh}*\Phi_{tsh}^{-m}$, respectively the total water saturation of the clay bound water and the conductivity of the clay bound water. However, as illustrated by Spooner (2018), due to the capillary water of the silt fraction of shale, $S_{bw}=V_{sh}*\Phi_{tsh}/\Phi_t$ is greater than the standard definition of $S_{bw}=V_{cl}*\Phi_{tcl}/\Phi_t$ thus needs to be implemented as such. It is also clear from Spooner (2018) that $C_{bw}=C_{sh}*\Phi_{tsh}^{-m}$ is not correct, again due to the silt in shale, not clay alone. Therefore it is proposed that,

$$C_{bw} = CSR\left(\frac{\varnothing_{tsh} - \varnothing_{tslsh}}{\varnothing_{tcl}}\right)^{-m}(C_w - C_{sh})$$

where Φ_{tsilt_sh} is the porosity of the silt in shale and calculated by $(\Phi_{e3}-\Phi_{e4})/V_{sh}$ (Spooner, 2018), CSR is the clay shale ratio. The effective porosity definitions are $\Phi_{e3}=\Phi_t-V_{cl}*\Phi_{tcl}$ and $\Phi_{e4}=\Phi_t-V_{sh}*\Phi_{tsh}$.

Method for Parameter Selection and Automated Workflow

Typically, a Petrophysicist employs either a total or effect porosity model and their respective water saturations are delivered. Worthington (1998) recommended that the total and effective porosity approaches should both be calculated and compared such that the hydrocarbon pore volume, $\Phi*(1-S_w)$, is the same from both approaches i.e. $\Phi_t*(1-S_{wt})=\Phi_e*(1-S_{we})$. A further complication is the aforementioned definitions of effective porosity namely Φ_{e3} and Φ_{e4}, that are from a total porosity, clay based approach and effective porosity, shale based approach respectively. Explicitly, the proposed workflow minimises $\Phi_t*(1-S_{wt})=\Phi_{e4}*(1-S_{we4})$.

To achieve the minimisation, the respective shale and clay volumes, both wet and dry along with the porosities Φ_{e3} and Φ_{e4} must be solved for. At a pragmatic level, petrophysicists can choose one of two paths. The effective porosity approach, Φ_{e4}, where the wet shale point is chosen from a density-neutron crossplot and the corresponding shale resistivity selected for the evaluation using an appropriate effective water saturation equation such as, Modified Simandoux (Bardon et al. 1969 and Simandoux. 1963). Alternatively, the total porosity approach, Φ_{e3} and Φ_t, where total porosity is calculated from the density curve and known grain density with a Φ_t/Q_v relationship used for effective porosity calculation, Φ_{e3}. Total water saturation is derived using an appropriate total water saturation equation such as Dual Water (Clavier et al. 1977 and 1984). The total porosity approach depends on core analysis or prior knowledge being available whilst the effective porosity approach does not but is more subjective though easier to implement. Some commercial software uses an approach where the individual clay types with respective adjustable bound water volume addresses the lack of core data.

The new workflow can simultaneously solve for both total and effective approaches (Calvert 2023). This is achieved by automatic parameter selection through a combination of minimum, maximum, 5%, and 95% percentiles, maximum distance from matrix-water line on the density-neutron cross plot and so on, to obtain the wet shale point by zone, see Figure 1. An iterative solver then finds formation water and shale resistivities, R_w and R_{sh}. Subsequently, a matrix inversion is used to solve for shale volume, mineral volumes, effective and total porosity, Φ_{e4} and Φ_t, with effective water saturation, S_{we4}. Default values are then used for the clay-shale ratio and dry shale density as illustrated by Spooner (2014 and 2018), to calculate the respective dry shale neutron porosity, wet and dry shale porosity along with their clay equivalents. This allows the correct clay bound saturation and conductivity to be obtained, S_{bw} and C_{bw}, and input into the Dual Water equation to estimate the total water saturation, S_{wt}. The hydrocarbon pore volumes are computed and the difference utilised. The whole process is iterated until convergence.

Gulf of Mexico Example

Our study used public datasets from the Gulf of Mexico (GOM) of around 200 wells. Manual interpretation was performed for each well taking several individuals and months to complete. In parallel, the automated workflow detailed above has been developed and refined. Figure 2 shows an example from the GOM dataset of the density-neutron wet shale parameter selection where the green triangle is defined by the quartz, water and wet shale points. In Figure 1, the GOM example well compares the automated and manual interpretation. In the new interpretation, total and effective porosity are different than the manual interpretation due to the silt in shale porosity being accounted correctly for in the new interpretation. Overall, the new workflow interpretation shows that the assumed fixed clay-shale ratio of 50% is not correct but is in fact closer to 40% meaning that there's greater portion of silt and associated capillary bound water. It is also notable that the clay bound water is higher in the new interpretation which is required to ensure the bulk volume of hydrocarbon even when this is zero. All wells were processed with the new interpretation workflow in a single batch in a few hours without the need for user input, saving time, improving quality, reducing cost and evaluation uncertainty.

Conclusions

The new interpretation workflow presented demonstrated that the total and effective porosities and their associated water saturations can be simultaneously solved for when the use of automated parameter selection is incorporated. This assists in reducing user bias and delivering consistent processing outputs for subsequent workflows at less cost and in a shorter timeframe. It is envisioned that a similar approach will be fruitful when applied to carbonate and unconventional formation once the appropriate adjustments are made for lithology, porosity and water saturation formulae.

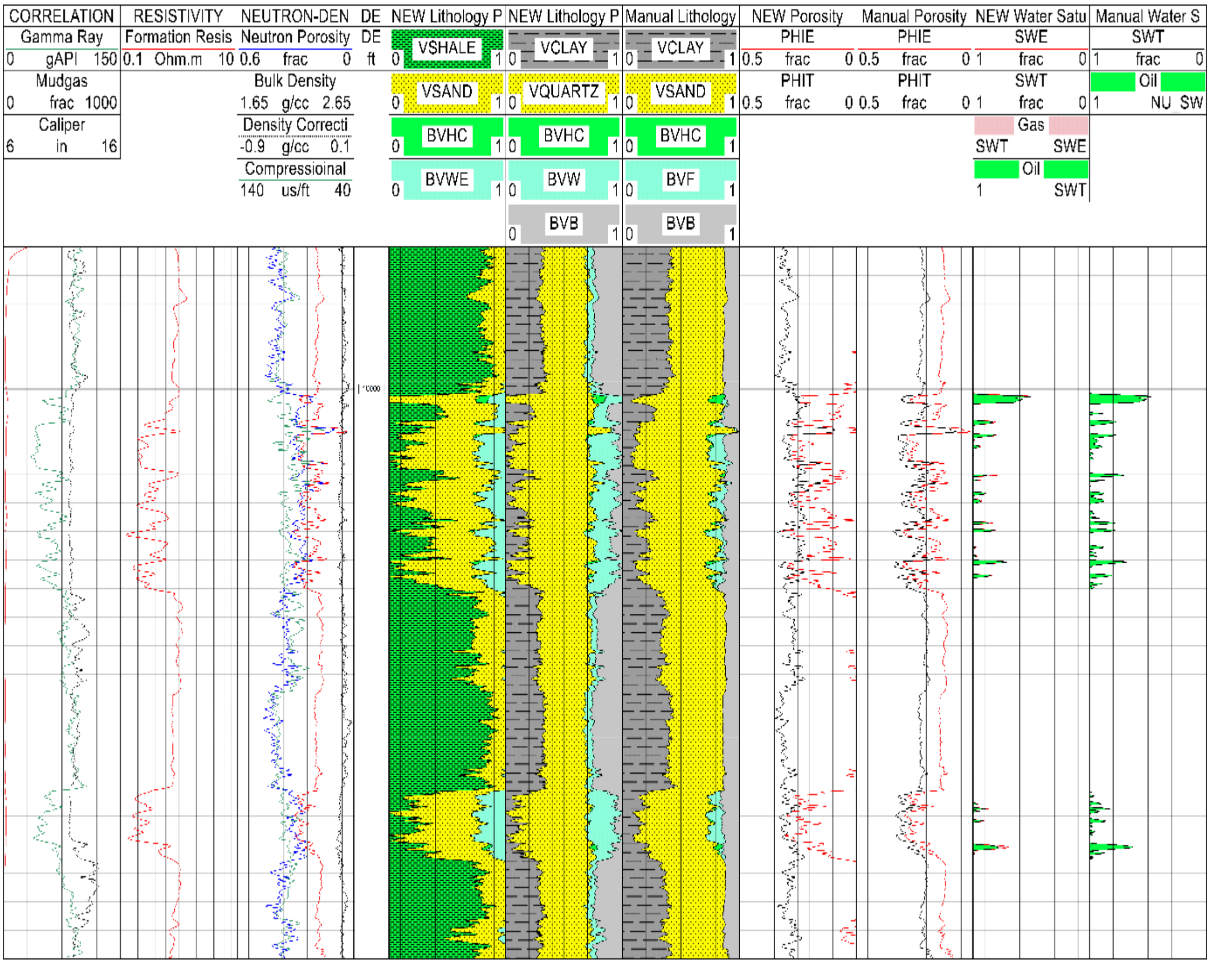

***Figure 1** Gulf of Mexico example automated interpretation compared with manual interpretation. Note that the new interpretation total and effective porosity are different than the manual interpretation due to the silt in shale porosity being accounted for in the new interpretation. Major depth grid lines are 100ft apart.*

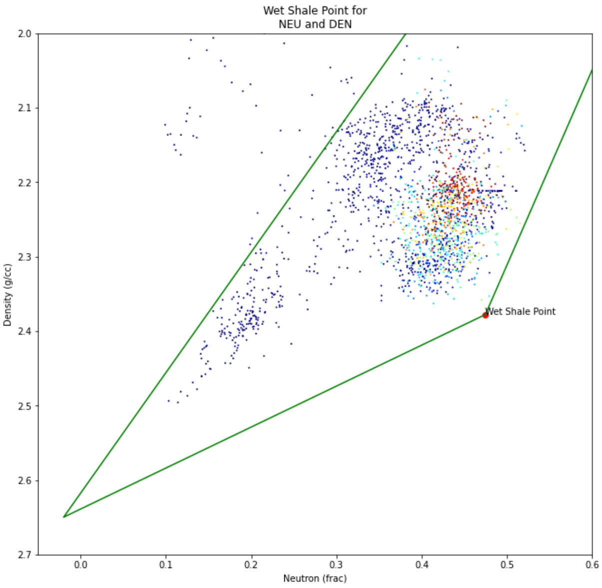

Figure 2 *Automatic wet shale point selection example*

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