P-71

On the Application of Simandoux and Indonesian Shaly Sand Resistivity Interpretation Models in Low and High R_w Regimes

K.C. Hari Kumar, *ONGC*

Summary

Present paper is a re-look at the oil industry practices in making use of the Simandoux and Indonesian shaly sand resistivity interpretation models for formation evaluation. Considering the genesis of Indonesian equation to meet the requirements of fresh water formations of Indonesia, application of Indonesian equation in low connate water resistivity regime is examined in contrast to the water saturation (S_w) output of the Simandoux model. It has been shown that the use of the tortuosity prefactor a less than unity is unwarranted if the Simandoux model is used in evaluating low R_w formations. Indonesian equation at low R_w regime demands truncation for the overshooting results of the model (S_w>1) at S_w =1 and yields relatively high values of S_w where S_w<1. Given the critical role of effective porosity, the significance of non-linear V_{sh} relations which may go neglected when an inappropriate model is used for log evaluation has been pointed out. Discussion has highlighted the need for appropriate core studies to estimate the real quantum shaliness from volume fraction of shale derived from different shale indicators. It is pointed out that the Simandoux model provides ample scope for customization using non-linear V_{sh} relations, R_{sh} and a, m, n values and this may be a better option than using the Indonesian equation which has no physical basis.

Further, it is proposed that the average shale resistivity R_{sh} may be replaced by the R_{shw} defined as the shale resistivity of wet zones where effective porosity is zero. Discussion has been made also of the scenario where effective porosity (ϕ_{eff}) is less than the cut-off porosity (ϕ_{co}) demanded by the respective model and the risk involved in calibrating or fudging the model for customized a, m, n values in such zones. Need for truncation in most cases arise out of incompatibility of ϕ_{eff} with average R_{sh} and ϕ_{co} implicit in the model anatomy. Truncation of S_w in shaly segments where $\phi eff \approx 0$ and calibration of the model in wrong place can be avoided if average R_{sh} can be replaced by R_{shw} i.e. R_{sh} at S_w =1 and $\phi_{eff} \approx 0$. It is shown that by acknowledging the impact of R_{shw} and ϕ_{co} in making the S_w values overshoot at S_w =1 the need for truncation can be avoided.

In the application of workflows for computing water saturation using assumed mineralogy, existing practice to avoid cosmetic truncation is to change the mineralogical composition without substantiating reasons. Application of this mineralogy alteration technique without explicit mention and explanation of the same may lead to unscientific application of arbitrary models such as Indonesian equation to a wide variety of formations to yield arbitrary values of saturation. Discussion as above if understood and applied may help to achieve a more objective application of Saturation models in formation evaluation.

Introduction

The state of the art well log interpretation software seeks to verify the choice and use of particular petrophysical models and assumptions with the re-computing of original curves subject to minimization of the error function. For this purpose, the different tool response equations as functions of fluid, clay and mineralogy are solved under the assumption of specific mineral model to achieve a volumetric picture of the complex lithology. Field observations and laboratory data can be incorporated for zone-wise interactive evaluations using error functions of reconstructed curves. Accuracy of the fluid and mineral interpretation thus appears to be ensured subject to the accuracy of the petrophysical model used in the inversion process. Apart from the limitations such as possibility of errors in the identification of 'earth'model, uncertainties of log errors arising from bad hole, depth-matching and non-linear aspects of tool response equations, method is prone to errors possible from the wrong application of the

CEWELL, ONGC, Baroda-9, 390009. hari_ongc@yahoo.com

petrophysical models such as Simandoux and the Indonesian equations. Present paper is an attempt to look at the application of above models vis-à-vis choice of parameters such as a, m, n, V_{sh} and R_{sh} in formation evaluation.

II. Implications of the Model Anatomy in Formation Evaluation

Simandoux model gave the algorithm for water saturation as:[i]

$$\left(\frac{\phi^m}{aR_w}\right)S_w^2+\left(\frac{V_{sh}}{R_{sh}}\right)S_w-\frac{1}{R_t}=0 \quad \Rightarrow (1)$$

$$S_w=\frac{-\frac{V_{sh}}{R_{sh}}\pm\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2+4\frac{\phi^m}{aR_wR_t}}}{\frac{2\phi^m}{aR_w}} \quad \Rightarrow 1(a)$$

This expression later got modified by the insertion of $(1-V_{sh})$ to give better accommodation for shaliness of the formation and came to be known as the Modified Simandoux equation.

$$\left(\frac{\phi^m}{(1-V_{sh})aR_w}\right)S_w^2+\left(\frac{V_{sh}}{R_{sh}}\right)S_w-\frac{1}{R_t}=0 \quad \Rightarrow 1(b)$$

i.e.

$$S_w=\frac{-\frac{V_{sh}}{R_{sh}}\pm\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2+4\frac{\phi^m}{a(1-V_{sh})R_wR_t}}}{\frac{2\phi^m}{a(1-V_{sh})R_w}} \quad \Rightarrow 1(c)$$

Equation 1(b) can be further generalized to account for dispersed clays by adding an exponent x to the linear V_{sh} term and introducing the variable saturation exponent n instead of 2 as:[ii]

$$\left(\frac{\phi^m}{(1-V_{sh}^x)aR_w}\right)S_w^n+\left(\frac{V_{sh}^x}{R_{sh}}\right)S_w^{\frac{n}{2}}-\frac{1}{R_t}=0 \quad \Rightarrow 1(d)$$

Indonesian equation introduced by Poupon[iii] and Leuveaux was a modification effected on the Simandoux equation to strike a

$$S_w=\frac{\sqrt{\frac{1}{R_t}}}{\left(\frac{V_{sh}^{\left(1-\frac{V_{sh}}{2}\right)}}{\sqrt{R_{sh}}}\right)+\sqrt{\left(\frac{\phi^m}{aR_w}\right)}} \quad \Rightarrow (2)$$

better evaluation of the fresh water formations:

In the application of these models to specific formations, industry follows no axiomatic approach in terms of critical factors such as –

1. Formation water resistivity (R_w) regime for Simandoux and Indonesian models
2. Choice of respective shale function V_{sh} from Gamma Ray, Spontaneous Potential or Sonic Δt index
3. Value of shale resistivity R_{sh}
4. Choice of a, m and n parameters

Use of the latest computing techniques involving inverse modeling offers no immunity to the mistakes possible in respect of the above. As for example, if we consider the formation water resistivity regimes of the aforesaid models, it can be easily understood that expressions 1(a) and 2(a) works fine at low R_w values as both numerator and denominator has the factor ϕ^m/R_w. Values of a less than unity does not impinge on the output of the Simandoux equation drastically because of the balance achieved in between the numerator and denominator. But this model was found to be deficient for relatively higher values of R_w as encountered in Indonesia and hence the Indonesian equation was given shape.

On the other hand, in the Indonesian model, denominator to R_t function has the critical component of formation characteristics viz., $\sqrt{(\phi^m/aR_w)}$ and therefore low values of R_w and values of a less than unity tend to reduce the S_w values significantly. Use of Indonesian equation to evaluate a low R_w regime may necessitate an a value less than unity such as 0.62 simply as a fudging parameter having no physical relevance. When the low R_w formations yield satisfactory S_w values with a =1, m = 2 and n =2 for the Simandoux equation, application of Indonesian equation to such situations with a = 0.62 may look quite odd and result will be a fudged evaluation whose merits shall be open to discussion.

It is worth mentioning here that the Simandoux equation alone has a theoretical basis[iv] as compared to the 'Indonesia', 'Nigeria' or the 'Venezuela' equations originally fudged for specific areas appearing in their names. Results of either of these models can be obtained using the variants of Simandoux equations with the adoption of appropriate shale functions and customization variables such as *a*, *m* and *n*, known respectively as the tortuosity prefactor, cementation exponent and saturation exponent.

Decisive Influence of the Shale Function

Limiting ourselves to a study in contrast of the Simandoux and Indonesian equations the respective shale modules of these expressions are:

$$\frac{V_{sh}^{x}}{R_{sh}} \times S_w^{\frac{n}{2}} \quad \Rightarrow \text{Simandoux} \qquad 1(e)$$

and

$$\left(\frac{V_{sh}^{\left(1-\frac{V_{sh}}{2}\right)}}{\sqrt{R_{sh}}}\right) \quad \Rightarrow \text{Indonesian} \qquad 2\ (a)$$

-where V_{sh} is the linear shale volume as computed from Gamma Ray or Spontaneous Potential etc.

Linear estimation of clay index from GR, SP, N-D cross plot, Density-Sonic cross plot etc in general over estimate V_{sh} if they are not calibrated using laboratory data. Most of the shale indicators (V_{sh}) render V_{sh} =1 in shaly zones which is rarely the case as noted by Hawkins[v] quoting the study of Hower et al.[vi] XRD study of shale cuttings from Gulf Coast formations had shown that average weight percent clay ranged only 55-68% in shale samples taken between 1850-5500 metres. A recent study[vii] on the use of ECS and NMR logs in combinaion to XRD and IR Spectroscopy studies on cores to evaluate the shaly sands has also stressed the need for derivation of 'shaliness' from the volume fraction of shale (V_{sh}). Therefore, non-linear relationships[viii] which have given better accommodation to shale effects as known in literature may also be used to arrive at results matching with field experience.

$$f(V_{sh}) = 0.33\left[2^{2*GRI} - 1\right] = V \Rightarrow \text{for}$$

older/consolidated formations (3)

$$f(V_{sh}) = 0.083\left[2^{3.7*GRI} - 1\right] = V \Rightarrow \text{for}$$

younger/unconsolidated formations 3(a)

Optimum shale values have to be derived from the above non-linear $f(V_{sh})$ value of shale volume or modifications thereof through Clavier, Steiber or any other corrections that may be found necessary for a sound evaluation.
Clavier[ix] et al in 1971 had introduced the formula:

$$V_{sh(optimum)} = 1.7 - \sqrt{3.38 - (V + 0.7)^2} \quad \Rightarrow \quad 3(b)$$

and Steiber[x] (1973) had introduced:

$$V_{sh(optimum)} = \frac{0.5 * V}{1.5 - V} \quad \Rightarrow \quad 3\ (c)$$

Errors associated with the shale indicators tend to increase the apparent shale volume and therefore the minimum value is desirable for use in log evaluation.[xi] Customization of the models to different regions of specific characteristics may demand the use of linear shale functions as such without going into the non-linear modifications and optimizations.

Critical Role of Shale Resistivity R_{sh}

The denominator in the shale terms is resistivity R_{sh} of the shale decided by the log analyst relying on shoulder beds vis-a-vis field experience. Despite the advent of volumetric analysis and inversion modeling to minimize the errors possible, the industry practice is still to assume a common value of R_{sh} for a location or for formations encountered in a well. Practice introduces an element of uncertainty in view of the effective shale content vis-a-vis shale effect and coupled with the uncertainty possible of the formation water resistivity R_w bring in a complexity that can become a source of error in formation evaluation. A glance over the model algorithms under discussion clearly suggests that –

1. It is the balance of the shale term and porosity term that decide the S_w values.

2. The use of effective porosity values tend to minimize the porosity contribution
3. Use of linear V_{sh} volume and assumed R_{sh} of a laminated formation model may introduce an unrealistic shale term into the evaluation process.
4. Factor (2) and (3) above may lead to wrong customization of the model at intervals where effective porosity is nearly zero.

It becomes therefore apparent that even the use of modern computing processes like Expert Log Analysis or Interactive Petrophysics does not offer blanket immunity from mistakes possible in the application of models and the choice of relevant parameters.

III. Axiomatic Approach to Select and Apply the Model

1. Application of Simandoux and Indonesian models only to their respective R_w regimes

Errors in customization and fudging over wet zones with departure from standard conditions of a =1, m =2 and n =2 can be avoided if we stick to the application of models to their respective R_w regimes. Little justification can be adduced in support of the application of Indonesian model to low R_w regimes, given the theoretical foundations of Simandoux model and its variants possible to satisfactorily account for shaliness.

2. Derivation of shale resistivity R_{sh} for the models under the limit S_w =1 shall be of great utility in overriding discrete values possible from the use of same average R_{sh} value across a zone.

Considering the Simandoux model, a cut off value of R_{sh} = R_{shw} for the wet zones can be derived as:

$$R_{shw} = \frac{V_{sh}}{\left(\frac{1}{R_t} - \frac{\phi^m}{aR_w\,(1 - V_{sh})}\right)} \qquad \Rightarrow (4)$$

Higher values of R_{sh} in wet shaly zones shall lead to S_w values higher than unity. Any effort to lower those S_w values by using lower R_{sh} values in the model shall lead to erroneous S_w values at S_w <1.

In the case of the Indonesian equation, R_{shw} can be approximated by putting ϕ_{eff}=0 and S_w =1 and we obtain –

$$R_{shw} = \left(V_{sh}^{\left(1 - \frac{V_{sh}}{2}\right)}\right)^2 R_t \qquad \Rightarrow (5)$$

3. Truncation of the S_w output for cosmetic purpose must be restricted to points where ϕ_{eff} is less than or equal to the cut off porosity (ϕ_{co}) of the model.

In the case of Simandoux model, considering the wet zones, we can rewrite the expressions and solve for porosity ϕ_{co} as:

$$\phi_{co} = \left[\left(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}\right) aR_w\right]^{\frac{1}{m}} \qquad \Rightarrow (6)$$

Now at this maximum of the function, S_w =1, porosity ϕ cannot be less than zero. It becomes therefore obvious that $1/R_t > V_{sh}/R_{sh}$ if the model is to give a genuine S_w =1 output (not truncated) over the wet zones. Further, it can be easily understood that for any formation, the equation (6) defines a porosity cut off (ϕ_{co}) for the minimum value of R_t encountered. Depending upon the value of R_w, magnitude of ϕ_{co} may increase or decrease. Application of the model to the high R_w regime may lead to a higher ϕ_{co} that may exceed the effective porosity over the shaly wet zones. Then the computed S_w will overshoot 1 and fudging of the same to S_w =1 by altering m and n leads to unrealistic values for hydrocarbon bearing zones.

In fact the Simandoux model gives a non-zero S_w output even when ϕ_{eff} = 0 as:

$$S_w = \frac{R_{sh}}{V_{sh}\,R_t} \qquad \Rightarrow (7)$$

Model can be therefore calibrated for choosing the value of R_{sh} at points where effective porosity is zero as R_{sh} = V_{sh}*R_t. Effect of a high R_{sh} value chosen at ϕ_{eff} =0 will be to make the S_w value overshoot in shales. Therefore when effective porosity is close to zero, the output of the Simandoux model is controlled by R_{sh} and not by a, m and

n. Care needs to be taken to see that the model is not calibrated or over-compensated in terms of low R_{sh} in shaly intervals where S_w may be more than unity when an average or common R_{sh} value is used. S_w output of the Simandoux model shall be representative of a, m and n only over intervals where $\phi_{\text{eff}} > 0$. For the Indonesian model ϕ_{co} may be derived as:

$$\phi_{co} = \left[\left(\frac{1}{\sqrt{R_t}} - \left(\frac{V_{sh}^{\left(1-\frac{V_{sh}}{2}\right)}}{\sqrt{R_{sh}}}\right)\right)\sqrt{(aR_w)}\right]^{\frac{1}{m}} \quad \Rightarrow \quad (8)$$

V_{sh}^$(1\text{-}V_{sh}/2)$ will be greater than V_{sh} always and when contrasted with the Simandoux equation, $1/R_t > V_{sh}^2/R_{sh}$ for $\phi > 0$ at $S_w = 1$. V_{sh} being close to V_{sh}^2 when V_{sh} is high with shaly formations, the situation is controlled by higher R_w values of the fresh water formations. When the Indonesian equation is applied to low R_w regime, the effective porosity corresponding to minimum R_t value encountered at which $S_w = 1$ will be low and in hydrocarbon zones the wrongly fudged models shall lead to under estimation of S_w and hydrocarbon reserves shall be inflated.

Discussion as above suggests that the models must be fudged over wet zones having effective porosity equal to or greater than the ϕcut off demanded by the model and not at zones where effective porosity is equal to zero. When contrasted with the Simandoux equation, Indonesian equation facilitates easier fudging by choosing $a < 1$even in shaly zones where $\phi_{\text{eff}} = 0$. Fudging Indonesian model over wet zones of $\phi_{eff} = 0$ or $\phi_{eff} < \phi_{co}$ by taking values of $a < 1$, or m and n lower than 2 shall lead to a wrong estimation of hydrocarbon reserves.

III. Examples

1. Sandstone PX1: Interval CAGG-CAHE

(a) Indonesian Model

Calcareous sandstone with average matrix density of 2.69 gm/cc processed using the complex lithology model and Indonesian equation presents the following details:

Zone parameters: $a = 0.62$, $m = 2$, $n = 2.15$, $R_{sh} = 2.4\Omega$-M, $R_w = 0.11\ \Omega$-M.

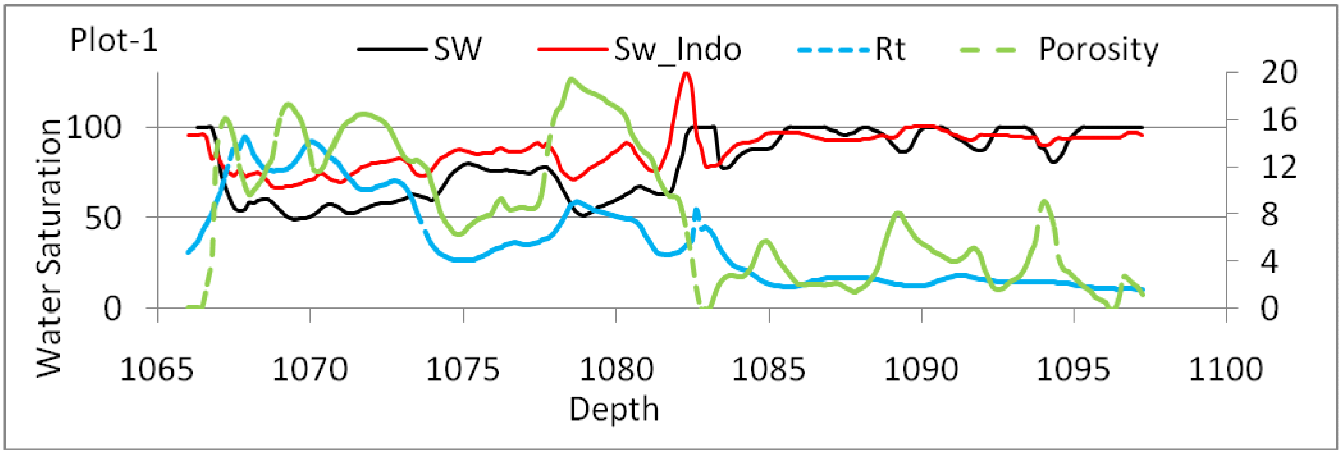
In Table-1 below S_w represents the output of a modern conventional processing software using complex lithology model while S_w_I are the raw values from Indonesian equation. $S_w\_\phi_{co}$ is a hypothetical S_w computed for ϕ_{co} of the model for respective R_t and ϕ. It is apparent from the ϕ_{co} data that the model used here is not applicable at effective porosities less than ϕ_{co} and the zone parameters fixed over wet zones of effective porosity less than the ϕ_{co} is not really representative of the formation. S_w computed as 100% or more are in fact less by more than 10% as this error can be understood to be arising from $a = 0.62$ adopted in the computation by applying the model to zero effective porosity.

S.No.	R_t	V_{sh}	ϕ_{eff}	ρ_b	S_w	S_{w}_I $a = 0.62$	ϕ_{co}	$S_{w}\_\phi_{co}$	S_{w}_I $a = 1$	S_{w}_I $a = 1.2$
1	4.71	0.58	0	2.72	100	105.21	0.037	83.8	105.21	95.6
2	5.16	0.56	0	2.74	100	104.41	0.034	84.31	104.41	95.53
3	5.75	0.53	0	2.73	100	103.57	0.03	84.92	103.57	95.47
4	6.47	0.49	0	2.7	100	103.56	0.027	85.93	103.56	95.95
5	7.28	0.46	0.02	2.67	90.4	90.26	0.024	87.56	93.01	93.93
6	8.13	0.42	0.05	2.66	75.9	75.53	0.022	90.15	80.69	82.51
7	9.03	0.11	0.13	2.69	66.3	65.76	0.042	159.74	80	86.01
8	10.05	0.03	0.15	2.69	59.2	58.87	0.044	203.38	73.9	80.54
9	11.31	0	0.16	2.69	55.4	55.11	0.041	237.52	69.92	76.56
10	12.71	0.01	0.16	2.69	54.2	53.6	0.036	53.6	67.81	74.16
11	13.94	0.05	0.14	2.69	54.7	54.24	0.03	222.46	67.73	73.64
12	13.59	0.1	0.12	2.69	58.4	57.92	0.028	181.07	70.74	76.17
13	14.54	0.15	0.11	2.69	58	57.48	0.022	149.14	68.42	72.89
14	13.96	0.19	0.1	2.69	59.5	59.33	0.02	132.89	69.42	73.45
15	13.17	0.18	0.1	2.7	60.4	59.89	0.022	135.97	70.36	74.57
16	12.45	0.18	0.11	2.71	60.1	59.74	0.024	137.98	70.47	74.8
17	11.97	0.18	0.11	2.71	58.5	58.06	0.026	138.56	68.74	73.08
18	11.73	0.18	0.12	2.7	56	55.61	0.026	139.01	66.1	70.39
19	11.66	0.18	0.13	2.69	53.3	53	0.027	139.4	63.23	67.42
20	11.67	0.12	0.15	2.69	51.1	50.67	0.031	162.35	61.74	66.43
21	11.69	0.06	0.17	2.69	49.8	49.3	0.035	199.24	61.45	66.77

Table-1

On the contrary when we take a =1, the change from a = 0.62 to a =1 has no effect at S_w of effective porosities less than ϕ_{co} but leads to increased S_w at effective porosities higher than ϕ_{co}. It may be noted that for the same S_w of water zones, at Sw ≈ 50%, the increase had been nearly 20% i.e. the model calibrated at $\phi_{eff} < \phi_{co}$ leads to significant over estimation of reserves.

Plot-1 below presents the evaluation along with R_t and ϕ on secondary axis for the complete zone. It is well evident that the S_w profile that make use of a = 0.62 is the result of fudging the model at porosities below the ϕ_{co} defined by equation (8).

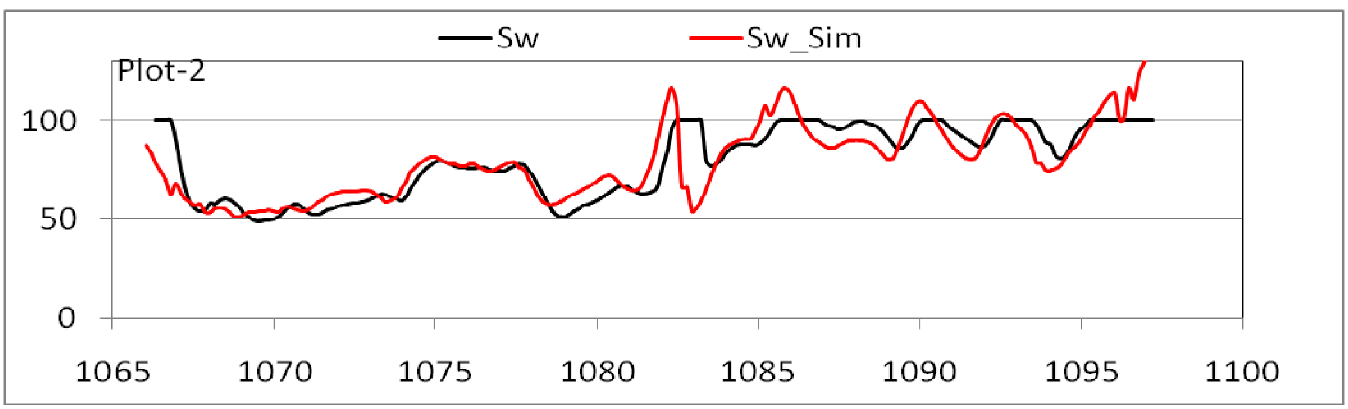


Plot-1

(b) Simandoux Model

Simandoux model is better suited in low R_w (=0.11) regime as above. Plot-2 depicts the original data of conventional complex lithology processing software with zone parameters a = 0.62, m = 2.15, n = 2, R_{sh} =2.4Ω-M, R_w =0.11 Ω-M applied in Indonesian equation in contrast to the output of Simandoux model (S_w_Sim) with parameters a =1, m =2 and n =2. R_{sh} has been taken to be 2.75 in the upper part and 2.0 ΩM in the lower part below 1085.36m so that the cosmetic requirement of avoiding S_w overshoot in ϕeff =0 points can be met with the untruncated output. Choice of average R_{sh} value say 2.5 or 2.75 affects only the maximum of the S_w function at $\phi_{eff} \approx 0$.

Plot-2: Indonesian S_w (a =0.62, m =2.15, n =2) versus Simandoux S_w (a =1, m =2, n =2).



Plot-2

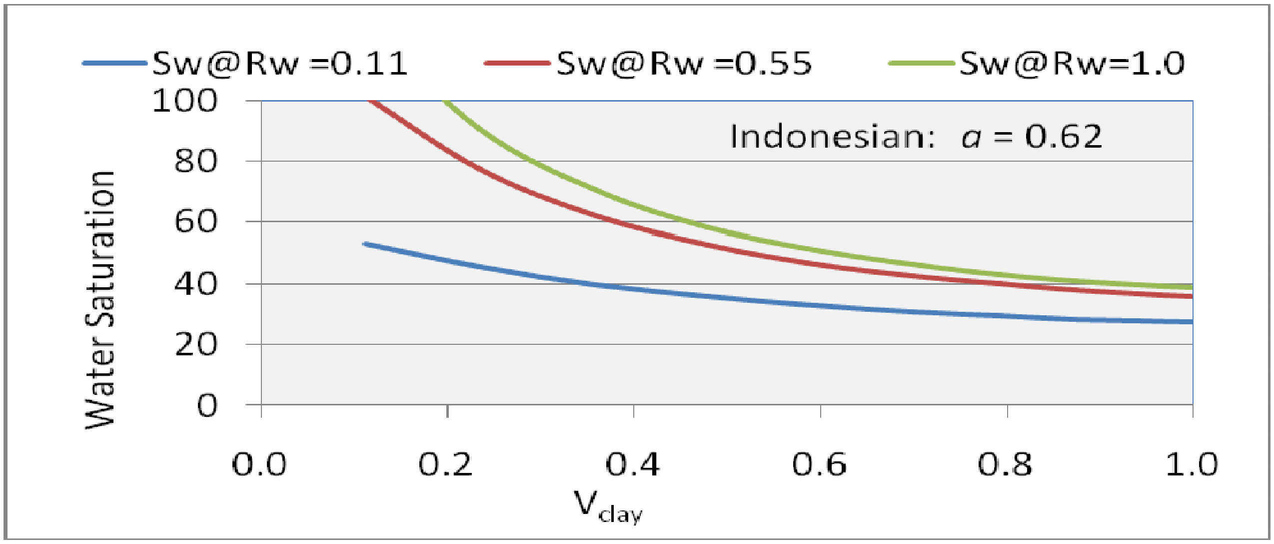
Discussion

When we inadvertently apply the different models to scenarios where it is not applicable, we end up creating a distorted petrophysical characterization. It may be noted that in the above example, the so called tortuosity coefficient *a* has a value of unity with Simandoux model while *a* = 0.62 with Indonesian equation. Plot-2 gives ample demonstration for the fact that the different models can be calibrated only for the respective R_w regime and porosity range as discussed earlier vis-a-vis the R_{sh} value. Table-2 is illustrative of the behavior of the Indonesian and modified Simandoux equation at different R_w values of 0.11, 0.55 amd 1.0 ΩM (arbitrary data under assumed conditions of same R_t and ϕ_{eff}).

R_t	ϕ_{eff}	V_{sh}	Indonesian $a = 0.62$			Modified Simandoux $a = 0.62$			Modified Simandoux $a = 1$		
			$S_w@R_w$ $=0.11$	$S_w@R_w$ $=0.55$	$S_w@R_w$ $=1.0$	$S_w@R_w$ $=0.11$	$S_w@R_w$ $=0.55$	$S_w@R_w$ $=1.0$	$S_w@R_w$ $=0.11$	$S_w@R_w$ $=0.55$	$S_w@R_w$ $=1.0$
10.05	0.15	0.1	53.07	101.39	125.23	45.64	89.66	111.64	55.10	102.87	124.39
10.05	0.15	0.2	45.56	77.12	90.18	39.21	69.29	81.38	44.53	71.88	80.90
10.05	0.15	0.3	39.86	62.09	70.28	33.90	55.29	62.51	36.50	53.55	58.09
10.05	0.15	0.4	35.75	52.65	58.43	29.48	45.37	50.09	30.46	42.28	45.06
10.05	0.15	0.5	32.84	46.58	51.04	25.70	38.07	41.44	25.83	34.92	36.93
10.05	0.15	0.6	30.80	42.58	46.28	22.38	32.46	35.08	22.11	29.78	31.46
10.05	0.15	0.7	29.38	39.90	43.14	19.30	27.91	30.14	18.87	25.88	27.49
10.05	0.15	0.8	28.39	38.10	41.03	16.18	23.89	25.97	15.68	22.51	24.24
10.05	0.15	0.9	27.70	36.88	39.62	12.36	19.49	21.72	11.78	18.58	20.71
10.05	0.15	1.00	27.24	36.06	38.68	0.17	0.38	0.50	0.21	0.48	0.64

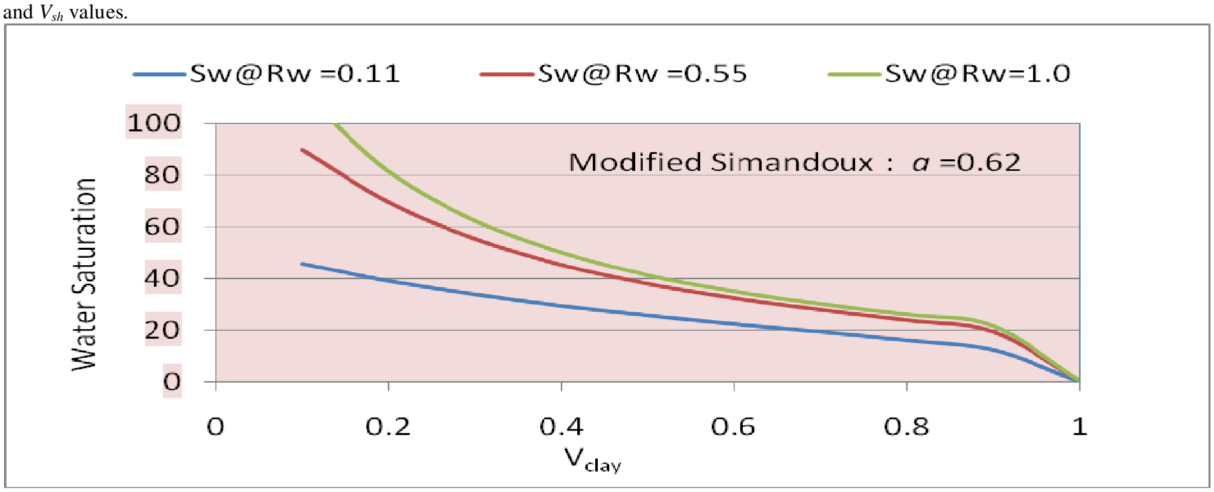
Table-2:

Respective plots are shown below: Plot-3: Indonesian equation for different R_w regimes



Plot -3

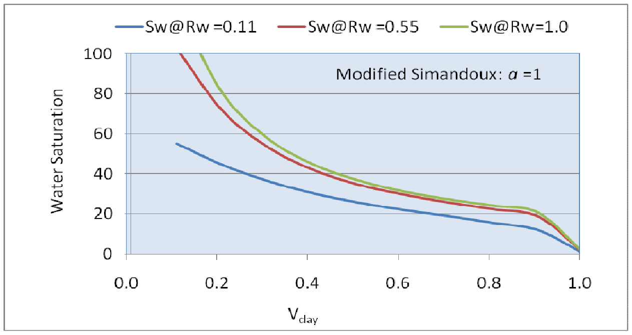
Plot-4: Modified Simandoux equation for different R_w regimes (a = 0.62). Simandoux model shows a different magnitude trends at differing R_w and V_{sh} values.



Plot-4

Modified simandoux at low R_w and a =*1* gives nearly the same trend as Indonesian with a =0.62. Indonesian being applied in wrong R_w regime demands arbitrary modification to the so called tortuosity constant *a*.

Plot-5: Modified Simandoux equation for different R_w regimes (a =1)



Plot-5

Re-processing the same sand with a non-linear Shale Function

It is clear from the above discussion that the formation under discussion could have been correctly evaluated using the Simandoux model with a =1 instead of a =0.62 demanded by the Indonesian equation. R_{sh} used in the above analysis had been 2.4ΩM and the conventional processing had used the gamma-ray index as shale function. Data reprocessed with the R_{shw} defined earlier for Simandoux model and the non-linear shale function using Gamma Ray Index (GRI) viz.,

$$f(V_{sh}) = 0.33[2^{2*GRI} - 1]]$$

is shown in plot-6. Original zone parameters adopted in the region a = 0.62, m = 2.15 and n =2 have been used.

Plot 6

The Simandoux curve *without any cosmetic truncation* has matched well in poor reservoir but has given improved hydrocarbon content of the order of 10% during intervals 1067-1074m and 1078-1080m. Also, as explained earlier, the change of a from 0.62 to 1.0 causes the Simandoux output to match the Indonesian S_w output for a =0.62 with an increase of nearly ten percent. This object had produced 24500M^3/d gas on conventional testing and was the first of its kind in cretaceous sand. Obviously, little field experience must have been there when the sand underwent conventional evaluation as explained earlier with Indonesian equation.

2. Sandstone PX2: Interval CBAA-CBCA

Plot-7 depicts conventional processing in contrast to Simandoux equation without the cosmetic truncation of S_w in shale. Parameters used are R_{sh} = 1.4, a =0.81, m =2 and n =2.

Plot 7

Truncation is visible between S_w_Indo and S_w_Ref curves. Simandoux curve apparently overshoots S_w =1more than that of Indonesian equation because of the use of average R_{sh} selected for Indonesian equation. Plot-8 depicts the same formation evaluation using R_{shw} i.e. R_{sh} of the respective model for S_w =1 and ϕ_{eff} =0.

Plot-8

It can be inferred from the curves that the average S_w of the zone is not affected by the use of R_{shw} and so the net pay for any interval shall not be affected. Truncation can be dispensed with and parameters a, m and n can be adjusted over wet zones without the risk of fudging the model in the wrong place. Further, it is evident that the use of a = 0.81 in fact serves only to make the Indonesian equation output equal to that of modified Simandoux at a =1 when formation water resistivity is low. On the other hand if we argue that the formation characteristics demanded a = 0.81 or 0.62, then the formation evaluation using Simandoux suggests the possibility of increase of reserves to the tune of ten percent. In fact the merging of S_w curves of the Indonesian equation for a less than 1 with that of modified Simandoux for a =1for the low R_w regime suggest the premises of the origin of the Indonesian equation i.e. Indonesian equation is meant for fresh water formations where the Simandoux may be failing.

Conclusions

Present study leaves us with the following conclusions:

1. In low R_w regimes modified Simandoux equation is preferred to Indonesian equation. Also it may be noted that the Simandoux model provides ample scope for customization using non-linear V_{sh} relations, R_{sh} and a, m, n values.
2. Ascribing a < 1 to a formation with Indonesian equation lacks any physical connotation in terms of

tortuosity or any other physical characteristic of the formation.

3. First choice in low R_w regimes must be Simandoux model and its variants so that wrong calibration of other models such as Indonesian in terms of *a, m* and *n* as well as conflict with laboratory studies are avoided.
4. Need for truncation in most cases arise out of incompatibility of ϕ_{eff} with average R_{sh} and ϕ_{co} implicit in the model anatomy. Truncation of S_w in shaly segments where ϕeff ≈ 0 and calibration of the model in wrong place can be avoided if average R_{sh} can be replaced by R_{shw} i.e. R_{sh} at S_w=1 and $\phi_{eff} \approx 0$.
5. Use of Indonesian equation in low R_w regime with a = 0.62 instead of modified Simandoux equation leads to under estimation of reserves by nearly 10%.
6. Present scenario of the use of softwares which are based on inversion modeling suggests that the concept of R_{shw} to replace R_{sh} and the need for incorporating a cutt off (ϕ_{co}) for the effective porosity to avoid irrational cosmetic truncation are yet to gain attention.

References

Simandoux, P., "Dielectric Measurements in Porous Media and Application to Shaly Formation," Revue del'Institut Francais du Petrole, Supplementary Issue, 1963, pp.193-215. (Translated text in SPWLA Reprint Volume Shaly Sand, July 1982).

Summers, John., Schlumberger Interpretation VI, p.43

Poupon, A. and Leveaux, J., "Evaluation of Water Saturation in Shaly Formations," Trans. SPWLA 12th Annual Logging Symposium, 1971, pp.1-2.

Summers, John., Schlumberger Interpretation VI, p.43

Hawkins, Jeff., Integration of Core Data for Calibrated Shaly Sand Log Analysis, SCA Conference 1992, Paper 9201, p.6

Hower, J., Eslinger, E. V., Hower, M. E., and Perry, A. P., 1976, Mechanism of burial metamorphism of argillaceous sediment: 1. Mineralogical and chemical evidence: Geological Society of America Bulletin, v. 87, p. 725- 737.

Airuwaili, Saleh, B., Petrophysical Models and Techniques for Shaly-sand formation evaluation, SPE 88686, 2004.

Dresser Atlas, 1979. Log interpretation charts, Texas, 107 P. Dresser industries, Inc., Houston, pp: 107.

Clavier, C., W.R. Hoyle and D. Meunier, 1971. Quantitative interpretation of TOT logs; part I and 11, Journal of Petroleum Technology, (6): 743-763. Colorado, D.W. Hilichie, Inc.

Steiber, R.G., 1973. "Optimization of shale volumes in open hole.

Ghorab, M., Ramadan Mohmed A.M., Nouh, A.Z., The Relation Between the Shale Origin (Source or non Source) and its Type forAbu Roash Formation at Wadi El- Natrun Area, South of Western Desert, Egypt, Australian Journal of Basic and Applied Sciences, 2(3): 360-371, 2008

Acknowledgements

Author is indebted to the parent organization Oil and Natural Gas Corporation Ltd and also to the Centre of Excellence in Well Logging Technology (CEWELL), Vadodara. Author expresses thankfulness to Mr. Asim Samanta, GM–HOI, which facilitated the present work. Thanks are also due to Mr. RR Tiwari, CG (Wells), Mr. Pradeep Kumar, CG (Wells) , Mr. R. Solomon, CG (Wells), Mr. Pramod Kuμar, DGM (Wells), Mr. T. Chatopadhyaya, CG (Wells) for inspiring discussions.

Certification

Opinions expressed in this paper are of the author only and ONGC owes no responsibility whatsoever.