

Review of Existing Shaly-Sand Models and Introduction of a New Method Based on Dry-Clay Parameters

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ABSTRACT

There are more than a dozen shaly-sand evaluation methods used on a regular basis. The two main groups are based on shale conductivity and cation exchange capacity, respectively. This study shows that they can be linked via the bound-water saturation, which is related both to the shale content and cation exchange capacity.

In this paper, the Archie, modified Simandoux, dual-water, Waxman-Smits, Indonesian, and Juhasz methods are compared, and a novel “difference” method is introduced. The latter, in contrast with all existing “logs only” methods, does not require log readings in adjacent shale beds, provided the clay type can be determined from cuttings, sidewall samples, or cores. For mixed clays X-ray diffraction (XRD) analyses are required to determine the clay types and dry-clay parameters, which in turn are used to calculate the cation exchange capacity.

A field study demonstrated that a judicious selection of input parameters produces water-saturation profiles that almost overlay for most methods. Hence, in this case the

choice of shale and clay parameters was more important than the choice of the evaluation method. The Indonesian method could not be reconciled with other methods, because it is, in contrast with all other methods, not based on a parallel resistor network.

A sensitivity study of input parameters highlighted that for the dual-water method, using logs only, small changes in shale density led to discrepancies of more than 10% in water saturation. It is recommended to use the bound-water conductivity relation given in Clavier’s original dual-water paper. The Waxman-Smits, Juhasz, and the novel difference methods were all, as expected, most sensitive to the cation exchange capacity, and the Juhasz method to the neutron porosity of an adjacent shale bed as well.

If for old wells, sidewall samples, cores or even cuttings are still available to determine the clay type, the new difference method promises to give more accurate hydrocarbon saturations.

INTRODUCTION

This paper takes up the challenge posed by Herrick and Kennedy (2009), to find a shaly-sand method that is derived from generally valid relations, and does not need the log properties of adjacent thick shale beds.

Comparing the results of different shaly-sand evaluation methods is difficult, because computer models are often not transparent, and relations between the parameters used in the various methods are not readily available. There are two groups of evaluation methods based on respectively shale conductivity, C_{sh} , and cation exchange capacity, Q_v . They can be linked via the bound-water saturation, S_b , because the bound water produces in all models the additional conductivity, which together with the pure sand conductivity, gives the total conductivity, C_t .

More than a dozen water-saturation equations and

numerous variations are used on a regular basis. We are aware that our choice of equations is not unique and possibly controversial. One of the controversies is which cementation exponent should be used. In Appendix 1 we prove with data from Waxman and Thomas (1974) and Clavier et al. (1984), that differences between Archie’s cementation exponent m , Waxman-Smits m^* , and dual-water m_o , have only a minor effect on calculated water saturations, S_w . The effect of variations in the saturation exponent is also small, as will be demonstrated later in the field study. These differences will therefore be ignored in the remainder of the paper, facilitating a direct comparison of the various methods.

For a more extensive review readers are referred to Patchett and Herrick (1982), and Worthington (1985). It is noteworthy that all of the fundamental papers had been published by the mid-1980s, and that no widely used alternative method has emerged since.

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Our first objective is to highlight major differences and similarities of the dual-water, modified Simandoux, Waxman-Smits, Indonesian, and Juhasz methods, and to come up with a new method that avoids the major shortcomings of the existing ones. We accomplished this by combining the responses of the neutron and density tools in the total-porosity system. This gives an estimate of the dry-clay volume, and allowed us to determine the cation exchange capacity for the Waxman-Smits method.

The second objective is to quantify the effect of variations of input parameters in the various methods, and this was achieved by a sensitivity study of a field example. However, we first had to relate the bound-water saturation used in the dual-water method, the cation exchange capacity used in the Waxman-Smits and Juhasz methods, and the shale volume used in the Simandoux and Indonesian methods. This is carried out in the next section.

All existing “logs only” methods assume that only one clay type is present and that the properties of the clay in adjacent shale beds are the same as in the reservoir. In contrast, the new difference method does not use log readings from adjacent shale beds, but XRD analysis on core or sidewall samples to determine clay type(s).

BOUND WATER

Bound-water saturation, S_b , is related to total porosity, ϕ_t , effective porosity, ϕ_{eff} and shale content, V_{sh} . These volume fractions are defined in Fig. 1 (Shaly-Sand Model).

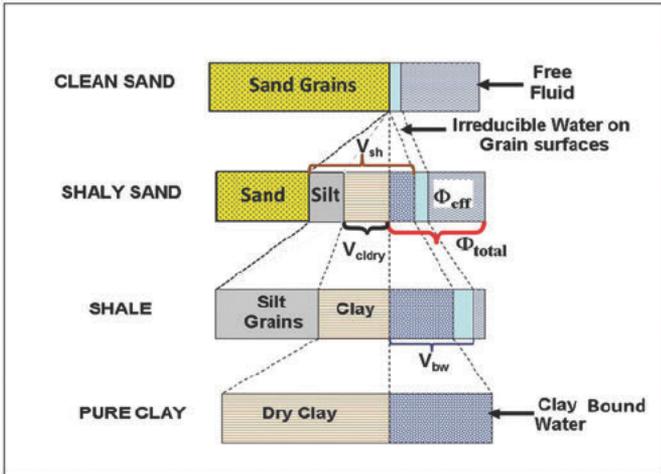


Fig. 1—Shaly-Sand Model.

$$S_b = (\phi_t - \phi_{eff}) / \phi_t \quad (1)$$

$$S_b = V_{sh} \phi_{tsh} / \phi_t, \text{ with} \quad (2)$$

$$\phi_{eff} = \phi_t - V_{sh} \phi_{tsh} \quad (3)$$

where ϕ_{tsh} is defined as the total porosity in a 100% shale layer adjacent to the shaly-sand reservoir, preferably based on the density log. The shale content, V_{sh} can be derived in many ways, but is usually based on either the gamma-ray log or the separation of the density- and neutron-log porosities, both corrected for hydrocarbon effects. Equation 1 is always valid, but Eq. 3 is, strictly speaking, only valid if the shale properties of the adjacent shale layers are the same as the shale in the productive intervals. The latter is a good assumption for structural and laminar shales, but usually not for dispersed shale. Hill et al. (1979), and Juhasz (1979) related ϕ_{eff} to ϕ_t and cation exchange capacity, Q_v :

$$\phi_{eff} = \phi_t \left[1 - \left\{ \frac{0.084}{\sqrt{C_0}} + 0.22 \right\} \frac{Q_v}{\rho_{CBW}} \right] \quad (4)$$

in which the clay-bound water density ρ_{CBW} (g/ml) is commonly assumed to be 1.0 (Juhasz, 1979). Salinity, C_0 , expressed in meq/l NaCl, is fixed by the formation water salinity:

$$C_0 [\text{meq/l}] = 0.017 \text{ salinity} [\text{ppm NaCl eq.}] \quad (5)$$

We derived the relation between bound-water saturation, S_b , and cation exchange capacity, Q_v by subtracting ϕ_{eff} from both sides of Eq. 4, and dividing by $-\phi_t$, which yields:

$$\frac{\phi_t - \phi_{eff}}{\phi_t} = \left[\frac{0.084}{\sqrt{C_0}} + 0.22 \right] \frac{Q_v}{\rho_{CBW}} \quad (6)$$

According to Eq. 1 the left-hand side is the bound-water saturation, S_b . Rearranging Eq. 6 produces the functional relation between bound water and cation exchange capacity, summarized as:

$$Q_v = \frac{\phi_t - \phi_{eff}}{\phi_t (0.22 + 0.084 / \sqrt{C_0})} \quad \text{or} \quad (7)$$

$$Q_v = \frac{S_b}{(0.22 + 0.084 / \sqrt{C_0})}$$

Using Eq. 2 for the bound-water saturation, S_b , produces:

$$Q_v = \frac{V_{sh} \phi_{tsh}}{(0.22 + 0.084 / \sqrt{C_0}) \phi_t} \quad (8)$$

Although this relation allows the calculation of Q_v and its entry in the Waxman-Smits model, its validity is questionable due to the assumption that shale in the reservoir has the same properties as in an adjacent bed. This is problematic when the clay is diagenetic and not depositional, such as for altered feldspar.

WAXMAN-SMITS (W-S) METHOD (1968)

Waxman and Smits (1968) introduced the use of the cation exchange capacity Q_v to quantify the shale conductivity. For this and all other methods we will use the convention that the pure sand contribution, $S_w^n C_w \phi_t^m$, to the total formation conductivity, C_f , is followed by the shale contribution:

$$C_f = S_w^n C_w \phi_t^m + B Q_v \phi_t^m S_w^{n-1} \quad (9)$$

The shale contribution in this case is proportional to both Q_v in meq/ml, and the equivalent cation conductance, B (mho.ml/(meq.m)). The equivalent cation conductance is only dependent on salinity and temperature (Thomas, 1976). If cation exchange capacities are not measured on core, nor related to the porosity, Q_v can be estimated using Eq. 8, although to our knowledge that has not been done in the past. We used Eq. 8 to estimate Q_v in our field study with excellent results. If the saturation exponent, n , is assumed to be 2.0, Eq. 9 reduces to a quadratic equation in S_w .

Strictly speaking, the Waxman-Smits model is not, as assumed by many authors, a parallel conductor model, because in that case the factor S_w^{n-1} would be absent in the shale-conductivity term. We will see this factor again in both the dual-water and modified Simandoux equations and its presence implies that free water should be present to accommodate the conductivity contribution of isolated clay volumes.

JUHASZ METHOD (1979)

This method is equivalent to the Waxman-Smits model, but offers a practical way to determine Q_v , based on the fundamental relation (Juhasz, 1979, Eq. 5):

$$Q_v = V_{cldry} \rho_{cldry} CEC_{cl} / \phi_t \quad (10)$$

where CEC_{cl} is the cation exchange capacity in meq/g, and ρ_{cldry} the density of dry clay in g/cm³. The dry-clay volume, V_{cldry} , is estimated from the difference of the neutron ϕ_N and density porosity ϕ_D . Juhasz (1979) recommends the use of ϕ_D as a first approximation of ϕ_t corrected for hydrocarbon effects.

$$Q_{v, Juhasz} = \frac{\phi_N - \phi_D}{\phi_{Nsh} \cdot \phi_t} \rho_{cldry} CEC_{cl} \quad (11)$$

The great advantage of the Juhasz method is that actual dry-clay parameters can be used if the clay type is determined on (sidewall) cores, or even from cuttings. However the assumption that ϕ_{Nsh} the apparent neutron porosity of 100% shale can be derived from adjacent shale layers suffers from

the same shortcomings as the use of the total shale porosity, ϕ_{tsh} , in Eq. 2.

DIFFERENCE METHOD

To avoid the use of log readings in adjacent shale beds, we came up with an alternative method to estimate the dry clay volume V_{cldry} that is required in Eq. 10. If the hydrogen index of the fluid is 1.0, and the density ϕ_D and neutron ϕ_N porosities are corrected for lithology and hydrocarbon effects, we can write:

$$\phi_N = V_{sh} \phi_{Nsh} + \phi_{eff} \quad (12)$$

$$\phi_D = V_{sh} \phi_{Dsh} + \phi_{eff} \quad (13)$$

where ϕ_{Dsh} and ϕ_{Nsh} are the density- and neutron-porosity readings in 100% shale on a quartz scale. The shale terms include all bound water. Hence, the balance of the fluid constitutes the effective porosity ϕ_{eff} . The density ϕ_D and neutron ϕ_N log responses can also be written as:

$$\phi_N = V_{cldry} \phi_{Ncldry} + \phi_t \quad (14)$$

$$\phi_D = V_{cldry} \phi_{Dcldry} + \phi_t \quad (15)$$

where ϕ_{Dcldry} and ϕ_{Ncldry} are the density- and neutron-porosity readings for 100% dry clay. The dry clay terms do not include any bound water. Therefore, all fluid is concentrated in the total porosity, ϕ_t . Taking the differences between Eqs. 12 and 13 and Eqs. 14 and 15 yields:

$$\phi_N - \phi_D = V_{sh} (\phi_{Nsh} - \phi_{Dsh}) \quad (16)$$

$$\phi_N - \phi_D = V_{cldry} (\phi_{Ncldry} - \phi_{Dcldry}) \quad (17)$$

or

$$V_{sh} = \frac{\phi_N - \phi_D}{\phi_{Nsh} - \phi_{Dsh}} \quad (18)$$

and

$$V_{cldry} = \frac{\phi_N - \phi_D}{\phi_{Ncldry} - \phi_{Dcldry}} \quad (19)$$

Equation 18 is the familiar shale volume estimate.

Using the value for the dry-clay volume, V_{cldry} , from Eq. 19 and entering the same in Eq. 10 yields:

$$Q_{v, dif} = \frac{\phi_N - \phi_D}{(\phi_{Ncldry} - \phi_{Dcldry}) \phi_t} \rho_{cldry} CEC_{cl} \quad (20)$$

where ϕ_t is again estimated from ϕ_D corrected for

hydrocarbon effects. This equation allows us to use actual dry-clay parameters that are available in the literature and log-interpretation charts, instead of log readings over adjacent thick shale beds. The difference $\phi_{Ncldry} - \phi_{Dcldry}$ can be calculated when the clay type or clay-type mixture is known. The range of this difference for various clays is surprisingly small; between 26 and 42%, as shown in Appendix 2. Hence, the dominant factor is appropriately CEC_{cl} .

By taking the differences in Eqs. 16 and 17, any debate on what exactly is included in effective and total porosities is not relevant, because they are eliminated. Shale and dry-clay volumes can be related by eliminating $\phi_N - \phi_D$ from Eqs. 18 and 19:

$$V_{cldry} = V_{sh} \frac{(\phi_{Nsh} - \phi_{Dsh})}{(\phi_{Ncldry} - \phi_{Dcldry})} \quad (21)$$

A typical separation of the apparent density and neutron porosities in shale is 15%. This ratio varies in that case over a rather narrow range from 0.36 to 0.59 for the different clay types.

DUAL-WATER METHOD (1984)

The dual-water method was introduced by Clavier et al. (1984). The free water with conductivity C_w , and bound water with conductivity C_b form a series of conductors:

$$C_t = S_w^n \phi_t^m C_w + S_w^{n-1} S_b \phi_t^m (C_b - C_w) \quad (22)$$

For “logs only” evaluations the bound-water saturation, S_b , can be derived using Eq. 2. A correction equal to $S_w^{n-1} S_b \phi_t^m C_w$ is made, because the bound water, S_b , is part of total water saturation, S_w , but does not have the same conductivity C_w . Assuming $m = 2$, C_b can be estimated from logs using the Archie equation:

$$C_b = C_{sh} / \phi_{ish}^2 \quad (23)$$

Shale conductivity, C_{sh} , and shale porosity, ϕ_{ish} , are customarily derived from an adjacent thick 100% shale layer. The dual-water model is attractive, because all parameters can be derived from logs, which is usually not possible for the Waxman-Smiths method. However it also has severe restrictions for “logs only” evaluations, because C_b is dependent on the square of the shale porosity ϕ_{ish} , which if derived from the density log, is strongly dependent on the apparent shale density ρ_{sh} . For $n = 2$ Eq. 22 is a quadratic equation in S_w .

INDONESIAN METHOD (1971)

This method introduced by Poupon (1971), is in contrast to all other models, not based on the parallel resistors (series

conductors) concept, and therefore lacks a firm physical basis. Moreover, in the original form clay resistivities and volumes were used instead of shale parameters:

$$\sqrt{C_t} = \left(\sqrt{C_{sh}} V_{sh}^{(1-V_{sh}/2)} + \sqrt{C_w} \phi^{m/2} \right) S_w^{n/2} \quad (24)$$

MODIFIED SIMANDOUX METHOD (1971)

This method is an adaptation by Poupon et al. (1971) of the original Simandoux (1963) model, and predates bound water and CEC models. It accounts for the additional conductivity by adding the product $V_{sh} C_{sh}$ to the Archie pure sand conductivity:

$$C_t = S_w^2 \phi^m C_w + V_{sh} C_{sh} S_w \quad (25)$$

Porosity, ϕ , should in theory be the effective porosity, and S_w , the effective water saturation. However, in our experience, the method works best for total porosities and total water saturations. This was confirmed by the field example. The addition of S_w in the second term is one of the modifications to Simandoux’s pure parallel resistors model. It implies that for low shale contents, shale needs free water to contribute to the total conductivity.

COMPARISON OF METHODS

If we replace V_{sh} in the Simandoux model by the relation for S_b (Eq. 2), ϕ_t by ϕ_{ish} , assume $n = 2$, and insert $C_{sh} = \phi_{ish}^2 C_b$ we find:

$$S_w^2 \phi_t^m C_w + S_w S_b \phi_t^m C_b - C_t = 0 \quad (26)$$

Substituting in the Waxman-Smiths model (Eq. 9) the relation between S_b and Q_v (Eq. 7) yields:

$$S_w^2 \phi_t^m C_w + \frac{S_w S_b \phi_t^m B}{0.22 + .084 \sqrt{C_0}} - C_t = 0 \quad (27)$$

In which $B/(0.22 + 0.084\sqrt{C_0})$ is the bound-water conductivity, C_b , and this makes Eq. 27 identical to Eq. 26. Rearranging the dual-water model (Eq. 22) produces:

$$S_w^2 \phi_t^m C_w + S_w S_b \phi_t^m C_b - S_w S_b \phi_t^m C_w - C_t = 0 \quad (28)$$

where the term $S_w S_b \phi_t^m C_w$ is usually small, in which case Eq. 28 is almost the same as Eq. 26. By taking in the Indonesian equation (Eq. 24) the square of both sides and $n = 2$ we find:

$$S_w^2 \phi^m C_w + C_{sh} V_{sh}^{(2-V_{sh})} S_w^2 + 2 \sqrt{C_{sh} C_w} \phi^{m/2} V_{sh}^{(1-V_{sh}/2)} S_w^2 - C_t = 0 \quad (29)$$

In Eq. 29, we recognize, with relief, the original Archie contribution $S_w^2 C_w \phi^m$, but the last cross term prevents a meaningful comparison with other models.

The foregoing proves that all methods, with the exception of the Indonesian equation, are similar, which is not surprising, because all are based on the parallel resistors network. The main differences are the way the bound-water saturation is estimated, either from shale resistivity, or from CEC. The severe shortcoming of using the shale resistivity of an adjacent bed is that the shale type and distribution in this bed can be quite different from the shale in the pores of the reservoir.

FIELD EXAMPLE

A composite log of the field case is shown in Fig. 2. The interval is a shaly sand of Jurassic age. The evaluation parameters are listed in Table 1. The presence of a water zone allowed us to pinpoint the water resistivity, R_w , and hence the salinity. The salinity and formation temperature fix the equivalent cation conductance, B , and salinity, C_0 expressed in meq/ml. These two parameters can therefore not be varied independently. That leaves as independent input parameters the gamma-ray log readings in clean and 100% shale (GR_{clean} and GR_{shale}), the shale conductivity, C_{sh} , and the density- and neutron-log shale porosities, ϕ_{Dsh} and ϕ_{Nsh} , respectively. The latter were derived from the shale layer on top of the reservoir, because the shale layer within the reservoir is badly washed out. Cation exchange capacity, Q_v , values were calculated for each layer using the appropriate Waxman-Smits, Juhasz, and difference equations (Eqs. 8, 11, and 20). The bound-water conductivity, C_b , was calculated using Eq. 23. In the base case, dry-clay parameters for illite were used (see Appendix 2). The parameters that gave the best agreement between the various methods are listed in Table 2.

DISCUSSION

Results are plotted in Fig. 3. Excellent agreement was obtained between the CEC-based methods: Juhasz, Waxman-Smits, and difference (plotted in Track 2); and with the total-porosity-based methods: dual water, and Simandoux (plotted in Track 3). The Archie base case is plotted in both tracks for comparison. The water saturation scale is 0 to 1.2, to show the variation around 100% in water zones. The results of the Indonesian method (plotted in Track 3) could not be reconciled with other methods. This is also illustrated by the step in the average water saturations in the sensitivity plot (Fig. 4). Even a wide variation in input parameters could not bring the average saturation to the level of the other methods. Steve Cuddy (personal communication, 2011) demonstrated that agreement with the Indonesian method can be attained

assuming that all layers have shale contents of more than 30%. However, equivalent values for GR_{clean} and GR_{shale} would be 0 and 100 API, respectively, which produces implausibly low water saturations for the other methods.

Saturation profiles based on different clay types and the Difference method are plotted in track 4. As expected the reduction from the Archie saturations is small for kaolinite and chlorite with low CEC's (see Appendix 2), followed by illite, which reduces the saturation by some 8%. Smectite reduces the saturations by another 8%, but also produces unrealistically low water saturations of around 5% in the main hydrocarbon bearing zone.

If the clay consists of a combination of types the difference method cannot be applied, without additional information. However, all "logs only" methods suffer from the same shortcoming, and this can only be resolved if CEC and XRD measurements are carried out on core samples. The Difference method has the distinct advantage that clay

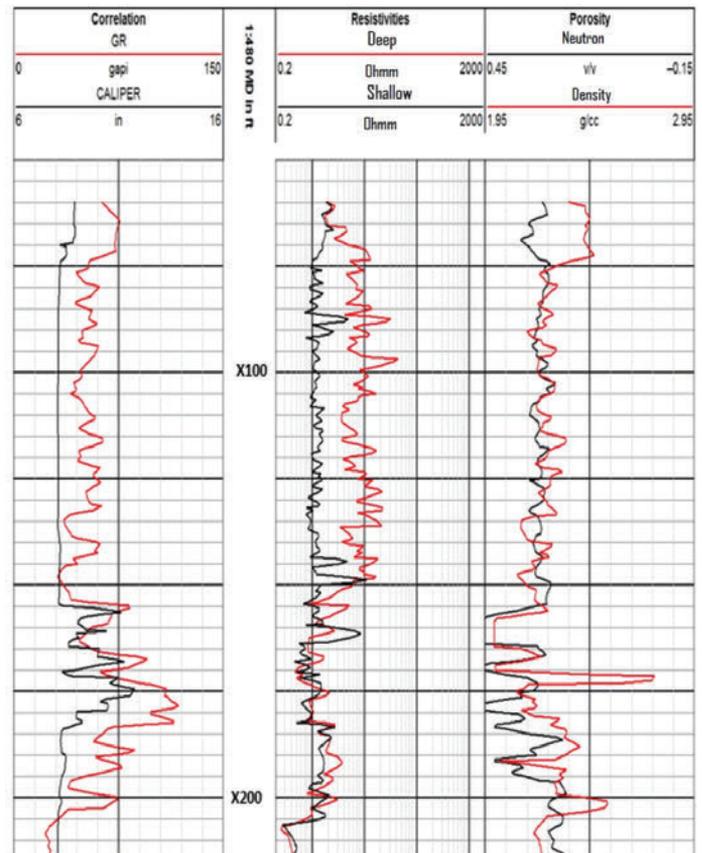


Fig. 2—Field-study well logs.

Table 1—Shaly-Sand Parameters for the Base-Case Log Evaluation

Base case	Best fit	Units	Input parameter name
R_{wa}	0.035	Ω -m	Formation-water resistivity
R_{sh}	2.5	Ω -m	Shale resistivity
R_b	0.019	Ω -m	Bound-water resistivity
ρ_{ma}	2.65	g/cm^3	Matrix density
ρ_n	1.0	g/cm^3	Formation-water density
ρ_{sh}	2.52	g/cm^3	Density 100% shale
ρ_{clay_dry}	2.68	g/cm^3	Dry-clay density
ϕ_{Nsh}	35	%	Apparent neutron-porosity shale
ϕ_{Dsh}	8	%	Apparent density-porosity shale
ϕ_{Nclay_dry}	25	%	Neutron porosity 100% dry clay
T	150	$^{\circ}C$	Reservoir temperature
CEC	0.25	meq/g	Cation exchange capacity
C_0	0.14	meq/ml	Water salinity
$m = n$	2	d.l.	Cementation / saturation exponents
GR_{clean}	20	API	Gamma ray 0% shale
GR_{shale}	110	API	Gamma ray 100% shale

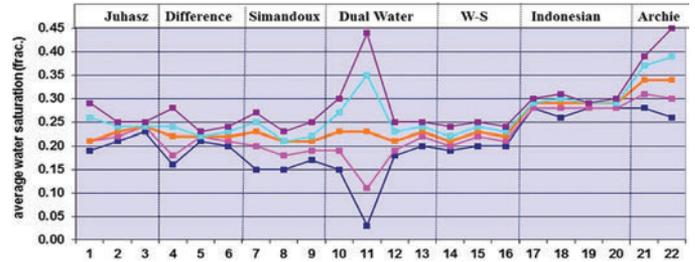


Fig. 4—Sensitivity of various models to input parameter variations numbered 1 to 22 (below).

Method	Parameters varied :
Juhasz	1-CEC, 2-neutron porosity shale, 3-dry shale density
Difference	4-CEC, 5-Neutron porosity dry clay, 6-dry clay density
Simandoux	7-shale resistivity R_{sh} , 8-GR 100% shale, 9-GR clean sand
Dual Water	10- R_{sh} , 11-shale density, 12-GR shale, 13-GR clean sand
Waxman-Smits	14-CEC, 15-GR 100% shale, 16-GR clean sand
Indonesian	17- R_{sh} , 18- Humble "a", 19-GR 100% shale, 20-GR clean
Archie	21-saturation exponent "n", cementation exponent "m"

types can still be derived from cuttings and (sidewall) core samples of old wells, allowing a more accurate reevaluation of “brown” fields.

Sensitivity analysis

A sensitivity study was carried out in which crucial parameters were varied over wide ranges (shale resistivity, R_{sh} , density and neutron porosities of shale, ϕ_{Dsh} and ϕ_{Nsh} , respectively, cation exchange capacity, CEC_{cl} , dry-clay neutron porosity, ϕ_{Ncldry} , shale and dry-clay densities, ρ_{shale} and ρ_{cldry} , respectively). The data ranges and corresponding average water saturations over the evaluation interval are listed in Table 2 and plotted in Fig. 4.

The cation exchange capacity, CEC_{cl} is the most sensitive parameter for the Juhasz and difference methods. The apparent neutron porosity of an adjacent shale layer ϕ_{Nsh} is also critical for the Juhasz method. For the difference method there is some effect of the dry-clay parameters. However, these parameters are much better defined than the wet-shale parameters, such as shale density ρ_{sh} , and shale resistivity R_{sh} , which can vary by a factor 2 to 3.

The Simandoux method using total porosities is obviously sensitive to variations in shale resistivity, while the dual-water method proved to be very sensitive to variations of the shale density, when the bound-water conductivity, C_b , is derived from logs. This is due to the quadratic relation between C_b and shale porosity. Varying shale density ρ_{sh} from 2.45 to 2.6 g/cm^3 corresponds to a range in C_b of 25 to 430 mho/m (S/m); C_b values in excess of 100 mho/m (S/m) are evidently unrealistic. It is therefore recommended to use the relation between bound-water conductivity and temperature shown by Clavier et al. (1984, Fig. 14). The bound-water resistivity, R_b , shale resistivity, R_{sh} , shale

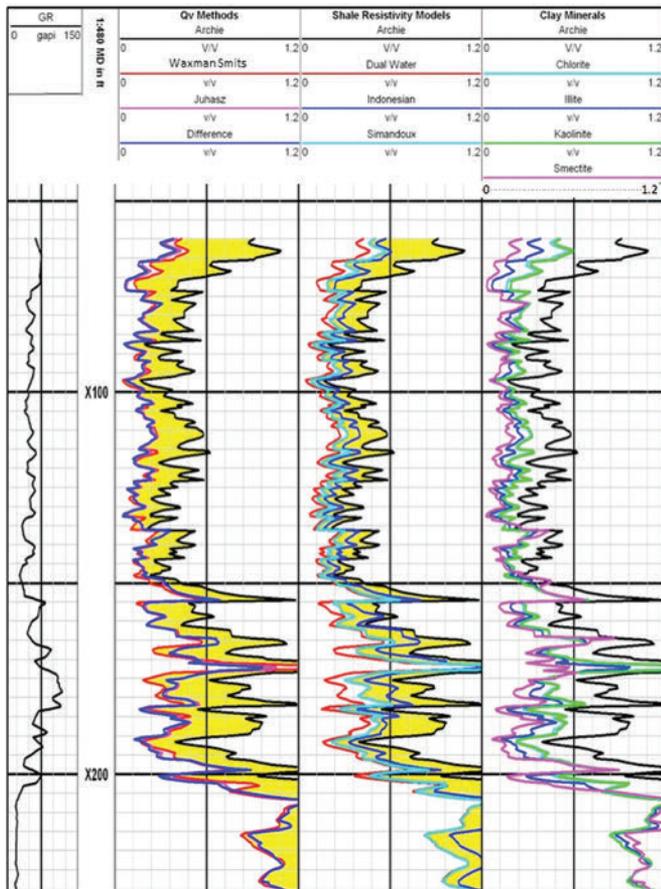


Fig. 3—Fractional water saturation for seven shaly-sand models (Tracks 2 and 3) and four clay types using the difference method (Track 4). The Archie model is repeated in Tracks 2, 3, and 4. The saturation profiles for kaolinite and chlorite in Track 4 almost totally overlay.

density, ρ_{sh} and shale porosity, ϕ_{tsh} , are linked and cannot be varied independently, as is permitted in some commercial log-evaluation programs.

The Waxman-Smiths method is not very sensitive to variation of most parameters, as long as the equivalent cation conductance, B , is fixed based on accurate salinity and temperature data, and reliable Q_v values are available based on core measurements.

The clean gamma-ray log reading is important in the log-based dual-water, Indonesian, and Simandoux methods that require estimates of the shale volumes. Wide variation of the saturation exponent from 1.6 to 2.4 produced a relatively small change of the average water saturation, while an identical spread for cementation factor m doubled this range. However, we reiterate that the effect of differently defined m exponents is minor.

Table 2—Sensitivity Analysis: Water Saturation S_w as a Function of Input Parameter Variation

Juhasz - CEC						Archie - m and n			
CEC	S_w	ϕ_{Nsh}	S_w	ρ_{clay_dry}	S_w	n	S_w	m	S_w
0.5	0.19	0.3	0.21	2.85	0.22	1.6	0.28	1.6	0.25
0.4	0.21	0.35	0.22	2.75	0.23	1.8	0.31	1.8	0.3
0.3 base >	0.23	0.4	0.23	2.65	0.23	2	0.34	2	0.34
0.2	0.26	0.45	0.24	2.55	0.23	2.2	0.37	2.2	0.39
0.1	0.29	0.5	0.25	2.45	0.24	2.4	0.39	2.4	0.45
Difference with Dry-Clay Values and CEC									
CEC	S_w	ϕ_{Nsh}	S_w	$\phi_{Ndryclay}$	S_w	ρ_{sh}	S_w		
0.5	0.17	0.3	0.17	0.2	0.17	2.6	0.2		
0.4	0.19	0.35	0.18	0.25	0.19	2.56	0.21		
0.3	0.21	0.4	0.19	0.3	0.21	2.52	0.21	<base	
0.2	0.24	0.45	0.21	0.35	0.22	2.48	0.22		
0.1	0.29	0.5	0.22	0.4	0.23	2.44	0.23		
Dual Water - R_b from Logs									
R_{sh}	S_w	GR_{shale}	S_w	GR_{clean}	S_w	r_{sh}	S_w		
1.5	0.14	70	0.2	15	0.18	2.6	0.04		
2	0.18	80	0.22	20	0.19	2.56	0.12		
2.5	0.21	90	0.23	25	0.21	2.52	0.21	<base	
3	0.24	100	0.24	30	0.23	2.48	0.29		
3.5	0.26	110	0.25	35	0.25	2.44	0.37		
Simandoux - Modified						Waxman-Smiths - Q_v from S_b			
R_{sh}	S_w	GR_{shale}	S_w	GR_{clean}	S_w	ϕ_{tsh}	S_w	GR_{cl}	S_w
0.5	0.14	70	0.17	15	0.17	0.35	0.2	15	0.21
0.4 base >	0.18	80	0.19	20	0.19	0.3	0.21	20	0.22
0.3	0.2	90	0.2	25	0.2	0.25	0.23	25	0.23
0.2	0.22	100	0.21	30	0.22	0.2	0.24	30	0.24
0.1	0.24	110	0.23	35	0.25	0.15	0.26	35	0.25

CONCLUSIONS

1. A new “difference” method was introduced that eliminates the use of log readings in thick adjacent shale beds for “logs only” shaly-sand reservoirs. This method uses dry-clay parameters, which are much better defined than wet-shale parameters, used in other methods.
2. Dry-clay volumes are derived from the difference of the apparent neutron and density porosities, in the total porosity system.
3. Dry-clay volume and dry-clay parameters together determine cation exchange capacities that are entered in the Waxman-Smiths equation.
4. Clay types can be identified in cuttings or (sidewall)

cores, which implies that this method can be used to re-evaluate old wells, and “brown” fields.

5. Bound-water saturation is a convenient parameter to compare various shaly-sand models. Relating bound-water saturation to shale content and cation exchange capacity allowed a direct comparison of the Archie, dual-water, Simandoux, Waxman-Smits, Juhasz, Indonesian, and the novel difference methods.
6. In a field study, the water-saturation depth profiles determined with the Waxman-Smits, Juhasz, difference, Simandoux, and the dual-water methods virtually overlaid, using one consistent set of input parameters.
7. The choice of input parameters proved therefore more important than the choice of the model.
8. The Indonesian method is not based on the parallel resistors model and this explains why it could not be reconciled with the other models.
9. Bound-water resistivity, shale resistivity, shale density and shale porosity, are linked and cannot be varied independently in the dual-water model, which is allowed in some commercial log-evaluation programs.

A sensitivity study in which clay and shaly-sand parameters were varied demonstrated that:

10. The Juhasz method is, as expected, most sensitive to cation exchange capacity CEC of dry clay followed by the neutron-log reading of a 100% shale bed.
11. The novel difference method is also sensitive to CEC followed by the dry-clay neutron and density porosities. However, once the clay type is known these uncertainties are small.
12. The modified Simandoux method using total porosity is most sensitive to the shale resistivity.
13. The Waxman-Smits method is not very sensitive for evaluation parameters provided the CEC is measured on cores, and the equivalent cation conductance, B , is well defined.
14. To apply the difference method for mixed clays, X-ray diffraction (XRD) analysis is required to resolve the contributions of the different clay types.
15. The dual-water method is very sensitive to the shale density if the bound-water resistivity is derived from logs. This shale-density dependency can be avoided by using the bound-water conductivity vs. temperature relation reported in the original dual-water paper.
16. The effect of the differences between Archie, Waxman-Smits, and dual-water cementation coefficients on calculated water saturations is minor, and can usually be ignored.

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NOMENCLATURE

B	= equivalent cation conductance, mho.ml/(meq.m)
CEC	= cation exchange, meq/g
CEC_{cl}	= CEC 100% dry clay, meq/g
C_b	= bound-water conductivity, mho/m (S/m)
C_{sh}	= shale conductivity, mho/m (S/m)
C_o	= formation water salinity, meq/ml
C_t	= total rock conductivity, mho/m (S/m)
C_w	= free water conductivity, mho/m (S/m)
GR_{clean}	= gamma-ray in clean sand, API
GR_{shale}	= gamma-ray in 100% shale, API
m	= Archie cementation exponent, dimensionless
m^*	= Waxman-Smits cementation exponent, dimensionless
m_o	= dual-water cementation exponent, dimensionless
n	= Archie saturation exponent, dimensionless
R_b	= bound-water resistivity, Ω -m
R_{sh}	= shale resistivity, Ω -m
S_b	= bound-water saturation, dimensionless
Q_v	= cation exchange capacity, meq/ml
V_{cldry}	= dry-clay volume fraction, dimensionless
V_{sh}	= shale volume, fraction
V_{bw}	= bound water volume, fraction
ϕ_D	= density log quartz porosity, fraction
ϕ_{Dcldry}	= density porosity dry clay, fraction
ϕ_{Dsh}	= density porosity in 100% shale, fraction
ϕ_{eff}	= effective porosity, fraction
ϕ_N	= neutron-log quartz porosity, fraction
ϕ_{Ncldry}	= neutron porosity in dry clay, fraction
ϕ_{Nsh}	= neutron porosity in 100% shale, fraction
ϕ_t	= total porosity, fraction
ϕ_{tsh}	= total porosity in 100% shale, fraction
ρ_{ma}	= matrix density, g/ml
ρ_{CBW}	= clay bound-water density, g/ml
ρ_{cldry}	= dry-clay density, g/ml
ρ_l	= fluid density, g/ml
ρ_{sh}	= density in 100% shale, g/ml

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APPENDIX 1: Cementation Exponents

In this Appendix we estimate the effect of Archie m , Waxman-Smits m^* , and dual-water m_o exponents on water saturation, S_w .

The Archie exponent m was backcalculated from the Waxman-Smits exponent m^* by equating the resistivities of the two models, assuming that the porosity in the Archie equation is the same as the total porosity in the Waxman-Smits equation, and by using the cation exchange Q_v , counterion conductivity, B , and formation-water resistivity, R_w , parameters:

$$m = m^* + \log(1 + R_w B Q_v) / \log(\phi) \quad (\text{A1-1})$$

A value of $B = 3.14 \text{ mho.ml}/(\text{meq.m})$ was calculated for 25°C and $R_w = 0.33 \Omega\text{-m}$. A total resistivity value of $R_t = 50 \Omega\text{-m}$ was selected to obtain S_w values close to the cutoff value of 50%. The water resistivity, R_w , was based on the middle salinity value of 17,500 ppm NaCl eq. used by Waxman and Thomas (1974).

In Table A-1, the water-saturation parameter $S_w(m)$ the Archie column is calculated using the Archie m exponent and Archie equation. The water-saturation parameter $S_w(m^*)$ in the Archie column is calculated using the Waxman-Smits m^* exponent and the Archie equation.

In Table A-1, the water-saturation parameter $S_w(m)$ in the Waxman-Smits column is calculated using the Archie m exponent and Waxman-Smits equation. The water-saturation parameter $S_w(m^*)$ in the Waxman-Smits column is calculated using the Waxman-Smits m^* exponent and the Waxman-Smits equation.

In Table A-1, in the dual-water column a bound-water conductivity value of 7.5 mho/m (S/m) was applied based on Fig. 14 of Clavier et al. (1977) for 25°C . Values for both m_o and m^* are provided by Clavier et al., (1977). The water saturation parameter $S_w(m^*)$ in the dual-water column is calculated using the Waxman-Smits m^* exponent and the water-saturation parameter $S_w(m_o)$ is calculated using the dual -water cementation factor.

The differences, ΔS_w , in the average water saturations due to the use of the “wrong” m exponent is only a few saturation percentage points, and demonstrates that it is a secondary effect.

APPENDIX 2: Clay and Shale Parameters

Dry-clay parameters extracted from publications are listed in Table A2-1. These data were used to determine the evaluation parameters for our field case and are shown in table 1 in the main text. Finally the dry clay parameters were

used to calculate the difference between dry clay neutron and density porosities. The range over the 4 main clay types is 0.26 to 0.42 as shown in the bottom row of Table A2-1. This range is rather limited, which implies that the uncertainty in the dry clay parameters has only a secondary effect on the calculation of Q_v , with the obvious exception of CEC values.

Table A1-1—Cementation exponents

Data from Waxman and Thomas (1974)					Archie			Waxman Smits		
Q_v	ϕ	m^*	m	m^*-m	$S_w(m)$	$S_w(m^*)$	ΔS_w	$S_w(m)$	$S_w(m^*)$	ΔS_w
0.06	0.14	1.82	1.79	0.03	0.49	0.50	0.01	0.46	0.47	0.01
0.11	0.23	1.88	1.81	0.07	0.30	0.32	0.02	0.25	0.27	0.02
0.12	0.30	1.91	1.81	0.10	0.24	0.26	0.01	0.19	0.20	0.01
0.24	0.28	1.96	1.79	0.17	0.25	0.28	0.03	0.16	0.18	0.03
0.24	0.24	1.98	1.83	0.15	0.30	0.34	0.04	0.20	0.24	0.03
0.36	0.27	2.06	1.82	0.24	0.27	0.32	0.05	0.14	0.18	0.04
0.28	0.19	2.10	1.95	0.15	0.40	0.46	0.05	0.28	0.34	0.05
0.28	0.12	1.79	1.67	0.12	0.47	0.53	0.06	0.34	0.40	0.06
0.32	0.12	1.79	1.66	0.13	0.49	0.56	0.08	0.35	0.42	0.07
0.41	0.13	1.89	1.72	0.17	0.47	0.56	0.09	0.30	0.39	0.08
Averages				0.13	0.37	0.41	0.04	0.27	0.31	0.04
Data from Clavier et al. (1977)					Archie			Dual Water		
Q_v	ϕ	m^*	m_0	m^*-m_0	$S_w(m)$	$S_w(m_0)$	ΔS_w	$S_w(m^*)$	$S_w(m_0)$	ΔS_w
0.22	0.18	1.90	1.87	0.03	0.41	0.43	0.01	0.37	0.36	-0.01
0.07	0.19	1.80	1.79	0.01	0.37	0.37	0.00	0.38	0.37	-0.01
0.24	0.19	1.80	1.76	0.04	0.36	0.37	0.01	0.34	0.33	-0.01
0.29	0.20	2.19	2.14	0.05	0.45	0.47	0.02	0.30	0.29	-0.01
0.33	0.20	1.99	1.93	0.06	0.38	0.40	0.02	0.30	0.29	-0.01
0.08	0.23	1.92	1.91	0.01	0.33	0.33	0.00	0.31	0.30	-0.01
0.35	0.16	2.12	2.06	0.06	0.53	0.56	0.03	0.38	0.36	-0.01
0.23	0.23	2.02	1.98	0.04	0.35	0.36	0.01	0.27	0.27	-0.01
0.25	0.24	2.04	1.99	0.05	0.34	0.35	0.01	0.26	0.25	-0.01
0.62	0.28	2.10	1.93	0.17	0.27	0.30	0.03	0.15	0.15	0.00
0.65	0.29	2.16	1.99	0.17	0.28	0.31	0.03	0.15	0.14	0.00
0.61	0.29	2.14	1.98	0.16	0.27	0.30	0.03	0.15	0.14	0.00
Averages				0.08	0.36	0.38	0.02	0.26	0.25	-0.01

Table A2-1—Dry-Clay Parameters

Cation Exchange Capacity CEC_{cldry} (meq/g)					Hydrogen Index ϕ_{Ncldry} d.I.			
Reference	Kaolinite	Chlorite	Montmor.	Illite	Kaolinite	Chlorite	Montmor.	Illite
Hill et al. (1979)	0.01–0.02	0.06–0.09	—	—	—	—	—	—
Johnson and Linke (1977)	0.03–0.06	0.00–0.10	0.08–1.50	0.1–0.4	—	—	—	—
Dewan (1983)	0.03–0.06	—	1.00	0.25	—	—	—	—
Fertl and Frost (1980)	0.03–0.15	0.1–0.4	0.8–1.5	0.1–0.4	0.36	0.34	0.13 [^]	0.12
Juhasz (1979)	—	—	—	—	0.36	0.34	0.13 [^]	0.12
Schlumberger (1997)	—	—	—	—	0.37	—	0.60	0.30 [*]
Hearst et al. (2000)	—	—	—	—	0.45	—	0.60	0.16
Applied	0.05	0.10	1.00	0.25	0.37	0.40	0.55	0.25
Clay Density ρ_{cldry} (g/cm ³)					Ratio Dry-Clay-Over-Shale Volumes [@]			
Reference	Kaolinite	Chlorite	Montmor.	Illite	Kaolinite	Chlorite	Montmor.	Illite
Hill et al. (1979)	—	—	—	—	0.44	0.36	0.36	0.59
Johnson and Linke (1977)	2.69	2.77	2.33	2.76				
Dewan (1983)	—	—	—	—				
Fertl and Frost (1980)	2.61	2.60–2.96	2.20–2.70	2.64–2.69				
Juhasz (1979)	2.61	2.60–2.96	2.20–2.70	2.64–2.69				
Schlumberger (1997)	2.41 [!]	2.76	2.12 [!]	2.52				
Hearst et al. (2000)	2.62	2.65–3.42	2.63	2.22–2.78				
Applied	2.62	2.70	2.45	2.68				
ϕ_{Dcldry}	0.03	–0.02	0.13	–0.01				
$\phi_{\text{Ncldry}} - \phi_{\text{Dcldry}}$	0.34	0.42	0.42	0.26				

[^]assumed to be values without crystal water and therefore ignored

^{*}including crystal water in illite

[!] assumed to be wet-clay parameters, and therefore ignored

[#] calculated using Eq. 21, a matrix density of 2.67 g/cm³ for the apparent dry clay density porosity ϕ_{Dcldry} and assuming a shale porosity separation $\phi_{\text{Nsh}} - \phi_{\text{Dsh}}$ of 15%

[@] $V_{\text{cldry}}/V_{\text{sh}}$

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Max Peeters is currently the Honorary consul for The Netherlands of the three Rocky Mountain states, volunteer for the National Renewable Energy Lab and host for open space parks. Before that taught petrophysical courses for Petro-Skills, and was professor of Borehole Geophysics and Petrophysics at the Colorado School of Mines from 1998 to 2007. From 1992 to 1998 he was professor of Petrophysics at the University of Technology in Delft, and Petrophysical Adviser at Shell Research, both in The Netherlands. Peeters received a MSc in Physics of Delft University of Technology in 1968, followed by two years lecturing at the Royal Dutch Navy Academy. In 1970 he joined Shell International, and worked as Petroleum Engineer and Chief Petrophysicist in Australia, England, Brunei, and California. In 1988 he returned to The Netherlands where he was in charge of Shell's global Formation Evaluation team, and headed a Petroleum Engineering team for the development of business opportunities in the former Soviet Union. Max Peeters founded and directed the Center for Petrophysics at the Colorado School of Mines and served

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