

# 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,  $\phi_t$ , effective porosity,  $\phi_{eff}$ , and shale content,  $V_{sh}$ . These volume fractions are defined in Fig. 1 (Shaly-Sand Model).

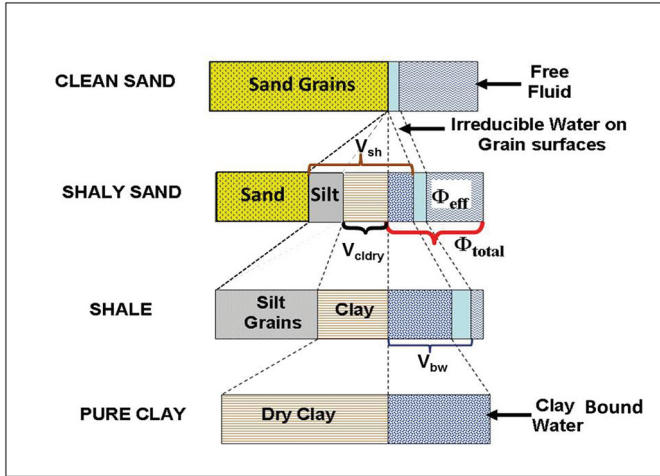


Fig. 1—Shaly-Sand Model.

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

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

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

where  $\phi_{ish}$  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  $\phi_{eff}$  to  $\phi_t$  and cation exchange capacity,  $Q_v$ :

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

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

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

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

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

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:

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

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

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

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

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  $\rho_{cldry}$  the density of dry clay in g/cm<sup>3</sup>. The dry-clay volume,  $V_{cldry}$ , is estimated from the difference of the neutron  $\phi_N$  and density porosity  $\phi_D$ . Juhasz (1979) recommends the use of  $\phi_D$  as a first approximation of  $\phi_t$  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  $\phi_{Nsh}$  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,  $\phi_{tsh}$ , 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  $\phi_D$  and neutron  $\phi_N$  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  $\phi_{Dsh}$  and  $\phi_{Nsh}$  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  $\phi_{eff}$ . The density  $\phi_D$  and neutron  $\phi_N$  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  $\phi_{Dcldry}$  and  $\phi_{Ncldry}$  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,  $\phi_t$ . 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  $\phi_t$  is again estimated from  $\phi_D$  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,  $\phi_{ish}$ , 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-Smits method. However it also has severe restrictions for “logs only” evaluations, because  $C_b$  is dependent on the square of the shale porosity  $\phi_{ish}$ , which if derived from the density log, is strongly dependent on the apparent shale density  $\rho_{sh}$ . 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,  $\phi$ , 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),  $\phi_t$  by  $\phi_{ish}$ , 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-Smits 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,  $\phi_{Dsh}$  and  $\phi_{Nsh}$ , 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

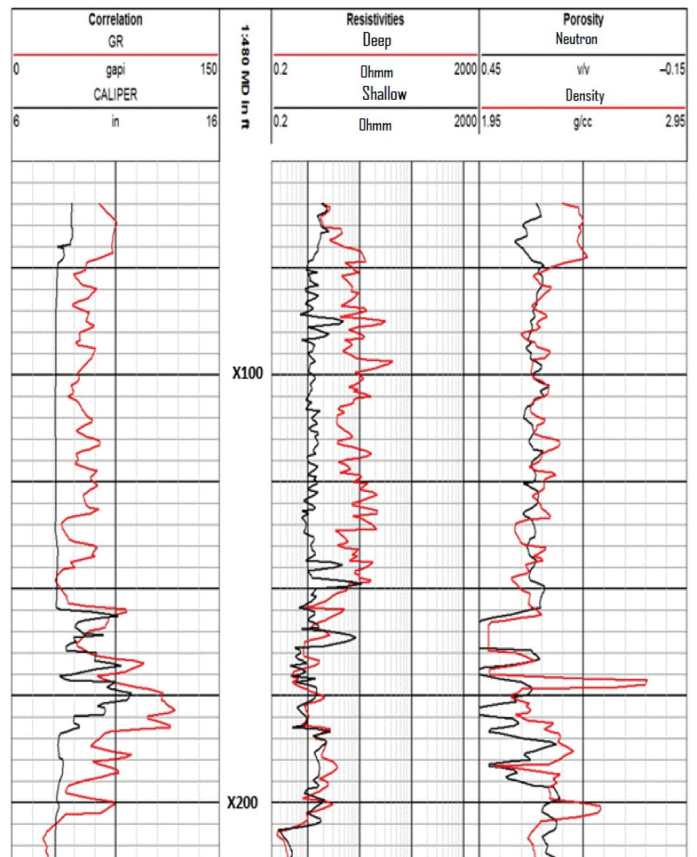
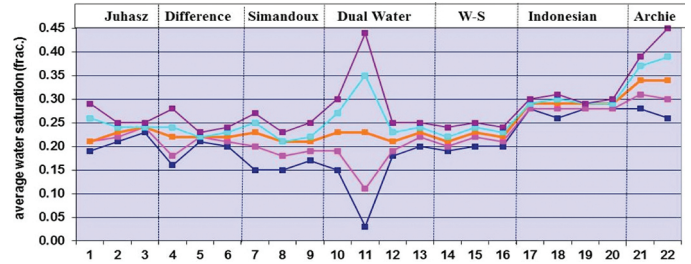


Fig. 2—Field-study well logs.

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

Base case	Best fit	Units	Input parameter name
$R_{wa}$	0.035	$\Omega\text{-m}$	Formation-water resistivity
$R_{sh}$	2.5	$\Omega\text{-m}$	Shale resistivity
$R_b$	0.019	$\Omega\text{-m}$	Bound-water resistivity
$\rho_{ma}$	2.65	$\text{g/cm}^3$	Matrix density
$\rho_f$	1.0	$\text{g/cm}^3$	Formation-water density
$\rho_{sh}$	2.52	$\text{g/cm}^3$	Density 100% shale
$\rho_{clay\_dry}$	2.68	$\text{g/cm}^3$	Dry-clay density
$\phi_{Csh}$	35	%	Apparent neutron-porosity shale
$\phi_{Dsh}$	8	%	Apparent density-porosity shale
$\phi_{Nclay\_dry}$	25	%	Neutron porosity 100% dry clay
$T$	150	$^{\circ}\text{C}$	Reservoir temperature
$CEC$	0.25	$\text{meq/g}$	Cation exchange capacity
$C_o$	0.14	$\text{meq/ml}$	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"

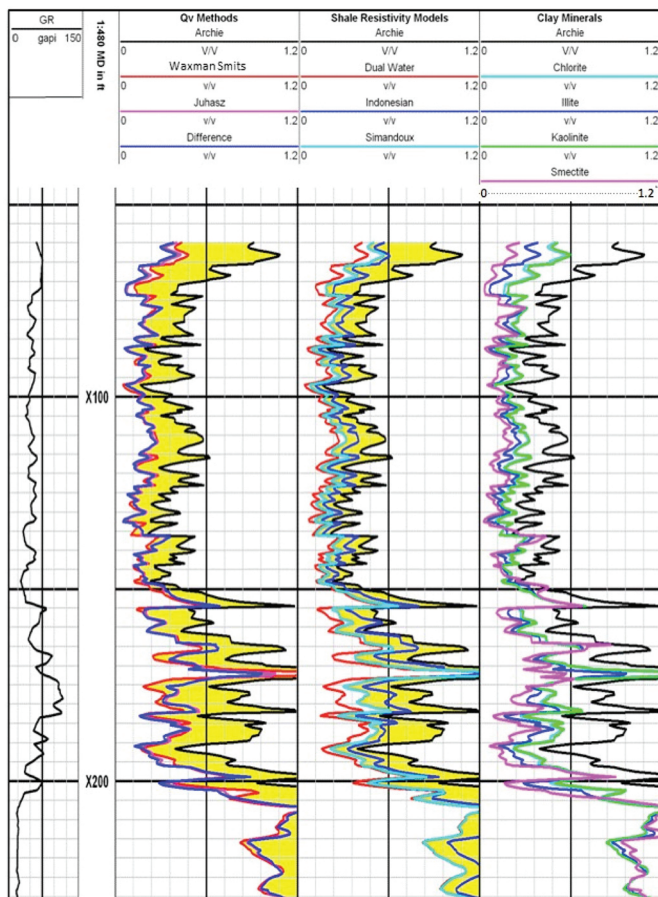
types can still be derived from cuttings and (sidewall) core samples of old wells, allowing a more accurate reevaluation of “brown” fields.

**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,  $\phi_{Dsh}$  and  $\phi_{Nsh}$ , respectively, cation exchange capacity,  $CEC_{cl}$ , dry-clay neutron porosity,  $\phi_{Ncldry}$ , shale and dry-clay densities,  $\rho_{shale}$  and  $\rho_{cldry}$ , 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  $\phi_{Nsh}$  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  $\rho_{sh}$ , 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  $\rho_{sh}$  from 2.45 to 2.6  $\text{g/cm}^3$  corresponds to a range in  $C_b$  of 25 to 430  $\text{mho/m}$  (S/m);  $C_b$  values in excess of 100  $\text{mho/m}$  (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,  $\rho_{sh}$  and shale porosity,  $\phi_{tsh}$ , 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	$S_w$	$\phi_{Nsh}$	$S_w$	$\rho_{clay\_dry}$	$S_w$	$n$	$S_w$	$m$	$S_w$
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	$S_w$	$\phi_{Nsh}$	$S_w$	$\phi_{Ndryclay}$	$S_w$	$\rho_{sh}$	$S_w$		
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 $S_b$			
$R_{sh}$	$S_w$	$GR_{shale}$	$S_w$	$GR_{clean}$	$S_w$	$\phi_{tsh}$	$S_w$	$GR_{cl}$	$S_w$
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, $\Omega$ -m
$R_{sh}$	= shale resistivity, $\Omega$ -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
$\phi_D$	= density log quartz porosity, fraction
$\phi_{Dcldry}$	= density porosity dry clay, fraction
$\phi_{Dsh}$	= density porosity in 100% shale, fraction
$\phi_{eff}$	= effective porosity, fraction
$\phi_N$	= neutron-log quartz porosity, fraction
$\phi_{Ncldry}$	= neutron porosity in dry clay, fraction
$\phi_{Nsh}$	= neutron porosity in 100% shale, fraction
$\phi_t$	= total porosity, fraction
$\phi_{tsh}$	= total porosity in 100% shale, fraction
$\rho_{ma}$	= matrix density, g/ml
$\rho_{CBW}$	= clay bound-water density, g/ml
$\rho_{cldry}$	= dry-clay density, g/ml
$\rho_l$	= fluid density, g/ml
$\rho_{sh}$	= 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  $25^\circ\text{C}$  and  $R_w = 0.33 \text{ }\Omega\text{-m}$ . A total resistivity value of  $R_t = 50 \text{ }\Omega\text{-m}$  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  $7.5 \text{ mho/m (S/m)}$  was applied based on Fig. 14 of Clavier et al. (1977) for  $25^\circ\text{C}$ . 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,  $\Delta S_w$ , 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		
$Q_v$	$\phi$	$m^*$	$m$	$m^*-m$	$S_w(m)$	$S_w(m^*)$	$\Delta S_w$	$S_w(m)$	$S_w(m^*)$	$\Delta S_w$
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
<b>Averages</b>				<b>0.13</b>	<b>0.37</b>	<b>0.41</b>	<b>0.04</b>	<b>0.27</b>	<b>0.31</b>	<b>0.04</b>
Data from Clavier et al. (1977)					Archie			Dual Water		
$Q_v$	$\phi$	$m^*$	$m_0$	$m^*-m_0$	$S_w(m)$	$S_w(m_0)$	$\Delta S_w$	$S_w(m^*)$	$S_w(m_0)$	$\Delta S_w$
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
<b>Averages</b>				<b>0.08</b>	<b>0.36</b>	<b>0.38</b>	<b>0.02</b>	<b>0.26</b>	<b>0.25</b>	<b>-0.01</b>

Table A2-1—Dry-Clay Parameters

Cation Exchange Capacity $CEC_{cldry}$ (meq/g)					Hydrogen Index $\phi_{Ncldry}$ 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 <sup>^</sup>	0.12
Juhasz (1979)	—	—	—	—	0.36	0.34	0.13 <sup>^</sup>	0.12
Schlumberger (1997)	—	—	—	—	0.37	—	0.60	0.30 <sup>*</sup>
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 $\rho_{cldry}$ (g/cm <sup>3</sup> )					Ratio Dry-Clay-Over-Shale Volumes <sup>@</sup>			
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 <sup>!</sup>	2.76	2.12 <sup>!</sup>	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				
$\phi_{Dcldry}$	0.03	–0.02	0.13	–0.01				
$\phi_{ncldry} - \phi_{Dcldry}$	0.34	0.42	0.42	0.26				

<sup>^</sup>assumed to be values without crystal water and therefore ignored

<sup>\*</sup>including crystal water in illite

<sup>!</sup> assumed to be wet-clay parameters, and therefore ignored

<sup>#</sup> calculated using Eq. 21, a matrix density of 2.67 g/cm<sup>3</sup> for the apparent dry clay density porosity  $\phi_{Dcldry}$  and assuming a shale porosity separation  $\phi_{Nsh} - \phi_{Dsh}$  of 15%

<sup>@</sup>  $V_{cldry}/V_{sh}$

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