Evaluation of the hydrocarbon potential in low-salinity shaly sand

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EVALUATION OF THE HYDROCARBON POTENTIAL IN LOW-SALINITY SHALY SAND

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
In partial fulfillment of the
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Master of Science
In Petroleum Engineering

in

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ABSTRACT

This research utilizes reservoir data from an oilfield in Indonesia, which is characterized by shaly sand and low salinity formation water. Both low salinity and shaliness reduce the resistivity contrast between oil and water. The aim of this research was to build a comprehensive interpretation algorithm to evaluate the shaly-sand reservoir in a low salinity formation water using limited well log data.

Shaly-sand interpretation is still evolving with numerous researchers conducting investigations of the clay minerals effect on rock conductivity through theoretical and experimental approach. These investigations can be loosely divided into either Fractional Shale Volume models or the Cation Exchange Capacity (clay-type) models.

This research emphasizes the Cation Exchange Capacity models. Cation Exchange Capacity (CEC) is essentially a reflection of the specific surface area of clay minerals, which causes additional conductivity in shaly-sands. The modified Silva-Bassiouni model was used to interpret shaly sand formations. This model is based on the dual water concept, however it considers that the counter-ion conductivity can be represented by an equivalent sodium chloride solution. Therefore, this method eliminates the requirement for actual CEC measurements from cores. The Shale Volume based Simandoux and Indonesia models were used for comparison. The results from the Archie clean sand model were also discussed. The model was evaluated using actual production and well test data.
The modified Silva-Bassiouni model was found to yield superior estimates of cation exchange capacity and fluid saturations in the reservoirs.
CHAPTER 1
INTRODUCTION

The interpretation of Shaly-Sands log data has long been a challenging problem. As a result, there are more than 30 shaly-sand interpretation models, which have been developed in the last 50 years. Interpretation difficulties arise whenever the portions of clay minerals in a shaly-sand formation is high. In Indonesian formation particularly, the limit is 30%. These clay minerals contribute to the increase of the overall conductivity. In a large quantity, their conductivity becomes as important as the conductivity of the formation water.

The well-known Archie formula for calculating water saturation in a shale-free reservoir is expressed as:

\[
S_w^n = \frac{C_t}{\phi^m C_w} \quad (1.1a)
\]

or as:

\[
S_w^n = \frac{R_w}{\phi^m R_t} \quad (1.1b)
\]

where:

- \( S_w \) = formation water saturation, fraction
- \( C_t \) = rock conductivity, mho/m
- \( C_w \) = brine conductivity, mho/m
- \( R_w \) = resistivity of formation water, ohm/m
- \( R_t \) = resistivity of formation rock, ohm/m
- \( \phi \) = porosity, fraction
\[ n = \text{saturation exponent} \]

\[ m = \text{cementation exponent} \]

Archie formula has been widely used by many log analyst especially when dealing with clean sand reservoir. This empirical formula provided the early basis of the quantitative petrophysical reservoir evaluation. Practically, there are several ways to estimate the formation water resistivity \( (R_w) \) such as from applying equation 1.1b to nearby water sand, from water sample measurements, and from the Spontaneous Potential (SP) log. The formation rock resistivity \( (R_t) \) is usually obtained from deep resistivity log reading such as deep Induction or deep Lateralog. Meanwhile the porosity data \( (\phi) \) can be estimated from several types of porosity logs, for instance Density, Neutron, or Sonic log. Finally, the saturation exponent \( (n) \) and cementation exponent \( (m) \) are estimate from core data analysis or from prior experience with local formation characteristics.

In evaluating shaly-sand reservoir, Archie formula may give a misleading result. This is because Archie formula assumes that the formation water is the only electrically conductive material in the formation. The shale effect on various log responses depends on the type, the amount, and the way it is distributed in the formation\(^5\).

Shale can be distributed in sandstone reservoirs in three possible ways as shown in Figure 1.1 they are\(^5\): (1) laminar shale, where shale can exist in the form of laminae between layers of clean sand; (2) structural shale, where shale can exist as grains or nodules within the formation matrix; and (3) dispersed shale, where shale can be dispersed throughout the sand, partially filling the intergranular interstices, or
can be coating the sand grains. All this form can occur simultaneously in the same formation. Each form can affect the amount of rock porosity by creating a layer of closely bound surface water on the shale particle.

Figure 1.1 - Different ways of shale distribution in formation.

The effect of shaliness on electrical conductivity is illustrated in Figure 1.2. The figure shows the conductivity of water-saturated sandstone ($C_o$) as a function of the water conductivity ($C_w$). The straight line of gradient $1/F$ represents the application of Archie’s equation on clean reservoir rock fully saturated with brine. However, in the other rock with same effective porosity but some of the rock matrix is replaced by shale, the straight line is displaced upward with respect to the original clean sand line. This increase of conductivity is because of the shaliness effect and known as the excess conductivity ($C_{excess}$).

Based on their different approach and concept, the shaly-sand models that currently available can be divided into two main groups: fractional volume of shale (Vsh) group and Cation Exchange Capacity (CEC) group.
1.1 Volume of Shale (Vsh) Models

The Vsh quantity is defined as the volume of wetted shale per unit volume of reservoir rock. Wetted shale mean that the space occupied by the water confined to the shale, known as bound water, should be taken into account to determine the total porosity.

These models are applicable to logging data without the encumbrance of a core sample calibration of the shale related parameter. However, they have also lead to certain misunderstanding and misusing because they are used beyond its limitation.

The Simandoux model\(^6\) that was introduced in 1963 is still widely used to some extent. This model basically use porosity from Density-Neutron data and shale fraction determined from GR, SP, or other shale indicator. This equation is only covering the linear zone of the schematic shown in Figure 1.2. However, to accommodate the non-linear zone, several Vsh models have also been introduced.
by various log-analyst. For instance the “Indonesia formula” proposed by Poupon and Leveaux\textsuperscript{2} in 1971. This equation was originally developed for used in Indonesia, but later was found applicable in some other area. It is important to note that each model can only give a partial correlation to the rock conductivity data zone, i.e., Simandoux and Poupon-Leveaux relationship accommodate linear and no-linear zone, respectively\textsuperscript{1}. The correction made in one zone will result in a mismatch of another zone. This problem shows a major limitation of using the Vsh models to interpret shaly-sand reservoir because no universally accepted equations exist.

Another major disadvantage of Vsh models is that they do not take into account the mode of distribution or the composition of different clay types. The variation of clay mineralogy can result in different shale effects for the same volume of shale fraction (Vsh). Further improved models, which take into account the shortage in Vsh model such as geometry and electrochemistry of mineral-electrolyte interfaces, start to become more reliable models in shaly-sand interpretation. These models can be classified into one group known as cation exchange capacity models.

1.2 Cation Exchange Capacity Models

Crystalline clay platelets are negatively charged as the result of ion substitutions in the lattice and broken bonds at the edge. Sodium cations (Na\textsuperscript{+}) is the typical charge-balancing cations. These cations are held in suspension close to the clay surface when the clay is in contact with saline solution. As a result, the Cl\textsuperscript{-} anions in the solution will be repelled from the clay surface.
As shown in Figure 1.3, a mono-layered of adsorbed water exists directly on the clay surface. To sufficiently balance the negative platelet charge, another layer of hydrated Na+ ions is also present.

The concentration of sodium cations can be measured in term of cation exchange capacity (CEC), expressed in milliequivalents per gram of dry clay. For practical purpose $Q_v$, cation exchange capacity per unit of pore volume, is usually used. This is the source of the excess conductivity shown in Figure 1.2.

In 1968, Waxman and Smits, based on extensive laboratory work and theoretical study, proposed a saturation-resistivity relationship for shaly formation using the assumption that cation conduction and the conduction of normal sodium chloride act independently in the pore space, resulting parallel conduction paths. This model can be expressed by:

$$C_t = \frac{S_w^n \cdot C_w}{F^*} + \frac{B \cdot Q_v \cdot S_w^{n-1}}{F^*}$$  \hspace{1cm} (1.2)
where:

\[ C_t = \text{rock conductivity} \]

\[ S_w = \text{water saturation} \]

\[ n_e = \text{saturation exponent for shaly formations} \]

\[ B = \text{equivalent conductance of clay counterions} \]

\[ C_w = \text{water conductivity} \]

\[ F^* = \text{formation factor of the interconnected porosity} \]

According to this model, a shaly formation behaves like a clean formation of the same porosity, tortuosity, and fluid saturation, except the water appears to be more conductive than its bulk salinity. In other words, it says that the increase of apparent water conductivity is dependent on the presence of counter-ion. A Dual-Water model based on this premise was introduced.

The Dual-Water model is a modification of Waxman-Smits equation by taking into account the exclusion of anions from the double-layer. It represents the counterion conductivity restricted to the bound water, where counterion reside and the free water, which is found at a distance away from clay surface. This model says that apparent water conductivity will depend on the relative volumes of clay bound water and free water. Dual-water equation is given by:

\[ C_t = \frac{1}{F_o} S_w^n [ \beta \cdot Q_v' + (1 - 0.28 \cdot \alpha \cdot Q_v'). C_w ] \]  \hspace{1cm} (1.3)

where:

\[ \beta = \text{equivalent conductivity of sodium counter-ions} \]

\[ \alpha = \text{expansion factor of diffuse layer} \]
\[ F_o = \text{idealized formation factor} \]

\[ Q_v' = \frac{Q_v}{S_w} \]  

(1.4)

Another model, which based on the dual-water concept was later proposed by Silva and Bassiouni in 1985. Although this model is based on dual-water concept it differs from the previous one. It considers that the equivalent counter-ion conductivity is related to conductivity of an equivalent sodium chloride solution. Therefore, it is a function of temperature and the conductivity of the free water. This model can be expressed as follow:

\[ C_t = \frac{S_w^n}{F_e} \left[ C_{eq}' \cdot Q_v' + (1 - v_{fdl}') C_w \right] \]  

(1.5)

where:

- \( C_{eq} \) = counter-ion conductivity
- \( v_{fdl} \) = fractional volume of the double layer
- \( F_e \) = equivalent formation factor

Compared to the previous two models, Silva-Bassiouni model has practical advantages since it does not need clay counter-ions data measured from core analysis because it can be represented by sodium chloride solution. This approach is applicable to the real field condition since the conductivity data of sodium chloride solutions can be obtained at high temperatures as in field condition.

This conductivity model together with another membrane potential model, which also proposed by Silva and Bassiouni in 1987, will be used to construct a
reliable algorithm to calculate the water saturation in shaly-sand reservoir using the data from one of the Central Sumatra oil field. Since both models are expressed in term of the cation exchange capacity of clay, $Q_v$, and the free electrolyte conductivity, $C_w$, so in water bearing zone these two unknown parameter can be determined simultaneously.
2.1 Silva-Bassiouni Conductivity Model

Silva and Bassiouni\(^9\) introduced a new conductivity model for shaly-sand. This model treats the equivalent counter-ion conductivity as that of an equivalent sodium chloride solution. It is assumed that the conductive behavior of a shaly-sand corresponds to that of a clean sand of the same porosity that contains water with effective conductivity, \(C_{we}\). The equation is given below:

\[
C_{we} = C_{cl} \cdot v_{fdl} + (1-v_{fdl}) \cdot C_{w}
\]

(2.1)

where \(C_w\) and \(v_{fdl}\) are, respectively, the conductivity of free electrolyte and the fractional volume occupied by double layer. The conductivity of exchange cations associated with clay, \(C_{cl}\), can be defined as:

\[
C_{cl} = C_{eq} \cdot n_{eq}
\]

(2.2)

where \(C_{eq}\) is the equivalent counter-ion conductivity. The concentration of clay counter-ion, \(n_{eq}\), can be expressed in terms of the counter-ion concentration per total pore volume, \(Q_v\), as:

\[
n_{eq} = \frac{Q_v}{v_{fdl}}
\]

(2.3)

Because the proposed shaly-sand conductivity model simulate the expression of clean sand, the total conductivity of a rock fully saturated with water is defined by:

\[
C_o = \frac{C_{we}}{F_e}
\]

(2.4)

substitution of equations (2.1) and (2.2) into equation (2.4) result in:
\[
C_0 = \frac{1}{F_e} \left[ C_{eq} \cdot n_{eq} \cdot v_{fdl} + (1-v_{fdl}) \cdot C_w \right]
\]  

(2.5)

Where \( F_e \) is the formation factor of an equivalent clean sand formation with the same total porosity, \( \phi_T \), that can be expressed as:

\[
F_e = \phi_T^{-m}
\]

(2.6)

where \( m \) is the cementation exponent.

In the condition where \( C_w \) and \( Q_v \) are unknown, S-B model requires the estimation of the fractional volume of the double layer, \( v_{fdl} \). Juhasz\textsuperscript{10} proposed the equation for \( v_{fdl} \) as:

\[
v_{fdl} = \left( \frac{0.084}{C_w} + 0.22 \right) \cdot Q_v
\]

(2.7)

S-B model also requires the estimation of the equivalent counter-ion conductivity, \( C_{eq} \). Since the equivalent counter-ion conductivity is treated as the equivalent sodium chloride solution, Silva, P (1986) provided the equation of concentration, \( n_{eq} \), and conductivity, \( C_{eq} \), which also based on the sodium chloride solution as:

\[
n_{eq} = \frac{3.571}{\left( \sqrt{\alpha - 0.188} \right)^2}
\]

(2.8)

\[
C_{eq} = \frac{C_{eq}'}{f_g \cdot F_{(ne)}}
\]

(2.9)

where:

\( C_{eq} ' \) = equivalent sodium chloride solution

\( f_g \) = geometric correction factor
\[ F(\text{ne}) = \text{empirical correction factor} \]

According to Silva\textsuperscript{11}, at temperature of 25\textdegree C:

\[ C_{\text{eq}}^{'} \text{ can be expressed as:} \]

\[ C_{\text{eq}}^{'} = \frac{12.645 + 7.6725 \sqrt{n_{\text{eq}}}}{1 + 1.3164 \cdot n_{\text{eq}}} \] \hspace{1cm} (2.10)

\( f_g \) is given by:

\[ f_g = \alpha^{1/\eta} \] \hspace{1cm} (2.11)

where \( \alpha \) is the expansion factor of the double layer and \( \eta \) is an empirical function of \( \alpha \) defined as:

\[ \eta = 0.6696 + 1.1796 \cdot \alpha - 0.14426 \cdot \alpha^2 \] \hspace{1cm} (2.12)

\( F(\text{ne}) \) can be presented as:

\[ F(\text{ne}) = 1.0; \quad \text{for } n_{\text{eq}} \leq 0.5 \text{ mol/l} \] \hspace{1cm} (2.13)

\[ F(\text{ne}) = 1 + 3.83 \times 10^{-2} (n_{\text{eq}} - 0.5) + 1.761 \times 10^{-2} (n_{\text{eq}} - 0.5)^2; \quad \text{for } n_{\text{eq}} > 0.5 \text{ mol/l} \]

\subsection*{2.2 Silva-Bassiouni Membrane Potential Model}

As an extension of the previous conductivity model, Silva and Bassiouni\textsuperscript{12} developed a model to predict the membrane potentials in shaly formation. This model is a modification of the basic expression for the membrane potential, \( E_m \), in shaly sand obtained by Smits\textsuperscript{13} and reported by Thomas\textsuperscript{14} in the form:

\[ E_m = \frac{-2.7 R T}{F} \int_{m_2}^{m_1} T_{Na^+} \cdot d\ln(m \cdot \gamma^\pm) \] \hspace{1cm} (2.14)

where:

\( m_1 \) and \( m_2 \) = molal concentration of two solutions separated by the membrane, mol/kg H\textsubscript{2}O
\[ R = \text{universal gas constant} \]
\[ T = \text{absolute temperature, } ^\circ\text{K} \]
\[ F = \text{Faraday constant} \]
\[ T_{Na}^+ = \text{sodium transport number, and} \]
\[ \gamma^\pm = \text{mean activity coefficient} \]

At high salinity solution, Silva-Bassiouni observed that Smits membrane potentials model deviate from the experimental data. The deviations are believed the result of different transport properties between the solution outside the rock and those of the equivalent fluid occupying the pore space. S-B introduced an empirical correction factor, \( \tau \), to account for the differences between the actual transport properties of the system and those of the outside solution. Accordingly, the membrane potentials is given by:

\[
E_m = \frac{-2. R . T}{F} \int_{m_1}^{m_2} \tau . T_{Na}^+. d\ln(m.\gamma^\pm) \tag{2.15}
\]

where:

\[
\tau = \begin{cases} 
1 - \frac{0.28Q_v}{C_w} (C_w - C_{WN}) ; & \text{for } C_w > C_{WN} \\
1 ; & \text{for } C_w \leq C_{WN} 
\end{cases} \tag{2.16}
\]

where at 25\(^\circ\)C, \( C_{WN} \) is equal to16.61 mho/m

2.2.1 Determination of Transport Number in Shaly Sands, \( T_{Na}^+ \)

Cation transport number, \( T_{Na}^+ \), is a representation of the fraction of electrical charges transported by cations during the conduction of the electrical current. With the assumption of the same ionic mobility during conduction, cation transport number can expressed as:
\[ T_{Na^+} = \frac{\text{Current transported by Na}^+}{\text{Total Current}} \]  

In developing the expression for \( T_{Na^+} \), Silva and Bassiouni were using the same assumption used by Smits where the current carried by the clay counter-ions is parallel to that carried by the solution saturating the pore space. Assuming equal composition and ionic mobility, according to S-B, the transport number in shaly sands can be expressed as:

\[ T_{Na^+} = \frac{C_{eq} \cdot Q_v + t_{Na^{hf}} \cdot (1 - v_{fdl}) \cdot C_w}{C_{eq} \cdot Q_v + (1 - v_{fdl}) \cdot C_w} \]  

(2.19)

Where \( t_{Na^{hf}} \) is the sodium’s Hittorf transport number that is known as the motion of ions relative to that of water. Substitute equation (2.19) to equation (2.14), yield the membrane potential equation:

\[ E_m = \frac{-2R.T}{F} \int_{h_2}^{h_1} \left[ \frac{C_{eq} \cdot Q_v + t_{Na^{hf}} \cdot (1 - v_{fdl}) \cdot C_w}{C_{eq} \cdot Q_v + (1 - v_{fdl}) \cdot C_w} \right] d\ln(m \cdot \gamma^\pm) \]  

(2.20)

2.2.2 Determination of Hittorf Transport Numbers, \( t_{Na^{hf}} \)

Stokes\(^{15}\), based on the Fouss-Onsager theory of conductance, tried to derive a theoretical expression to approximate the Hittorf transport numbers. For NaCl slolution at 25\(^{\circ}\)C, the Stoke equation is given by:

\[ t_{Na^{hf}} = \frac{50.1 + 55.402 \sqrt{n}}{126.45 + 155.726 \sqrt{n}} \]  

(2.21)

where \( n \) is the electrolyte concentration in molar units, and at the same condition the molal concentration, \( m \), of NaCl solution can be calculated as\(^{16}\):
\[ m = \frac{n \times 10^3}{9.8986 \times 10^2 + 41.839n^{0.96} - 58.448n} \]  \hspace{1cm} (2.22)

2.2.3 Determination of Mean Activity Coefficient, \( \gamma^\pm \)

The Debye-Hückel theoretical expression for the mean activity coefficient for the NaCl solution at 25°C is given by\(^{15}\):

\[
\log \gamma^{298}_\pm = \frac{-0.5115 \sqrt{n}}{1 + 1.3065 \sqrt{n}} - 1.75 \log a_A - \log(1 - 0.027m) \]  \hspace{1cm} (2.23)

where:

\[ a_A = 9.9948 \times 10^{-1} - 3.059 \times 10^{-2} m - 1.5075 \times 10^{-3} m^2 \]  \hspace{1cm} (2.24)

where \( m \) is the electrolyte concentration in molal units.

2.2.4 Solving the Membrane Potential

The membrane potential equation (2.20) can be solved using the procedures suggested by Thomas\(^{14}\) based on the relationships between the main variables and the electrolyte concentration:

1. Divide the concentration interval, \( m \), into 100 subinterval points \( m(i) \).
2. For each \( m(i) \), the corresponding molarity \( n(i) \) is calculated by a trial-and-error procedure using equation (2.23).
3. The magnitudes of \( C_{eq}, v_{fdl}, t_{Na}^{hf}, \gamma^\pm, \) and \( C_w \) are evaluated for each concentration subinterval, and each \( T_{Na}^+(i) \) is computed.
4. Multiply the result by 51.38, the value of the constant \( 2RT/F \) at 25°C.
5. The final result is then taken as the magnitude of the membrane potential.

This procedure is repeated for each case and for each concentration interval.
2.3 LSU Model

Although S-B models is a reliable models to express the resistivity behavior and membrane potential of a shaly sand, the use of some empirical parameters such as \( f_{g} \), \( F_{(ne)} \), and \( \tau \) which can not be adapted to the high temperature condition, have created some limitations in the application of S-B models to field condition.

A new modification of S-B model by Lau\(^{16,17,18}\) to eliminate the use of empirically derived correction factor is known as the LSU model. The modification is based on electrochemical properties of sodium chloride solutions and experimental observation. This model has further extended the application to temperature more than 25\(^{\circ}\)C.

2.3.1 Conductivity Model

According to S-B model, the concentration of clay counter-ion, \( n_{eq} \), is assumed to be independent of \( Q_{v} \), and only a function of the free electrolyte concentration as shown in equation (2.8). To satisfy this assumption, an empirically determined correction factor, \( f_{g} \), was introduced so that the curve fitting can be improved. On the other hand, LSU model assumes that the counter-ion concentration is a function of both \( Q_{v} \) and the free electrolyte concentration so that the need of \( f_{g} \) can be eliminated. Therefore, LSU model use equation (2.3) by Waxman and Smits\(^{7}\) to calculate \( n_{eq} \). At temperature higher that 25\(^{\circ}\)C the expression becomes:

\[
\begin{align*}
\text{n}_{eq} &= \frac{Q_{v}}{v_{f}} \frac{T_{a}}{298} \\
\end{align*}
\]

(2.25)

where \( T_{a} \) is the absolute temperature, \(^{\circ}\)K.
For sodium chloride solutions at 25°C, S-B model expressed the equivalent counter-ion conductivity, $C_{eq}$, as shown in equation (2.9). This model utilized the empirically determined correction factor, $F_{(ne)}$, to address the ionic interactions at moderate and high concentration. LSU model eliminate the use of $F_{(ne)}$ by using an analytical expression for $C_{eq}$ from published experimental data\textsuperscript{18}:

$$\ln(C_{eq}) = -58.84 - 0.1026 n_{eq} - 0.787 \ln(n_{eq}) - 0.0216 T_a + 11.85 \ln(T_a)$$  \hspace{1cm} (2.26)

According to LSU model, fractional volume occupied by the double layer, $v_{fdl}$ is expressed as:

$$v_{fdl} = (0.28 - 0.0344 \ln(T/25)) \cdot f_{dl} \cdot Q_v$$  \hspace{1cm} (2.27)

where:

$$f_{dl} = \sqrt{\frac{T_a}{X_H^2 \cdot B_0^2 \cdot n.298}}$$  \hspace{1cm} (2.28)

$$X_H = 6.18 \text{ Å}$$

$$B_0 = 0.3248 + 1.5108 \times 10^{-4} T + 8.935 \times 10^{-7} T^2$$  \hspace{1cm} (2.29)

$$\ln(n) = 68.1 - 13.58 \ln(T_a) + 0.0229 T_a + 1.1851 \ln(C_w) + 0.00467 C_w$$  \hspace{1cm} (2.30)

2.3.2 Membrane Potential Model

LSU model modify the basic expression of the membrane potential in shaly-sands obtained by Smits\textsuperscript{13} and reported by Thomas\textsuperscript{14} shown in equation (2.14) to become:

$$E_m = \frac{-2.R.T}{F} \int_{m_{1/2}}^{m_{1/2}} \left[ \frac{C_{eq} \cdot Q_v + t_{Na^+} \cdot (1 - v_{fdl}) \cdot C_w}{C_{eq} \cdot Q_v + (1 - v_{fdl}) \cdot C_w} \right] \ln(m \cdot \gamma^\pm)$$  \hspace{1cm} (2.31)

where $t_{Na^+}$ the transport number of electrolyte corrected for the transport of water.
The expression of Hittorf transport number of NaCl solution at 25°C as shown in equation (2.21) is reliable only when the concentration is below 0.3 mol/l. In the condition where NaCl solution has a concentration of greater than 0.3 mol/l, Hittorf transport number $(t_{Na^{\text{hf}}})$ is obtained by analyzing some experimental data from several sources\textsuperscript{17}. The result for the concentration between 0.25 and 4.0 mol/l is given as:

$$t_{Na^{\text{hf}}} = -0.009 \ln(n) + 0.366 \quad (2.32)$$

LSU model also introduced the used of water transport number $(t_{w})$ to improve the membrane potential calculation, especially when the ions are hydrated in the aqueous solutions at moderate and high concentrations\textsuperscript{18}. It can be written as a function of $Q_{v}$ and free water molar concentration:

$$t_{w} = t_{fw} \cdot Q_{v} \quad (2.33)$$

where:

$$t_{fw} = -0.07 \ln(n) + 0.98 \quad \text{for } n < 0.7 \quad (2.34a)$$

$$t_{fw} = -0.006n^{3} - 0.052n^{2} - 0.1626n + 0.251 \quad \text{for } n \geq 0.7 \quad (2.34b)$$

### 2.3.3 THE SP MODEL

According to LSU model the SP log response in mainly the result of electrochemical potential rather than electrokinetic. Since the electrokinetic effects are considered small, it will be neglected. In front of a permeable zone, SP log response can be expressed as\textsuperscript{19}

$$SP = E_{m_{sh}} - E_{m_{ss}} \quad (2.35)$$

where $E_{m_{sh}}$ and $E_{m_{ss}}$ is the electrochemical potential of shale and sand, respectively. In term of transport numbers, this model in given as:
$$SP = \frac{-2RT}{F} \int_{m_2}^{m_1} \left( T_{Na^{sh}} - T_{Na^{ss}} \right) d\ln(m_{\gamma^\pm})$$  \hspace{1cm} (2.36)$$

where $T_{Na^{sh}}$ and $T_{Na^{ss}}$ is the sodium transport number in shale and sand, respectively.

Applying the general expression of the sodium transport number ($T_{Na}$), the equation (2.36) becomes:

$$SP = \frac{-2RT}{F} \int_{m_2}^{m_1} m_{\text{eff}} d\ln(m_{\gamma^\pm})$$ \hspace{1cm} (2.37)

$$+ \frac{2RT}{F} \int_{m_2}^{m_1} \left[ \frac{C_{eq} n_{eq} v_{fdl} + \mu_{Na}^+ (1 - v_{fdl}) C_w}{C_{eq} n_{eq} v_{fdl} + (1 - v_{fdl}) C_w} \right] d\ln(m_{\gamma^\pm})$$

where $m_{\text{eff}}$ is the membrane efficiency. In a perfect or ideal shale membrane, only sodium ions will transport the current. Therefore the membrane is assigned as 100% membrane efficiency. In a less perfect or non-ideal membrane where chloride ions will also contribute to the conductivity across the shale, the membrane efficiency will be less than 100%. This membrane efficiency, $m_{\text{eff}}$, is an empirical determined factor that equivalent to $T_{Na^{sh}}$.

Membrane efficiency ($m_{\text{eff}}$), $\gamma^\pm$ and $\mu_{Na}^+$ can be expressed as function of $Q_v$ and $C_w$. The expressions will be discussed hereafter.

In order to determine the value of $m_{\text{eff}}$, equations (2.35) and (2.5) are re-arranged to become:

$$m_{\text{eff}} = \frac{-F}{2RT} \left( \frac{SP + E_{m_{ss}}}{m_{\text{eff}}} \right)$$ \hspace{1cm} (2.38)

and
\[ C_{o,F_e} = \frac{C_{eq,nEq \cdot v_{fdl}} + (1 - v_{fdl})C_w}{T_{Na_{ss}}} \]  

(2.39)

There are three unknown in both equation, namely \( Q_v \), \( C_w \), and \( m_{eff} \). The value of \( Q_v \) is zero if clean sand is present, so \( m_{eff} \) can be calculated simultaneously using both equations. Otherwise, \( m_{eff} \) value can be determined using trial and error method on the same equations.

The relation between mean activity coefficient, \( \gamma_{\pm} \), and \( C_w \) is given as:

\[
\log(\gamma_{\pm}) = \log(\gamma_{\pm}^{298}) + 0.5Y.L_{298} - 0.5Z.J_{298}
\]

(2.40)

where the calculation of mean activity coefficient at 25\(^0\)C, \( \gamma_{\pm}^{298} \), is shown in equation (2.23) and equation (2.24), the rest are given as:

\[
Y = \frac{298.15 - T_a}{8.3147(298.15)2.3026(T_a)}
\]

(2.41)

\[
Z = 298.15 Y - \frac{1}{8.3147} \log\left(\frac{T_a}{298.15}\right)
\]

(2.42)

\[
L_{298} = \frac{2878.6 \sqrt{m}}{1 + \sqrt{m}} - 3182.8m + 986.5 \sqrt{m^3}
\]

(2.43)

\[
J_{298} = \frac{43.5 \sqrt{m}}{1 + \sqrt{m}} + 72m - 20.36 \sqrt{m^3}
\]

(2.44)

where for sodium chloride solutions the molality, \( m \), can be calculated using the relation with the molarity, \( n \) as:

\[
\ln(m) = 1.5054 + 1.0142 \ln(n) + 0.272 \ln(T_a)
\]

(2.45)

The sodium chloride transport number, \( t_{Na}^+ \), can be associated to \( Q_v \) and \( C_w \) through the given equation:

\[
t_{Na}^+ = t_{Na}^{hf} + t_w
\]

(2.46)
where:

\[
\ln(t_{Na}^{hf}) = -2.5089 - 1.8038 \times 10^{-2} \ln(m) + 0.2647 \ln(T_a) \\
- 1.4176 \times 10^{-5} \cdot T_a \cdot m)
\]  

and

\[
t_w = 0.053m - 0.43 + (0.196 \ln(m) + 0.1244)Q_v; \text{ for } m \leq 1.0 \\
t_w = 0.036m^{1.1} - 0.04377 + 0.04Q_v; \text{ for } m > 1.0
\]

In water bearing sand the value of \(C_o\) and \(SP\) can be obtained from wireline logs. Consequently, it is possible to calculate the value of \(Q_v\) and \(C_w\) simultaneously since both conductivity and spontaneous potential can be expressed exclusively as function of \(Q_v\) and \(C_w\).
3.1 Field Description

JR field was discovered in 1973 and has been producing since then. It is located in Central Sumatra Basin, Indonesia. As shown in Figure 3.1, there are 3 oil-bearing formations in the JR field: X, Y and Z. The Z formation contributes 80% of the overall JR field oil production. Z formation is characterized by thick layer of well-developed stacked-channel sand that has better reservoir quality such as porosity and permeability compared to the other two. X and Y formation have lower reservoir quality due to the occurrence of clay minerals. Between those two formations, Y formation is often being under estimated because of its higher shaliness and low resistivity. Several production tests from different wells indicated the presence of hydrocarbon in some intervals of Y formation. The shale effect in the reservoir rock with low salinity formation water has created a complication in the interpretation process. In the current approach, many interpretations models were used because it was difficult to find a unique model that gives reliable results.

The LSU model\textsuperscript{18} will be tested to determine whether this model is applicable to the typical reservoir characteristics in JR field. The result will be then compared to other models that are frequently used in this area. For discussion purpose, Archie model that was designed for use in clean sand formation will also be used to evaluate the same shaly sand interval beside other models such as: Simandoux Model and Poupon-Leveaux “Indonesia” Model. The results will then be validated using production test result from wells that has perforation interval in Y formation.
Figure 3.1 – Typical log curves of three oil-bearing formations in JR field

Data are available from 27 wells in JR field. Most of them have the basic log curves: Gamma Ray (GR), Spontaneous Potential (SP), Resistivity (Deep and Shallow), and Density (RHOB). Few wells have additional curves: Sonic (DT),
Neutron (NPHI), and Micro Resistivity (MSFL). There are also other useful data such as water analysis, core analysis, and production test results.

3.2 Archie Model

Archie, using experimental studies of clean formations came to an empirical relationship to calculate the water saturation of a hydrocarbon-bearing zone when an obvious water-bearing zone of the same porosity and water salinity is close by. The relation is given as:

\[
S_w = \frac{n \cdot a \cdot R_w}{\phi^m \cdot R_t}
\]  

(3.1)

where:

- \( S_w \) = water saturation, fraction
- \( n \) = saturation exponent
- \( a \) = cementation factor
- \( m \) = cementation exponent
- \( \phi \) = porosity, fraction
- \( R_w \) = formation-water resistivity, ohmm
- \( R_t \) = invasion corrected deep resistivity, ohmm

3.3 Simandoux Model

Simandoux in 1963 published his saturation model, which initially gained a wide acceptance. This saturation model is based on resistivity, density and neutron logs data. The model as shown in chapter one, is expressed as:

\[
C_t = \frac{C_w \cdot S_w^n}{F_e} + V_{sh} \cdot C_{sh}
\]  

(3.1)

In different form and for sandstone reservoir, this equation can be expressed as:
\[ S_w = \frac{0.4 \cdot R_w \cdot 5 \cdot \phi_e^2}{R_w \cdot R_t + \frac{V_{sh}}{R_{sh}}} - \frac{V_{sh}}{R_{sh}} \] (3.2)

Where:

- \( V_{sh} \) = shale volume, fraction
- \( R_{sh} \) = deep resistivity reading in adjacent shale, ohmm
- \( \phi_e \) = effective porosity, fraction

The effective porosity is calculated from:

\[ \phi_e = \sqrt{\frac{(\phi_{dc}^2 + \phi_{nc}^2)}{2}} \] (3.3)

where \( \phi_{dc} \) and \( \phi_{nc} \) are shale corrected porosities for density and neutron, respectively. In the case where neutron logs are not available, the effective porosities will only be determined from density logs. In Simandoux equation, the Volume of shale (Vsh) term does not correspond fully to the original Vsh definition because of clay mineral (montmorillonite) used in his experiments was not in a fully wetted state when the mixture was made.

### 3.4 Indonesia Model

In 1971, Poupon and Leveaux\(^2\) proposed an empirical model called “Indonesia formula”. This equation was developed based on the typical characteristic of fresh formation waters and high degrees of shaliness that presents in many oil reservoirs in Indonesia. In this model the conductivity relationship between \( R_t \) and \( S_w \) is a result of conductivities of the clay, formation water and additional conductivity from the interaction between both of them. The empirical relationship can be written as:
This equation introduced an exponent of $V_{sh}$ that is itself a function of $V_{sh}$ to accommodate the non-linear zone of Figure 2 in chapter one. Effective porosity calculations are also based on equation (3.3).

### 3.5 LSU Model

LSU model was proposed by Lau and Bassiouni\textsuperscript{14,15,16} as a modification of previous Silva-Bassiouni model\textsuperscript{12} by eliminating some empirically derived correction factors so that the application can be easily extended to formation temperatures other than 25°C. This model is based on the assumption that clay counter-ions behave as an equivalent sodium chloride electrolyte.

There are two equations in LSU model that should be used together: (1) conductivity model and (2) spontaneous potential model. The conductivity and spontaneous potential are given, respectively, by:

$$C_t = \frac{S_w^n}{F_0} \left[ C_{eq} \cdot n_{eq} \cdot v_{fdl} + (1-v_{fdl}) \cdot C_w \right]$$  \hspace{1cm} (2.5)

$$SP = \frac{-2\cdot R \cdot T}{F} \int_{m_2}^{m_1} m_{eff} \ln(m \cdot \gamma^\pm) \, \, dm$$  \hspace{1cm} (2.37)

$$+ \frac{2 \cdot R \cdot T}{F} \int_{m_2}^{m_1} \left[ \frac{C_{eq} \cdot n_{eq} \cdot v_{fdl} + t_{Na} \cdot (1-v_{fdl}) \cdot C_w}{C_{eq} \cdot n_{eq} \cdot v_{fdl} + (1-v_{fdl}) \cdot C_w} \right] \ln(m \cdot \gamma^\pm) \, \, dm$$

There are four unknowns in the above equations, namely $C_w$, $m_{eff}$, $S_w$, and $Q_v$. The best method to determine $C_w$ is by chemical analysis of formation water samples. Because this field is characterized by low salinity formation water that makes the water analysis very sensitive to contaminant, it is difficult to determine the...
correct $C_w$ from water analysis. The low salinity can be observed from water analysis listed in Table 3.1. The analysis is from several wells in different intervals. It is possible to calculate $C_w$ and $m_{eff}$ simultaneously by applying the LSU model in a clean water bearing formation because $S_w$ and $Q_v$ values are equal to 1 and 0, respectively. By applying the $C_w$ and $m_{eff}$ from clean sand water analysis to LSU model in shaly sand containing potential hydrocarbon, $S_w$ and $Q_v$ can also be determined simultaneously. The consistency of $C_w$ and $m_{eff}$ calculated in water zone from several wells using LSU model can be observed in Table 3.2. This result shows that LSU model is a better tool for determining the both parameters where other methods have failed.

Table 3.1 – Water salinity analysis from different well in different intervals

<table>
<thead>
<tr>
<th>Well</th>
<th>Formation</th>
<th>NaCl Eq. (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Z</td>
<td>1758.7</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>342.6</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>472.9</td>
</tr>
<tr>
<td>C</td>
<td>Y</td>
<td>2887.3</td>
</tr>
<tr>
<td>D</td>
<td>Z</td>
<td>595.7</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>853.8</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>762.3</td>
</tr>
<tr>
<td>G</td>
<td>Z</td>
<td>732.4</td>
</tr>
<tr>
<td>M</td>
<td>X</td>
<td>5556.1</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>143.7</td>
</tr>
<tr>
<td>N</td>
<td>Z</td>
<td>1433.5</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>1510.6</td>
</tr>
<tr>
<td>O</td>
<td>Z</td>
<td>650.2</td>
</tr>
<tr>
<td>P</td>
<td>Z</td>
<td>352.6</td>
</tr>
<tr>
<td>Q</td>
<td>Z</td>
<td>698.7</td>
</tr>
<tr>
<td>R</td>
<td>Z</td>
<td>930.6</td>
</tr>
</tbody>
</table>
Table 3.2 – Water conductivity and membrane efficiency calculated from LSU models

<table>
<thead>
<tr>
<th>Well</th>
<th>Cw (mho-m)</th>
<th>meff</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1.441</td>
<td>0.946</td>
</tr>
<tr>
<td>C</td>
<td>1.656</td>
<td>1.025</td>
</tr>
<tr>
<td>D</td>
<td>1.537</td>
<td>1.040</td>
</tr>
<tr>
<td>E</td>
<td>1.691</td>
<td>1.025</td>
</tr>
<tr>
<td>P</td>
<td>1.423</td>
<td>1.091</td>
</tr>
<tr>
<td>S</td>
<td>1.547</td>
<td>0.836</td>
</tr>
<tr>
<td>T</td>
<td>1.527</td>
<td>1.098</td>
</tr>
<tr>
<td>U</td>
<td>1.537</td>
<td>1.040</td>
</tr>
</tbody>
</table>

The input data for LSU model consist of: spontaneous potential (SP), formation conductivity (Cs), and formation factor (Fe). While SP and Cs can be determined directly from the logs, Fe need to be calculated using:

$$F_e = \frac{a}{\phi^m}$$

(3.5)

In order to get an accurate Fe, the value of a and m usually need to be determined using special core analysis. Unfortunately, there are no core data available in Y formation, so all the evaluation are using core data from the formation above and below the zone of interest such as X and Z formation. An a value of 1 and m value of 1.6 were determined from the average value from all the cores because they all corresponded to a similar trend as shown in Figure 3.2. Those values will be used to determine the formation factor, Fe, for the rest of the wells.

In some of the wells porosity, \(\phi\), are determined using the neutron-density cross-plot method, while in most of the other wells the porosity data can be determined either from density log or neutron log alone. The porosities obtained from cross-plot or one log method was compared to porosity from core analysis of
well B, well K and well L. The result showed a reasonable agreement (Figure 3.3).

The measured porosity and formation factor values are listed in Table 3.3.

Table 3.3 – Measured formation factor from special core analysis

<table>
<thead>
<tr>
<th>Well</th>
<th>Formation</th>
<th>Depth</th>
<th>Porosity</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Z</td>
<td>5122.0</td>
<td>0.176</td>
<td>16.332</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5133.1</td>
<td>0.161</td>
<td>17.177</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5136.8</td>
<td>0.181</td>
<td>15.441</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5144.8</td>
<td>0.373</td>
<td>4.615</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5151.8</td>
<td>0.181</td>
<td>15.702</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5168.5</td>
<td>0.207</td>
<td>13.011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5184.3</td>
<td>0.195</td>
<td>13.354</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5192.2</td>
<td>0.211</td>
<td>12.444</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5212.6</td>
<td>0.164</td>
<td>17.545</td>
</tr>
<tr>
<td>K</td>
<td>Z</td>
<td>5134.9</td>
<td>0.183</td>
<td>15.064</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5154.2</td>
<td>0.226</td>
<td>10.891</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5166.5</td>
<td>0.197</td>
<td>13.308</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5183.4</td>
<td>0.202</td>
<td>12.659</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5196.0</td>
<td>0.138</td>
<td>23.535</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5204.5</td>
<td>0.197</td>
<td>13.212</td>
</tr>
<tr>
<td>L</td>
<td>X1</td>
<td>4670.5</td>
<td>0.209</td>
<td>13.529</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4686.3</td>
<td>0.229</td>
<td>10.953</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4696.5</td>
<td>0.253</td>
<td>9.793</td>
</tr>
</tbody>
</table>

Figure 3.2 – Relationship between formation factor ($F_e$) and porosity ($\phi$) from special core analysis
3.6 Result Analysis and Discussion

Log data of Y formation from 11 wells were analyzed using various shaly sand interpretation models. These wells were chosen because of the availability of production data from the interval analyzed. The water cut ($f_w$) will be used to validate the calculated water saturation values. Validation was done by comparing the average calculated water saturation to the production test result within the same test interval.

Since Y formation in these different wells were from the same depositional environment, therefore the clay type and formation water resistivity were also presumably similar. This similarity made it possible to use some parameters that
could directly be calculated using data from one well, such as water conductivity and membrane efficiency, to other near by well where direct calculation was not possible.

Archie model was used to generate a base value. It is known that in a shaly sand formation, this technique overestimated the value of water saturation. Thus, in a shaly formation, a shaly sand model should yield a saturation value less than that given by Archie’s model. How much can other model results differ from Archie’s in a shaly formation will be evaluated using some core and fluid analysis data.

**Figure 3.4a** indicated that at well C, the existing perforation intervals were set on 70% of water saturation cut off. This cut off is based on the commonly used Indonesia model.

![Diagram](image-url)  
**Figure 3.4a** – Water saturation comparison between Indonesia and LSU models at well C
However, as shown in Figure 3.4b this model has failed to identify a potential hydrocarbon zone at well B in the upper part of Y formation because the calculated water saturations are above the water saturation cut off. On the other hand, in the same zone, LSU model has indicated a potential bypassed hydrocarbon potential. The validation of LSU model using production data is very important to improve the confidence of its calculation result.

Figure 3.4b – Water saturation comparison between Indonesia and LSU models at well B
Figure 3.5 shows a comparison of the result from LSU model and the others such as Archie, Simandoux and Indonesia model from all wells. This graph clearly indicates that the water saturations calculated from LSU model are approximately 20% lower than others. In most of the cases result from Simandoux and Indonesia model are very close to the result of Archie model. Since the Archie could not generate a good estimation of water saturation in shaly sand formation, therefore Simandoux and Indonesia are not appropriate models for this formation.

Figure 3.5 – Comparison of calculated water saturation between LSU model and Archie, Simandoux and Indonesia model from 11 wells.
The difference between Simandoux and Indonesia models from Archie’s can be observed from Figure 3.6. Water saturation calculation from both equations showed approximately 5% - 7% lower than Archie method. In fact in the range of saturation of interest, i.e 20%-40%, these three methods give the same value. The insignificant difference made by these two methods compared to Archie method has demonstrated that Simandoux and Indonesia model are not making a substantial improvement of water saturation analysis in this particular shaly sand reservoir characterized by low water salinity formations.

![Figure 3.6](image-url)
The relationship between calculated result and actual test data was done by comparing the average calculated water saturation within the perforated zone with the fractional water, $f_w$, calculated from production test.

**Figure 3.7** shown a familiar shape of the relationship between the calculated water saturation and fractional water from production data using LSU and Indonesia models. Unlike the result from Indonesia models, the irreducible water saturation, $S_{wirr}$, of 27% and residual oil saturation, $S_{or}$, of 30% from LSU correspond well to those from core analysis of several wells. Core analysis indicated value of 20% - 30% of irreducible water saturation and 30% - 40% of residual oil saturation. The other points (**Figure 3.7**) that fall off from the common trend were possibly caused by water channeling from the watered out Z formation below.

<table>
<thead>
<tr>
<th>Well</th>
<th>Water Cut ($f_w$), fraction</th>
<th>Water Saturation ($S_w$), fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indonesia</td>
</tr>
<tr>
<td>A</td>
<td>0.96</td>
<td>0.727</td>
</tr>
<tr>
<td>B</td>
<td>0.05</td>
<td>0.502</td>
</tr>
<tr>
<td>C</td>
<td>0.28</td>
<td>0.645</td>
</tr>
<tr>
<td>D</td>
<td>1.00</td>
<td>0.670</td>
</tr>
<tr>
<td>E</td>
<td>0.10</td>
<td>0.563</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>0.618</td>
</tr>
<tr>
<td>F</td>
<td>0.99</td>
<td>0.742</td>
</tr>
<tr>
<td>G</td>
<td>0.10</td>
<td>0.564</td>
</tr>
<tr>
<td>H</td>
<td>0.20</td>
<td>0.558</td>
</tr>
<tr>
<td>I</td>
<td>0.70</td>
<td>0.503</td>
</tr>
<tr>
<td>J</td>
<td>0.98</td>
<td>0.452</td>
</tr>
<tr>
<td>L</td>
<td>0.80</td>
<td>0.648</td>
</tr>
</tbody>
</table>
Figure 3.7 – Relationship between average calculated water saturation and fractional water value from production test using LSU and Indonesia model
CHAPTER 4
SHALY SAND INTERPRETATION ALGORITHM

The practical approach to the use of the LSU model is to set up a comprehensive spreadsheet that incorporates the conductivity and membrane potential models. This spreadsheet can then be used for all the simultaneous calculations.

Preparation and quality check of all input data is very important to a representative output, especially for low SP deflection, which is encountered in low-salinity of the formation water conditions. Simple statistical methods can be used to determine the data distribution and to make a reasonable normalization. Borehole corrections are applied to resistivity and neutron-density data to determine the input conductivity and porosity, respectively.

There are typically four keys unknown parameters that need to be determined using both the conductivity and the membrane potential model. The four parameters are water conductivity ($C_w$), membrane efficiency ($m_{eff}$), cation exchange capacity ($Q_v$), and water saturation ($S_w$). It is necessary to assign a temporary value for the unknown in order to set up the calculation spreadsheet. The average value of water conductivity determined from laboratory analysis is a good starting point for $C_w$. Local knowledge of membrane efficiency is a valuable source a preliminary assigned value for $m_{eff}$; Value between 0.8 to 1.0 are also applicable. $S_w$ value of 1 and $Q_v$ value of 0 are also a reasonable preliminary value for establishing the comprehensive spreadsheet.
The algorithm described hereafter is a step-by-step approach using a set of data from one depth point. Same steps are repeated for the rest of intervals of interest.

4.1 The Algorithm of Conductivity Model

The conductivity model analysis is based on the following equation:

\[ C_t = \frac{S_w^n}{F_e} \left[ C_{eq} \cdot n_{eq} \cdot v_{fdl} + (1-v_{fdl}) \cdot C_w \right] \]  \hspace{1cm} (2.5)

The calculation algorithm of LSU conductivity model to interpret the water saturation in a shaly sand is shown in Figure 4.1 and described as following:

1. Prepare the temperature data in two units: \( T_a \) in Kelvin and \( T \) in Celcius.

2. Calculate the molarity of sodium chloride solutions \( (n_1) \) and mud filtrate \( (n_2) \), using a preliminary assigned value of \( C_w \) and the value of \( C_{mf} \) from mud data:

\[ \ln (n_1) = 68.1 - 13.5791 \ln(T_a) + 2.289 \times 10^{-2} + 1.1854 \ln(C_w) + 4.6761 \times 10^{-3} C_w \]  \hspace{1cm} (2.30)

\[ \ln (n_2) = 68.1 - 13.5791 \ln(T_a) + 2.289 \times 10^{-2} + 1.1854 \ln(C_{mf}) + 4.6761 \times 10^{-3} C_{mf} \]

3. Calculate the double layer thickness, \( f_{dl} \):

\[ f_{dl} = \sqrt{T_a / 6.18^2 \cdot B_o^2 \cdot n_1 \cdot 0.298} \]  \hspace{1cm} (2.28)

where:

\[ B_o = 0.3248 + 1.5108 \times 10^{-4} T + 8.935 \times 10^{-7} T^2 \]  \hspace{1cm} (2.29)

4. Calculate fractional volume of double layer, \( v_{fdl} \), using a preliminary assigned value of cation exchange capacity, \( Q_v \):

\[ v_{fdl} = (0.28 - 0.0344 \ln (T/25)) \cdot f_{dl} \cdot Q_v \]  \hspace{1cm} (2.27)
5. Calculate the equivalent counter-ion concentration, \( n_{eq} \):

\[
 n_{eq} = \frac{Q_v \cdot T_a}{v_{fdl} \cdot 298}
\]  

(2.25)

6. Calculate the molar counter-ion conductivity, \( c_{eq} \):

\[
c_{eq} = \exp \left( -58.84 - 0.1026 n_{eq} - 0.0787 \ln(n_{eq}) - 0.0216 T_a + 11.85 \ln T_a \right)
\]  

(2.26)

7. Calculate the true conductivity, \( C_t \) by using a preliminary assigned \( S_w \):

\[
 C_t = \frac{S_w^n}{F_e} \left[ c_{eq} \cdot n_{eq} \cdot v_{fdl} + (1 - v_{fdl}) \cdot C_w \right]
\]  

(1.7)

---

Figure 4.1 – Flow chart of formation conductivity calculation using Conductivity Model
4.2 The Algorithm of Membrane Potential Model

The analysis of Membrane Potential model is based on the following equation:

\[
SP = -\frac{2R\cdot T}{F} \int_{m_1}^{m_2} m_{\text{eff}} \, d\ln(m\cdot \gamma^\pm) 
+ \frac{2R\cdot T}{F} \int_{m_1}^{m_2} \left[ \frac{C_{eq}\cdot n_{eq}\cdot v_{fdl} + t_{Na^+} \cdot (1 - v_{fdl}) \cdot C_w}{C_{eq}\cdot n_{eq}\cdot v_{fdl} + (1 - v_{fdl}) \cdot C_w} \right] \, d\ln(m\cdot \gamma^\pm)
\]

(2.37)

The equation consists of two parts: first part is known as sodium transport number in shale and second part is in sandstones. In order to calculate spontaneous potential (SP), the equation above will be evaluated in two separate calculations then combined together at the end. Both calculations can be done using a simple trapezoid rule. Equation 2.37 will be schematically expressed as:

\[
SP = -\frac{2R\cdot T}{F} \left( m_{\text{eff}}^+ + h\cdot T_{Na^+} \right)
\]

(4.1)

4.2.1 Determination of \( m_{\text{eff}}^+ \):

Figure 4.2 shows the algorithm to calculate \( m_{\text{eff}}^+ \), with each step described as follows:

1. Calculate the molality of sodium chloride solutions (\( m_1 \)) and mud filtrate (\( m_2 \)):

\[
\ln (m_1) = 1.5054 + 1.0142 \ln (n_1) + 0.2721 \ln (T_a)
\]

(2.45)

\[
\ln (m_2) = 1.5054 + 1.0142 \ln (n_2) + 0.2721 \ln (T_a)
\]

2. Calculate the mean activity coefficient, \( \gamma^\pm \):

\[
\log (\gamma^\pm)^a = \log (\gamma^\pm^{298})^a + 0.5Y \cdot L_{298}^a - 0.5Z \cdot J_{298}^a
\]

(2.40)

\[
\log (\gamma^\pm)^b = \log (\gamma^\pm^{298})^b + 0.5Y \cdot L_{298}^b - 0.5Z \cdot J_{298}^b
\]

where:
\[
\log (\gamma^{298})^a = -0.5115 \sqrt{n_1} - 1.75 \log(a_A)^a \log(1-0.027m_1) \\
\log (\gamma^{298})^b = -0.5115 \sqrt{n_2} - 1.75 \log(a_A)^b \log(1-0.027m_2)
\]

\[(a_A)^a = 0.99948 - 3.0959 \times 10^{-2} (m_1) - 0.0015 m_1^2 \quad (2.24)\]

\[(a_A)^b = 0.99948 - 3.0959 \times 10^{-2} (m_2) - 0.0015 m_2^2 \]

\[Y = \frac{298.15 - T_a}{8.3147 (298.15) 2.3026(T_a)} \quad (2.41)\]

\[Z = 298.15 Y + \frac{1}{8.3147} \log(T_a / 298.15) \quad (2.42)\]

\[L_{298}^a = \frac{2878.6 \sqrt{m_1}}{1+\sqrt{m_1}} - 3182.8 m_1 + 986.5 \sqrt{m_1}^3 \quad (2.43)\]

\[L_{298}^b = \frac{2878.6 \sqrt{m_2}}{1+\sqrt{m_2}} - 3182.8 m_2 + 986.5 \sqrt{m_2}^3 \]

\[J_{298}^a = \frac{43.5 \sqrt{m_1}}{1+\sqrt{m_1}} + 72 m_1 - 20.36 \sqrt{m_1}^3 \quad (2.44)\]

\[J_{298}^b = \frac{43.5 \sqrt{m_2}}{1+\sqrt{m_2}} + 72 m_2 - 20.36 \sqrt{m_2}^3 \]

3. Solving the first part of the equation calculate \(m_{\text{eff}}^+\), using a temporary assigned \(m_{\text{eff}}^+\):

\[m_{\text{eff}}^+ = m_{\text{eff}} (\ln(m_1 \cdot \gamma^a) - \ln(m_2 \cdot \gamma^b)) \quad (4.2)\]

\(m_{\text{eff}}^+\) is equal to \(\int_{m_2}^{m_1} m_{\text{eff}} \, d\ln(m \cdot \gamma)\)
Figure 4.2 – Flow chart of $m_{\text{eff}}^+$ calculation using Membrane Potential Model

4.2.2 Determination of $T_{Na}^+$:

Figure 4.3 shows the algorithm to calculate $T_{Na}^+$, with detail description as following:

1. Divided the differences between $m_1$ and $m_2$ by 100:

   $$ h = \frac{m_1 - m_2}{100} \quad (4.3) $$

2. Set up a spreadsheet started with $m_2$ and keep adding $h$ until it reach the value of $m_1$. 

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3. For every point on step no.2, calculate hittroff transport number, \( t_{Na^{ht}} \):

\[
\ln(t_{Na^{ht}}) = -2.5089 - 1.8038 \times 10^{-2} \ln(m_1) + 0.2647 \ln(T_a) \\
- 1.4176 \times 10^{-5} T_a m_1
\]  
(2.47)

4. For every point on step no.2, calculate the water transport number, \( t_w \):

\[
t_w = 0.053 m_1 - 0.43 + (0.1961 \ln(m_1) + 0.1244)Q_v ; \text{ for } m \leq 1.0 \]  
(2.48)

\[
t_w = 0.036 m_{11.1} - 0.04377 + 0.04Q_v ; \text{ for } m > 1.0 \]  
(2.49)

5. For every point on step no.2, calculate the sodium chloride transport number, \( t_{Na^+} \), with equation:

\[
t_{Na^+} = t_{Na^{ht}} + t_w
\]  
(2.46)

6. For every point on step no.2, calculate the \( T_{Na^+(i)} \):

\[
T_{Na^+(i)} = \frac{c_{eq} \cdot n_{eq} \cdot V_{fdl} + t_{Na^+} (1 - V_{fdl}) \cdot C_w}{c_{eq} \cdot n_{eq} \cdot V_{fdl} + (1 - V_{fdl}) \cdot C_w}
\]  
(2.19)

7. Calculate \( T_{Na^+} \) by adding together all the \( T_{Na^+(i)} \):

\[
T_{Na^+} = (0.5T_{Na^+(1)} + T_{Na^+(2)} + \ldots + 0.5 T_{Na^+(101)})
\]  
(4.4)

8. Solving the second part of the equation by multiplying \( h \) and \( T_{Na^+} \).

\[
h \cdot T_{Na^+} \text{ is equal to } \int_{n2}^{n1} \left[ \frac{c_{eq} \cdot n_{eq} \cdot V_{fdl} + t_{Na^+} (1 - V_{fdl}) \cdot C_w}{c_{eq} \cdot n_{eq} \cdot V_{fdl} + (1 - V_{fdl}) \cdot C_w} \right] d\ln(m_{r\pm})
\]
4.3 The Simultaneous Solution

The calculated data that has been arranged in a spreadsheet format, are used as a pre-set up data with four keys unknown namely $C_w$, $M_{eff}$, $Q_v$, and $S_w$. The real calculations should commence when the measured input data from the log such as spontaneous potential (SP) and the formation conductivity ($C_f$) are incorporated.

In a water-bearing clean sand formation, two key parameters are known. They are the water saturation, $S_w$, equal to 1 and the cation exchange capacity, $Q_v$. 
equal to 0. Therefore the other two unknown namely water conductivity \((C_w)\) and membrane efficiency \((m_{\text{eff}})\) can be calculated simultaneously.

To evaluate water-bearing shaly sand, there are three keys unknown: water conductivity \((C_w)\), water saturation \((S_w)\), and cation exchange capacity \((Q_v)\). Using an iteration approach, these unknown can also be determined.

In hydrocarbon-bearing shaly sand, LSU models provide a possibility to calculate water saturation \((S_w)\) and the cation exchange capacity \((Q_v)\) simultaneously by incorporating the previous information found either in water-bearing clean sand formation or shaly sand.
CHAPTER 5

CONCLUSIONS

Modified Silva-Bassiouni model known as LSU models are based on cation exchange capacity and dual water concept where it treats the excess conductivity generated by the counter-ions associated with clay bound water as that of an equivalent sodium chloride solution. The models make use of a conductivity and a spontaneous potential model.

Using log data from 11 well of JR field in Central Sumatra Basin, Indonesia, these models were a superior to Vsh models in predicting the hydrocarbon potential of shaly sands containing low-salinity formation water. This is because of its ability to take into account not only the amount of shale in the formation but also the clay type. The analysis of irreducible water saturation and residual oil saturation using water cut data from production tests and special core analysis are in good agreement with the calculated water saturation using LSU models.

In clean water-bearing sand, water conductivity, $C_w$, and the membrane efficiency, $m_{\text{eff}}$, can be solved simultaneously. The results were more consistent and showed a better estimation of $C_w$ compared to other conventional methods. The ability of LSU models to determine the cation exchange capacity, $Q_v$, from log data has created an opportunity to supplement the $Q_v$ data which usually obtained from conventional core analysis.
NOMENCLATURE

\( a \quad = \quad \text{Archie’s constant} \)

\( a_A \quad = \quad \text{equivalent ion size, \( Å \)} \)

\( B \quad = \quad \text{Waxman’s equivalent counter-ion conductivity} \)

\( C_{\text{cl}} \quad = \quad \text{clay conductivity, mho-m} \)

\( C_{\text{eq}} \quad = \quad \text{equivalent counter-ion conductivity, mho-m} \)

\( C_{\text{eq}}^* \quad = \quad \text{equivalent vounter-ion conductivity for } S_w < 1, \text{ mho-m} \)

\( C_{\text{mf}} \quad = \quad \text{mud filtrate conductivity, mho-m} \)

\( C_{\text{sh}} \quad = \quad \text{shale conductivity, mho-m} \)

\( C_o \quad = \quad \text{conductivity of formation fully saturated with water, mho-m} \)

\( C_t \quad = \quad \text{formation conductivity, mho-m} \)

\( C_w \quad = \quad \text{water conductivity, mho-m} \)

\( C_{\text{we}} \quad = \quad \text{equivalent water conductivity, mho-m} \)

\( C_{\text{wN}} \quad = \quad \text{water conductivity at the neutral point, mho-m} \)

\( E_m \quad = \quad \text{electrochemical potential, mV} \)

\( E_{m_{\text{sh}}} \quad = \quad \text{electrochemical potential across shales, mV} \)

\( E_{m_{\text{ss}}} \quad = \quad \text{electrochemical potential across shaly sand, mV} \)

\( F \quad = \quad \text{Faraday’s constant} \)

\( F \quad = \quad \text{formation factor} \)

\( F^* \quad = \quad \text{formation factor in W-S model} \)

\( F_e \quad = \quad \text{formation factor in LSU model} \)

\( F_o \quad = \quad \text{formation factor in D-W model} \)
f_{dl} = expansion factor of the double layer

f_g = empirical correction factor

F_{(ne)} = empirical correction factor

GR = gamma ray log reading, API

J = total current in system

J_{Na^c} = current carried by clay counter-ion

J_{Na^b} = current carried by Na+ ions in the bulk phase

m = molality, mol/Kg H_2O

m = cementation exponent

m_{eff} = membrane efficiency

n = molarity, mol/l

n = saturation exponent

n_{eq} = equivalent counter-ion concentration, mol/l

Q_v = cation exchange capacity, meq/cc

Q_v' = cation exchange capacity for S_w < 1, meq/cc

R = universal gas constant

R_{sh} = shale resistivity, ohm/m

R_t = formation resistivity, ohm/m

R_w = formation water resistivity, ohm/m

SP = spontaneous potential log reading, mV

S_w = water saturation, fraction

T = temperature, °C

T_a = absolute temperature, °K
\( T_{\text{Na}^+} \) = sodium transport number
\( t_{\text{Na}}^{\text{hf}} \) = Hittorf transport number
\( T_{\text{Na}}^{\text{sh}} \) = shale transport number
\( T_{\text{Na}}^{\text{ss}} \) = shaly sand transport number
\( t_{\text{fw}} \) = free water transport number
\( t_{\text{w}} \) = water transport number
\( v_{\text{fdl}} \) = fractional volume of the double layer
\( v_{\text{fdl}}' \) = fractional volume of the double layer for \( S_w < 1 \)
\( V_{\text{sh}} \) = fractional volume of shale, fraction
\( X_H \) = 6.18 Å
\( \alpha \) = clavier’s double layer expansion factor
\( \beta \) = 2.05, constant
\( \gamma^\pm \) = mean activity coefficient
\( \gamma^\pm_{298} \) = mean activity coefficient at 25°C
\( \eta \) = empirical function of \( \alpha \)
\( \tau \) = empirical correction factor
\( \phi \) = porosity, fraction
\( \phi_{\text{dc}} \) = corrected density porosity, fraction
\( \phi_e \) = effective porosity, fraction
\( \phi_{\text{nc}} \) = corrected neutron porosity, fraction
\( \phi_T \) = total porosity, fraction
BIBLIOGRAPHY


APPENDIX A

COMPARISON OF CALCULATED VS. EXPERIMENTAL CORE POROSITY
Well K
APPENDIX B

RESULT COMPARISON OF LSU MODEL VS. ARCHIE MODEL, SIMANDOUX MODEL AND INDONESIA MODEL
Well B
Well C
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**Legend:**
- SP_2: SP_2 measurement
- LLD_1: LLD_1 measurement
- SWE LSO1: SWE LSO1 measurement
- SWE SIM: SWE SIM measurement
- SWE INDO: SWE INDO measurement
- SWE LSU: SWE LSU measurement
- SWE LDO: SWE LDO measurement
- SP_2: SP_2 measurement
- LLD_1: LLD_1 measurement
- SWE LSO1: SWE LSO1 measurement
- SWE SIM: SWE SIM measurement
- SWE INDO: SWE INDO measurement
- SWE LSU: SWE LSU measurement
- SWE LDO: SWE LDO measurement

**Well E Diagram**

- Well E Diagram showing various measurements and layers.
Well J
Well L
Sample No. : 1
Air Perm., (mD) : 81.83
Porosity, (%) : 18.144
Well B

Sample No. : 2
Air Perm., (mD) : 107.9
Porosity, (%) : 19.471
Sample No. : 3
Air Perm., (mD) : 249.4
Porosity, (%) : 22.985
Well K

Sample No. : 1
Air Perm., (mD) : 597.4
Porosity, (%) : 20.19
Sample No.       : 1
Air Perm., (mD) : 617.3
Porosity, (%)      : 22.873
APPENDIX D

CALCULATED WATER SATURATION DATA USING DIFFERENT MODELS
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VITA

(Bobby) Kurniawan was born in Jambi City, Indonesia, in July 18, 1973. In October 1996, he received a degree of Bachelor of Science in Geology from the Institute of Technology Bandung, Indonesia. In December 1996, he joined Schlumberger Oilfield Services as a field engineer and was assigned to Japan and Thailand. In March 1998, he accepted a job as a development geologist with Caltex Pacific Indonesia, a major oil company operating in Indonesia. In January 2001, he joined the Craft & Hawkins Petroleum Engineering Department at Louisiana State University to work towards a Master of Science degree in petroleum engineering. He is a member of Pi Epsilon Tau, the Society of Petroleum Engineers, and Indonesian Geologist Association.