Development of a Petrophysical Workflow for Low Resistivity Low Contrast Reservoir

By

Dayang Nadzirah Binti Haji Awang Jaafar

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
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In partial fulfilment of the requirement for the
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Approved by:

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(Dr. Gamal Ragab Gaafar)

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(AP Dr.Ismail Mohd Saaid)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH PERAK
JULY 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Dayang Nadzirah Binti Haji Awang Jaafar [G02372]

ABSTRACT

LRLC pay zone is generally recognized, due to low resistivity and low contrast reading from the well logs. This is associated with a variety of factors such as micro-porosity, very low water salinity of formation water, rock's mineral content such as conductive minerals and very thin inter-bedding of sand and shale. Due to limitation performance of conventional logging tool, many potential productive zones commonly with high irreducible water saturation are by passed and quantification of hydrocarbon volumes is under estimated. The main objective of this project is to propose a workflow diagram for LRLC formations evaluation specifically on clastic reservoirs. This is done by first trying to understand the depositional environment of LRLC formation; then later to the phenomenon involved in LRLC that is in other words the causes and relatively how it can affect the performances of logging tools. Some researchers have come up with a few approaches in order to solve the problems in LRLC formation. Their techniques are mostly using the advanced tools such as Nuclear Magnetic Resonance (NMR), Multi-component induction tool (3Dex^{TM}) and electrical borehole imaging (EBI). Main indicator in hydrocarbon determination is to compute the water saturation (S_w). Therefore, many published works carried out the special core analysis (SCAL) to determine the water saturation from this LRLC formation. The workflow can at least help petrophysicists to facilitate critical decision making for LRLC formation evaluation in a timely manner.

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ABBREVIATION & NOMENCLATURE

LIST OF ABBREVIATION

CEC - Cation exchange capacity

DW - Dual water model

EBI - Electrical borehole image

LRP - Low resistivity pay

LRLC - Low resistivity low contrast

LWD - Logging while drilling

NMR - Nuclear Magnetic Resonance

SP - Spontaneous Potential

WS - Waxman Smith Model

LIST OF NOMENCLATURE

S_w = Water saturation (Fractional)

S_{wirr} = Irreducible water saturation

R_w = Resistivity of the formation water (ohm-meters)

R_t = True Resistivity of the rock (ohm-meters)

m = Archie cementation Exponent

n = Archie Saturation Exponent

a = constant value

ϕ = Porosity (Fractional)

V_{lam} = bulk volume fraction of shale in lamina

R_{sd} = resistivity of clan sand lamina

R_{sh} = Resistivity of shale lamina

ϕ_{im} = Inter matrix porosity (includes pore occupied by fluids and dispersed shale)

q = fraction of inter matrix porosity occupied by dispersed shale

C_t = formation conductivity (obtained from deep resistivity log)

C_w = formation water conductivity

B = Specific conductivity of exchangeable cations (mohm/m or meq/cc)

Q_v = Clay cation exchange capacity

m^o = cementation factor of Waxman-Smiths

n^o = saturation factor of Waxman-Smiths

C_{wf} = Conductivity of free water

S_{wf} = Formation water saturation (not clay bound water)

S_{wt} = Total water saturation

C_{bw} = Clay bound conductivity

CHAPTER 1

INTRODUCTION

1.1 Background Study

Low resistivity low contrast (LRLC) reservoirs have been encountered throughout logging activities in the past. This type of reservoir has been found in several basins which are Angola, Argentina, Gulf of Mexico, North Sea, Indonesia, Malaysia, Italy, India, Nigeria and Venezuela [1]. The Gulf of Mexico basin is well known as the world's leading oil and gas producer from the LRLC reservoirs.

LRLC pay zone is generally recognized, due to its low resistivity and low contrast reading from the well logs. This is associated with a variety of factors such as micro-porosity, very low water salinity formation water, rock's mineral content such as conductive minerals and very thin inter-bedding of sand and shale [1].

Historically, LRLC pay zone is frequently interpreted either as a tight formation or water bearing zone from the conventional logging tools specifically resistivity logs. At the same time, some of the experts have over looked the economic significance of this LRLC pay zones. The resistivity log is use to differentiate between water bearing zones and oil bearing zones. The conventional logging often interprets LRLC as a pay zone containing high water saturation. However during production this zone turns out to produce hydrocarbons. Therefore, lately interest on this area has grown.

1.2 Problem Statement

Determination of petrophysical parameters in the LRLC reservoir with the conventional resistivity log is very complicated. During data acquisition using conventional logging tools, actual resistivity of such thin-bedded pay zones are not measured or misjudged due to its poor vertical resolution. Due to this limitation, many potential productive zones commonly with high irreducible water saturation are by passed and quantification of hydrocarbon volumes is under estimated.

In a low resistivity beds there is a small resistivity contrast between the water bearing zone and oil bearing zone. This often led to misinterpretation of the fluid formation, in other words whether the formation contain oil bearing zone or water bearing zone. On the other hand, water bearing zones containing relatively fresh water (or water of low salinity) will give high resistivity readings or resistivity readings will be variable. It commonly shows a high level of irreducible water saturation (S_{wiir}) that reduces further the resistivity readings [1][2].

However the LRLC phenomenon is primarily due to the shale content and clay mineral within the sand beds which generally known as shaly sand formation. Factors such as micro-porosity, conductive minerals and their distribution are commonly discussed among the petrophysicists and log analyst [2] [3].

1.3 Objectives

The main objective of this project is to propose a workflow diagram for LRLC reservoirs evaluation specifically in clastics reservoirs. This is by first trying to review on the problems and their causes that contribute to the LRLC phenomenon. Secondly is reviewing on approaches made by some researchers for the LRLC evaluations. Hence with the workflow diagram developed can at least guide the petrophysicist and the log analyst in timely manner in order to facilitate critical decision making on the LRLC formation evaluation. Producibility prediction for this type of reservoirs can also be improved.

1.4 Scope of Study

Referring to many researches which have been carried out, the way to approach the LRLC reservoirs is possibly using different types of data from different resource such core laboratory test, wireline logs, mud logs and from the sedimentological analysis.

Nuclear Magnetic resonance (NMR) became one of the most favourable advance tools used to identify the LRLC pay zone. This can help to define the irreducible and free water saturation and it also can define the effective porosity by integrating laboratory test on core to choose the T2 cut offs [4].

Resistivity and conductivity plays an important role in formation evaluation especially to identify the potential hydrocarbons within the beds. Recently some of the researchers have been looking at the resistivity tool with high vertical resolution and magnetic resonance tools to evaluate the LRLC problem. The grain size, fluid types and mobility, and clay distribution can now be characterized by using modern borehole imaging tools (E.g. magnetic resonance image logging [MRL] and electrical micro imaging [EMI]). These tools have been proved in the Gulf of Mexico on identifying the LRLC reservoir [5].

Baker Hughes Company has come up with their sophisticated multi-component induction tool which specifically able to identify the low resistivity zones which cause by finely laminated sand and shale intervals. It has the ability to measure the formation resistivity of a high anisotropy zone both vertically and horizontally [6].

In this project, firstly to appreciate the LRLC phenomenon, I need to understand and familiar with the geological factor that controls this phenomenon. This is especially trying to understand on the appearance of shale and clay effects behaviour in the formation. Then later, to understand theoretically the responses of those logging tools commonly used for LRLC evaluations. That is by looking at their techniques or tools used to solve the problems during their evaluation and involvement of analysis study from the laboratory. Determination of water saturation (S_w) is the key point to estimate the volume of hydrocarbon produce. Therefore this factor is the main aim on trying to relate all the techniques to predict whether in the end LRLC reservoirs may produce some hydrocarbons or vice versa. Result and discussion section will be referred to a case study of LRLC formation in clastic reservoir of Malay, Sarawak and Sabah Basin.

CHAPTER 2

LITERATURE REVIEW

2.1 Low Resistivity Low Contrast Reservoir

Low resistivity low contrast term is often grouped together however there are differences for both terms. Low resistivity pays is generally defined as a pay zone that gives lack contrast interpretation in electrical resistivity data, distinguishing the hydrocarbon pay zone and water bearing zone within the same reservoirs. Generally, deep resistivity log reading will be recorded around 0.5 ohm-m to 5 ohm-m [2] in the LRLC pay. Mentioned characteristics commonly occurs in sandstone or carbonate formations but often described in sandstones where it associates with thinly bedded low resistivity of shaly sand formation [7]. In a "Low Contrast" pay describes lack indication of resistivity contrast between adjacent shales and sands [2][8]. Poor vertical resolution from the conventional log to determine individual bed's properties leads to difficulty in distinguishing the potential interval from the adjacent shales. This also causes misinterpretation of resistivity data where it records high water saturation, however during production, oil was seen produced.

2.1.1 Depositional Environment of LRLC

According to Darling and Sneider [5], LRLC formation is usually found in major siliciclastic depositional environments with the exceptions of Aeolian deposits and alluvial fans. Figure 2.1 is showing model of principle depositional environment containing the LRLC reservoirs.

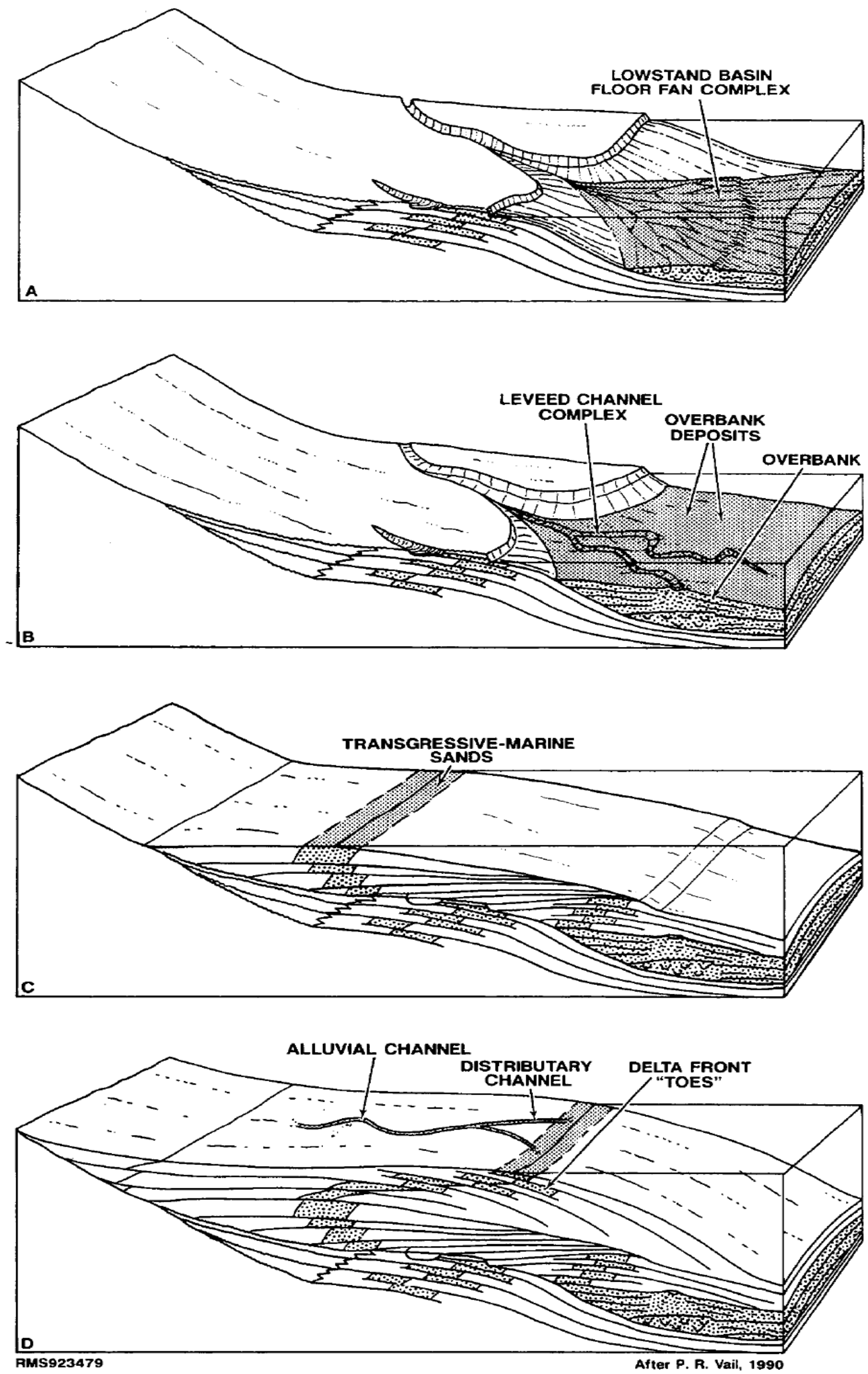

Figure 2.1: Common Depositional Environment for LRLC reservoir. A and B are lowstand systems, C is the transgressive system and D is the highstand alluvial and deltaic system (after Darling and Sneider) [5]

Fanini et al. [8] mentioned that world's hydrocarbon reserves which are contained in low resistivity, thinly laminated, low contrast, shaly sand formations normally found in deep water turbidities. Statistical studies recently reveal that globally turbidities are in immature exploration stage which in future believe to play an important economic role in exploration and production [3] [9].

2.1.2 Problems on Identifying LRLC Formation

Identification of LRLC pay problems from log data have been recognized since the first discovered in Pleistocene sandstone in Gulf of Mexico, Louisiana of the United States of America [10][11]. Figure 2.2 shows some overview behaviour of the LRLC phenomenon in well log data and lithological results from core data. From the resistivity log column, it can be seen that resistivity value gives a very low reading (mostly less 5 ohm.m) in the log and lithology analysis from laboratory shows that formation is mainly shaly sand formation with a thinly-bedded sequence.

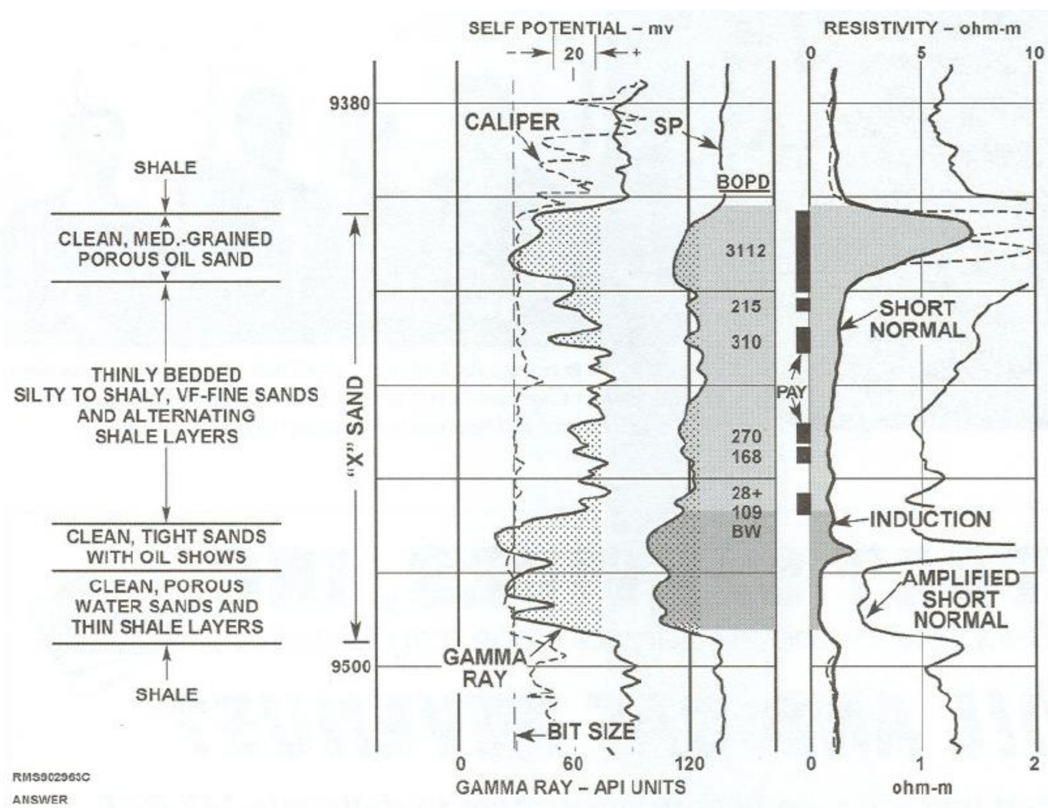

Figure 2.2: A sample of well logs and rock type obtained from "G" field of coastal Louisiana (after Sneider) [1].

Determination of this LRLC formation can be complicated to obtain straight away from the conventional logging. Shaly sand formation with thin bedded sequence is often by passed during data acquisition due to their limitation and their poor vertical resolution. Darling and Sneider [5] stated that resolution of the LRLC zone is thinner than the resolution available in the conventional logging tools. The normal resistivity tools commonly have twice vertical measurement than their coil spacing, whereas the modern induction device with special processing is able to reduce their vertical to about half of the coil spacing hence providing better resolutions (Figure 2.3). Besides being called as "Sand indicator", the resolution of the spontaneous potential is also a function ratio of mud filtrate to water formation and also bed thickness. Problem arises when the SP deflection is hard to define in the thin bed as shown in Figure 2.4.

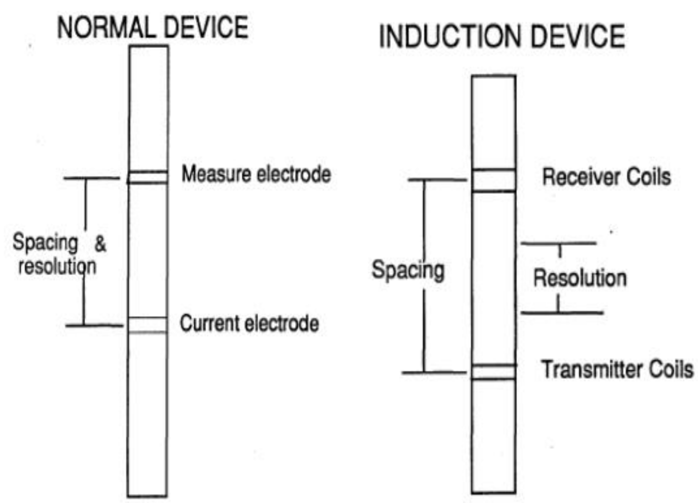

Figure 2.3: Schematics diagram of Normal and Induction resistivity device showing vertical resolutions (after Darling and Sneider) [5]

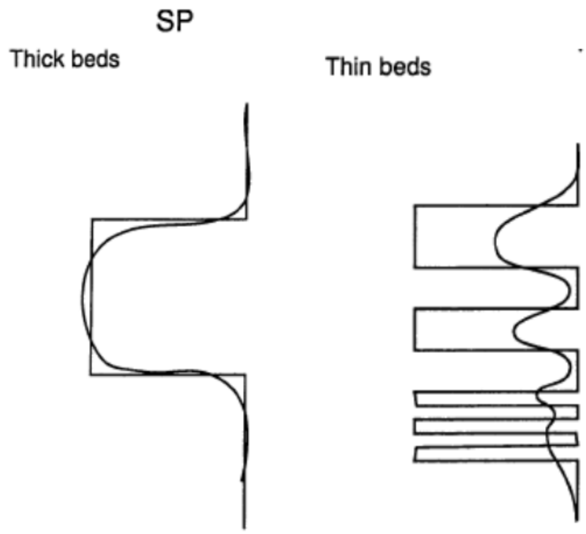

Figure 2.4: Schematics diagram of spontaneous potential deflection in thick and thins beds (after Darling and Sneider) [5]

Fresh formation water also plays an important role to the cause of the LRLC formation, especially when water bearing contains fresh formation water. It will give small resistivity contrast between water bearing and oil bearing which is often misleading. When the water salinity is low (less than 15 000 ppm equivalent to NaCl) the resistivity will be vary or high in resistivity readings and possible high irreducible water saturation [2] [3]. Other geological cause in LRLC formation includes conductive minerals (e.g chlorite and pyrite), fine grained (silty) sands, laminated sand/shale sequence, micro-porosity [2] [3]. Also, LRLC phenomenon may perhaps due to deep invasion by conductive mud, presence of fractures, presences of high capillary bound water and high relative angle well during drilling [7][11]. In short the primary cause towards this LRLC phenomenon is due to the shale and clay mineral contains especially shaly sand formation. These matters will be further discussed throughout this chapter.

2.2 Resistivity Anisotropy Associate with Vertical Resolution

Passey et al. [12] stated that there are three main reasons why evaluating the hydrocarbons pore thickness in thin bedded formation can be difficult, this is due to:

1. The well logs only records the petrophysical properties instead of the reservoir properties such as net sand thickness, sand porosity or water sand saturation.
2. Since the beds are too thin, the petrophysical log measurement takes an average value.
3. Some petrophysical properties are anisotropic.

Resistivity of the reservoir is a function of formation water salinity, effective porosity and volume of hydrocarbon present in pore space. Therefore it is one of important properties in order to evaluate whether formation can be producible [13]. Fluid in the formation is commonly known having two kinds of properties that are resistivity and conductivity. Electrical resistivity is the ability of electrical current flow through the substance represent by unit of ohm.m. Meanwhile electrical conductivity is the reciprocal of resistivity and having a unit of milliohms per meter (mmohm/m) [14]. When the interstitial water contains dissolved salt, later it will dissociate into cations (positive charge) and anions (negative charge). Existence of electric field allows ions to move, creating a current within the solution. This is also one of the reasons why resistivity recorded in fresh formation water low because it depends on the amount of the salt concentration it contains.

An anisotropic property depends on orientation or direction of measurement such as resistivity, conductivity and permeability. Figure 2.5 illustrates a volume measurement on too thinly bedded rock types, superposed system of x, y and z coordinate [12]. Passey et al. [12] stated that the effective conductivity of current flow in parallel bedding plane (Q_p) is different from conductivity of current flow in transverse bedding plane (Q_t).

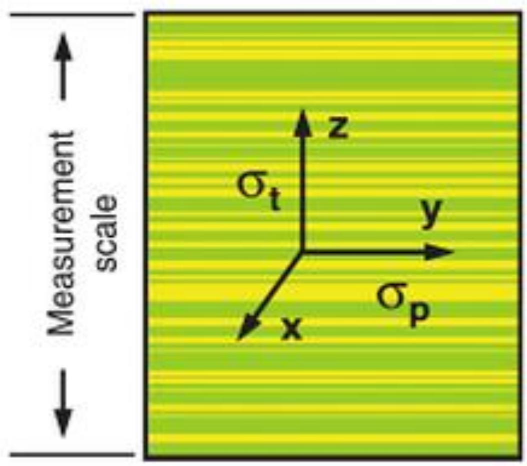

Figure 2.5: Anisotropic conductivity in thin-bedded formation (after Passey et al.) [12]

Due to some limitation in conventional logging tools, it becomes challenging when the petrophysicists or log analyst to evaluate those thinly bedded or laminated formation, dip beds or deviated drilled well at high angle [7]. Table 2.1 shows variation of bed thickness measurement adapted from Majid and Worthington[19] from their evaluation towards hydrocarbon reservoirs in thin bed sequences. Oifoghe [15] mentioned that the thin bedded is commonly exhibit resistivity anisotropy. He mentioned that when high resistivity sand layer bedded with low resistivity shale it will give significantly high resistivity reading in vertical (R_t) than the horizontal bedding (R_h). Instead of recording the hydrocarbon bearing resistivity, it measures the bed parallel (horizontal) resistivity of low shale resistivity domination which leads to low average resistivity reading from vertical resolution and high water saturation computed [15]. Figure 2.6 shows thinly bedded of shale-sand sequence containing hydrocarbon, where using multi-component induction tools gives a true value of vertical resistivity (R_t). Latest multi-component induction tool (3Dex™) from Baker Hughes is able to provide tensorial information on volumetric properties (e.g. saturation, porosity) and even on orientation and structure of the internal rock [8]. Therefore it helps to enhances evaluation on water saturation in conjunction with the capillary pressure curve and production data.

Table 2.1: Estimated bed thickness ranges for thin beds adapted from Majid and Worthington [19].

Estimated Bed Thickness Range (cm)	Types of thin bed
10 - 60	Moderately Thin
3.0 – 10	Thin
1.0 – 3.0	Very thin
0.1 – 1.0	Laminated

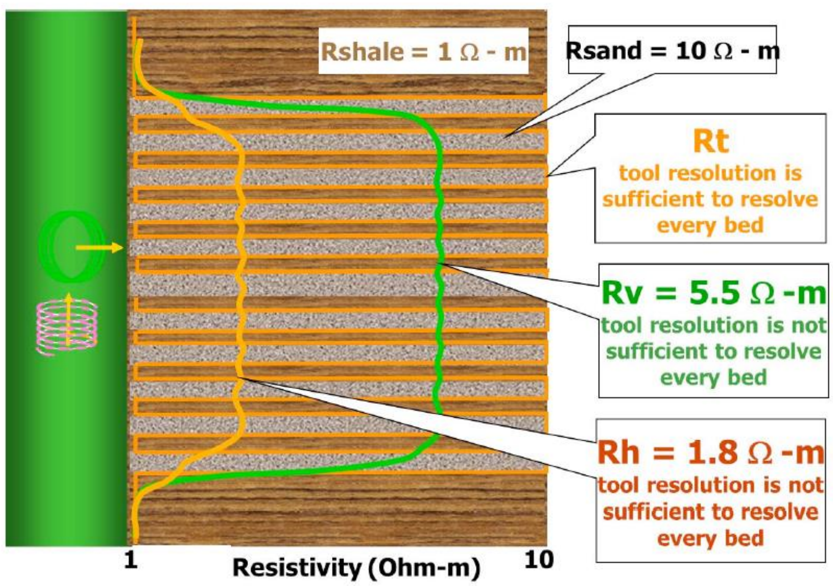

Figure 2.6: Measurement uncertainty in thin bedded formation (after Oifoghe) [15]

2.3 Shale and Clay Distribution in LRLC Formation

Petrophysicists' definition in formation evaluation of shale and clay has been used synonymously. Shale is made up of clastic sediments which comprised dominantly 60% of clay minerals and some silt-sized grains (e.g Feldspar, Quartz or organic fragments) [17]. Meanwhile clay is clastic sediments with a grain size diameter of less than 0.004 mm (less than 4 microns). It is an alumino silicate minerals consisting of smectite, chlorite, illite, montmorillonite and kaolinite [17].

Laminar clays are distributed in a reservoir as relatively thin layers of allogenic clay or shale that has been deposited between clean layers of sand [18]. Shaly sand from the name itself deduces formation containing sand and shale. Since 1950, it was only then shaly sand problems are fully recognized by petrophysicists and log analyst. They have been trying to develop over 30 water saturation (S_w) models in order to encounter the problems [19]. Whenever there is a substantial portion of clay minerals in the formation it will tend to complicate the evaluation. Due to inherent conductivity of the clay and shale, their presence may contribute to overall conductivity within the LRLC formation and even can be as crucial as the water formation's conductivity [2][20].

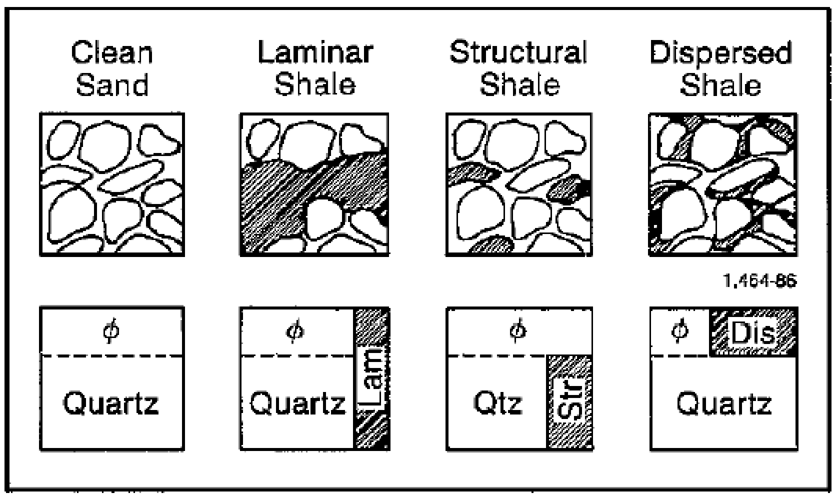

Figure 2.7: Forms of shale classified by manner of distribution in formation. Pictorial represent above, volumetric represent below (formation evaluation)[14].

Initially clean bearing sandstone usually has a high resistivity. However, when it contains shale, volume of clay or conductive minerals such as pyrite or chlorite, the resistivity reading will be reduce. Shaly formation's resistivity depends on its volume, type and distribution in the rock [21]. Meanwhile, Dr. S, S, Prasad et al [18] said that laminar clays are distributed in a reservoir as relatively thin layer of allogenic clay or shale that has been deposited between clean layers of sand. This statement can be seen in Figure 2.7 where shale distribution in sandstones reservoirs portrayed in three sorts of behaviour [14]:

1. Laminar shale where it forms a lamina between the sand layers. This type does not affect permeability and porosity.
2. Structural shale is when shale exists as grain in formation matrix.
3. Dispersed shale usually formed diagenetic or authigenic origin dispersed throughout the sand and these types will cause reduction in permeability, porosity and in fact cause to increase in water saturation.

The dispersed clays tend to have more bound water as they are only subjected to hydrostatic pore pressure other than overburden pressure as shown in Figure 2.8 [13]. G.M.Hamada and M.N.J. Al-Awad [21] also stated that each behavior mentioned has different effect towards, resistivity, radioactivity, spontaneous potential and water saturation. Therefore, it is important to identify their distribution, volume and type as it will affect its performance and characteristics of the formation.

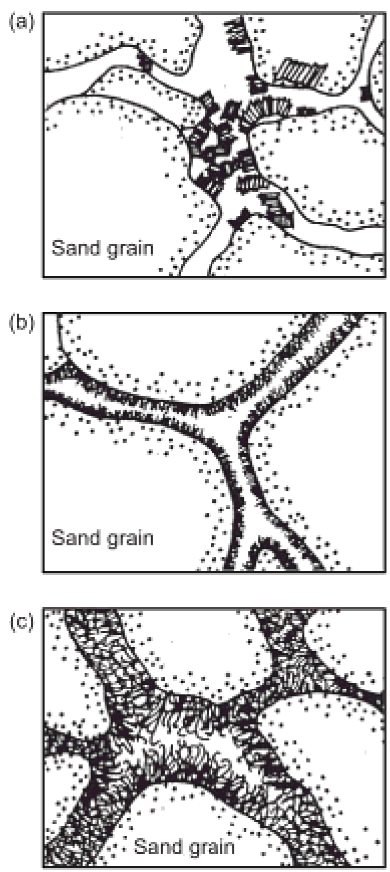

Figure 2.8: Types of dispersed shale; a) discrete particle kaolinite, b) pore-lining chlorite & c) Pore bridging illite (after Tiab and Donaldson)[13]

2.4 Micro-porosity and Cation Exchange Capacity (CEC) in LRLC formation.

In Figure 2.9, the black shaded is showing a pore space that is filled with water and it can be seen that each clay type is having high percentage of micro-porosity. Darling and Sneider [5] stated the common cause of LRLC is due to clay minerals based upon their water-filled micro-porosity and their cation exchange capacity (CEC) contained within its pore fluid. This statement is supported by Claudine Durand et al [22] where upon their research, micro-porosity associated with pore lining clay such a chlorite contributes to their electrical behavior. Micro-porosity is a pore where its diameter is significantly smaller less than 1 micron and relative to its volume, this is the major factor controlling water saturation in hydrocarbons reservoir [3][23]. Worthington [3] described there are two types of micro-porosity:

1. Internal micro-porosity which is pore having dimension less than 1 micron and it is commonly confined in carbonate and chert grains.
2. Superficial micro-porosity usually caused by clay minerals coating quartz matrix or confined within sand lamination.

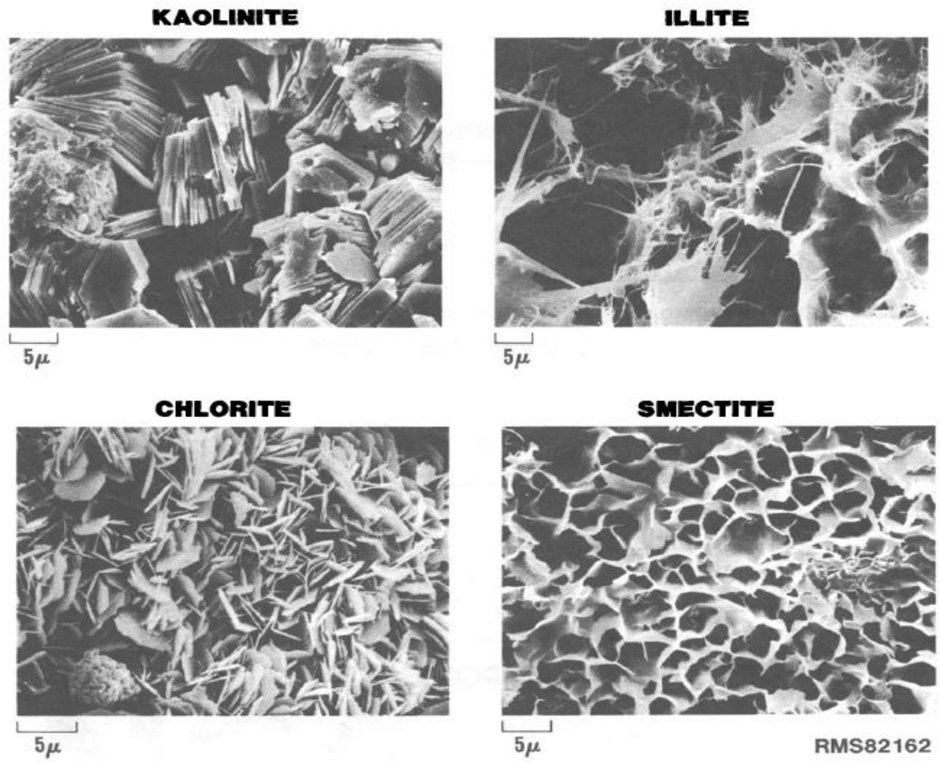

Figure 2.9: SEM photographs of the most common clay minerals in the Gulf of Mexico reservoirs (after Darling and Sneider) [5].

Sedimentary formations are capable of transmitting an electric current only by means of their interstitial and absorbed water content and it became non-conductive once it is dry. Presences of dry clay minerals in sand formation will cause a substitution within the clay lattice of atoms with lower positive (cations) and leaving clay negative (anions) surface charge [2]. This behaviour of cation exchange with clay minerals within the formation is known as cation exchange capacity (CEC). It is expressed in units of milliequivalent per 100 grams (meq/100g) to measure capacity of cation release from clay [2]. When there is high CEC value in clay, it will lower the resistivity log reading. Pyrites and Chlorite are type of conductive mineral commonly affecting the formation resistivity and it will give a higher water saturation reading than its true water saturation value [21]. It is generally known that pyrites have a higher electrical conductivity than the water formation with resistivity of dry pyrite range 0.03 to 0.8 ohm-m [24]. Conversion of ionic to electronic conduction or vice versa between the pyrite and water lead to polarization at the water-pyrite interfaces corresponding with frequency-dependent electrical properties [24]. Meanwhile chlorite is a phyllosilicate (sheets of silicate mineral) that have similarities with clay minerals [25]. They have low value of CEC and where it was thought that they contribute to superficial micro-porosity within the layers of grain [26].

2.5 Approaches on LRLC Formation Evaluations

Few techniques have been carried out by many petrophysicists and log analysts on evaluating and characterizing the LRLC formation. Some of their methods are as such that they are trying to define the thinly bedded sequence, integrating data from production and logging data, multi component induction tools, analyzing using shale and clay model, determining capillary pressure curve from laboratory and NMR techniques. Most of their aims were trying to determine the water saturation parameter in order to get the producible hydrocarbon volume. Some of these methods have made the LRLC formation possible to produce significant hydrocarbons than it was before. Hence, this section will be divided into few small section, that is discuss on well log and core data, shale and clay model, capillary pressure and lastly brief discussion on NMR techniques of previous research approached.

Souvick [7] has come up with general step by step method on defining workflow development for low resistivity pay formation which as below:

1. On identifying and proven the low resistivity pay zone, various data source like mud logs, wireline formation pressure and sample test, the drill stem and production data are needed to be obtained and gathered.
2. Find the cause of the LRP so that decision on selecting suitable models or solution can be applied or developed.
3. Correct the original water saturation (S_w) to low value, unless if it is from high capillary bound water (high S_w)
4. Compare the results obtained with core data for validation.

1.5.1 Using Well Logging and Core Data.

Fanini et al. [8] came up on study integrating the latest multi-component induction tool with the NMR, nuclear and borehole image measurement. Borehole image can provide refined evaluation on net-to gross, fluid saturation, the structural and lamina resistivity while ensuring quality control with the multi-component induction data. Combining the tensorial data (directional) obtained from the induction tool with nuclear measurement interpretation for porosity and the volume and types of shale in rock composition will enhance the volume analyses in laminated formations. The last one is its combination with NMR tool, one of the well-known tools in LRLC evaluation. Combination of tensorial data from the induction tool with the NMR-derived average permeability leads to refined vertical and horizontal permeability of laminated sands. NMR techniques will be briefly discussed in the later sections.

Passey et.al [12] presented solution on evaluating hydrocarbon pore thickness in thinly bedded reservoirs. They acquired electrical borehole imaging (EBI) and also core photograph to give refined overview of the formation. Figure 2.10 is showing a depth tie between EBI and core photograph, white light image was photographed under natural lighting while the UV light give distinction between reservoir and non-reservoir beds. Meanwhile Figure 2.11 is an illustration of a well-documented core photograph taken at half scale which considers an ideal digital image resolution. Their technique is actually looking at high and low resolution log, depending on the bed thickness which is simplified in table 2.2.

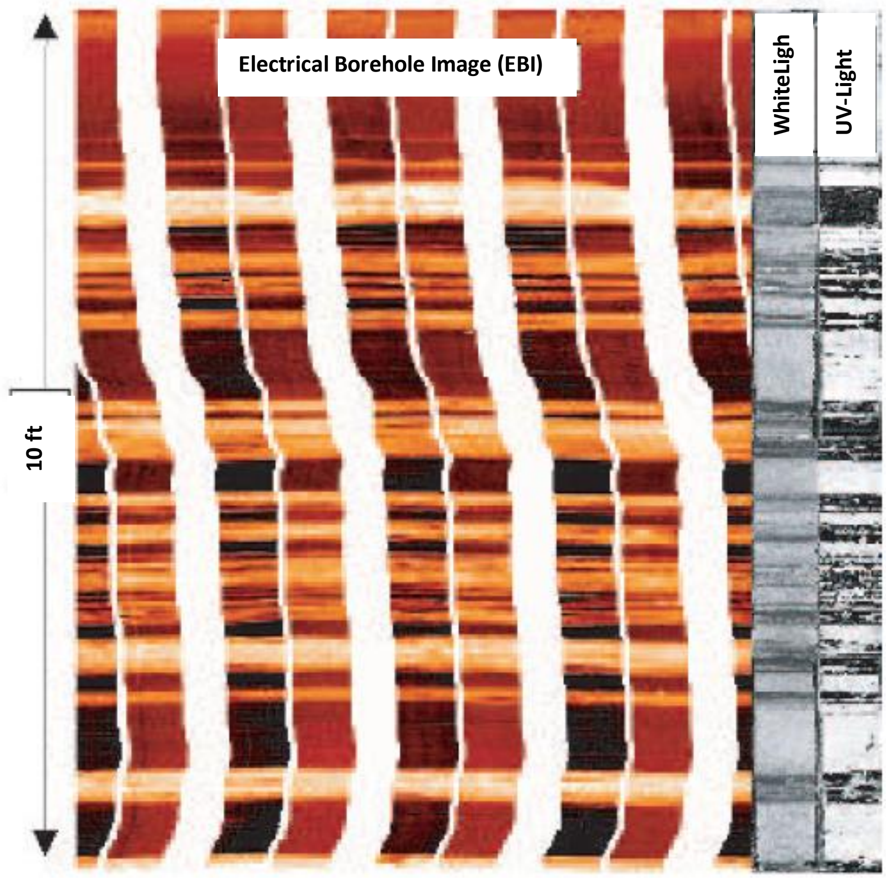

Figure 2.10: Depth alignment of electrical borehole imaging and Core photograph (after Passey et al.) [12]

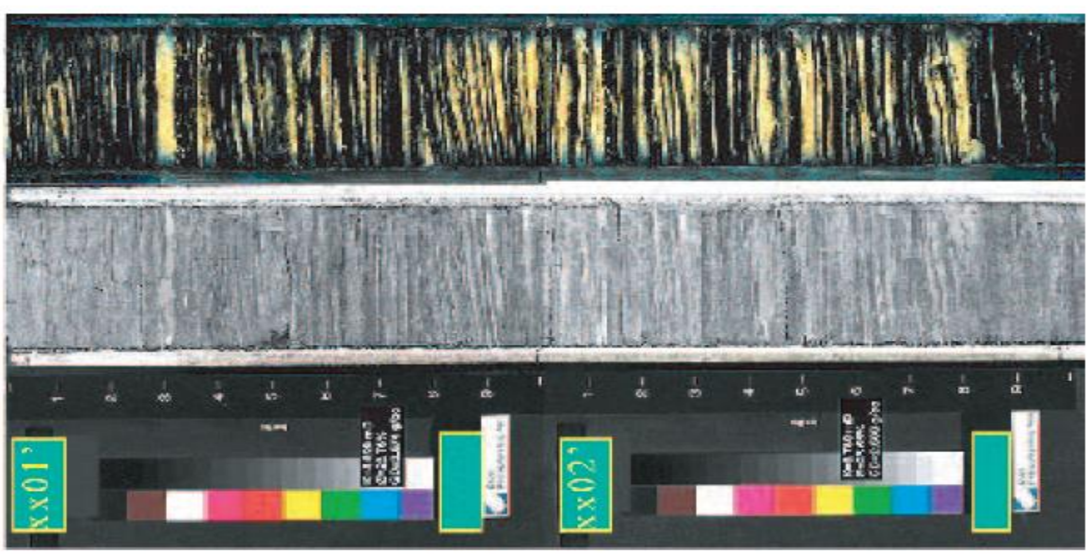

Figure 2.11: Well-documented core photograph (after Passey et al.) [12]

Table 2.2: Table of summary of low and high resolution method [12]

Method(s)	High Resolution		Low Resolution
Type (s)	Log Convolution Modelling (LCM)	Resistivity log modelling	Volumetric Laminated Sand Analysis (VLSA)
Objective	Each thin bed can be identified and analyzed individually		It provide an average bed properties and HPT
Application	Bed thickness is greater than 2 ft.		Bed thickness less than 2 ft.
Advantage	It can produce detailed data for identification of each reservoir beds and properties presented in familiar well log format		Boundaries of each thin bed are not required.
Limitation	Uncertainty in non-unique of inversion results.		It does not produced detailed results for bed

2.6 Petrophysical Models of Shale and Clay.

The petrophysicists and the log analyst will evaluate volume of water present in pore space in order to determine the amount of hydrocarbons present in the reservoirs. Water saturation (S_w) is the one of many properties of rock used to determine their fluid system where it represent the pore volume occupied by water whereas fraction of pore volume contain hydrocarbon represented by (1-S_w). Common technique to calculate water saturation is by running resistivity logs. Problem arises, once the water present held in place by capillary forces and it refrained from flowing. The resistivity tool will not able to differentiate between the immovable water and freely produced water (Figure 2.12). This is known as irreducible water saturation (S_{wirr}) which commonly determine from special core analysis (SCAL). Compare this value with the water saturation obtained from the downhole log, if the water saturation does not exceed the irreducible water saturation hence only hydrocarbon will produce [29]. Computing the water saturation value requires the Archie's equations. However Archie's law is only specifically applicable for clean sands formation, increasing awareness on shaly sand problem interpretation leads to development of shale model [18] [21]. Shahzad [30] stated that water saturation can be computed based on shale model and clay model. In shale model, the water saturation calculated depends on the volume of shale in the formation and their types of distribution. The clay model is more focus on electrochemical properties of clay minerals and calculated based from Waxman-Smiths (WS) and Dual Water Models (DW). Since the LRLC phenomenon are mostly contribute from shale and clay contents, therefore this petrophysical models can be apply to determine water saturation in the reservoir.

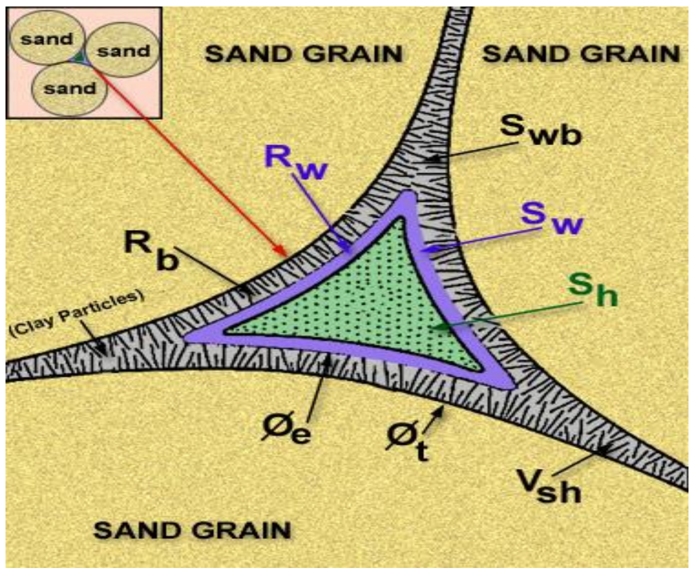

Figure 2.12: Water at the inter-granular scale [29]

2.6.1 Archie's Equation

Archie's Equation is the most renowned empirical equation used to determine water saturation from the free-clay minerals formation and assuming only the water formation as the electrically conductive material in the formation [31]. This is why Archie's equation is not valid when clay is present in formation due to its extra conductivity will lead to overestimation of the water saturation. This formula is express as below:

$$S_w^n = \frac{a.R_w}{\phi^m.R_t} \qquad \textbf{(2.1)}$$

Where: S_w = Water saturation (Fractional)

n = Archie Saturation Exponent

a = constant value

R_w = Resistivity of the formation water (ohm-meters)

ϕ = Porosity (Fractional)

m = Archie cementation Exponent

R_t = True Resistivity of the rock (ohm-meters)

Resistivity values in equation 2.1 are determined from several ways: 1) True resistivity rock (R_t) is usually obtained from deep resistivity log such as deep laterolog and induction log; (2) Resistivity of the water (R_w) can be obtained from spontaneous potential (SP) log, resistivity-porosity log or water sample [13]. While for the porosity value it can be estimated from porosity logs such as density, neutron or sonic log. Lastly the Archie saturation component (n), Archie cementation exponent (m) and constant value (a) are normally obtained from the laboratory core analysis, the constant value is normally assumes as one [13].

2.6.2 Water saturation in Shale Models

Tixier et.al [10] mentioned that finer grain and silty sands contain high irreducible water saturation. The clean water sand resistivity may approximately range from 0.2 to 1.0 ohm.m and shaliness factor may also contribute to increase in the resistivity. He stated that identifying this pay zones may be difficult but can be possible. This situation can be resolved by integrating the resistivity logs with porosity log (density, neutron and sonic), SP, Gamma ray curve and sidewall core samples. As mentioned earlier, there are two types of shale model that is laminated sand-shale simplified model and dispersed sand-shale simplified model. Furthermore, regardless of the shale distributions within the formation, total shale relationship equation was also once introduced.

Laminated Sand-Shale Simplified Model

In this model, the resistivity (R_t) in direction of bedding plane is parallel to resistivity of shale lamina and clean sand lamina [30]. Below is the resistivity relationship equation:

$$\frac{1}{R_t} = \frac{1-V_{lam}}{R_{sd}} + \frac{V_{lam}}{R_{sh}} \qquad \textbf{(2.2)}$$

Where: V_{lam} = bulk volume fraction of shale in lamina

R_{sd} = resistivity of clean sand lamina

R_{sh} = Resistivity of shale lamina

Meanwhile, water saturation is computed using equation below:

$$\frac{1}{R_t} = \frac{\phi^2 S_w^2}{(1-V_{lam})aR_w} + \frac{V_{lam}}{R_{sh}} \qquad \textbf{(2.3)}$$

Dispersed sand-shale simplified Model

Dispersed shale model is developed by taking into account on the extra conductivity contribute from pore water and dispersed clay [30]. Their simplified form of water saturation relationship is as below:

$$S_w = \frac{\sqrt{\frac{aR_w}{\phi_{im}^2} + \sqrt{\frac{q^2}{4}} - \frac{q_w}{2}}}{1-q} \qquad \textbf{(2.4)}$$

Where: ϕ_{im} = Inter matrix porosity (includes pore occupied by fluids and dispersed shale)

q = fraction of inter matrix porosity occupied by dispersed shale

Total Shale Relationship

For practicality, regardless of their distribution, water saturation is computed based on total shale relationship equation as below [30]:

$$\frac{1}{R_t} = \frac{\phi^2 S_w^2}{(1-V_{sh})aR_w} + \frac{V_{sh}S_w}{R_{sh}} \tag{2.5}$$

1.6.3 Water saturation in Clay Model

Waxman-Smiths Model

Water saturation in Waxman-Smith equation was defined as BQ_v/S_{wt} for which Shazad [30] stated that this parameter works independently in pore space reservoir. This is also applicable to the conductivity of the formation water and clay cations. The equation is shown as:

$$C_t = \phi_{total}^{m^0} S_{wt}^{n^0} \left\{ C_w + \frac{BQ_v}{S_{wt}} \right\} \tag{2.6}$$

Where: C_t = formation conductivity (obtained from deep resistivity log)

C_w = formation water conductivity

B = Specific conductivity of exchangeable cations (mohm/m or meq/cc)

Q_v = Clay cation exchange capacity

m^o = cementation factor of Waxman-Smiths

n^o = saturation factor of Waxman-Smiths

Clay cation exchange capacity, Q_v can be determined from experimental core samples and fluids by computing the below equation:

$$Q_v = \rho_{dry-clay} Vol_{dry-clay} CEC/\phi_{total} \qquad \textbf{(2.7)}$$

Dual Water Model

Dual water model was developed due to in the past they are facing difficulty on measuring the in-situ CEC. Shahzad [30] stated that the model is based on three principles:

i. Conductivity of clay due to its CEC
ii. CEC of pure clay is proportional to the specific surface area of clay
iii. Anions in the saline solution are excluded from a layer of water around the surface of grain.

He also stated that in dual water model consist of two components that are clay minerals and bound water. Depending on the clay type, it will contribute to a variation of bound water. Dual water model equation is expressed as below:

$$C_t = \phi_{total}^{m^0} S_{wt}^{n^0} \left\{ C_{wf} \frac{S_{wf}}{S_{wt}} + C_{cbw} \frac{S_{cbw}}{S_{wt}} \right\} \qquad \textbf{(2.8)}$$

Where: C_{wf} = Conductivity of free water

S_{wf} = Formation water saturation (not clay bound water)

S_{wt} = Total water saturation

C_{cbw} = Clay bound conductivity

Below is the simplified equation in order to determine the effective water saturation:

$$S_{w_{effective}} = \frac{S_{wf}}{(1 - S_{cbw})} \qquad \textbf{(2.9)}$$

2.7 Capillary Pressure Curve Analysis.

Maximum possible oil saturation is controlled by the relative number of large capillaries or small pore throats which commonly found in shaly and silty formations (commonly found in LRLC formations). Determination of irreducible water saturation (S_{wiir}) and residual oil saturation (S_{or}) helps to calibrate water saturation from log in hydrocarbons reservoirs above transition zone. Figure 2.13 is trying to show the concept of capillary pressure at four different rock systems. Capillary pressure (P_c) curve is derived from special core analysis (SCAL) which by means of desaturating the core plugs either by porous plate apparatus or centrifuge apparatus. The saturation test is mean to look at the pore size distribution and interfacial solid fluid systems.

Souvick [7] and Riepe et al. [34] used core capillary pressure measurement to validate the water saturation in LRLC formation which obtained from log data. According to Souvick [7] in Figure 2.14 (left) is a P_c versus S_w derives from few samples taken from reservoir, showing sample plot increase in porosity permeability towards left. On the other hand, capillary pressure is converted to height (H) calibrated to reservoir condition (Figure 2.14 right) indicating sample above FWL, though it has high porosity permeability somehow it gives a low S_w and vice versa.

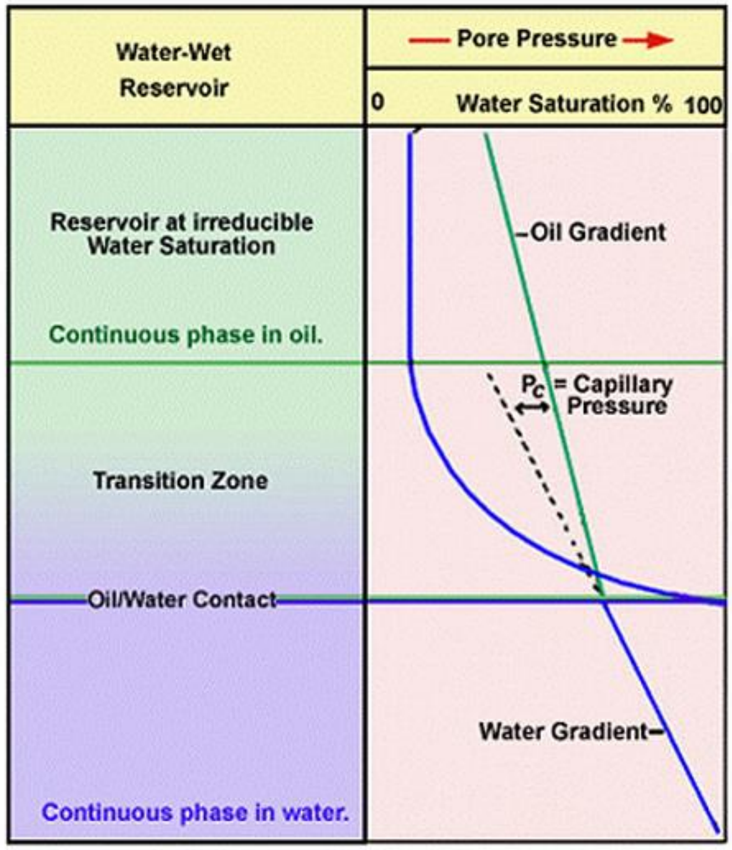

Figure 2.13: Capillary Pressure curve in different rock systems [29]

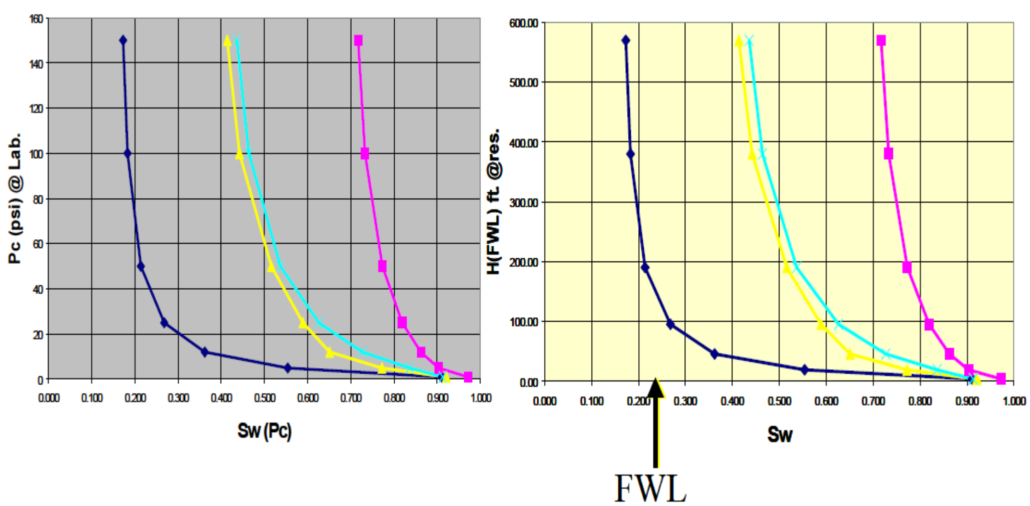

Figure 2.14: Capillary Pressure Measurement (after Souvick) [7]

2.8 Analysis using Nuclear Magnetic Resonance (NMR)

NMR logging was first introduced in the 1980s, it has the abillity to measure directly the porosity, differentiate the fluid type and irreducible water saturation (differentiate free fluid and bound water) (Figure 2.15) [32]. Due to its advanced ability, it has become one of the favourable tools to determine producibility properties of the LRLC formations. Passey et al. [12] also mentioned that porosity determination from NMR also helps to detect the presences of thin beds of sand shale sequence in a light oil bearing reservoir.

Hamada and Al-Awad [4] described that in analysing the LRLC formation using the NMR data, there are several aspects of NMR technique that they used :

1) For fluid identification, T1/T2 ratio was used
2) For determination of type of clay minerals, the differece of NMR porosity and total porosity was taken.
3) For identification of the fluid nature and rock properties of the LRLC formation are identified from the NMR relaxation was used.

In laboratory, Special core analysis (SCAL) used the NMR tool to characterize the pore size distribution [14]. This method bring advantage over the traditional mercury injection methods. Hamada and Al-Awad [4] stated that in low resistivity pay the NMR analysis has significantly contributed producibility of the pay zone. It helps to validate lithology independent porosity and differentiate bound water and free fluids. Meanwhile in low contrast reservoirs, based from high contrast NMR relaxation parameters, it helps to identify the fluid nature in the formation and also height of oil column. However using the NMR tools during the formation evaluation can be time consuming and high cost.

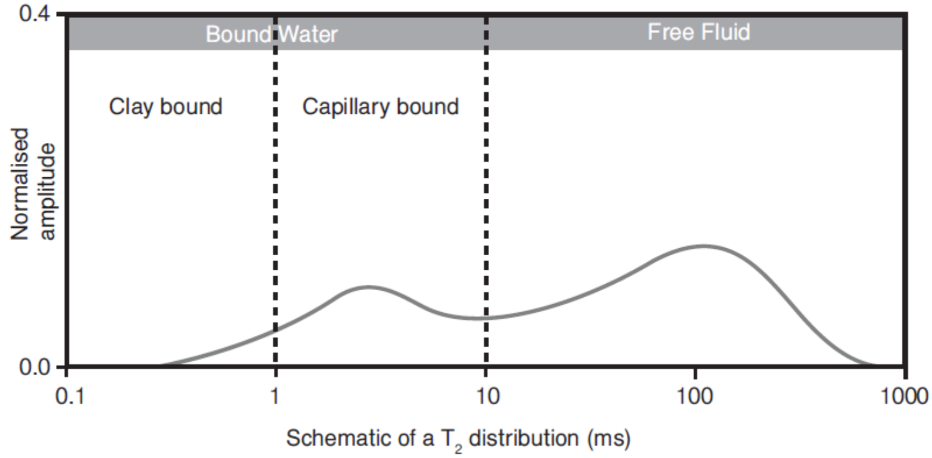

Figure 2.15: Schematic of a T2 distribution to determine bound water and free fluid (formation evaluation) [14]

CHAPTER 3

METHODOLOGY

3.1 Methods used for LRLC Characterization

The workflow which can be used to characterize the LRLC formation is divided into four parts where raw data obtained from logs response, core data, advanced tool and list some of depositional environment containing LRLC formations (figure 3.1). Therefore from this evaluation, final aim is actually trying to link the computed water saturation mentioned in 2.6 section; "Only dry hydrocarbon produce when $S_w \leq S_{wiir}$".

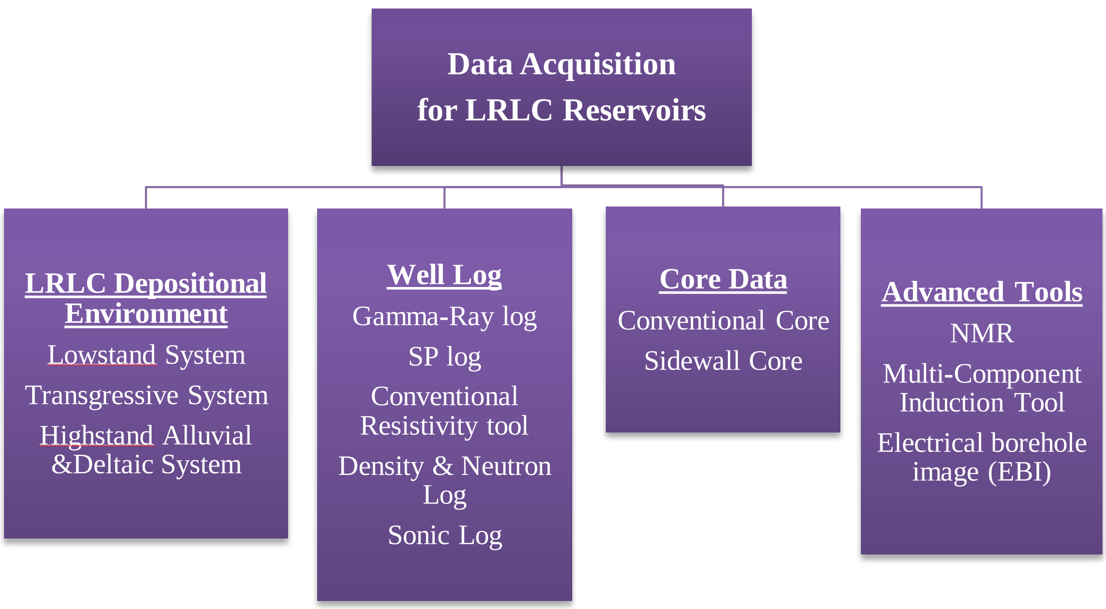

Figure 3.2: Data Acquisition workflow to characterize LRLC formation

3.1.1 LRLC Depositional Environment

The purpose of this section is just to understand the geological condition which can give the low resistivity low contrast reservoir as we have in the distal part of the deltaic sequence, where we have intercalation of silt, clay, and also sand. So, by knowing the depositional environments in advance, it helps a lot to run the proper logging tools to characterize the reservoir. Moreover, during acquiring the data it helps to get the earlier prediction on what the reservoir properties. As been mentioned earlier in the literature, adapted from Darling and Sneider [5] findings, there are three environmental systems:

1. Lowstand System.
2. Transgressive System.
3. Highstand alluvial and deltaic system.

3.1.2 Well Logging Response

Well logging using the gamma-ray log, spectral Gamma ray, density, sonic, neutron, SP and conventional resistivity tool are the principle rules for the petrophysicists to evaluate desired formation boundaries. Gamma-ray log is used to differentiate between sands and shale for which the log recorded will be used to compute the volume of shale present in the reservoir as in equation 3.1 below [14]. Sonic log can provide porosity, whereas density and neutron cross over can guide to possible hydrocarbon which later validate from high deep resistivity log reading. SP tool is used to measure R_w and can help to measure the salinity in fresh formation water.

$$\boldsymbol{V_{sh} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}} \qquad \textbf{(3.1)}$$

Some common characteristics of LRLC formation will usually have a very low resistivity ranging from 0.5 ohm.m to 5 ohm.m. Lithologies interpretation from gamma ray log show thinly bedded shaly sand. This can be the starting point of indicating the LRLC formation. However both parameters need to validate from more further data such as taking core and using advance tool which both of this will further explain preceding this chapter.

Due to the resolution of the standard logging tools, it was recommended to use some advanced logging tools to characterize the LRLC reservoir like image tools, 3Dex^{TM} resistivity tools and NMR tools.

3.1.3 Core Data

The present analysis will be looking at conventional core and sidewall core. Conventional core is used for routine core analysis. In the case of LRLC formation, it can provide values on the porosity, permeability and the important one is to detect presence of minerals. Core photograph was used to define lithology of the desired formation especially to identified thin bed sequence containing shaly sand bed.

When there is high percentage of minerals especially the conductive minerals sidewall core is required for SCAL. For LRLC, there are few things SCAL are useful, that is to obtain cementation (m) and saturation (n) factor, determine pore distribution using NMR tool and derive the capillary pressure curve. This whereby a decision from section 2.6 either Archie's equation or shale model or clay model can be applied to compute the water saturation or irreducible water saturation in the case of using NMR tool. SCAL also helps to define the amount and distribution of the clay.

Core data can helps to characterize LRLC. In core image, the interval of hydrocarbon fluorescence shown can help to indicate the low resistivity beds. Meanwhile, XRD, SEM, petrographic studies can help to characterize the conductive minerals as well as clay minerals that cause to low resistivity.

3.1.4 Advanced Tools

Based from literature, the NMR tools, multi-component induction tool (3Dex^{TM}) and also electrical resistivity becomes the handiest tools in evaluating the LRLC formation. Also its reliable sources can in providing data, can be used to compute the water saturation and irreducible water. Meanwhile, the EBI provides a better contrast for thin bed formation.

3.2 Methodology for this Project

Methodology for this project can be explained from below diagram. This project is basically just a literature study basis from journals, books and validates websites. Incorporating all my findings from the literature review and also one case study, the product of this project is to propose a workflow diagram for LRLC evaluation.

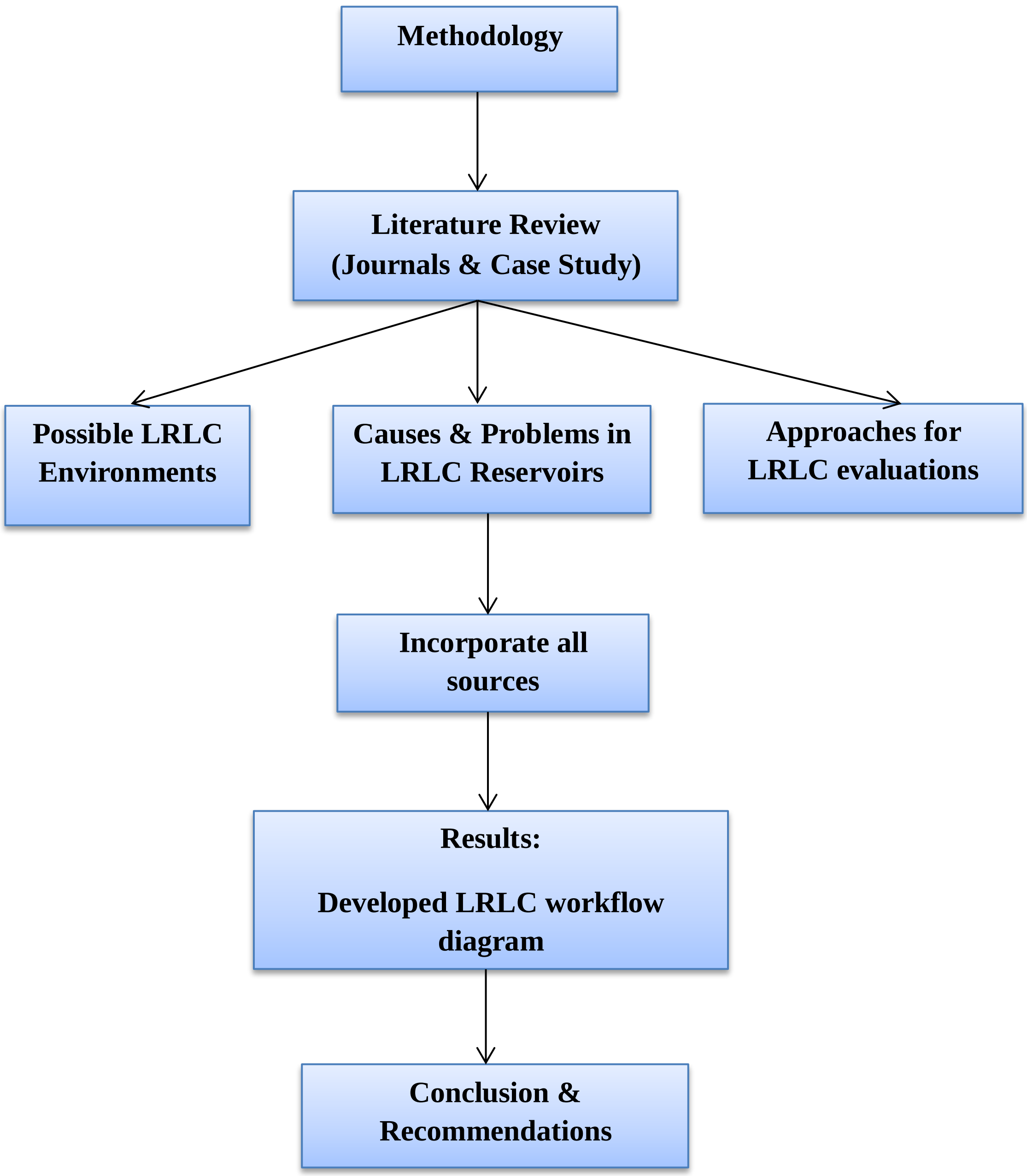

Figure 3.2: Flow diagram for this project

CHAPTER 4

RESULT AND DISCUSSION

4.1 Case Study on LRLC Formation in Clastic Reservoir of Malay, Sarawak and Sabah Basins

Gosh et al [33] stated that Malay basin is one of the deepest basins in the part of the SE Asia with a depth of 12 km at the center. It is made up of mid Miocene coaly shale at the terrestrial origin and lacustrine shale of Oligocene-Miocene age. It was believed that it contains an excellent source rock. Meanwhile geological sequence for Sarawak basin is late Eocene to recent and Sabah basin is made up of mid-Miocene to recent. Since oil was discovered in Miri, Sarawak in 1882, exploration and exploitation activity starting to widespread. These three basins are operated by PETRONAS, basins are considered as mature fields and among the most productive around the region (Figure 4.1).

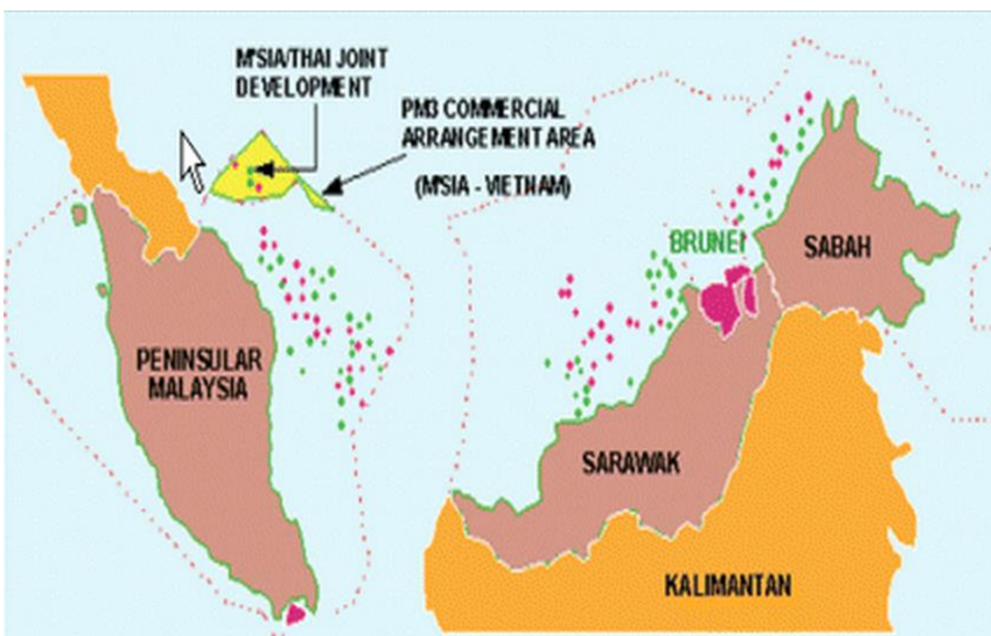

Figure 4.1: Malay, Sarawak and Sabah Basins for oil and gas (after Gosh et al.) [33]

Malay, Sarawak and Sabah basins are mainly made up of shaly and silty sandstones. Problems arise when they realized during formation evaluation, some of the pay zones were by-passed by the conventional logging tools. In general resistivities of these formations range between 2 to 4 ohm.m which is almost close to the resistivity of fresh water bearing formation (1 to 2 ohm.m). Figure 4.2 is trying to show one of the typical LRLC gas pay zones in Malay Basin. From borehole log data it was recorded that the resistivities ranging from 1.5 to 3 ohm.m. Meanwhile the water saturation varies from 60% to 80% and high porosities of 25% to 28%. The core log analysis found out that it contained silty/shaly argillaceous sand. Therefore due to this Riepe at el [34] notified these regions as the LRLC pay zone basins.

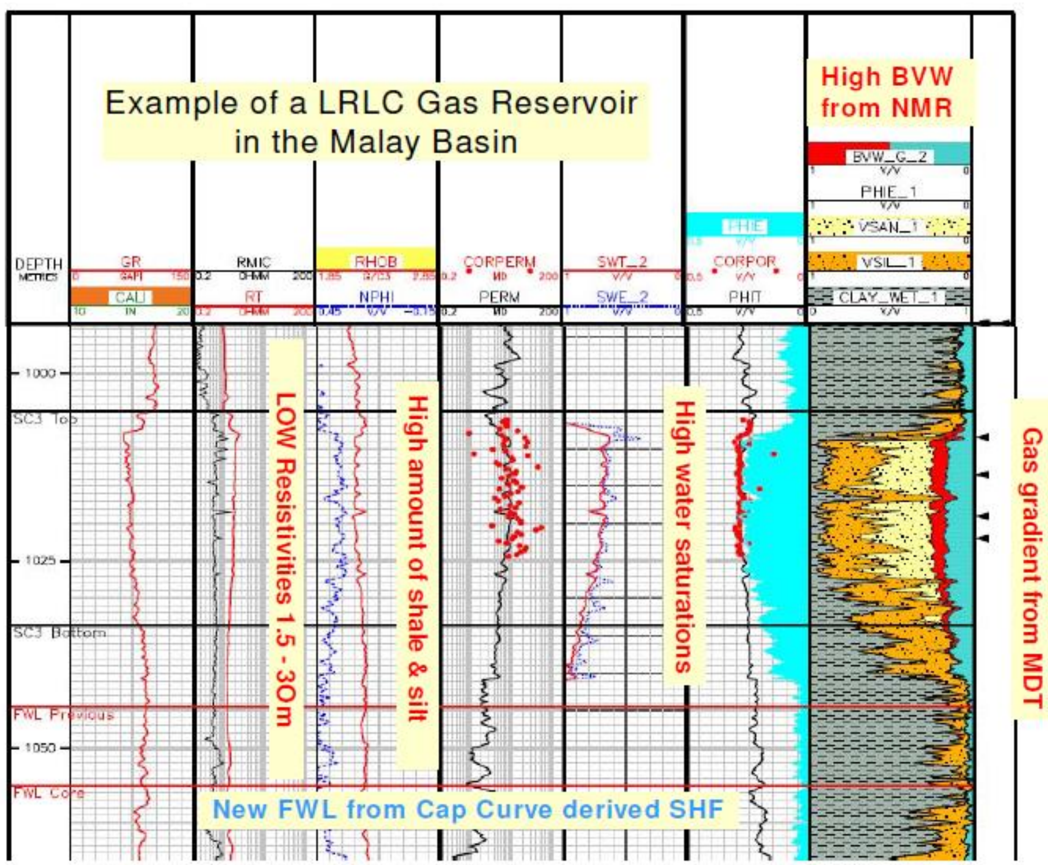

Figure 4.2 : Log and core obtained from typical LRLC pay zone of Malay Basin (after Riepe et al.) [34]

4.1.1 Petrophysical Analysis Methods

Riepe et al. [34] identified two types of problem hydrocarbon production in LRLC pay zones: 1) Errors in deriving water saturation S_w from resistivity logs, 2) High water saturation (related S_{wirr}) obtained from resistivity log and eliminating the error by taking conventional S_w-cutoff. The second problem is actually the focus of this study, since S_{wirr} believes containing hydrocarbon that can be produced. Factors contributing to this pay zone are due to high volume of capillary bound water, their grain size, high amount of bio-turbated fine silts and shales and lastly high volume of clay with high CEC.

Assessment on this formation was carry out based on integrating the log and core data to derive the parameters from the log evaluation then later determine the cut-off criteria for "net pay" and lastly possible adjustment in saturation equations. Workflow for the assessment is divided into three stages as below:

1) **Well selection**:

   Select wells that are producing from LRLC zone. Ensuring all those advanced logging data are there like NMR, images, testing data which are sufficient to characterize the irreducible water. Sufficient amount of core and NMR log, image log is used to identify the thinly laminated bedded sand/shale sequence.

2) **Special core analysis (SCAL)**:

   Special core analysis was used to define the T2 cut off from NMR. Capillary pressure is used to define the irreducible water and the height above free water level. Also, the electrical properties (*a*, *m*, and *n*), resistivity index (RI), and cation exchange capacity (CEC) were also measured from core. Having these parameters, it helps a lot to get the actual water saturation of the reservoir and overcame the extra conductivity came from the shaly part of reservoir. Figure 4.3 shows schematic process in SCAL.

3) **Well Log Analysis:**

At this stage, focus is mainly on obtaining parameters from resistivity and NMR log to compares their saturation profile. Corrections were made on resistivity value by using the resistivity models to compute the S_w. These are shown in Figure 4.4.

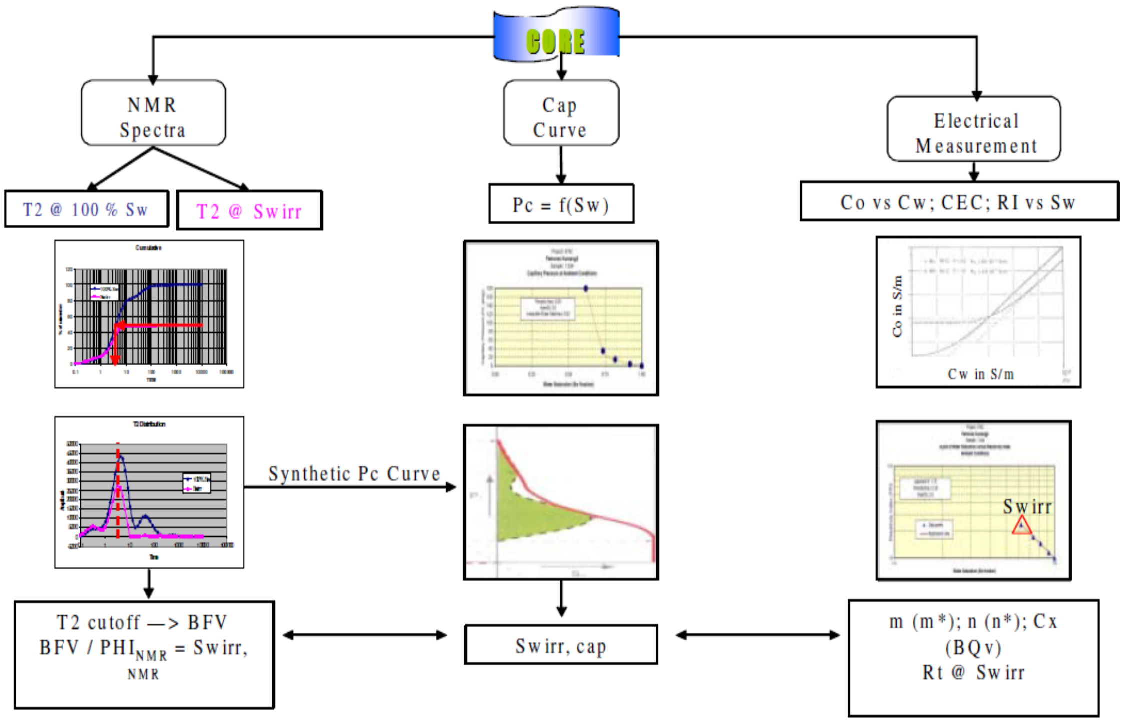

Figure 4.3: Workflow for the evaluation and reconciliation of irreducible water saturation S_{wirr} from Special Core Analysis (after Riepe et al.) [34]

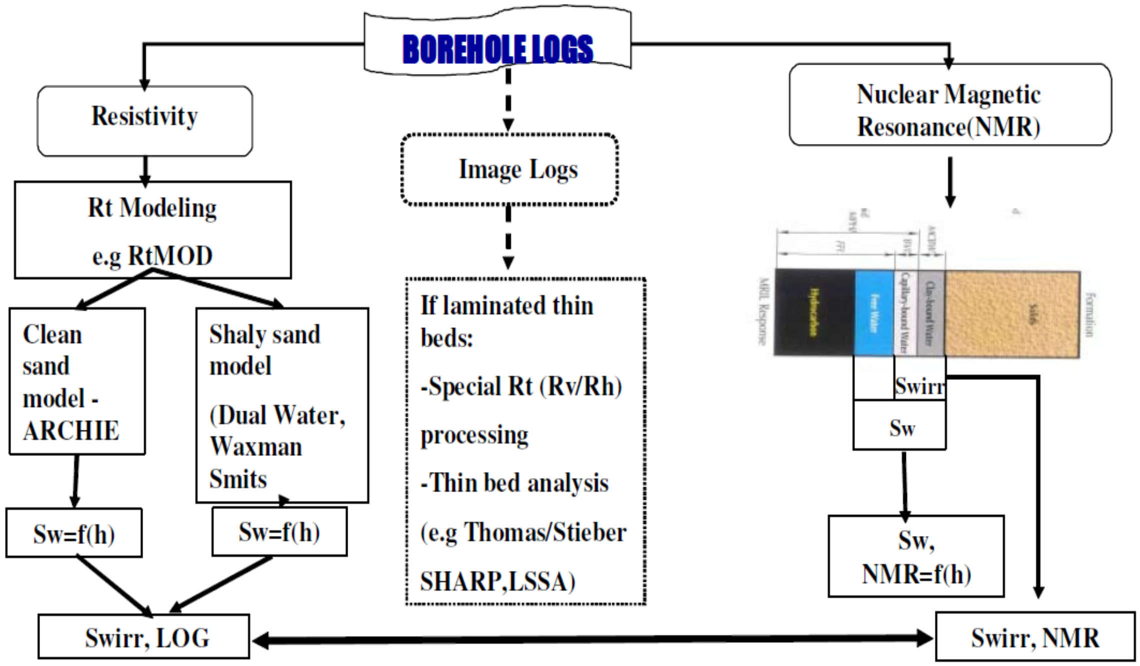

Figure 4.4: Workflow for the evaluation and reconciliation of irreducible water saturation S_{wirr} from resistivity logs and NMR logs (after Riepe et al.) [34]

4.2 Discussions

As from case studies above, it can be seen that their techniques on solving the LRLC formation evaluation are divided into two workflows, analysis from borehole and core data. However above techniques are mostly just focusing on the how to determine the water saturation from LRLC payzone.

Meanwhile Souvick [7] provides the solution ideas from each possible cause of the LRLC formation. Table 4.1 shows some of the combination solution ideas towards the cause in LRP zone adapted from Souvick [7]; Passey et al. [12] and Hamada [27]:

Table 4.1: Summary of solution ideas for each cause in low resistivity pay zone [7][12][27]

Cause(s)	Descriptions	Solution(s)
Deep invasion by conductive muds	Drilling well with high salinity or conductive mud cause to low resistivity and high water saturation computation.	1. Run array laterolog or array induction tool 2. Run LWD
Presence of clay	Clay contains CEC which impart extra conductivity to the formation. (Commonly found in shaly sand formation)	2. Run Gamma ray spectroscopy and elemental capture spectroscopy. 3. Data acquired will then computed using the WS or DW equations.
Presence of fracture	Open fractures are easily penetrate by the conductive mud from the wellbore which this cause to reduction in the resistivity of the formation. (Commonly found in carbonate rocks)	2. Run the borehole imaging tool together with the wireline or LWD [both are in water based and oil based mud] 3. Carry out the core plug measurement to calculate S_w
Micro-porosity	It is a micro-porous (micritic) grains contain water and acts as conductor which cause to reduction in resistivity. Commonly occurs in carbonate rocks.	1. Carry out core measurement on cementation exponent ("m") & saturation exponent ("n") 2. Run NMR tool either wireline or LWD
Presence of high capillary bound water	It is related to grain size. When it decreases in size, there is increase in surface to volume ratio grains and cause the capillary force to hold significant volume of water. This cause low resistivity interpretation	Run resistivity log and NMR tool
Conductive Minerals	Minerals such as pyrite can subdue the resistivity log and misinterpretation on evaluating S_w Its effect can be vary depends on their distribution or morphology.	1. Run lithology indicator log to determine volume of mineral.(NMR tool) 2. It will be more effective when using elemental spectroscopy (wireline logging tool) 3. Carry out measurement on conductivity of an oven dried core plug.

Well with high relative angle	Increase in relative angle even in thick bed cause it to become pronounced and low resistivity reading	Implementing a new interpretation technique in induction type tool based on maximum-entropy inversion of borehole-corrected array data [28]
Laminated Formation (sand/shale formation)	Problems in defining the individual beds and gives below vertical resolution of conventional logging tool. Hence apparent decrease in resistivity log reading.	1. Run multi-component induction tools 2. Borehole imaging tool with oil and water based environment.

On the other hand, Darling and Sneider [5] have provided information on the principles of the likely depositional environment in LRLC reservoirs. Therefore combining above findings, figure 4.5 is the suggested theoretical workflow diagram on step by step method to encounter the LRLC formation evaluation. This workflow diagram may only feasible to apply for clastic reservoirs.

From the diagram, it can be seen that each causes were encounter based on their respective tools and techniques. Example when the formation containing conductive minerals, sidewall core is required and oven dried the plug to carry on for SCAL process. Then later the petrophysical model equation is used to determine the water saturation for the formation. As been stated from the literature review, when the water saturation is less than the irreducible water saturation, only dry hydrocarbon will produce. By relating this factor we can make prediction whether the LRLC formation is producible or vice versa.

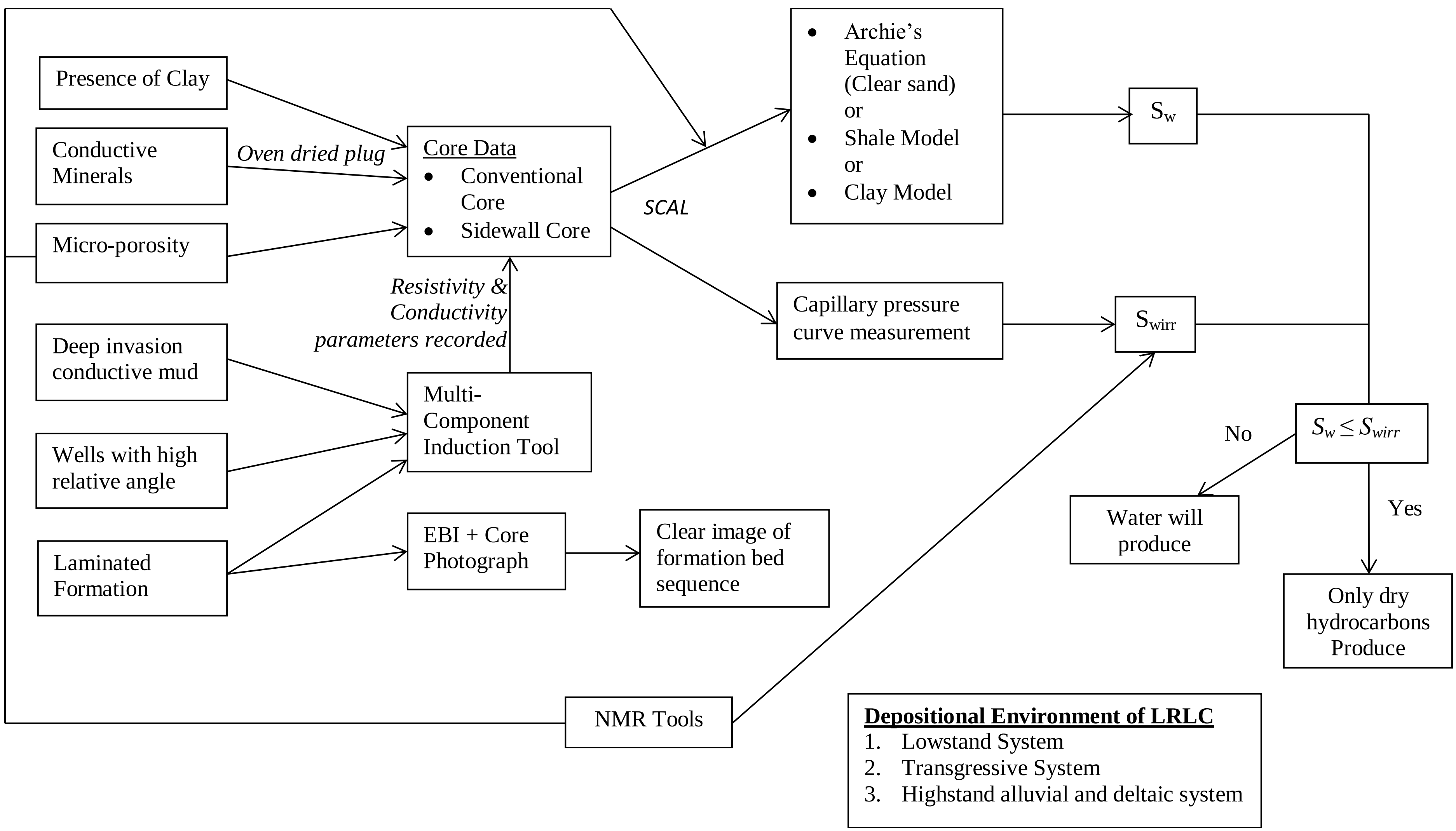

Figure 4.5: Theoretical workflow for LRLC formation evaluation adapted from Darling and Sneider [5], Souvick [7], Passey et al. [12], Hamada [27] and Riepe [34]

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusion

Low resistivity low contrast pay (LRLC) becomes one of the main goals for most of the oil company nowadays, the main challenge is how to identify, evaluate, and characterize this kind of reservoir. Early days we lost a huge amount of oil and gas due to using the old and traditional logging tools and traditional log analysis approaches, after recognizing how much potential we can lost, and having some sort of new technology, and change the mindset in term of formation evaluation approaches it becomes easy to evaluate this kind of reservoir.

To understand this LRLC phenomenon we need to look at the geological control and understand the formation behaviour that contributes to low resistivity reading. When the formation contains clay, conductive minerals and also fresh water formation it can significantly effect to the logging tools. Shaly sand formation is considered as the primary caused towards the LRLC phenomenon and also the reason why that LRLC have high irreducible water.

Integration tools or techniques, as such core data and advanced tool can obviate the problem faced by the conventional logging tool. Combinations of EBI and core photograph enhance the evaluation towards the lithology of the formation bed sequence.

Determination of water saturation is the key point to estimate the volume of hydrocarbon that can be produced from the LRLC formation. Computation from core data and using the shale and clay model and validate the data with the NMR tool techniques help the prediction of possible hydrocarbon produce.

With the propose workflow diagram will at least guide the petrophysicist and log analyst to analyze this kind of formation.

5.2 Recommendations

However there is still a doubt towards the uncertainty of obtaining data and computing the correct water saturation value. As for reality check on feasibility of the suggested workflow, it should be test to real field data especially in clastic reservoirs.

Based on the survey I did during my study I would recommend to carry out the detailed study of the reservoir geology in advanced, probably by mapping the entire production field from the LRLC payzone. Define the depositional environment and where we are going to drill our prospect that help us to define where we expect LRLC pay, and based on that we can design the right logging program to identify this kind of reservoir.

I also recommend having as much as we can in terms of data like image tools, NMR data, RT scanner, 3Dex^{TM}, core data, and integrate all of these information to characterize this kind of reservoir using sophisticated approaches.

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