Resistivity Modeling of Shaly Sand Formation in High Water Salinity

by

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Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
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Approved by,

____

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September 2012

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 references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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SYED HAMIMIE FAKHRI BIN SYED MOHAMAD

ABSTRACT

The evaluation of shaly sand formation has a very close relationship with the study of electrical properties exhibits by the formation itself. The project done is based on the earliest resistivity model which proposed by Archie in 1942. Since this equation is only valid for clean sand, the model was modified by Patnode and Wyllie in 1950 to encounter the shale conductivity effect in shaly sand formation. However, this resistivity model contains limitation which is in high salinity of water, the shale conductivity will not able to significantly affect the total conductivity of the formation. In other words, when the water salinity is sufficiently high, the resistivity model of shaly sand formation will reduced closely to Archie's equation. Based on this hypothesis, the theory is brought into laboratory work where shaly sand core sample is tested for its resistivity in high salinity of water. Three types of core sample were being prepared by varying the shale content. The general properties of the samples were recorded as references. The result of core sample resistivity measurement will be able to describe concisely the accuracy of this model and generally draw its limitation or exception to be made for the model especially when the shaly sand formation encounters high water salinity.

ACKNOWLEDGEMENT

In completion of this Final Year Project, I would like to express my deepest gratitude to all parties that involved in making this project as a meaningful and great achievement for me. Throughout the project timeframe, I have learned a lot of new things and gained so much experience that will be a huge value for me in the future.

First and foremost, I would like to thank UTP's Petroleum Engineering Department for providing me guidance to complete the project and in the same time arranging the project activities for me. With their strong support and advice, I was able to plan and conduct my project very well.

Special thanks should go to my Final Year Project supervisor, Dr. Hilfan Khairy who becomes the most important person to teach and guide me in conducting this project. His strong support and willingness to share his knowledge and wide expertise has given me a very important experience in this project study.

Besides that, I would like to thank the lab assistants who had helped me to complete the project especially in conducting the laboratory work. I truly appreciate their help and their sharing of information in order for me to execute the experiment well.

Finally, my deepest appreciation goes to my family and my friends in UTP for their continuous support and encouragement which have enabled me to do my best for this project. I hope that after this project completion, all the findings and knowledge that I have shared through this dissertation would be useful for everyone in the study field.

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ABBREVIATIONS AND NOMENCLATURES

F	Formation Factor
V_{sh}	Shale Volume Fraction
R_w	Aqueous Electrolyte Resistivity
R_o	Formation Rock Resistivity
C_w	Aqueous Electrolyte Conductivity
C_o	Formation Rock Conductivity
Ohm-m	Ohm-meter (Resistivity Unit)
S/m	Siemens/meter (Conductivity Unit)
Sw	Water Saturation
TDS	Total Dissolved Solids

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CHAPTER 1

INTRODUCTION

1.1 Background Study

For more than 70 years, the electrical properties that are measured in the reservoir have been used to assess the hydrocarbon saturation. The introduction of electrical measuring device especially into the well logging activities had provided a stepping stone in understanding and predicting formation behavior in the subsurface.

The earliest model formulated using the electrical properties came from Archie (1942) who empirically equated the fluid saturation as the function of electrical resistivity of rocks, their porosity and brine saturation. However, the equation that he made is only provided for good saturation estimation of clean sand in which is unable to satisfy the condition; if the rock have significant amount of shale presents in the formation pore spaces. The presence of shale in sand formation is what has been called as “shaly sand” that will be the main subject of this study.

In general, the increase of shale content will cause the rock matrix to become more conductive. Therefore, the conductivity effects of the shale minerals cause the Archie’s equation to become invalid for evaluating the shaly sand formation. Hence, several empirical saturation equations have been formulated in which most of them were modified from Archie’s equation itself. The modifications were done in order to take into account the effect caused by shale minerals conductivity (Stenson, 1988).

The simplest modification of Archie’s equation was done by accommodating shale presence effect in term of an excess conductivity (Patnode and Wyllie, 1950). The excess conductivity is expressed as an additional term added to the first of three equations proposed by Archie (1942) that was used to define the formation factor as relation of aqueous electrolyte conductivity with the conductivity of its reservoir rock.

According to the modified equation stated above, there are possibilities that the resistivity model suggested for shaly sand formation to come close towards the original Archie's equation. These possibilities can be achieved when the model is applied in formation with high water salinity in which the fluid conductivity is very large compared to the conductivity caused by shale presence. In this situation, shale conductivity has relatively small influence on the total conductivity of the reservoir rock.

1.2 Problem Statement

1.2.1 Problem Identification

Critical analysis toward resistivity model is one of the ways to have a better understanding of the application or the limitation for each model formulated to solve problems associated with respective formation condition. In the case of shaly sand formation, the modification of Archie equation will be the main focus in order to gain a larger scope of knowledge in dealing with this type of formation.

In shaly sand formation with high water salinity, there are possibilities for the resistivity model to come close to Archie's equation. This possibility should be tested and analyzed in order to see if the deduction can be further described for the betterment of the resistivity model itself.

In order to do so, laboratory work can be done in determining the resistivity model behavior for shaly sand formation in specific condition (high water salinity) where its limitation and exception can be drawn.

1.2.2 Significance of the Project

Upon completion of this project, the data obtained from the laboratory work will enable the author to draw limitation and exception towards the chosen resistivity modeling in shaly sand formation. The author will also be able to provide critical analysis regarding the theory using a real tested data.

In addition, by completing this project, the author will also be able to improve and enhance his petrophysics theory and practical knowledge especially in the formation evaluation of shaly sand formation. This is due to the circumstances that the author is required to have deep understanding about the emergence of the shaly sand problem, existing resistivity modeling, and laboratory work practice.

1.3 Objective and Scope of Study

1.3.1 Objectives of the Project

By using the data from laboratory test and analysis, there are three main goals to be achieved from this project which are:

- To investigate the effect of high water salinity towards the resistivity behaviors of shaly sand formation.
- To estimate the value of water salinity that can turns the shale excess conductivity to be negligible.
- To draw the limitation and exception for shaly sand resistivity model in high water salinity.

1.3.2 Scope of Study

In completing this project, there are several scopes of study that will be emphasized and explained throughout the project's process flow. The basic understanding starts with the earliest and fundamental resistivity modeling proposed in Archie's equation. However, since the equation is only valid for the clean sand formation, the study will move on to the closest modified Archie's equation proposed by Patnode and Wyllie for shaly sand formation.

Although the modified equation introduces additional term for excess conductivity caused by shale, this effect can be insignificant when the formation involves high salinity of water. To prove this presumption, the theory is brought into lab work to be studied further.

The scope of study will be concluded in the form of research data to see whether or not high water salinity can bring resistivity model of shaly sand formation to come close to Archie's equation.

1.4 The Relevancy of the Project

This project is relevant to the author as a Petroleum Engineering student who had already completed the courses related to the petrophysicals study, well logging and formation evaluation. Moreover, the understanding about the subsurface formation and their properties such as resistivity is crucial in determining the presence of hydrocarbon located deep in the earth.

This project could also provide critical analysis towards the proposed resistivity model in which its limitation and exception can be better understood. The analysis process that is supported with experimental data will be able to improve author's ability to make significant reasoning.

1.5 Feasibility of the Project within the Scope and Time Frame

Author had been given full two semesters of studies to complete the final year project which is divided into Final Year Project I and Final Year Project II. The time given is almost 8 months and sufficient for the author to complete the project. During Final Year Project I, the author will spend more time to do research and background studies for subject matters that are related to the project. In Final Year Project II, the author will conduct the major part of the project which is to carry out laboratory test for designed experiment. After the two phases, the author will finally implement all the theories and knowledge he obtain from the laboratory research and provide conclusion for the project.

CHAPTER 2

LITERATURE REVIEW

Worthington in 1985 has acknowledged the period prior to 1950 as a "shale-free" period from a petrophysical standpoint. It is because the shaly-sand problem has been fully recognized and addressed only after this date. The emergence of shaly sand problem has given great impact on the formation evaluation which is closely associated to the determination process for water saturation and hence hydrocarbon in place.

A chronological table taken from Worthington (1985) is showing several selected petrophysical developments during the "shale-free" period. Moving fifteen years after the period, Wenner in North America and Schlumberger brothers in Europe remarkably pioneered the surface resistivity prospecting to be the precursor of geophysical well logging.

CHRONOLOGICAL LANDMARKS OF THE SHALE FREE PERIOD (PARTIALLY EXTRACTED FROM JOHNSON, 1961)

1812	Electrical phenomena measured in the walls of Cornish tin mines
1869	Downhole temperature measurements
1883	In-situ determination of rock resistivity by measurement at the earth's surface
1912	Resistivity prospecting established
1927	First electric log
1932	Quantitative resistivity tool (Normal device)
1939	Natural gamma tool*
1942	Archie's laws
1947	Induction log
1947	Recognition of interface conductivity in reservoir rocks*
1948	Determination of R_w from the SP log
1949	Appreciation of SP response in shaly sands*

*denotes shale-related development

Table 1: Chronological Landmarks of the Shale Free Period

Source: Worthington, P.F. 1985. The Log Analyst p.24

Ten year after the shale-free period, quantitative resistivity tools were first developed called Normal device. Along with this development, Archie's empirical formula was published and both of these two events provided foundation for the quantitative petrophysical evaluation of sand reservoirs. Even though Archie's equation was made only for clean sands, there was an indication of increasing awareness for interpreting complexities related to the shaly sand problems based on the growing number of shale related developments during the previous 10-12 years of the shale-free period.

Procedures of evaluating shaly sand formation have a very wide variety where each of them is able to significantly provide different assessment result by giving the focus on several important based concepts. These concepts are evolving from time to time as more knowledge been acquired from experiment and study. Discussion about the shaly-sand models that introduced since 1960 can been divided into two groups.

The first group provides the concepts based on the fraction of shale volume, V_{sh}. The problems associated with these models are their result often turns to be scientifically inaccurate. This disadvantage makes them open to misunderstanding and wrongly use. However, the application of these models is at least theoretically applicable to logging data without the difficulty of doing calibration on a core sample for the shale related parameter.

Meanwhile, improvements can be seen in the second group with the concepts based on the ionic double-layer phenomenon. These models are more interesting as they are derived from better scientific background. Nevertheless, these models require calibration of core sample for the related shale parameter alongside with several log derivable petrophysical measurement when they are wanted to be strictly applied. If not, the models' field application may include approximations that will effectively reduce the shale term to one in shale volume fraction.

Shaly sand evaluation can be conducted using the relationship of the most common element present in any formation which is water. According to Worthington (1985), the emergence of the shaly-sand problem which gives impacts on resistivity data can be more easily observed by addressing only the conditions with full water saturation. A convenient starting point is the definition of formation factor (denoted as **F**) which was the first among the three equations proposed by Archie (1942).

$$F = \frac{R_o}{R_w} = \frac{C_w}{C_o}$$

The equation above showing F in form of relationship between R_o that is the resistivity of a reservoir rock when fully saturated with aqueous electrolyte with resistivity of R_w, while C_o and C_w are the corresponding conductivities. Archie was able to satisfy this relationship when he gained a straight line of gradient 1/F in a plot of C_o against C_w using experimental condition of a clean sand formation which fully saturated with brine.

Since the Archie definition of formation factor with respect to resistivity was only valid for clean sand formation, more general relationship between C_o and C_w was brought into further study. As regard to this matter, Patnode and Wyllie (1950) proposed modification on Archie's equation to include the contribution of conductivity due to shale,

$$C_o = \frac{C_w}{F} + X$$

where X is the effect to the formation total conductivity caused by shale. The modification proposed is valid for reservoir formations which are fully saturated with water. In clean sand formation, value of X is equal to 0 and the equation is reduced to the original Archie's equation. Meanwhile in shaly sand formation with high salinity of water, the value for C_w is very large and causes X to have relatively small influence on C_o which again reduced the equation to the Archie definition.

In conducting this project, the ratio of C_w/C_o is better to be regarded as F_a which represents formation factor approximation that is dependent to water salinity. This step is made after considering that the study is conducted to investigate shaly sand resistivity model in high salinity of water. The theory for this project is better viewed using the schematic variation presented by Worthington (1985).

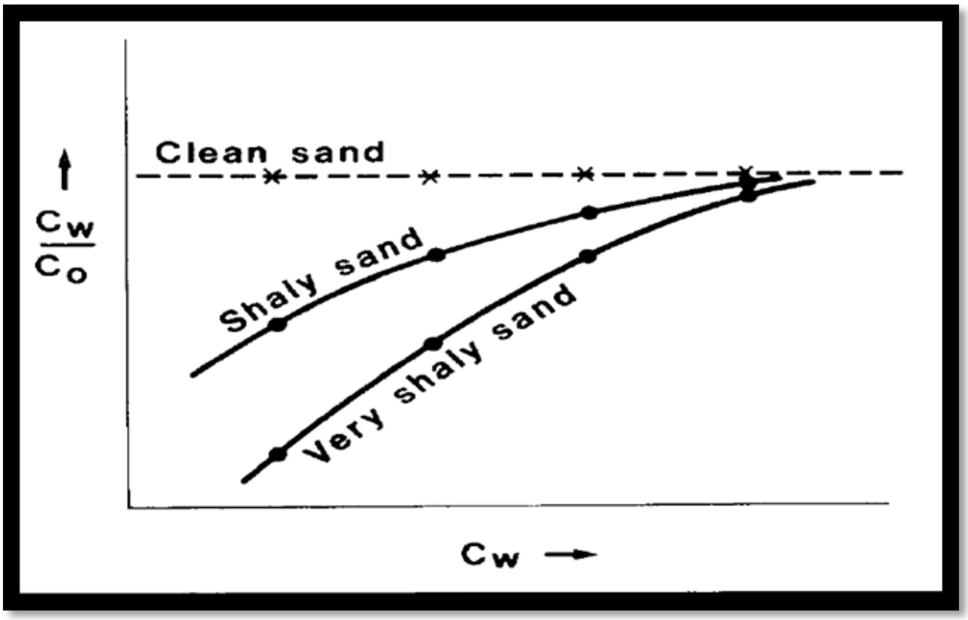

Figure 1: Schematic Variation of the Ratio C_w/C_o (=F_a) with C_w for Shaly Sand

Source: Worthington, P.F. 1985. The Log Analyst p.24

The role of C_w/C_o ratio in shaly sand formation will become close to Archie's equation only when X value is sufficiently small or C_w is sufficiently large. Hence, the appearance of shale conductivity in shaly sand formation is also controlled by the value of X relative to the expression of C_w/F which on the other hand comes from the water salinity. From this mathematical reasoning, this project aims to search for the sufficient value of C_w to indirectly neglect the shale conductivity effects by referring to the experimental resistivity result.

CHAPTER 3

METHODOLOGY

3.1 Project Planning

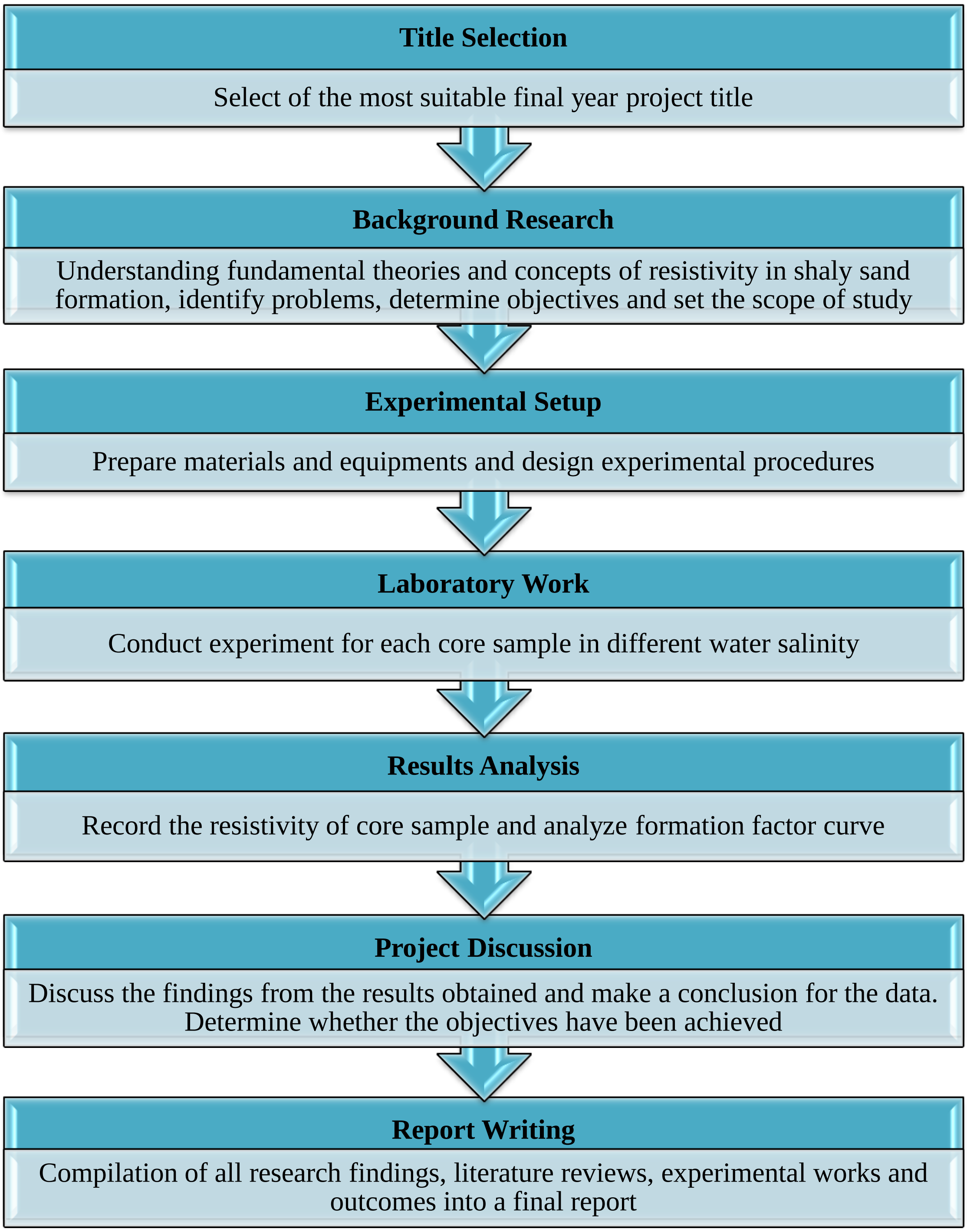

Figure 2: Project Planning Flow Line

3.2 Experimental Procedures

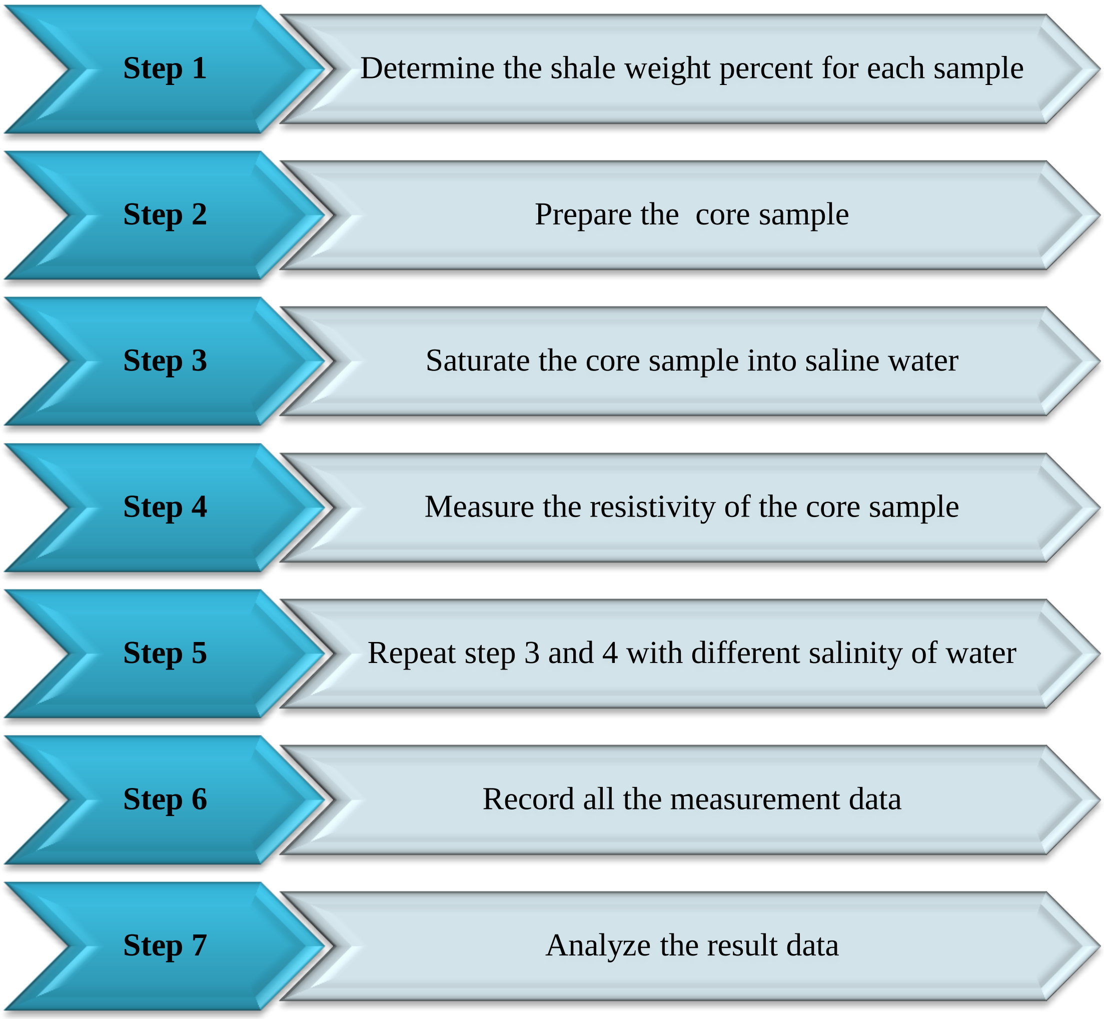

Figure 3: Experimental Procedures for Shaly Sand Resistivity Model

To characterize electrical properties, author will utilize CoreTestSystem™. The instrument is dedicated to allow both two-electrode and four-electrode resistivity measurements as a function of frequency. To avoid parasitic impedance in higher frequency, it is suggested to use two-electrode for the most resistive samples, whereas for the lesser resistive sample it is better to use four-electrode modes. Electrode polarization noise can be separated from the rock once it is plotted in Argand diagram. The frequency characteristic is a border between sample response and electrode polarization.

3.3 Project Gantt Chart/Key Milestone

Final Year Project 1:

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Selection of Project Topic:** Resistivity Modeling of Shaly Sand Formation in High Water Salinity														
2	**Preliminary Research Work:** Research on literatures related to the topic														
3	Submission of Extended Proposal						●								
4	Proposal Defense (Oral Presentation)							**Mid Sem Break**							
5	Project work continues: Further investigation on the project and do modification if necessary														
6	Submission of Interim Draft Report													●	
7	Submission of Interim Report														●

Table 2: Project Gantt Chart for FYP 1

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Final Year Project 2:

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Project Work Continues:** Part 1: Preparing the core samples							**Mid Sem Break**							
2	Submission of Progress Report								●						
3	**Project Work Continues:** Part 2: Resistivity Measurement														
4	Pre-SEDEX										●				
5	Submission of Draft Report											●			
6	Submission of Dissertation (soft bound)												●		
7	Submission of Technical Paper												●		
8	Oral Presentation													●	
9	Submission of Project Dissertation (Hard Bound)														●

Table 3: Project Gantt Chart for FYP 2

3.4 List of Materials

Part 1: Core Sample Preparation

Material for preparing the core samples are:

1. Clean Sand
2. Shale
3. Resin
4. Hardener
5. Acetone

Figure 4: Example of Core Samples for the Experiment

Part 2: Resistivity Measurement

Materials for resistivity measurement are:

1. 3 core samples of different shale content:
   - Sample A: Clean Sand (0% weight of shale)
   - Sample B: Shaly Sand (15% weight of shale)
   - Sample C: Very Shaly Sand (30% weight of shale)
2. Deionized Water
3. Salt (99.9% Sodium Chloride)

The experiment for this project is planned to be conducted in a controlled environment in which all the parameters are being set using desired value.

For Shale Content:

- Core samples are self-made by mixing uniform size of sand with pre-determined weight percent of shale. Both materials are bonded together using resin to form the core samples.
- The shale content is measured based on the weight percent of shale from the total core weight.

For Water Salinity:

- The water salinity is measured based on the ratio of salt content (g/L) and water conductivity produced (S/m).

3.5 List of Apparatus and Equipment

1. Resistivity Measuring Device
    - Acoustic Velocity (Brand: Coretest Inc. Auto Lab 500)

The AutoLab 500 is a laboratory system with three integrated components:

a) A pressure vessel and the associated pressure intensifiers to generate stresses (pressures) on a test specimen.
b) An electronics console that interfaces with the mechanical system to condition and amplify signals from the transducers and devices measuring pressure and velocity.
c) A data acquisition system to acquire data and to process the data collected on each experiment.

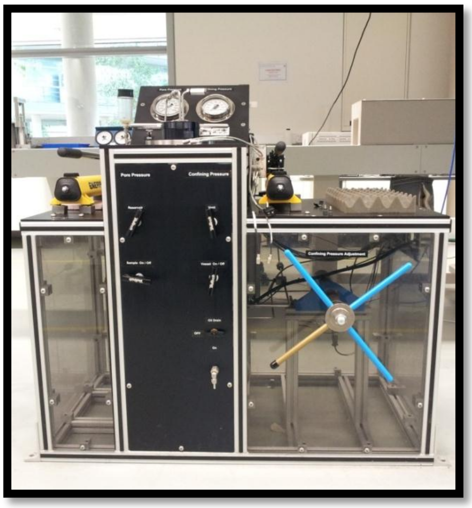


Figure 5: Pressure Vessel Container

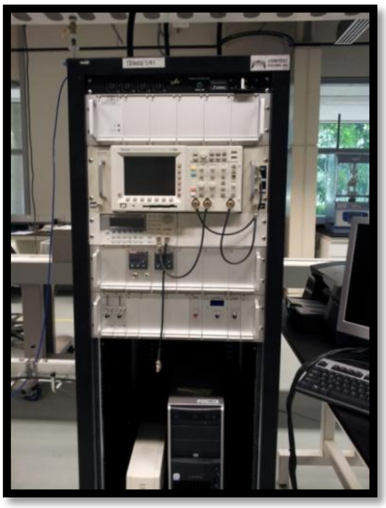


Figure 6: Electronic Console

2. Core Sample Preparation Apparatus
    - Mortar Mixture
    - Steel Cube Mould
    - Coring Device

Figure 7: Mortar Mixture

Figure 8: Steel Cube Mould

CHAPTER 4

RESULT AND DISCUSSION

4.1 Core Sample General Properties

The first step done for the project was to prepare three (3) groups of core sample to be tested in the resistivity measurement. Among the activities done in the process of preparing and evaluating the general properties of all core samples are as follows:

1. Collect the raw materials – sand and shale
2. Sieve sand to determine the grain size.
3. Grind shale into powder.
4. Mix raw materials with chemicals (resin, hardener and acetone).
5. Put the mixture into steel mould.
6. Keep the mixture in oven to be heated and harden.
7. Cut the moulded mixture into desired core size.
8. Record the weight of each core sample type.
9. Measure the porosity and permeability of each core sample type.

Table 4 below shows the result of evaluating the general properties of all the core samples which have different weight percent of shale.

	Core A	Core B	Core C
Weight Percent of Shale (%)	0	15	30
Weight (g)	47.3	45.7	44.8
Diameter (inch)	1.0	1.0	1.0
Length (inch)	2.3	2.3	2.3
Average Porosity	0.28	0.21	0.25
Average Permeability (mD)	328	290	182
From sieving, the grain size used for preparing the core samples were ranging from **300 µm - 1180 µm**.			

Table 4: Core Sample General Properties

Core Sample A – Clean Sand

Core Sample B – 15% Shale

Core Sample C – 30% Shale


Table 5: Core Sample After Drying Process

4.2 Resistivity Measurement

Three samples (Core A, B, C) prepared in previous part of the project were used for the resistivity measurement. These samples were cut and trimmed according to core-holder size as below:

Diameter	: 25.4 mm / 1.0 inch
Length	: 58.42 mm / 2.3 inch

Synthetic brine water (aqueous electrolyte) was created with different salinity by dissolving salt into deionized water. Seven values of salinity were used ranging from 20,000 to 50,000 ppm. The fluid conductivity and Total Dissolved Solids (TDS) were measured for each salinity values. Table 5 describes the dissolving salt composition and Table 6 lists the aqueous electrolyte properties.

No.	Description	Composition
1	Sodium Chloride (w/w)	99.9%
2	Calcium (mg/kg)	0.04%
3	Magnesium (mg/kg)	0.02%
4	Moisture (w/w)	0.2%
5	Iron (mg/kg)	17.8 ppm

Table 6: Dissolving Salt Composition

Aqueous Electrolyte No.	Total Dissolved Solids (g/L)	Fluid Conductivity (S/m)
1	20.0	3.22
2	25.0	3.93
3	30.0	4.62
4	35.0	5.30
5	40.0	5.97
6	45.0	6.54
7	50.0	7.13

Table 7: Aqueous Electrolyte Properties

To characterize electrical properties, AutoLab 500 having a schematic diagram as in Figure 9 and core holder system as in Figure 10 was used. The instrument is designed to allow both two-electrode and four-electrode resistivity measurements as a function of frequency, pressure, and temperature.

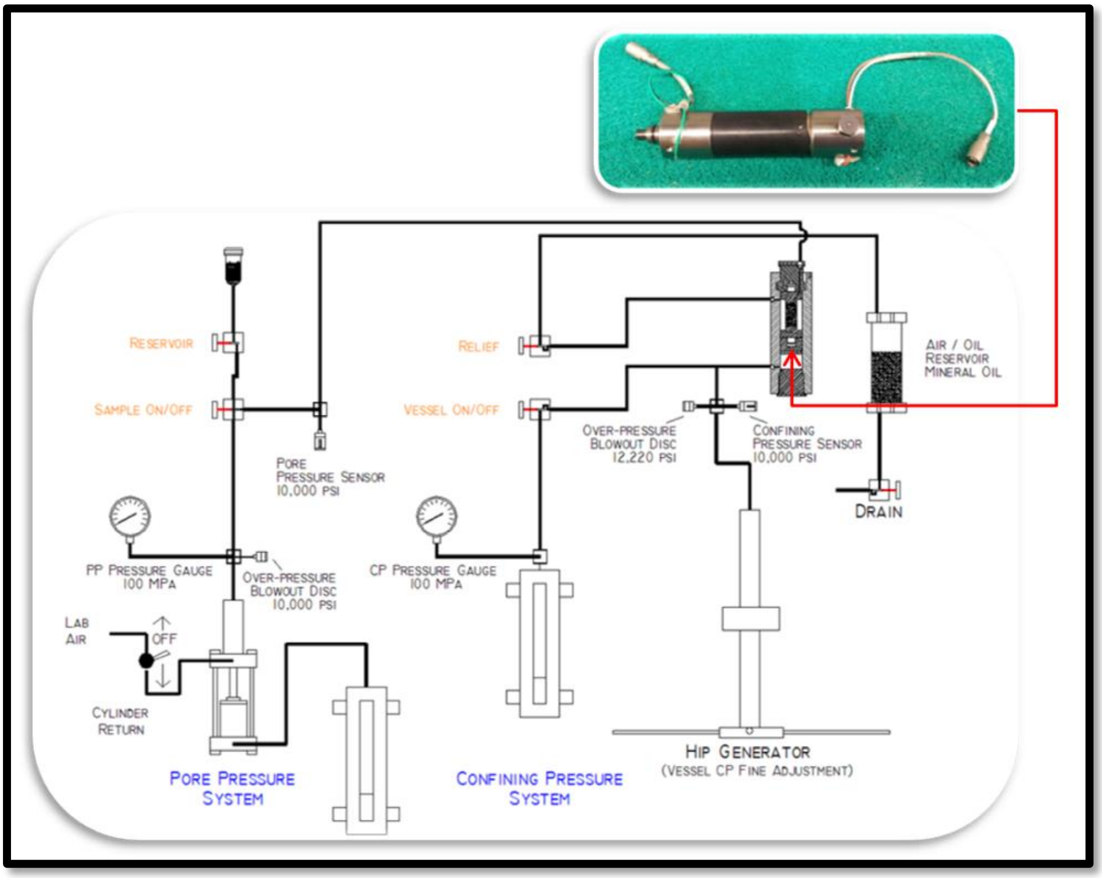


Figure 9: Schematic Diagram of Resistivity Measurement System

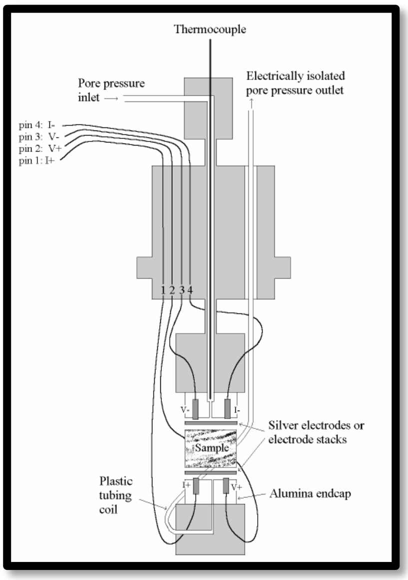


Figure 10: Core Holder Diagram

As the resistivity measurement is estimated to measure quite resistive samples, the equipment is being set for two electrodes mode. In this mode, a single electrode (silver filter) is placed between each end of caps and the sample (Fig. 10). Each electrode has to make a contact with both silver contacts on the face of the respective end of cap. The acrylic disk is placed between the end of cap and the electrode stack with the grooves facing the sample. The disk is required to be properly oriented to allow the silver electrical contacts touch the silver electrode membranes. The grooves uniformly distribute the pore fluid over the face of the sample.

The resistivity core-holder components consist of two silver electrical contacts embedded in the face of each end of cap (Fig. 10). The end of caps is made of a non-conducting material such as alumina or plastic. One end is mounted with the pore pressure inlet port containing the contacts for the negative current (I–) and negative voltage (V–) electrodes. The other end is electrically isolated from the apparatus and contains the contacts for the positive current (I+) and positive voltage (V+) electrodes.

The measurements for all 21 core samples resistivity were recorded by the computer in each run. The frequency range of electrical pulse must be pre-tested to ensure the real resistivity value can be captured. Figure 11 on the next page shows the initial setting used to measure the resistivity values of all core samples. In this experiment, the range was set to start at 1 Hz and stop at 20 000 Hz with 30 frequencies number. The amplitude was set at 0.5. Sinusoid relationship was used and the result was set to be in logsweep mode. Confining pressure inside the pressure vessel container was set at 1000 psi.

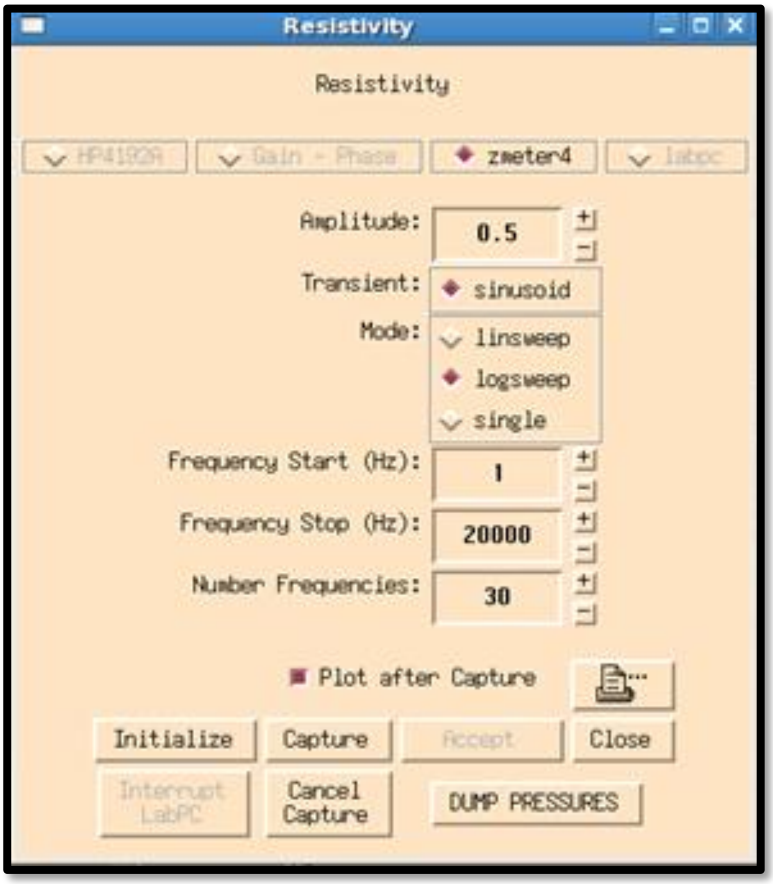


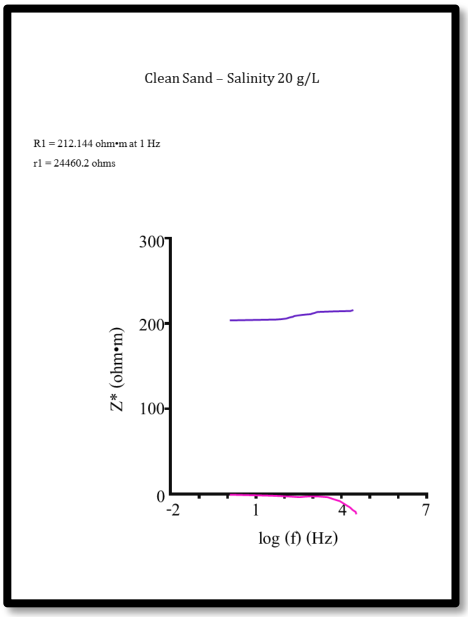
Figure 11: Initial Setting for Resistivity Measurement

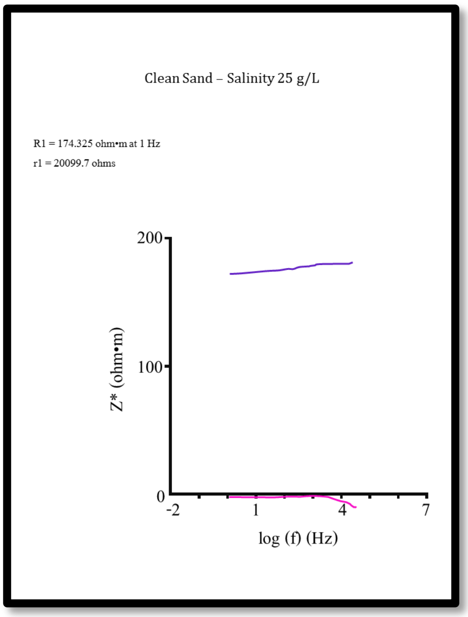
The recorded resistivity values in each run will then be tabulated as R_o, in which C_o were calculated by reciprocating them. Formation factor were also be calculated by using the formula of:

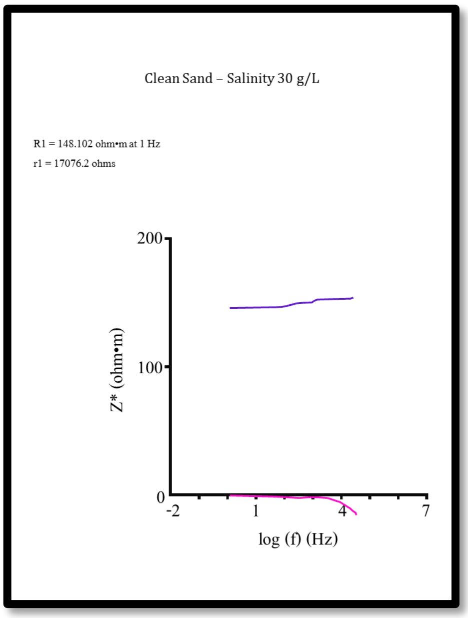
$$F = \frac{R_o}{R_w} = \frac{C_w}{C_o}$$

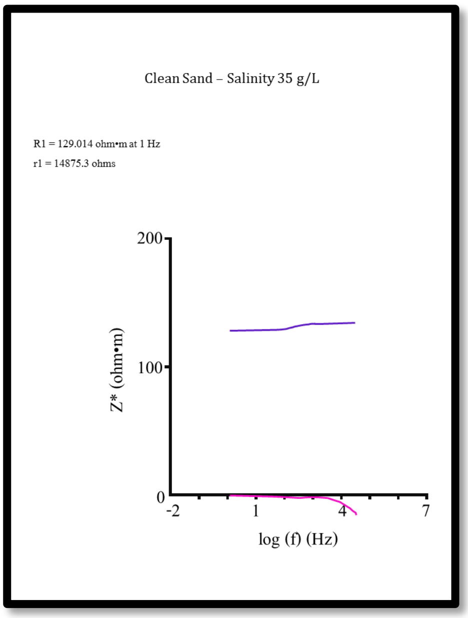
Result for Clean Sand (Core A)

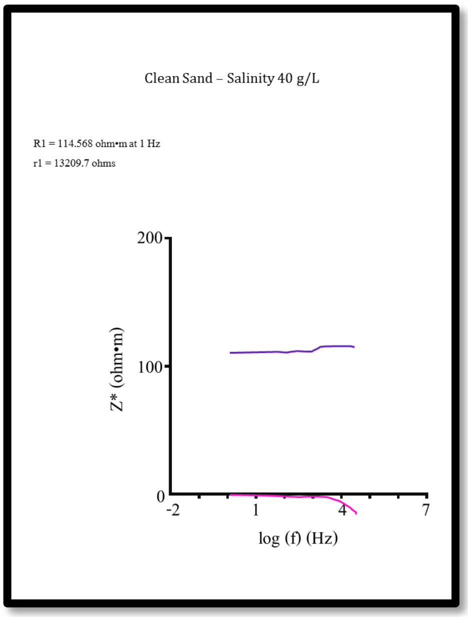
AutoLab 500 Resistivity Reading for Clean Sand

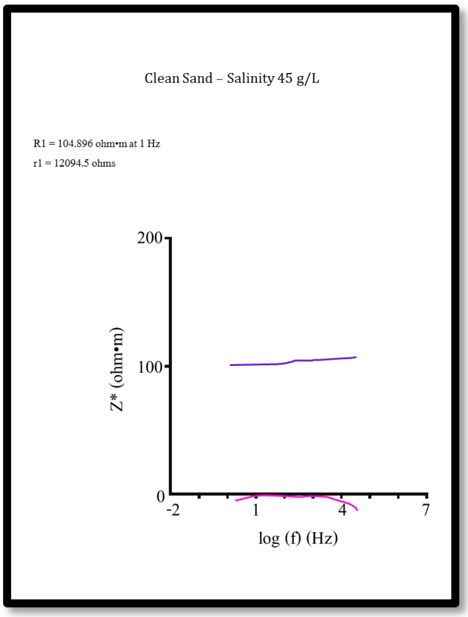












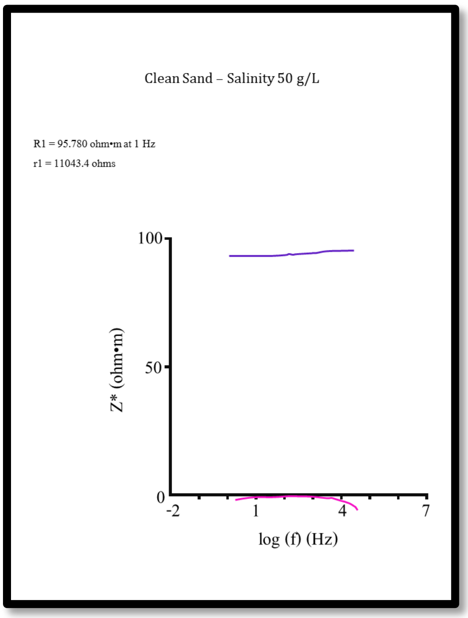


Table 8: AutoLab 500 Resistivity Reading for Clean Sand

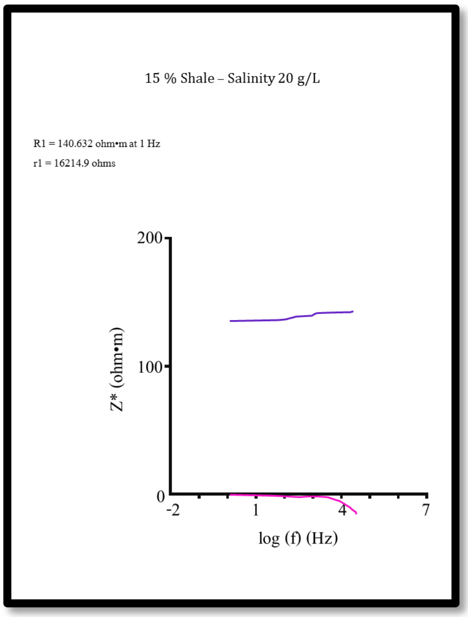
Clean Sand			
Water Salinity (g/kg)	R_w	R_o	F (Ro / Rw)
20.0	0.31	212.14	682.57
25.0	0.25	174.33	684.43
30.0	0.22	148.10	684.39
35.0	0.19	129.01	684.06
40.0	0.17	114.57	684.40
45.0	0.15	104.90	686.49
50.0	0.14	95.78	683.17

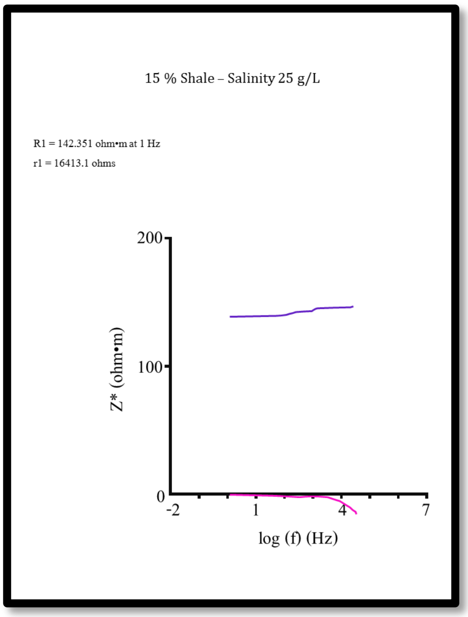
Clean Sand			
Water Salinity (g/kg)	C_w	C_o	F (C_w / C_o)
20.0	3.218	4.714E-03	682.57
25.0	3.926	5.736E-03	684.43
30.0	4.621	6.752E-03	684.39
35.0	5.302	7.751E-03	684.06
40.0	5.974	8.728E-03	684.40
45.0	6.545	9.533E-03	686.49
50.0	7.133	1.044E-02	683.17

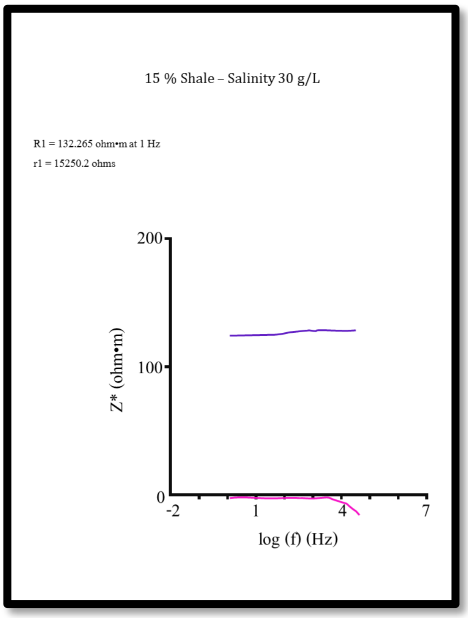
Table 9: Overall Results for Clean Sand

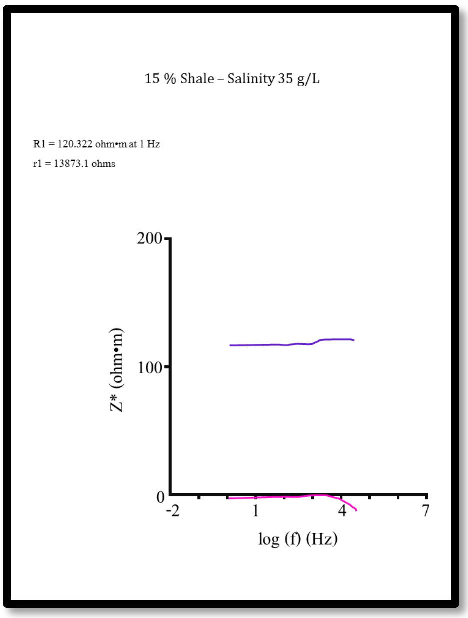
Result for 15% Shale (Core B)

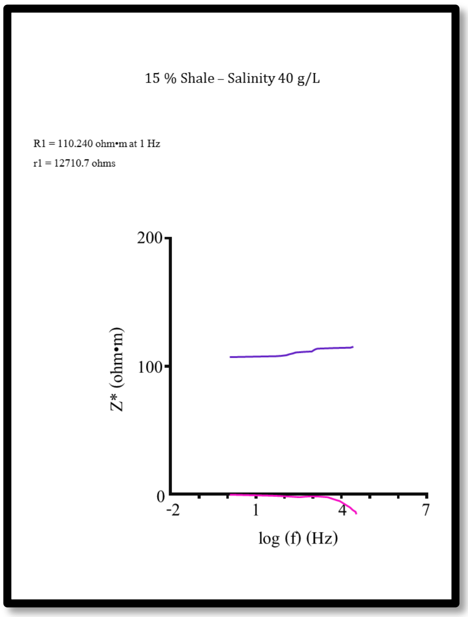
AutoLab 500 Resistivity Reading for 15% Shale

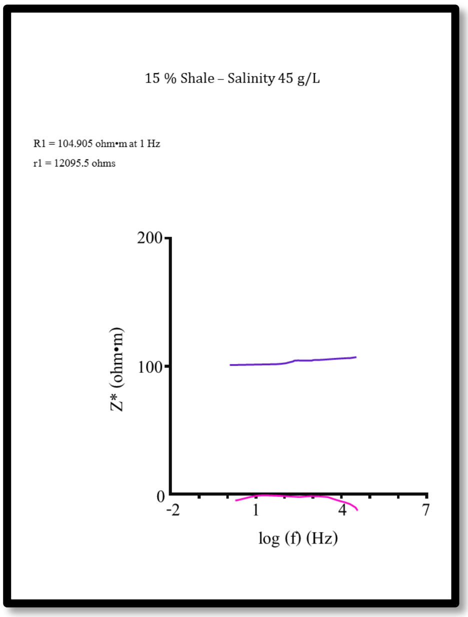












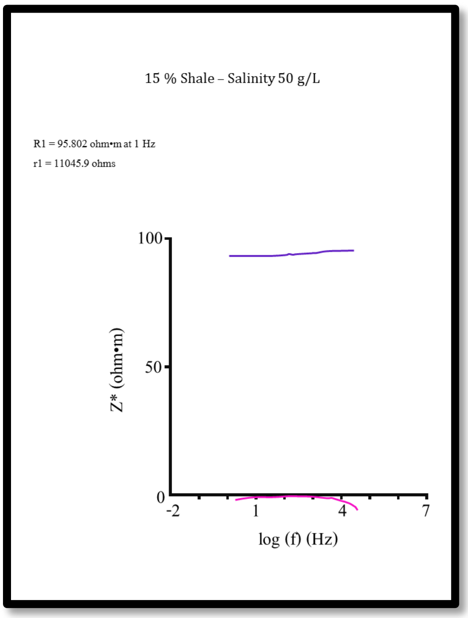


Table 10: AutoLab 500 Resistivity Reading for 15% Shale

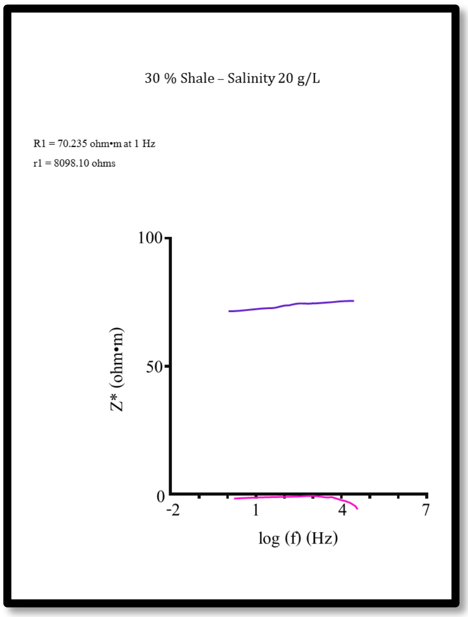
15 % Shale			
Water Salinity (g/kg)	R_w	R_o	F (Ro / Rw)
20.0	0.31	140.63	452.48
25.0	0.25	142.35	558.90
30.0	0.22	132.27	611.21
35.0	0.19	120.32	637.97
40.0	0.17	110.24	658.54
45.0	0.15	104.91	686.55
50.0	0.14	95.80	683.32

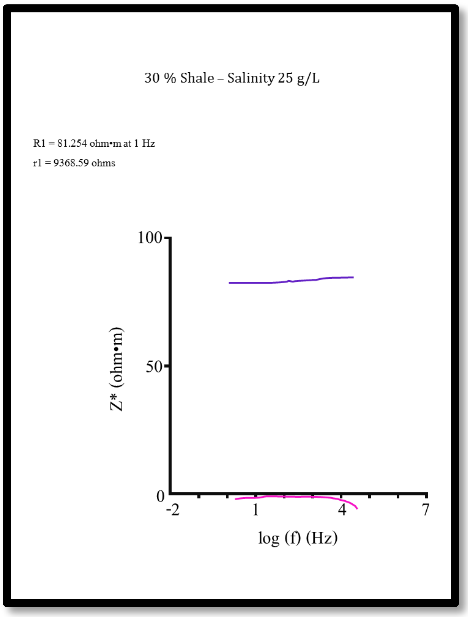
15 % Shale			
Water Salinity (g/kg)	C_w	C_o	F (C_w / C_o)
20.0	3.218	7.111E-03	452.48
25.0	3.926	7.025E-03	558.90
30.0	4.621	7.561E-03	611.21
35.0	5.302	8.311E-03	637.97
40.0	5.974	9.071E-03	658.54
45.0	6.545	9.532E-03	686.55
50.0	7.133	1.044E-02	683.32

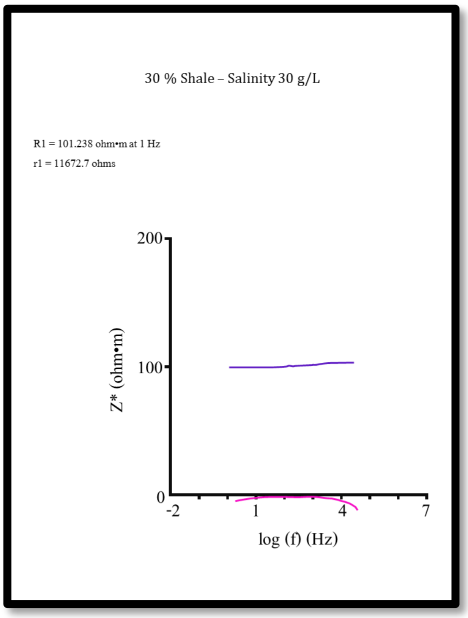
Table 11: Overall Results for 15% Shale

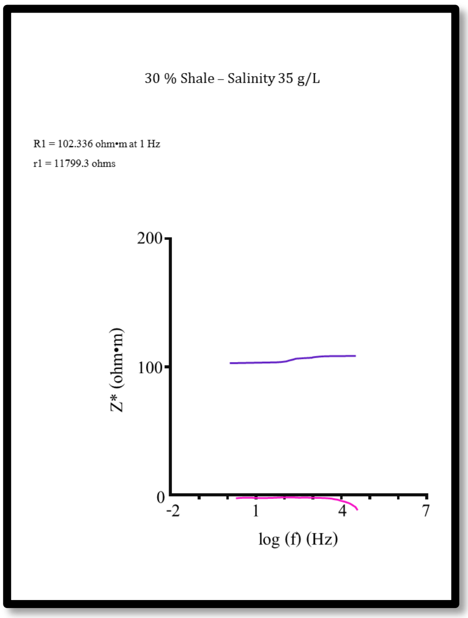
Result for 30% Shale (Core C)

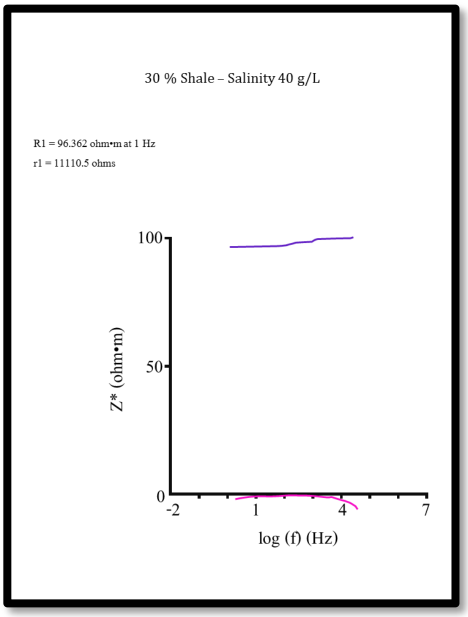
AutoLab 500 Resistivity Reading for 30% Shale

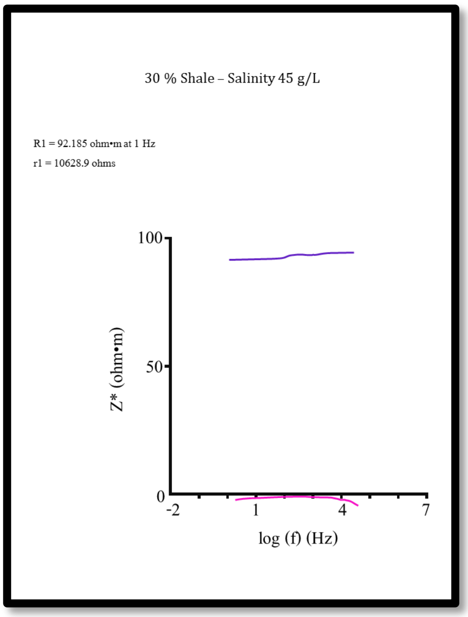












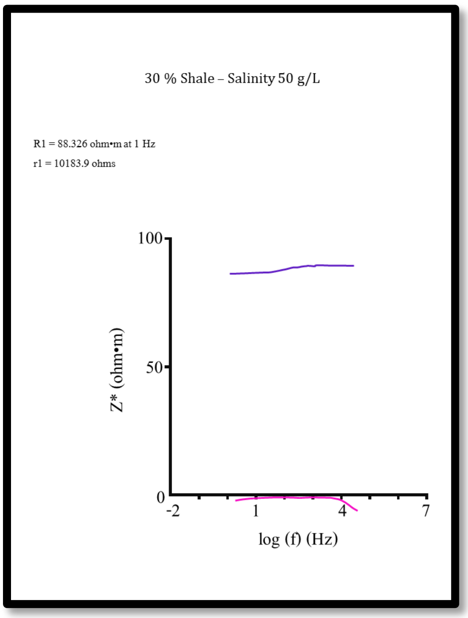


Table 12: AutoLab 500 Resistivity Reading for 30% Shale

30 % Shale			
Water Salinity (g/kg)	R_w	R_o	F (Ro / Rw)
20.0	0.31	70.24	225.98
25.0	0.25	81.25	319.02
30.0	0.22	101.24	467.83
35.0	0.19	102.34	542.61
40.0	0.17	96.36	575.64
45.0	0.15	92.19	603.30
50.0	0.14	88.33	630.00

30 % Shale			
Water Salinity (g/kg)	C_w	C_o	F (C_w / C_o)
20.0	3.218	1.424E-02	225.98
25.0	3.926	1.231E-02	319.02
30.0	4.621	9.878E-03	467.83
35.0	5.302	9.772E-03	542.61
40.0	5.974	1.038E-02	575.64
45.0	6.545	1.085E-02	603.30
50.0	7.133	1.132E-02	630.00

Table 13: Overall Results for 30% Shale

4.3 Discussion of Result

In well logging activities, electrical resistivity has been utilized to evaluate the properties and behavior of subsurface formation. Resistivity is defined as a bulk property of material which describes how well that material allows electric current to flow through it.

Ohm's Law characterized resistance as the ratio of potential voltage by the flowing current. However, resistance will change in several conditions. This situation happens when the volume, measurement geometry or the liquid saturation of the material changes. Therefore, it can be understood that material resistance is not a physical property and its mechanism relies on the surrounding condition.

In this project, resistivity acts as the main indication for the study of shale effect. Shale which is known as the conductive element will has a significant effect on rock resistivity. When the shale content in the rock increases the resistivity measurement of the respective rock will be reduced.

The excess conductivity effect caused by the presence of the shale yet can be less significant to the reduction in rock resistivity when the rock encounters or being saturated by high water salinity. As the water salinity gets higher, the resultant conductivity will become much greater than the shale conductive effect.

The relationship between these two variables can be defined better in term of apparent formation factor of the rock itself. In clean sand rock, the apparent formation factor will remain constant. This constant clean sand line is marked as the reference in order to see the shale effect. The increment in shale content will reduces the rock apparent formation factor and caused it to deflect away from the constant clean sand line. Higher shale content will caused greater deflection of the formation factor.

Nevertheless, this reflected apparent formation factor of rock with shale content (shaly sand) will be lower as the rock moves towards higher salinity value. The earlier deflection which comes from the shale excess conductivity becomes less significant in higher water salinity. It is because conductivity produced from the water salinity has weaken the shale conductive effect which therefore, the shaly sand apparent formation factor line is coming closer toward the constant clean sand line when the rock travels towards higher water salinity region.

Generally, normal sea water salinity is at TDS range of 30-35g/L. The experiment has considered taking the values from 20-50 g/L. This means that the values higher than 35g/L are considered as high water salinity. Each value for water salinity will have its respective associated conductivity which is measured before all the samples are being saturated in them. These associated values of water salinity (g/L) and water conductivity (S/m) are shown in Table 14.

The results gained from the experiment in this project are the resistivity readings of the three core sample types with different shale content. The readings reflected the rock resistivity when completely saturated with the water (Sw=1) and denoted as R_o. Since resistivity and conductivity are inversely related, the resistivity readings are converted into core conductivity (S/m). Table 14 below shows the overall results of the calculated saturated core conductivity and formation factor.

Water Salinity (g/L)	Saturated Core Conductivity, Co S/m			Water Conductivity Cw (S/m)	Apparent Formation Factor, F (Cw/Co)		
	Clean Sand	15% Shale	30% Shale		Clean Sand	15% Shale	30% Shale
20.0	4.71E-03	7.11E-03	1.42E-02	3.22	682.57	452.48	225.98
25.0	5.74E-03	7.02E-03	1.23E-02	3.93	684.43	558.90	319.02
30.0	6.75E-03	7.56E-03	9.88E-03	4.62	684.39	611.21	467.83
35.0	7.75E-03	8.31E-03	9.77E-03	5.30	684.06	637.97	542.61
40.0	8.73E-03	9.07E-03	1.04E-02	5.97	684.40	658.54	575.64
45.0	9.53E-03	9.53E-03	1.08E-02	6.54	686.49	686.55	603.30
50.0	1.04E-02	1.04E-02	1.13E-02	7.13	683.17	683.32	630.00

Table 14: Calculated Saturated Core Conductivity and Formation Factor

The results shown in Table 14 are plotted into a graph that depicts the calculated formation factor against the aqueous electrolyte conductivity. In this graph (Fig.12), the relation between both changing variables (shale content and water salinity) as discussed previously has been justified by the result from the resistivity measurement.

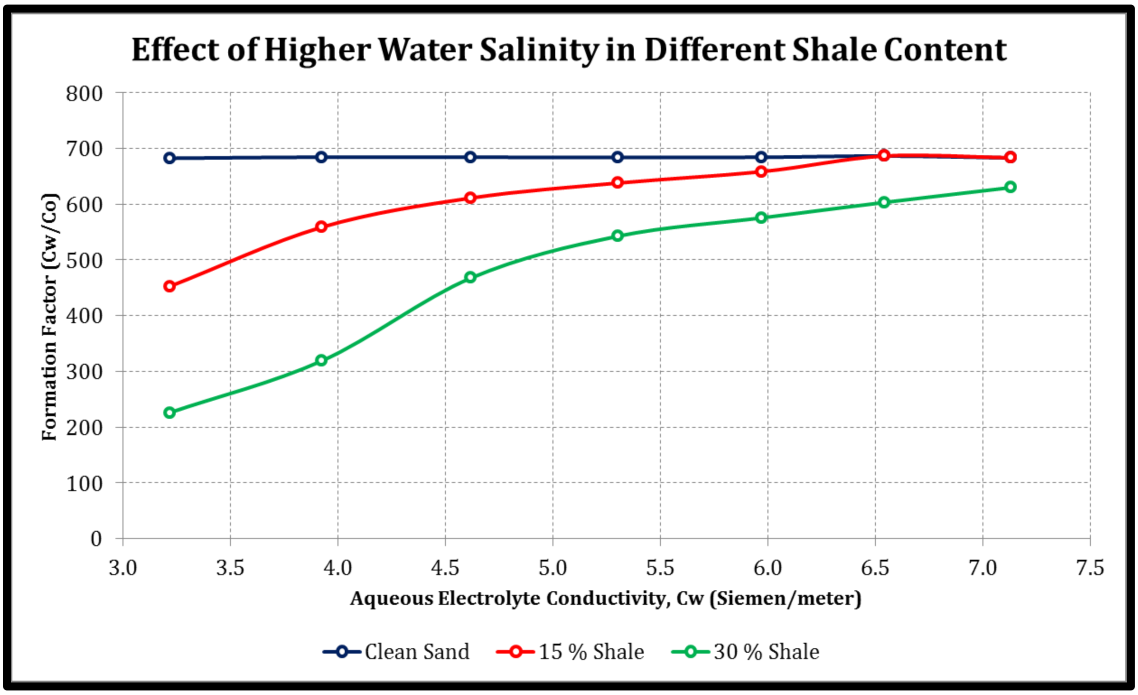


Figure 12: Effect of Higher Water Salinity in Different Shale Content

Clean sand constant line exists at formation factor value of 684 (±2). The 15% shale core sample shows smaller deflection of formation factor from the clean sand constant line as compared to the 30% shale core sample. When the aqueous electrolyte conductivity increases as a result of increasing water salinity, both shaly sand formation factor lines move towards the constant clean sand line.

From the two shaly sand lines, only the 15% shale has the intersection with the clean sand constant line at fluid conductivity around 6.5 S/m. The intersection line means that the ratio of shale excess conductivity to fluid conductivity is close to zero. In this situation, conductive shale effect is considered as insignificant. In other words, this shaly sand core sample has similar formation factor properties as clean sand at fluid conductivity of 6.5 S/m and higher.

Meanwhile, the 30% shale core sample does not show any intersection with the clean sand constant line within the range of fluid conductivities that were used in this project (3.22-7.13 S/m). With the current trend of increasing formation factor by this shaly sand core sample, there are possibilities that it will eventually intersect with the clean sand constant line in higher fluid conductivity.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The electrical conductivity of Earth's materials varies over many orders of magnitude. It depends upon many factors, including: rock type, porosity, connectivity of pores, nature of the fluid, and metallic content of the solid matrix. This project was planned to have a controlled environment which mean that other related factors should be kept constant. This has been achieved by preparing the core sample in the laboratory instead of taking the real core sample from the real oil field.

The controlled environment helps to make sure only two major changing variables to present in the study. By this way, the effect of shale content and water salinity can be better understood. This project is capable of looking at the effects caused by high water salinity towards the resistivity modeling of shaly sand formation. The results from the designed experiment were obtained by measuring the core sample resistivity in different salinity of water. Core sample resistivity measurement will be used to relate with high water salinity effect as well as with the excess conductivity caused by shale.

From the experiment and resistivity measurement, the results showed that high water salinity effect is able turn the shale excess conductivity to be negligible. However, the 30% shale content in this study is considered as very shaly because of its low ability to mix which caused by swelling effect. Future study in this subject should consider having resistivity modeling to be conducted using a wider range of shale content and water salinity. As more data and results are being collected, a better understanding can be drawn about this subject of study.

In order to improve the project execution and experimental result, there are several recommendations that need to be considered which are:

1. The experiment need to be conducted in a controlled environment. Therefore, the core sample should be self-made and not taken from the real field.
2. The saturation process for the core samples should be done using vacuum chamber to ensure that the core samples are fully saturated.
3. Measurement should be taken repetitively in order to gain a more reliable and accurate result. Then, we need to consider the average value for the measurement.
4. An early preparation need to be done in order to ensure the materials and equipment are being set up properly and ready for the experiment.
5. Future study in this subject should consider having resistivity modeling to be conducted using a wider range of shale content and water salinity.

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[9] Hilfan Khairy and Zuhar Zahir Tn. Harith, "Surface Conductivity, Pore Radius Distribution and Their Effect to Electrical Dispersion: Study in Shaly Sandstones", International Conference on Integrated Petroleum Engineering and Geosciences, June 15-17 2010.

[10] New England Research, Inc., “AutoLab 500 Manual”, printed August 2007.

APPENDICES

Appendix I: Materials for Core Sample Preparation

Sample of sand collected

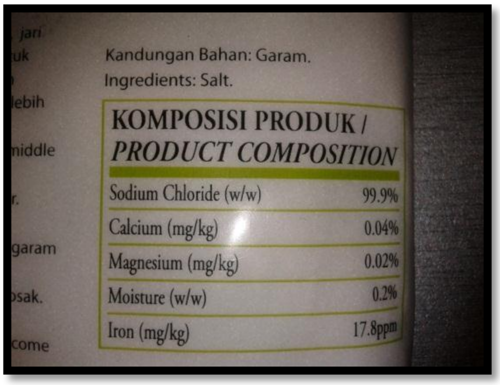
Sample of shale collected

Resin (Clear) & Hardener (Black)

Acetone

APPENDICES

Appendix II: Saturation Process for Core Samples



Salt composition used in saturation process

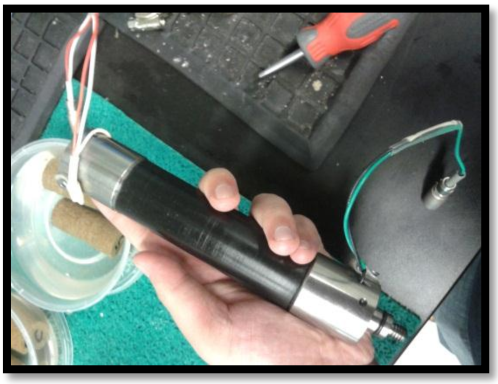
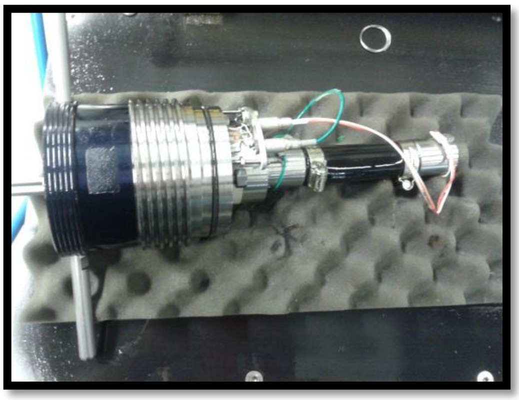
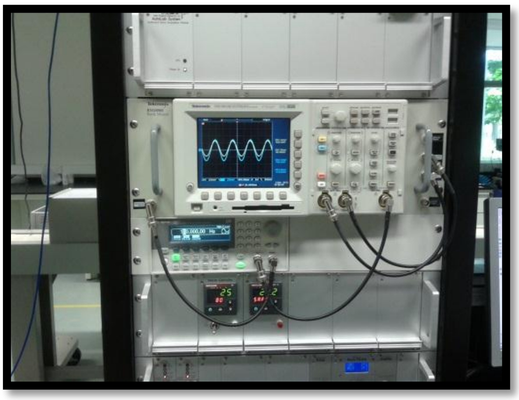
Core samples saturated at room condition

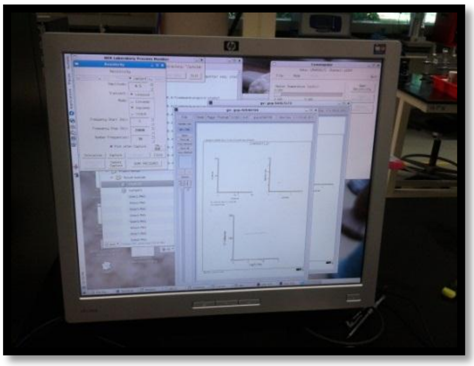
Early stage of saturation

Core Sample before the measurement process

APPENDICES

Appendix III: Resistivity Measurement Process

	
Core sample inserted into holder	**Both transducers were connected**
	
Core holder assembled with top coupling	**Electronic console measured the responses**



Result appeared on computer screen

Resistivity Modeling of Shaly Sand Formation in High Water Salinity

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Abstract – **The evaluation of shaly sand formation has a very close relationship with the study of electrical properties exhibits by the formation itself. The project done is based on the earliest resistivity model which proposed by Archie in 1942. Since this equation is only valid for clean sand, the model was modified by Patnode and Wyllie in 1950 to encounter the shale conductivity effect in shaly sand formation. However, this resistivity model contains limitation which is in high salinity of water, the shale conductivity will not able to significantly affect the total conductivity of the formation. In other words, when water salinity is sufficiently high, the resistivity model of shaly sand formation will reduced close to Archie's equation. Based on this hypothesis, the theory is brought into laboratory work where shaly sand core sample is tested for its resistivity in high salinity of water. Three core samples were prepared by varying the shale content. The general properties of the samples were recorded as references. The result of core sample resistivity measurement will be able to describe concisely the accuracy of this model and generally draw its limitation or exception to be made for the model especially when the shaly sand formation encounters high water salinity.**

I. INTRODUCTION

For more than 70 years, electrical properties that are measured in the reservoir have been used to assess the hydrocarbon saturation. The introduction of electrical measuring device especially into the well logging activities had provided a stepping stone in understanding and predicting formation behavior in the subsurface.

The earliest model formulated using the electrical properties came from Archie (1942) who empirically equated the fluid saturation as the function of electrical resistivity of rocks, their porosity and brine saturation. However, the equation made by him is only provided good saturation estimation for clean sand in which unable to satisfy the condition; if the rock have significant amount of shale presents in the formation pore spaces. The presence of shale in sand formation is what has been called as "shaly sand" that will be the main subject of this study.

In general, the increase of shale content will cause the rock matrix to be more conductive. Therefore, the conductivity effects of the shale minerals turn the Archie's equation to become invalid for evaluating the shaly sand formation. Hence, several empirical saturation equations have been formulated in which most of them were modified from Archie's equation itself. The modifications were done in order to take into account the effect cause by shale minerals conductivity (Stenson, 1988).

The simplest modification of Archie's equation was done by accommodating shale presence affect in term of an excess conductivity (Patnode and Wyllie, 1950). The excess conductivity is expressed as an additional term added to the first of three equations proposed by Archie (1942) that was used to define the formation factor as relation of aqueous electrolyte conductivity with the conductivity of its reservoir rock.

According to the modified equation stated above, there are possibilities that the resistivity model suggested for shaly sand formation to come close towards the original Archie's equation. These possibilities can be achieved when the model is applied in formation with high water salinity in which the fluid conductivity is very large compared to the conductivity caused by shale presence. In this situation, shale conductivity has relatively small influence on the total conductivity of the reservoir rock.

A. Problem Statement

Critical analysis toward resistivity model is one of the ways to have a better understanding of application or limitation for each model formulated to solve problems associated with respective formation condition. In the case of shaly sand formation, modification of Archie equation will be the focal point to gain the larger scope of knowledge in dealing with this type of formation.

In shaly sand formation with high water salinity, there are possibilities for the resistivity model come close to Archie's equation. This possibility should be tested and analyzed to see if the deduction can be further described for the betterment of the resistivity model itself.

In order to do so, laboratory work can be done in determining the resistivity model behavior for shaly sand formation in specific condition (high water salinity) where its limitation and exception can be drawn.

B. Significant of the Project

Upon completion of this project, the data obtained from laboratory work enable the author to draw limitation and exception towards the chosen resistivity modeling in shaly sand formation. The author will also be able to provide critical analysis regarding the theory using the real tested data.

By completing this project, the author can improve and enhance his petrophysics theory and practical knowledge especially in formation evaluation of shaly sand formation. This is because in order to complete this project, the author is required to have deep understanding in the emergence of the shaly sand problem, existing resistivity modeling, and laboratory work practice.

C. Objectives of the Project

By using the data from laboratory test and analysis, there are three main goals to be achieved from this project which are:

- To investigate the effect of high water salinity towards the resistivity behaviors of shaly sand formation.
- To estimate the value of water salinity that turns the shale excess conductivity to be negligible.
- To draw the limitation and exception for shaly sand resistivity model in high water salinity.

D. Scope of Study

In completing this project, there are several scopes of study that will be emphasized and explained throughout the project's process flow. The basic understanding start with the earliest and fundamental resistivity modeling proposed in Archie's equation. However, since the equation is only valid for the clean sand formation, the study will move on to the closest modified Archie's equation proposed by Patnode and Wyllie for shaly sand formation.

Although the modified equation introduce additional term for excess conductivity caused by shale, this effect can be insignificant when the formation have high salinity of water. To prove this presumption, the theory is brought into lab work to be studied further.

The scope of study will be concluded in form of research data to see whether or not high water salinity of water can bring resistivity model of shaly sand formation come close to Archie's equation.

II. THEORY

Worthington in 1985 has acknowledged the period prior to 1950 to be seen as a "shale-free" period from a petrophysical standpoint. It is because the shaly-sand problem has been fully recognized and addressed only after this date. The emergence of shaly sand problem has given great impact on the formation evaluation which is closely associated to the determination process for water saturation and hence hydrocarbon in place.

A chronological table taken from Worthington (1985) is showing several selected petrophysical developments during the "shale-free" period. Moving fifteen years after the period, Wenner in North America and Schlumberger brothers in Europe remarkably pioneered the surface resistivity prospecting to be the precursor of geophysical well logging.

Ten year after the shale-free period, quantitative resistivity tools were first developed called Normal device. Along with this development, Archie's empirical formula was published and both of these two events provided foundation for the quantitative petrophysical evaluation of sand reservoirs. Even though Archie's equation was made only for clean sands, there was an indication of increasing awareness for interpreting complexities related to the shaly sand problems based on the growing number of shale related developments during the previous 10-12 years of the shale-free period.

CHRONOLOGICAL LANDMARKS OF THE SHALE FREE PERIOD (PARTIALLY EXTRACTED FROM JOHNSON, 1961)

1812	Electrical phenomena measured in the walls of Cornish tin mines
1869	Downhole temperature measurements
1883	In-situ determination of rock resistivity by measurement at the earth's surface
1912	Resistivity prospecting established
1927	First electric log
1932	Quantitative resistivity tool (Normal device)
1939	Natural gamma tool*
1942	Archie's laws
1947	Induction log
1947	Recognition of interface conductivity in reservoir rocks*
1948	Determination of R_w from the SP log
1949	Appreciation of SP response in shaly sands*

*denotes shale-related development

Table 1: Chronological Landmarks of the Shale Free Period

Source: Worthington, P.F. 1985. The Log Analyst p.24

Procedures of evaluating shaly sand formation have a very wide variety where each of them is able to significantly provide different assessment result by giving the focus on several important based concepts. These concepts are evolving from time to time as more knowledge been acquired from experiment and study. Discussion about the shaly-sand models that introduced since 1960 can been divided into two groups.

The first group provides the concepts based on the fraction of shale volume, V_{sh}. The problems associated with these models are their result that often turns to be scientifically inaccurate. This disadvantage makes them open to misunderstanding and wrongly use. However, the application of these models is at least theoretically applicable to logging data without the difficulty of doing calibration on a core sample for the shale related parameter.

Meanwhile, improvements can be seen in second group with the concepts based on the ionic double-layer phenomenon. These models are more interesting as they are derived from better scientific background. Nevertheless, these models require calibration of core sample for the related shale parameter alongside with several log derivable petrophysical measurement when they are wanted to be strictly applied. If not, the models' field application may include approximations that will effectively reduce the shale term to one in shale volume fraction.

Shaly sand evaluation can be conducted using the relationship of the most common element present in any of formation which is water. According to Worthington (1985), the emergence of the shaly-sand problem which gives impacts on resistivity data can be more easily observed by addressing only the conditions with full water saturation. A convenient starting point is the definition of formation factor (denoted as F) which was the first among three equations proposed by Archie (1942).

$$F = \frac{R_o}{R_w} = \frac{C_w}{C_o}$$

The equation above showing F in form of relationship between Ro that is the resistivity of a reservoir rock when fully saturated with aqueous electrolyte with resistivity of R_w, while C_o and C_w are the corresponding conductivities. Archie was able to satisfy this relationship when he gained a straight line of gradient 1/F in a plot of C_o against C_w using experimental condition of a clean sand formation which fully saturated with brine.

Since the Archie definition of formation factor with respect to resistivity was only valid for clean sand formation, more general relationship between Co and Cw was brought into further study. As regard to this matter, Patnode and Wyllie (1950) proposed modification on Archie's equation to include the contribution of conductivity due to shale,

$$C_o = \frac{C_w}{F} + X$$

where X is the effect to the formation total conductivity caused by shale. The modification proposed is valid for reservoir formations which are fully saturated with water. In clean sand formation, value of X is equal to 0 and the equation is reduced to the original Archie's equation. Meanwhile in shaly sand formation with high salinity of water, value for C_w is very large and causes X to have relatively small influence on C_o which again reduced the equation to the Archie definition.

In conducting this project, the ratio of C_w/C_o is better to be regarded as F_a which represents formation factor approximation that is dependent to water salinity. This step is made considering that the study is conducted to investigate shaly sand resistivity model in high salinity of water. The theory for this project can be better viewed using the schematic variation presented by Worthington (1985).

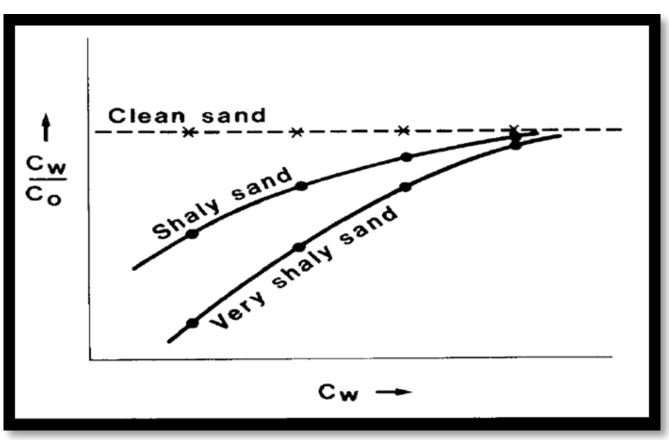


Figure 1: Schematic Variation of the Ratio C_w/C_o (=F_a) with C_w for Shaly Sand

Source: Worthington, P.F. 1985. The Log Analyst p.24

The role of C_w/C_o ratio in shaly sand formation will become close to Archie's equation only when X value is sufficiently small or C_w is sufficiently large. Hence, the appearance of shale conductivity in shaly sand formation is also controlled by the value of X relative to the expression of C_w/F which on the other hand comes from water salinity. From this mathematical reasoning, this project aims to search for the sufficient value of C_w to indirectly neglect the shale conductivity effects by referring to the experimental resistivity result.

III. METHODOLOGY

A. Experimental Procedures

Figure 2: Experimental Procedures for Shaly Sand Resistivity Model

B. Core Sample Preparation

The first step done for the project is to prepare three (3) groups of core sample to be tested in the resistivity measurement. Among the activities done in the process of preparing and evaluating the general properties of all core samples are as follows:

1) Collect the raw materials – sand and shale
2) Sieve sand to get the proper grain size.
3) Grind shale into powder.
4) Mix raw materials with chemicals.
5) Put the mixture into steel mould.
6) Keep the mixture in oven to be heated and harden.
7) Cut the moulded mixture into desired core size.
8) Record the weight of each core sample type.
9) Measure the porosity and permeability of each core sample type.

C. Measuring the Core Resistivity

Three samples (Core A, B, C) prepared in previous part of the project were used for the resistivity measurement. These samples were cut and trimmed according to core-holder size as below:

- Diameter : 25.4 mm / 1.0 inch
- Length : 58.42 mm / 2.3 inch

Synthetic brine water (aqueous electrolyte) was created with different salinity. Seven values of salinity were used ranging from 20,000 to 50,000 ppm. The fluid conductivity and Total Dissolved Solids (TDS) were measured for each salinity values. Table 3 describes the dissolving salt composition and Table 4 lists the aqueous electrolyte properties.

No.	Description	Composition
1	Sodium Chloride (w/w)	99.9%
2	Calcium (mg/kg)	0.04%
3	Magnesium (mg/kg)	0.02%
4	Moisture (w/w)	0.2%
5	Iron (mg/kg)	17.8 ppm

Table 3: Dissolving Salt Composition

Aqueous Electrolyte No.	Total Dissolved Solids (g/L)	Fluid Conductivity (S/m)
1	20.0	3.22
2	25.0	3.93
3	30.0	4.62
4	35.0	5.30
5	40.0	5.97
6	45.0	6.54
7	50.0	7.13

Table 4: Aqueous Electrolyte Properties

To characterize electrical properties, AutoLab 500 having a schematic diagram as in Figure 3 and core holder system as in Figure 4 is used. The instrument is designed to allow both two-electrode and four-electrode resistivity measurements as a function of frequency, pressure, and temperature.

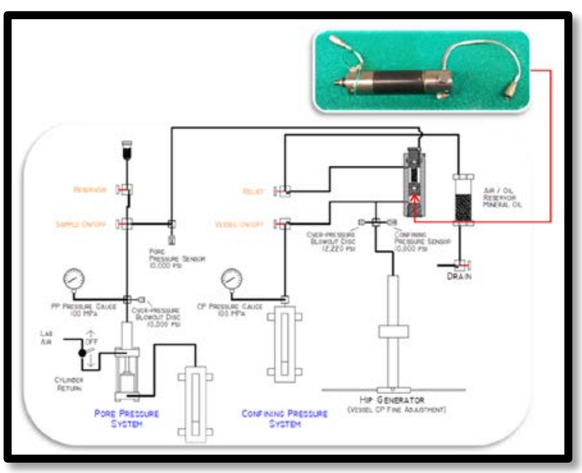


Figure 3: Schematic Diagram of Resistivity Measurement System

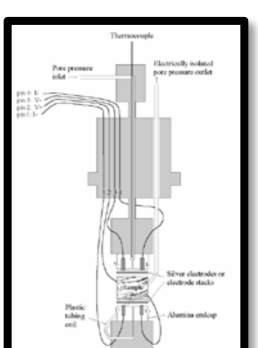


Figure 4: Core Holder Diagram

As the resistivity measurement is estimated to measures quite resistive samples, the equipment is being set for two electrodes mode. In this mode, a single electrode (silver filter) is placed between each end of caps and the sample (Fig. 4). Each electrode has to make a contact with both silver contacts on the face of the respective end of cap. The acrylic disk is placed between the end of cap and the electrode stack with the grooves facing the sample. The disk is required to be properly oriented to allow the silver electrical contacts touch the silver electrode membranes. The grooves uniformly distribute the pore fluid over the face of the sample.

The resistivity core-holder components consist of two silver electrical contacts embedded in the face of each end of cap (Fig. 4). The end of caps is made of a non-conducting material such as alumina or plastic. One end is mounted with the pore pressure inlet port containing the contacts for the negative current (I–) and negative voltage (V–) electrodes. The other end is electrically isolated from the apparatus and contains the contacts for the positive current (I+) and positive voltage (V+) electrodes.

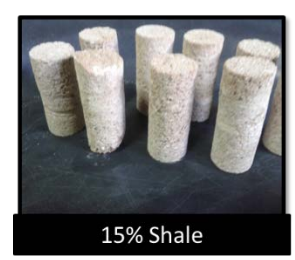
In this experiment, the range was set to start at 1 Hz and stop at 20000 Hz with 30 frequencies number. The amplitude was set at 0.5. Sinusoid relationship was used and the result was set to be in logsweep mode.

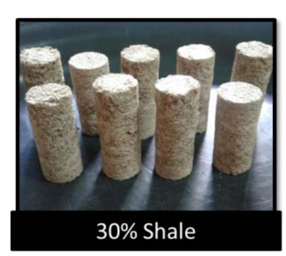
IV. RESULTS

A. Core Sample Analysis

	Core A	Core B	Core C
Weight Percent of Shale (%)	0	15	30
Weight (g)	47.3	45.7	44.8
Diameter (inch)	1.0	1.0	1.0
Length (inch)	2.3	2.3	2.3
Average Porosity	0.28	0.21	0.25
Average Permeability (mD)	328	290	182
From sieving, the grain size used for preparing the core samples are ranging from **300 µm - 1180 µm**.			

Table 5: Core Sample General Properties





B. Resistivity Measurement

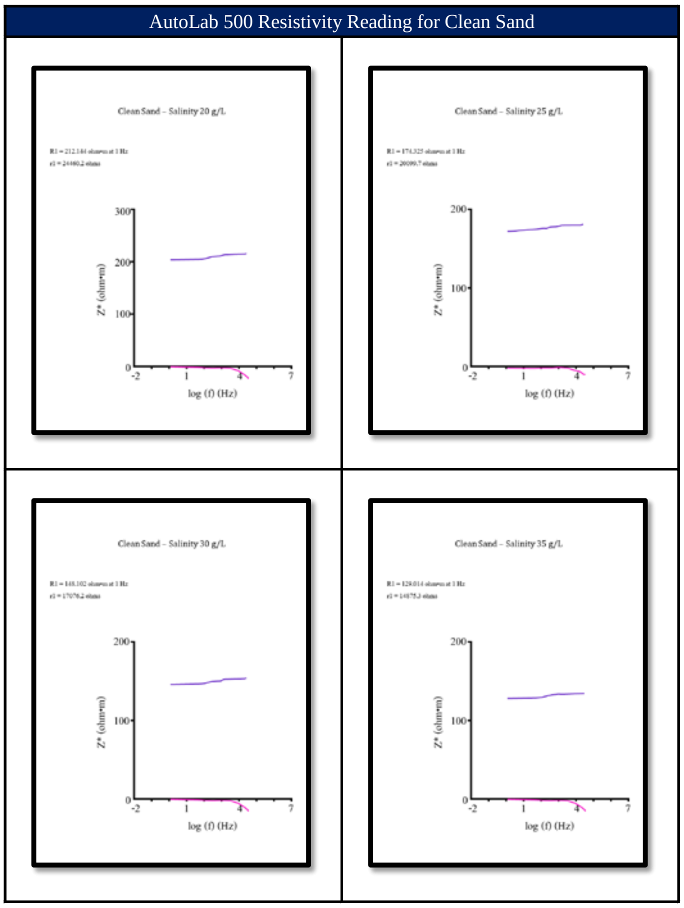


Figure 5: Some of Results from Resistivity Measurement for Clean Sand

Clean Sand			
Water Salinity (g/kg)	R_w	R_o	F (Ro / Rw)
20.0	0.31	212.14	682.57
25.0	0.25	174.33	684.43
30.0	0.22	148.10	684.39
35.0	0.19	129.01	684.06
40.0	0.17	114.57	684.40
45.0	0.15	104.90	686.49
50.0	0.14	95.78	683.17

Table 6: Resistivity Readings for Clean Sand

15 % Shale			
Water Salinity (g/kg)	R_w	R_o	F (Ro / Rw)
20.0	0.31	140.63	452.48
25.0	0.25	142.35	558.90
30.0	0.22	132.27	611.21
35.0	0.19	120.32	637.97
40.0	0.17	110.24	658.54
45.0	0.15	104.91	686.55
50.0	0.14	95.80	683.32

Table 7: Resistivity Readings for 15% Shale

30 % Shale			
Water Salinity (g/kg)	R_w	R_o	F (Ro / Rw)
20.0	0.31	70.24	225.98
25.0	0.25	81.25	319.02
30.0	0.22	101.24	467.83
35.0	0.19	102.34	542.61
40.0	0.17	96.36	575.64
45.0	0.15	92.19	603.30
50.0	0.14	88.33	630.00

Table 8: Resistivity Readings for 30% Shale

Water Salinity (g/L)	Saturated Core Conductivity, Co S/m			Water Conductivity Cw (S/m)	Apparent Formation Factor, F (Cw/Co)		
	Clean Sand	15% Shale	30% Shale		Clean Sand	15% Shale	30% Shale
20.0	4.71E-03	7.11E-03	1.42E-02	3.22	682.57	452.48	225.98
25.0	5.74E-03	7.02E-03	1.23E-02	3.93	684.43	558.90	319.02
30.0	6.75E-03	7.56E-03	9.88E-03	4.62	684.39	611.21	467.83
35.0	7.75E-03	8.31E-03	9.77E-03	5.30	684.06	637.97	542.61
40.0	8.73E-03	9.07E-03	1.04E-02	5.97	684.40	658.54	575.64
45.0	9.53E-03	9.53E-03	1.08E-02	6.54	686.49	686.55	603.30
50.0	1.04E-02	1.04E-02	1.13E-02	7.13	683.17	683.32	630.00

Table 9: Calculated Saturated Core Conductivity and Formation Factor

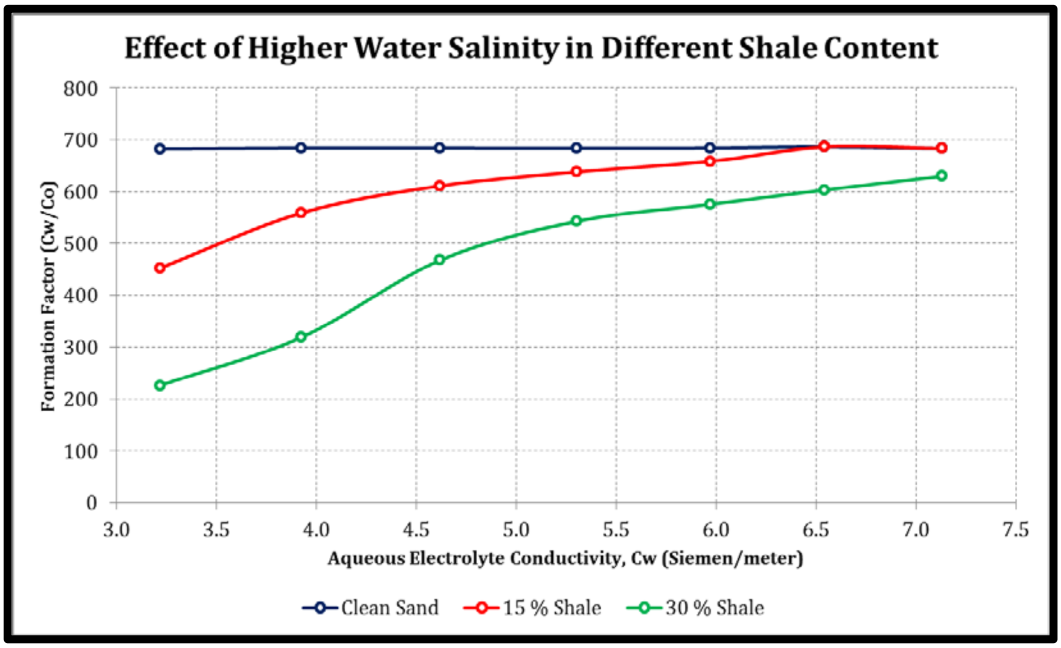


Figure 6: Effect of Higher Water Salinity in Different Shale Content

V. DISCUSSION

In well logging activities, electrical resistivity has been utilized to evaluate the properties and behavior of subsurface formation. Resistivity is defined as bulk property of material which describes how well that material allows electric current to flow through it.

Ohm's Law characterized resistance as the ratio of potential voltage by the flowing current. However, resistance will change in several conditions. This situation happen when the volume, measurement geometry or the liquid saturation of the material changes. Therefore, it can be understood that material resistance is not a physical property and it relies on the surrounding condition.

In this project, resistivity acts as the main indication for the study of shale effect. Shale which is known as the conductive element will has a significant effect on rock resistivity. When shale content in the rock increases the resistivity measurement of the respective rock will be reduced.

The excess conductivity effect caused by the shale present yet can be less significant to the reduction in rock resistivity when the rock encounter or being saturated by high water salinity. As the water salinity gets higher, the resultant conductivity will become much greater than the shale conductive effect.

The relationship between these two variables can be better defined in term of apparent formation factor of the rock itself. In clean sand rock, the apparent formation factor will remain constant. This constant clean sand line is marked as the reference to see the shale effect. The increment in shale content will reduces the rock apparent formation factor and caused it to deflect away from the constant clean sand line. Higher shale content will caused greater deflection of the formation factor.

Nevertheless, this reflected apparent formation factor of rock with shale content (shaly sand) will be lower as the rock moves towards higher salinity value. The earlier deflection which comes from the shale excess conductivity becomes less significant in higher water salinity. Conductivity produces from the water salinity weaken the shale conductive effect which therefore, the shaly sand apparent formation factor line is coming closer toward the constant clean sand line when the rock travels towards higher water salinity region.

Generally, normal sea water salinity is at TDS range of 30-35g/L. The experiment has considered taking values from 20-50 g/L. This means that the values higher than 35g/L are considered as high water salinity. Each value for water salinity will have its respective associated conductivity which is measured before all the samples are saturated in them. These associated values of water salinity (g/L) and water conductivity (S/m) are shown in Table 9.

The results gained from the experiment in this project are the resistivity readings of three core sample types with different shale content. The readings reflected the rock resistivity when completely saturated with the water (Sw=1) and denoted as Ro. Since resistivity and conductivity are inversely related, the resistivity readings are converted into core conductivity (S/m). Table 9 shows the overall results of the calculated saturated core conductivity and formation factor.

Results shown in Table 9 are plotted into a graph that relates the calculated formation factor against the aqueous electrolyte conductivity. In this graph (Fig.6), the relation between both changing variables (shale content and water salinity) as discussed previously has been justified by result from the resistivity measurement.

Clean sand constant line exists at formation factor value of 684 (±2). 15% shale core sample shows smaller deflection of formation factor from the clean sand constant line as compared to 30% shale core sample. When the aqueous electrolyte conductivity increases as the result of increasing water salinity, both shaly sand formation factor lines move towards the constant clean sand line.

From the two shaly sand lines, only 15% shale has the intersection with the clean sand constant line at fluid conductivity around 6.5 S/m. The intersection line means that the ratio of shale excess conductivity to fluid conductivity is close to zero. In this situation, conductive shale effect is considered as insignificant. In other words, this shaly sand core sample has similar formation factor properties as clean sand at fluid conductivity of 6.5 S/m and higher.

Meanwhile, 30% shale core sample does not show any intersection with the clean sand constant line within the range of fluid conductivities that were used in this project (3.22-7.13 S/m). With the current trend of increasing formation factor by this shaly sand core sample, there are possibilities that it will eventually intersect with the clean sand constant line in higher fluid conductivity.

VI. CONCLUSION

The electrical conductivity of Earth's materials varies over many orders of magnitude. It depends upon many factors, including: rock type, porosity, connectivity of pores, nature of the fluid, and metallic content of the solid matrix. This project was planned to have a controlled environment which mean that other related factors should be turned constant. This has been achieved by preparing the core sample in the laboratory instead of taking the real core sample from the real oil field.

The controlled environment only making sure two major changing variables to be exist in the study. In this way, the effect of shale content and water salinity can be better understood. The project is capable to study the effects caused by high water salinity towards the resistivity modeling of shaly sand formation. Results of designed experiment are acquired by measuring the core sample resistivity in different salinity of water. Core sample resistivity measurement will be used to relate with high water salinity effect as well as with the excess conductivity caused by shale.

From the experiment and resistivity measurement, the results show that high water salinity effect is able turn the shale excess conductivity to be negligible. However, the 30% shale content in this study is considered as very shaly because of its low ability to mix which caused by swelling effect. Future study in this subject should consider having resistivity modeling to be conducted using a wider range of shale content and water salinity. As more data and results are acquired, a better understanding can be drawn about the subject of study.

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