WELL LOG INTERPRETATION AND EVALUATION OF GAS HYDRATE

FORMATIONS USING MATHWORKS MATLAB

A Graduate Research Project

by

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ABSTRACT

Well Log Interpretation and Evaluation of Gas Hydrate Formations Using Mathworks

MATLAB

(August 2017)

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Gas Hydrates or clathrates occur both on onshore and offshore regions where the environment has low temperature and high pressure. Many gas hydrate wells have been drilled and the cores of the respective wells have been recovered. Their abundance and the properties of gas hydrates made oil and gas industry believe that gas hydrates can be a potential resource.

Conventional well logging methods cannot distinguish hydrates from water, they can be used to detect free gas and porosity. In this research project, three wells were located that are expected to bear gas hydrates. The well log data from each of the wells were acquired. Electrical resistivity logs were used on one well to estimate the gas hydrate saturations using Modified Archie's equation. The estimated seawater salinities from NASA Aquarius satellite and temperature log data were used to calculate the in-situ pore water resistivity. Nuclear Magnetic Resonance log was used to estimate the reservoir fluid content. Density-Nuclear Magnetic Resonance method was used on two of the wells to estimate gas hydrate saturations. Modified Archie's method is an empirical relationship whereas Density-Nuclear Magnetic Resonance method is the direct response of reservoir fluid content only. Thus, Density-Nuclear Magnetic Resonance method is superior to that of Modified Archie's equation.

The processing of the well log data of three wells were performed in Mathworks MATLAB software. A user-friendly MATLAB interface was created to generate well logs and to estimate hydrate saturation in these wells. The results show that three wells are highly gas hydrate-saturated.

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Finally, and most importantly, I thank my parents and my younger brother for loving me, teaching me wisdom and for the continuous support all the time. To them I dedicate this research project.

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LIST OF WELL LOG ABBREVIATIONS

DNMR   -   Density-Neutron Magnetic Resonance.

DRHO   -   Density Correction (g/cc).

NMR   -   Nuclear Magnetic Resonance.

RHOB   -   Bulk Density (g/cc).

SGR   -   Standard Gamma Ray tool reading (gAPI).

SP   -   Spontaneous Potential (mV)

CHAPTER 1

INTRODUCTION

1.1 Overview

Gas hydrates or Clathrates occur naturally in association of natural gas (predominantly methane) and water in the constrained environment of high pressure and low temperature that form ice-like substances. Gas hydrates were thought to be uncommon in nature, but now they are known to form and exist in great plentitude in areas such as arctic regions and in the shallow sediments of the oceanic continental shelves. The gas hydrates have captured the interests of oil and companies and proved that they are a potential energy source to all the countries. The latest assessments of gas hydrate deposits suggest that they contain maybe more natural hydrocarbon that all the world's oil, gas, and coal put together [21].

(a)   **(b)**
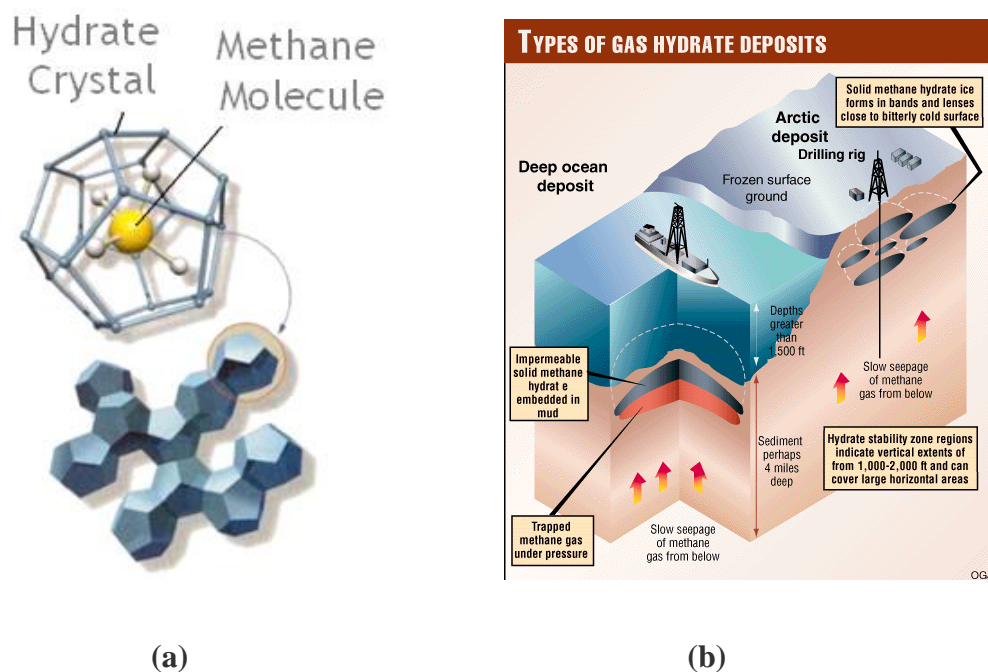
Figure 1.1 (a): The structure of gas hydrate molecule shows gas enclosed in a cage-like structure made up of water (ice).

(b): The picture shows the zones where gas hydrates can occur in both offshore and in permafrost regions (arctic regions).

1
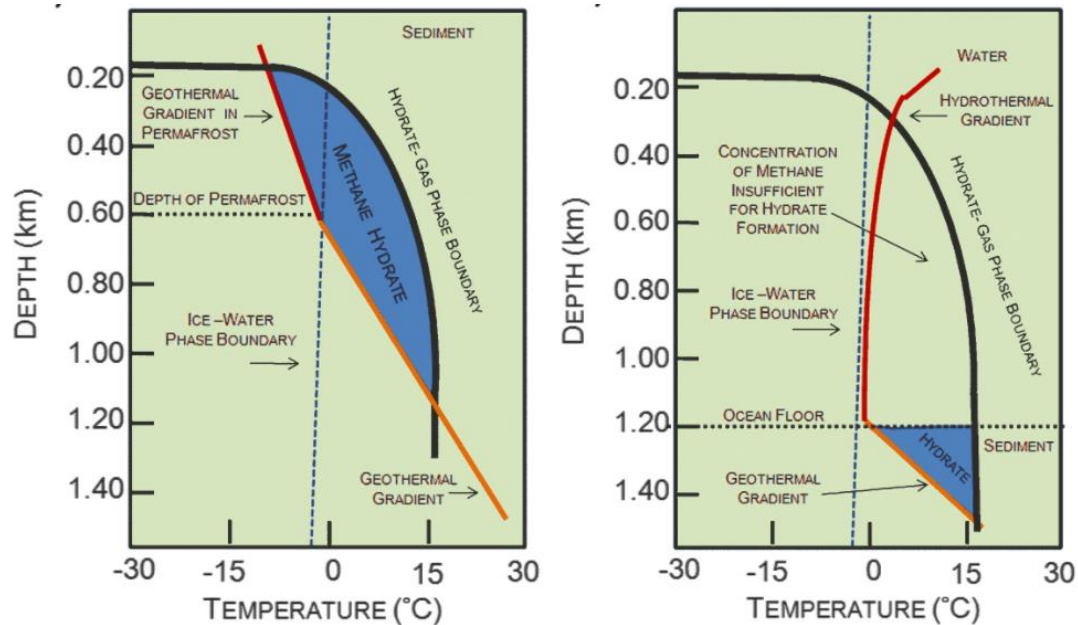
Figure 1.2: The picture shows the Gas Hydrate Stability Zone (GHSZ) in both permafrost and offshore locations.

Gas molecules (guest molecules-) occupy the centers of the cage-like structures of ice (host) as shown in a typical schematic in figure 1.1(a). The stability of gas hydrates is mainly governed by temperature and pressure. The other factors that can influence the stability of clathrates are water salinity and composition [22]. Guest molecules are mostly methane, but ethane, propane, butane and some inert gases can also occupy the centers in different and bigger structures of ice thus influencing the composition.

The downhole well logs deployed in the wellbore after drilling can be utilized to characterize the physical properties of Gas Hydrate-Bearing Sediments (GHBS) and to calculate the gas hydrate saturations. Well logs used in this research project are Gamma Ray, Density, Deep Resistivity, Temperature and Nuclear Magnetic Resonance (NMR) logs. Acoustic logs, Dipole-Sonic imager logs and Formation imager logs can also be used to evaluate the GHBS but are not used in this study due to the lack of availability of data. Gas hydrates are electrical insulators thus give a similar resistivity response to that of oil and gas.

Thus, Archie's equation can be used to estimate the in-situ hydrate saturations. NMR measurements responds only to hydrogen atoms in pore-fluid. Since hydrates are solids, they are undetectable to wellbore NMR instruments. Subsequently, NMR porosity speaks to non-gas hydrate porosity. At the point when contrasted with the density porosity log, NMR porosity deficiency can be utilized to compute accurate determination of hydrate saturations and gas hydrate volumes [1]. NMR technique is superior to Archie's equations because Archie's equations are empirical equations while NMR technique is a direct measurement of properties of hydrates and simple physics is implemented to estimate hydrate saturations. However, borehole washouts can adversely influence the Density and NMR estimations since they are moderately shallow-reading [1].

1.2 Objective

Once a well is drilled, the wireline logging tools are deployed into the borehole and record the data (data is stored in Log ASCII format or in excel format). The data is processed to obtain the well log responses. The first objective in this research project is to identify the GHBS using the logs. The second objective is to calculate the petrophysical properties (Density porosity, NMR porosity and Gas Hydrate Saturation) of gas hydrates using Resistivity technique (Archie's Equations) and NMR technique. The log data of different wells have been obtained from databases of United States Geological survey (USGS) and International Ocean Discovery Program (IODP) and supporting data have been obtained from various sources.

The results will give an idea to companies about the extent and stability of gas hydrates over a region and to decide whether to produce from such zones or not. Mathworks MATLAB was used as the software to process all the data (MATLAB codes have been included in the Appendix).

1.3 Problem Statement

Gas hydrate responses of logs are entrenched. While the conventional logging tools can't differentiate a gas hydrate from water, these conventional logging tools can be utilized to determine porosity and to detect free gas. Archie's law can be used to determine the hydrate saturations. The shortcoming of this approach is that Archie's law parameters are obscure [1] [2]. NMR measurements offer a better and more reliable values of saturations. The two techniques used in this study and the results are processed in a user interface developed using MATLAB. This is makes our processing less tedious and less time taking than using Microsoft Excel.

CHAPTER 2

LITERATURE REVIEW

2.1 Evidence of occurrence and existence of Gas Hydrates

Marine gas hydrates usually occur within the top few hundred meters of sediments in continental margin worldwide. The density of gas hydrate is 0.91 g/cm^3, which is similar to that of water (1 g/cm^3) and much different than that of free gas (0.1 to 0.2 g/cm^3) [3]. The evidence for the presence and distribution of gas hydrates fall into two categories: direct and inferred. Direct evidence consists of actual recovery of core samples by drill coring. The indirect evidence consists of observations in sediments through geologic, geophysical techniques within the predicted GHSZ (Gas Hydrate Stability Zone) [4]. Since the coring data is proprietary, the data is unavailable to study properties of gas hydrates in this research project.
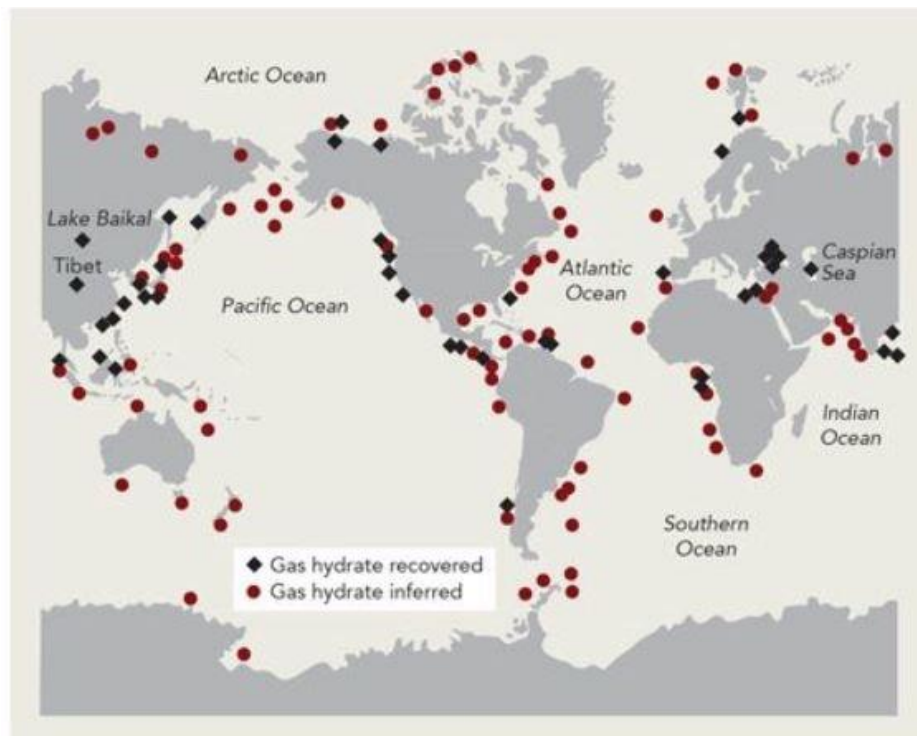
Figure 2.1: The picture depicts the gas hydrate wells that have been drilled and the cores of gas hydrates that have been recovered. (*source from USGS)
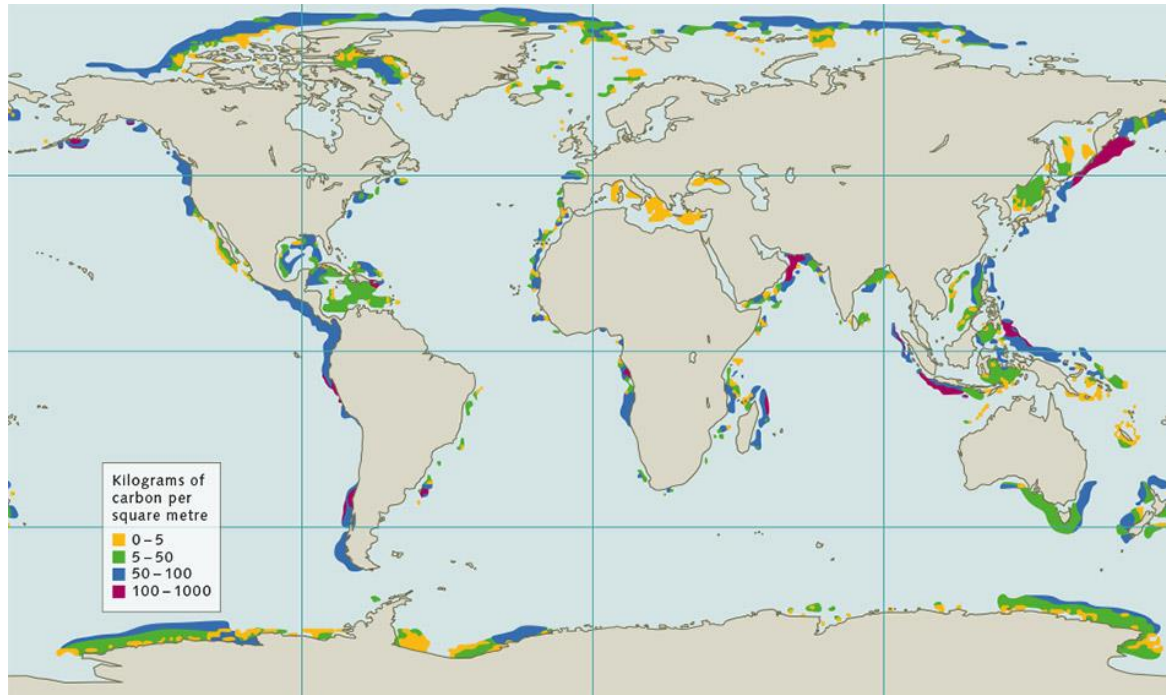
Figure 2.2: The picture depicts the amount of carbon present across continental shelf signifying a potential natural resource, gas hydrates (**source from World Ocean Review)* [14].

Gas Hydrate Stability Zone (GHSZ) can be predicted using seismic methods. GHSZ refers to a region of marine environment at which the clathrates normally exist in the Earth's crust. The limits depth of gas hydrate stability is constrained by the geothermal gradient. As depth below seafloor increases, the temperature sooner or later becomes prohibitive for gas hydrates to exist.

2.1.1 Well-Log response

The primary objectives of well logging in gas hydrates are gas hydrate identification, characterization of gas hydrate reservoirs (homogeneity of hydrate distribution, porosity determination, mode of occurrence of hydrate within the reservoir at pore level and determination of gas hydrate saturation) [4]**.** The bulk physical properties of sediments are affected by inclusion of gas hydrates in pore spaces of marine sediments. Specifically, in light of the fact that gas hydrates are portrayed by low bulk densities and high electrical resistivities,

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zones containing massive gas hydrates in GHBS can be recognized by observing the responses of the well logs. As soon as drilling is completed and the well is ready to log, logging tools are deployed and measurements are taken. Continuous exposure of hydrates to drilling mud (mostly sea water) and heat caused by friction between drill bit and hydrate results in increase of formation temperature. The thermal invasion of drilling mud during drilling and logging causes hydrates to thaw (decompose) around the wellbore, can result in well log responses like those from zones having free gas.
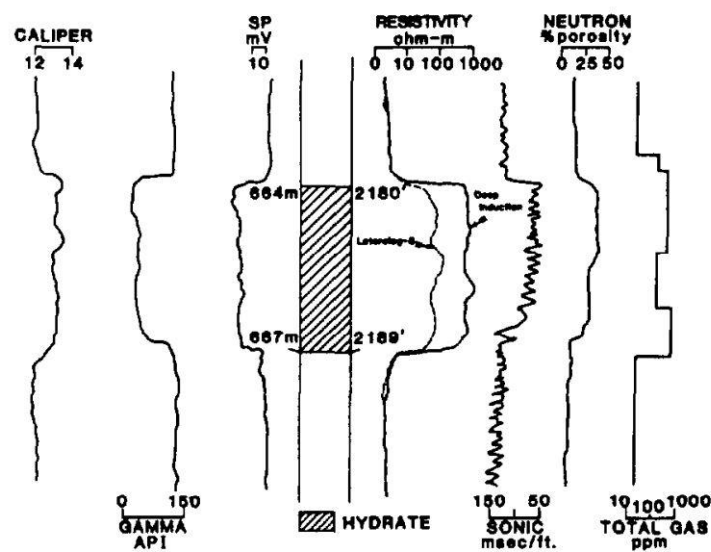
Figure 2.3: The typical well log tool responses of gas hydrate formations [4].

In this study, Track-1 consists of Caliper log and Gamma ray log, track-2 consists of density log, track-3 consists of shallow and deep resistivity log and Track-4 represents NMR measurements. Caliper tool reads enlarged diameter than the drill bit's diameter because of the invasion of drilling mud and contact of tool pads (especially pads of shallow resistivity tools) to borehole. This indicates an ice-bearing formation. The Gamma ray tool gives low readings indicating an ice-bearing zone with low clay content. The Deep resistivity logs show high resistivity readings when gas is present in ice-bearing sediments (gas hydrates) consistent with the track-1 logs. If we observe there is no separation between shallow and deep resistivity

readings this signifies that gas hydrates are not dissociated. Hydrate is invisible to NMR tool, thus Total NMR porosity is abnormally low when hydrate is present.

2.1.2 Petrophysical parameters

Estimations from NMR porosity and density porosity logs rely only on the bulk volume of gas hydrate in pore-space. However, resistivity depends on pore-scale interactions between the gas hydrate and porous media, and also on the bulk volume of gas hydrates. The pore-scale interactions that can affect the resistivity are reservoir fluid distributions, pore-space and rock geometry or pore geometry. The conductive fluid distribution and quantity in the reservoir change considerably owing to pore structure variations, which generates resistivity fluctuations in reservoir rocks [24][25]. Without a conductive mineral layer, the electrical current can stream just through the fluid in the interconnected pores of the rock. The impact of pore structure on the electrical resistivity may be separated into two contributions: the decrease in the cross section that is present for conduction and the alignment and length of conduction path. Confinement or overburden pressure may cause a significant increase in resistivity by blocking of some conduction paths and reduction in the cross sections which are available for flow. This usually occurs in rocks with low porosity or that are not well cemented [23]. Gas hydrates estimates from NMR logging methods can be used as reference hydrate saturations, and enable us to assess the exactness of properties from other well logs, and to improve the rock physics models [2] [5].

a. Density porosity

The density tool holds a source ($^{137}_{55}Cs$) emits gamma rays in to the formation. The gamma rays are then Compton-scattered by electrons present in the formation. A fraction of scattered gamma rays will travel back to the gamma ray counter present in the tool. The number of Compton-scattering collisions are directly related to number of electrons present in the

formation. Thus, the number of gamma rays received depends on electron density, and electron density is closely proportional to formation bulk density.

The bulk density (ρ_b) of GHBS can be calculated as:

$$\rho_b = \rho_{fl}\phi_D + \rho_{ma}(1 - \phi_D) \qquad (2.1)$$

where ϕ_D is the density porosity, ρ_{ma} and ρ_{fl} are densities of matrix and drilling mud (in gm/cm^3) respectively. The equation 2.1 can be rearranged to estimate the density porosity. Hence,

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}} \qquad (2.2)$$

The type of matrix considered in this study is limestone and the density is 2.71 g/ cm^3. The matrix densities of other lithologies is shown in table 2.1.

Table-2.1: The matrix densities of typical formations.

Matrix	Density (g/cm^3)
Sandstone	2.65
Limestone	2.71
Dolomite	2.876
Salt	2.032
Anhydrite	2.997

b. Resistivity

The connection between rock and resistivity of the pore fluid has been studied by conducting various laboratory and field experiments. In 1927, Conrad and Marcel Schlumberger run the first log in Pechelbron field in France. In 1942, Gus Archie presents his work at a conference quantifying the relationship between formation resistivity and fluid saturation. Thus, it took 15 years to jump from qualitative method to a quantitative method. The Archie's equation is written as;

$$R_o = \frac{aR_w}{\phi_o^m} \tag{2.3}$$

where, R_o(Ω-m) is the formation resistivity of water-saturated sediment, R_w(Ω-m) is the connate water resistivity, Archie's constants a and m are called tortuosity factor and cementation factor and ϕ_o is the total porosity. The Archie's constants depend on interaction between the gas hydrates and the sediments. A modified Archie (1942) relationship is used to relate computed true formation resistivity (R_t) to the water-filled porosity ϕ (Paull et al., 1996);

$$R_t = \frac{aR_w}{\phi^m} \tag{2.4}$$

The equation (2.3) was initially formulated for clean, water bearing formations, it is purely empirical or experimental and can be utilized with diversity of lithologies, given that a and m apply to particular environment [5]. Equation (2.4) uses the fact that R_t equals R_o if the formation is completely saturated with water (because water filled porosity is nothing but the total porosity). The existence of free gas or gas hydrates in the pores will decrease the water filled porosity [5].

c. Temperature

The hydrate-gas phase boundary curve in figure 1.2 isolates the balanced region of gas hydrates on the left side from the unbalanced region on the right. The geothermal line gives sediment temperature which rises with depth and the hydrothermal lines give water temperature [6].The base of Gas Hydrate Stability Zone (GHSZ) indicates the bottom limits of gas hydrate formation. Thus, it is important to know the temperature conditions to estimate stability and dissociation of hydrates. In equation (2.4), the resistivity of seawater (R_w) an be estimated using the following equations;

$$R_{w_{Tr}} = \left(\frac{400000}{T_r(°F)\times(salinity)}\right)^{0.88} \tag{2.5}$$

where, $R_{w_{Tr}}$ is resistivity of seawater at reference temperature (T_r) at a particular salinity (ppm). The reference temperature (T_r) assumed here in this study is 20°C (68°F) [7]. Now, we can calculate the resistivity of seawater (R_w) corrected at formation temperature using Arp's formula [8]; for formation temperatures (T_f) in Fahrenheit;

$$R_w = R_{w_{Tr}}\left[\frac{T_r + 6.77}{T_f + 6.77}\right] \tag{2.6(a)}$$

And, for formation temperatures (T_f) in Celsius;

$$R_w = R_{w_{Tr}}\left[\frac{T_r + 21.5}{T_f + 21.5}\right] \tag{2.6(b)}$$

Since the formation temperatures are available from Temperature logs we can calculate the seawater resistivity easily. The seawater salinities can be estimated from the figure 2.4 as shown below.
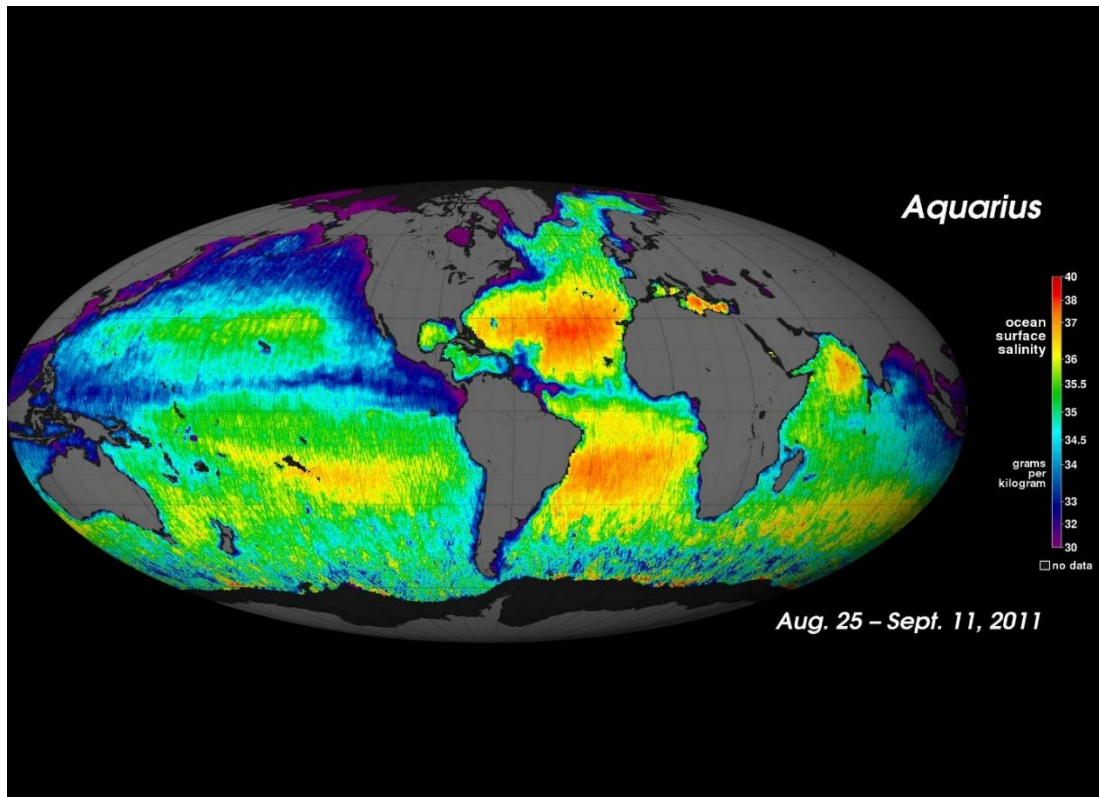
Figure 2.4: The Ocean Salinities. (*source from NASA 'Aquarius' Satellite)* [15].

d. Nuclear Magnetic Resonance (NMR) porosity

The NMR measurement consists of two steps. First, a net magnetization of the reservoir fluids is created using permanent magnets fitted inside the NMR tool. The magnetization is done by generating a magnetic field of vector, B_o, where hydrogen nuclei in the reservoir fluids are polarized. This magnetization is along the longitudinal direction. Now the relaxation of the hydrogen nuclei is recorded and is called longitudinal relaxation time T_1. Immediately another magnetic field of vector of B_o' is generated perpendicular to B_o and polarizes the hydrogen nuclei which is in transverse direction. The relaxation time recorded in the transverse direction is called transverse relaxation time or spin-echo relaxation time T_2. The echo decay curve (T_2 relaxation curve) is plotted between the amplitude versus time. The echo signal received by the NMR tool is the summation of the contributions of all the pores in the formation, and the amplitude of the first signal received represents the porosity of the formation.
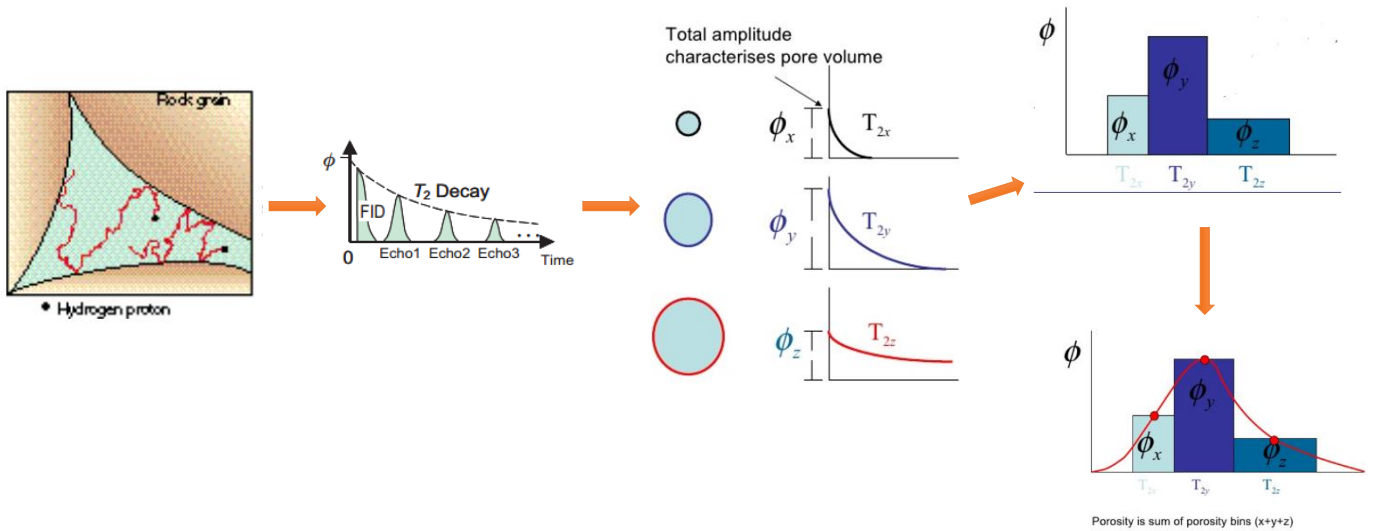
Figure 2.5: The principle of NMR measurement is described in each step [9].

Converting to the T_2 distribution curve as shown in last step of figure 2.5, will result in peaks and the summation of peaks represent formation porosity and T_2 values representing sizes of pores.

The volume measured by Nuclear Magnetic Resonance tool consists of millions of pores with the distribution of T_2 values. The area under the T_2 distribution curve is directly proportional to formation porosity and is not dependent on type of matrix, since only reservoir fluids are measured.
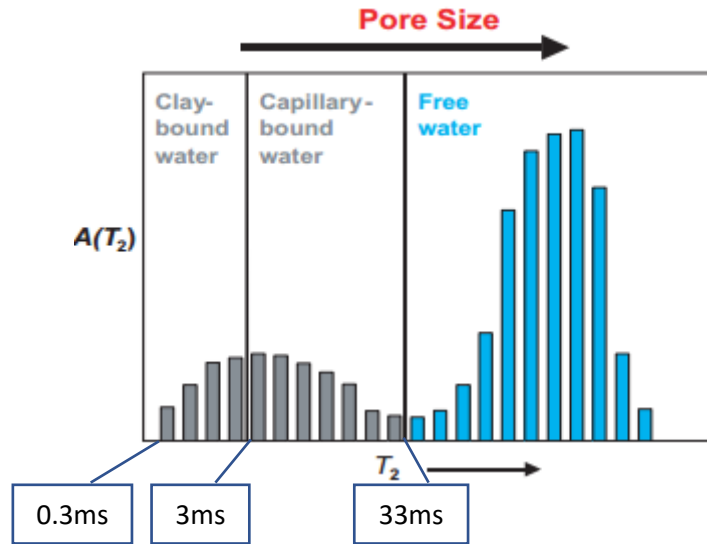
Figure 2.6: The T2 distribution curve and the T2 cutoff. Each zone after some millieconds signifies the type of fluid content in the pores [9].

As depicted in figure 2.6, the T_2 distribution values generally span less than 1 ms (milliseconds) to several seconds and from several decades. The vast range of T_2 values detected in sedimentary rocks is caused by broad distribution of pores sizes [9]**.** The clay-bound water is in very small pores, also called small porewater. These fluids are unmovable and the porosity is called small pore porosity. Capillary bound water is in pores small enough for the fluids to move. While free fluid region is where the pores containing fluids which are expected to flow. Thus, T_2 cut-off can be found from experimenting with core-samples. The value below which fluids inside pores consists only non-producible fluids is called T_2 free fluid cut-off. The table 2.2 indicates the cut-off values for sandstone and carbonate formations.

Table 2.2: T_2 distribution cut-offs for some typical formation. (note that the units are in milliseconds)

Formation	T_2 cut-off value
Sandstone	33
Carbonate	100

e. Gas hydrate saturation

i. Resistivity method (Modified Archie's equation)

Gas hydrate saturation (S_h) can be approximated using modified Archie's equation. Some assumptions are made to effectively use the equation [2] [5] [6]:

- Measured resistivity is a function of the sediment resistivity, water resistivity and an insulator in the pore space. Here the pore-space insulator is gas hydrates.

- The sediments should be water-wet as in the case of ocean sediments.

Thus, Modified Archie's equation (1942);

$$S_w = \left(\frac{aR_w}{\phi^m R_t}\right)^{\frac{1}{n}}$$

(2.7)

And the hydrate saturation is calculated as,

$$S_h = 1 - S_w$$

(2.8)

$$\Rightarrow S_h = 1 - \left(\frac{aR_w}{\phi^m R_t}\right)^{\frac{1}{n}}$$

(2.9)

where, S_h is gas hydrate saturation, R_t is true formation resistivity, S_w is water saturation, R_w is the resistivity of formation water, m is cementation factor, n is saturation exponent and a is tortuosity factor. We can calculate ϕ using equation 2.4.

ii. Density-Nuclear Magnetic Resonance (DNMR) method

T_2 distributions from NMR tool portrays fluid discrimination. Since fluids confined to tiny pores have quick or short T_2 relaxation times and fluids in big pores have large T_2 relaxation times, partitioning the T_2 relaxation time distributions allow differentiation between various fluid components [10].

$$S_h = \frac{\phi - \phi_{NMR}}{\phi}$$

(2.10)

Where,

$$\phi = \frac{\phi_D + \lambda_h \phi_{NMR}}{1 + \lambda_h} \text{ and } \lambda_h = \frac{\rho_{fl} - \rho_h}{\rho_{ma} - \rho_{fl}}$$

(2.11)

Note that ϕ_D is the conventional density porosity we calculate using equation 2.2. ρ_h is density of hydrate (in gm/cm^3), ρ_{fl} is density of drilling fluid and ϕ is the total porosity [2]. The hydrate saturations calculated from NMR tool and density porosity don't rely on models or parameters, thus the exactness of the calculation depends on the quality and accuracy of density and NMR logs. Hence, it is assumed that saturations calculated using DNMR method is the most accurate in-situ gas saturation [2].

CHAPTER 3
METHODOLOGY

The drilling and logged data are proprietary, but some governments and Exploration and Producing (E&P) companies have a policy where the data is put on the government websites. The data files are in either Log ASCII data format ('.las' files) or in excel spreadsheet ('.xlsx' or '.xlsm' format). The data must be processed to produce quality well logs using a user-friendly software such as Mathworks MATLAB. Each company has a specific format of the way the data is stored in LAS files. In this study, a user-interface was created where the user will be asked to upload the required data and MATLAB produces the well logs and the final gas hydrate saturations of the respective wells.
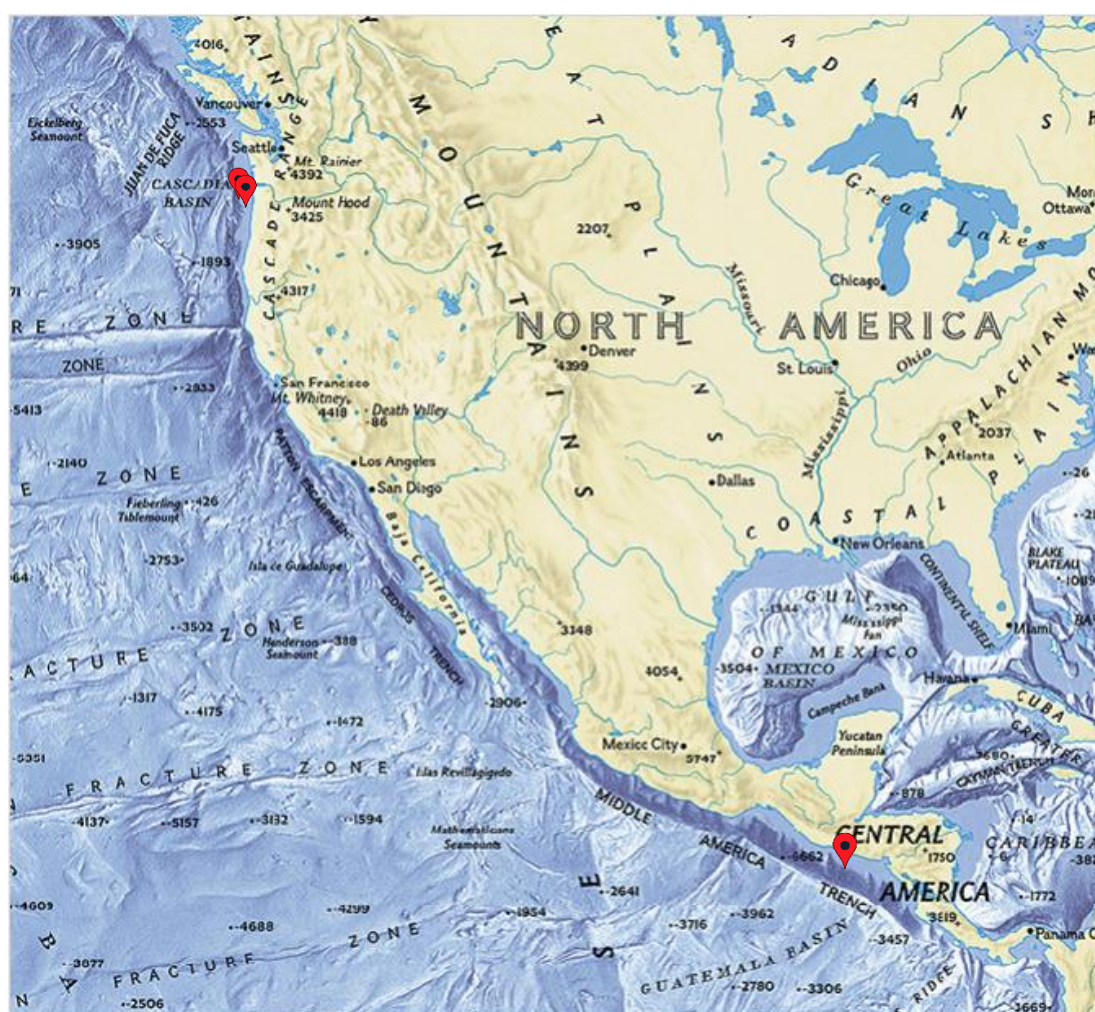

Figure 3.1: Location of the three gas hydrates wells used for this study (*source of well locations from USGS; Source of map from National Geographic website*) [16][17].

The software packages that companies use are built to analyse data for any type of formation or reservoir and are very sophisticated. In this study, the user interface created is specific for Gas Hydrate reservoirs. However, this interface can be updated so that it can evaluate other formations types effectively.

3.1 Interpreting gas hydrate formations

Given the properties of gas hydrates, using figure 2.3 the user can recognize the probable gas hydrate formations from the well logs generated. The user carefully marks the gas hydrate formations in these three wells. This is done by observing the lithology, resistivity and porosity logs simultaneously. NMR log is also generated to for respective wells, the NMR can give us idea of the free fluid content in the formation with respect to depth. Low gamma ray indicates low shale content in the zone. Fluctuation in the logs responses indicate the extent of well rugosity.

3.2 Calculating petrophysical parameters

From density log the user can calculate the density porosity using equation 2.2 provided, the densities of drilling mud and matrix must be known. The type matrix assumed in this study is limestone. From table 2.1 the density of limestone matrix can be taken into consideration. Thus, the density porosity (ϕ_D) is expressed as:

$$\phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

The bulk density can be taken from log and MATLAB does it automatically. The drilling mud density is assumed as 1.03 gm/cm^3 (Drilling mud is seawater). From figure 2.4, the user estimates the sea water salinities for the three wells according to their locations. Not all companies perform NMR logging. In this study, two wells have NMR logs and one well has temperature log which we can use to calculate gas hydrate saturations using resistivity method. Thus, for Density-Nuclear Magnetic Resonance Method (DNMR method) the user

need to find the NMR porosity which is the area under each T$_2$ distribution curve at each depth. The MATLAB interface created for this study can efficiently find the NMR porosity (used Trapezoidal rule to calculate Area under curve; a built-in code in MATLAB). Now, the MATLAB software proceeds to calculate gas hydrate saturations using equations 2.2, 2.10 and 2.11 as;

$$S_h = \frac{\phi - \phi_{NMR}}{\phi}$$

Where,

$$\phi = \frac{\phi_D + \lambda_h \phi_{NMR}}{1 + \lambda_h} \text{ and } \lambda_h = \frac{\rho_{fl} - \rho_h}{\rho_{ma} - \rho_{fl}}$$

Now, the gas hydrate saturation (in %) is plotted as a new track with lithology, resistivity and porosity logs for easy depth matching and to easily identify the gas hydrate zones. NMR log is plotted in separate track as we discussed in section 2.1.1.

Now, using Resistivity method the user can find gas hydrate saturations but first the user need to define all the required empirical parameters and Archie's constants. The logs generated has true formation resistivity (R_t) plotted against depth (in meters). The Archie's parameters are calculated from core samples tested in laboratories. But lack of core data limits our calculation thus, commonly used Archie's constants for gas hydrates are assumed [11-13];

Table 3.1: The values assumed in Modified Archie's equations.

Parameter	Symbol	value
Gas Hydrate density	ρ_h	0.91g/cm^3
Tortuosity factor	a	1.7
Cementation factor	m	2.0
Saturation Exponent	n	1.9386 or 1.94

Now, the user can use resistivity logs and temperature logs to calculate gas hydrate saturation. First, the resistivity of porewater must be calculated using the salinities we deduced from figure 2.4 and those salinities of each well will be used in equation 2.5 to calculate reference resistivity at reference temperature at respective salinity as;

$$R_{w_{Tr}} = \left(\frac{400000}{T_r(°F) \times (salinity)}\right)^{0.88}$$

Now, correcting the reference resistivity ($R_{w_{Tr}}$) to get to the reservoir conditions which is at formation temperature. Using equation 2.6(a) and 2.6(b), based on the units of temperature (Arp's formula);

For formation temperatures (T_f) in Fahrenheit;

$$R_w = R_{w_{Tr}} \left[\frac{T_r + 6.77}{T_f + 6.77}\right]$$

And, for formation temperatures (T_f) in Celsius;

$$R_w = R_{w_{Tr}} \left[\frac{T_r + 21.5}{T_f + 21.5}\right]$$

Now, the user have porewater resistivity (R_w) at formation temperature. The user can use the help of Modified Archie's equations (2.7), (2.8) and (2.9), and values from table 3.1 to estimate the gas hydrate saturation (S_h);

$$S_w = \left(\frac{aR_w}{\phi^m R_t}\right)^{\frac{1}{n}}$$

Hence,

$$S_h = 1 - \left(\frac{aR_w}{\phi^m R_t}\right)^{\frac{1}{n}}$$

Finally, after obtaining the gas hydrate saturation curve with respect to depth, it will be plotted adjacent to well logs to efficiently identify the potential gas hydrate zones.

CHAPTER 4

RESULTS

After understanding the techniques mentioned in this research project, the well logs have been generated by processing the well log data by using MATLAB interface.

A. Well 1: (Resistivity method)

    Location: Mid-American Trench Slope   Sea water salinity: 33500 ppm

    Ocean: Tropical NE Pacific $\rho_{fl} = 1.03$g/cc

    Start of well log: 42.1343 meters $R_w = 1.5$ ohm-meters (log reading)

    End of well log: 386.8632 meters
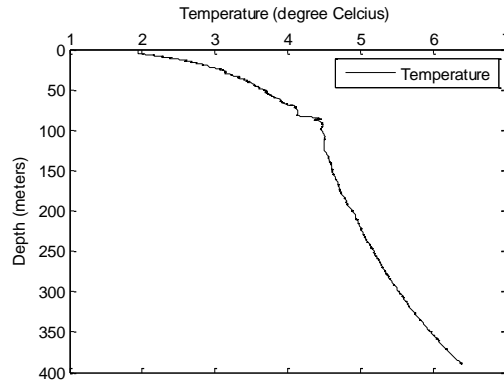
Figure 4.1: The temperature log of well-1.

B. Well 2: (DNMR Method)

    Location: Hydrate Ridge Cascadian Margin   Sea water salinity: 30000 ppm

    Ocean: NE Pacific $\rho_{fl} = 1.03$g/cc

    Start of well log: 0.0180 meters T_2-cutoff = 33 ms

    End of well log: 351.3572 meters.

C. Well-3: (DNMR method)

    Location: Hydrate Ridge Cascadian Margin   Sea water salinity: 31000 ppm

    Ocean: NE Pacific $\rho_{fl} = 1.03$g/cc

    Start of well log: 14.9292 meters T_2-cutoff = 33 ms

    End of well log: 64.0016 meters

Well logs of well-1 show two massive zones of gas hydrates occurrences, first at depth ranging from 240-265 meters and second at 335-365 meters. The Gamma ray in the second zone reads lower to that of first zone indicating that the second zone might contain sand associated with gas hydrates. The first zone might contain a few radioactive elements or minerals. The resistivity in the two zones read a high value indicating a good presence of gas. The gas hydrate saturation values calculated from Modified Archie's equation for the well-1is plotted adjacent to the well logs and clearly indicating gas inside ice-like substances.

Well logs of well-2 shows the responses of gamma ray, density, resistivity and NMR logs with estimated gas hydrate saturations. NMR tool reveals the presence of mobile guest molecules (gas) and this capability is useful in establishing the presence of gas hydrates. The gas hydrate saturation from NMR tool can tell us the amount of free fluid content. Thus in well-2, NMR response reveal that there are intervals of free fluid at the depths ranging from 280-345meters roughly. The free fluid content can be identified by the long T_2 relaxation times. The T_2 cut-off assumed here is 33ms. The relaxation times exceed this cut-off indicating that the pores are big and simultaneously the resistivity reads moderate values. Also, with the low reading of gamma ray values this clearly indicate the presence of gas hydrates. The gas hydrate saturation ranging from as low as 15% to 55% at several intervals indicating gas hydrate presence.

Similarly, well logs generated from well-3 log data show clearly, the presence of good free fluid content. Also, the high resistivity responses and moderately low gamma ray values indicate a massive presence of gas hydrates at the depth ranging from 18.5-52 meters. The gas hydrate saturation values reveal the presence of gas.
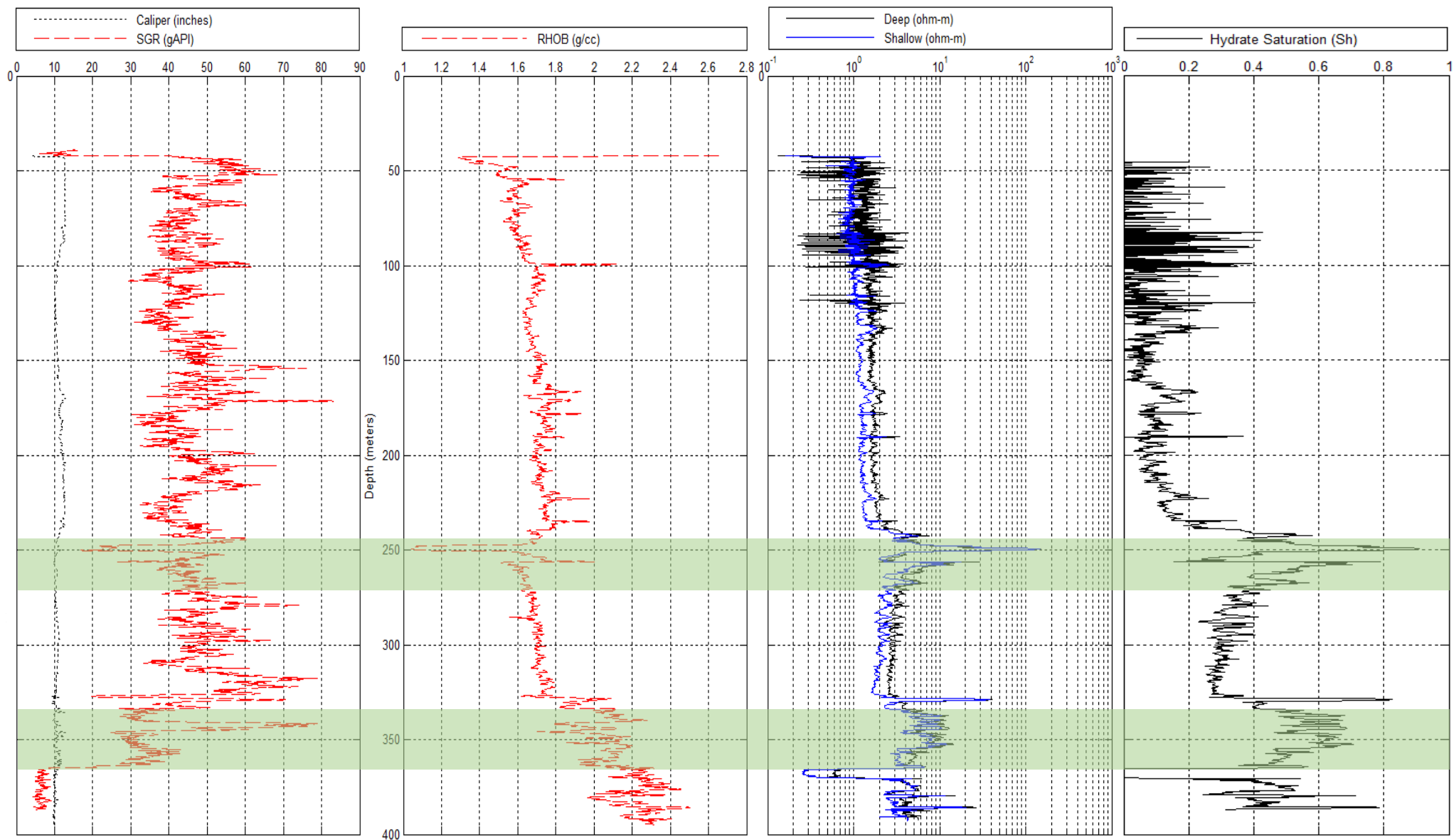
Figure 4.2: These well logs are developed by analyzing the well log data obtained from Well-1. It can be clearly seen that the two potential zones of gas hydrates are at the depths ranging from 240-265 meters and at 335-365 meters.
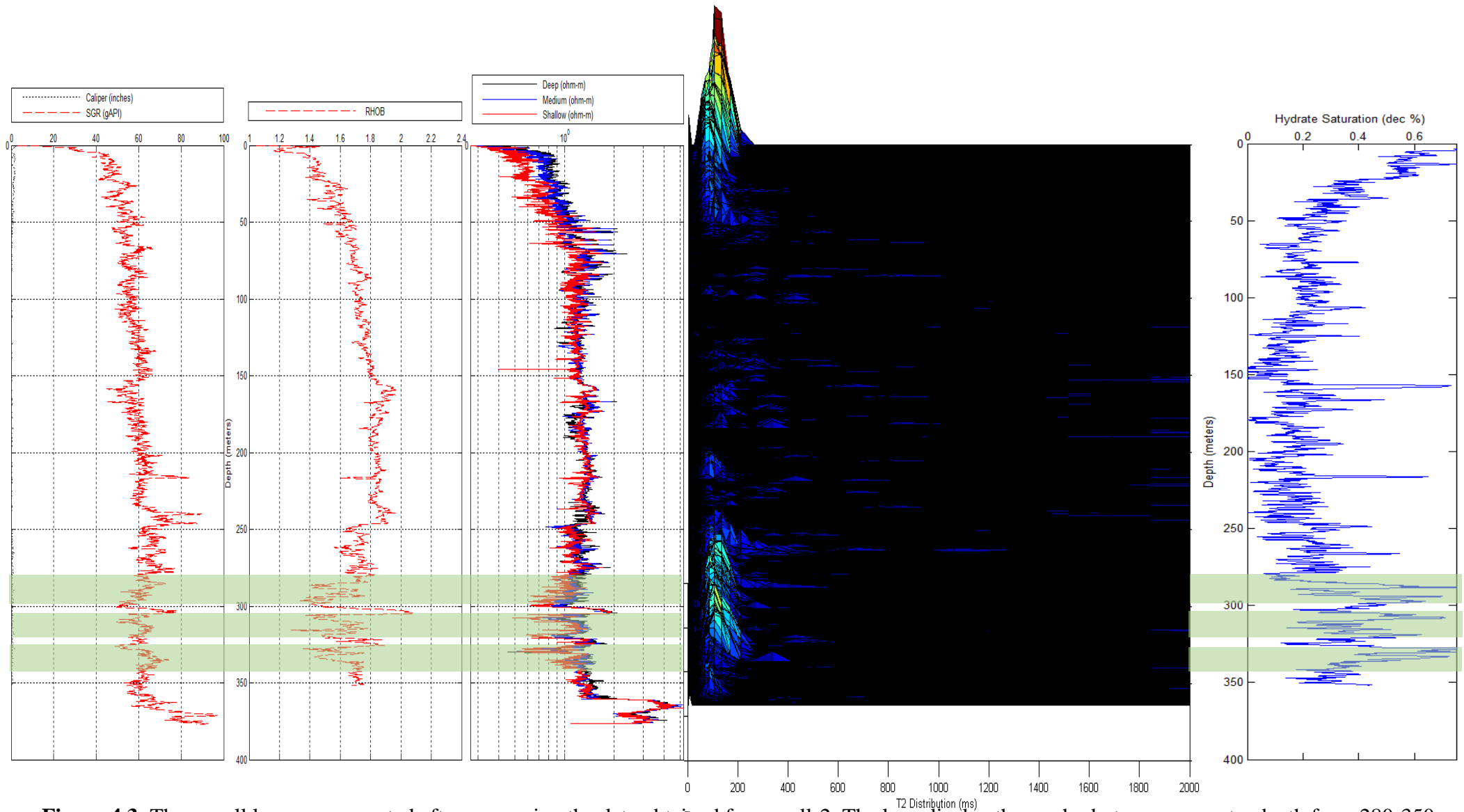
Figure 4.3: These well logs are generated after processing the data obtained from well-2. The logs display the gas hydrate presence at a depth from 280-350 meters. However, only certain hydrates are holding gas within. The shaded region signifies the potential gas hydrate presence. NMR showing free fluid content.

Figure 4.4: These well logs were generated by processing the well log data of well-3. Clearly, there is a potential gas hydrate zone at a depth ranging from 18-51 meters. The free fluid content at the potential zone is significant as per the NMR results.

CHAPTER 5

CONCLUSIONS

The methods presented in this research project helps the user to efficiently identify the gas hydrate formations. The DNMR method is superior to that 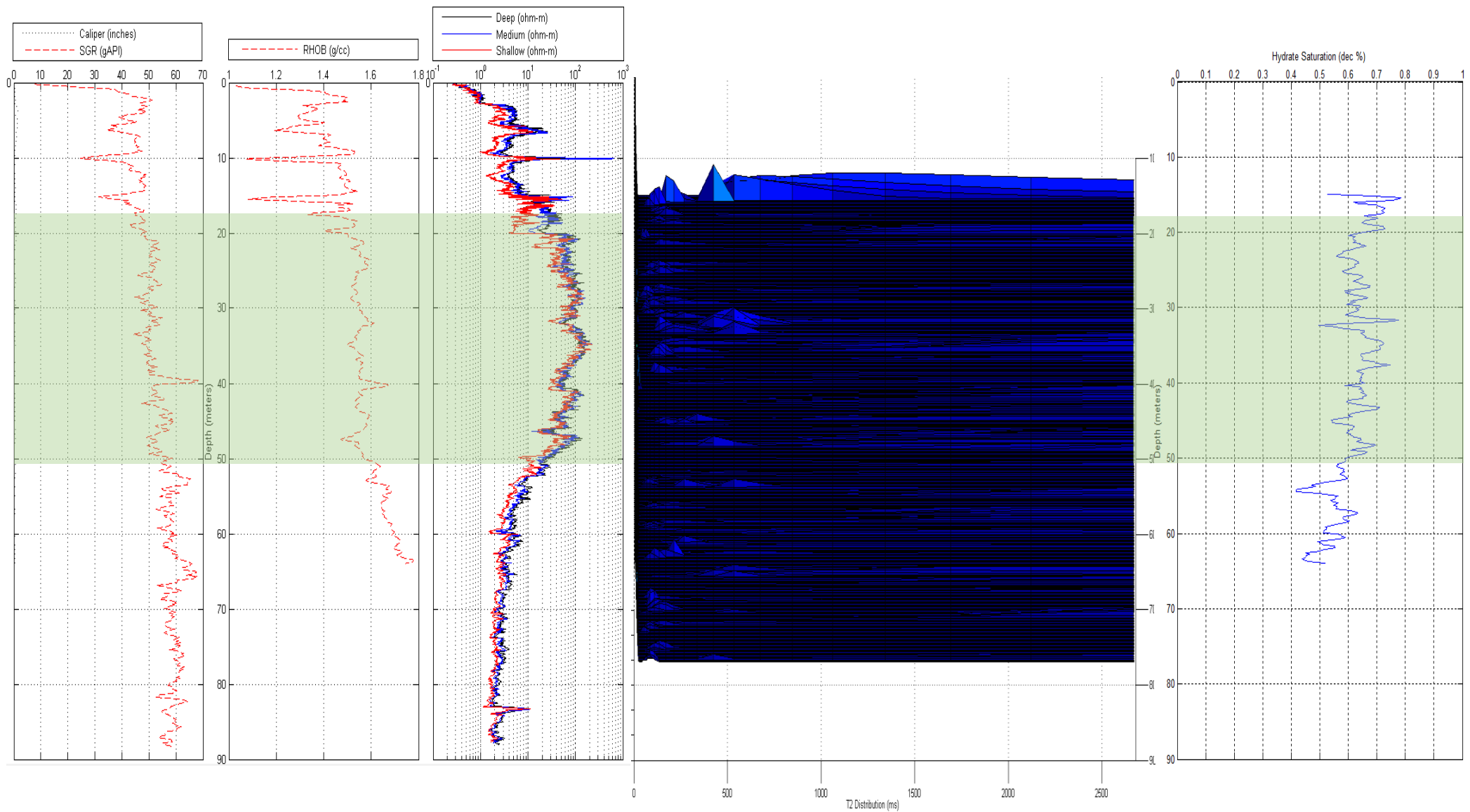of Resistivity method because the Resistivity method is based on empirical relations where as DNMR method is direct responses from reservoir fluid and is independent of matrix. Hydrate saturations were calculated and presented. These three wells are highly gas hydrate-saturated because gas hydrate saturations are greater than 0.5 [2,12,18]. DNMR method provided us a better understanding of the clay-bound water and free fluid content.

Further studies and tests can be done on core samples to improve the reliability and accuracy of these generated well logs. Testing core samples can give a better estimate of the saturation exponent *n,* a better understanding of the gas hydrate composition, growth of gas hydrates and the nature of dissociation of gas hydrates. Furthermore, geophysical studies can also give an estimate of presence of gas hydrates and the stability formation. It can be concluded that simultaneously observing the well logs, core data results and seismic survey results can help us greatly understand the gas hydrate zones and its importance as a potential resource.

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APPENDIX: A1
WELL LOG VIEWER

WELCOME NOTE

```
% It is important to make our code to look a bit more user-friendly, thus a welcome note.
display('Welcome to Well-log Viewer');
```

CALIPER LOG DATA

Asking User to upload a well log in (ASCII) data type or '.txt' or '.xlsx' files. User will be able to choose between the options:

```
display('Import the Caliper Log data');
display('Choose the file-type of Log data: 1.Excel file 2.Text file');
choice=input('1 or 2: ');
switch choice
    case 1
        [FileName,PathName] = uigetfile('*.xlsx','Select the Excel file');
        [CALI, text, alldata]=xlsread(FileName);
    case 2
        [FileName,PathName] = uigetfile('*.txt','Select the Text file');
        CALI=dlmread(FileName,'\t',6,0);
    otherwise
        display('file not supported!');
end
```

SPECTRAL GAMMA RAY LOG

```
display('Import the Gamma ray data.');
display('Choose the file-type of Log data: 1.Excel file 2.Text file');
choice=input('1 or 2: ');
switch choice
    case 1
        [Filename,PathName] = uigetfile('*.xlsx','Select the Excel file');
        [GR, text, alldata]=xlsread(Filename);
    case 2
        [Filename,PathName] = uigetfile('*.txt','Select the Text file');
```

```matlab
        GR=dlmread(Filename,'\t',6,0);
    otherwise
        display('file not supported!');
end
```

LITHO-DENSITY & RESISTIVITY LOG DATA

```matlab
display('Import the Density log data.');
display('Choose the file-type of Log data: 1.Excel file 2.Text file');
choice=input('1 or 2: ');
switch choice
    case 1
        [filename,PathName] = uigetfile('*.xlsx','Select the Excel file');
        [DEN, text, alldata]=xlsread(filename);
    case 2
        [filename,PathName] = uigetfile('*.txt','Select the Text file');
        DEN=dlmread(filename,'\t',6,0);
    otherwise
        display('file not supported!');
end
%-----
display('Do you have Resistivity log data? 1.Yes  2.No');
i=input('1 or 2: ');
if i==1
    display('Import the Resistivity log data.');
    display('Choose the file-type of Log data: 1.Excel file 2.Text file');
    choice=input('1 or 2: ');
    switch choice
        case 1
            [fname,PathName] = uigetfile('*.xlsx','Select the Excel file');
            [RES, text, alldata]=xlsread(fname);
        case 2
            [fname,PathName] = uigetfile('*.txt','Select the Text file');
            RES=dlmread(fname,'\t',6,0);
```

```matlab
        otherwise
            display('file not supported!');
    end
else
    display('Analysing & Processing the logs');
end
```

GENERATING THE COMPOSITE LOG

```matlab
grid on
subplot(1,3,1);
plot(CALI(:,2),CALI(:,1),'k:',GR(:,2),GR(:,1),'r--');
legend('Caliper','SGR')
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
hold on
%----------it begins here-------
grid on
subplot(1,3,2);
plot(DEN(:,2),DEN(:,1),'r--');
legend('RHOB');
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
hold on
% and Here---------------------
grid on
subplot(1,3,3);
semilogx(RES(:,2),RES(:,1),'k');
legend('Deep (ohm-m)');
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
```

NUCLEAR MAGNETIC RESONANCE LOG

Asking user to upload the NMR data:

```matlab
display('Do you have special logs such as the NMR log data? 1.Yes  2.No');
i=input('1 or 2: ');
if i==1
    display('Import the NMR log data.');
    display('Choose the file-type of Log data: 1.Excel file 2.Text file');
    choice=input('1 or 2: ');
    switch choice
        case 1
            [Fname,PathName] = uigetfile('*.xlsx','Select the Excel file');
            [NMR, text, alldata]=xlsread(Fname);
        case 2
            [Fname,PathName] = uigetfile('*.txt','Select the Text file');
            fid=fopen(Fname);
            S = textscan(fid,'%s','delimiter','\n');
            fclose(fid);
            S = S{1};
            %Get positions
            idx1 = find(not(cellfun('isempty',strfind(S, 'T2')))); % T2 position
            idx2 = find(not(cellfun('isempty',strfind(S, 'DEPTH')))); % T2 position
            idx3 = idx2:length(S);
            % Get the required
            x = cell2mat(cellfun(@str2num,strsplit(S{idx1}),'un',0));
            depth = cell2mat(cellfun(@str2num,strsplit(S{idx2}),'un',0));
            data = cell2mat(cellfun(@str2num,S(idx3),'un',0)) ;
            y = data(:,1);
            data = data(:,2:end);
        otherwise
            display('file not supported!');
    end
    % plotting NMR data----------------------------
```

```matlab
if choice==1
    grid on
    subplot(1,4,1);
    plot(CALI(:,2),CALI(:,1),'k:',GR(:,2),GR(:,1),'r--');
    legend('Caliper','SGR')
    ylabel('Depth (meters)');
    set(gca,'YDir','Reverse');
    set(gca,'XAxisLocation','top');
    hold on
    %-------
    grid on
    subplot(1,4,2);
    plot(DEN(:,2),DEN(:,1),'r--');
    legend('RHOB');
    ylabel('Depth (meters)');
    set(gca,'YDir','Reverse');
    set(gca,'XAxisLocation','top');
    hold on
    %-------
    grid on
    subplot(1,4,3);
    semilogx(RES(:,2),RES(:,1),'k');
    legend('Deep (ohm-m)');
    ylabel('Depth (meters)');
    set(gca,'YDir','Reverse');
    set(gca,'XAxisLocation','top');
    hold on
    %-------
    [m,n]=size(NMR);
    grid on
    subplot(1,4,4);
    x=NMR(1:m,(2:n));
    y=NMR((6:m),1);
```

```matlab
        z=NMR((6:m),(2:n));
        surface(x,y,z);
        xlabel('T2 Distribution');
        set(gca,'YDir','Reverse');
        set(gca,'XAxisLocation','top');
    else
        grid on
        subplot(1,4,1);
        plot(CALI(:,2),CALI(:,1),'k:',GR(:,2),GR(:,1),'r--');
        legend('Caliper','SGR')
        ylabel('Depth (meters)');
        set(gca,'YDir','Reverse');
        set(gca,'XAxisLocation','top');
        hold on
        %-------
        grid on
        subplot(1,4,2);
        plot(DEN(:,2),DEN(:,1),'r--');
        legend('RHOB');
        ylabel('Depth (meters)');
        set(gca,'YDir','Reverse');
        set(gca,'XAxisLocation','top');
        hold on
        %-------
        grid on
        subplot(1,4,3);
        semilogx(RES(:,2),RES(:,1),'k');
        legend('Deep (ohm-m)');
        ylabel('Depth (meters)');
        set(gca,'YDir','Reverse');
        set(gca,'XAxisLocation','top');
        hold on
        %--------
```

```matlab
        grid on
        subplot(1,4,4);
        surface(x,y,data);
        xlabel('T2 Distribution');
        set(gca,'YDir','Reverse');
        set(gca,'XAxisLocation','top');
    end
end
```

TEMPERATURE LOG DATA

```matlab
display('Do you have Temperature log data (choose between options)?');
point=input('1.Yes or 2.No: ');
switch point
    case 1
        display('Import the Temperature log data.');
        display('Choose the file-type of Log data: 1.Excel file 2.Text file');
        choice=input('1 or 2: ');
        switch choice
            case 1
                [FName,PathName] = uigetfile('*.xlsx','Select the Excel file');
                [TEMP, text, alldata]=xlsread(FName);
            case 2
                [FName,PathName] = uigetfile('*.txt','Select the Text file');
                TEMP=dlmread(FName,'\t',6,0);
        otherwise
        display('file not supported!');
        end
        grid on
        figure;
        plot(TEMP(:,2),TEMP(:,1),'k');
        legend('Temperature');
        xlabel('Temperature (degree Celcius)');
        ylabel('Depth (meters)');
```

```matlab
        set(gca,'YDir','Reverse');
        set(gca,'XAxisLocation','top');
    case 2
        display('continuing to process the data');
end
display('Processing complete!');
```

APPENDIX: A2

RESISTIVITY METHOD

Calculation of Hydrate Saturation using Modified Archie's Equation

Before we can start calculating the hydrate saturation, we need to study the well logs carefully and interpret the gas hydrate zones. The following code can calculate the hydrate saturation along the composite log.

```
display('First, calculating the sea water resistivity at a salinity(in ppm) of seawater measured at reference temperature of 20 degrees celcius (68 degrees Fahrenheit):');
display('Please enter the salinity of seawater.');
SAL_NaCl=input('Salinity (ppm)= ');
Rw_Tr=(400000/(68*SAL_NaCl))^0.88          %Resistivity of seawater measured at a salinitiy (at Reference Temperature,Tr)
```

We need to correct this resistivity of seawater to resistivity at Formation Temperature using Arp's Formula. Formation Temperature can be in Fahrenheit or Celsius.

```
display('Is your Temperature log in: 1.degree F or 2.degree C?');
option=input('choose between 1 or 2: ');
switch option
    case 1
       Rw_Ft=Rw_Tr.*((68+6.77)./(TEMP(362:9079,2)+6.77));
    case 2
       Rw_Ft=Rw_Tr.*((20+21.5)./(TEMP(362:9079,2)+21.5));
end
```

Since we do not have core samples and its data the following values are assumed; a=1.7, m=2.0, n=1.9386 for most of the gas hydrate wells

```
a=1.7;
m=2.0;
n=1.9386;
```

Now we need to calculate Density porosity by assuming the type of matrix or grains: Limestone, Sandstone or Dolomite. We can write a code such as:

```matlab
display('choose the type of matrix: 1. Sand-stone, 2.Limestone, 3.Dolomite');
choice=input('1 or 2 or 3');
switch choice
        case 1
         Rho_mat= 2.65;   %gm/cc
        case 2
         Rho_mat= 2.71;   %gm/cc
        case 3
         Rho_mat= 2.87;   %gm/cc
end
```

Now we can calculate the density porosity, by observing the resistivity logs carefully:

```matlab
display('Enter the density of Drilling Mud in gm/cc.');
Rho_mud=input('Rho_mud= ');
display('Enter the Resistivity of formation water (Ro) by observing the resistivity log carefully (true resistivity).');
Ro=input('Resistivity of formation water= ');
Phi_D=(Rho_mat-DEN(:,2))/(Rho_mat-Rho_mud);
```

Now we can calculate the total porosity as:

```matlab
PHI_t=(a.*((Rw_Ft)./(RES(159:3899,2)))).^(1./m);
```

Now we can efficiently calculate the Hydrate Saturation as:

```matlab
Sw=(Ro.*((PHI_t).^m)/(a.*Rw_Ft)).^(1/n);                %Water Saturation
Sh=1-Sw;                                %HYDRATE SATURATION
```

Plotting the Final Composite Log

```matlab
grid on
subplot(1,4,1);
plot(CALI(:,2),CALI(:,1),'k:',GR(:,2),GR(:,1),'r--');
legend('Caliper','SGR');
```

```matlab
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
hold on
%-------
grid on
subplot(1,4,2);
plot(DEN(:,2),DEN(:,1),'k--',DEN(:,3),DEN(:,1),'r--');
legend('RHOB','DRHO');
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
hold on
%-------
grid on
subplot(1,4,3);
semilogx(RES(:,2),RES(:,1),'k');
legend('Deep (ohm-m)');
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
hold on
%-------
grid on
subplot(1,4,4);
plot(Sh,RES(1:2263,1),'k');
legend('Hydrate Saturation (Sh)');
ylabel('Depth (meters)');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
```

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APPENDIX: A3

DENSITY-NUCLEAR MAGNETIC RESONANCE METHOD

Calculating Hydrate Saturation using Density-Nuclear Magnetic Resonance(DNMR) data

DENSITY LOG DATA: We need density log data to calculate the TCMR porosity and Hydrate saturation.

```matlab
display('Import the Density log data.');

display('Choose the file-type of Log data: 1.Excel file 2.Text file');

choice=input('1 or 2: ');

switch choice

    case 1

        [filename,PathName] = uigetfile('*.xlsx','Select the Excel file');

        [DEN, text, alldata]=xlsread(filename);

    case 2

        [filename,PathName] = uigetfile('*.txt','Select the Text file');

        DEN=dlmread(filename,'\t',6,0);

    otherwise

        display('file not supported!');

end

% We ask user to upload the NMR data in only ASCII or text format.

display('Please inport the NMR data in Log-ASCII file format or ".txt" file format.');

[Fname,PathName] = uigetfile('*.txt','Select the Text file');

fid=fopen(Fname);

S=textscan(fid,'%s','delimiter','\n');

fclose(fid) ;

S = S{1} ;
```

Get positions

```matlab
idx1 = find(not(cellfun('isempty',strfind(S, 'T2'))));          % T2 position

idx2 = find(not(cellfun('isempty',strfind(S, 'DEPTH'))));        % Depth position

idx3 = idx2:length(S) ;
```

Get the organized data

```matlab
x = cell2mat(cellfun(@str2num,strsplit(S{idx1}),'un',0)) ;

depth = cell2mat(cellfun(@str2num,strsplit(S{idx2}),'un',0)) ;
```

```matlab
data = cell2mat(cellfun(@str2num,S(idx3),'un',0)) ;
y = data(:,1) ;
Data=data(:,2:end);
dataCBW = data(:,2:5) ;
grid on
surface(x,y,Data)
xlabel('T2 Distribution');
set(gca,'YDir','Reverse');
set(gca,'XAxisLocation','top');
```

Area under each curve

```matlab
[m,n]=size(dataCBW);
%N = length(depth) ;
Area = zeros(m,1) ;
for i = 1:m
    Area(i) = trapz(x(1,1:4),dataCBW(i,:)) ;
end
display('Please enter the following values:');
RHO_mat=input('Enter the density of the matrix (in g/cc): ');
RHO_mud=input('Enter the density of the drilling mud (in g/cc): ');
Phi_D=(RHO_mat-DEN(:,2))./(RHO_mat-RHO_mud);               %Density Porosity
LAMDA=(RHO_mud-0.91)/(RHO_mat-RHO_mud);
PHI=(Phi_D(98:420,1)+(LAMDA.*(Area(1:323,1))./100))./(1+LAMDA);          %Total
Porosity
Sh=(PHI-(Area(1:323,1))./100)./PHI                         %Hydrate Saturation
figure;
plot(Sh,y(1:323,1))
xlabel('Hydrate Saturation (dec %)');
ylabel('Depth (meters)');
set(gca,'XAxisLocation','top');
set(gca,'YDir','Reverse');
```

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