QUANTITATIVE WELL LOG INTERPRETATION WITH IMPLICATIONS OF WATER SATURATION ESTIMATES

A Dissertation report submitted in partial fulfillment of the requirements for the Degree of

Master of Technology

(Petroleum Exploration)

By

Jitendra Singh Solanki

Enrollment No. R770209009

M.Tech-Petroleum Exploration (2009-11)

Under the guidance of

External Guide	**Internal Guide**
Dr. Indrajit Dutta	Dr. K. S. Misra
(HOD, Dept. of Well Logging, and DGM),	Professor,
Directorate General of Hydrocarbons,	UPES,
Noida (U.P.)	Dehradun (U.K.)

College of Engineering Studies
University of Petroleum & Energy Studies
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Approved

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हाईड्रोकार्बन महानिदेशालय
(पैट्रोलियम एवं प्राकृतिक गैस मन्त्रालय के अधीन)

DIRECTORATE GENERAL OF HYDROCARBONS
(Under Ministry of Petroleum & Natural Gas)

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DGH/ADMN/SI-III/2011 5th April 2011

TO WHOM IT MAY CONCERN

This is to certify that Sh. Jitendra Singh Solanki student of University of Petroleum and Energy Studies, Dehradun has successfully completed his training in DGH from 15/02/11 to 05/04/11.

This training emphasized mainly on **Quantitative Well Log Interpretation With Implications of Water Saturation Estimates**. His overall conduct and performance during the training was found to be good.

We wish him all success in his career.

HOD (Logging & NDR)

Dr. INDRAJIT DUTTA
DGM (Geoph.-Wells)
Directorate General of Hydrocarbons
NOIDA

CERTIFICATE

This is to certify that the Dissertation Report "**Quantitative Well log interpretation with implications of Water saturation estimates**", completed and submitted to University of Petroleum and Energy Studies, Dehradun, by **Jitendra Singh Solanki**, in partial fulfillment of the degree of **Master of Technology (Petroleum Exploration),** is a bonafide work carried out by him under my supervision.

To the best of my knowledge and belief, the work has been based on investigation made, data collected and analyzed by him and this work has not been submitted anywhere else for any other University or Institution for the award of any Degree or Diploma.

Dr. K. S. Misra

Professor,

Deptt. of Petroleum Engg. & Earth Sciences,

University of Petroleum & Energy Studies,

Dehradun (U.K.)

DECLARATION

I, **Jitendra Singh Solanki** student of **M.Tech- Petroleum Exploration (2009-11)** from University of Petroleum & Energy studies, Dehradun hereby declare that this dissertation work titled **"Quantitative Well log interpretation with implications of Water saturation estimates"** is a work of originality done during the dissertation work at **Directorate General of Hydrocarbons, Noida** for a scheduled duration of 15/02/11 to 05/04/11.

The following content is a work of constructiveness and bears the importance of genuine findings and references. The contents of this report will not be reciprocated or replicated by any means and is deemed confidential.

JSolanki
5/5/11

Jitendra Singh Solanki

M.Tech-Petroleum Exploration (2009-11)

University of Petroleum & Energy Studies,

Dehradun (U.K.)

ACKNOWLEDGEMENT

I feel very much elevated to present this intern report titled **"QUANTITATIVE WELL LOG INTERPRETATION WITH IMPLICATIONS OF WATER SATURATION ESTIMATES"** which is a complied detail of invaluable experience sought in this prestigious organization M/s. **Directorate General of Hydrocarbons.**

I would like to sincerely thank to **Directorate General of Hydrocarbons, Noida** especially to **Dr. Indrajit Dutta (HOD, Dept. of Well Logging, and DGM)** and all staff for giving me a great chance to do this project and also provide me with the company's data needed for this project.

I take extreme pleasure in expressing my deepest sense of gratitude and sincere thanks to **Mr. Bikram Singh, Senior Advisor (Petrophysics/Well Logging)** who has been a constant source of inspiration and through whom this intern duration has become worthy by his immense expertise and enduring assistance in the course of internship that has made my short tenure a genuine experience.

My sincere thanks and gratitude to **Mr. Promothes Barauh (Sr. Petrophysicist)** for sharing his valuable experience and enlightening me with surplus knowledge through his versatile wisdom and helped me familiarize with the nuances of the organization as well as the industry.

I owe my sincere gratitude to my internal guide **Dr. K. S. Misra, Professor (Geology)** and **Dr. Pradeep Joshi, HOD (Department of Petroleum Engineering & Earth Sciences)** for their invaluable guidance and encouragement made this work a very enjoyable and educational experience. The work contained this report would not have been accomplished without their advice and support.

ABSTRACT

The Estimation of Water Saturation (Sw) is one of the prime aspects taken into consideration for the crucial phases of Oil & Gas field Development and Production for an E&P Operator. The conventional method of estimating Sw by Archie's Law and other quick look techniques often take a generalised approach and eventually leads to the over estimation of the reservoir sands. These over estimation arise due to presence Shale in the reservoir sand. Shale offers variation in petro-physical properties by virtue of its occurrence in different forms as Dispersed, Laminar & Structural. The presence of shale requires us to follow more than the conventionally used Archie's model in order to attain an accurate estimate of water saturation.

This Project signifies the study of a gas field of a Petroliferous Basin of India taken from the Well log data of Well A. The published literature is used for review and for the understanding of background of the study area. This dissertation is a scratch of attempts made in the evaluation of the Water saturation estimate.

The Well log Data is acquired by using Calliper Log ,Gamma Log, Neutron Log, Resistivity Logs (Deep, Medium, Micro-Spherical), Neutron Porosity Log, Density Log and digitised to an MS Excel Worksheet to compute saturation parameters and other accountable factors. The 4 zones are identified as reservoir zones by well logging interpretation, mainly based on gamma ray, resistivity, neutron and density logs. Shale volume (Vsh) was then determined based on gamma ray logs. The porosity was calculated based on density and neutron log. An emphasis was placed on determining clay minerals presence in the reservoirs and shale formation. The RHOB and NPHI plot method suggest that all reservoirs zones are clean gas sand reservoir. An important parameter of water saturation is the water resistivity, which is determined by Pickett plot. The water resistivity was found to be around 0.098ohm-m @ 98.8 Deg C. The water saturation based on Archie, Simandoux, Indonesian and Waxman-Smits, respectively are identified. The most reasonable Sw is obtained by using Indonesian equation because of its consistency with net clay volume reservoir.

The Interactive Petrophysics software has been used for plotting of output curves of water saturation by using digitised data which is calculated in MS Excel Worksheet.

In conclusion, a methodology to evaluate water saturation for the shaly formation was successfully applied and could help solving the problem of high water saturation at the study gas field.

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CHAPTER 1

1. INTRODUCTION

1.1 Introduction

The most common technique to determine petro physical parameters is well logging. Log derived parameters such as porosity and water saturation are the key parameters for characterizing a reservoir to estimate the hydrocarbon volume.

Petrophysical evaluation was performed on a well A to quantify the clay volume, effective porosity and water saturation of the significant hydrocarbon bearing pay sands. The parameters can be formed for the foundation to calculate the oil & gas reserves. The Archie water saturation approach is over estimated the water saturation due to presence of clay mineral in the reservoir rocks of available gas field well log data. The effect of shaliness causes the problem to estimate water saturation. However, there are several methods for estimating of water saturation. A comparison is drawn out between the saturation models to suggest the best fitting model in accordance to the reservoir rocks of the study area.

1.2 Objectives of study

The objectives of this thesis are focused below.

1. Perform well logging interpretation to determine petro physical parameters such as porosity, and water saturation for a Well A of study area.
2. Study on the different approaches of water saturation at the study area and find out the most suitable method to determine it.

1.3 Scopes of works

The scopes of study are following,

1. Review on the regional and local geological conditions of the study area & basic well logging interpretation techniques.
2. Collection of well logging data.
3. Perform an interpretation of well logging to define petro physical parameters such as porosity, and water saturation.
4. Determine type of clay mineral and type of shale distribution of study area.
5. Using the Log data to estimate water saturation using different shaly sand (Archie, Waxman–Smits, Simandoux and Indonesian) approaches.

1.4 Area of study

The study well is located within a gas field of an offshore basin of India.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Background

The study area is proven petroliferous basin of India which comes under I type of category basin. The basin contains about 5 km thick sediments with several cycles of deposition, ranging in age from Late Carboniferous to Pleistocene. The major geomorphologic units of this basin are Upland plains, Coastal plains, Recent Flood and Delta Plains. In the study area sandstone plays the role of reservoir along with above shale as a cap rock. The source rock of hydrocarbon is shale. It has a good source rock potential with rich organic matter with TOC average ranging between 0.5 to 3%.

2.2 Background Formation Evaluation

Formation evaluation is the process of using borehole measurements to evaluate the characteristics of subsurface formations. Formation evaluation helps to identify and evaluate commercial hydrocarbon-bearing formations. A wide variety of in-situ measurements are available for evaluating formations in an individual well.

2.3 Formation Petrophysical Parameters

2.3.1 Porosity:

Porosity is defined as the ratio of the pore volume to the bulk volume of material. The pore volume is available for the accumulation and storage of oil, gas and water in hydrocarbon reservoir. Porosity can be expressed as a percentage of bulk volume as follow:

$$\phi = \frac{V_b - V_s}{V_b} = \frac{V_p}{V_b} \tag{2.1}$$

Where:

Φ = porosity, fraction

Vb = bulk volume of rock, cm^3

Vs = solid volume, cm^3

Vp= pores volume, cm^3

- **Total porosity:**

Total porosity is defined as the ratio of the volume of all the pores to the bulk volume of a material:

$$\phi_t = \frac{V_b - V_s}{V_b} = \frac{V_p}{V_b}$$

(2.2)

Where:

Φ_t = total porosity, fraction

V_b = bulk volume of rock, cm3

V_s = solid volume, cm3

V_p = pore volume, cm3

We can distinguish two components in total porosity, and namely:

$$\phi_t = \phi_1 + \phi_2$$

(2.3)

Where:

Φ1 is the primary porosity that can correspond to the porosity existed at the time of the sediment deposition. It is intergranular or intercrystalline. It depends on the shape, size and arrangement of the solids, and is the common type of porosity encountered in clastic rocks. It has effect on sediment deposition due to compaction and diagenetic effects. (Tiab and Donalson, 2004)

Φ2 is the secondary porosity which is made up either molds or vugs caused by dissolution or transformation of certain minerals by water circulation or of cracks, fissures, or fractures generated by mechanicals forces. The secondary porosity does not increase porosity significantly but it may increase permeability. Secondary porosity is generated after lithification. (Tiab and Donalson, 2004)

- **Interconnected porosity (Φcon):**

This is made up of only those spaces which are in communication. This may be considerably less than the total porosity, e.g. pumice has a total porosity of 50%, but an interconnected porosity is zero because each pore-space is isolated. (Tiab and Donalson, 2004)

- **Potential porosity (Φpot):**

This is that part of the interconnected porosity in which the diameter of the connecting channels is large enough to permit the fluid to flow (greater than 20 μm for oil, and 5 μm for gas). Potential porosity in some cases is considerably smaller than the connected porosity, e.g. clays or shales can have very high connected porosity (40-50%) when compacted and as much as 90% for newly deposited mud). However, owing to their very small pores and channels, molecular attraction prevents fluid circulation.

- **Effective porosity (Φe):**

This is a term used specifically in log analysis. It is the porosity that is accessible to free fluids, and excludes, therefore, non-connected porosity and the volume occupied by the clay-bound water or clay hydration water (adsorbed water, hydration water of the exchange cations) surrounding the clay particles(Fig. 2.1).

2.3.2 Water saturation for clean sand

Fluid saturation is the ratio of the volume occupied by specific fluid to the total pore volume. The fraction of the pore volume occupied by formation water is called water saturation, Sw, the complementary fraction, (1-Sw), is occupied by hydrocarbon, S_h.

$$S_w = \frac{V_w}{V_p} \tag{2.4}$$

Where:
Sw = water saturation of the rock, fraction
Vw = water volume, cm3
Vp = pore volume, cm3

Archie's formula has been widely used by log analysis especially when dealing with clean sand reservoir. This empirical formula provided the early basis of the quantitative petro physical reservoir evaluation. (Archie, 1942)

For Water Formation;

$$C_o = \frac{C_w}{F} \tag{2.5}$$

For Hydrocarbon bearing Formation:

$$C_t = \frac{C_w}{F} S_w^n \tag{2.6}$$

$$S_w^n = \frac{aR_w}{\phi^m R_t} \tag{2.7}$$

Where:
Sw= water saturation, fraction
n = saturation exponent
m = cementation exponent
Rw= water resistivity, Ωm
Rt = true resistivity, Ωm

- **Conventional Determination of a and m**

The determination of a, m is based on formation resistivity factor as follows:

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

$$\log F = \log a - m \log \phi \qquad (2.8)$$

Where:
F = formation resistivity factor, fraction
a = empirical constant
Φ = porosity, fraction
m = cementation exponent (= slope)

Cross plot of log F versus log Φ is used to determine a, m for the core sample. Cementation factor (m) is determined from the slope. The intercept of the line is a.

- **Conventional Determination of n**

The saturation exponent can be determined based on relationship between index resistivity (I) and water saturation (Sw):

$$I = \frac{R_t}{R_o} = S_w^{-n}$$

$$\log I = -n \log S_w \qquad (2.9)$$

Where:
I = resistivity index, fraction
Rt = true resistivity, Ωm
Ro = true resistivity of 100 percent water saturated rock, Ω m
Sw = water saturation, fraction
n = saturation exponent

Making a cross plot of log I vs. log Sw provides a straight line with negative slope to be **n**.

For evaluating shaly sand reservoir, Archie formula may give a misleading result. Because it assumes that the formation water is the only electrically conductive material in the formation, which is not true for the case of shaly sand. The shale effect on various log responses depends on the type, the amount, and the way it is distributed in formation.

2.3.3 Water Saturation for Shaly Sand

- **The Effect of clay on Porosity & Resistivity of Logs**

The presence of clay minerals or shale in porous formations presents problems from the interpretation of wire line logs. For most logs these problems have been discussed in the relevant chapter. The problem is, however, especially bad in the interpretation of resistivity data, and also affects the porosity logs. This is not only because the presence of clays and shale have a gross effect upon resistivity values, but because such data affects the final calculated STOOIP for a given formation. Even small amounts of clay can have a large effect, which is important because most reservoir sands contain some degree of shaliness.

Shale can be distributed in sandstone reservoirs in three ways as described in Fig. 2.2 that consists of **Laminar** shale, where shale can exist in the form of laminae between layers of clean sand, **Structural** shale which can exist as grains or nodules within the formation matrix and **Dispersed** shale that is to be dispersed throughout the sand, partially filling the intergranular in interstices. All form can be occurred in the same formation.

The conductivity of water bearing clean rock, Co, varies linearly with the conductivity Cw of saturating fluid as;

$$C_o = \frac{C_w}{F} \tag{2.10}$$

However, shaly sands exhibit a complex behaviour as illustrated in Fig. 2.3. At low salt concentrations of the saturating electrolyte, the conductivity of a shaly sand rapidly increases at a greater rate than can be counted by the increase in Cw. With further increase in solution conductivity, the formation conductivity increases linearly in a manner analogous of clean rocks. The magnitude of formation conductivity for shaly sand is generally larger than the magnitude of formation conductivity for a clean formation at same porosity. The excess conductivity is attributed to the presence of shaly material.

A more general relationship between the conductivity of formation, Co, and conductivity of free water, Cw for shaly sand formations can be described by following equations;

For water formation

$$C_o = \frac{C_w}{F} + X \tag{2.11}$$

Where,
Co = Conductivity of the formation when fully saturated with water
Cw = Conductivity of water
F = Formation factor
X = Shale conductivity term

For hydrocarbon-bearing formation;

$$C_t = \frac{C_w}{F} S_w^n + X \tag{2.12}$$

The ratio of Cw/Co is effectively equal to the intrinsic formation factor only if shale conductivity is sufficiently small and/or Cw is sufficiently large. Additionally, the value of X is not always constant. The most accepted fact regarding the effect of shaliness on the conductivity behaviour of a rock sample is that the absolute value of X increases with Cw to some maximum level after which it remains constant at higher salinities. This corresponds to respectively to non-linear and linear portions of the shaly formation conductivity of Figure 2.3.

The adulteration of shale was overcome by proposal of correcting the respective water saturation (Sw) which is incorrectly estimated due to the presence of shales. Thus two groups of shaly sand models have been categorised which select the Volume of Shales (Vsh) and Cation Exchange Capacity (Qv) as their correction factors respectively, these approaches are

(1) Simandoux Equation, Indonesian Equation - (Vsh)
(2) Waxman-Smits, Dual Water Equation

- **Volume of shale (Vsh) Shaly Sand Models**

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

Simandoux (1963) proposed this equation based on an experiment with mixtures of sand and montmorillonite. Shale volume does not correspond to the wetted shale, because the natural calcium montmorillonite was not in the fully wetted state. Simandoux's proposed shaly sand equation for water formation and hydrocarbon formation as follows;

$$C_o = \frac{C_w}{F} + V_{sh} C_{sh} \tag{2.13}$$

$$C_t = \frac{C_w}{F} S_w^n + V_{sh} C_{sh} \tag{2.14}$$

$$S_w^n = \frac{aR_w}{\phi^m}\left[\frac{1}{R_t} - \frac{V_{sh} S_w}{R_{sh}}\right] \tag{2.15}$$

Where:
Rt = true resistivity, Ωm
Φ = porosity, fraction
Sw = water saturation, fraction
Rw= water resistivity, Ωm
Vsh = volume of shale, fraction
Rsh = resistivity of shale, Ωm
n = saturation exponent
m = cementation exponent

Poupon and Leveaux (1971) proposed an empirical model called "**Indonesia formula**". This equation was developed based on the typical characteristic of fresh formation waters and high degrees of shaliness that presents in many oil reservoirs in Indonesia. In this model the conductivity relationship between Rt and Sw is a result of conductivities of the clay, formation water and additional conductivity from the interaction between both of them. The empirical relationship can be written as:

For water formation:

$$\sqrt{C_o} = \sqrt{\frac{C_w}{F}} + V_{sh}^{\,1-\frac{V_{sh}}{2}} \sqrt{C_{sh}} \tag{2.16}$$

and for hydrocarbon formation:

$$\sqrt{C_t} = \sqrt{\frac{C_w}{F}} S_w^{n/2} + V_{sh}^{\,1-\frac{V_{sh}}{2}} \sqrt{C_{sh}} S_w^{n/2} \tag{2.17}$$

$$S_w = \frac{1}{R_t}\left[\frac{V_{sh}^{5V_{sh}}}{R_{sh}^{0.5}} + \frac{\phi^{\frac{m}{2}}}{R_w^{0.5}}\right]^{-2/n} \tag{2.18}$$

Where:
Rt = true resistivity, Ωm
Φ = porosity, fraction
Sw = water saturation, fraction
Rw= water resistivity, Ωm
Vsh = volume of shale, fraction
Rsh = resistivity of shale, Ωm
n = saturation exponent
m = cementation exponent

- **Cation Exchange Capacity (CEC) Model**

The clay minerals are phylosilicates; they have a sheet of structure somewhat like that of micas. The principal building elements of clay mineral are (1) a sheet of silicon (Si) and oxygen (O) atoms in a tetrahedral arrangement and (2) a sheet aluminium (Al), oxygen and hydroxyl (OH) arranged octahedral pattern. These sheets of tetrahedral and octahedral are arranged in different fashions to give the different group of clay minerals.

In the tetrahedral sheet, tetrahedral silica (Si^{+4}) is sometimes partly replaced by trivalent aluminium (Al^{+3}). In the octahedral sheet, there may be replacement of trivalent aluminium by divalent magnesium (Mg^{+2}).When an atom of lower positive valence replaces one of higher valance, a deficiency of positive charges results. This excess negative charge is compensated for by the adsorption onto the layer surfaces of cations that are too large to be accommodated in the interior of the crystal. The accumulated ions are called counterions.

In the presence of water, the compensating cations, such as Mg, Na and Ca, on the layer surfaces may be easily exchange by other cations, when available in solution; hence they are called exchangeable cations. The number of these cations can be measured and is called cation exchange capacity, CEC, of the clay. The replacement power of different cations depends on their type and relative concentration. There is also definite order of replaceability, namely Na<K<Mg<Ca<H. This means that hydrogen will replace calcium, calcium replaces magnesium, etc.

The concentration of sodium cations can be measured in term of cation exchange capacity (CEC), expressed in milli equivalents per gram of dry clay. For practical purpose Qv, cation exchange capacity per unit of pore volume, is usually used. The most commonly used cation exchange capacity models are Waxman and Smits, Shaly Sand Model and Dual Water Shaly Sand Model.

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

For Water Formation;

$$C_o = \frac{1}{F*}\left(BQ_v + C_w\right) \tag{2.19}$$

For Hydrocarbon bearing Formation;

$$C_t = \frac{1}{F*}\left(C_w + BQ_v / S_w\right) \tag{2.20}$$

$$S_w^{-n*} = \frac{R_t \phi^{m*}}{R_w}\left[1 + \frac{BQ_v R_w}{S_w}\right] \tag{2.21}$$

Where:
Sw = formation water saturation
Rw = formation water resistivity
Rt = true formation resistivity
F* = formation resistivity factor independent of clay conductivity = a*/Φ^m*
F = formation resistivity factor
n* = saturation exponent independent of clay conductivity (slope of I versus Sw plot)
B = specific counterion activity, 1/ohm-m/equiv/liter
Qv = quantity of cation exchangeable clay present, meq/ml of pore space
CEC = cation exchange capacity, meq/100 gm
ρ_{ma} = grain density of rock matrix, g/cm3
a = tortuosity coefficient (intercept on F versus Φ plot)
m* = cementation exponent (slope of F* vs Φ plot)
Φ= measured porosity, fraction

- **Conventional Determination of m*, n*, B and Qv**

Conventional Determination of B

Juhasz proposed that B related to formation temperature and water saturation, is as follows (Well logging and formation Evaluation-Toby darling):

$$B = \frac{(-1.28 + 0.255 * T - 0.0004059 * T^2)}{(1 + (0.045 * T - 0.27) * R_w^{1.23})} \tag{2.22}$$

Conventional Determination of Qv

$$Q_v = CEC * \rho_b / (100 * \phi) \tag{2.23}$$

Where:
CEC = cation exchange capacity
Φ = porosity, fraction
ρb = bulk density, g/cm3

Where no CEC is available, Lavers has suggested the following relationship. (Source: Petrolog Help manual)

$$Q_v = A_q * \Phi t \wedge B_q \tag{2.24}$$

Where

Φt = Total Porosity which includes clay associated water

Aq = Constant: Default = 0.0029

Bq = Exponent: Default = -3.0590

Conventional Determination of m*

In a conventional cementation-exponent (m) measurement makes cross plot F against Φ on a log-log scale in Archie's model. For Waxman-Smits equation uses below:

$$F = (R_o / R_w) = \phi^{-m} \tag{2.25}$$

$$F^* = (1 + R_w B Q_v) * F = \phi^{-m^*} \tag{2.26}$$

Where:

F = formation resistivity factor

F*= formation resistivity factor

m*= cementation exponent

Ro = true resistivity of 100 percent water saturated rock, Ω m

Rw = water resistivity, Ω m

Make cross plot F* against Φ on log-log scale, it is indeed the case that the gradient yields m*.

Conventional Determination of n*

Using Archie's model is determined for saturation exponent (n*) Make cross plot Log I vs Log Sw. For Waxman-Smits equation is necessary to derive I*, given by

$$I^* = (1 + R_w B Q_v / S_w) * I / (1 + R_w B Q_v) = S_w^{-n^*} \tag{2.27}$$

Plotting Log I* versus Log Sw, the gradient should yield the corrected saturation exponent, n*(Source: Petrophysics-Dr. Paul W.J. Glover).

2.4 Well Logging

- **Resistivity**

The measurement is used to estimate the amount of hydrocarbon present in the well. The formation resistivity depends on resistivity of the formation water (Rw), the amount of water and pore structure geometry. The electric currents are forced to flow in the formation either by direct contact from electrodes, or by induction. The formation resistivity is measured by measuring the currents and voltages produced. It is the measure of its opposition to the passage of electric current. Formation resistivity measurement is shown in Fig 2.4. The unit is expressed in Ω·m. The resistivity is an inverse of the conductivity.

$$V = RI$$

$$V = \rho \frac{l}{A} I \qquad (2.28)$$

Where:
I = current intensity, A
V = current voltage, V
R = material resistance, Ω m
ρ = resistivity, Ω m
l = material length, m
A = cross section area, m^2

Applications:

1. Calculation of formation water resistivity, formation resistivity.
2. Identify & differentiate Hydrocarbon and Water zone.
3. Quantification of water saturation in reservoir zone.

- **Gamma Ray Logs**

Gamma ray emission is produced by three natural radioactive elements in the formation, Potassium (K40), Uranium (U) and Thorium (Th). The Gamma Ray log is a measurement of the emission of Gamma ray. When pass through rocks, Gamma ray are slowed and absorbed at a rate which depends on formation density. The less dense formation shows more radioactivity than more dense formation. It is measured in API unit. In general, high activity of a shaly formation is only due to presence of clay minerals (radioactivity minerals not present). So the shale volume can be estimated from GR log.

$$V_{sh} = \frac{GR - GR_{clean}}{GR_{sh} - GR_{clean}} \qquad (2.29)$$

Where:
Vsh = clay volume, fraction
GR = Gamma ray reading from log, API
GRsh = Gamma ray reading from shale, API

GRclean = Gamma ray reading from clean sand formation, API

Applications:

1. Depth correlation & Delineation of bed boundaries.
2. Well to well correlation
3. Lithology and Sedimentology
4. Shale volume estimation

- **Neutron Logs**

The neutron log basically measures slowing down properties of the neutrons in the formation. The showing down of fast neutrons is primarily caused by interaction with hydrogen atoms. The hydrogen density inferred by the measurement is then related to porosity. Therefore, the behaviour of emitted neutrons affords a means of evaluating the fluid content of a formation.

Applications:

1. Evaluation of porosity.
2. Detection of gas or light hydrocarbons.
3. Identification of lithology (in conjunction with other logs).
4. Correlation (particularly where shales are non-radioactive).

- **Density Logs**

Density log is a measure of the formation's bulk density and is mostly used as a porosity measurement that is measured electron density formation. The device is a contact tool which consists of a medium energy gamma ray source that emits gamma rays into a formation. However, the advantages of density log obtain to identify evaporite mineral, detect gas-bearing zones, determine hydrocarbon density and evaluate shaly sand reservoir and complex lithologies.

$$\phi_D = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} \tag{2.30}$$

Where:

Φ_D= Density porosity, fraction

ρ_m= matrix density, g/cm3

ρ_b= density reading from log, g/cm3

ρ_f= fluid density, g/cm3

Applications:

1. The porosity can be calculated directly if the density of the mineral component (matrix) and fluid are known, or, if not, by combination with the neutron log.
2. The density provides a base log for the determination of mineral component for non-porous formations or in combination with other logs for porous formations.
3. In the study of compaction and abnormal pressure zones.
4. This curve is used in the definition of electrofacies and correlation of facies.

CHAPTER 3

3. METHODOLOGY

3.1 General

This chapter shows that well log interpretation method determines some petrophysical parameters in the study area. The procedures perform an integrated interpretation of well logging data to characterize the reservoir formation. Therefore, the three petrophysical parameters (porosity, water saturation, Volume of Shale) will be estimated for reservoir characterization.

3.2 Data Collection

The data of gas field of petroliferous basin of India is related to well log analysis (porosity, cementation exponent, saturation exponent) involving gamma ray, resistivity, density and neutron logs which was collected and reviewed.

3.3 Well Location in Study Area

The study well is located within a gas field of a Continental passive margin Pericratonic basin of India.

3.4 Well Logging Interpretation

Well logging interpretation provides the output of log analysis in term of reservoir parameter. Quicklook log interpretation is generally used in formation evaluation using well logs. This interpretation method provides the information which help geologists, geophysicists, reservoir engineers and drilling engineers in short time. Basically, it relies on overlays of logs, interpretation charts, or graphic methods such as cross plots to minimize methods requiring detailed calculation.

The interpretation can derive shale volume, porosity, water saturation from available well logging data. The zones of reservoir can be identified by many parameters.

3.4.1 Zone of reservoir

Zone of reservoir is determined by gamma ray, resistivity, density and neutron logs. Make cross plot GR to separate shale and sand lines, and the greater the crossover between the density and neutron logs, the better the quality of the reservoir. Resistivity log is fundamental in formation evaluation because hydrocarbons do not conduct electricity. Therefore, the well logs are split into interval of porous and non-porous rock, permeable and non-permeable rock or shaly and clean sand rock.

- **GR log**

The clean sands and sandstones are determined by GR log are low radioactive because GR log records the abundance of the radioactive isotopes of thorium, uranium and potassium. They are usually concentrated in shales and less concentrated in sandstones, so high GR reading can be observed normally and can be used as regional marker because shale is deposited in wide area.

- **Resistivity log**

Resistivity curve can indicate hydrocarbon in porous and permeable rock.

- **Density and Neutron log**

Cross plot between density and neutron can indicate the reservoir zones.

3.4.2 Vsh Determination

From well logging tools, GR is used for shale volume determination which will be used for correction of porosity and saturation.

$$V_{sh} = \frac{GR - GR_{clean}}{GR_{sh} - GR_{clean}}$$

Where:
Vsh = clay volume, fraction
GR = Gamma ray reading from log, API
GRsh = Gamma ray reading from shale, API
GRclean = Gamma ray reading from clean sand formation, API

3.4.3 Porosity determination

- **Density Porosity (Φ_D):**

The density tool is selected to calculate the porosity in a good borehole condition. The density log is used as porosity method, the equation to calculate the porosity based on the density log is as follows:

$$\phi_D = \frac{\rho_m - \rho_b}{\rho_m - \rho_f}$$

Where:
Φ_D= Density porosity, fraction
ρ_m= matrix density, g/cm3
ρ_b= density reading from log, g/cm3
ρ_f= fluid density, g/cm3

- **Neutron Porosity (Φ_N):** The Neutron Porosity is directly measured from neutron log.

- **Shale Correction for Porosity:** The presence of shale in reservoir affects the porosity calculated from Density & Neutron log. This porosity is required some correction to calculate connected porosity. This correction is known as shale correction for porosity. The empirical relation uses for shale correction for density & neutron porosity are as follow;

  Corrected Density Porosity (Φ_{DC}):

$$\phi_{DC} = \phi_D - V_{sh}\phi_{Dsh} \tag{3.1}$$

  Corrected Neutron Porosity (Φ_{NC}):

$$\phi_{NC} = \phi_N - V_{sh}\phi_{Nsh} \tag{3.2}$$

- **Gas Correction for Porosity:** The presence of Gas in reservoir affects the porosity calculated from Density & Neutron log. This porosity is required some correction to calculate effective porosity. This correction is known as gas correction for porosity.

  The effective porosity (Φ_e): The equation which used for gas correction is as follow;

$$\Phi_e = 0.707*\{(\Phi^2_{NC} + \Phi^2_{DC})\text{^}0.5\} \tag{3.3}$$

3.4.4 Clay minerals & shale quantification

The crossplot between RHOB & Φ_N can be used to identify the clay minerals which are presence in the reservoir sand and shale formation of the gas field. This crossplot also quantifies the presence of shale volume. The crossplot between plot RHOB and Φ_N is shown in Fig. 3.1, 3.2 and 4.2 to 4.8.

3.4.5 Formation water resistivity determination

Formation water resistivity estimated from using cross plot between Log (Rt) and Log (Φe) which is known as Pickett Plot (Fig. 4.11, 4.12). A Pickett plot between true resistivity (Rt) and Effective Porosity (Φe) yield us the Resistivity of the formation fluid (Rw) and slope of the plot gives us the cementation exponent "m".

3.4.6 Water saturation determination

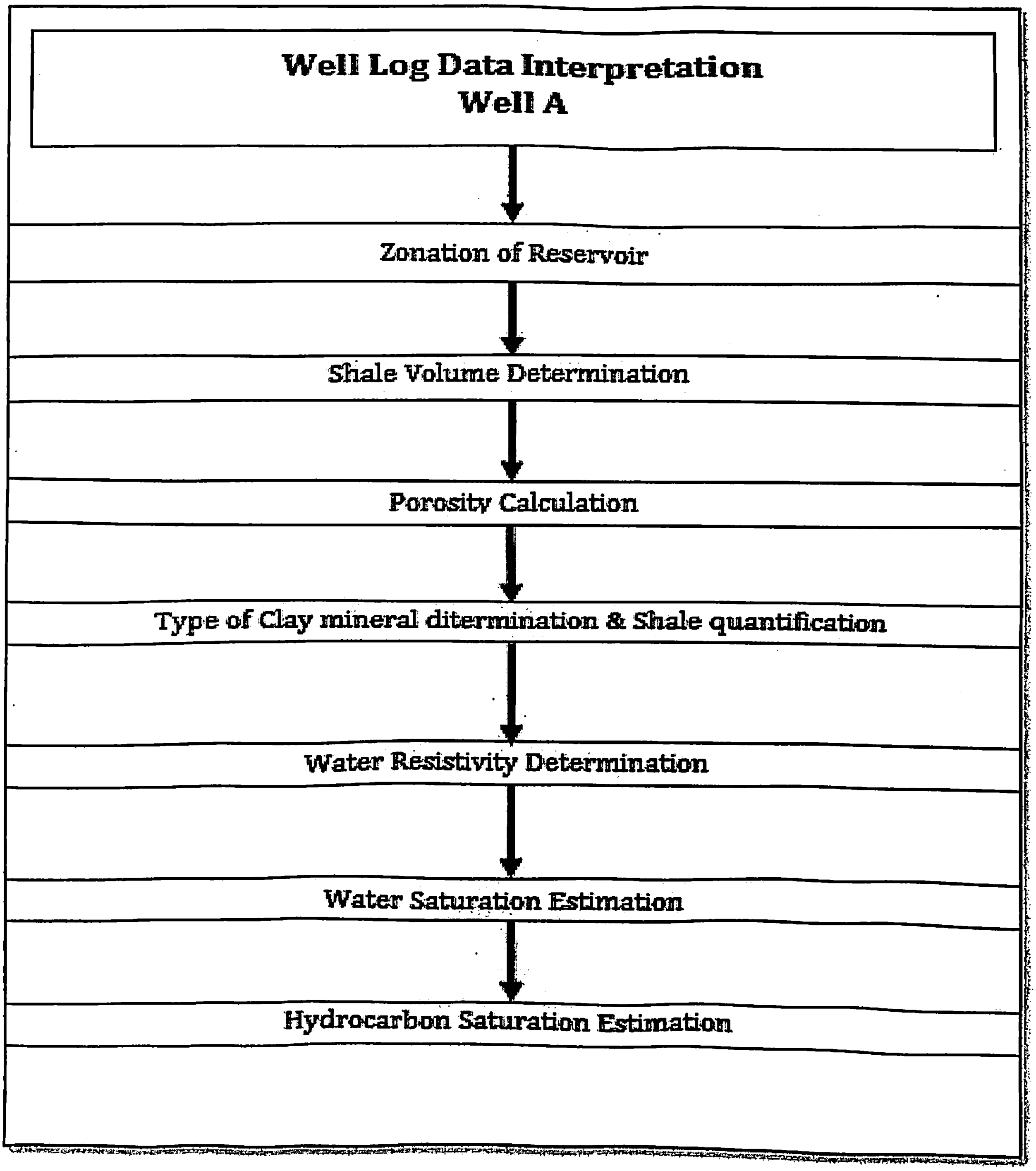
For determination of water saturation in a Reservoir zones different water saturation approaches like Archie, Simandoux, Indonesian and Waxman-Smits Eq. 2.7, 2.15, 2.18, 2.21 are used.

3.4.7 Hydrocarbon saturation determination

The subtraction of water saturation from value 1 is gives the hydrocarbon saturation. So the hydrocarbon saturation is estimated for different approaches after calculation of water saturations.

$$S_H = 1 - S_w \qquad (3.3)$$

3.5 The Procedure of Well Logging Interpretation



3.6 The Analysis of Support Software

The INTERACTIVE PETROPHYSICS^{TM} (IP) Log analysis software developed by PGL (a subsidiary of Senergy Ltd.), Scotland has been used for carrying out the current well Log data interpretation. This leading-edge capability dramatically reduces the time required to work up prospects. Interactive Petrophysics^{TM} provides these capabilities in a multi-user, scalable, secure, 32-bit or 64-bit Windows 2000, XP operating system.

- **Procedure of Well Log Data Interpretation by using IP software:**

The procedure of well log data interpretation by using the IP software comprises the following steps;

(a) Creation of Project

(b) Loading of Data (Las file)

(c) Plotting of log data

(d) Editing in Curves

(e) Corrections in Plotting Curves

  - Environment Corrections
  - Depth Corrections

(f) Making of Cross-Plots

(g) Estimation of R_w from Pickett Plot and other parameters

(h) Computation of Porosity and Water saturation

(i) Reservoir Characterization

CHAPTER 4

4. RESULTS AND DISCUSSIONS

4.1 Data Collection and Preparation

The data are from the well A, of Gas field were collected, including Well Log data.

- **Well Log Data**

Well logging is one of the necessary methods for petrophysicist to understand the subsurface formations. Well Log data used in this study include gamma ray (GR), resistivity (RESD), density (RHOB) and neutron (NPHI) logs. The depth level X670-X780 m is used for this work of well A (Fig. 4.1). The lowest value of gamma ray is 55 API and the highest value is 135 API. The lowest value of resistivity is 0.70 Ohm-m and the highest value of resistivity is 122 Ohm-m. The lowest value of density is 1.80 g/cc and the highest value is 2.42 g/cc. The lowest value of neutron porosity is 0.16 and the highest value is 0.54.

4.2 Result of Well Log Interpretation

4.2.1 Zonation of reservoir

Zones of reservoir formation can be identified based on gamma ray (GR), resistivity, density (RHOB) and neutron (NPHI) logs. The zones of interest include these of reservoir rock and shale or high shaly content rocks (non-reservoir rock). The average line of the highest gamma ray curve is called shale line and the sand line is the average line of lowest gamma ray that can be drawn for clean sands. Generally, shales are conductive and have low resistivity. Resistivity log is fundamental in formation evaluation because hydrocarbons do not conduct electricity. While all formation waters do on the resistivity log when resistivity is high it means a possible reservoir zones. Combination of neutron and density logs can be the most reliable indicator of reservoir rock. When density curve moves to the left that means lower density and neutron moves to the right one say there is a cross-over that it (Fig 4.1) indicate of zones of reservoir. Integrating GR, RESS, RHOB and NPHI logs is the best way to identify the reservoir zones. The 4 zones are identified as reservoir zones which shown in Table 4.1, 4.2.

4.2.2 Shale volume determination

GR was used for shale volume (Vsh) determination. The sand line is drawn at 55 API and the shale line drawn 135 API in well log data as shown in Fig 4.1. The shale volume is calculated by Eq. 2.29 and the range of shale volume is from 0.06 to 0.28.

4.2.3 Determination of porosity

The density log is selected to calculate density porosity, using Eq. 2.30. The matrix density and fluid density are 2.65 g/cc and 1.00 g/cc. The Neutron Log gave the direct porosity which is known as Neutron porosity. The porosity can be corrected for shale volume fraction and gas presence by Eq.3.1, 3.2 and Eq. 3.3. The porosity is calculated based on density & Neutron log and the ranges of total and effective porosity are from 0.12 to 0.29 and 0.10 to 0.26.

4.2.4 Determination of clay mineral & shale quantification

The crossplot between RHOB & Φ_N is used to quantify and identify the clay minerals which are presence in the reservoir sand and shale formation of the gas field. The result from crossplot shows that Kaolinite and Illite minerals are presented in the shale formations. The crossplot also shows that the all 4 reservoir zone are clean gas sand reservoirs. The crossplot between RHOB and Φ_N for all 4 reservoirs are shown in Fig.4.2 to 4.6.

4.2.5 Water resistivity determination

Formation water resistivity is determined by Archie's law. In this study, The R_w has been determined by examination of resistivity data and Archie's law. The Pickett Plot which is crossplot between R_t and Φ_e on a Log-Log scale for a number of water zones is used (Fig. 4.11, 4.12). It gives us the Rw and Cementation exponent (m). The water resistivity value is about 0.12 ohm-m in water zones (X326-29m, X420-26m) at a formation temp 79.40 Deg C (Fig 4.16). The water resistivity value in reservoir zone (X693-X757m) is about 0.098 ohm-m at formation temperature 98.80 Deg C by using Eq. 4.1. The cementation exponent (m) value is 1.71 from Pickett chart (Fig 4.11). The Cementation factor m* for Waxman-Smits is calculated by using another Pickett Plot (Fig. 4.12) and it's value is 1.95. An approximated value of m=m*=2 and n=n*=2 has been used for the calculation purpose.

$$R_{wT2} = R_{wT1}\left(\frac{T_1 + X}{T_2 + X}\right) \tag{4.1}$$

$$X = 10^{-\left(0.340396 \times \log_{10} R_{wT1} - 0.641427\right)} \tag{4.2}$$

Where:

R_{wT1} = the resistivity of the fluid at temperature T_1
R_{wT2} = the resistivity of the fluid at temperature T_2
T_1 = the temperature T_1
T_2 = the temperature T_2

4.2.6 Water saturation estimation

Water saturation for clean sand can be calculated based on Archie's law as shown in Eq. 2.7, which can see that estimation of Sw depends on many parameters such as porosity, water resistivity, true resistivity, cementation exponent (m) and saturation exponent (n). The cementation exponent can be determined from Archie's relationship by plotting formation factor calculated on Ro/ Rw against known effective porosity as in figure 4.11. The core data is used to calculate the Saturation exponent (n) but due to absence of core data the generalised value of n=2 is used for this study. In this study, the gamma ray log shows the presence of shale in the reservoirs zones.

However, water saturation in shaly sand formation can be determined from other methods which use shale volume and CEC to identify parameters on different formulas. Water saturation used total shale volume was calculated by Simandoux's equation and Indonesian's equation as shown is Eq. 2.15 and Eq. 2.18. The parameters are based on Archie's law and shale volume is determined by GR log as shown is Eq. 2.29.

Waxman Smith is calculated by Eq. 2.21. B and Qv are determined from Eq. 2.22, 2.24. The temperature gradient has been used to determine a temperature in well A. As bottom temperature at 4800 m is 100 Deg C and surface temperature is 28 Deg C. Both temperatures are known that can assume a linear gradient from top to bottom. Temperature gradient at well A is 0.015 degree C per m.

Cementation-exponent (m*) measurement makes cross plot F* against Φe on a log-log scale in Archie's model. For Waxman-Smits equation is used Eq. 2.21. The gradient of the line gives m*. From Fig 4.12 Formation factor and porosity relationship, slope of graph gives m*of well A. The value of m* is 1.95. In this study we used generalised cementation exponent (m*) is 2 and saturation exponent (n*) is 2. The results of water saturation by different approaches are shown on Table 4.6, 4.7.

CHAPTER 5

5. CONCLUSIONS

1. The 4 zones were identified as reservoir zones by well logging interpretation, mainly based on gamma ray, resistivity, density and neutron logs (Table 4.1, 4.2).

2. The thicknesses of all 4 reservoir zones are 6m, 17m, 5m, and 21m respectively.

3. Shale volume (Vsh) was determined based on gamma ray log and the range of shale volume is from 0.06 to 0.28.

4. The porosity was calculated based on density & Neutron log and the ranges of total and effective porosity are from 0.12 to 0.29 and 0.10 to 0.26.

5. The RHOB and Φ_N crossplot method suggest that all four reservoirs are clean gas sand reservoir (Fig. 4.2 to 4.8). It also indicates that shale of study area is consisting of Kaolinite and Illite clay minerals (Fig. 4.7).

6. The water resistivity (Rw) is calculated from Pickett plot (Fig. 4.11, 4.12) and (Rw) was found to be around 0.098 Ohm-m for hydrocarbon zones.

7. The estimated results of water saturation based on Archie to be 0.12 to 0.60, Indonesian to be 0.09 to 0.54, Simandoux to be 0.02 to 0.37, and Waxman-Smits to be 0.04 to 0.34 (Fig. 5.1, 5.2).

8. The Qv value used for Waxman smits water saturation is calculated by a equation (Eq. 2.24). We cannot much relay on this Qv value because mostly it is calculated in laboratory by a core sample.

9. The Simandoux water saturation method is also underestimating the water saturation value like Waxman Smits because this model suited for shaly-sand reservoir with montmorillonite clay mineral.

10. The water saturation derived from Indonesian method is consistent with net clay volume of reservoir and it gives a reasonable water saturation compare to other water saturation approaches. So methodology to evaluate the shaly-sand formation was successfully applied and could help solving the problem of high water saturation at the study gas field.

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LIST OF ABBREVIATIONS

GR	:	Gamma Ray log
NPHI	:	Thermal neutron porosity log
RHOB	:	Bulk density log
RESD	:	Resistivity log- deep investigation
CEC	:	Cation Exchange Capacity
Qv	:	Cation exchange capacity per unit pore volume
F	:	Formation factor
Rw	:	Water resistivity
Rt	:	True resistivity
Rsh	:	Resistivity of shale
B	:	A constant related to temperature
Vsh	:	Shale volume
Sw	:	Water saturation
S_H	:	Hydrocarbon saturation
m	:	Cementation exponent
n	:	Saturation exponent
a	:	Tortuosity factor
I	:	Resistivity index
Ro	:	True resistivity of 100 percent water saturated rock
V_b	:	Bulk volume of rock
V_s	:	Solid volume
Φ	:	Porosity
Φ_e	:	Effective Porosity

TABLES

Table 4.1 Reservoir zone No. 1 & No. 2 by using gamma ray, resistivity, density and neutron data at well A

RESERVOIR ZONE	DEPTH (m)	CALIPER (in)	GR (API)	LLD ohmm	LLM ohmm	LLS ohmm	ΦN	RHOB (G/CC)	Crossover in ΦN & RHOB
Zone No. 1	X693	8.46	65.78	11.20	8.10	6.70	0.22	2.26	Yes
	X694	8.45	66.14	23.51	20.54	17.06	0.20	2.17	Yes
	X695	8.39	63.91	51.68	54.66	58.69	0.16	2.13	Yes
	X696	8.42	64.74	56.64	60.29	64.30	0.19	2.09	Yes
	X697	8.41	64.66	34.20	36.52	41.63	0.18	2.08	Yes
	X698	8.49	77.68	12.15	10.50	8.72	0.24	2.15	Yes
	X699	8.42	67.83	14.38	14.37	15.60	0.22	2.08	Yes
Zone No. 2	X710	8.50	76.26	9.94	8.55	7.15	0.26	2.26	Yes
	X711	8.49	66.78	37.88	38.83	44.63	0.20	2.06	Yes
	X712	8.48	65.84	32.05	25.02	21.95	0.19	2.24	Yes
	X713	8.43	69.19	42.43	39.90	35.99	0.21	2.13	Yes
	X714	8.43	71.99	101.28	106.37	107.20	0.18	2.05	Yes
	X715	8.43	72.55	142.63	151.17	154.10	0.18	2.07	Yes
	X716	8.44	70.68	141.65	141.62	146.16	0.17	2.10	Yes
	X717	8.51	62.90	101.94	94.75	67.90	0.19	2.35	Yes
	X718	8.46	77.31	98.22	99.07	94.18	0.16	2.17	Yes
	X719	8.46	80.25	99.63	98.55	91.33	0.19	2.05	Yes
	X720	8.44	70.24	108.04	105.78	98.65	0.18	2.06	Yes
	X721	8.42	74.10	114.82	111.34	101.05	0.19	2.06	Yes
	X722	8.44	71.74	109.40	113.12	114.93	0.18	2.04	Yes
	X723	8.43	66.19	84.10	86.64	92.44	0.18	2.02	Yes
	X724	8.44	63.24	49.60	47.96	44.74	0.20	2.04	Yes
	X725	8.46	65.90	30.12	28.31	26.56	0.23	2.00	Yes
	X726	8.42	68.62	17.85	15.16	13.79	0.26	2.05	Yes
	X727	8.46	68.38	17.04	18.02	19.05	0.23	2.01	Yes

Table 4.2 Reservoir zone No. 3 and No. 4 by using gamma ray, resistivity, density and neutron data at well A.

RESERVOIR ZONE	DEPTH (m)	CALIPER (in)	GR (API)	LLD ohmm	LLM ohmm	LLS ohmm	ΦN	RHOB (G/CC)	Crossover in ΦN & RHOB
Zone No. 3	X729	8.48	65.44	48.20	36.48	28.19	0.20	2.22	Yes
	X730	8.43	73.53	78.80	59.77	47.16	0.20	2.08	Yes
	X731	8.43	75.99	102.44	99.58	97.42	0.19	2.02	Yes
	X732	8.42	80.12	120.74	120.42	122.96	0.19	2.01	Yes
	X733	8.42	76.49	113.70	89.92	92.20	0.19	2.01	Yes
	X734	8.40	76.58	37.66	32.34	27.54	0.19	2.10	Yes
Zone No. 4	X736	8.46	73.56	15.04	13.37	11.87	0.28	2.20	Yes
	X737	8.42	74.73	28.94	28.89	28.45	0.21	2.06	Yes
	X738	8.45	77.36	34.37	34.81	32.75	0.20	2.04	Yes
	X739	8.43	78.26	43.28	36.54	35.05	0.21	2.06	Yes
	X740	8.43	71.20	54.10	51.71	47.37	0.21	2.04	Yes
	X741	8.42	68.16	61.25	64.42	67.69	0.18	2.04	Yes
	X742	8.39	71.31	52.57	54.81	65.60	0.18	2.04	Yes
	X743	8.42	68.82	31.79	30.83	32.80	0.19	2.04	Yes
	X744	8.41	71.57	12.69	11.37	10.19	0.24	2.13	Yes
	X745	8.41	68.54	33.06	31.21	29.39	0.21	2.08	Yes
	X746	8.43	70.77	43.64	45.53	47.39	0.19	2.02	Yes
	X747	8.41	66.94	51.11	52.40	53.36	0.20	2.00	Yes
	X748	8.36	70.74	39.75	41.93	46.16	0.19	2.01	Yes
	X749	8.38	71.11	20.52	17.93	17.84	0.21	2.07	Yes
	X750	8.45	72.92	7.10	6.58	5.64	0.24	2.27	Yes
	X751	8.42	67.97	10.64	10.94	11.36	0.22	2.17	Yes
	X752	8.38	67.53	13.54	13.99	15.07	0.21	2.12	Yes
	X753	8.39	67.43	9.71	9.15	8.82	0.23	2.12	Yes
	X754	8.42	67.85	8.09	7.73	7.50	0.23	2.12	Yes
	X755	8.39	66.23	8.20	7.84	7.61	0.23	2.13	Yes
	X756	8.42	65.85	11.55	11.37	11.10	0.21	2.15	Yes
	X757	8.39	65.98	14.69	14.44	14.33	0.21	2.13	Yes

Table 4.3 Summary of parameters calculated by Pickett Plot

Plot	R_w @ T_f (ohm-m @ Deg C)	m	m*
Pickett Plot for Water Zone	0.12 @ 77.40	1.71	1.95

Table 4.4 Summary of parameters used in each method

Method	Rw (ohm-m)	a	m	n	m*	n*
Archie	0.098	1	2	2		
Simandoux	0.098	1	2	2		
Indonesian	0.098	1	2	2		
Waxman Smits	0.098	1	2	2	2	2

Table 4.5 Shale Parameters from well log data is used for study.

Shale Resistivity (R_{SH}) (ohm-m)	Φ_{NSH} (fraction)	Φ_{DSH} (fraction)	ρ_{bSH} (G/CC)
0.95	0.40	0.19	2.38

Table 4.6 Summary of well logging interpretation results of Reservoir Zone No. 1 & 2.

RESERVOIR ZONE	DEPTH (m)	V_{SH} (fraction)	Φt (fraction)	Φe (fraction)	Sw (Archie) (fraction)	Sw (Indonesian) (fraction)	Sw (Simandoux) (fraction)	Sw (Waxman-Smits) (fraction)
Zone No. 1	X693	0.15	0.20	0.15	0.51	0.49	0.33	0.32
	X694	0.15	0.25	0.21	0.31	0.28	0.18	0.17
	X695	0.12	0.24	0.22	0.20	0.17	0.11	0.08
	X696	0.13	0.26	0.24	0.17	0.15	0.09	0.08
	X697	0.13	0.26	0.25	0.22	0.19	0.13	0.12
	X698	0.29	0.27	0.20	0.46	0.36	0.21	0.34
	X699	0.17	0.28	0.24	0.34	0.29	0.22	0.24
Zone No. 2	X710	0.27	0.25	0.17	0.58	0.43	0.27	0.43
	X711	0.16	0.28	0.25	0.20	0.18	0.11	0.11
	X712	0.15	0.22	0.18	0.30	0.28	0.15	0.14
	X713	0.19	0.26	0.22	0.22	0.19	0.10	0.12
	X714	0.22	0.27	0.24	0.13	0.11	0.04	0.05
	X715	0.23	0.26	0.23	0.12	0.09	0.03	0.04
	X716	0.21	0.25	0.22	0.12	0.10	0.03	0.04
	X717	0.11	0.18	0.15	0.21	0.17	0.07	0.04
	X718	0.29	0.23	0.17	0.18	0.12	0.03	0.06
	X719	0.32	0.28	0.22	0.14	0.11	0.03	0.06
	X720	0.20	0.27	0.24	0.13	0.11	0.04	0.05
	X721	0.25	0.27	0.23	0.13	0.10	0.03	0.05
	X722	0.22	0.28	0.24	0.12	0.10	0.04	0.05
	X723	0.15	0.28	0.26	0.13	0.11	0.06	0.06
	X724	0.11	0.28	0.27	0.17	0.16	0.10	0.09
	X725	0.15	0.31	0.29	0.20	0.19	0.13	0.13
	X726	0.18	0.31	0.27	0.28	0.26	0.18	0.20
	X727	0.18	0.31	0.27	0.28	0.24	0.18	0.20

Table 4.7 Summary of well logging interpretation results of Reservoir Zone No. 3 & 4.

RESER-VOIR ZONE	DEPTH (m)	V_{SH} (fraction)	Φt (fraction)	Φe (fraction)	Sw (Archie) (fraction)	Sw (Indonesian) (fraction)	Sw (Siman-doux) (fraction)	Sw (Waxman -Smits) (fraction)
Zone No. 3	X729	0.14	0.23	0.20	0.23	0.22	0.11	0.10
	X730	0.24	0.27	0.23	0.16	0.14	0.05	0.07
	X731	0.27	0.29	0.24	0.13	0.10	0.03	0.06
	X732	0.32	0.29	0.23	0.12	0.09	0.02	0.05
	X733	0.28	0.29	0.25	0.12	0.11	0.03	0.05
	X734	0.28	0.26	0.20	0.25	0.20	0.08	0.14
Zone No. 4	X736	0.24	0.28	0.21	0.39	0.32	0.20	0.28
	X737	0.26	0.28	0.23	0.25	0.20	0.11	0.16
	X738	0.29	0.29	0.23	0.23	0.18	0.08	0.14
	X739	0.30	0.28	0.22	0.21	0.18	0.07	0.13
	X740	0.21	0.29	0.25	0.17	0.15	0.07	0.09
	X741	0.17	0.28	0.25	0.16	0.13	0.07	0.08
	X742	0.21	0.27	0.24	0.18	0.15	0.07	0.09
	X743	0.18	0.28	0.25	0.22	0.19	0.12	0.13
	X744	0.22	0.28	0.22	0.39	0.34	0.23	0.29
	X745	0.18	0.28	0.24	0.23	0.20	0.12	0.13
	X746	0.21	0.29	0.25	0.19	0.16	0.08	0.10
	X747	0.16	0.30	0.27	0.16	0.14	0.08	0.09
	X748	0.21	0.29	0.26	0.19	0.16	0.09	0.11
	X749	0.21	0.28	0.24	0.29	0.26	0.16	0.19
	X750	0.23	0.24	0.17	0.69	0.51	0.39	0.52
	X751	0.17	0.26	0.21	0.45	0.37	0.30	0.32
	X752	0.17	0.26	0.23	0.38	0.31	0.24	0.25
	X753	0.17	0.27	0.23	0.43	0.38	0.30	0.32
	X754	0.17	0.28	0.24	0.46	0.41	0.33	0.36
	X755	0.15	0.27	0.23	0.47	0.42	0.35	0.35
	X756	0.15	0.26	0.22	0.41	0.36	0.29	0.28
	X757	0.15	0.26	0.23	0.35	0.31	0.24	0.24

FIGURES

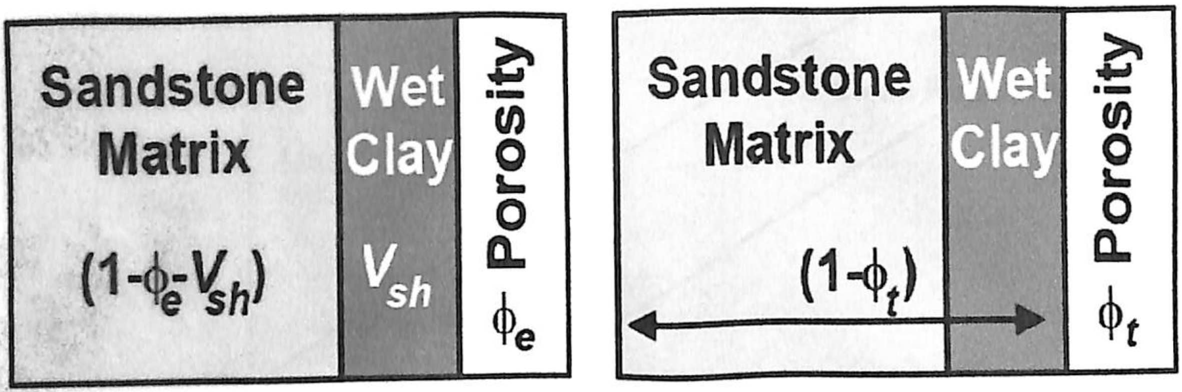

Figure 2.1 Sandstone is showing different types of porosity (Source: Petrophysics Dr. Paul W.J. Glover).

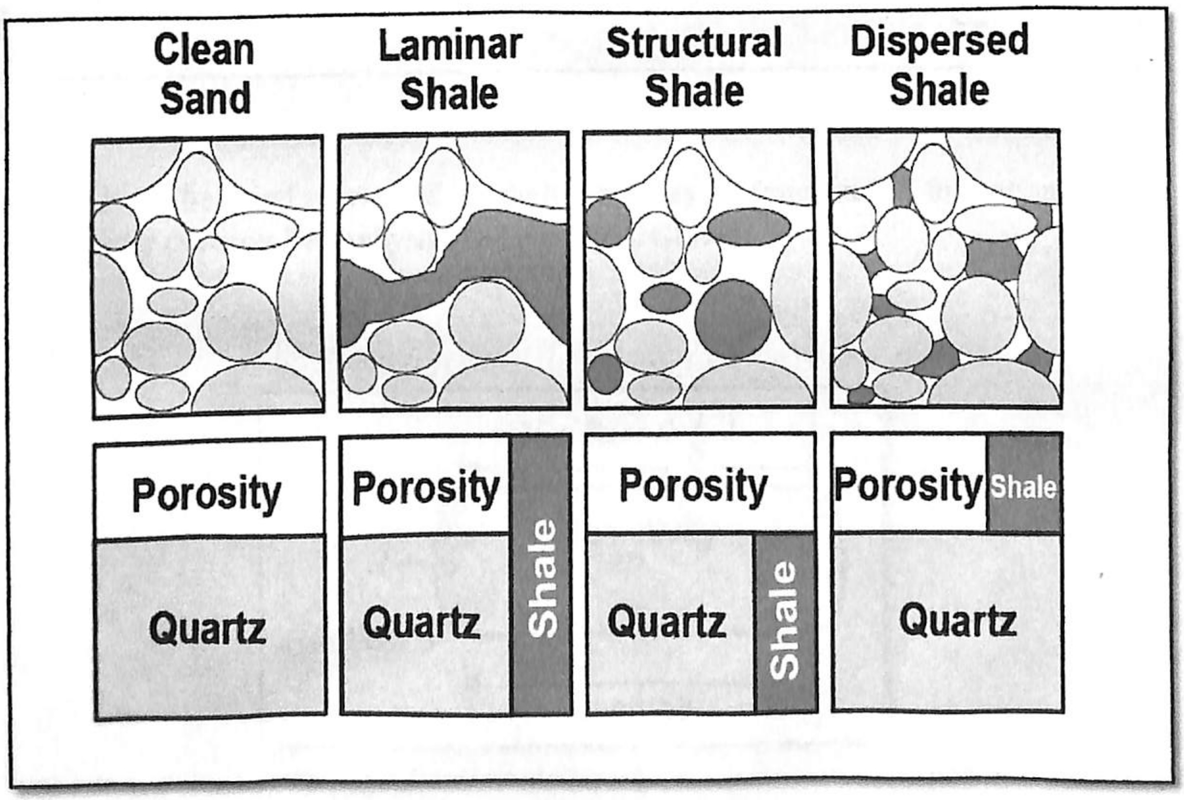

Figure 2.2 Different modes of clay distribution in Reservoir Sands.

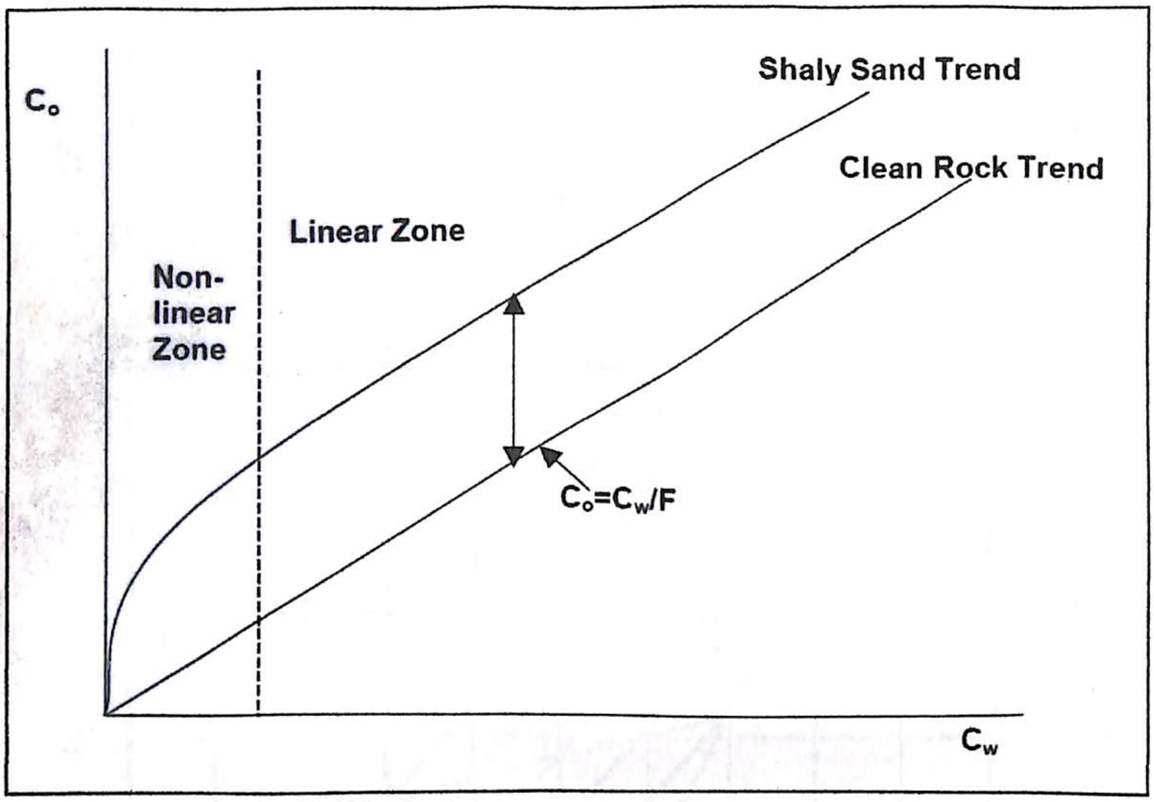

Figure 2.3 The conductivity of a shaly sand as a function of formation water conductivity (Source: Petrophysics-Dr. Paul W.J. Glover).

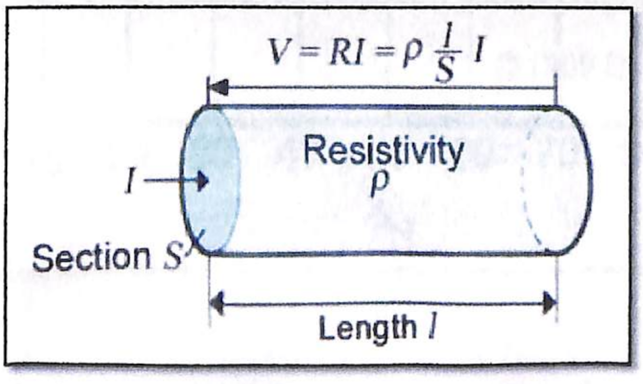

Figure 2.4 The sketch explaining the resistance of material (O.Serra, 2004)

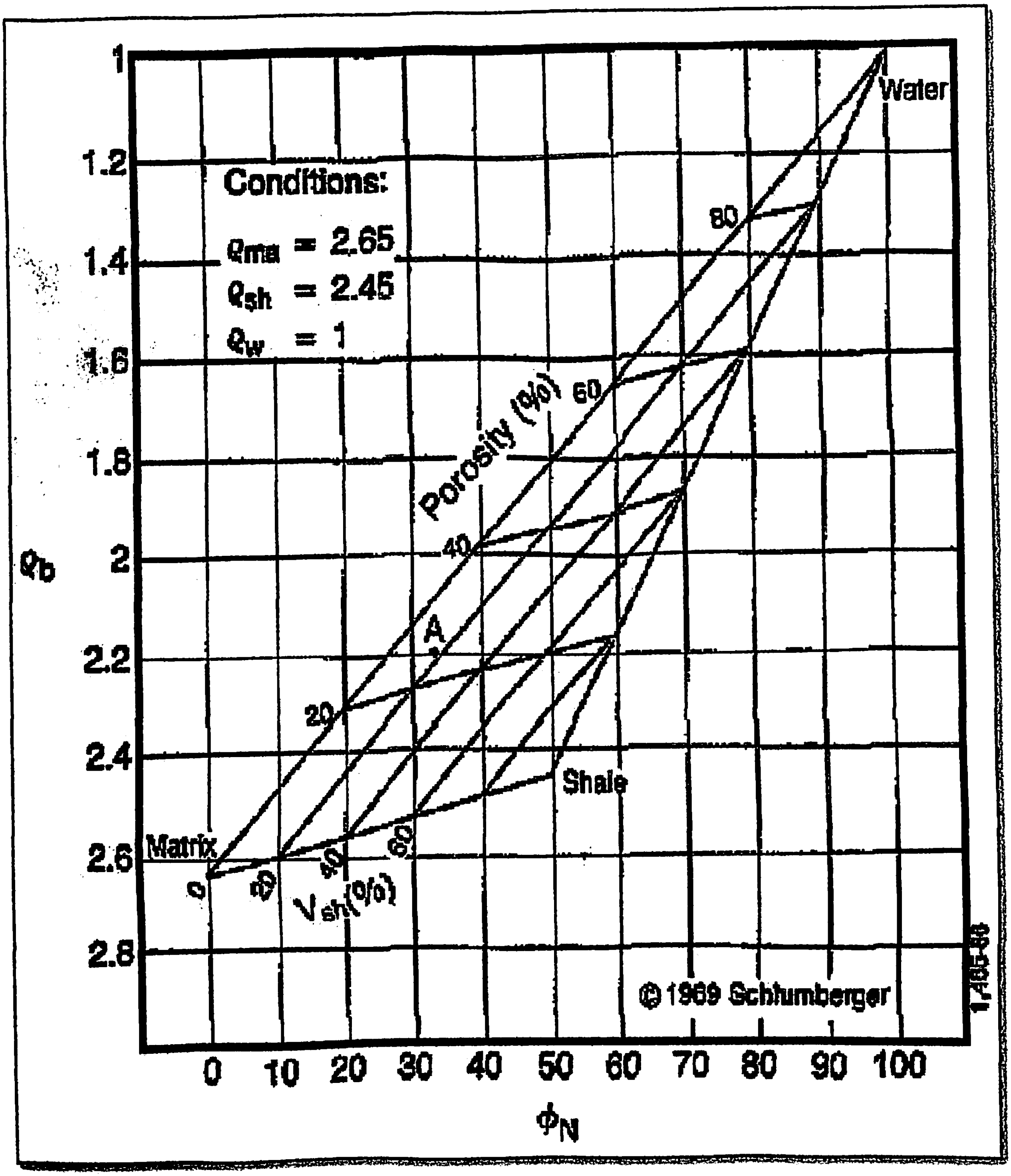

Figure 3.1 Neutron-density crossplot showing matrix, water and shale points, scaled for determination of V_{sh} and Porosity (Source: Schlumberger Log Interpretation Principles/Applications).

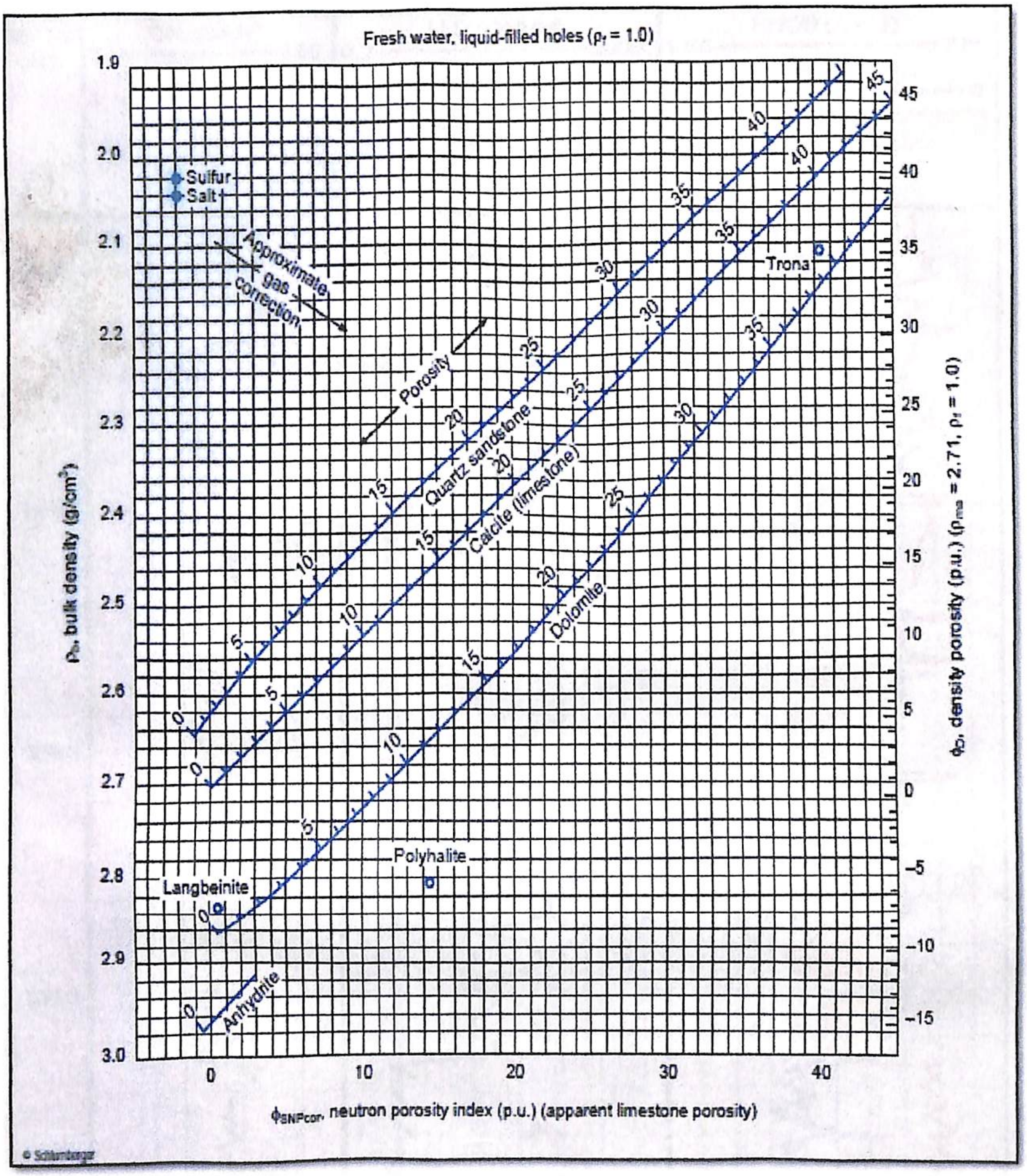

Figure 3.2 The Neutron-density crossplot charts provide insight into lithology and permit the determination of porosity. (Source: Schlumberger Log Interpretation)

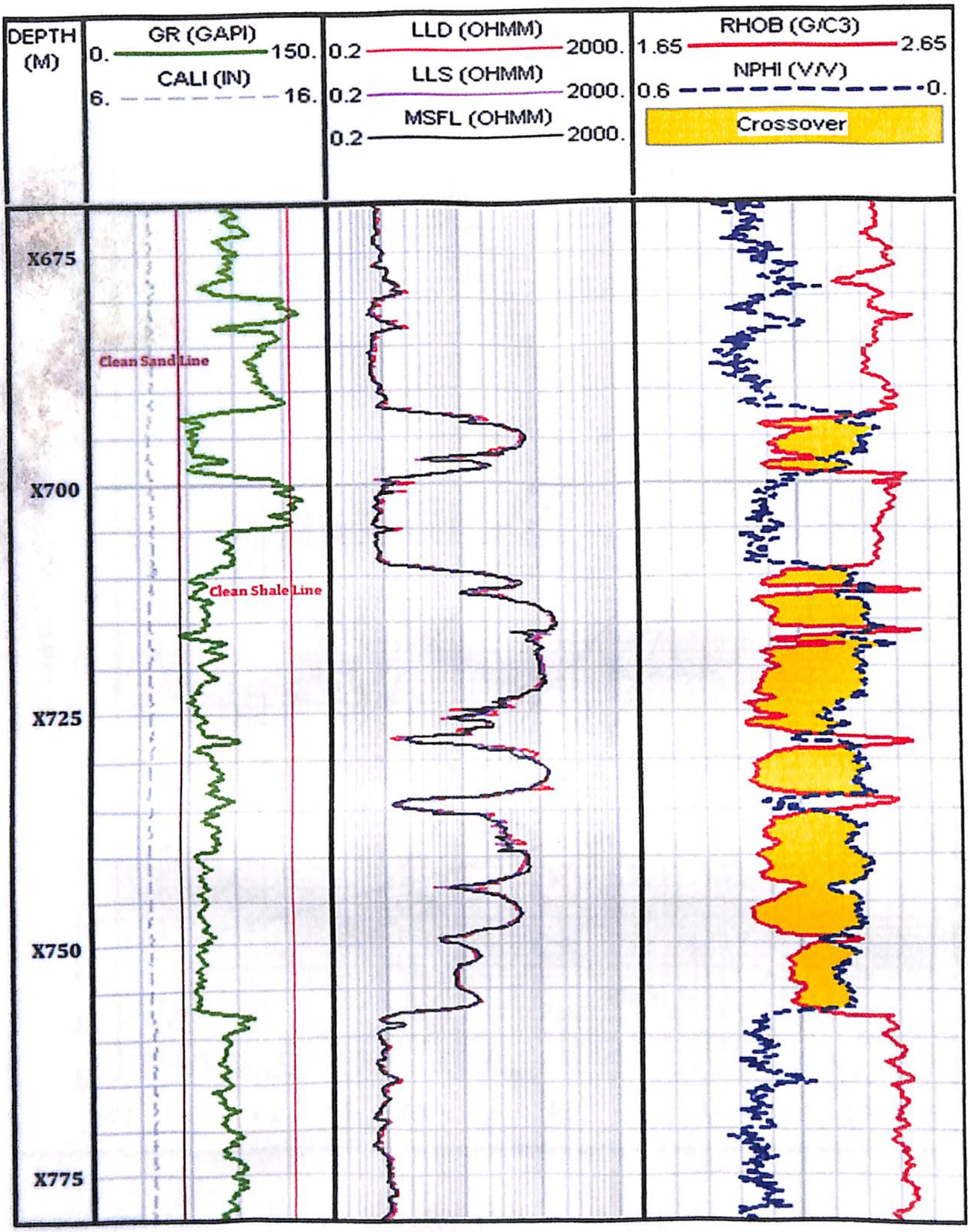

Figure 4.1 The GR, resistivity, density (RHOB) and neutron (NPHI) data for identification of reservoir zones at well A.

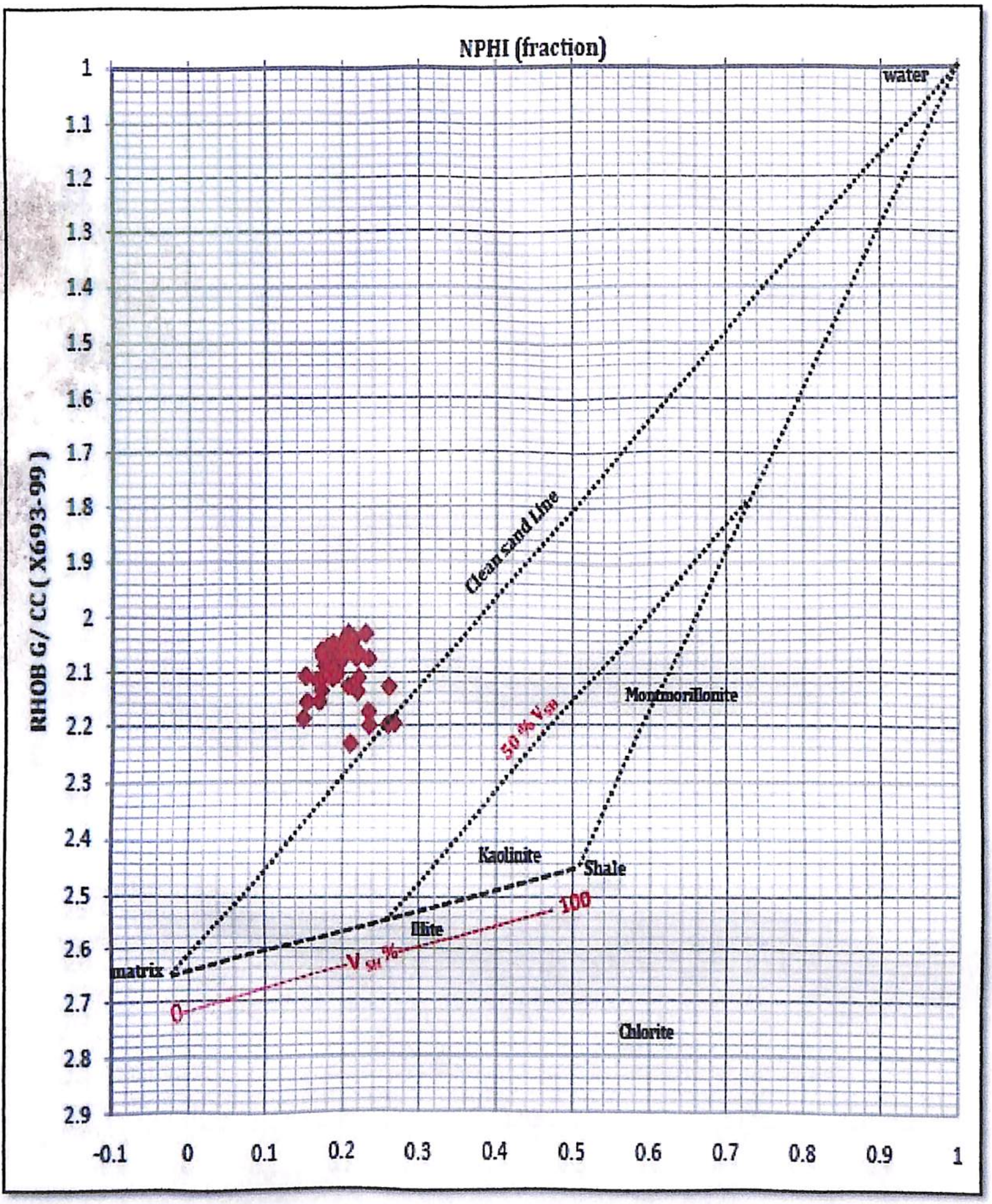

Figure 4.2 Neutron-density crossplot for the Reservoir Zone No. 1 (X693-99m) is showing clean gas sand.

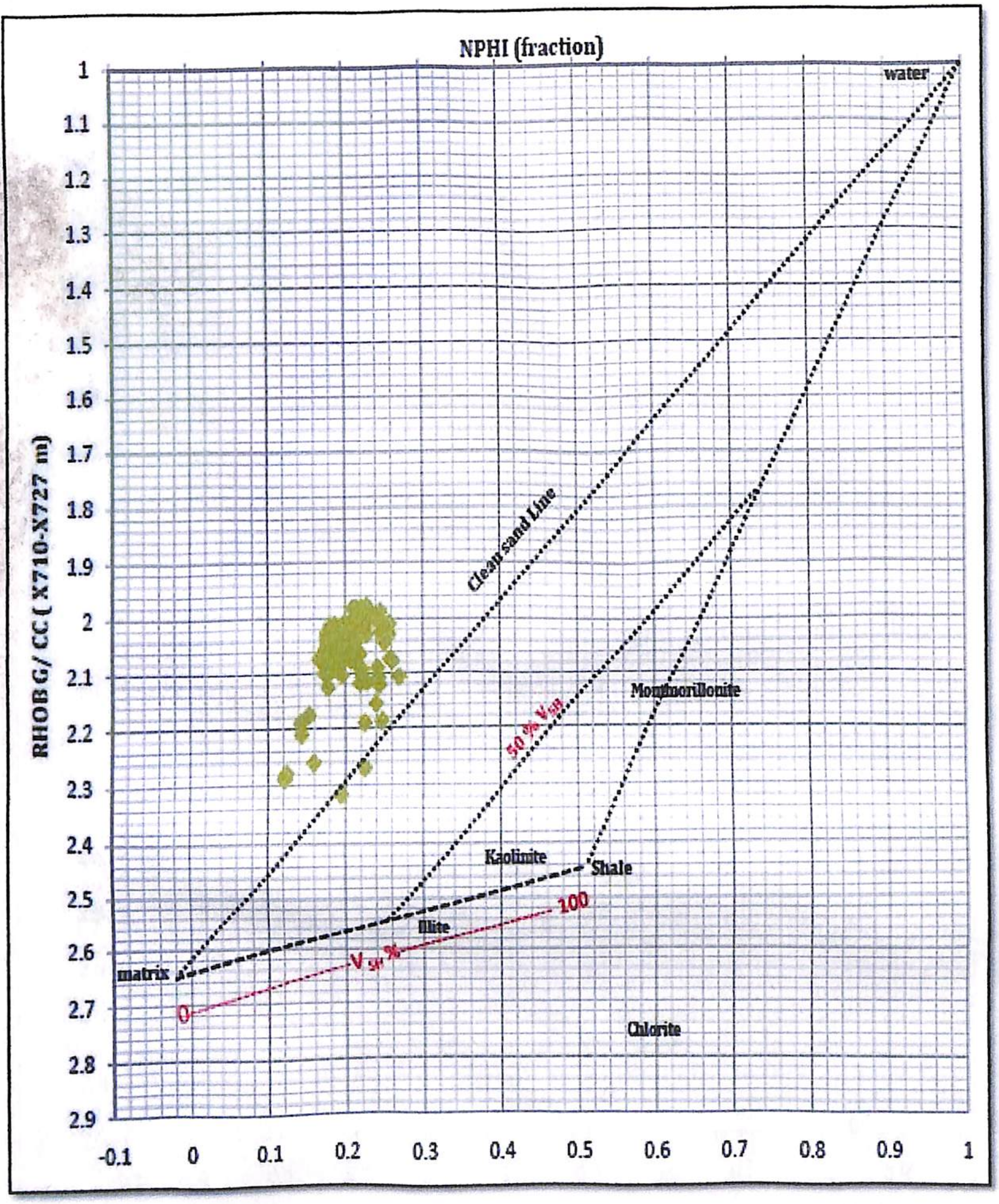

Figure 4.3 Neutron-density crossplot for the Reservoir Zone No.2 (X710-27m) is showing clean gas sand.

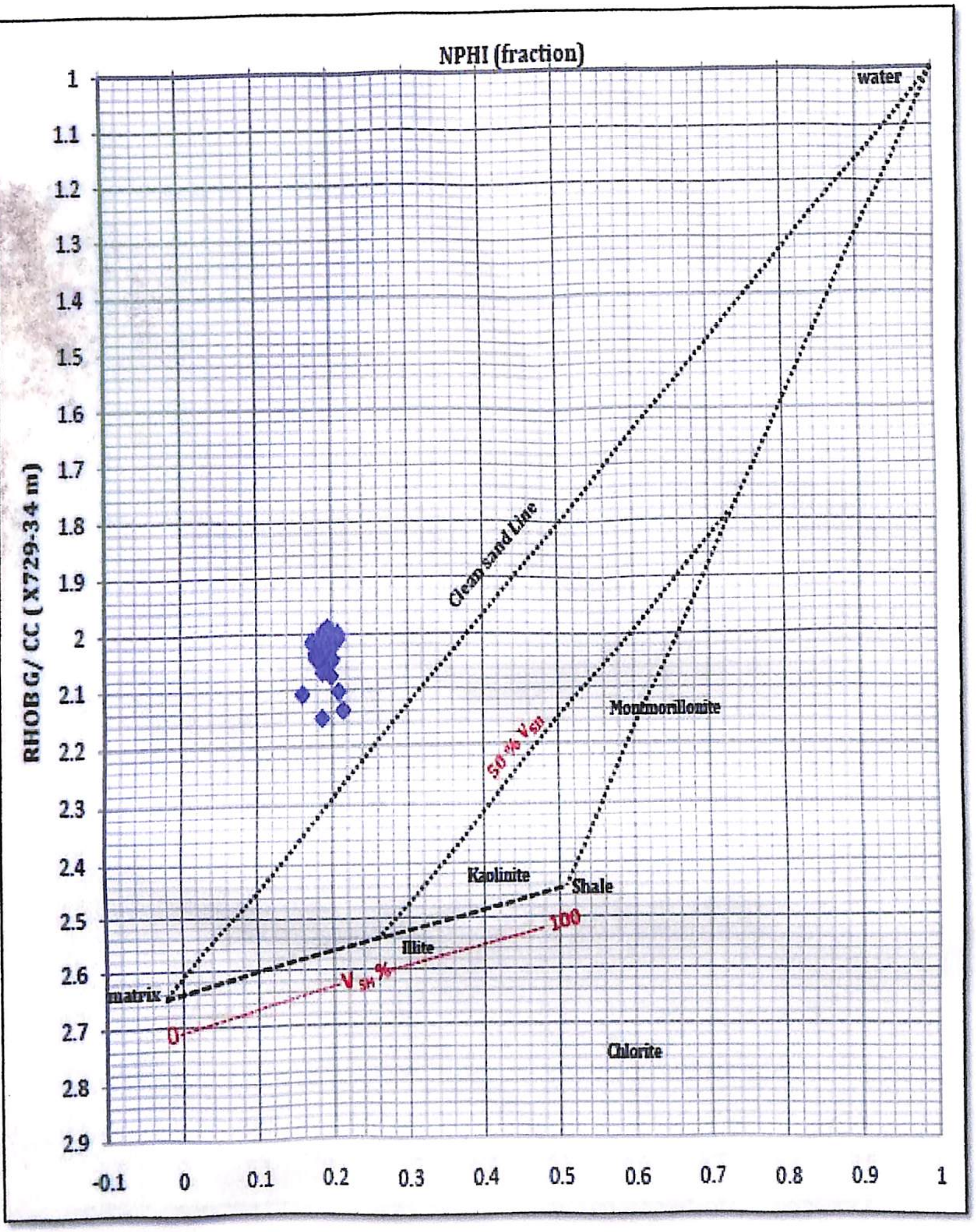

Figure 4.4 Neutron-density cross-plot for the Reservoir Zone No.3 (X729-34m) is showing clean gas sand.

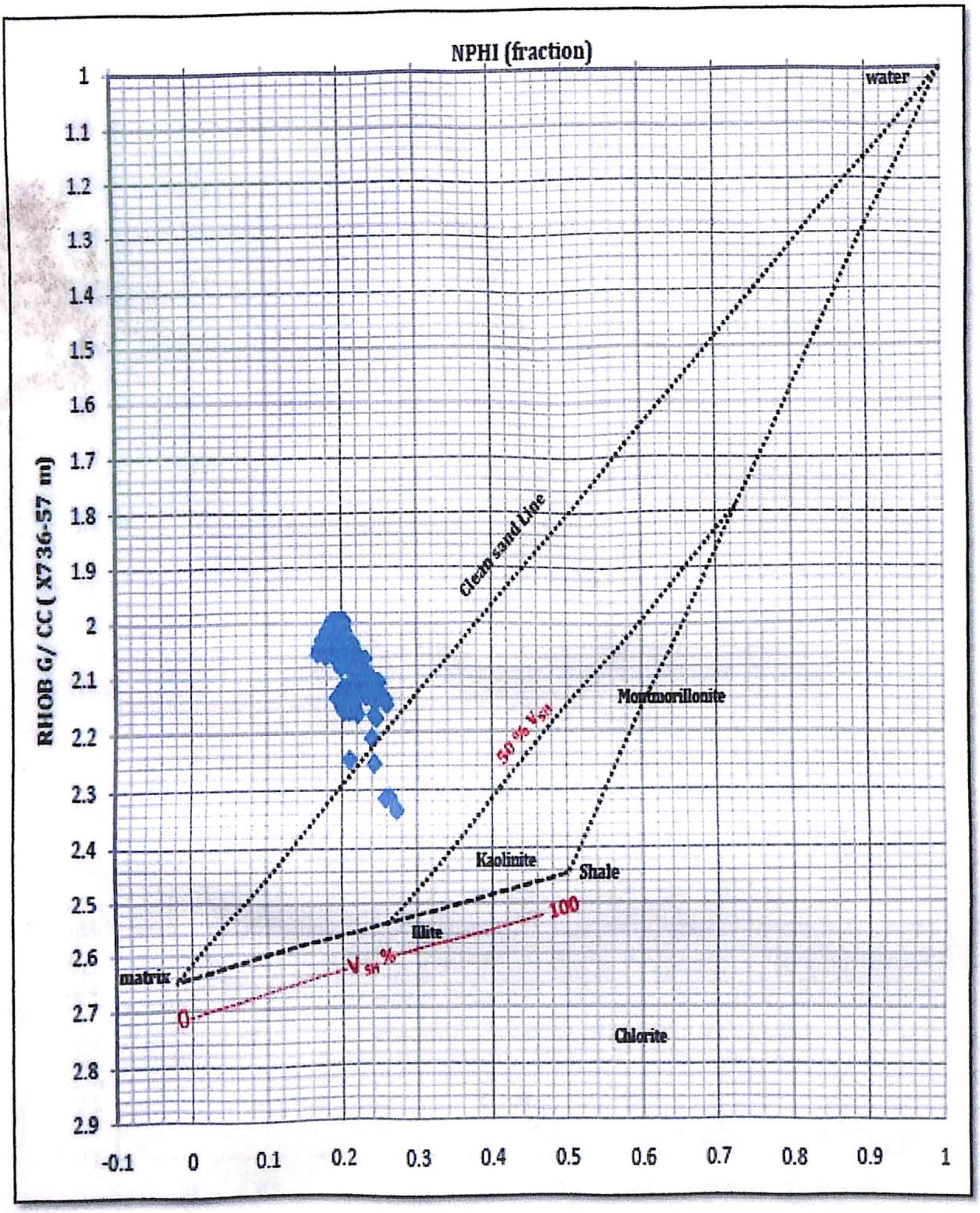

Figure 4.5 Neutron-density cross-plot for the Reservoir Zone No.4 (X736-57m) is showing clean gas sand.

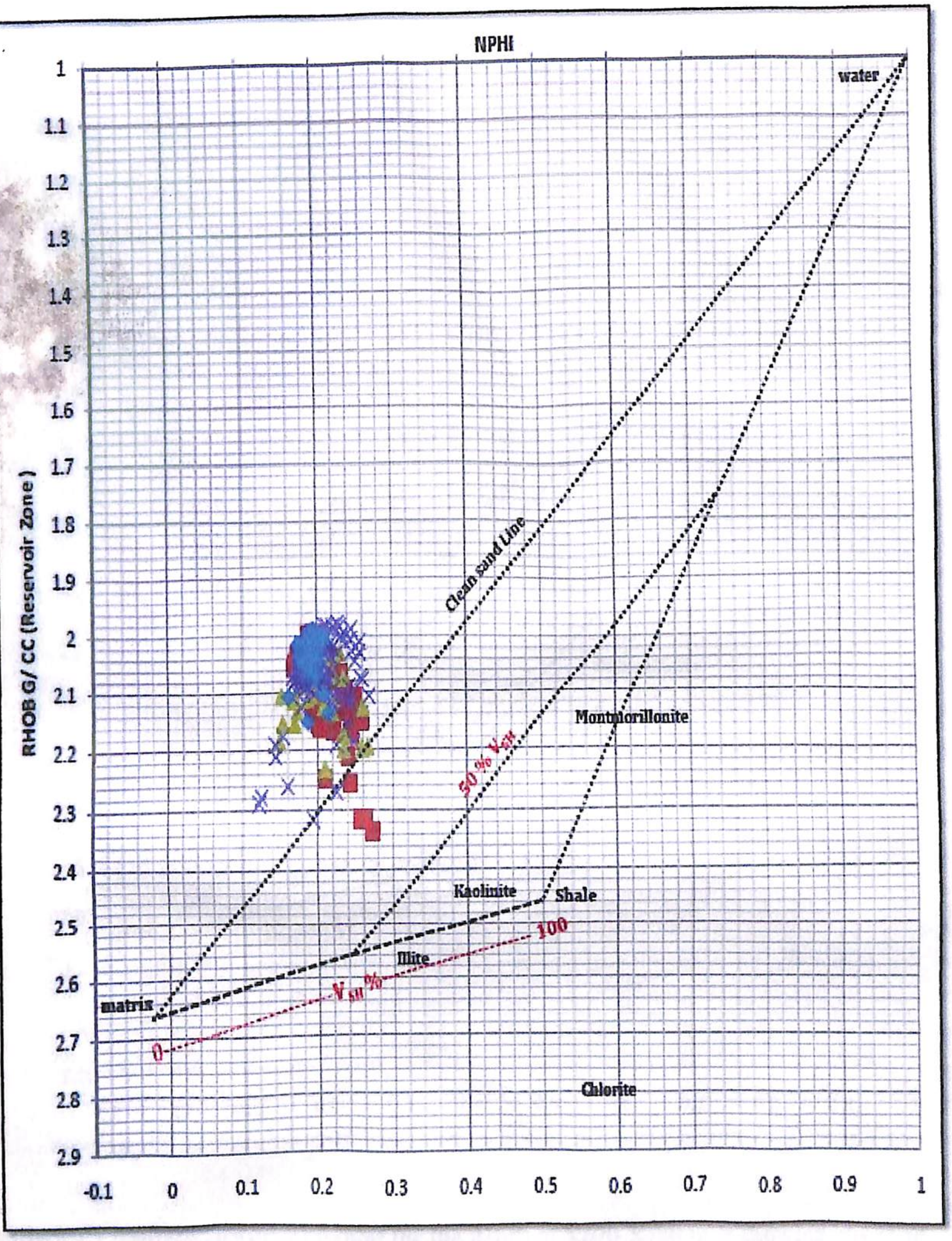

Figure 4.6 Neutron-density crossplot for the all 4 Reservoir Zone is showing clean gas sand and few shale points.

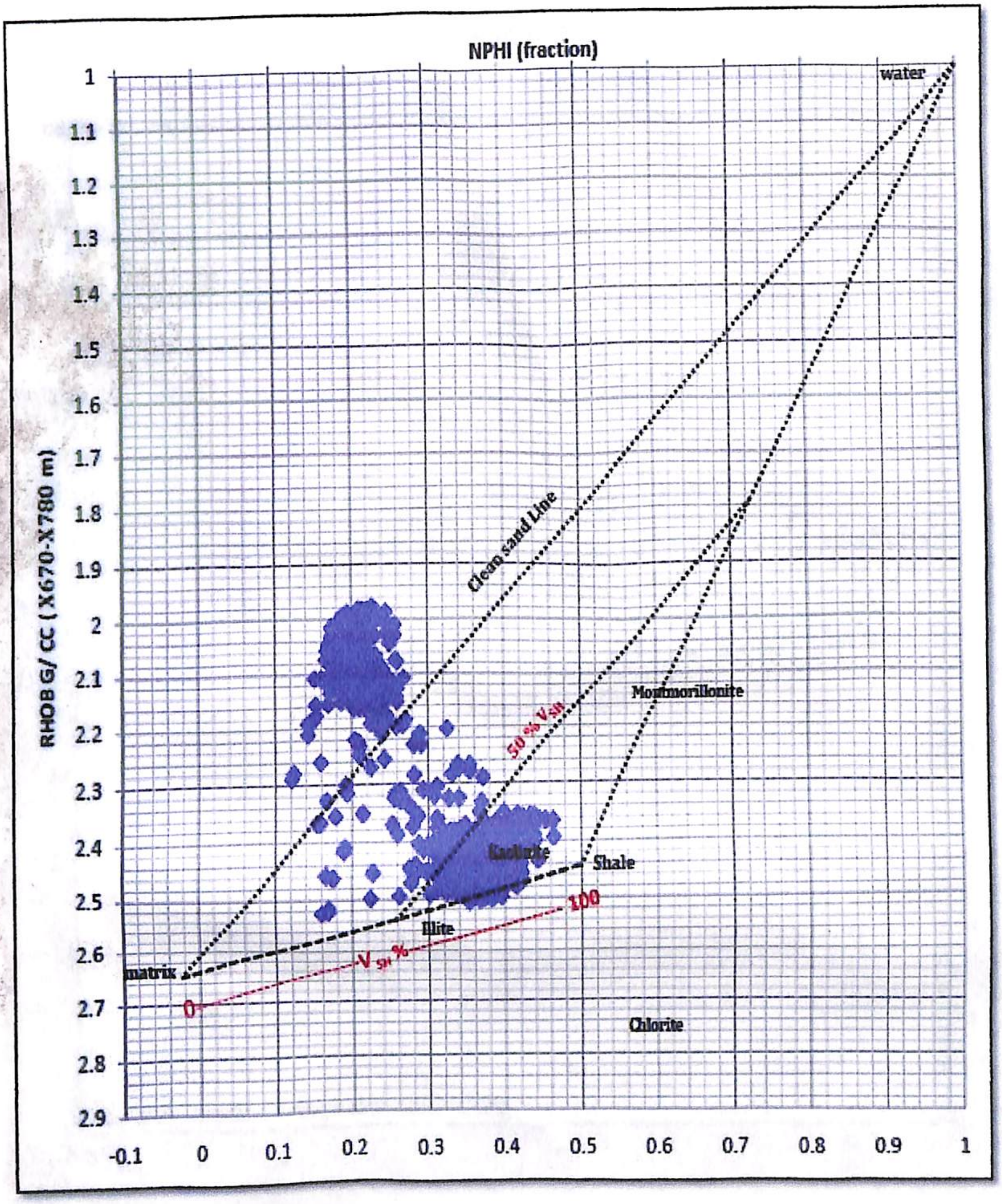

Figure 4.7 Neutron-density crossplot for the depth of X670-X780 m is showing gas sand and shale points.

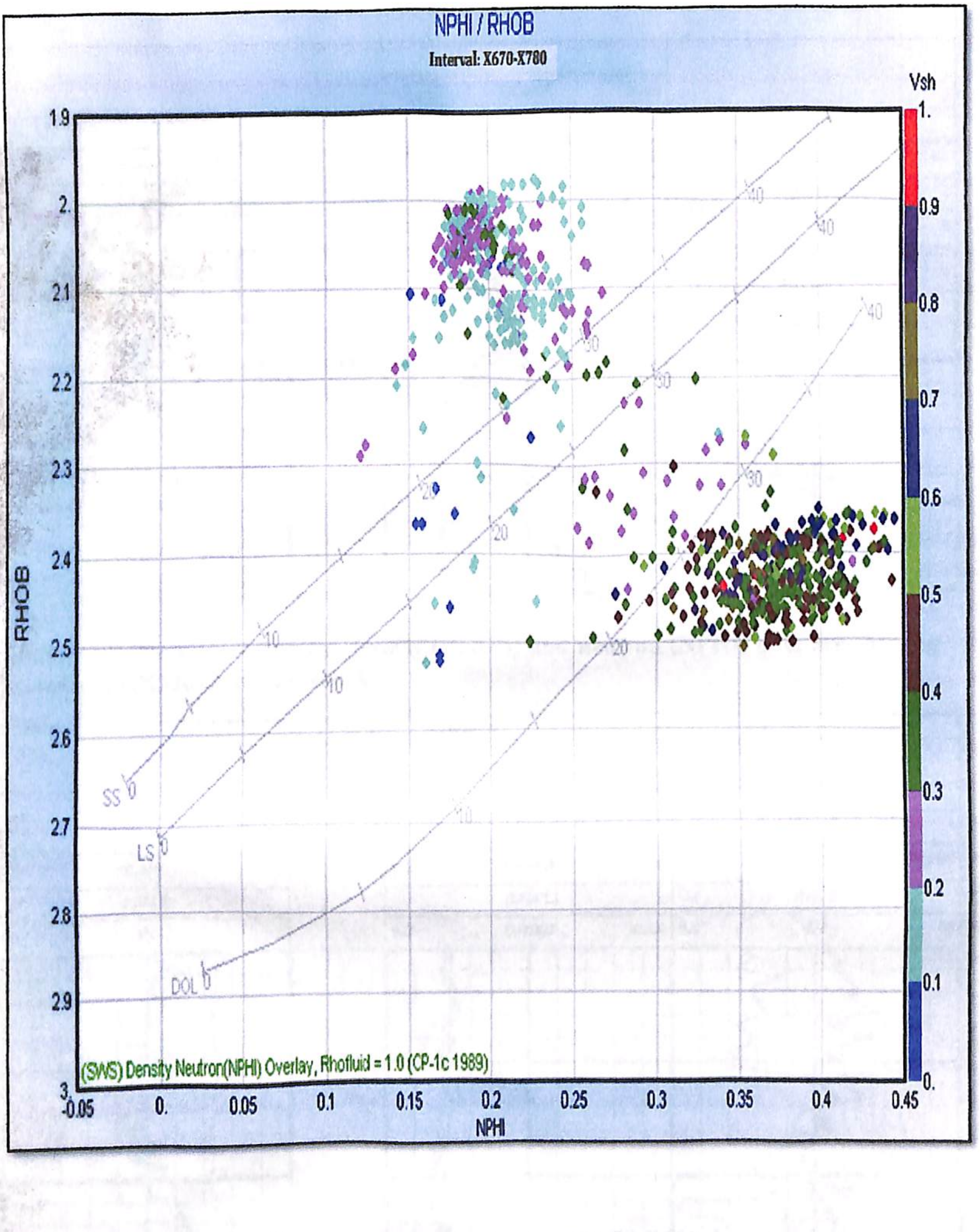

Figure 4.8 Neutron-density crossplot for the depth of X670-X780 m is showing gas sand and shale points.

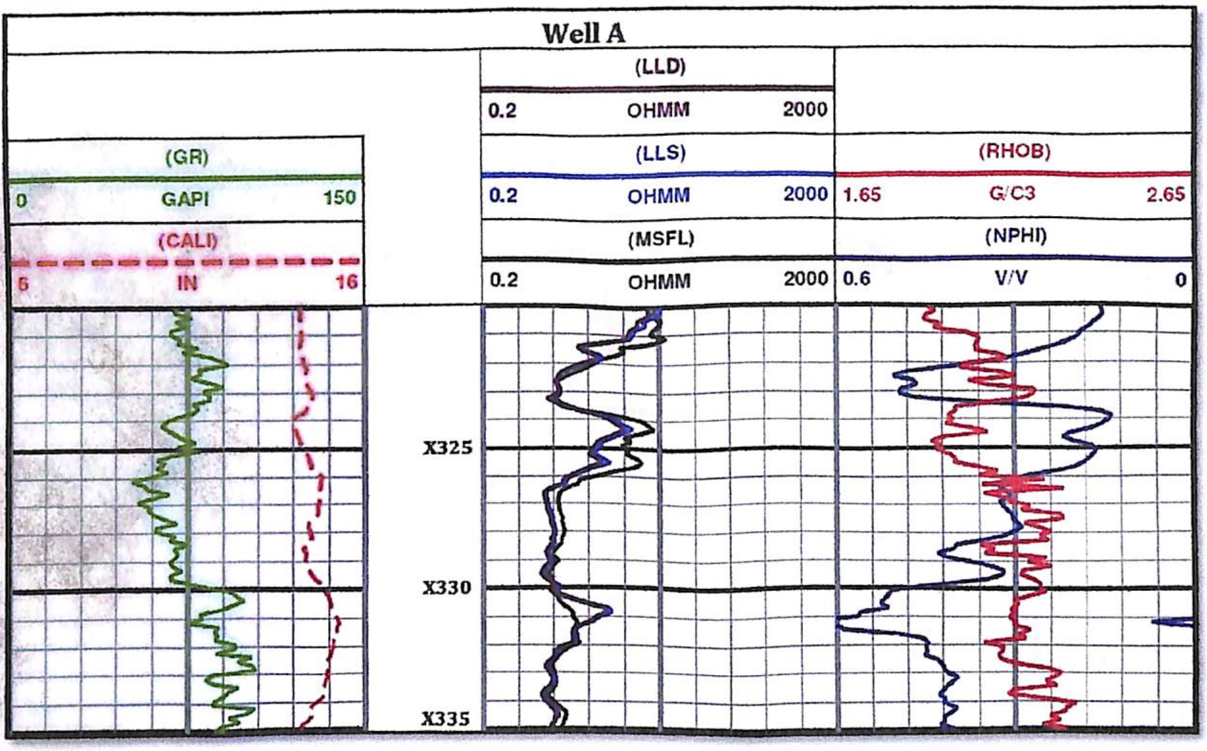

Figure 4.9 The GR, resistivity, density (RHOB) and neutron (NPHI) data are showing water zone (X326-30m) at well A.

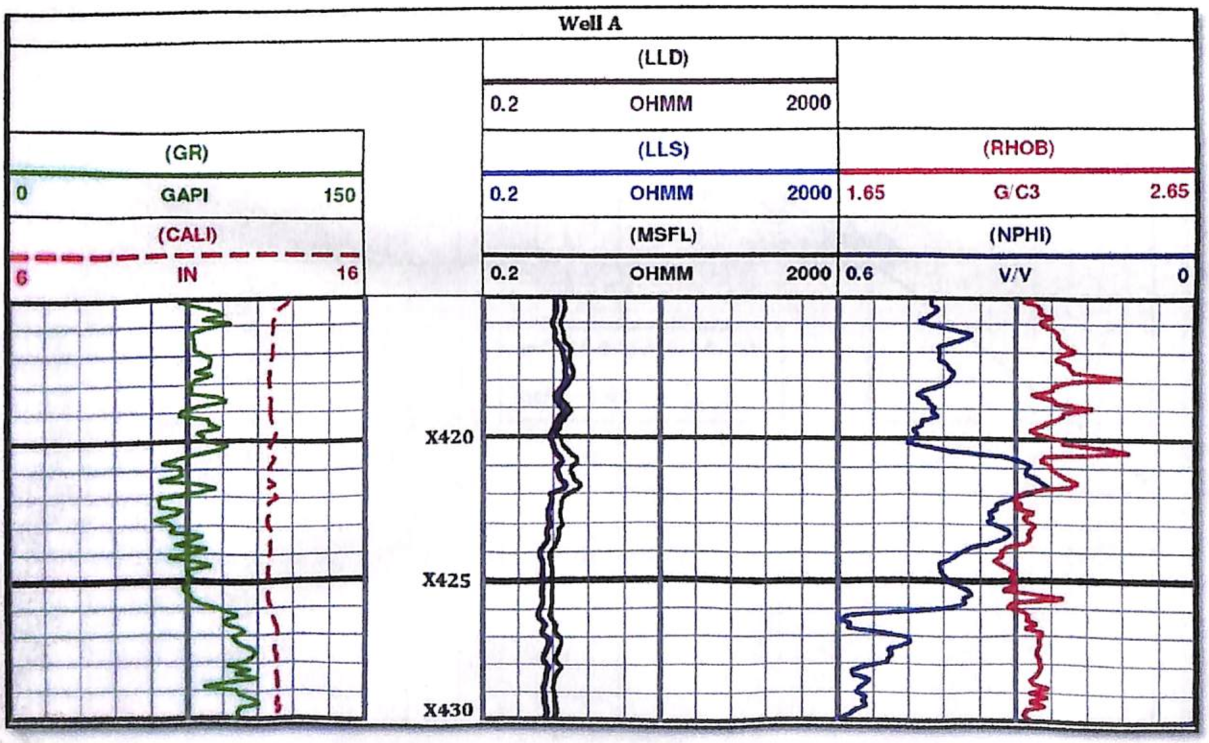

Figure 4.10 The GR, resistivity, density (RHOB) and neutron (NPHI) data are showing water zone (X420-26m) at well A.

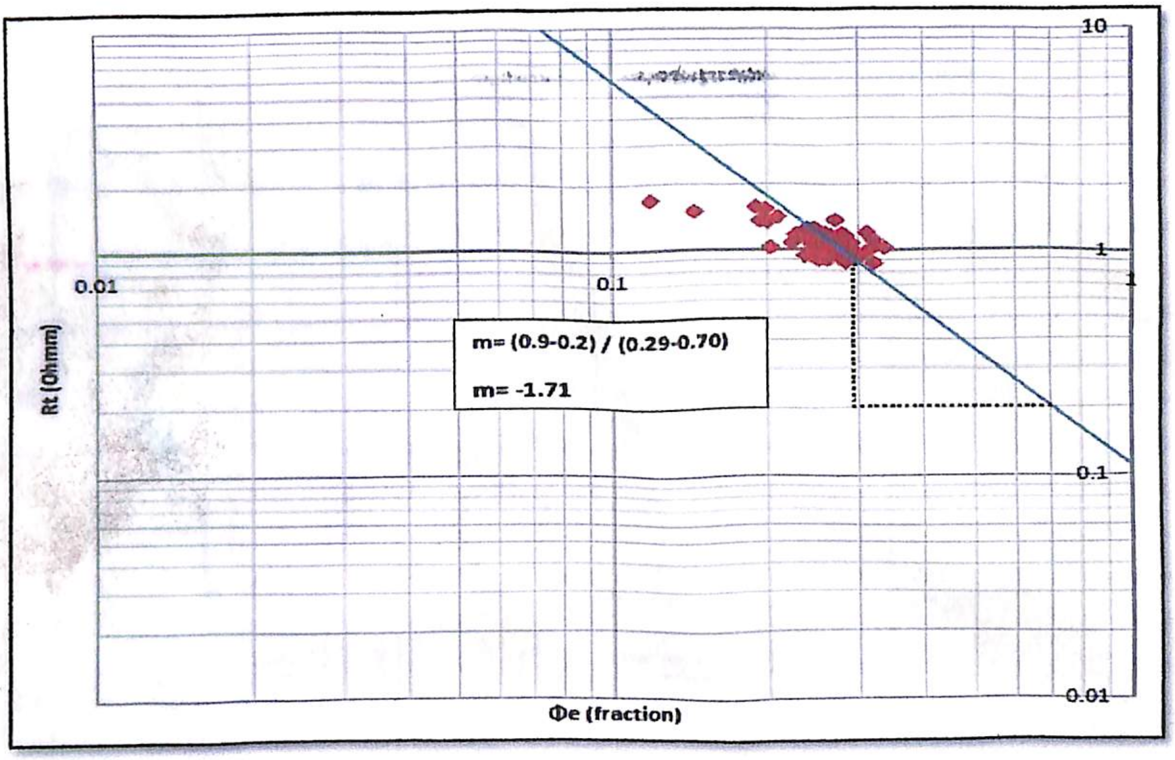

Figure 4.11 Determination of water resistivity, Rw and Cementation exponent, m for water zone (X326-30, X420-26m) by Pickett plot.

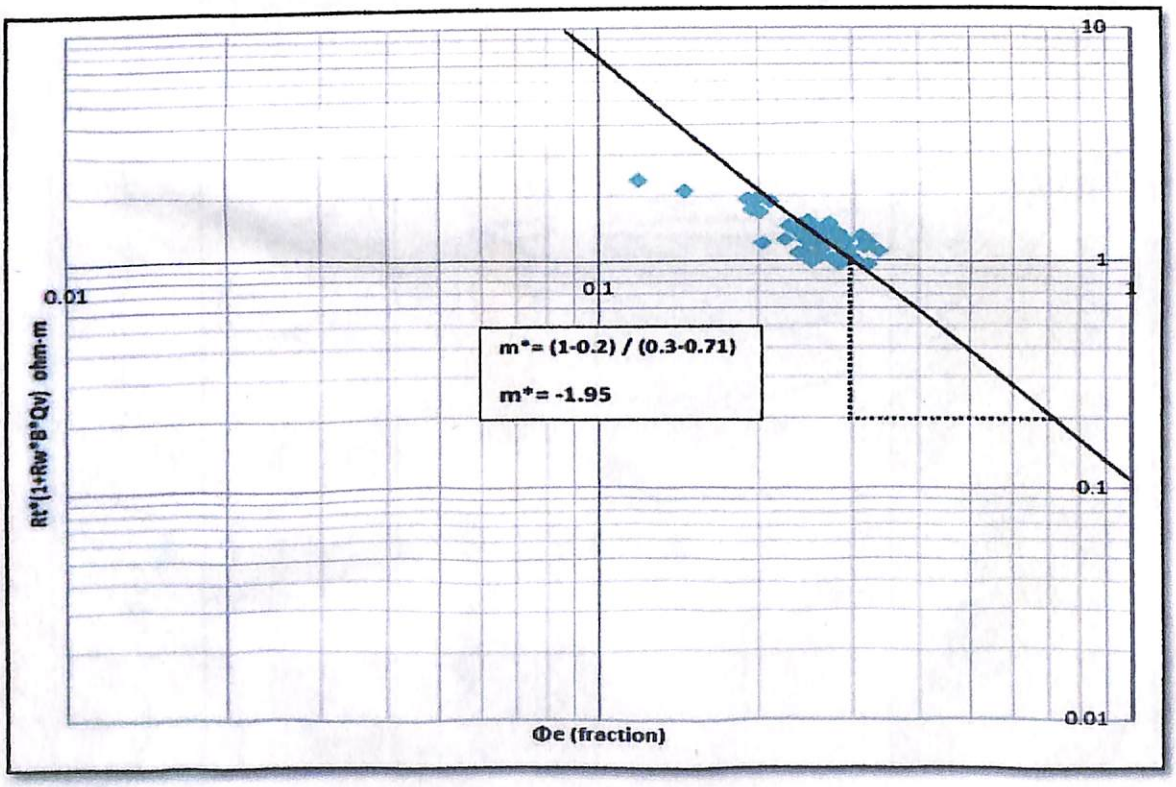

Figure 4.12 Determination of Waxman-Smits Cementation exponent, m* for water zone (X326-30, X420-26m) by Pickett plot.

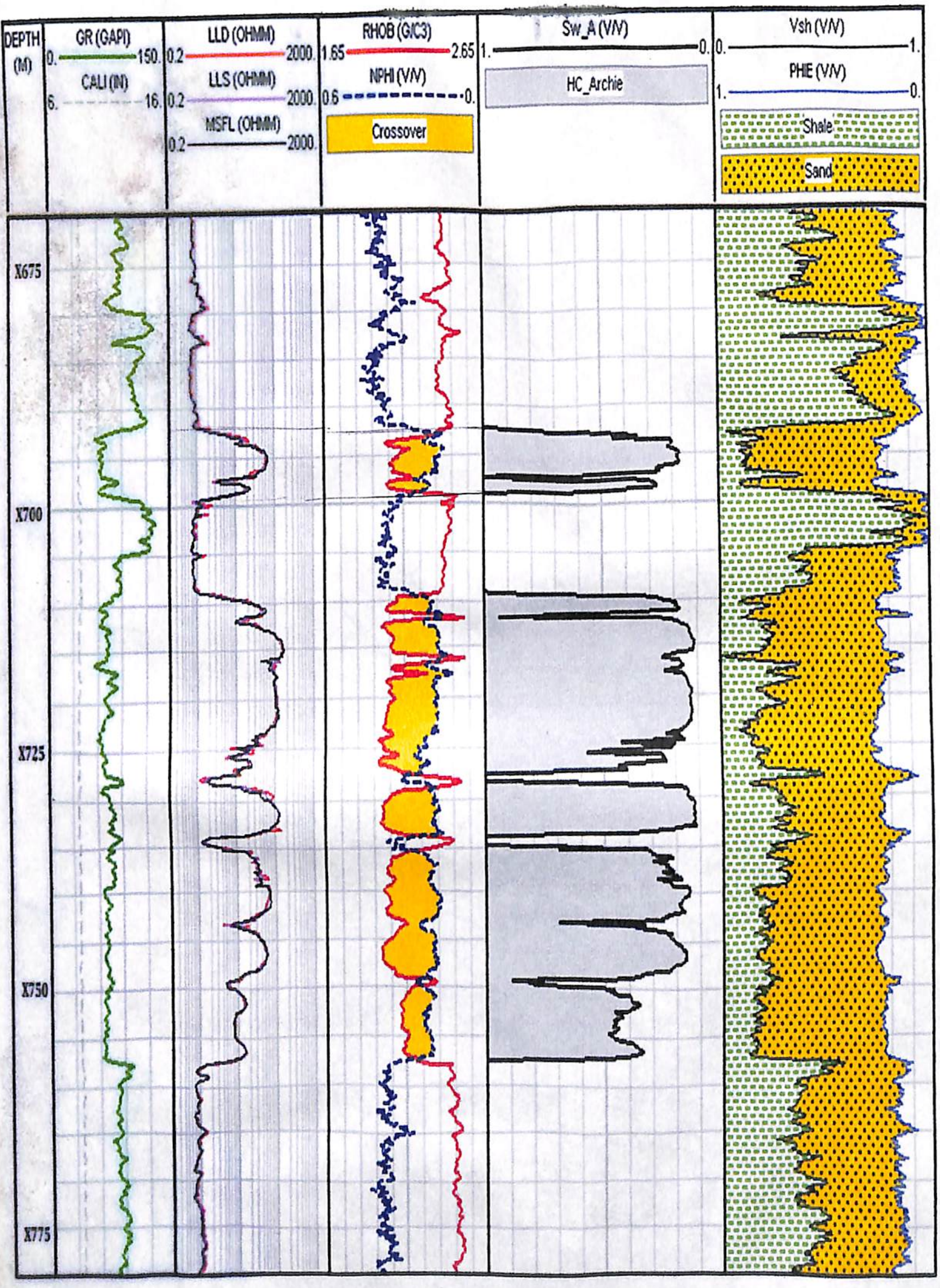

Figure 5.1 The GR, resistivity, density (RHOB) and neutron (NPHI) data with calculated Archie water saturation for reservoir zones at well A.

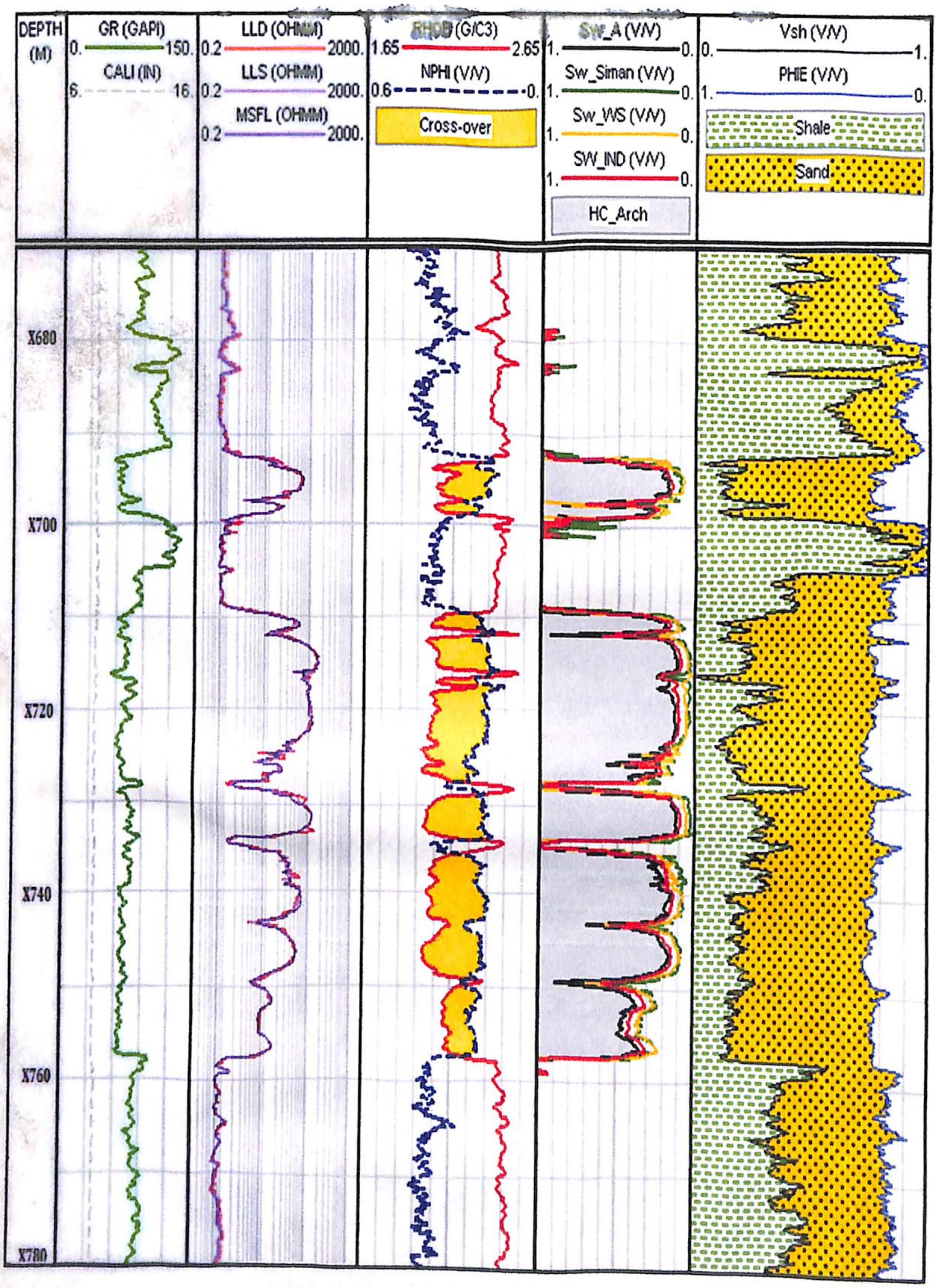

Figure 5.2 The GR, resistivity, density (RHOB) and neutron (NPHI) data with calculated different approaches of water saturation for reservoir zones at well A.

(A) 2/20/5