

Quantitative interpretation of carbonate reservoir rock using wireline logs: a case study from Central Luconia, offshore Sarawak, Malaysia

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Accepted: 21 May 2017 / Published online: 29 June 2017
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Abstract The current study focuses on the quantitative evaluation of petrophysical parameters of selected wells using wireline log data in Central Luconia, offshore Sarawak. Based on the relatively high resistivity and, low-neutron/-density log responses, three major zones are identified. These include gas-bearing zones (Zone-1 and Zone-3) and mixed zone (Zone-2). The gamma ray, neutron and density logs confirmed that Well A was composed of carbonate rocks ranging from limestone to dolomite. Zone-1 and Zone-3 consist of limestone, whereas Zone-2 contains dolomite. The average porosity of these zones (Zone-1, Zone-2 and Zone-3) are 15.7, 4.3 and 13.7%, whereas gas saturation is 83, 41 and 93%, respectively. The

permeability values are 543 mD (Zone-1), 47.7 mD (Zone-2) and 601.5 mD (Zone-3). The water saturation value in Zone-2 is very high, up to 66% compared to Zone-1 and Zone-3 which are 17 and 7%, respectively. It is pertinent to mention that Zone-1 and Zone-3 contain movable gas (i.e., HC movability index is less than 0.7). Furthermore, bulk volume water values in three zones (0.012, 0.0083 and 0.009) indicate the presence of irreducible water. In contrast, pore-filled dolomite cement is mostly from Zone-2, indicating high water, low gas saturation, low porosity and less movability index values, which indicate the presence of high microporosity. Additionally, bulk volume water suggests that these micropores are saturated with irreducible water. High microporosity affects the wireline log response in Zone-2 and therefore provides misleading information.

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Keywords Miocene carbonates · Central Luconia · Petrophysical properties · Reservoir potential

List of symbols

I_{GR}	Index gamma ray
P_b	Formation bulk density
Φ_{ND}	Neutron–density porosity
S_w	Water saturation
R_w	Resistivity of formation water
R_{xo}	Shallow resistivity
a	Tortuosity factor
V_{Shale}	Volume of shale
P_{ft}	Fluid density
$\Phi_{Ncorrected}$	Corrected neutron porosity
S_{xo}	Water saturation of flushed zone
R_t	True formation resistivity
BVW	Bulk volume water
m	Cementation exponent

P_{ma}	Apparent matrix density
Φ_D	Density porosity
$\Phi_{Dcorrected}$	Corrected density porosity
S_h	Hydrocarbon saturation
R_{mf}	Resistivity of mud filtrate
K	Permeability
n	Saturation exponent

Introduction

Petrophysical studies help to define the physical parameters of reservoirs such as porosity, permeability, water saturation, hydrocarbon saturation, lithology identification and hydrocarbon movability (Tiab and Donaldson 2015). In this study, petrophysical interpretation of wireline logs is used in deciphering lithology identification, porosity distribution, permeability, water saturation, hydrocarbon saturation, hydrocarbon movability and bulk volume of water.

A suit of logs including gamma ray (GR), spontaneous potential (SP), resistivity (MSFL, LLM, LLD), neutron and density logs are incorporated to define the physical characteristics of reservoirs such as porosity, permeability, water and hydrocarbon saturation and hydrocarbon movability (Lee and Collett 2009; Tiab and Donaldson 2015). Such techniques are essential for the estimation of hydrocarbon reserves.

The assessment of gas resources in Miocene carbonate reservoir Central Luconia, offshore Sarawak, Malaysia, is a critical component to quantify the potential gas. The quantitative estimation of petrophysical properties contributes in predicting reservoir quality and formation evaluation processes. The major goal of this study is to investigate the use of wireline log data to characterize the reservoir behavior and estimate the petrophysical parameters of hydrocarbon-bearing zones of Well A, Central Luconia, offshore, Sarawak, Malaysia. Specific objectives of this paper are to (1) identify the reservoir characteristics using wireline log data of Well A; (2) identify the saturation zones; (3) and analyze the petrophysical parameters of gas-bearing zones.

Geological settings

In the Sarawak basin, carbonate buildups were deposited in the Central Luconia, offshore northwest Borneo (Fig. 1) during the Miocene to Holocene period (Koša 2015). The Sarawak basin can be divided into a basement high and basal area based on the current basement topography (Mat-Zin and Swarbrick 1997).

Central Luconia province is an area of rifted continental block in which 12 km of tertiary siliciclastic and carbonate

sediments are deposited (Doust 1981; Madon 1999). The Central Luconia foreland basin most likely originated as a result of the collision of the Luconia block with the West Borneo Basement (Madon et al. 2013). The prolific growth of mega carbonate platforms and the lack of tectonic activity show that the Central Luconia carbonate growth was governed mainly by eustatic sea level fluctuation (Vahrenkamp 1998).

Initially, the general understanding of the lithostratigraphy of rock successions onshore Sarawak remained unchanged as it was originally outlined by Liechti et al. (1960). However, limitations arose when correlating onshore successions to subsurface sedimentary successions offshore. Many Tertiary formations were then described using biostratigraphy methods and wireline log data from drilled wells. Ho (1978) introduced a genetic sedimentary cycle concept to subdivide the Upper Eocene to Pleistocene sedimentary sequence into eight sedimentary cycles that have been recognized within the entire Tertiary sedimentary succession of offshore Sarawak. The cycles are described as follows: Cycle I and II (Upper Eocene to Lower Miocene age) was interpreted as channel sands, overbank clays and coal deposited. Cycle III (Lower-Middle Miocene age) contains shale with thin limestone and sandstone, Cycle IV (Middle Miocene age) is composed of limestone with minor quantity of mixed clastics, Cycle V (middle to upper Miocene) is recognized as limestone, Cycle VI to Cycle VIII (Upper Miocene to Pleistocene age) is composed of open marine to coastal clays and sand, respectively. The prograding sediments of Cycle VI to Cycle VIII have stifled the extensive carbonate buildups progressively until the present day. In Central Luconia, carbonate deposition began in the early Miocene (Cycle III) and grew extensively in Cycles IV and V, during the middle to late Miocene (Vahrenkamp et al. 2004; Fyhn et al. 2013).

In Central Luconia, most of the sediments are dominated by prograding clinoforms. These cycles started from transgressive basal part followed by a regressive unit which in turn is overlain by the basal transgressive unit of the next cycle (Doust 1981; Hageman 1987; Mat-Zin and Swarbrick 1997; Mat-Zin and Tucker 1999). During Cycle I, deep-water argillaceous and shallow marine siliciclastic successions were deposited in an early synrift graben-filling sedimentation process (Fig. 2). This was followed by a late phase of synrift sedimentation through Cycles II and III during the opening of the South China Sea. Continuous subsidence and formation of half-grabens resulted in widespread Middle to Upper Miocene carbonate deposition during Cycles IV and V (Fig. 2).

This was eventually stopped by the influx of siliciclastic sediments derived from the uplifted Rajang Fold-thrust Belt during Cycle V and VIII (Madon 1999). According to Epting (1980), all four of these events occurred in a

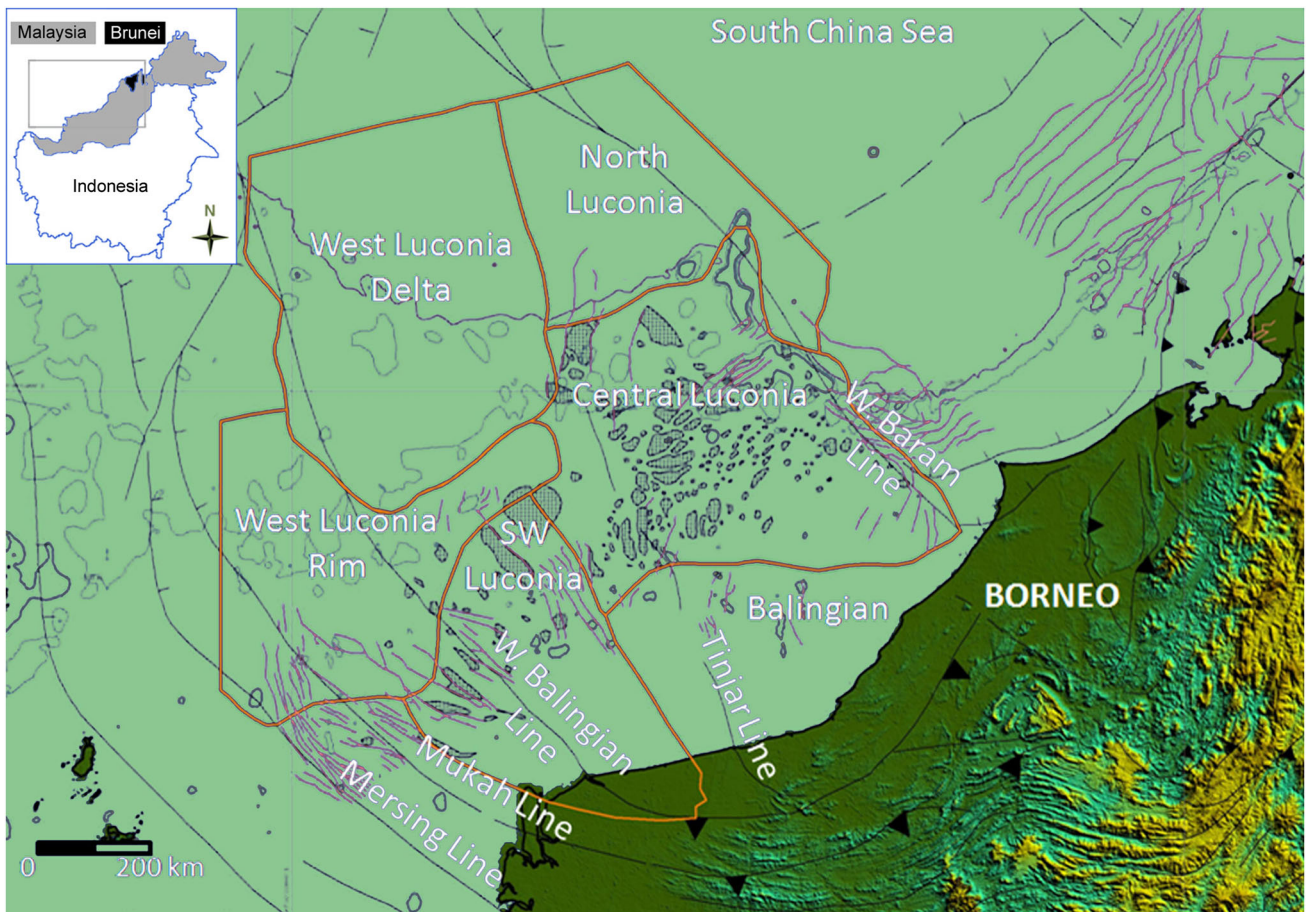
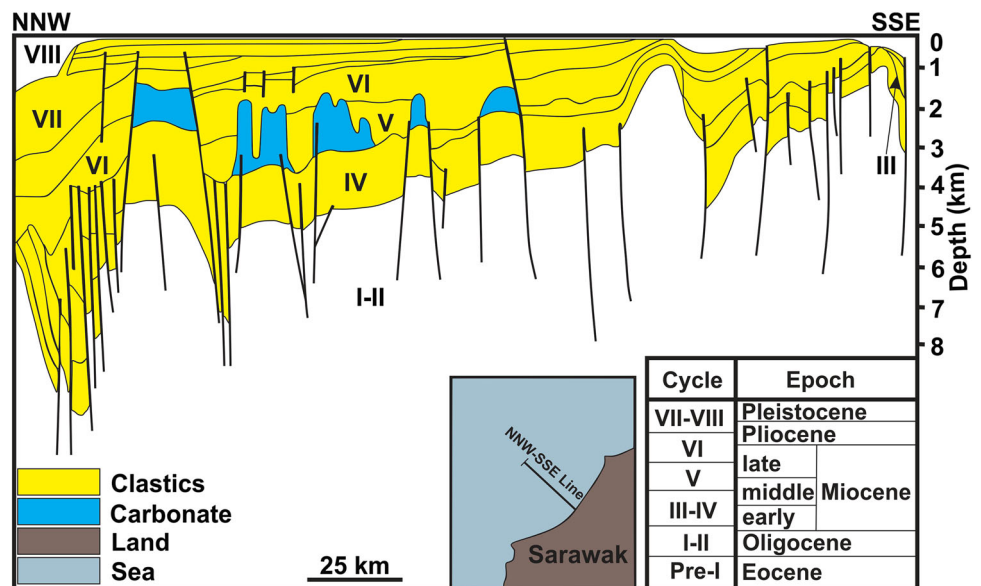


Fig. 1 Location map of Central Luconia Carbonate Platform offshore Sarawak, Malaysia (Janjuhah et al. 2017b)

Fig. 2 A schematic cross section along the NNW–SSE direction across the continental shelf of offshore Northwest Sarawak; modified from (Janjuhah et al. 2017b)



specific pattern in space and time in the Miocene carbonate platforms of Central Luconia. In general, carbonate build-ups became thinner (<500 m) toward the southern side,

and on the northern side they became thicker, up to 3000 m (Doust 1981; Epting 1989; Vahrenkamp et al. 2004; van Vliet and Krebs 2009).

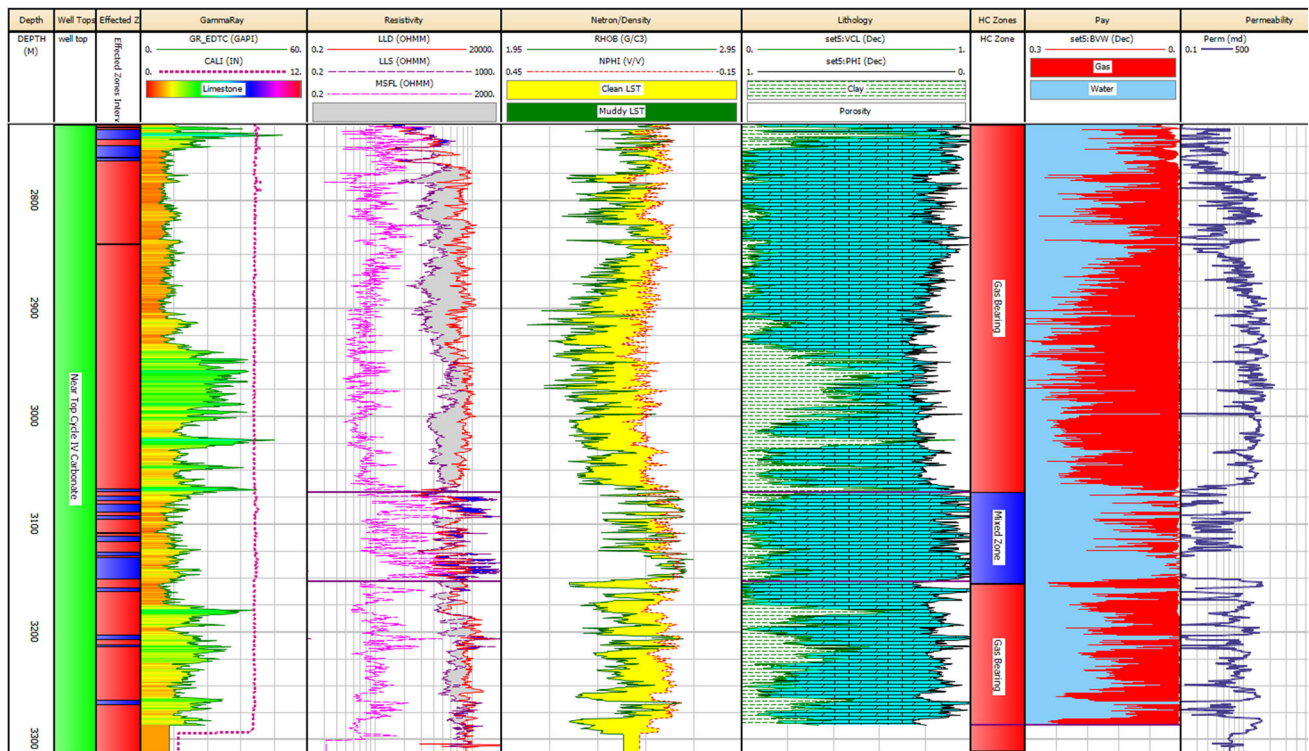


Fig. 3 Composite logs of Well A, Miocene age, Central Luconia, offshore, Sarawak, Malaysia

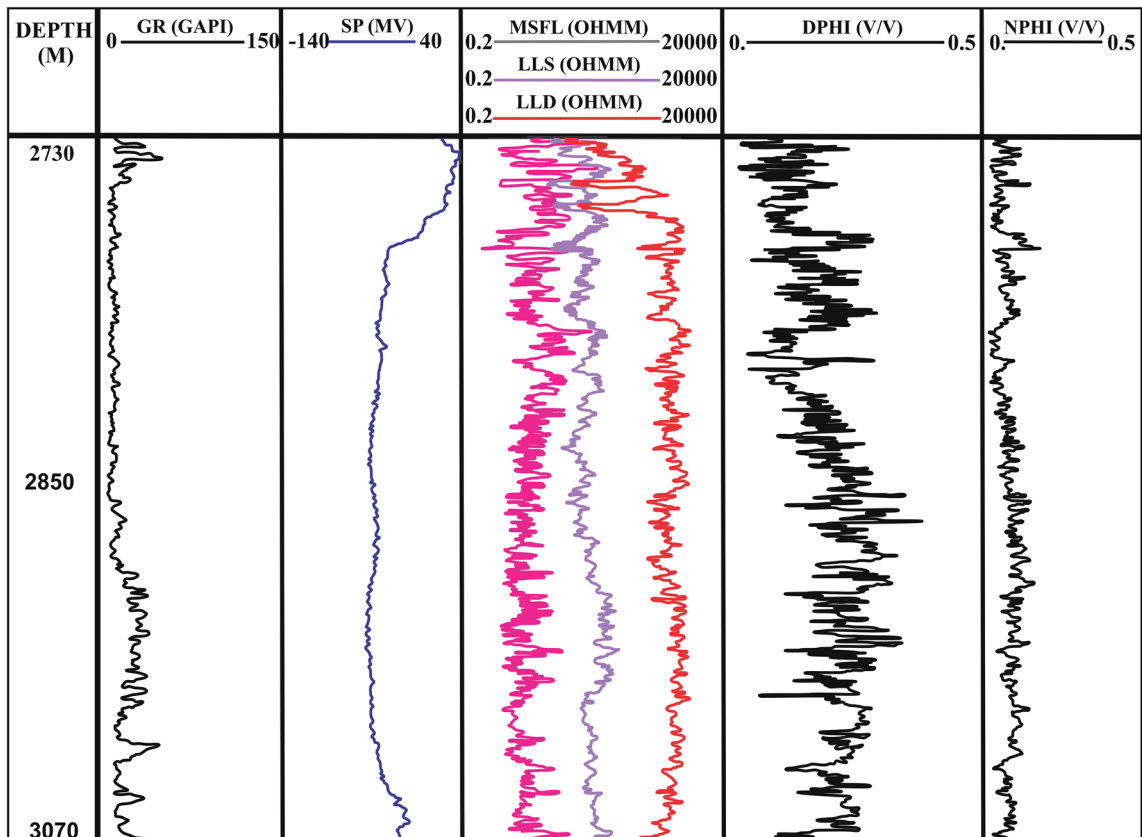
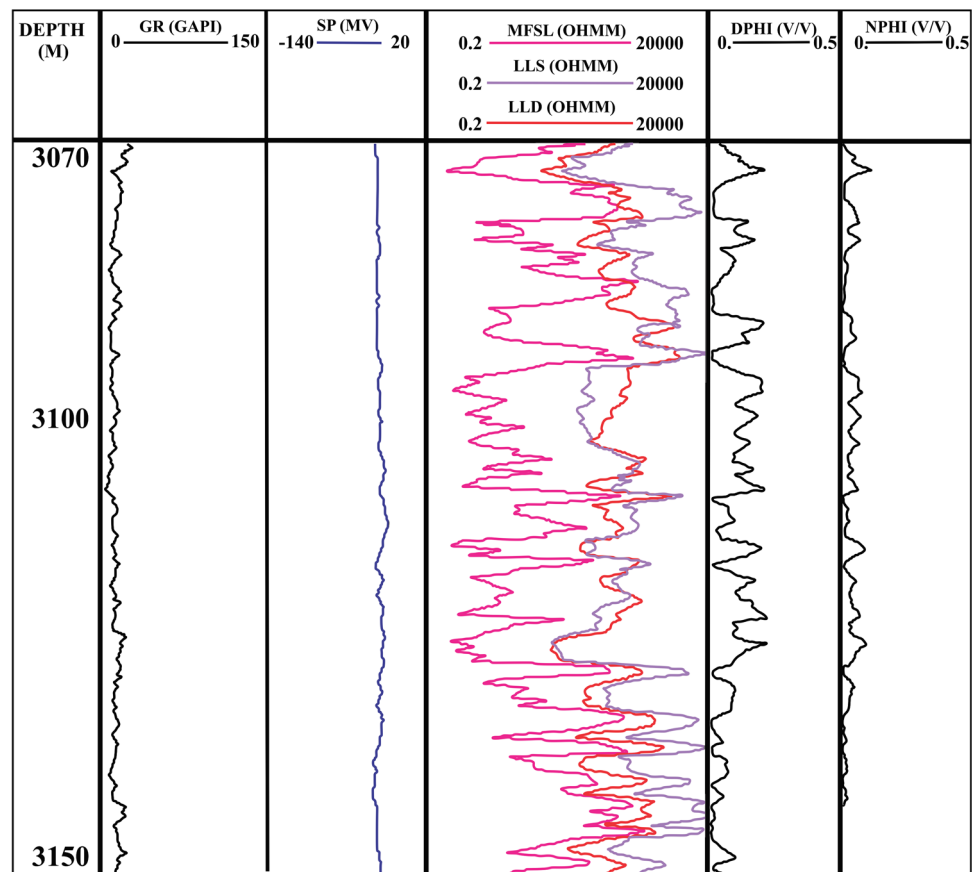


Fig. 4 Composite log responses of the gas-bearing Zone-1 (2730–3070 m) of Well A in Central Luconia, offshore Sarawak, Malaysia

Fig. 5 Composite log responses of the mixed bearing Zone-2 (3070–3150 m) of Well A in Central Luconia, offshore Sarawak, Malaysia



Janjuhah et al. (2017a, b) recently provided a detailed sedimentological description of carbonate reservoir rocks from Central Luconia based on two reference wells. According to the core and petrographic study, Central Luconia carbonates are composed of 80% of limestone with 20% of dolomitic limestone. The dominant pore types are moldic, vuggy and with intraparticle porosity. He mentioned that the Central Luconia experienced different diagenetic processes and the presence of dominant moldic porosity is the best example of dissolution.

Methods

The wireline log data of Well A from Central Luconia, offshore Sarawak, Malaysia, was used to evaluate and summarize the petrophysical parameters of the studied area. Several wireline logs including resistivity log (ILD, ILM, and MSFL), density log, neutron log, gamma rays log and SP log were used to describe the petrophysical characteristics of Well A. Log analysis is first done using computer software and formulas before pre-establishing the charts and cross plots needed for the petrophysical parameters, such as the lithology, porosity, permeability and water saturation. The Interactive Petrophysics (IP)

software has been used for the determination of clay volume and effective porosity.

Furthermore, the log responses are calculated from the hard copy and compared with computer-generated data before finalizing the actual results. The procedure for calculating the petrophysical parameters are as follows.

Gamma ray log is a good source of predicting volume of shale in reservoirs. Gamma ray index (I_{GR}) calculation is the first step to determine V_{Shale} for Tertiary rocks (Atlas 1979; Archie 1942; Ajisafe and Ako 2013):

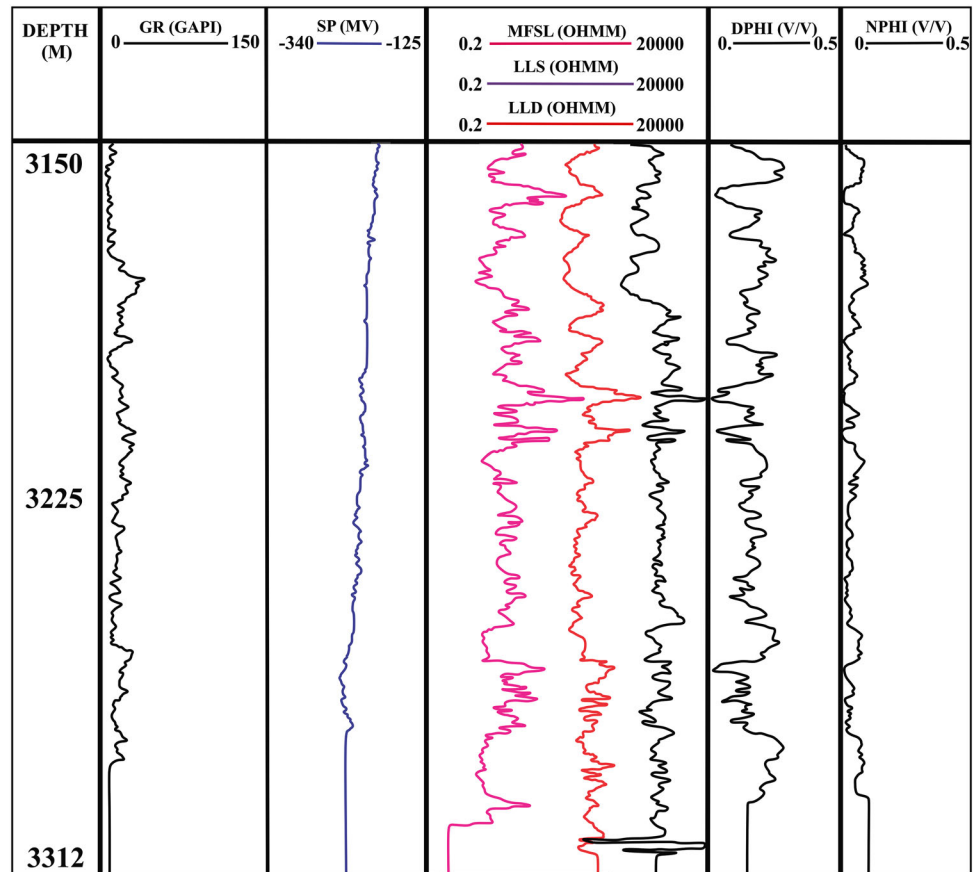
$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

The most commonly used formula in the petroleum industry to calculate the volume of shale is written as (Asquith et al. 2004; Islam and Islam 2014):

$$V_{Shale} = 0.083 (2^{3.7 \times I_{GR}} - 1).$$

Although each log produces porosity values from basic measurements, none of the logs calculate porosity directly except density and neutron logs. After working out the values of V_{Shale} , the next step is to correct the V_{Shale} effect from neutron and density logs before calculating the porosity from the neutron and density logs. According to Atlas (1979) and Xue and Wu (2014),

Fig. 6 Composite log responses of the gas-bearing Zone-3 (3150–3312 m) of Well A in Central Luconia, offshore Sarawak, Malaysia



porosity can be preconceived from neutron and density logs.

The following formula is used to calculate the porosity from neutron and density logs which was proposed by Atlas (1979):

$$\Phi_D = \frac{P_{ma} - P_b}{P_{ma} - P_{ft}} - V_{sh} \frac{P_{ma} - P_{sh}}{P_{ma} - P_{ft}}$$

The following are the formulas used for correcting the neutron and density logs for volume of shale (Bateman and Konen 1978; Islam et al. 2009):

$$\Phi_{Ncorrected} = \Phi_N - \left[\left(\frac{\Phi_{Nclay}}{0.45} \right) \times 0.30 \times V_{Shale} \right],$$

$$\Phi_{Dcorrected} = \Phi_N - \left[\left(\frac{\Phi_{Dclay}}{0.45} \right) \times 0.13 \times V_{Shale} \right].$$

The calculation of porosity values is obtained by using corrected density–neutron logs (Asquith et al. 2004):

$$\Phi_{ND} = \sqrt{\frac{\Phi_{Ncorrected}^2 + \Phi_{Dcorrected}^2}{2}}$$

Mineral identification is often useful to know the grain size and to predict their cementation. The mineral

identification is calculated by the following formula (Asquith et al. 2004):

$$P_{maa} = \frac{P_b - \Phi_{ND} \times P_{ft}}{1 - \Phi_{ND}}$$

After the shale effect is corrected from the porosity-derived logs, the water saturation is calculated using Archie water saturation (Archie 1942). The following are the three more common formulas used to calculate and compare the water saturation values before getting the actual water saturation (Archie 1942; Asquith et al. 2004):

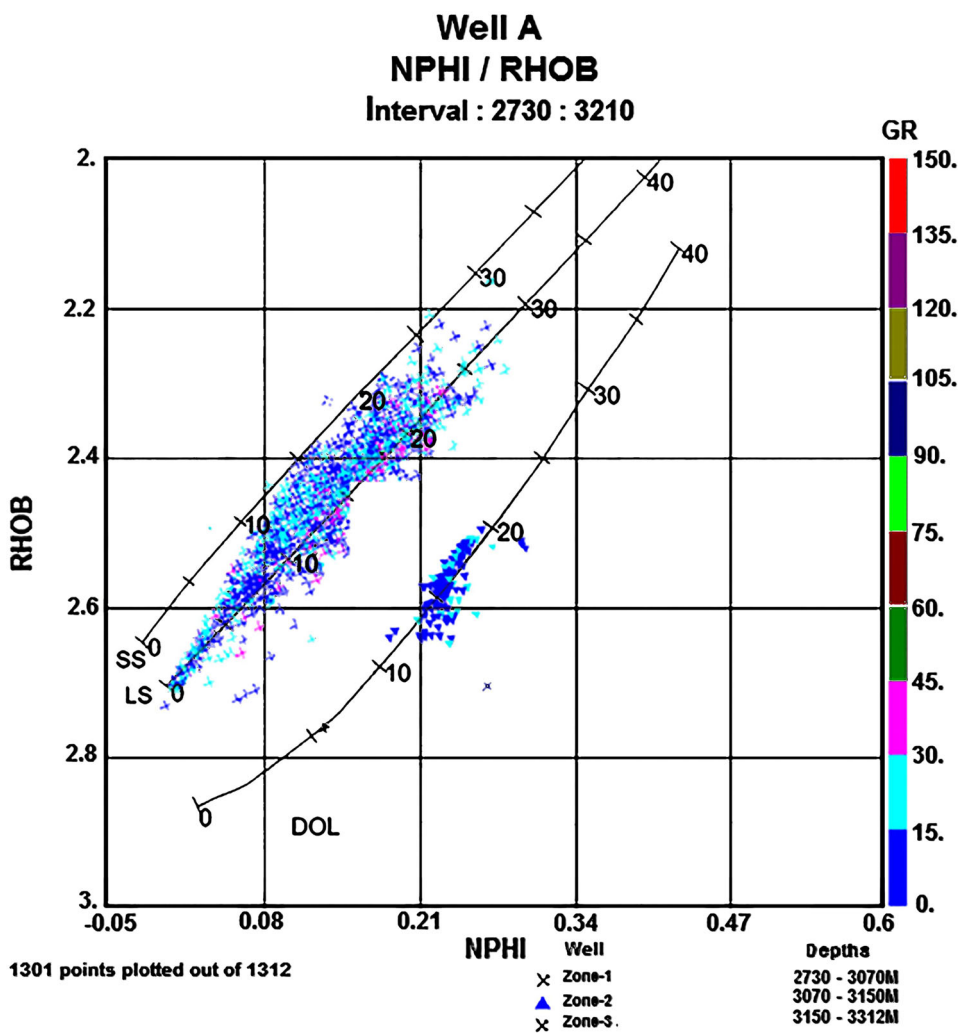
$$S_w = \left(\frac{a \times R_w}{R_t \times \Phi^m} \right)^{\frac{1}{n}}$$

The Archie equations also used to calculate the R_w from the adjacent water-bearing zone (Atlas 1979; Mustafa 2012) are

$$S_w = \frac{1}{\Phi} \times \left[\sqrt{\frac{R_w}{R_t} + \left(\frac{axV_{sh}}{2} \right)} - \frac{axV_{sh}}{2} \right],$$

$$S_w = \left(\frac{0.4 \times R_w}{\emptyset^2} \right) \times \left(\sqrt{\left(\frac{V_{sh}}{R_{sh}} \right)^2 + \frac{5 \times \emptyset^2}{R_t \times R_w}} - \frac{V_{sh}}{R_{sh}} \right).$$

Fig. 7 A cross plot of bulk density (RHOB) versus neutron porosity (NPHI) for determining the lithology of Well A in Central Luconia, offshore Sarawak, Malaysia



The Archie water saturation model was preferred because the Archie equation for calculating water saturation is well known. The Archie equation is developed based on some hypothesis which is well applicable to clean carbonate rocks. The Archie equation cannot be used for the mixed siliciclastic–carbonate rocks. In other models, the small amount of shale cannot be neglected as in the Archie equation. Therefore, the Archie water saturation value was preferred to other models in the current study.

The following is the formula by Bateman and Konen (1978) which is used to calculate the formation water resistivity (R_w) of the gas-bearing zone in the reservoir (Alam et al. 2003):

$$R_w = 10^{\left(\frac{SSP}{K} + \text{Log}R_w\right)}$$

Water saturation of the uninvasion zone is a significant element while predicting the reservoirs. Reservoir

hydrocarbon saturations can be calculated using the water saturation data (Serra 2007):

$$S_h = 1 - S_w$$

The permeability (K) is controlled by the grain size and pore throat of the grain size (Zhang et al. 2007). Permeability in this study is calculated using the formula proposed by Asquith et al. (2004):

$$K = a \times \frac{P_{hi}^b}{S_{wi}^c}$$

The permeability calculation is also verified using the formula proposed by Wyllie and Rose (1950) which is as follows (Hilchie 1978):

$$K = \left(79 \times \left(\frac{\Phi^3}{S_{wr}}\right)\right)^2$$

Hydrocarbons are identified from the difference between the water saturation (S_{xo}) in a flushed zone and the

Fig. 8 Matrix identification plot Umaa vs Rhomaa for the resulting lithology estimation of Well A in Central Luconia, offshore Sarawak, Malaysia

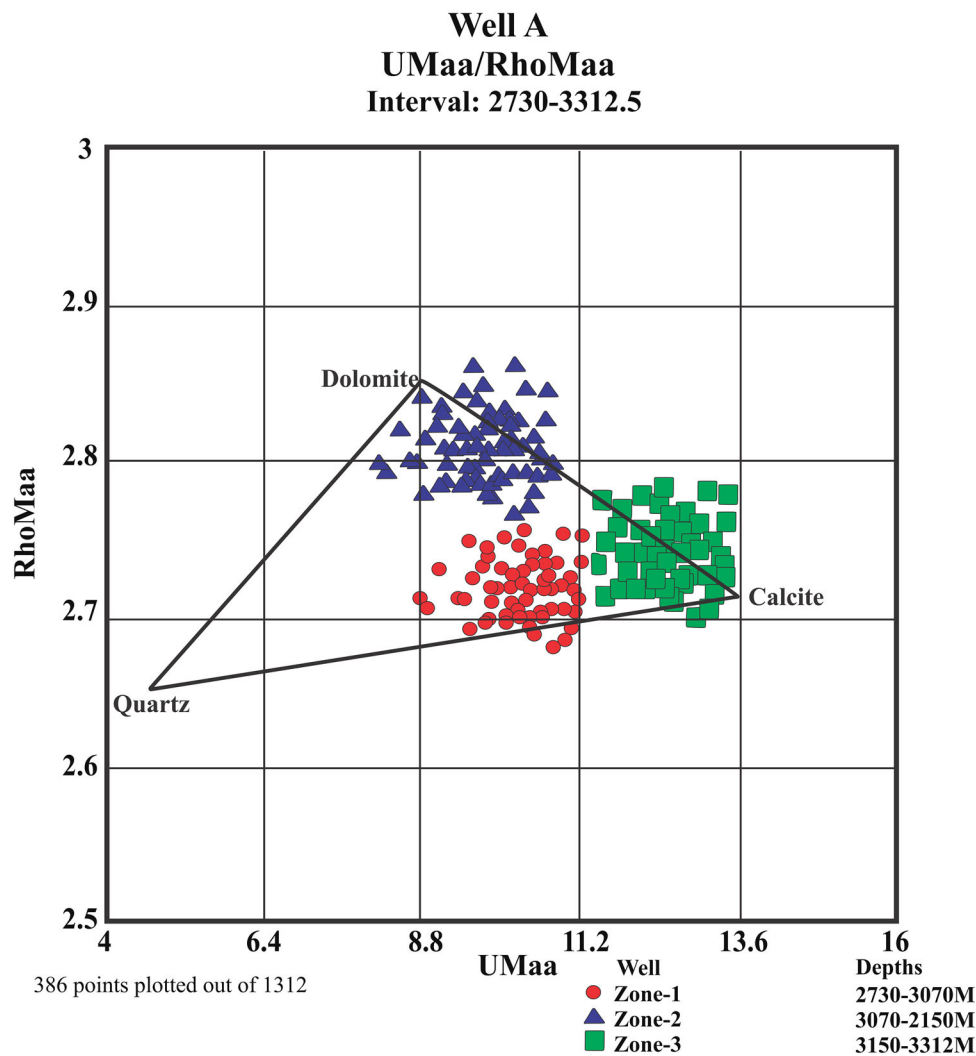


Table 1 The calculated values of the total thickness of three individual zones

Zones	Depth range (m)	Thickness (m)	Volume of shale (%)	Average volume of shale (%)	Porosity range (%)	Average porosity range (%)
Zone-1	2730–3070	340	0.01–0.35	0.11	0.95–19	15.7
Zone-2	3070–3150	84	0.05–0.12	0.09	0.01–7	4.3
Zone-3	3150–3312	156	0.02–0.26	0.11	11–18	13.7

The average volume of shale and porosity of gas-bearing zones in the Miocene succession of Well A, Central Luconia, offshore Sarawak, Malaysia

uninvaded zone (S_w) (Heidari et al. 2011). Movable index ratio is important when dealing with the water saturation ratio of the uninvaded zone and flushed zone. The movable hydrocarbon index is calculated by using the Archie equation (Archie. 1942; Islam et al. 2009):

$$\frac{S_w}{S_{xo}} = \left[\frac{R_{xo}/R_t}{R_{mf}/R_w} \right]^{1/2}$$

The bulk volume water (BVW) is the product of formation water saturation (S_w) and its porosity (Φ) is the bulk volume water (Harrison and Jing 2001; Heidari et al. 2011). The BVW of the studied gas reservoirs was calculated using the following equation (Alam et al. 2003):

$$BVW = S_w \times \Phi.$$

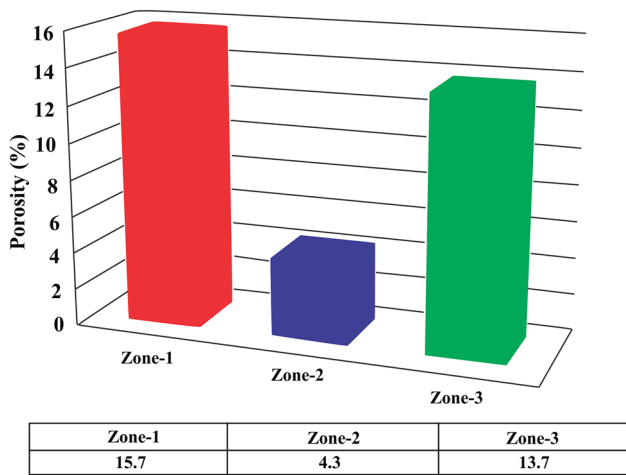
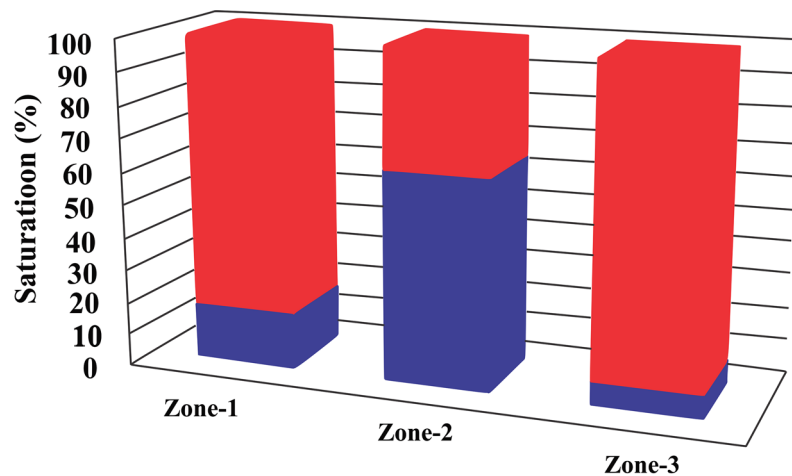


Fig. 9 A cross plot of average porosity value of Zone-1, Zone-2 and Zone-3 of Well A in Central Luconia, offshore Sarawak, Malaysia

After the water saturation of a hydrocarbon-bearing zone is determined, the quantity of hydrocarbons is determined by the following equation (Atlas 1979):

$$G = 43560Ah\theta(1 - S_w)/B_{gi},$$

Fig. 10 A cross plot of average water saturation and hydrocarbon saturation value of Zone-1, Zone-2 and Zone-3 of Well A in Central Luconia, offshore Sarawak, Malaysia



	Zone-1	Zone-2	Zone-3
■ Sh	83	38	93
■ Sw	17	69	7.6

Table 2 The calculated values of water saturation, gas saturation, permeability, movability hydrocarbon index and bulk volume water of individual zones in the Miocene succession of Well A, Central Luconia, offshore Sarawak, Malaysia

Zones	Depth range (m)	Thickness (m)	Water saturation (%)	Gas saturation (%)	Permeability (md)	MHI (S_w/S_{xo})	BVW
Zone-1	2730–3070	340	17	83	543	0.075	0.012
Zone-2	3070–3150	84	69	38	47.7	25.90	0.0083
Zone-3	3150–3312	156	7.6	93	601.53	0.043	0.010

whereas the B_0 is equal to 0.0041, which is calculated from temperature and pressure data.

Results

The wireline log analysis is performed on Well A, using measurements of gamma ray, resistivity, spontaneous potential and a combination of neutron and density log to determine the lithology, porosity, permeability, water saturation, hydrocarbon saturation and bulk volume of water identification (Fig. 3). The calliper log shows relatively constant hole diameter indicating good data quality (Fig. 3). The resistivity curves (LLD, LLM and MSFL) are separated from 2730 to 3070 m in Zone-1 (Fig. 4) and 3156 to 3312 m in Zone-3 (Fig. 6), whereas in Zone-2, the shallow resistivity is higher than the deep resistivity (Fig. 5).

Lithology identification

The combination of gamma ray, neutron and density logs can be used to determine the reservoir lithology

(Schlumberger 1975). In Well A, neutron–density cross plot shows a mixture of lithologies (Fig. 7) ranging from limestone to dolomite within the reservoir. Both Zone-1 and Zone-3 contain the limestone, but Zone-2 is more dominantly composed of dolomite. The neutron–density log is also used to calculate the apparent matrix density and Rhomaa for matrix identification.

Photoelectric logging measurements have proved to be an essentially useful tool in identifying minerals (Gardner and Dumanoir 1980). The common use of density and photoelectric absorption cross section is a powerful method to determine and estimate the minerals in mixed lithologies, as demonstrated in the studied Well A. Fluid-filled pores influence log measurements, which can be corrected by estimating the rock matrix framework. A Umaa versus Rhomaa cross plot of logging zones provides an excellent medium for mineral analysis (Doveton et al. 1996). This cross plot is indexed with quartz, calcite and dolomite, which serves as a reference line to characterize logging zones (Fig. 8). All the points fall within the quartz–calcite–dolomite triangle, and all the points toward dolomite and calcite, which indicates that Zone-1 and Zone-3 contain limestone whereas Zone-2 represents dolomites. The presence of dolomite in Zone-2 confirms earlier results as shown in Fig. 7.

Neutron–density log responses curve in Zone-3 approximately overlies, which indicates the presence of limestone (Fig. 3). In the dolomite zone, the neutron log should give a higher reading than the density log, but due to the presence of gas, the recorded neutron response tends to be decreased. In some cases, the neutron response is less than the density reading in Zone-2 from a depth range of 3070–3150 m (Fig. 3).

Volume of shale

The volume of shale in three different zones of the Neogene succession in Well A has been calculated using Asquith et al. (2004) and Islam and Islam (2014) formulas. The percentage of shale volume is very low within Zone-1 (0.01–0.35%), Zone-2 (0.05–0.12%) and Zone-3 (0.02–0.26%) of the Miocene reservoir in Well A (Table 1). The range of the calculated values of the volume of shale for different zones also reflects the log response (Fig. 3).

Porosity distribution

The porosity determination is a very important approach for calculating the fluid saturation during reservoir evaluation (Ruhovets 1990). The average porosity value is calculated using both neutron and density logs (Fig. 9). The porosity value of Zone-2 (4.8%) is lower than those of Zone-1 (15%) and Zone-3 (13%). The

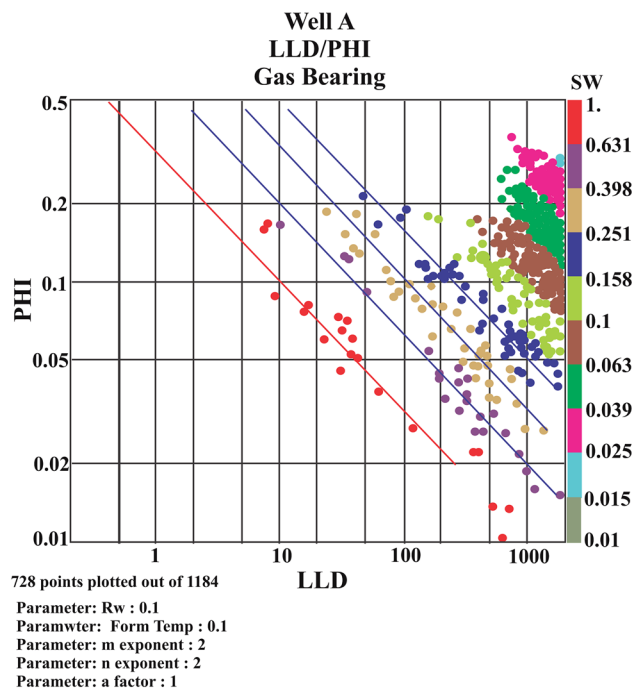


Fig. 11 Pickett point of Well A, Central Luconia, Offshore Sarawak Malaysia

porosity in Zone-2 could be affected by the presence of dolomite (Fig. 7) which acts as a cement and fills the pore spaces between the grains (Janjuhah et al. 2017b). According to the porosity values and neutron–density log response, Zone-1 has the highest potential to bear gas compared to the other two zones. The calculated value of porosity also reflects the log response as well (Fig. 3).

Water and hydrocarbon saturation

The water saturation of Zone-1 is 17%, Zone-2 69% and Zone-3 7.6%, respectively (Fig. 10). The gas saturation of Well A reservoir is determined by the total saturation (100%) minus water saturation. The average gas saturation of Zone-1 and Zone-2 is 83 and 93% respectively (Figs. 3, 10; Table 2). The hydrocarbon saturation values of Zone-1 and Zone-3 are greater than 60% (Fig. 10; Table 2), which is considered as a criterion of gas-bearing zones (Asquith et al. 2004; Jenkins and Boyer 2008), whereas in Zone-2 the gas saturation value is <40%, which is less than the average value to consider it as a gas-bearing zone (Fig. 10; Table 2).

On the basis of the calculated porosity, the R_w value is calculated using the SP log and validated from the well completion report and Pickett plot which is 0.1 O-m (Fig. 11). The scatter of points makes the selection of slope (from which to determine “m”) of carbonate rocks, which

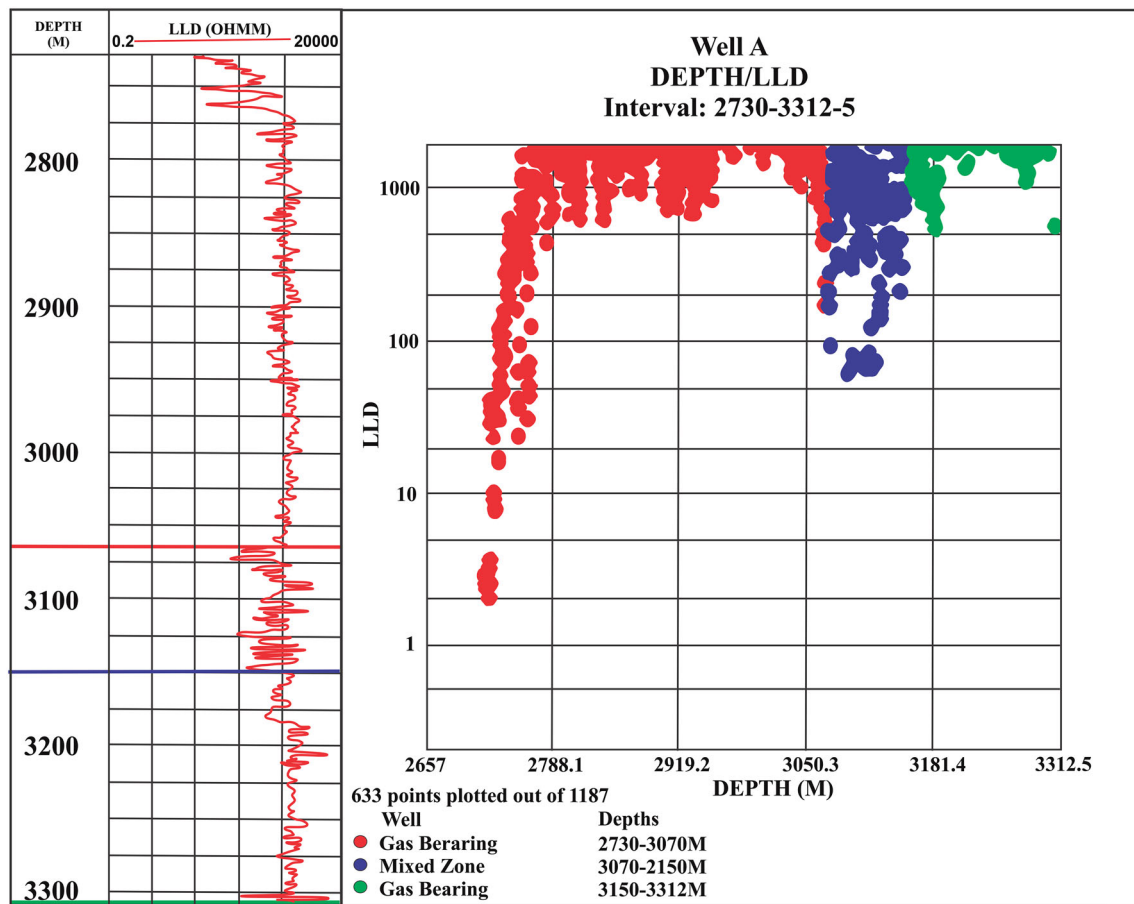


Fig. 12 Comparison of graphical presentation and cross plot of depth vs deep resistivity of three zones of Well A in Central Luconia, offshore Sarawak, Malaysia

in general is a reliable fit. The R_o line is set among the lowest group of points, at a porosity of about 5%. The group of points by which the 100% water saturation line is set is recorded from Zone-2 rather than the underlying Zone-3. Log responses and lithological description provide evidence of a permeability barrier between Zone-2 and Zone-3. Most of the points recorded from the highest zone lie in Zone-1 and Zone-3, and they indicate low water saturation. Low recorded points are from Zone-2 with high water saturation (Fig. 11).

To support the statement more clearly, deep induction resistivity of the stratigraphic section of Zone-2 is less than Zone-1 and Zone-3 (Fig. 12). The likelihood of production of water from Zone-2 is also indicated by the Pickett cross plot (Fig. 11). Most of the data points of Zone-2 show that water saturation is greater than 0.075.

The measured deep resistivity versus water saturation cross plot shows that the water saturation value in Zone-1 and Zone-3 decreases while the resistivity value increases. However, an inverse phenomenon has been observed in Zone-2 (Fig. 13). A similar relationship has also been

observed in the porosity versus water saturation cross plot (Fig. 14).

The porosity response is more effective in Zone-2 as compared to Zone-1 and Zone-3. As the porosity in Zone-2 decreases up to 0.01% (Fig. 14), the water saturation increases dramatically up to 0.8% compared to other zones (Zone-1 and Zone-3). It also supports the earlier statement that Zone-2 contains a higher water saturation than Zone-1 and Zone-3.

Gas-bearing zone and water-bearing identification

The gamma ray log shows low response almost throughout the whole interval from 2730 to 3312 m (Fig. 3). The resistivity log response in Zone-1 (Fig. 4) and Zone 3 (Fig. 6) is higher than that in Zone-2 (Fig. 5). Generally, in gas-bearing zones, deep resistivity (LLD) is higher than the shallow resistivity (LLS) and micro-resistivity (MSFL) which can be observed in Zone-1 and Zone-3. However, in the water-bearing zone, the shallow resistivity is higher than deep resistivity at certain depths of Zone-2 (Fig. 5).

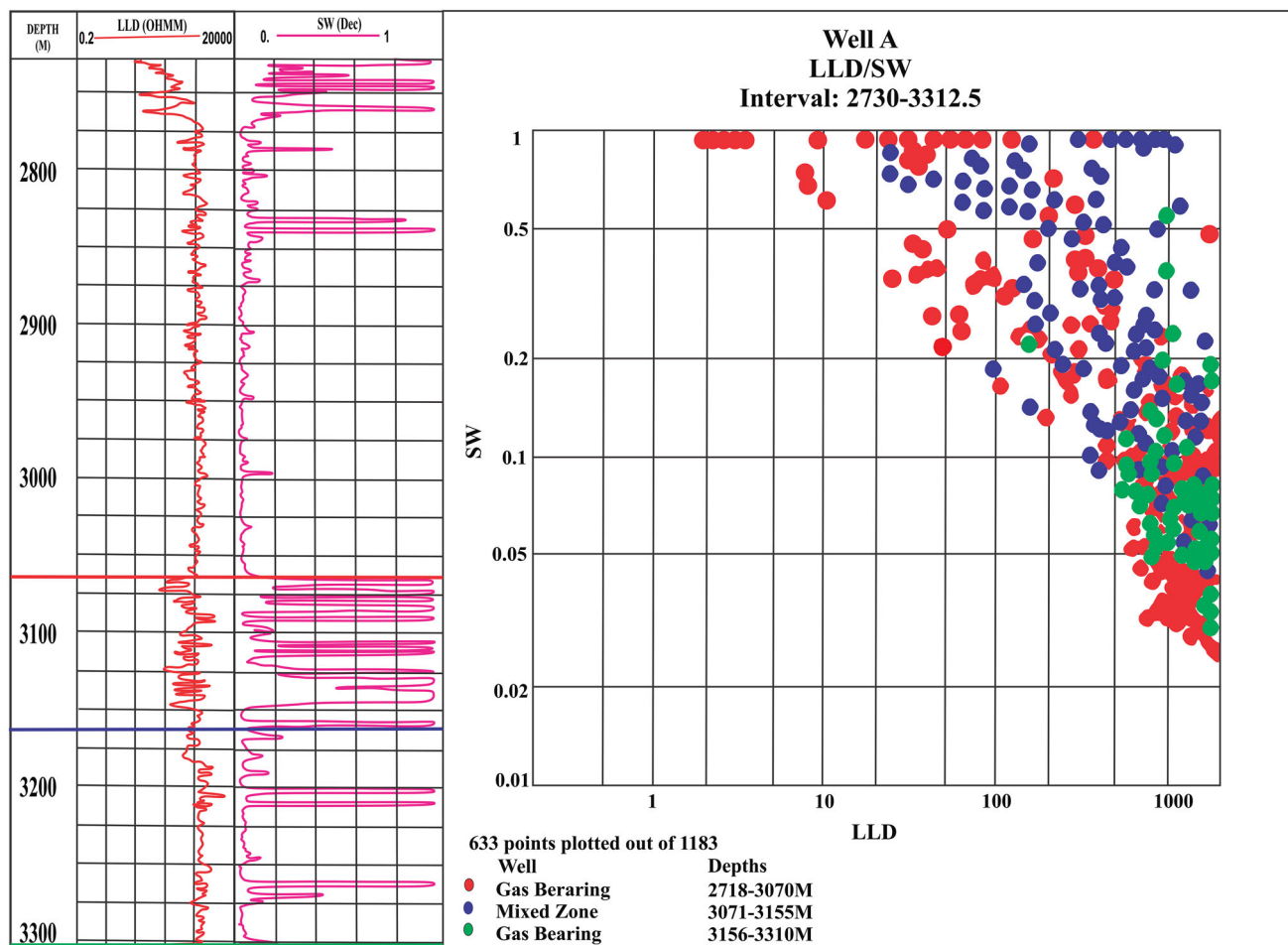


Fig. 13 Comparison of graphical presentation and cross plot of deep resistivity vs water saturation of three zones of Well A in Central Luconia, offshore Sarawak, Malaysia

Permeable zones

The calculation of permeability is shown in Table 2 and graphically represented in Fig. 3. Three major permeable zones (Zone-1, Zone-2 and Zone-3) have been recognized from the thorough studies of different logs (Table 3). The average permeability of all three zones is 543 md (Zone-1), 47.7 md (Zone-2) and 601.53 md (Zone-3), respectively (Fig. 15). Zone-1 (2730–3070 m) and Zone-3 (3150–3312 m) are interpreted as gas-bearing zones, whereas Zone-2 (3070–3150 m) is considered a mixed zone. Among these three zones, Zone-1 is the thickest with a total thickness of 340 m followed by Zone 2 (80 m), and Zone 3 (162 m), respectively (Table 3).

Gas mobility index (S_w/S_{x0})

When the hydrocarbon mobility index is equal to or greater than 1.0, the gas will not move toward the well bore

(Horst and Creager 1974). The calculated value of hydrocarbon mobility index in Zone 1 is 0.075, Zone 2 is 25.90 and Zone 3 is 0.043 (Table 2). In Zone-1 and Zone-3, the hydrocarbon mobility values are less than 0.7, which indicates that the gas in these two zones is movable. In Zone-2, the hydrocarbon mobility value is greater than 1.0, which suggests that the hydrocarbon in Zone-2 is not movable.

Bulk volume of water (BVW)

Formation water saturation and irreducible water saturation can be recognized by using bulk volume water. If the calculated value of bulk volume water ranges from 0.035 to 0.07, it indicates that the formation water is not irreducible and the reservoir will produce some water (Enikanselu and Ojo 2012). The bulk volume water value of Zone-1 (0.012), Zone-2 (0.083) and Zone-3 (0.009) shows that all zones contain irreducible water saturation (Table 2).

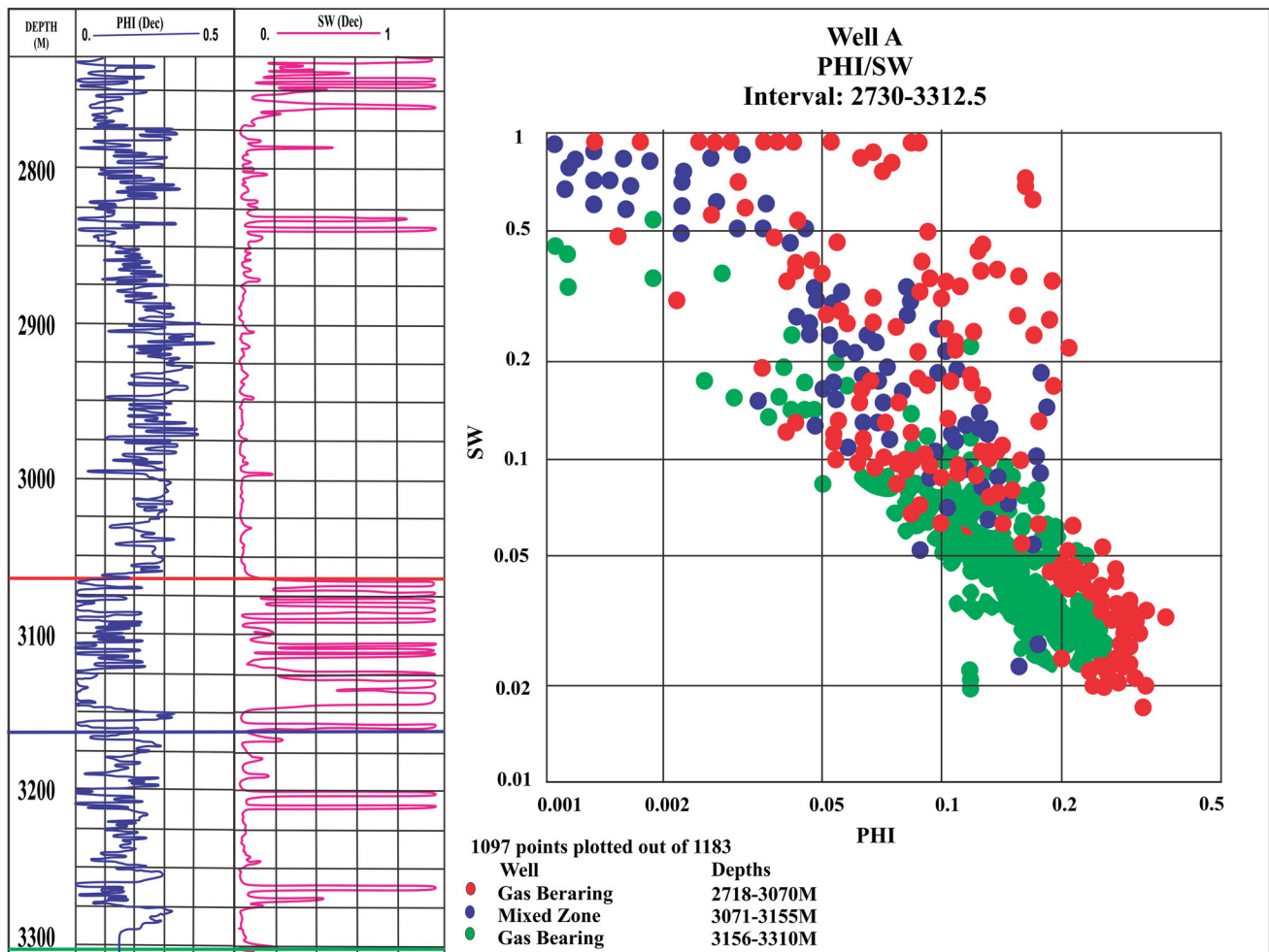


Fig. 14 Comparison of graphical presentation and cross plot of porosity vs water saturation of three zones of Well A in Central Luconia, offshore Sarawak, Malaysia

Table 3 The calculated thickness of permeable zones of Well A, Central Luconia, offshore, Sarawak, Malaysia

Zones	Zones type	Depth range	Total thickness	Net to gross ratio	Hydrocarbon determination (BCF/acre)
Zone 1	Gas-bearing zone	2730–3070	340	$327.4/340 = 0.96$	1.50
Zone 2	Mixed zone	3071–3155	84	$49.5/84 = 0.59$	0.02
Zone 3	Gas-bearing zone	3156–3312	156	$148.5/156 = 0.95$	0.66

The bulk volume water cross plot (Figs. 16, 17, 18) also confirms that all the zones are at irreducible water saturation. The BVW values cluster around the line 0.0083 in Zone-2 (Fig. 17), which suggests that the formation contains a mixture of vuggy and intergranular porosity. A similar pattern is observed in Zone-3 (Fig. 18). The position of data in Zone-1 indicates differences in the types of carbonate rock porosity. Point values are below 0.035, which generally represents rock with vuggy porosity with some intercrystalline porosity (Fig. 16).

Discussion

In Miocene carbonate reservoir in Well A, two gas-bearing zones (Zone-1 and Zone-3) and one mixed zone (Zone-2) are identified based on the wireline logs responses (Fig. 3). The depth ranges of these zones are 2730–3070 m (Zone-1), 3070–3150 m (Zone-2) and 3150–3312 m (Zone-3) with an average thickness of 340, 80 and 156 m, respectively (Table 3).

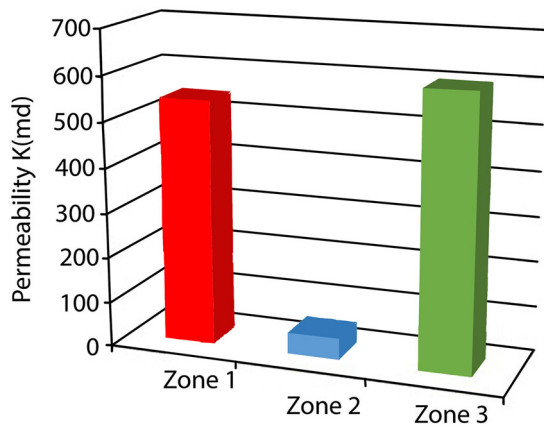


Fig. 15 A cross plot of average permeability values of the gas zones of Well A in Central Luconia, offshore Sarawak, Malaysia

The average log porosity values of these three zones are 15.7, 4.3 and 13.7%, respectively (Table 1). Zone-1 and Zone-3 show good porosity with average permeability

values (543 and 601.53 mD) in gas-bearing zones (Fig. 15; Table 2). However, in Zone-2, the water saturation value is very high, up to 69% compared to Zone-1 and Zone-3 (Fig. 10; Table 2). Lithology identification cross plot indicates the presence of dolomite in Zone-2 (Fig. 7). The quartz–calcite–dolomite triangle of mineral identification also describes that dolomite and calcite minerals act as cement in different zones (Fig. 8).

The presence of dolomite is an indicator of high cementation of grains in Zone-2. A Low BVW value of 0.012 (Zone-1), 0.083 (Zone-2) and 0.009 (Zone-3) indicates irreducible water saturation and different types of rock porosity. High permeability values in Zone-1 and Zone-3 also give a sign of the possible presence of vuggy porosity in gas-bearing zones, whereas Zone-2 contains intergranular porosity with low porosity and permeability value. Based on BCF calculations it is confirmed that Zone-1 and Zone-3 contain more gas-bearing reserves (i.e., 1.5 BCF and 0.66 BCF in per acre, respectively), whereas Zone-2 contributes less than 0.1 BCF per acre (Table 3).

Fig. 16 Bulk volume cross plots of porosity vs water saturation of Zone-1 of Well A to identify the irreducible water saturation

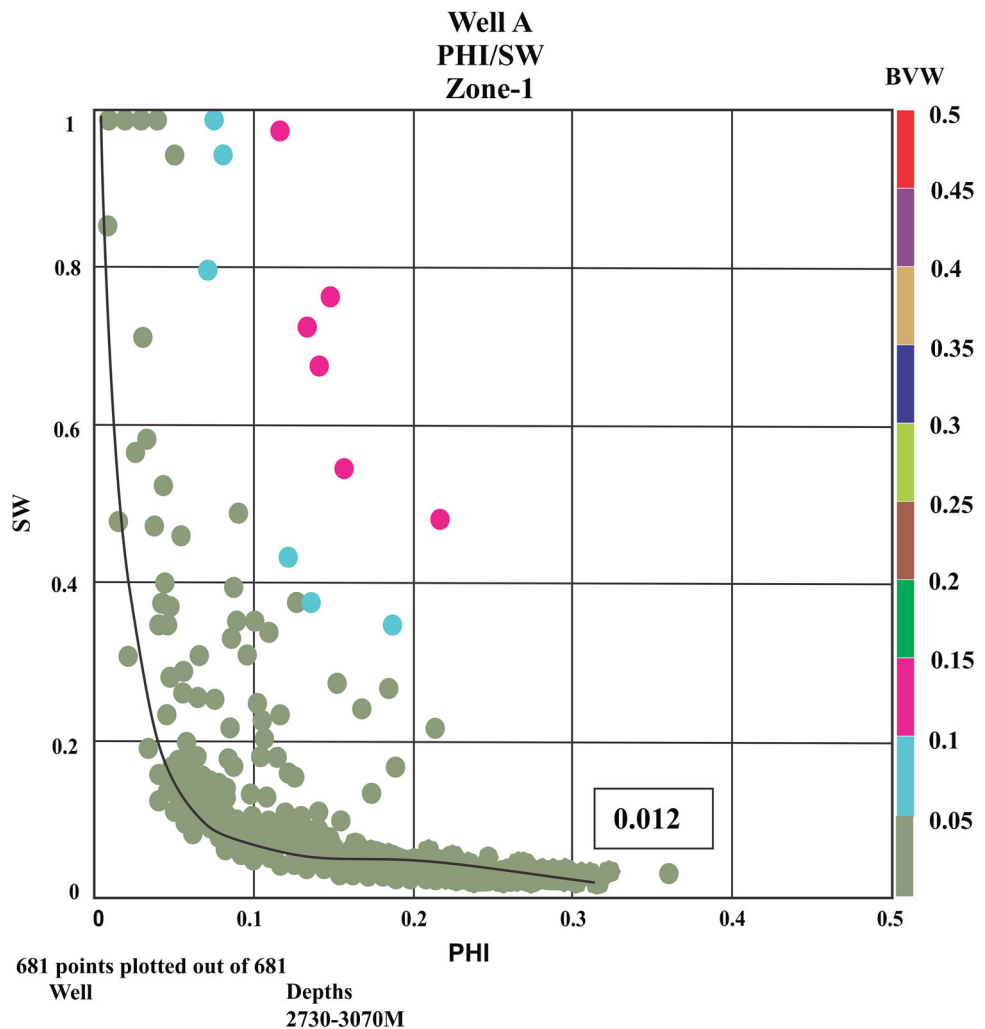
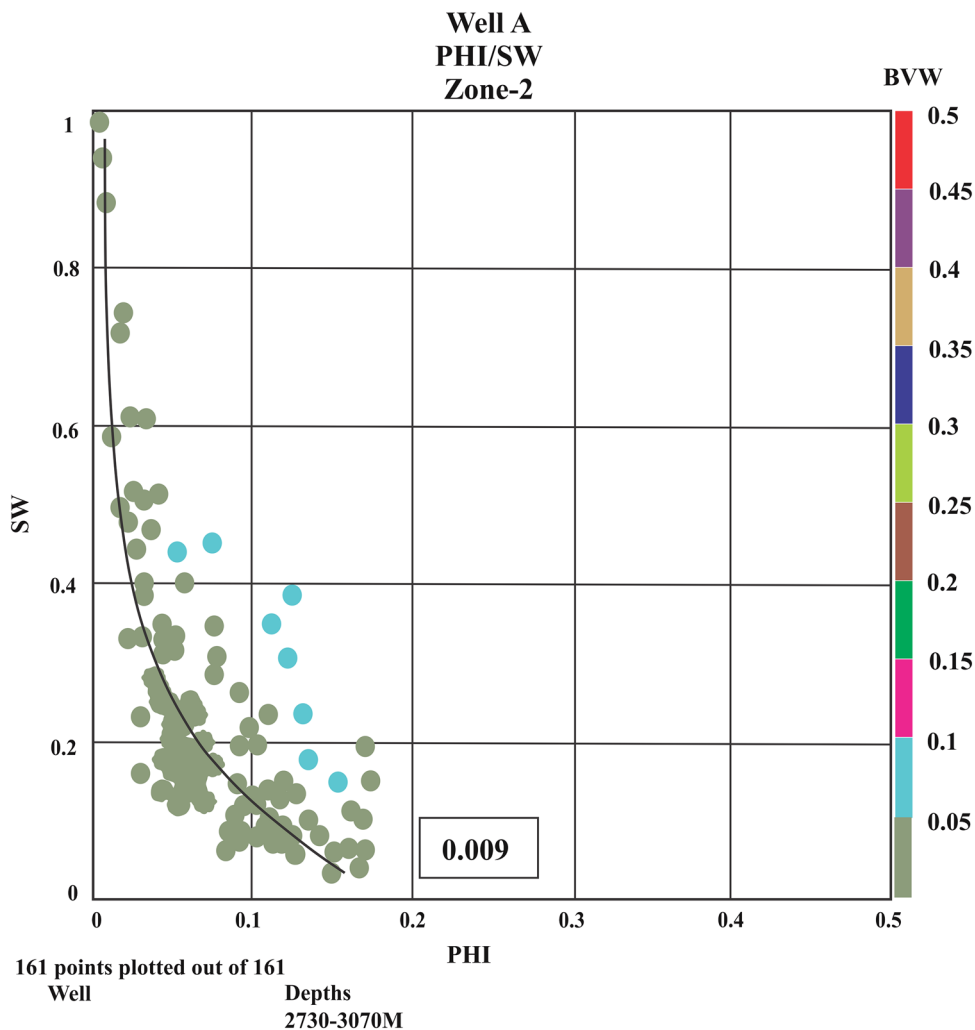


Fig. 17 Bulk volume cross plots of porosity vs water saturation of Zone-2 of Well A to identify the irreducible water saturation



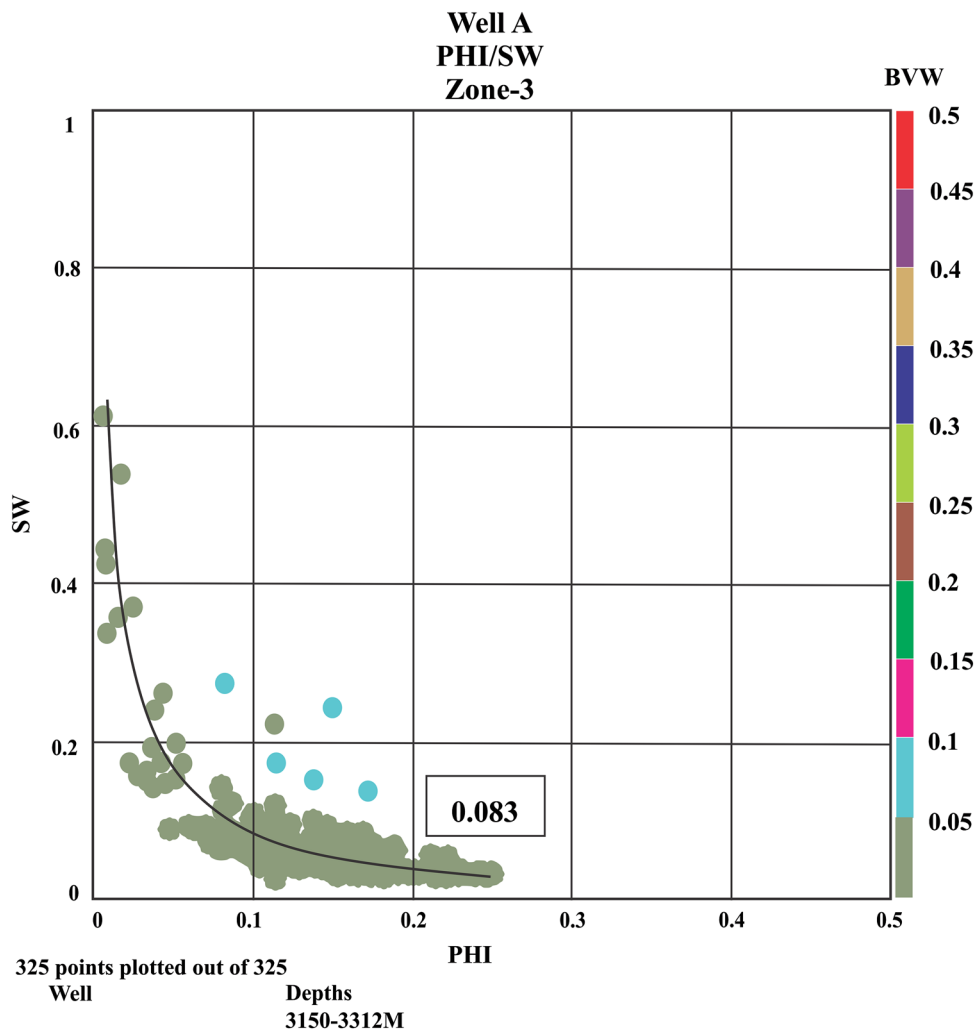
Low porosity, low permeability, high water saturation, low hydrocarbon saturation and high irreducible water saturation in Zone-2 might be the reason of the presence of high microporosity. The presence of microporosity (porosity with diameters of less than 10 μm) has been proven by Rahman et al. (2011), in the Miocene gas reservoirs of offshore Sarawak, Malaysia. The presence of microporosity in Zone-2 affects the wireline log response as well.

When the resistivity tool passes in Zone-2, it passes through a low resistivity area, and low resistivity is the area where high microporosity is present (Kieke and Hartmann 1974). The resistivity tools record the reading of area filled with irreducible water, but neglect other areas which are filled with hydrocarbon, causing misleading information that this area is a water-saturated rather than hydrocarbon-saturated zone.

Conclusions

Three permeable zones are identified. Zone-1 and Zone-3 are gas bearing and Zone-2 is described as a mixed zone. The hydrocarbon type is identified based on the high resistivity, low-neutron and low-density log responses which indicate that the hydrocarbon type is gas. Zone-1 and Zone-3 represent good porosity with an average gas saturation of 83 and 93%, indicating excellent reserve of gas. Zone-2 is degraded based on high water saturation value. Lithology identification values indicate that these three zones are carbonate rocks with lithology ranging from limestone to dolomite. Dolomite is more dominant in Zone-2. Average BVW values suggested that the present water is irreducible in all the zones. These zones contain different porosity types from vuggy to intergranular porosity. Irreducible water saturation is mostly held in micropores because of high capillary pressure. Zone-

Fig. 18 Bulk volume cross plots of porosity vs water saturation of different Zone-3 of Well A to identify the irreducible water saturation



2 represents high irreducible water saturation with the presence of dolomite which acts as cement. There might be chances that the presence of high water saturation in Zone-2 is held in micropores, and hydrocarbon saturations are underestimated by the effect of micropores on wireline logs.

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