Journal of Geological Society of Sri Lanka Vol. 22-2 (2021), 27-37

RESERVOIR POTENTIAL OF THE CAMPANIAN SANDSTONE IN THE DORADO-NORTH WELL ON THE MANNAR BASIN, OFFSHORE SRI LANKA

MINTHARI BANDARA[1], UPUL PREMARATHNE[1,*]

[1]*Department of Oceanography and Marine Geology, Faculty of Fisheries and Marine Sciences & Technology, University of Ruhuna, Wellamadama, Matara, Sri Lanka*

**Corresponding Author: email - premarat@yahoo.com*

(Received 4th January 2021; accepted 16th April 2021)

ABSTRACT

The Mannar Basin is located offshore in between the west coast of Sri Lanka and the east coast of India. It is a Mesozoic failed rift basin filled with Late Jurassic to recent sediments. The basin is one of the main targeted areas for oil and gas exploration in Sri Lanka. In 2011, the existence of an active petroleum system in the basin was confirmed by discovering natural gas from Dorado and Barracuda wells. Although the petroleum system of the Mannar Basin is known to some extent, the porosity and permeability of potential reservoirs in the basin are little known. Previous basin modeling studies have reported that the Late Cretaceous section in the northern part of the Mannar Basin has potential reservoirs. However, their porosity and permeability have not been investigated in detail due to the lack of availability of well data. The objective of this study was to estimate the porosity of approximately 431 m thick Late Cretaceous (Campanian) sandstone section in the Dorado-North well, located on the northern part of the Mannar Basin. The results show that the Campanian section is mainly composed of shaly sandstone. Almost half of the section shows very good reservoir potential, while the rest of the section has fair to good reservoir potential. The quality of a hydrocarbon reservoir depends on its shale fraction. Shale degrades the reservoir quality. Caving in give rise to uncertain data in petrophysical logs. The Campanian section in the Dorado-North has very good hydrocarbon potential.

Keywords: *Campanian, Dorado-North, Mannar Basin, Porosity, Sri Lanka*

1. INTRODUCTION

The Gulf of Mannar basin is located between the south and southeast coast of India and the western coastline of Sri Lanka. The Sri Lankan sector of the Gulf is commonly recognized as the ‘Mannar basin’ (Premarathne et al., 2016). The Mannar basin is considered to be one of the major geological provinces for hydrocarbon exploration in Sri Lanka. This Late-Jurassic to Neogene failed rift basin has been evolved due to the multiphase break-up of Gondwana (Baillie et al., 2002). The thickness of sedimentary succession of Late Jurassic to recent sediments varies from 4 km in the northern part to more than 9 km towards the south of the basin (Premarathne et al., 2015, 2016; Bandara et al., 2019).

Mannar basin extends over 45,000 km^2 in water depths ranging from 20 m in the north part of the basin to more than 3,000 m towards the south (Premarathne et al., 2016). It can be considered as a deep-water basin as the majority of the basin lies below 400 m water depth. The tectonic history of the basin has been discussed in detail by (Baillie et al., 2002; Premarathne et al., 2015, 2016; Herath et al., 2017; Kularathne et al., 2017; Ratheesh-Kumar et al., 2020; Premarathne and Ranaweera, 2021; Singh and Rao, 2021).

The history of the hydrocarbon exploration in Sri Lanka can be divided into two phases, the first phase lasted from 1957 to 1984 and the second phase began in 2001 and continues to date. In the first phase, several hydrocarbon exploration wells (Pesalai-1, 2 & 3 and, Palk Bay-1, Delft-1, and Pedro-1) were drilled in the Cauvery basin and (Pearl-1) in the northern part of the Mannar Basin (Premarathne, 2015). However, all of these wells failed to encounter any economically feasible hydrocarbon deposits and they were plugged and abandoned as dry holes. A little further exploration took place in Sri Lanka during the 1984 to 2000 period. The 2nd exploration phase in Sri Lanka began with the acquisition of 1,050 km^2 two-dimensional (2D) marine seismic data over the Mannar Basin by a Norwegian geophysical company (TGS-NOPEC) in 2001. Based on the interpretation of this data, the Mannar Basin was identified to have a significant hydrocarbon potential with a rift-basin structure and more than 9 km thick sediment succession on the crystalline basement (Baillie et al., 2002; Bandara et al., 2019).

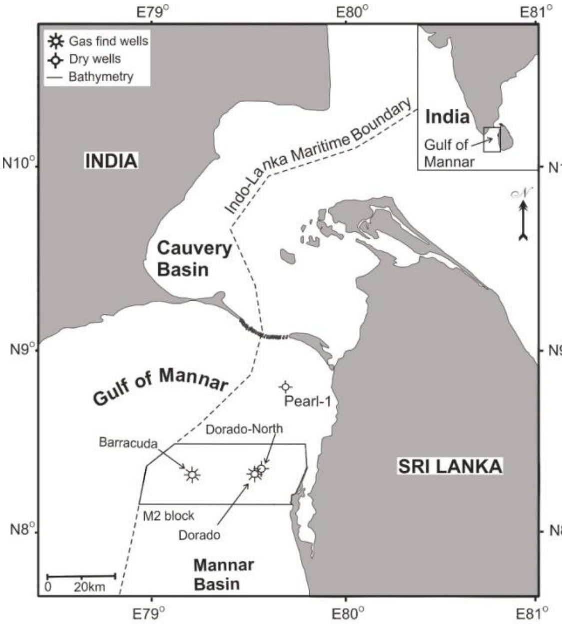

Fig. 1: *Location of the SL 2007-01-001 block and hydrocarbon exploration wells drilled in the Mannar Basin in Sri Lanka (Modifled after Premarathne et al., 2013)*

In 2008, the Sri Lankan government offered M2 hydrocarbon exploration block (Figure 1) to Cairn Lanka Private Limited (Cairn) (Premarathne et al., 2013). In 2011, Cairn drilled three hydrocarbon exploration wells named Dorado, Barracuda, and Dorado-North (well locations: Figure 1). Among them, Dorado and Barracuda wells penetrated natural gas-bearing Campanian and Maastrichtian sandstones, respectively (Figure 2B & D) (Premarathne et al., 2013). Ratnayake et al. (2017) report that the natural gas deposits encountered in the Dorado and Barracuda wells contain 90%wt and 85%wt of methane, respectively. Even though the tectonostratigraphic setting of the well was roughly similar to that of the Dorado well, Dorado-North was unable to encounter any hydrocarbon deposit (Figure 2C).

Several scientific studies published recently, (e.g. Premarathne et al., 2013, 2015, 2016; Ratnayake et al., 2018; Kularathne et al., 2020; Galushkin and Dubinin, 2021) contributed to gaining some insight into the petroleum system of the Mannar Basin. Due to the lack of well penetration, the major portion of the Mannar Basin remains little understood.

Premarathne et al. (2015), based on a basin modeling study, concluded that the Late Cretaceous section in the Mannar Basin could accommodate potential reservoirs. This opinion is supported by the discovery of natural gas from Campanian and Maastrichtian sandstone in the Dorado and Barracuda wells, respectively (Figures. 2B & D). Though natural gas was encountered in the Campanian sandstone layer in the Dorado well, the same stratigraphic section in the Dorado-North, which is located about 2.5 km northeast of Dorado (Figure 1), did not have natural gas in it. Dorado-North, which was drilled in 1,343 m water depth, penetrated a 2,279 m thick Recent to the Santonian stratigraphic column. The Pearl-1 well also penetrated about 900 m thick Late Cretaceous sandstone (Figure 2A).

Like other petroleum system elements, the quality of potential reservoirs in the Mannar Basin is little known due to the lack of availability of well data, because of their commercially sensitive nature. Among a handful of papers available in the public domain, that of Wijesuriya et al. (2017) compares the water saturations of some stratigraphic intervals penetrated by the Dorado and Barracuda wells using five water saturation models namely Archie's equation, Equivalent model, Indonesia model, Duel model, and Juhasz model.

Porosity among others is a basic parameter used in understanding the reservoir potential. It is also vital in reserve calculations. Therefore, the objective of this study was to estimate the porosity distribution in the 431 m thick Campanian sandstone section lies in the depths interval of 3,150 m to 3,581 m in the Dorado-North well using its petrophysical logs.

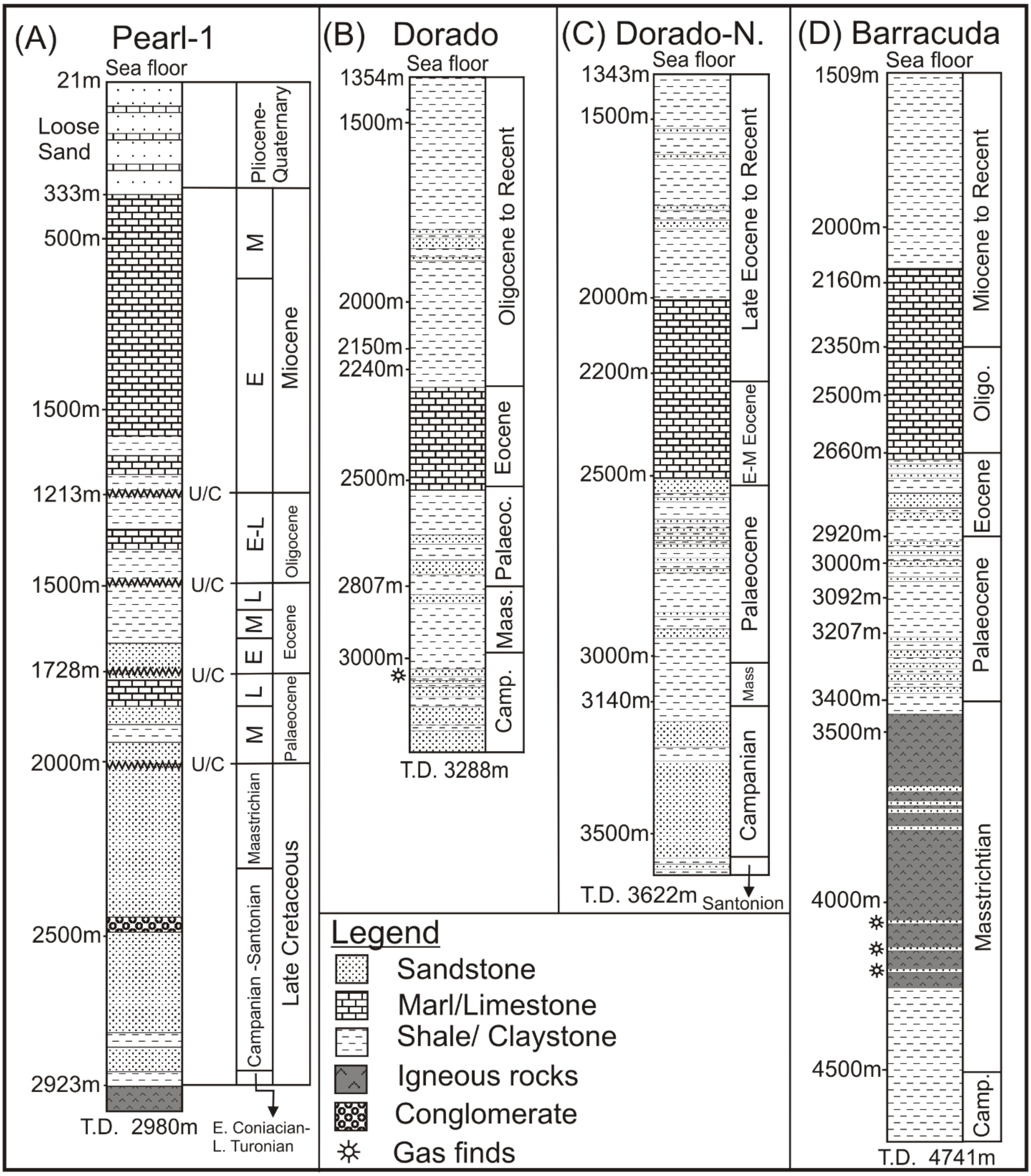

Fig. 2: *Generalised stratigraphic sections of the wells (a) Pearl-1, (b) Dorado, (c) Dorado-North and (d) Barracuda (modified after Premarathne et al., 2015). Oligo. = Oligocene, Palaeoc. = Palaeocene, Maas. = Maastrichtian, Camp. = Campanian, E = Early, M = Middle, L = Late, U/C = unconformity, and T.D. = total depth.*

2. METHODOLOGY

2.1 Data collection

Petrophysical logs from the Dorado-North well were collected from Petroleum Resource Development Secretariat (PRDS). Petrophysical logs were acquired by the LWD003 (Logging While Drilling) tool string. All data were from the tool memory. Gamma Ray has been corrected for mud weight, bit size, and collar size, and potassium concentration in mud. Data between 3,150 to 3,581 m depths has been acquired in an open hole. The datum for all measured depths (MD) in this study was Rotary Kelly Bushing (RKB), which was 28.3 m above the mean sea level.

Data in caliper, natural gamma-ray, bulk density, and thermal neutron porosity logs from 3,150 to 3,581 m depth interval were resampled at every 1 m depth interval. Hence the vertical resolution of the study was around 1 m. Several empirical equations and standard charts, which are described below, were used to calculate and correct porosity values.

2.2 Estimation of shale fraction

The natural gamma-ray log was used to calculate the shale fraction (V_{sh}) in the stratigraphic section between the depths of 3,150 to 3,581 m in the Dorado-North well. Linear gamma ray index (lGR) (Eq. 1) was used to calculate the shale fraction.

$$V_{(sh)} = \frac{\mathrm{GR}_{(\mathrm{zone})} - \mathrm{GR}_{(\mathrm{sand})}}{\mathrm{GR}_{(\mathrm{shale})} - \mathrm{GR}_{(\mathrm{sand})}} \qquad \text{(Equation 1)}$$

Where, $V_{(sh)}$ = shale fraction, $GR_{(zone)}$ = natural gamma ray reading of the zone, $GR_{(Sand)}$ = minimum gamma ray count recorded in the log, $GR_{(shale)}$ = maximum gamma ray count recorded in the log.

Figure 3 shows the variation in natural gamma-ray count in the Campanian section with depth. The depth intervals that recorded the least and the highest values in the entire petrophysical log are thought to have clean sandstone and 100% shale, respectively. The least (GR_{sand}) and the highest (GR_{shale}) values recorded in the whole of the gamma ray log were 32 gAPI at 3,201 m and 130 gAPI at 2,732.8 m, respectively.

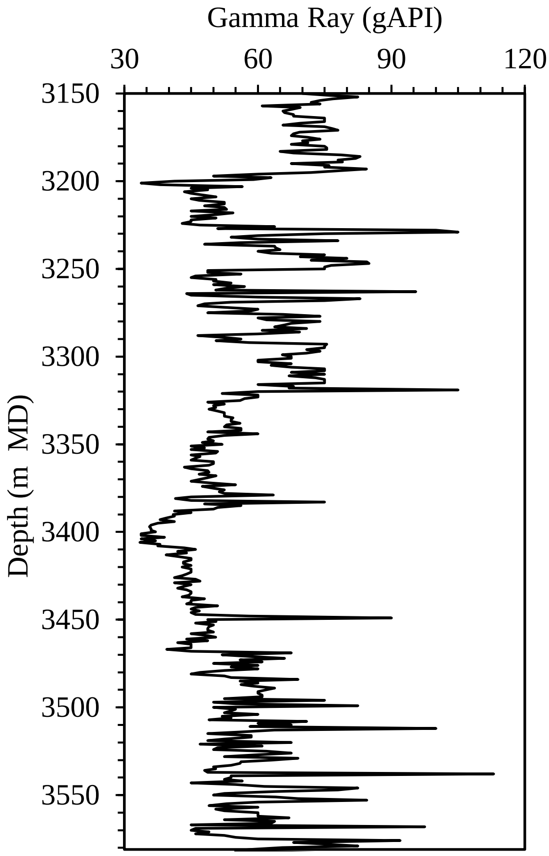

Fig. 3: *The variation of natural gamma ray count in the Campanian section between the depths of 3,150 to 3,581 m*

2.3 Density Porosity

Porosity calculation using the bulk density (density porosity) was performed using the following empirical equation (Eq. 2). A cross plot of bulk density and neutron porosity for the Campanian section is shown in Figure 4

$$\emptyset_d = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}} \qquad \text{(Equation 2)}$$

Where, $\emptyset_d$ = density porosity, ρ_{ma} = matrix density, ρ_b = formation bulk density, and ρ_{fl} = density of the fluid saturating the rock immediately surrounding the borehole.

The clay correction for bulk density was performed using the following equation (Eq. 3). The matrix density (ρ_{ma}) and the density of pore fluid were taken 2.65 and 1.0 g cm^{-3}, respectively (Gardner et al., 1974). The bulk density log at 2,732.8 m depth recorded 2.45 g cm^{-3}. The natural gamma-ray log indicates that sediment at this depth was 100 % shale. Hence, the density of shale was taken as 2.45 g cm^{-3}.

$$\rho_{(b\,corr)} = \rho_b + V_{cl}\,(\rho_{ma} - \rho_{cl}) \quad \text{(Equation 3)}$$

Where, $\rho_{(b\,corr)}$ = clay corrected density porosity, ρ_b = density porosity, ρ_{ma} = density of matrix, ρ_{cl} = density of clay and V_{sh} = shale fraction.

2.4 Neutron porosity

2.4.1 Borehole correction

The variation of neutron porosity alongside the bulk density between the depths of 3150 to 3581 m is shown in Figure 4. First, the neutron porosity in limestone porosity units (LPU) was subject to borehole correction. The petrophysical log for the Dorado-North well reports that the salinity of the drilling mud was 80,000 ppm. The caliper log indicated that the borehole diameter in the Campanian section was approximately 30.48 cm (12 inches). Therefore, the correction chart available for 100,000 ppm NaCl equivalent and 12 inches borehole diameter was used for this study.

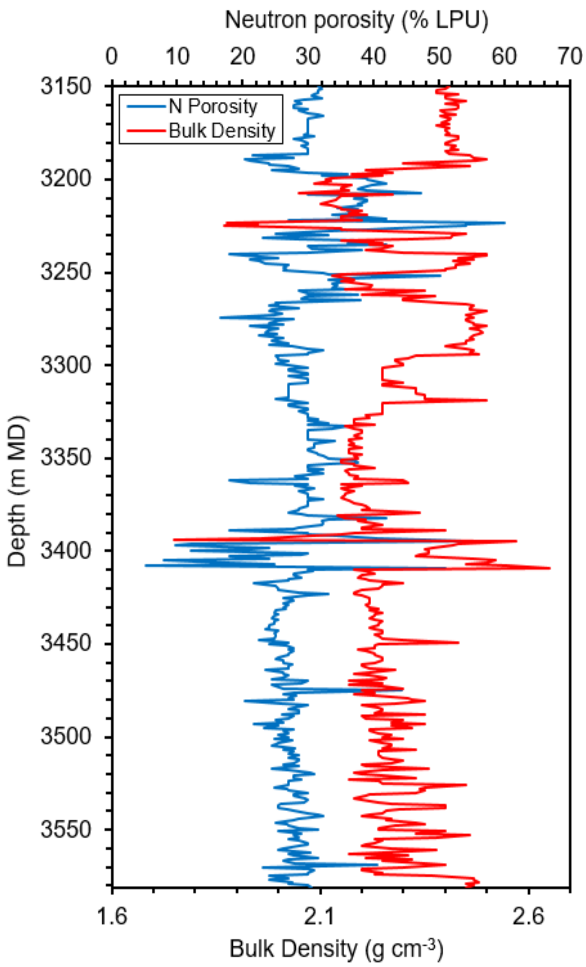

***Fig. 4:** Bulk density and neutron porosity cross plot for the Campanian section before applying any correction*

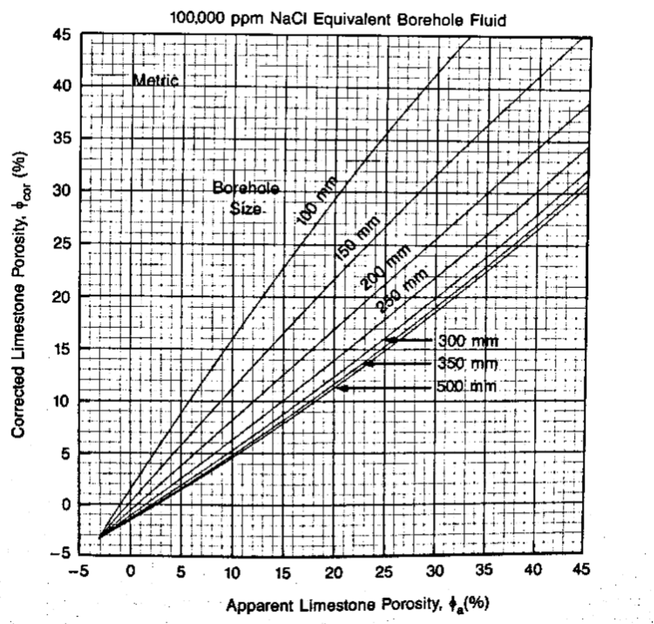

***Fig. 5:** Chart used to apply borehole correction for neutron porosity (Source: Introduction to Wireline Log Analysis, 2002)*

2.4.2 Lithology correction

The neutron porosity tool is calibrated to give accurate porosity values for limestone formations. Therefore, the unit of porosity is expresses as Limestone Porosity Units (LPU). The generalized stratigraphic section for the Dorado-North well shows that the Campanian section from 3150 -3581 m depth is mainly composed of sandstone (Figure 2C). Borehole correction was followed by lithology correction using the chart shown in Figure 3. After lithology correction, neutron porosity is in sandstone porosity units.

2.4.3 Clay correction

Clay in a formation gives raise to overestimate the neutron porosity (Kim et al., 2013). This is mainly due to the effect of hydrogen atoms adsorbed on to clay minerals. Therefore, neutron porosity was corrected to remove the effect of clay using the following empirical equation (Eq. 4).

$$\phi_{N\,corr} = \phi_N - V_{sh} * \phi_{cl} \quad \text{(Equation 4)}$$

Where, $\phi_{N\,corr}$ = clay corrected porosity, ϕ_N = neutron porosity, V_{sh} = clay fraction and ϕ_{cl} = porosity of clay assumed as 30%.

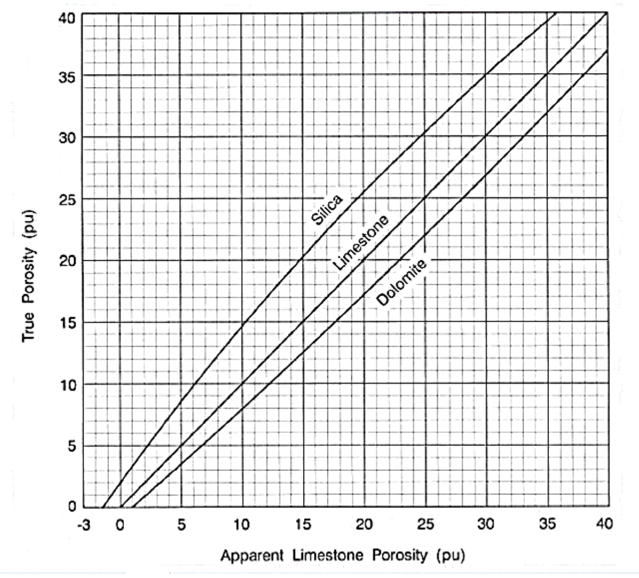

Fig 6: *Compensated neutron chart used to apply lithology correction for neutron porosity (Source: Introduction to Wireline Log Analysis, 2002)*

2.5 Mean porosity

Depending on whether or not a formation has natural gas, two different equations are used to average the density porosity and neutron porosity. The sum of the squares method is used for gas bearing reservoir, while the simple average is used for reservoirs without gas (Das and Chatterjee, 2018). Resistivity logs for the Campanian section in the Dorado- North well roughly overlap and their values range from 0.3 to 1 Ω in most of the section, indicating no show of hydrocarbons. Therefore, the simple average of the corrected neutron porosity and density porosity was calculated using the following equation (Eq. 5).

$$\emptyset_T = \frac{\emptyset_D + \emptyset_N}{2} \qquad \text{(Equation 4)}$$

Where, $Ø_T$ = Total porosity, $Ø_D$ = Density porosity, $Ø_N$ = Corrected neutron porosity

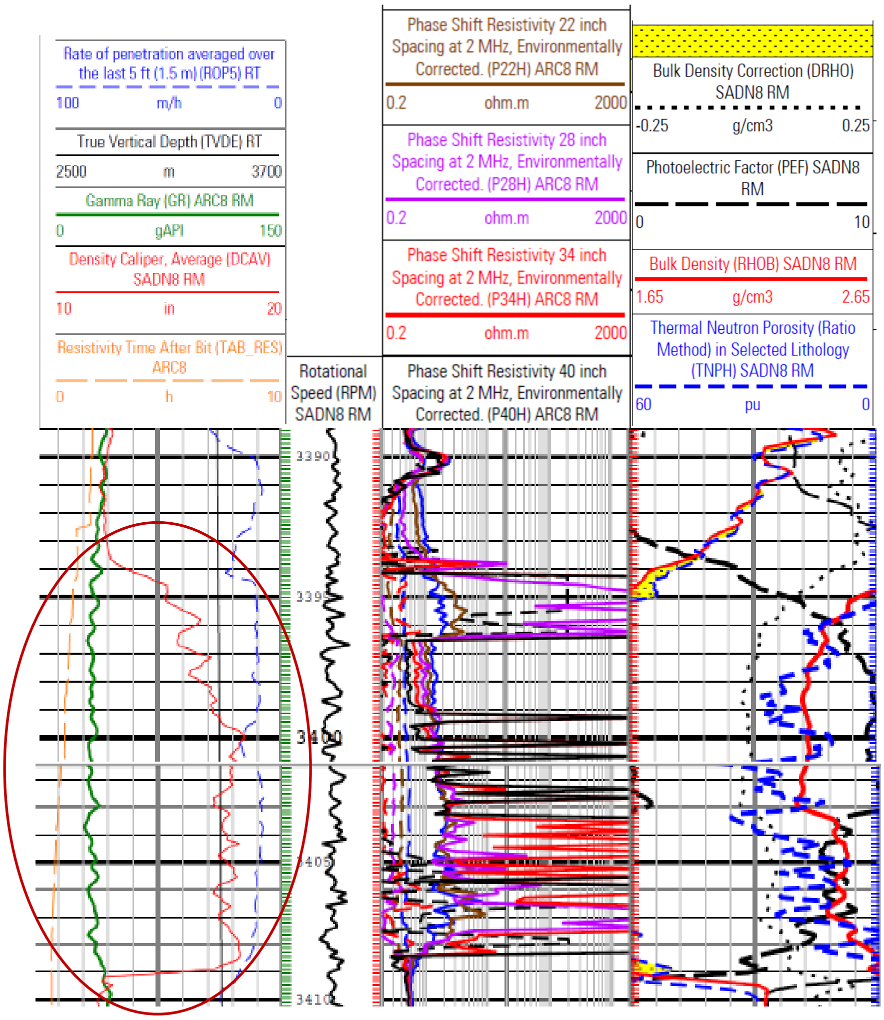

Fig. 7: *Section of the petrophysical log that shows caving in from 3393 to 3410 m in the Dorado-North well (the section with in the red circle)*

2.6 Checking the accuracy of logs

A uniform borehole is essential for the accuracy of petrophysical logs. Caving in gives rise to erroneous/ spurious data. Therefore, the caliper log, which records borehole diameter, is frequently used to determine the accuracy of petrophysical logs.

3. RESULTS AND DISCUSSION

The diameter of the borehole through the Campanian section is around 30.48 cm (12 inches). However, the caliper log has recorded a borehole diameter of about 48.26 cm (19 inches) between 3,393 to 3,410 m depths (Figure 7). This indicates the borehole collapse (caving in) in that depth interval. Petrophysical logs (neutron porosity, bulk density, resistivity, etc.) have recorded spurious data in this depth interval.

3.1 Shale fraction

The variation of the shale fraction through the Campanian section in the Dorado-North well is shown in Figure 8. Average shale fractions in five depth intervals of the Campanian section (Figure 8) are given in Table 1.

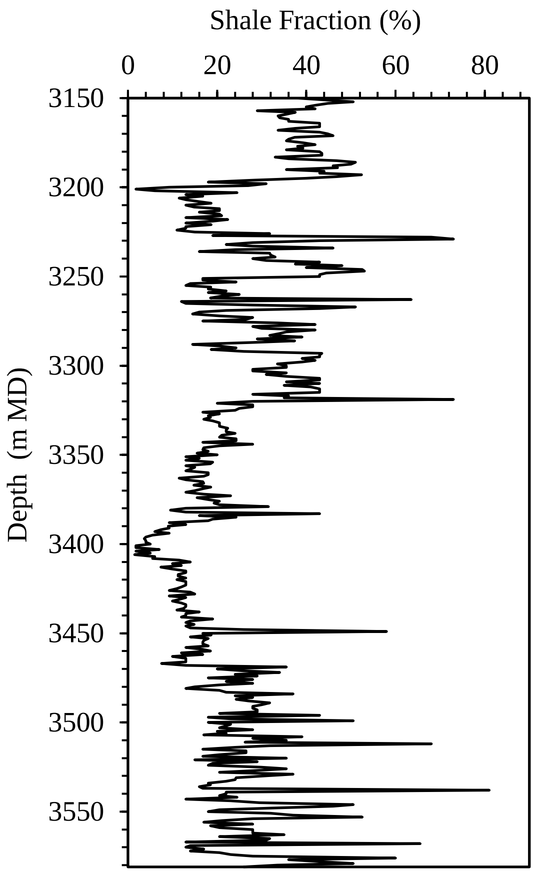

Fig. 8: *The variation of shale fraction in the Campanian section between the depths of 3150 to 3581 m in the Dorado-North well*

Except for a few relatively thin layers (thickness ≤ 1m), a major portion of the Campanian section has less than 50% shale. The shale fraction between the depths of 3393 to 3410 m shows anomalously low values.

The relatively low shale fractions that appear between the depths of 3393 to 3410 m in Figure 8 could be due to erroneous natural gamma counts recorded by caving in between that depth interval. A larger portion of the Campanian section seems to be composed of shaly sand.

3.2 Density Porosity

The cross plot of density porosity and shale fraction in Figure 9 shows that the two parameters have a negative relationship. Density porosity from 3223 to 3225 m depth interval ranges 41% - 44.5%. These values are anomalously high compared to the surrounding porosity values, which is around 25 % (Figure 9).

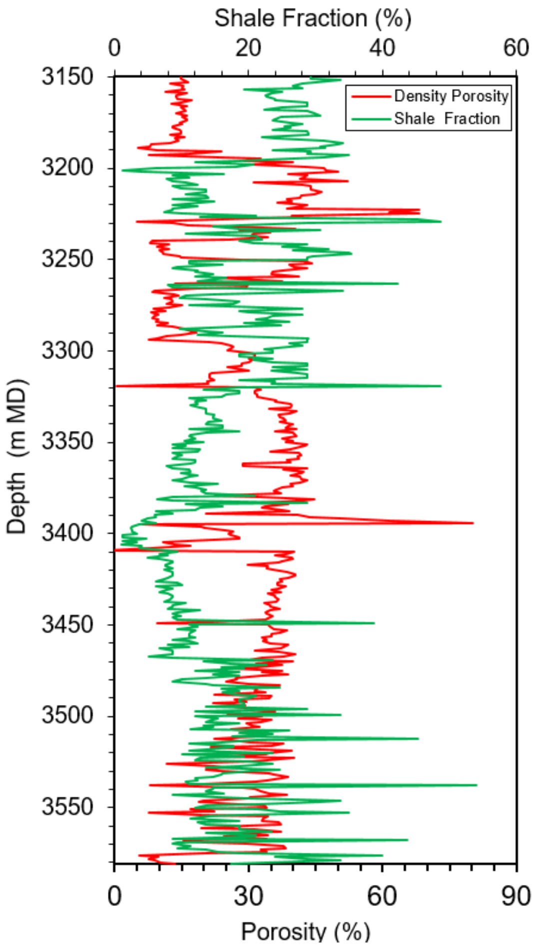

Fig. 9: *The variation of the density porosity and shale fraction in the Campanian section with depth*

Bulk density in this depth interval is around 1.9 g cm^{-3} (Figure 4). Though this is an anomalously low value compared to the surrounding bulk density values, data from the density log seem to be accurate since the caliper log does not show any sign of caving in between the 3223 to 3225 m depth interval (Figure 7).

Density porosities at 3393 m and 3394 m are 41.09% and 53.42%, respectively. These values are anomalously high compared to the porosity values immediately above and below them (Figure 9). In addition, shale fraction and density porosity between the depths of 3393 to 3410 m show anomalously low values (Figure 9). This is due to the caving in from 3393 to 3410 m depth interval in the Dorado-North well (Figure 7).

3.3 Neutron porosity

The cross plot of neutron porosity and shale fraction for the Campanian section is given in Figure 10. Lithology, borehole environment, and clay corrections reduce the porosity values from the neutron porosity log (Figures. 4 & 10).

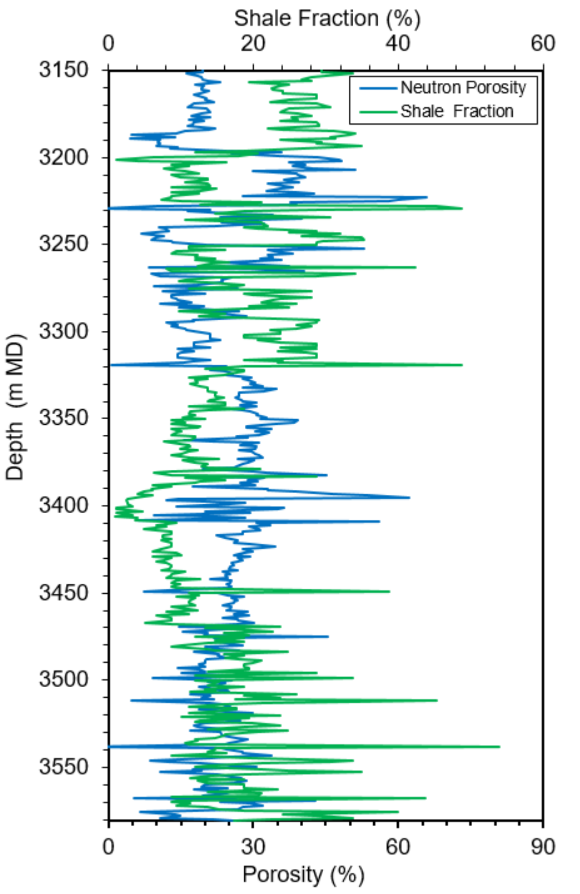

Fig. 10: *The variation of the neutron porosity and shale fraction in the Campanian section with depth*

Similar to the density porosity, neutron porosity also shows a negative relationship with shale content in the Campanian section.

Neutron porosity values from 3395 to 3410 m depths are anomalously low, while that at 3393 m and 3394 m depths are anomalously high (~31% and 35.8%, respectively) compared to the surrounding data (Figure 10).

Corrected neutron porosity values between the depths of 3223 to 3225 m range from ~38.7% to ~43.9%. These values are anomalously high compared to the average values in the section (Figure 10). However, the caliper log does not show any sign of caving in between that depth interval. Therefore, the neutron porosity log in this depth interval should be reasonably accurate.

3.4 Density porosity Vs Neutron porosity

Density porosity and neutron porosity in the Campanian section show roughly similar fluctuations (Figure 11).

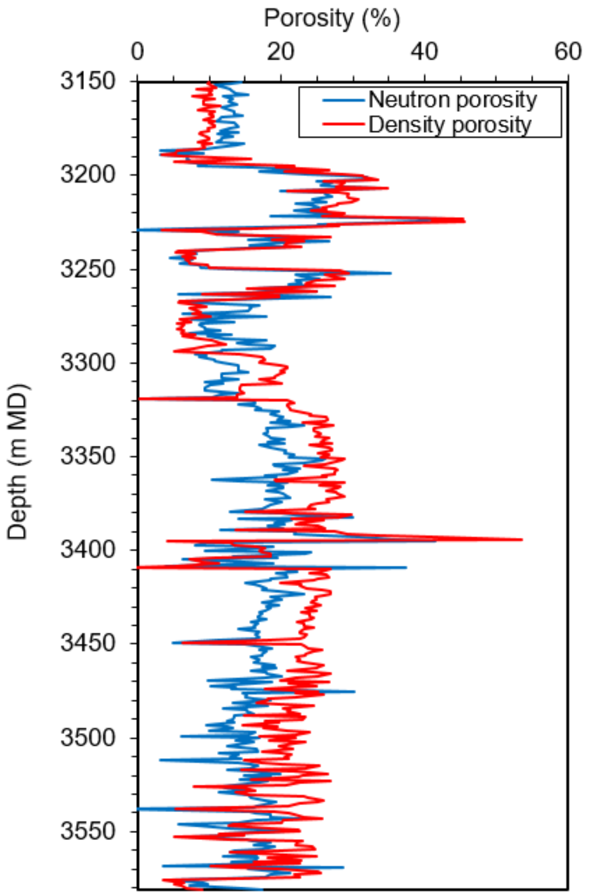

Fig. 11: *Cross plot of corrected neutron porosity and density porosity in the Companian section*

However, the density porosity values are slightly greater than the neutron porosity values. The difference is greater in the depth interval from 3,300 to 3,581 m, compared to the rest of the section above it.

Usually in clean sandstones filled with water, the density porosity overlaps with the neutron porosity (Kim et al., 2016). On the contrary in shale, density porosity values are lesser than neutron porosity values due to the effect of hydrogen atoms adsorbed onto clay (Kim et al., 2016). Accordingly, lithology in the Campanian section cannot be referred to either as clean sandstone or as pure shale. It should be a mixture of sandstone and shale (sandy shale or shaly sandstone). The density porosity and neutron porosity plots between 3,393 to 3,410 m depths overlap each other (Figure 11). This is related to caving in, rather than due to the depth interval having clean sandstone filled with water.

3.5 Average porosity

The distribution of average porosity in the Campanian section, calculated using Eq. 5 is shown in Figure 12. Data from 3,393 to 3,410 m depths are not plotted in the figure, because of their unreliability due to caving in. Based on the average porosity, the Campanian section can be divided into 5 depth sections, of which boundaries are marked in dashed lines in Figure 12.

Table 1 shows the mean porosity values for the five depth intervals. The porosity data between the depths of 3,393 to 3,410 m, where there was caving in, were not taken into account when calculating the mean porosity and the standard deviation for 3,326 to 3,475 m depth interval.

The depth intervals 3,186 – 3,260 m and 3,326 – 3,475 m have an average porosity of around 20%. The depth intervals, 3,150 – 3,185 m, 3,261– 3,325 m, and 3,476 – 3,581 m have average respectively. Averages porosities for the 3,186 - 3,260 m depth interval have a relatively higher standard deviation (9.9 %) compared to the other four depth intervals porosities of 11.3%, 13%, and 16.7 %.

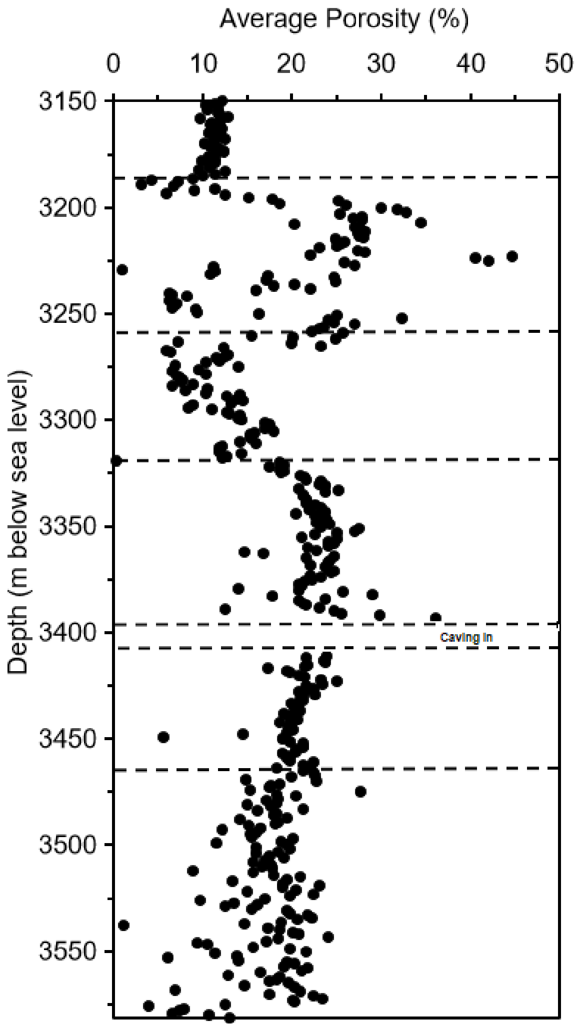

Fig. 12: *The variation of average porosity in the Campanian section with depth*

Table 1: *The mean porosity of the 5 depth intervals shown in Figure 12*

No.	Depth interval (m)	Thickness (m)	Mean porosity (%)	Mean shale fraction (%)
1	3150 - 3185	35	11.3 ± 0.8	39.6 ± 4.7
2	3186 - 3260	74	20.1 ± 9.9	28.0 ± 15.1
3	3261 - 3325	64	13.0 ± 4.6	32.5 ± 11.3
4	3326 - 3475	149	20.5 ± 5.5	15.4 ± 7.38
5	3476 - 3581	105	16.7 ± 4.6	27.8 ± 12.2

Amigun and Odole (2013) and Rider (1986) introduced a qualitative discerption to relate the hydrocarbon reservoir potential of rock to its porosity (Table 2). Based on this classification, it can be inferred that the depth intervals from 3,186 – 3,260 m and 3,326 – 3,475 m in the Campanian section can act as very good hydrocarbon reservoirs. Thickness-wise, these two sections occupy around 46% of the Campanian section. The rest of the three depth intervals, (3,150 – 3,185 m, 3,261 – 3,325 m, and 3,476 – 3,581 m) show fair to good hydrocarbon reservoir potential.

Table 2: *A qualitative description Porosity values for reservoirs (after Amigun and Odole, 2013; Rider, 1986)*

Percentage porosity	Qualitative description
0-5	Negligible
5-10	Poor
10-15	Fair
15-20	Good
20-30	Very good
> 30	Excellent

Though porosity is a parameter frequently used to estimate the reservoir potential of rocks, permeability is also useful to fully understand the reservoir potential of rocks. Islam et al. (2013) state that the quality of a reservoir could be expressed in terms of its shale content. This opinion is supported by the result of this study because the depth intervals having relatively low porosity values have higher shale content and vice versa (see Figures. 9 & 10 and Table 2).

4. CONCLUSIONS

The Campanian section between 3,150 and 3,581 m in the Dorado-North well is mainly composed of shaly sandstone. Almost half of the Campanian section shows very good reservoir potential, while the remainder of the section has fair to good reservoir potential. The quality of a hydrocarbon reservoir depends on its shale fraction. Shale degrade the reservoir potential. Caving in give rise to uncertain data in petrophysical logs. The Campanian section in the Dorado-North well block has very good hydrocarbon potential.

ACKNOWLEDGEMENTS

Authors are thankful to Mr. Saliya Wickramasooriya, former Director General of Petroleum Resources Development Secretariat (PRDS), for providing data; to Mrs. Preeni Withanage, Direct Benefits at PRDS for her myriad support and words of encouragement; two anonymous reviewers for their valuable review comments, and the National Research Council (NRC) Grant No. 17-028 for providing computer workstation for data analysis.

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