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Petrophysics based Reservoir Evaluation of the Cretaceous Lower Goru "C" Sands, Middle Indus Basin, Sindh, Pakistan

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Abstract: This study demonstrates the reservoir investigation of the Cretaceous Lower Goru "C" sand interval using exploratory well data from the middle Indus basin of Sindh. The petrophysical parameters including volume of shale, effective porosity, and water saturation of the investigated reservoir interval were calculated. The shale volume calculation results in 30–35% of non-clean (shale) lithology, which is high as compared to Sawan-01 and Sawan-08 wells. The effective porosity ranges from 12–16%, while the average value of water saturation in the complete interval of "C" sand falls in the range of 50–60%. However, certain zones with relatively lower water saturation values of around 30-50% are also observed. These zones are considered better pay zones in comparison to the other intervals. A "gas effect" phenomenon observed on cross plots represents the area of neutron-density cross-over indicating the presence of lighter hydrocarbons in this reservoir zone interval.

Keywords: Petrophysical parameters; hydrocarbon prospect; reservoir; middle Indus basin.

Introduction

The Sawan gas field is situated in the middle Indus basin, Sindh province (Fig. 1), covering the prospective zone II (Pakistan Petroleum Limited (2018). The Cretaceous rocks of Aptian-Albian Lower Goru Formation (LGF) are widespread in the middle Indus basin and these siliciclastic rock units are thought to have been derived from the Indian Shield (Kadri, 1995). The Aptian-Albian LGF is considered a prolific hydrocarbon reservoir and many gas discoveries are credited to this formation including Sawan, Miano, Kadanwari, and Latif fields (Baig et al., 2016; Dar et al., 2021). Lithostratigraphically, the LGF is composed of sand packages categorized as A, B, C and D sands separated by shale intervals (Fig. 2).

Earlier work on the LGF is documented by various researchers using sedimentological, well log and seismic data (Berger et al., 2009; Baig et al., 2016; Dars et al., 2020). The focus of current study is petrophysical investigation of the Lower Goru "C" sands within the Cretaceous LGF using exploratory well data. The Sawan gas field is comprised of stratigraphic traps and their shape is distally up-dip in the lateral position (Afzal et al., 2009). The Aptian-Albian LGF is characterized by an uninterrupted stratum of sand and shale acting as reservoir rock units with variable reservoir characteristics (Kadri, 1995).

Geological Setting

The Indus Basin is separated into three parts, namely upper, middle, and lower Indus basin (Berger et al., 2009). The study area is situated in the middle Indus basin, district Khairpur, Sindh province (Fig. 1). The area constitutes exploratory well Sawan-01 (longitudes 68°56'01.7"E and latitude 26°59'30.5"N) and Sawan-2 (longitudes 68°54'25.17"E and latitudes 27°01'22.7"N and), whereas Sawan-08 is located in between Sawan-01 and -02. The Sulaiman Range lies in the west and it separates the Sawan gas field from the Baluchistan province.

According to Kazmi, and Jan (1997), the region is surrounded by the Sargodha High in the north whereas the Jacobabad and Mari-Kandkot Highs are located in the south. The eastern side is bounded by the Indian Shield, whereas the Kirthar and Suleiman fold-thrust belts represent the western boundary (Fig. 1).

The Sawan gas field is located at the junction of the middle and lower Indus basins (Ashraf et al., 2020). The regional geology reveals the structural development of the afore-mentioned gas field was rightly organized due to three after-rift tectonic events: (a) Late Cretaceous uplift and erosion, (b) NNW–SSE trending thick-skinned wrench faulting, and (c) Late Tertiary to Recent tectonic uplift of the Jacobabad and Khairpur Highs (Ahmed et al., 2004), resulting in the development of structural traps in the Sawan, Kadanwari, and adjoining extents (Ahmad and Chaudhry, 2002; Berger et al., 2009). The area is characterized by the presence of structural-cum-stratigraphic traps which were formed as a result of the inversion of Jacobabad-Khairpur highs (Berger et al., 2009).

The orientation of the faults is primarily in the NNW-SSE direction in the study area, whereas, most of the fractures are characterized in the SE–NW direction (Ashraf et al., 2020). The region has a high geothermal gradient (Mehmood et al., 2017), where the LGF is acting as a territorial clastic reservoir, and the Sembar Shale as a source rock (Raza et al., 1990). Transgressive marine shales provide a quality seal for reservoir sands (Krois et al., 1998). The Sawan gas field is reported to comprise stratigraphic traps and their shape is distally up-dip in the lateral position (Afzal et al., 2009).

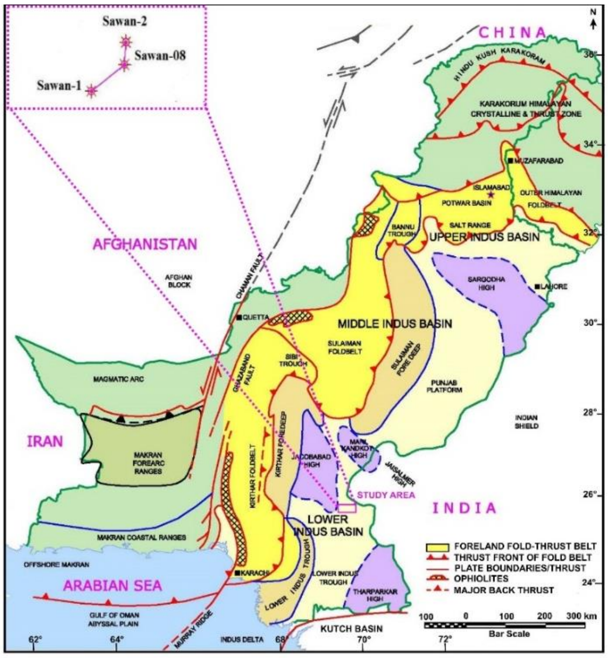

Fig. 1: Tectonic map of Pakistan (modified after Kazmi and Raza, 1982) and location of study area

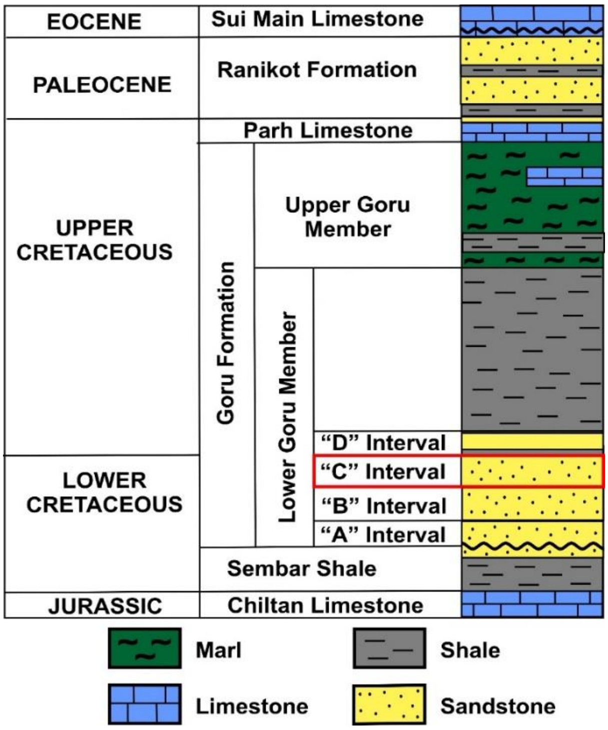

Fig. 2 The stratigraphic column showing the subdivisions of the Lower Goru Formation (modified after Krois et al., 1998; Ahmed et al., 2004) and the study interval "C" sand

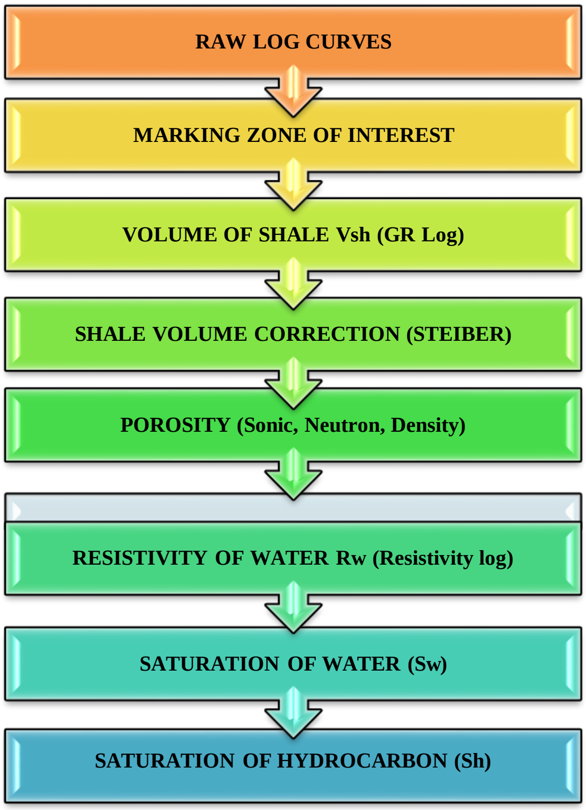

Fig. 3: Flow chart representing the work flow of petrophysical analysis

Initially, zonation on the criterion of clean and non-clean volume was identified. Afterwards, in the light of effective porosity (PhiE ND) further demarcation of promising reservoir units was carried out. Fluid content is usually the last cut-off for conventional petrophysical analysis. Normally, a lower value of water saturation indicates a favorable pay zone, but in the case of the Sawan gas field, the low resistivity phenomenon must be considered during zone demarcation on the basis of fluid content. Conventionally, higher resistivity indicates the presence of hydrocarbons as the pore-filling fluid of the rock, in comparison to the LGF water, which is generally saline in nature. Hydrocarbons are much more resistive to these logs. However, in the low-resistivity case, since there is the presence of conductive minerals in the matrix of the rock unit, the otherwise high resistivity of the hydrocarbon-bearing reservoir is marked by the higher conductivity of the matrix. Also, these low resistivity values are translated quantitatively while calculating water saturation for the reservoir zones. Basic petrophysical parameters that have been worked out from the electrical logs of Sawan-01, Sawan-02 and Sawan-08 wells are presented in Tables 1–6. The zones of interest were marked reading results from all log curves simultaneously including the indication of cross-over between neutron and density log, and the distance between resistivity curves with non-shale sedimentary strata from GR.

Shale Volume

It is computed using a GR log having a scale ranging from 0 to 150 and runs in the first track. For calculation of shale volume, the following equation was used (Rider, 1996):

$$Vsh = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (1)$$

Here, Vshl= Shale volume; GRlog= GR log value; GRmin= slightest value of GR log (clean carbonate and sand); GRmax= Maximum value of GR log (shale).

Calculation of Porosity

The density porosity (ØD), sonic porosity (ØS), average porosity (ØA), and effective porosity (ØE) were calculated using the formulae mentioned below (Asquith and Gibson, 1982; Crain, 1986; Rider,1996)

$$\emptyset D = \frac{\rho ma - \rho b}{\rho ma - \rho f} \quad (2)$$

$$\emptyset S = \frac{\Delta tlog - \Delta tma}{\Delta tf - \Delta tma} \quad (3)$$

$$\emptyset A = \frac{\emptyset N + \emptyset D}{2} \quad (4)$$

$$\emptyset E = \emptyset A \times (1 - Vsh) \quad (5)$$

Where, ØD= density porosity; ρb= log density; ρma= matrix density and ρf= fluid density; ØS =sonic porosity; Δtlog = log interval transit time; Δtma = matrix interval transit time, and Δtf = fluids interval transit time; $\emptyset N$= neutron porosity; $\emptyset A$= average porosity; $\emptyset E$= effective porosity.

Saturation of Water (Sw)

During the log examination of wells Sawan-01, Sawan-02 and Sawan-08, water saturation (Sw) was calculated using Indonesian Equation:

$$Sw = [(a/\emptyset^m) \times (Rw/Rt)]^{1/n} \quad (6)$$

Where, Sw = Space occupied by water, Rw = Resistivity of water, Ø = average porosity, which contains the pore spaces in shale and sand, Rt= observed bulk resistivity, m = cementation factor, n= saturation exponent.

Water and Hydrocarbons Saturation

The hydrocarbon saturation (Shc) is evaluated by the following equation (Rider, 1996):

$$Shc = 1 - Sw \quad (7)$$

Results and Discussion

Petrophysics of Sawan-01

In Sawan-01, the "C" sand of LGF with 71m thickness was examined for Petrophysical attributes. This zone is encountered at the depth of (3284–3355m). The layout of the Petrophysical explanation of the Sawan-01 well is shown in Figure 4a–b comprising seven tracks in total, out of which three tracks show the raw electrical logs, followed by tracks for the volume of shale, effective porosity, saturation of water and a zonation track. The results indicate the shale fraction in the range of 30–40% in the analyzed interval with slight variations. This shale volume has, in turn, affected the effective porosity and two excellent porosity zones are identified with lesser shale volume. The effective porosity is fair to good in the whole "C" sand interval (10–15%) and the water saturation falls in the range of (45–60%) and should be dealt with considering the low resistivity of these sands.

Table 1: Zone of interest in Sawan-01

Zone	Formation	Starting depth (m)	Ending depth (m)	Total thickness (m)
1	Lower Goru (C sand)	3286	3290	4
2	Lower Goru (C sand)	3313	3318	5

Table 2: Summation of Petrophysical properties of reservoir zones of Sawan-01

Property	Zone 1 (3286 - 3290) meters	Zone 2 (3313 - 3318) meters
Volume of Shale	15.44%	11.18%
Porosity	15.92%	15.72%
Effective Porosity	13.42%	13.95%
Water Saturation	48.48%	51.6%
Hydrocarbon Saturation	51.52%	48.4%

For quantification purpose, zones were identified as the most favorable pay zones indicating lower shale volume (33%), good effective porosity (16%), and lower water saturation (~50%). These zones are concluded as potential intervals in terms of hydrocarbons (Figs. 4a–b). A neutron-density cross-over (highlighted as green) is conventionally taken as a direct hydrocarbon indicator (DHI) in these logs.

The target zone in Sawan-01 was marked with a thickness of 4m prospect zone from 3286m to 3290m and thickness of 5m from 3312m to 3318m in Lower Goru "C" sand. The GR curve was leaning towards the non-shale lithology. There was marked separation between LLD > LLM > LLS depicting the hydrocarbon zone. The curve cross-over between porosity logs (neutron and density) indicates the gas effect (Fig. 4).

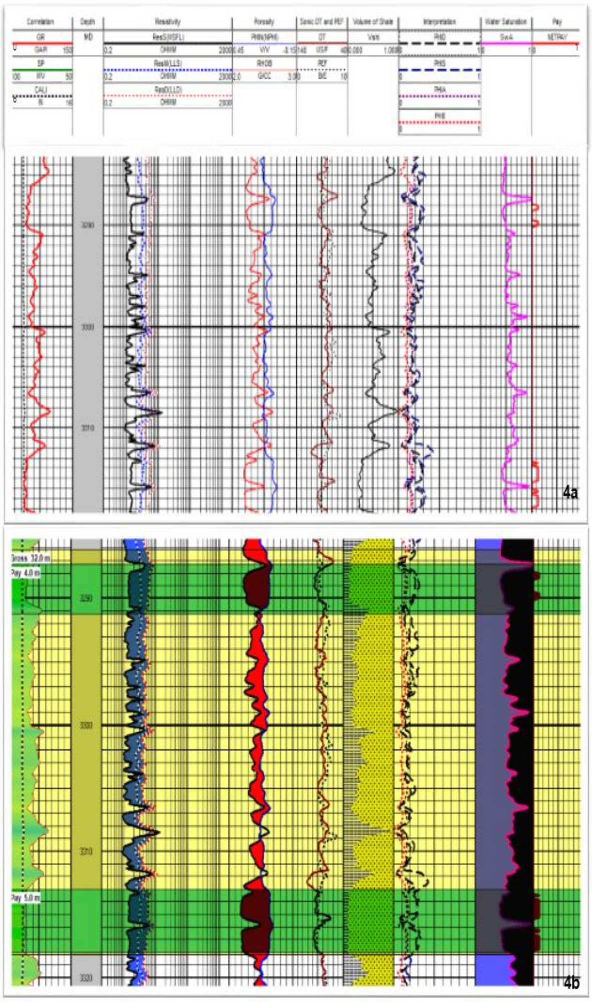

Fig. 4a Raw log display of reservoir zone "C" Sand in Sawan-01. **4b** Petrophysical interpretation of reservoir zone

Petrophysics of Sawan-02

The thickness of "C" sand in this well is around 110m and is encountered at the depth of (3260–3370m) (Figs. 5a–b). The shale fraction appears to be negligible to very minimal (3–5%) in the complete zone of "C" sand. The effective porosity is fair to good (12–14%) whereas the water saturation in this well is higher than that of the Sawan-01 well, ranging from 50% to 70%.

In the Sawan-02 well, the target zone was marked from 3289m to 3303m of 14m thickness in the Lower Goru ("C" sand). The GR curve in the interval was relatively low showing sandy behavior and good borehole condition. The curve cross-over between neutron and density porosity shows a clear gas zone (Figs. 5a–b) (Asquith and Krygowski, 2004).

Table 3: Zone of Interest in Sawan-02

Zone	Formation	Starting depth (m)	Ending depth (m)	Total thickness (m)
1	Lower Goru (C sand)	3289	3303	14

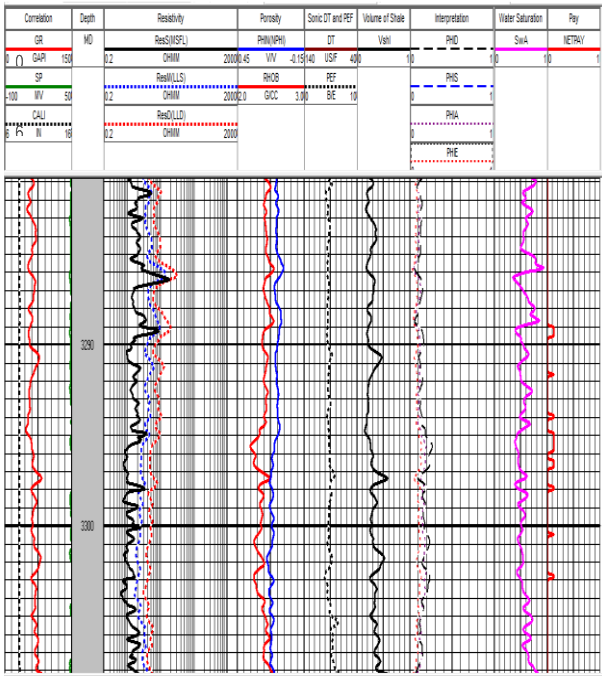

Fig. 5a Raw log display of reservoir zone ("C" Sand) in Sawan-02

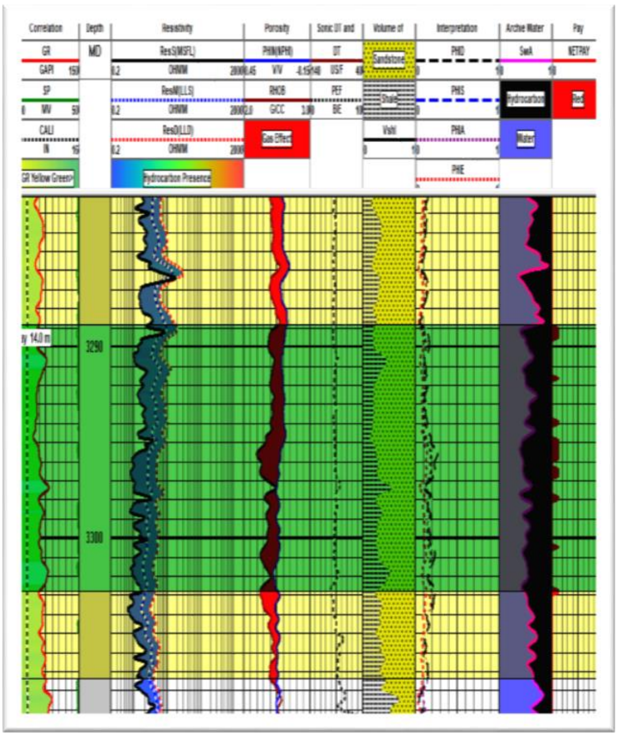

Fig. 5b: Reservoir zone of ("C" Sand) in Sawan-02

Table 4: Summation of Petrophysical Properties of reservoir zones of Sawan-02

Property	Zone 1 (3289 – 3203 meters)
Volume of Shale	25.39%
Porosity	15.11%
Effective Porosity	11.11%
Water Saturation	49.43%
Hydrocarbon Saturation	50.57%

Petrophysics of Sawan-08 Well

The reservoir zone throughout Sawan well-08 displayed very good porous zones with high hydrocarbon saturation. The interval zone was marked from 3265m to 3320m in the Lower Goru "C" sand (Figs. 6a–b). The GR curve in formation was relatively low, showing sandy behavior. The borehole was gauged and in good condition in the interest zone.

Table 5: Zone of interest in Sawan-08

Zone	Formation	Starting depth (m)	Ending depth (m)	Total thickness (m)
1	Lower Goru (C Sand)	3265	3320	55

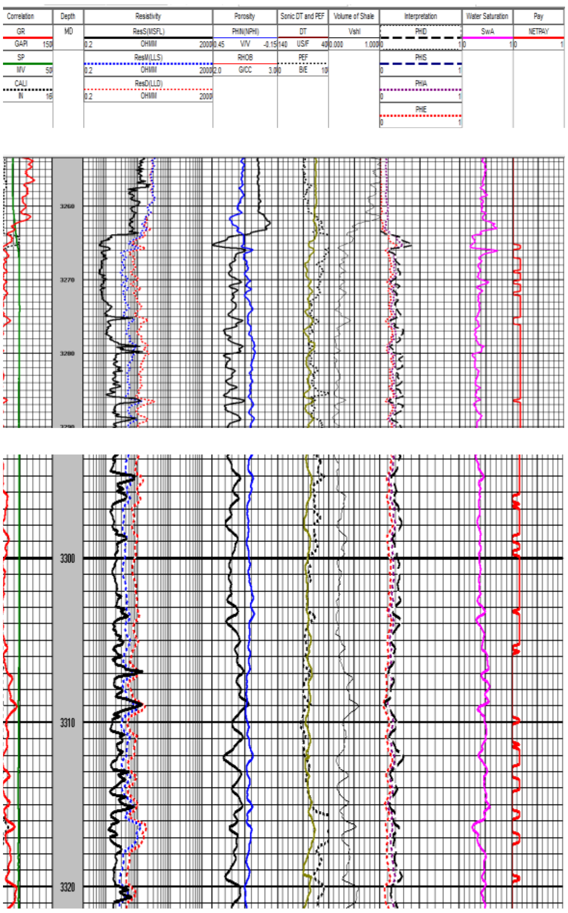

Fig. 6a: Raw log display of reservoir zone (C Sand) in Sawan-08 (3265m – 3294m) and (3294m – 3320m)

Table 6: Summation of petrophysical properties of reservoir zones of Sawan-08

Property	Zone (3265 - 3320) meters
Volume of Shale	22.21%
Porosity	16.19%
Effective Porosity	12.58%
Water Saturation	39%
Hydrocarbon Saturation	61%

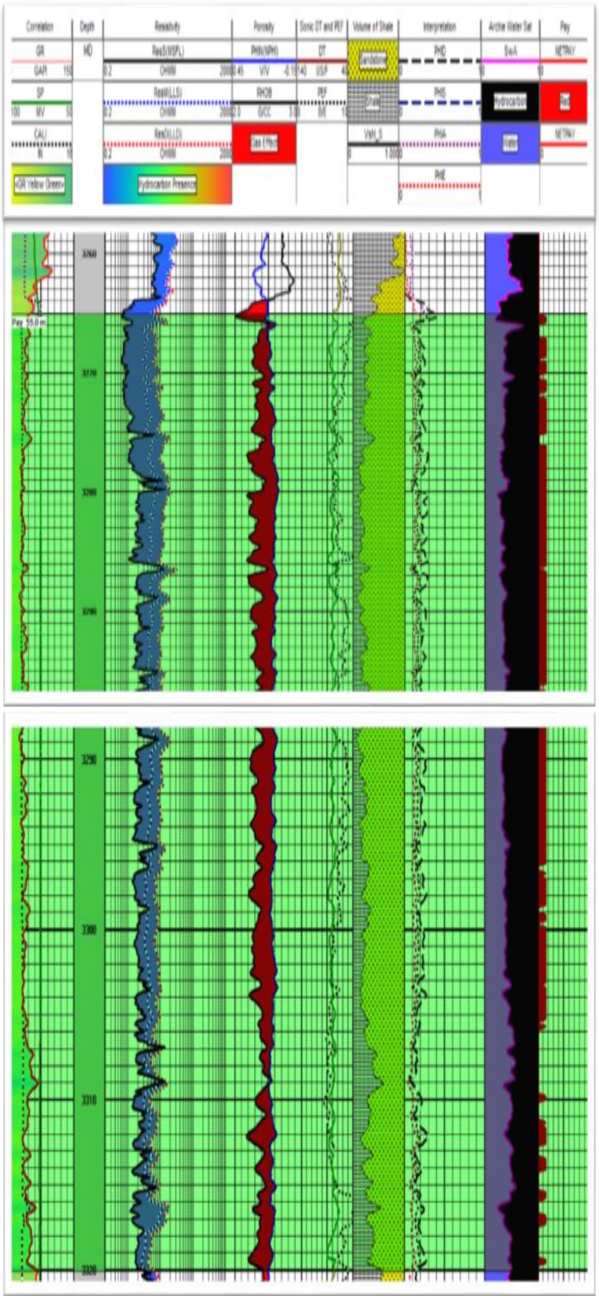

Fig. 6b: Reservoir zone ("C" Sand) in Sawan-8 (3265m – 3297m), and (3297m – 3320m)

Neutron-density Cross plots

For conventional rocks like sandstone, dolomite and limestone, neutron-density cross plots are very helpful. However, a bit more complex lithology like calcite cemented sandstone or dolomitic limestone cannot be demarcated. The cross plots were prepared for three wells (Figs. 7–9). All the three cross plots indicate sandstone lithology for "C" sand horizon thus reaffirming the suitability of this zone for further analysis. An interesting phenomenon termed as "gas effect" is visible on these cross plots, particularly in the Sawan-01 well. This represents the area of neutron-density cross-over on the electric log layout and represents the presence of lighter hydrocarbons in this reservoir zone.

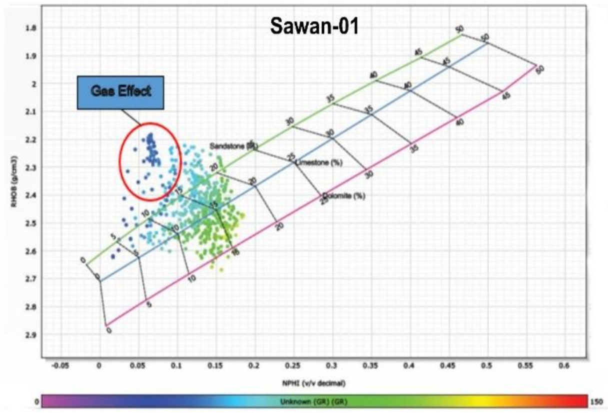

Fig. 7: Neutron-density cross plot of Sawan-01 well

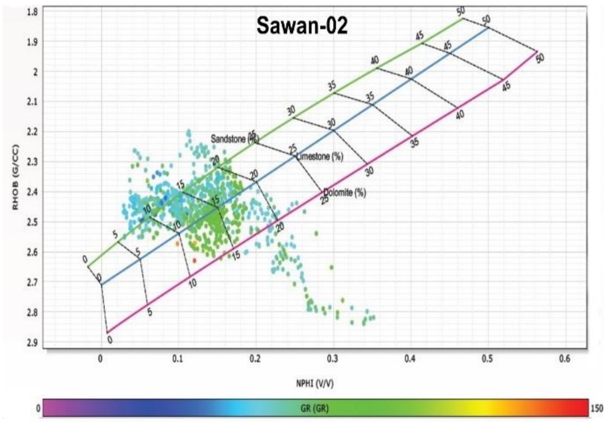

Fig. 8: Neutron-density cross plot of Sawan-02 well

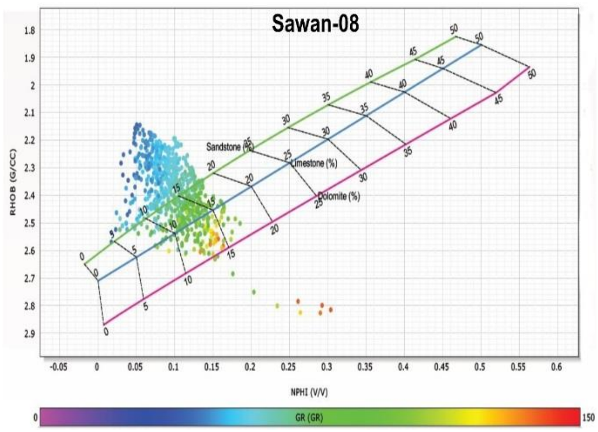

Fig. 9: Neutron-density cross plot of Sawan-08 well

Conclusion

The results of the Petrophysical investigation of three wells support and validate the highly prospective nature of "C" Sand member of the LGF in the Sawan gas field. The "C Sand" member has shown good reservoir potential in Sawan-01, Sawan-02 and Sawan-08 on basis of Petrophysical analysis of prospective zones. The "C" Sand in Sawan-08 has shown greater net pay potential and hydrocarbon saturation compared to Sawan-01 and Sawan-02. The reservoir zone is pinching out towards the east and south-east of Sawan wells.

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