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# Petrophysical modelling of the Cretaceous Lower Goru Formation, Lower Indus Basin, Pakistan

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## Abstract

In this paper, a comprehensive petrophysical investigation of the Cretaceous Lower Goru Formation in six wells of Sawan Gas Field was made. For this purpose, the clay volume, types of porosities, qualitative permeability, hydrocarbon and water saturation, movable hydrocarbon index, bulk volume of water, and dominant lithology were assessed. On the basis of these petrophysical parameters, two hydrocarbons bearing zones were identified in studied reservoir. The zone-01 having considerable thickness with good reservoir characteristics in all wells with estimated gas in place of 223124813.6 cf while zone-02 has good reservoir characteristics only in Sawan-07 and -08 wells with estimated gas in place of 53471927.4 cf. The proposed stratigraphic model of reservoir levels showed the pinching of pay zones towards NE of the field. This pinching of the pay zones towards NE can be attributed to the lateral facies changes triggered by sea level fluctuations.

*Keywords:* Petrophysical modelling; Hydrocarbon; Reservoir characterization; Cretaceous; Goru Formation; Lower Indus Basin

## 1. Introduction

In Pakistan's Lower Indus Basin, the Sawan Gas Field is considered to be one of the primary gas-producing areas (Kazmi and Jan, 1997). The Indian Shield, the Indian Plate's margin, and the Sukkar Rift all encircle the Lower Indus Basin to the east, west, and north, respectively (Kazmi and Jan, 1997). It is comprised of the Kirthar Fold Belt, Kirthar Foredeep, and Thar Platform (Fig. 1). The Kirthar Fold Belt, which is thrusted southward along the western margin of the Indian Plate, was created as a result of transpression along the Chaman Fault (Jadoon et al., 1994). The Kirthar Foredeep is a longitudinally leaning region of subsidence with perpendicular orientation towards its southern margin. (Kadri, 1995). The Thar Platform, which makes up the Lower Indus Basin's eastern region, is a broad monocline that dips westward and lacks any sedimentary surface outcrops. It is tectonically the stable part due to greater distance from the collisional zone of the Eurasian and Indian plates (Kadri, 1995).

The Lower Indus Basin's generalized stratigraphy ranges from Triassic Wulgai Formation to the Pliocene Siwaliks. The Early Cretaceous (Neocomian) Sembar Formation is the principal source rock of the study area, while the shales of the Lower Goru, Mughal Kot, Ranikot and Ghazij formations are also considered the potential source rocks. The Lower Goru Formation, Sui Upper, and Sui Main Limestone serve as the basin's major reservoirs, In addition, a secondary reservoir may be found in the Habib Rahi limestone (Ali et al., 2005). The Sirki shale caps the Habib Rahi limestone, and the Ghazij shales serve as seal rocks for the Eocene reservoirs (Kadri, 1995; Fig. 2). Formations encountered in Sawan Gas Field range from Cretaceous to Quaternary (Fig. 2). The Lower Goru Formation of Pakistan's Southern and Central Indus Basin has been a substantial hydrocarbon producer over the past twenty years. (Munir et al., 2011). The Lower Goru Formation is comprise of two parts: the upper part, which is primarily made of shale, and the lower part, which is made up of medium- to coarse-grained reservoir character sandstone. The lower part is further separated into the sand-intervals i.e., A, B, C, and D intervals (Krois et al., 1998). During 1990's these sands were investigated over the wider region and subsequent to the internal studies of OMV Pakistan of Sawan "C" sand, the Oolithica Geoscience Ltd. created the first comprehensive sequence stratigraphic model in 2003.

The sand type, porosity, permeability, hydrocarbon bearing zones and depositional environment of these sands were discussed by different researchers using data from different wells of Sawan Gas field (McPhee and Enzendorfer, 2004; Berger et al., 2009; Munir et al. 2011; Azeem et al., 2016). The current research work is more focused on the reservoir characterization as well as lateral facies change of C-sand using wireline logs.

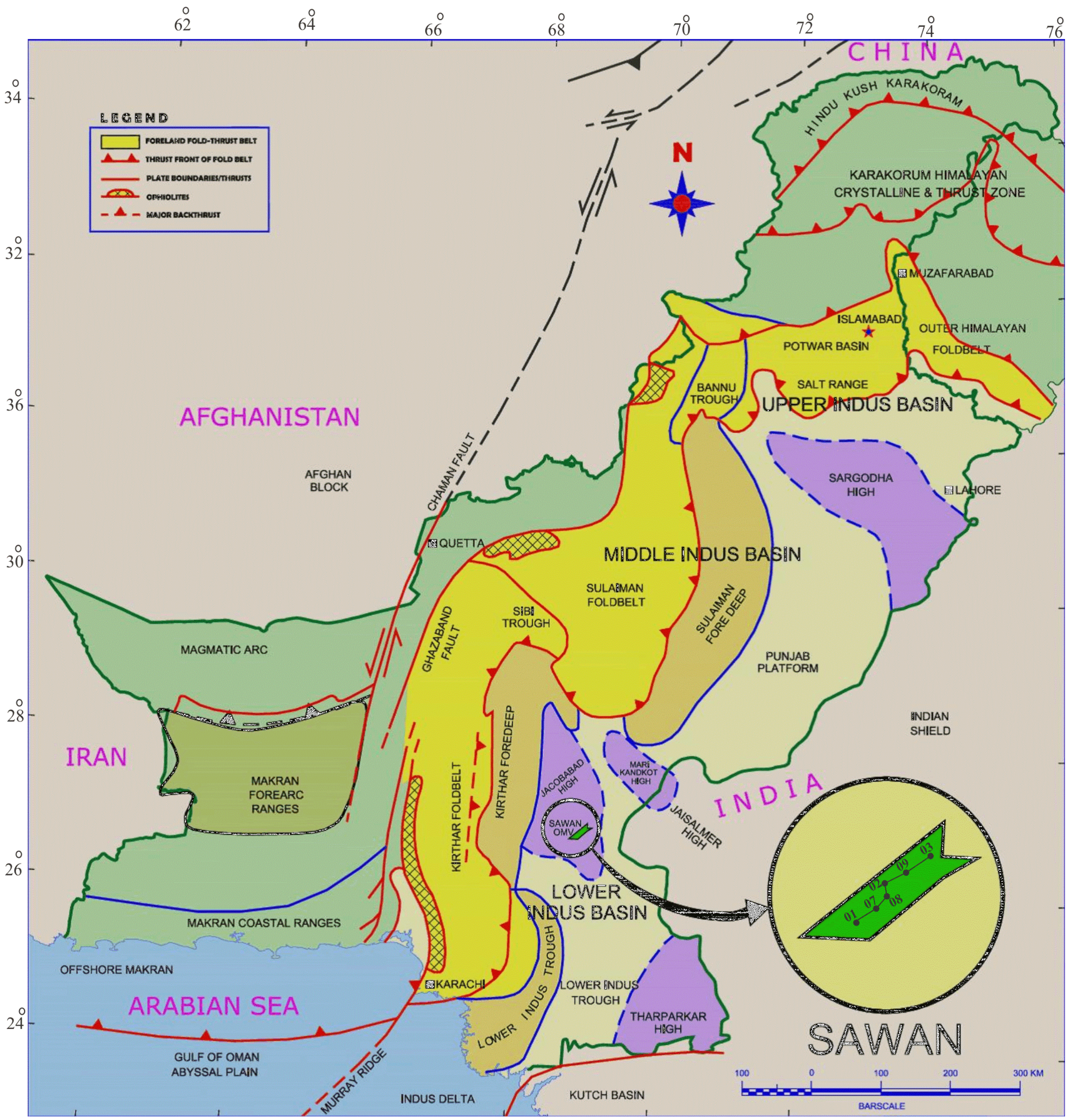


Fig. 1. Map of Pakistan's tectonic and sedimentary basins (after Aziz and Khan, 2003).

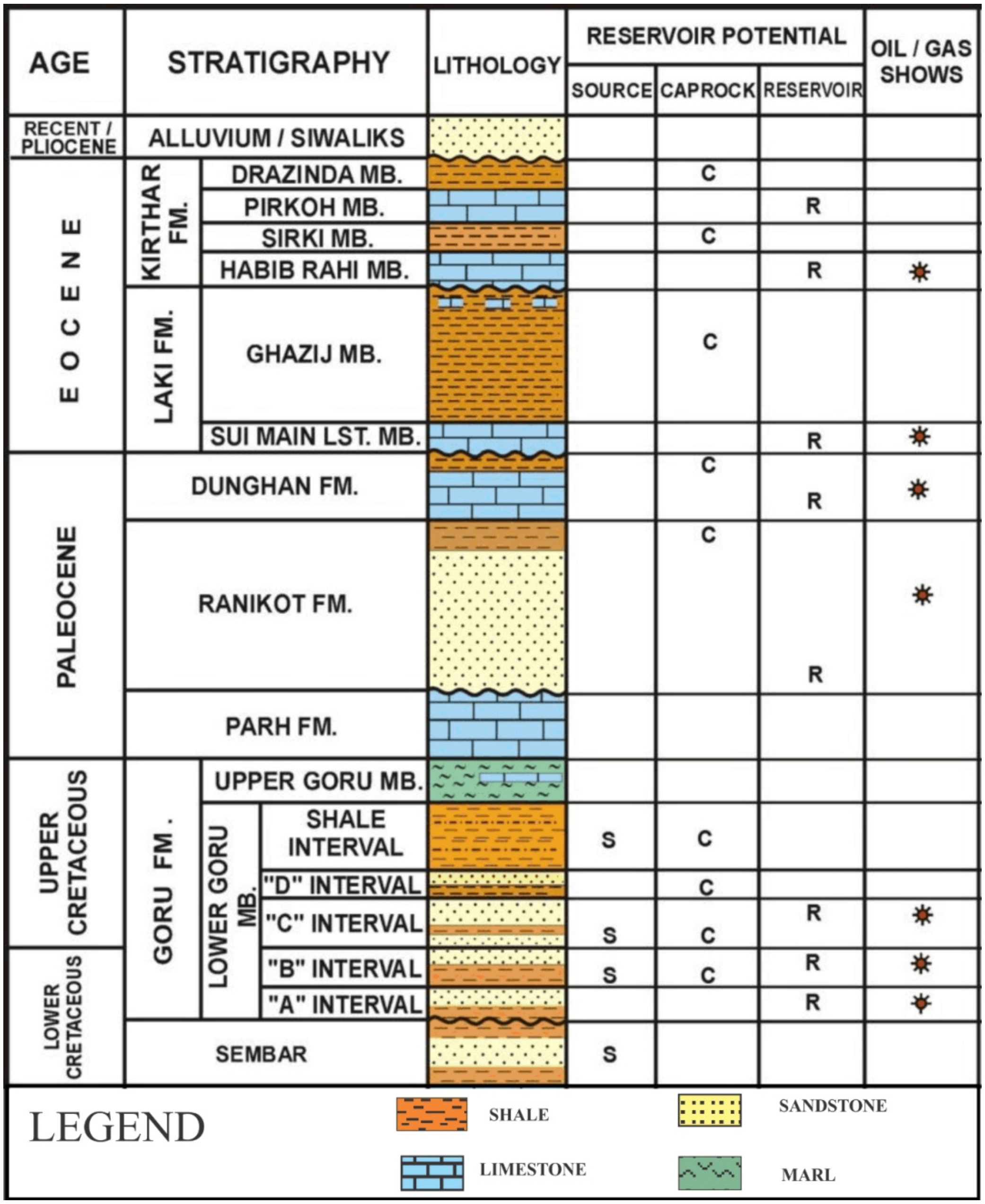

Fig. 2 The generalized stratigraphic chart of Sawan gas field (after Anwer et al., 2017).

## 2. Materials and methods

To achieve the objectives of the current research, a complete suite of conventional well logs of six public domain wells (i.e., Sawan-01 to -03 and Sawan-07 to -09) were obtained from Landmark Resources, via the Directorate General of Petroleum Concession (DGPC), Pakistan. These logs include Gamma Ray (GR), Caliper (Cali), Spontaneous Potential (SP), Resistivity (MSFL, LLS, LLD), Neutron (NPHI), Density (Rhob) and Sonic log (DT). Different zones of interest were marked for hydrocarbons using the following formulas:

### *2.1. Volume of Shale*

The shale volume (Vsh) was computed from Gamma Ray Log (GR) with the following formula (Rider, 1996):

$$V_{sh} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

Where, Vsh = volume of shale; $GR_{log}$= reading of GR log; $GR_{min}$ = minimum GR log and $GR_{max}$ = maximum GR log

*2.2. Porosity*

The density ($\Phi_S$), sonic ($\Phi_S$), average ($\Phi_A$) and effective ($\Phi_E$) porosities were calculated in the current study by the formulas of different researcher (Asquith and Gibson, 1982; Crain, 1986; Rider, 1996; Asquith et al., 2004).

*2.3. Water and Hydrocarbons saturation*

The Modified Simindox equation was applied to compute the formation's water saturation (Sw), and the following equation was used to get the formation's hydrocarbon saturation (Shc) (Rider, 1996):

$$Shc = 1\text{-}Sw$$

*Bulk Volume of Water (BVW)*

The portion of the overall volume of rock that is filled with water is known as BVW. According to BVW values, clastic sedimentary rocks have a range of grain sizes. (Fertl and Vercellino, 1978) and the formula below is used to calculate it (Asquith and Gibson, 1982; Crain, 1986):

$$BVW = (\Phi_E) \times Sw$$

*2.4. Hydrocarbons' Movability*

The movable hydrocarbon index was computed from the formation water saturation of the uninvaded zone and the water saturation of the flushed zone (Asquith and Gibson, 1982; Crain 1986; Rider, 2002).

$$MHI = Sw/Sx_o$$

Where, Sw = uninvaded zone's water saturation, $Sx_o$= flushed zone's water saturation

*2.5. Net pay*

In order to determine the net pay in the examined wells of Lower Goru Formation, the following cut-off values for petrophysical characteristics were used:

$$Vshl < 0.40,\ Sw < 0.50 \text{ and } \Phi E > 7$$

The formation water resistivity (Rw) was calculated by SP charts, while neutron and density curves of Schlumberger (2009) were employed to determine the lithology of the examined reservoir. All these logs were analyzed in Geographix software of Landmark Resources (LMKR).

## 3. Results and discussion

*3.1 Attributes of the reservoir zones*

*3.1.1 Sawan-01 well*

In Sawan-01 well, total two reservoir zones were finalized after detailed interpretations. Both zones are clean with volume of shale 17.1% in Zone-01 and 9.6% in Zone-02, density porosity ranging between 8-20%, neutron porosity between 6-12%, average between 7-16%, and effective porosity between 5-13 %. Calculated water saturation ranges between 50-63 %. Each zone has qualitative permeability with lower moveable hydrocarbon index (i.e. 0.24-0.35), which shows that the hydrocarbon in pore spaces of the formation are moveable. The petrophysical results for these zones are given in Figure 3a, b and Table 1.

*3.1.2 Sawan-02 well*

Two reservoir zones were marked in Sawan-02 well, the zone-01 is at the depth interval 3272-3303 m (31 m) and zone-02 range in depth between 3313-3318 m, having five meters thickness. The average values of Vsh, ($\Phi_A$), ($\Phi_E$) Sw and Shc is 4 %, 13 %, 12 % , 66 % and 34 % respectively (Fig. 4a; Table 1). These petrophysical parameters indicate that zone 1 is clean, having good effective porosity but has little hydrocarbon potential. The zone-02 has 26 % Vsh, 13 % ($\Phi_A$) and 9% ($\Phi_E$), 74% Sw and 26 % Shc (Fig. 4b; Table 1). The MHI is 0.45 which indicates that hydrocarbon can move to the well bore during production.

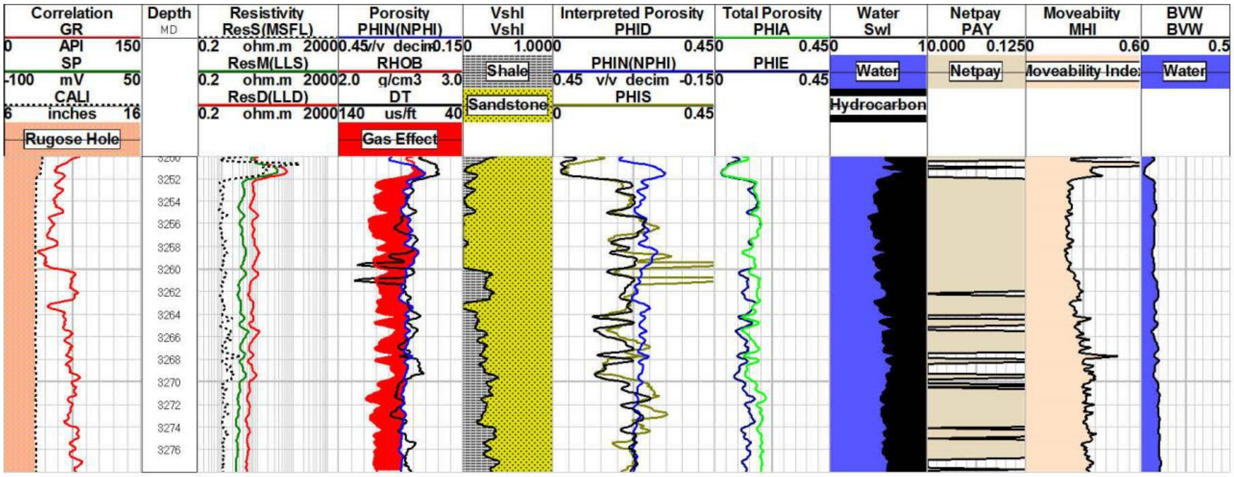


Fig. 3a. Petrophysical interpretations of zone-01 of the studied formation in Sawan-01

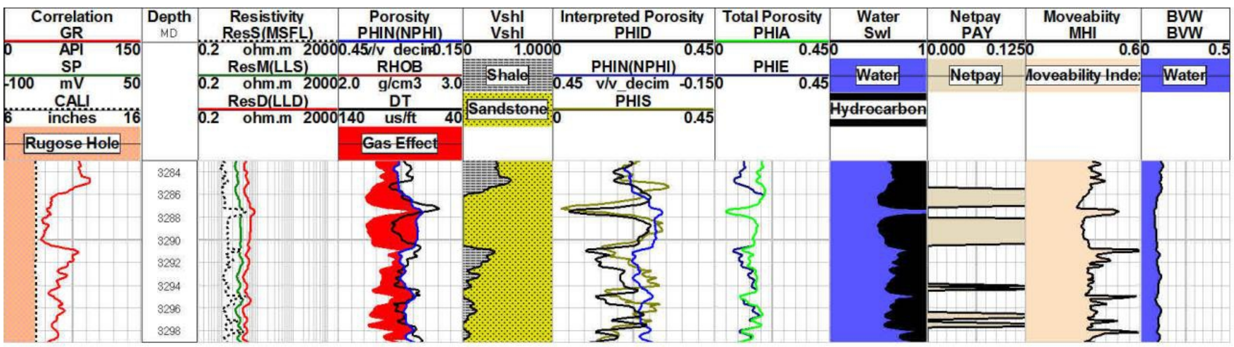


Fig. 3b. Petrophysical interpretations of zone-02 of the studied formation in Sawan-01

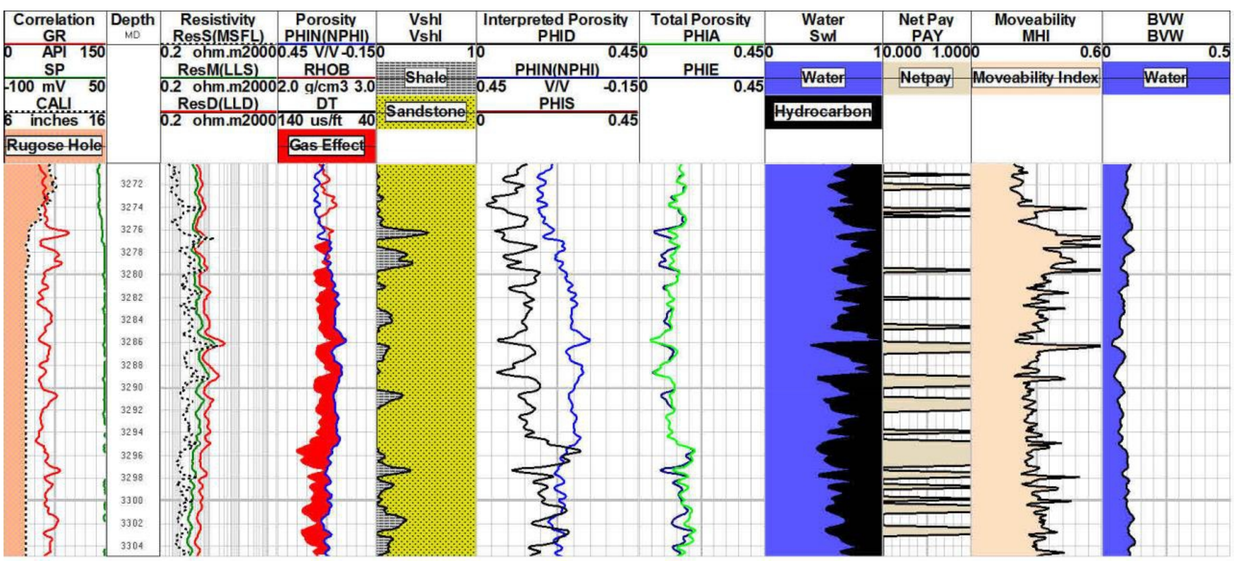


Fig. 4a. Petrophysical interpretations of zone-01of the studied formation in Sawan-02.

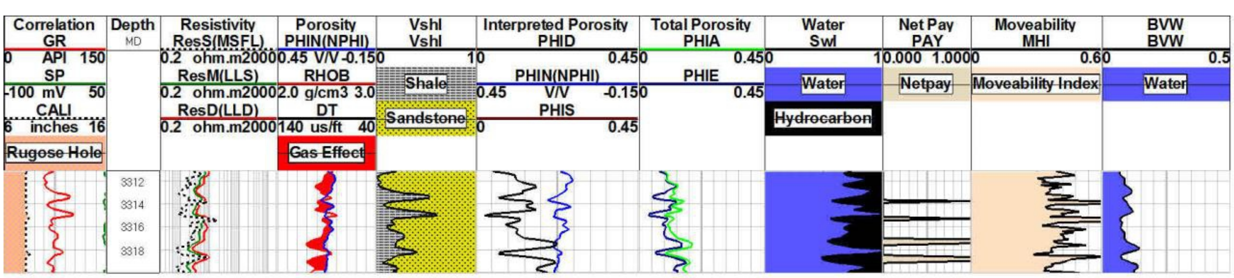


Fig. 4b. Petrophysical interpretations of zone-02 of the studied formation in Sawan-02.

### *3.1.3 Sawan-03 well*

Only one zone of interest was identified in the studied formation with depth interval 3405-3424 m (19 m) in Sawan-03 well. The calculated average Vsh for this zone is 9 %, average $(\Phi_A)$ and effective $(\Phi_E)$ porosities are almost the same, i.e. 16%, density porosity is 21 % and neutron porosity is 11 %. The water saturation interpreted for this zone is 57 % and hydrocarbon saturation is 43%. The BVW is almost constant throughout the zone, indicating irreducible water saturation as result of this type of water, the formation will yield water free hydrocarbons. The borehole condition was observed as good and the zone also has qualitative permeability. The detail petrophysical results for this zone is given in Fig. 5 and Table 1.

### *3.1.4. Sawan-07 well*

In Sawan -07 well, two zones of interest were identified, where the zone-01 starts at depth intervals 3275-3305 m (29 m). The petrophysical parameters for this interval show 3% volume of shale, 7% neutron porosity, 21% density porosity, 14% average porosity, 14% effective porosity, 44% water saturation and 56% hydrocarbon saturation (Fig. 6a; Table 1). There is no rugosity in the borehole, so all these parameters are reliable. Due to cross ever existence between neutron and density, high resistivity and more than 50% hydrocarbon saturation, this zone is considered as sweat. The second zone, i.e, zone-02, lies at depth 3313-3329 m (17 m), having negligible shale volume, high effective porosity (i.e., 13%) but low hydrocarbon saturation (i.e. 40%) (Fig. 6b; Table 1).

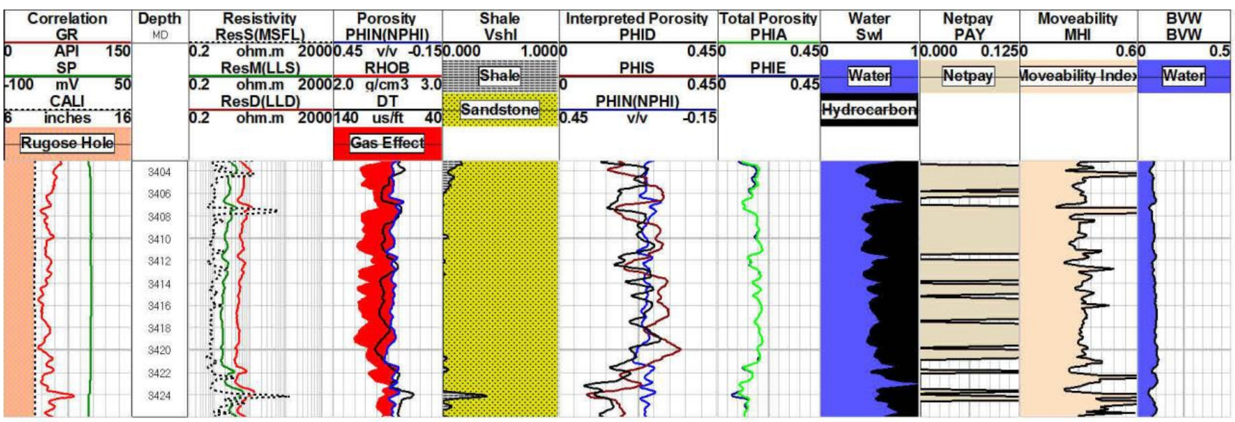


Fig. 5. Petrophysical interpretations of zone-01 of the studied formation in Sawan-03.

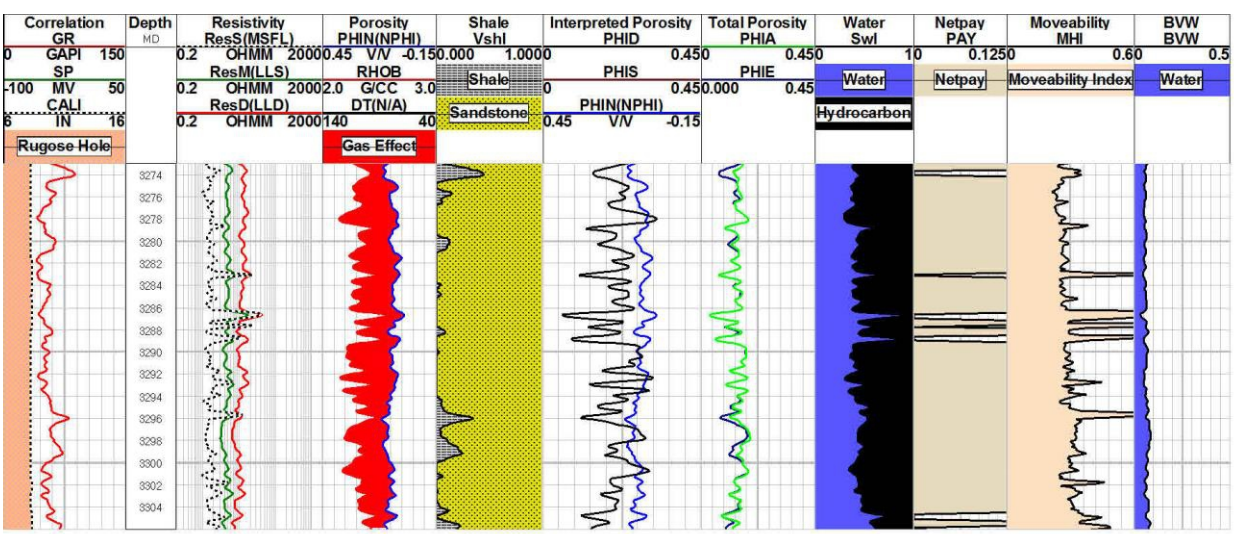


Fig. 6a Petrophysical interpretations of zone-01 of the studied formation in Sawan-07.

*3.1.5 Sawan-08 well*

Again, two zones after log interpretation have been finalized for hydrocarbon potential. The average petrophysical parameters Vsh, ($\Phi_A$), ($\Phi_E$), Sw and Shc for zone-01 having 29 m thickness are 3 %, 14 %, 14 %, 44 % and 56 % respectively (Fig. 7a, Table 1). Qualitative permeability and gas effect have also been observed. The MHI value for this zone indicates that the hydrocarbon will move to the wellbore and will produce, while due to almost constant BVW value, the hydrocarbon will be water free. The zone-02 with 17m thickness is similar to zone-01 in petrophysical parameters except water saturation which is high (i.e., 60%) in the latter case (Fig. 7b; Table 1).

*3.1.6 Sawan-09 well*

In this well, one zone, i.e., zone-01, ranging in depth 3275-3304m was finalized after its logs interpretation. It is very clean with effective porosity of 15%, neutron porosity of 15 %, density porosity of 15% and water saturation of 57% (Fig. 8; Table 1). Borehole condition is good throughout the zone and MHI revealed the movability of hydrocarbon to the wellbore. This zone has less hydrocarbon potential in the well.

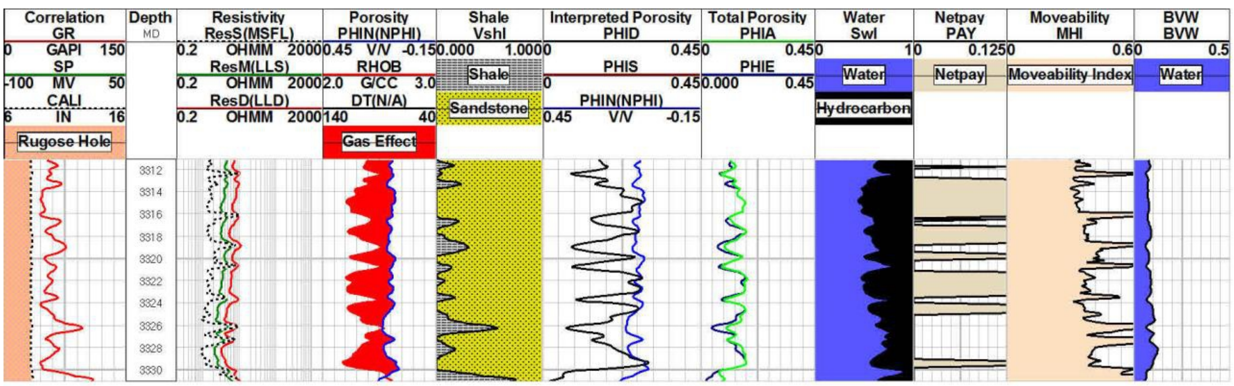


Fig. 6b. Petrophysical interpretations of zone-02 of the studied formation in Sawan-07.

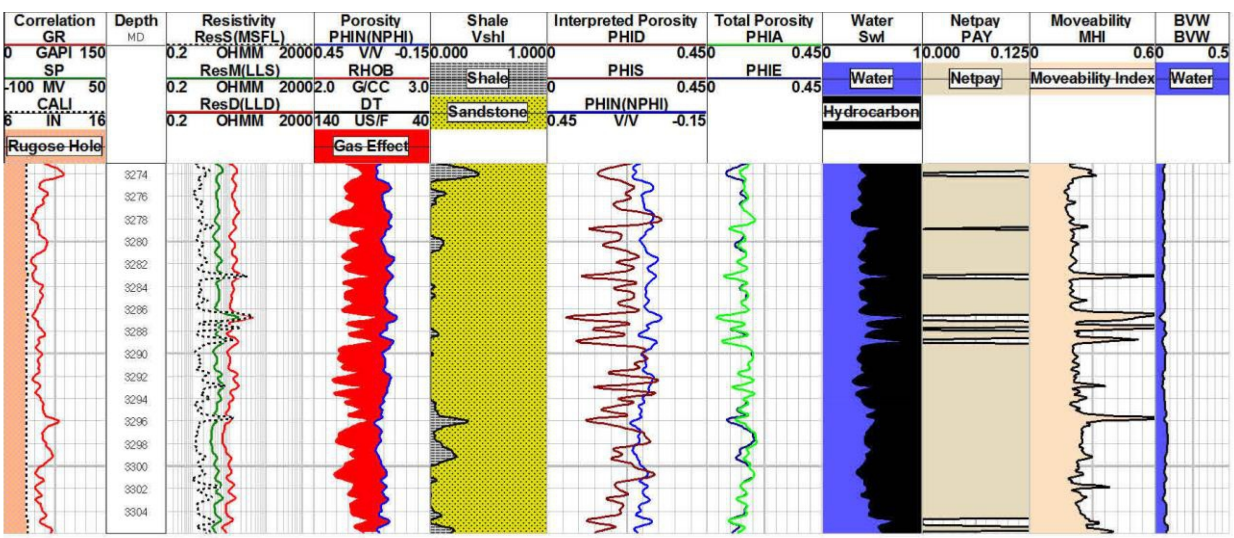


Fig. 7a Petrophysical interpretations of zone-01 of the studied formation in Sawan-08.

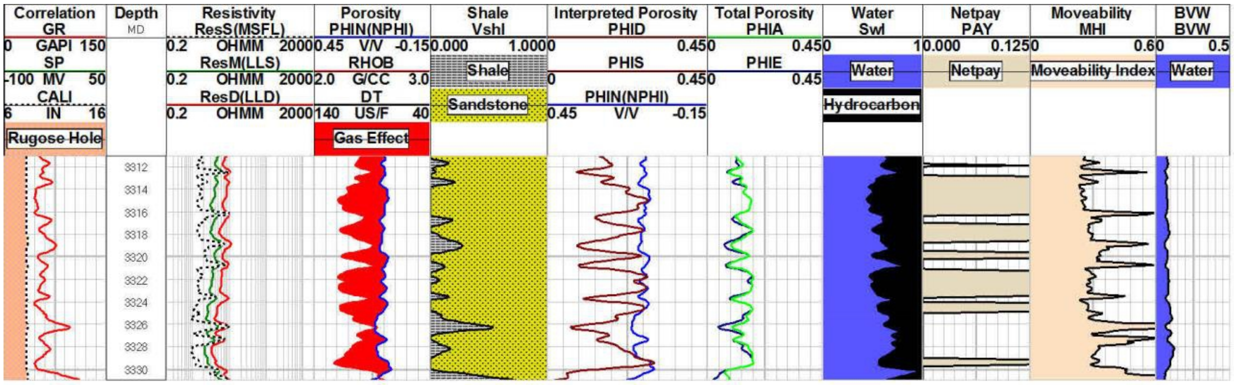


Fig. 7b Petrophysical interpretations of zone-02 of the studied formation in Sawan-08.

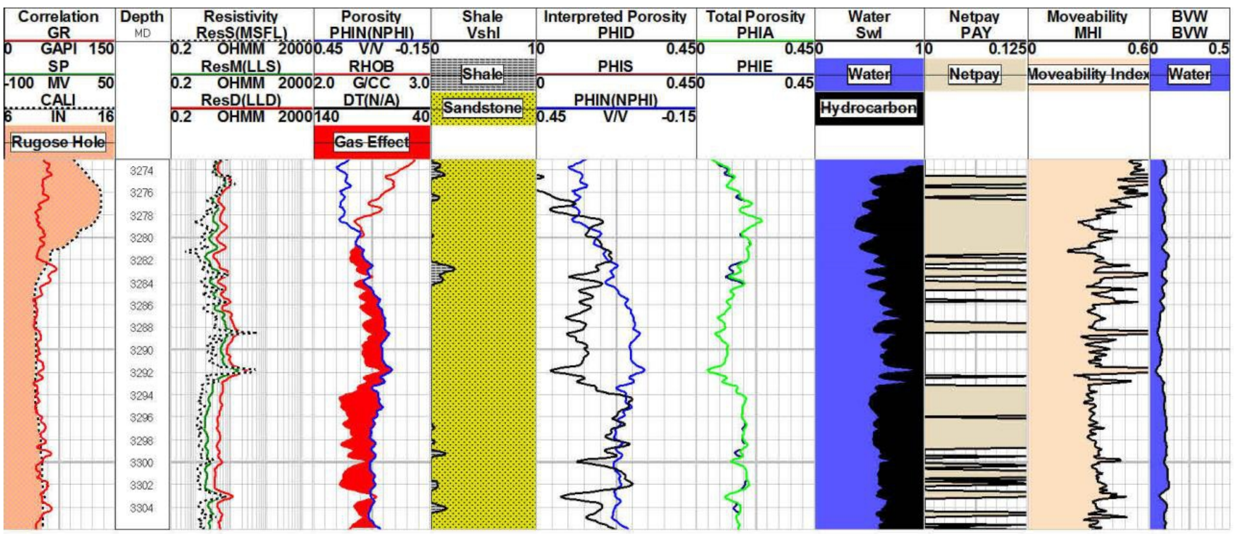


Fig. 8 Petrophysical interpretations of zone-01 of the studied formation in Sawan-09.

Table 1. Petrophysical results of different zones in the studied formation, Sawan Gas Field.

| Well | Zones | Thickness | VSH % | ΦD % | ΦN % | ΦA % | ΦE % | Sw % | SH % | MHI | BVW | Net Pay% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sawan-01 | i.3252m-3276m | 24m | 17.1 | 20.2 | 12 | 16.1 | 13.3 | 50 | 50 | 0.27 | 0.08 | 86 |
| | ii.3285m-3297m | 12m | 9.6 | 20 | 10 | 15.3 | 13.8 | 59 | 41 | 0.35 | 0.09 | 40.2 |
| Sawan-02 | i.3272m-3302m | 30m | 07 | 14.4 | 12 | 13.2 | 12.2 | 48 | 52 | 0.32 | 0.08 | 31.3 |
| | ii.3313m-3318m | 5m | 26 | 12.8 | 14 | 13.4 | 9.9 | 60 | 40 | 0.45 | 0.09 | 14.7 |
| Sawan-03 | i.3405m-3424m | 19m | 0.9 | 21.4 | 11 | 16.6 | 16.4 | 57 | 43 | 0.36 | 0.09 | 73.2 |
| Sawan-07 | i.3275m-3304m | 29m | 03 | 21.8 | 07 | 14.7 | 14.2 | 40 | 60 | 0.32 | 0.06 | 95.2 |
| | ii.3313m-3329m | 16m | 09 | 20 | 09 | 14.6 | 13.4 | 50 | 50 | 0.43 | 0.08 | 55.6 |
| Sawan-08 | i.3275m-3304m | 29m | 03 | 21.8 | 07 | 14.7 | 14.2 | 40 | 60 | 0.25 | 0.06 | 94.4 |
| | ii.3313m-3329m | 16m | 08 | 20 | 09 | 14.6 | 13.5 | 50 | 50 | 0.34 | 0.08 | 55 |
| Sawan-09 | i.3275m-3304m | 29m | 1.6 | 15.7 | 15 | 15.6 | 15.3 | 57 | 43 | 0.37 | 0.08 | 57.5 |

*3.2 Lithology*

The neutron & bulk density cross plots of Schlumberger (2009) reveal that the studied formation is dominantly consist of sandstone as shown in Figure 9.

*3.3. Gas in place (Cubic feet)*

The volume of gas in place in zone-01 and 02 of the studied six wells was determined by using Dewan (1983) formula;

$$G = 43560 \times \Phi\ (1\text{-}Sw) \times h \times A$$

Where, G=gas, 43560= conversion factor from acre-ft to $ft^3$ , A= Area in acre h = Height in feet, $\phi$ = Average porosity, 1-SW = Hydrocarbon saturation (gas saturation).

*3.4 Stratigraphic correlation*

The stratigraphic correlation of the Lower Goru Formation in the studied wells were carried out, which showed the thinning to the north-east direction (Fig. 10; Table 1). Thickness of the Zone 01 reduced in the Sawan-03, whereas the Zone-02 is not present in the Sawan-09 and Sawan-03 which are located in the NE of the Sawan block (Fig. 10). It is either due to graben structures in the area or due to stratigraphic pinch out. Seismic data interpretation of the area is needed for its confirmation.

Table 2. Total Gas in place in Zone-01 and Zone-02 of the studied formation, Sawan Gas Field.

| Reservoir | Zones | Total Gas in Place |
|---|---|---|
| Lower Goru | Zone-01 | 223124813.6 cf |
| | Zone- 02 | 53471927.4 cf |

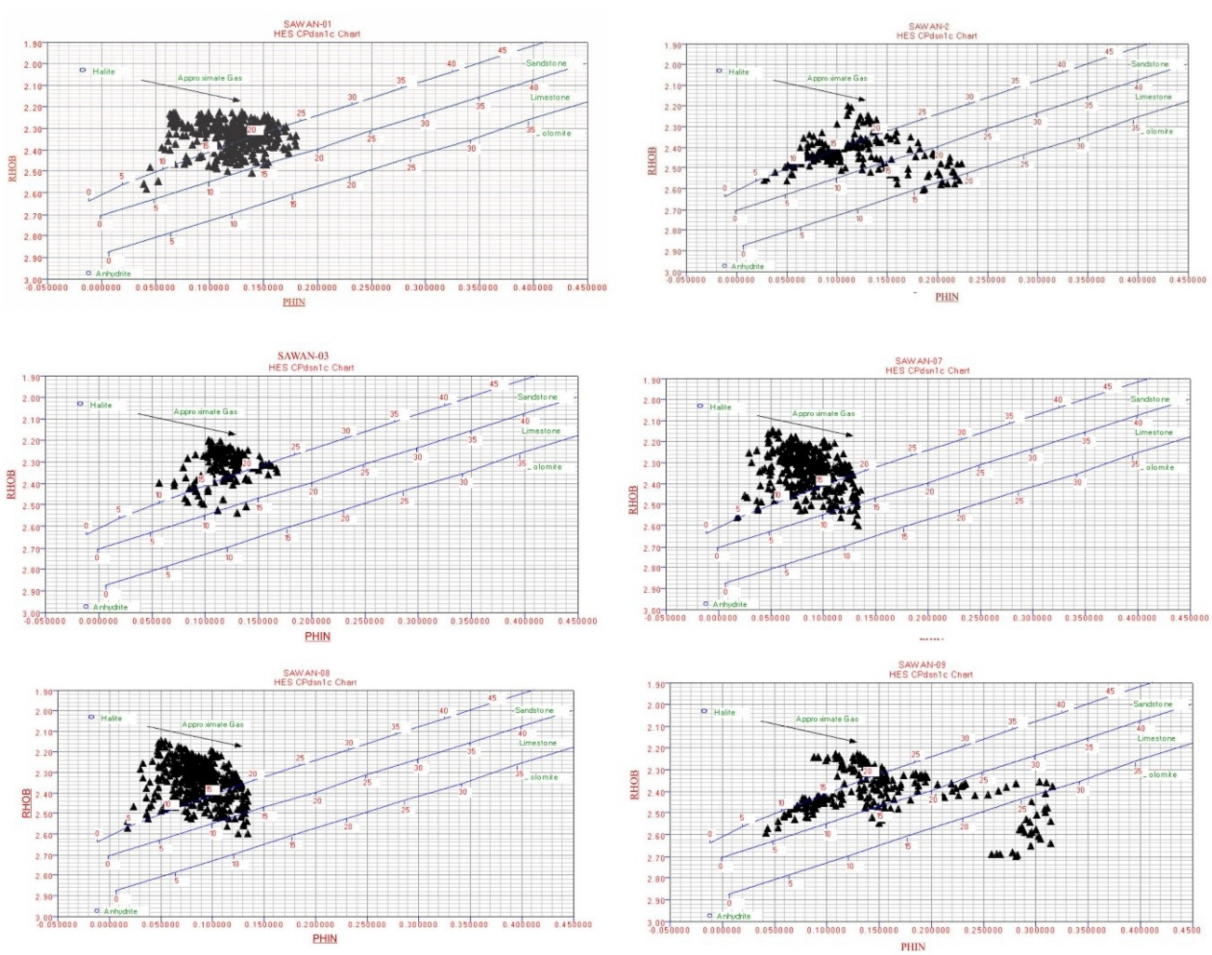


Fig. 9. Lithology of the studied formation encountered in Sawan Gas Field.

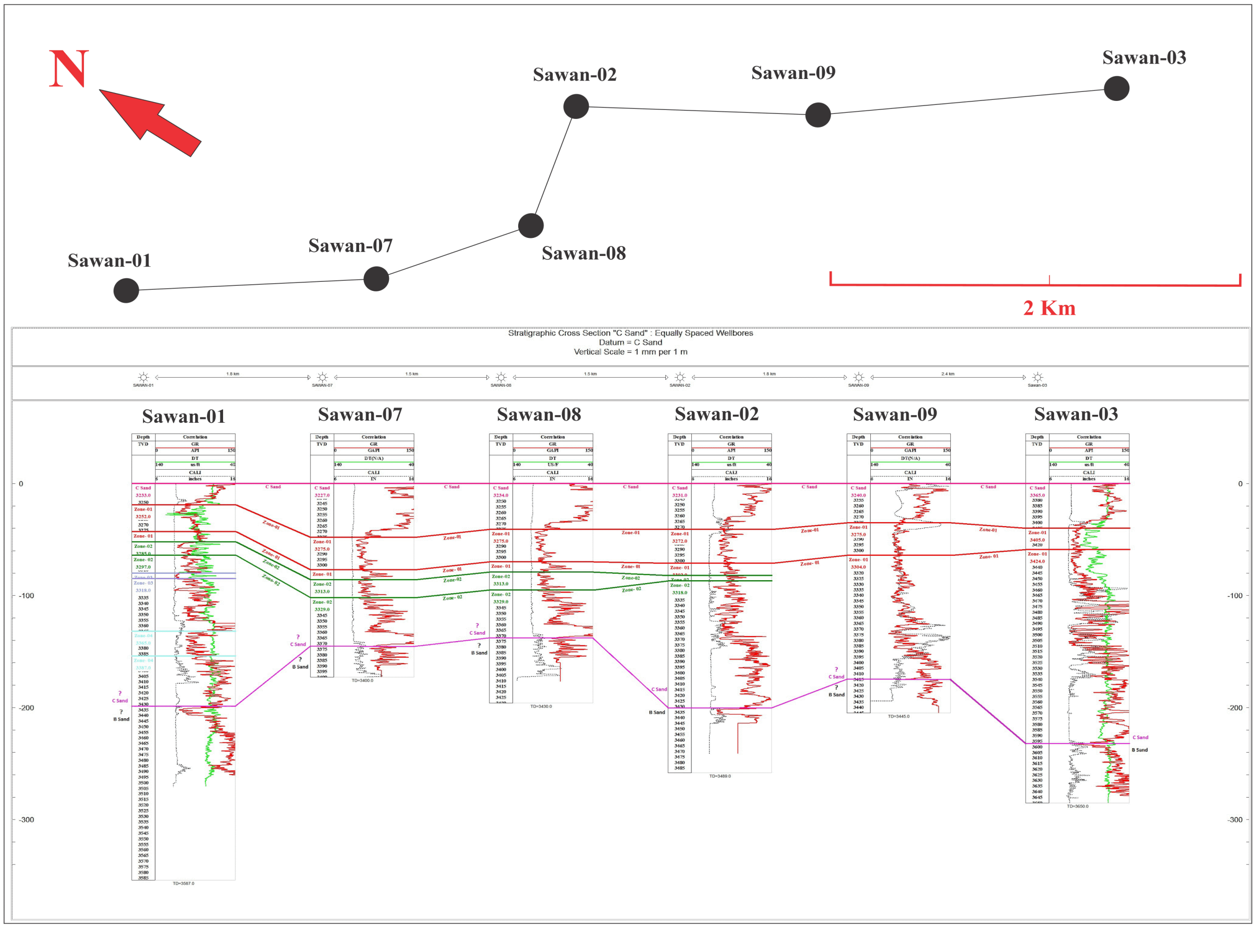


Fig. 10 The spatial Distribution of possible zones of interest in C-sand, Lower Goru Formation.

## 4. Conclusions

Different petrophysical parameters from the six wells (Sawan-01 through 03 and Sawan-07 through 09) of the Sawan Gas Field, Central Indus Basin, Pakistan, were used to determine the reservoir properties of the Cretaceous Lower Goru Formation. After a detailed investigation, following conclusions are drawn:

- Zone-01 in all wells except Sawan-03 and -09 is very clean, permeable having good porosity (i.e. 13-16%) and high hydrocarbon potential ranging between 50-60%. The low movable hydrocarbon index (MHI) values show that the hydrocarbon in the pores of reservoir will flow easily to the well bore.
- Zone-02 is poor in hydrocarbon in all wells except Sawan-07 and -08 where the hydrocarbon saturation is 50%, effective porosity is 13 % with good borehole conditions and qualitative permeability. The neutron porosity and bulk density cross plots indicated that the studied formation is dominantly comprised of sandstone with subordinate clay and other minerals.
- The petrophysical parameters of the studied wells revealed that reservoir quality decreases in NE direction due to possible lateral facies change.

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## *Author's Contribution*

*Waqar Ahmad, Nowrad Ali and Khalid Latif proposed the main concept and involved in write up. Shah Faisal Zeb and Shahab Khan helped in collection of field data and preparation of figures. Syed Mamoon Siyar did provision of relevant literature, review and proofread of the manuscript. All authors have read and agreed to the published version of the manuscript.*

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