Reservoir Potential Evaluation of the Middle Paleocene Lockhart Limestone of the Kohat Basin, Pakistan: Petrophysical Analyses

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Abstract: The Lockhart Limestone is evaluated for its reservoir potential by utilizing wireline logs of Shakardara-01 well from Kohat Basin, Pakistan. The analyses showed 28.03% average volume of shale (Vsh), 25.57% average neutron porosity (NPHI), 3.31% average effective porosity (PHIE), 76% average water saturation (Sw), and 24.10% average hydrocarbon saturation (Sh) of the Lockhart Limestone in Shakardara-01 well. Based on variation in petrophysical character, the reservoir units of the Lockhart Limestone are divided into three zones i.e., zone-1, zone-2 and zone-3. Out of these zones, zone-1 and zone-2 possess a poor reservoir potential for hydrocarbons as reflected by very low effective porosity (1.40 and 2.02% respectively) and hydrocarbon saturation (15 and 5.20%), while zone-3 has a moderate reservoir potential due to its moderate effective porosity (6.50%) and hydrocarbon saturation (52%) respectively. Overall, the average effective porosity of 3.31% and hydrocarbon saturation of 24.10% as well as 28.03% volume of shale indicated poor reservoir potential of the Lockhart Limestone. Lithologically, this formation is dominated by limestone and shale interbeds in the Shakardara-01 well. Cross-plots of the petrophysical parameters versus depth showed that the Lockhart Limestone is a poor to tight reservoir in Shakardara-01 well and can hardly produce hydrocarbons under conventional drilling conditions.

Key words: Lockhart Limestone, Paleocene, reservoir, Shakardara, Kohat Basin.

Introduction

Kohat Basin (Figs. 1A, 1B) is assumed to be one of the most prolific basins for hydrocarbon exploration in Pakistan because of the recent discoveries of various oil fields such as Nashpa, Makori, Gurguri and Shakardara (Nawaz et al., 2015). This sub-basin is comprised of those sedimentary sequences which provide potential reservoirs in many oil fields like Triassic Kingriali, Jurassic Datta and Cretaceous Lumshiwal formations (Kadri, 1995; Nawaz et al., 2015). The Kohat Basin contains hydrocarbon fields, which are of prime importance from hydrocarbon exploration point of view also include Shakardara Oil Field. This field is situated in Kohat district and Chanda-1 well was the first exploratory well, drilled in 1999 to a total depth of 4,788 meters (m) followed by Chanda deep-1, drilled in the year 2000 to a total depth of 5,100 m. Both drilled wells proved to be commercially productive which further increased the reservoir worth of the field. The OGDCL has recently, successfully explored four oil fields in the Shakardara area with the cumulative production of 1,200 barrels per day (i.e. 190 m^3/d) of oil and around 5 million cubic feet (i.e. 140,000 m^3) of gas. However, in early nineties, a number of oil wells were left abandoned, which primarily included Tolanj-1, Kahi-1 and Sumari-1 and thus, search for other reservoir rocks like Lockhart Limestone started (Nawaz et al., 2015).

The Lockhart Limestone was studied extensively by the geoscientists (Sameeni et al., 2009; Hasany and Saleem, 2012; Hanif et al., 2013; Ahmad et al., 2014; Ali et al., 2014; Nawaz et al., 2015; Khan et al., 2016; Saddique et al., 2016; Ahsan and Shah, 2017; Khattak et al., 2017; Khan et al., 2018; Siyar et al., 2018; Awais et al., 2019). According to Hasany and Saleem (2012), Lockhart Limestone is comprised of massive, argillaceous limestone in the Meyal Oil Field, Potwar sub-basin, Pakistan. The Lockhart Limestone is penetrated in few wells and is a heterogeneous quality reservoir thereby produced very limited hydrocarbons (Hasany and Saleem, 2012). In the Hazara area, 11% porosity is recorded in the Lockhart Limestone (Nawaz et al., 2015). The Lockhart Limestone encountered in the Chanda deep-1 well of the Kohat Basin has 9.5% porosity, 5.5% volume of shale and 70.6% hydrocarbon saturation and considered as a good quality reservoir (Nawaz et al., 2015). According to Saddique et al. (2016), the Lockhart Limestone is mainly comprised of 36 m limestone in Kahi-1 well, Kohat Basin, Pakistan. The limestone is characterized by vuggy and crystalline porosities and is considered as a hydrocarbon bearing formation (Saddique et al., 2016). In the Hazara-Kashmir basin, the porosity of the Lockhart Limestone ranges from 0.5% (tight) to 4% (Ahsan and Shah, 2017). Siyar et al. (2018) studied reservoir properties of the Paleocene Lockhart Limestone in Chanda-1 well, Kohat Basin and interpreted a reservoir zone within this formation having 4% volume of shale, 5% average porosity, 4% effective porosity and 85% hydrocarbon saturation.

Recently, Awais et al. (2019) did reservoir potential evaluation, interpretation of lithology, depositional environments and transgressive–regressive sequences using petrophysical logs of the Lockhart Limestone of Meyal Oil Field, Potwar sub-basin, Pakistan.

The main objective of present study involve the reservoir potential evaluation of the Lockhart Limestone in Kohat Basin at Shakardara Oil Field, using various petrophysical properties, i.e. porosity, permeability, volume of shale, water saturation and hydrocarbon saturation. The study is proved helpful in identification of various hydrocarbon bearing zones in the reservoir compartments of this formation.

Table 1 Stratigraphic log presenting stratigraphic formations encountered within the Shakardara-01 well. The lithological description is adopted from Shah, 1977.

| Age	Formation	Thickness (m)	Lithology Pattern	Description
Pliocene	Nagri Formation	695		Sandstone with interbedded clay.
	Chinji Formation	1541		Sandstone with clay and siltstone.
Miocene	Kamlial Formation	640		Sandstone, shale with siltstone.
	Murree Formation	1265		Grey clay with sandstone.
Eocene	Jatta Gypsum	35		Gypsum; white, hard and massive.
	Kuldana Formation	22		Shale, marl with bed of sandstone.
	Kohat Formation	5		Nodular limestone with marl and shale.
Paleocene	Patala Formation	143		Shale; dark greenish grey.
	Lockhart Limestone	148		Limestone; grey, medium to thick bedded.
	Hangu Formation	28		Sandstone; grey, reddish fine to coarse.
Cretaceous	Lumshiwal Formation	18		Sandstone with sandy silty shale.
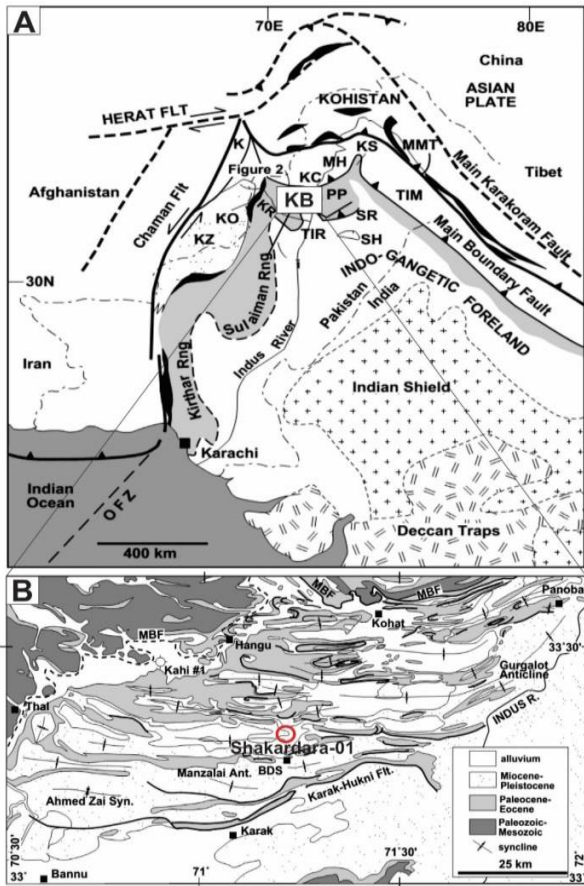
Fig. 1A Tectonic map of Pakistan. Abbreviations includes: K-Kabul block; KB-Kohat Basin; KC-Kala Chitta Range; KO-Khost Block; KR-Kurram River; KS-Kashmir Syntaxis; KZ-Katawaz Basin; MH-Margalla Hills; MMT-Main Mantle Thrust; OFZ-Owen Fracture Zone; PP-Potwar Plateau; SH-Sarghoda Hills; SR-Salt Range; TIR-Trans Indus Salt Ranges (after Treloar and Izatt, 1993; Pivnik and Wells, 1996). Fig. 1B Structural map of the Kohat Basin showing location and tectonic setting of the Shakardara-01 well (red circle). Abbreviations includes: J-Jozara; K-Karak; M-Mardan Khel; P-Panoba; S-Shekhan Nala. (after Meissner et al., 1975; Pivnik and Wells, 1996).

The study area (i.e. Kohat Basin) constitutes part of the Indian Plate of Gondwanaland (Kazmi and Rana, 1982; Valdiya, 1997; Fig. 1B). The Kohat Basin is one of the most complex and geologically active zones in Pakistan (Abbasi and Mc Elroy, 1991; Pivnik and Wells, 1996). It is surrounded by Kala Chitta Ranges and MBT in north and Trans Indus Ranges in south while Kurram River and Potwar Plateau surround it in the west and east respectively (Pivnik and Wells, 1996; Ahmad, 2010).
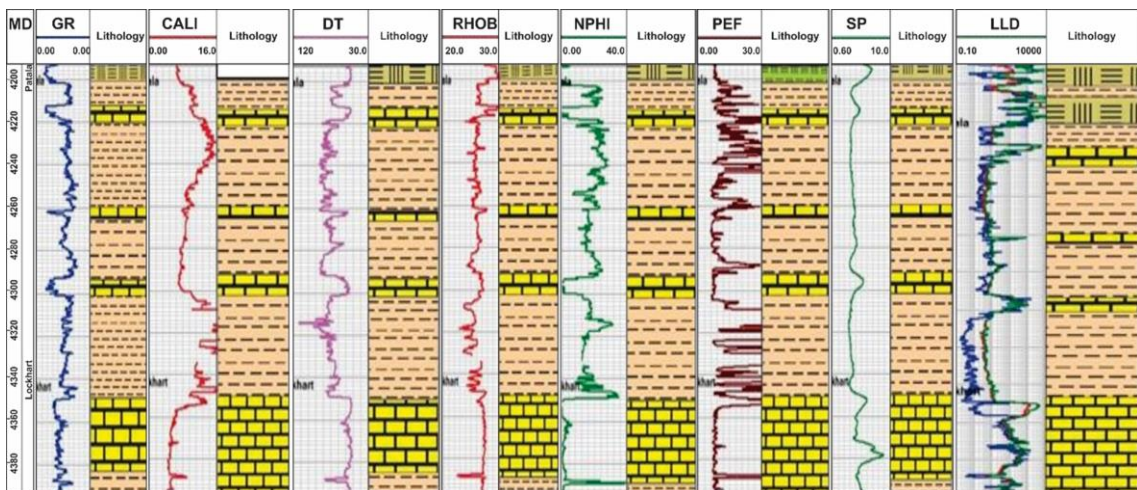

Fig. 2 The GR log responses in Shakardara-01 well at depth 4200-4400m in the Kohat sub-Basin.

Table 2. Interpreted petrophysical parameters and results of reservoir zone-1, zone-2 and zone-3 of the Lockhart Limestone within Shakardara-01 well, Kohat Basin.

S. No	Petrophysical Parameters	Zone-1	Zone-2	Zone-3	Average
1.	Volume of Shale (VSH)	32.80	38.04	13.25	28.03
2.	Density Porosity (PHID)	2.55	2.00	2.90	2.48
3.	Neutron Porosity (NPHI)	5.50	35.60	35.60	25.57
4.	Total Porosity (PHIT)	3.07	4.80	6.00	4.96
5.	Effective Porosity (PHIE)	1.40	2.02	6.50	3.31
6.	Water Saturation (Sw)	85.00	95.00	48.00	76.00
7.	Hydrocarbon Saturation(Sh)	15.00	5.20	52.00	24.10

The stratigraphy of Kohat Basin ranges from Jurassic to Miocene and Pleistocene with intermittent unconformities (Shah, 2009; Table 1). The exploratory

Formation, Lockhart Limestone and Patala Formation are well-developed and nicely exposed both at outcrops and subsurface in the Kohat Basin and are encountered within the drilled well (Table 1).

Material and Methods

The petrophysical properties of a rock such as porosity, water saturation, hydrocarbon saturation, lithology identification and hydrocarbon movability are helpful in reservoir potential evaluation of a formation (Lee and Collett, 2009; Tiab and Donaldson, 2015). To find out these mentioned properties petrophysical logs including gamma ray (GR), caliper log, sonic log,
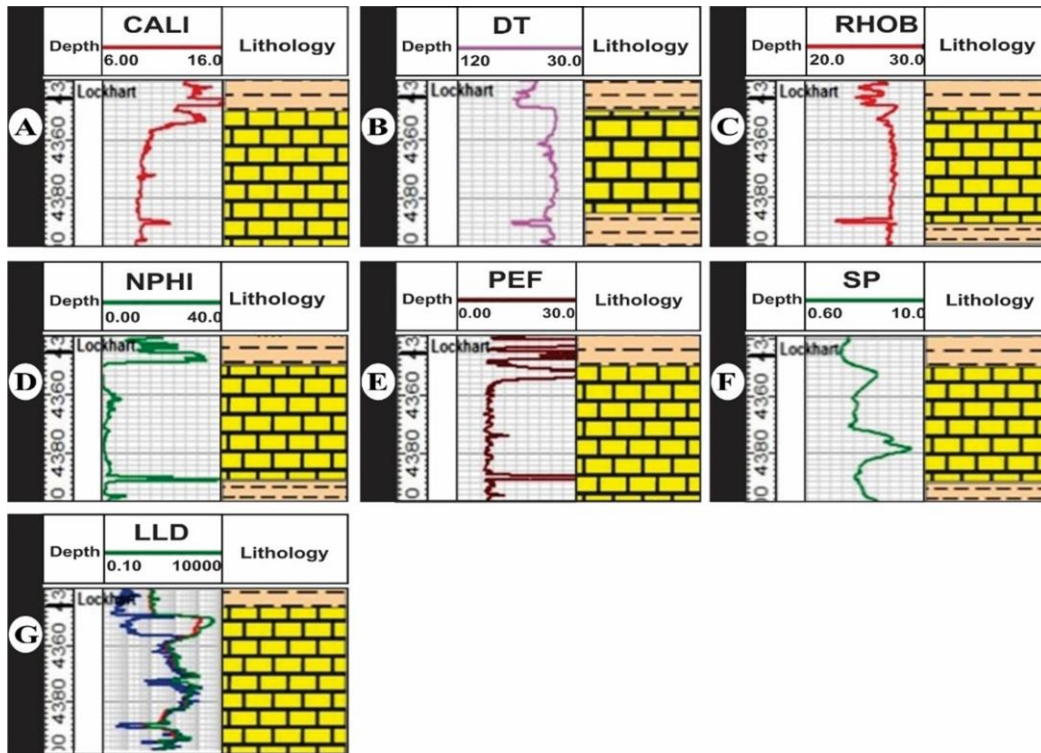

Fig. 3 The wireline logs utilized in the reservoir zone of the Shakardara-01 well; **A** Caliper log curve, **B**) The interpreted sonic log curve, **C)** The curve of density log, **D)** The neutron log curve in the Shakardara-01 at depth of 4200-4400m, **E)** Showing the PEF log, **F)** Showing the SP log, **G)** Showing the Resistivity log.
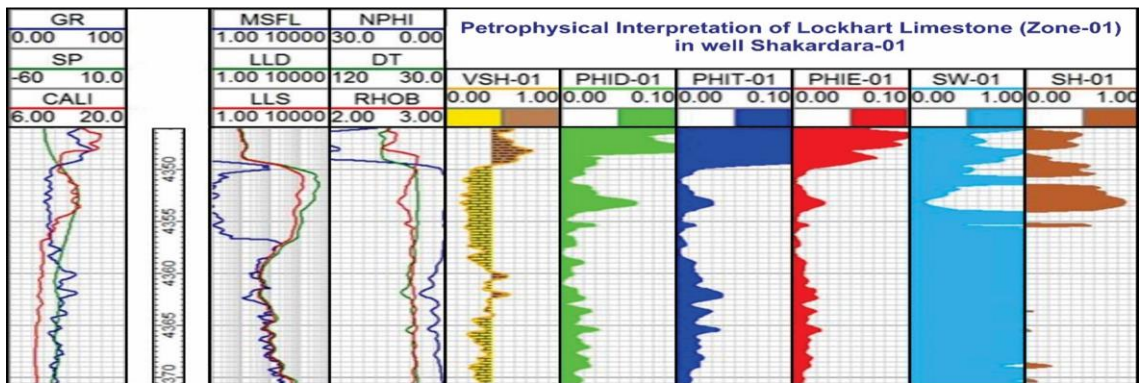

Fig. 4 Petrophysical interpretation of zone-01 in the Lockhart Limestone of Shakardara-01 well.

wells and the surface geology provide information about the regional stratigraphic framework and sedimentary sequence of an area (Khan et al., 1986). The rocks of the Paleocene age including, Hangu

density log, neutron log, litho-density log, spontaneous potential (SP) log and resistivity log were used to estimate and evaluate reservoir potential of the Lockhart Limestone (Figs. 2 and 3A-G).

The gamma ray (GR) log is used to measure the volume of shale, sedimentary facies and depositional environment interpretation of the formation (Bjørlykke, 2010; Kennedy, 2015; Fig. 2). The caliper

i.e. shale (Peters, 2012). SP log for shale will be positive because it has clay minerals (Fig. 3F). Resistivity log measures the resistivity of formation's water by passing a known direct current through the
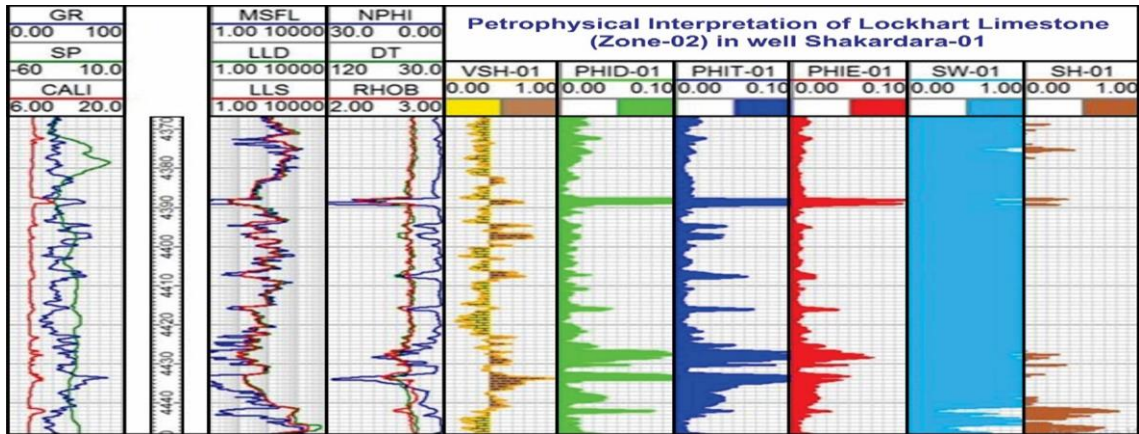

Fig. 5 Petrophysical interpretation of zone-2 in the Lockhart Limestone of Shakardara-01 well.
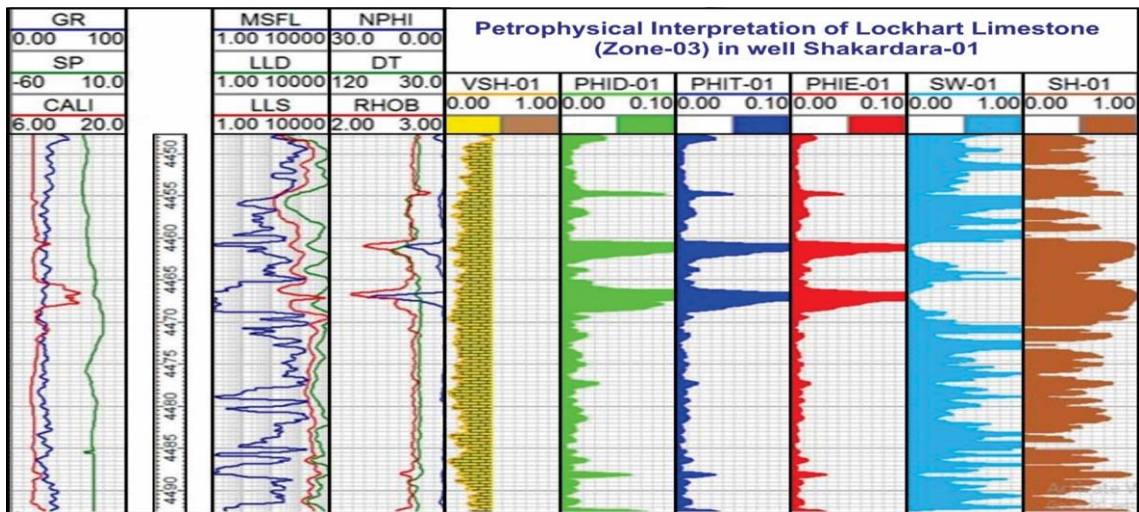

Fig. 6 Petrophysical interpretation of zone-3 in the Lockhart Limestone of Shakardara-01 well.

log is used to measure the radius and diameter of the borehole (Fig. 3A). The high values of caliper log show some loose lithology like shale (Hakimi et al., 2012; Schön, 2015; Fig. 3A). Sonic log is used to measure the velocity of elastic waves passing through the formation in meter per second (Buryakovsky et. al., 2012; Fig. 3B). It measures the bulk density of a formation within borehole (Baker, 1957; Fig. 3C). Neutron log is used to find out the porosity of a targeted formation (Schlumberger, 1989; Fig. 3D). It can also be used to detect gas and distinguish it from oil (Bjørlykke, 2010). The litho-density log is one of the useful and sophisticated log for lithology identification at subsurface (Mondol, 2015; Fig. 3E). The spontaneous potential (SP) log measures the natural potential difference that exists between two electrodes in which one of the electrodes is kept within the borehole while the other one is at the surface in the absence of any artificially applied current (Wallace, 1968). The natural potential difference is developed because of the water action present in the formation, circulating drilling mud and rocks which have free ions

formation and assessing the electrical potential from galvanic devices (Asquith et al., 2004). Generally, the resistivity of hydrocarbon is much more than the resistivity of formation's water (Patchett, 1975). When a formation is porous and contains salty water, the overall resistivity will be low but if a formation contains hydrocarbons, its resistivity will be high (Clavier et. a1., 1984; Fig. 3G).

Results and Discussion

The gamma ray log of the studied well is used to demarcate the shale and carbonates (reservoir) intervals within the Lockhart Limestone (Hakimi et al., 2012; Fitch et al., 2015). The shale intervals are defined above 50 API while the reservoir units are defined below 50 API (Figs. 2 and 3). In Shakardarra-01, the lithology is interpreted to be dominantly limestone because the GR log is below the shale baseline throughout the interval (Janjuhah et al., 2017; Fig. 2). The caliper log response is also uniform (~9 inches throughout the interval) except for a small zone

(Fig. 3A). The resistivity logs (MSFL, LLS and LLD) shows higher values reflecting hydrocarbon containing limestone. According to Rider (2002), the density log values for limestone is 2.71 gm/cc and likewise, throughout the interval the density log values are uniform (approximately at 2.71 gm/cc) except for very localized fluctuations at certain intervals. The sonic log values are also close to the matrix transit time for limestone (Janjuhah et al., 2017; Fig. 3A).

Different logs were used to interpret lithology and facies variations in the Lockhart Limestone. The positive curves of GR log above shale base line show shale intervals, while the negative curves below shale base line indicates limestone beds (Hakimi et al., 2012; Fais et al., 2015; Fig. 3). The negative curves also presume the presence of dolomite patches in the formation (Fitch et al., 2015). The caliper log response showed limestone and shale beds at sub-surface. In case of shale the caliper log value in negative while in case of limestone the caliper log value is positive and hence also shows appropriate compaction of the strata (Schön, 2015). Lockhart Limestone has high DT values because it is less porous, and is compacted which has the capacity to transmit seismic waves, however, shale is less compacted and porous so DT is low (Fig. 3B).

From density log (Fig. 3B), it is interpreted that the formation is dominated by limestone and shale intervals as the positive trend of density log above base line indicates limestone while the negative trend below base line represents a loose lithology like shale (Ahmed et al., 2012; Hakimi et al., 2012). Thus, the positive trend of density log indicates that limestone is compacted and negative curve of density log in shale indicate that shale is highly porous and not compacted (Fig. 3B). From neutron log, the lithology and porosity are interpreted which are same as interpreted from density log but here from high NHPI curve means the

material is highly porous and not compacted very well and vice versa. The negative trend of litho-density log also shows the presence of limestone. SP log curve/value is low and reflects limestone beds (Fig. 3F). Generally, shale has high SP and limestone has low SP values (Fitch et al., 2015; Khalid et al., 2015). The resistivity log showed limestone beds with some intervals of shale in the Lockhart Limestone (Fig. 3G). Thus, the petrophysical logs results indicates that the Lockhart Limestone in the investigated well is entirely dominated by limestone and shale with minor marl beds at Shakardara Oil Field.

Reservoir Potential

The petrophysical results are used to delineate the reservoir zones within the Lockhart Limestone at Shakardara-01 well (Figs. 4-6). The petrophysical characteristics, utilized in reservoir potential evaluation of the formation are shown in table 2. Based on variations in petrophysical results and reservoir characteristics the reservoir compartments of the formation are divided into three zones such as zone-1, zone-2 and zone-3.

Reservoir Potential of Zone-1: The zone-1 of the Lockhart Limestone in Shakardara-01 has low hydrocarbon saturation (15%) and high-water saturation (85%) (Fig. 4; Table 2). The shale volume is 32.80 %, effective porosity is 1.40% and neutron porosity is 5.50% (Fig. 4; Table 2). These values show that Zone-1 can act as poor reservoir unit in the Lockhart Limestone (Hakimi et al., 2012; Fais et al., 2015).

Reservoir Potential of Zone-2: The zone-2 of the Lockhart Limestone in Shakardara-01 has very low hydrocarbon saturation (5.20%) and very high-water saturation (95%) (Fig. 5). The effective porosity (2.02%) and neutron porosity (35.60%) of zone-2 are comparatively low and hence cannot act as good
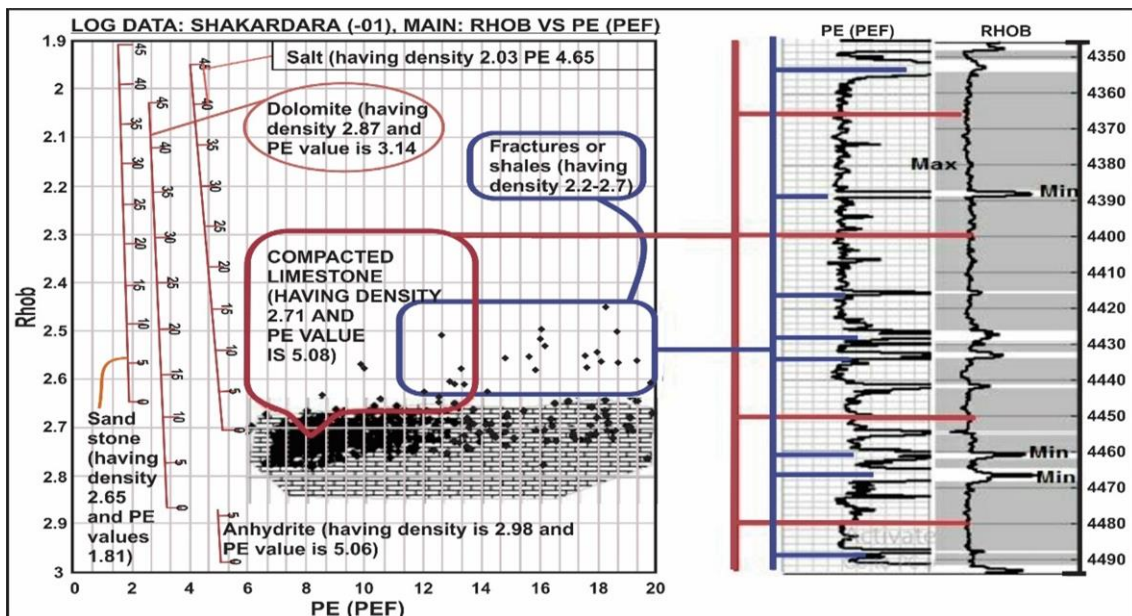

Fig. 7 Interpreted cross-plot of PEF versus RHOB using porosity as reference line for the Lockhart Limestone in Shakardara-01 well.

reservoir (Ahmed et al., 2012; Siyar et al., 2018; Fig. 5; Table 2). The shale volume is very high i.e. 38.04 % which further decrease the reservoir potential and hence zone-2 acts as a very poor reservoir unit in the formation (Hakimi et al., 2012; Siyar et al., 2018).

Reservoir Potential of Zone-3: The zone-3 of the Lockhart Limestone in Shakardara-01 has very high hydrocarbon saturation i.e. 52% and high-water saturation i.e. 48% (Fig. 6; Table 2). The shale volume is 13.25 which is comparatively low. The effective porosity and neutron porosity are comparatively good that is 6.50% and 35.60 and hence provide good character to the reservoir. Thus, the Zone-3 is can act as moderate to good reservoir unit in the formation (Hakimi et al., 2012; Fitch et al., 2015; Nawaz et al., 2015).

Cross-Plots of Logs

A two-dimensional cross plot with one variable scaled in the vertical (Y) direction and the other in the horizontal (X) direction. The scales are usually linear but other function may be logarithmic. Using color symbols on the data points may represent additional dimensions. These plots are common tools in the interpretation of petrophysical and engineering data (Rider, 2002; Kennedy, 2015).

Photoelectric factor and Density Log Cross-Plot

Cross-plots between Photoelectric Factor (PEF) and density log in the Lockhart Limestone intervals in well Shakardara-01 of Kohat Basin are plotted against each other (Fig. 7). The porosity lines in the cross-plot is used as reference line (legend) in order to make the differentiation of shale dominated and carbonate dominated lithofacies easy. PEF and Bulk density (RHOB) are linearly plotted i.e. that PEF are in

increasing order on x-axis and density in decreasing order on y-axis. Though, high-density limestone is clustered with low porosity value as shown by gray limestone fill polygon, however, the scatter points to the right side of limestone line (red line in Fig. 7) showing low density and high porosity showing fracture porosity or impurities i.e. shale. The interpretation drawn from study of cross-plots is summarized as Lockhart Limestone have high density value 2.71 and PEF valve is 5.8 so it means that Lockhart Limestone is compacted as shown in Figure 7. Moderate to low density and relatively low PEF values together with high porosity values on reference line (red line) are interpreted as fractured limestone or shale as shown by blue color polygon.

Neutron and Density Logs Cross-Plot

The combination of the density and neutron logs provides a good source of porosity data, especially in formations of complex lithology (Hartmann et. al., 2000). Better estimates of porosity are possible with the combination than using either tool or sonic separately because inferences about lithology and fluid content can be made (Hartmann et. al., 2000). The density-neutron log is a combination log that simultaneously records neutron and density porosity (Hartmann et. al., 2000; Kennedy, 2015). In some zones, porosities recorded on the logs differ for three reasons: The matrix density used by the logging program to calculate porosity is different from the actual formation matrix density. Gas is present in the formation pore space. Shale/clay is present in the formation (Fitch et al., 2015; Kennedy, 2015).

Cross-plot is plotted between Neutron Log (NPHI) and density log (RHOB) in the Lockhart Limestone (predominantly composed of Limestone) intervals in well Shakardara-01 of Kohat Basin. The reference line
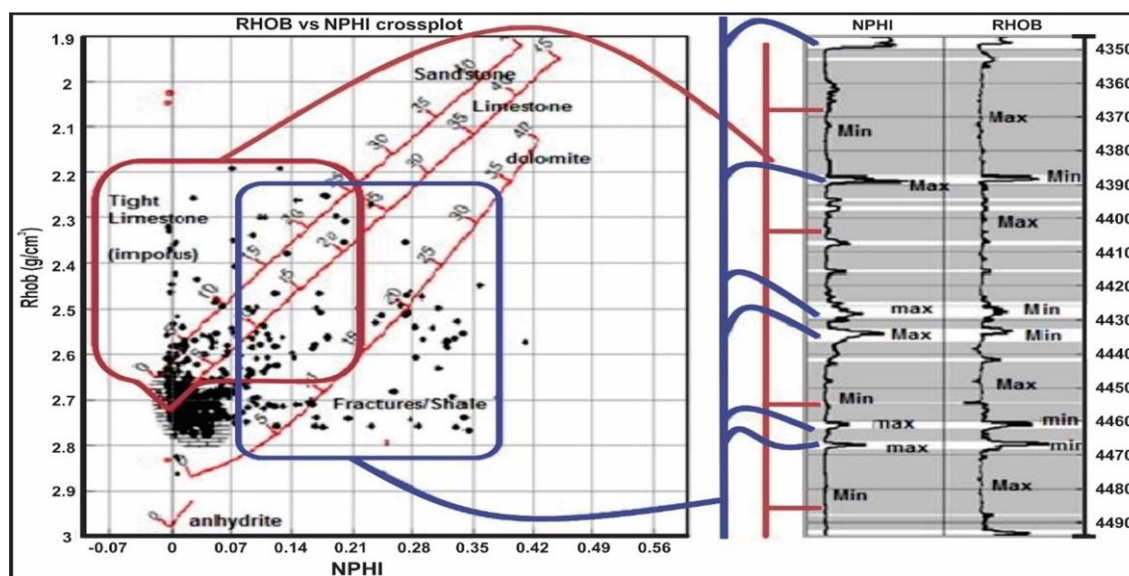

Fig. 8 Interpreted cross-Plot of NHPI versus RHOB using porosity as reference line for Lockhart Limestone in Shakardara-01 well.

porosity lines in the cross-plot is used in order to differentiate the shale dominant or carbonate dominant lithofacies easily (Ahmed et al., 2012; Khalid et al., 2015). NHPI and RHOB are linearly plotted i.e. NHPI is plotted in increasing order on x-axis while the density (RHOB) is plotted on y-axis in decreasing order. Though, high-density limestone is clustered with low porosity value as shown by gray limestone fill polygon, however, the low density and high porosity which represent the fracture porosity or impurities i.e. shale, is shown by scatter points to the right side of limestone line and dolomite line (red line in Fig. 8) encircled with blue colored polygon. The summarized study of the interpreted drawn cross-plots is given below: Tight/low porosity and high density (4344m thick rocks unit exerted overburden pressure) limestone is differentiated on the basis of NHPI values (low) together with porosity reference lines (red color lines shown in Figure 8), which shows gray color fill on the logs as shown in Figure 8. Moderate to low density and relatively low NHPI values together with intermediate to high porosity values on reference line (red line) are interpreted as fractured limestone or shale as shown by green color polygon in Figure 8. To approve the lithology and reservoir potential in terms of porosity is the main theme of this interpretation. Because the sample cuttings leave very imprecise record of the formation's samples during drilling, therefore for remaining part cross-plots can be used to identify lithology.

Conclusion

The petrophysical analyses carried out on the Paleocene Lockhart Limestone in Shakardara-01 well resulted into the following conclusions;

The Lockhart Limestone reservoir compartments are divided into three zones. Based on petrophysical interpretation the zone-1 and zone-2 constitute poor reservoir compartments in the Lockhart Limestone, while the zone-3 can acts as moderate to good reservoir zone for hydrocarbons.

The zone-1 and zone-2 showed least hydrocarbon saturation while zone-3 showed high hydrocarbon saturation within the formation.

The petrophysical interpretation showed that the Lockhart Limestone is highly compacted, having low porosity and permeability which decreased its reservoir worth (accept zone-3) in the study area.

Overall, this formation is a tight reservoir and can seldom act as excellent reservoir for hydrocarbon exploration in Shakardara Oil Field.

Acknowledgement

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