DOI 10.4430/bgta0340

Petrophysical evaluation of reservoir rocks of Rajian-01, Daiwal-01, and Kal-01 by well log data, Potwar Plateau, upper Indus basin, Pakistan

M. Sajid[1,2], M. Kashif[2], M.A. Zahid[3], A. Javed[4] and A. Shaikh[5]

[1] *Department of Earth Sciences, Abbottabad University of Science and Technology, Havelian, Pakistan*

[2] *Department of Earth Sciences, University of Sargodha, Sargodha, Pakistan*

[3] *Department of Earth Sciences, Lasbella University of Agriculture, Water and Marine Sciences, Lasbella, Pakistan*

[4] *Oil and Gas Development Corporation Limited, Islamabad, Pakistan*

[5] *School of Petroleum Engineering, China University of Petroleum, Qingdao, China*

(Received: 16 May 2020; accepted: 7 July 2020)

ABSTRACT The present study is an integrated approach to derive reservoir characteristics from well log data. The studied wells, Rajian-01, Daiwal-01, and Kal-01, have been drilled by the Oil and Gas Development Company Limited in the south-eastern part of Potwar Plateau. The petrophysical analysis of these three wells has been done on the basis of well logs (Gamma-ray log, resistivity log, density log, sonic log, and neutron log) which helps to evaluate the hydrocarbon saturations, water saturations, volume of shale, net pay, porosity, and permeability. Rajian-01 gives approximately 65% hydrocarbon saturation in the reservoir rocks. The most promising reservoir rocks of this well are Khewra Sandstone and Jutana Dolomite; the Tobra Formation, however thinly bedded, also acts as a reservoir. Daiwal-01 is an abandoned well and Khewra Sandstone, Jutana Dolomite, and Dandot Formation act as reservoir rocks, whereas the reservoir rocks in well Kal-01 comprises 68% hydrocarbon saturation. The best reservoir rocks in the Kal-01 are Khewra Sandstone, Jutana Dolomite, and Warchha Sandstone (poor to moderate reservoir intervals). The overall petrophysical analysis shows that Rajian-01 and Kal-01 have significant hydrocarbon potential, whereas Daiwal-01 well is uneconomical due to the structural complexity. The Khewra Sandstone and Jutana Formation in Rajian-01 and Kal-01 have favorable petrophysical characteristics for commercial hydrocarbon accumulation. The effective porosity in the Jutana Formation can be increased by induced fracturing. Fracturing work in the Jutana Formation can increase oil recovery. The detailed subsurface studies (including subsurface structure) will enable a better understanding of the hydrocarbon potential in the Potwar Plateau.

Key words: petrophysical parameters, hydrocarbon prospect, reservoir, Potwar Plateau.

1. Introduction

Potwar Plateau (upper Indus basin) in Pakistan is a highly petroliferous basin that produces hydrocarbon (oil and gas) commercially. Hydrocarbon bearing reservoirs are a heterogeneous geological structure having large integral intricacy properties (Verma *et al.,* 2012). Basic reservoir characteristics are directly associated with the porosity (storage capacity), the composition of the rock, and the percentage of hydrocarbon in pore volume (Verma *et al.,* 2012; Singha and Chatterjee, 2014; Kashif *et al.,* 2019a, 2019b; Singh, 2019). In this study, an attempt is made to predict the reservoir characteristics in Potwar Plateau by using well log data.

The wells (Rajian-01, Daiwal-01, and Kal-01) are located within latitude 32° 59’ 16.21” N and 33° 02’ 11.31” N and longitude 73° 06’ 24.86” E and 73° 10’ 16.11” E in the Potwar Plateau (Fig. 1). Well logging is the practice of making a detailed record of the geologic formations penetrated by the wells. The geophysical well logging technique was introduced by Schlumberger brothers in Alsace, France in 1927. The general purpose of well log analysis is to convert the raw log data into estimated quantities of oil, gas, and water in a formation (Luthi, 2001; Asquith and Krygowski, 2004; Dolson, 2016). The basic tools used in the study include the Gamma Ray (GR) log, resistivity log (LLD, LLS), sonic log, neutron log (PHIN), and porosity density logs (PHID, RHOB) to evaluate the lithologic units, differentiating between hydrocarbon-bearing and non-hydrocarbon bearing zones within identified reservoirs. Furthermore, the reservoir geometry is evaluated by well to well correlation and determination of zone of interest such as porosity, permeability, gross thickness, water saturation and hydrocarbon saturation by petrophysical parameters (Rider, 1978; Rider and Laurier, 1979).

The overall well-log derived information is helpful to evaluate the reservoir and suitable for estimating hydrocarbon quantities in a reservoir rock (Asquith and Krygowski, 2004; Dolson, 2016; Chongwain *et al.,* 2018, 2019; Kashif *et al.,* 2019a, 2019b). The reservoir evaluation (porosity, permeability, water saturation) enhance the ability to estimate the hydrocarbon reserves and reservoir bed thickness, as well as to distinguish between oil and gas and water-bearing strata by observing their electrical resistivity and relative permeability values (Hilchie, 1990; Schlumberger *et al.,* 1996; Uguru *et al.,* 2002; Hill, 2017).

The main objectives were to evaluate 1) the reservoir properties and 2) reservoir potential of different horizons of the Rajian-01, Daiwal-01, and Kal-01 through wireline logging techniques. Petrophysical analysis was done on the rock units that were drilled in Potwar Plateau to evaluate the reservoir potential and establish the stratigraphic relationship between the identified reservoirs in these wells.

2. Geological background

The Himalayan collisional orogeny started in Cretaceous age as a result of the continent-volcanic arc-continental collision (LeFort, 1975; Kazmi and Jan, 1997; Zhang *et al.,* 2012). The complex north-western Himalayan tectonic domain is divided into major tectonic zones (Fig. 2) such as the Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), and Himalayan Frontal Thrust (HFT) (Tahirkheli *et al.,* 1979; Ghazanfer, 1993; Miller *et al.,* 2001). The Potwar sub-basin is a broad plateau, about 130-150 km wide, having rock sequences from Precambrian to Recent.

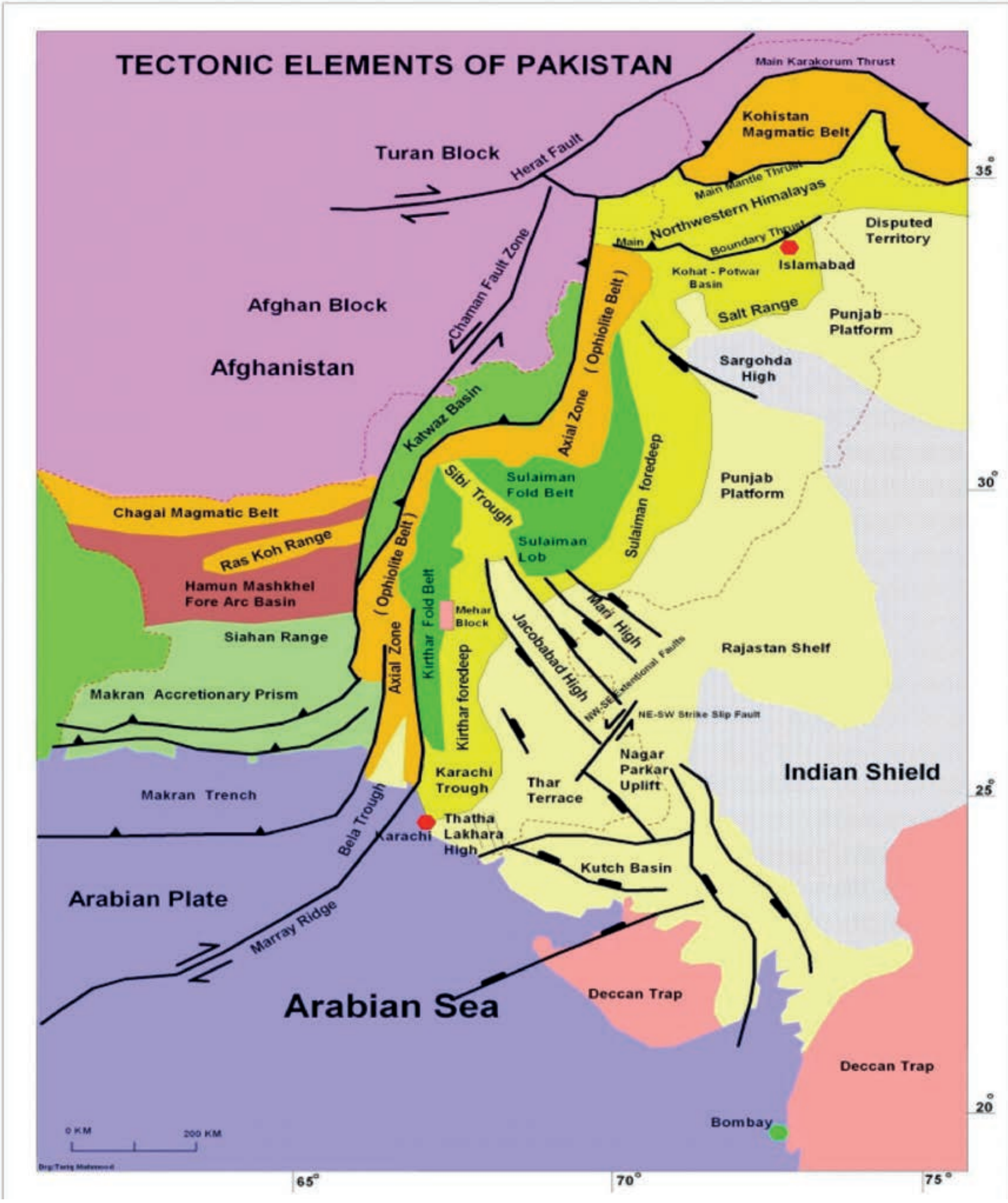


Fig. 1 - Tectonic elements of Pakistan (modified after Kazmi and Rana, 1982).

The Main Boundary Thrust (MBT), active since 15 Myr, and the Salt Range bound the Potwar sub-basin to the north and south, respectively. Left lateral Jhelum and right lateral Kalabagh strike-slip faults demarcate the basin to the east and west (Kadri, 1995; Grelaud *et al.,* 2002; Jadoon *et al.,* 2003; Moghal *et al.,* 2007; Abir *et al.,* 2015), respectively.

The Potwar sub-basin represents a deformed thrust sheet comprised of the Northern Potwar Deformed Zone (NPDZ) and Southern Potwar Platform Zone (SPPZ) separated by the asymmetrical

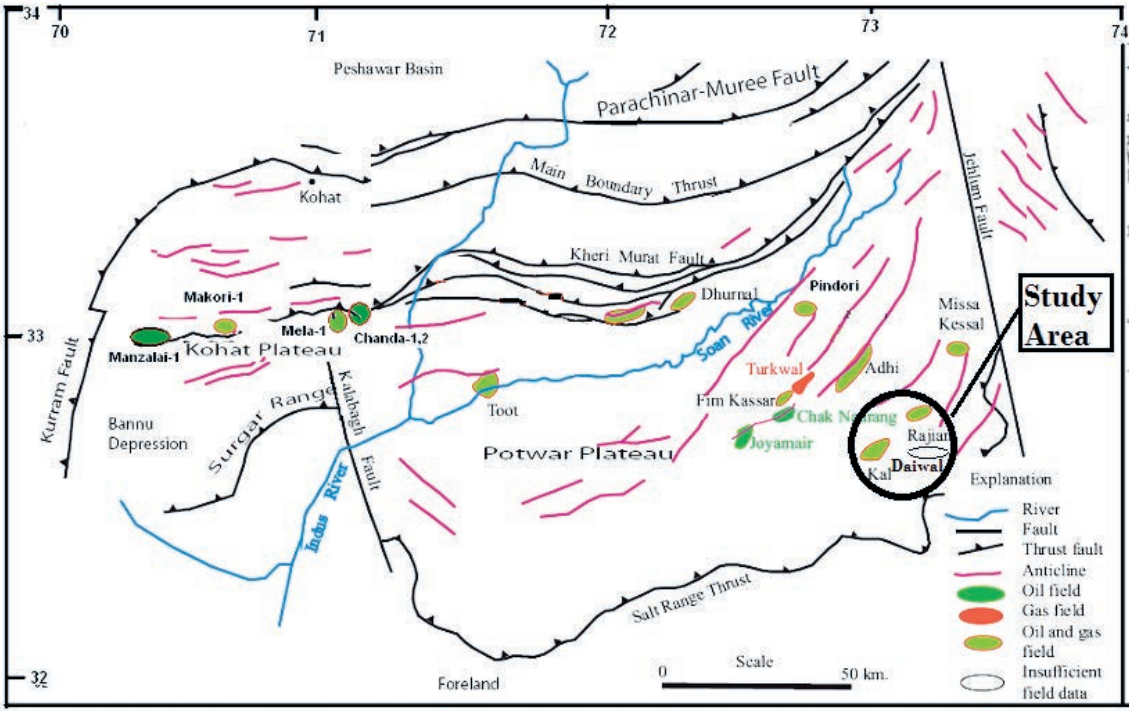


Fig. 2 - Generalised location, tectonics, and oil and gas map of Kohat-Potwar area (modified from Kazmi and Rana, 1982; Khan *et al*., 1986; Kemal, 1992).

Soan syncline (Fig. 2) (Jaswal *et al.,* 1997; Jadoon *et al.,* 2003, 2015; Hasany and Saleem, 2012). The rate of complexity in the structures located to the north (NPDZ) is higher as manifested by the occurrence of tight fold sand complex faults as compared to isoclinal fold and thrusts present in the south. Studies by Jadoon *et al*. (2003) and Aamir and Siddiqui (2006) show popup structures in the eastern Potwar sub-basin. In most cases, the detachment plain as a *décollement* is in the Salt Range Formation. Moreover, the study of geophysical data along various transects indicates that the structural elements of the Potwar sub-basin exhibit wide variation from east to west (Aamir and Siddiqui, 2006; Iqbal *et al*., 2015). These structural complications are attributed to a different mechanical behaviour during detachment and propagation between Jhelum and Kalabagh strike-slip faults and the presence of salt. In the eastern Potwar sub-basin, the structures are left-stepping, whereas the right-stepping structures in the en-echelon pattern are present in the east of Kalabagh Fault.

Subsurface geological data from wells Rajian-01, Daiwal-01, and Kal-01, drilled in the study area, indicate the presence of Precambrian-Eocambrian, Cambrian, Permian, Permian-Paleocene, and Miocene breaks in the deposition. Eocambrian Salt Range Formation unconformably overlies the basement rocks, composed of metamorphic and volcanic rocks of Indian Shield (Yeast and Lawrence, 1984) and overlain unconformably by Early Cambrian Khewra Sandstone. According to wells data obtained from Rajian-01, Daiwal-01 and Kal-01, Kussak, Jutana and Baghanwala Formations were encountered in Rajian-01 and Kal-01 while Baghanwala Formation was not encountered in Daiwal-01. The Tobra Formation (conglomerates) of Lower Permian age unconformably overlies the Khewra Sandstone. Dandot, Warchha, and Sardhai Formations of

Lower Permian age mainly composed of sandstone (Dandot and Warchha Formations) and shales (Sardhai Formation) successively overly the Tobra Formation. The area remained exposed from the Upper Permian through the Lower Paleocene. In Danian, a Tertiary sequence with Hangu Formation at the base was deposited over the Sardhai Formation. In the central and northern Salt Range, for instance at Karsal, Dhurnal, Meyal, and Dakhni wells (Moghal *et al.,* 2007), a Permian, Triassic, Jurassic, and Cretaceous sequence is present (Shah, 2009; Dominik *et al.,* 2013). In the study area, Permo-Triassic (between Chhidru and Mianwali Formations) and Triassic-Jurassic (between Kingriali and Datta Formations) unconformities overstep a Permian-Tertiary (between Sardhai and Hangu formations) composite unconformity. The Paleocene sequence comprising Hangu, Lockhart and Patala Formations is well developed. Nammal, Sakesar, and Chorgali Formations of Lower and Middle Eocene age conformably overlie Paleocene strata (Fig. 3). The Rawalpindi Group (Murree and Kamlial Formations) with Himalayan provenance (Chaudhry and Zaka, 1998) was deposited unconformably over the Middle Eocene Chorgali Formation. Chinji and Nagri Formations are present at the top of the Miocene molasses sequence in the study area.

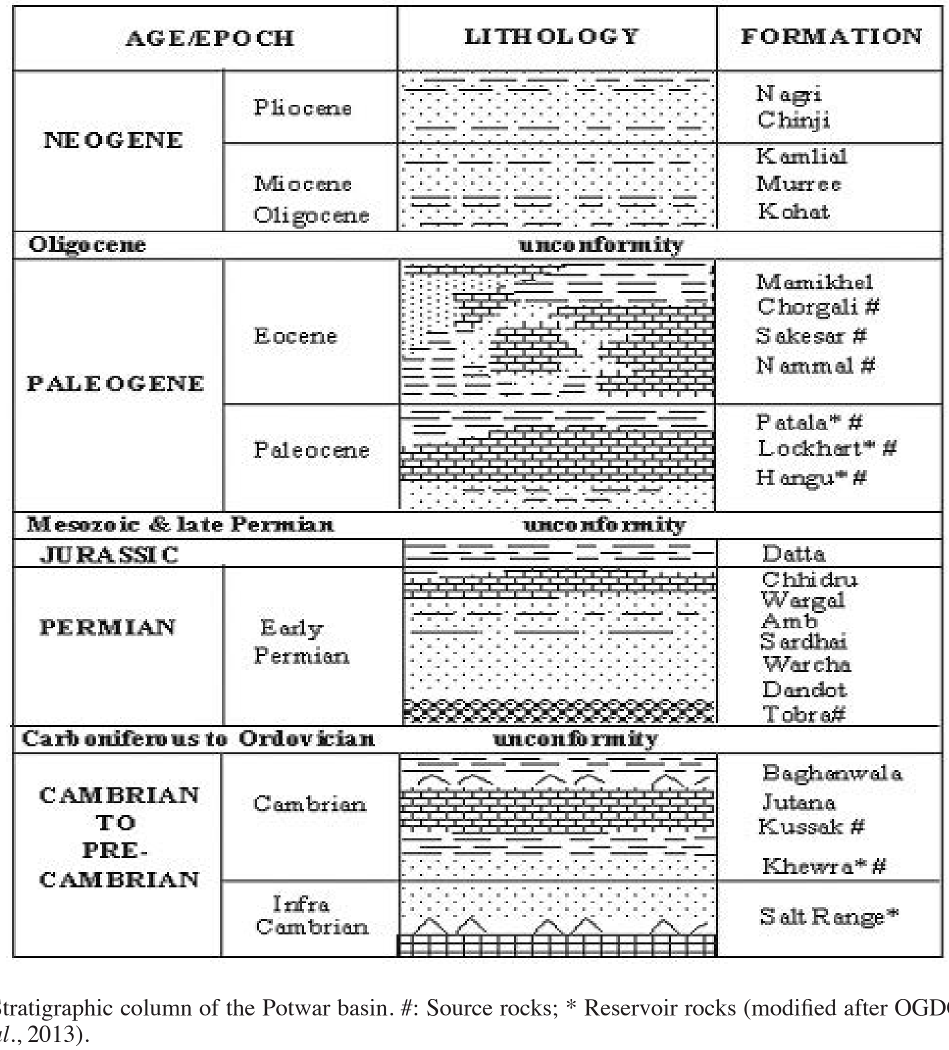


Fig. 3 - Stratigraphic column of the Potwar basin. #: Source rocks; * Reservoir rocks (modified after OGDCL, 1996; Zaidi *et al*., 2013).

3. Methodology

Three methods have been used to evaluate various potential zones: mud logging, coring, and wireline logging. To use these three methods, the chemical and physical properties of rock and the nature of fluid has been studied. The petrophysical analysis is the key to determine the porosity, permeability, water saturation, lithology, and density of the rock. The petrophysical analysis gives information about the reservoir; while wireline logging is used to record the different properties of rock (Mavko *et al.,* 2011).

A comprehensive petrophysical approach was carried out over the valuable zones of reservoir in the study area, using several qualitative and quantitative well logging analyses. The approach adopted for petrophysical analysis is well log correlations that have been used to track the general trend and lateral distribution of the reservoir units in the Rajian-01, Kal-01, and Diawal-01. Well logs, including caliper log, GR log, resistivity log, density log, neutron log, and sonic log, were used to meet the requirements of our objective. GeoGraphic Software has been used to draw all the logs and cross plots.

The wells data including wireline data for this study were obtained from the data management and archiving division of the Land Mark Resources (LMKR) and the Director-General of Petroleum Concessions (DGPC) Pakistan, providing information about the location, type, and depth of formations.

4. Results and discussion

4.1. Log analysis

Rock physics generally depict the link between the physical and elastic characteristics of rock to enhance the understanding and relationship between rock characteristics and physical measurements. Generally, it focuses on velocity (v) data (sonic log) combined with reservoir characteristics [density (ρ), porosity, clay contents, and fluid saturation] that has been obtained from seismic inversion and well log data. Well log data is a prime source to generate the rock physical model constrained by seismic data. Linking fluid properties to velocities is the basis of quantitative seismic interpretation and allows a better understanding of the seismic response. The seismic reflections are generated by the difference of acoustic impedance ($v \times \rho$). Rock physics are usually quantified in terms of elastic moduli, later used for velocity compensation. The elastic properties of a reservoir are very important for the assessment of rock fracturing, particularly for hydraulic fracturing and borehole stability. The fluid content and mineral contents of a reservoir can be evaluated by cross plotting the V_P/V_S ratio against acoustic impedance of P waves. Elastic properties and reservoir characteristics of reservoir formations were investigated by seismic attributes derived from sonic logs. Compaction also has a significant impact on petrophysical characteristics; the deeper the reservoir rock, the lower the porosity and higher the velocity. The deeper the buried rocks, the higher the acoustic impedance and lower the V_P/V_S ratios. The presence of clay content increases the clay volume and causes a decrease in P-waves velocity rather than porosity. The V_P and PHIT have significance relationship i.e. to evaluate the porosity; the high porous zone resulted in decreased P-waves velocity. Hence, for the formation undergoing the compaction effect at deeper depth, the porosity will be low and velocity will be high. On the basis of the volume fraction of individual minerals, it was possible to make a lithological discrimination (calculated with the help of GR log, sonic Log, density log, etc.). The V_P/V_S ratio is used to distinguish the composition as well as being a good indicator of the gas content.

The first step in the log analysis is to identify the zone of interest, i.e. clean sand with presence of hydrocarbon. GR log is used to measure the natural radioactivity within the formations (Track 1) was used to identify sand/shale lithology within the study area. The resistivity log (laterolog deep LLD) combined with GR log (Track 2) were used to differentiate between hydrocarbon and non-hydrocarbon zones. Consequently, the zone of interest for the petrophysical interpretation was defined in terms of clean zones with hydrocarbon saturation (low GR and high resistivity values).

The density log and neutron log were used to differentiate the various fluid types. The gas zones are interpreted from the crossover of the porosity logs, i.e. density log and neutron logs. Whereas, oil zones are interpreted from high resistivity log values and water zones are interpreted by corresponding to very low resistivity.

4.1.1. Volume of shale

The next step is the shale volume estimation; shale volume can be evaluated with the help of a GR log. Shale volume (V_{Sh}) was calculated by using the Dresser Atlas (1979) formula in Eqs. 1a and 1b. The values used were taken from GR in the following equations (Larionov, 1969):
for Tertiary rocks

$$V_{Sh} = 0.083(2^{3.7IGR} - 1) \tag{1a}$$

for older rocks

$$V_{Sh} = 0.33\times (2^{2IGR} - 1) \tag{1b}$$

$$IGR = (GR\ log_{value} - GR_{min} / GR_{max} - GR_{min}) \tag{2}$$

In Eqs. 1a, 1b, and 2, IGR is the GR index, $GR\ log$ is the picked log value while GR_{min} and GR_{max} indicate values picked in the sand and shale baseline, respectively.

4.1.2. Porosity

Density porosity (φ_D) was determined (Dresser Atlas, 1979) by substituting the bulk density readings obtained from the formation density log within each reservoir into the following equation:

$$\varphi_D = (\rho_{ma} - \rho_b / \rho_{ma} - \rho_f) \tag{3}$$

where ρ_{ma} is matrix density, ρ_b bulk density, and ρ_f fluid density, respectively.

4.1.3. Water saturation

The pore fluid properties depend on the reservoir temperature, pressure and water saturation (S_w). To calculate S_w, the value of resistivity of water (R_w) at formation temperature is required, calculated from the porosity and resistivity logs within clean water zone, using R_0 values given in the following equation:

$$R_w = \varphi^m R_0 / a \quad (4)$$

where R_w represents the resistivity of water at formation temperature, φ is the total porosity, and R_0 is the deep resistivity values in the water zone respectively. Tortuosity factor is represented as a and m is the cementing exponent, usually 2 for sand (Asquith and Krygowski, 2004; Arns *et al*., 2005; Sultana and Kumar, 2014). In a water zone, saturation should be equal to 1, as R_w at formation temperature is equal to the water resistivity in the zone of interest (R_{wa}).

S_w can be calculated by using Archie's method given by:

$$S_w = (R_w / R_{wa})^{1/n} \quad (5)$$

where n is the saturation exponent and R_{wa} is calculated in the same manner as R_w at formation temperature (Archie, 1942).

4.1.4. Hydrocarbon saturation

Reservoir fluids consist of gas, oil, and water. Hydrocarbon saturation (S_{hc}) is the percentage of pore volume in a formation occupied by hydrocarbons. It can be determined by subtracting the volume obtained from water saturation from 100%:

$$S_{hc} = (100 - S_w)\ \%. \quad (6)$$

4.1.5. Permeability

Permeability (K) of each identified reservoir is calculated using the following equation:

$$K = \sqrt{250 \times \varphi^2 / Swir} \quad (7)$$

where $Swir$ is the irreducible water saturation (Tixier, 1949).

The productivity of each delineated reservoir rock at the zone of interest is estimated by the evaluating results of their calculated petrophysical parameter by using Eqs. 1 to 7.

4.2. Petrophysical analysis

Various reservoir zones have been identified with the help of various log tools, i.e. GR LLD, LLS, NPHI, RHOB and Spontaneous Potential (SP) logs (Aguilera and Aguilera, 2003; Attia, 2005; Mavko *et al*., 2011; Moore *et al.,* 2011; Alexeyev *et al.,* 2017). All estimated zones of interest are marked and interpreted with the help of curve response that has been interpreted using various acronyms, i.e. RHOB measures the density of the borehole and the rocks penetrated by the drill bit. The NPHI, φN, PHIN logs measure the hydrogen content in a formation. In clean shale free formations, where the porosity is filled with water or oil, the φN, PHIN, NPHI logs measure liquid filled porosity; photoelectric effect (PEF) measures the emission of electrons when electromagnetic radiation, like light, hits a material; density porosity [in a decimal (*v*/*v*) where high *v*/*v* values represent high porosity and low *v*/*v* values represent low porosity] measures water saturation at formation that has been encountered in the well (S_w); resistivity of water at formation temperature (R_w), ResD or laterolog deep (LLD) is a resistivity tool used for deep investigation in undisturbed zones; ResS laterolog shallow (LLS) is a resistivity tool used for shallow investigation in transition zones; ResM or MSFL (Micro Spherically Focused Log) is a resistivity tool to measure flush zone resistivity, and G/C3 is unit of density (g/cm^3).

A zone can be marked as a reservoir if it has low GR log values, low SP log values, high NPHI values, and high LLD values. On the bases of cut-off factors, reservoir zones are marked by the following cut-off parameters; V_{Sh}<30%, S_w<60% and effective porosity φ_E>7% (rock with primary porosity) and V_{Sh}<30%, S_w<60% and φ_E=1% (Table 1) (rock with secondary porosity/carbonate rock).

Table 1 - Petrophysical analysis of the studied wells.

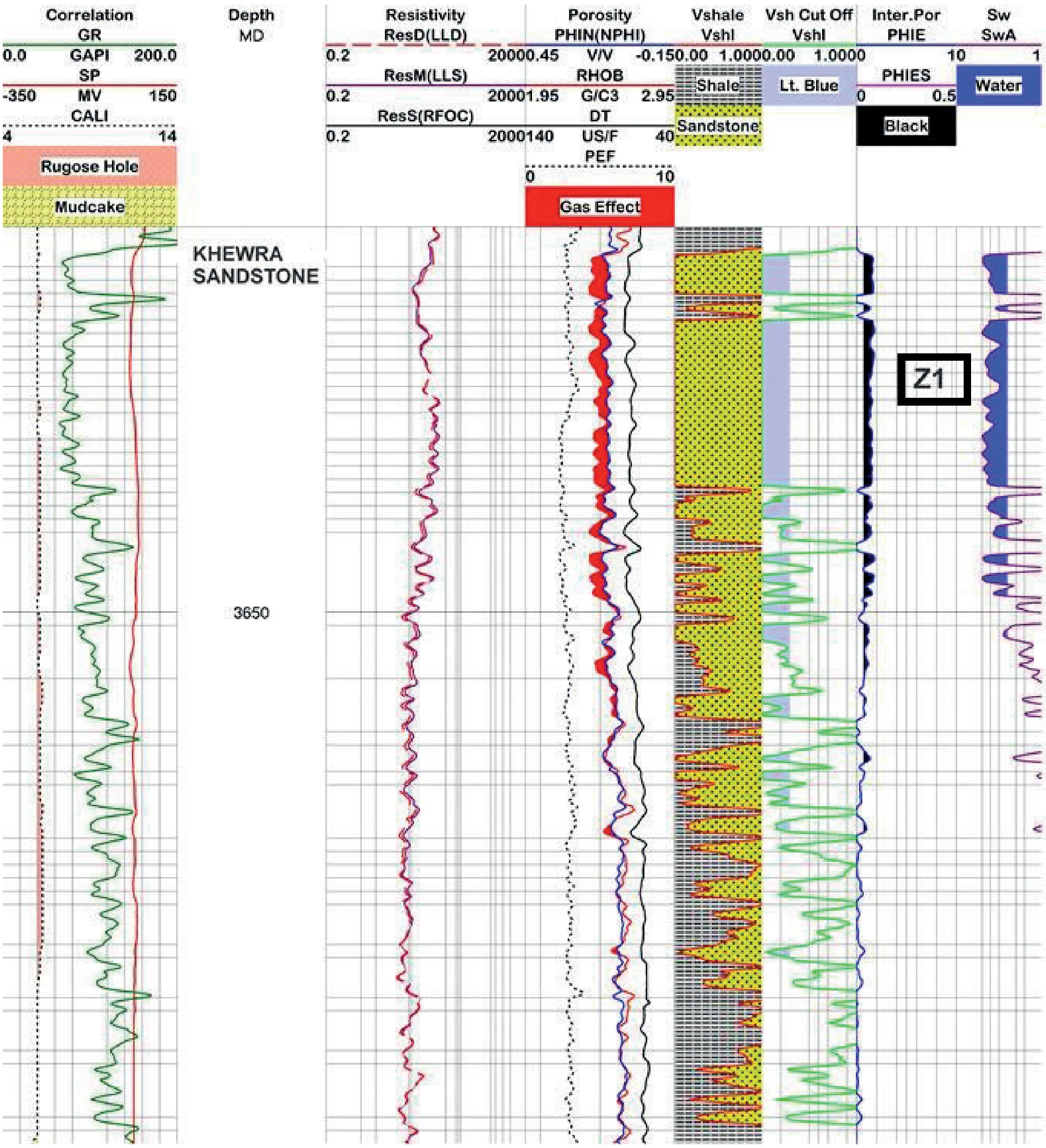
Well names	Formation names	Avg. volume of shale %	Avg. effective porosity %	Resistivity of water (Ω/m)	Average water saturation %	Avg. hydro-carbon saturation %
Rajian-01	Khewra Sandstone	20	15.0	0.34	38	62
Rajian-01	Jutana Formation	22	1.5	0.33	36	64
Rajian-01	Tobra Formation	16	22.0	0.33	52	48
Daiwal-01	Khewra Sandstone	27	12.0	0.31	75	25
Daiwal-01	Jutana Formation	16	0.0	0.34	78	22
Kal-01	Khewra Sandstone	28	14.0	0.36	42	58
Kal-01	Jutana Formation	25	1.0	0.36	44	56
Kal-01	Warchha Sandstone	15	12.0	0.34	20	80

4.3. Reservoir zones

Zone 1 (Rajian-01) consists of medium grain, micaceous, flaggy bedded sandstone (Khewra Sandstone). A zone of interest has been marked from 3623 to 3652 m. The total thickness of the zone is about 27 m (Fig. 4a). Average volume of shale is 0.20 (20%). The average value of the effective porosity is 13.2%. In this zone, the R_w is found to be 0.34 Ω/m with the help of the Schlumberger chart. The average value of water saturation is 38% and hydrocarbon saturation (S_{hc}) is about 62% (Table 1).

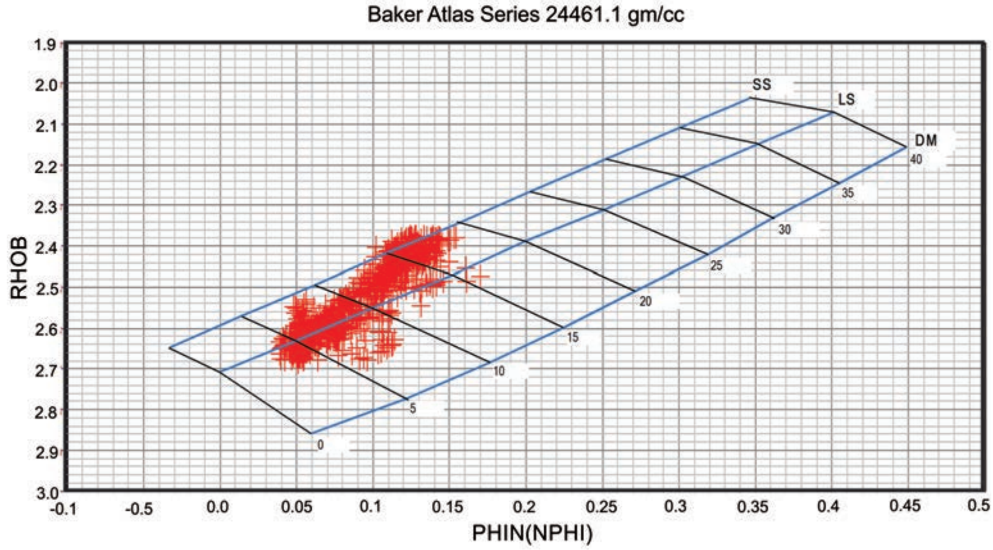
Zone 2 (Rajian-01) is comprised of the Jutana Formation; its thickness ranges from 3505 to 3537 m. In Zone 2, three productive zones Z2A, Z2B, and Z2C have marked, ranging from 3505 to 3514 m, 3520 to 3523 m, and 3529 to 3537 m (Fig. 5a). The total thickness of the zone of interest is 20 m. In the Z2A subzone, the volume of shale is 0.26 (26%). The average value of effective porosity is 1%. The Jutana Formation mostly comprises dolomite and consists of secondary porosity that can be measured with the help of advance logs. The resistivity of water is obtained from the Schlumberger chart that is about 0.33 Ω/m. The average water saturation is 40% and hydrocarbon saturation is 60%. In subzone Z2B, the shale volume is 0.23 (23%). Effective porosity is 8%, R_w is 0.33 Ω/m, average water saturation is 35% and hydrocarbon saturation is 65%. In subzone Z2C, the average volume of shale is 0.29 (29%), effective porosity is 0%, R_w is 0.33 Ω/m, water saturation is 39% and hydrocarbon saturation is 61%. Fig. 5a shows the zone of interest in the Jutana Formation with sufficient values to become a good reservoir zone.

Zone 3 (Rajian-01) consists of the Tobra Formation (Rajian-01) ranging from 3483 to 3495 m. The average volume of shale in Zone 3 is 0.16 (16%). R_w, obtained from the Schlumberger chart, is about 0.33 Ω/m. The effective porosity is 23%, average water saturation is 52% and hydrocarbon saturation is 48% (Fig. 6a).



a)

Fig. 4 - Khewra Sandstone in Zone 1 (Rajian-01): a) petrophysical analysis; b) cross-plot for lithology.



b)

Fig. 4 - continued.

Zone 4 (Daiwal-01) represents the Khewra Sandstone ranging from 4890 to 4955 m. In Zone 4 one productive zone is marked ranging from 4890 to 4910 m (Fig. 7a). The average shale volume is 0.27 (27%). R_w is 0.31 Ω/m as obtained from the Schlumberger chart. The effective porosity is about 11.7%. Average water saturation is 75% and hydrocarbon saturation is 25% (Table 1).

Zone 5 (Daiwal-01) consists of the Jutana Formation starting from 4763 to 4809 m. In Zone 5, two subzones of interest are marked ranging from 4762 to 4790 m and 4803 to 4809 m. The total thickness of the zone of interest is 34 m. In the subzone Z5A, average volume of shale is 0.16 (16%). R_w obtained from the Schlumberger chart is 0.34 Ω/m. The effective porosity of this subzone is 0% because the Jutana Formation comprises carbonate rock and has secondary porosity. Water saturation is 78% and hydrocarbon saturation is 22%. In subzone Z5B, the volume of shale is 0.20 (20%), whereas effective porosity is 0%, R_w is 0.34 Ω/m, water saturation is 76% and hydrocarbon saturation is 24% (Fig. 8a).

Zone 6 (Daiwal-01) is comprised of the Dandot Formation ranging from 4740 to 4755 m. Zone 6 is marked from 4741 to 4753 m. The average shale volume is 0.26 (26%). R_w is 0.27 Ω/m as obtained from the Schlumberger chart. The average effective porosity is 11%. Water saturation is 73% and hydrocarbon saturation is 27% (Fig. 9a).

Zone 7 (Kal-01) is further divided into two subzones, Z7A and Z7B, ranging from 2650 to 2672 m and 2674 to 2680 m, respectively. In Z7A, the volume of shale is 0.28 (28%). R_w is 0.38 Ω/m as obtained from the Schlumberger chart. The average effective porosity is 13%. Saturation of water is 40.2% and hydrocarbon saturation is 59.8%. In Z7b, average shale volume is 0.35 (35%). R_w is 0.38 Ω/m and effective porosity is 10 %. Saturation of water is 42% and hydrocarbon saturation is 58% (Fig. 10a).

Zone 8 (Kal-01) is further divided into two subzones, Z8A and Z8B, ranging from 2518 to 2539 m and 2557 to 2564 m, respectively. In Z8A, the volume of shale is 0.25 (25%). R_w obtained

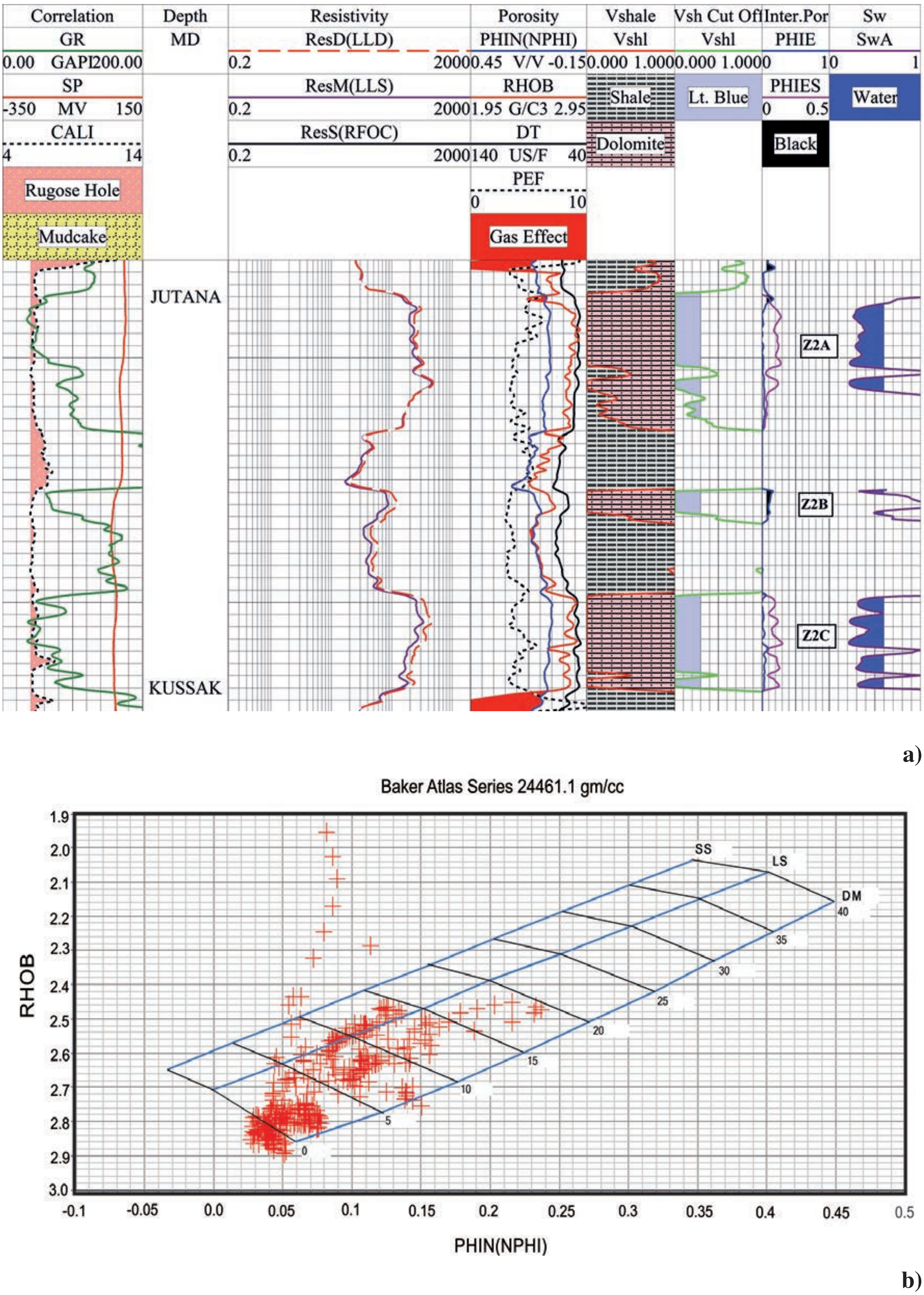
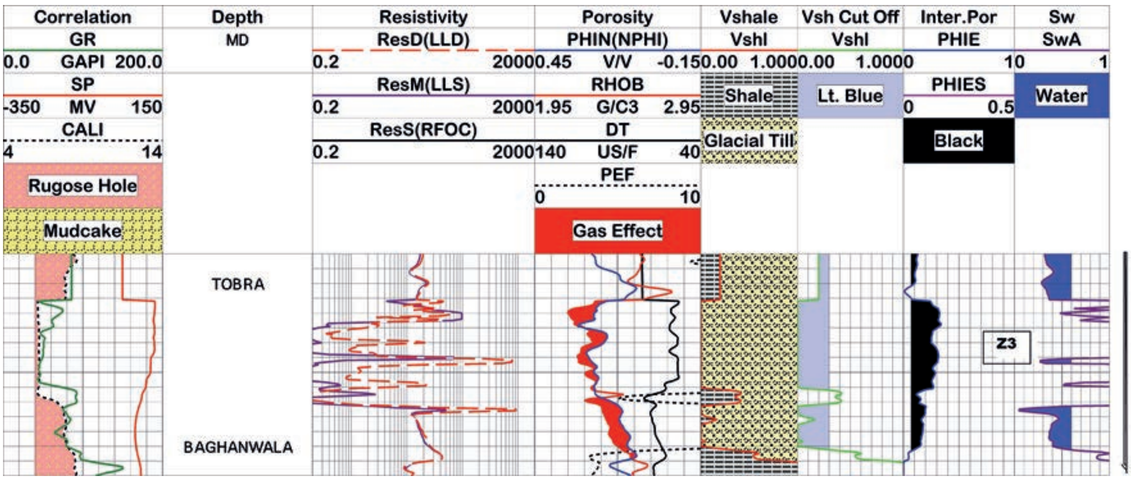
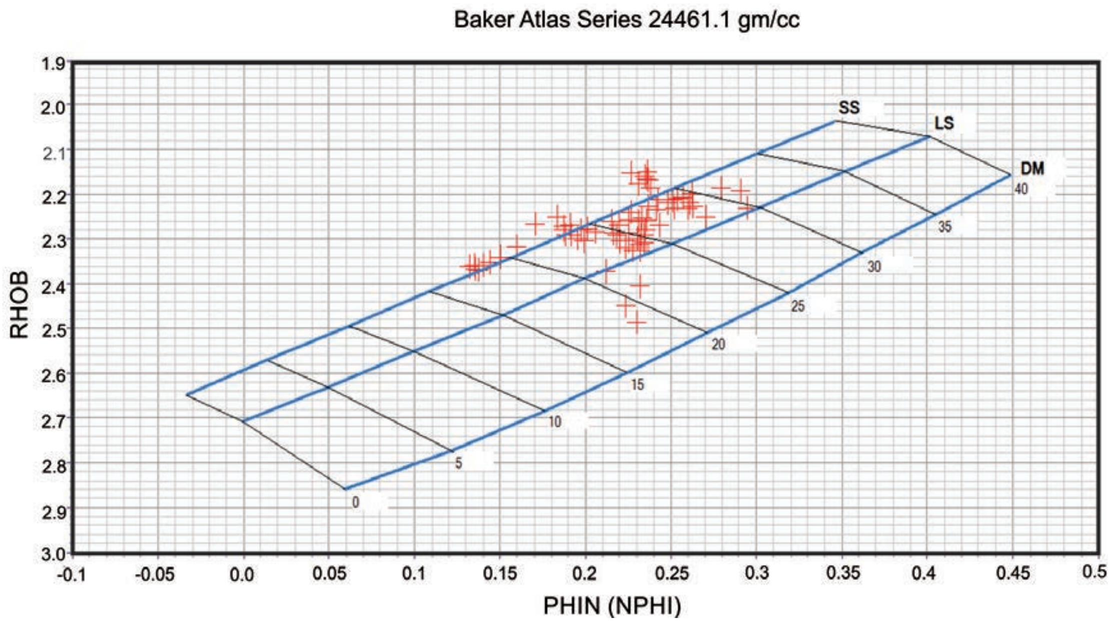


Fig. 5 - Jutana Formation in Zone 2 (Rajian-01): a) petrophysical analysis; b) cross-plot for lithology.



a)



b)

Fig. 6 - Tobra Formation in Zone 3 (Rajian-01): a) petrophysical analysis; b) cross-plot for lithology.

from the Schlumberger chart is 0.37 Ω/m. The effective porosity is 1%, water saturation is 44.3% and hydrocarbon porosity is 55.7%. In Z8B, the shale volume is 0.32 (32%) (Table 1). R_w is 0.37 Ω/m and effective porosity is 0%, water saturation is 43%, and hydrocarbon saturation is 57% (Fig. 11a).

In Zone 9 (Kal-01) the productive zone ranges from 2497 to 2509 m. In this zone the volume of shale is 0.15 (15%). R_w is 0.34 Ω/m as obtained from the Schlumberger chart, whereas the effective porosity is 10.3%, water saturation is 20%, and hydrocarbon saturation is 80% (Fig. 12a).

4.4. Lithology identification through cross-plots

RHOB-NPHI cross-plot is the most effective combination for lithology identification. NPHI is plotted on X-axis and RHOB is plotted on Y-axis. Lines of lithology on cross-plots are sandstone, limestone, and dolomite (SS, LS, DM). Points will fall on one of the lines for clean formation. If points fall between the lines, it shows that mixtures of two or three lithologies are present. If the cement is calcareous, then, sandstone lithology can be displaced slightly towards the limestone line (Rider, 1996). The interpretation of the cross-plot models allowed us to identify the rock lithology (see some examples in Figs. 4b, 5b, 6b, 7b, 8b, 9b, 10b, 11b, 12b).

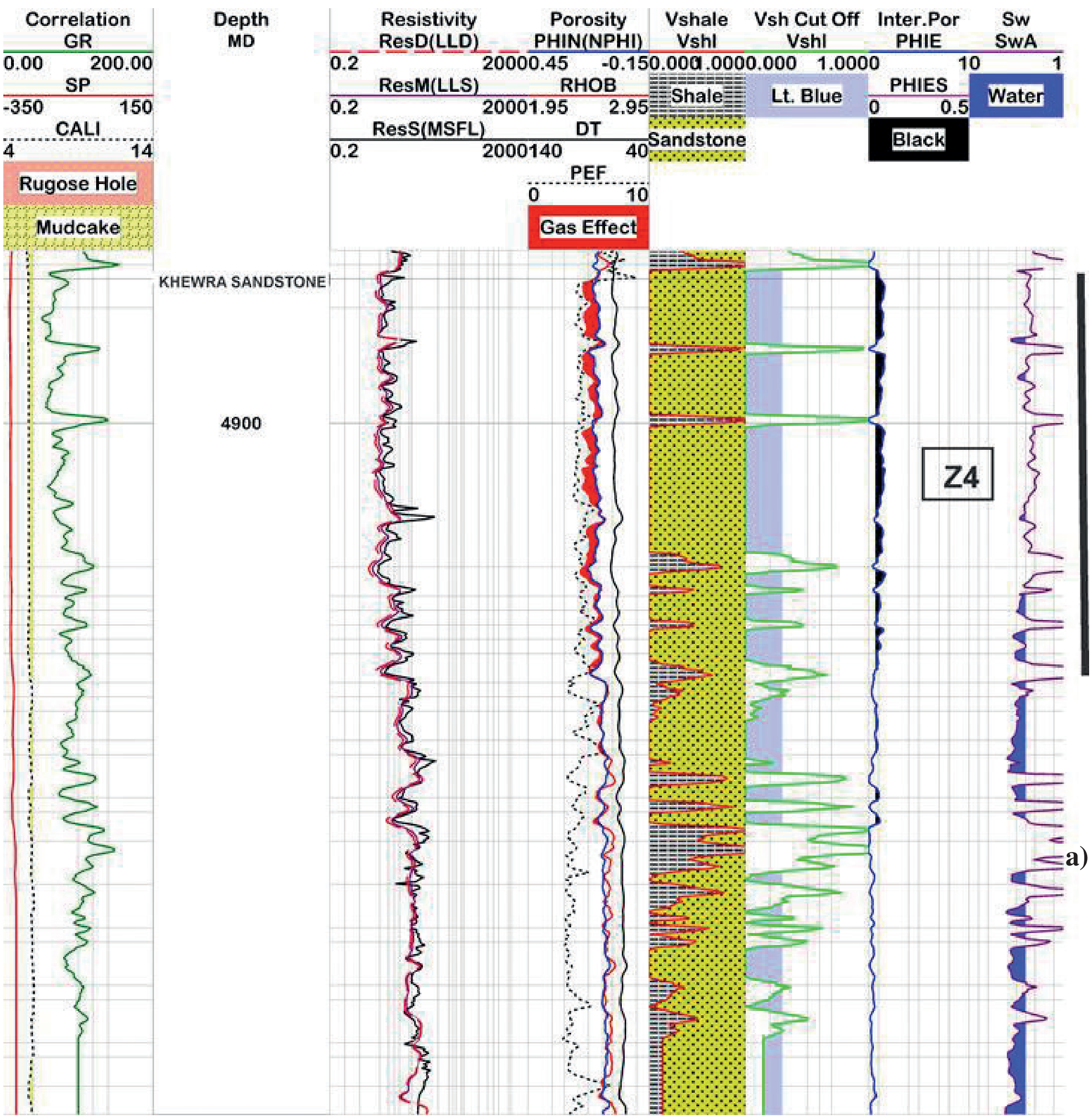
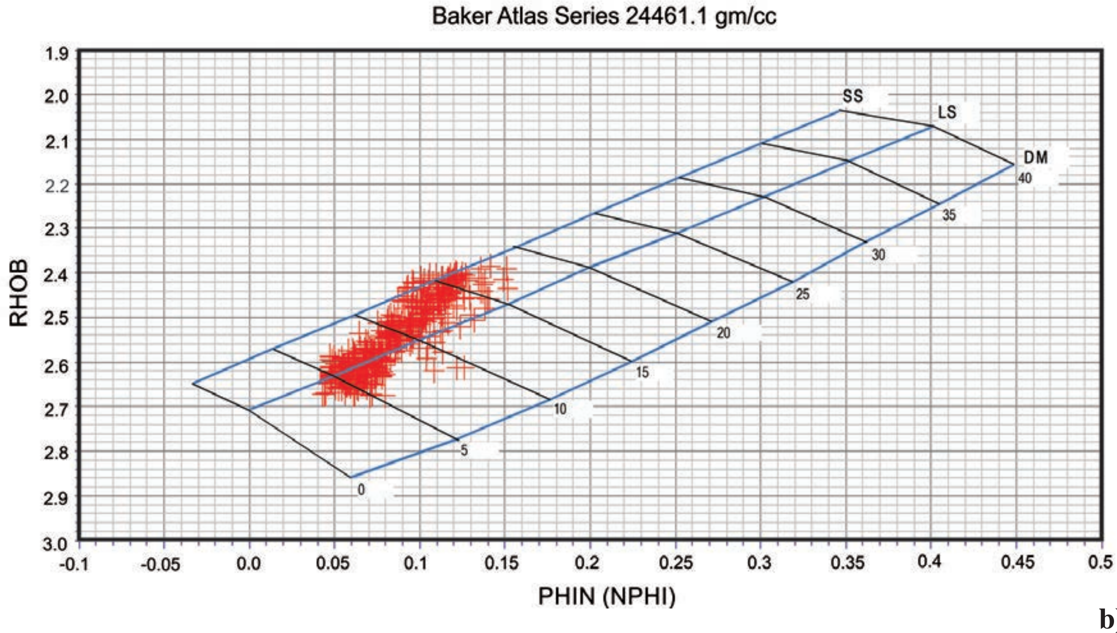


Fig. 7 - Khewra Sandstone in Zone 4 (Daiwal-01): a) petrophysical analysis; b) cross-plot for lithology.



b)

Fig. 7 - continued.

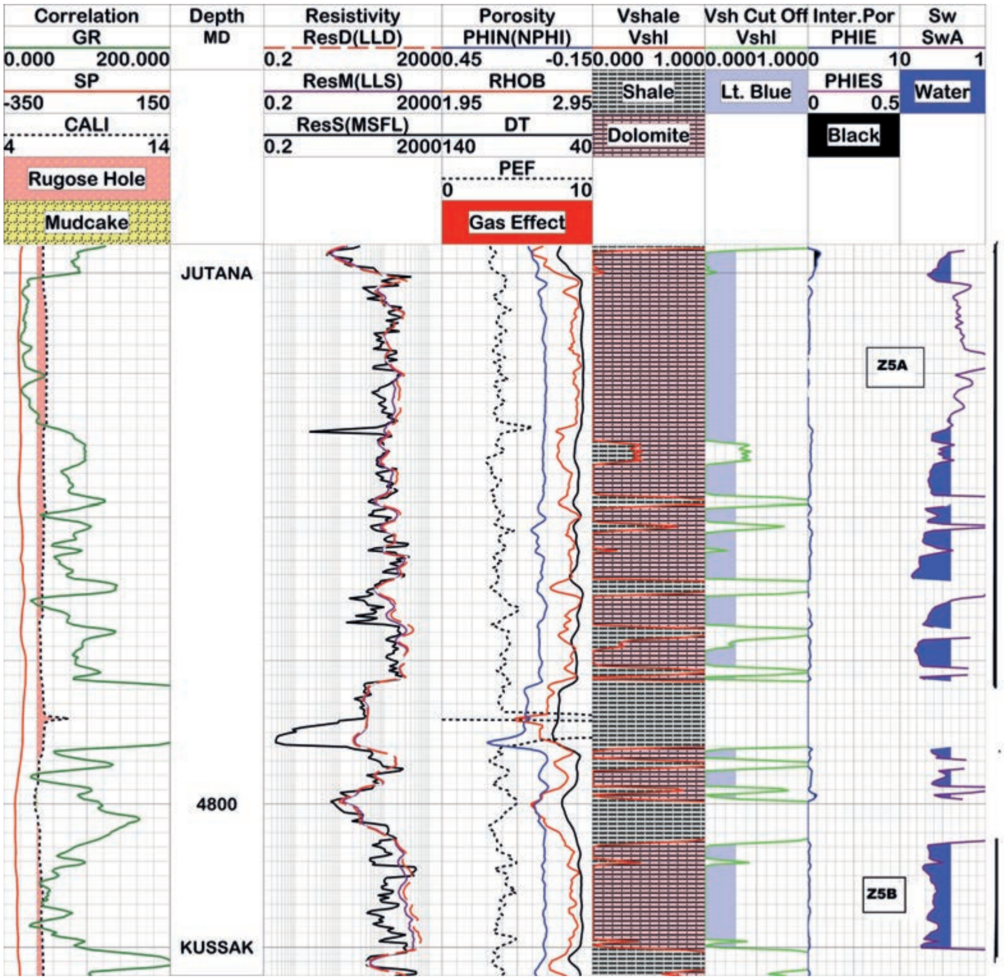
4.5. Correlation

Correlation is an important geological technique and it provides the information on the changes that have taken place at various stages within the Earth's history. It also indicates the times at which such changes have occurred (Pillow *et al*., 2008; Naqash and Khan, 2016).

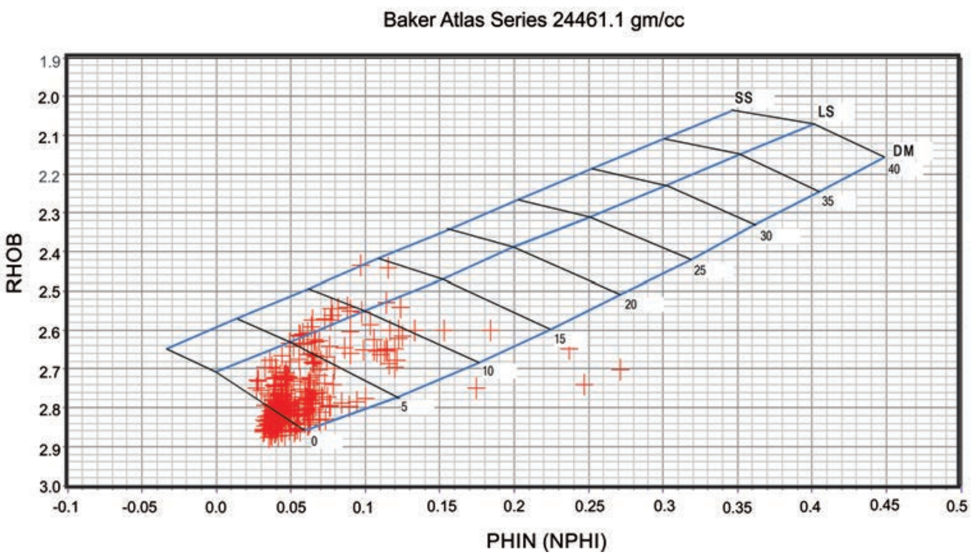
Stratigraphic correlation is used to compare geologic phenomena based purely on rock type. In such a correlation, the rock of one area is correlated with another area of rocks and the depositional environment of the rock is interpreted. The stratigraphic correlation of these three wells (Rajian-01, Daiwal-01, and Kal-01) is given in Fig. 13. Datum line is taken from the top of the Hangu Formation of these three wells.

The total depth of the Rajian-01 is 3700 m. The stratigraphy of the well ranges from Cambrian (Khewra Sandstone) to Pliocene (Chinji Formation), whereas the total depth of the Daiwal-01 is 4950 m. Daiwal-01 is drilled along the thrust fault; stratigraphy of the well (Daiwal-01) is divided into two sheets. The upper sheet (above the thrust fault) consists of formation ranges from Precambrian (Salt Range Formation) to Pliocene (Nagri Formation) and thickness from very small to 3224 m. The lower sheet (below the thrust fault) is composed of the formation ranges from Cambrian (Khewra Sandstone) to Miocene-Oligocene (Murree Formation) and thickness ranges from 3224 to 4950 m. The lower sheet of the Daiwal-01 well is correlated with the other two wells formation (Rajian-01 and Kal-01). While the total depth of the Kal-01 well is 2790 m, in the Salt Range Formation and Chinji Formation it is very small. Stratigraphically Kal-01 starts from Precambrian (Salt Range Formation) to Pliocene (Chinji Formation).

Khewra Sandstone of Cambrian age is the producing reservoir in Rajian-01 and Kal-01 wells and has good hydrocarbon potential. Subsurface studies continued and more wells were drilled to estimate the quality of reservoirs. As the effective porosity in the Jutana Formation can be

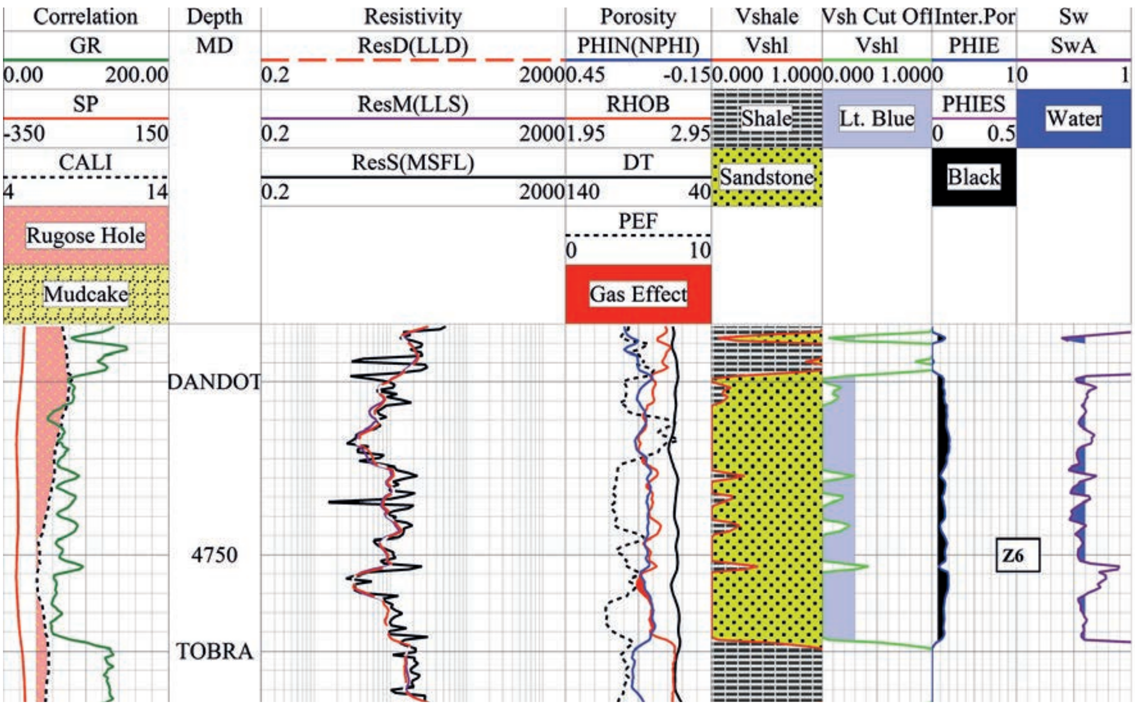


a)

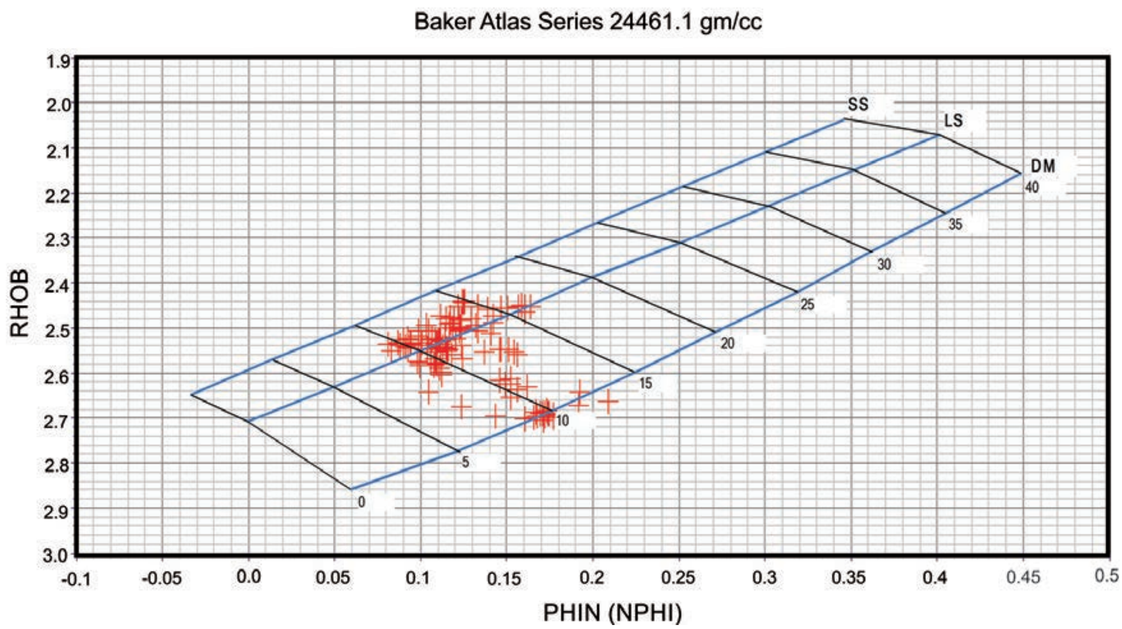


b)

Fig. 8 - Jutana Formation in Zone 5 (Daiwal-01): a) petrophysical analysis; b) cross-plot for lithology.

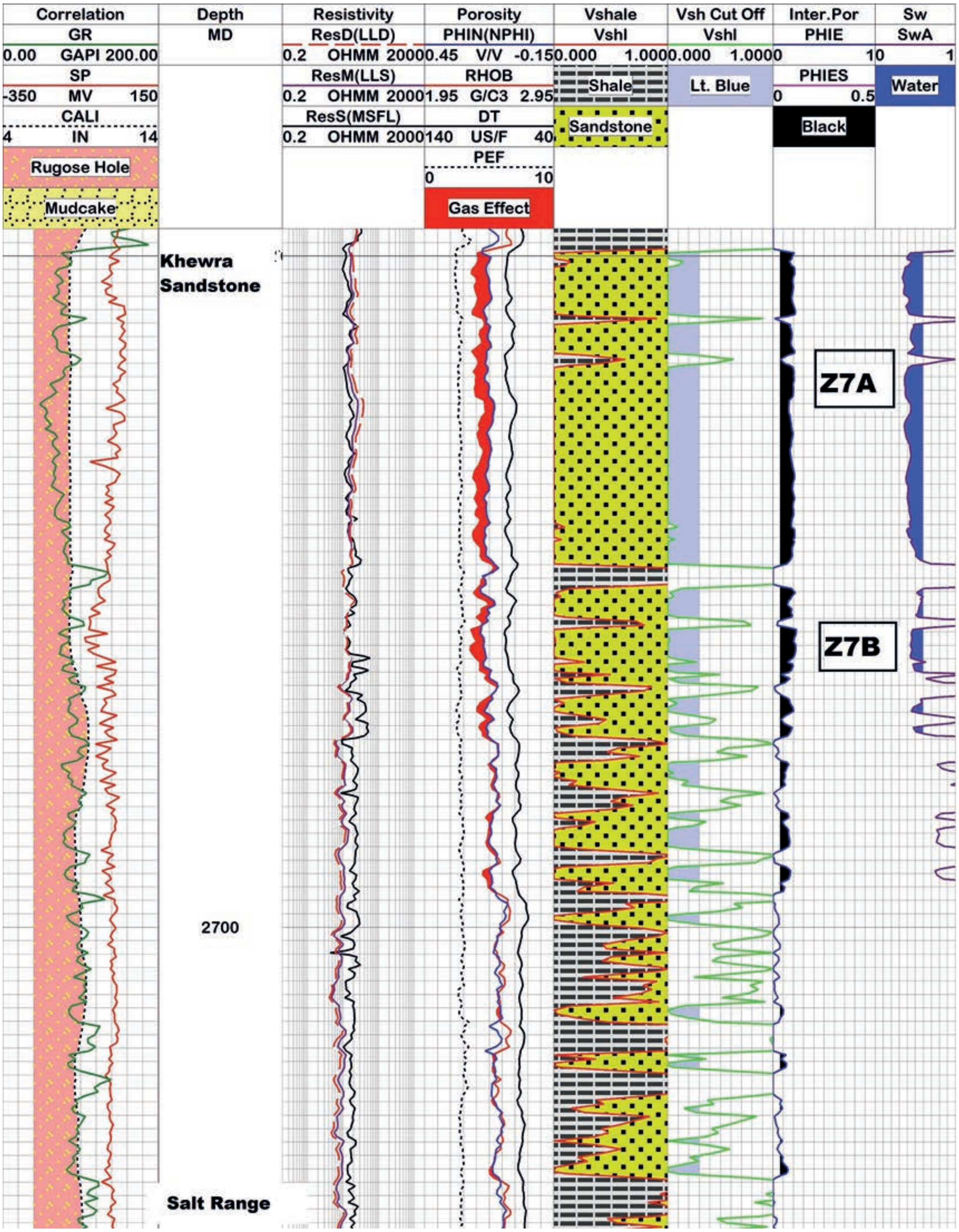


a)



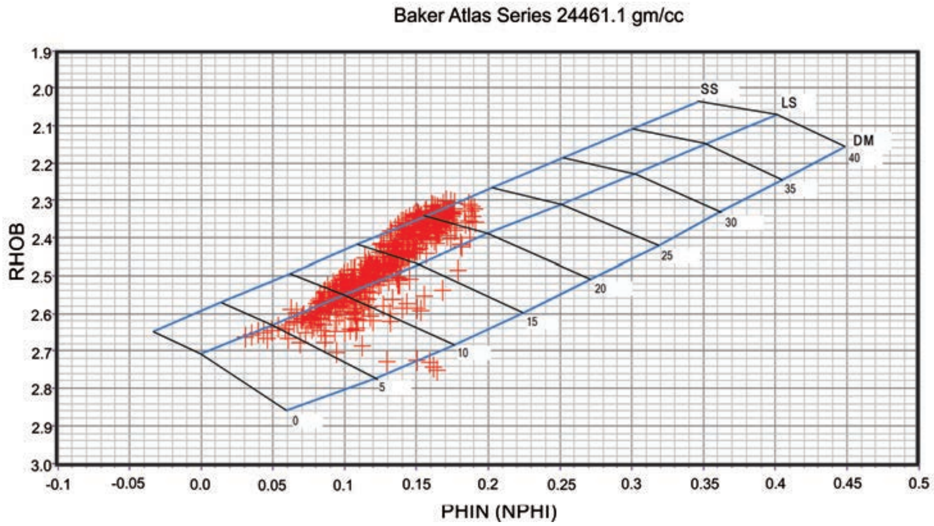
b)

Fig. 9 - Dandot Formation in Zone 6 (Daiwal-01): a) petrophysical analysis; b) cross-plot for lithology.



a)

Fig. 10 - Khewra Sandstone in Zone 7 (Kal-01): a) petrophysical analysis; b) cross-plot for lithology.



b)

Fig. 10 - continued.

increased by induced fracturing, these operations could increase the oil production. The Daiwal-01 well was found to be uneconomical because of the structural complexity; this finding could be better verified by detailed subsurface studies (including subsurface structure).

5. Conclusions

The potential reservoirs are Khewra Sandstone, Jutana Formation, Tobra Formation, Dandot Formation, and Warcha Sandstone. Based on the petrophysical interpretation of wells, it has been concluded that Khewra Sandstone and Jutana Formation are the most promising reservoirs, however the thin and poor-to-moderate reservoir intervals of the Tobra Formation, Dandot Formation, and Warchha Sandstone also act as a reservoir.

The petrophysical analysis showed that the Rajian-01 and Kal-01 have good hydrocarbon potential, whereas Daiwal-01 was found not to be economic valuable. The water saturation encountered in Rajian-01 and Kal-01 ranges from 20 to 44%, whereas Daiwal-01 has > 72%.

GR and SP logs are used to identify the lithology. GR values greater than 60% indicate the presence of shale and less than 60% indicate sandstone, dolomite, and limestone. Furthermore, from the correlation of GR log and sonic log, the lithologies are better confirmed. From the interpretation of the well logs, the dominant lithologies are shale, sandstone, dolomite, limestone, and their mutual interaction.

The effective porosity in Rajian-01, Daiwal-01, and Kal-01 spans from 8 to 23%. The hydrocarbon saturation is higher in Rajian-01 and Kal-01 than in Daiwal-01. In Rajian-01 and Kal-01, hydrocarbon saturation reached 80 to 56%, whereas in Daiwal-01 hydrocarbon saturation is < 28%. Thus, the Rajian-01 and Kal-01 have better reservoir characteristics than Daiwal-01.

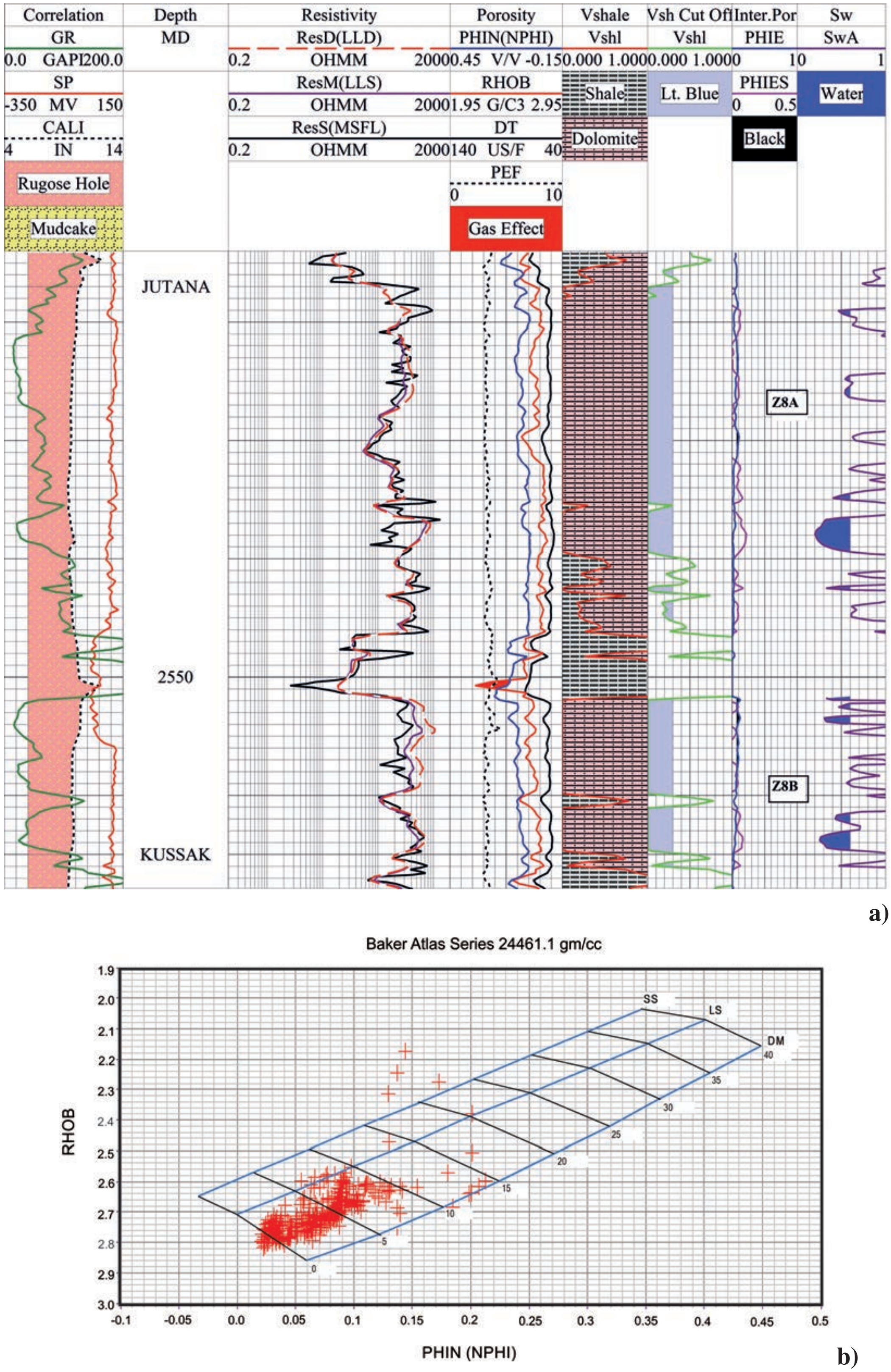


Fig. 11 - Jutana Formation in Zone 8 (Kal-01): a) petrophysical analysis; b) cross-plot for lithology.

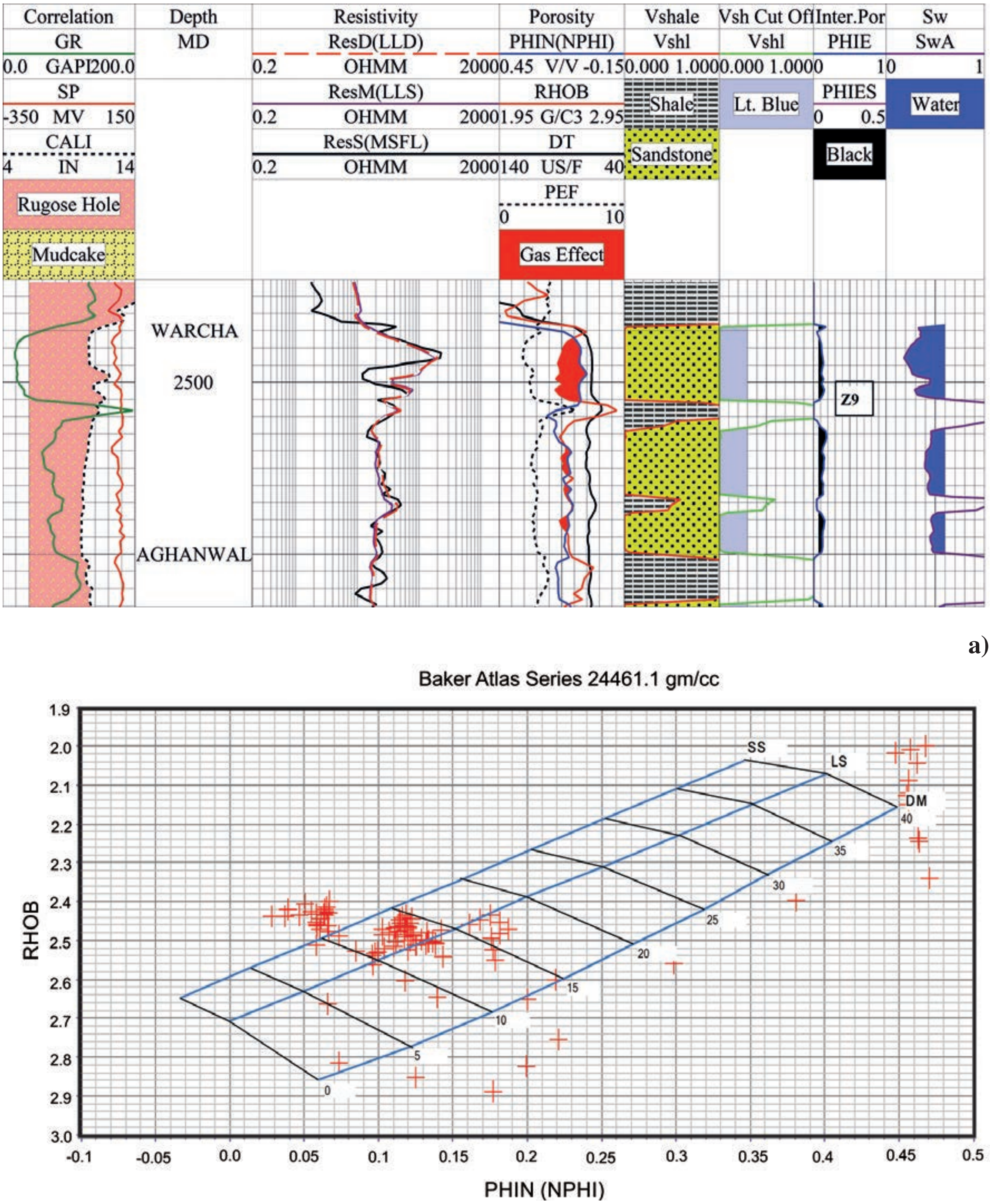


Fig. 12 - Warcha Sandstone in Zone 9 (Kal-01): a) petrophysical analysis; b) cross-plot for lithology. **b)**

Acknowledgements. We would like to thank the Department of Earth Sciences, University of Sargodha, Director General Petroleum Concession (DGPC), Islamabad, Pakistan for providing well data. Special thanks to Oil and Gas Development Company (Reservoir Department) who spared their precious time to review and provide useful comments.

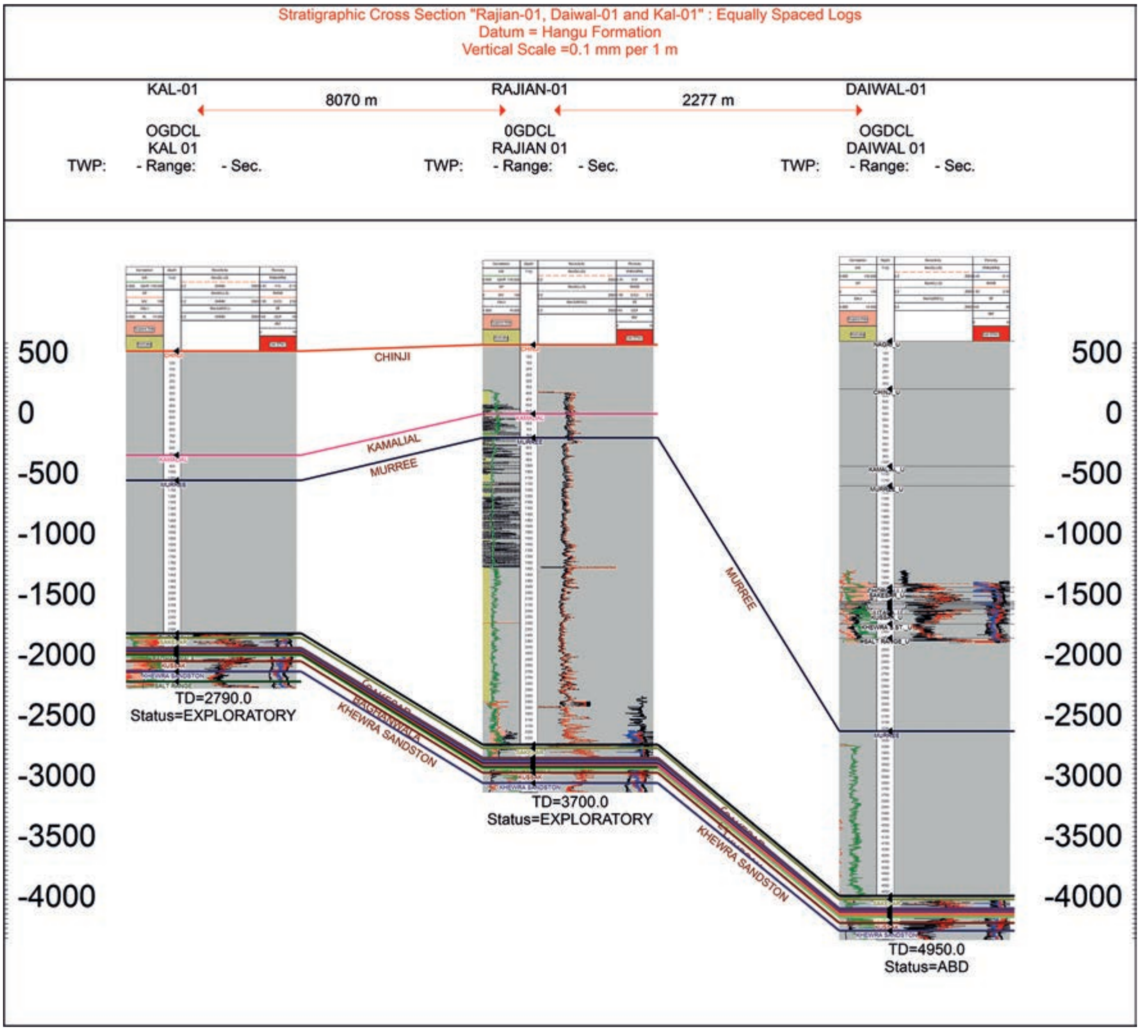


Fig. 13 - Stratigraphic correlation of the Rajian-01, Daiwal-01, and Kal-01 of the study area.

REFERENCES

Aamir M. and Saddiqui M.; 2006: *Interpretation and visualization of thrust sheet in triangle zone in eastern Potwar, Pakistan*. The Leading Edge, **25**, 24-37.

Abir I.A., Khan S.D., Ghulam A., Tariq S. and Shah M.T.; 2015: *Active tectonics of western Potwar Plateau - Salt Range, northern Pakistan from InSAR observations and seismic imaging*. Remote Sens. Environ.**, 168,** 265-275.

Aguilera M.S. and Aguilera R.; 2003: *Improved models for petrophysical analysis of dual porosity reservoirs*. Petrophys., **44**, 21-35.

Alexeyev A., Ostadhassan M., Mohammed R.A., Bubach B., Khatibi S., Li C. and Kong L.; 2017: *Well log based geomechanical and petrophysical analysis of the bakken formation*. In: Proc. 51st US Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, San Francisco, C.A., U.S.A., APMA 17-942, 9 pp.

Archie G.E.; 1942: *The electrical resistivity log as an aid in determining some reservoir characteristics*. Pet. Trans. AIME, **146,** 54-62.

Arns C.H., Bauget F., Sakellariou A., Senden T.J., Sheppard A.P., Sok R.M., Ghous W.V., Pinczewski M.A. and Kelly J.C.; 2005: *Digital core laboratory: petrophysical analysis from 3D imaging of reservoir core fragments*. Petrophys., **46**, 260-277.

Asquith G.B. and Krygowski D.; 2004: *Basic well log analysis: methods in exploration*. Am. Ass. Pet. Geol., Tulsa, OK, USA, Vol. 16, 2nd ed., 244 pp.

Attia A.M.; 2005: *Effects of petrophysical rocks properties on tortuosity factor*. J. Pet. Sci. Eng., **48**, 185-198.

Chaudhry M.N. and Zaka K.J.; 1998: *Petrographic evolution of alkali aggregate reaction in concrete structures of Warsak Dam, NWFP Pakistan - A case study.* In: Proc., 8th International Congress, Association of Engineering Geology and Environment, Vancouver, Canada, pp. 2841-2846.

Chongwain G.M., Osinowo O.O., Ntamak-Nida M.J. and Nkoa E.N.; 2018: *Seismic attribute analysis for reservoir description and characterization of M-Field, Douala sub-basin, Cameroon*. Adv. Pet. Explor. Dev., **15,** 41-50, doi: 10.3968/10220.

Chongwain G.C., Osinowo O.O., Ntamak-Nida M.J. and Nkwanyang T.L.; 2019: *Lithological typing, depositional environment, and reservoir quality characterization of the "M-Field," offshore Douala basin, Cameroon*. J. Pet. Explor. Prod. Tech., **9,** 1705-1721.

Dolson J.; 2016: *Basic log analysis, quick-look techniques, pitfalls and volumetrics*. In: Understanding oil and gas shows and seals in the search for hydrocarbons, Springer International Publishing, Cham, Switzerland, pp. 315-347.

Dominik W., Raymond L.B. and Taseer H.; 2013: *A systematic, biographic and paleogeographic reevaluation of siwaliks hipparion horse assemblages from the Potwar Plateau, northern Pakistan*. Paleontograp., Abteilung A, **300,** 1-115, doi: 10.1127/pala/300/2013/1 (in German).

Dresser Atlas; 1979: *Log interpretation charts*. Dresser Atlas Division, Dresser Industries, Houston, TX, USA, 107 pp.

Ghazanfer M.; 1993: *Petrotectonic elements and tectonic framework of northwest Himalaya*. Ph.D Thesis, University of Punjab, Lahore, Pakistan, 380 pp.

Grelaud S., Sassi W., DeLamotte D.F., Jaswal T. and Roure F.; 2002: *Kinematics of eastern Salt Range and south Potwar basin (Pakistan): a new scenario*. Mar. Pet. Geol., **19**, 1127-1139.

Hasany S.T. and Saleem U.; 2012: *An integrated subsurface geological and engineering study of Meyal field, Potwar Plateau, Pakistan*. Search and Discovery, Article No. 20151, 41 pp.

Hilchie D.W.; 1990: *Wireline: a history of the well logging and perforating business in the oil fields, 1st ed*. Hilchie D.W. (ed), Golden, CO, USA, 200 pp.

Hill D.G.; 2017: *Formation evaluation*. In: Hsu C.S. and Robinson P.R. (eds), Springer Handbook of Petroleum Technology, Springer International Publishing, Cham, Switzerland, pp. 433-500.

Iqbal S., Akhter G. and Bibi S.; 2015: *Structural model of the Balkassar area, Potwar Plateau, Pakistan*. Int. J. Earth Sci., **104**, 2253-2272.

Jadoon M.S.K., Hameed A., Akram M.M., Bhatti A.H., Ali A. and Rizvi I.; 2003: *An integrated reservoir simulation study of Fimkasser oil field*. Pakistan J. Hydrocarbon Res., **13**, 37-58.

Jadoon I.A., Hinderer M., Wazir B., Yousaf R., Bahadar S., Hassan M. and Jadoon S.; 2015: *Structural styles, hydrocarbon prospects, and potential in the Salt Range and Potwar Plateau, north Pakistan*. Arabian J. Geosci., **8**, 5111-5125.

Jaswal T., Lillie R.J. and Lawrence R.D.; 1997: *Structure and evolution of northern Potwar deformed zone, Pakistan*. Am. Assoc. Geol. Bull., **81**, 308-318.

Kadri I.B.; 1995: *Petroleum geology of Pakistan*. Pakistan Petroleum Ltd, Karachi, Pakistan, 275 pp.

Kashif M., Cao Y., Yuan G., Asif M., Javed K., Mendez J.N. and Miruo L.; 2019a: *Pore size distribution, their geometry and connectivity in deeply buried Paleogene Es1 sandstone Reservoir, Nanpu Sag, east China*. Pet. Sci., **16**, 981-1000.

Kashif M., Cao Y., Yuan G., Jian W., Cheng X., Sun P. and Hassan S.; 2019b: *Diagenesis impact on a deeply buried sandstone reservoir (Es1 Member) of the Shahejie Formation, Nanpu Sag, Bohai Bay basin, east China*. Aust. J. Earth Sci., **66**, 133-151.

Kazmi A.H. and Jan M.Q. (eds); 1997: *Geology and tectonics of Pakistan*. Graphic Publishers, Karachi, Pakistan, 554 pp.

Larionov E.A.; 1969: *On the number of fixed point of all linear-fractional transformation of an operator ball onto itself*. Math. USSR-Sbornik**,** **7**, 195.

Lefort M.; 1975: *Various processes occuring in strong interaction between heavy ions: compound nucleus formation, incomplete fusion, and quasifission*. Phys. Rev. C, **12**, 686.

Luthi S.; 2001: *Geological well logs: their use in reservoir modeling*. Springer Science and Business Media, Berlin/Heidelberg, Germany, 373 pp.

Mavko G., Mukerji T. and Dvorkin J.; 2011: *Rock physics handbook, 2nd ed.: tool for seismic analysis of porous media*. Cambridge University Press, New York, NY, USA, 511 pp.

Miller C., Thoni M., Frank W., Grasemann B., Klotzli U., Guntli P. and Draganits E.; 2001: *The early Paleozoic magmatic event in the north western Himalaya, India: source, tectonic setting and age of emplacement*. Geol. Mag., **138**, 237-251.

Moghal M.A., Saqi M.I., Hameed A. and Bugti M.N.; 2007: *Subsurface geometry of Potwar sub-basin in relation to structuration and entrapment*. Pak. J. Hydrocarbon Res., **17**, 61-72.

Moore W.R., Ma Y.Z., Urdea J. and Bratton T.; 2011: *Uncertainty analysis in well-log and petrophysical interpretations*. In: Ma Y.Z. and La Pointe P. (eds), Uncertainty analysis and reservoir modeling, American Association of Petroleum Geologists Memoir, **96**, 17-28.

Naqash Z. and Khan H.A.; 2016: *Structural analysis using seismic interpretation techniques and petrophysical analysis of Rajian Oil Field, Upper Indus basin, Pakistan, 2-D Seismic Data interpretation and petrophysical analysis of Kandra area, central Indus basin, Pakistan*. Thesis in Geophysics, Department of Earth and Environmental Sciences, Bahria University, Islamabad, Pakistan, 87 pp.

OGDC (Oil and Gas Development Corporation); 1996: *Pakistan petroleum prospects - An overview*. Oil & Gas Development Corporation, Islamabad, Pakistan, 22 pp.

Pillow J.W., Shlens J., Paniski L., Sher A., Litke A.M., Chichilnisky E.J. and Simoncelli E.P.; 2008: *Spatio-temporal correlation and visual signalling in a complete neuronal population*. Nature, **454**, 995-999.

Rider M.H.; 1978: *Dipmeter log analysis, an essay*. In: Trans., 19th Annual Logging Symposium Transactions, Society Professional Well Log Analysts, El Paso, TX, USA, Paper G, 18 pp.

Rider M.H. and Laurier D.; 1979: *Sedimentology using a computer treatment of wells logs*. In: Trans., 6th European Symposium, Society Professional Well Log Analysts, London, England, Paper J, 12 pp.

Schlumberger M., Challeton C., De Vathaire F. and Travagli J.P.; 1996: *Radioactive iodine treatment and external radiotheraphy for lungs and bones metastates from thyroid carcinoma*. J. Nucl. Med., **37,** 598-605.

Shah S.M.I.; 2009: *Stratigraphy of Pakistan*. Mem. Geol. Surv. Pak., **22,** 1-381.

Singh N.P.; 2019: *Permeability prediction from wireline logging and core data: a case study from Assam - Arakan basin*. J. Pet. Explor. Prod. Tech., **9**, 297-305.

Singha D.K. and Chatterjee R.; 2014: *Detection of overpressure zones and a statistical model for pore pressure estimation from well logs in the Krishna - Godavari basin, India*. Geochem. Geophys. Geosyst., **15**, 1009-1020.

Sultana A. and Kumar A.; 2014: *Development of tortuosity factor for assessment of lignocellulosic biomass delivery cost to a biorefinery*. Appl. Energy., **119**, 288-295.

Tahirkheli R.A.K., Mattauer M., Proust F. and Tapponier P.; 1979: *The India - Eurasia suture zone in northern Pakistan: synthesis and interpretation of recent data at plate scale*. In: Farah A. and DeJong K.A. (eds). Geodynamics of Pakistan, Geological Survey of Pakistan, Quetta, Pakistan, pp. 125-130.

Tixier M.P.; 1949: *Evaluation of permeability from resistivity gradient on electric logs*. Tulsa Geol. Soc. Digest, **17**, 68-73.

Uguru C.I., Onyeagoro O.U. and Sikiru I.O.; 2002: *Permeability modeling for reservoirs in the Niger Delta based on geological descriptions and core data*. SIPM Review Report., pp. 4-98.

Verma A.K., Cheadle B.A., Routray A., Mohanty W.K. and Mansinha L.; 2012: *Porosity and permeability estimation using neural network approach from well log data*. In: Extended Abstract, Annual Technical Conference and Exhibition, Society of Petroleum Engineers, San Antonio, TX, USA, pp. 1-6.

Yeats R.S. and Lawrence R.D.; 1984: *Tectonics of the Himalayan thrust belt in northern Pakistan*. In: Haq B.U. and Milliman J.D. (eds), Marine geology and oceanography of the Arabian Sea and coastal Pakistan, Van Nostrand Reinhold, New York, NY, U.S.A., pp. 117-198.

Zaidi S.N.A., Brohi I.A., Ramzan K., Ahmed N., Mehmood F. and Brohi A.U.; 2013: *Distribution and hydrocarbon potential of Datta sands in upper Indus basin, Pakistan*. Sindh University Research Journal-SURJ (Science Series), **45**, 325-331.

Zhang J., Santosh M., Wang X., Guo L., Yang X. and Zhang B.; 2012: *Tectonics of the northern Himalaya since the India - Asia collision*. Gondwana Res., **21,** 939-960.

Corresponding author: Muhammad Kashif
Department of Earth Sciences, University of Sargodha
University Road, Sargodha 40100, Pakistan
Phone: +92 3346893113; e-mail: Kashifyaqub@yahoo.com