

Reservoir Characterization of Eocene Carbonates of Central Indus Basin, Pakistan

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Abstract: The present study is based on petrophysical analysis of the Eocene Sui Main Limestone (SML) penetrated in wells of Qadirpur Gas Field, Central Indus Basin, Pakistan. The analyzed petrophysical property of SML includes shale volume, total porosity, effective porosity, water saturation, hydrocarbon saturation and net pay thickness. The result from the study shows that the Sui Main Limestone reservoir is capable of yielding appreciable hydrocarbon. The petrophysical interpretation revealed that the studied SML has productive reservoir characteristics with average (total and effective) porosity is in K-1, 15% in K-2 15% and 17% in K-3, average saturated hydrocarbon in SML is (70-100%) indicating that zones in wells are purely saturated with hydrocarbon, and average volume of shale in the zone of K-1, 23% in K-2, 27% and in K-3, 25% respectively delineating clean formation. Facies modeling revealed that the studied Eocene formation consist of clean limestone, shaly limestone and shals. The isopach thickness map and stratigraphic correlation helps to understand the thickness of Sui Main Limestone in the field.

Keywords: Reservoir Geology, Sui Main Limestone, Well logging, Interpretation

INTRODUCTION

Geologically, Qadirpur is located with the Mari Kandkot High and Central Indus Basin of Pakistan. The location of the area that fall down within this block in Central Indus Basin is enclosed by Sargodha high in the north, Indian Shield in the east, marginal region of Indian Plate in the west, and Sukkar Rift in the south. The basin is set apart from Upper Indus Basin by Sargodha High and Pezu Uplift in the north (Kazmi & Jan, 1997). Area lies down within the latitude approximately 27° 55' to 28° 09' N and longitude 69° 11' to 69° 31' E and it is about 820 sq. kilometers.

Qadirpur area geographically reclines in Ghotki and Jacobabad districts of Sindh Province. Qadirpur block contains most productive gas reservoir(s) in central Pakistan, and the impact from these reservoir(s) unaided was about 55% of the country's annual gas production of 0.924 tcf at an average of 2.53 bcf/ day during 2001–2002. So far, more than 20 tcf of natural gas reserves, with insignificant condensate, have been revealed in Sui Main Limestone in the 14 gas fields found in the region. This calculation is about 50% of the 42 tcf of gas discovered in Pakistan in the last 50 years.

According to Asquith & Krygowski (2004) well logs are used to correlate zones appropriate for hydrocarbon accumulation, recognize prolific zones, examine depth and thickness of zones, and differentiate between gas, oil and water in a reservoir and to estimate hydrocarbon reserve. Figure 1 shows the isopach map to identify the thickness of reservoir and locality.

Most valuable source rocks in prominent hydrocarbon producing province i.e. Central Indus Basin are shales of Sember, Mughalkot, Ranikot, Ghazij, and Sirki Formations. Sui Main

Limestone SML and Sui Upper Limestone are the main reservoir formations whereas limestone of Habib Rahi is recognized as secondary reservoir (Ali et al., 2005). The Sui Main Limestone (SML) sequence comprises a thick carbonate overlain by muddy to grainy limestone with diverse skeletal assemblages. The upper part of SML consists of argillaceous, fossiliferous limestone interbedded with thin, calcareous shale. Only localized packs of diagenetically poor-quality Sui Main have been encountered, as found in some dry wells within the productive range. Reservoir-quality rock of the Sui Main is restricted (in subsurface) within lat. 29–27°N, long. 67–70°E, covering an area of about 50,690 km² (19,572 mi²). The available rock volume and the voidage are estimated to be about 4790 and 718.5 km³ (1142 and 171 mi³) (25.4 tcf), respectively (Siddiqui, 2004). The study is to utilize a combined approach dependent on rock physics model and petrophysical evaluation to identify the diverse effects of rock. Commercial and systematic oil and gas proffering is highly depending on productive properties of reservoir rock, such as porosity, permeability, and wettability.

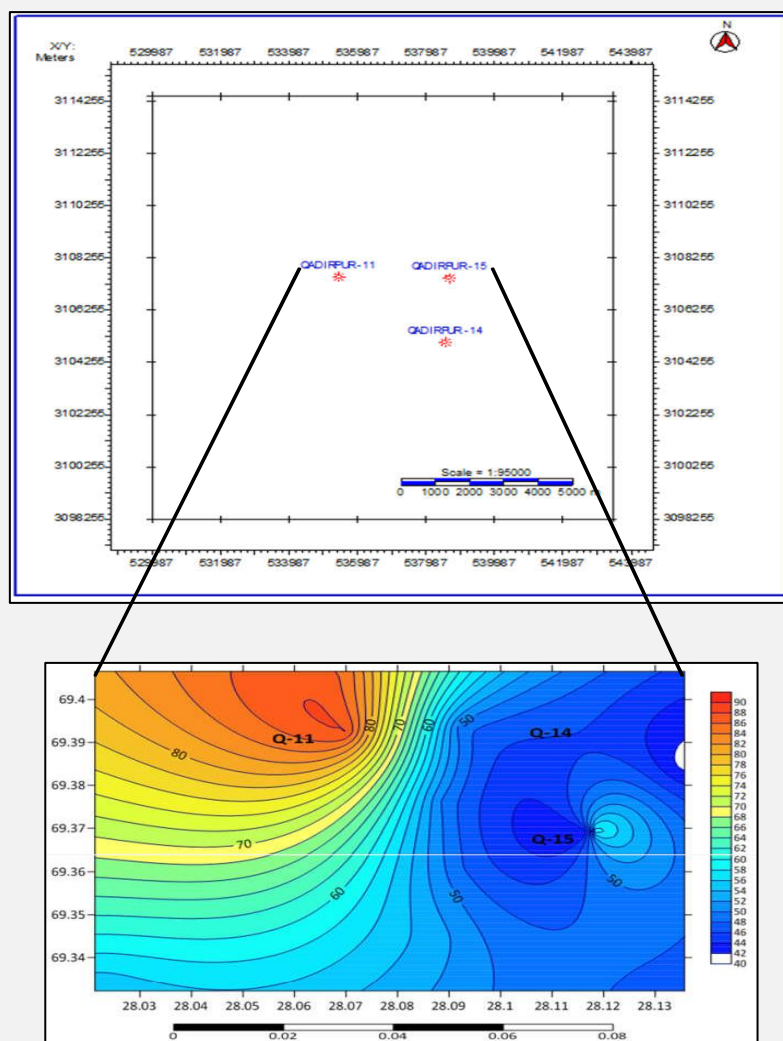


Figure 1. Isopach map to identify the thickness of reservoir and locality

Literature Review

The area was tectonically disturbed after the rifting occurred until early Mesozoic. Later, the rifting stopped and initially rifted crust remained as Indus basin failed rift (Zaigham & Mallick, 2000). Bannert & Raza (1992) and Bender & Bender (1995) suggested that the inclined strike of the

Eurasian and Indo Pakistan plates give rise to the evolution of large scale, N-S running, left-lateral strike-slip faults in the vault which are accountable for the division. Throughout the breaking phases the deposition of siliciclastic sourced from uplifted Indian shield took place above Jurassic chiltan Limestone, while carbonates of Parh and Fort Munro were deposited during the time of transgression (Zaigham & Mallick, 2000). Bender & Bender (1995) suggested that the oblique collision of the Eurasian and Indo Pakistan plates caused the development of large scale, N-S running, left-lateral strike-slip faults in the basement which cause the partition of the Indo-Pakistan Plate. It is considered that East Suleiman structural play of narrow straight anticlines as Flower Structure due to large scale wrench faults present there.

The generalized stratigraphy of the study area ranges from Triassic to Recent with non-deposition and erosion at various stratigraphic levels (see Figure 2). Sedimentary strata are detached from basement with a floor thrust in Paleozoic strata and roof-thrust in cretaceous (Sembar formation) except in the frontal part of Suleiman fold belt where it occurs in Eocene sequence (Bannert et al., 1989; Bannert et al., 1995) The thickness of the sediments increases westward. Intra-formational sedimentation breaks are pronounced in Permian and Jurassic, while Cretaceous Tertiary unconformity is regional (Bannert & Raza, 1992). The Ghazij Shale act as cap for Sui Main Limestone and Sui Upper Limestone while Sirki Shales over Habib Rahi Limestone present as a cap rock (Kadri, 1995). The SML is overlain by the shales of Shaheed Ghat Formation and underlying by the limestone of the Dunghan Formation (Paleocene) (Siddiqui, 2004).

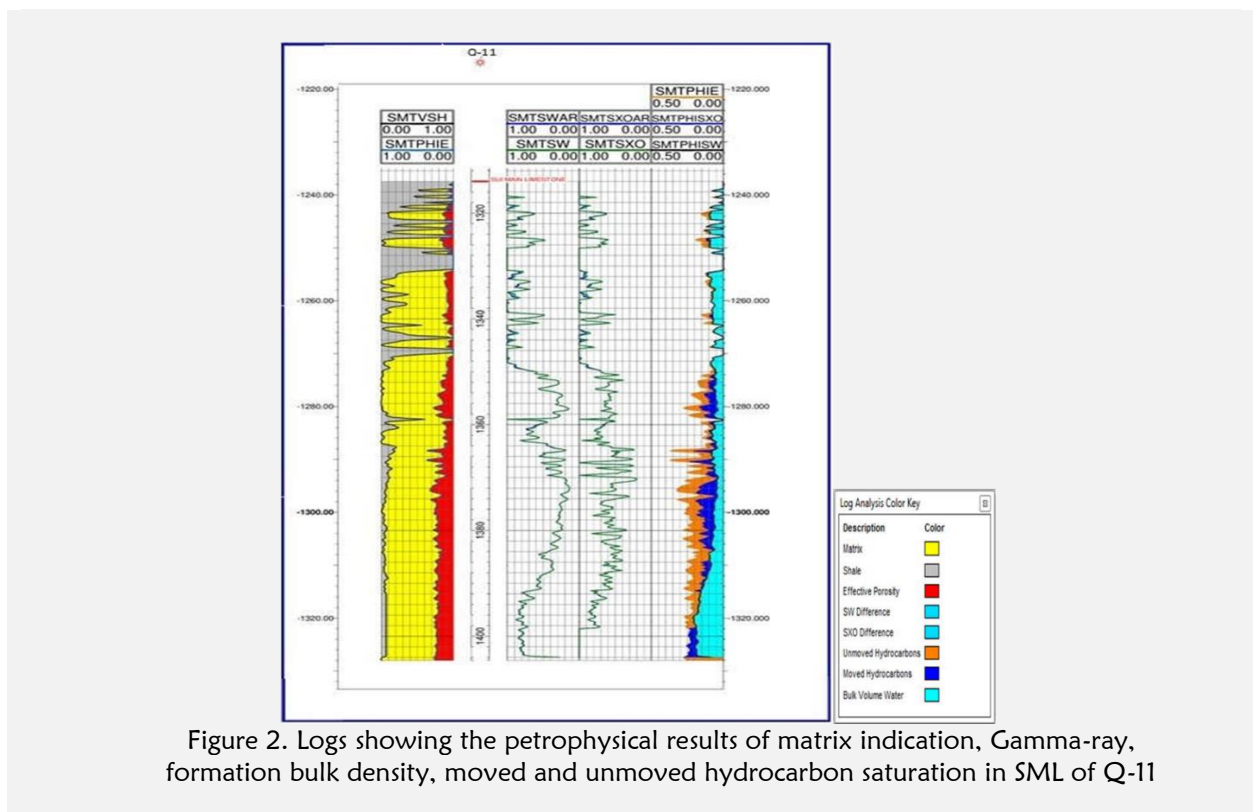


Figure 2. Logs showing the petrophysical results of matrix indication, Gamma-ray, formation bulk density, moved and unmoved hydrocarbon saturation in SML of Q-11

METHODS

Well log data are provided for current research work in the form of digital format (LAS format). Well log data comprises caliper log, self-potential log, gamma ray log, resistivity logs (shallow, medium and deep), porosity logs (neutron, density and sonic logs) are used in this research work (Schlumberger, 1989) and the data analysis is done using Kingdom Software 8.6. The raw data was issued by Land Mark Resources (LMKR) with the approval of Director General of Petroleum Concession, Pakistan (DGPC). The given logs are vulnerable to errors from various sources as borehole rugosity due to washouts, numerous tools, and absence of data and invasion

of mud filtrate. Therefore, well logs are requisite to be corrected for above mentioned errors. Well logs data includes caliper log, sp log, gamma ray log, resistivity logs (shallow, medium and deep), porosity logs (neutron, density and sonic logs) are used in this research work to manipulate the reservoir properties (Schlumberger, 1989).

The precise information of wells including latitude/longitude and well tops of three wells were also provided by the authorities. Creation of zones to finding the potential hydrocarbon, shale volume calculation (Linear and Clavier methods) of potential zones, average effective porosity calculation (from neutron and density porosity), saturation of water and hydrocarbon calculation (From Modified Archie Equation), flag calculation (rock, reservoir and pay zone thickness) and well to well correlation is done for analyzing data. The potential zones are commonly recognized by analyzing the well logs using the gamma ray log behavior, quick look technique from resistivity logs, neutron-density large negative separation. Three prospective zones of reservoir are identified in this research work. Flag calculation governs which cut-off curve will be used to define the rock, reservoir and pay. Pay defines the hydrocarbon infuse in the reservoir so the shale volume, porosity and water saturation are taken into interpretation. Volume of shale is used to characterize the shale distribution of a reservoir. The porosity estimations are important for determining fluid saturation in the reservoir. The average effective porosity is estimated while defining sonic porosity, density porosity and neutron porosity. For water saturation calculation Archie equation (1942) is not directly used here as the equation is valid for limestone. Due to lack of core data, Indonesia equation (derived from Archie equation) is used to identify saturated fluids. This method has useful that it is used without core derived parameters (although core derived tortuosity exponent (a), cementation exponent (m), and saturation exponent (n) are preferred) (Puopon & Leveaux, 1971). The values of resistivity of water (R_w) are derived from pickett plot using least value of R_w from nearby limestone zone saturated with 100% water. Finally, the average water saturation of hydrocarbon-bearing zones is calculated and converted to the average hydrocarbon saturation. Further, well correlation has been made from available well logs data. GR log is used to interpret the lithology of SML. In addition, neutron-density and resistivity logs are also used as validating.

Neutron log specifies the concentration of hydrogen and density of formation, NPHI-RHOB crossover mark the density. The DT-NPHI logs can be combined to identify the porosity and lithology of formation (Schlumberger, 1989). The volume of shale (V_{shl}), effective porosity (PHIE), and net pay were calculated from standard mathematical formulas. The isopach thickness map was made by (Surfer), the well tops of three wells of the field. The cut-off values of each fluid were used to distinguish between oil and water concentration.

RESULTS

Stratigraphic correlation of Qadirpur wells Q-11, Q-14 and Q-15 was prepared to understand the distribution of reservoir lithology in the field. The distance carried out in between these wells is 4.5km from Q-11 to Q-14 and 2.5 km from Q-14 to Q-15(see Figure 3).

Sui Upper limestone and Sui Main limestone are present in the area with almost uniform thickness. SUL and SML are separated by a regional shale unit, the Sui shale unit. Log SML shows that there is no major lateral variation in Qadirpur well 11, 14 & 15 well but it shows minor lateral variations. Based upon the correlations, Sui Main Limestone has been divided into five zones as follows, Zone 1 is mainly composed of shale these shales increase thickness from W-SW. Zone 2 is composed of limestone and shale interbeds and thickness increase forward W-SW. Zone 3 is composed of shales. Zone 4 is comprised of clean limestone there is a reservoir facies which can be corelateable in field. Zone 5 comprised of limestone there is no lateral variation of reservoir facies and these minor reservoir facies are corelateable. Zone 6 is composed of Habib Rahi limestone. Zone 7 is mainly composed of ghazij shales.

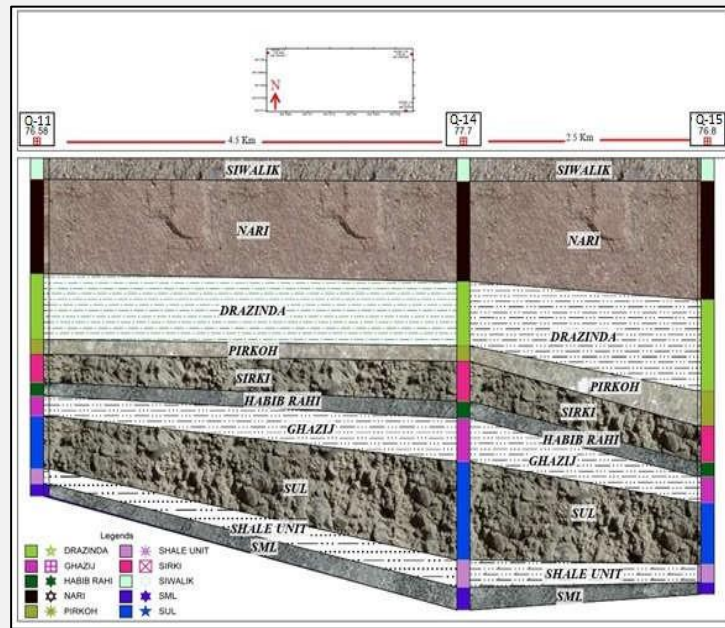


Figure 3. Generalized stratigraphic columns of Q-11, 14, 15 to estimate the sequence of stratigraphy

Lithology Estimation (NPHI vs. RHOB Cross plots) Isopach Map and stratigraphic correlation

NPHI and RHOB cross-plots are fine indicator to estimate the lithofacies. In zone of Q-11 top of SML is 1314 m and drilled down to 1406 m total thickness of reservoir is 92m (see Figure 4).

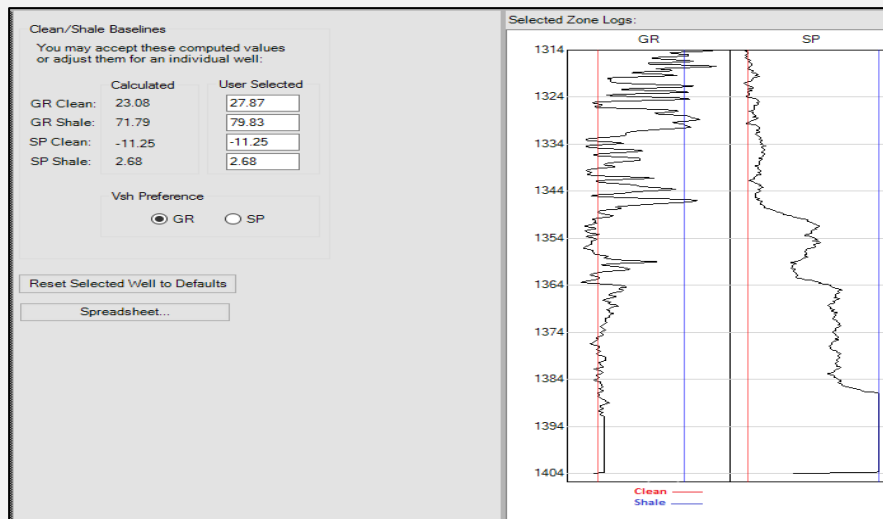


Figure 4. Calculated volume of GR Clean, GR Shale, SP Clean, SP Shale, in SML reservoir of Q-11 with vsh preference

The calculated value of RHOB in total matrix concentration is 2-2.7 while in X-axis value of NPHI will reach up to 0.07-0.35 while amount of clean limestone present in SML reservoir is 15-25%, Limestone 10-25% and Dolomite is 10-20% (see Figure 5).

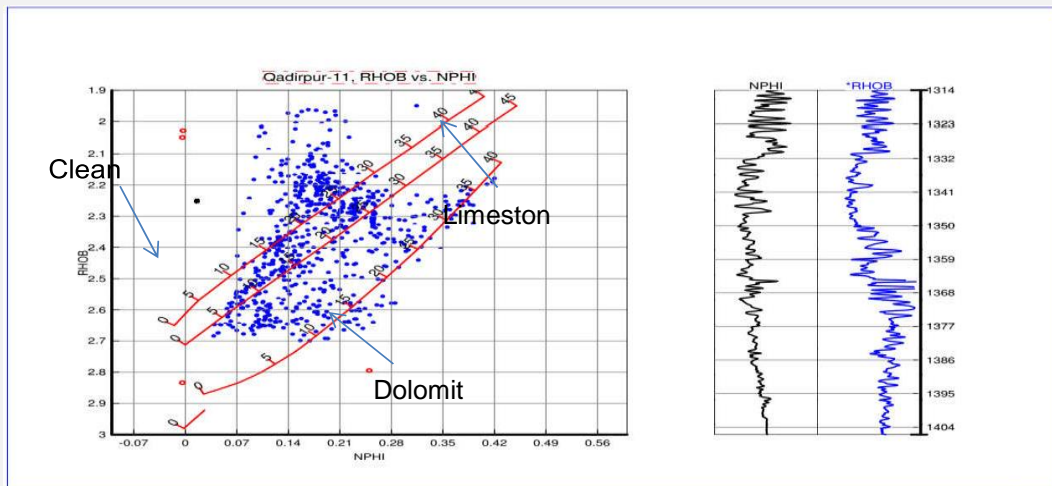


Figure 5. Cross plots showing the matrix clean sand, limestone, dolomite, in relation of RHOB vs NPHI in SML reservoir of Q-11

in Q-14 Top of SML is at 1784m and drilled down to 1862 and total thickness is 78m drilled in this well (see Table 1). NPHI vs. RHOB cross plot observed the lithology of reservoir observable components are mostly dolomite 15-30%, clean limestone 20-25% and limestone 5-20% (see Figure 6) Q-15 Top of SML is 1706 and drilled down to 1787 total thickness is 81m (see Table 1).

Table 1. Results shows petrophysical parameters use to estimate the SML reservoir potential

Parameter	Range	Average	Q-14		Q-15	
			Range	Average	Range	Average
RHOB	1.9-3	2.45	1.9-3	2.45	1.9-3	2.45
NPHI	-0.07-0.56	0.28	-0.07-0.56	0.28	-0.07-0.56	0.28
BVW	30-70	50	15-50	32.5	10-50	30
GR Clean	23.08-27.8	25.47	23.25-32.9	28.8	25.68-25.68	25.68
GR Shale	71.79-79.8	75.81	74.27-60.7	67.5	72.03-72.03	72.03
SP Clean	-11.25-.11.25	11.25	88.13-86.4	87.28	14.70-14.70	14.70
SP Shale	2.68-2.68	2.68	71.19-71.19	71.19	27.06-27.06	27.06
Shale	25.47	25.47%	27	27%	25.68	25.68
Sw	0-40	20%	0-30	15	0-25	12.5
Hc	60-100	80%	70-100	85	75-100	87.5
Total porosity	12-40	26%	0-22	11	0-17	8.5
Effective porosity	0-35	17.5%	0-15	7.5	0-12	6

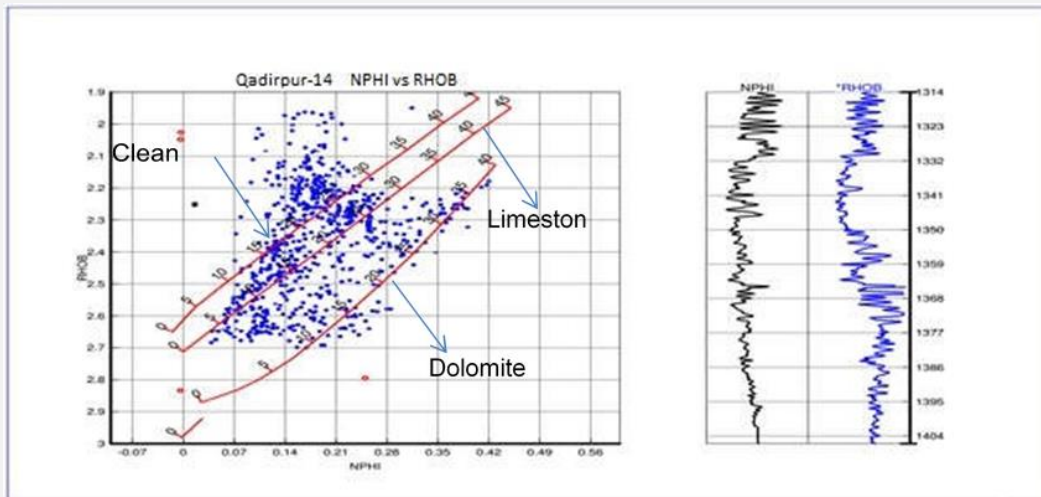


Figure 6. Cross plots showing the matrix clean sand, limestone, dolomite, in relation of RHOB vs NPHI in SML reservoir of Q-14

When we cross-plot the lithological components of Q-15, RHOB plotted along Y-axis which range from 1.9-3 and NPHI along X-axis from – 0.07- 0.56 (see Table 2) then we get these values of matrix which consist of clean limestone 15-25%, limestone 5-20% and dolomite 10-20% respectively (see Figure 7). Facies in reservoir is clean limestone 1740-1785, Shaly limestone 1715-1735 and Shale 1700-1710.

Table 2. Calculated averages petrophysical values and Cut-offs for Q-11, Q-14 and Q-15

	Qadirpur-11				Qadirpur-14				Qadirpur-15	
Well	To	Botto	Net Pa	Vsh	Sw %	Sh %	Rw (ohm-ra	π	Cut-offs	
Q-11	131	140	92m	25	0-40	60-10	0.0117	1	2	$\Phi > 10$,
Q-14	178	186	78m	27	0-30	70-10	0.012	1	2	Vshl < 3
Q-15	170	178	81m	25	0-25	75-10	0.029	1	1.5	Sw < 40

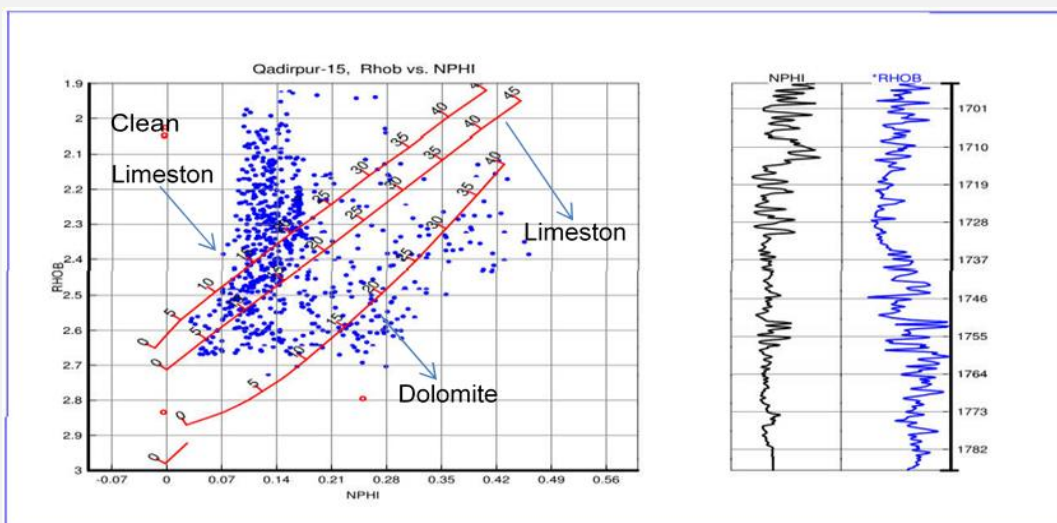


Figure 7. Cross plots showing the matrix clean sand, limestone, dolomite, in relation of RHOB vs NPHI in SML reservoir of Q-15

Volume of shale (GR&SP) Clean limestone/Shale base line

Total calculated values in Q-11 are GR-Clean- 23.08 and GR Shale is 71.79. SP clean is -11.25 and SP shale is 2.68. (Figure 8) At 1314-1320 and then 1328-1330, in Q-14 GR Clean is 23.5 and GR shale is 74.27 SP clean -88.13 and SP shale is -71.19 (Figure 2) and in Q-15 Value of GR clean is 25.68 GR shale is 72.03 SP clean 14.70 and SP shale is 27.6(Figure 9).

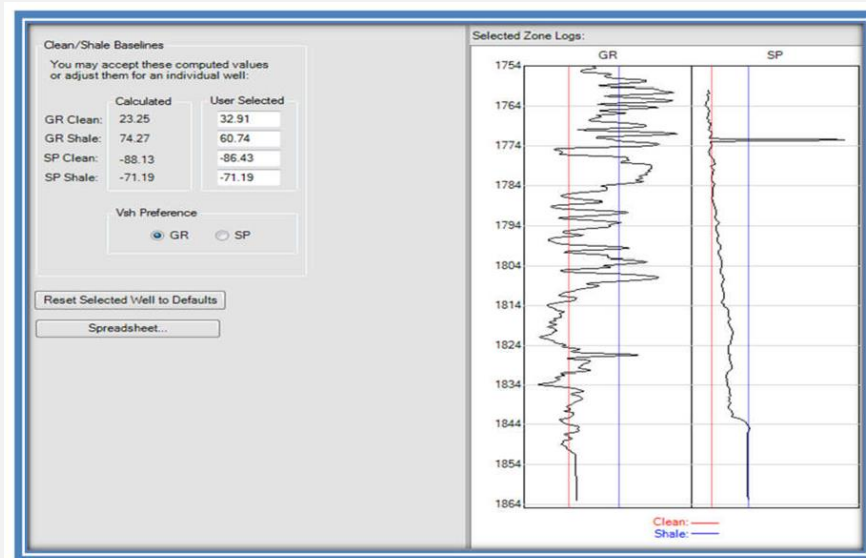


Figure 8. Calculated volume of GR Clean, GR Shale, SP Clean, SP Shale, in SML reservoir of Q-14 with vsh preference.

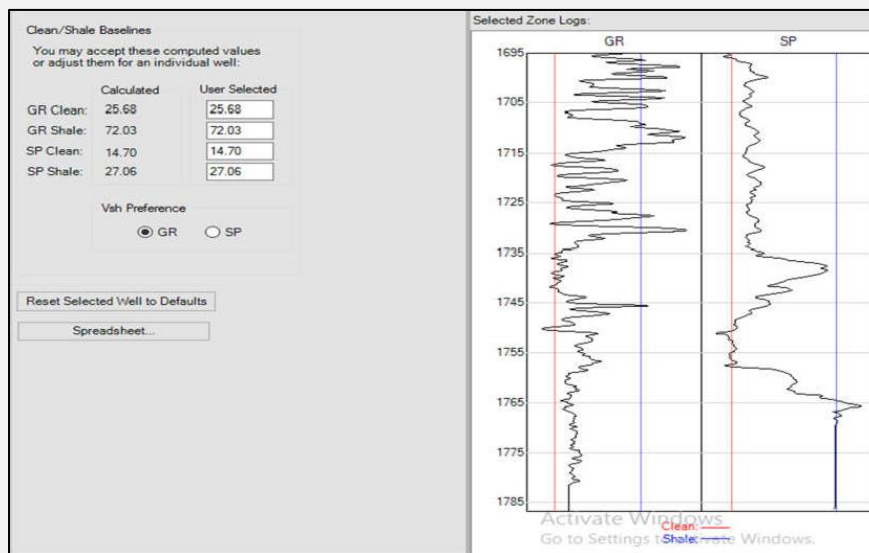


Figure 9. Calculated volume of GR Clean, GR Shale, SP Clean, SP Shale, in SML reservoir of Q-15 with vsh preference

Porosity Calculation (Total and Effective)

Q-11 results of total porosity is 0-35% and effective porosity is 12-40%, (Figure 10) Q-14 total porosity 0-22% and effective porosity values ranges from 0-15% respectively (Figure 11) Q-15 Total porosity range from 0-17% while effective 0-13% (Figure 12).

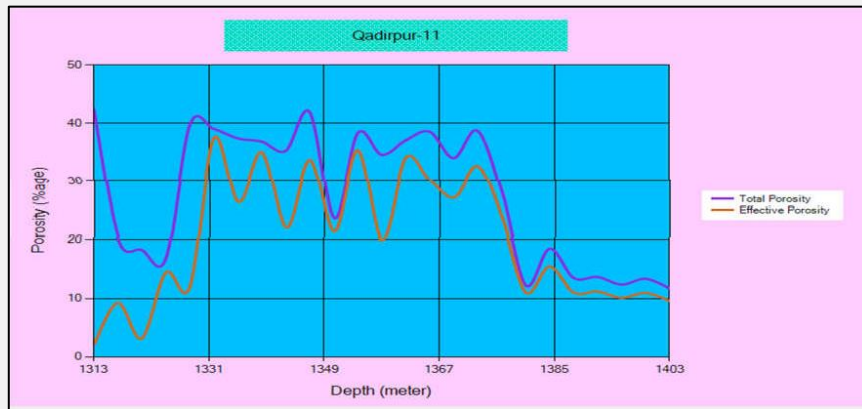


Figure 10. Showing the porosity estimation (total and effective) in SML of Q-11

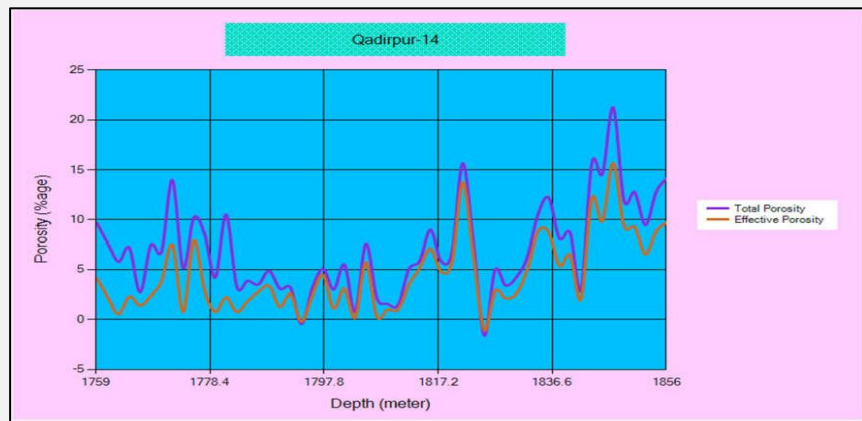


Figure 11. Showing the porosity estimation (total and effective) in SML of Q-14

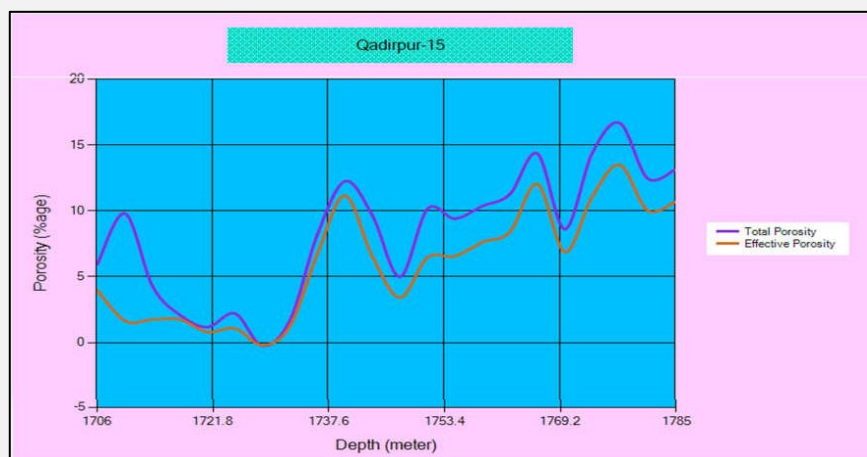


Figure 12. Showing the porosity estimation (total and effective) in SML of Q-15

Fluid Saturation (S_h and S_w) and Resistivity

(S_w) in Q-11 is 0-25% While (S_h) ranges in SML is 60-100%, moved (S_w) 4-10% in relation with Bulk volume of Water (Figure 13). The value of R_w (ohm-m) was 0.117 (Figure 14) Resistivity

values of water saturated in SML of Q-14 is $R_w=0.004$ ohm-m (Figure 15) Sw 0- 30% while Sh 70-100%. In Q-15 Value of R_w is 0.029 near about 10-40% water saturated. Water saturated in reservoir is 0-25% and calculated hydrocarbon saturated is 75-100%.

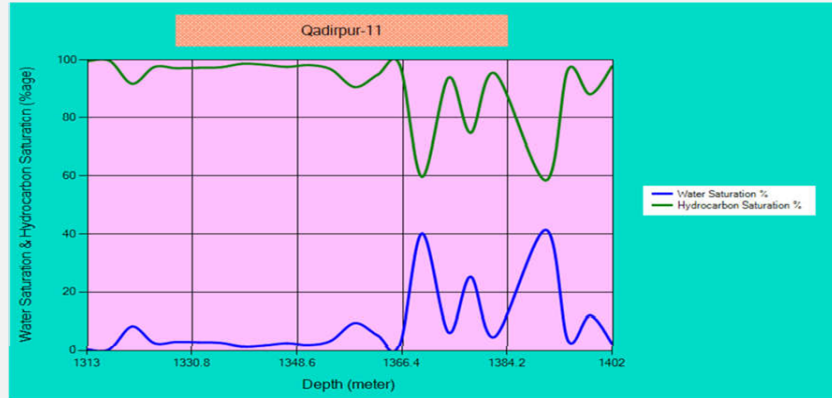


Figure 13. Showing water (sw) and hydrocarbon (sh) saturation in SML reservoir of Q-11

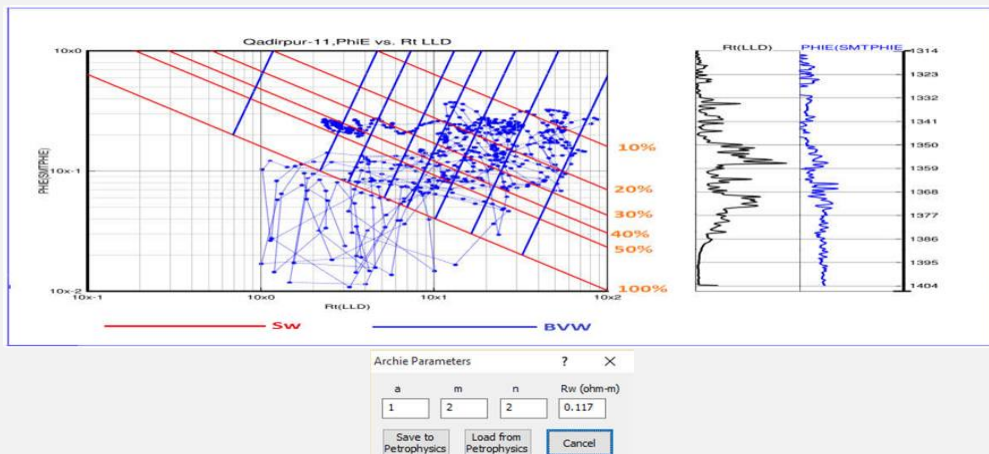


Figure 14. Picket Plot for calculating the resistivity of water saturated and BVW

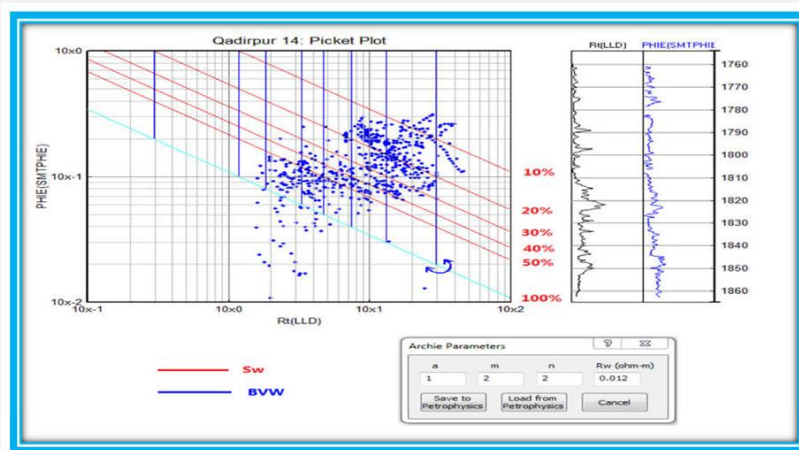


Figure 15. Picket plots for calculating the resistivity of water saturated and BVW in SML reservoir of Q-11

DISCUSSION

In zone of Q-11 Top of SML is 1314m and drilled down to 1406m total thickness of reservoir is 92 m (see Figure 2), which predict that the zone is fairly composed of fine material like limestone, and upward shaly material which definitely have an attractive accumulation of hydrocarbons Scattering points in relation of density and neutron porosity cross plots evaluate the matrix present in formation relation also confirms the porosity of reservoir. Result reveals that SML is mainly composed of Limestone while dolomite and sand matrix are also concerned. If maximum percentage of shale is present then value of carbonates is not in productive range because shale block pore spaces which badly effect on fluid saturation. Environment of deposited material is both the mixture of limestone and shaly limestone in SML reservoir which gently visible from facies modeling. Top of SML is at 1784m and drilled down to 1862 and total thickness is 78m drilled in this well (Table 1). which basically determine the matrix as closer to SUL but when we move down toward SML there is pure limestone with some amount of matrix.

SML of Q-14 have fine hydrocarbon saturation values with respect to environment of deposited material within reservoir which is some clean limestone from 1845-1860 purely fine material and shaly limestone and shale from 1760-1810 which also confirm the lithological structure (Figure 16). Q-15 Top of SML is 1706 and drilled down to 1787 total thickness is 81m (Table 1). When we cross plot the lithological components of Q-15, RHOB plotted along Y-axis which range from 1.9-3 and NPHI along X-axis from - 0.07- 0.56 (Table 2) Facies in reservoir is clean sand 1740-1785, Shaly limestone 1715-1735 and Shale 1700-1710. Results reveal that the Matrix and carbonates in SML is in relative range with the total and effective porosities without any minor Shale and clay presence. Volume of shale is calculated by using GR log and sand shale base line SP log curve move opposite to GR curve because shale has higher density and porosity then carbonates and limestone then the overall observation of shale in reservoir as a seal rock will be very prominent for hydrocarbons.

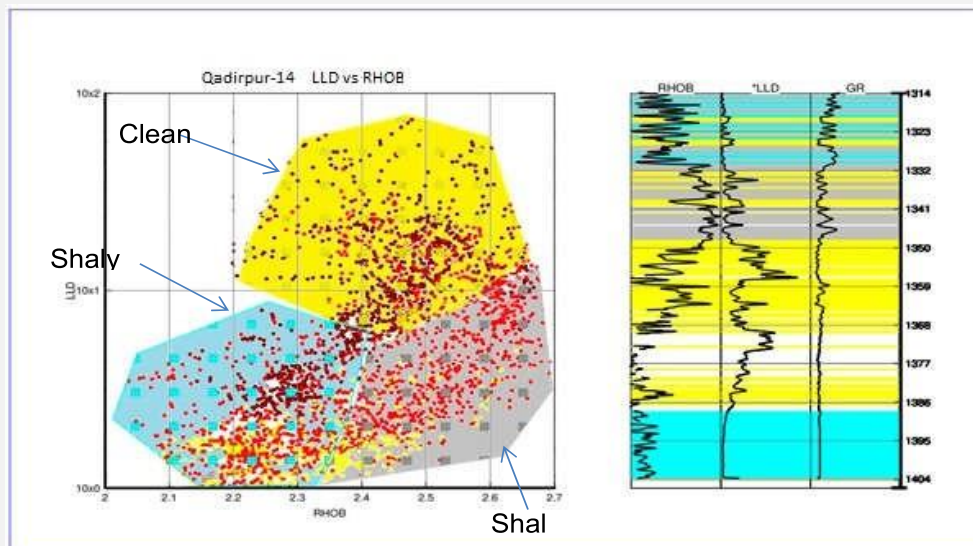


Figure 16. Facies modeling showing the different type of environment of deposited material in SML reservoir of Q-14

At 1314-1320 and then 1328-1330 there is a higher value of shale and SP curve will deflect to a minimum range results into a lower value of effective porosity (Figure 2). Shale Volume map is prepared for observation that Q-14 have enough V_{shl} for fluid saturation. Volume of shale which indicates the carbonates lithology (Figure 8) at depth from 1804-1864 GR curve show quite minimum value because effective porosity of SML in Q-14 is high as

require for favorable production. From 1710 to 1714 shale presence with in high amount as confirmed by low deflection of SP curve toward minimum value and up to 1714 affected porosity will be in low range (Figure 17). Porosity estimation is key element for fluid determination. Q-11 from 1331 to 1380 SML has favorable range of porosity values. Lithology of formation as relation of total and effective porosity confirms that the reservoir is very productive for fluid saturation and has definite space for moveable hydrocarbons in relation with water (Figure 10). Q-14 porosity measurement results that reservoir of Q-14 have no effect of any clay particles and shaly material as we move vertically down. Results of total and effective porosity when basically clear the zone either it will be saturated or not have enough pore spaces. As clear that reservoir of Q-15 have some effect of diagenesis as not much productive for fluid saturation. Similarly, resistivity in bearing zone was calculated by using formation temperature and pressure data and Picket plots (Rt/LLD and PHIE). The (BVW) bulk volume in uninvaded zone and flushed zone (SXO) is estimated by multiplying by water saturation and effective porosity (Figure 14). Results reveal that SML in Q-11, well exhibit moderate to high hydrocarbon saturation ranges from while the moved (SW) hydrocarbon saturation ranges from 4-10% in relation with Bulk volume of Water. (Figure 13) SML are completely saturated with fluid as some remaining hydrocarbon will move upward with BVW and density. Unmoved hydrocarbon stay remains at depth in Q-14.

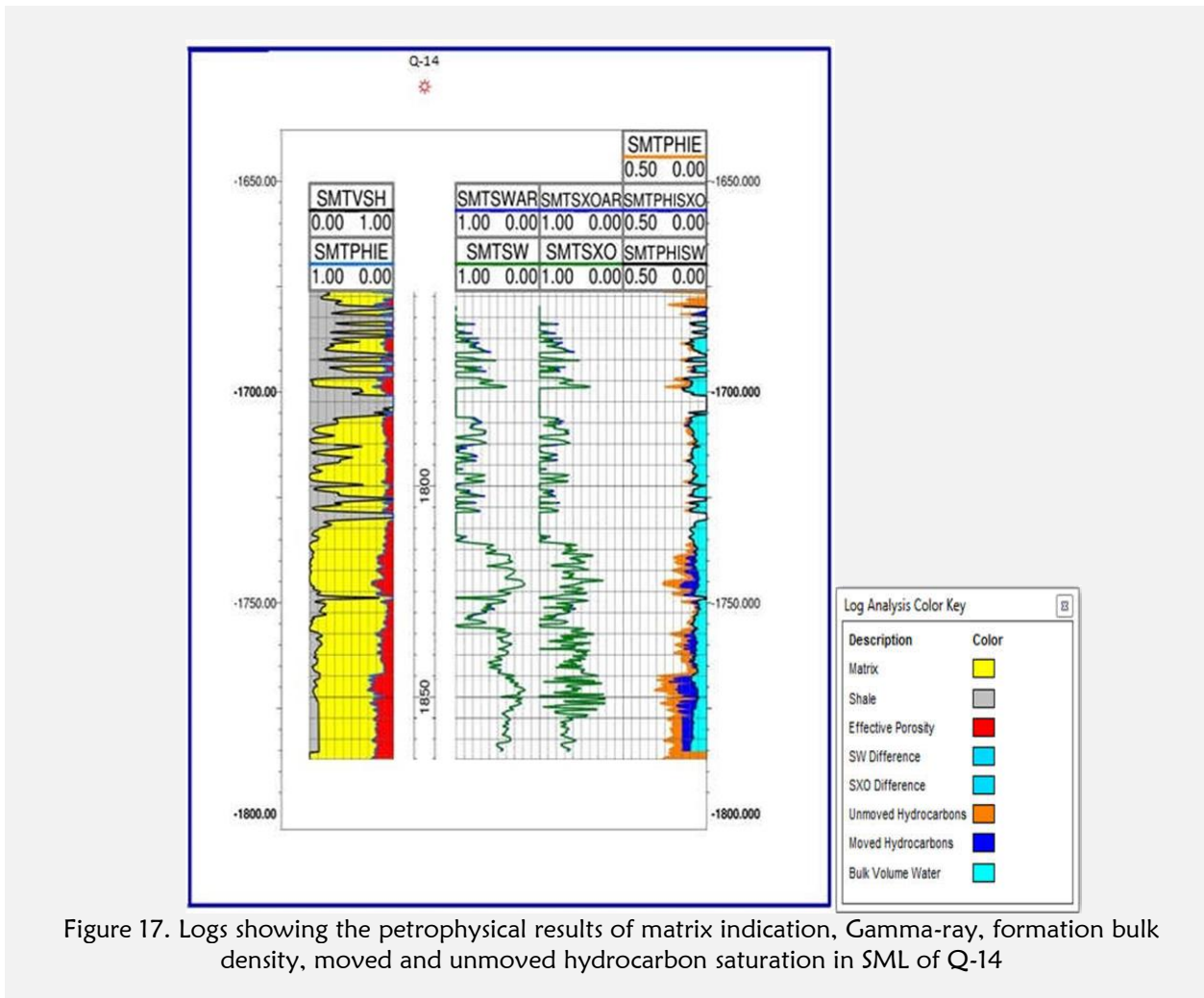


Figure 17. Logs showing the petrophysical results of matrix indication, Gamma-ray, formation bulk density, moved and unmoved hydrocarbon saturation in SML of Q-14

CONCLUSION AND RECOMENDATION

The mean porosity of Sui Main Limestone 15% respectively having no dual porosity due to any patent faults drift or fracture present in SML reservoir, moved hydrocarbon divulges that permeability of this reservoir is more than 50md due to effective porosity is in fertile reach. The average saturation of hydrocarbon in Q-11, Q-14, and Q-15 of Sui Main limestone 70- 100% and volume of shale 17% respectively. Correlation of wells revealed that Sui Main Limestone thickness in the south west direction i.e. from well and 11.14 to 15. On the Basis of Well Correlation, it can be seen that Sui main limestone and Sui Upper Shale units become deeper as we move from NW to SE. Reservoir of Qadirpur gas field is mostly composed of clean limestone and dolomite with calcite cementation which can be percieve by cross- sections which are matrix indicator. Abundant Bulk volume of water and moved hydrocarbon in relation with BVW to invaded zone assuredly indicates that SML reservoir is purely saturated with fluids. Porosity Water and Hydrocarbon Saturation of Well 15 is not in flattering range as contrast to well 11, 14 dues to sequel of diagenesis on reservoir rock of well 15. Moved hydrocarbon means zone abutting to borehole that is invaded by mud fluid. Net pay thickness show disparity and utterly decreases in Q-14 and 15 as reveal that Q-11 is much productive then Q-14, 15. SML reservoir the environment of deposited material in SML reservoir purely identified presence of lime particles with minor package of shale which act as a reservoir and reveal that SML have quite worthy fluid saturation. The petrophysical framework like SP, GR, Shl, Sw RHOB, NPHI, and Porosity estimate the potential of the which are in intermediate too high in range.

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