PETROPHYSICAL ANALYSIS OF KAL-01 WELL, UPPER INDUS BASIN, PAKISTAN

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A Thesis submmitted to Bahria University, Islamabad in partial fulfillment of the requirement for the degree of BS in Geology

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DEDICATION

We dedicate this research work to our parents who always loved and appreciated us. We thank them for providing us support and encouragement. We are also grateful to our teachers and class fellows who assisted, cooperated and guided us throughout our research work.

CHAPTER 1
INTRODUCTION

1.1 General introduction

The thesis is focused on the zone of active folding and thrusting in the foreland of Himalayas in Pakistan. The prime purpose is to aware of the structural styles and to calculate the hydrocarbon reserves in Gujar khan area and to understand the structural geometries in Potwar along with the sedimentations. Because of the ductility, distinctive tectonic styles are evolved in Potwar Sub Basin. Basal evaporite sequence lying beneath a thin section of competent platform rocks and thick molasses (Leather. M, 1978).

Gujar khan lies in the prolific hydrocarbon rich Potwar Sub Basin. Hydrocarbons have been discovered from the compressional structural traps in Potwar. Study of cross section across Potwar has shown the presence of fault-related folds, pop ups and triangle zone, all with limited calculated shortening as favorable traps. Deformation is interpreted to have occurred during preceding 8 million years. The timing of development of the discovered oilfields has been estimated to be around 3.5 to 1.8 Mya. (Jadoon, Frisch, 2008). Analysis has been delineating the pop-up structure of Gujar Khan and well data from Kal-01 well for the rocks properties and reserves estimation.

1.2 Location of the study area

Kal-01 is located at Latitude of 32° 59’ 18.21’’N and Longitude of 73° 06’ 24.86 ’’E in Gujar Khan 100 Km in south-east of Islamabad. The field was discovered in June 1995 and came on regular production from August 1995. The structure lies in Gujar Khan Exploration License and is located eight kilometers, south west of Rajian oil field. The first discovery well Kal-01 was drilled in February 1995. Figure 1.1 shows the location map of the study area.

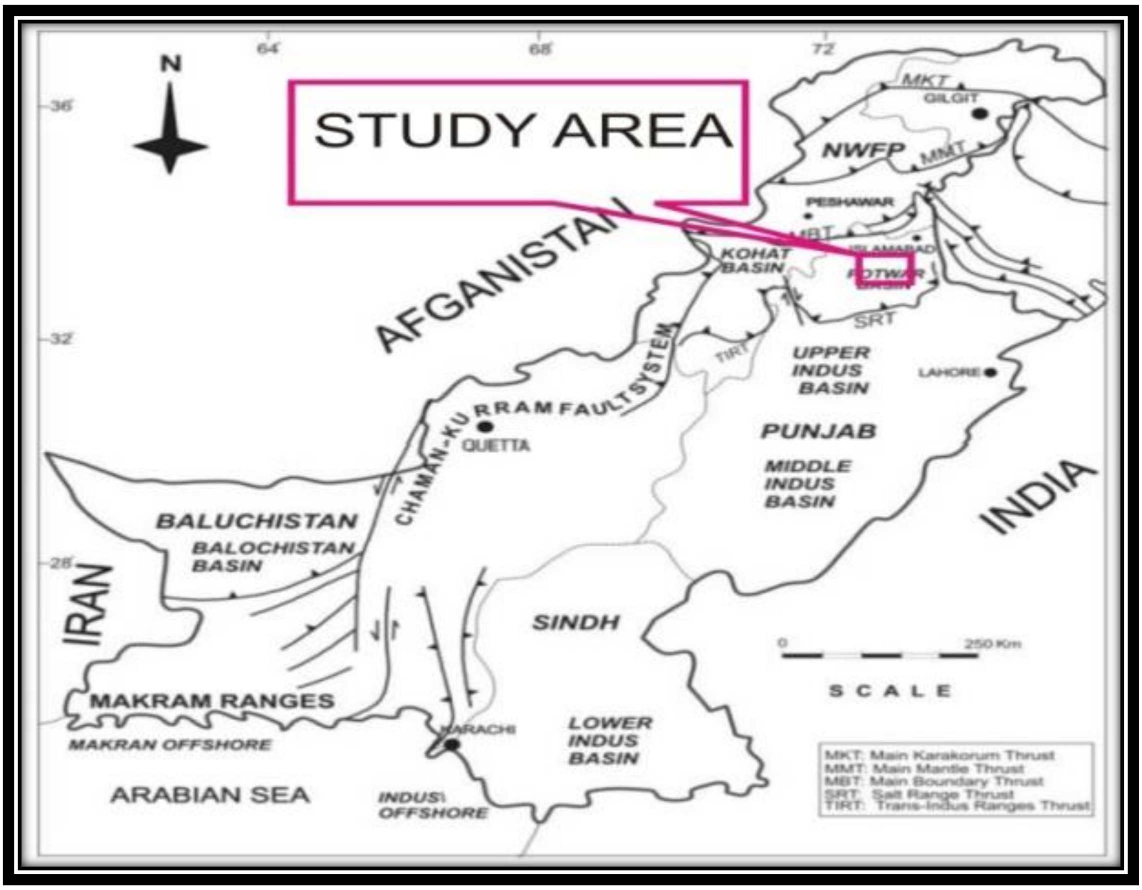

Figure 1.1.Location map of study area (Survey of Pakistan).

1.3 Research objectives

The objectives were as follows:

(1) To evaluate reservoir properties of Kal-01.

(2) To delineate the hydrocarbon potential of the zone of interest in the reservoir.

1.4 Well data for KAL-01

(1) Lithological Logs

(2) Fluid indicator Logs

(3) Porosity Logs

1.5 Research methodology

The methodology adopted for the research work is to evaluate Petrophysical analysis includes raw log curves, calculation of volume of shale, neutron, density and sonic porosity, resistivity of water and finally, water and hydrocarbon saturation The conclusion is drawn at the end of the study as shown in figure 1.2.

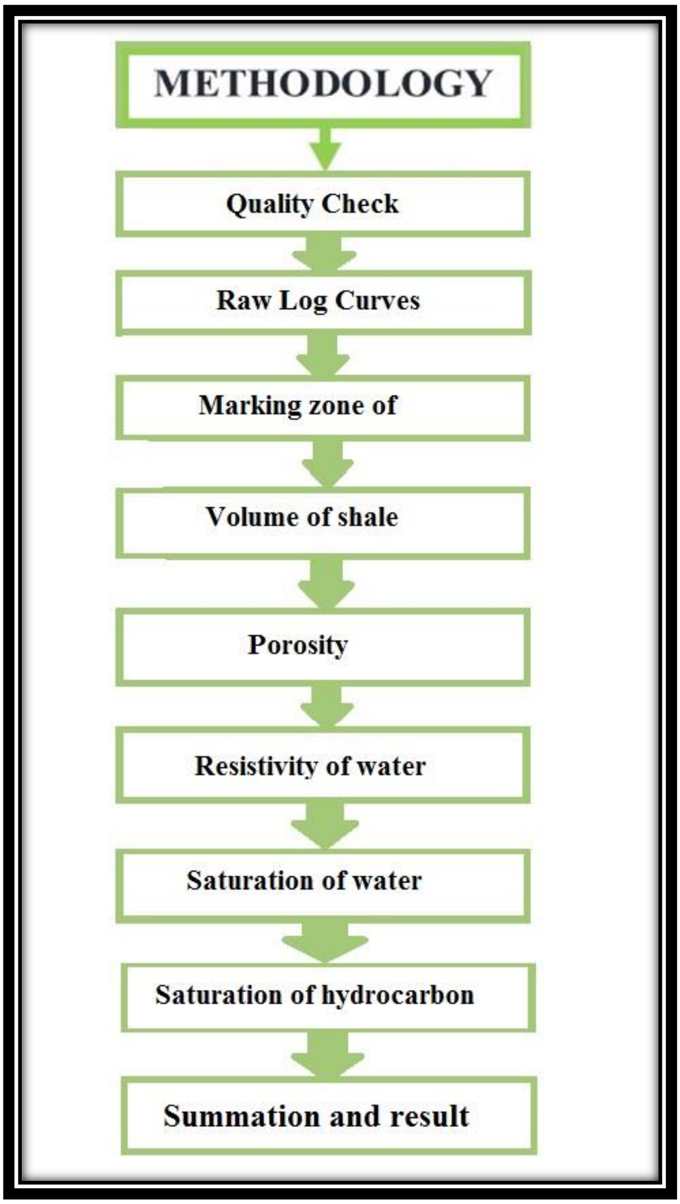

Figure 1.2.Methodology flow chart.

CHAPTER 2
REGIONAL GEOLOGY, TECTONICS AND STRATIGRAPHY

2.1 Regional setting

The Salt range and Potwar/Kohat Plateaus of Northern Pakistan represents a foreland fold and trust belts in the active collision zone between the Indo-Pakistani shield and Eurasian Plate. The convergent plate boundary is characterized by both northward underthrusting of thick shield lithosphere and southward obduction of upper crustal rocks and sediments. This has resulted in dramatic horizontal tectonics and crustal shortening since initial collision, in latest Cretaceous to middle Eocene, between the Indo-Pakistan shields and the Kohistan island arc terrane (Powell and Conaghan, 1973; Stonley, 1974; Stocklin, 1974; Molnar and Tapponier, 1975; Quittmeyeret, 1979).

Closure of the back arc basin, Shyok basin or Paleo-tethys Ocean, between the Kohistan Island arc and the Asian plate, may have occurred subsequent to the arc/Indian continental collision (Kennett, 1982). The corresponding southern margin of the Neo-tethyan sea way, which rammed the Indo-Pakistani subcontinent, was incorporated into the Indus Suture Zone (MMT) (Miall, 1984) and the Tethyan Himalayas (Lefort, 1975, Molnar and Topponier 1977, Stocklin, 1980; Malinconico, 1986).

The lesser and Sub Himalaya, including the Potwar Plateau and Salt Range, were well craton ward of the shelf margin at the time of the collision and suturing (Powell and Conaghan, 1973), yet by Late Miocene this area had been influenced by the southward progressing deformation now concentrated along the Salt Range.

The study area represent some of the most Recent deformation of the Himalayan frontal ranges, and lies at the north-western end of the 2500 km long Himalayan mountain belt (Figure 2.1). At the Hazara-Kashmir syntaxes, the ranges departs from the northwesterly trend of the Himalayas and forms a west southwesterly trending link to the north trending Sulaiman Ranges. This distinctive, oroclinal geometry may be due to a counter-clockwise pivot around the pole of rotation, driven by converging regional stress vectors (Crawford, 1974; Klootwijk, 1979). Alternatively, a non-rotational model (Powell, 1979) suggests that the oroclinal geometry is due to the initial angular geometries of the colliding plates.

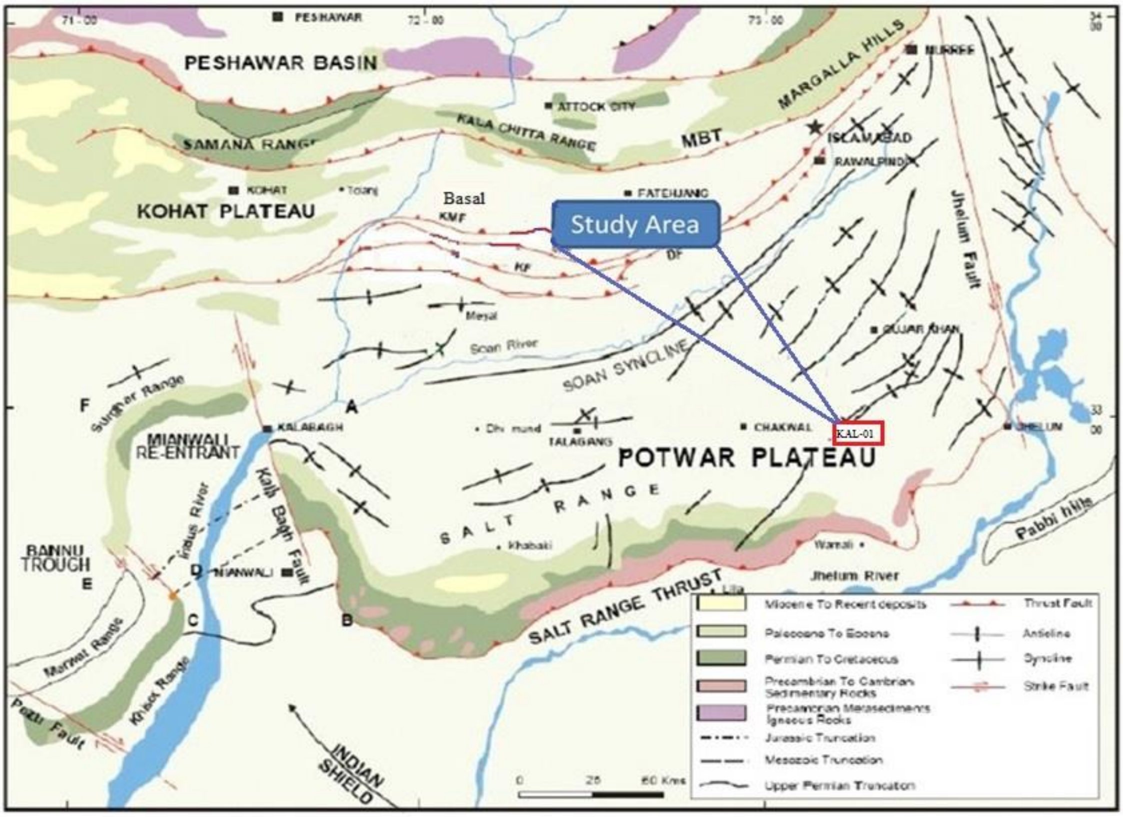

Figure 2.1.General tectonic of the Potwar sub-basin (Kazmi and Raza 1984).

In Pakistan, the Sub Himalayan molasse belt is anomalously wide, as compared with the zone bounding the Ganges plain in India. The thesis area encompasses a zone of southward progressing deformations as the Indo-Pakistani shield is over bidden by its own Northern margin in the series of south werging thrusts, with the salt range representing the active deformation front (Yeats and Lawerence, 1984). Thrusting probably first occurred in India, along the Indus Suture zone, at the time of collision (Mattauer, 1975). Initial obduction of the Kohistan arc terrane occurred along with MMT with rapid uplift north of the fault occurring between 30 and 15 Mya (Tahirkheli et al., 1979; Zietler et al, 1980) and is the southernmost thrust involving lower-crust, crystalline rocks of the Indo-Pakistani shield.

Continental thrusting was transferred, or distributed southward, to a zone of weakness defined by the Main boundary thrust in early Miocene (Lefort, 1975; Bied, 1978). The MBT is poorly defined as it wraps around Hazara-Kashmir syntaxes, but the series of thrusts that border the Peshawar Basin on the south (equivalent to the Hazara thrust zone of Seeber et al., 1981) define the boundary between the Lesser

Himalaya and Sub Himalaya. Metamorphosed Paleozoic and Mesozoic rocks and unmetamorphosed lower Tertiary rocks (partially distinctive with the Paleogene rocks exposed in the Kohat Plateau) , Seeber and Gornitz (1983), and Yeats and Lawrence (1984) feel that the MBT in Pakistan may be only superficially involved in continental underthrusting and that, through active, this fault does not define a significant tectonic or topographic boundary.

2.2. Tectonics of Potwar Area

In the south of Potwar Basin, Salt Range is a topographic ridge representing the uplifted edge of the thrust block, but the topographically subducted Potwar Plateau is a well-defined structural depression, North of the axis of Soan syncline lies the Northern Potwar Deformed depression (NPDZ), representing considerable shortening in a zone of imbricate faults.

Bounding the NPDZ to the North are Hill ranges, a series of thrust imbricates that displace a Cretaceous to Lower Tertiary sequences over the Rawalpindi molasse of the northern Potwar Plateau (Pinfold, 1918). The Hill ranges are comprised of three separate uplifts namely, AttockCherat, Kala Chitta and Margalla ranges. They represent the uplifted southern margin of the Peshawar Basin. This “piggy-back” intermountain basin developed in the hanging wall of a south verging thrust system, as thrusting transferred from the northern margin to the southern margin of the basin between 3.5 and 3.0 MY (Burbank and Johnson, 1982; Burbank, 1983). The frontal thrust of the Kala Chitta and the Margalla Uplifts, Murree thrust, is often called the MBT, although a series of both blind and emerging thrust between the Khauri Murat fault and the southern edge of the Peshawar basin probably represents the zone of displacement equivalent to the MBT in India (Yeats and Lawrence, 1984; Thakur, 1986). These thrusts subdivide the basin formed on their backs into the Nizampur and Cambellpor Basin to south, and the larger Peshawar Basin to the north.

In the west, The Salt Range/Potwar Plateau thrust block appears to be abruptly truncated by the Kalabagh transpressional fault system. This fault extends 20 km north from the Indus River before bending to the west along several norths dipping reserves fault (McDougall, 1985).

In the Eastern Potwar plateau, displacement along the SRT dies out, and shortening is distributed along a segmented, range bounding thrust system and a paraautochthonous en-echelon fold system, that may be only partially decoupled from the basement.

2.3 Stratigraphy

The structure lies within the Potwar sedimentary basin whose geology have been extensively studied, mapped and its stratigraphic units are well established by (Aamir, 2006).

2.4 Stratigraphy of the Potwar Area

The stratigraphic column is divided into three unconformity-bounded sequences. These unconformities in the study area are Ordovician to Carboniferous, Mesozoic to late Permian and Oligocene in age. The unconformities are not easily identified due to complex thrusting. The Potwar Sub basin is filled with thick pre Cambrian evaporites deposits overlain by relatively thin Cambrian to Eocene age platform deposit by thick Miocene-Pliocene molasses deposits. This whole section has been severely deformed by intense tectonic activity during the Himalayan orogeny in the Pliocene to Middle Pleistocene time. The oldest formation penetrated in this area is the pre Cambrian Salt Range Formation, which is dominantly composed of halite with subordinate marl, dolomite and shales.

The Salt Range is best developed in Eastern Salt range. The salt lies unconformable on the Pre-Cambrian basement. The overlying platform sequence consists of Cambrian to Eocene shallow water sediments with major unconformities at the base of Permian and Paleocene. The Potwar basin was uplifted during Ordovician to Carboniferous; therefore no sediments of this time interval were deposited in this basin. The second abrupt change to the sedimentary regime is represented by the complex absence of Mesozoic sedimentary succession, including Late Permian to Cretaceous, throughout the Eastern Potwar area. In Mesozoic time, the depocenter is located in central Potwar, where a thick Mesozoic sedimentary section is present. A major unconformity is also found between the platform sequence and overlying molasse deposits include the Murree, Kamlial, Chinji, Nagri and Dhok Pathan Formation.

Rock units ranging in the age from Pre-Cambrian to Cambrian are exposed in the Potwar Province of the Indus basin, where the Salt Range Formation with salt, Marl salt seams and dolomite is the oldest recognized unit through surface and subsurface geological information and forms the basement for the fossiliferous Cambrian sequence (Shah, 1977).

The stratigraphy in the study area has been established on the basis of both surface and sub-surfaces data from Potwar sub-basin, Punjab platform and Bianer-Nagaur basin of India and is based on the information by (Shah, 1977; Pareek, 1981; Khan et al., 1986; Gupta, 1988; Pennock et al., 1989, Kemal et al., 1991; Gupta and Balgauda, 1994, Siddiqui et al., 1998; Sheikh et al., 2003, Moghal et al., 2003).

2.4.1 Salt Range Formation

The Salt Range Formation consists of red, gypsiferous, claystone without any apparent bedding. Interacted thick salt bodies are being mined at Khewra, Warcha, Kalabagh and some other localities in salt range. The middle part of the Salt Range Formation consists of alteration of gypsum, dolomite, shale, siltstone with oil shale layers, particularly western salt ranges.

2.4.2 Khewra Sandstone

Khewra Sandstone is divided into three units. The lower unit often called the maroon shale group consists of thin bedded, dark red to purple argillaceous siltstone with intercalation of purple shale. The middle unit is thin bed, flaggy red sandstone. It is generally micaceous, fine grained and silty at the base and the grain size increases towards top. The lower unit consist of sandstone which is medium hard and friable. It gets coarser towards top.

2.4.3 Khussak Formation

Wyne (1878) used the name “Obolus beds” or “siphonotreta beds” for a predominantly greenish grey, glauconitic, micaceous sandstone and siltstone units. Waagen (1985) applied the name “Neobolus beds” for the same units.

Neotling (1894) proposed the name Khussak group and finally the stratigraphic committee of Pakistan approved the name of the unit as Khussak Formation. The type localities lie near Khussak fort in the eastern salt range. The formation consist of greenish grey, glauconitic, micaceous sandstone, greenish grey siltstone and glaucontic shale interbedded with light grey dolomite and some ooliticarenaceous dolomite.

The extent of the formation is more restricted to the east as compared to the underlying Khewra sandstone. The thickness of the formation at the type locality is 70 meters and in the study area ranges between 35 to 70 meters from west to east.

2.4.4 Jutana Formation

The name magnesium sandstone was given by Fleming (1853) for this unit and Jutana stage by Neotling (1894). The stratigraphic committee of Pakistan formalized the named as Jutana Formation. The type locality lies near Jutana village in Eastern Salt Ranges. The Lower part of Formation consists of light green, hard, thick to massive partly sand dolomite and upper part is composed of light green to dirty white massive dolomite. In the study area, the formation is conformably underlain by the Khussak Formation and overlain by the Baghanwala Formation with thickness ranges of 0 to 80 west to east. It is less widely distributed than the underlying Kussak Fomation.

2.4.5 Baghanwala Formation

The name Baghanwala Fomation has been approved by the Stratigraphic committee of Pakistan for the rocks of "Pseudomorph Salt Crystal Zone" of Wyne(1878), the "Baghanwala Group" of Neotling (1894), the salt pseudomorphs beds of Holland(1926) and "Baghanwala stage" of Pascoe(1959). The type locality is near Baghanwala village in Eastern salt range.

The formation mainly consists of reddish brown shale and clay, alternating with flaggy sandstone and is characterized by an abundance of salt pseudomorphs. The flaggy sandstone exhibits several colors indicating pink grey or bluish green, especially in the lower half of the formation.

In the study area, its thickness ranges from 0 in the west to 116 m in east. The contact of the Baghanwala Formation with the overlying Tobra Formation of Permian age is unconformable; whereas the lower contact with the Jutana Formation is conformable with limited extend towards the western part.

2.4.6 Warcha Formation

Named by Hussain (1967), the Warcha sandstone rests conformably upon the Dandot Formation. It represents the middle part of the "speckled sandstone" of Wage

(1879) and the lower part of "Warcha group" of Neotling (1901). Type locality is the WarchaNala in west-central Salt Range. The Warcha sandstone is widely exposed in Salt Ranges and Khisor Range. The sandstone is generally thick-bedded to massive, reddish-brown cross bedded, medium to coarse grained and arkosic. The sand grains are angular to sub angular in the lower part. The higher horizons are very coarse grained and conglomeratic with angular or sub angular pebbles of quartzite, red felsite and the underlying Jutana Formation.

The Warcha sandstone is unfossiliferous. The thickness of Warcha sandstone reaches almost 150m-165m in the salt range. In the Kohat-Potwar foredeep, the thickness generally increases from the south east to the northwest.

2.4.7 Sardhai Formation

The Formation has been named by Gee (Shah 1977) after the SardhaiNala in Eastern salt Ranges. The prevailing lithology in the Eastern and Central Salt Range is bluish grey, purple or reddish claystone which become dark violet to black towards the western Salt Range. The thickness of the Formation ranges from about 50-70 m. the paleo environment is interpreted as mainly terrestrial, partly lagoonal, with marine incursions which become frequent towards the west. Plant remains and fish scales have occasionally been found. According to Nawazawa and Dickins (1985), the Sardhai Formation is overlain by Amb Formation along a disconformity.

2.4.8 Hangu Formation

A series of quartzitic sandstone and shale at the base of the Paleocene sequences in Kohat was given name Hangu sandstone and Hangu shale respectively by Davies (1930). These names are after the town of Hangu and now formalized as Hangu Formation. The formation at its type locality is Samana-Kohat area is dominantly comprised of dark brown to reddish brown, medium to thick bedded quartzose sandstone and a few meter thick shale interbedded with lenticular coal seam in its upper part. The sandstone is fine to medium grained hard and compact, and medium to well sorted, with common rusty spots and solution rings. The shale sequence is about 6m thick, hosting 1-2 m thick coal seam in the upper part of the formation (Shah, M.R. 2001). The formation at the type locality is 95 m thick (Shah,M.R. 2001).

The Hangu Formation has a variable unconformable lower contact with its various formations ranging from Cretaceous in Kohat, Permian in Salt Range and Cambrian in Hazara area the upper contact with Lockhart Formation is conformable in all these area

Rich fossils assemblages including foraminifers, corals, gastrpods and bivalves are reported by Cox (1930), Davies (1930), Iqbal (1972) and Smout and Haque (1956).

2.4.9 Lockhart Formation

The term Lockhart limestone was introduced by Davies (1930) for a Paleocene limestone unit in Fort Lockhart area, District Kohat. The Lockhart Limestone is also well exposed in Salt ranges, Kala-Chitta and Hazara area. At these localities it has a fairly uniform lithology and is comprised of grey to dark grey, medium to thick bedded, nodular and highly fossiliferous limestone. The limestone is rich with organic matter and has strong odour when freshly broken. The limestone is rich with organic matter and has strong. The limestone is 60 m thick in the type locality, 40 m at Thal, over 150 m thick at Mazari Tang and Tarkhobi area, District Kohat (Meissner et al. 1974), 70 meters in Salt range and Trans Indus ranges, 260 meters in Kala-Chitta and over 200 meters thick in Hazara (Cheema et al. 1977). The limestone has a conformable lower and upper contact with the Hangu Formation and Patala Formation.

The limestone is interpreted as bioclastic wackstone (Akhter and Butt 2001) that contains abundant foraminifera, corals, mollusks, echinoids and algae. The Lockhart limestone is interpreted to have been deposited under stable, broad shelf/ramp setting in most part of Hazara, Kala-Chitta and Salt Range area.

2.4.10 Patala Formation

For this Formation Davies and Pinfold (1973) proposed the name “PatalaShale ”PatalaNala, in Western Salt Range, and it was later formalized as Patala Formation (Fatmi, 1973). This formation also includes part of the Hill limestone of Wynne (1873) and Coter (1933) in Kala-Chitta area.

At the type locality and upper part of salt range the formation is comprised of shale with marl with subordinates limestone and sandstone interbeds. The shale is dark greenish grey, carbonaceous as well as calcareous and friable with selenite crystals distributed throughout. The limestone is light to dark grey in color, medium bedded and nodular, whereas the sandstone is yellowish brown and is located in the upper part of the Formation.

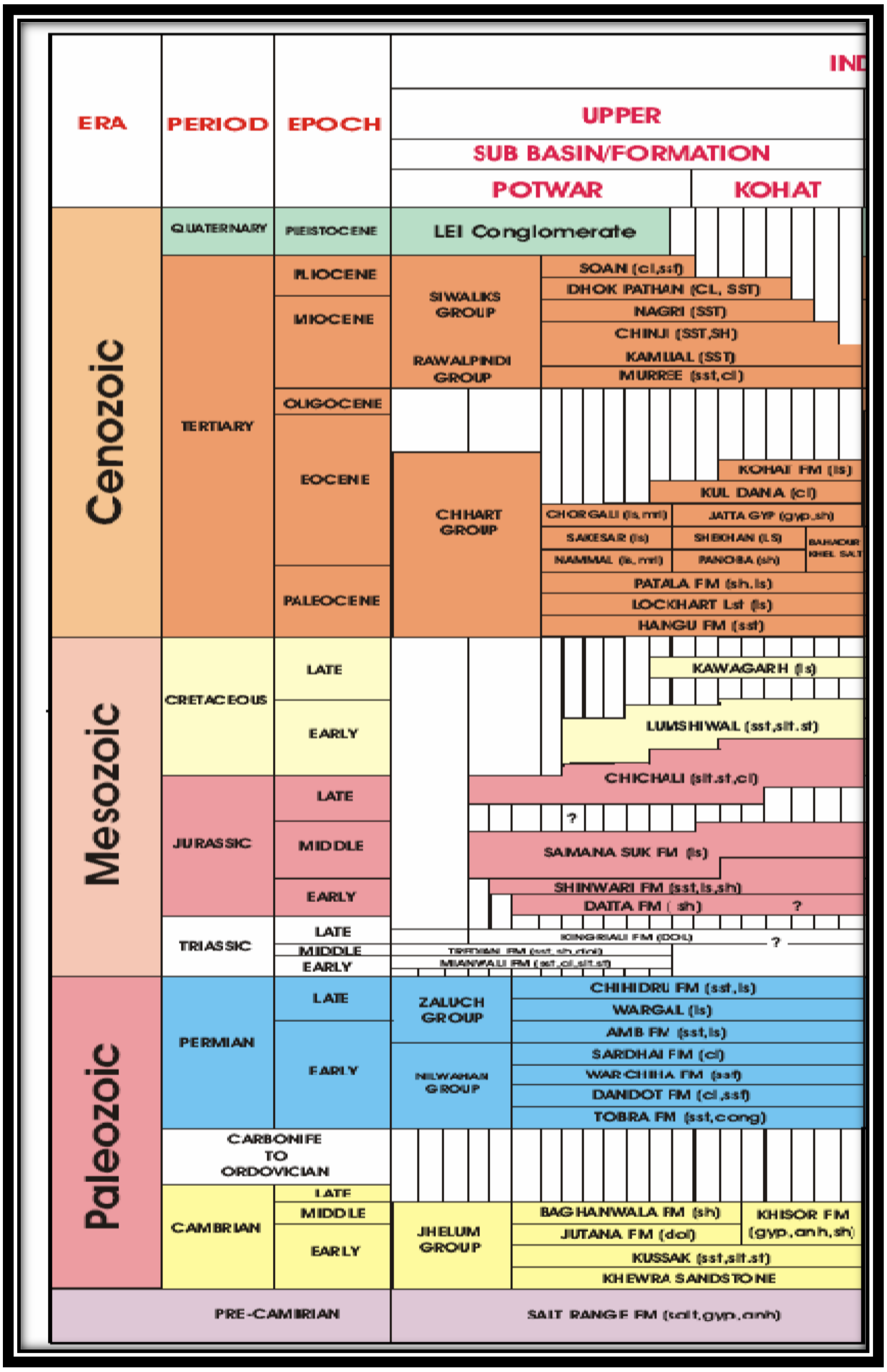

Figure.2.3. Stratigraphic columns of Potwar sub basin (Ammir et al., 1997).

2.5 Borehole Stratigraphy

KAL-01 is located in Gujar Khan, district Islamabad Pakistan. Lithostratigraphic columns of these drilling contain geological formation of Precambrian to Pliocene depositional system units of this sedimentation cycle follow each other with continuous transition or in some cases erosional discordance (sedimentation hiatus), as a result of more transgressive/regressive cycles. All of these formations have marine sedimentary facies although significant influence of terrestrial fluvial detritus input could be detected in many cases table shows the borehole stratigraphy of the borehole.

Table.2.1.Borehole stratigraphy of KAL-01.

Formation	Age	Lithology	Well tops (m)	Thickness (m)
CHINJI	Pliocene	Clay, Sandstone	8.00	852.00
KAMLIAL	Miocene	Sandstones, Shale	860.00	210.00
MURREE		Clay, Sandstone	1070.00	1264.50
CHORGALI	Eocene	Marl	2334.50	35.50
SAKESAR		Marl	2370.00	84.00
NAMMAL		Limestone	2454.00	8.00
PATALA	Paleocene	Shale	2462.00	12.00
LOCKHART		Limestone	2474.00	8.00
HANGU		Sandstone	2482.00	5.00
SARDHAI	Permian	Clay	2487.00	10.00
WARCHA		sandstone	2497.00	4.00
DANDOT		Clay, sandstone	2501.00	1.50
TOBRA		Sandstone, cong	2502.50	7.50
BAGHANWALA	Cambrian	Shale	2510.00	7.00
JUTANA		Dolomite	2517.00	48.00
KUSSAK		Sandstone silt	2564.00	84.50
KHEWRA		Sandstone	2543.50	132.50
SALTRANGE	Pre Cambrian	Gypsum, Dolomite, Shale, Silt	2782	8.00

2.6 Petroleum system

Petroleum system incorporates the study of origin, occurrence, movement, accumulation, and exploration of hydrocarbon fuels. It refers to the specific set of geological disciplines that are applied to the search for hydrocarbons i.e., oil exploration (Selly, 1975).

2.6.1 Petroleum system of Potwar Sub-basin

The salt range Potwar foreland basin (SRFBB) belongs to the category of extra continental down wrap basins. This accounts for the 48% of the world known petroleum. It has several features suitable for hydrocarbon accumulation including continental margin, thick marine sedimentary sequence, potential source, reservoir and cap rock.

2.6.2 Source rock

The oldest potential source rock in the KAL oil field is the Salt range Formation (Wandrey et al, 2004). Pre-Cambrian Salt range Formation contains oil shale intervals, which shows source rock potential.

Shales of Khewra Formation are of lacustrine to marine origin and contain woody, coaly to variously amorphous (with significantly woody herbaceous) kerogene, which are capable of generating paraffinic to normal crude and gas.

2.6.3 Reservoir rock

The Khewra sandstone has been studied previously by many authors including Baqri and Ragpar (1991) who worked on clay minerals analysis of Khewra sandstone from Khewra area, eastern Salt range. (Khan et al., 2012) calculated its porosity using Helium porosimeter and suggested the Khewra Sandstone a potential reservoir.

Khewra Formation is the main potential Cambrian reservoir. The intergranular primary porosity ranges from 10-12%. The uniform grain size and moderate sorting of sandstone indicates excellent reservoir nature. The sandstone also displays fracture and jointing which may contribute to increase in effective permeability. Oil is produced in Potwar area from Khewra Formation in Adhi.

2.6.4 Traps

Traps have been developed due to thin-skinned tectonics, which has produced faulted anticlines, pop-up and positive flower structures above Pre-Cambrian salt. The clays and shales of the Murree Formation provide efficient vertical and lateral seal to Eocene reservoirs wherever it is in contact.

CHAPTER 3
PETROPHYSICAL INTERPRETATIONS

3.1 Introduction

Petrophysical analysis is performed to delineate the zone of interest in a borehole. It is performed using different log curves that are procured by wire line logging. Wire line logging is carried out by lowering a single logging tool or a set of logging tools by a cable from a wench, which is generally mounted on the logging truck or offshore unit. The logging tools then record the petrophysical properties of the formation. The data is recorded in digital format either on the surface or either it is recorded in the borehole by using a cartridge. Print record or the electronic record known as well log are obtained from data.

The well logging operations can be performed during drilling known as logging while drilling or after the drilling of the borehole, reaching the desired depth. Once the logs are procured, zones of interest are marked on log curves depending upon borehole conditions, resistivity log trends and neutron-density cross over. Volume of shale, volume of sand, porosity, water saturation and hydrocarbon saturation are calculated for the zone of interest to estimate the potential of the zone.

3.2 Marking zone of interest

One zone of interest has been marked in Khewra Formation using log curves ranging from 2650m to 2670m (Table 3.1). It is evident from the log curves that gamma ray is showing a decreasing trend confirming that the zone is comprised of shale free lithology and has very low radioactive content. Resistivity logs also confirm the potential of the zones where MSFL reads low and LLS and LLD are reading high.

There is a considerable separation between LLS and LLD which further supports the presence of fluids in the zones of interest. Neutron-Density cross over is also corroborating the potential of the zones.

Figure 3.1 represents zone showing low gamma ray, under-gauge caliper, cross over between density and neutron and a distinct separation between LLD and LLS.

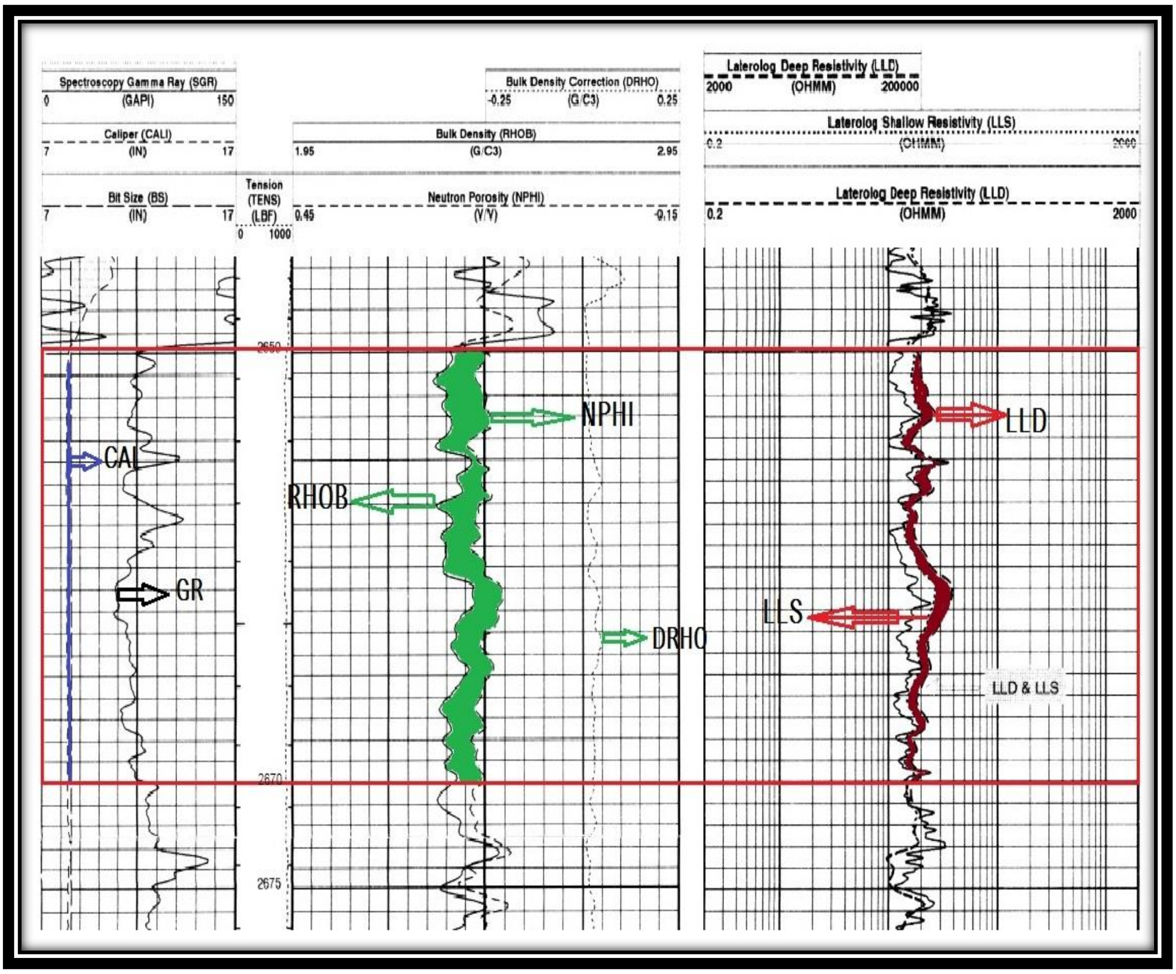

Figure.3.1.Zone of interest of Khewra Formation.

Table.3.1.Zone of Khewra Formation.

Zone	Starting depth (m)	Ending depth (m)	Total thickness (m)
Khewra	2650	2570	20

3.2.1 Volume of shale (Vsh)

Volume of shale is the quantitative measure of dirtiness in the zone of interest. It is usually calculated using gamma ray log. Increasing gamma ray represents high radioactive content in the lithology making it a dirty lithology. On the other hand decreasing gamma ray represents a clean lithology where radioactive content is either absent or very low.

Volume of shale can be calculated utilizing both the gamma ray and spontaneous potential. We have estimated the shale volume using gamma ray log. The volume of shale can be applied for the analysis of reservoir properties of rocks. This is calculated using the following equation.

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

Where,

Vsh = volume of shale

GRlog = GR reading of Formation

GRmin = minimum GR (clean sand or carbonate)

GRmax = maximum GR (shale)

Figure 3.2 represents volume of shale and volume of clean with respect to depth in reservoir zone of Khewra Formation ranging from 2650m-2670m. The average value of volume of shale turned out to be 28.43% while that of sand turned out to be 71.56%.Volume of shale first increases and reaches the maximum value of 44.19% at the depth of 2657m and then decreases reaching minimum value of 17.34% at the depth of 2661m. However volume of clean decreases in the beginning and reaches the minimum value of 57.80% at the depth of 2657m and then increases reaching the maximum value of 82.65% at the depth of 2661m.

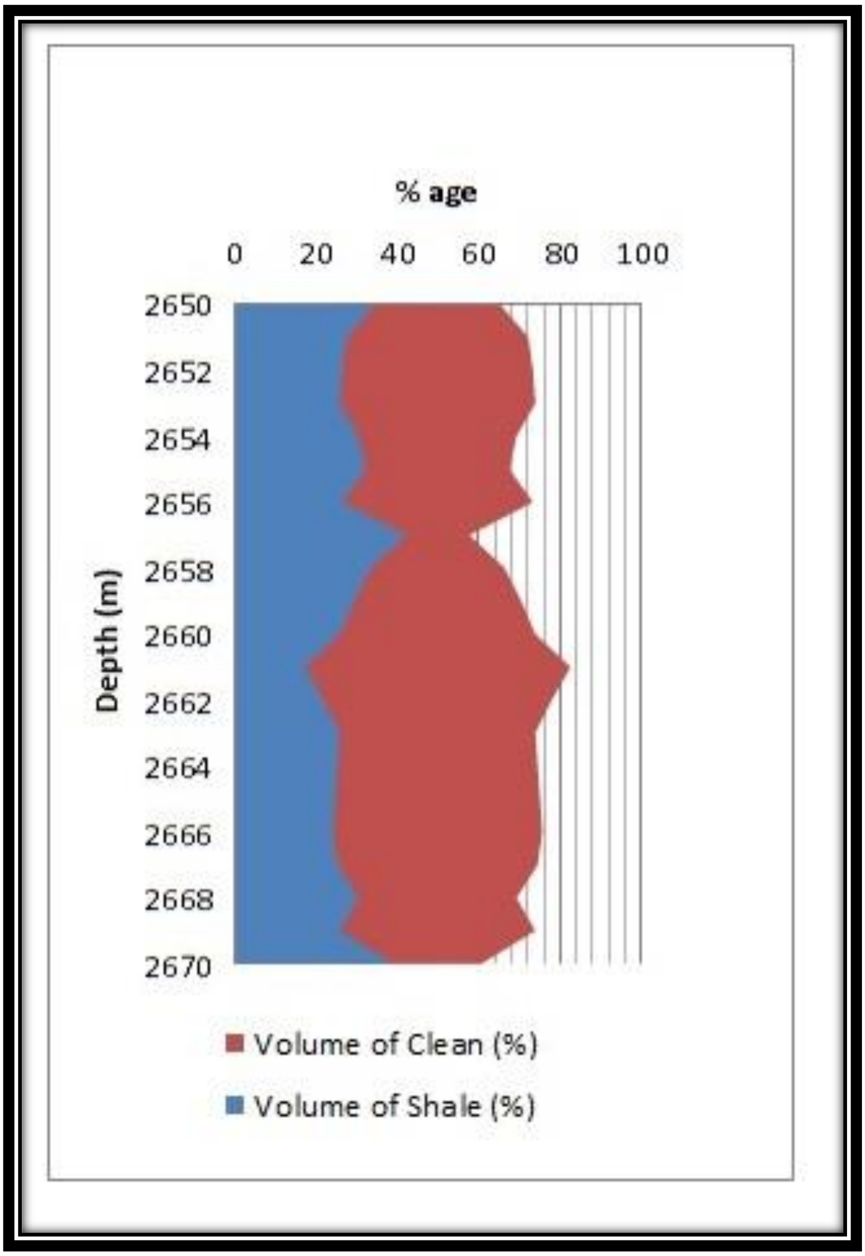

Figure.3.2.Relationship between volume of shale and volume of clean in zone of interest.

Table.3.2.Average volume of shale and clean in %.

Zone	Formation name	Average shale volume (%)	Average clean volume (%)
(2650-2670) (m)	Khewra	28.43	71.56

3.2.2 Calculation of porosity

Porosity is the measure of the percentage of pore spaces per bulk volume.

$$\emptyset = \frac{Vb - Vs}{Vb} = \frac{Vp}{Vb}$$

Where,

$\emptyset$ = porosity

Vb = bulk volume

Vs = solid or grain volume

VP = pore volume

Porosity can also be measured using wireline logging with the help of porosity logs which are

(1) Density log

(2) Sonic log

(3) Neutron log

All the porosity logs were available and calculated different porosities using porosity logs.

3.2.2.1 Bulk density and Density porosity

In geology, bulk density is a function of the density of the minerals forming a rock (i.e. Matrix) and the fluid enclosed in the pore spaces Density porosity gives an account of how dense a lithology is. If density porosity is high, the formation under consideration is not highly dense; rather it has pore spaces which may allow the existence of hydrocarbons. Bulk density and density porosity show indirect relationship. Increase in bulk density results in the decrease in density porosity and vice versa. Density porosity is calculated using the following formula:

$$\emptyset_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Where,

$\emptyset_D$ = density porosity

ρ_{ma} = matrix density (2.65 for sandstone matrix)

ρ_b = Formation bulk density

ρ_f = fluid density (1.1 for salt mud)

As it is evident from figure 3.3(a) and 3.3(b) that Bulk density and density Porosity have converse relationship. Density porosity decreases in the beginning and reaches its minimum value of 13% at the depth of 2659m however bulk density increases in the beginning and reaches its maximum value of 2.42 g/cc at the depth of 2656m. The maximum value of density porosity is 24.84% at the depth of 2654m where bulk density reaches its minimum value of 2.24g/cc at the depth of 2653m. The average value of density porosity is 17.25% in the zone of interest and that of bulk density is 2.45 g/cc.

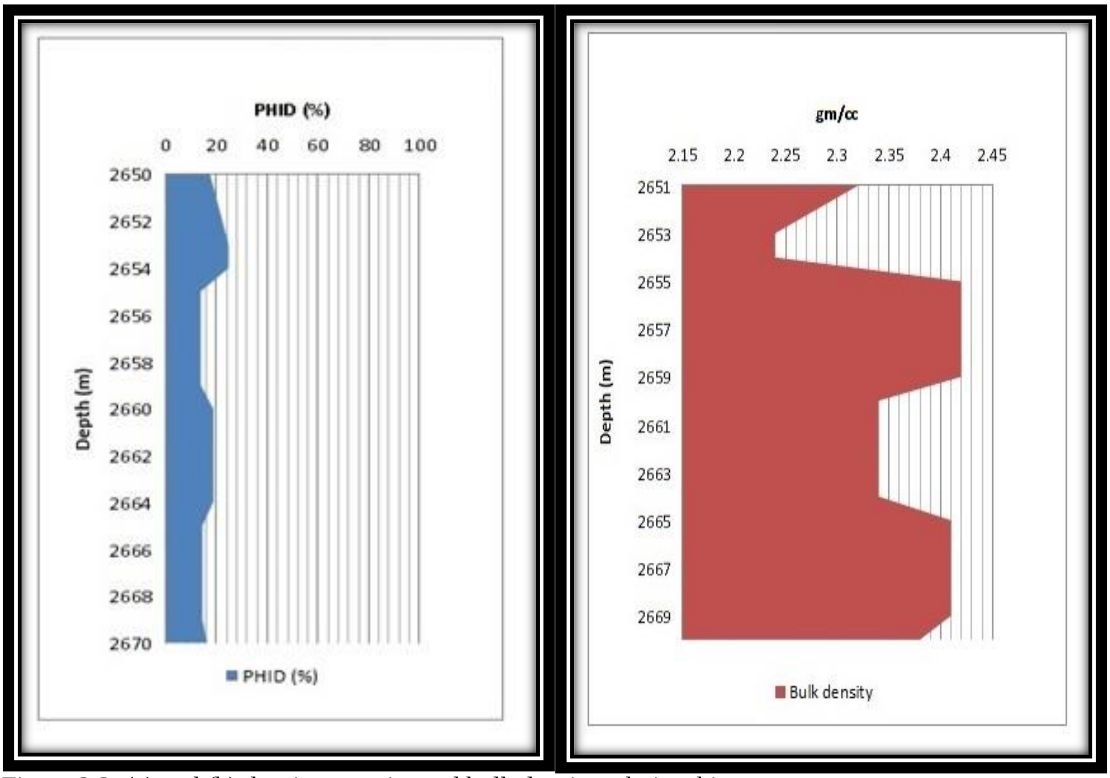

Figure.3.3. (a) and (b) density porosity and bulk density relationship.

Table 3.3.Average density porosity of zone.

Zone	**Formation**	**Average ρ (g/cc)**	Average **$Ø_D$** (%)
(2650-2670) (m)	Khewra	2.45	17.25

3.2.2.2 Neutron Porosity

Neutron porosity is the measure of amount of liquid filled porosity which is measured by using neutron logs. Neutron logs measure the hydrogen ion concentration in a Formation. In a clean Formation (i.e. shale free) where the pores are filled with water or oil, the neutron measures liquid filled porosity. The neutron log is sensitive mainly to the amount of hydrogen atoms in a Formation. Its main use is in the determination of the liquid filled porosity of a Formation.

In formations with a large amount of hydrogen atoms, the neutrons are slowed down and absorbed very quickly in a short distance. The count rate of slow neutrons or capture gamma rays is low in the tool. Hence, the count rate will be low in high porosity rocks.

Figure 3.4 elucidates the behavior of neutron porosity in the marked zone of interest. In the beginning, neutron porosity tends to decrease and reaches its minimum value of 12% at the depth of 2660m and then abruptly starts climbing up reaching its maximum value of 17% at the depth of 2670m. The average value of neutron porosity is 15.33%

Table.3.4.Average neutron porosity.

Zone	Formation	Average Neutron (%)
(2650m-2670m)	Khewra	15.33

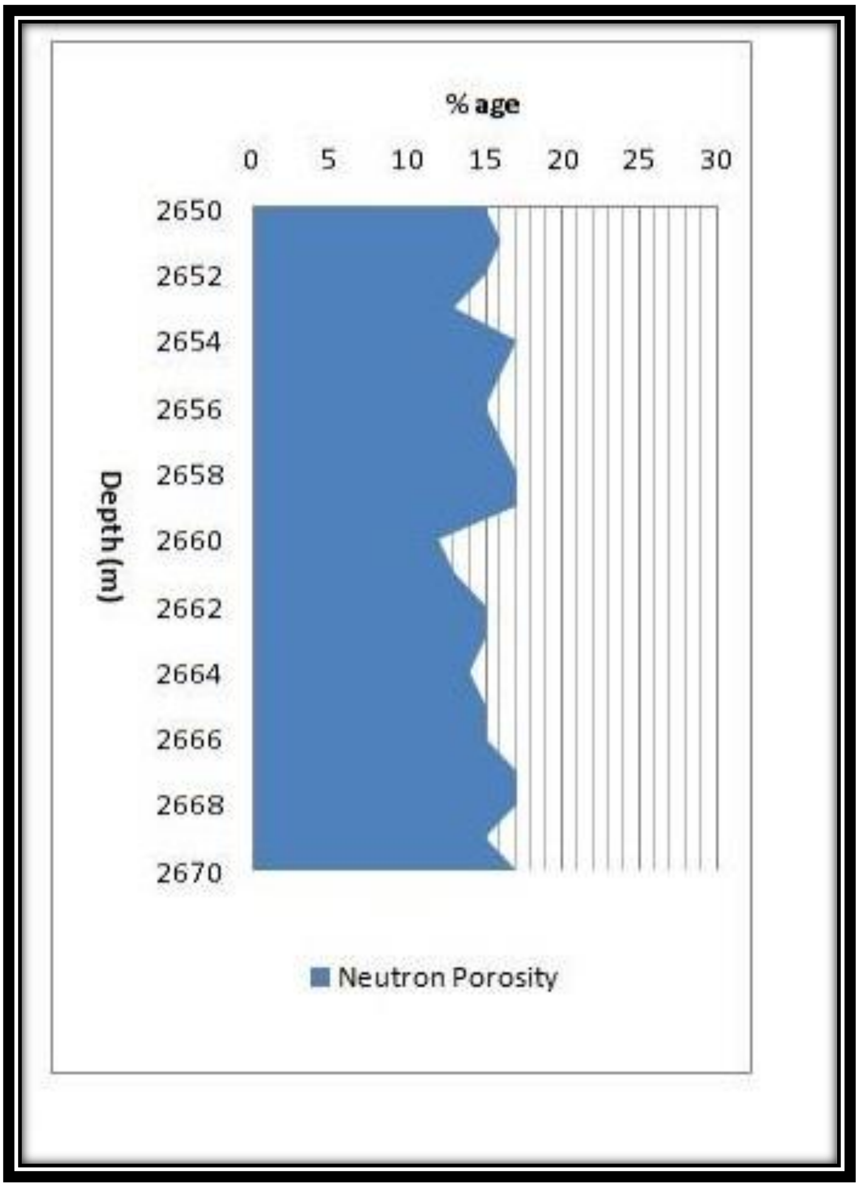

Figure.3.4.Neutron porosity variation graph of the zone of interest.

3.2.2.3 Average porosity

Average porosity is computed from the neutron log and density log. This is estimated by noting down NPHI and DPHI readings at every interval and averaging down these values.

Average porosity is finally estimated by summing up the Neutron porosity and Density porosity values and dividing them by 2. This is represented with formula as follows.

$$\varnothing_{av} = \frac{\varnothing_N + \varnothing_D}{2}$$

Where:

$Ø_{av}$ = Average porosity

$Ø_N$ = Neutron porosity

$Ø_D$ = Density porosity

Figure 3.5 represents the average porosity present in reservoir zone of Khewra Formation ranging from 2650m–2670m. Average porosity shows an increasing trend where it reaches maximum value of 20.92% at the depth of 2654m and then it starts decreasing with a little fluctuation. The minimum value is attained in the beginning which is 14.96% at the depth of 2655m. However the average value turned out to be 16.29% in the zone of interest which is fair enough for a reservoir to be in a producing state.

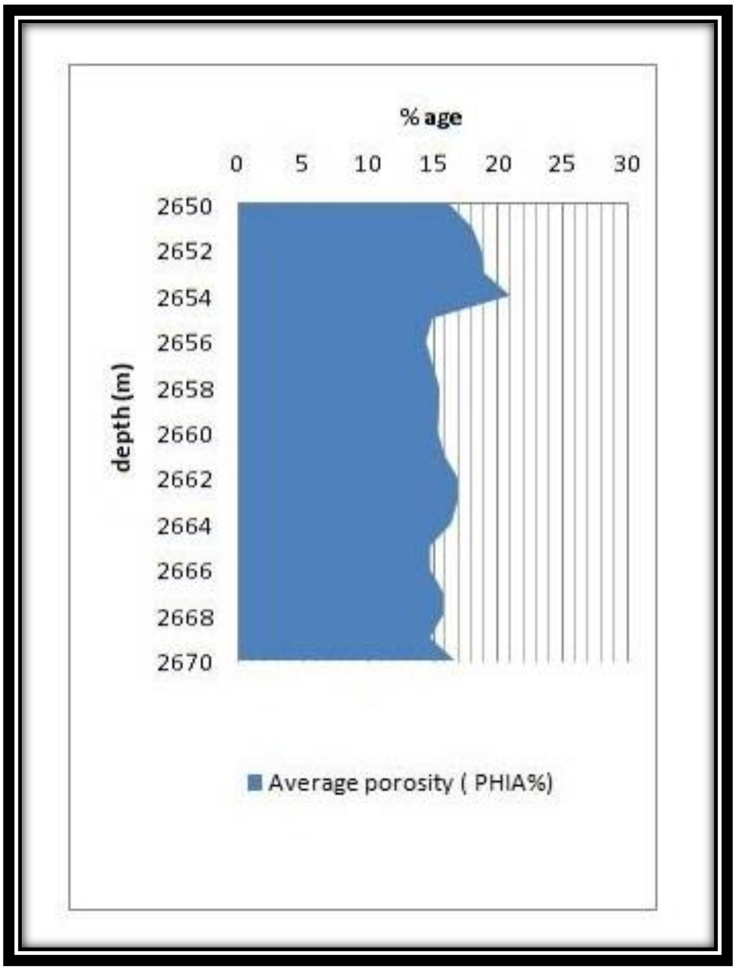

Figure.3.5.The average porosity of zone.

Table.3.5.The average porosity of zone in percentage.

Zone	Formation	Average Porosity (%)
(2650m-2670m)	Khewra	16.29

3.2.2.4 Effective porosity

Effective porosity is the percentage of interconnected pore spaces. The effective porosity is the value that is used in calculations because it represents the interconnected pore spaces that contain the recoverable fluids. Effective porosity is calculated by correcting the shale effect from average porosity.

$$Ø_e = Ø_{av} * (1 – Vshale)$$

Where,

$Ø_e$ = Effective porosity

$Ø_{av}$ = Average porosity

Figure 3.6 represents the effective porosity present in reservoir zone of Khewra Formation ranging from 2650m–2670m.Effective porosity first shows a decreasing trend reaching the minimum value of 8.65% at the depth of 2657m and then shows fluctuating behavior. The maximum value is observed at the depth of 2651m which is 13.73%. The average value of effective porosity is 11.66%.

Table.3.6.The average effective porosity in percentage.

Zone	Formation	Effective Porosity (%)
(2650m-2670m)	Khewra	11.65

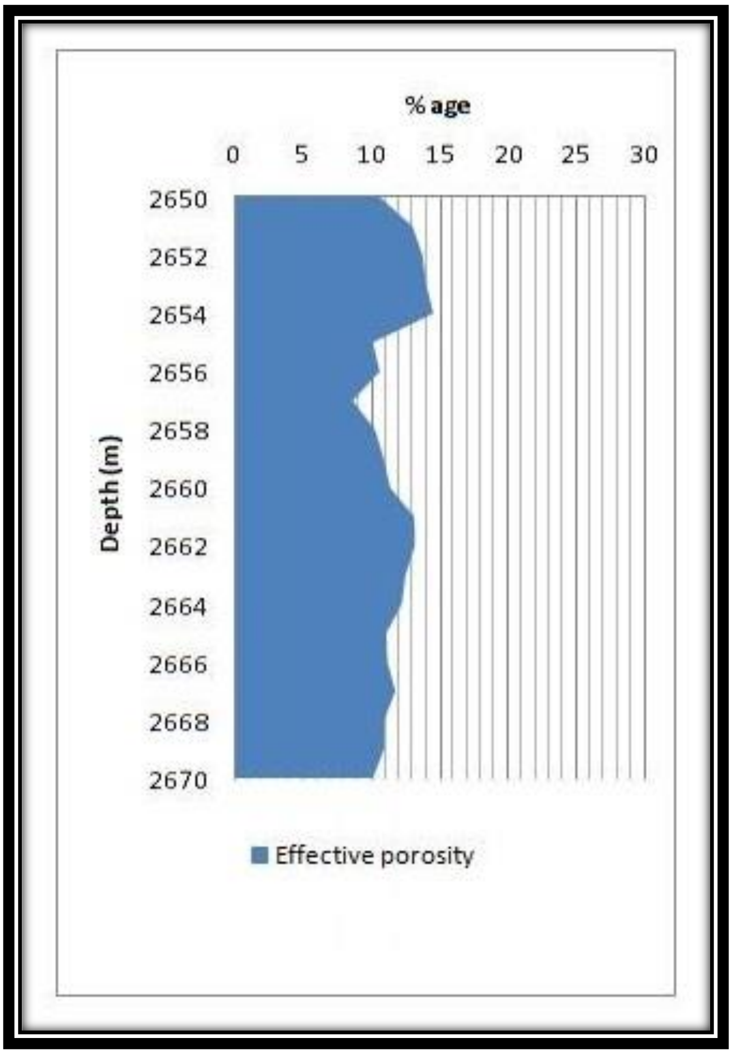

Figure.3.6.The effective porosity graph.

3.2.2.5 Relationship between average porosity, effective porosity.

Figure 3.8 explains the relation between effective porosity and average porosity in zone. It can be clearly seen from the graph that there is a direct relationship between average porosity and effective porosity. Incrementing average porosity results in incrementing effective porosity and vice versa.

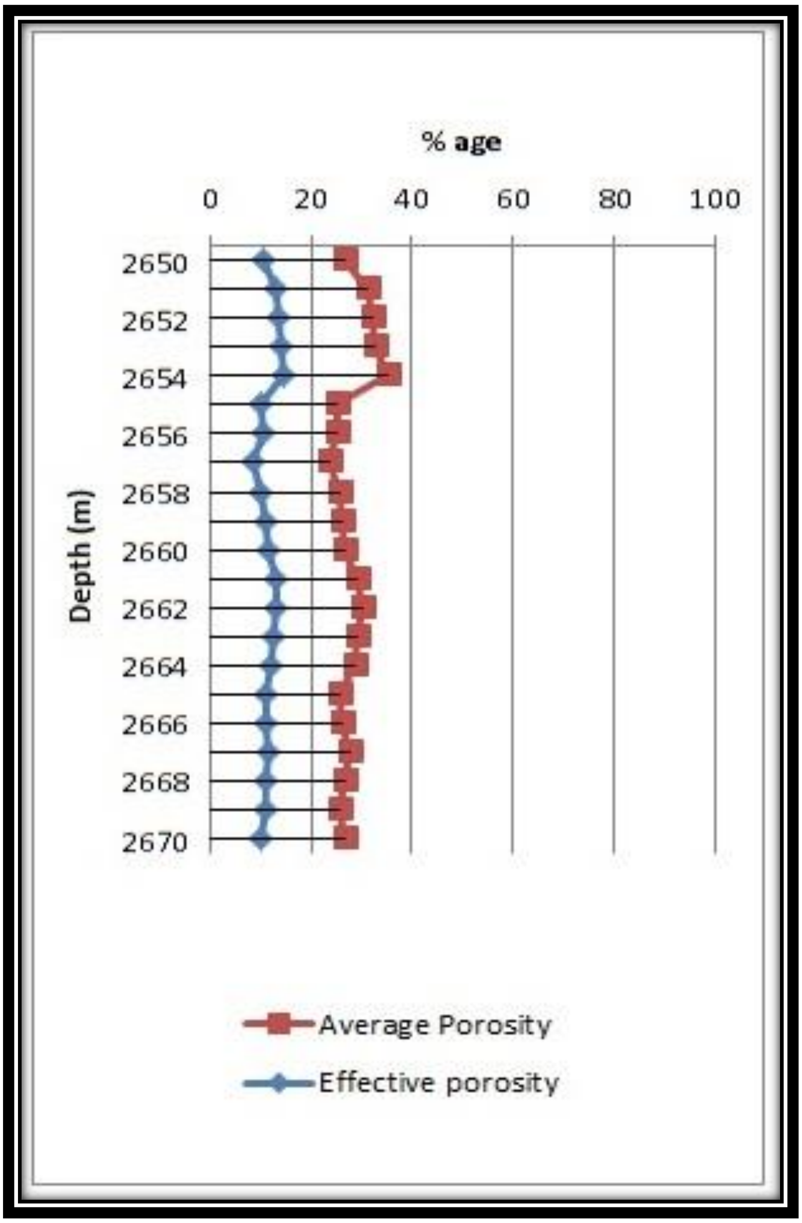

Figure.3.7.Relation between average, effective porosity and volume of shale.

3.2.3 Estimation of resistivity of water (Rw)

It is the most sensitive parameter in the determination of water saturation. Gen 9 charts are used for the determination of Rw. The procedure for the calculation of Rw using Gen 9 charts is as follows:

Resistivity of water turned out to be 0.06 ohm-m for Khewra Formation. The calculated water resistivity will be used in the Archie's equation to determine the water saturation and ultimately hydrocarbon saturation.

3.2.4 Water saturation

The fraction of pore spacing that contains water is termed as water saturation; denoted by Sw. Water saturation gives the indication of hydrocarbon presence in the reservoir. If saturation of water is less, saturation of hydrocarbon is high, but if Sw is 100%, it indicates hydrocarbons are absent in that interval. During the log analysis of study well water saturation is calculated with the help of Archie Equation.

$$Sw = \sqrt{(Rw/Rt)*(1/Øe^2)}$$

Where,

Rw = Resistivity of water

Rt = True resistivity

$Ø_e$ = Effective porosity

Figure 3.12 shows the saturation of water (Sw) of the zone of interest in Khewra Formation. The average value of saturation of water (Sw) is 44.81% in the zone of interest. In the beginning, water saturation increases reaching the maximum value of 64.94% at the depth of 2657m and then starts declining reaching the minimum value of 29.66% at the depth of 2661m.

Table 3.7.Average water saturation (%) in zone of interest of Khewra Formation.

Zone-01	**Formation Name**	**Water Saturation(%)**
(2650-2670) **(**m**)**	Khewra	44.81

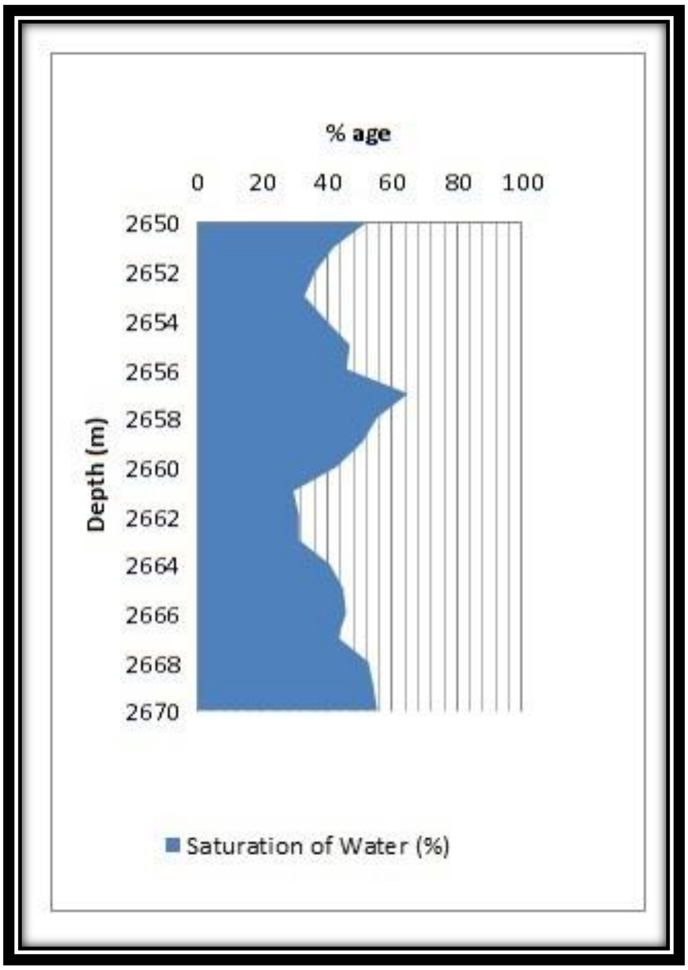

Figure.3.8.The water saturation.

3.2.5 Hydrocarbon saturation

Hydrocarbon saturation accounts for the percentage of pore fraction that contains hydrocarbon. The values of hydrocarbon saturation are calculated with the help of the following formula.

$$Sh = 1-Sw$$

Where,

Sh = hydrocarbon saturation

Sw =water saturation

The percentage of hydrocarbon in the zone of interest is fairly high in the zone of interest. Maximum value of hydrocarbon saturation is observed at 2661m which is 70.33% and minimum value of 35.05% is observed at the depth of 2657%. The average value of hydrocarbon saturation is 55.18% in the zone of interest.

Table 3.8.The average hydrocarbon saturation (%) in zone of interest.

Zone-01	Formation Name	Hydrocarbon Saturation (%)
(2650-2670) (m)	Khewra	55.18

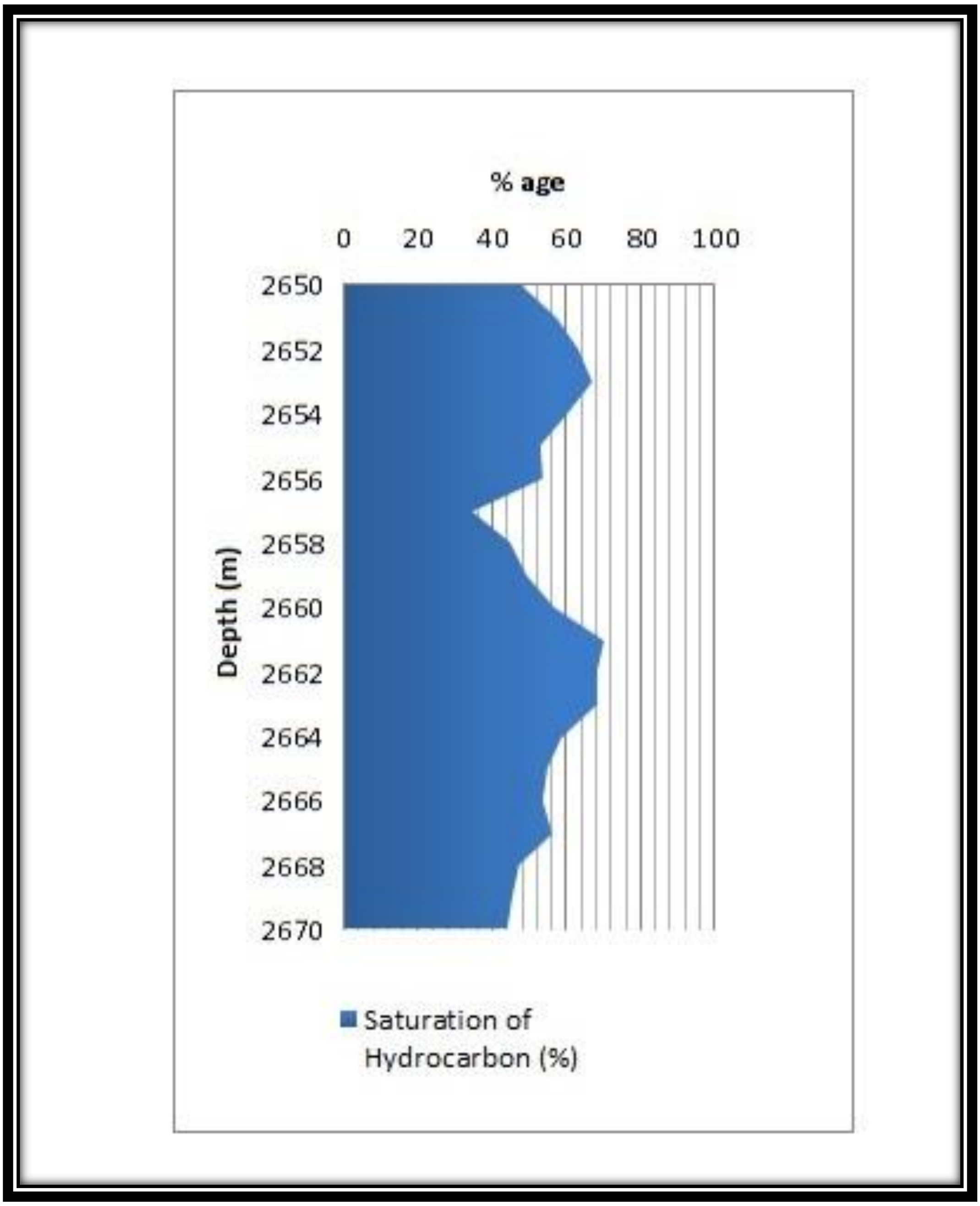

Figure.3.9.Average Hydrocarbon saturation in zone of Khewra Formation.

3.3 Summation of Petro physical properties

Table 3.9 shows the petro physical properties of the zone of interest of Khewra Formation depth ranging from 2650 to 2670 (m).

Table 3.9.Summation of Petrophysical Properties

Property	**Zone of interest (2650-2670)**
Volume of shale (%)	28.43%
Average porosity (%)	16.29%
Effective porosity (%)	11.66%
Avg, Saturation of water (%)	44.81%
Avg, Hydrocarbon saturation (%)	55.18%

CONCLUSIONS

On the basis of petrophysical evaluation of KAL 01 well, it is concluded that in Khewra sandstone hydrocarbon saturation is 55.18%. Petrophysical parameter including percentage of volume of shale and more percentage of hydrocarbon saturation, it can be concluded that KAL 01 well has fair hydrocarbon potential.

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APPENDIX

(1) Calculation of Geothermal Gradient

Geothermal gradient = Bottom hole temp – surface temp / total depth

= 88C°-43C°/ 2790m

= 0.016C°/m

(2) Calculation of formation Temperature = Surface temperature + (Geothermal Gradient * Formation top)

= 43 + (0.016*2649.5)

= 43 + 42.39 C°

= 85.39 C°

(3) Calculation of R_{mf} at formation temperature using Gen-9 charts. i.e.0.8 ohm-m

Rmf at formation temperature= 0.8 ohm-m

(4) Calculation of R_{mf}eq using R_{mf}eq=Rmf*0.85 (i.e. Rmf>0.9)

= 0.8*0.85

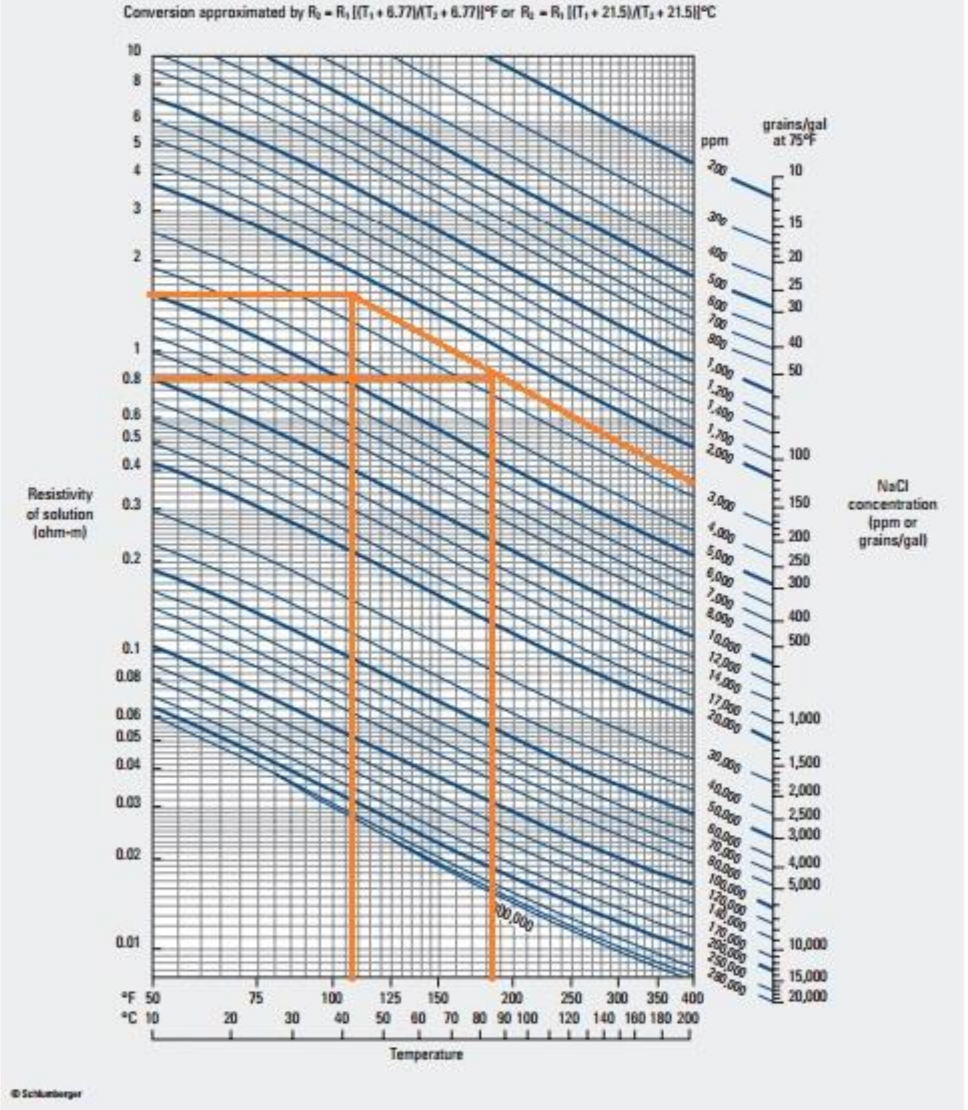
=0.68 ohm-m

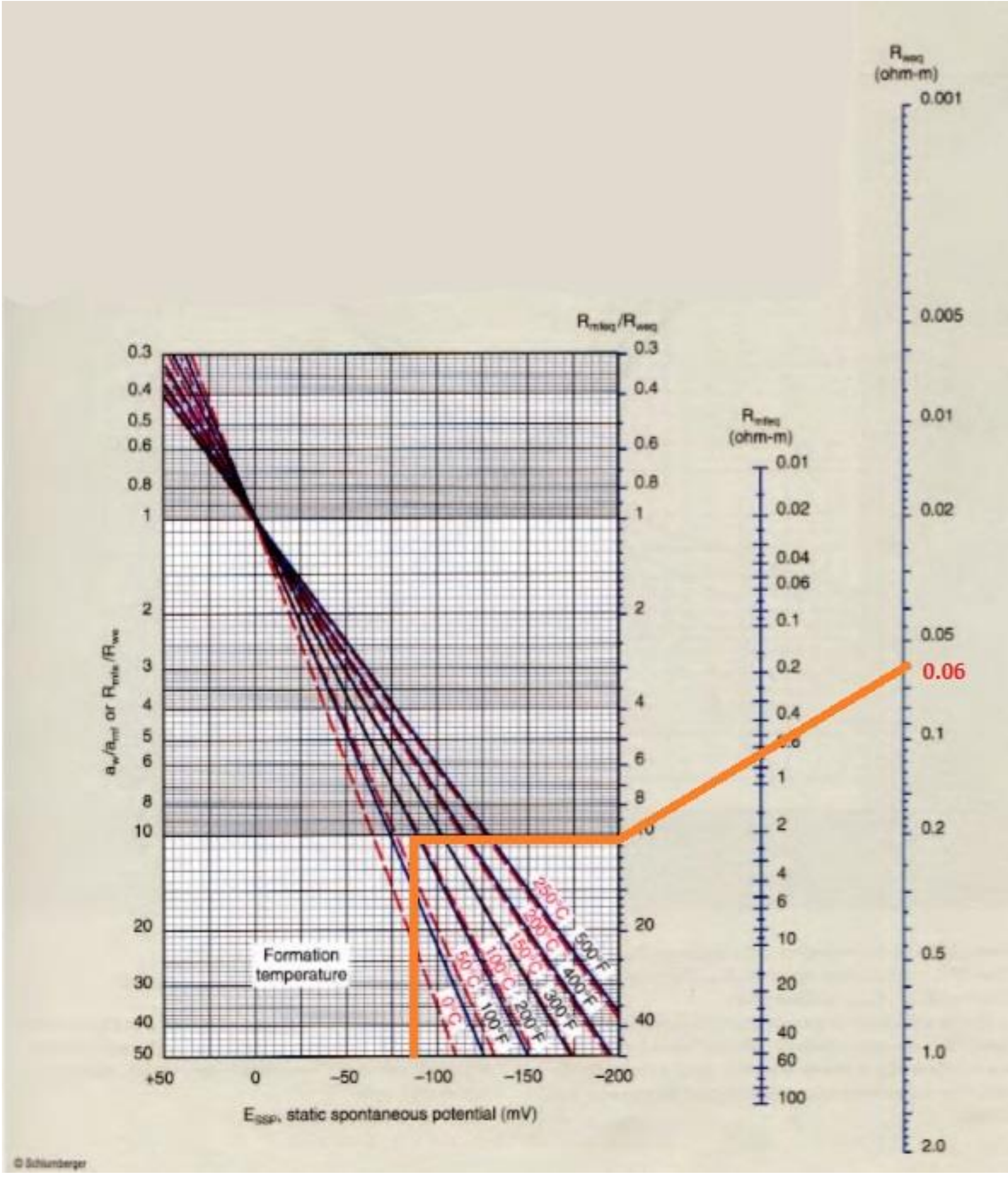
(5) Calculation of SSP using SP log i.e. maximum deflection off the SP curve i.e. -80

(6) Calculation of resistivity of water equivalent

Resistivity of water equivalent = 0.06 ohm-m

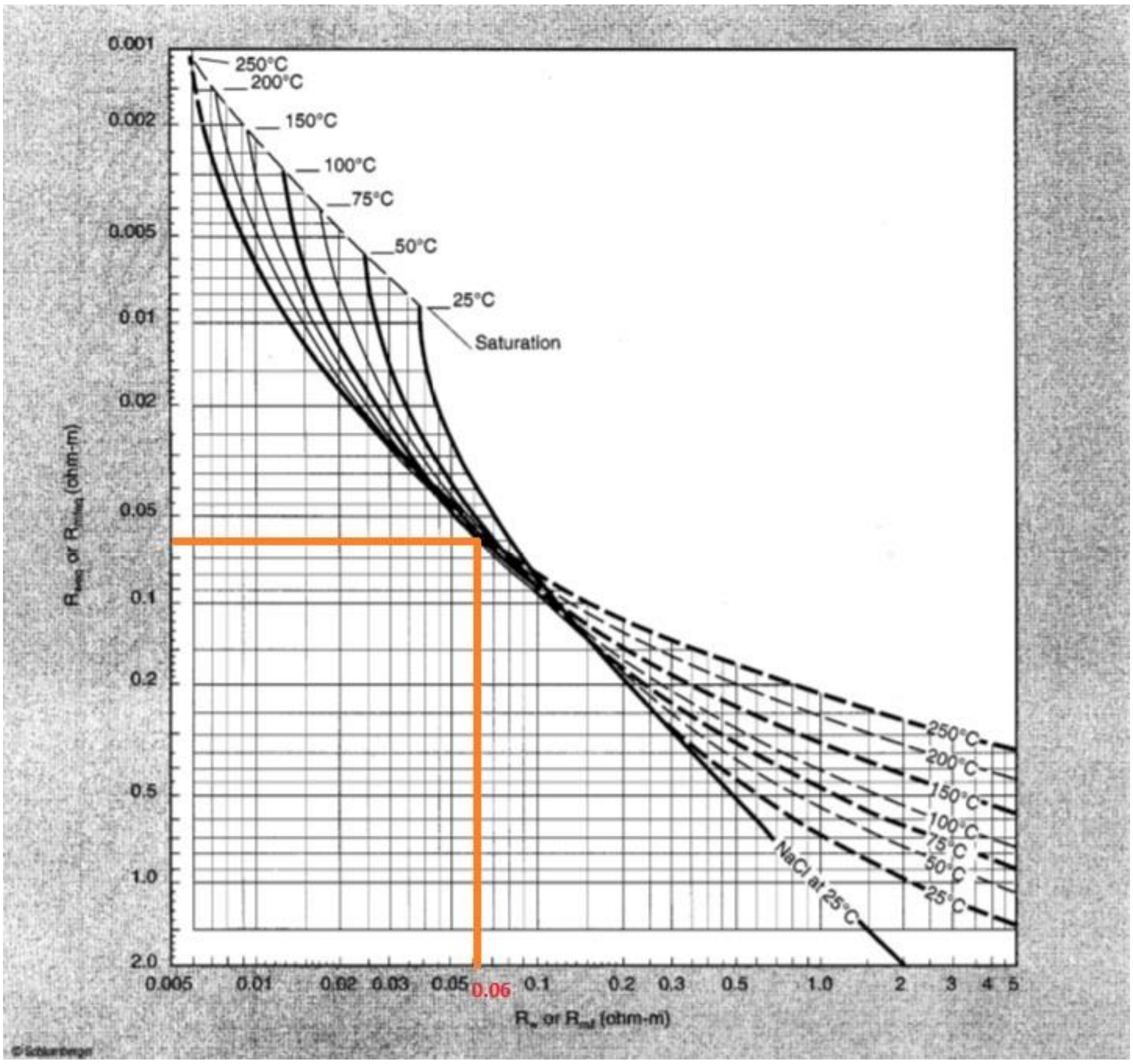
(7) Calculation of resistivity of water (Rw)


Conversion approximated by R₂ = R₁ [(T₁ + 6.77)/(T₂ + 6.77)]°F or R₂ = R₁ [(T₁ + 21.5)/(T₂ + 21.5)]°C
Resistivity of solution (ohm-m)
ppm
grains/gal at 75°F
NaCl concentration (ppm or grains/gal)
Temperature
°F
°C
© Schlumberger



R_{weq} (ohm-m)
R_{mfeq}/R_{weq}
R_{mfeq} (ohm-m)
0.06
a_w/a_{mf} or R_{mfe}/R_{we}
Formation temperature
E_{SSP}, static spontaneous potential (mV)
© Schlumberger

.



250°C
200°C
150°C
100°C
75°C
50°C
25°C
Saturation
NaCl at 25°C
0.06
R_w or R_{mf} (ohm-m)

ABSTRACT

Petrophysical evaluation of KAL-01 was carried out to highlight the reservoir area which included the selection of zone of interest followed by log interpretation. The petrophysical interpretation includes Shale volume, effective porosity, permeability, saturation of water and hydrocarbon. On the basis of petrophysical evaluation it was noted that hydrocarbon and the reservoir of Khewra Sandstone (Cambrian) is of good porosity and is hydrocarbon bearing.

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