WELL LOG STUDY AND PETROPHYSICAL PROPERTIES OF THE EARLY PERMIAN WARCHHA SANDSTONE, POTWAR BASIN, PAKISTAN

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ABSTRACT: The Chak Naurang Well1-A, drilled by Oil and Gas development company limited (OGDCL) in the eastern Potwar Basin, encountered thickness of 82 m for the Early Permian Warchha Sandstone. The sedimentological and reservoir aspects of the Warchha Sandstone from the response of various wireline logs have been investigated. This study is focused on the response of log signatures against the sediments within the Warchha Sandstone reveals an overview of depositional setting. Large-scale subsurface facies architecture based on the gamma-ray log including, channel fill deposits, point bar and flood plain have been identified. They show a characteristic vertical stacking pattern on the logs. The depth interval from 2357m to 2439m has been investigated for the petrophysical properties by examining the response of the various wireline logs recorded at 1m interval. The result of this study suggests that the Warchha Sandstone possess considerable storage capacity for holding moveable hydrocarbon.

Key words: Warchha Sandstone, wireline logs, gamma-ray log, petrophysical properties, moveable hydrocarbon.

INTRODUCTION

The Chak Naurang Well 1-A (32^0 59‟ 39” N and 72^0 55‟ 37.04”E) was drilled in the Chakwal District of the Punjab Province to a total depth of 2687m as shown in Fig. 1.

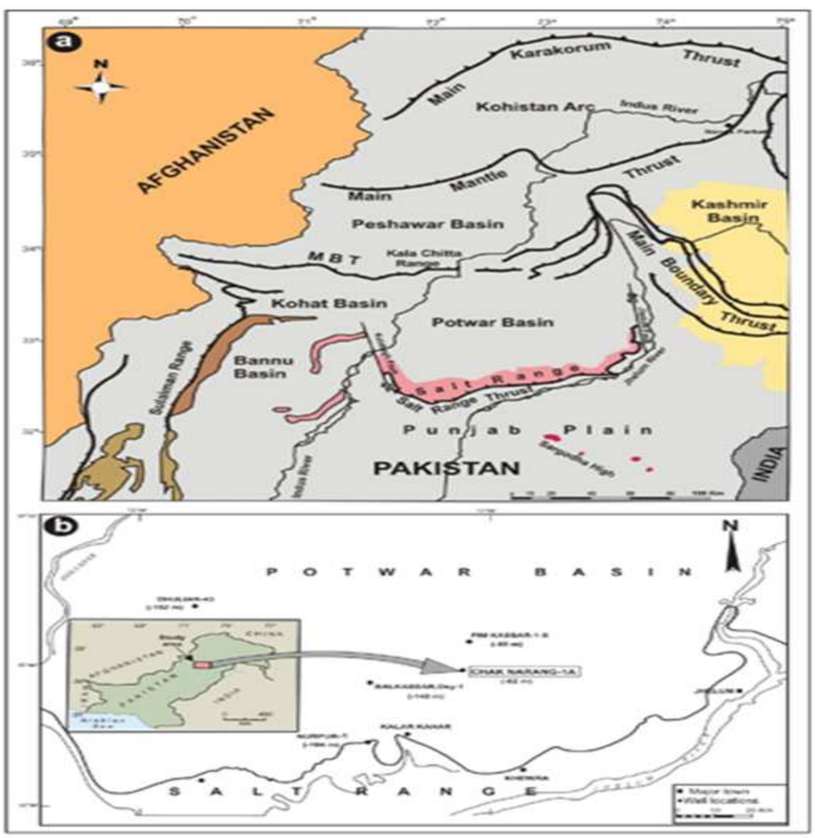

Fig. 1-(a) Location map of the major tectonic features of the Potwar Basin and Northern Pakistan, (b) location map of the Chak Naurange Well-1A and drilled thickness of the Warchha Sandstone in different wells.

It lies in east of the Joyamir on the seismic line no 794-cw-35, which crosses the Chak Naurang in the north-east and the south-west directions. The average ground elevation of this well is 549.01m above sea level and the Kelly Bushing elevation is 556.67m. The main objectives of the well were to drill and investigate the Khewra, Tobra, Sakesar and Chorgali formations, whereas the secondary objective was to test the Dandot and Warchha formations. The sequence encountered in this well is given in Table 1.

Table 1. Main Lithologies and Formations encounted in the Chak Naurang Well-1A

Age	Formation	Thickness (m)	Main Lithology
Early Pliocene	Chinji	875	Claystone with Sandstone
Upper Miocene	Kamlial	157	Sandstone with Claystone and Siltstone
Middle Miocene	Murree	1064	Sandstone with Claystone
Middle Eocene	Chorgali	38	Limestone with Minor Shale
Early Eocene	Sakesar	110	Limestone with Shale and Marl
Upper Palaeocene	Patala	09	Shale with minor Limest
Early Palaeocene	Lockhart	11	Limestone with minor shale
Early Permian	Sardhai	99	Shale with Minor sandstone
Early Permian	Warchha	82	Sandstone with Shale
Early Permian	Dandot	29	Sandstone with Shale
Early Permian	Tobra	26	Sandstone with Shale
Middle Cambrian	Kussak	24	Sandstone, Silstone and Shale
Early Cambrian	Khewra	122	Sandstone, Siltstone and Shale
Pre-Cambrian	Salt Range	+47	Salt, Marl with Dolomite and Anhydrite

The oldest formation drilled in this well is the Salt Range Formation of Precambrian age. While, the youngest formation encountered is the Chinji Formation of the Late Miocene to Early Pliocene age (Fatmi, 1973). Pakistan has a distinction because of its presence at the junction of the Indian and the Eurasian Plate and the palaeomagnetic data confirms that 1500 to 3500 km convergence has occurred between these two plates (Molnar and Tapponnier, 1975). This convergence is largely accommodated by the underthrusting of one continental block beneath the other (Molnar and Tapponnier, 1975). The Potwar Basin has several features that make it favourable site for the accumulation of hydrocarbon and the basin is filled with thick deposits of source, reservoir and the cap rocks. It contains thick overburden of sediments that provide the optimum geothermal gradient for the formation of the hydrocarbons. The present study is mainly focused on the Early Permian Warchha Sandstone. The Warchha Sandstone is composed of light-pink, red, reddish-brown and white-coloured fine-to coarse-grained sandstone, which is conglomeratic in places and has interbeds of siltstone and claystone. It is characteristically speckled in places. Several fining-upward cycles are recognised within the formation and these are composed of conglomerate and cross-bedded sandstone in their basal part and bioturbated siltstone and claystone / mudstone in their upper part (Ghazi, 2005, 2009). Clasts are mainly of plutonic and low-grade metamorphic origin, with an additional minor sedimentary component. Textural properties of the sandstone are fine- to coarse-grained, poorly- to moderately-sorted, sub-angular to sub-rounded and generally with a loose packing. Based on petrographic modal analyses, the sandstone is dominantly a sub-arkose to arkose (Ghazi, 2007, 2009). A broad range of sedimentary structures are recognised, including different forms of bedding, cross bedding, ripple forms, ripple stratification, channels, flute casts, load casts, desiccation cracks, rain imprints, cone-in-cone structures, a variety of concretions and bioturbation (Ghazi, 2009).

This study is the first comprehensive assessment of its kind and the aim of this paper is to describe the large-scale fluvial facies architecture and the reservoir potential of the Warchha Sandstone based on the sedimentological interpretation of wireline logs.

Geological Setting: The Chak Naurang Well-1A lies in the north-eastern part of the Potwar Basin (Fig.1). The Chak Naurang seismic time structure map drawn on the top of the Chorgali Formation shows the presence of eastern, western and the southern three independent fault blocks having closed areas of 20 square km, 7.5 square km and 9.0 square km respectively. The Chak Naurang Well-1A bottomed into the Salt Range Formation is located in the structurally higher western fault block. The Salt Range–Potwar Foreland Basin (SRPFB) is bounded by the Salt Range Thrust in the south and the Main Boundary Thrust (MBT) in the north. It is bounded by left lateral Jehlum Fault and right lateral Kalabagh Fault in the east and west respectively. The Eocambrian to Cenozoic sedimentary sequence of the Indian Plate is exposed in SRPFB. Structurally, the SRPFB comprises of the Northern Potwar Deformed Zone (NPDZ), the Soan Syncline and the Southern Potwar Platform Zone (SPPZ).

The SRPFB is covered by the molasses sediments ranging in age from Miocene to Pleistocene. The Eocambrian to Tertiary sedimentary sequence in SRPFB is exposed along ranges in the south. The sedimentary rocks of the SRPFB are deformed during thin-skinned Himalayan tectonics, forming the structural trap for hydrocarbons. Hence the SRPFB is structurally favourable site for the hydrocarbon accumulation. This foreland basin is filled with thick sequence of the source, reservoir and seal rocks (e.g., Raza et al., 1989; Kadri, 1995; Shah, 2009). It contains 1980m to 3050m thick overburden of fluvial sediments which provide burial depth and optimum geothermal gradient favourable for the formation of hydrocarbon in the SRPFB.

METHODOLOGY

The fluvial system was reconstructed and the entire succession was subdivided on the basis of identification of stacked large-scale elements. The present research is based on the well log data of the Chak Naurang well-1A provided with the courtesy of the Directorate General Petroleum Concessions (DGPC), Islamabad, Pakistan. The response of logs were noted at one meter interval and the volume of the shale is calculated by gamma-ray log. The porosity is calculated from the Density-Neutron porosity logs, and finally the Neutron-Density combined logs. The Resistivity of the invasion zone (R_i), the flushed zone (R_{x0}), uninvaded zone or true resistivity of the Formation (R_t) is evaluated with the help of resistivity of the formation water at formation temperature (R_W), water saturation (S_W) and moveable hydrocarbon index (S_W/S_{XO}).

The top and bottom of the Warchha Sandstone in the examined well logs have been marked previously by operating company (OGDCL), their interpretations having themselves been based partly on previous oil company investigations and partly on information from driller logs

Log Characters: Most of the Warchha Sandstone in the Chak Naurang Well 1-A has constant log character and identifiable (e.g., Ghazi and Mountney, 2010). However shape of the log in few intervals is variable and difficult to identify. The Warchha Sandstone is lithologically characterised by conglomeratic sandstone, sandstone, siltstone, shale and mudstone (Ghazi and Mountney, 2010). It is best delineated on the gamma-ray log; however, many difficulties arose in the interpretation of the shape of gamma-ray logs because of the presence of naturally radioactive minerals, detrital mica and pure carbonate within some sandstone facies (Hurst, 1990; Rider, 1990). To solve such problems log motifs (trends) and well cutting data at particular depth intervals were compared with other logs curves. It shows low to moderate values of the gamma-ray against porous and moderately to well-sorted sandstone intervals as shown in Fig. 2.

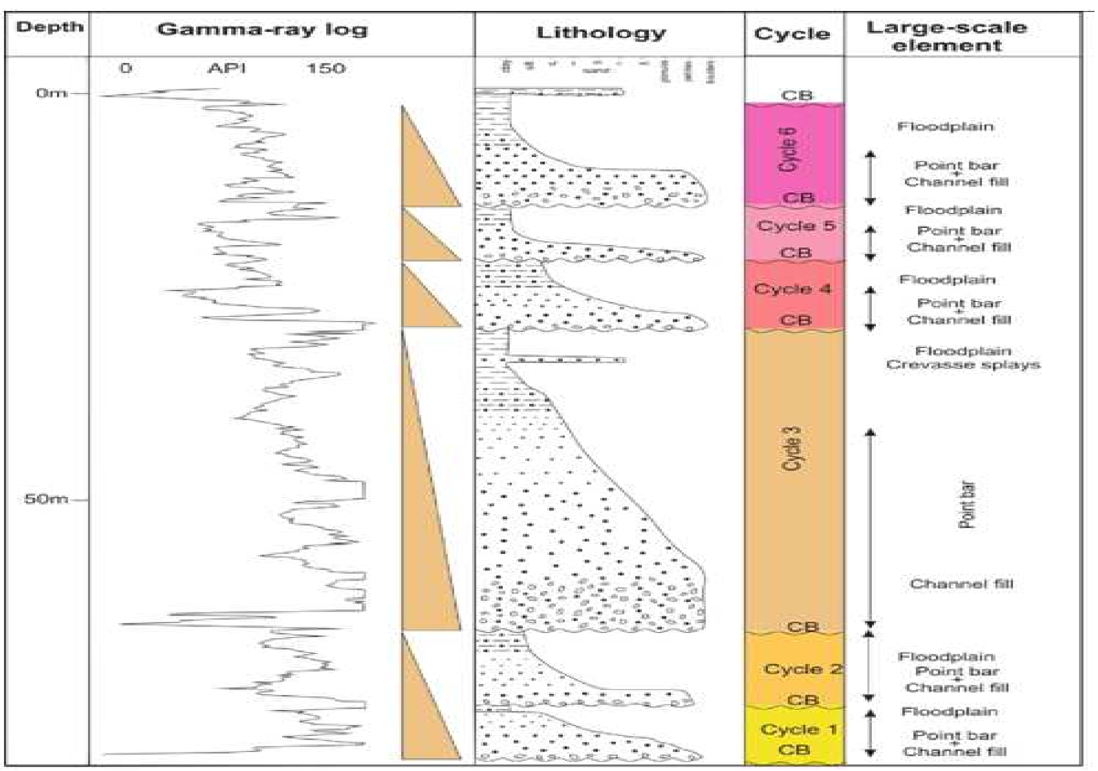

Fig. 2- Characteristic gamma-ray log response against the Warchha Sandstone in Chak Naurang Well-1A.

The porous sandstone intervals delineate generally cylindrical shape in Sp curves. While porous sandstone intervals show wide separation between the shallow and deep induction curves.

Accumulations of sediments that reflect different depositional environments tend to display characteristic log motifs and the recognition of these log motif trends can be used as an indicator of the likely depositional setting of the facies succession (Ghazi, 2009). At a basic level, a gamma-ray log motif indicates the variation in grain size. However, in fluvial successions the relationship between grain size change and type of sandstone facies is additionally significantly affected by the presence of a clay matrix within sand-dominated beds (Rider, 1990). The presence of claystone clasts or mud pebbles in a channel deposit will generate higher values on the gamma-ray log, even if the parent material is a „clean‟ sandstone (Ghazi, 2009). Similarly, the presence of carbonaceous material will also act to increase the value of the gamma-ray log (Chow et al, 2005).

Identification of Large-Scale Fluvial Facies: On the basis of the well-log shapes and stacking of vertical profiles not only can lithological interpretation be made but also the subsurface facies analysis ("electrofacies") as well as the environmental and stratigraphic interpretation (Pirson, 1970; Serra, 1985; Juhász et al., 2004; Chow et al., 2005; Ghazi and Mountney, 2010). The logs shape may provide a general larger-scale stratigraphic and sedimentological interpretation (Ghazi and Mountney, 2010). The overall tendencies and the larger-scale depositional elements of a thick sedimentary succession (i.e. fining-upward cycles) are more easily identifiable (Juhász et al., 2004). However, the sedimentary structures and the other important details remain hidden in this kind of interpretation (Juhász et al., 2004).

The main lithology identified through gamma-ray log shape characteristics and their vertical stacking pattern provides a view on the overall large-scale architectural build-up (Ghazi and Mountney, 2010). The main depositional elements distinguished on the basis of gamma-ray log in the Warchha Sandstone include, channel, point bar, and floodplain deposits (Fig. 2). However, thin alternate fine-grained sandstone and siltstone beds indicate the presence of natural levee and the crevasse splay (Ghazi, 2009).

a. Channel-fill deposits: The sandy channel-fill deposits have a very characteristic appearance on the gamma-ray log (Fig.2). The log motif can be either a cylinder or bell-shaped and smooth or slightly serrated (Ghazi, 2009; Ghazi and Mountney, 2010). Generally their sharp bases indicate downcutting into clay- or silt-rich floodplain sediments (cf. Juhász et al., 2004). Therefore, they show great variability in terms of thickness, stacking and the overall character. Analyzing the well-log response several completely different channel forms can be identified. Only the vertical continuity of the channel fill can be observed and almost nothing is known about their lateral dimensions and the relationships.

b. Point bar deposits: Five point bar deposits have been identified in the Warchha Sandstone of the Chak Naurang Well-1A (cf. Cant, 1994; Ghazi and Mountney, 2010; Fig. 2). The Point-bar deposits are connected to the meandering channel fills and have a characteristic bell-shaped on the gamma-ray log (Ghazi, 2009; Ghazi and Mountney, 2010). The fining-upward succession appears on the log in the shape of a pine tree with "branches" becoming finer upward in corresponding grain size (Fig. 2). This is quite common in the Warchha Sandstone and generally overlies the thin layer of conglomerate and very coarse-grained sandstone channel-fill or the channel lag deposits (Ghazi, 2009; Ghazi and Mountney, 2010). Its maximum thickness developed up to 10 m in cycle 2 (Fig.2).

c. Floodplain deposits: Log of this element shows high variability in shape from symmetrical to extremely serrated. In a few places, small-scale cylinder- and funnel-shaped motifs transform into small bell-shaped motifs before returning once more to funnel-shaped again. Usually, this pattern records a fining-upward trend but, in few places, a coarsening-upward trend was also observed (Ghazi and Mountney, 2010). Upper boundaries in many cases show an erosional contact. The Floodplain deposits include the fine-grained overbank sediments of the floodplain and cover a wide flat basinal area where several rivers flowed across the alluvial plain and their floodplains merged. Floodplain deposits are comprises of the fine grained over bank deposits. The serrated gamma ray log shape indicates the presence of alternating silt and mud in the Warchha Sandstone (Ghazi, 2009: Ghazi and Mountney, 2010; Fig. 2).

Petrophysical Properties: The petrophysical properties of the Warchha Sandstone in Chak Naurang Well-1A are based on interpretation of the Spontaneous potential (millivolts), Total gamma-ray (API units), Sonic (microsecond per foot), Density (gm/cc), Neutron (limestone equivalent porosity units), Micro spherically focused (ohm-metres), Shallow latro (ohm-metres) and Deep latro (ohm-metres).

1. Shale content: Both the spontaneous potential and gamma-ray logs data are interpreted for the determination of shale content as shown in Fig. 3.

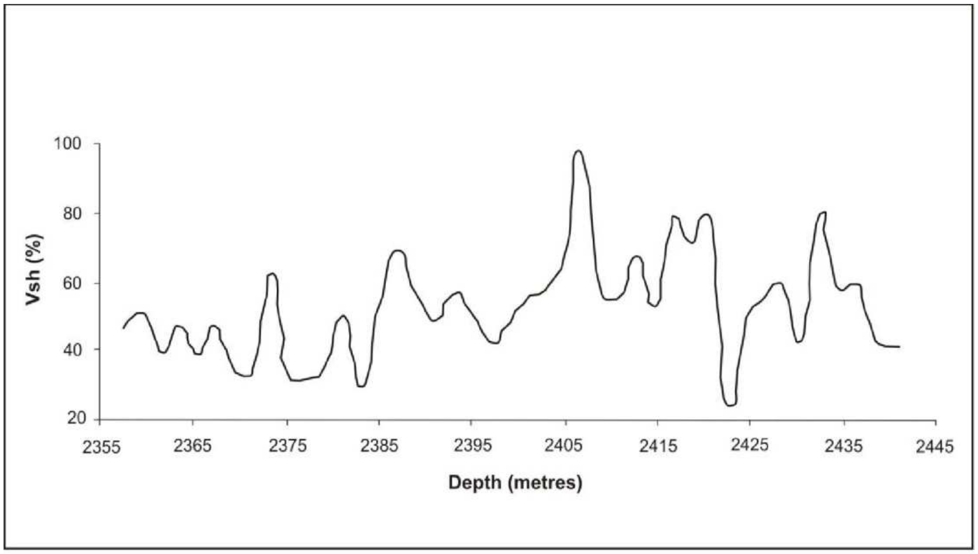

Fig. 3- The distribution of the volume of shale in different intervals in the Warchha Sandstone

The value of the gamma-ray log is high in shale lithology, whereas it is low in sandstones (Fig. 2). The depth intervals such as A (2361m - 2363m), B (2367m - 2369m), C (2379m - 2381m), D (2389m - 2365m), E (2399m - 2403m), F (2425m - 2427m), G (2435m - 2437m) show low values of the gamma-ray indicating low percentages of shale and mud and presence of dominantly sandstone in the Warchha Sandstone in above mentioned depth intervals (Table 2).

Table 2: Possible hydrocarbon bearing intervals in the Warchha Sandstone in Chak Naurang Well 1A.

Interval	Depth	Lithology	Vsh (%)	N - D Φ (%)	Rt ohm-m	Rw ohm-m	Sw / Sxo	Comments
A	2361m - 2363m	Sandstone	43.1	34.5	2.1	0.346	0.59	Good porosity and permeability, possibility of moveable hydrocarbon
B	2367m - 2369m	Sandstone	41.5	33.5	2.7	0.393	0.45	Good porosity and permeability, possibility of moveable hydrocarbon
C	2379m - 2381m	Sandstone	42.5	32.1	3.2	0.369	0.67	Good porosity but poor permeability
D	2389m - 2395m	Sandstone	52.7	31.6	3.5	0.357	0.61	Good porosity and permeability, possibility of moveable hydrocarbon
E	2399m - 2403m	Sandstone	53.3	32.0	3.0	0.359	0.51	Good porosity and permeability, possibility of moveable hydrocarbon
F	2425m - 2427m	Sandstone	52.5	32.0	5.6	0.341	0.41	Good porosity and permeability, possibility of moveable hydrocarbon
E	2435m - 2437m	Sandstone	59.0	26.7	8.0	0.342	0.38	Good porosity and permeability, possibility of moveable hydrocarbon

2. Porosity: The Warchha Sandstone is not composed of mixture of lithology from conglomerate -to-clay-sized gains. This made porosity calculation complex corresponding to lithology. A single log data can not produce accurate porosity values; hence, combination of neutron-density log and the cross-plots are used to mark lithologies. The porosity of the Warchha Sandstone is calculated with the help of the neutron and density logs data as shown in Fig. 4.

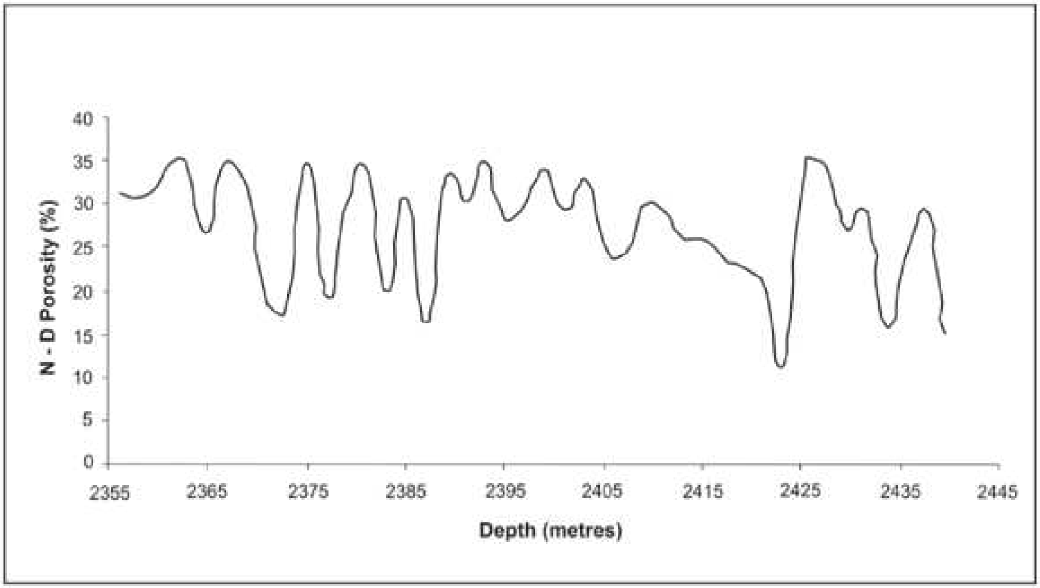

Fig. 4- Cross-plot of the Neutron-Density porosity percentage verses depth in the Warchha Sandstone.

The porosity values in the Warchha Sandstone calculated from predominantly sandstone lithology in depth intervals A (2361m - 2363m), B (2367m - 2369m), C (2379m - 2381m), D (2389m - 2365m), E (2399m - 2403m), F (2425m - 2427m), G (2435m - 2437m) are high, whereas the depth interval C (2373m - 2375m) having higher shale contents show low porosity (Fig. 4; Table 2). The porosity values in sandstone lithology ranging from 26.75% to 34.5%, indicating highly porous sandstone.

3. Resistivity: The resistivity of the invasion zone (Ri), surrounding the borehole, measured with the help of LLS Log data and of the flushed zone resistivity (R_{Xo}) measured by MSFL log data. Resistivity of the invaded zone or true resistivity (R_t) of the formation is calculated with the interpretation of LLD log data. In clean formations or formation saturated with water R_t, R_{Xo} and R_i log curves give the same response but in hydrocarbon-bearing zones R_t gives high values than R_{Xo} and R_i with fresh water based mud. Depth intervals, A (2361m - 2363m), B (2367m-2369m), C (2379m - 2381m), D (2389m - 2365m), E (2399m - 2403m), F (2425m - 2427m), G (2435m - 2437m) show high values of resistivity (Fig. 5) The formation water resistivity (R_w) at formation temperature (T_f) is calculated with the help of resistivity of mud (R_m), resistivity of invasion zone (R_i) and SP log values. Resistivity values decrease with increase in formation temperature (T_f).

4. Moveable Hydrocarbon Index: The Moveable Hydrocarbon Index (MHI) also gives information about formation permeability. A roughly estimation of the permeability of formation is possible with the help of moveable hydrocarbon index. It is the ratio between water saturation of the uninvaded zone (S_W) to water saturation of the invaded zone. If S_W / S_{XO} value is greater than 1 then the hydrocarbon is not moved during invasion. If S_W / S_{XO} value is less than 0.6 then hydrocarbon is moveable. Index having values less than 0.6 in depth intervals, A (2361m - 2363m), B (2367m - 2369m), C (2379m - 2381m), D (2389m - 2365m), E (2399m - 2403m), F (2425m - 2427m), G (2435m - 2437m), indicate porous sandstone lithology in which hydrocarbon is moveable due to presence of permeability (Fig. 6). The index value less than 0.6 indicate only rough estimation of the permeability, however it is not possible to measure the exact permeability of the formation with the help of index value.

Conclusions: The Early Permian Warchha Sandstone in Chak Naurang Well-1, Potwar Basin demonstrate characteristic log responses of dominantly sandstone, shale and mudstone, which can be identified and interpret fluvial depositional environment. Based on log pattern three types of large-scale facies architectural elements, channel, point bar and floodplain have been identified. A cylinder-shaped log motif is indicative of abandoned channels; a bell-shape motif is indicative of point bar deposits and symmetrical to extremely serrated log motifs are indicative of fine-grained overbank deposits. The petrophysical properties of the Warchha. Sandstone indicate the presence of storage capacity for moveable hydrocarbon in the Warchha Sandstone.

Acknowledgements: The author would like to acknowledge Director General Petroleum Concession (DGPC), Islamabad, Pakistan for providing well data. Specifically thanks to Nigel Mountney (University of Leeds) and Adrian Hartley (University of Aberdeen) for valuable discussions regarding the interpretation of parts.

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