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Integrating Core and Wireline Log Data to Evaluate Porosity of Jurassic Formations of Injra-1 and Nuryal-2 Wells, Western Potwar, Pakistan

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Abstract: Petrophysical properties of rocks can be better understood by core and well log analysis. Exact porosity estimation in the Potwar sub-basin of Pakistan is one of the main issues because of complex tectonic settings. Core and wireline log data of two wells: Injra–1 and Nuryal–2 drilled in the study area are used for the porosity evaluation in the Jurassic reservoirs. The log interpretation and laboratory analysis show that the Datta Formation of the early Jurassic is mainly sandstone with minor shaly beds. A workflow is developed to correlate the calculated porosity from logs with the measured porosity from core plug samples. The results show that log porosity and core porosity of Datta sandstone are comparable. Porosity in the younger formations is higher than in the older formations, which is an indication of presence of secondary porosity and structurally deformed fractures in sandstone. The Datta sandstone encountered in Nuryal–2 is about 20–30 % less porous than in Injra–1 well.

Keywords: Wireline log, Porosity, Jurassic, Potwar, Pakistan.

INTRODUCTION

A reservoir rock is a sub-surface sedimentary rock having interconnected porosity and permeability which may contains exploitable/producible quantity of oil/gas. Formation evaluation is undertaken to determine its capability to store and transmit fluid. The reservoir characteristics include formation temperature and pressure, pore and grain size distributions, pore shape, porosity (effective and total), permeability, facies distribution, and depositional environment (Holland, 1984; Chilingarian et al., 1996). Among these characteristics, reservoir porosity is a fundamental rock property which relate to the fluid saturation contained in the pores and its ability to flow when subjected to pressure gradients (Abu-Khamsin, 2004) and has a significant impact on petroleum fields operations and reservoir management. Various theoretical and experimental models and correlations are in practice to relate rock porosity with other rock and fluid properties (Gassmann, 1951; Wyllie et al., 1956; Geertsma and Smit, 1961; Gardner et al., 1974; Brown and Korringa, 1975; Raymer et al., 1980; Han et al., 1986; Tao and King, 1993; Gist, 1994; Khalid et al., 2013). However, all these models have some limitations and are valid under a set of specific conditions.

The velocity of elastic waves through a given lithology is a complex function of various parameters (Mavko et al., 2009). Among these parameters porosity is an important quantity which directly affects the velocity of elastic waves. Although Wyllie et al. (1956) proposed relationship is frequently used but this relationship is unable to give exact values especially in fractured or unconsolidated reservoirs. Another aim of formation evaluation is to enhance the certainty associated with reservoir appraisal. The attainment of this objective will require a more effective integration of core and log data that contribute to the reservoir model as well as for reservoir monitoring. A key component of the integration process is the reconciliation of data measured at different scales. Seismic reflection data give information upto few tens of meters, whereas the scale of investigation of wireline logs is of the order of 1 to 10 feet, depending on the specifications of the device used. The analysis of core involve much smaller volumes, ranging from 10^{-3} to 10^{-1} cubic feet (Adaeze et al., 2012). There are nine orders of magnitude from one extreme to the other, so it is not surprising that porosity estimates using different tools and techniques does not always give the same results.

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The exact porosity measurement in the reservoirs of the Kohat-Potwar basin is a big challenge due to the complex tectonic setting and various deformation cycles. Due to this reason many wells tested in this area are not successful in terms of their production. Therefore, in this work, we developed a flow chart for core-log integration to identify ways in which uncertainty in porosity measurement might be reduced. The work, therefore, focuses on formation evaluation at the mesoscopic scale (Worthington, 1990; 1991). In this work, firstly the wireline logs of two wells, Injra–1 and Nuryal–2 of the Kohat-Potwar basin are interpreted to identify lithologies and reservoirs. Secondly, to find out the exact porosity values in the identified zones in the wells, porosities calculated from logs are correlated with the porosities measured from core samples.

The Potowar sub-basin is one of the oldest oil producing regions in Pakistan (Wandrey et al., 2004a) with total known hydrocarbon volumes: 0.3 billion barrels of oil (BBO) and 1.9 trillion cubic feet of gas (TCFG) for a total resource of 0.7 billion barrels of oil equivalent (BBOE). The location of study area along with prominent geological features is shown in figure 1. Based on analysis of geophysical and geological data from 1996 to 2004, the Kohat-Potwar basin is 174th largest basin of the world in terms of cumulative production and reserves of oil and gas (Klett et al., 1997). In the Kohat-Potwar basin, more than ten oil fields have been discovered (Khan et al., 1986) and hundreds of wells have been drilled but unfortunately most of them were abandoned. The major reasons for abandonment are porosity related issues.

Injra–1 was drilled to a depth of 4739 m in the Potwar sub-basin. The wireline logging and coring operations were conducted at depth interval of 4602 m to 4618 m. This well produced for a limited period of eight months. Total production of oil and gas was 5760 barrels and 12330 million standard cubic feet (MMSCF) respectively. An abrupt decline was observed in the production of Injra–1. Nuyral–2 was drilled to a depth of 4807 m, northeast of Toot oil field in Attock district, Punjab, Pakistan. The wireline logging and coring operations were conducted at depth interval of 4513 m to 4807 m. The well produced non-commercial oil and gas and was abandoned.

GEOLOGY OF THE STUDY AREA

The study area lies in the Potwar sub-basin, a part of the Kohat-Potwar geological province or plateau (Fig. 1), which is a part of the upper Indus basin. The Parachinar-Murree fault formed the northern boundary whereas the Surghar range and the Salt range thrust make the southern boundary of the Kohat-Potwar province. The eastern and western boundaries of the province are marked by the Jehlum fault and the Kurram fault respectively. Based on tectonic setting and local geological structures, this province can be divided into the Soan syncline, the northern Potwar deformed zone, the Salt Range, the Kohat plateau, the Bannu depression and the Trans-Indus ranges (Khan et al., 1986). A variety of faulted and unfaulted structural features trending southwest – northeast are present in the area (Fig. 1). The predominant features include shallow northeast-trending anticlines and overturned folds developed on multiple detachment surfaces, which are deep upto the Eocambrian salts (Kemal et al., 1992; Jaswal et al., 1997). Most of these structural features are parallel to the plate-collision boundary. The continuous crustal shortening in the

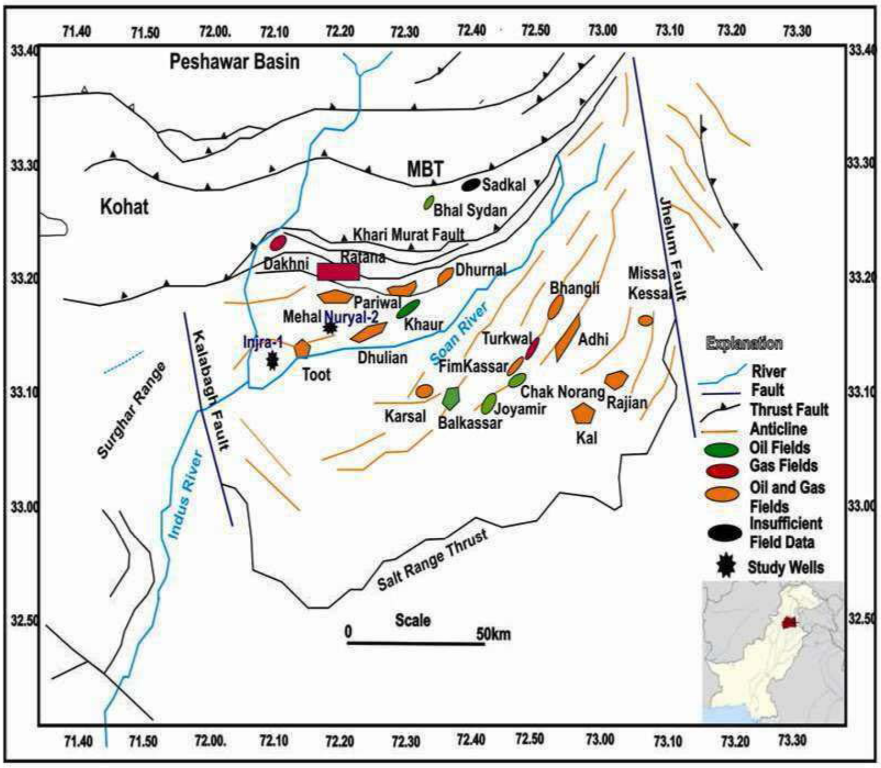

Fig.1. Location and geological map of study area (modified after Raza, 1992).

Kohat-Potwar plateau is also reported (Wandrey et al., 2004a).

The area is basically a part of a shallow continental shelf on which siliciclastics rocks and carbonates are deposited (Wandrey et al., 2004b). The depositional history of the Kohat-Potwar basin is relatively complete from the late Proterozoic to the Holocene. The metamorphic basement rocks of the late Proterozoic are overlain by organic rich shales, sandstones, interbedded carbonates and evaporate of the late Proterozoic and the Salt range Formation of the Precambrian (Shah et al., 1977; Iqbal and Shah, 1980). However, the outcrops and geophysical sub-surface data indicate that Precambrian to Quaternary rocks are present with some structural gaps and unconformities. These structural gaps are due to overthrusting. The upper Cambrian to Devonian and possibly Carboniferous are missing in the province due to non-deposition and/or erosion represented by an unconformity separating the middle Cambrian and lower Permian strata (Yeats and Lawrence, 1984). A major unconformity at the base of the Paleocene strata represents tilting, uplifting and erosion from late Cretaceous to Paleocene. This may be responsible for the partial to complete removal of the upper Permian to Mesozoic section in the east (Gee, 1980; 1989). In the Potwar sub-basin and the adjacent Kohat plateau, Eocene limestone, evaporites, and red beds of sandstones are exposed, which indicate fluvial sediments of the Miocene to Pleistocene with terrace gravel. Holocene alluvium is found on the exposed surface (Warwick and Wardlaw, 1992).

PETROLEUM SYSTEM IN POTWAR SUB-BASIN

Although several individual total petroleum systems (TPS) of different ages are present in the Potwar sub-basin (see Fig.2), for the assessment of oil and gas reservoirs in this region, these are divided into Precambrian-Permian, Jurassic-Cretaceous, Eocambrian-Miocene and Paleocene-Eocene TPS. It is difficult to mark a sharp boundary between two individual TPS due to presence of extensive fault systems and deformation, which may allow the migration of hydrocarbon from different source rocks.

Source Rock

The Precambrian Salt Range Formation, the Nammal and Patala formations of the Jurassic and the Paleocene appears to be the primary source of hydrocarbons in the study area, but other potential source rocks may be contributing in different parts of the basin (Qadri, 1995).

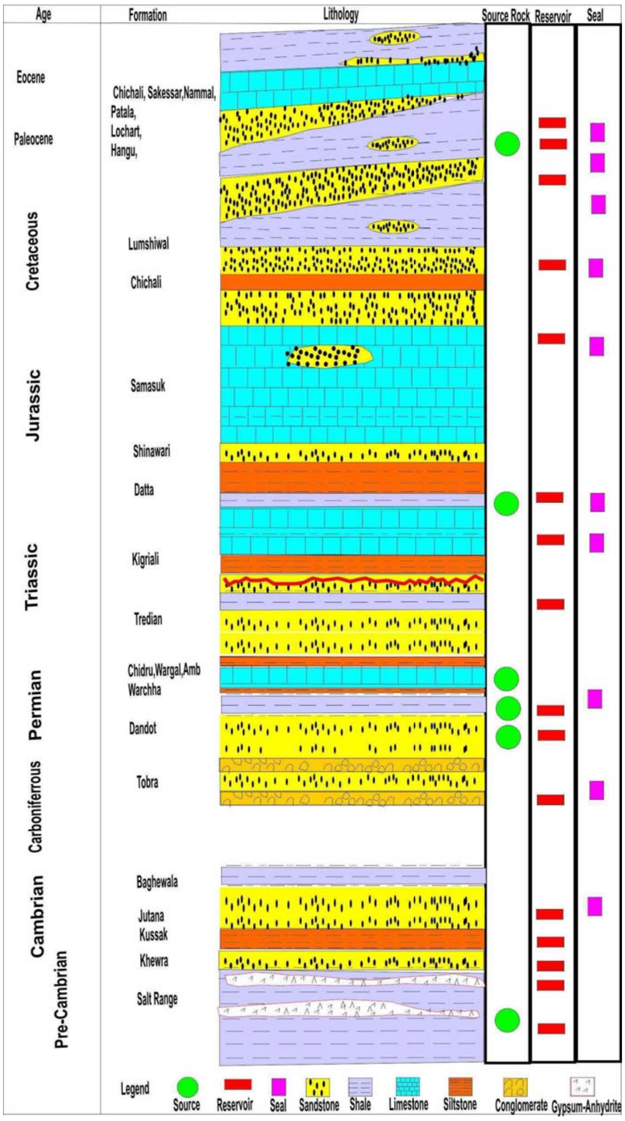

Fig.2. Generalized petroleum system chart of the Kohat-Potwar geologic province of Pakistan (modified after Quadri and Quadri, 1996; Iqbal and Shah, 1980).

In our study area the main source rocks are shale of the Datta Formation (Jurassic), having good potential while shale of the Mianwali Formation (Triassic) have low potential but can also be considered to charge the reservoir.

Reservoir Rocks

The Datta sandstone (Jurassic) and the Sakasser limestone (Eocene) are the major reservoir rocks in study region. Some other reservoir rocks are Miocene alluvial sandstones, Paleogene shelf carbonates, Jurassic and Permian continental sandstones, and Cambrian alluvial and shore face sandstones (Shah et al., 1977; Iqbal and Shah, 1980).

Traps and Seals

In the Potwar sub-basin the majority of the oil and gas discoveries to date are either on overturned faulted anticlines, popup structures, or fault-block traps. In study area, the anticlinal features generally follow east-northeast to west-southwest trend and are approximately parallel to the plate-collision zone. Many of these folded structures are augmented, or they are only present above a detachment zone in the Precambrian salts. These thrusting events form the latest structural traps that began at approximately 2 to 5 Ma (Jaswal et al., 1997). Seals include fault truncations and interbedded shales of Datta Formation (Jurrasic), Chichali and Lumshiwal formations (Cretaceous), thick shales and clays of Siwalik Group of Miocene and Pliocene may also act as a seal.

METHODOLOGY

Normally, the available wireline log data include the resistivity logs of various scales (deep- medium, spherically focused etc.) bulk density, interval transit time, gamma ray (GR), caliper, spontaneous potential (SP), neutron etc. The parameters derived from core data through laboratory measurements contain bulk density, porosity, shale content, permeability and fluid content. Since the reservoir in this area is the Datta sandstone of the Jurassic, therefore our porosity estimation is focused only at that interval. The porosity and density of the above mentioned wells is first measured from the analysis of core plug samples. It is assumed that the samples are isotropic horizontally at the sample scale; therefore, horizontal plugs are sampled in the bedding plane (parallel to the strike) in all reservoir intervals in both wells. The standard procedure was adopted for porosity measurement in the laboratory using the Helium Porosimeter PHI -220. The details of core data collected from Injra–1 and Nuryal–2 wells are given in Table 1. Similarly, porosity at the same intervals is also estimated from porosity logs (sonic, density and neutron). After calibrating the log derived porosity, a comparison is made between the measured porosity and the log derived porosity. Total thirty one core plug samples of Injra–1 and forty four of Nuryal–2 are taken and tested in laboratory for porosity measurement and mineralogy prediction.

For the evaluation and integration of the density and porosity, the following steps are taken in order to calibrate core data with log data.

Depth Calibration on Log

Sometimes some well logs exhibit log response against incorrect depth or depths with errors due to cable tension, tight pulls or overpulls, incorrect depth caliberation, incorrect deviation readings etc. Therefore it is necessary to check the quality and calibrate logs to depth. Most of the errors are examined and adjusted before the final logs. The depth errors of log curves in our study are matched to within a range of 0.2 m.

Well Deviation Correction

Deviation correction is applied to adjust the effects of borehole deviation on log response and vertical depth. Yangjian (1995) equation was used to correct the measured depth to true vertical depth.

$$z_2 - z_1 = \int_{\varphi_1}^{\varphi_2} \frac{b_1 - b_2}{\varphi_2 - \varphi_1} \cos \varphi d\varphi = \frac{b_1 - b_2}{\varphi_2 - \varphi_1} (\sin \varphi_1 - \sin \varphi_2)$$

Where b_1 and b_2 are the start and end depth of a deviated hole, z_1 and z_2 are relative vertical depth interval; j_1 and j_2 are angles of deviation. We divided the whole deviated interval into M-1 small intervals and applied this correction simultaneously. Here M is the total number of points taken in whole deviated interval.

Rebuilding of Logs

Sometimes log data at certain depths show abnormal variations or lost. This abnormality in log values is corrected either by developing a new relationship between erroneous log and other logs or using some existing relationship. Schlumberger (1994) relationship is used in this work to reconstruct incorrect logs and replace the abnormal interval.

Log Normalization

It is common observation that if we examine multi-well data, log response, in two wells in the same area, from the same lithology is different. To normalize this reading difference, a clean lithology, normally shale, is taken as reference and the log values in both wells are adjusted.

Core Re-position

For the integration of log data with core data, depths from log are compared with the depth at which core samples are taken along with one or two more accurate log. In this study, density log is taken for depth comparison as depth from the density log is considered as accurate and can be used to calibrate core depth. Figure 3 represents a plot drawn between density measured from core and depth to calibrate the density log in the same depth interval for both wells.

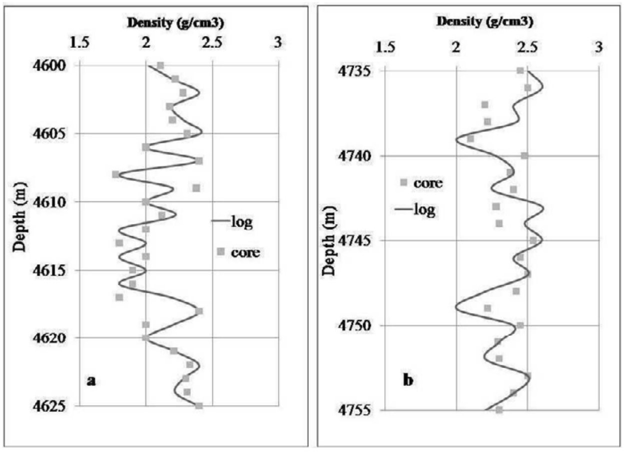

Fig.3. Log density and density measured from core plug samples of Injra–1 **(a)** and Nuryal–2 **(b)** in the same straitigraphic interval of Datta formation.

Core Matching

The vertical resolution of log data is generally poor than that of core data. A smoothing technique is used here to match the vertical resolution, and the distance from the source to the receiver of a log instrument is used to decide a suitable filtering method.

RESULTS

Log Interpretation of Injra–1 and Nuryal–2

GR, SP, density and sonic logs are used to mark various lithologies encountered in Injra–1 and Nuyral–2. For water saturation and formation evaluation resistivity logs are also interpreted. The log response and lithologies encountered in Injra–1 and Nuryal–2 are shown in Figs. 4 and 5 respectively. The wireline logs interpretation of both wells indicates that the Datta (Jurassic) is sandstone dominant. Although the log response of sonic and neutron is not much clear due to high deviation of borehole but the response of sonic log tends towards sandstone. The density log is very much affected to detect lithology and porosity in deviated boreholes. In density curve, the upper portion of the Datta Formation consists of sandstone. The core samples confirmed this interpretation. The Datta sandstone is mainly composed of fine to coarse grains quartz (60 – 70 %) with some other clay minerals. The formation is dominated by clean sands with some miner interbeded shales in the upper part. This demonstrates good matrix porosity of the formation and also indicates the presence of hydrocarbon.

Porosity Measurement from Cores and Logs of Injra–1 and Nuryal–2

Porosity is derived from various logs (neutron, density and sonic), however for its calibration, information about lithology, properties of the grain matrix, pore fluid etc. needs to be derived from core samples through laboratory analysis. The neutron porosity is showing low values in upper part of the Datta Formation (Jurassic) while high porosity in lower part of the formation. Porosity values determined by core analysis are generally accepted as superior to log estimates. The same stratigraphic interval of Injra–1 and Nuryal–2 was interpreted using core data as given in Table 1. Thirty one core samples of Injra–1 were analyzed from three intervals cored in the reservoir: 4595 – 4605 m, 4609 – 4618 m and 4620 – 4627 m. In Nuryal–2 forty four core samples were analyzed in four intervals cored at the following depths: 4709 – 4718 m, 4725 – 4735 m, 4740 – 4750 m and 4752 – 4760 m. The details of bulk volume, grain volume and grain density are given in Table 2.

The log porosity derived from density log and measured porosity from core of well Injra–1 and Nuryal–2 is plotted

Table 1. Average porosities calculated from porosity logs and measured porosities from core samples in Injra–1 and Nuryal–2

Well	Age/ Formation	Depth intervals (m)	Average porosity from wireline logs (%)	Core interval (m)	Porosity from Core (%)
INJRA–1	Jurassic/Datta	4595 – 4625	17 – 20	Core-1: 4595-4605 Core-2: 4609-4618 Core-3: 4620-4627	18 – 22
NURYAL–2	Jurassic/Datta	4710 – 4760	19 – 22	Core-1: 4709-4718 Core-2: 4725-4735 Core-3: 4740-4751 Core-4: 4751-4760	20 – 23

Table 2. Dimensions of core samples and laboratory tests results of in Injra–1 and Nuryal–2

Sample ID	Average sample length (cm)	Average sample diameter (cm)	Bulk volume (cc)	Dry weight (gm)	Test type	Grain volume (cc)	Pore volume (cc)	Porosity (%)	Grain density (g/cc)	Rem. Billet volume (cc)	Conf pressure (psi)	Temp C	Pore Volume (cc)
Injra–1	5.1	3.75	56.156	148.58	GV	54.721	1.435	18	2.715	58.969	500	29.3	1.435
Nuryal–2	5.1	3.75	56.156	151.58	GV	54.150	1.445	20	2.715	58.969	550	31.3	1.435

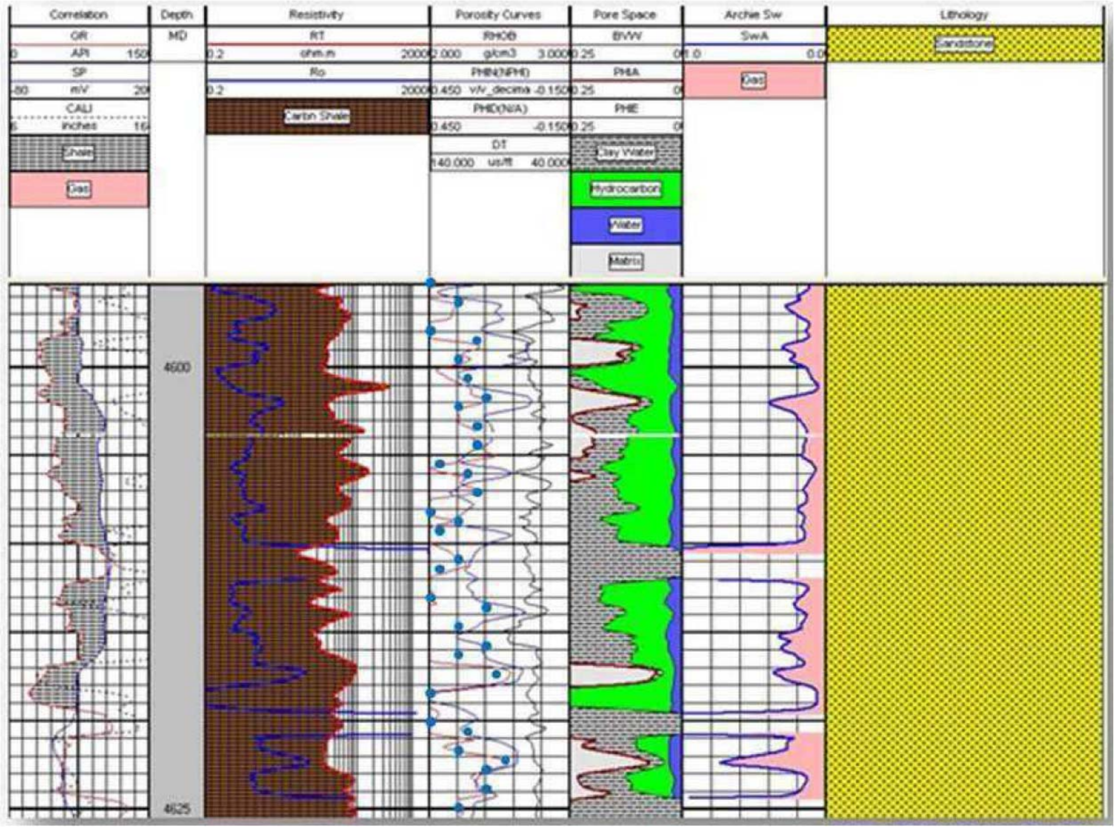

Fig.4. Log interpretation of the Datta Formation interval encountered in Injra–1.

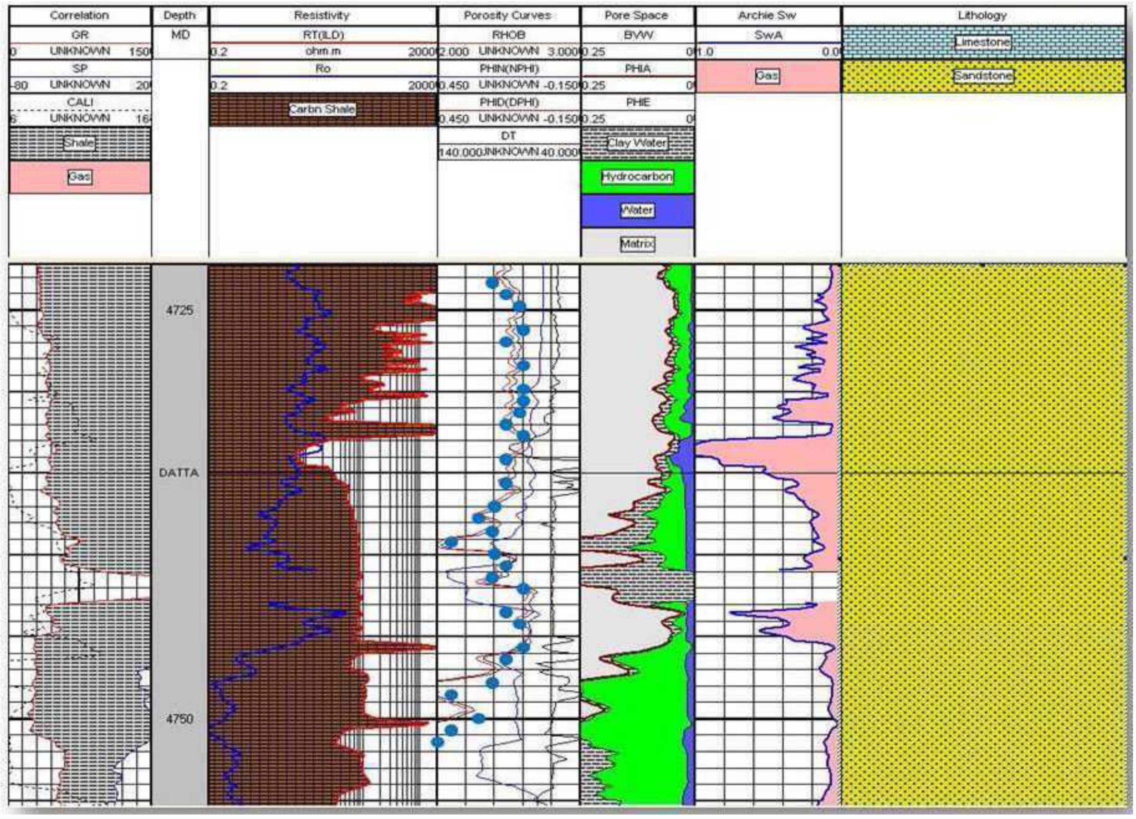

Fig.5. Log interpretation of the Datta Formation interval encountered in Nuryal–2.

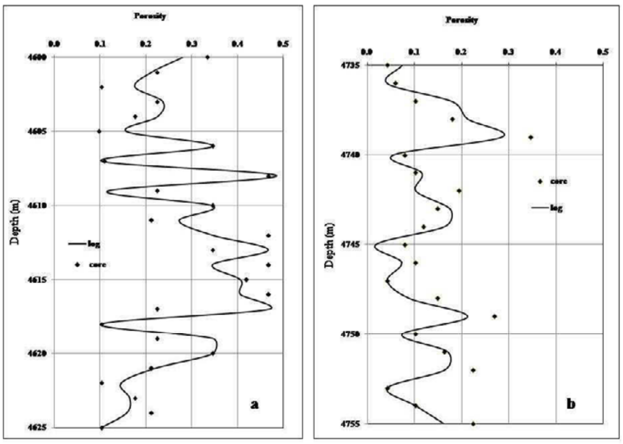

Fig.6. Core porosity and well log derived porosity of the Datta Formation interval encountered in Injra–1 **(a)** and Nuryal–2 **(b)**.

against depth intervals in Figs.6a and b respectively. It reveals good to excellent agreement with the porosity values determined by the logs and the core samples in both wells. The porosity measured from core plugs is in the range of 0.1 to 0.47 in Injra–1 and in Nuryal–2 it is 0.04 – 0.35. Whereas the log porosity in Injra–1 is 0.1 – 0.49 and in Nuryal–2 is 0.04 – 0.29. The measured core porosities and log porosities giving higher values greater than 40% at some intervals (4608 m and 4613 – 4617 m) in Injra–1, which indicate the secondary porosity. In reservoirs large scale secondary porosities are usually developed either due to the presence of fractures or due to large scale dissolution. Considering the fact that the present reservoirs are sandstones, in a highly deformed portion of the basin, presence of fractures is the more likely cause of unusually high porosities recorded. Further, the porosities computed by the combination of sonic-neutron logs and sonic-density logs confirm the presence of fractures in sandstone. As the study area lies in the Kohat-Potwar basin, which is highly deformed zone, therefore these fractures may be produced due to deformation. The average porosity in Injra–1 is in the range of 18 – 22 % whereas in Nuryal–2 it is bit low (15–18 %) at the same straitigraphic intervals. The reason of lower porosity values in Nuryal–2 is greater depth, more compaction and a relatively poor development of fractures.

DISCUSSION

The estimation of petrophysical parameters in reservoir rocks is fundamental for reservoir estimation and hydrocarbon production. Wireline logs are generally excellent tool to measure petrophysical properties of porous rocks. However, in complex tectonic framework like in Kohat-Potwar basin, it is difficult to infer petrophysical parameters with high accuracy from wireline logs only. Thus the prediction of porosity and mineralogy may be complicated and is best accomplished by using core data and complete log sets. A workflow has been developed and presented to find out correct porosity in two wells of the Potwar sub-basin. All available electrical logs including gamma ray, resistivity, neutron, density, and sonic of Injra–1 and Nuryal–2 wells in the study are examined to mark various lithological boundaries and payable zones. The clastic "Datta Formation" of the Jurassic is marked as reservoir rock in both wells Injra–1 and Nuryal–2 at a depth of 4595 m and 4720 m respectively. The upper contact of the Datta formation in Nuryal–2 is with the Lockhart limestone of the Paleocene, while in Injra–1 it is with the Hangu Formation of the Paleocene. There is an unconformity between the Datta and the Lockhart, and between the Datta and the Hangu. Generally older rocks have lower values of porosity due to compaction and overburden than younger. However, the porosity values derived from porosity logs indicate high values in older strata (Chorgali formation, Sakessar limestone and Datta Formation) as compared to that of younger formations (Chinji, Kamlial and Muree). The average porosity values in these formations are given in Table 3. This trend indicates the presence of some fractured lithology. Further, the core analysis also confirmed the presence of fractures in the Datta Formation.

Grain size and mineralogy of reservoir sediments is of great importance for the accumulation and flow of hydrocarbon. The core analysis and logs response reveal that the Datta Formation is mainly sandstone with intercalated shale. The sandstone is typically fine to coarse grained with rounded to sub-rounded quartz grains about 60 – 70 % by volume imbedded in a dense matrix composed of clay and mica minerals. The sandstones exhibit a relatively uniform framework-grain composition with only minor variations within and between the wells.

Density and porosity of the Datta sandstone is derived from logs and compared with core. The density values of Datta Formation estimated from logs and core plugs are

Table 3. Average porosity values of older and younger formations encountered in Injra–1 and Nuryal–2 wells of Western Potwar sub-basin.

Formation	Age	Average porosity
Chinji Formation	Late Miocene	15 – 17 %
Kamlial Formation	Middle to Late Miocene	12 – 15 %
Murree Formation	Early Miocene	11 – 14 %
Chorgali Formation	Early Eocene	12 – 15 %
Sakessar Limestone	Early Eocene	06 – 10 %
Datta Sandstone	Early Jurassic	18 – 22 %

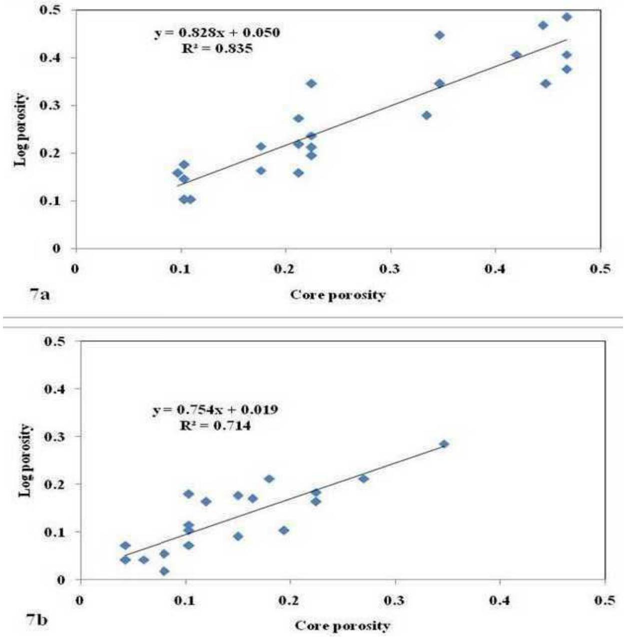

Fig.7. Crossplot of core plug porosity vs. log porosity for the Datta formation interval encountered in Injra–1 **(a)** and in Nuryal–2 **(b)** wells.

significantly close to each other in both wells. Similarly, the porosity from log is very close to porosity from core data. The log porosity and the core analysis porosity at the same stratigraphic intervals encountered in both wells are cross-plotted in Figs.7a and b. Approximately linear relationship exists between the two porosities. The value of regression coefficient R^2 is 0.835 in Injra-1 and 0.714 in Nuryal-2 respectively. The porosity values in Nuryal–2 are lower than the porosity values in Injra–1 at the same stratigraphic interval. The higher porosity values at Injra-1 represent secondary porosity which may be due to dissolution of authigenic mineral cements and to some extent detrital framework grains in addition to fractures.

These secondary porosities are due to the presence of fractures and moulds whereas these fractures are absent (or of low concentration) in Nuryal–2. Therefore, the post-depositional alteration in sandstones includes mechanical and chemical compaction, diagenetic cementation, mineral dissolution and structural deformation and may be the possible reasons of the development of fractures in the sandstone. Textural features indicate various degrees of mechanical and chemical compaction, depending on the extent to which the rocks have been buried. Datta sandstone is thermally mature rock and preserved porosity records extent to which diagenesis had modified the sandstone before the emplacement of oil from shale sources. The other reason of relatively low porosity values in Nuryal–2 is the burial depth and high compaction (Datta sandstone is encountered in Nuryal–2 at a depth of 4700 m). The overall porosity of the Datta sandstone in Nuryal–2 is 20 – 30 % lower than in Injra–1. The resistivity log shows relatively higher resistivities opposite the sandstone intervals in both wells, especially in Nuryal-2 where low porosity values are observed. However, in Injra-1 the resistivity values are much lower opposite to those intervals where high porosity exists.

CONCLUSIONS

This paper presents an integration technique from well log data to core data for the estimation of porosity of Jurassic reservoir in the Potwar sub-basin of Pakistan. The area surrounded by studied wells contains large volumes of sandstone reservoirs, displaying wide range of porosity and permeability characteristics. Based on known hydrocarbon source rocks, observed reservoir parameters, and log-indicated hydrocarbon shows, there appears to be considerable potential for the discovery of high productive of oil and gas zones in the Datta Formation in the study area.

The comparison between the porosity calculated from the porosity logs (density, sonic, neutron) and that measured from cores in laboratory is done by comparing average values of porosity over representative zones. Quantitative comparison of log porosity values and core plugged porosity values show very good to excellent agreement in all the stratigraphic intervals of the Datta Formation encountered in Injra–1 and Nuryal–2 wells. However, in Injra–1, the sandstone of Datta Formation has much higher values of porosity upto 0.49, which is an indication of presence of secondary porosity and fractures or vugs. The distribution and formation of fractures in the sandstone of the Datta Formation can be linked to the level of thermal maturity. Further detailed investigations are required to understand the causes of fractures in the sandstone.

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