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A geological study of reservoir formations and exploratory well depths statistical analysis in Sindh Province, Southern Lower Indus Basin, Pakistan

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Abstract

Pakistan being a developing country is facing significant challenges of energy crises due to a deficit of hydrocarbons. So, it is essential to explore and develop new oil and gas fields with increasing drilling rate to meet energy requirements. The study area administratively lies in Sindh Province of Pakistan, basin wise in the Southern Lower Indus Basin of Pakistan and petroleum concession zone III. The software tools used are the IHS Kingdom and IBM SPSS Statistics 20. A statistical approach like central tendency and dispersion are applied on reservoir formations data, which showed that Chiltan Formation of Jurassic age had an average depth of 3578m in which 38 wells have been drilled, which is 4% of the total well drilled in the area. Cretaceous Sembar, Lower Goru (L.G) and Pab formations having average depths of 3542m, 2359m, and 2254m respectively, which contribute a total of 737 wells with the highest contribution to total wells drilled in the study area. Paleocene age is not well developed in the study area, Ranikot Formation with an average depth 2082m and has a contribution of 18 (2%) wells only. Eocene age Sui Main Limestone (SML) and Habib Rahi Limestone (HRL) have an average depth of 1496m and 812m respectively, and a total of 158 wells has been drilled into these formations, which are 15% of the total wells drilled. The study showed that exploration and production (E&P) companies must target L.G, SML, and HRL due to low well density in these formations are low, as compared with world standards.

Keywords: Formation; Lower Goru; statistical analysis; Southern Lower Indus Basin; well depth.

1. Introduction

Pakistan petroliferous basins have vast areas that remain unexplored. Independent international studies indicate that it has much more hydrocarbon potential than these proven reserves (MPNR, 2013). The primary purpose of this study is the geological study of reservoir formations and statistical analyzes of the wells drilled in these formations for exploration and development in the study area. Pakistan is facing significant challenges of energy crises due to a deficit of hydrocarbons. So, it is essential to know about the hydrocarbon potential of the reservoir formations as well as to explore and develop new oil and gas fields by increasing the drilling rate to meet energy requirements of the country.

While 35-40% of the import bill of Pakistan is of hydrocarbons in the form of oil, gas and coal imports (Survey, 2014), these reasons strongly suggest that there is a need for exploration and production of hydrocarbon resources in Pakistan. It will help in filling the electricity deficit, while at the same time hydrocarbons will be supplied for industry and household usage. Keeping the scenario at hand, Southern Lower Indus Basin of Pakistan is being observed and analyzed. Southern Lower Indus Basin of Pakistan, situated in Sindh Province, is considered as a sedimentary basin with immense hydrocarbon potential (Quadri & Shuaib, 1986).

The success rate of the well is 1:3.3, which is much higher than the total success rate anywhere else in the whole world, which is 1:10. According to Ministry of Petroleum and Natural Resources, Government of Pakistan, the drilling density is 2.44 wells per 1,000 Km^2 in all basins in Pakistan quite less than average world rate of 10 wells per 1,000 Km^2 (Ziad, 2012; MPNR, 2013). On the other hand, cost of drilling is relatively lower than in other parts of the Indus Basin, and the region possesses conventional reservoirs. Despite this much of potential and ease to explore and produce, there has been not much investment in the area (GOP, 2012).

In this paper, we have analyzed and discussed the geological aspects of the formations in the study area, and statistical analysis is presented for drilled wells data, with evidence, which has been analyzed and explained. This study will explain the profitability of the exploration and production (E&P) companies to invest in the region. This study will also help to increase awareness among the domestic and international investors about the hydrocarbon potential of Southern Lower Indus Basin of Pakistan, while exploitation and production of hydrocarbons will result in recovery from the energy crisis and an economic boost to Pakistan in the long run.

2. Basins of Pakistan

Pakistan has a total sedimentary basin area of almost 827,000 Km^2, with only 10-20% explored area (Jamil *et al*., 2012; Quadri & Shuaib, 1986; Raza, 1985). The area is divided into three sedimentary basins; Indus Basin, Baluchistan Basin, and Pishin Basin. Indus Basin is further divided into Upper, Northern and Southern basins. The resource estimation of each basin is given in Table 1. The basin classification of Pakistan is illustrated in Figure 1 (Hanif *et al*., 2014).

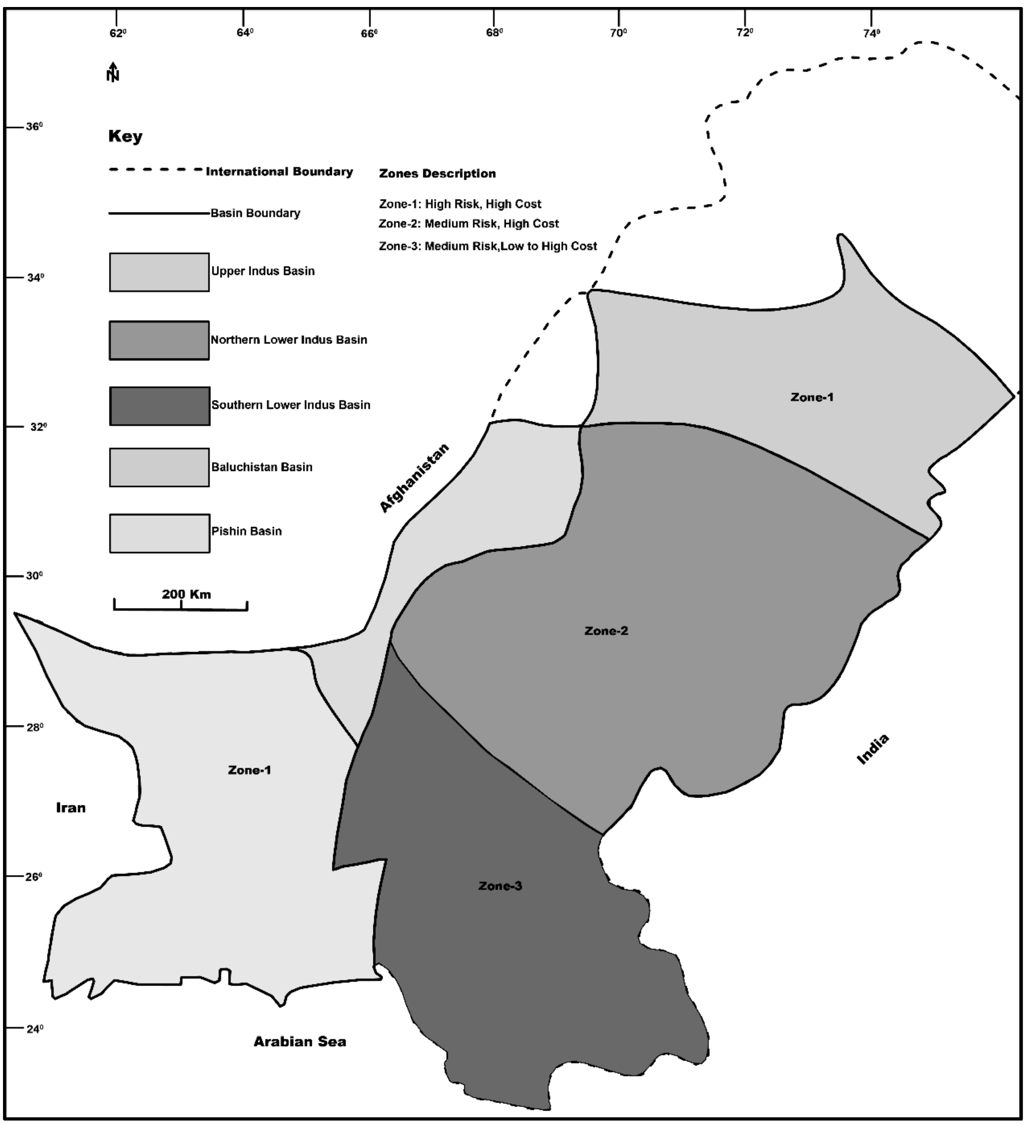

Fig. 1. Basins of Pakistan with marked exploration zones of the study area (after GOP, 2012; Hanif *et al*., 2014).

The Southern Lower Indus Basin is geographically located in Sindh Province (SE) of Pakistan. It is extended approximately between 24°-28° N and 66° E to the south boundary of Pakistan. In a broader view, it is north-south trending sedimentary basin, which has thick tertiary sequence underlined by older sequences (Permian sequence) and overlaid by Quaternary sediments. Its width is almost 250 Km and was relatively stable during the Mesozoic period. Tectonically it has been divided into Kirthar Fold Belt, Foredeeps, Zone of Upward, Zone of Downwarp and Plateform Slop. Structural highs in the basin are in the form of a finger-like extension of Indo-Pakistan Shield (Gansser, 1964; Kazmi & Jan 1997; GSP, 2012).

Table 1. Resource estimation of each basin in Pakistan (Ahmed, 1998; Raza & Ahmed, 1990).

Name of Basin	Indus (Onshore)			Offshore	Baluchistan	Pishin
	Upper	Northern	Southern			
Volume of Sediments (cubic mile)	70000	240000	224000	185000	241000	400000
Recovery Factor (barrels per cubic mile)	60000	60000	75000	90000	90000	20000
Ultimate Recovery (million barrel oil and equivalent gas) per cubic mile	4200	14400	15800	16650	21690	800
Percentage of gas	10	80	70	60	60	60
Oil (million barrels)	3780	2880	4740	6660	8676	320
Gas (trillion cubic feet)	7.5	69.12	64.75	60	78	2.88

3. Dataset

Data about 1027 drilled wells, which includes Kelly bushing (KB), drilled formations depths and year of drilling, published in annual energy year book of Pakistan, 2012 is used in this research paper. It includes data from the year 1948 upto 2012.

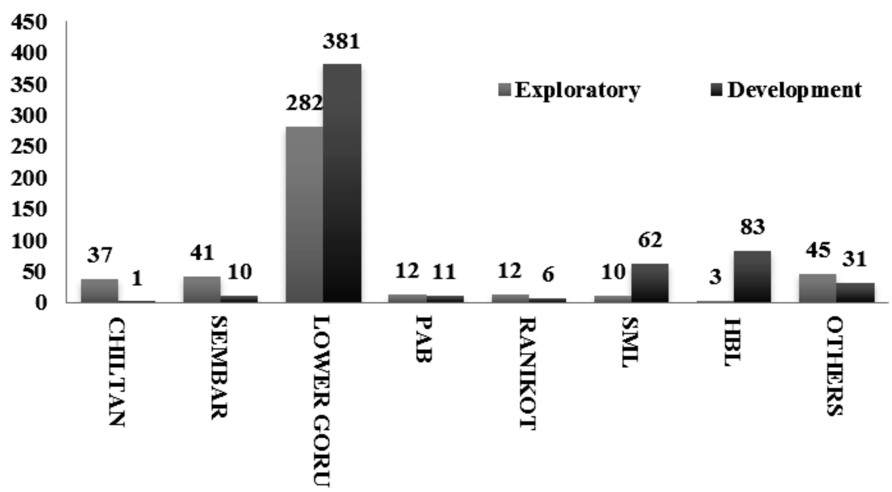

Fig. 2. Bar chart display showing exploratory and developments wells numbers in each reservoir formations in which Formation names are plotted on x-axis and number of drilled wells are plotted on y-axis

4. Methodology

The resource estimation of each basin, in Pakistan, by Ahmed (1998) and Raza & Ahmed (1990) has been followed in the study. After an extensive study of geological characteristics of all the formations, source rocks (Table 2) and reservoir rocks (Table 3) table is developed. Source rocks table in the study area is prepared by using works of Jamil *et al*. (2012), Shuaib (1982) and Quadri & Shuaib (1986). The source rocks are classified as fair, moderate, good, and good to very good by their characteristics adopted by the classification system of Peters & Cassa (1994). Reservoir rocks table developed by Kadri (1995), Moghal *et al*. (2012) and Mahmud & Sheikh (2012) are classified by their reservoir quality from good to excellent. Subsurface structural features are studied by using seismic, well logs and stratigraphy data of the study area. Formation horizons are marked on the basis of formations tops and stratigraphic chart. IHS Kingdom software is utilized for structural interpretation.

Drilled well data is first converted into mean sea level (MSL) and then to international units of measurement (m). The central tendency (mean, median, and mode) and dispersion (minimum, maximum, and range) are applied to reservoir formations data. The data is arranged according to ascending order and then applied the technique of histogram with a normal curve on it. The software tool applied is IBM SPSS Statistics 20.

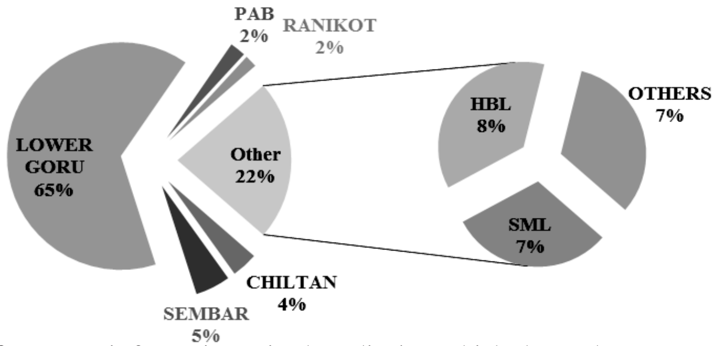

Fig. 3. Reservoir formations pie chart display, which shows the percentage of wells drilled in each formation of the study area.

After reviewing all the data sets, which included seismic, geology and wells, we chose seven reservoir formations on the basis of drilled wells numbers. The contribution percentage with respect to each formation in Sindh Province is given in the reservoir formations pie chart as shown in Figure 3. The formations, which have greater than 2% of total wells drilled in the basin are chosen. On the basis of depth, we categorize reservoir formations into three types, which are deep, deep to shallow and shallow.

5. Petroleum play in the study area

Petroleum play system of Sindh Province along with each formation is given with generalized stratigraphic column of the study area in Figure 4.

5.1. Source rock

Wulgai Formation of the Triassic age (lithology shale/ limestone), which has a depositional environment in outer shelf has the potential for source, good to very good detail is given in Table 2, based upon the total organic carbon content. The primary source rock in the Lower Indus Basin is Sembar Formation of Cretaceous-age is present almost in the entire Indus Basin.

Goru Formation has a significant role in Pakistan from hydrocarbon point of view; it has an amazing role, as it acts as a source, a reservoir, and a seal rock. Goru Formation has two part Upper Goru and Lower Goru; Upper Goru acts as seal rock, and Lower Goru has an excellent reservoir and moderate source rock. Talhar Shale member of Lower Goru has a considerable amount of unconventional resources. Mughalkot, Ranikot, and Laki formations have good source potential the detail is given in Table 2.

5.2. Reservoir rock

Jurassic age Chiltan Formation acts as a fractured reservoir in the study area. Lower Goru acts as very good to excellent reservoir; the primary composition is sandstone and mudstone. The sand facies are dominant in the southern part of the basin (Quadri & Shuaib, 1986). Porosity and permeability data results indicate that Lower Goru Formation has very good to excellent reservoir quality (Khattak *et al.*, 1999). Pab and Ranikot formations are considered to be good reservoirs. The Neogene Nari and Gaj formations have good reservoir quality; but still, no potential exploration of these formations has been processed. The detail of each reservoir formation in the study area is given in Table 3 on the basis of reservoir formations porosity and permeability values.

Table 2. Source rocks in Southern Lower Indus Basin (developed after Jamil *et al.*, 2012; Peters & Cassa, 1994; Shuaib, 1982; Quadri & Shuaib, 1986)

Age	Formation	Depositional Environment	Rock type	Remarks
	Southern Lower Indus Basin			
Eocene	Laki	Basin	Shale	Good
Paleocene	Ranikot	Outer Shelf	Shale &Packstone	Good
Cretaceous	Mughalkot	Shelf	Shale &Packstone	Good
	Parh	Shelf	Shale &Packstone	Fair
	Goru	Slope turbidites	Wackestone&Mudstone	Moderate
	Sembar	Basinal Mud	Mudstone	Main Source
Jurassic	Chiltan	Outer Shelf	Limestone	Fair
Triassic	Wulgai	Outer Shelf	Shale/Limestone	Good to Very Good

Table 3. Reservoir rocks in Southern Lower Indus Basin (developed after Kadri, 1995; Moghal *et al*., 2012; Mahmud & Sheikh, 2012).

Age	Formation	Potential Reservoir Porosity	Rock type	Remarks
	Southern Lower Indus Basin			
Miocene	Gaj	Intergranular	Sandstone	Good
Oligocene	Nari	Intergranular	Sandstone	Good
Eocene	Laki	Fracture	Limestone	Good
	HRL	Fracture	Limestone	Good
	SML	Fracture	Limestone	Very Good
Paleocene	Ranikot	Fracture	Limestone	Good
	Ranikot	Intergranular	Sandstone	Good
Cretaceous	Pab	Intergranular	Sandstone	Good
	Lower Goru	Intergranular	Sandstone &Mudstone	Very Good to Excellent
Jurassic	Chiltan	Fracture	Limestone	Good

5.3. Seal rocks

Sembar Formation acts as seal rock for Chiltan Formation. Upper Goru Formation is mainly composed of shale and marl; that is why it can act as seal rock. Hence it is serving as an excellent cap rock for underlying Lower Goru sand reservoir (Raza *et al*., 1990). Ranikot and Ghazij formations also act as a seal as shown in Figure 4.

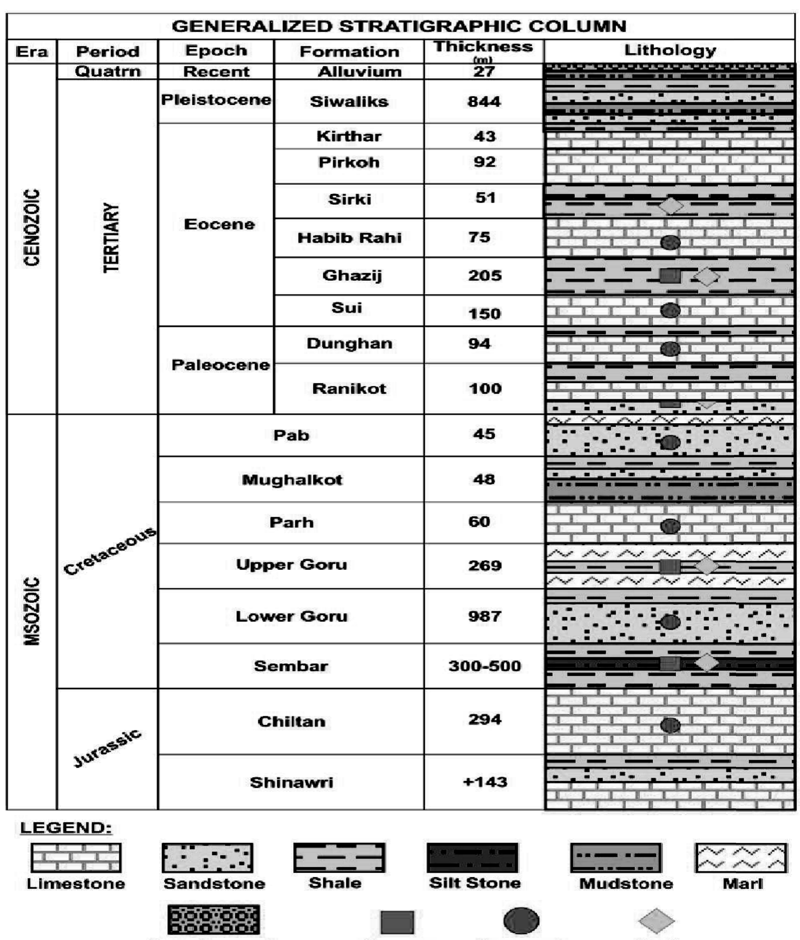

Fig. 4. A generalized stratigraphic column of the study area with an average thickness of reservoir formations, which are further divided into units by lithology, which is mention in legend. In Figure Sui stands for SML (GOP, 2012).

5.4. Trap mechanism

The study area lies on the extensional regime and hence regional scale normal faults are observed on seismic section. Horst and graben structural are observed, which are favorable for the accumulation of hydrocarbons. The local scale normal fault is also observed (Naeem *et al*., 2016; Quadri & Shuaib, 1986). Figure 6 shows Pab, Ranikot, SML and HRL on a seismic section having normal faults associated structures. Pab and SML, also have a stratigraphic trap.

Lower Goru has many structural traps due to the presence of a high number of horst and graben structure, making it good reservoir rock in the area.

6. Results and discussions

The exploratory well location for drilling starts from known areas with their comprehensive study (seismic, geological setting, wells logs, etc.) and reservoir characteristics are vital for searching and discovering new drilling targets for oil and gas E&P companies to invest in these areas (Li & Guo, 2007). To meet the global need for oil and gas, it is essential to increase drilling rate. In this study, we suggest that to meet the energy demands of Pakistan, we may increase the drilling rate in Southern Lower Indus Basin of Pakistan.

In this manuscript, we have only discussed well drilling density of Southern Lower Indus Basin of Pakistan. The area understudy is 1,40,914 Km^2 and has 1027 drilled

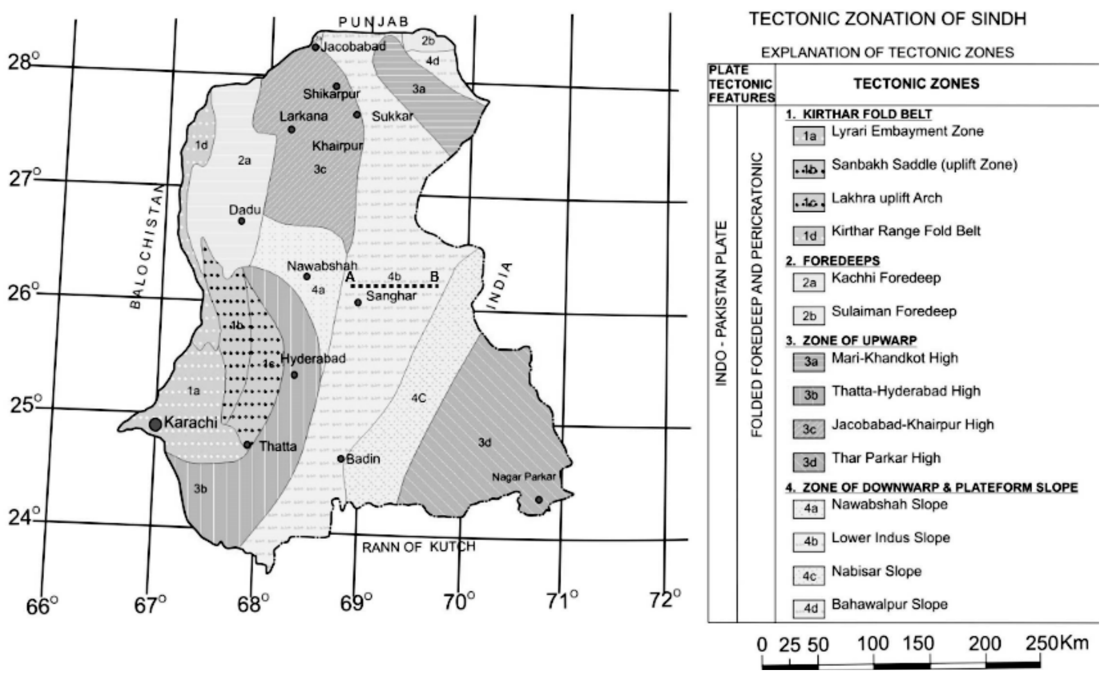

Fig. 5. Tectonics zone map of study area, maximum oil and gas discoveries lie in 4b Lower Indus Slop as mentioned in Figure (GSP, 2012) with AB cross section.

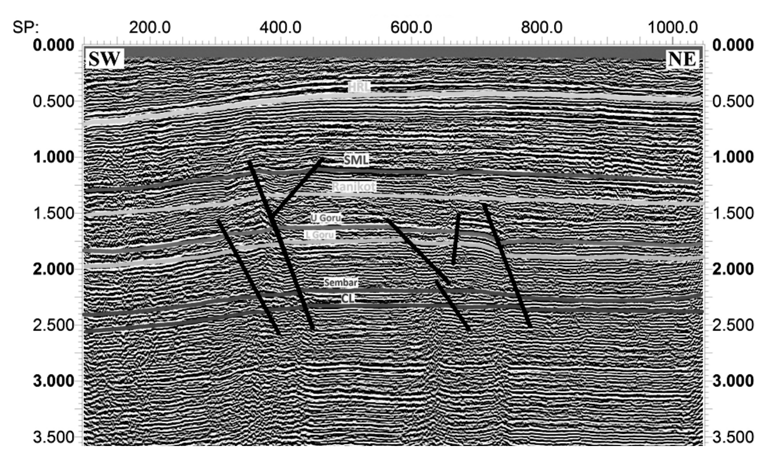

Fig. 6. Cross section AB, which shows horizons subsurface structural features of reservoir formations in Figure Cl stands for Chiltan Formation in x-axis plots shot point (SP) on the y-axis plot time in milisec.

wells. The drilling density of exploratory wells is 3.14 wells per 1,000 square kilometers, which indicates that drilling density is low as compared to world standards. This motivates the E&P companies to invest more to explore the hidden potential of Southern Lower Indus Basin, Pakistan.

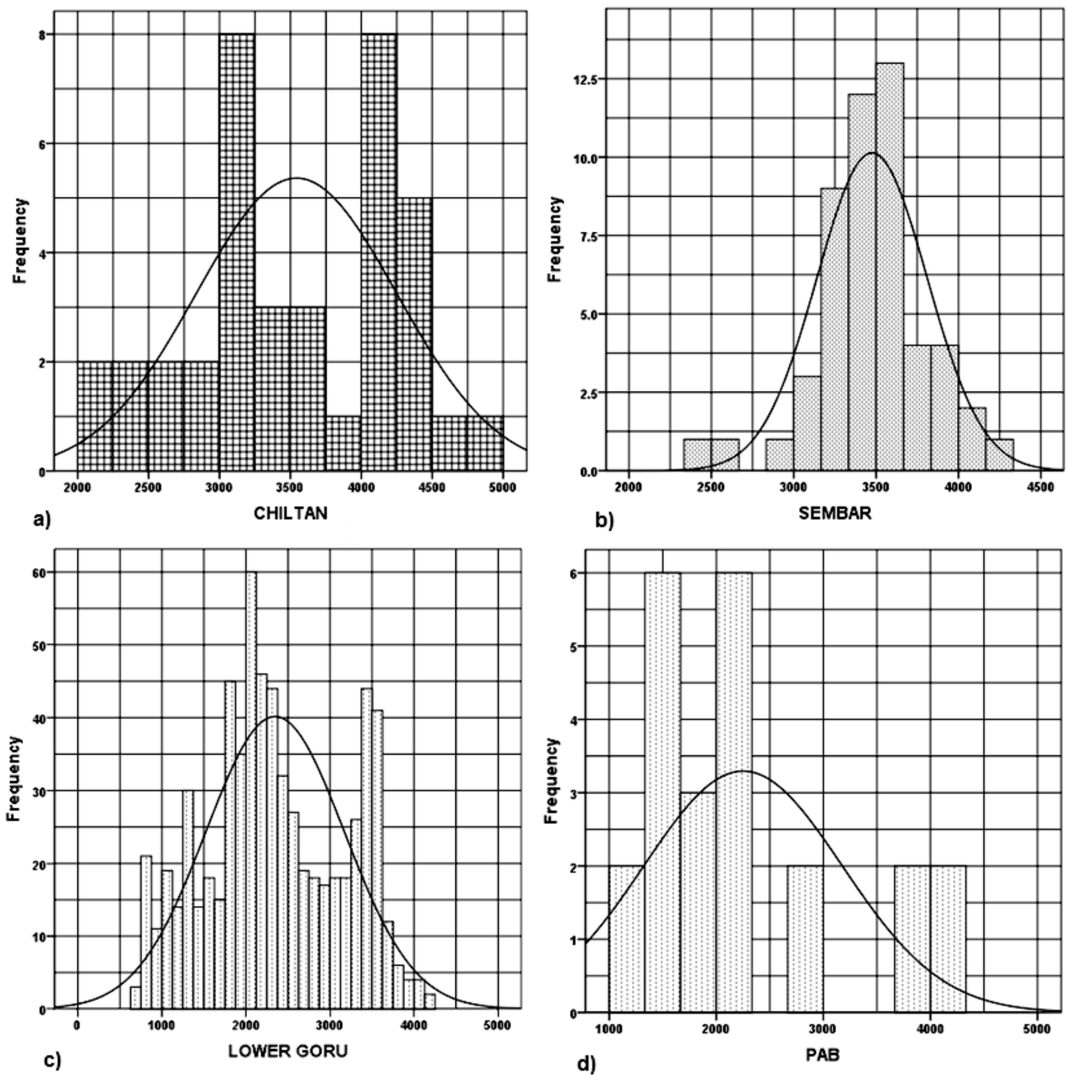

Fig. 7. In histogram plots wells drilled depth (m) is plotted on the x-axis, and their frequency is plotted on the y-axis a) Chiltan Formation b) Sembar Formation c) Lower Goru Formation d) Pab Formation.

For Southern Lower Indus Basin, Jurassic is mostly nonclastic and Chiltan Formation is deep (Kadri, 1995). Chiltan Formation histogram and statistical analysis of 38 wells depth results indicate that maximum cluster of data lies in ranges of 3000 m to 4200 m depth as shown in Figure 7 (a).

The average value of depth is 3543m, and its mode value is 4065m. It means that Chiltan Formation reservoir is deep. Negatively skewed data shows that most of the wells are deeper and have greater depth than average. It is suggested to E&P companies that this formation is deeper and involves massive investment for exploration.

The Cretaceous system is prominent in Pakistan. It covers almost 52% sedimentary area, and its large part lies in Southern Lower Indus Basin (Kadri, 1995). Depth results for the primary reservoir formations are Sembar, Lower Goru, and Pab. For Sembar Formation histogram and statistical analysis of 51 wells indicate that maximum cluster of data lies at ranges of 3200m to 3800m depth and frequency of data in this range is 36 as shown in Figure 7 (b). The average value of depth is 3542m, and its mode value is very close to 3510m. Negatively skewed data shows that most of the wells are deeper and have greater depth than average. It means that Sembar Formation reservoir is deep.

Depth results of Lower Goru (L.G) histogram and statistical analysis of 663 wells indicate that maximum cluster of data lies at ranges of 1700m to 2400m depth as shown in Figure 7 (c). The average value of depth is 2359m, which is very close to the mode value (2134m). It means that L.G reservoir is deep to shallow. It is suggested to E&P companies that in this formation success rate is high and the terrain of the study area is plain and hence it is quite easy to explore this formation.

Depth results of Pab Formation histogram and statistical analysis of 23 wells indicate that maximum cluster of data lies in ranges between 1260m to 2300m depth, as shown in Figure 7 (d). The average value of depth is 2253m, and its mode value is 1600m. It means that the Pab Formation reservoir is deep to shallow.

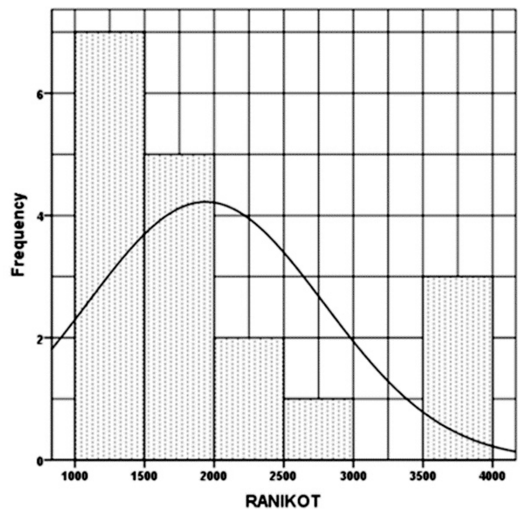

Fig. 8. Ranikot Formation histogram plot display wells drilled depth (m) is plotted on the x-axis, and their frequency is plotted on the y-axis.

Depth results of Ranikot Formation histogram and statistical analysis of 18 wells indicate that maximum cluster of data lies between ranges of 1300m to 2300m depth as shown in Figure 8. The average value of depth is 2081m, and its mode value is 1302m. It means that Ranikot Formation reservoir is deep to shallow. It is suggested to E&P companies that this formation is deep to shallow. Exploration of this formation involves a massive investment because it is not well developed in the study area.

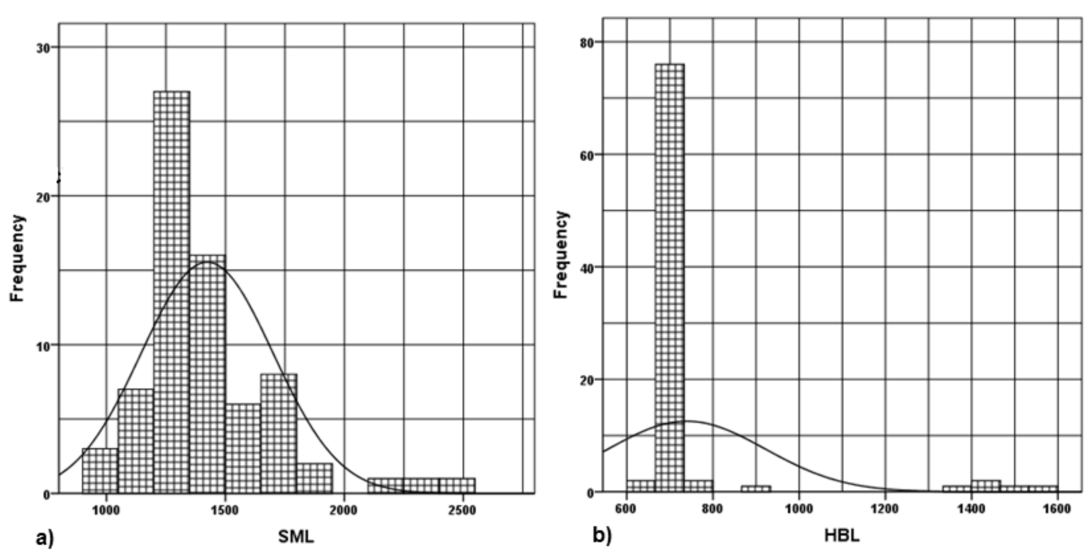

Fig. 9. In histogram plot, wells drilled depth (m) is plotted on the x-axis, and their frequency is plotted on the y-axis a) Sui Main Limestone Formation b) Habib Rahi Limestone Formation.

For Sui Main Limestone (SML) histogram and statistical analysis of 72 wells, depth results indicate that maximum cluster of data lies between ranges of 1300m to 1500m depth as shown in Figure 9 (a). The average value of depth is 1496m, and its mode value is 1104m. It means that SML Formation reservoir is shallow.

For Habib Rahi Limestone (HRL) histogram and statistical analysis of 86 wells, depth results indicate that maximum cluster of data lies between ranges of 740m to 800m depth as shown in Figure 9 (b). The average value of depth is 812m, and its mode value is 757m. It means that HRL Formation reservoir depth is most shallow. It is suggested to E&P companies to explore SML and HRL formations due to their shallow depth as they are quite easy to explore and involve low investment.

7. Conclusions

The reservoir formations can be classified into three categories on the basis of their depth, namely deep (Chiltan, Sembar), deep to shallow (L.G, Pab, and Ranikot) and shallow (SML, HRL) reservoirs. The Cretaceous-age contribution is most significant in the study area, which is almost 72% of the total drilled wells. The main reservoir is Lower Goru (L.G) Formation, having 65% wells drilled from the total. It is convenient to explore it, because of its higher success rate as well as due to its deep to a shallow depth. Lower Goru has good structural traps due to the presence of horst and graben geometry that is identified by seismic structural interpretation. The shallow reservoirs such as SML & HRL of Eocene age, mainly composed up of limestone have good potential and need low investment. In a nutshell, we can conclude that E&P companies must invest more in L.G, SML and HRL formations and their associated fields as the density of wells in these formations is low, as compared with global world standards.

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دراسة جيولوجية عن تكوين الخزانات الجوفية والأعماق المصاحبة للآبار تحليل إحصائي في محافظة سينده، لحوض أندس الجنوبي المنخفض – باكستان

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الملخص

تواجه باكستان، كدولة نامية، تحديات رئيسية في مجال الطاقة بسبب النقص في الكربونات المائية. لذلك، فإنه من الضروري استكشاف وتطوير حقول جديدة للغاز والنفط مع زيادة معدل الحفر للوصول إلى متطلبات الطاقة. موقع هذه الدراسة يقع في محافظة سنده في باكستان في المنخفض الجنوبي السفلي لباكستان ومنطقة III لامتياز البترول. برامج الكمبيوتر المستخدمة هي HIS Kingdom وبرنامج IBM SPSS Statistics 20. تم استخدام طرق إحصائية مثل مقاييس النزعة المركزية والتشتت على بيانات تكوين الخزانات والتي أوضحت أن تكوينات شيلتان من العصر الجوراسيك لها متوسط عمق 3578 متر، وتم حفر 38 بئر والذي يمثل %4 لإجمالي عدد الآبار المحفورة في منطقة الدراسة. تكوينات كرتاسوس سمبارولوار جورو (.L.G) وباب لها على الترتيب متوسط عمق 3542 متر و 2359 متر و 2254 متر وتساهم بإجمالي 737 بئر وهي أعلى نسبة للآبار المحفورة في منطقة الدراسة. العصر باليوسين لم يتم تصويره في منطقة الدراسة. تكوينات رانيكوت لها متوسط عمق 2082 متر ولها 18 بئر (%2) فقط العصر الأوسيني سوي ملن للحجر الجيري (SML) وحبيب راهي للحجر الجيري (HRL) لهما على الترتيب متوسط عمق 1496 متر و 812 متر وإجمالي 158 بئر وتمثل %15 لإجمالي الآبار المحفورة. تشير الدراسة أنه يجب أن تستهدف شركات الإنتاج والاستكشاف المناطق HGL، SML، .L.G لإنخفاض كثافة الآبار في هذه المناطق بالمقارنة بالمعايير الدولية.