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Sedimentology and Reservoir characterization of the Pirkoh Formation in well-1 Guddu E.L Sindh, Pakistan

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Abstract

The sedimentology and reservoir characteristics of the Pirkoh Formation in the middle Eocene have been investigated in well -1 of Guddu E.L. This formation, consisting entirely of limestone, was the main target reservoir in this well, with a thickness of 102m. Two cores were obtained from depths of 590-599m and 625-634m and were studied in this analysis. The sedimentological investigation revealed that the Pirkoh Formation is primarily composed of Wackestone-Packstone microfacies with abundant larger benthic foraminifera (LBF) assemblages, such as Discocyclina and Nummulite sp. The presence of these microfossils, along with bioclasts of the same type, suggests deposition under high-energy conditions in a middle ramp setting. The micrite groundmass and Discocylonoids Wackestone-Packstone microfacies further support this interpretation. The dominance of micrite as the major ground mass matrix indicates a relatively deep depositional environment, likely in middle ramp settings. The Pirkoh Formation has also undergone various diagenetic processes, including micritization, dolomitization, microfractures, stylolitization, dissolution, and cementation. These processes have resulted in vuggs and molds, which contribute to good reservoir quality in terms of porosity. The dissolution and replacement of original grains or shells also increase the porosity of the carbonate rocks. Stylolites and microfractures have been observed, further enhancing reservoir quality. The Core Measuring System (CMS) data confirms good porosity and permeability of core plugs, while the hydrocarbon saturation results from the Deen Stark apparatus are also within a good range. Overall, the Pirkoh Formation in well -1 of Guddu E.L. exhibits favorable reservoir characteristics and is a promising target for hydrocarbon exploration.

Introduction

Guddu Exploration Lease is located in district Ghotki of Sindh province (Fig-2). The sedimentological study of the Pirkoh Formation in Well #1 will provide essential information for the characterization and evaluation of the reservoir, and will aid in the successful exploration and development of the Guddu Exploration Lease. Well#1 is selected as case study for the Pirkoh Formation. This well shows a thickness of approximately 800 meters and is located in in Guddu E.L. on

Latitude: 28°- 03‘– 55” N

Longitude: 69°- 50‘– 09.7” E

Elevation: 78.50 m (AMSL).

Geologically, the project area lies in the northeastern part of Mari Bugti transverse uplift zone which forms a part of Suleiman foreland fold and thrust belt system along the northern and northwestern margin of the Indo-Pak Plate (Jadoon, I. A. K. bet al 1994). The project area includes many anticlinal features like Mari and Kund Kot anticlines which are well developed, preserved and expected to provide reasonable subsurface closures. The discovery of major gas fields such as Qadirpur and Kund Kot in the immediate southeast neighborhood shows the presence of a dynamic petroleum system in the area.

Seismic surveys (Jadoon, 1991 and Jadoon et al 1994) show up to 10 km of Permian-Recent sediments at the deformation front,

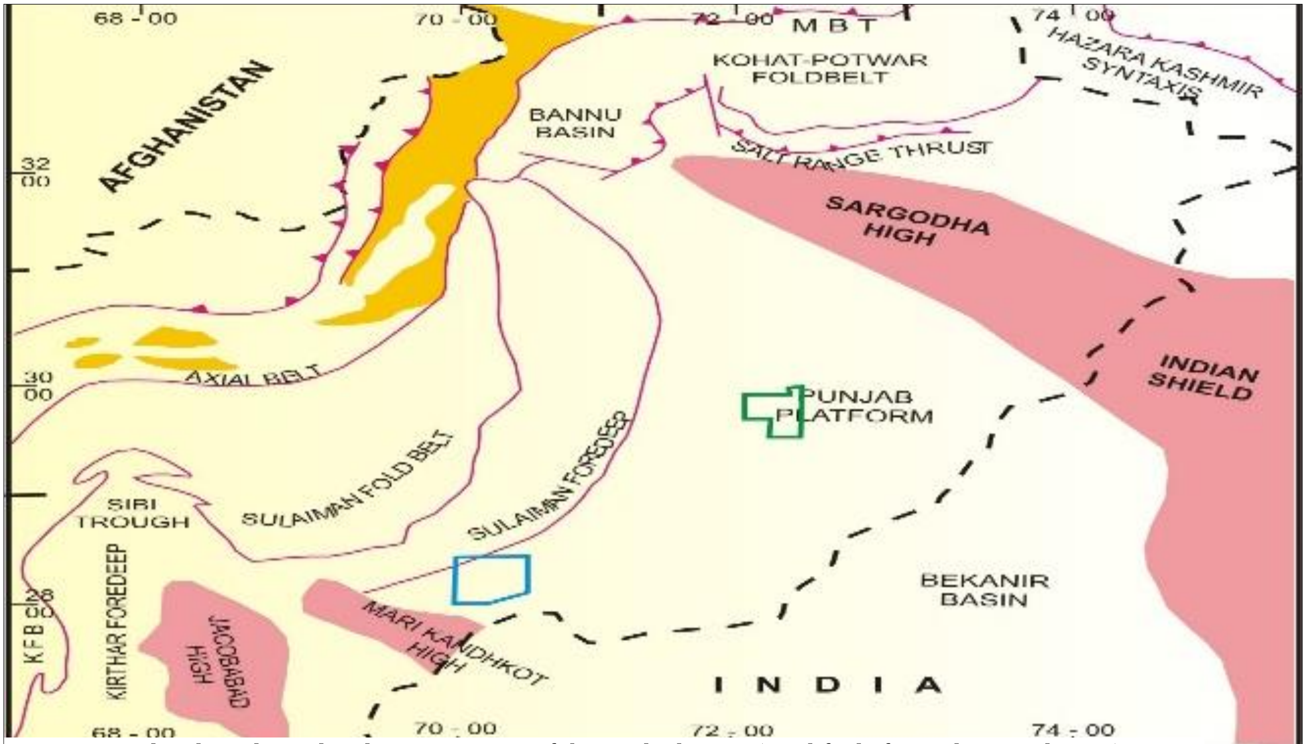

Fig 1: Generalized Geological and Tectonic Map of the Studied Area. (Modified after Jadoon et al 1994).

increasing to 20 km (tectonic thickening) at the suture zone. Gravimetric data (Jadoon and Khurshid, 1996) show that the Suleiman fold belt is underlain by 15 to 17 km of transitional crust of the Indian passive margin. Structural trends in the Suleiman Lobe are mainly E-W oriented folds and thrusts, whereas structural trends in the Suleiman and Kirthar Ranges are mainly N-S oriented folds and faults. A drastic change in structural style occurs across the eastern Suleiman Range to central part of the Suleiman Lobe owing to the corresponding oblique movement of the Indian plate along the former and transverse perpendicular transport direction in the latter. A left lateral strike slip fault makes the dividing line that separates the N-S to NNE-SSW aligned structures in the eastern Suleiman from the roughly E-W aligned structures in the Central Suleiman Lobe.

General Stratigraphy of Well-1.

The general stratigraphic succession in the Guddu E.L concession area comprised of Siwalik Group, Drazinda, Pirkoh, Sirki and Habib Rahi Limestone. The sandstone with conglomeratic beds of Siwalik group has been encountered in the well up to 550m depth. The sand is loose, multicolored, and fine to very coarse grained with conglomerates of pebbles and gravels size. The Drazinda Formation consist of marl of off-white dull white, pasty and amorphous nature with shale of olive green, light green, laminated and pyritic nature. The Pirkoh Formation at 590m is the primary objective reservoir in this well. This formation is undertaken for the said study and is the thickest formation in the drilled sequence with a thickness of 102m (Fig-3). It is mainly composed of limestone. Two cores have been retrieved from this formation

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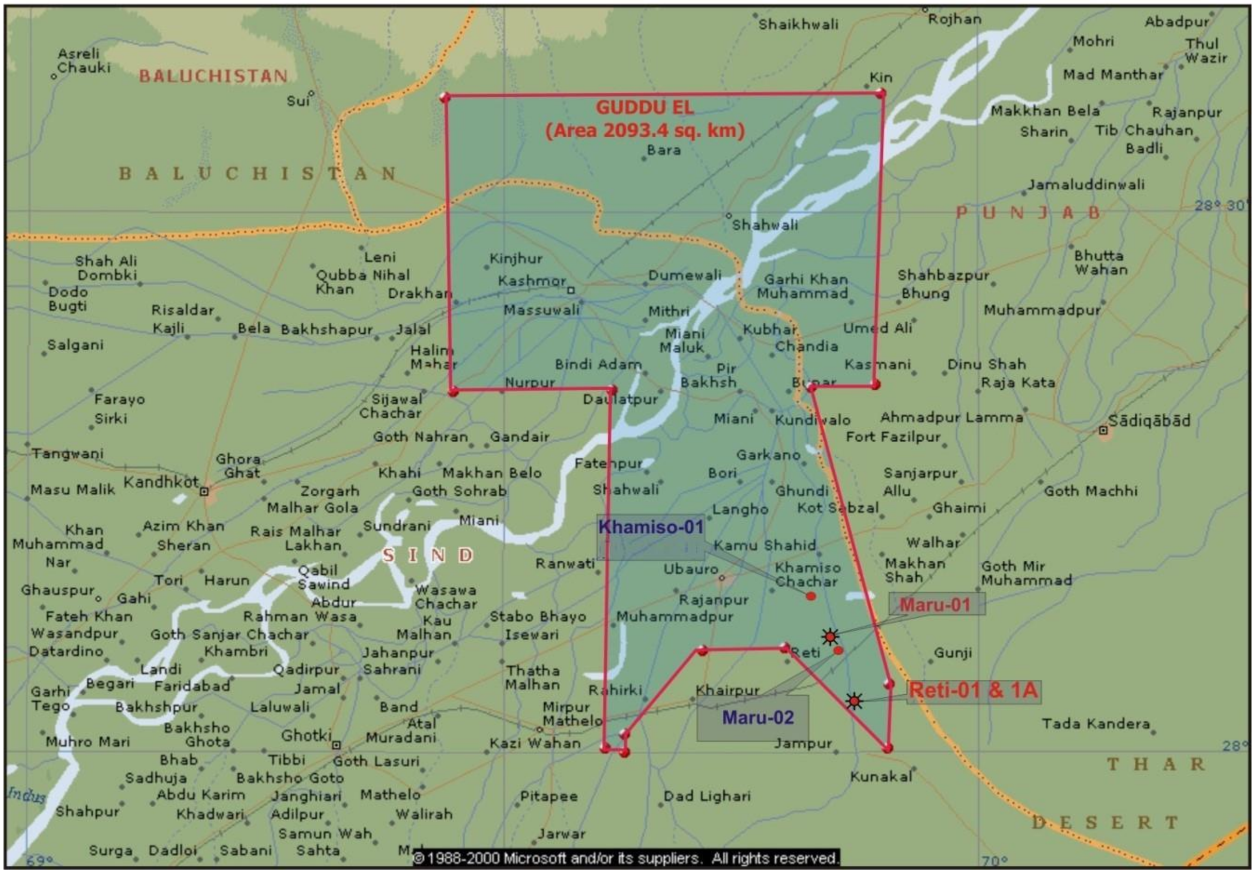

Fig 2 Location Map of Well-1 in Guddu E.L Ghotki, Sindh

(590-599m, 625-634m) and also incorporated in this study. The lower contact of Pirkoh Formation is with the Sirki Formation. The Sirki Formation is mainly claystone with shale. The Habib Rahi Limestone is last penetrated formation in this well up to target depth i.e. 800m. The limestone of this formation is dirty white to creamy, medium hard, microcrystalline and fossiliferous in nature.

Material and Methods

The study of the Pirkoh Formation in this well focused on analyzing two cores (590-599m, 625-634m) and well cutting samples to understand the presence of petroleum system. The cores were slabbed to study the sedimentology and reservoir properties, and photo-micrographs were taken for lithofacies analysis. Additionally, 10 thin sections were prepared for microfacies identification using a Trinocular/Petrographic zoom microscope.

The main objective of this study was to construct the litho and microfacies of the Pirkoh Formation in order to determine the depositional environment. The potential source rock of the formation was also analyzed using a TOC analyzer and Rock-Eval-6.

Another goal of the study was to delineate the reservoir characteristics of the Pirkoh Formation. This was done through plug analysis, which involved examining porosity, permeability, and grain density using an instrument called CMS-300. Additionally, the hydrocarbon saturation in the Pirkoh Formation was determined using the Deen Stark apparatus.

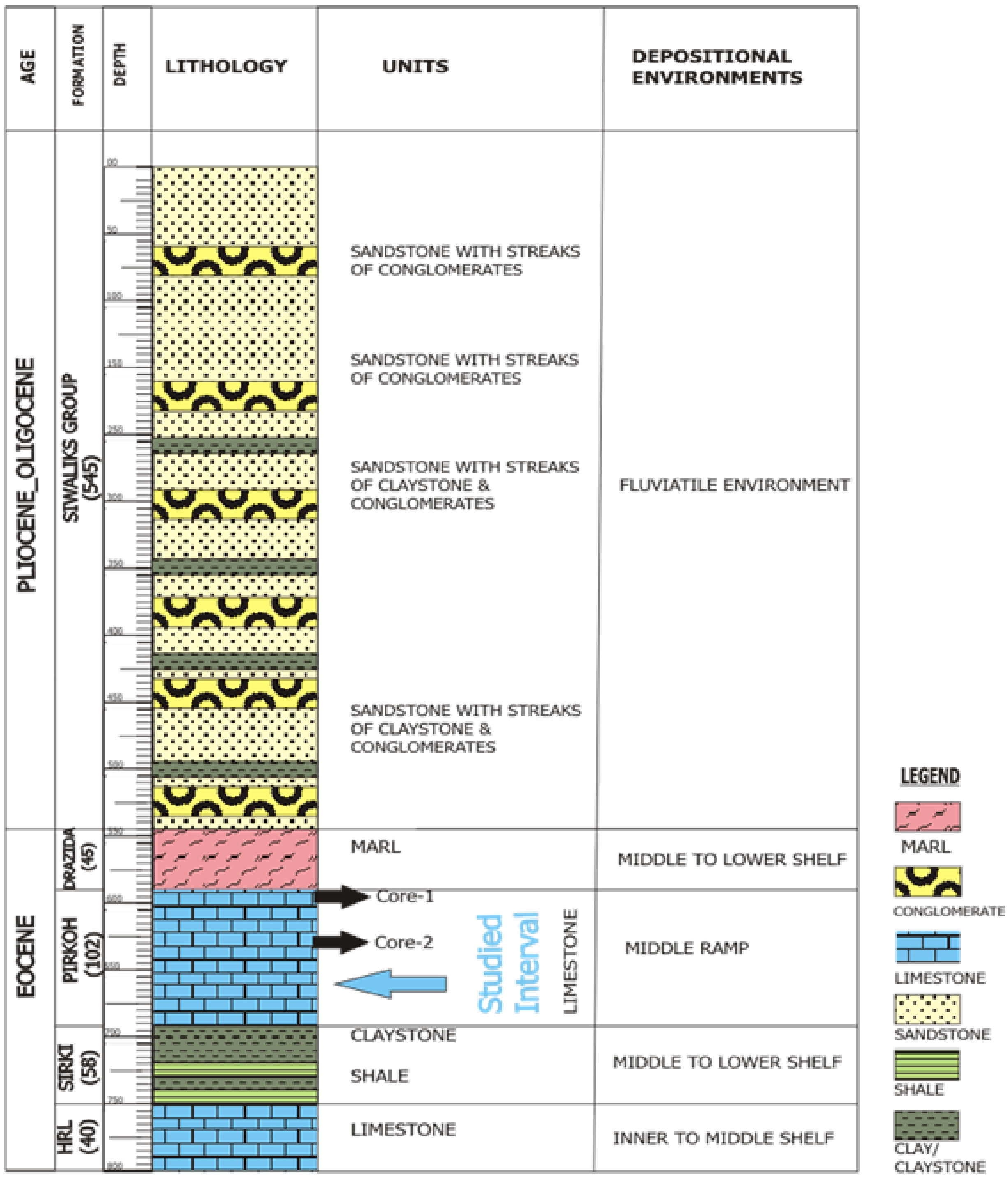

Fig 3 : Stratigraphic Column of Well #01 Guddu E.L

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Timing of Structuration and Migration

The tectonic, structural, and stratigraphic elements in the investigated area create favorable conditions for the formation and storage of hydrocarbons. However, the Suleiman sub-basin has primarily been known for its natural gas deposits, with no significant oil discoveries thus far. Structural deformation in the basin occurred in the Pliocene-Pleistocene period, resulting from the collision between the Eurasian and Indo-Pakistani plates. By this time, the main source rock horizons (Early Eocene) had already undergone hydrocarbon generation, primarily producing dry gas. In the Suleiman Fore deep, before the structural deformation took place, studies have shown that the majority of the generated hydrocarbons had already migrated out of the traps. Currently, the area falls within the dry gas zone, with the possibility of up-dip migration to the reservoirs of the Late to Early Eocene formations for gas accumulation. If there is still some potential in the early Eocene source rocks, the migration to younger horizons may occur through faults that traverse the non-porous thick carbonate section.

The Pirkoh Formation, which is of Eocene age, has not reached the necessary thermal maturity for oil generation during the Eocene period. It is anticipated that these rocks are still in the immature gas window and can supply the reservoirs in structural traps within the fold zone (as shown in Figures 4 & 5).

Thermal Maturation

The present day geothermal gradients for the parts of the Suleiman fold belt basin where data exist are generally above the global average. A zone with a gradient in excess of 40°C/km is found in the area. In the Mari gas field, the geothermal gradients range from 3 to 3.4" °C /100 m (M. A. Khan and Hilal A. Raza. 1986).

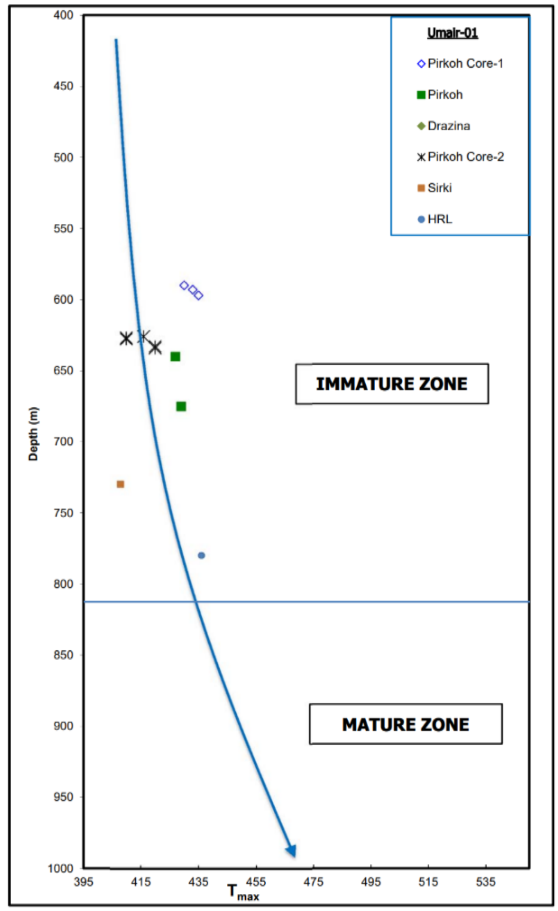

Fig 4 Thermal Maturity Trends in Well-1.

The thermal maturity of the Pirkoh Formation based upon our core data revealed that it has not attained proper maturity. TOC values are not good enough to act as a source rock and showing still in immature zone (Table-1 & 2 & Fig-4 & 5).

Microfacies Analysis

1) **Wackestone-Packestone Microfacie**

The petrographic data including the skeletal and non-skeletal grains is used to classify the carbonate of Pirkoh Formation using the scheme of Dunham classification (Dunham, 1962) and construct the microfacies.

Table 1 Geochemical data Core-1 of the Pirkoh Formation (590-599m)

Section 590-599m	**TOC wt%**	**S_1 mg/g**	**S_2 mg/g**	**T_{max} (°C)**	**GP kg/t**	**S_2/S_3**	**PI**	**HI**	**OI**	**Min C (%)**
Min Value	0.13	0.01	0.08	430	0.09	0.27	0.08	47	153	7.33
Max Value	0.21	0.02	0.24	435	0.26	0.46	0.18	114	252	11.57
Average	0.16	0.01	0.13	432	0.19	0.37	0.12	74	194	10.02
No of Samples	10	Three (03) Sample								
Conclusion	Poor to fair	Poor	Poor	immature	Poor	Type IV		Type III	Gas Source	Limstone.

Table 2 Geochemical data of Core-2 the Pirkoh Formation (625-634m)

Section 625-634m	**TOC wt%**	**S_1 mg/g**	**S_2 mg/g**	**T_{max} (°C)**	**GP kg/t**	**S_2/S_3**	**PI**	**HI**	**OI**	**Min C (%)**
Min Value	0.06	0.03	0.14	410	0.17	0.28	0.12	96	170	11.01
Max Value	0.33	0.57	0.88	420	1.45	1.13	0.39	268	486	12.52
Average	0.14	0.14	0.38	415	0.53	0.67	0.20	167	297	11.90
No of Samples	30	Five (05) Sample								
Conclusion	Poor to fair	Poor	Poor	immature	Poor to fair	Type IV		Type III	Gas Source	Limestone.

Petrographic Description

The dominant constituents of bioclastic wackestone-packestone microfacies are including LBF foraminifera (60%) matrix and cement and veins/microfractures with an average of (20%) and (2%) (10%) respectively. Bioclasts (5%), stylolites amplitudes and dissolutions and

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replacements of original grains are often found among the allochemical components (Fig-9.)

Interpretation

This microfacies is characterized by the following diagnostic feature:

i) Presence of bioclasts, bivalves and foraminifera shallow marine conditions (Scholle and Umer Scholle 2003; Flügel 2010).

ii) Calcite vein and cementation reduce porosity while fractures may enhance permeability and porosity (Flügel 2010).

iii) Middle ramp depositional environment is proposed for the microfacies.

1) Discocylonoid Wackestone-Packstone Microfacie

Discocylonoid wackestone to packestone microfacies comprised of fossiliferous limestone mostly of discocyclina species. Larger benthic foraminifera are dominant skeletal grains that ranges in abundance from 60%. Most of the foraminifera belongs to genera *Discocyclina, Nummulite* and *Assilina* which are present in abundance with size ranges from 1-5mm in diameter (*Discocyclina)* which shows the shallow marine environment for its deposition with relatively high energy environment. The faunal assemblages and wackestone to packestone types of limestone facies analyzed in the core studies suggests the

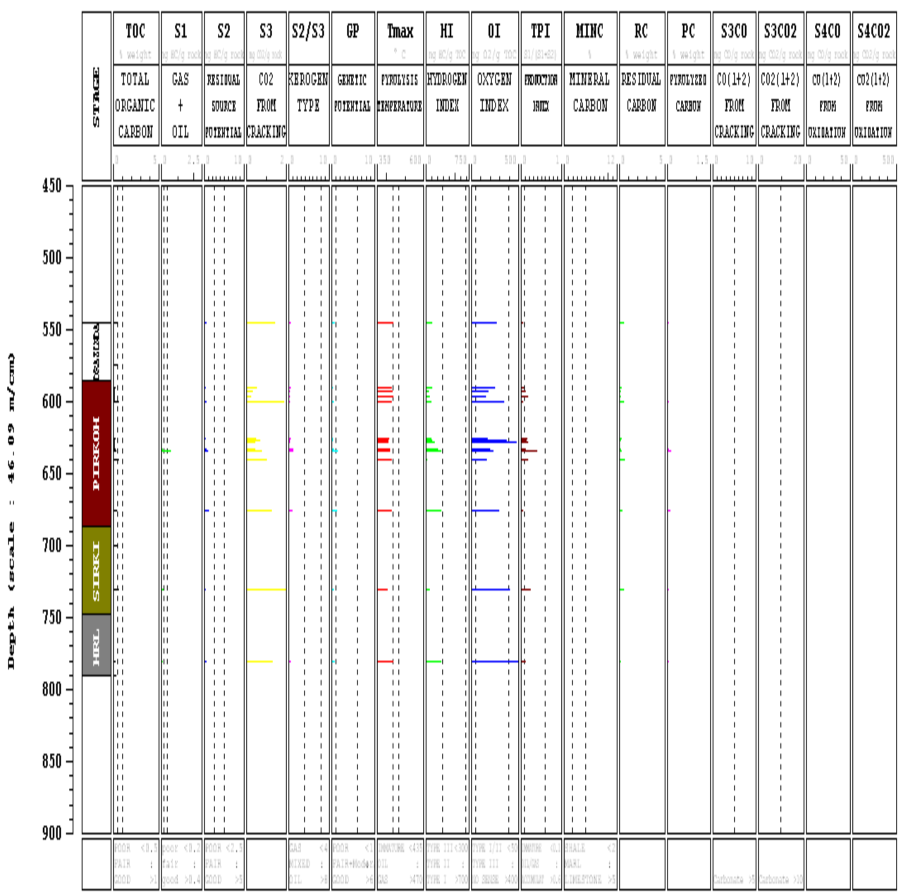

Fig 5 Geochemical Log of Well-1

Eocene age for its deposition.

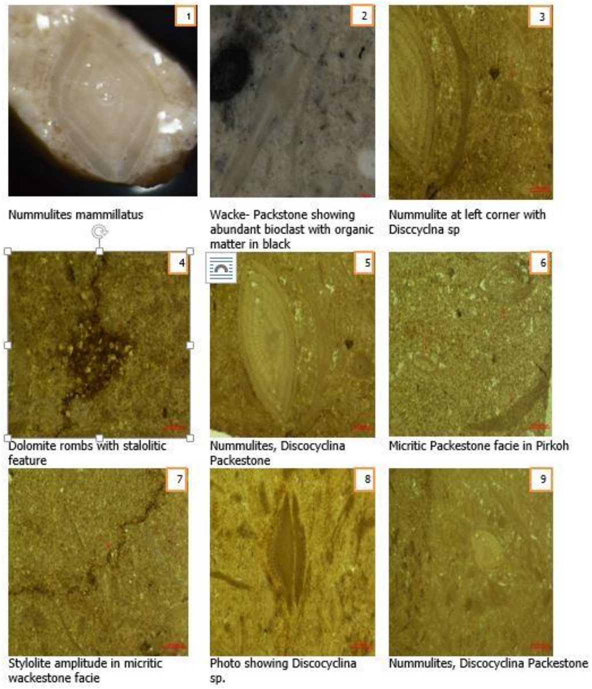

Fig-6 Microfacies and Reservoir Characteristics of the Pirkoh Formation from Core & Well Cuts Data in Well-1 (PPl 10X) magnification

The mode of foraminiferal preservation is good. Due to well preservation, benthons are easily recognizable to genera level. The identified benthic genera are *Discocyclina, Nummulites* and *Assilina* (Fig-6). Other than these skeletal grains, the broken shells of these organisms also occur in significant amounts and range from 5% to 8%. The intact to broken ratio is estimated at 5:3. Among the benthons, *Discocyclina* is the most frequently occurring skeletal type of this microfacies. *Nummulites* are subordinate to *Discocyclina* and *Assilina.* The size of benthons generally ranges from 1.4mm to 4mm. These grains are distributed in the micrite ground mass and disseminated pyrite also noticed.

Petrographic Description

This microfacies is comprised of dominantly larger benthic forams, bioclasts and bivalves. Further the diagenetic features such as veins, and cementation were also observed under microscope. This microfacies is mainly consists of benthic forams (60%), bioclasts (10%), bivalves (10%) and micrite cement (18%). The visual porosity is only 2 %.

Interpretation

This microfacies is characterized by the following diagnostic feature:

i) Presence of benthic forams, and bioclasts represent their shallow marine existence in the photic zone above the fair-weather normal wave base (Flügel 2010).

ii) Diagenetic features such as fracture enhance the permeability whereas veins and cementation reduce the porosity (Flügel 2010).

iii) This microfacies represent the high energy middle ramp setting (Flügel 2010).

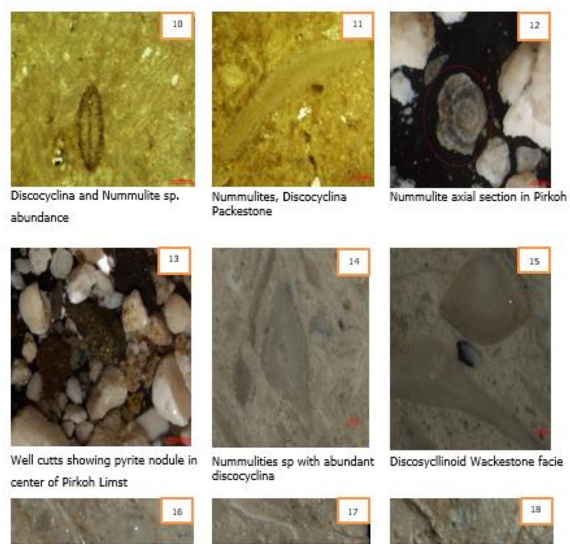

Fig-7 Microfacies and Reservoir Characteristics of the Pirkoh Formation from Core & Well Cuts Data in Well-1 (PPl 10X) magnification

Reservoir Characteristics

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Paleogene carbonate rocks are the most significant hydrocarbon reservoirs in Pakistan. The Pirkoh Formation in Pakistan has been found to have good reservoir quality based on laboratory analysis using conventional core analysis (RCA). The porosity of the formation ranges from 14.94% to 20.36%, while the permeability ranges from 0.19 md to 2.3 md. (Table-3). The hydrocarbon saturation, determined using the Deen Stark apparatus, is between 0.01 ml and 2.00 ml. (Table 4 & 5). The reservoir characterization of the formation reveals distinct features. Visual porosity mainly consists of vuggs, which are pores larger than 1/16 mm in diameter and have a somewhat equal shape. Moldic porosity is also present, which is created through the dissolution of a pre-existing constituent of the rock, such as a shell or grain. Micro-fracture porosity, mostly parallel or slightly inclined to the bedding plane, is also observation n thin section analysis, good inter-granular to intra-granular porosity has been noticed. This indicates that there are pores between the grains within the rock,

Fig-8 Slabbed Core of the Pirkoh Formation consists of Wackestone-Packestone type which can serve as reservoirs for hydrocarbons. (Fig-9)

Overall, the analysis of the two cores from the Pirkoh Formation suggests that it has good reservoir properties and characteristics for hydrocarbon production.

Porosity

Total porosity includes all the pore spaces in a rock while the effective porosity includes only the pore spaces which are interconnected and effective as a void, which can be filled and drained of fluids. Porosity varies with grain size, shape and distribution. It is generally said that porosity (ϕ) is (Ologe Oluwatoyin 2017):

a. If (ϕ) < 5% = Negligible
b. If (ϕ)>5 & < 10% = Low
c. If (ϕ) >10% & < 20% = Good
d. If (ϕ) > 20% = Very Good

Here average plugs porosities for both cores of Pirkoh Formation is near about 17% attained by CMS-300 which is in the good range. (Table-3).

Grain Density

Grain density is determined from the grain volume and the weight of the cleaned and dried core plugs (Grain density = Dry weight /Grain Volume). The calculated grain density serves as a check on the complete cleaning of the core sample. Too low a grain density would indicate the presence of oil in the formation, water still in pore spaces.

Permeability

The permeability of a porous media is a measure of its ability to transmit fluids. Permeability ranges from 0.0002 milli darcy to more than 10 and 15 darcy. Permeability depends upon pore dimensions and configurations. An oolitic limestone will have high permeability and an intercrystalline limestone will have very low permeability.

Permeability like porosity also depends on rock properties such as grain shape, grain and cement texture and size distribution. If the grain size is smaller, it will impede the flow of fluids through the pores thus decreasing the permeability. It is generally said that permeability (K) is (Ologe Oluwatoyin 2017):

a. If (K) < 0.01 md. = Negligible
b. If (K) 0.01 - 1.0 md. = Low
c. If (K) 1.00 - 10 md. = Fair
d. If (K) 10 - 100 md = Good.
e. If (K) 100 - 1000 md. = Very Good

Here plugs permeability for both cores of Pirkoh Formation is near about 1milli Darcy attained by CMS-300 which is in the fair range. (Table-3).

Fluids Saturation

The Deen Stark apparatus is used to measure the water and hydrocarbon saturation in the Pirkoh Formation. This formation is believed to have been completely saturated with water before the migration of hydrocarbons occurred. As a result, when oil migrates into the water-filled reservoir, it displaces some of the water but not all of it. This displacement process results in the presence of connate water saturation in the reservoir rock pores.

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Table 3 Routine Core Analysis of Core 1 & Core 2 Showing Porosity, Permeability and Grain Density in the Pirkoh Formation of Well-1 by CMS-300

Well No-1 **Pirkoh Formation**			**CORE ANALYSIS** Preliminary Data Routine Plugs (1.5" Dia)			
Plug no	**Core # 1**	**Depth**	**Permeability (md)**		**Porosity He (%)**	**Grain density (Gm/cc)**
		m	**kg**	**ki**	**Hor**	
1	1	590.30	0.48	0.35	18.92	2.70
2	1	591.50	1.5	1.1	17.29	2.71
3	1	592.70	0.96	0.70	14.94	2.70
4	1	593.90	1.5	1.1	16.87	2.70
5	1	594.80	3.1	2.3	20.22	2.73
6	1	596.30	2.2	1.6	16.75	2.71
7	1	598.40	2.0	1.5	17.10	2.70
Plug no	**Core # 2**	**Depth**	**Permeability (md)**		**Porosity He (%)**	**Grain density (Gm/cc)**
		m	**kg**	**ki**	**Hor**	
1	2	625.30	0.79	0.58	18.83	2.68
2	2	626.50	0.37	0.27	16.94	2.70
3	2	627.70	0.54	0.40	20.36	2.70
4	2	628.60	0.27	0.19	17.31	2.69
5	2	630.10	0.34	0.24	18.81	2.70
6	2	631.60	1.0	0.69	20.21	2.70
7	2	633.70	1.2	0.87	18.20	2.70

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The fundamental property of porous media states that when one fluid displaces another in a porous medium, the displaced fluid saturation can never be reduced to zero. This is due to the finite surface tension at the interface between immiscible fluids. Therefore, even though the oil displaces some of the water in the reservoir rock, it cannot completely eliminate the presence of water.

Reservoir rocks typically contain both petroleum hydrocarbons and connate water, as both fluids occupy the pores. In the Pirkoh Formation, the Deen Stark apparatus is used to measure the saturation of water and hydrocarbons present in the reservoir rock. (Table-4 & 5). This apparatus provides data that can be used to analyze the fluid content and distribution within the formation.

Fractures, Stylolites /Dolomitization

The various phases of fracturing, along with stylolitization, filled with calcite, were observed in the petrographic investigation of the core (Fig-6,7). These fractures disrupted the calcite veins within the wackestone micro-facies. Stylolites, which are low-amplitude irregularities on bedding surfaces, developed within these fractures. In addition to stylolites, dolomite precipitation was also observed along with the stylolites, forming a type of dolomite called stylocummolate. Dolomitization of limestone is a common

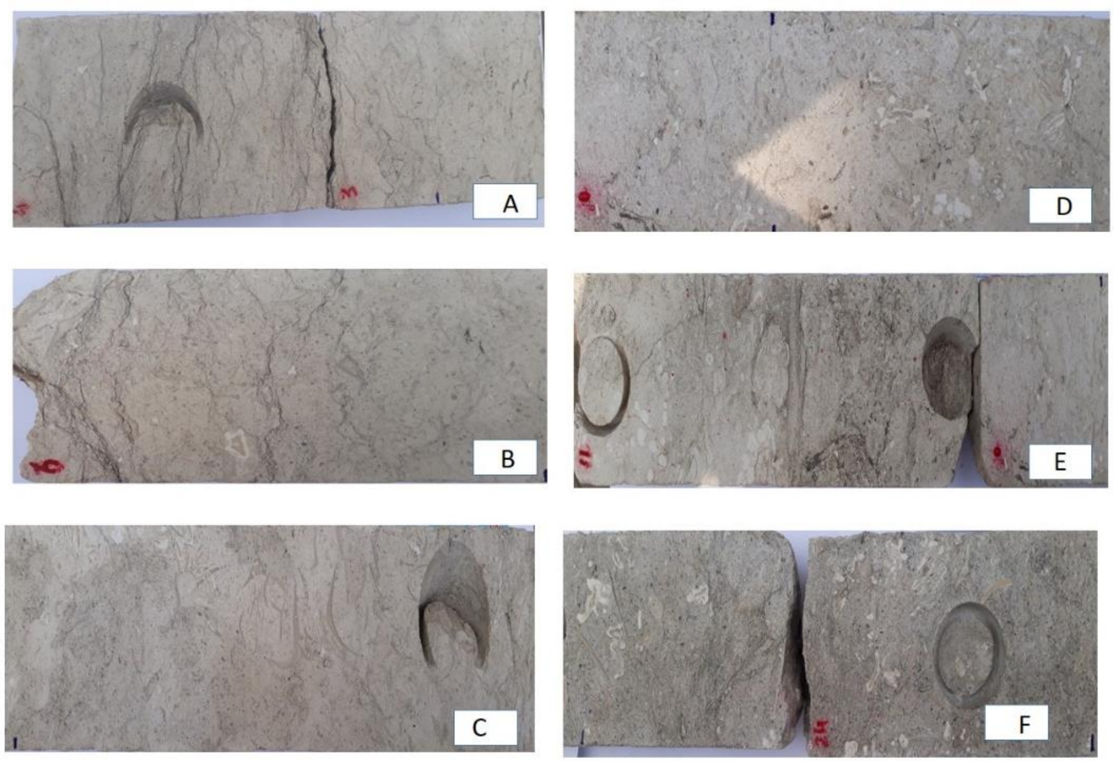

Fig-9 Selected Samples from Core of Pirkoh Formation with Prominent Features highlighted in the slab. (A) Wackestone-Packestone Discocyclina & Nummulite sp. Highly Fractured (2mm-2cm), parallel to bedding plane. (B) Highly fractured porosity, parallel to bedding plane. (C) Abundance of foraminifera's (Discocyclina sp.) (D) Packestone Discocyclina & Nummulite sp. & extensive replacement (E) Vuggy and moldic porosity (F) Replacement and dissolutions of Bioclast

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Table 4 Core-1, Analysis Showing Water and Hydrocarbon Saturation in the Pirkoh Formation of Well-1 by Dean Stark Apparatus

S/NO.	REG. NO.	SAMPLE DEPTH (m)	WEIGHT OF CRUSIBLE (g)	WT. OF CRUS+ SAMPLE (g)	WT. OF CRUS+ SAMPLE A(Ext.) (g)	TOTAL FLUID (ml)	WATER REC. (ml)	H.C REC. (ml)
1	1085	590.30	61.83	81.80	80.20	1.60	1.50	0.10
2	" A	590.60	62.26	85.14	83.43	1.71	1.70	0.01
3	" B	590.90	62.32	77.76	76.62	1.14	1.10	0.04
4	" C	591.20	62.30	103.84	100.73	3.11	3.10	0.01
5	" D	591.50	62.07	89.02	87.49	1.53	1.50	0.03
6	" E	591.80	62.37	74.39	73.72	0.67	0.60	0.07
7	" F	592.10	61.33	76.36	75.59	0.77	0.60	0.17
8	" G	592.40	65.80	91.53	90.35	1.18	1.10	0.08
9	" H	592.70	65.61	110.92	108.98	1.94	1.80	0.14
10	" I	593.00	61.02	121.27	119.19	2.08	2.00	0.08
11	" J	593.30	65.5	88.37	87.45	0.92	0.90	0.02
12	" K	593.60	66.18	103.85	101.34	2.51	2.50	0.01
13	" L	593.90	61.3	92.34	91.12	1.22	1.20	0.02
14	" M	594.20	61.35	94.84	92.96	1.88	1.80	0.08
15	" N	594.50	61.93	103.34	100.44	2.90	2.80	0.10
16	" O	594.80	61.21	106.42	103.88	2.54	2.50	0.04
17	" P	595.10	61.67	97.93	95.85	2.08	2.00	0.08
18	" Q	595.40	61.30	83.29	81.60	1.69	1.60	0.09
19	" R	595.70	61.41	84.74	82.27	2.47	2.40	0.07
20	" S	596.00	61.3	89.71	88.22	1.49	1.40	0.09
21	" T	596.30	61.02	95.62	93.89	1.73	1.60	0.13
22	" U	596.60	61.14	89.08	86.67	2.41	2.20	0.21
23	" V	596.90	60.94	84.83	83.63	1.20	1.10	0.10
24	" W	597.20	65.72	89.46	87.84	1.62	1.40	0.22
25	" X	597.50	61.99	85.74	83.96	1.78	1.00	0.78
26	" Y	597.80	62.30	107.63	104.87	2.76	1.70	1.06
27	" Z	598.10	61.79	100.03	98.39	1.64	1.50	0.14
28	" A-1	598.40	61.76	105.15	103.10	2.05	1.80	0.25
29	" B-1	598.70	62.70	88.9	86.43	2.47	2.40	0.07
30	" C-1	599.00	62.58	111.74	107.96	3.78	3.60	0.18

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Table 5 Core-2, Analysis Showing Water and Hydrocarbon Saturation in the Pirkoh Formation of Well-1 by Dean Stark Apparatus

S/NO.	REG. NO.	SAMPLE DEPTH (m)	WEIGHT OF CRUSIBLE (g)	WT. OF CRUS+ SAMPLE (g)	WT. OF CRUS+ SAMPLE A(Ext.)(g)	TOTAL FLUID (ml)	WATER REC. (ml)	H.C REC. (ml)
1	1086	625.30	61.84	106.95	103.92	3.03	2.50	0.53
2	" A	625.60	62.26	84.75	83.28	1.47	1.40	0.07
3	" B	625.90	62.32	96.38	94.13	2.25	2.10	0.15
4	" C	626.20	62.29	107.77	105.02	2.75	2.50	0.25
5	" D	626.50	62.07	96.33	94.28	2.05	1.80	0.25
6	" E	626.80	62.37	94.83	92.07	2.76	2.70	0.06
7	" F	627.10	61.33	99.13	96.45	2.68	2.60	0.08
8	" G	627.40	65.81	107.65	104.31	3.34	3.20	0.14
9	" H	627.70	65.62	113.01	109.66	3.35	3.30	0.05
10	" I	628.00	61.02	85.98	84.17	1.81	1.80	0.01
11	" J	628.30	65.51	118.05	114.55	3.50	1.50	2.00
12	" K	628.60	66.28	108.08	105.26	2.82	2.80	0.02
13	" L	628.90	61.3	94.61	92.74	1.87	1.60	0.27
14	" M	629.20	61.36	92.60	90.88	1.72	1.20	0.52
15	" N	629.50	61.93	114.71	110.70	4.01	4.00	0.01
16	" O	629.80	61.31	96.33	94.01	2.32	2.00	0.32
17	" P	630.10	61.68	82.54	81.03	1.51	1.50	0.01
18	" Q	630.40	61.29	91.04	89.01	2.03	2.00	0.03
19	" R	630.70	61.41	97.89	95.3	2.59	2.50	0.09
20	" S	631.00	61.29	94.47	91.93	2.54	2.50	0.04
21	" T	631.30	61.02	104.21	101.01	3.20	2.70	0.50
22	" U	631.60	61.14	79.05	77.87	1.18	0.60	0.58
23	" V	631.90	60.95	107.72	104.78	2.94	2.90	0.04
24	" W	632.20	65.72	83.40	82.16	1.24	1.00	0.24
25	" X	632.50	62.01	102.59	99.24	3.35	3.00	0.35
26	" Y	632.80	62.31	86.66	85.09	1.57	0.80	0.77
27	" Z	633.10	61.79	80.8	79.40	1.40	1.10	0.30
28	" A-1	633.40	61.76	81.36	80.05	1.31	1.00	0.31
29	" B-1	633.70	62.70	72.60	71.96	0.64	0.60	0.04
30	" C-1	634.00	62.60	117.23	113.86	3.37	1.90	1.47

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diagenetic process, and it was found to occur at various levels in the core, both as cement and as replacement. Dolomitization was also observed along the amplitudes of the stylolites (Fig-7). The dolomitization process is significant as it increases the porosity of carbonate rocks. In this case, the porosity increased up to 19%, making the carbonate rocks a potentially good reservoir for hydrocarbons or other fluids.

Depositional Environments

The Pirkoh Formation is composed of limestone that is off white, white, chalky, and highly fossiliferous. It was deposited in shallow marine shelf conditions and contains many genera of foraminifera, such as Discocyclina, Nummulites, and Assilina, which indicate an Eocene age.

Microfacies analyses and faunal types in the Pirkoh Formation suggest that it was deposited in well-circulated, open marine conditions. The absence of carbonate shoals, organic barriers, and reefal deposits suggests that the formation was deposited in a ramp setting. Various workers (e.g. Abbas, 1999; Afzal *et al*., 1997; Ahsan *et al*., 1994) interpreted the homoclinal ramp for the deposition of Paleogene sequence of Suleiman Basin. The ramp is further divided into inner, mid, and outer zones, with different microfacies corresponding to each zone based on the occurrence of skeletal grains and their paleoecology.

The Discocyclina-Nummulites microfacies are characterized by the dominance of larger benthic foraminifera, including Discocyclina and Nummulites. The presence of these organisms, along with their broken fragments, suggests deposition under relatively high-energy conditions over the ramp. Micrite, a fine-grained carbonate mud, is the major groundmass matrix in this microfacies, indicating a relatively deep environment, possibly within the middle ramp settings. The low frequency of larger benthic foraminifera and presence of smaller benthic foraminifera in minor amounts suggest deposition over the distal shelf and deep water settings, such as the proximal to distal outer ramp. Overall, the carbonate facies of the Pirkoh Formation represents a ramp environment dominated by larger benthic foraminifera, which is typical of many Paleogene carbonate sequences. (Flügel, 2004).

Conclusions

Following conclusions have been drawn from the research work of the Middle Eocene Pirkoh Formation.

- The Pirkoh Formation has not reached proper thermal maturity, indicating that it may not have the necessary properties to act as a source rock for hydrocarbons.
- Petrographic analysis of the formation reveals a rich abundance of larger benthic foraminifera, with a smaller presence of smaller benthons. Two main microfacies have been identified based on this analysis.
- Based on the microfacies and environmental interpretation, it is concluded that the Pirkoh Formation was deposited in middle ramp settings.
- The core analysis shows good reservoir quality, with visual porosity predominantly found in vuggs and molds. Dissolution and replacement of original grains contribute to the enhanced porosity, along with micro-fractures that are generally parallel or slightly inclined to bedding.
- Laboratory analysis of the Pirkoh Formation consistently shows good reservoir quality.

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- Core plugs data reveals porosities ranging from 14.94% to 20.36% and permeability ranging from 0.19 to 2.3 md.

- Hydrocarbon saturation of the cores ranges from 0.01 to 2.00 ml.

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