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Hydrocarbon Potential Of Zinda Pir Anticline, Eastern Sulaiman Fold Belt, Middle Indus Basin, Pakistan.

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ABSTRACT

The synthesis of biostratigraphic information from Well X-1 geochemical data from Zindapir-1 well, wireline logs of Well X-1 and Zindapir-1 in eastern Sulaiman Fold Belt, in middle Indus basin and Sequence Stratigraphic studies of Lower-Middle Indus bBasin indicate that Lower Cretaceous Sembar Formation, considered to be the principal source rock of Lower and Middle Indus Basin is absent. The Well X-1 and Zindapir-1 at Zindapir Anticlinorium were drilled and abandoned as dry holes. The source rocks identified in clastic and carbonate facies of Jurassic Chiltan Formation and Cretaceous Goru Formation encountered in Zindapir-1, comprising of gas prone Kerogen type III have poor source rock potential in the area indicating possible generation of hydrocarbons in limited quantity, lacking expulsion, migration and accumulation of hydrocarbons in the reservoirs.

Discovery of hydrocarbons of varying composition at Dhodak, Rodho and Afiband anticlines of Zindapir Anticlinorium located from north to south along the strikes indicates multiple source rocks with various level of maturity, possibly expelled and migrated through fault as conduits within the potential kitchen area in Sulaiman Foredeep in the east and Barthi Syncline in the west , due to increased overburden or being generated by indigenous potential source rocks of varying composition. It seems that Zindapir structure is still virgin to flow hydrocarbons, and there are ample chances of compartments, developed as a consequence of transpressional movement at the periphery of the structure. These compartments may host hydrocarbon, generated and migrated either from Barthi syncline and Sulaiman Foredeep or generated by indigenous source rocks possibly deposited in the south of Zindapir-1 and Well X-1. It is therefore recommended that the sub-surface structure pattern of Zindapir Anticlinorium may be investigated in detail, using additional seismic data . In addition source of hydrocarbons discovered at Dhodak , Rodho and Afiband structure may be identified for the inference of possible hydrocarbon source in the southern part of Zindapir Anticlinorium.

INTRODUCTION

Pakistan is endowed with two major sedimentary basins, namely Balochistan and Indus, separated by left-lateral Bela-Ornach-Chamman transform fault system in the onshore and Murray ridge in the offshore. These two basins are carved with spectacular mountain ranges, fore-deeps, ocean trench and platforms (Figure 1). The study area situated in eastern Sulaiman Fold Belt of Middle Indus Basin lies in the southern part of Zindapir Anticlinorium comprising Dhodak, Rodho, Afiband and Zindapir Anticlines. These structures were one of the main focus for petroleum exploration which resulted in the discovery of gas and condensate in Jurassic to Paleocene clastic and carbonate reservoirs in the north, where as the two exploratory wells: Zindapir-1 and Well X-1 drilled at 70km long and 14km wide Zindapir surface anticline hosted in the study area were dry (Figure 2). Despite the voluminous discoveries of hydrocarbons, the age and type of source rocks have not been thoroughly investigated. The reconnaissance source

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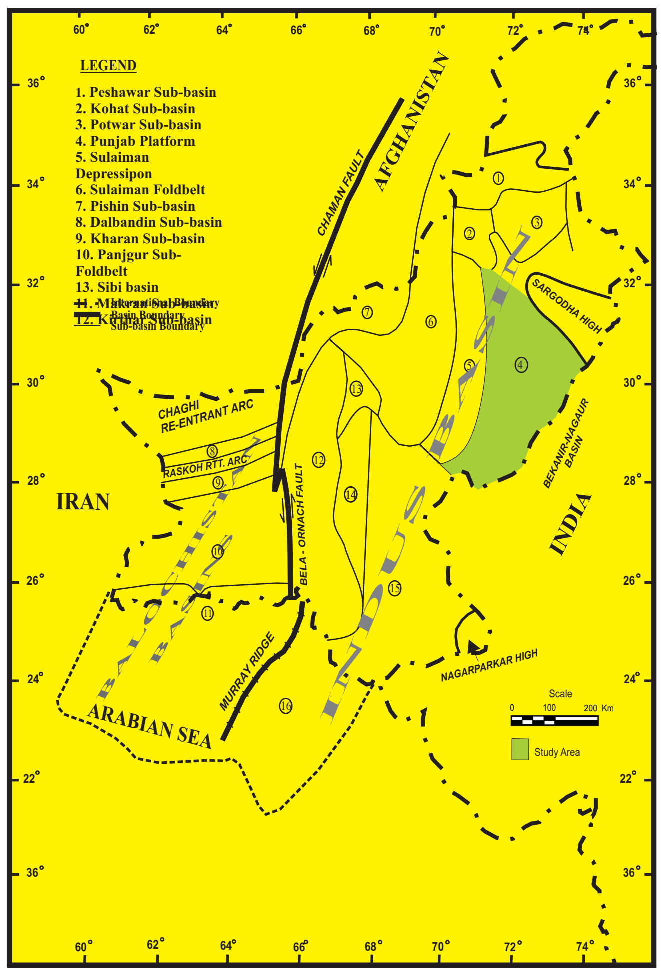


Figure 1 - Sedimentary Basins of Pakistan (Modified after Raza et al, 2008).

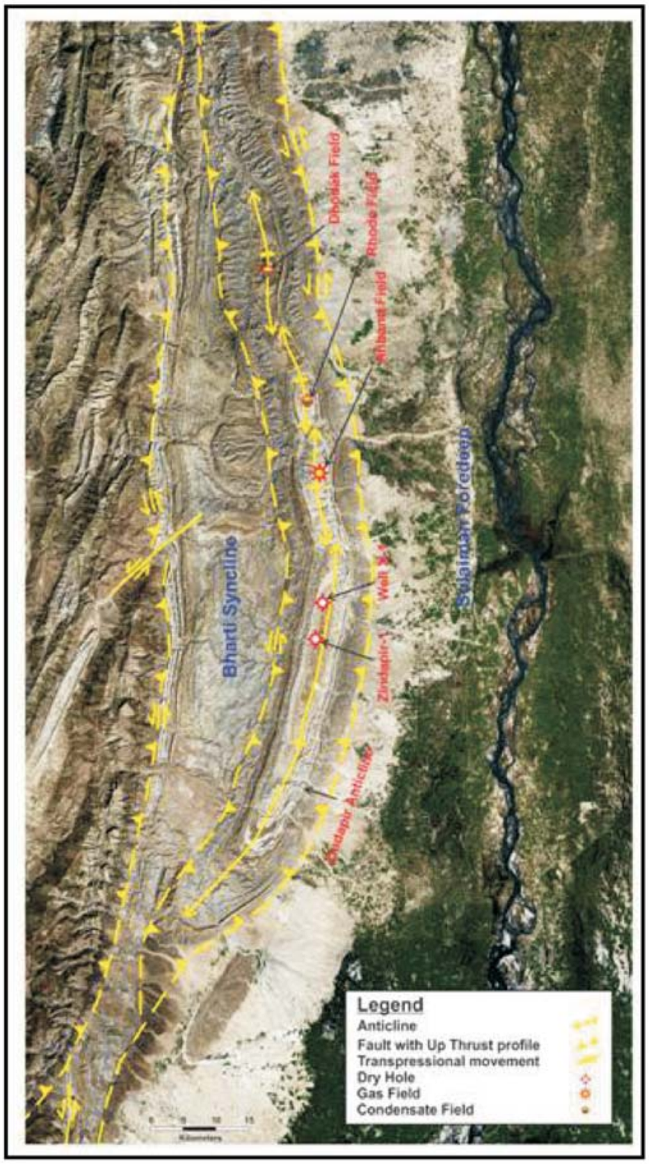


Figure 2 - Structure and tectonic features, location of dry holes and producing fields in the eastern part of Sulaiman Fold Belt.

rock studies of surface samples in the eastern Sulaiman Fold Belt, carried out by Hydrocarbon Development Institute of Pakistan (HDIP) in collaboration with Bundesanstalt für Geowissenschaften und Rohstoffe (BGR); (Raza et al, 1989), provides some useful information about the source potential of Cretaceous to Eocene formations, yet detailed surface and sub-surface geochemical studies are required for proper understanding of petroleum system in the region.

This paper aims to establish the presence or absence of effective source rock(s) in the stratigraphic sequence drilled in the study area and likely reasons of Zindapir-1 and Well X-1 failure. In this context biostratigraphy of ditch cutting samples of Well X-1 was carried out at the Centre of Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan in collaboration with Dewan Petroleum Limited and the results were integrated with sequence stratigraphy studies of Zindapir-1 well, wire-line logs of Well X-1 and Zindapir and available source rock data of Zindapir-1 well. The identity of Well X-1 is not disclosed as it falls in the area of active exploration license

GEOLOGICAL SETTINGS

The tectonic episodes of Indus Basin began with the intra-cratonic rifting of Gondwanaland Super Continent in Late Protozoic followed by Permian-Triassic rift event. The last phase of Mesozoic rifting and sag resulted in the separation of Indian Plate from Afghan, Africa and Seychelles cratonic elements which began drifting northwards and a massive plate convergence (presently ongoing) with Eurasian mass occurred during Cenozoic time (Kemal et al, 1991). The oblique collision of the Indo-Pakistan Plate with Eurasian Plates rotated the Indo-Pakistan Plate anticlockwise which resulted in the opening of large scale basement faults namely Kirthar Basement Fault, Sulaiman Basement Fault and Jhellum Basement fault that segmented Indo-Pakistan plate into several basement blocks. The movement of these blocks during ongoing collision resulted in different tectonic patterns on the individual basement block (Bannert and Raza ,1992). The diverse geodynamic conditions through geological time in present Indus Basin resulted in wide spread deposition of Infra Cambrian-Eocene source and reservoir rocks pertaining to both carbonate and clastics origin which have been described mainly by Khan et al (1986), Malik et al (1988), Raza et al (1989), Raza et al (1990), and development of different structural and stratigraphic traps associated with transpressional-transtensional regimes, salt tectonics, rift-inverted extensional episodes, unconformities, clastic and carbonate units / facies of low-high stand system tracts (Soulsby, Kemal, 1988, Raza et al., 1989, Ahmed and Ali, 1991, Bannert et.al,1992, Ali et al, 1995; Ahmad et al, 2004; Iqbal et al, 2008; Afzal et al, 2009. According to Ali et al (1995), the Sulaiman Fold Belt developed in the Late-Tertiary time as a consequence of left and right lateral transpressional regime related to wrench tectonics in the east and west respectively. Wrench related thick-skinned tectonic features on surface are manifested by left- lateral en-echelon folds and associated thrust faults in the east, right-lateral en-echelon folds and related fault systems in the west (Figure 3), positive flower structure, thrust and sub-thrust structural patterns in the subsurface.. In Safed Koh Range, situated in the eastern part of Sulaiman Fold Belt (Ali et al. 1995), the left- lateral wrench regime has created a number of north-south oriented left-lateral en echelon folds having hydrocarbon pools associated with positive flower structures (Figure 4). Wrench related positive flower structures have also been interpreted by Bannert et al (1995), Iqbal (2004, PhD) , Iqbal et al (2008), Peresson and Daud (2009) in the eastern part of Sulaiman Fold Belt. Iqbal et.al (2008) described the young age (Late Tertiary) and fast uplift rate of the Sulaiman Fold Belt as possible reasons for the mostly under filled structures and even the absence of hydrocarbon accumulation in some of the structures, and considered the Sulaiman Foredeep as hydrocarbon kitchen to charge the anticlines. Our interpretation of Landsat imagery of eastern Sulaiman Fold Belt also indicate left-lateral transpressional regime (Figure-2). However Banks and Warburton (1986), Humayon et. al. (1991), Jadoon (1992), Jadoon et al (1994) have proposed a

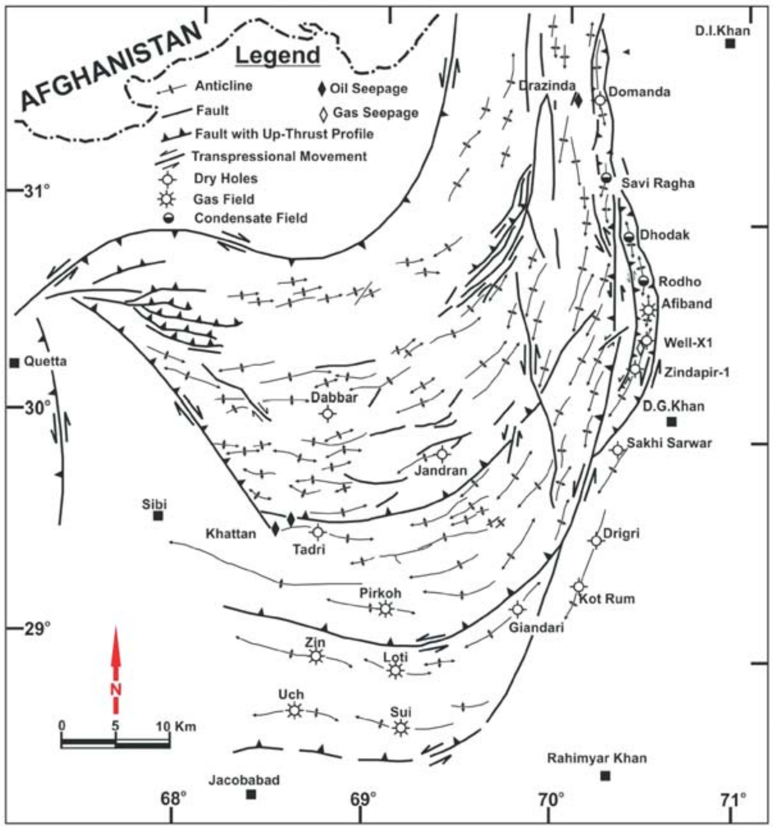


Figure 3 - Structural and tectonic features of Sulaiman Fold Belt; locations of dry holes and producing fields (after Ali et.al, 1995).

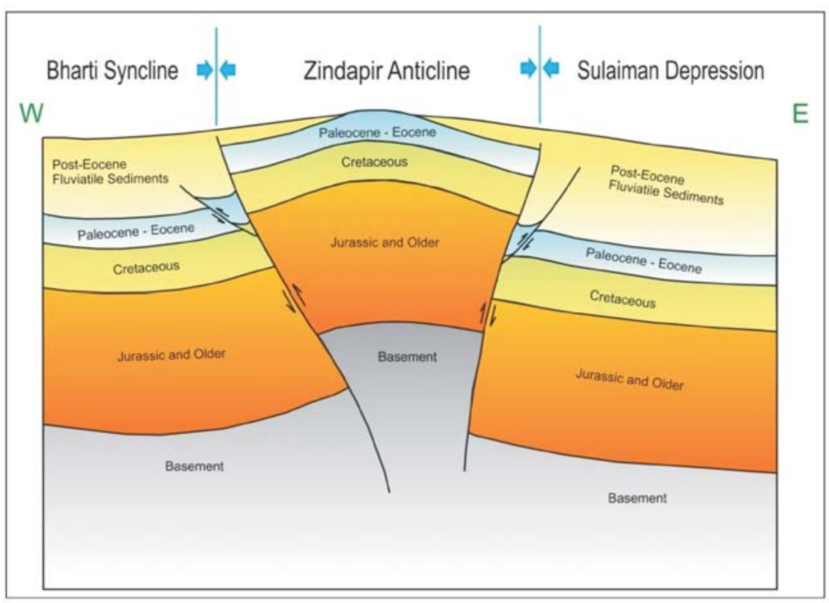


Figure 4 - Schematic cross-sections across Sulaiman Depression, Zindapir Anticline and Bharti Syncline showing structural pattern associated with transpressional regime (after Ali. et.al, 1995).

passive roof duplex model related to thin-skinned tectonic for Sulaiman Fold Belt. The exposed rocks in Sulaiman Fold Belt range in age from Triassic to Tertiary (Raza et al, 1989; Hunting Survey Corporation, 1960; Baker and Jackson, 1964; Kazmi and Jan, 1997; Shah, 2009; Bannert et.al, 1989). The Triassic Alozai Formation has also been drilled in Zindapir Anticlinorium (OGDCL, 1989). The older rocks are exposed in the Hinterland with progressively younger rocks in the Foreland areas. The total sediments thickness ranges from 5000-10000 meters (Kamel et al, 1982) with an estimated thickness of more than 7000 meters of Mesozoic and early Tertiary formations (Raza et al, 1989). The Paleozoic sedimentary rocks overlying the basement are not exposed. These have been drilled in several wells of the adjoining region of Punjab Platform and extend in the west towards Sulaiman Lobe (Raza et al, 1989) indicating the presence of Infracambrian-Permian rocks in the sub-surface of Sulaiman Fold Belt. Humayon et al, (1991), Jadoon (1992), Jadoon et al (1994) have also assumed the presence of Precambrian Permian strata in the subsurface. Generalized Stratigraphy of Sulaiman Fold Belt is shown in figure 5.

The Zindapr Anticlinorium is bounded in the east by Sulaiman depression and in the west by Barthi Syncline (Figure-1). The anticlinorium covers an area of approximately 6000sq.km with Eocene formations exposed in the core of Dhadak, Rodho and Afiband structures whereas Zindapir Anticline has Paleocene rocks in its core. The carbonates of Chiltan Formations (Jurassic), sandstones of Lower Goru (Early Cretaceous) and Pab Formations of Late Cretaceous, Ranikot Sands and Dunghun Limestone of Paleocene age are proved reservoirs of Zindapir Anticlinorium.

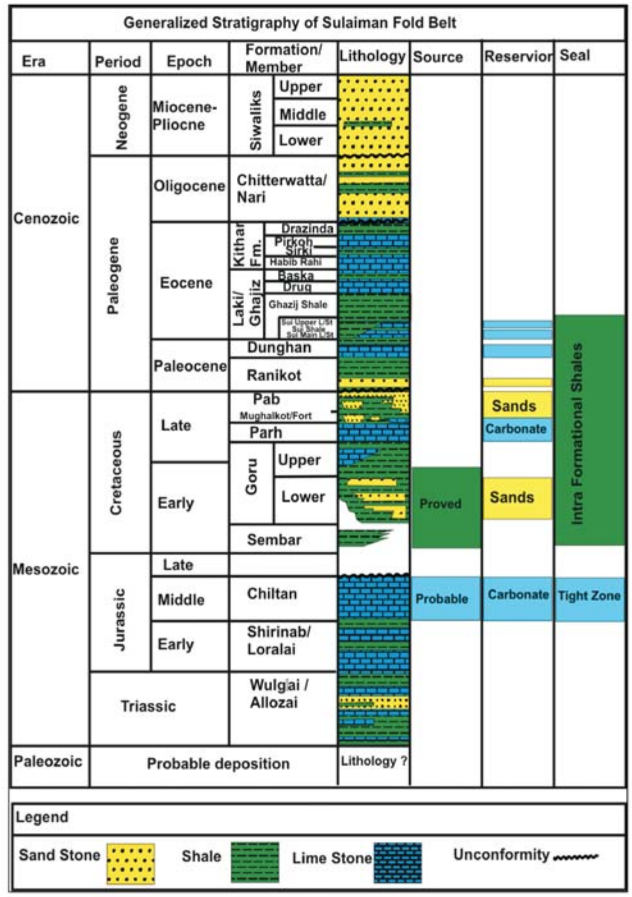


Figure 5 - Generalized stratigraphy of Sulaiman Fold Belt.

Biostratigraphy

Ditch cutting samples of Well X-1 known to be of Cretaceous Sembar-Goru intervals were provided by Dewan Petroleum Limited to the Centre of Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan for biostratigraphic studies. Initially washing of the samples was carried out through 63 micron sieve with water in association with few drops of hydrogen peroxide for proper disintegration of grains. The samples were soaked, washed and dried in oven. Fossils were picked three times. Ornamentation and texture of specimens were studied under the microscope and Scanned Electron Microscope (SEM). Due to poor fossilization (Figure 6 and 7) it is not possible to identify all the specimens on species and generic level.

In total four genera and five species have been identified from planktonic foraminifera study of 24 well cutting samples. All the identified specimens are zone markers of Cretaceous from Late Barremian to Early Turonian in age. The detailed biostratigraphic zonation is given in figure-8. The fossils identified in well X-1 are: Globigerina Ilioides blowi (Late Barremian-Early Aptian), Hedbergella grobachikae (Middle-Late Aptian) which is very primitive, small in size and rare, Ticinella bejaouansis (Late Aptian), Rotalipora subticinensis (Late Albian), and Whitnella archaeocretcea (Late Cenomanian-Early Turonian). These according to lithostratigraphic units correspond to Lower-Upper Goru formations. The planktonic foraminifera of Oxfordian-Hauterivian stage which are the zone marker of Sembar Formation could not be found indicating probable absence of Sembar in the study area.

Sembar Formation is not everywhere present in Sulaiman Fold Belt and Kirthar Fold Belt. For example, east of Khuzdar, more than 100km SE of study area, the Goru Formation directly overlies the Jurassic limestone and the Sembar Formation is missing (Shah 2009). Iso-Maturity Map of Sembar Formation (Wandrey et al. 2004 clearly shows that Sembar is absent in some parts of Indus Basin. Similarly Iqbal et.al (2011) interpreted the Sembar Formation at Mekhtar Section (100km NE of study area) equivalent to IEDS Sequence 2 on the basis of available fossils record. The formation is overlain by Lower Goru equivalent to IEDS Sequence 7, represents a major hiatus. Further the Sembar Formation (IEDS Sequence) unconformably overlie the Chiltan Formation (Jurassic).The unconformities present between Chiltan and Sembar formation, and between Sembar and Goru formation indicates continuous tectonic activity related to Mesozoic rifting which resulted in horst and graben structure patterns. The Sembar Formation was deposited in structural low at Mekhtar. Iqbal et.al (2011) also related the unconformities at Mekhtar Section to localized tectonic event. The absence of Sembar Formation at Zindapir may be related to structural high at the time of deposition.

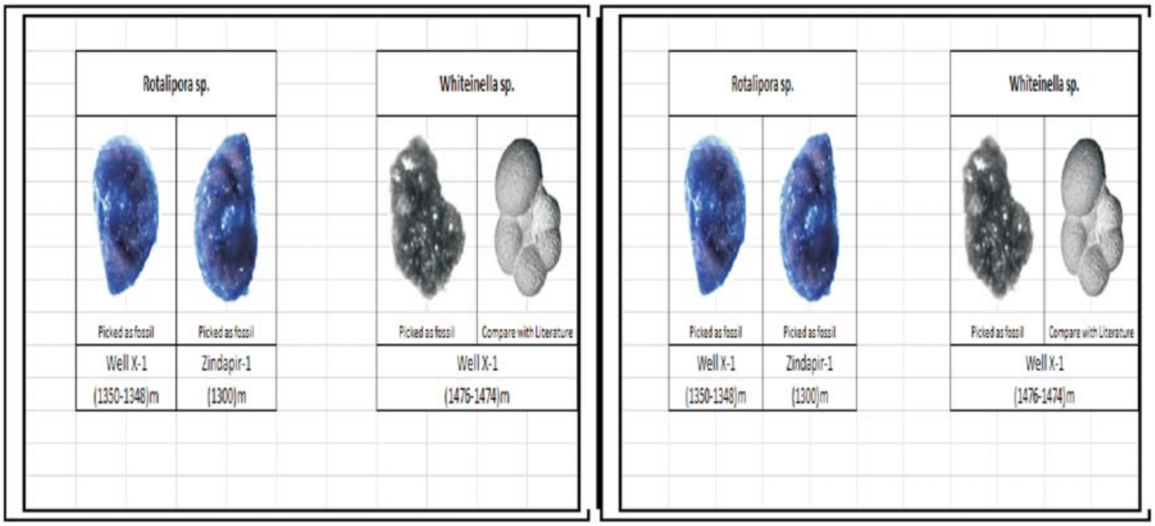


Figure 6 - Microphotographs showing poorly preserved Rotalipora and Whiteinella species in Wells X-1 and Zindapir-1.

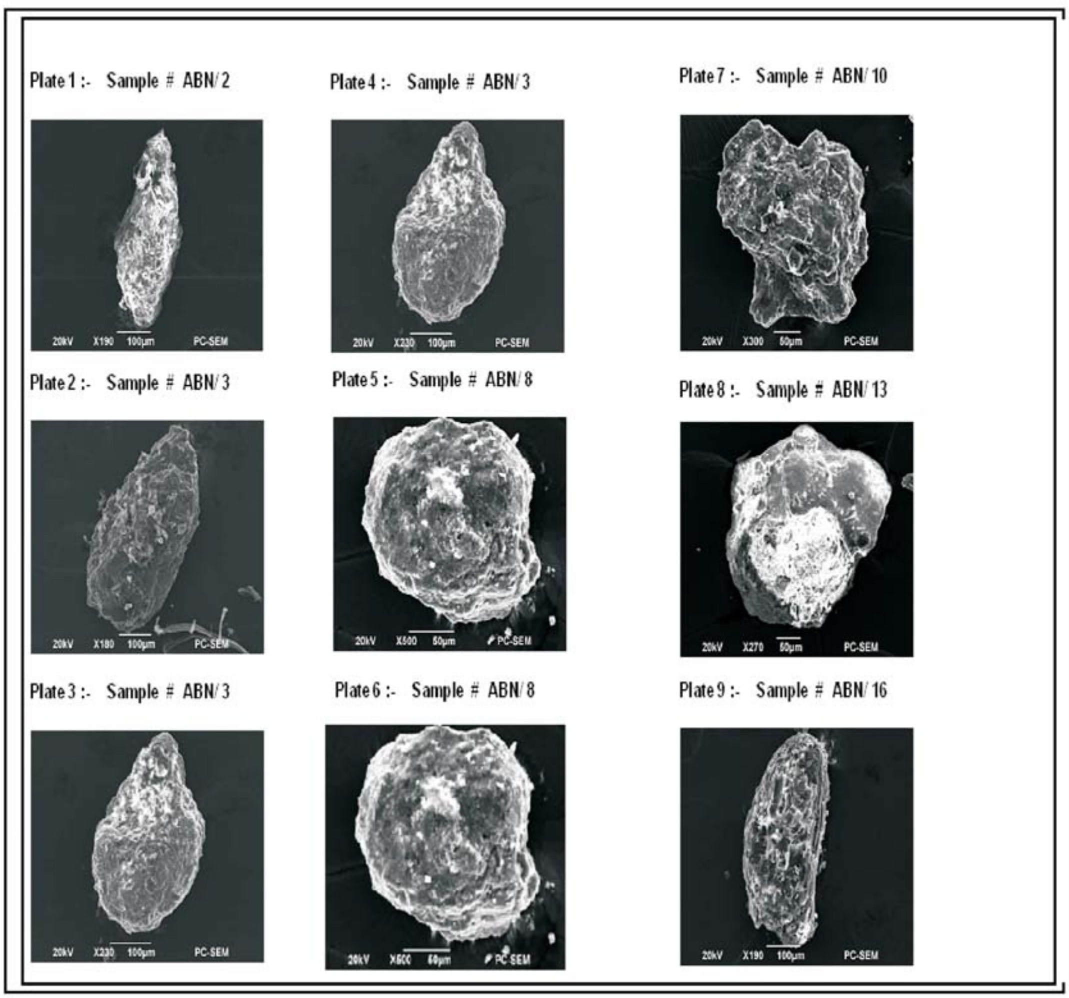


Figure 7 - SEM Photographs of poorly preserved fossils in Well X-1.

SEQUENCE STRATIGRAPHY

In 1995, Integrated Exploration and Development Services (IEDS) conducted regional Sequence Stratigraphic studies in the lower and middle part of Indus Basin and identified nine sequences which are described as follows: Sequence 1 to 3 correspond to Oxfordian-Hauterivian stage and represent lithostratigraphic units of Sembar Formation. Sequence 4 to 7 range from Early Barremian to Late Aptian. Lithostratigraphically Lower Goru Formation falls in this unit. The Sequence 9 and 8 completely and Sequence 7 partly are referred to Upper Goru Formation of Late Albian-Turonian stage (Figure-8).

The study further indicates that Sequence 1 to 3 representing Early Cretaceous Sembar Formation is absent in the sub-surface of Zindapir-1 well drilled on Zindapir structure and Jurassic Chiltan Limestone is un-conformably overlain by Sequence 4 of Lower Goru Formation. This is in accordance with our biostratigraphic findings, which also shows that Sembar Formation is absent (Figure 8 and 9) in well X-1 drilled on Zindapir Structure and Lower Goru Formation un-conformably overlying the Chiltan Limestone. List of sample used for biostratigraphy is shown in Table 1 and Table 2 which clearly shows that stratigraphic section of well X-1 was investigated as whole.

WIRELINE LOG

Gamma ray (GR) log response and IEDS Sequences, 1995 identified in Zindapir-1 well have been correlated with GR log response of Well X-1 (Figure 9). The log response of Chiltan

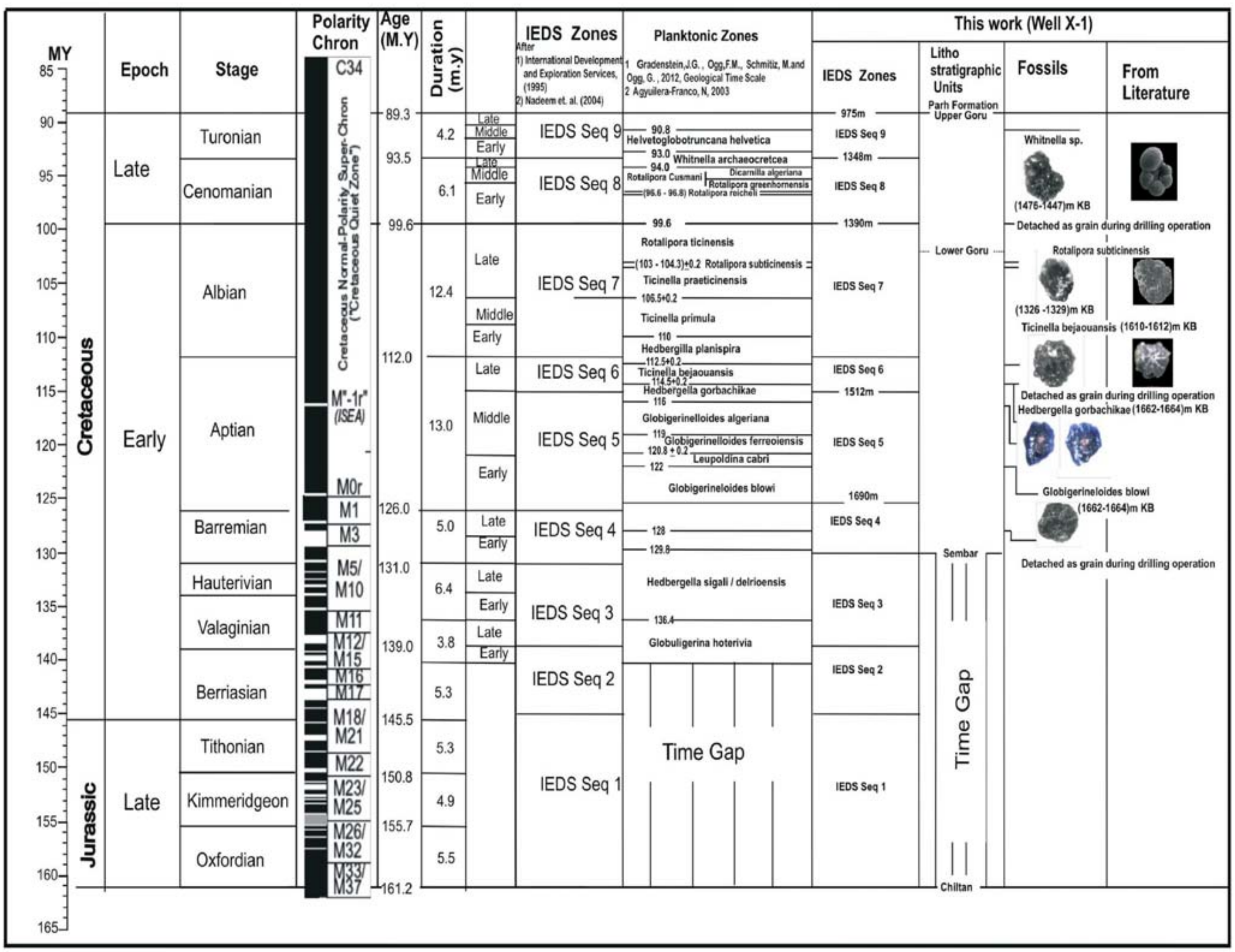


Figure 8 - Results of Biostratighic study showing absence of Sembar formation in Well X- 1.

Table 1 - Biostratigraphic study showing very poor Fossilization.

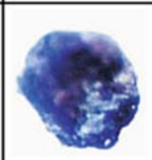
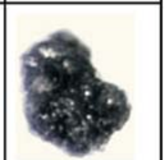
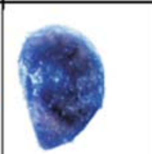
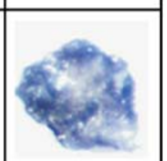
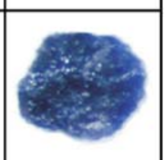
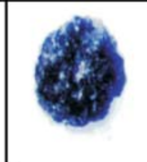
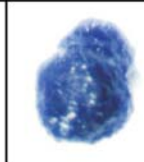
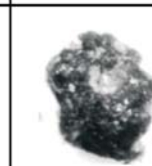
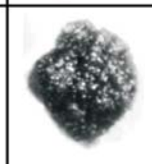
Sample N0	Well Cuttings Depth (m)	Fossil	Sample N0	Well Cuttings Depth (m)	Fossil
ABN/1	1326-1329 (Nodosaria sp.)		ABN/5	1450-1452	
ABN/1	1326-1329		ABN/5	1450-1452	
ABN/2	1326-1329 (Rotallipora substinencis)		ABN/6	1474-1476 (Whiteinella sp.)	
ABN/2	1348-1350 (Rotalipora sp.)		ABN/6	1474-1476	
ABN/3	1376-1378		ABN/7	1530-1532	
ABN/3	1376-1378 (Rotalipora sp.)		ABN/7	1530-1532	
ABN/4	1422-1424		ABN/8	1560-1562	

Table 2 - Biostratigraphic study showing very poor Fossilization.

Sample N0	Well Cuttings Depth (m)	Fossil	Sample N0	Well Cuttings Depth (m)	Fossil
ABN/9	1580-1582	X	ABN/14	1684-1686	
ABN/10	1594-1596		ABN/14	1684-1686	
ABN/11	1610-1612		ABN/15	1732-1734	
ABN/11	1610-1612		ABN/16	1774-1776	
ABN/12	1650-1652		ABN/17	1834-1836	
ABN/13	1662-1664 (Globigerineloides blowi)		ABN/17	1834-1836	
ABN/13	1662-1664 (Hedbergella gorbachikae)		ABN/18	1834-1836	

Limestone and Lower Goru Formation in both the wells is nearly identical, which also indicates the absence of Sembar Formation in the sub-surface of Zindapir Structure. Sequences of Upper Goru Formation could not be correlated on the basis of log response; due to non availability of GR Log data of Well X-1. The top of Upper Goru from Zindapir-1 has been correlated/marked in Well X-1 on the basis of both biostratigraphic (Figure 8) and lithostratigraphic information.

GEOCHEMICAL ANALYSIS

The following parameters (Table-3) are used to evaluate the source rock potential of Mesozoic formations encountered in Zindapir-1 well. In summary, shales of Upper Goru Formation have poor to very good source rock potential (TOC between 0.25-2.25%) (Figure 10), bulk of Lower Goru shales show fair to very good source potential (TOC ranges between 0.5-2.75%), The carbonates of Chiltan Formation have generally poor with limited fair source potential (TOC <0.3-0.45%), The Loralai Limestone has also predominance of poor organic content with limited fair to good organic richness (TOC <0.3-1.0%). Hydrogen Index (HI) Vs Oxygen Index (OI) plot (Figure 11) shows that the aforementioned formations contain typically gas prone type III Kerogen.

Kerogen Type III is mostly derived from terrestrial higher plants. It is less favorable for oil generation and may generate dry gas in large quantity at optimal thermal maturity (Tissot and Welt, 1978). However none of the formations fall within dry gas generation phase. The main gas generation phase for Type III organic matter (OM) occurs at Tmax value of 465 °C - 470°C (Teichmüller and Durand, 1983). Hydrogen Index (HI) Vs Tmax plot (Figure 12) shows that the source rocks of

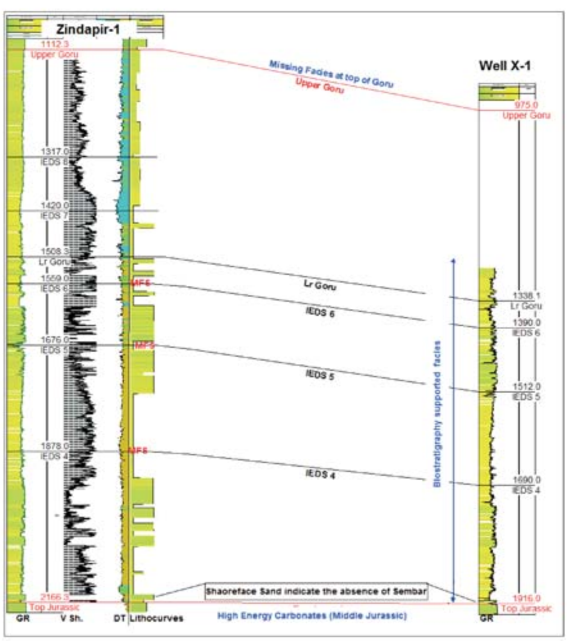


Figure 9 - Correlation of Chiltan-Upper Goru Formation, Zindapir-1 and Well X-1.

Zindapir-1 lie in oil and wet gas/ condensate zone (Tmax value between 435°C -470°C). The Vitrinite reflectance (Ro) and Production Index (PI) values plotted against depth (Figure 13 and14) also show that the source rocks fall within the zone of oil and wet gas/condensate (Ro 0.5 ≈ 1.4; PI between 0.1- 0.7).

Lower and Upper Goru Shales contain fair to very good source potential (Figure 10).PI data which also indicates the

Table 3 - Source rock evaluation guidelines (modified after Tissot and Welte, 1978;Teichmuller and Durand, 1983 and Abeed et al, 2011.

Source Rock Generation Potential	
Quality	TOC (Wt. %)
Poor	0.0 - 0.5 (for clastics) 0.0 - 0.3 (for carbonates)
Fair	0.5/0.3 - 1.0
Good	1.0 - 2.0
Very Good	>2.0

Level of Thermal Maturation			
Maturation	R_o (%)*	T_{max} (^oC)*	PI*
Top Oil window	~ 0.5	~ 430	~ 0.1
Top Condensate/Wet Gas window	~ 1.0	~ 455	~ 0.4
Top Dry Gas window	~ 1.4	~ 470	~ 0.7
* Varies depending upon the type of Kerogen.			

Type of Hydrocarbons (HI)= HC(mg)/TOC(g)	
Gas prone	0-150
Oil & Gas prone	150-300
Oil prone	>300

Transformation Index (PI) = S1/ (S1+S2)	
0.1 ~ 0.4	No significant generation or accumulation of hydrocarbons
0.4 ~ 1.0	Possible accumulation of generated or migrated hydrocarbons

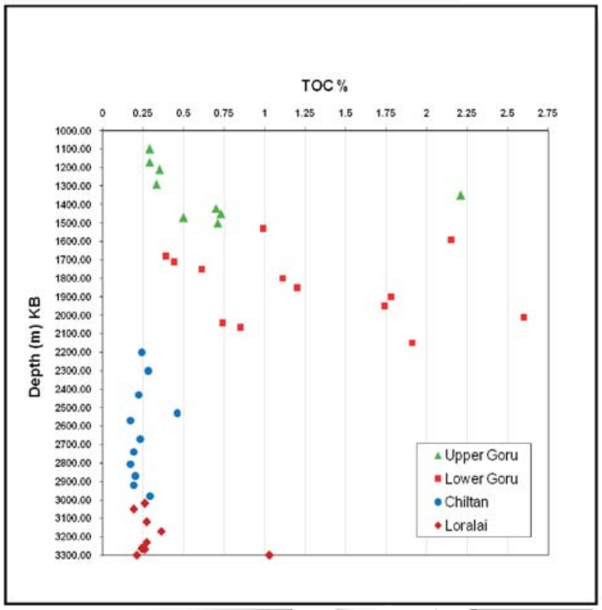


Figure 10 - TOC versus Depth plot of Zindapir # 1 well showing source rock potential.

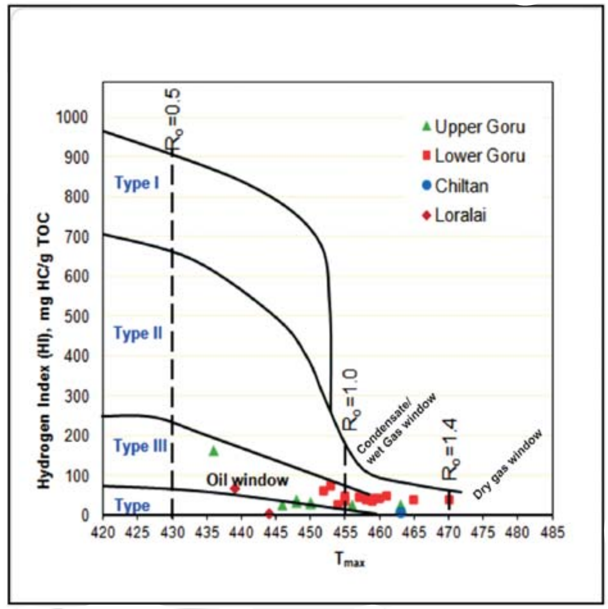


Figure 12 - Hydrogen Index versus Tmax plot showing source rock Maturity in Zindapir-1 well (modified after Abeed et. al. 2011).

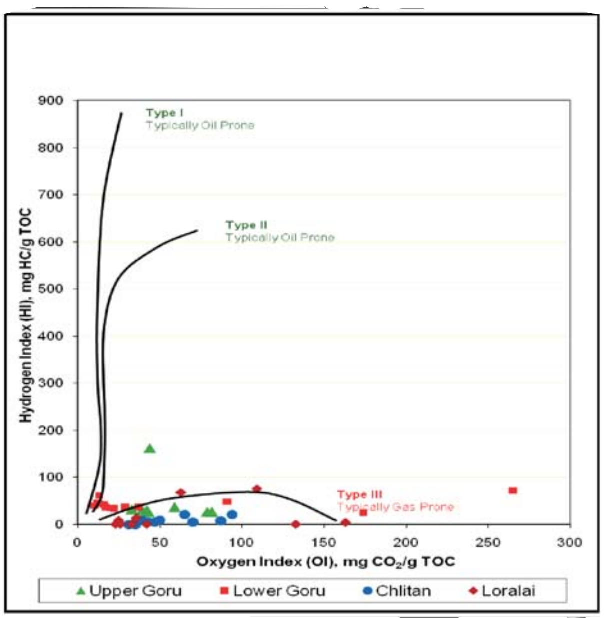


Figure 11 - Cross plot of Hydrogen Index versus Oxygen Index showing type of source rocks encountered in Zindapir-1 well (modified after Espitalie' et. al. 1977)

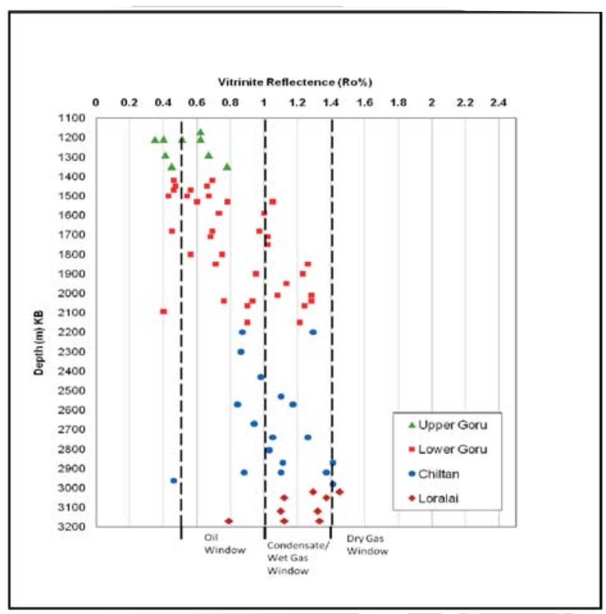


Figure 13 - Depth versus Vitrinite Reflectance (Ro) showing maturation pathways of source rocks encountered in Zindapir # 1.

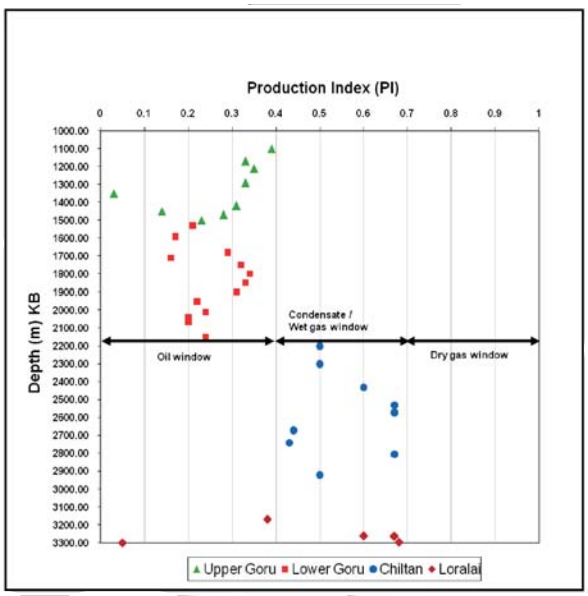


Figure 14 - Depth versus Production Index (PI) plot of Zindapir-1 source rocks showing maturation pathways.

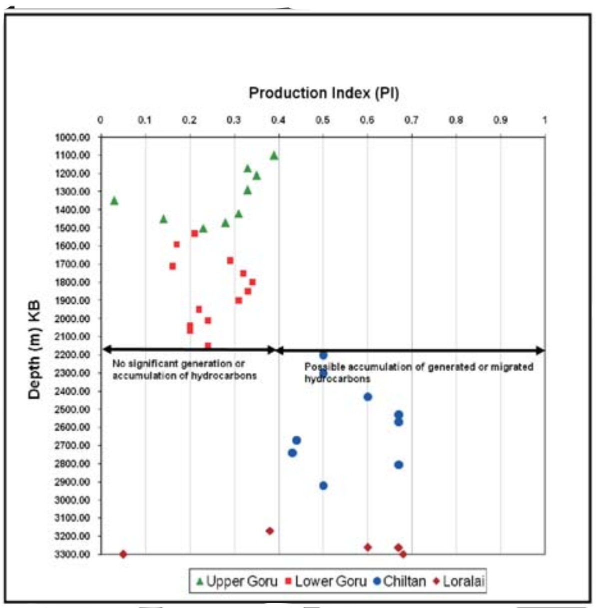


Figure 15 - Depth versus Production Index (PI) plot for samples from Zindapir-1 well showing various degrees of hydrocarbon generation and accumulation.

presence of epigenetic hydrocarbons, shows no significant accumulation or generation of hydrocarbons (PI between 0-0.4) (Figure 15). According to Espitalie et al (1985), in some of the sediments with high TOC values much of the organic matter (OM) may be essentially inert and therefore have very little productivity due to sedimentary reworking, oxidation or advanced levels of thermal maturity. It seems that at Zindapir-1 location, the organic matter is reworked and oxidized, consequently Lower and Upper Goru source rocks show high TOC values with low PI. Loralai and Chiltan Formations have predominantly low or no source potential (TOC <0.3) (Figure 11) with possible accumulation of generated or migrated hydrocarbons (PI between 0.4-0.7) (Figure 15). From the aforementioned results it is inferred that the possible hydrocarbons produced may be insufficient to be expelled, migrate and accumulate in the reservoirs to form hydrocarbon pools. The inference is substantiated by the presence of moved hydrocarbons in Lower Goru sands of Zindapir-1 well (Figure 16)

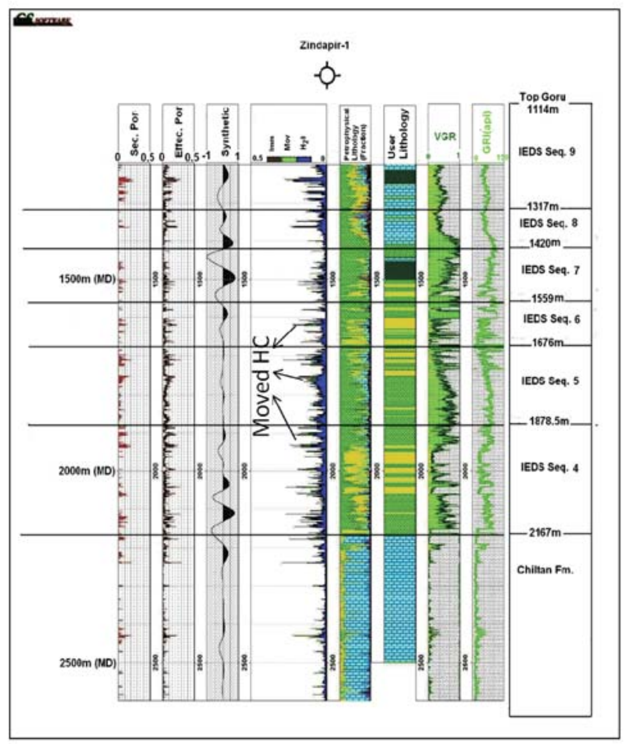


Figure 16 - Petrophysical interpretation of Zindapir-1 showing small quantity of moved hydrocarbons.

Conclusion

Shales of Lower Cretaceous Sembar Formation which are considered to be the principal source of hydrocarbons in Lower and Middle Indus regions are absent in both Zinapir-1 and Well X-1.

The gas prone type III, source rocks of Loralai, Chiltan, Lower Goru and Upper Goru formations identified in Zindapir-1 have generated hydrocarbons due to elevated temperature, probably in such quantity which could not attain the required level of expulsion. As a result, Zindapir-1 and well X-1 were dry.

The Zindapir anticline is a large structure, developed as a consequence of transpressional movements, which generally create partitions in the structure.

It is assumed that the hydrocarbons generated from the effective source rocks deposited in the Sulaiman depression and Barthi Syncline surrounding the Zindapir structure might have migrated through wrench related fault conduits and trapped in some compartments (if available) of Zindapir anticline. In this regards, the sub-surface structure pattern may thoroughly be investigated using additional seismic data.

The other possibilities of hydrocarbon generation and accumulation in compartment is from the indigenous effective source rocks of Lower and Upper Goru Formation deposited in the south of Zindapir-1 and Well X-1 locations.

The present study is based on two dry wells drilled at Zindapir anticline. It is proposed that a detailed investigation regarding the source of hydrocarbons discovered in Afiband, Rodho and Dhodak fields situated north of Zindapir structure may be carried out, which would help in understanding the source potential of various stratigraphic sequences, their maturity level and trapping mechanism in Safed Koh area as well as in the surrounding regions.

Previously, Sembar was marked in well reports of Zindapir-1 (OGDCL, 1989) on the basis of lithostratigraphy without scientific investigations.

Basic principal of sequence stratigraphy for the identification of Sembar Formation and Goru Formation were not applied in well report of Zindapir-1(OGDCL, 1989).

Later studies of International Exploration and Development Services (IEDS), 1995 shows that Sembar was absent in Zindapir-1 and their study was based on the basis of regional stratigraphic framework by integrating wireline logs, seismic data and biostratigraphy as basic tool of sequence stratigraphy.

Present study proved that Sembar is absent in Well X-1 on the basis of biostratigraphy. Well X-1 was drilled in Zindapir-1.

Present study shows that absence of Sembar in Zindapir Anticline does not reduce quality of petroleum system in study area because source rock is present in Goru shale.

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