SUBSURFACE STRUCTURAL INTERPRETATION AND PETROPHYSICAL ANALYSIS OF BADIN AREA, SOUTHERN INDUS BASIN, PAKISTAN

BY

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Abstract: *Seismic as well as Petrophysical techniques were exploited to annotate the subsurface structural interpretation using 2D seismic reflection profiles and petrophysical analysis of the Jabo Field (Jabo-01 & Jabo-05) which lies in the eastern block of Badin district, Southern Sindh Monocline, Pakistan. Geologically, the area is characterized by extensional tectonic activity associated with the rifting phases of Indo-Pakistan plate during Cretaceous. Eleven seismic lines interpreted by Kingdom suite 8.8 and the results revealed the geological implications of the extensional regime in Badin area. Study area is characterized by horst and graben structures which can be promising hydrocarbon traps. Isopach maps, two-way time contour maps and 3D visualization of all horizons show same thickness, trends of depressions and slopes. Petrophysical parameters including porosity, permeability, water saturation, shale volume, and reservoir thickness were calculated for each hydrocarbon-bearing zone, by using Schlumberger-Techlog software. Gamma-ray log response of zone 2 of Jabo-05 is showing mixed sand-shale lithology. Jabo-01 well is observed as SWD (saltwater waste disposal). Based on log responses, two zones from each well are selected that is having good reservoir quality. Results of log interpretation recommend that oil-bearing zones of Jabo-05 are porous and permeable with water saturation ranging from 18 41%, shale volume 18-42% representing the reservoir rock potential. Zone 1 of Jabo-05 is clean sand and is correlated with Zone 1 of Jabo-01 that is also the clean sand. Lower Goru Formation of the Jabo-01 and Jabo-05 has been correlated and it is interpreted that Jabo 5 field of Badin area has better reservoir potential than Jabo 1 that has little hydrocarbon potential.*

INTRODUCTION

The study area lies in the eastern block of Badin district, Sindh Province located about 185 kilometers SE from Karachi. The district lies between 24° 5'N to 25° 25'N Latitude and 68° 21' E to 69° 20' E Longitude (Fig. 1). Geologically, the study area is a part of in the Southern Sindh Monocline, Southern Indus Basin where the extensional tectonics lead to the formation of normal faults. This is evidenced by the presence of horst and graben structures underneath the base Paleocene unconformity in Cretaceous and older strata. Badin area shows a short-term degree of deformation as it is distal from the actual deformation zone formed due to the collision of India and Seychelles (Alam et al., 2003; Munir et al., 2014). Tectonic forces play an important role in the direction, geometry and shape of deformation of geological features which in turn form good petroleum system (Ahmed et al., 2014; Khan et al., 2019). The Southern Indus Basin which is comprised of the Southern Sindh Monocline, is the divergent boundary of the Indo-Pakistan plate with Madagascar that was formed during the age Early to Middle Cretaceous (130-110 Ma). These extensional settings play an important role in the formation of major entrapment mechanisms (horst and graben-like structures) in the Southern Sindh Monocline and Jabo field (Ahmed et al., 2014; Khan et al., 2019). Grabens play a major role in hydrocarbon production and faults provide the migration pathway for hydrocarbons from source to reservoir rocks and also they provide the trapping mechanisms for hydrocarbon potential (Ahmed et al., 2014). In this regard, understanding of the faults is necessary to delineate the structural type, fault components, and hydrocarbon traps. The faulted structure of Southern Sindh Monocline is providing an important petroleum system. In the study area, the approximated spreading rate of tectonic instability is 20-30cm/year. The deformation extent of the Badin area is relatively low and progressively growing from East to West (Kemal et al., 1991; Khan et al., 2019).

The focus of this study is analysis and estimation of petrophysical data for accessing the hydrocarbon potential in Jabo-01 and Jabo-05 well Badin Block, structural interpretation of different rock units and 3D model generation. Petrophysics is one of dimensional method for learning of hydrocarbon system and geological environments, porosity calculation, water saturation, permeability, volume of shale and net-to-gross ratio, etc.

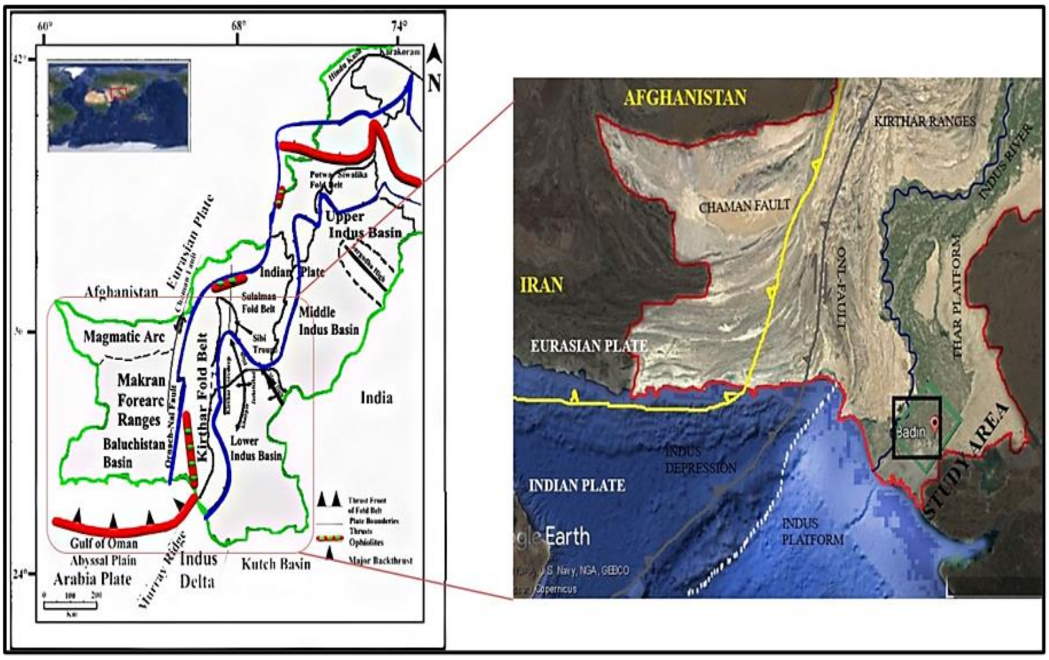

Fig. 1 Location of the study area (S.M. Mozzaffar Alam, 2003, BP Pakistan Exploration and Production.

Stratigraphy

The study area consists of rocks ranging from Chiltan Formation of Jurassic age to recent Alluvium/ Siwaliks Group (Solangi et al., 2015) Table 1.

Table 1 General stratigraphy of Southern Sindh Monocline (Abbasi et al., 2015)

ERA	EPOCCH		FORMATION	LITHOLOGY	RESERVOIR	SEAL	SOURCE	DISCOVERIES
CENOZOIC	NEOGENE		SIWALIKS/ ALLUVIUM					
			GAJ/ NARI					
	PALEOGENE	EOCENE	KIRTHAR Fm.					
			LAKI					
		PALEOCENE	RANIKOT VOLCANICS					
MESOZOIC	CRETACEOUS	LATE	PARH					
			UPPER GORU					
		EARLY	LOWER GORU – UPPER SAND: TURK SHALE, BADIN SHALE, JHOL SHALE (A SAND, B SAND, C SAND, D SAND)					BADIN
			LOWER GORU – UPPER SHALE					
			LOWER GORU – MIDDLE SAND					BADIN
			LOWER GORU – LOWER SHALE					
			LOWER GORU – BASAL SAND					ADAM X-1, BADIN,
			TALHAR SHALE					
			MASSIVE SAND					ADAM X-1
			SEMBAR					
	JURSSIC	LATE	CHILTAN					
		MIDDLE						

Hydrocarbon Potential

The geology of the area indicates the favorable conditions for the production and trapping of hydrocarbons (Zaigham and Mallick, 2000). Shales of Sembar and Lower Goru formations are the major source rock units while Lower Goru sandstone have good potential to act as a reservoir and have the porosity in range from 25% to 30% and permeability reaches upto 1 Darcy in this area (Quadri and Shuaib, 1986; Hussain et al., 1991). The major seal rocks are Upper Goru shales. The regional seals are provided by intraformational shales of the Lower Goru Formation. The Upper sand of the Lower Goru Formation is sealed by Upper Goru shales from both top and sides. (Zaigham and Mallick, 2000).

The first exploration in Southern Indus Basin was performed near Karachi by Burmah Oil Company (BOC) in 1939. United Energy Pakistan Limited (UTP) drilled the Jabo-01 exploratory well, which was discovered in 1986 at a total depth of 2228 meters at the top of Lower Goru. Jabo-05 was drilled by the British Petroleum in 2003 at a depth of 2077 meter up to the top of Lower Goru and produced oil.

Table 2 is showing source and reservoir rocks of study area. Shale rocks are mainly source rocks and sandstone is major reservoir rock in southern Indus basin.

Table 1 Source and reservoir rocks of Southern Indus Basin (modified after Quadri and Shuaib, 1986; Sheikh and Giao, 2017).

SOUTHERN INDUS BASIN			
Age	**Formation**	**Rock type**	**Remarks**
Source Rocks			
Eocene	Laki	Shale	Good
Paleocene	Ranikot	Shale	Good
Cretaceous	Mughalkot	Shale	Good
	Parh	Shale	Fair
	Goru	Shale and mudstone	Moderate
	Sembar	Limestone	Main source
Jurassic	Chiltan	Shale/Limestone	Fair
Reservoir Rocks			
Eocene	Laki	Limestone	Good
	Habib Rahi Limestone	Limestone	Good
	Sui Main Limestone	Limestone	Very good
Paleocene	Ranikot	Limestone/ Sandstone	Good
Cretaceous	Pab	Sandstone	Good
	Lower Goru	Sandstone and Mudstone	Very good to excellent
Jurassic	Chiltan	Limestone	Good

MATERIALS AND METHODS

The dataset is facilitated by the Directorate General Petroleum Concessions of Pakistan (DGPC). Seismic data is provided in SEG-Y format. Eleven 2D lines of the seismic sections have been used as shown in Table 3. The borehole Jabo-01 is located on the seismic line GPK86-1200 (Fig. 2). Kingdom suite 8.8 was used to interpret the seismic lines of the Jabo field.

Figure 2 is showing a base map on which eleven seismic lines are displayed. Out of these eleven seismic lines, 6 are the Strike lines and the remaining 5 are the Dip lines (Table 3).

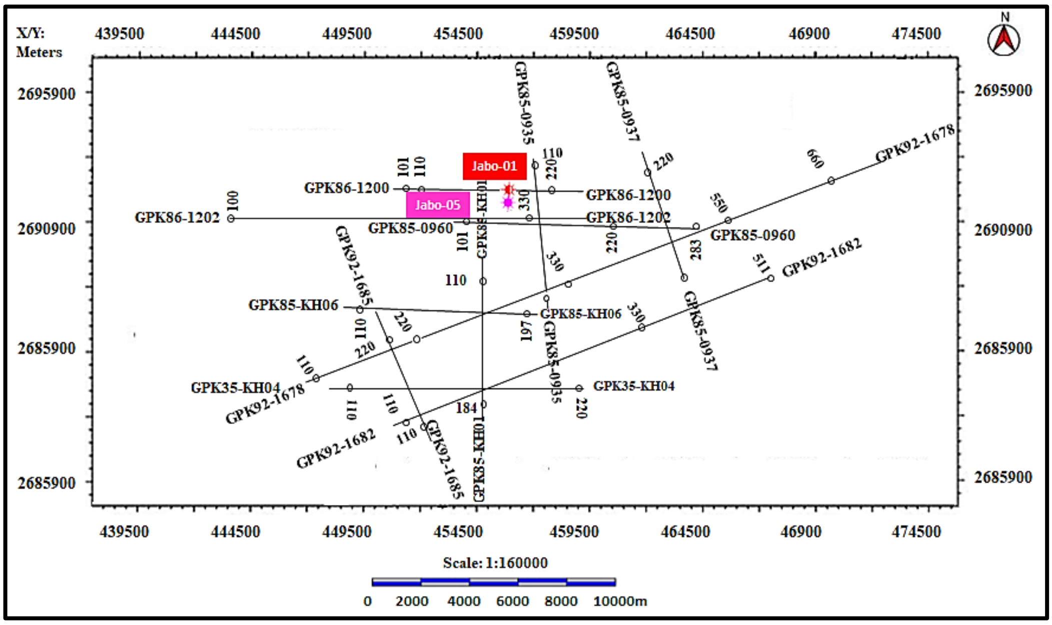

Fig. 2 Base map showing seismic lines and well location with the scale of 1:160000 (Kingdom Suite 8.8).

Table 2 Details of seismic data used in the research.

Sr. No.	Line name	Orientation	Nature of line	Well name	Well type
1	GPK86-1200	E-W	Dip	Jabo-01 Jabo-05	SWD (Salt Water Disposal Well) Exploratory Gas/Con.
2	GPK86-1202	E-W	Dip		
3	GPK85-0960	E-W	Dip		
4	GPK85-KH06	E-W	Dip		
5	GPK85-KH04	E-W	Dip		
6	GPK85-KH01	N-S	Strike		
7	GPK85-0937	NNW-SSE	Strike		
8	GPK92-1678	NNE-SSW	Strike		
9	GPK92-1682	NEE-SSW	Strike		
10	GPK92-1685	NNW-SSE	Strike		
11	GPK85-0935	NNW-SSE	Strike		

Seismic Data Interpretation

Horizon Picking

Three horizons were traced and these horizons were picked on the base of well tops of the Jabo-01 and Jabo-05. GPK86-1200 was then flattened as one seismic section in seismic view. Keyline GPK86-1200 (E-W) was tied with the GPK85-0935 strike line (NNW-SSE) to track the horizons on the strike line shown in Figure 2. Seismic line GPK85-0935 is comprised of more straight reflectors that are indicative of lesser deformation (Fig. 5). In this way, it is easier to track horizons on other dip lines from the strike line.

Fault Marking

The Badin area of Jabo-01 and Jabo-05 well exhibits extensional tectonics that forms the normal fault, resulting in horst and graben (Fig. 3, Fig. 4 and Fig. 5)

Faults are marked easily on these dip lines (GPK 86-1200, GPK 86-1202) as shown in Fig. 2 and Fig. 3. The dip of faults on dip lines is in the E-W direction.

Petrophysics

Petrophysical parameters give a direct indication of permeability, water saturation, and hydrocarbon movability, the volume of shale, porosity, net-to-gross ratio (both primary and secondary), lithology, sedimentary environments, formation dip and structure and hydrocarbon type (gas, oil, or condensate). A single logging tool cannot extract all the necessary information from a reservoir. Hence different logging tools are designed for different operations as listed in Table 4.

Data provided for petrophysical study of Jabo-01 and Jabo-05 well of Badin Block are different geophysical logs such as, digital wireline logs LAS format including GR log, resistivity log (MSFL, LLD, LLS), caliper log, SP log, neutron porosity logs and density logs for petrophysical analysis. Techlog software 2015.3 (64-bit) approaches were utilized for interpretation.

Table 4 General classification of loggng tools on basis of log type.

No.	Logging Tool	Log Type	Information
1	Gamma Ray	Nuclear	Shale Volume
2	Density Log	Nuclear	Bulk Density
3	Neutron Porosity Log	Nuclear	Porosity Calculation
4	Spontaneous Potential Log	Electrical	Permeability Estimation
5	Resistivity Log	Electrical	True Resistivity of Formation
6	Sonic Log	Acoustic	Interval Transit Time

RESULTS AND DISCUSSIONS

The structure of the Jabo Field is inferred using seismic interpretation of seismic lines GPK 86-1200, GPK86-1202, and GPK-0935. These normal faults are forming the horst and graben, half grabens, and crotch structures. Horst and graben geometry is crucial for hydrocarbon accumulation and grabens are the kitchen zone for their production (Munir et al., 2014). Mostly, the Cretaceous portion is showing faults that represents the tectonic history of the area. The Eocene portion is also showing the tilted faults and disturbances in the strata due to the forces applied in nature.

On the dip line GPK-1200, Khadro Formation is dipping towards the east. Host-graben system is present at Parh Limestone and Goru Formation level, half-grabens and crotches are formed.

On the dip line GPK-1202, there is uplifting of Khadro stratum in the east direction and deepening of this stratum is in the west direction (Fig. 4). Normal faulting is observed at Parh Limestone and Goru Formation level whereas fault (F6) is also cutting the overlying Khadro Formation. The horst-graben sequence, which leads to half grabens, crotches and faulted blocks in the study area, is considered to cause extensional rifting (Fig. 3 and

Fig. 4). The throw of fault 4 at Goru Formation level is 0.032 seconds, at Parh Limestone is 0.065 seconds and at Khadro Formation is 0.023 seconds (Fig. 3). Throw at Parh Limestone level is comparatively higher.

On the strike line GPK-0935, horst and graben structure is formed at Parh Limestone and Goru Formation (Fig. 5).

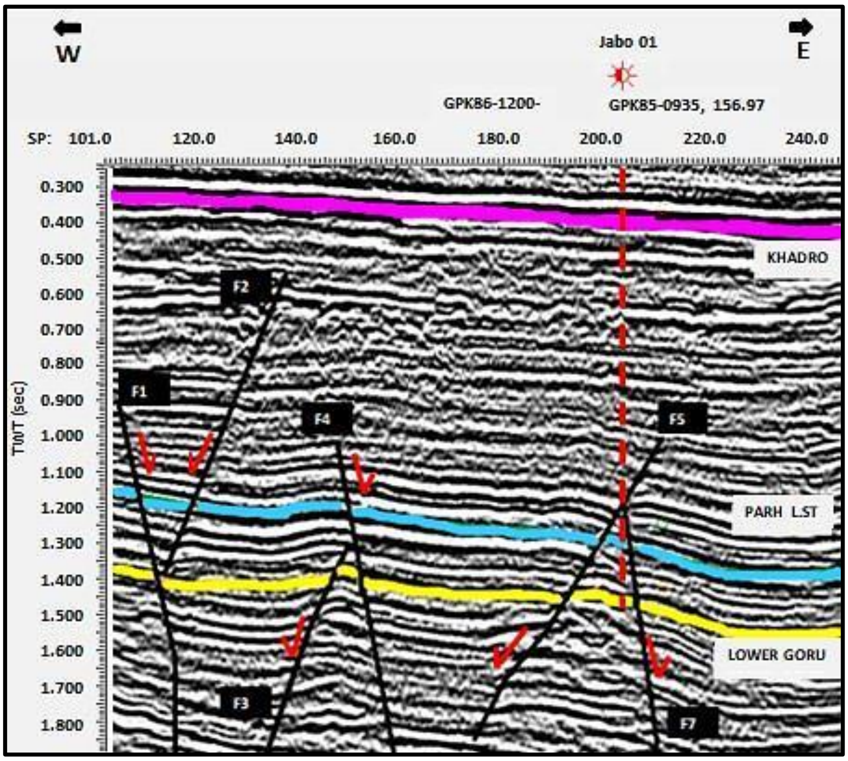

Figure 3 Interpreted seismic line 1200 a dip lin

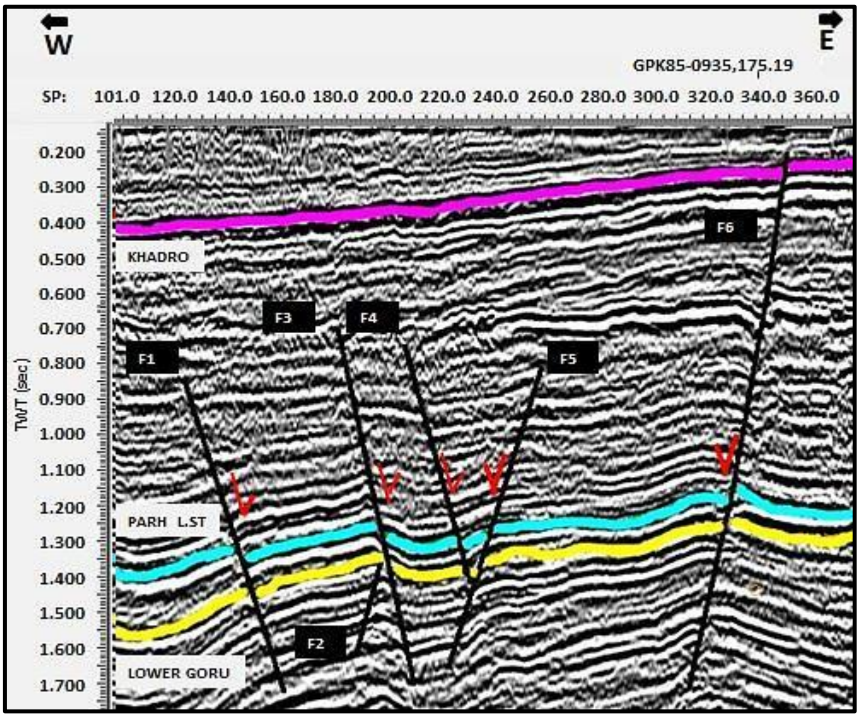

Fig 4 Interpreted seismic line 1202 a dip line.

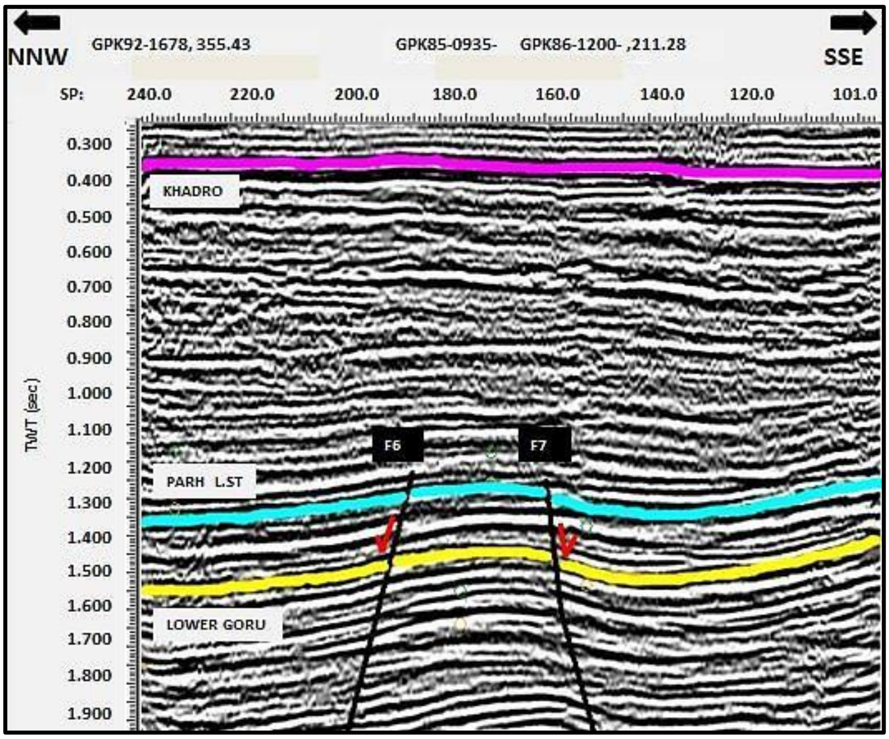

Fig 5 Interpreted seismic line 0935 a dip line.

Time Contour Maps

In this research, the reflectors of relevance are Goru, Parh and Khadro Formations. On the base map, the time contour maps of these three major reflectors on eleven seismic sections are projected.

The contour maps are created to enhance subsurface vision and to observe lateral and vertical time changes in the subsurface. Two features are observed in TWT contour maps i) shallower area (high area with low contour values) and ii) deeper area (low area having higher values of contours).

TWT structure maps are generated for three horizons that are Goru Formation, Parh Limestone, and Khadro Formation.

Goru Formation

The reflection time is increasing from 1.150 to 1.968 s. Contour interval is 0.04 sec. shallowest contour Value is at time 1.150 s whereas deepest contour value is at time 1.968 s. At Jabo-05 well location contours are forming dome and time value is shallowest 1.150s. There is probably a trap. Toward Jabo-05 well contour values are decreasing whereas to the further N and S contour values are increasing. Horst and Graben system is present here (Figure 6).

Parh Limestone

The reflection time is increasing from 1.046 to 1.835 s. Contour interval is 0.06 sec. shallowest contour value is at time 1.046 s whereas

Deepest contour value is at time 1.835 s. Jabo-01 and Jabo-05 are at shallow time. To the S of them, a basin is formed where the contour values are increasing inward. Half Grabens and Horst and Graben are present here (Figure 7).

Khadro Formation

The reflection time is increasing from 0.167 to 0.591 s. Contour interval is 0.03 sec. shallowest contour value is at time 0.167 s whereas deepest contour value is at time 0.591 s. Khadro is deepening towards E. A dome is formed at the Jabo-05 well location. Horst and Graben system is present here (Figure 8).

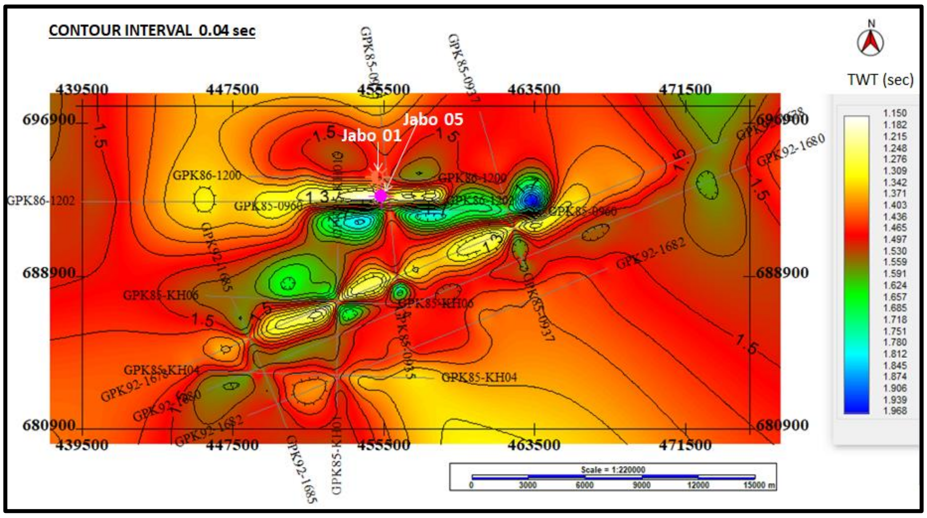

Fig. 6 Time structure map of Goru Formation.

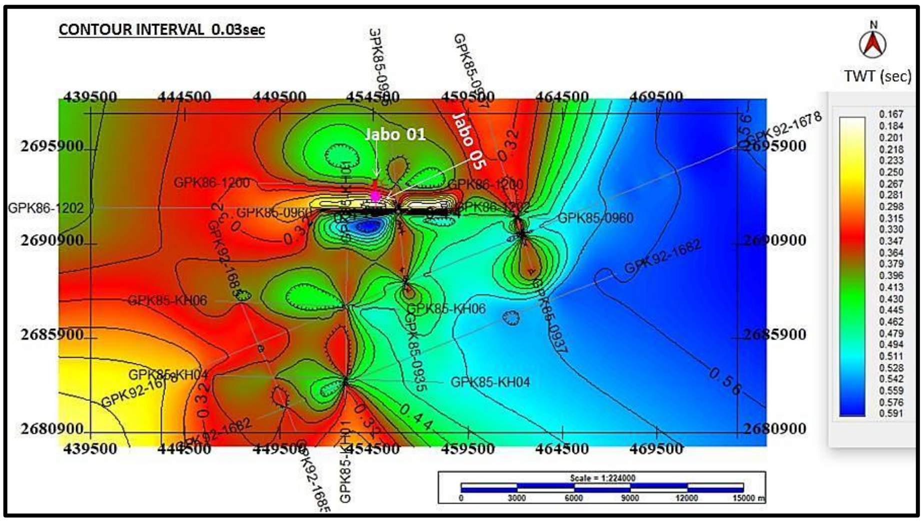

Fig. 7 Time structure map of Parh Limestone

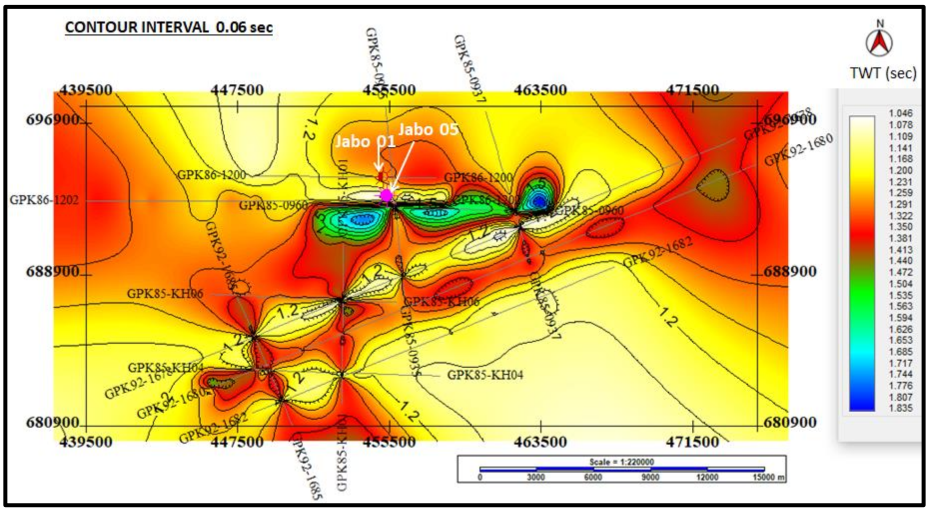

Fig. 8 Time structure map of Khadro Formation.

Isochron maps

Isochron maps show the changes in thickness with respect to variations of two way travel time between reflectors. We can delineate the relationship between tectonic surface and fault analyses at various levels; isochron maps of Khadro Formation and Parh Limestone.

Fig. 9 shows an isochron map of Khadro Formation two way travel time in seconds. Vertical and horizontal axes are geographical coordinates in meters. TWT ranges from 1.415 to 0.622s. Isochron map indicate that Khadro Formation is thinner to the SE (Fig. 9).

Fig. 10 shows an isochron map of Parh Limestone two way travel time in seconds. TWT ranges from 0.443 to 0.048s.

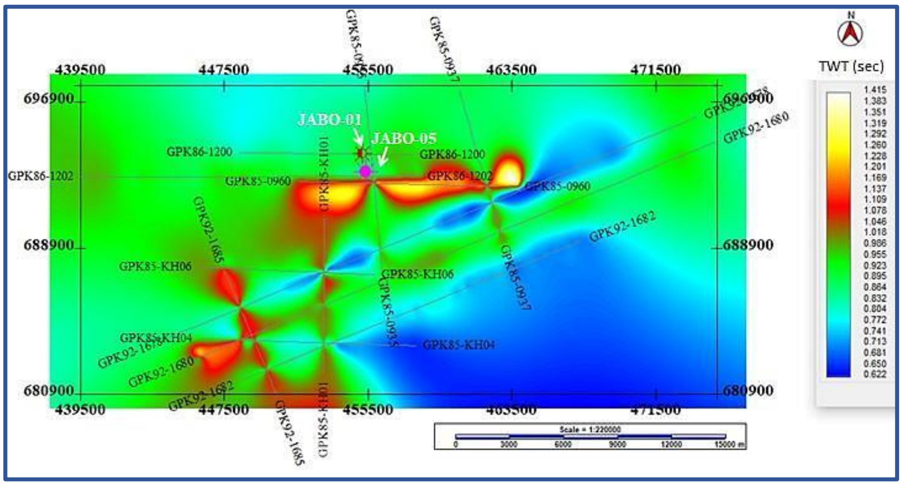

Fig. 9 Isochron map of Khadro Formation

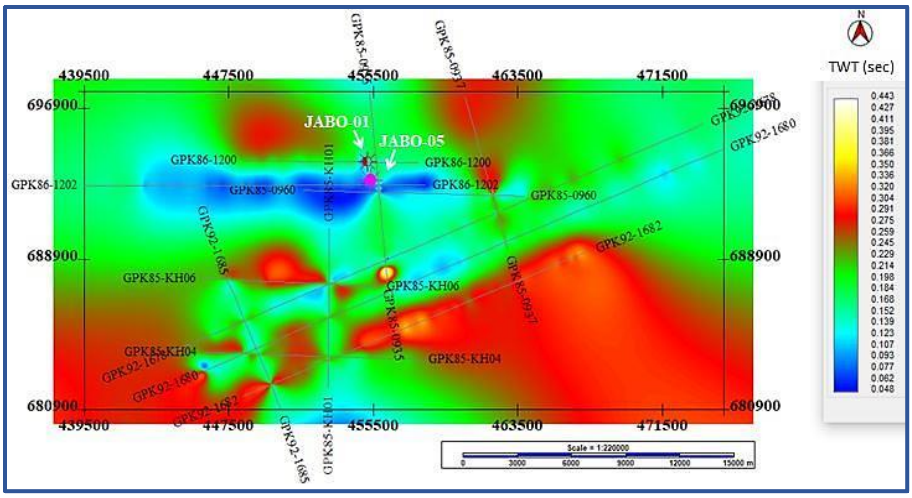

Fig. 10 Isochron map of Parh Limestone

3-D Grids

Figures 11,12,13,14 are showing the 3-D subsurface structural models of the study area. In these figures, subsurface structural patterns of Khadro Formation, Parh Limestone, and Goru Formation are shown.

Figure 11 is showing a deepening trend of the Khadro Formation towards east. Fault is present and some depressions are shown but the overall trend is almost straight. Towards E, it is sloping deep. Khadro is shallower in the west and deeper in the east. In the middle of grid, there is Horst and Graben system. Figure 12, 13 are showing the network of Horst and Grabens or Half Grabens. Figure 13 is the 3D model of the reservoir rock (Goru Formation). Trap and depressions are visible in Figures 12, 13.

Figure 14 is the 3D model of all the reflectors. The same trend is observed in all the reflectors. Khadro Formation is most straightening comparative to the other Formations. Goru and Khadro Formation are showing clearer structures.

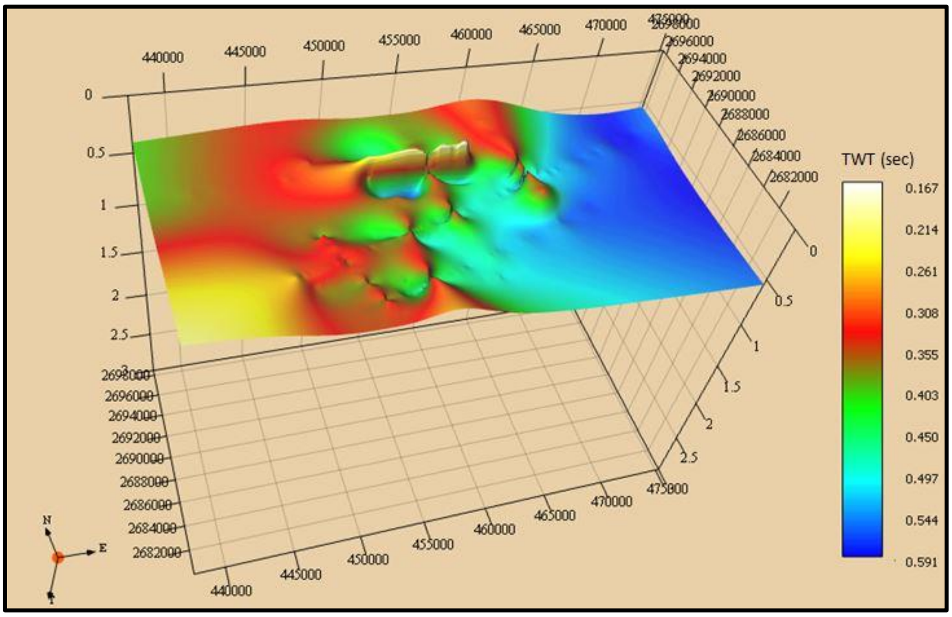

Fig. 11 3D model at the Khadro Formation level.

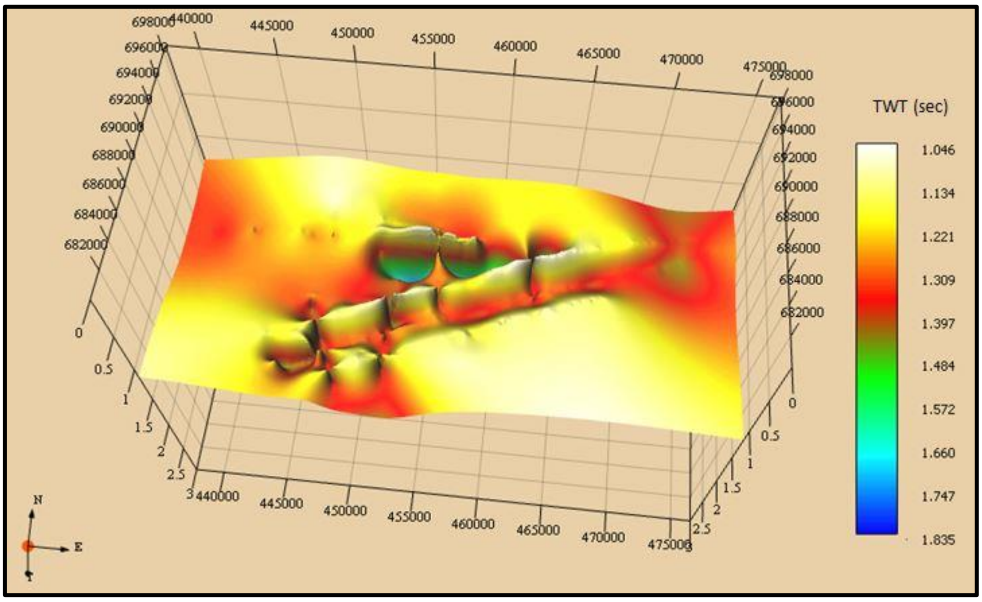

Fig. 12 3D model at the Parh Limestone level.

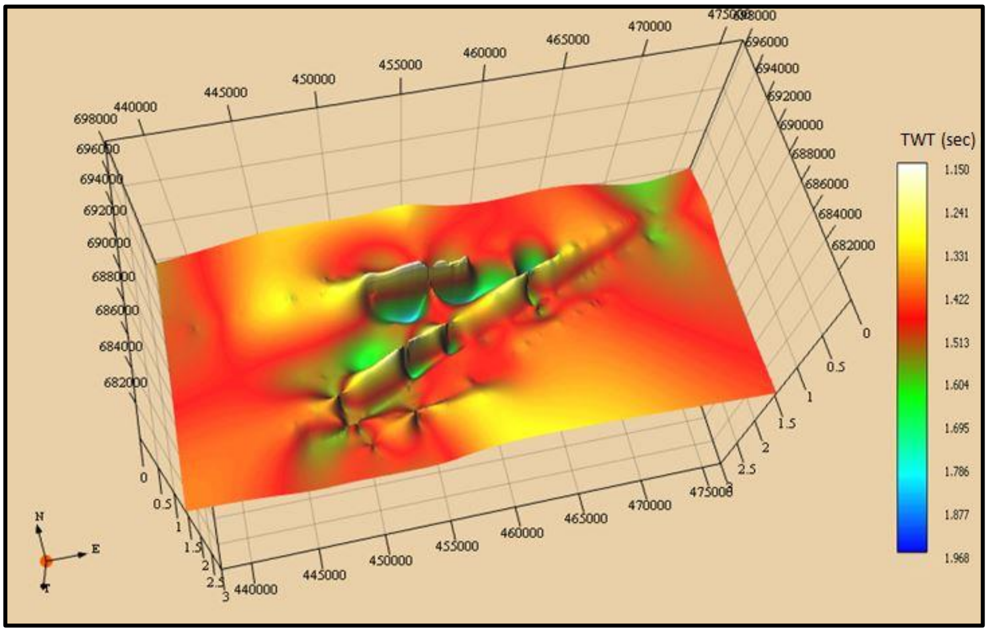

Fig. 13 3D model at the Goru Formation level.

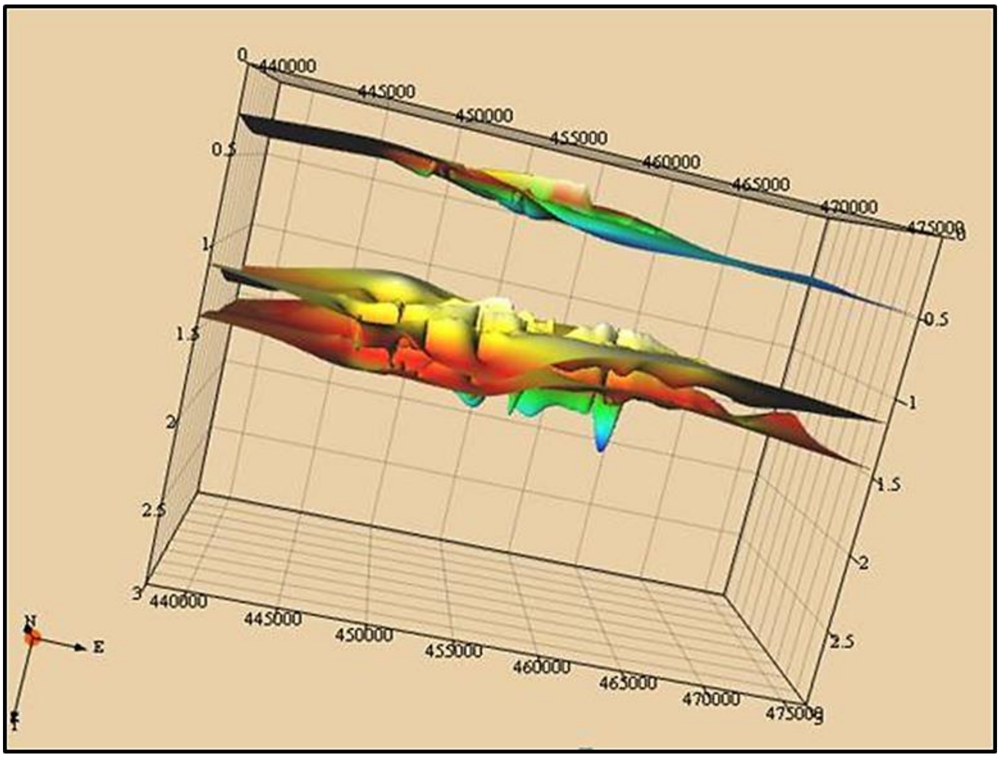

Fig. 14 3D model of all the reflectors.

Petrophysical Analysis

From petrophysical calculations, Jabo-01 is interpreted as salt-water waste disposal with maximum saturation of saline water with small patches of hydrocarbon saturation. Two reservoir zones are observed in the Jabo-05 field at the depth interval from 1952-1968m and 1989-2007m with thicknesses 16m and 18m respectively.

Between these two zones are alternate beds of shale and sand as indicated by GR-log. Sand is indicated by low values of gamma ray log while shale has higher GR-log values. To mark the zone of interest, different logs were used (Fig. 15).

Gamma-ray log is used to calculate the shale volume from which pure sand is of our interest, total porosity was calculated by PHIT-ND porosity log while the permeability was calculated by Wellies Equation. Spontaneous log (Sp) is commonly used for permeability purposes that indicate interest zone with a negative value, resistivity logs were used to calculate fluid saturation. Generally, MSFL<LLS<LLD is the trend for the required hydrocarbon-bearing zone of interest (Fig. 15). These two zones were quantitatively analyzed and the values of shale volume, water saturation, permeability, porosity, and resistivity were calculated. At the depth of 1997m, there is a thin bed of shale that is indicating the regressive conditions at the time of deposition marked by high values of gamma-ray log.

The resistivity log shows that there is oil in the Jabo-05. The average porosity calculated is 13% for both zones and average shale volume is 18% and 42% for zone 1 and zone 2 respectively. The average saturation of water is 20% for zone 1 and 41% for zone 2 indicating that void space proportion is very low for water and consequently with high saturation of hydrocarbon (80% and 59%) with net pay zone of 16m and 18m thickness, respectively, that is characterized by high hydrocarbon saturation, low shale content and good porosity. Hydrocarbon type is observed from the density-porosity cross over that is oil in both zones. Particular response of well logs is shown in Fig. 15 and Fig. 18 showing hydrocarbon-bearing zones.

Wells Correlation

On the top of the Lower Goru Formation, Jabo1 and Jabo 5 are correlated (Fig. 18). Based on log responses, two zones from each well are selected that is having good reservoir quality. Zone 1 of Jabo 5 is clean sand and is correlated with Zone 1 of Jabo1 that is also the clean sand. Gamma-ray log response of zone 2 of Jabo 5 is showing mixed sand-shale lithology. With the help of gamma ray (GR), resistivity logs (MSF, LLS, LLD), and neutron-density porosity crossover both the zones are marked. The depth of zone 1 in Jabo 5 is 1952-1968m and in Jabo 1 is 1977-1993 whereas the depth of zone 2 in Jabo 5 is 1989-2007 and in Jabo 1 is 1994-2011. In Jabo 1, gamma ray log response of zone 1 is serrated-cylindrical shaped and zone 2 is smooth- cylindrical shaped while in Jabo 5, gamma-ray log response of zone 1 is smooth-cylindrical shaped whereas that of zone 2 is serrated-cylindrical shaped.

Smooth-cylindrical shaped log response shows the uniform deposition whereas serrated-cylindrical shaped gamma-ray log response shows proximal deep-sea fan (Bjorlykke, 2010) with total thickness of zone 1 is 16m and zone 2 is 18m. RHOB-NPHI crossover in Jabo 5 is showing good hydrocarbon potential whereas in Jabo 1 small patches of hydrocarbon are observed in both zones. Although resistivity logs showing a good reservoir potential trend that is, MSFL<LLS<LLD but this trend is not observed continuously. From these log responses, it is interpreted that Jabo 5 field of Badin area has better reservoir potential than Jabo 1 of this area that has little hydrocarbon potential. It is easily concluded from the GR log response that both zone are gradually deposited or comprised of proximal deep-sea fans deposits. Schematic diagram of well correlation (Fig. 19).

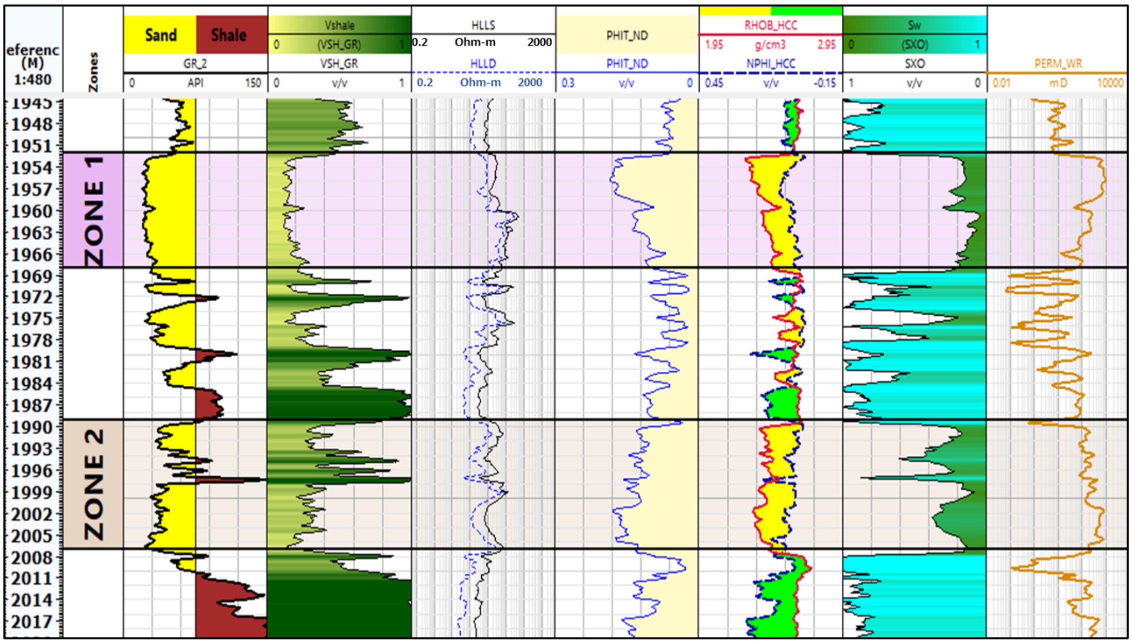

Fig. 15 Response of different well logs (GR, Vs, RHOB, NPHI, HLLS, HLLD, Sw, PHIT-ND and PERM_WR) of Jabo-05.

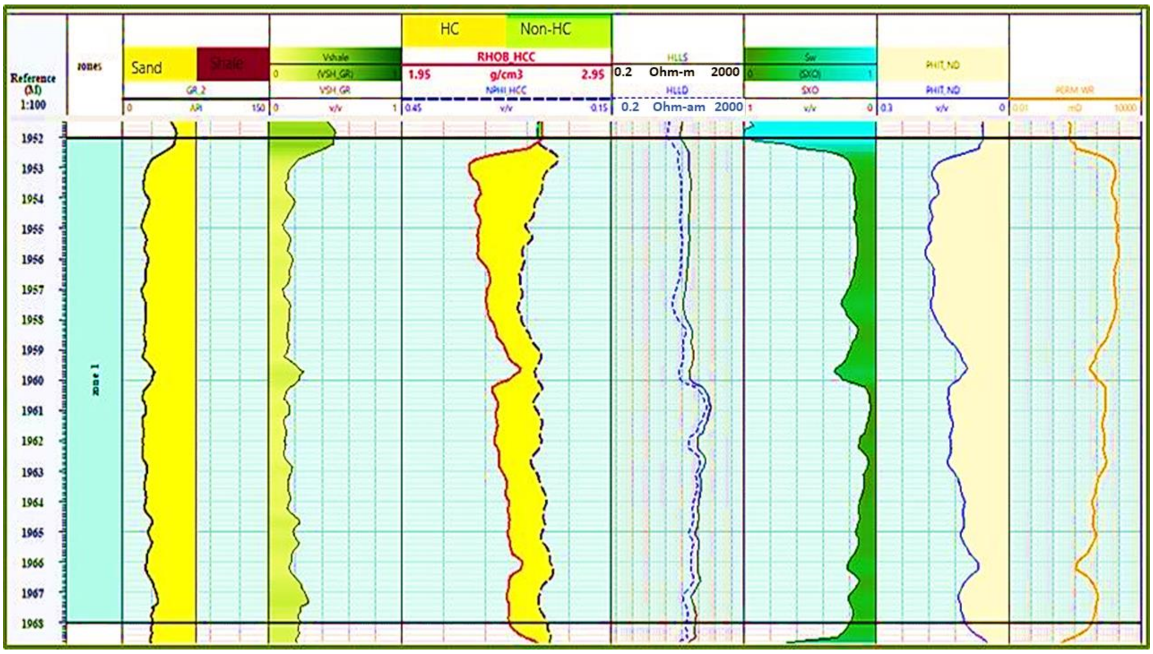

Fig. 16 Hydrocarbon bearing zone 1 of Jabo 5 well from NPHI and RHOB crossover.

Table 3 Summary of the results from log analysis of Jabo-05

Zone 1									
Interval (m)	V_{sh}	Φ_{avg}	Net Pay (m)	S_w	S_{hc}	LLD (Ωm)	LLS (Ωm)	K (mD)	Hydrocarbon Predicted
1952-1968	18%	13%	16	20%	80%	126.75	91.84	351.08	Oil
Zone 2									
Interval (m)	V_{sh}	Φ_{avg}	Net Pay (m)	S_w	S_{hc}	LLD (Ωm)	LLS (Ωm)	K (mD)	Hydrocarbon Predicted
1989-2007	42%	13%	18	41%	59%	33.71	29.4	276.03	Oil

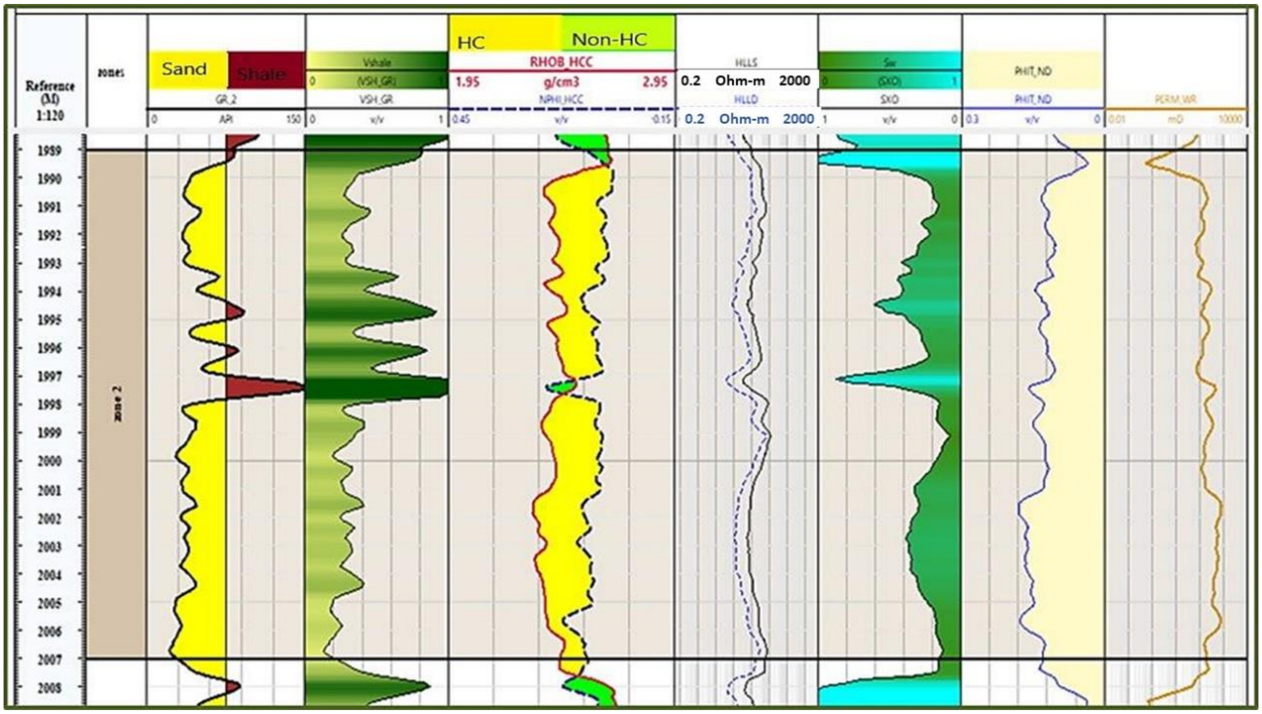

Fig. 17 Hydrocarbon bearing zone 2 of Jabo 5 well from NPHI and RHOB crossover.

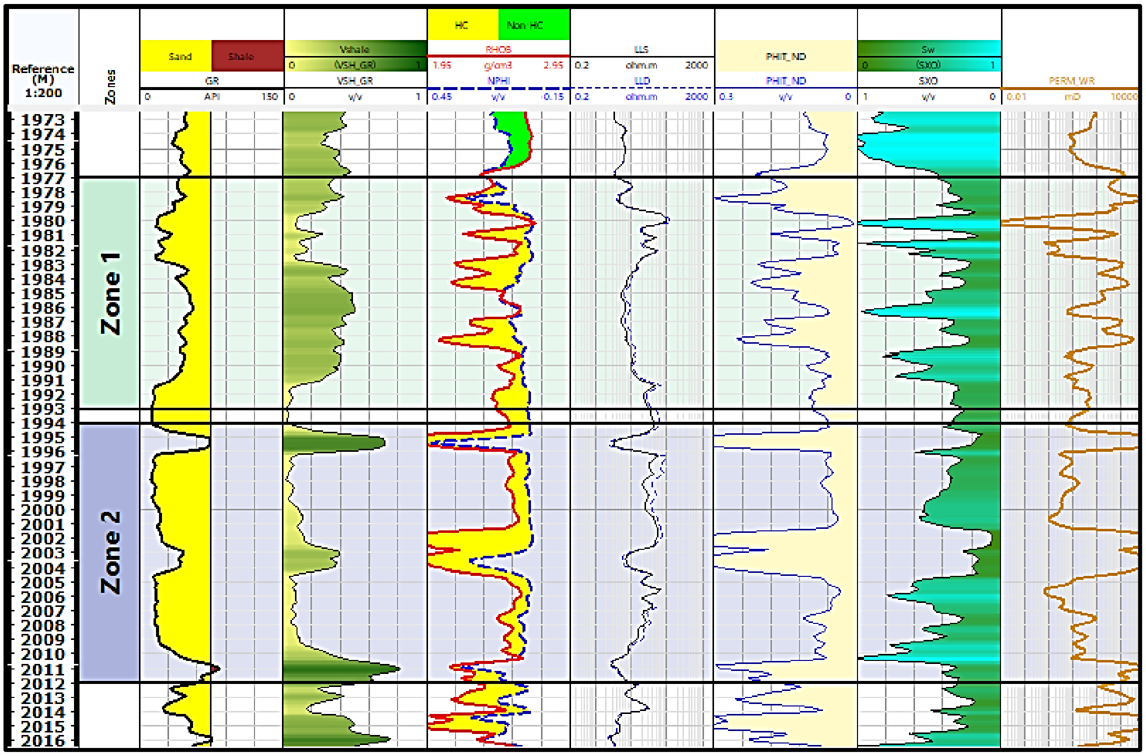

Fig. 18 Hydrocarbon bearing zones 1 and 2 of Jabo-01 well.

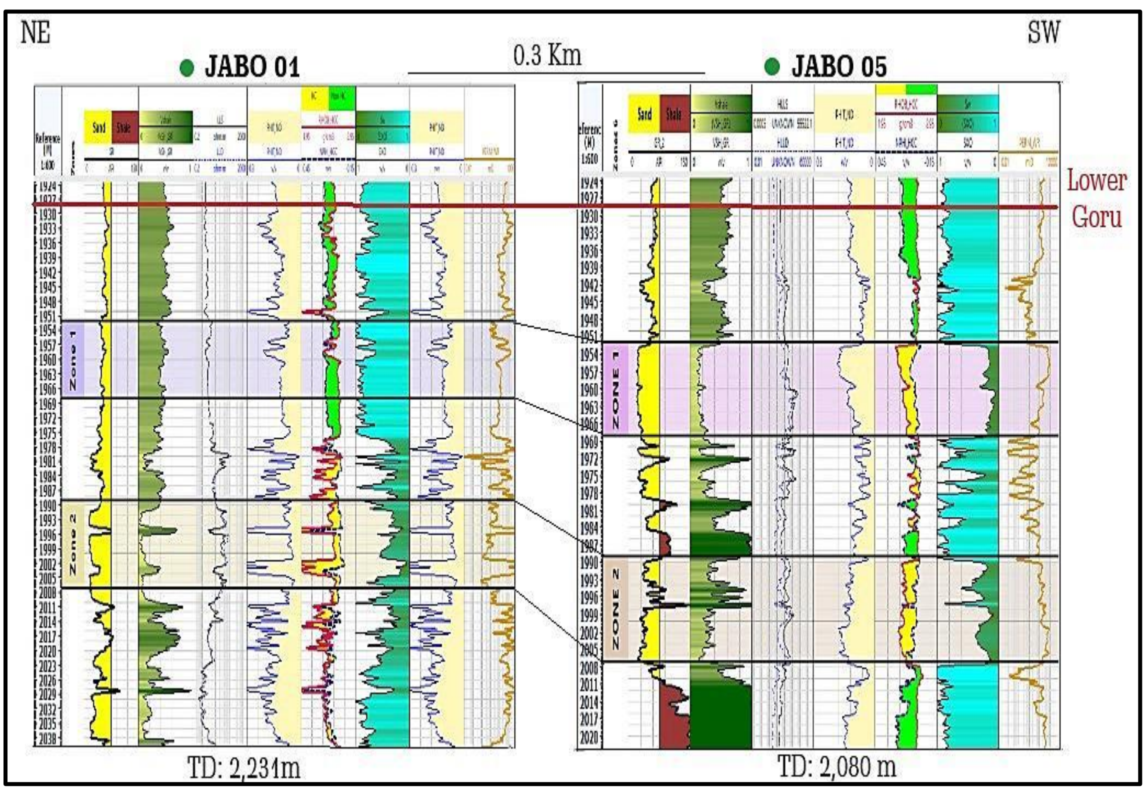

Fig. 19 Schematic diagram Jabo-01 and Jabo-05 well correlation

CONCLUSIONS

The structures of the current study area revealed evidence for three major structural episodes, which can be characterized as: structures associated with rifting during the Late Jurassic to Early Cretaceous, modification reactivation during the Middle Cretaceous, and reactivation of earlier structure at the time of Indian plate collided with Asia. These results are based on an extensive review of published literature on tectonic episodes of the Indian plate and seismic data interpretation (Chatterjee et al., 2013). Seismic results of 2-D interpretation and 3-D visualization of grids interpret that the study area is an extensional regime. The study presents the structural perspective of the research area. The appearance of normal faulting in Jabo field, which suggested extensional stresses at the southern side of Sindh Monocline, reveals the presence of horst and graben structure at the Lower Goru level (Cretaceous) mainly and at Parh. The throw of the main fault line interpreted in this research work is 0.032 seconds at Goru Formation level. The petroleum system of the area is proven by the number of oil and gas fields there. In the Badin area, major reserves and production are from the Lower Goru Formation. The study area is located in the Lower Goru Formation, which increases the potential of future exploration in this area (Wandrey, 2004). A comprehensive wireline logs analysis is performed on two wells, Jabo1 and Jabo 5 on the reservoir unit of the study area that is the Lower Goru Formation (Cretaceous). After calculation of different petrophysical parameters, Jabo 1 is observed as SWD (salt water disposal) while hydrocarbon type observed in Jabo 5 is oil that is confirmed by cross over of neutron and density logs. The sand of the Lower Goru Formation constitutes the main gas and oil-producing reservoir in the study area following to the petrophysical analysis. The two promising sand zones with good reservoir quality are recognized using correlation with the well data. The findings of this study indicate that an analysis of seismic parameters combined with petrophysics can aid in the prediction of unexploited zones in an already developed region.

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