Indian Journal of Geo Marine Sciences
Vol. 49 (4), April 2020, pp. 678-685

Integrated approach for reservoir characterization and field development of Meyal area, Upper Indus basin, Pakistan

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Received 01 October 2018; revised 01 December 2018

Seismic data commonly provides insight into subsurface reservoirs. However, only seismic is not capable to completely evaluate reservoir pore fluid heterogeneities. Therefore, an integrated approach of seismic interpretation, petrophysical analysis and Gassmann fluid substitution is used in Meyal area, for its reservoir depiction and field development. The results of seismic analysis reveal that the study area is in compressional regime and thrust bounded pop-up structure makes it appropriate for hydrocarbon accumulation. A new lead is identified that could be probable hydrocarbon potential zone. Petrophysical investigation depicts that the zone is saturated with hydrocarbon and hold suitable effective porosity. In addition, fluid substitution in desired zone reflects variations in elastic properties (P, S-wave velocity and density) when substituted with brine. The maximum variations are perceived at maximum saturation of brine. This approach can be confidently applied to quantify reservoir potential in any sedimentary basin of the world.

[Keywords: Fluid substitution, Petrophysics, Reservoir characterization, Seismic interpretation]

Introduction

Reservoir characterization is a multidisciplinary process and needs different types of data, which provides direct or indirect information about subsurface[1]. In reservoir characterization, various reservoir properties are deliberated using an integrated set of presented data[2]. Most of the reservoirs consists of two (gas–water or oil–water) or three (gas, oil and water) different phases of liquid required to be characterized[3,4]. Most significant task in reservoir characterization is its economic value estimation and future performance prediction, so it requires accurate methods utilization to obtain error free results[3]. Seismic interpretation assists to delineate hydrocarbon accumulating subsurface structure by time and depth contour maps[5-8]. Furthermore, petrophysical analysis supports to quantify diverse physical characteristics including volume of shale, porosity, water and hydrocarbons saturation[3]. In addition, fluid substitution provides away for identification and quantification of fluid in reservoir. Principal cause in failure of development well is rising of water saturation[6]. It is very intricate to evaluate water saturation information from seismic data unless we include rock physics modeling. Rock physics will facilitate to delineate fluid depletion impact on different seismic elastic properties such as P- and S-wave velocity as well as density[9,10].

Meyal area is a foremost oil and gas producing field in the Potwar Basin[7,8,11]. In the Meyal field (1968), Pakistan Oil-fields Limited (POL) revealed the petroleum system and at present, 16 exploratory wells are inspected. Most of the wells in the Meyal area are drilled on the basis of conventional structural interpretation, seismic amplitude anomalies related to the pore fluid are ignored. In the current study, prime objective is to present an integrated analysis of seismic interpretation, petrophysics response and fluid substitution for reservoir characterization and field development of Meyal area, upper Indus basin, Pakistan.

Materials and Methods

Geological setting

Geologically, Meyal field lies in Potwar sub-basin[7,8,11] (Fig. 1). This sub basin was generated owing to the tectonic activities in Post-Eocene time hence it is extremely affected by the transpressional forces[12,13]. These transpressional forces developed pop-up structures and faults termination from basement depicting thick-skinned tectonics[7,14]. The main boundary thrust (MBT), Salt Range Thrust (SRT), Kurram and Khair-i-Murat thrust faults, Jhelum and Kalabagh faults are the foremost geologic structures of the Potwar area[15-17]. Fold structures in this area are normally oriented in a sublatitudional fashion and these structural complexities are increased toward northward. Most of the wells in Potwar sub-basin are drilled on the basis of structural interpretation[15].The Potwar area is divided into two broad zones by Soan syncline, the North Potwar Deformed Zone (NPDZ) and South Potwar Platform Zone (SPPZ)[7,8,18]. It is approximately extended 130 kms from MBT in north to SRT in south, and Jhelum strike slip fault is on the eastern boundary while Indus river and Kalabagh strike slip marks the western periphery[19,20]. Study area is situated at the northern flank of the Soan syncline[7,8,11,21]. The whole region is linked with Neogene buckling and outcrops as well as faults commonly reveal ENE-SSW trend at number of places. The subsurface structure of the Meyal area does not lie directly underneath the surface structure[22].

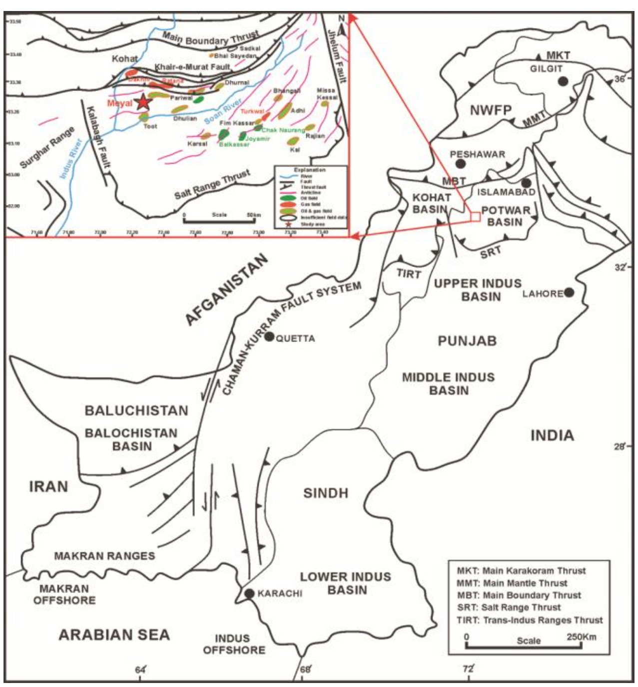

Fig. 1 — Generalized tectonic map of Pakistan showing Sedimentary Basins (Modified in GIS 10 after Farah *et al*.[23]). The red rectangle show the tectonic framework of the Potwar Basin where red star indicates the location of the study area

Potwar sub-basin contains varieties of rocks having age from Precambrian to Recent[22]. These rocks are deposited in fluvial to marine environmental settings[11]. The maximum depth reached by a well drilled in the Meyal field penetrated the Permian sequence (Fig. 2; Meyal-13 well). Prior investigations[7,8,11,22,24] propose the primary source rock in the study area is the Patala Formation of Paleocene age. The limestone's of Eocene are recognized as major hydrocarbon producing reservoir. Furthermore, the shale's of Miocene are identified as seal rocks[15].

Methodology

Data available for this study include six 2D seismic lines and wireline logs of two wells Meyal-01 and Meyal-17. Seismic lines orientation and location of the wells is illustrated on base map in Figure 3. The five lines S97-MYL-06, S97-MYL-07, S97-MYL-08, S97-MYL-09, and S97-MYL-10 are dip lines and S97-MYL-12 is strike line. This data was obtained by Directorate General of Petroleum Concessions (DGPC), Pakistan. Seismic Micro Technology Kingdom software was used to interpret seismic data and perform petrophysical analysis.

Era (Age)	Period (Age)	Epoch (Age)	Formation		Lithology	Lithological Discription	Drilled Thickness (m)
		Plio-cene	Nagri			Claystone & sandstone	Surface +157-672
Cenozoic		Miocene	Chinji			Claystone & siltstone	1340-1919
			Kamlial			Sandstone & claystone	156-225
			Murree			Sandstone, claystone & conglomertae	1341-1918
		Unconformity					
		Eocene	Kuldana			Shale	36-58
			Chorgali			Limestone & shale	63-78
			Sakesar			Limestone	81-107
			Nammal			Shale, limestone	13-32
		Paleocene	Ranikot			Limestone & shale	89-143
			Patala			Shale	11-19
			Lockhart			Limestone	44-76
			Dhak Pass			Sandstone, Mudstone	15-23
		Unconformity					
Mesozoic	Jurassic		Datta	Jurassic Variegated		Sandstone, Mudstone	66-84
				Jurassic Main Sand		Sandstone, Mudstone	15-36
	Triassic		Mianwali			Sandstone, Shale	155
Paleo-zoic	Permian						44

Fig. 2 — Generalized Stratigraphic Column of the Meyal Field (modified after Hasany & Saleem[22]; Riaz *et al*.[7,8])

Seismic interpretation is a way to transform subsurface information into a geological section structural interpretation sketches out structural traps which are plausive for hydrocarbon accumulation[5,25]. For seismic interpretation well to seismic tie is an important and essential step[5]. Datum adjustment has been done by subtraction of well Kelly bushing (KB) and seismic reference datum (SRD) from formation tops. The Kelly bushing (KB) in Meyal-01 and Meyal-17 is 374.71 m and 0.0 m respectively, while seismic reference datum is 350 m above sea level. Generalized workflow for seismic analysis is given in Figure 4(a).

Synthetic of wells Meyal-01 and Meyal-17 is displayed on seismic section along with marked horizons and well tops in Figure 5. On the basis of discontinuous and character two faults were identified as F1 and F2 Frontal thrust and back thrust respectively.

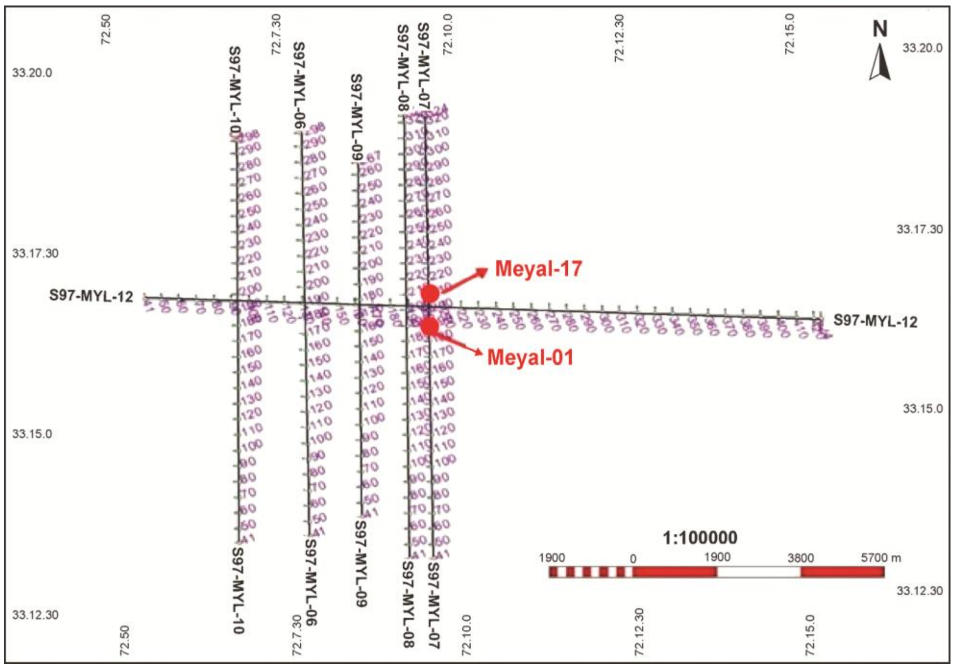

Fig. 3 — Base map of the study area showing location of seismic lines and well

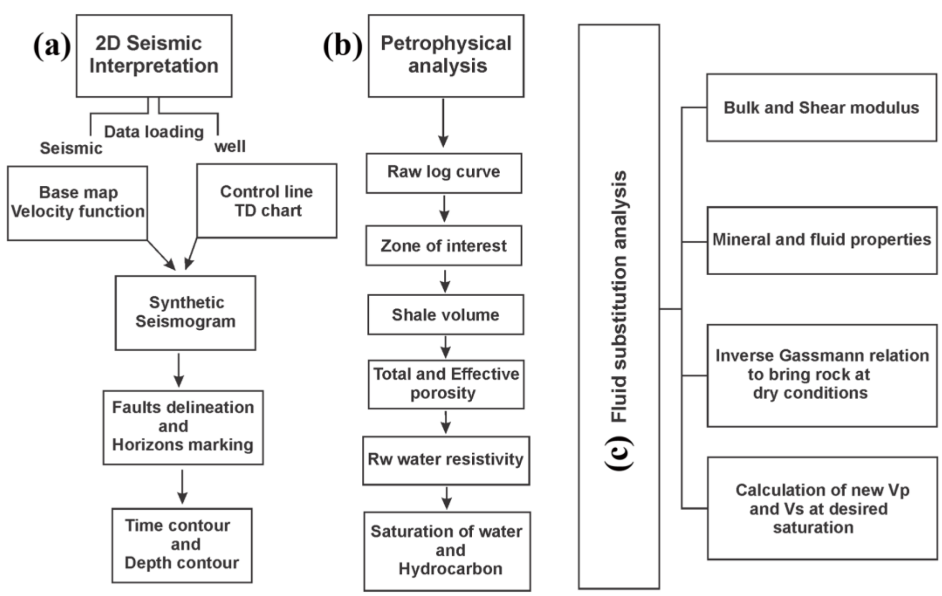

Fig. 4 — Work flow: (a) Seismic interpretaion, (b) Petrophysical analysis, and (c) Fluid substitution

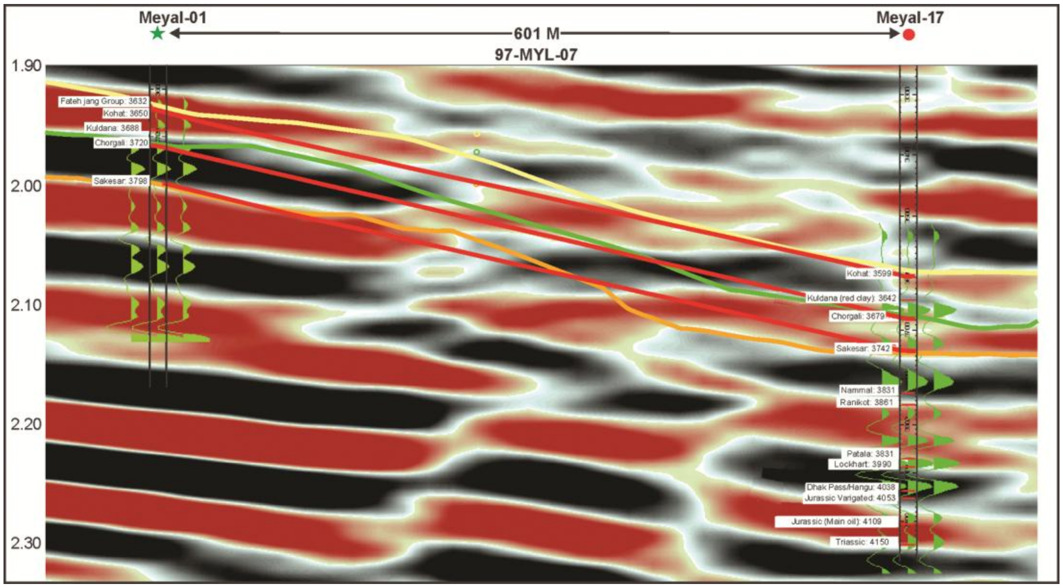

Fig. 5 — Synthetic of wells Meyal-01 and Meyal-17

The next part was to mark horizons, four horizons Chorgali (Green), Sakesar (Purple), Lockhart (Blue) and Jurassic sand (Yellow) were marked. On the top of the marked horizons two-way time (TWT) and depth, contour maps were generated to identify favourable hydrocarbon leads.

Furthermore, petrophysical analysis was performed on well Meyal-17. First of all, in desired zone shale volume was calculated with the help of gamma ray log, after that total porosity and effective porosity was calculated by using neutron and density logs.

$$V_{shale} = GR_{log}\text{-}GR_{min}/GR_{max}\text{-}GR_{min} \quad \ldots (1)$$

In next part using Archie equation water and hydrocarbon saturation was calculated.

$$Sw= \{Rw/(Rt*\phi m)\}1/n \quad \ldots (2)$$

Where Rw = Resistivity of Water, Rt = True Resistivity (obtained from LLD log), Φ = Porosity (PhiE - Effective Porosity), m = Cementation factor and n = Wettability factor. Complete workflow for petrophysics analysis is given in Figure 4(b).

In last part of study Gassmann fluid substitution analysis was performed. The workflow for fluid substitution is described in Figure 4(c). In fluid substitution initial step is to calculate bulk and shear modulus at in situ saturation conditions. The 2nd step is to compute dry rock bulk modulus that was calculated by using formula given by Zhu and McMechan[26].

$$K_{dry} = \frac{k_{sat}\left(\frac{\phi Kmat}{Kfl} + 1 - \phi\right) - Kmat}{\frac{\phi Kmat}{Kfl} + \frac{Ksat}{Kmat} - 1 - \phi} \quad \ldots (3)$$

In equation (3) K_{mat}, K_{fl}, K_{sat} and K_{dry}, are the bulk modulus of mineral matrix, fluid, saturated and dry rocks respectively. The ϕ is effective Porosity acquired from petrophysical analysis.

Voigt-Ruess-Hill averaging method[27] was used to calculate mineral matrix bulk modulus, while minerals matrix density was estimated by averaging the densities of individual minerals[28]. For fluid parameters determination Wood's relations were used[29]. The densities and bulk moduli of brine and hydrocarbon was obtained by Batzle and Wang relations[30]. When we have dry rock bulk modulus by using original equation of Gassmann[31], we can get desired saturated bulk modulus.

$$k_{sat} = k_{dry} + \frac{\left(1 - \frac{k_{dry}}{k_{mat}}\right)^2}{\left[\frac{\phi}{k_{fl}} + \frac{(1-\phi)}{k_{mat}} - \frac{k_{dry}}{k_{mat}^2}\right]} \quad \ldots (4)$$

and

$$\mu_{sat} = \mu_{dry} \quad \ldots (5)$$

The μ_{sat} and μ_{dry} are represent shear moduli of saturated and dry rock. The equation (5) tells us its independency from presence of fluid. Saturated density was calculated by relations of Kumar[28].

$$\rho_{sat} = \phi \rho_{fl} + (1-\phi)\rho_{mat} \qquad \ldots (6)$$

In equation 6 ρ_{sat} is saturated density, ϕ represents porosity, ρ_{fl} is fluid density and ρ_{mat} is matrix density.

For saturated P and S-wave velocity equation (7) and (8) were used.

$$Vp = \sqrt{k + 4/3\mu \big/ \rho} \qquad \ldots (7)$$

and

$$Vs = \sqrt{\mu / \rho} \qquad \ldots (8)$$

Results and Discussion

Seismic interpretation exhibits four marked reflectors and two thrusts F1 and F2 (Fig. 6). The pop-up anticlinal structure is produced owing to these thrusts which is present in the center of the line. Moreover, the throw of fault F1 is greater than the throw of thrust fault F2, which depicts the forces of hinterland are greater than the foreland[7,8]. This interpretation suggests that the pop-up structure is most likely to be the trap for the hydrocarbon.

Time and depth couture map on the top of marked horizon are shown in Figure 7. The time structure map of Sakesar Limestone (Eocene) portrays plunging anticline, which is bounded by the thrust from north and south. The Eocene unit also depicts the pop-up structure in which central block moved upward up to the 2.141 sec to 1.795 sec. The depth map of Sakesar Limestone also calrifies the pop-up structure in which center

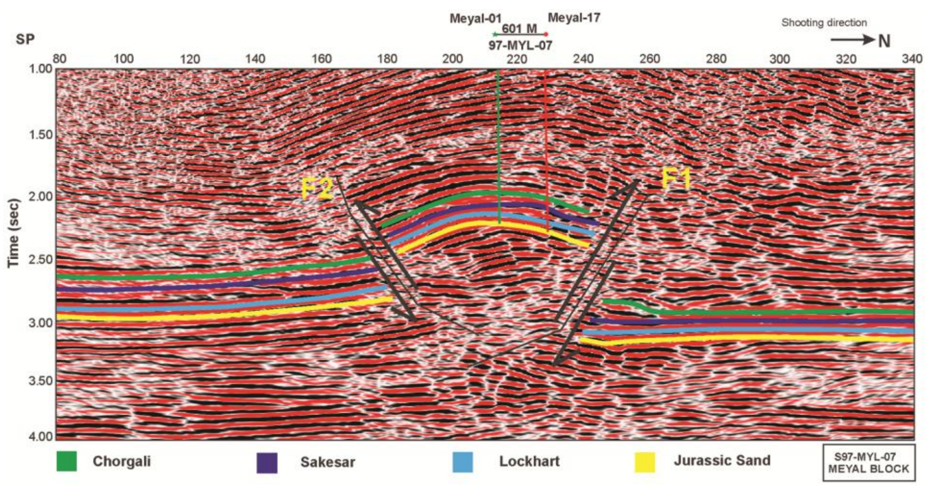

Fig. 6 — Interpreted seismic section with marked horizons and faults

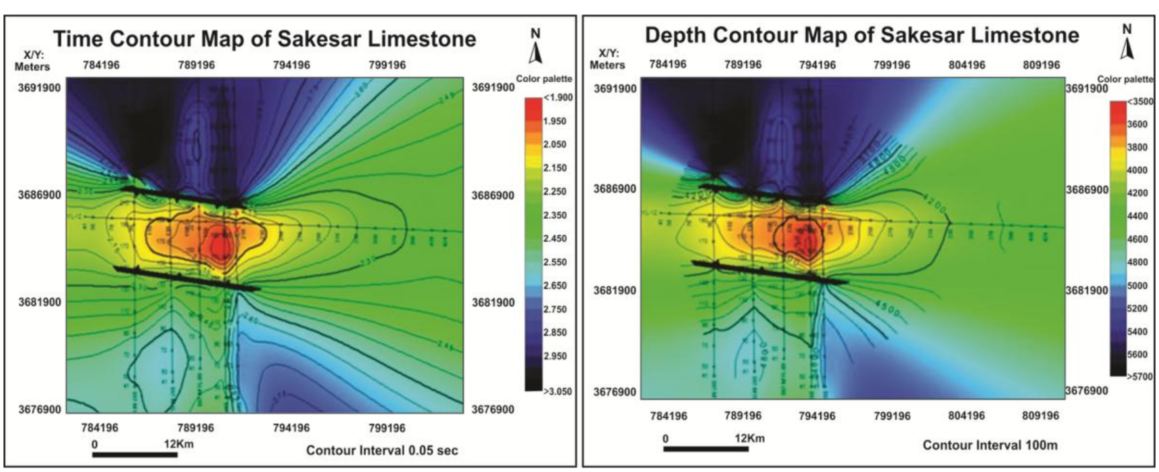

Fig. 7 — Time and depth contour map on top of marked horizon. Color bar represents variation of time and depths in seconds and meters respectively

portion of the map show thick sedimeatry cover as compared to the surronding area.

On the basis of seismic analysis, new lead have been identified in research area. In Figure 8(b) arrow is pointing the formation of structural High and time is decreasing at that location and two small red dots are the position of already drilled wells Meyal-01 and Meyal-17. This is on seismic line 97-MYL-08 (Fig. 8a) and pop-up structure is present. Hydrocarbon most probably trapped in this pop-up structure where structural High is formed and this fulfils the requirement of hydrocarbon presence. The identified structure High can be turned into prospects by detailed analysis using all geological and geophysical data along with statistical risk assessment.

Petrophysicl analysis results in desired 83 m thick zone for well Meyal-17 are shown in Figure 9. In 1st track gamma ray curve indicate change in lithology. The 2nd track depicts shale volume with an average value is 27.71 %. In addition, the 3rd track associated

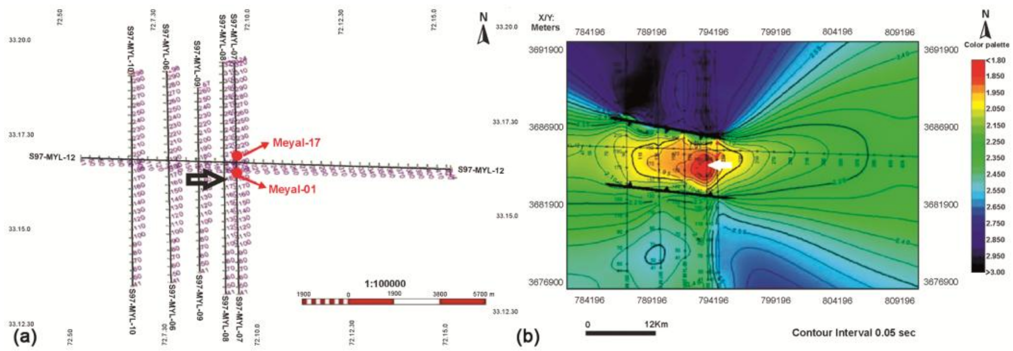

Fig. 8 — (a) New lead on base map along seismic line; and (b) Structural High on time contour map

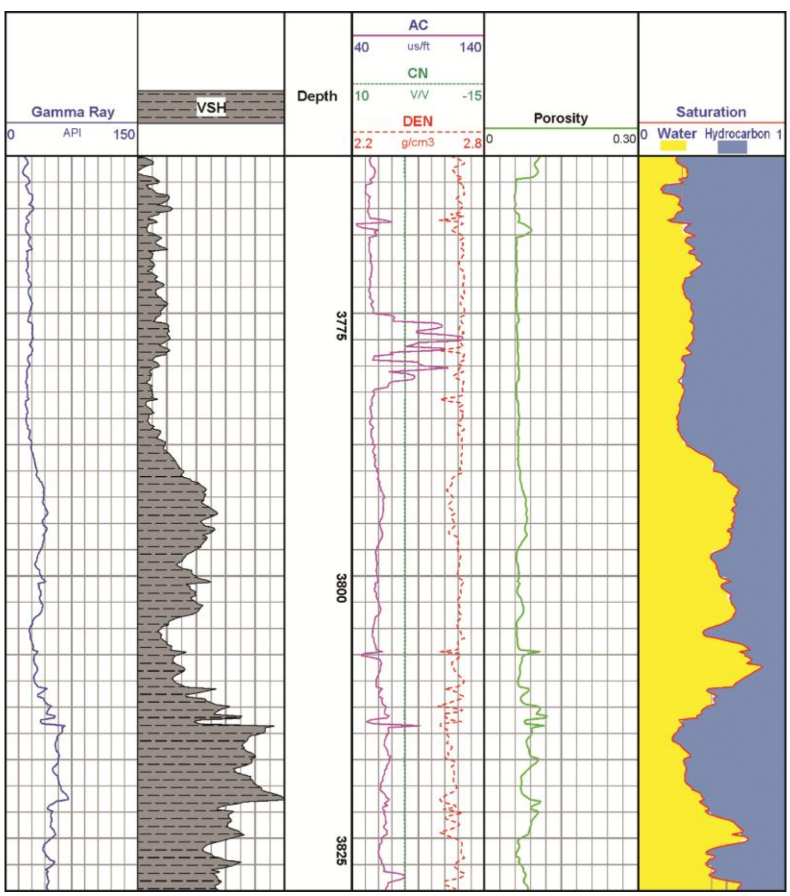

Fig. 9 — Peterophysical analysis of well Meyal 17

with resistivity logs shows mix trend while 4th track contains sonic and density logs in lower part having the low acoustic values.

In subsequent portion, the effective porosity represents low values in upper part whereas higher values in lower part. The determined average effective porosity is estimated to be 9.4 % in the entire zone. Furthermore, in last track, the evaluated average water and hydrocarbon saturation is 43.6 and 56.4 % respectively. The higher hydrocarbon saturation in comparison to water suggests that the zone is hydrocarbon saturated.

Finally, the last part of study characterizes application fluid substitution to impede development well failure. Velocity and density changes as the level of satuartion changes. Ealstic properties changed with the extraction of hydrocarbons. This change of velocity and density is useful in order to propose development well. We compare our results at 80 and 90 % water satuartion with orignal satuartion in Meyal-17 well (Fig. 10). It can be observed that there is quite significant change in P-wave velocity when water is substituted. At maximum (90 %) water satuartion, we have highest variation in P-wave velocity.

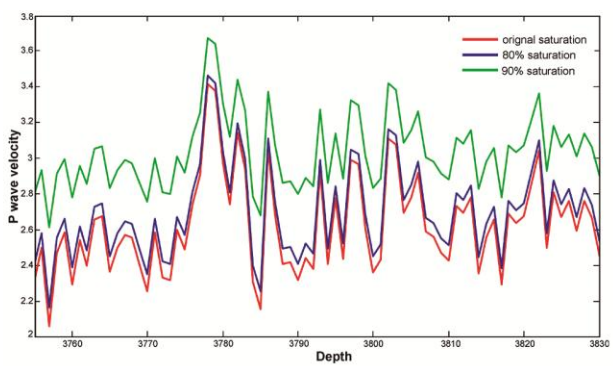

Fig. 10 — Variation of P-wave velocity at different levels of saturation

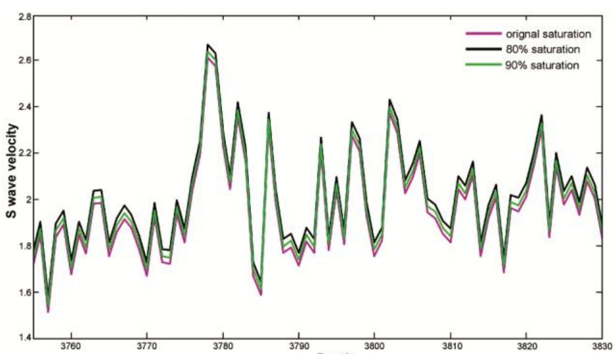

Fig. 11 — Variation of S-wave velocity at different levels of saturation

There is no significance increase in S-wave velocity as described previously shear modulus is independent of fluid type (Fig. 11). This small change is due to density, hence at maximum satuartion we have high density that will cause slightly decrease in S-wave velocity.

Conclusion

In this research, we integrate seismic interpretation, pertrophysics and fluid substitution analysis on Meyal field, upper Indus basin Pakistan. Our results demonstrate that the study area is present in compressional regime having number of thrusts. The pop-up structure bounded by thrust on either side is making favorable hydrocarbon accumulation trap. These results are also verified by time and depth contour maps. The current research identifies new prospect location from time map that is most probably potential zone for hydrocarbon. In addition, the petrophysical analysis of well Meyal-17 has revealed that it has good reservoir potential with 9.4 % effective porosity and 56.4 % hydrocarbon saturation. From fluid substitution it is clear that there is increase in P-wave velocity with increasing level of saturation. The results of this model can assist us to attain the change in subsurface with saturation level if compared with newly acquired seismic (if available).

Acknowledgements

We are grateful and deeply acknowledge to Zainul Sajjad Asgharon providing some graphical contents. We are also thankful to Department of Earth and Environmental Sciences, Bahria University for support in work station facility.

Conflict of Interest

There is no conflict of interest among the authors.

Author Contributions

All the authors have actively participated in the preparation of this manuscript. MA proposed the main concept of the manuscript. MR and TZ involved in write up. MA and MAK prepared the maps on the software. US deeply reviewed the manuscript and involved in the response of reviewers comments.

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