An integrated approach to evaluate the hydrocarbon potential of Jurassic Samana Suk Formation in Middle Indus Basin, Pakistan.

Muhammad Armaghan F. Miraj[1,*], Abid Ali[1], Hassan Javaid[1, 2], Pal Washa S. Rathore[1], Naveed Ahsan[1], Rana F. Saleem[1], Sher Afgan[1], Muhammad B. Malik[1]

[1]Institute of Geology, University of the Punjab, Lahore 54000, Pakistan
[2]Oil & Gas Development Company, Pakistan
[*]Corresponding author: armghan.geo@pu.edu.pk

Abstract

The Indus Basin is considered as prolific hydrocarbon-bearing province of Pakistan. The study area is located in the Middle Indus Basin. Two wells (Bagh-X-01 and Budhuana-01) were drilled in the vicinity of the study area to determine the hydrocarbon potential of the area. Both wells show no hydrocarbon reserves and are thus abandoned. The present study emphasizes two-dimensional subsurface seismic interpretation and rock physics evaluation to estimate reservoir properties of the Jurassic Samana Suk Formation. Data from nine 2-D seismic lines and two wells have been utilized to evaluate the potential. The time contour maps indicate the existence of subsurface structural features in the study area. With the help of the 3-D geological model, the faults are marked in the Samana Suk Formation and the structure is identified as a monocline. The 3-D geological modeling results also reveal that Samana Suk Formation tends to become thin in the northeast, and thick in the southwest. The petrophysical interpretation was performed to find the hydrocarbon potential of the Formation. The cross plot between P-impedance and Vp/Vs ratio shows that the lithology cannot be differentiated by the logs. Rock physics parameters such as Poisson's ratio, bulk modulus, shear modulus, shear wave velocity, primary wave velocity, Vp/Vs ratio, and density indicate that there are no considerable hydrocarbon reserves in the Samana Suk Formation.

Keywords: Indus Basin; petrophysical interpretation; rock physics; seismic interpretation; subsurface structure.

1. Introduction

Different workers had introduced various geological tools and geophysical methods for petroleum appraisal like seismic reflection technique, which is significant in interpreting the subsurface geology (Iqbal *et al*., 2015; Al-Sulaimi & Al-Ruwaih, 2004). A precise description of the subsurface is a basic element for hydrocarbon potential assessment that gives knowledge regarding the development and set up of fields (Iqbal *et al*., 2015). Rock physics links the geological and reservoir properties to improve the quality of seismic data interpretation. According to Avseth (2010), quantitative prediction of geologic parameters like cementation and lithofacies using seismic amplitude needs to be studied further. Most of the quantitative seismic interpretation is focused on the estimation of porosity from seismic information (Munyithya *et al*., 2020; Brown, 2011). Commonly, a direct connection between impedance and porosity is utilized. This is an area where pore types, minerals, and lithofacies affect the velocities and impedances similarly to the porosity values (Eberli *et al*., 2003). Carbonate reservoirs account for about half of hydrocarbon production globally, and thus there is a need for the development of rock physics modeling to avoid risk in carbonate exploration (Shiri & Falahat, 2019; Chopra & Marfurt, 2007). The main reason behind this is heterogeneity in the carbonate reservoirs and their pore type distribution. Usually, a single porosity type is present in the clastic rocks, which is inter-particle porosity. However, carbonates comprise a variety of porosity types including moldic, vuggy, and fractured porosity. The sonic velocity is determined by porosity in clastic rocks whereas in carbonates it is mainly dependent on porosity types along with porosity quantity in a reservoir (Xu & Payne, 2009; Chopra & Marfurt, 2007; Al-Ruwaih, 1998). Therefore, to understand the seismic response in carbonates, a rock physics model is required that can handle different porosity types (Xu & Payne, 2009).

The study is conducted to interpret the two-dimensional seismic data and rock physics analysis of the carbonate reservoir of the Samana Suk Formation (Jurassic). Limited seismic data quality and complex tectonic features are accountable for less than ideal interpretation conditions. The study area (Figure 1) lies in the Middle Indus Basin, which consists of duplexes, having large anticlines and domes in the passive roof sequence of the Sulaiman Fold Belt. Its eastern side gently dipping the strata of the Punjab monocline, which has few tectonic folds and faults. In Punjab Platform, wells drilled are Panjpir, Nandpur, Bagh-X-01, and Budhuana-01etc.

Fig. 1. Location of the study area in the Middle (central) Indus Basin, Pakistan (modified after Hanif *et al*., 2013).

The basin contains a sedimentary sequence ranging from Precambrian to recent and it is essentially a natural gas-bearing zone (Table1).

Table 1. Generalized stratigraphy of Middle Indus Basin (modified after Kadri, 1995

AGE		FORMATION	LITHOLOGY	PLAY ELEMENTS
QUATERNARY		ALLUVIUM		
MIOCENE	UPPER	SWALIKS		
	MIDDLE			
	LOWER	NARI/GAJ		
OLIGOCENE				
EOCENE	UPPER	KIRTHAR		
	MIDDLE			
	LOWER	GHAZIJ/SUI		
PALEOCENE		DUNGHAN		
		RANIKOT		SOURCE
CRETACEOUS	UPPER	PAB		
		MUGHAL KOT		
		PARH		
	LOWER	GORU/ LUMSHIWAL SEMBAR		SOURCE/GAS SOURCE/GAS
JURASSIC	UPPER			
	MIDDLE	SAMANA SUK SHINAWARI DATTA		SOURCE
	LOWER			
TRIASSIC		KINGRIALI/ WULGAI		
PERMIAN		AMB/WARCHA/ DANDOT/ TOBRA		
CAMBRIAN		KUSSAK/ KHEWRA		
INFRACAMBRIAN PRECAMBRIAN		SALT RANGE GROUP		SOURCE/OIL SOURCE/OIL
		BASEMENT		

2.6 TCF recoverable reserves (Raza *et al*., 1989). The main producing strata range in age from Cretaceous to Eocene. The basin has a wide variety of geothermal gradients where the zone of very low geothermal gradient near the Sargodha Shahpur (buried ridge) is mainly due to the high thermal conductivity of the shield. However, in the Punjab Platform, there is a zone with a high geothermal gradient of 4.1°C/100m (Sheikh *et al*., 2003).

The main gas fields of Mari-Kandhkot, Sui, and Uch are concentrated in this region. The oil window may be below the gas-producing horizon with the possibility of oil occurrences in the Cretaceous sediments.

2. Regional Geology and Tectonic Settings

During the Neoproterozoic, the exposure of Gondwana, accompanying the amassing of continents at a huge scale, led to the configuration of isolated unit Pangaea (Stampfli *et al*., 2013). The Indian Plate was once part of Gondwanaland and separated because of fragmentation (Powell *et al*., 1979).

Finally, the drift of the Indian plate ended around 55 Ma years ago. The southern part of Pakistan lies in the Gondwana (Kazmi & Jan, 1997). The extreme north and western area of Pakistan lies in the Tethyan part and comprises complex geology and complicated crustal structures

Indus Basin is a type of extra continental trough downwarp basin and is the largest producing sedimentary basin of Pakistan. It constitutes an area of about 54,000 km^2 (Sheikh *et al*., 2017). The basin is oriented in NE-SW direction where, the basement is exposed at two places, in NE (Sargodha High) and SE corner (Nagar Parker High). It has a vast easterly platform region with a gentle dip, which acts as a monocline towards the west. Whereas Suleiman Fore Deep acts as a ring of trough or depression in which the platform dips. On the western side of Suleiman fold and thrust belt is present due to which this area was a topographically uplifted region (Sheikh *et al*., 2017; Aziz *et al*., 2020).

Technically, Pakistan is situated at the junction of three lithospheric plates, the Indian Plate, Eurasian Plate, and the Arabian Plate (Kazmi & Jan, 1997). Indus Basin is divided into three sub-basins. These sub-basins are named as Upper (Northern), Middle (Central), and Lower (Southern) Indus Basin, respectively (Figure 1). Some basement highs act as dividers, which are present in the platform region. Sargodha High separates the Upper Indus Basin from the Middle Indus Basin. Whereas, the Middle Indus Basin is separated from the lower Indus Basin by Jacobabad High (Abbasi *et al*., 2014; Ehsan *et al*., 2018).

The geological history of the Indus Basin is from the Precambrian. The depositional features show the limit of the basin, its extensions, and its divisions (Kadri, 1995).

A better understanding of the geological evolution of the basin may provide strategies for new oil and gas discoveries in Pakistan. The geological history of the basin can be understood by keeping in view the tectonics and depositional sequence (Sheikh *et al*., 2017).

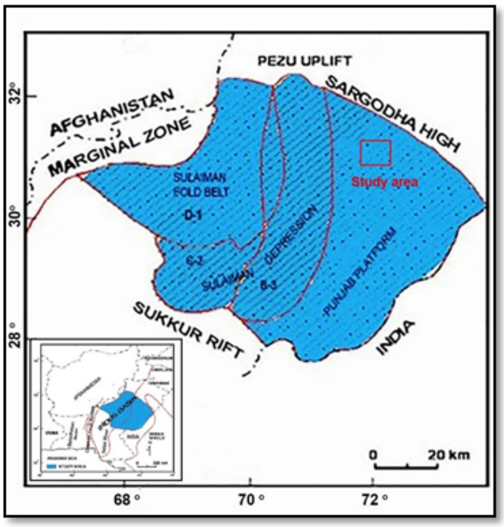


Fig. 2. The divisions of the Middle Indus Basin (Raza *et al*., 1989).

The basin comprises a huge area of Pakistan and the adjoining western parts of India. The thick succession of sedimentary strata is 10 km resting over the crystalline Precambrian basement (Kingston *et al*., 1983). The depositional history of the Middle Indus Basin shows a wide range of sedimentary environments ranging from deep marine to continental.

The Middle Indus Basin is separated from the Upper Indus Basin by the Sargodha High and Pezu uplift in the north. On its eastern side, Indian Shield is present, the marginal zone of the Indian Plate in the west, and on its southern side are separated by Jacobabad-KhairPur and Mari-Kandhkot highs (Aziz *et al*., 2020). Both these highs join to form Sukkur Rift in the south (Raza *et al*., 1989). In the north of the basin, the Himalayan Mountain ranges are situated, whereas offshore basins run along the south of the basin (Battani, 2000). The oldest rocks exposed to the surface in this basin are of Triassic (Wulagi Formation) while the oldest rocks drilled in this region is Precambrian Salt Range Formation on the Punjab Platform. The depth to the basement is about 15,000 meters in the trough areas. Due to Pre-Himalayan non-orogenic movements, there is prolonged uplifts/sea regression, which results in unconformities due to which there are huge gaps in successions. Precambrian rocks are largely missing from the basin although; Precambrian shield rocks are present along the edges of the Indian plate. The Middle Indus basin consists, from east to west, three main units based on the geology of the Indian shield and further development, as follows (Figure 2):

- Punjab Platform
- Sulaiman Depression
- Sulaiman Fold Belt

3. Data and Methodology

The data used for subsurface interpretation and rock physics was obtained from Landmark Resources (LMKR) after getting approval from the Directorate General of Petroleum Concession (DGPC), Pakistan. The wireline log data of Bagh-X-1 and Budhuana-01 wells is used for petrophysical interpretation in the present study. Total nine seismic lines are used for the interpretation of the subsurface structure of the Budhuana area shown on the base map (Figure 3). The subsurface structure is interpreted by utilizing seismic lines (867-TTS-01, 867-TTS-02, 867-TTS-03, 867-TTS-04, 867-TTS-18, 875-TTS-215, 875-TTS-216, 875-TTS-218, and 875-TTS-219) (Table 2).

The significance of each seismic reflector controlled by the TWT is correlated with well tops to assign an age.

4. Results and Discussion

4.1 Seismic Interpretation

The strike lines show the continuous reflectors, while along dip lines faults are identified based on breaks in the continuity of reflectors. Five horizons including Salt Range Formation (Pre-Cambrian), Amb Formation (Permian), Samana Suk Formation (Jurassic), Dungan Formation (Paleocene), and Eocene age were identified as shown in Figure 4. Several normal faults were marked on interpreted seismic lines and distinguished as shallow faults (F2A, F2B, and F2C) and deep faults (F1, F1A, F1B, F1C, and F1D) (Figures 4b-c).

Table 2. Seismic lines used in the study area

Line No.	Length (km)	Direction
867-TTS-01	8.3/25.15	S-N
867-TTS-02	30.675	NE
867-TTS-03	32.5	S-N
867-TTS-04	22.95	W-E
867-TTS-18	43.875/20.9	W-E
875-TTS-215	25.425	SW-NE
875-TTS-216	30.45	SE-NW
875-TTS-218	25.65	SE-NW
875-TTS-219	18.1	S-N

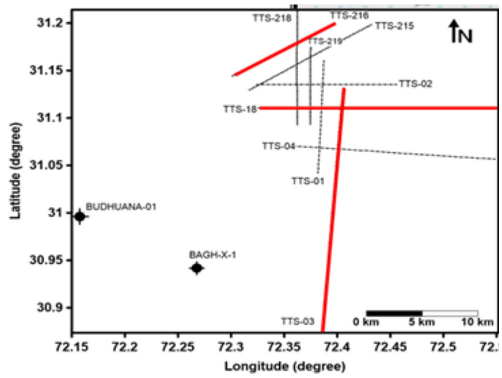


Fig. 3. Base map of the area under study showing seismic lines and nearby wells.

4.2 Time-contour map of Samana Suk Formation

A time structure map on top of the Samana Suk Formation was constructed (Figure 5). The time contour interval is 100 milliseconds. Closed contours with the highest times in the cores show synclines. Closed contours with the lowest times in the cores show anticlines. The contour map shows the presence of some flat-lying strata while at some places contours are closing with the lowest times in the cores which indicates the anticline. These anticlines can be explored for hydrocarbons and can be productive if tested carefully. Time is increasing towards the South which shows that the horizon is dipping toward the Southern side. The contours show the exact locations of the structures present in the area (Groshong *et al*., 2006).

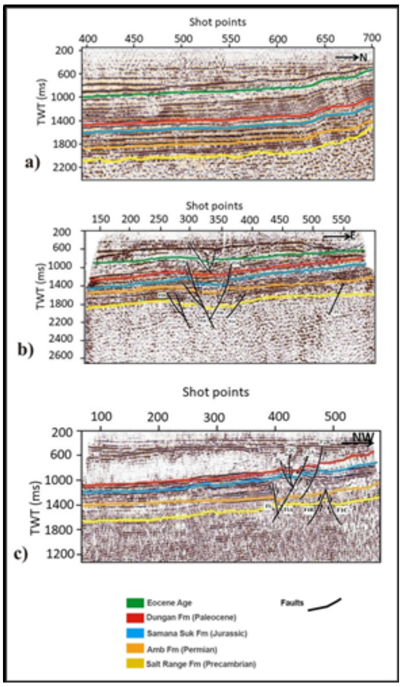


Fig. 4. Interpreted key seismic lines of the study area: (a) 867-TTS-03, (b) 867-TTS-18, and (c) 867-TTS-216. For the location of the lines see Figure 3.

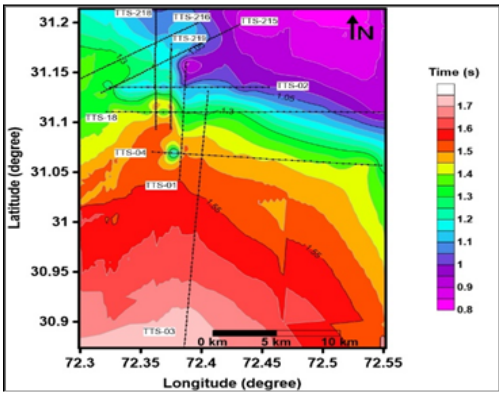


Fig. 5. Time contour map of Samana Suk Formation (Jurassic).

4.3 Three-dimensional Geological Modeling of Samana Suk Formation

Geologic modeling is very helpful in displaying a real picture of the subsurface especially oil and gas fields. In the oil and gas industry, a detailed study of reservoirs is performed with the help of modeling which tells us the behavior of rocks under various hydrocarbon recovery scenarios. Three-dimensional modeling gives a great deal of information regarding the structure (Robinson *et al*., 2008). With the help of 3D modeling, the structure and horizons from different angles enabling us to recognize the structure easily.

If we see the overall contour pattern of the Samana Suk Formation, then mainly it is forming a monocline with small anticlines. This can be viewed from the 3D model of this horizon and we can interpret it from the time contouring map. From the interpreted 3D model, we can also view the faults present in this horizon. Time is increasing towards the south which shows that the horizon is dipping towards the southern side. The contours show the exact locations of the structures present in the area. Closed contours with the highest times in the cores show synclines while closed contours with the lowest times in the cores show anticlines. The three-dimensional model of the Samana Suk Formation indicates the presence of monocline along with a few anticlines and synclines (Figure 6).

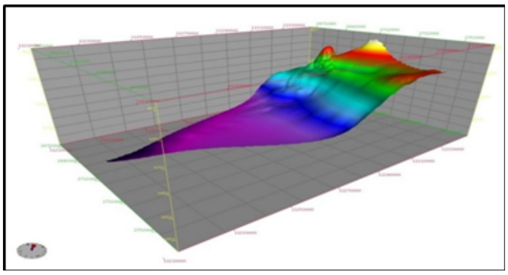
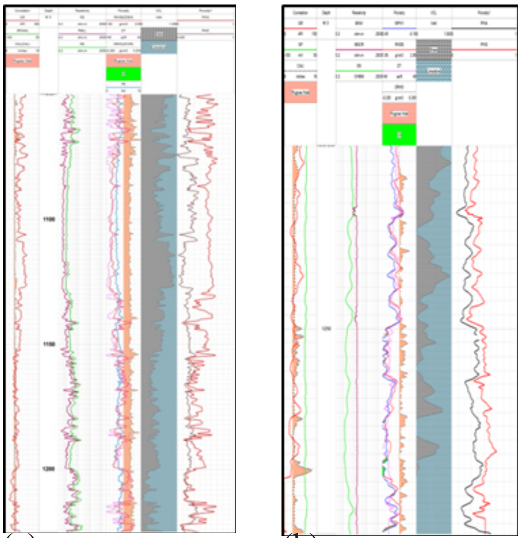


Fig. 6. 3D model of Samana Suk Formation.

A flat-lying stratum is also seen in this horizon along with faults that can be viewed in interpreted three-dimensional models (Figures 7a and b). Time is increasing towards the south, which shows that the horizon is dipping towards the southern side. The contours show the exact locations of the structures present in the area.

4.4 Petrophysical Interpretation

Petrophysical interpretation of both Bagh-X-1 and Budhuana-01 was done to see the log responses. The logs show great rugosity in both wells that indicate the data is not reliable. The log responses in both wells show no hydrocarbon reserves in the two wells as shown in (Figures 8a and b).



(a) (b)

Fig. 8. (a) Petrophysical log of Bagh-x-1 (b) Petrophysical of Budhuana-01 well.

P-impedance is finding out by using the formula:

$$P\text{-}impedance = Vp \times Density$$

Cross plots show the scattered lithology that indicates the logs readings are not reliable because of hole rugosity. The readings of the padded tools are not accurate and also the corrections are not applied to the data. Thus, log data cannot differentiate the facies and cannot be used for rock physics.

As the good data is not reliable so there is a need of using seismic data for finding the elastic parameters and conducting rock physics modeling to find the hydrocarbon reserves in the study area.

4.5 Rock Physics Interpretation

Out of many, the one essential aspect of evaluating the reservoir parameters is rock Physics by developing the empirical relationships with rock properties. Many researchers have developed different relationships. Castagna *et al*. (1985, 1993)

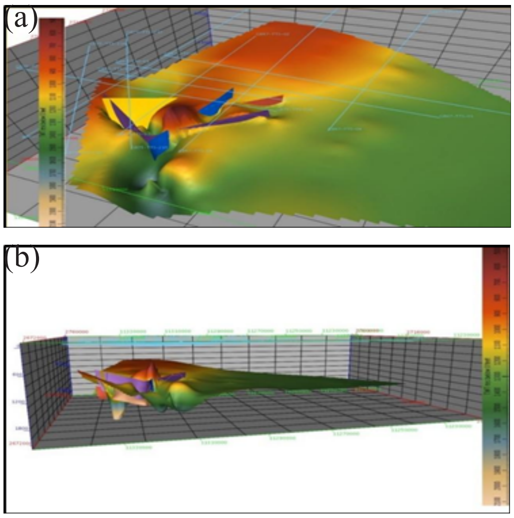


Fig. 7. 3D model of Samana Suk Formation along with faults. (a) Side view (b) Top view.

(a)

(b)

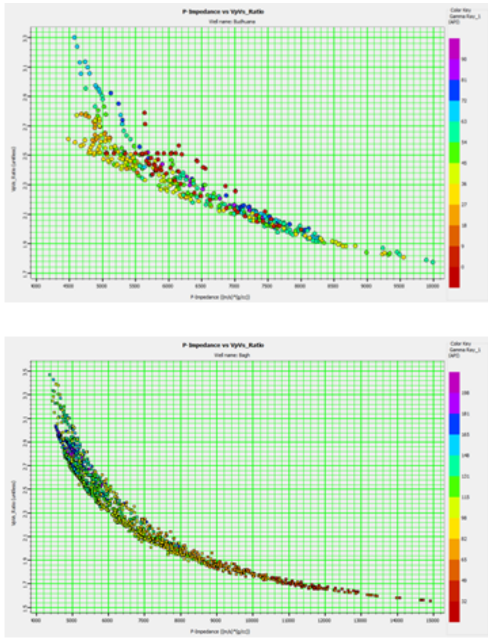


Fig. 9. The cross plot between Vp/Vs along Y-axis and P-impedance along x-axis whereas along z-axis gamma-ray values are plotted. (a) Budhuana well cross plot (b) Bagh-x-01 cross plot

developed a relationship between compressional and shear wave velocities of Physics by developing the empirical relationships with rock properties. Many researchers have developed different relationships. Castagna *et al.* (1985, 1993) developed a relationship between compressional and shear wave velocities of siliciclastic and carbonate rocks. Furthermore, Lee (2010) developed relationships for unconsolidated rocks present near the surface. Gardner *et al.* (1974) presented a relationship between compressional velocity and density. The rock physics parameters like Shear waves velocity, Density, Bulk modulus, Primary wave velocity, Shear modulus, Vp/Vs Ratio are calculated using different equations that determine the hydrocarbon presence.

For finding shear wave velocity, Castagna's normal equation (Avseth *et al.*, 2010) of mudrock is used. The relation used for this is:

$$Vp = 1.16Vs + 1.36, \qquad (2)$$

Where Vp and Vs both are in km/sec.

Density is the mass per unit volume and can also be determined by using the compressional wave velocity in m/sec (Badley, 1985). The relation used for this is:

$$Density = \rho = 0.31 \times (Vp)^{\frac{1}{4}} \qquad (3)$$

From the interaction of density and compressional and shear wave velocity data it is possible to calculate bulk modulus which describes the elastic properties of a rock (Avseth *et al.*, 2010). The relation used for determining bulk modulus (k) is:

$$k = \rho\left(Vp^2 - \frac{4}{3}Vs^2\right) \qquad (4)$$

Shear modulus can be determined in the same way as calculations for bulk modulus have done. It is an important parameter that also describes the elastic properties of rock (Keary *et al.*, 2002). The relation used for determining shear modulus (μ) is:

$$\mu = \rho\,(Vs). \qquad (5)$$

Poisson's ratio (σ) can be found by using given relation as under (Avseth *et al.*, 2010).

$$\sigma = \frac{1}{2}\frac{(Vp^2 - 2Vs)^2}{Vp^2 - Vs^2} \qquad (6)$$

The ratio of Compressional and shear wave velocity also describes the elastic properties of rock as there are elastic moduli involved in the relation used for it (Keary *et al.*, 2002). The relation used to determine the Vp/Vs ratio is:

$$\frac{Vp}{Vs} = \left(\frac{k}{\mu} + \frac{4}{3}\right)^{1/2} \qquad (7)$$

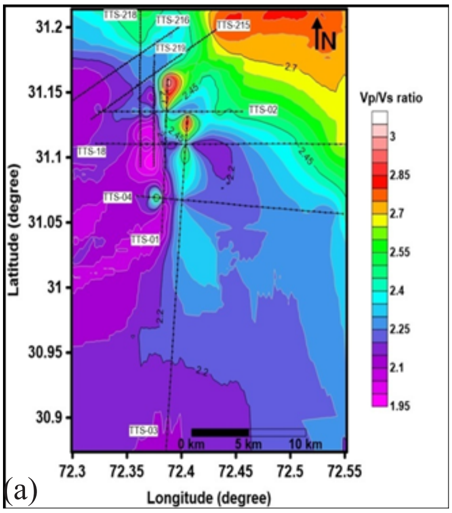
The measured values of all the mentioned rock physics parameters of the reservoir in the area i.e. Samana Suk Formation mentioned in Table 3.

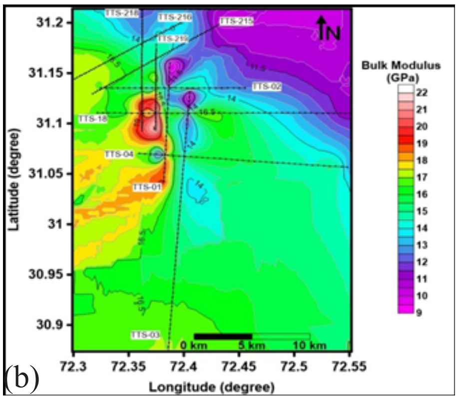
The range of each parameter of the Samana Suk Formation falls under the specific ranges that show the presence of hydrocarbon in the study area.

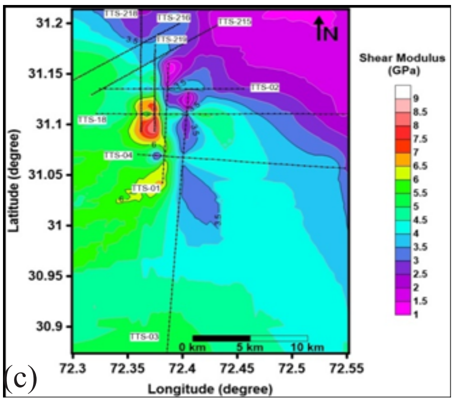
Table. 3. Rock physics parameters used for Samana Suk Formation (Jurassic) characterization

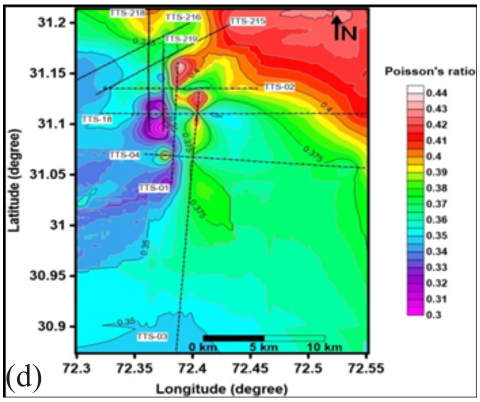
Parameters	Values Observed	Units
Poisson's ratio	0.31 to 0.43	
Shear waves velocity	0.75 to 2.89	km/sec
Shear modulus	1.2 to 8.5	GPa
Density	2.13 to 2.39	kg/cm^3
Bulk modulus	9.43 to 21.67	GPa
Primary wave velocity (Vp)	2.23 to 3.55	km/sec
Vp/Vs Ratio	1.96 to 3.018	

The maps of rock physics parameters were generated as shown in the figures below (Figure 10). All the parameters are clearly showing that there is no hydrocarbon in the zone of interest. All parameters are showing the values that are of pure limestone thus indicating the absence of hydrocarbon in the area.









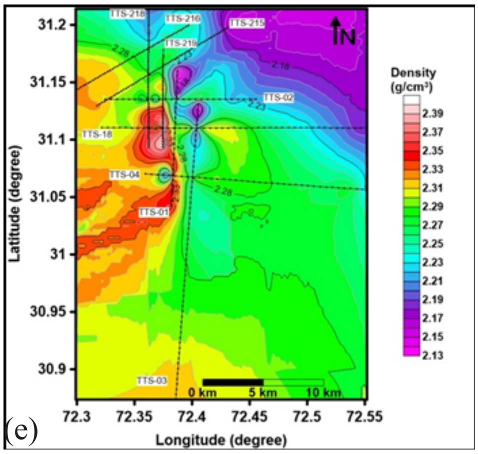


Fig. 10. Maps showing elastic properties (a) Vp/Vs ratio, (b) Bulk Modulus, (c) Shear Modulus, (d) Poisson's Ratio, and (e) Density.

5. Conclusions

The time contour map for the reflector of the Samana Suk Formation was constructed based on interpreted seismic lines. With the help of a correlative study of all seismic lines with a time contour map, and we conclude the following results of structural interpretation.

- All the sedimentary strata are dipping towards the southwest. No definite fault trend is present but localized normal faults do exist. The normal faults make local scale horst and graben geometries favorable for the accumulation of oil.
- The localized normal faults with a gentle trend exist due to extensional tectonic activity in the early Paleocene.
- There is a thickening of the strata in the southwest direction. This effect might be the result of the release of stresses of Aravalli Orogeny and its counter-clockwise

rotation, which resulted in an extension to the west and marginal compression to the east. A clear change in the depositional environment is indicating by the phenomenon of thinning and thickening.

- Petrophysical interpretation of both wells (Bagh-X-1 and Budhuana-01) shows no hydrocarbon reserves in the wells. The cross plots generated between the elastic properties show that the logs were not acquired properly. In addition, the observed rock physics parameters in this study, also suggest that the reservoir does not have hydrocarbon potential.
- Results obtained from Poisons ratio, Bulk Modulus, Shear Modulus, Shear wave velocity, primary wave velocity, Vp/Vs ratio & density model indicate that there are no hydrocarbon reserves in the study area.

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