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Exploring the untapped gas potential of Ghazij shale in Pirkoh area, Pakistan: Integrated approach of attribute analysis and maturity modeling

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Abstract: A correlative maturity study integrated with seismic attributes for determining the shale gas potential of Ghazij Formation is carried out. Analysis of post-stack seismic attributes has been frequently used to identify areas of high exploration potential within shale resource plays. Seismic and well data have been utilized for the analysis of maturity trends in the shale facies of Ghazij Formation. Total organic carbon content (TOC), burial history, Vitrinite Reflectance (Ro), thermal history and porosity values have been computed at Pirkoh-01 well, which are laterally compared with the maturity results in Bambor and Sui areas. In addition, analysis is carried out to detect the bright spots using the seismic attributes, which depicts positive results for the presence of the sweet spots around 1100–1350 ms in the southern synclinal part of the study area. The computed results showed that Ghazij shales lie within the oil and gas generation window having temperature values ranging between 90–150 °C with 0.7%–1.3% Ro. This correlative maturity study declares Ghazij Formation as a potential shale gas reservoir. After analyzing all these facts, it can be concluded that the shales of the Ghazij Formation do have some potential of a source rock.

Key words: Attribute analysis, Ghazij Formation, Bright spots, total organic carbon (TOC), maturity study

1. Introduction

Unconventional shale gas and shale oil plays have jumped into the spotlight over the last several years and appear to be the future of our business. Traditional hydrocarbon reserves are depleting, which has compelled the industry to shift the exploration paradigm from conventional to unconventional exploration techniques. During the past few decades, improved exploration and production technologies in the oil and gas industry led to a significant increase in commercial production from a new class collectively called *unconventional resources* (Wang et al., 2016).

An important unconventional source of natural gas is *shale gas* involving shale rock acting as the source, reservoir, and trap for the natural gas. Natural gas, which is found in the fine-grained, organic rich rocks (gas shales) is referred as the shale gas. Gas shales are those source rocks that have generated the hydrocarbons but have not released all of it. More precisely, the best prospects for shale gas potential are those source rocks, which are "tight" or "inefficient" in order to expel the hydrocarbons. In gas shales, to complete the components of the petroleum system, the shale is acting as the source, reservoir, and trap for the natural gas. So, the natural gas found in these rocks is considered unconventional. Unconventional plays are unique because certain procedures or techniques that work well in one play may not translate well to another (Glorioso and Rattia, 2012).

Throughout the world, a significant number of geologic basins contain the unconventional gas reservoirs (Holditch et al., 2007). Estimated values of unconventional gas resources in the world (Mohr et al., 2015) are 16,000 Tcf of gas in place in shale gas, 9000 Tcf of gas in place in coal bed methane, and 7400 Tcf of gas in place in tight gas sands. The shale gas resources identified in the world by Mohr et al. (2015) and US Energy Information Administration (EIA) are 16,112 Tcf and 25,300 Tcf, respectively with 3528 Tcf and 5661 Tcf are identified in Asia (EIA, 2011) (Table 1). Apart from the estimates made by EIA of the total shale gas reserves of Pakistan, Jadoon (2011) provided estimation of the shale gas reserves of different formations in Pakistan.

At present, no shale gas play has been developed to a production level in Pakistan (Abbasi et al., 2014;

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Table 1. Risked gas-in-place and technically recoverable shale gas resources (EIA, 2011).

Continent	Region	Country	Risk Gas in-Place (Tcf)	Technically Recoverable Resource (Tcf)
Asia	China		5,101	1,275
	India/Pakistan	India	290	63
		Pakistan	206	51
	Turkey		54	15
	Total		5,661	1,404

Saleh, 2015). Technically, recoverable shale gas resources identified in southern Indus basin of Pakistan are about 105 Tcf (WRI, 2014). Pirkoh gas field is in Baluchistan province about 100 km north-west of the Sui gas field. The field was discovered with estimated initial recoverable reserves of 1.35 Tcf (Ayaz et al., 2012). This is one of the favorable targets for exploring the possibility of gas shales because of the shallow depth sequence of Ghazij Formation (Wandrey et al., 2004).

Tectonically, Pirkoh structure is in the central part of Mari-Bugti transverse uplift, which corresponds to the uplifted part, adjacent to Sibi Trough in the west and Sulaiman foredeep in the north-east (Figure 1). In Mari-Bugti region, this part of fold belt becomes convex arcuate to the south ending of Kirthar and Sulaiman ranges. In this region, there is no sharp boundary between the fold belt and the adjoining foredeep (Shah, 2009).

Ghazij Formation of the Early Eocene age is spread widely in the Sulaiman province, Kirthar province and along the axial belt (Shah, 2009). Running across the western margin of the axial belt in north-central Pakistan, the Ghazij Formation has been exposed for approximately 750 km stretch. Marine shelf deposits of Jurassic to Paleocene age underlie and the sedimentary cover of both marine and nonmarine origin of the Middle Eocene to Miocene overlie the Ghazij Formation, which is further covered by the molasse deposits of the Pliocene and Pleistocene age (Johnson et al., 1999). The generalized stratigraphical column with the formations and ages of lower Indus basin has been shown in Figure 2.

After Early Cretaceous, Sembar and Eocene Ghazij formations are considered as the possible source rock in the Indus Basin. The recorded TOC is usually high for the Ghazij shale at places up to 3% in the northern Kirthar Range (Hasany et al., 2007; Khan and Clyde, 2013). Depth and thickness of Ghazij Formation varies in the Sulaiman and Kirthar ranges. Thickest deposits of the Ghazij Formation of 3300 m have been reported at Mughal Kot (Shah, 2009). Due to this variation in depth and thickness, maturity of the Ghazij Formation varies in the basin. High TOC values for the shale facies of Ghazij Formation in the Kirthar Range corresponds to the deeper depth intervals where the formation has been exposed to greater overburden. In response to this overburden pressure, maturity level of the Ghazij shales increased and the formation lies within the oil and gas generation window. In the shallow depth areas, Ghazij shales are considered to be immature or at early maturation stage. However, the oil-source correlation data is not available to verify and establish whether the Ghazij Formation has any role in hydrocarbon generation. Ghazij shale can be a source rock in the middle Indus basin, thereby charging hydrocarbon for reservoirs like Habib Rahi limestone, Sui Main limestone and Kirthar Formation (Wandrey et al., 2004).

Raza et al. (1990) reported two oil shows from Ghazij strata, one in Mari-1 well from thin interbedded limestone and the other from calcareous shale in Sunbak-1 well. Though Ghazij is a shale facies and a possible source rock (TOC: 6.89%, VR: 0.65) (Sheikh and Giao, 2017; Al-Areeq, 2018), the interbedded sandstone and limestone can serve as a reservoir in Sindh monocline, Kirthar and Karachi depressions and Offshore areas. Table 2 shows present-day TOC and Tmax (°C) of different formations in Mari Deep-1 and Mari Deep-2 wells (Khoso et al., 2003).

The TOC for Sembar Formation, on an average, appears lower than Ghazij and intra-formational shales. Table 3 shows the values of TOC for Ghazij Formation acquired by the geochemical analysis of surface rock samples in the Kirthar Range (Raza et al., 1990). Geophysical techniques have been widely used in hydrocarbon exploration (Nisar et al., 2016). Rock properties response to seismic waves reveals subsurface information. Shale, a comparatively weak rock, tends to response less to seismic waves. This character can help in the identification of shale beds in subsurface based on weak response to seismic signal.

The main objective of this study is to evaluate the source rock potential of the Ghazij Formation with the help of a correlative study. For this purpose, burial history diagrams (Alizadeh et al., 2012) of Pirkoh gas field have been made, and its correlation is generated with the adjacent areas of Bambor and Sui. To propose the probable measurements for the maturity study of Ghazij Formation, several parameters were taken under consideration,

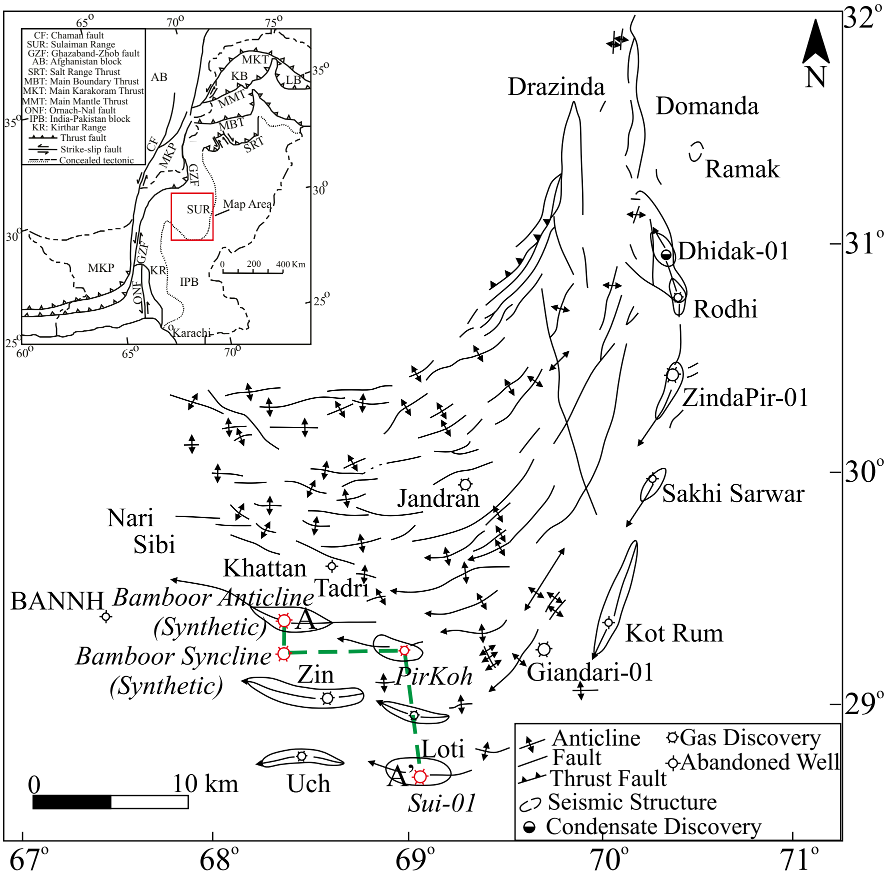

Figure 1. Location map of study area with detailed structure and tectonics of the region. Location of the wells used for the correlation is also shown in the map along with cross-section line AA' (modified after Ali et al. (1995) and Nazeer (2017)).

including the burial history, isotherms, depth, overburden, eroded strata, porosity, and the maturity trend. Seismic data were used for seismic attributes, which characterized the key shale beds by predicting the sweet spots and for the identification of the gas bearing-zones.

2. Materials and methods

In order to identify whether given shale play fulfills enough characteristics to call it as unconventional resource, a detailed information of the geological, geophysical (seismic) and geochemical data (from core samples) are required. The factors, which are most important for the determination of the shale gas potential of rock, are as follows: thermal maturity, reservoir thickness, and areal distribution, Total organic carbon (TOC), vitrinite reflectance (VR), permeability, mineralogy and gas in place (Raza et al., 2018). The methodology adopted in order to achieve the desired information is described below and completed in three phases. In first phase, seismic interpretation was carried out to identify the lateral and vertical extent of Ghazij formation. Then, in order to identify the presence of hydrocarbon at the target level, seismic attribute analysis was performed. Finally, maturity study was done to evaluate the source rock potential of Ghazij shales.

2.1. Seismic interpretation

The prime objective of this research is to evaluate source potential of Ghazij deposits so it's necessary to mark its lateral and vertical extent in terms of thickness to better locate the structural patterns and gas presence. For this purpose, SEG-Y data of five 2D seismic lines and two wells of the Pirkoh gas field are utilized. Five horizons (Ghazij, Dungan, Ranikot, Pab and Mughal Kot formations) along with six thrust faults were marked in order to confirm the structural behavior. Figure 3 shows the original seismic section along with the interpreted ones of the depositional thickness of the Ghazij Formation, i.e. the top of Ghazij to the top of Dungan Formation.

2.2. Seismic attributes analysis

Seismic attributes are a quantitative measure of a seismic characteristic of interest, usually based on basic information of the time, amplitude, frequency, and attenuation, either

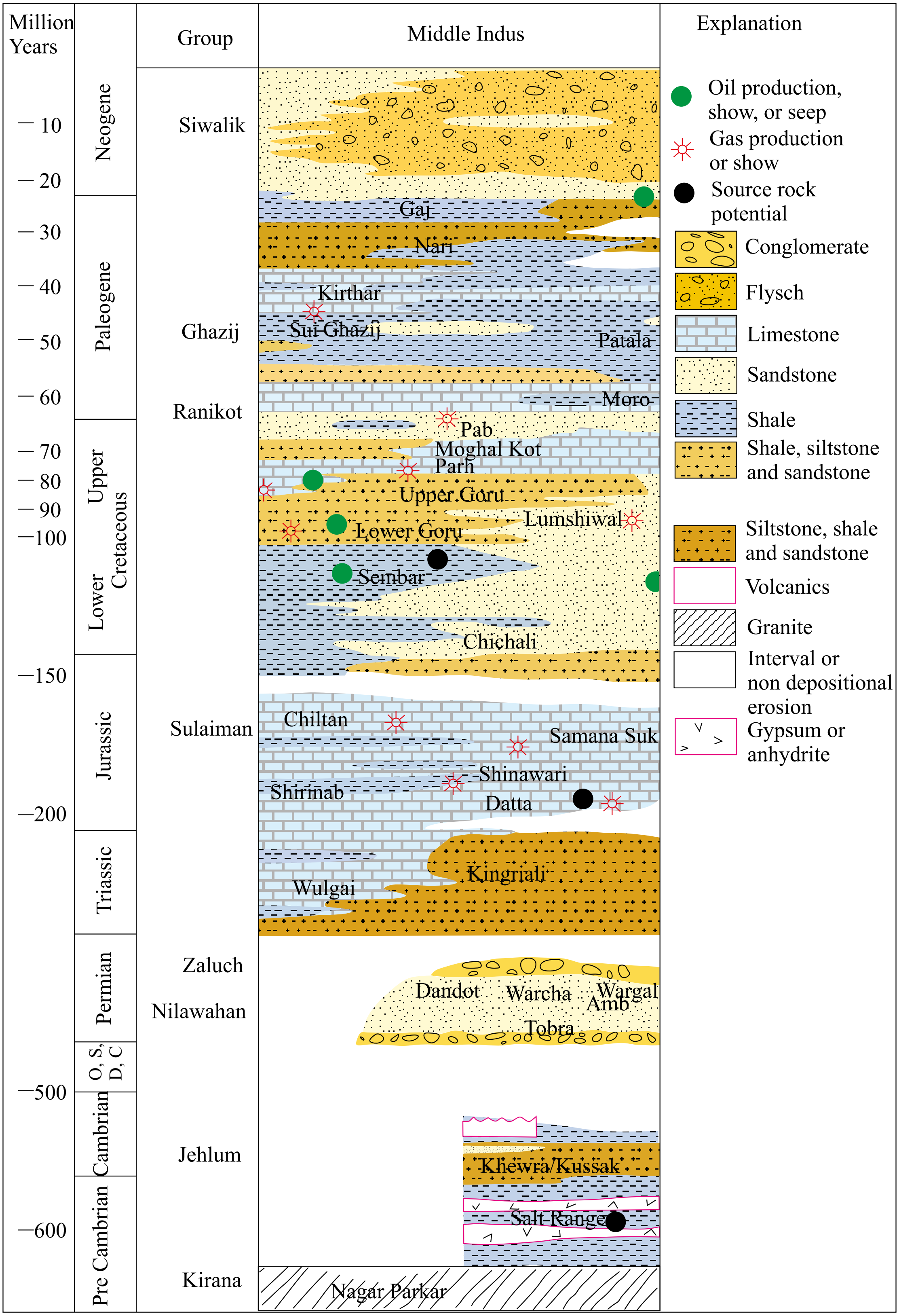

Figure 2. Generalized stratigraphic column of Middle Indus Basin showing ages, lithologies, and hydrocarbon potential of stratigraphic formations (Wendrey et al., 2004).

Table 2. Total organic content and Tmax of different formations in Mari Deep-01 and Mari Deep-02 wells (Khoso et al., 2003).

Formation	Mari Deep-1		Mari Deep-2	
	TOC	Tmax (°C)	TOC	Tmax (°C)
Ghazij	0.28	415	0.20	--
Lower Goru D	0.60	435	0.71	432
Lower Goru C	0.95	446	0.80	440
Lower Goru B	1.50	450	0.74	434
Sembar	0.69	439	1.04	445

Table 3. Geochemical analysis of surface rock samples in Kirthar Range (Raza et al., 1990).

Age	Formation	Sample No.	Lithology	TOC	VR	HI
Eocene	Ghazij	13	Shale	6.89	0.65	398
		14		6.43	0.66	480
		15		0.38	1.70	
		16		0.32	1.68	
		17		0.35	1.68	
		18		0.61	1.17	
		19		1.11	1.04	90
		20		0.99	0.99	<121
		21		1.01	1.06	96

by direct measurements or by logical or experience-based reasoning (Azeem et al., 2018). Seismic attributes are commonly used to delineate the seismic features of interest and be applied for several purposes like bright spots, sweet spots, fault interpretation, porosity detection, and to locate the features associated with them. Seismic attributes have a lot of discrepancies, including data quality, processing errors, acquisition footprints, etc. Moreover, all attributes do not work well on every seismic data e.g., there are plenty of attributes used for structural delineation like curvature, amplitude, and phase. Likewise, there are some used to highlight the presence of hydrocarbon (chimney effect) like energy, frequency, amplitude, etc.

For better results of the seismic attribute in any part of the area, proper energy penetration with good seismic data quality is required. Bambor syncline is a regional geological feature extending towards other gas fields including Bambor, Pirkoh, and Zin with nominal Ghazij shales thickness. Evaluation of source potential of Ghazij shales in the part of Bambor syncline extending towards Pirkoh filed is the main focus of the study. The area under study consisted of two geological features: Pirkoh anticline and Bambor syncline. In the case of the study area, an unusual geological behavior and overturned strata is observed at anticlinal part due to which seismic energy does not penetrate properly and hence attributes do not provide the sufficient information regarding the bright spot occurrence. While moving away from that anticline in west ward direction towards the Bambor syncline and flanks of the region, the strata was much preserved and retained some seismic information, with high seismic energy penetration and good data quality, so bright spot was indicated by the application of applying multiple attributes.

In this study, standard wave and trace based seismic attributes have been used to analyze the pore fluid characteristics of reservoir interval. Sonneland et al. (1989) introduced the interval attributes while Dalley et al. (1989) introduced the wave and horizon based seismic attributes. These attributes are helpful to interpret the reflector characteristics, which cannot be easily observed on the seismic sections (Azeem et al., 2015). Three seismic based attributes have been applied to the seismic cross section in order to highlight the bright spots and gas presence.

2.2.1. Spectral decomposition

Spectral decomposition is a powerful seismic imaging and mapping tool that provides the useful quantitative information for determination of bed thickness, tuning

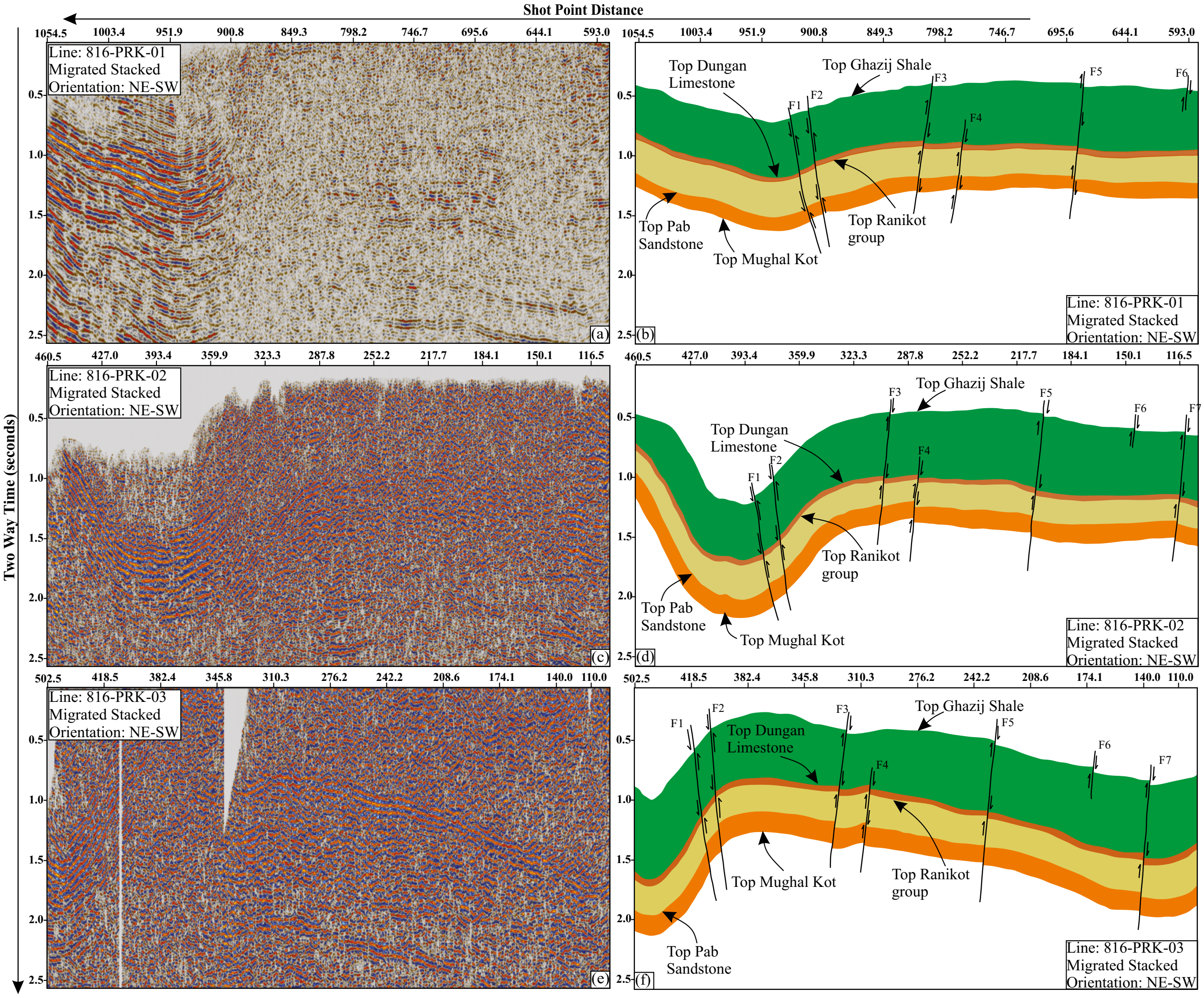

Figure 3. Seismic section of line 816-PRK-01 (a) 806-PRK-02 (c) and 806-PRK-03, (e) on the left side while geocross-sections of line 816-PRK-01, (b) 806-PRK-02, (d), and 806-PRK-03, (f) with marked horizons and faults are shown on the right side. South-western side of sections is representing the part of Bambor syncline within Pirkoh field.

and attenuation changes and above most hydrocarbon detection to a level that was previously impossible (Ismail et al., 2020). In spectral decomposition, the seismic data are converted from time domain to the frequency domain and decomposed into frequency components that unravel the seismic signal into its constituent frequencies, which allows the user to see phase and amplitude tuned to specific wavelengths (Ahmad and Rowell, 2012). Changes in the behavior of frequency directly indicate the gas anomaly. Spectral decomposition is the frequency attribute that returns the amplitude spectrum or wavelet coefficients. The amplitude component excels at quantifying bright spots, thickness variability and detecting lateral discontinuities while the phase component detects lateral discontinuities (Castagna et al., 2003; Portniaguine and Castagna, 2004; Rastogi, 2013; Othman et al., 2018).

2.2.2. Energy attribute

This attribute calculates the squared sum of the sample values in the specified time-gate divided by the number of samples in the gate Equation (1). The energy is a measure of reflectivity in the specified time-gate. Higher the energy, higher is the amplitude (Hardy et al., 2003).

$$E = \frac{1}{N}\sum_{n=1}^{N} X_n^2 \tag{1}$$

where, E=Average energy, N = number of samples, x_n = amplitude.

This attribute enhances the lateral variations within seismic events and is, therefore, useful for seismic object detection (e.g., chimney detection) (Brown, 2001; Chopra and Merfurt, 2007). The bright spots represent the high amplitude areas in the seismic section, and, for their identification, energy attribute was used with default time gate from –28 ms to 28 ms.

2.2.3. Instantaneous amplitude attribute

Amplitude is directly linked with reservoir properties and stratigraphic events. The instantaneous amplitude measures the reflectivity strength, which is proportional to the square root of the total energy of the seismic signal at an instant of time. The instantaneous phase is used to emphasize the continuity of events on a seismic section. It also takes into account the lateral changes caused by any hydrocarbon anomaly specially gas effect (Ismail et al., 2020). This attribute outputs the instantaneous amplitude of the selected data volume at the sample location. It is used as an effective tool to identify acoustic impedance contrast, bright spots, possible gas accumulation, bed boundaries, and spatial correlation to lithologic variations (Taner, 2001; Subrahmanyam and Rao, 2008). The attribute is used with the default time gate from –28 ms to 28 ms.

2.3. Maturity study

Maturity study for the Ghazij Formation has been performed in order to evaluate its source potential in the study area. TOC computation, burial history, maturity, and porosity plots have been generated with the help of the wireline data of Pirkoh-01 well. GVERSE Petrophysics software has been used for the TOC computation using the wireline log data, whereas BasinMod software has been used for the generation of burial history, maturity, and porosity plots. These results for the PIrkoh-01 well were then compared with the maturity level of the Ghazij Formation in Bambor syncline area, and final correlation is prepared using the stratigraphic sequences of Bambor, Pirkoh, and Sui wells.

2.3.1. TOC computation

Wireline log data of Pirkoh-01 has been used for the computation of TOC using Passey's DLogR method. Resistivity and sonic log curves were used for marking the baseline and DLogR intervals. The method was applied on the complete thickness of Ghazij Formation with resistivity and sonic log plotted on the logarithmic scale. Sonic log has been scaled in such a way that one logarithmic cycle on the scale must be equal to 50μs/feet (Rider, 2002). The separation between the resistivity and sonic values, in such a way that both the curves should be trending towards the higher values, is termed as the DLogR interval indicating the probable source potential. However, the nonsource interval is marked by the low values or overlay of both the curves and is marked as baseline interval. Total organic content, Tmax, and geochemical values of different rocks in the study area and its vicinity have been considered for the correlation (Raza et al., 1990; Khoso et al., 2003). Porosity computation and volume of shale has also been evaluated for the Ghazij Formation.

2.3.2. Burial history

Burial history plot of Pirkoh-01 well is prepared using information of stratigraphy, formation thickness, formation tops, and ages of deposition, lithologies, thermal history, and petroleum system information. For this correlative maturity study, encountered and/or predicted stratigraphy, depth, thickness of the eroded strata of one exploratory (Pirkoh-01) and one synthetic (Bambor syncline) well have been used. With the help of the encountered and/or predicted stratigraphy of the same location along with the depth and thickness values, stratigraphic correlation of the four wells, including Pirkoh-01, Sui-01, Bambor Anticline (synthetic), and Bambor syncline (synthetic) was made. The probable and estimated values for the depth, overburden, eroded strata, and isothermal history were obtained from the burial history diagrams.

2.2.3. Maturity and thermal history

Maturity trends were predicted from the burial and thermal history information given as the input data sets in the software. Present thermal state can be determined directly by measuring the borehole temperature through logs. Heat flow can also be estimated by comparing temperature data from the logs with laboratory data of thermal conductivity of the related formations (Nazeer et al., 2012). Borehole temperature can be used to find the geothermal gradient. If there is no paleo-temperature data available, then borehole temperature can be used to interpolate data between current and past temperature. Maturity (Ro) plot has been generated with the Temperature curve of Pirkoh-01 well and is compared with the maturity information of Bambor syncline.

2.2.4. Porosity plot

Porosity in the rocks in not only dependent on the depth factor, but it is also dependent upon the effective stress. It cannot be always true that porosity might have an indirect relation with depth (Zhang, 2013). In general, there would always be a decrease in the porosity of the rocks as the depth increases. BasinMod software uses the porosity-effective stress compaction method (formerly called the Statoil Fluid Flow Method) for computing the porosity reduction trend along with depth. The fluid flow model for the compaction of sedimentary basins relates that the compaction of the strata is governed by porosity, which is the function of pressure (Wangen et al., 1990).

3. Results

3.1. Seismic interpretation

Seismic interpretation shows the series of anticline associated with the syncline. The syncline is termed as Bambor syncline, which is the main area of interest in terms of hydrocarbon evaluation. The deepest part of the formation is located in the southern side of the structural high, while the central high structure also dips in the north and south direction with some gradual decrease in the dip values. The abrupt change in the dip value at the southern flank of the central structural high shows a synformal anticline. The eastern flank is marked by gentle dip pointing towards the Punjab Platform.

Depth contour map of Ghazij Formation to exactly demonstrate the structural trend depicted the increase in values in southern part representing the synclinal part, while the northern part is representing the structural high where the Pirkoh wells were drilled (Figure 4). The spacing of contour in the central part and structural high depicted the gentle dip, while moving away from this central high towards north or south on each flank represents the synformal structure (deeper zone). The narrower contour lines represent the sharp changes in the dip values, especially on the southern flank of interested area. The same structural trends delineated on seismic sections have been depicted by the depth map confirming the structural analysis. The southern synformal part is the main focus of the study for hydrocarbon prospective where the seismic data has shown the bright spots after applying the various attributes.

3.2. Seismic attribute analysis

Seismic attribute analysis was performed on all seismic lines, but the best output in terms of bright spot identification turned out on seismic line 816-PRK-01. Seismic attributes are executed only on package of the target i.e., Ghazij Formation for better visualization of the gas presence in the synclinal part. Most direct hydrocarbon indication relates to gas rather than oil reservoir as the effect on acoustic properties of gas in pore space is significantly greater than oil (Kalkomey, 1997; Ibe and Oyewole, 2019). We can directly determine hydrocarbons (mainly gas) by change in frequency, energy, polarity, phase, and amplitude. Figures 5a–5d represent the cross sections of seismic line 816-PKR-01 on which the seismic attributes are performed at the Ghazij interval.

The time-frequency spectrum at the trace number 1540 is shown in Figure 6. Sudden high amplitude (blue color) at the time interval between 1100 and 1300 ms can be clearly seen on that amplitude spectrum. Anomalous attenuation can also be observed on spectrally decomposed sections. For example, anomalous attenuation of high frequencies has been used to indicate the bright spot and presence of gas. Spectral decomposition attribute applied on the cross section indicates the bright spots (yellow color) on the lower part of the Ghazij Formation at the same time interval shown by amplitude spectrum (Figure 5b).

For highlighting the gas presence at the lower part of target formation in the Bambor syncline, the energy envelope attribute was applied. The energy shows anomalous behavior and forms cluster while passing through the hydrocarbon bearing zone specially gas. Energy attribute has been extracted, since it is one of the best amplitude-based attributes to highlight gas zones and lateral continuity of gas prone zones. Here, it is represented by the maximum energy range with the yellow and blue color at two-way time ranging in the same interval as shown by the amplitude and time-frequency spectrum (Figure 5c). These bright spots are frequently related to the abrupt change in facies/lithologies and most common with gas accumulations.

In the present study, instantaneous amplitude attribute is also used for the confirmation of the bright spot occurrence on the seismic section at Ghazij level (Figure 5d), as amplitude is the key attribute in direct hydrocarbon indication and its response varies in different fluids. Gas occurrence in the pores of rock often produces visible changes on seismic section. The acoustic impedance of gas is less than oil and water, so there is maximum chance to have high anomalous amplitudes in gas filled zones. Bright spots always have negative reflection coefficient with abrupt amplitude behavior. These high amplitude values are often associated with lithological changes, channel sand bodies, porous lithology, bright spots, and especially gas saturated zones. High amplitude zones can be clearly observed on the seismic cross section in yellow color (Figure 5d). Multiple bright spots laterally and vertically extending in the lower part of targeted zone clearly designate the gas occurrence. Thus, the attributes applied on the seismic data provide the evidence of the chimney effect at the Ghazij Formation.

3.3. Maturity study

3.3.1. TOC computation

Ghazij Formation is encountered at the depth of 560 m in Pirkoh-01 well with a total thickness of around 1100 m (Figure 7). Results have been plotted in four tracks including shale volume, porosity, DLogR, and TOC. Ghazij Formation is composed of several facies, including sandstone, siltstone, limestone and clays; however, shale facies are the major lithological unit (Shah, 2009). Top and bottom part of the formation shows variation in the shale volume but due to limitation of data, only volume of shale is estimated, and other facies have not been determined. Middle part of the formation is mainly composed of the shale facies, which is the major prospect for the TOC computation.

Top part of the Ghazij Formation up to the depth of around 100 m shows the DLogR interval, whereas the bottom part is marked as the baseline interval (Figure 7). The TOC computed from the log data shows good results in the middle part, as it has the maximum shale volume. Although DLogR overlay shows separation in the top part, due to low shale volume, it shows only few small peaks of TOC at around 600 and 700 m depths. Maximum TOC values in the formation goes up to 2.5 % at multiple depths

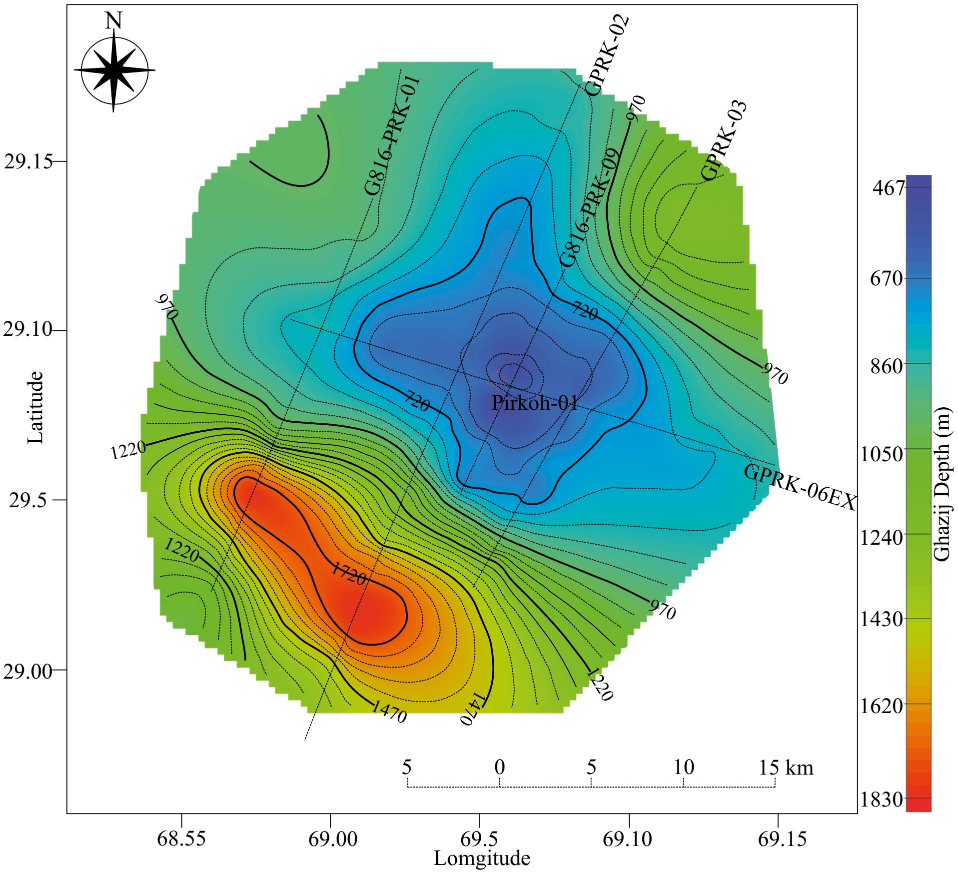

Figure 4. Depth contour map prepared for Ghazij Formation. South-western part of the map shows the synclinal part (orange color) as interpreted in the seismic sections. The depth of Ghazij Formation is around 560 m at the Pirkoh-01 well that extends around 1700 m in the synclinal part within Pirkoh field. The depth of Ghazij Formation further increases in the westward direction towards Bambor syncline (synthetic) location as depicted in well correlation.

in between 1200–1300 m interval, but the average TOC value in the formation is around 0.43 %.

3.3.2. Burial history

Burial history plot for Pirkoh-01 well has been prepared for determining the maturity level of Ghazij Formation in response of the overburden pressure and geothermal gradient (Figure 8). The depositional trend during the Mesozoic Era is relatively stable, but the increase in the sedimentation rate during Cenozoic Era shows subsidence due to increase in the overburden pressure. Upper part of the Ghazij Formation lies within the early maturation stage (yellow color) having % Ro ranging between 0.5–0.7, and the temperature varies between 70–90 °C. The lower part of the formation shows mid-level maturity (green color) with % Ro ranges of 0.7–1, and temperature values are between 90–100°C.

The burial history diagram of Bambor syncline (synthetic) has been taken for the comparison of maturity potential of Ghazij Formation in the area (Figure 9). At this location, the burial history diagram, prepared by the synthetic well gives some probable answers. It is clear that the major source rock of the area, i.e. Sembar Formation at this locality, is highly over-cooked, lying in the temperature window of 210 °C to 240 °C whilst Habib Rahi Limestone falls in the oil window, whereas the Ghazij Formation is in the gas window (Figure 9). This change in the maturity level is the result of the increased depth of Ghazij Formation in Bambor syncline area. Top of the Ghazij Formation is around 4000 m at this location, which is approximately km westward of the Pirkoh-01 well where top of the Ghazij Formation is at 560 m.

Figure 10 displays the stratigraphical correlation between four wells. The correlative maturity study reveals the Ghazij Formation is buried at greater depths with a considerable overburden at the Bambor syncline (synthetic) location as compared to the Pirkoh-01 well. This overburden plays an important role in the maturation of source rock. At Pirkoh-01 well location, around 1400 m

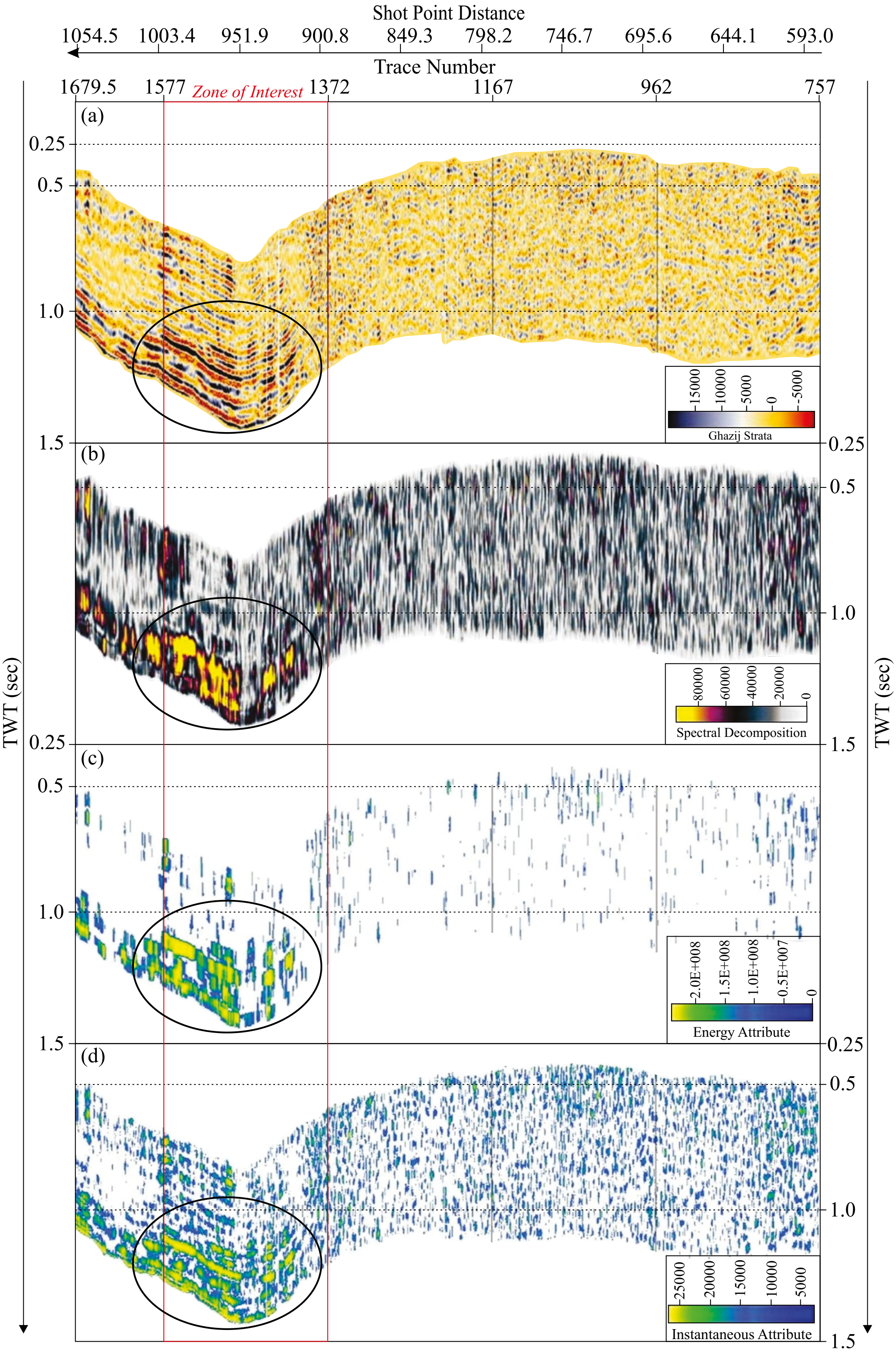

Figure 5. Seismic attributes with bright spot occurrence are represented on line 816-PRK-01 at 1100–1350 ms. Anomalous behavior of amplitudes, energy, and frequency in terms of bright spot (chimney effect) can be observed on seismic section (a) spectral decomposition, (b) energy envelope, (c) and instantaneous amplitude (d).

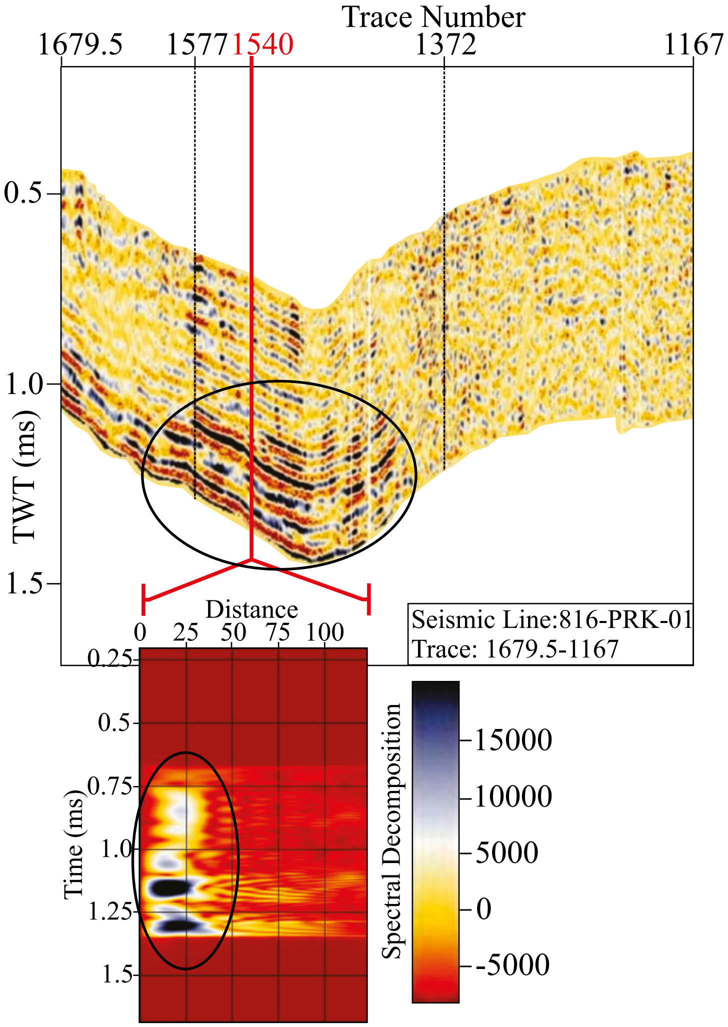

Figure 6. Time frequency spectrum at the 1540 trace number (line 816-PRK-01) using spectral decomposition attributes. The spectrum shows the bright spot around 1100–1350 ms with high amplitude.

of eroded strata has been estimated, whereas at Bambor anticline (synthetic) location, 3300 m of strata has been eroded due to uplifting. This erosional event is considered as the major cause of the low maturation level of Ghazij Formation where the depth is shallow.

3.3.3. Maturity and thermal history

The third main parameter for maturity correlation of Ghazij Formation is determination of maturity level (Ro) along with the thermal history. According to the maturity trend at Pirkoh-01 well, top of the Ghazij Formation shows around 0.5% Ro and 50 °C temperature, which increases up to 0.9% Ro at depth 1650 m with the temperature of around 100 °C (Figure 11). Maturity curve (blue color) is plotted with the temperature curve (red) to show the variation in the maturity level along with the increase in depth. Maturity value of Ghazij Formation at the Bambor syncline (synthetic) is higher as compared to Pirkoh-01 well location. Ro% value of Ghazij Formation at this location is approximately ranging from 0.9 to 1.3 with the temperature values of 145–165 °C (Figure 12).

3.3.4. Porosity plot

Using the porosity-effective stress compaction method in BasinMod software, porosity reduction has been computed for Pirkoh-01 well (Figure 13). The blue color curve shows the porosity reduction (fraction) with depth, which represents that the porosity of Ghazij Formation at the top is around 0.22 (fraction), which is decreasing up to 0.14 (fraction) at the bottom. The general trend for the decrease in porosity is related with the increase in burial depth and overburden; however, in some cases, porosity may not follow this trend if the effective stress does not follow the normal compaction trend. This is mainly caused

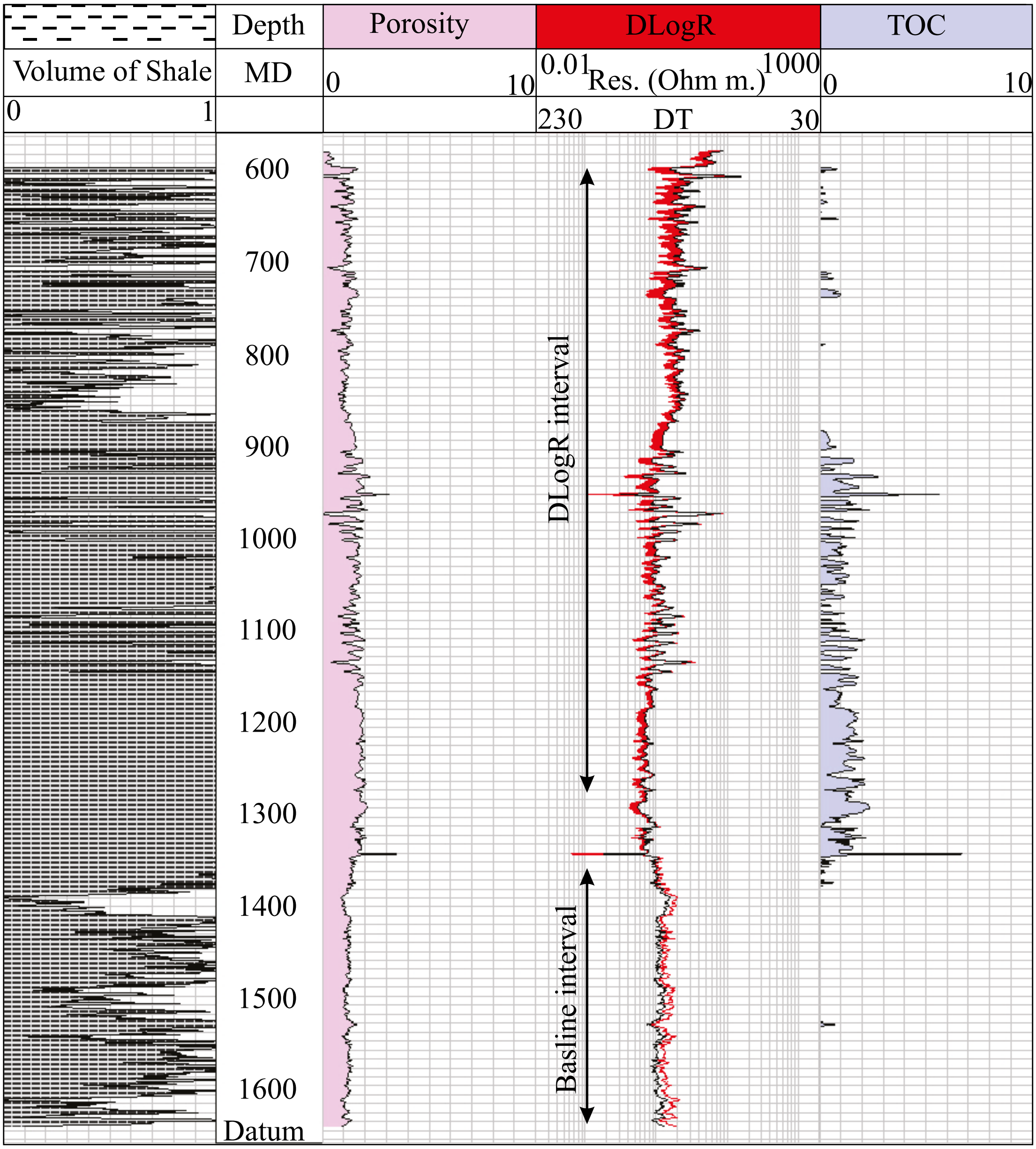

Figure 7. Wireline log plot of Pirkoh-01 well for the computation of TOC in Ghazij Formation. Shale volume, porosity, DLogR, and TOC results are shown in separate tracks. DLogR interval is marked with the separation of resistivity and sonic curves in the top part of the formation and baseline interval is marked at the bottom part of the formation. Computed TOC values of Ghazij shales in the middle part are ranging up to 2.5% where maximum shale facies are present as shown in shale volume track.

in low permeability lithologies like shales and clays. It can be seen in Figure 13 that, at greater depths, decrease in the porosity is very less as compared to the shallow formations. Figure 14 shows the porosity-depth trend of Ghazij Formation at Bambor syncline (synthetic) well. The porosity value of 0.06 to 0.07, equivalent to 6 to 7% in the Ghazij shales shows a very low decrease as compared to Pirkoh-0 due to its greater depth.

4. Discussion

Seismic attribute analysis was performed to interpret the gas accumulation within the targeted interval in terms of litho-fluid distribution. In seismic line 816-PRK-01, bright spot was labeled as a direct hydrocarbon indicator. This spot has a lateral extent from trace number 1372–1680 and vertically located between 1–1.45 s. Furthermore, these bright spots occur at greater depths in synclinal

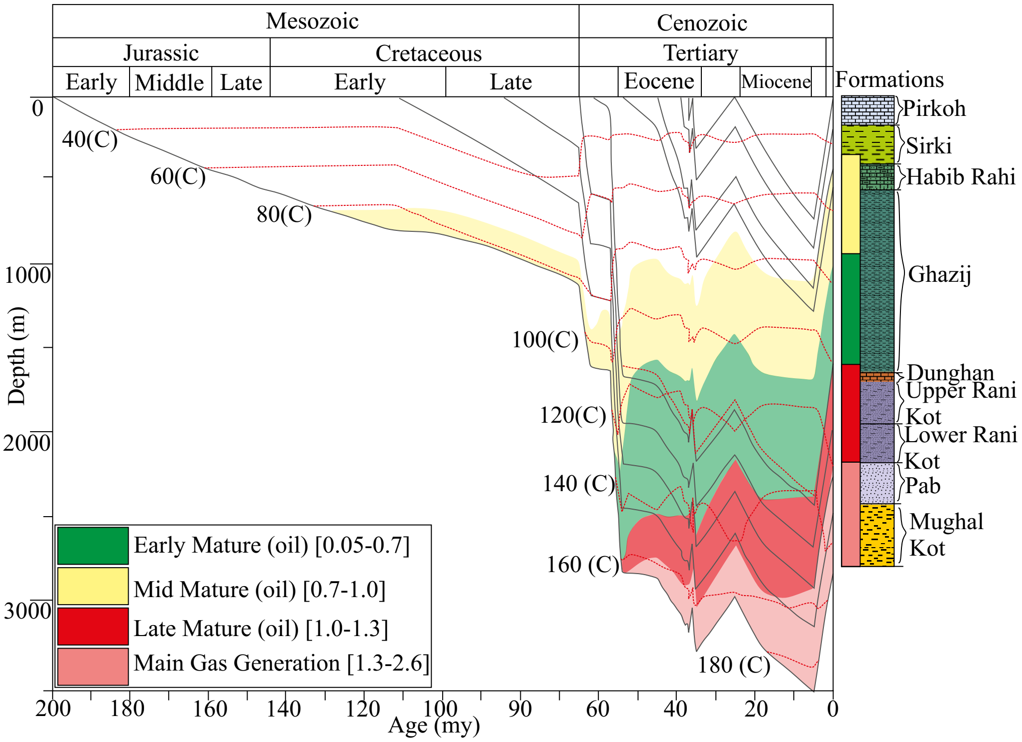

Figure 8. Burial history plot representing burial depth (m) of the stratigraphic sequence at the Pirkoh-01 well location. Isotherms (red lines) represent the depth and time of oil and gas generation windows. Ghazij Formation lies at the depth ranges between 560–1650 m in the oil window (green color) having 0.7 to 1 % Ro depicting the mid maturity level of the formation.

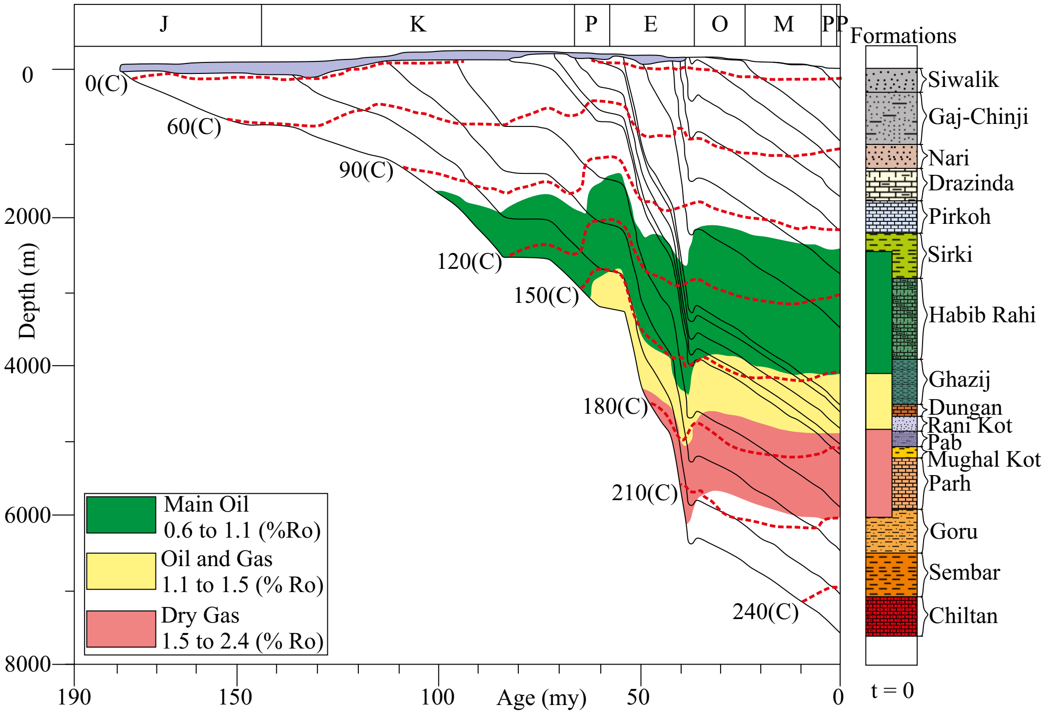

Figure 9. Burial history plot representing burial depth (m) of the stratigraphic sequence at the Bambor syncline (synthetic) location. Isotherms (red dotted lines) represent the depth and time of oil and gas generation windows. Ghazij Formation lies at the depth of around 4000 m in the oil and gas window (yellow color) having 1.1 to 1.5 % Ro (Mujtaba, 1999).

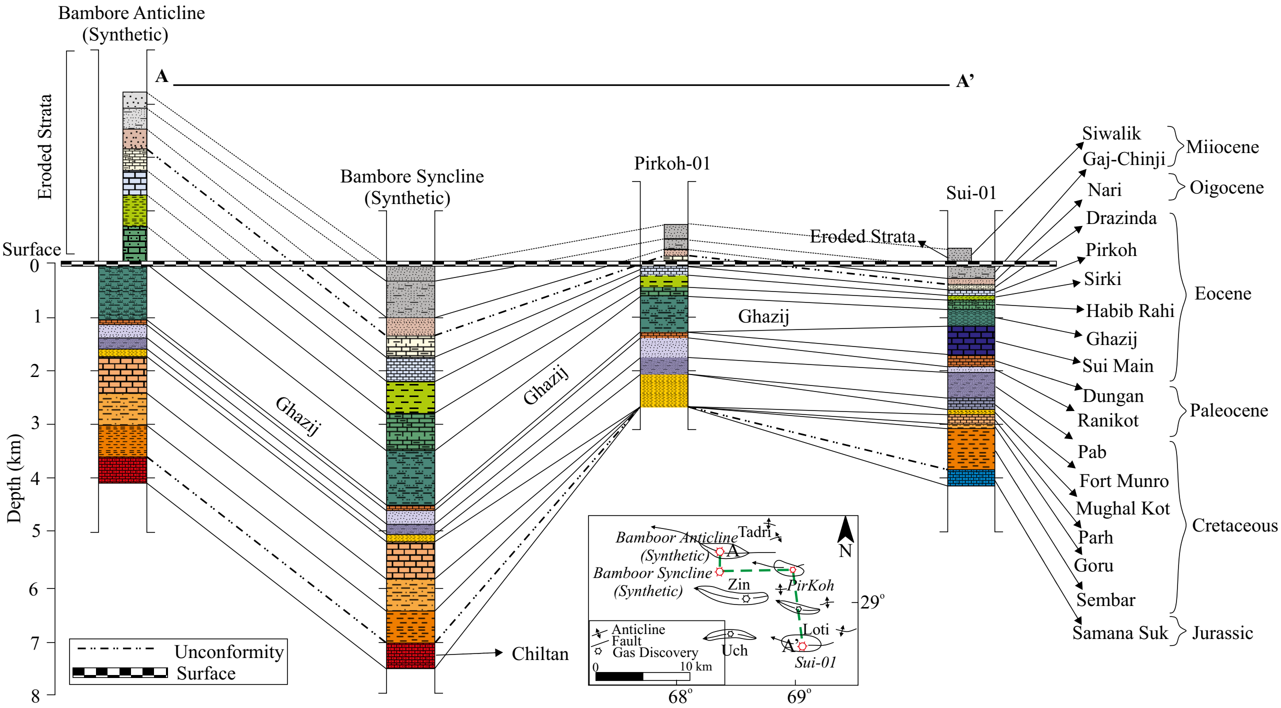

Figure 10. Stratigraphic correlation along cross sectional line AA' with index map of Bambor anticline (synthetic), Bambor syncline (synthetic), Pirkoh-01 and Sui-01 wells (left to right). Well correlation clearly shows the increase in depth of Ghazij Formation from Pirkoh-01 to Bambor syncline (synthetic). The overburden stress at the Bambor syncline (synthetic) location increased the maturity level of Ghazij Formation from oil window (at Pirkoh-01) to gas window (at Bambor syncline).

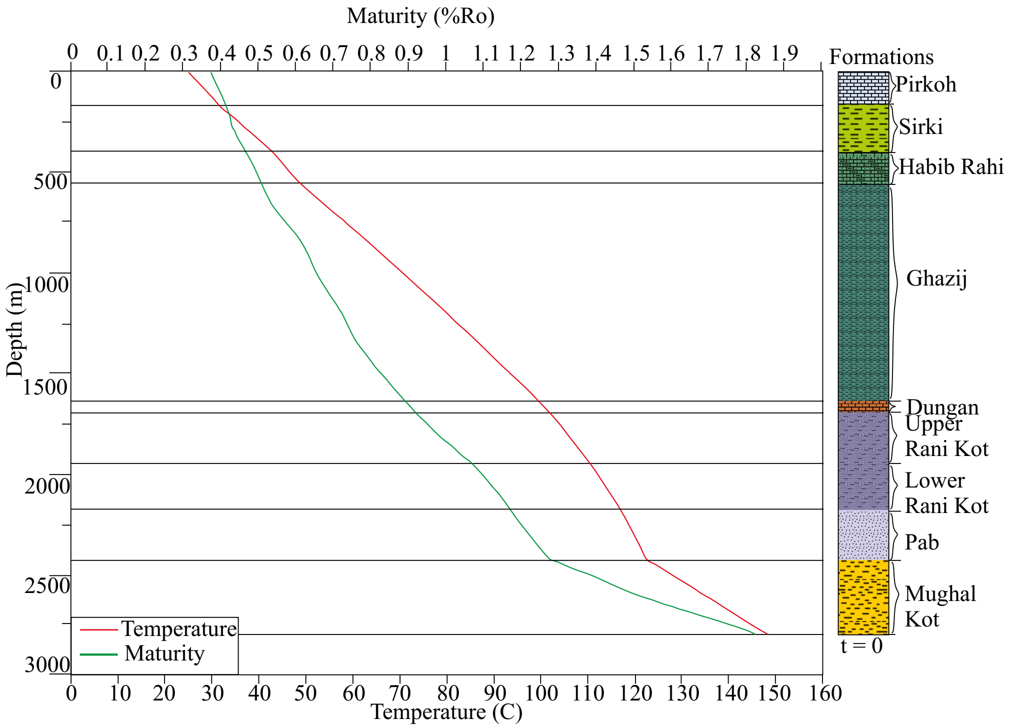

Figure 11. Maturity curve (blue) for the stratigraphic sequence of the Pirkoh-01 compared with the temperature curve (red). Top of the Ghazij Formation at 560 m shows around 0.5 % Ro, which increases up to 0.9 % Ro at depth 1650 m.

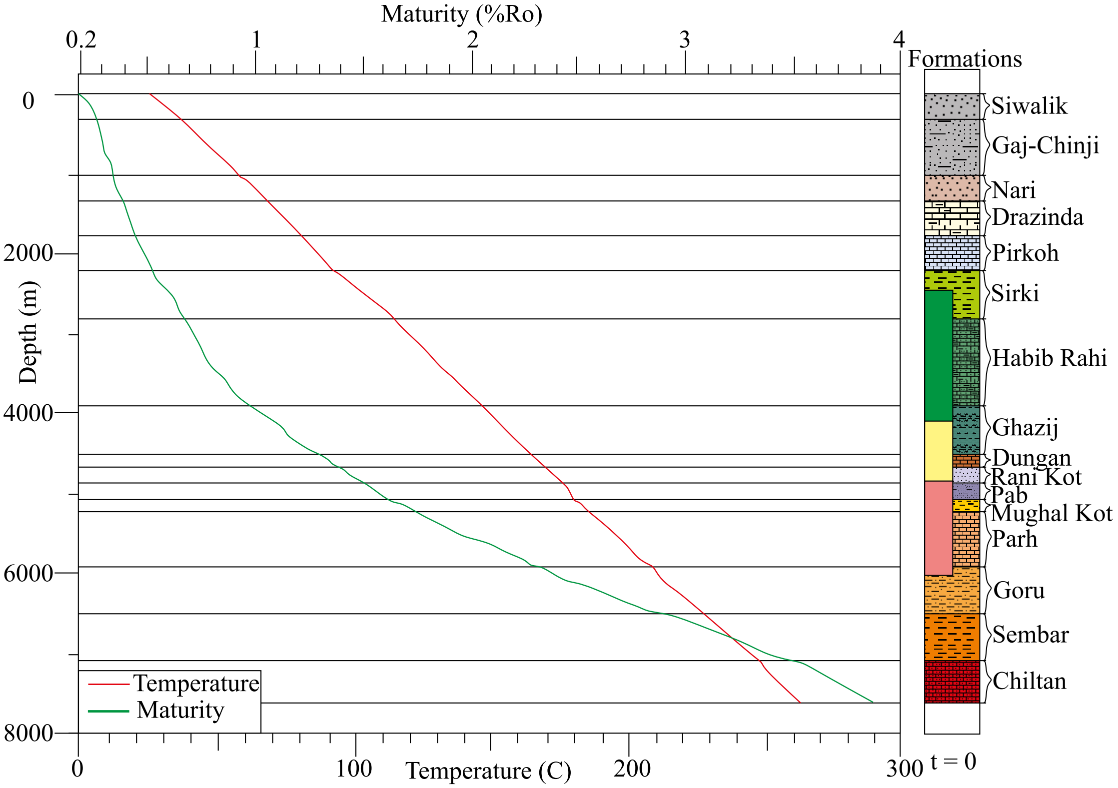

Figure 12. Maturity curve (blue) for the stratigraphic sequence of the Bambor syncline (synthetic) compared with the temperature curve (red). Top of the Ghazij Formation at around 4000 m shows around 0.9 % Ro which increases up to 1.3 % Ro at depth 4500 m (Mujtaba, 1999).

part and, thus, are favorable for hydrocarbon maturity. The presence of gas in pores of the rocks often produces detectable changes on a seismic section. Application of spectral decomposition, energy envelope, and amplitude enhanced the confidence in terms of bright spot existence at the level of Ghazij Formation. As the shale has low impedance, the value ranges for the amplitude up to 2000–2500 and energy 1.5e–2.0e confirm the presence of gas (Zhang et al., 2020; Zeng et al., 2021). Time-frequency spectrum extracted from spectral decomposition showed the signs of gas presence around 1100–1350 ms, while energy cluster and high amplitude behavior at the same level second the applied attribute outputs. The distribution of energy envelope attribute at the lower part indicated the gas prone zone.

Apart from the fact that the Sembar Formation is the main source rock in the Middle and Southern Indus Basin, the Ghazij shales have been recognized as the source rock in the Khuzdar area, Kirthar Range, Baluchistan (PPL, 2011; Nosheen and Giao, 2017). The Ghazij Formation is at early maturation stage in Pirkoh-01 well, but it has achieved the gas generation window in the Bambor syncline area. Hence, there might be a possibility that the gas has been generated from shales of the Ghazij Formation at the depth of 4000 m, at the temperature ranged from 120 °C to 150 °C. Such temperature conditions are favorable for the gas generation (Durrani et al., 2020).

The burial history diagram indicates that the Ghazij Formation could be a possible source rock in the study area. But still, there is a need for the gas source correlation data for the confirmation. The TOC values of the formation have been recorded up to 2.5 % in Pirkoh-01 well, but the maturity level is low in the shallower part as compared to the synclinal part. There are some gas shows reported in the Ghazij Formation at the Mari and Domanda area (Shuaib et al., 1993). It might be possible that the shales of the Ghazij Formation could be the probable source rock in the middle Indus basin and charging hydrocarbon for reservoirs like Habib Rahi limestone, Sui Main Limestone, and Kirthar Formation. However, source oil/gas correlation data will help to establish the Ghazij source rock effectiveness.

Rokosh et al. (2009) showed a maturity value above 1.0 to 1.1% Ro indicates that the organic matter is sufficiently mature to generate gas and could be an effective source rock. The observed values of Ghazij shales in Pirkoh and Bambor area show good maturity level for a rock unit to be termed as a potential source rock. The depth of the

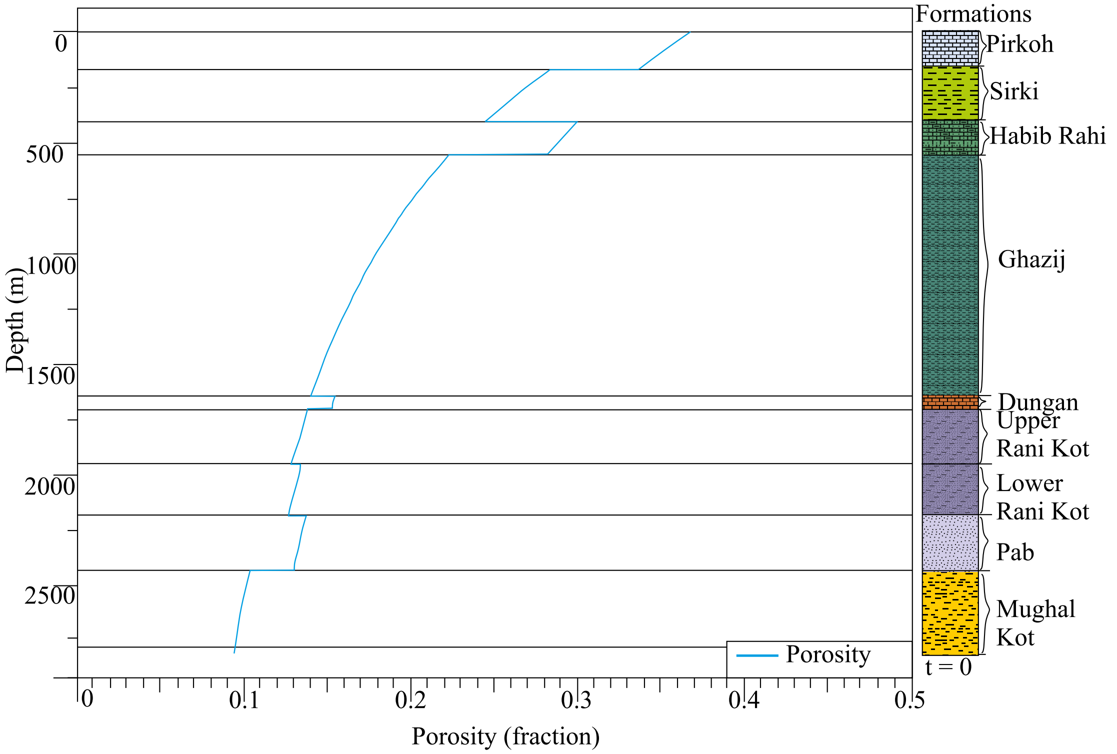

Figure 13. Porosity reduction curve (blue) with burial depth of the stratigraphic sequence at Pirkoh-01 well. The porosity trend is decreasing from 0.22 (fraction) at top of Ghazij Formation up to 0.14 (fraction) at the bottom.

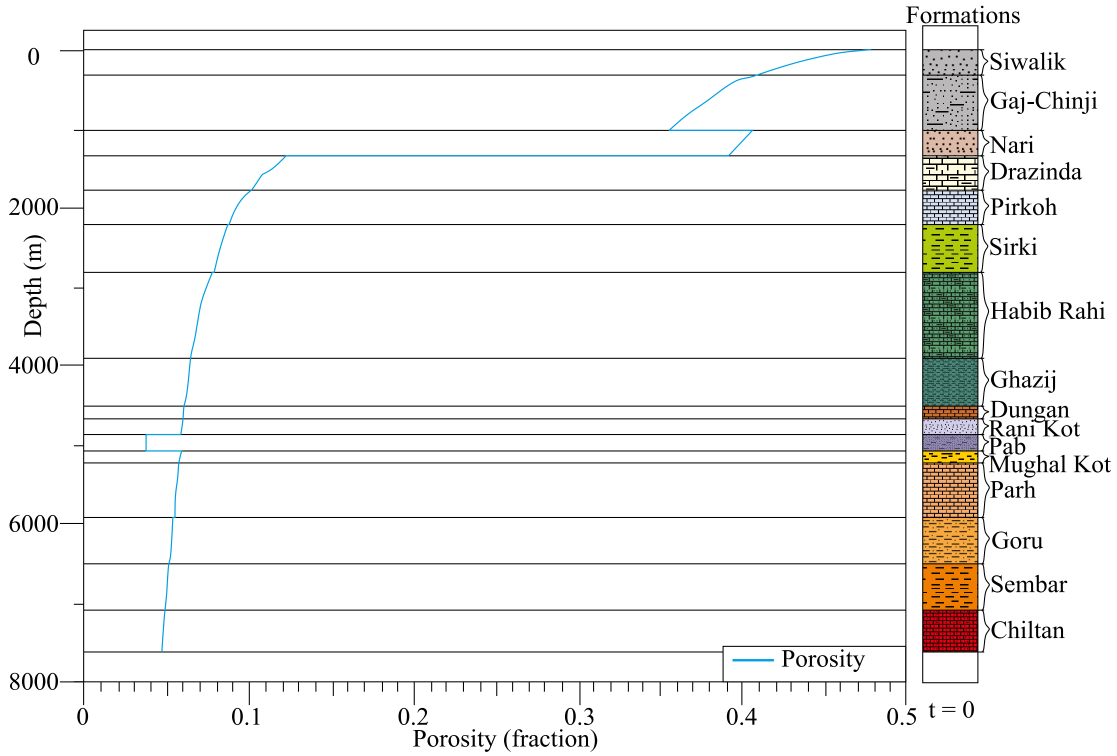

Figure 14. Porosity reduction curve (blue) with burial depth of the stratigraphic sequence at Bambor syncline (synthetic). The porosity trend is decreasing from 0.07 (fraction) at top of Ghazij Formation up to 0.05 (fraction) at the bottom (Mujtaba, 1999).

formation at this location is 4000 m, which is considered suitable overburden. Although the temperature and maturity of Ghazij shales lies within the oil window, the temperature of the formation in the synclinal part of the Bambor is within the temperature window suitable for the generation of gas. Core measurements indicate that shales having 1 to 12% effective helium porosity are usually called gas-filled porosity excluding pore spaces filled with clay bound water (Cluf, 2009). Based on the evidences discussed in this study, further steps can be taken for a detailed maturity study.

5. Conclusion

Maturity study for evaluating the source rock potential of Ghazij Formation has been successfully performed using well log and seismic data. Qualitative and quantitative analysis of seismic attributes have proved to be helpful in delineating the promising bright spot from 1100–1350 ms in Bambor syncline. TOC computation and maturity modelling confirmed that Ghazij shales indicate good maturity level at deeper synclinal parts with favorable conditions for oil and gas generation. Thermal history and porosity curves further strengthen seismic and burial history results by indicating gas-filled porosity from 8%–14%. As depth is the main controlling factor for maturation, the Ghazij Formation do have a fair amount of source potential.

The seismic data, TOC values, burial history, geothermal gradients, and the maturity trend in different locations are recorded at such levels that are suitable for a potential source rock. The gas-source correlation data are needed to be verified to establish the Ghazij Formation a potential source rock in the middle and lower Indus basin.

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