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Structural and Seismic Attribute Analysis of the Paleocene Carbonate Reservoir from the Balkassar Field, Potwar Plateau, Pakistan

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Abstract

The structural and seismic properties of the Paleocene carbonate reservoir are re-evaluated, using 3D seismic data multi-attributes, to improve reservoir prediction accuracy rarely documented earlier. This study highlights a number of relevant post-stack seismic attributes for understanding the structural setup and seismic properties of a carbonate reservoir. The structural analysis was carried out using seismic interpretation, combined with multi-attribute analysis for prospect actualization and generation of a 3D structural model to determine the structural aspect. The structural interpretation reveals the presence of faults and an asymmetrical anticlinal structure demonstrating a four-way closure, confirming compressional tectonics. The high amplitude anomaly (-6 to 12) combined with the RMS attribute (23 to 32) suggests bright spots in the Paleocene carbonate reservoir and gas saturated zone, the variance attribute (0.05 to 0.03) highlights the presence of two major faults, and the lower instantaneous frequency demonstrates the presence of hydrocarbons. The attribute results indicate that the Lockhart Limestone possesses good reservoir potential as revealed by DHI (bright spot), gas saturated zone and a trapping mechanism supported by four-way structure closure in the region and can help to understand analogous carbonate reservoirs in similar geological settings around the world.

Keywords: Seismic interpretation, carbonate reservoir, seismic attributes.

تحليل السمات الزلزالية والتركيبية للمكمن الجيري الباليوسيني في حقل بالكاسار، هضبة بوتار، باكستان

الخلاصة:

تم إعادة تقييم الخصائص الزلزالية والتركيبية للمكمن الجيري الباليوسيني باستخدام البيانات الزلزالية ثلاثة الابعاد والمتعدد السمات لغرض تحسين التقييم المكمني والذي لم يوثق في الدراسات السابقة. تسلط الدراسة الضوء على عدد من السمات الزلزالية المهمة بعد التكديس لفهم الوضع التركيبي والخصائص الزلزالية لتركيب جيري. تم إجراء التحليل البنيوي باستخدام تفسير البيانات الزلزالية، وذلك بالاشتراك مع تحليل متعدد السمات لتحديد وتكوين نموذج ثلاثي الأبعاد للمساعدة في تحديد البنية التركيبية للحقل. يظهر التفسير التركيبي وجود الصدوع وطية مقعرة غير متناظرة تبين انغلاقاً رباعي الاتجاهات مما يؤكد وجود فعاليات تكتونية

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انضغاطية. ان قيمة الشذوذ العالية (-6 الى 12) المترافقة مع قيمة RMS بين 23 و 32 تشير الى وجود نقاط ساطعة في المكمن الجيري الباليوسيني ونطاق غاز مشبع، كما ان سمة التباين من 0.05 الى 0.03 تشير الى وجود صدعين رئيسين اما التردد الأقل فيشير الى وجود الهيدروكاربونات. أشار تحليل السمات الى ان الحجر الجيري اللوكارهتي يمتلك إمكانيات مكمنية جيدة وذلك بناءً على قيمة الـ DHI (نقطة ساطعة)، ووجود نطاق تشبع غازي وآلية احتجاز مدعومة بأغلاق تركيبي في المنطقة والذي يساعد في فهم الخزانات الجيرية المماثلة في البيئات الجيولوجية حول العالم.

1. Introduction:

The discovery of carbonates as hydrocarbon carriers in the late 50s triggered intensive research on the evaluation of their reservoir characteristics. Numerous studies have been carried out to understand the nature, characteristics and mechanics of carbonates based on which several models for carbonate reservoirs were established (e.g. [1]; [2]; [3]; [4]; [5]). Structurally complex areas have turned out as a challenge for reservoir characterization of carbonates ([4]; [6]; [7]; [8]). This problem can be resolved by using advanced techniques like attribute extraction from seismic data. These attributes can be connected physically to the reservoir properties ([9]; [10]). Seismic attribute technology is reliably used to derive useful and latent information from providing seismic data in abundance and effective data for oil field exploration and development. It also serves as a potential tool for solving complex geological identifications. Therefore, it improves the value of seismic information in the application of oil and gas exploration and development [11].

Carbonates are widely distributed in the different geological provinces of Pakistan including the Indus Basin, Pishin Basin, Makran Basin, Hazara Basin, Kashmir Basin and Potwar Basin [12]; [13]. The first discovery in Khaur (Potwar Basin) was made in 1914. About 150 wells have been drilled in the Potwar Basin so far for exploration of hydrocarbons and most of these wells failed. One of the major concerns behind the failure of these wells is complex subsurface structures [14]. The Balkassar Oilfield is situated in the southern part of the Soan Syncline in the eastern Potwar Basin (Figure 1). This field has been producing oil and gas from fractured carbonate deposits of the Eocene and Paleocene ages [15]. The understanding of the seismic properties using multi-variant seismic attributes is largely described in the literature ([16]; [17]), however, seismic properties of the studied Paleocene carbonate reservoirs are rarely documented. This work presents a case study using their application to the existing hydrocarbon field for better reservoir depiction that could aid in the identification of future hydrocarbon prospects in the region and in similar compressional tectonic settings around the world, where the hydrocarbon accumulation and trapping mechanisms are largely controlled by the presence of faults and anticlinal closures.

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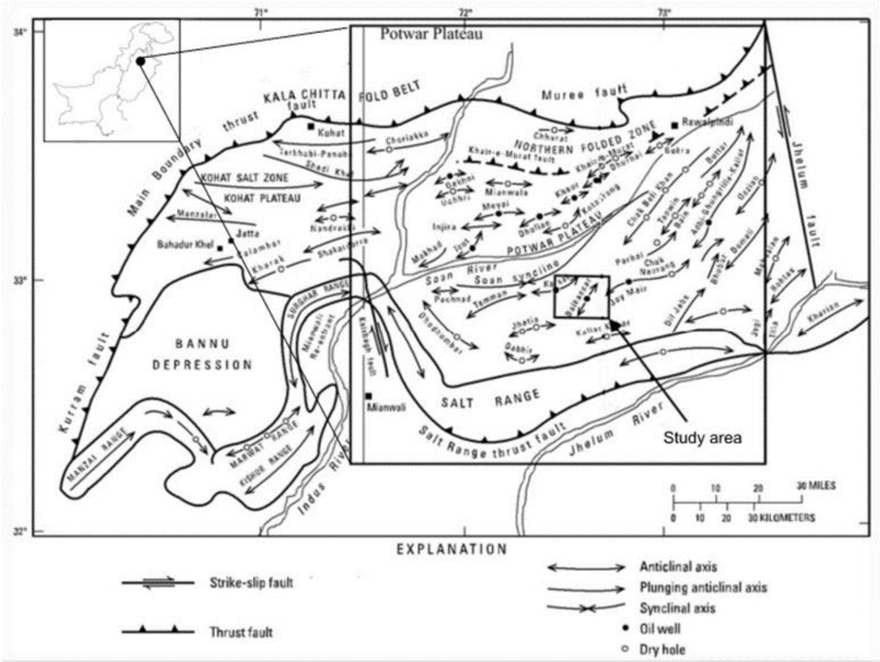

Fig. (1): Generalized location, tectonics and oil and gas map of the Potwar area shown in the inset box

In order to delineate the hydrocarbon potential of the Paleocene carbonate reservoir at the Balkassar area multi-attribute analysis techniques were utilized. The multi-attribute analysis fundamentally incorporates the analysis of different seismic attributes simultaneously or in combination [10]. The workflow included the preparation of time and depth contour maps for subsurface structure and stratigraphic interpretation, and seismic attributes analysis using 3D seismic data to evaluate the possible reservoir characteristics of the Paleocene carbonate reservoir at the Balkassar area. The seismic attributes such as amplitude, phase, variance, RMS and instantaneous frequency are applied to seismic data that help to identify prospective reservoir zones and the distribution of hydrocarbons. The phase of seismic data is used as a good continuity indicator in poor reflectivity areas, variance is applied to image discontinuity-related faulting or stratigraphy. The instantaneous frequency may have a variation due to stratigraphy and can help to identify condensate reservoirs and gas reservoirs, which tend to attenuate high frequencies [18]. This study not only makes it possible to estimate the lithology, texture, indicators, fluid movement, and lithology but will also help in monitoring hydrocarbon production in the reservoirs. This real-world case study demonstrates that the selected multi- variant attributes combined with structural interpretation are able to effectively improve reservoir characteristics prediction accuracy.

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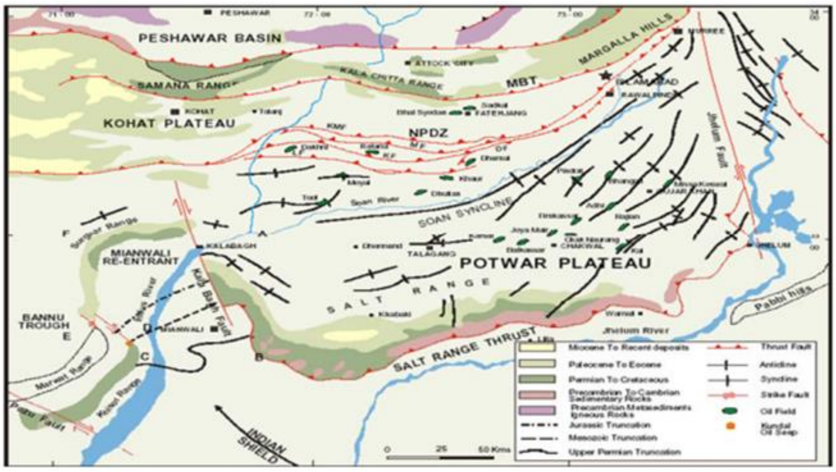

Fig. (2): Tectonic map of the Potwar and the surrounding area

2. Geology and Tectonics

Potwar Plateau is bounded by Salt Range Thrust (SRT) in the south and main boundary thrust (MBT) in the north. The sinistral Jhelum Fault lies at the eastern boundary of the Potwar sub Basin and Kohat Plateau in its west. The River Indus acts as a boundary line to separate the Potwar Plateau to the east and Kohat Plateau to the west within the Upper Indus Basin. The Potwar Basin is divided into the southern Potwar deformation zone and northern Potwar deformation zone on the basis of structural trends.

There is intense and complex deformation in the northern Potwar deformed zone [19] as compared to the Southern Potwar Deformed Zone [20] (Figure 2). The structural trend of the Balkassar Oil Field is northeast to southeast doubly plunging anticline which emerged as a result of a collision between the Indian-Eurasian block succeeded by the inflow of salt evaporates. The Balkassar Oilfield is one of the main oil producing fields in this area [21].

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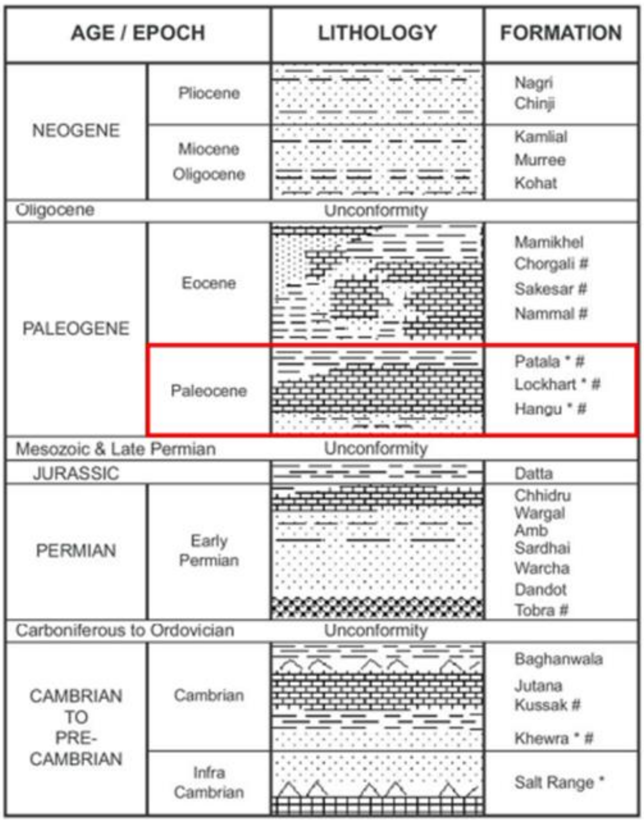

Fig. (3): Stratigraphic column for the Potwar Basin, the red box shows the stratigraphic position of the Paleocene Lockart Limestone

Stratigraphically, the Potwar Basin is characterized by a thick infra-Cambrian evaporate sequence to the comparatively thin stratigraphic portion of the Eocene. Abundant Miocene Pliocene molasses deposits are associated with extreme uplift in late Pliocene. During Himalayan orogeny in Pliocene to Pleistocene time extreme deformation occurred throughout the region. The stratigraphic column of the Upper Indus Basin is presented in Figure (3). Three unconformities were observed which are Ordovician to Carboniferous, Late Permian to Mesozoic and Oligocene in geological time scale [14].

Throughout the period of Ordovician to Carboniferous, the Potwar Basin was elevated leading to no deposition. The next abrupt alteration in sedimentary classification in eastern Potwar is signified by the lack of the Mesozoic sedimentary series [22].

3. Methodology and Workflow

Seismic attributes are changes in the seismic wave signatures that provide specific quantities of geometric, kinematic, dynamic, or statistical features computed from seismic data [23]. The first classification for seismic attributes was documented by Taner (2001) [24]) by

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proposing two general categories for seismic attributes: geometrical and physical. Geometrical attributes enhance geometrical characteristics of the input data (dip, azimuth and continuity) whereas, physical attributes are related to physical properties of the subsurface delineating lithology and include attributes derived from amplitude, frequency and phase components of the trace. This study utilizes the post-stack seismic data for the computation of physical seismic attributes.

In order to carry out this research, 3D seismic data, check shot/VSP survey data and digital well logs data were used. Basic seismic interpretation establishes outsets for the stratigraphic and structural interpretation of the subsurface. The subsurface reflectors were marked on the basis of reflection continuity. Afterward, faults were marked on seismic sections. The time of each marked horizon and faults were picked. The depth information was extracted using picked time and velocity information. Time and depth contour maps were prepared for selected horizons. 3D sub-surface models were prepared. Finally, attributes analysis was applied on the selected horizon. The generalized workflow chart is given in Figure (4). The results obtained were then compared to optimize the results of the interpreted reservoir properties.

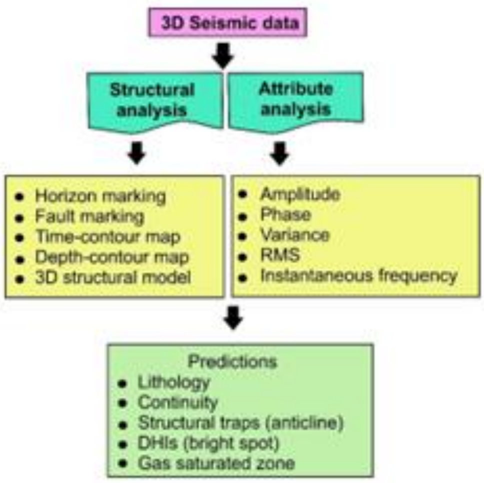

Fig. (4): Workflow chart for structural interpretation and seismic attribute analysis from seismic data

Phase attribute is useful in investigations related to discontinuities, faults and pinch-outs of the reflections [16]. According to [25], hydrocarbon reservoirs on thin beds often cause local phasing due to the accumulation of hydrocarbons, which explains classifying the instantaneous phase as a potential Direct Hydrocarbon Indicator (DHI). The mathematical forms are given below:

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$$\Phi (t) = \arctan |H (t)/T (t) \quad (1)$$

The seismic trace T (t) and its Hilbert transform H (t) are related to the envelope E (t) and the phase φ (t) by the following relation:

$$T (t) = E (t) \cos (\varphi (t)) \quad (2)$$

$$H (t) = E (t) \sin (\varphi (t)) \quad (3)$$

Variance attribute is used to analyze subsurface structure discontinuity in seismic data such as a fault or micro fault. According to Pigott et al. (2013) [26]), different values for each of the first two directions can essentially reflect features in the preferred direction in space (such as non-meandering channels).

RMS Amplitude is a type of post-tack attribute that is used for the direct hydrocarbon indicator in a zone of interest. RMS amplitude was calculated from the root square of the sum of the square amplitude number of samples divided within the specified time window [27].

$$A_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} A\,(i)^2} \quad (4)$$

Where A_{rms}= is the amplitude, N= is the number of samples and A= is the amplitude of the sample. According to Li et al. (2016), RMS attribute can detect sand beds if the bed thickness is more than 10m and vice versa. [28] reported that the high values of RMS amplitudes are commonly related to high porosity lithologies.

The instantaneous frequency is the time derivative of the instantaneous phase [24]). In areas where reservoir beds are thick and porous, the interpreted frequency is very low. The presence of hydrocarbon bearing reservoir beds is indicated by low frequency anomaly, which is predictable to illuminate the high porosity and permeability [29]:

$$F (t) = d (\Phi (t))/ dt \quad (5)$$

4. Results and Discussion

4.1 Seismic Structural Interpretation

Using data from check shot survey and well tops information of Balkassar-Oxy-01, various stratigraphic horizons were picked and identified. All these horizons are marked on the in-line and cross-line as shown in Figures (5a-b).

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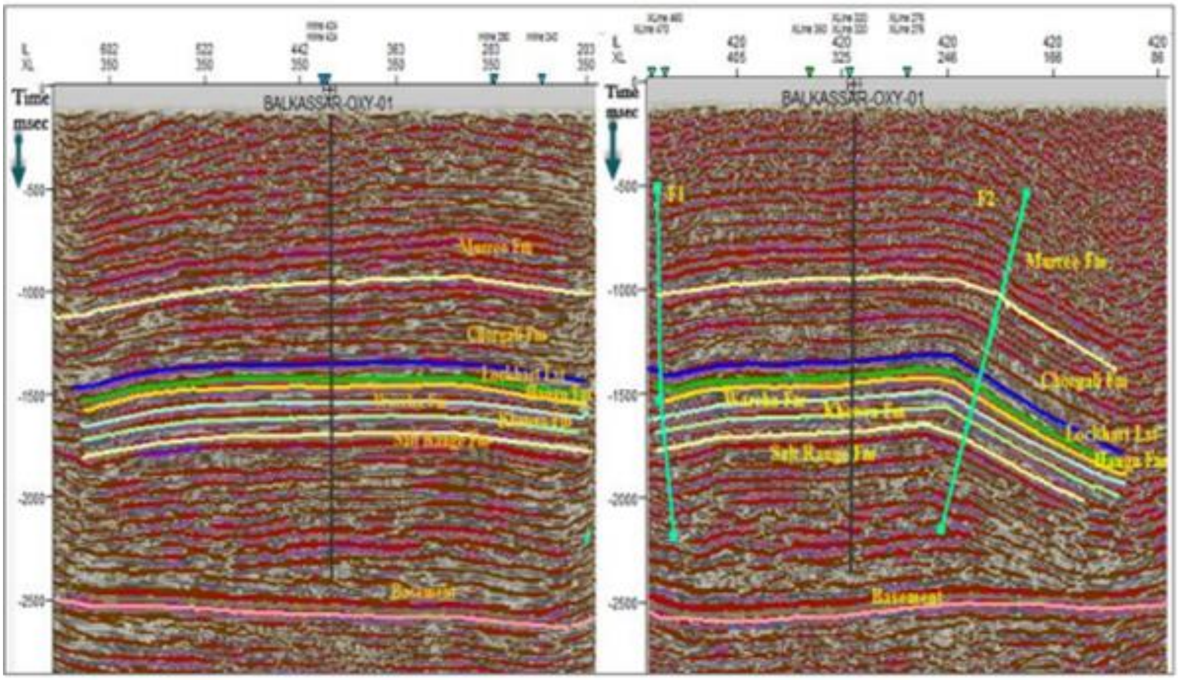

Fig. (5): a) Showing in-line and b) cross-line of 3D seismic

4.1.1. Time/ Depth Contour Maps and 3D Structural Modeling

The time contour map (TCM) and depth contour map (DCM) of Lockhart Limestone Figures (6a and, 6b). TCM of Lockhart Limestone was created using a contour interval of 100 msec (Figure 6a). Some contours close against F1 and F2 making an anticlinal structure for Balkassar-Oxy-01. Similarly, the depth contour map (DCM) of the Lockhart Formation used a 100m contour interval. It was observed in DCM that the central part of the studied area is shallower (Figure 6b). The depth of Lockhart Limestone in Balkassar-Oxy-01 was encountered at 2624 m.

A 3D model for Lockhart Limestone was prepared to visualize the subsurface structural trend (Figure 7). It can be inferred from the 3D model that asymmetrical anticlinal structure exits in the subsurface. The northwest limb has a steep dip whereas it has a gentle dip in the southeast limb. Thus, the Balkassar subsurface structure at the level of Paleocene Lockhart Limestone is an asymmetrical anticlinal structure (Figure 7).

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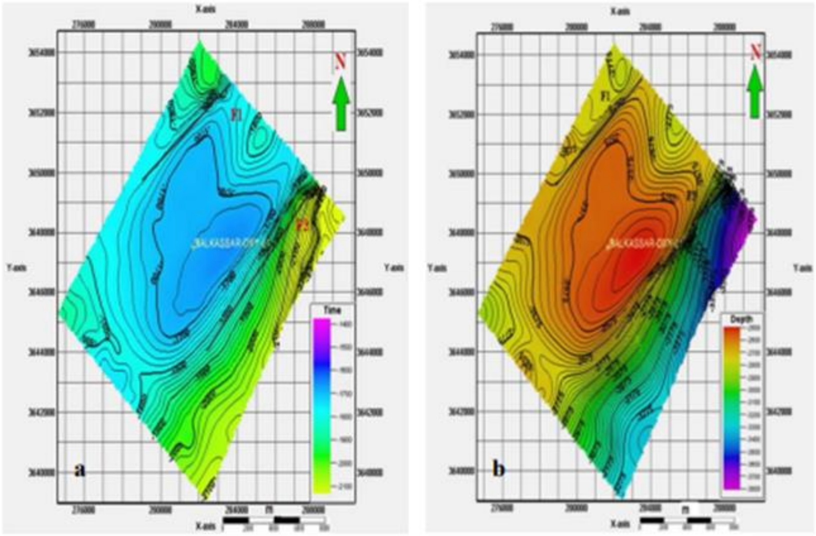

Fig. (6): a) Time Map of Lockhart Limestone   b) Depth of Lockhart Limestone

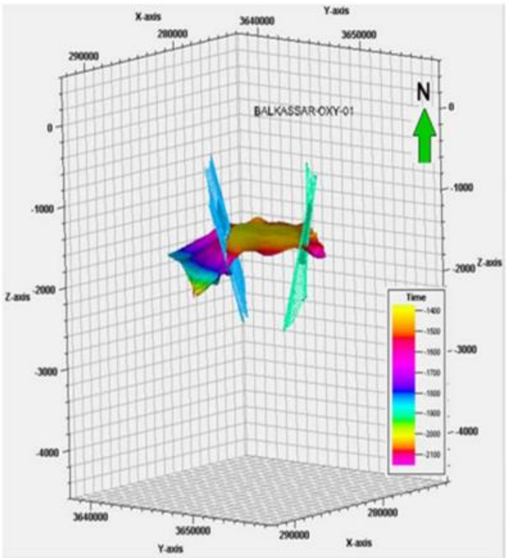

Fig. (7): Structural model (3D) of the Paleocene Lockhart Limestone

The 3D models illustrate that the subsurface structure is a four-way closure for the hydrocarbon trap mechanism. This phenomenon may likely have attributed to the dip of the Indo-Pak plate in the NW direction, therefore, the four-way closure also has similar dips [30]. Due to the movement of the Indo-Pak plate toward NW, the strata become thicker in the NW direction, which facilitated up dip migration of hydrocarbon and its accumulation in the central fan anticlinal structure.

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4.2 Seismic Attributes

The seismic attributes are powerful tools for monitoring and predicting hydrocarbon reservoirs [31]. Seismic attribute measures the characteristics of interest in the exploration and exploitation of hydrocarbon resources [32]. The use of seismic attributes on the raw seismic data helps the interpreters to extract more information about the geologic features on seismic profiles [33].

The structural feature appearance is enhanced by structural dip and variance attributes on the seismic sections [34], [35]. In the current study, multi-attribute analysis was applied to evaluate the reservoir potential of Lockhart Limestone comprising amplitude, phase, variance, RMS and instantaneous frequency attributes.

Amplitude attribute mainly depends upon wave impedance variation [36]. In the Balkassar area, a high amplitude anomaly is seen along the carbonate reservoir of the Paleocene. The black circle indicates an anomaly ranging from -32 to -70 in the reservoir. This high amplitude corresponds to the compact carbonate lithology of the reservoir (Figure 8a).

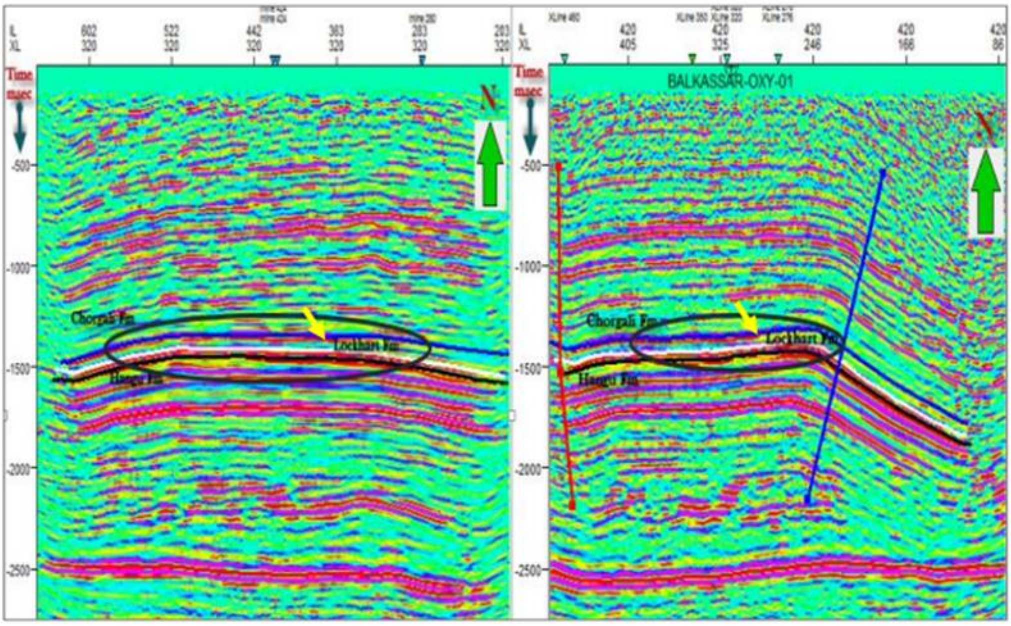

Fig. (8): a) Applied amplitude attribute on in-line and cross-line

The phase is a seismic attribute, which is free of the trace amplitude and related to wavefront. Traditionally, wavefronts have been defined as permanent phase lines, the phase attribute is also a physical attribute and can be used as a discriminant for classifying formal shapes.

The computed phase attribute indicate the angle range picked along the reservoir from 14 to -6 in-line, and cross-line 7.76 to -16 (Figure 8b).

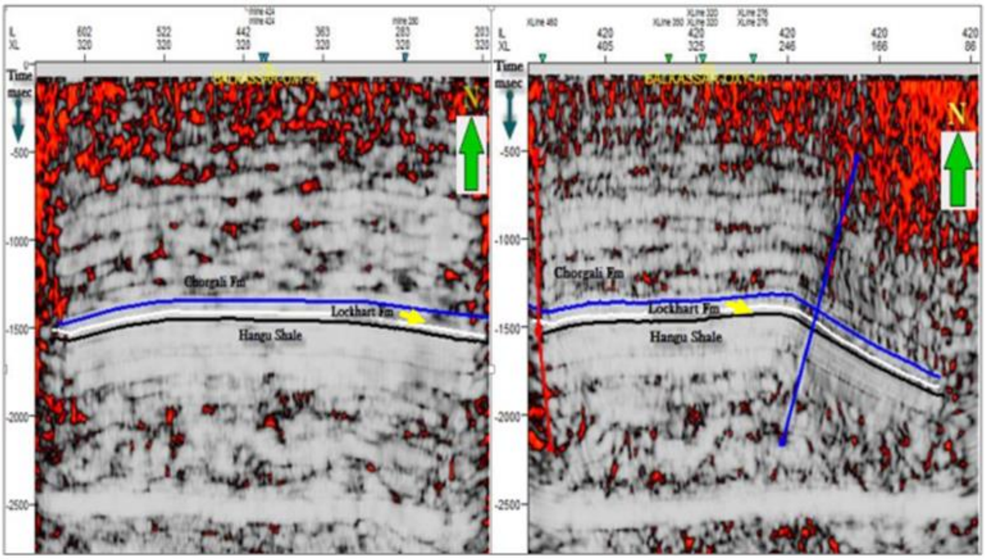

Fig. (8): b) Applied phace attribute on in-line and cross-line

Variance attribute is demonstrated to aid imaging of channels, faults, fractures, unconformities and the major sequence boundaries [25]. In the study area, two major faults are interpreted (Figure 9a). The change or range of variance in reservoir picked horizon 0.13 to 0.20 in-line and cross-line 0.11 to 0.02.

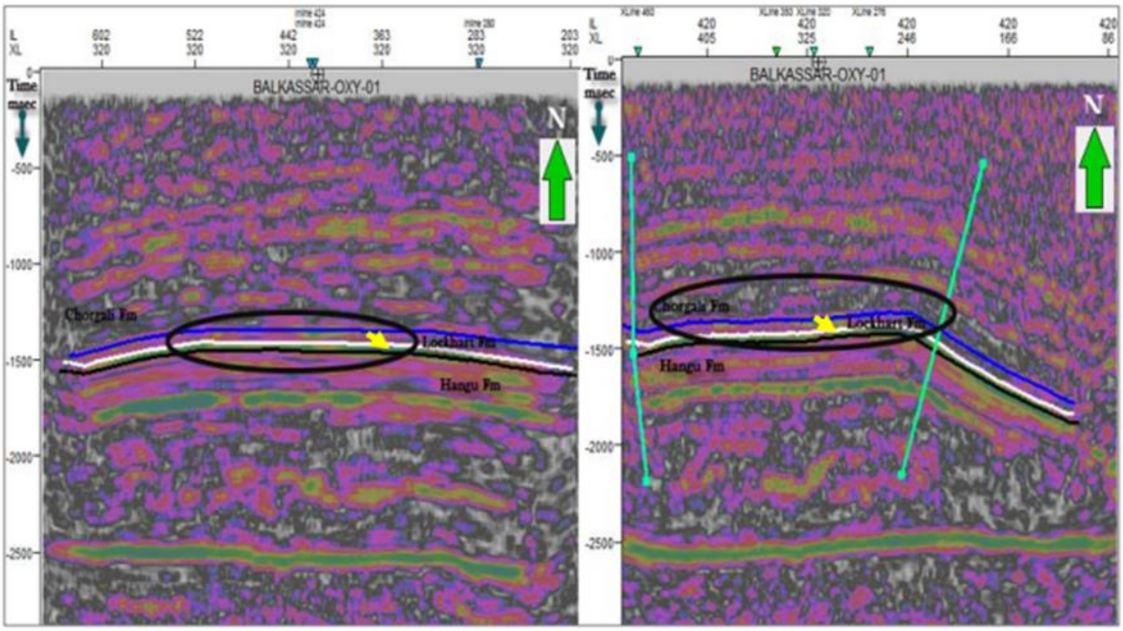

Fig. (9): a) Applied variance attribute on in-line and cross-line

In the Balkassar area, the computed RMS value range of amplitude from low to high, that are associated with lithological variations indicating bright spot and gas saturated zone (Figure 9b).

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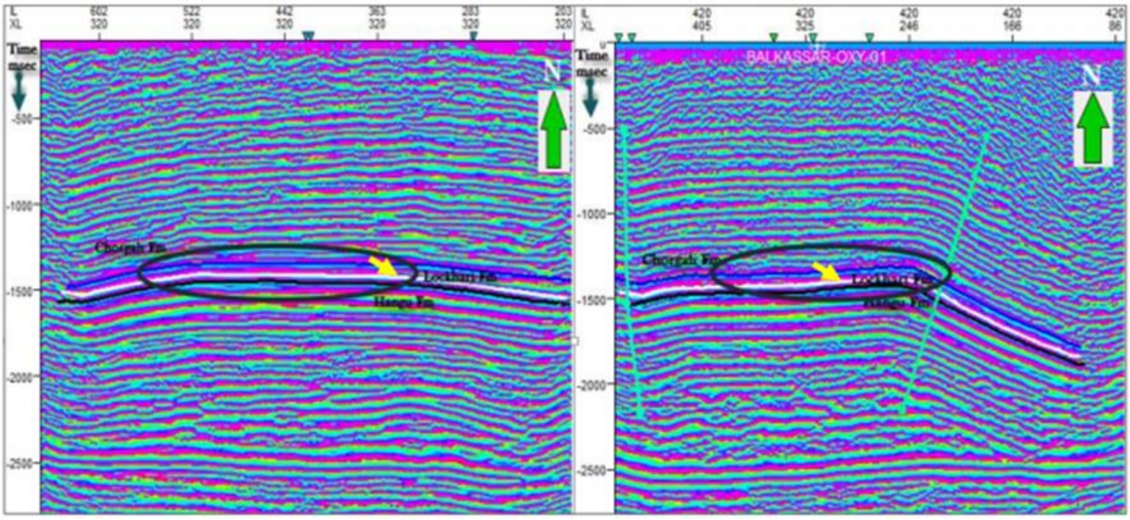

Fig. (9): b) Applied RMS attribute on in-line and cross-line

Within the area of the reservoir, patches of lower instantaneous frequencies indicate the presence of hydrocarbon. An increase in frequency is associated with the presence of shale. Higher frequency values are observed above the reservoir levels. It is due to the presence of shale as shown in Figure (10).

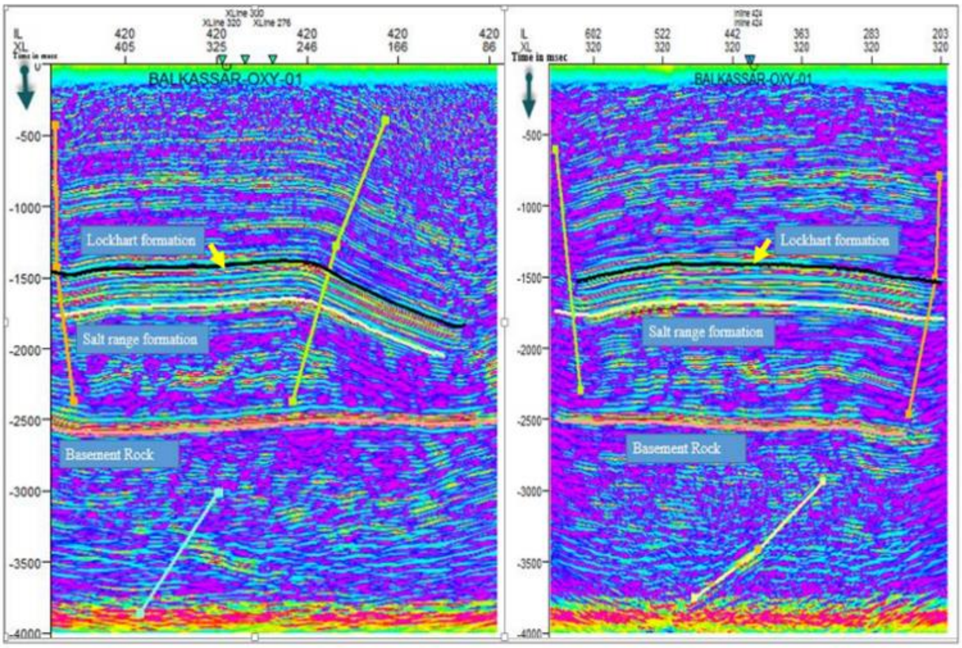

Fig. (10): Applied frequency attribute on in-line and cross-line

The application of seismic attributes in reservoir depiction involves deciphering reservoir properties such as porosity, thickness, lithology, direct hydrocarbon indicators (such as bright spot, flat spot, and dim spot), and traps (faults and anclines) [31].

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The findings from the structural interpretation which include time and depth contour maps demonstrate the closing of some contours against F1 and F2 faults generating an anticlinal trap structure for Balkassar-Oxy-01. This result confirms the presence of structural trap in the area. The 3D structural model supports the presence of asymmetrical anticlinal structure in the subsurface with the steep dip in the northwest limb and gentle dip in southeast limb, proposing an asymmetrical anticlinal structure. The 3D further demonstrates that the subsurface structure is a four-way closure for hydrocarbon accumulation.

High amplitude is observed along the Paleocene carbonate reservoir wherein the high amplitude anomaly (-32 to -70) corresponds to the compact lithology and texture of the Lockhart Limestone. The phase/instantaneous phase attribute is considered a significant DHI as shown in the Figure 8a-b. The computed variance attribute from the 3D seismic data set reveals two major faults and the range of variance in the reservoir horizon (Lockhart Limestone) falls in the range of 0.13 to 0.20 in-line and cross-line 0.11 to 0.02. The presence of DHIs in the carbonate reservoir of the Balkassar area is further supported by the RMS values ranging from low to high, associated with lithological variations, the occurrence of bright spot and gas saturated zone. Additionally, the computed lower instantaneous frequency in the reservoir interval demonstrates the presence of hydrocarbon, whereas the higher frequency reveals the presence of shale, which is observed above the Paleocene reservoir interval.

5. Conclusion

The current study was carried out to re-examine the reservoir depiction of the Paleocene Lockhart Limestone using structural interpretation by generating time and depth structure maps combined with post-stack seismic attributes analysis. The structural modelling reveals a compressional tectonics structural style in the study area demonstrating an anticlinal structural trap bounded by thrust faults. The structure interpretations show that the study area is in a compressional tectonic regime because both F1 and F2 faults are thrust faults indicating compressional tectonics in the Balkassar area. Pop-up structures are generated in the Balkassar area due to the Himalayan orogeny-related compressional forces and the inflow of salt evaporates. Thrust faults have fold axis trending from ENE to WSW.

The identification of the prospect was carried out using multi-attribute analysis which included amplitude attribute, phase attribute, RMS amplitude, variance and frequency attribute. The values

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of amplitude attribute, phase attribute variance attribute and RMS attribute along the reservoir of Lockhart Limestone vary between -6 to 12, 144 to -172, 0.05 to 0.03 and 23 to 32 respectively. The instantaneous phase and RMS values indicate the presence of possible DHIs (bright spot) and gas saturated zone in the carbonate reservoir interval. Also, lower frequencies indicated in the instantaneous frequency attribute match with the rest of the attributes' results. The values of different attributes were in good agreement with basic seismic and structural interpretations and suggest that the Lockhart Limestone possesses promising reservoir potential for future hydrocarbon exploration.

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