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Model-Based Seismic Inversion to Delineate Tight Carbonate Reservoirs, Dhulian Area, Upper Indus Basin, Pakistan

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ABSTRACT

Development of new technologies and integration concepts are required for remunerative exploration and effective exploitation of hydrocarbons. Seismic inversion is one of these latest techniques which allows accurate prediction of reservoir litho-facies and distribution of petrophysical properties (e.g., clay volume and porosity) within intricate corridors. Seismic inversion is a technique that brings out purposeful information from seismic data for reservoir characterization. In this study, an effort has been made to establish a correlation between the conventional method for exploration of hydrocarbons and post-stack model-based seismic inversion. The research work done on Dhulian area mainly exhibits complex features due to the compressional regime. Petrophysical analysis has indicated reservoir formations at the level of Paleocene and Eocene formations and has shown fair potential of hydrocarbon accumulation in Sakesar Limestone as compared to other zones. Structure studied through geology and literature review is popup anticline with thrust faults which is also clearly delineated on seismic data. Seismic Attribute analysis provides a clearer image of the subsurface, highlighting reservoir qualities and indicating the presence of hydrocarbons at the level of Paleocene and Eocene formations. Contour maps and 3D depth maps show structure is deepening towards North-East and is shallow in South-West. Estimated porosities from seismic inversion also give adequate limestone porosities for Sakesar Limestone to be a reservoir. Geo-statistical analysis is applied to establish a relationship between well-log data and seismic data to study rock properties and has shown a good correlation coefficient between them.

Keywords: *Compressional Regime, Popup Anticline, Thrust Faults, Seismic Attribute Analysis, Model-Based Inversion*

1. Introduction

Carbonate rocks are considered major host rocks for hydrocarbon accumulation. Approximately 60% of the world's oil and 40% of gas reserves are found in carbonate reservoirs [1]. For the demarcation of carbonate reservoirs, seismic inversion is widely used nowadays. Seismic inversion is a quantitative interpretation of seismic measurements. It attempts to acquire spatially variable physical parameters utilizing measured seismic data. These parameters represent the Earth's subsurface media having physical and geological meanings [2]. Using available well-log and seismic data for reservoir characterization, spatial variability of petro-physical properties can be acquired [1]. There are several examples around the globe showing the successful implementation of this technique. Some of these are; Seismic inversion for acoustic impedance and porosity of Cenozoic cool-water carbonates on the upper continental slope of the Great Australian Bight [3]. Liuhua 11-1 Field, South China Sea: A shallow carbonate reservoir developed using ultrahigh-resolution 3-D seismic, inversion, and attribute-based reservoir modeling [4]. The technique of seismic inversion and use of the relation between inversion results and porosity log for predicting porosity of a carbonate reservoir in a South Iranian Oil Field [5]. A tight carbonate gas reservoir of early Eocene (S1 formation) in the Middle Indus Basin, onshore Pakistan has shown a correlation of ≈94% for total porosity prediction through the Probalistic Neural Network [6].

In Upper Indus Basin very limited work has been conducted in this regard. The aim of this research is the delineation of hydrocarbons using Post-Stack Seismic Inversion in Dhulian area, Upper Indus Basin. Following an integrated approach, a customized solution is required for every seismic reservoir characterization project as it always presents a unique problem [6]. Quantitative interpretation can minimize exploration and development risks by the integration of various data sets. Porosities calculated from available well-log data are very low in the area which is mainly due to the presence of tight carbonates. Therefore, seismic inversion is adopted to highlight rock properties in the zone. An inverse problem is proposed to observe seismic amplitude variation in terms of rock properties. Seismic inversion transforms geophysical seismic attributes using seismic data, well logs, seismic velocities, and interpreted horizons into rock properties (Primary-wave impedances, Primary-wave velocity (Vp) Secondary-wave velocity (Vs) ratio, density, and porosity). Data quality (both seismic and well) is seen as an important requisition for a reliable well to seismic calibration and thus acquiring geological information (depositional and sedimentological) of the area. The workflow involves well-log analysis for the assessment of petrophysical properties such as porosity, the volume of shale, and fluid saturation. Seismic interpretation and seismic attribute analysis are used for the delineation of favorable traps for hydrocarbon accumulation. Rock properties are estimated by tying a synthetic model to surface seismic data. Model-based seismic inversion has provided a better vision of various subsurface features. Geo-statistical analysis has been used for correlation of well-log and seismic inversion results of rock properties.

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The study area of Dhulian region lies in the eastern Potwar basin (Fig. 1). Dhulian Anticline is located in the eastern part of the Potwar sub-basin and is a compressional symmetric fold with faulted layers. It is enriched with major induced faulted contact to the north, along with salt present in the core. Salt has provided decollement to the faults, resulting in thin-skinned tectonics.

Structural analysis suggests the presence of numerous geological structures, predominantly anticlines. The classic sequence of the Cambrian, Permian, Jurassic, and carbonates of the Paleocene and Eocene are proven reservoirs in the area [7]. The study involves the demarcation of carbonate reservoirs in Chorgali Formation and Sakesar Limestone belonging to Eocene and Lockhart Formation of Palaeocene age. Based on integrated seismic and well data, the petroleum system of Dhulian Field is assessed that will be constructive for upcoming exploration in Potwar Basin and adjoining areas.

In the Upper Indus Basin of Pakistan, proven reservoir rocks are Tertiary carbonate rocks, as they contain potential hydrocarbons. Late Jurassic to Early Cretaceous black shales are considered important source rocks [8]. Eocene sequence is serving as a major oil-producing reservoir in the Dhulian Field [9]. The regional seal in the area is Murree Formation of Miocene age for the respective reservoirs, whereas, the migration of hydrocarbons is along the faults [8].

2. Geology and Stratigraphy

Significant hydrocarbons are present in Potwar Basin located in the Sub-Himalaya division. These hydrocarbons are restricted in compressional as well as transpressional structures [5]. It has been proposed by several researchers [7, 9, 10] that at the level of Eocene; a general trend of geological structures is in an east-west direction. Anticlines are bounded by reverse and thrust faults and have salt-core structures in dominance. Dhulian Field has primarily a structural trapping mechanism having slightly tighter folds in the eastern part in comparison to the western part [7].

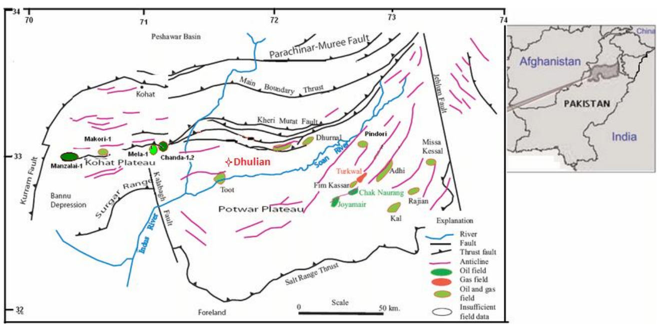

Fig.1: Geological framework and generalized oil and gas field of Potwar Basin in northern Pakistan [8, 9, 11, and 12].

East northeast-south southwest is the normal trend of faults in the entire Dhulian Field area corresponding to the Neogene deformation belt. The less deformed Southern Potwar Platform Zone (SPPZ) and more deformed Northern Potwar Deformed Zone (NPDZ) are isolated by east-west Soan syncline [5, 9, 13-16] (Fig. 1).

Thick Infra-Cambrian Evaporite deposits are the distinguishing feature of Potwar subsurface geology [17]. The maximum depth of well drilled in the Dhulian Field is up to 12,428 feet which led to Infra-Cambrian [5, 9, 10, 18]. Dhulian-Khaur is an important geological structure in the Potwar Basin and is since ever a key target for petroleum geologists [10].

3. Methodology

The research is mainly based on (1) evaluation of petro-physical rock properties, (2) evaluation of the volume of shale and fluid saturation, (3) identification of geological formations on seismic sections in comparison to formation tops and faults demarcation on basis of incoherency of reflectors, (4) seismic to well tie for synthetic seismogram generation, (5) creation of impedance models and inverted velocity sections using acoustic wavelet from seismic data, and (6) generation of porosity section for correlation.

3.1. *Petrophysical Analysis*

Lithology log, Resistivity log, and Porosity logs are available for petro-physical analysis of well Dhulian-43 (Fig. 7). Petrophysical analysis has been carried out to investigate lithology, porosity, the volume of shale, water, and hydrocarbon saturation of well. Well (Dhulian-43) has been inspected comprehensively, allowing for a salient calibration, as it was located along the studied seismic lines (Fig. 3).

All the available wireline logs of Dhulian-43 well have been evaluated. The methodology adopted for petrophysical analysis is shown in (Fig. 2).

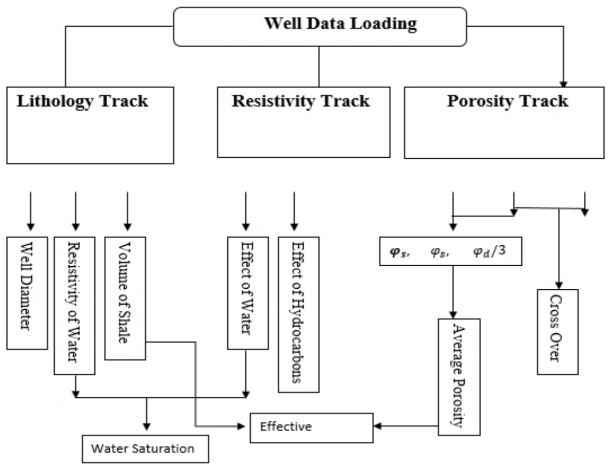

Fig. 2: Workflow observed for Petro-physical analysis.

The gamma-ray log is used to differentiate between clean and dirty zones. Using the Gamma-Ray Log in the correlation track, clean zones have been marked (Fig. 6). The gamma-ray log helps to define the shale beds and estimate shale volume. Lower values are an indication of a clean zone whereas the shaley zone has a high gamma-ray value. While analyzing quantitative evaluation of shale content, radioactive minerals other than shale are assumed to be absent. The caliper log shows a linear trend indicating normal borehole conditions.

Porosity is computed from the neutron log and density log. The log trends of Neutron and Density logs have been recognized at clean zones. Crossovers have been observed between Neutron and Density log curves (Fig. 6). These crossovers are an indication of hydrocarbons in that particular zone. Average porosity is computed by combining neutron-density porosity and then effective porosity is calculated. Resistivity curves have also shown the presence of hydrocarbons in the same zone.

Depending on the type of mud filtrate and formation fluid, respective resistivity responses are observed in the resistivity tract of the well-log. Thus suspected fluid-saturated zones are marked on basis of varying resistivity (Fig. 6). Fluid saturation is computed using the resistivity log. Well-water saturation is calculated using Archie's Equation. Hydrocarbon saturation is calculated by subtracting the water saturation from the total fluid content of the reservoir.

Based on these observations, two zones of interest have been marked (Table 1).

Table 1: Zones of interest.

Zones	Formations	Starting depth (meter)	Ending depth (meter)	Thickness (meter)
Zone 1	Sakesar Limestone	2604m	2609.1 m	5.1m
Zone 2	Lockhart Formation	2822m	2825.5 m	3.5m

3.2. *Seismic Interpretation*

A base is generated using the available seismic data set. Three strike lines (SPDK-112, 113, 114) and five dip lines (SPDK-101, 102, 103, 104, and 105) were used for structural analysis of the sub-surface.

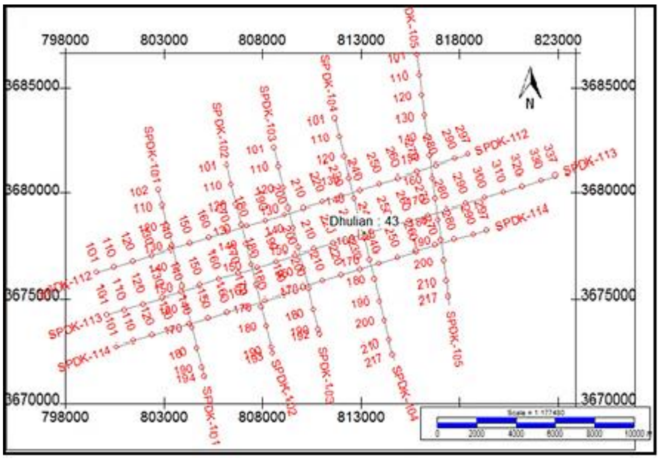

Fig. 3: Strike lines (SPDK-112, 113, 114) and dip lines (SPDK-101, 102, 103, 104, 105) are plotted for the generation of the Base map of Dhulian area. Well (Dhulian-43 lies at the intersection of SPDK-113 and SPDK-104). It reached a depth of 3788m.

Three prominent reflectors have been marked on the seismic lines for structural and stratigraphic evaluation. To confirm the position of distinct reflectors and for allocation of a specific age, calculated depths of the seismic reflectors, are correlated with well tops. The strike lines depict continuous reflectors, while the dip lines show breaks in the continuity of the reflectors, illustrating major faults. The methodology adopted for seismic interpretation is as follows (Fig. 4).

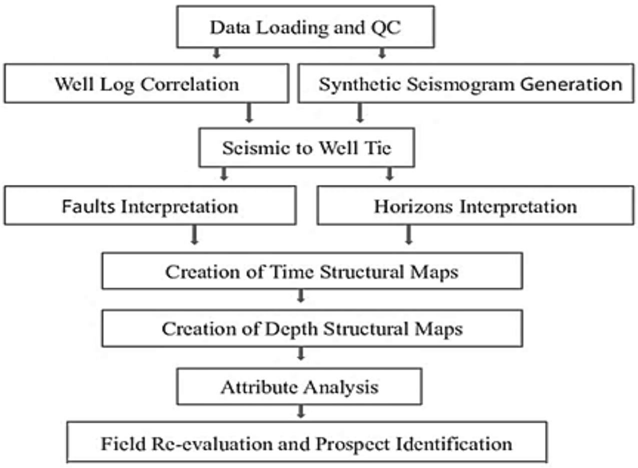

Fig. 4: Workflow observed for seismic interpretation.

PDK-113 (Fig. 7a) helps determine the age of the reflectors as it contains well (Dhulian-43). Moreover, the reflectors of PDK-113 are nearly flat, thus picking the prominent reflectors is relatively easy. So this line is used as a reference line for interpretation.

Seismic attributes are applied on the control line (PDK-104) for reservoir characterization and enhancement of structural, stratigraphic, and petrophysical aspects of subsurface rocks. These attributes are defined as all the implied, computed, and measured quantities obtained from seismic data [19].

Time-derived attributes give structural information, whereas, information regarding stratigraphy and reservoir is obtained from amplitude-derived attributes. Whereas, frequency attributes provide information regarding stratigraphy and reservoir along with bed thickness and microfracture identification.

Seismic attributes applied in the research are as follows:

i. Trace Envelope (Instantaneous Amplitude) is applied for indication of lithological variation, thin-bed tuning effects, bright spots (presence of gas), etc.

ii. The presence of hydrocarbons, fracture zones, and bed thickness is identified by Instantaneous Frequency

iii. Average Energy indicates reflection strength and lateral continuity of reflector.

Time and depth contour maps were constructed for major Paleocene and Eocene reservoir formations. The Contour interval for the time map and depth map is 0.05sec and 100m respectively. These maps portray the presence of geologic structures particularly folds and faults along with numerous other structures in terms of contours.

3.3. Seismic Inversion

Quantitative interpretation can provide a myriad of geological and geophysical data to identify zones with better reservoir quality for the right drilling location and provide cost-effective appraisal and development plans [6].

Seismic inversion aims to reconstruct an Earth subsurface model based on seismic measurements. Such a subsurface model is quantitatively represented by spatially variable physical parameters and is extracted from seismic data by solving an inverse problem [1]. Model-based inversion is applied for the computation of total porosity as it provides greater bandwidth and detail of variation of the acoustic impedance over the study area [20]. A forward model is used to calculate synthetic seismic data as a part of model-based inversion algorithm. The principle of one dimension convolution model is used for post-stack inversion. The equation used is as follows:

$$S(t) = R(t) \times W(t) + N(t) \qquad \text{(i)}$$

S (t) = seismic trace,

R (t) = earth's reflection coefficient,

W (t) = seismic wavelet,

N (t) = noise component

*convolution process

To investigate response of seismic inversion on seismic data, seismic to well tie is performed on the well point. Zero phase statistical wavelet is extracted to align reflection on the synthetic trace. When a good correlation between seismic and well is achieved, seismic horizon is identified and marked on 2D seismic line PDK-104.

The methodology adopted for seismic velocity inversion on Hampson Russel Suite has been explained below (Fig. 5):

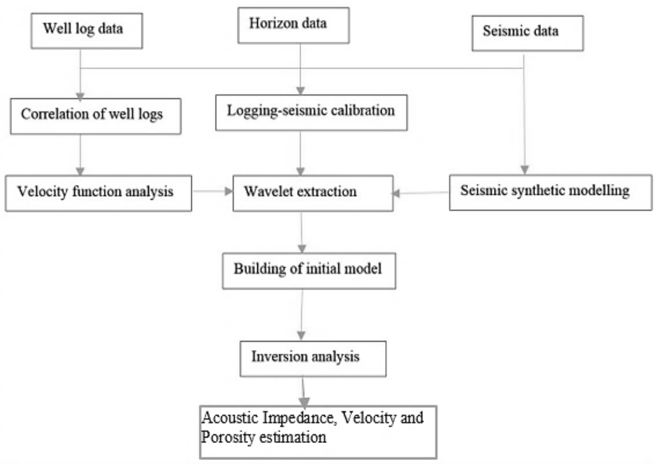

Fig. 5: Workflow observed for generating initial impedance model.

For different types of seismic inversion (pre-stack and post-stack) 'STRATA' module is used in Hampson Russel software. Seismic volume along with well-log data is the basic HRS input in post-stack seismic inversion which gives acoustic impedance volume as the final product. Seismic inversion depends on the convolution model in which synthetic trace can be developed from the convolution of Earth's reflectivity series with a chosen wavelet [21-23]. Extracted and inverted correlation from seismic data at well is projected using a constant phase wavelet. The extracted wavelet should be at zero or minimum phase to get accurate results for building Seismic inversion [24]. The degree of variation in the phase of the input wavelet greatly affects the inversion results [25].

An initial guess model or low-frequency model is required for relative Acoustic Impedance for its control because it is a relative layer property. It is used in qualitative analyses, while absolute Acoustic Impedance is an absolute layer property used for better analysis [22]. Absolute Acoustic Impedance is obtained when a suitable low-frequency module (approximately 0–15 Hz) is combined in inversion systems [22]. Sparse spike inversion describes relative acoustic impedance inversion. It supports the qualitative interpretation of seismic data. Sparse spike inversion for its estimation does not need the development of a low-frequency model, which is added separately in sparse spike inversion [26]. Finest optimization of inversion parameters is at well control, where well logs define the ground truth for p-impedance [18]. Therefore, dip line PDK-104, where well Dhulian-43 lies is chosen for inversion. SEG Y of seismic line PDK-104 is exported from the kingdom software, along with interpreted horizons Chorgali Formation, Sakesar Limestone, and Lockhart Formation into Hampson Russel Software (HRS). Seismic velocities from velocity functions are inserted as (primary-wave) data.

A wavelet is extracted from seismic data within a specific time window and is convolved with the reflectivity series gained from density logs, whereas velocities from seismic velocity function at well Dhulian-43 to develop a synthetic seismogram.

For Model-Based Seismic Inversion, a universal linear inversion algorithm to identify the wavelet and trace extracted from seismic is used to modify the initial build model. Several iterations are made until the misfit between real and calculated data is not removed to a suitable range [27]. A good correlation between synthetic seismogram and seismic traces at well Dhulian-43 has been observed, shown in Fig.12. Model-Based inversion has been decided to be applied in this area. We can update the geological model until the misfit between the synthetic and original seismic traces is not removed. The simple methodology applied in the inversion procedure is, to amount any errors between real and synthetic data [27].

3.4. Geo-statistical Analysis

A geo-statistical analysis is applied to relate the spatial distribution of rock elastic properties (i.e. petrophysical) to seismic data [28]. Geo-statistical methods are normally applied for calculating the relationship between several petrophysical parameters obtained from both borehole and seismic data [29]. In these measurements, linear regression is used to develop a statistical relationship between well-log data and seismic-derived properties. This relationship is used to estimate porosity (reservoir properties) in the whole available seismic volume.

Porosity is statistically estimated after successfully inverting the seismic data and generating an impedance model. The inverted impedance model is used for the calculation of porosity. The estimated porosities are compared with the borehole calculated porosities to check the precision.

4. Results and Discussions

4.1. Petro-physical Analysis

Considering integrated log response, zone1 within Paleocene strata (Sakesar Limestone) is more promising in terms of a reservoir. It lies between 2604-2609.1 m in depth, having a total thickness of 5.1 meters. GR log trend observed in this zone was low, ranging between 27-30 API and thus the volume of shale to be 9.126%, indicating it to be a low shale or clean zone. The resistivity log shows a very high trend which is the indication of hydrocarbon presence, which is further confirmed by the presence of cross-over between neutron and density log. Integrated log results have confirmed lithology to be Limestone. Average porosity is up to 4.3 % and effective porosity is up to 3.06%. The porosity range is considered fair enough for limestone because commonly it has secondary porosity. Hydrocarbon saturation is 30.31% in the marked zone for Sakesar Limestone.

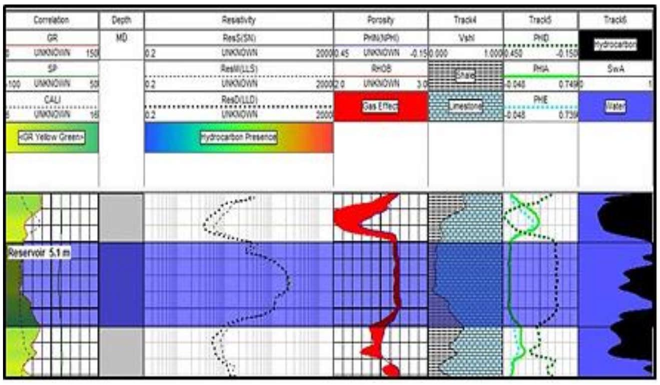

Fig. 6: Reservoir prospect zone in Sakesar Limestone from 2604-2609.1 meters. The lithology log shows it to be limestone. It appears to be a tight reservoir as can be observed in resistivity and porosity track. Neutron-Density crossover is showing gas effect. Fluid saturation can be seen in the last track.

4.2. Seismic Interpretation

According to literature, structures are bounded mostly by thrust and back thrusts faults in the Central Potwar region. Anticlinal structural trap bounded by thrust faults has confirmed the presence of compressional tectonics in the study area. According to seismic sections, the trend of the fold axis of the thrust faults is from ENE to WSW. This is further confirmed by the time and depth contour mapping.

Two major thrust faults have been observed on the seismic lines. The throw of the two faults is not equal. Throw of the northern thrust (F2) is greater than the southern thrust (F1). The fold bulge is also more prominent in the north. The northern limb is considered as fore thrust and southern limb is considered as back thrust. The main collisional force and sediment transport direction is from the South towards the North. Two-way-travel time of the reflectors is increasing in the east of the seismic sections. The strata is shallow in the west and is deepening in the east. Whereas the centre of the pop-up structure is at the highest point. (Fig. 7a). The pop-up structure extends on all the lines incorporating Paleocene and Eocene strata, signifying that the study area is subjected to compressive forces from the post-Eocene (Fig. 7b).

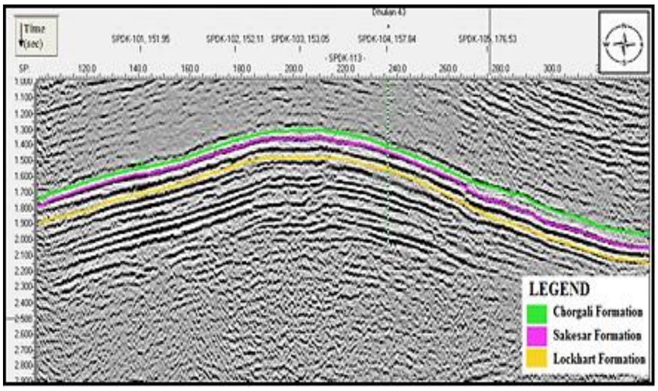

Fig. 7a: Interpreted Seismic Line PDK-113. The reflectors on line PDK-113 run in an east-west direction. This line cut all the dips lines as presented in the base map. The TWT of these reflectors is greater on the eastern part than the central and western part.

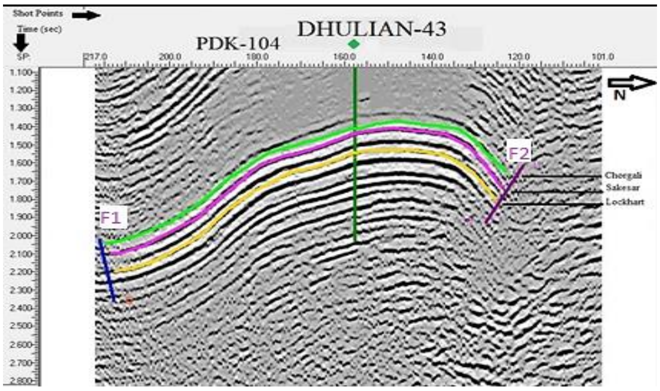

Fig. 7b: Interpreted Seismic Line PDK-104. The reflector on the line PDK-104 runs in the North-South direction. The shot points increase south to the north and the pop-up structure is deciphered between the shot points 120 to 190.

The seismic amplitude attribute has shown high reflection strength at the level of Paleocene and Eocene Formations due to compact lithology (Fig. 8a). Instantaneous Frequency Attribute has shown patches of low frequency within the reservoir zone indicating the presence of fluid (hydrocarbon) (Fig. 8b). The average energy attribute applied on the seismic line has shown the continuity of reflectors clearer than the ordinary seismic section (Fig. 8c). High energy levels have been observed at the level of Chorgali Formation, Sakesar Limestone, and Lockhart Formation, which is a sign of good reservoir quality.

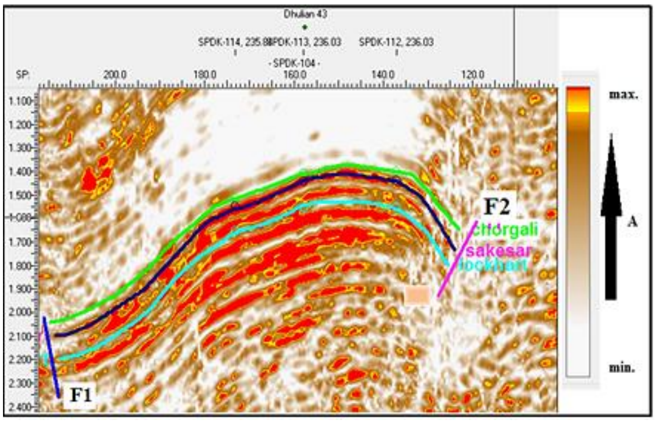

Fig. 8a: Trace Envelope applied on seismic line PDK-104. At the level of Chorgali Formation high amplitude is observed due to compact lithology. Sakesar Limestone and Lockhart Formation has given even higher values than Chorgali Formation. However, the presence of significant anomaly is not identified in reservoirs which are taken as bright spots. Reflection strength decreases above and below levels of the reservoir.

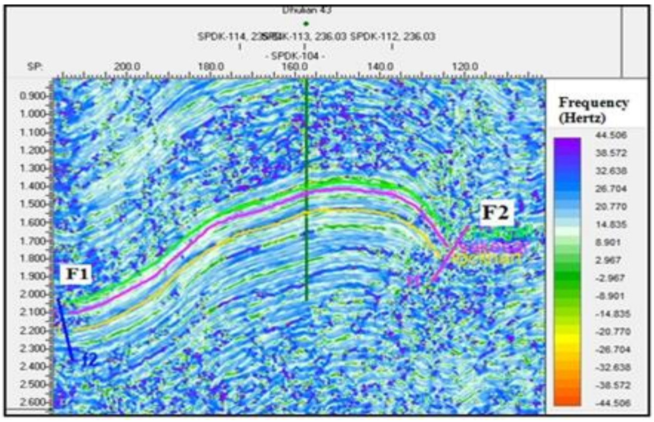

Fig. 8b: Instantaneous frequency applied on seismic line PDK-104. Comparatively higher frequencies are being observed at the level of Chorgali Formation, Sakesar Limestone, and Lockhart Formation. Within the area of the reservoir, there are patches of lower frequencies indicating the presence of fluid (hydrocarbon). Higher frequency values are observed above the reservoir levels.

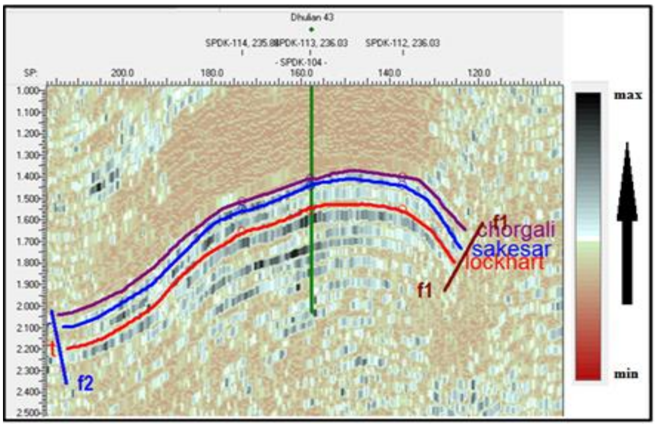

Fig. 8c: Average energy attribute applied on seismic line PDK-104. High energy at levels of Formation, Sakesar Limestone, and Lockhart Formation is observed. A high energy level is an indication of good reservoir quality. The average energy attribute applied on the seismic line is showing the continuity of reflectors clearer than ordinary seismic section. Low energy above and below the reservoir can be seen.

Prospect is present at the level of Eocene and Paleocene Formations. TWT contour map of Sakesar Limestone was generated having 0.05-sec contour interval (Fig. 9). Several contours were closed against F1 and F2 making an anticlinal structure for the Well Dhulian-43. The structure is depicted by the closure of faults northward and southward. The TWT of the reflector is greater in the east as compared to the west, hence, exhibiting the presence of a pop-up anticline. In the generated Depth contour map, Dhulian43 was encountered at depth of 2540m for Sakesar Limestone (Fig. 10). Correlation of well-log data for well top gave a difference of 20m.

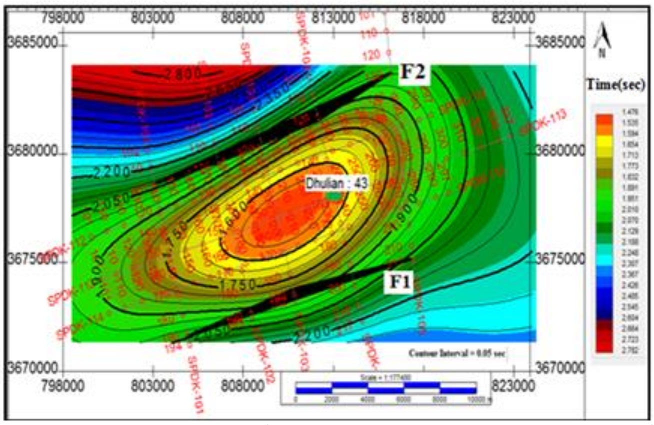

Fig. 9: Time contour map of Sakesar Limestone. TWT contour map of Sakesar Limestone had a contour interval of 0.05 sec. Shallow values of contour show structural high while deep values show structurally low area. Closure of contour and faults indicates an anticlinal structural trap.

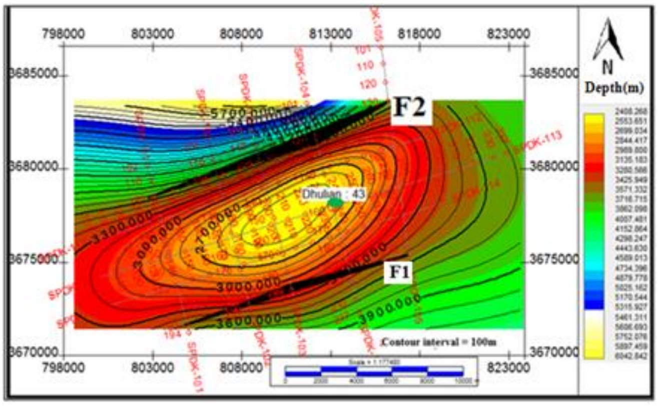

Fig. 10: Depth Contour map of Sakesar Limestone. Depth contours of Sakesar Limestone used 100 m contour interval deepening outwards from the central part of the structure. In the generated Depth contour map, Dhulian43 was encountered at depth of 2540 m for Sakesar Limestone giving a difference of 20m as compared to well-log data.

3D depth surface of targeted reflectors depicts the structure is shallow in North-east and is deepening in South-west direction, while well Dhulian-43 lies at the highest point (Fig. 11).

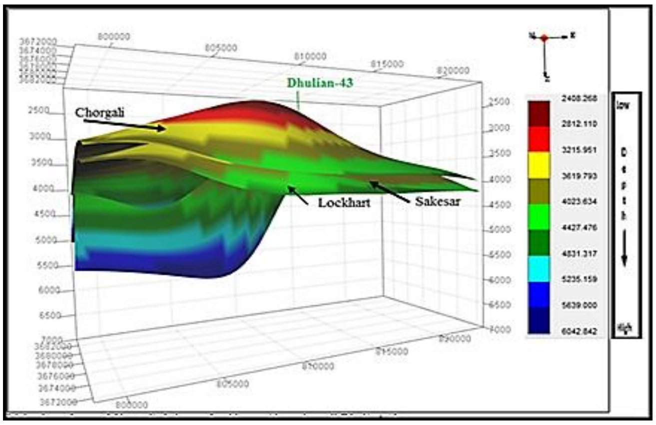

Fig. 11: 3D depth surfaces of Formation, Sakesar Limestone, and Lockhart Formation with well Dhulian-43. Well Dhulian43 is located at the structural high of Formation, Sakesar Limestone, and Lockhart Formation reservoir formations of Dhulian area. Towards North-East structure is shallow and is deepening towards South-West.

4.3. *Seismic Inversion*

An initial model is generated within the time range of the formation of interest (Eocene formations) by using the impedance curve developed by well-log data. Sakesar Limestone is demarcated starting from 1350ms to 1900ms. To get the best-fit model between synthetic trace and seismic data an iterative process is done after an initial model is developed. 20 iterations are applied to adjust after which, the correlation is nearly 0.9963 which is 99.6% accuracy (Fig. 12). This high percentage of correlation (Dhulian-43) leads to the generation of a good impedance model (inverted model).

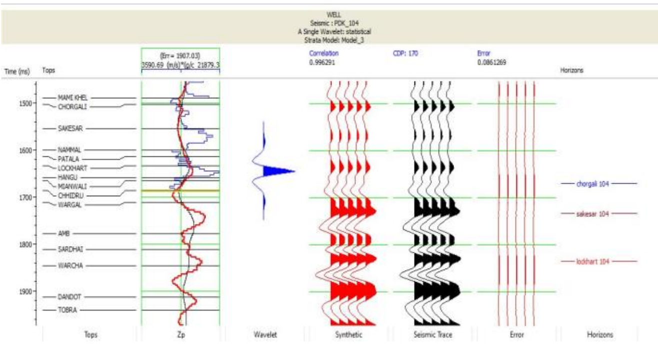

Fig.12: In the error analysis curve (Z_p) black, blue and red curves are representing low frequency, well-extracted data, and inverted seismic respectively. Several iterations are performed for the best fit model between seismic data and synthetic trace. 99% correlation is achieved in the best-fit model.

An initial model is generated within the time range of 1300millisec to 1900millisec by using the impedance curve developed by well-data (Fig. 13). The formation of interest (Sakesar Limestone) also lies in the same time range. The low frequencies lost during processing and stacking of data are regained with the help of this initial model is an important parameter for model-based inversion. A Low-frequency model (initial model) has been generated using interpreted horizons and missing frequencies (0-10Hz) from the wells (Fig. 13).

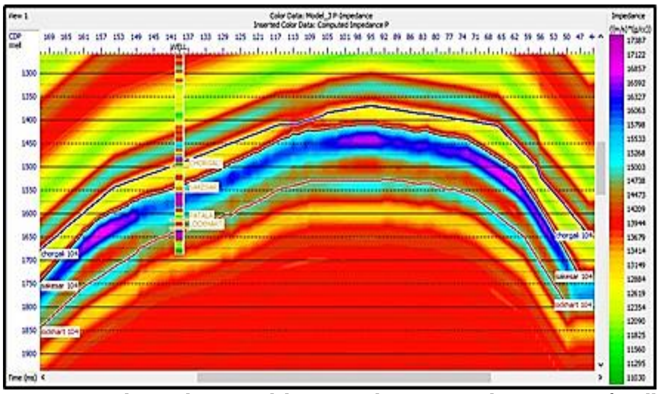

Fig.13: Initial impedance model generated using impedance curve of well Dhulian-43. The formation of interest (Sakesar Limestone) lies between 1370millisecond - 1660millisecond.

4.4. *Geo-statistical Analysis*

Along with the impedance model for well Dhulin-43, the impedance log is also shown for correlation of the well-log and seismic data. Chorgali Formation and Sakesar Limestone are the main producing reservoir in Dhulian field. Final inverted impedance results displayed at this level suggest low to moderate impedance values across the entire reservoir. High porosity ranges are present at well location (Fig. 14) as porosity depends on the lithology and fluid content in it.

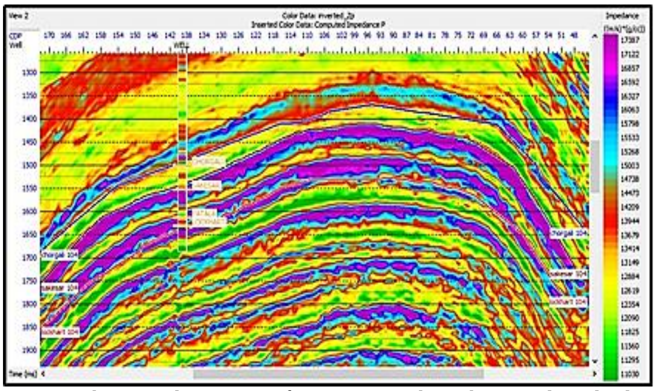

Fig. 14: The impedance map for PDK-104 has shown relatively low impedance within the reservoir zone than its surrounding. Impedance ranges from 11200 kgm^{-2}s^{-1}-13300 kgm^{-2}s^{-1} for Chorgali Formation, whereas in Sakesar Limestone, within formation there is low impedance layer ranging from 12000 kgm^{-2}s^{-1}-13500 kgm^{-2}s^{-1}. For Lockhart Formation, it varies between 11030 kgm^{-2}s^{-1}-12350 kgm^{-2}s^{-1}. In a zone of low velocity and high porosity, acoustic impedance contrast is observed to be low, generally due to porous strata and the possible presence of fluids. The lowest impedance values are observed at well location in both formations highlighted in green and yellow color.

The final inverted velocity section of seismic line PDK-104 has shown low velocity and high porosity zone at SP-155 (Fig. 15). Well-log Dhulian-43 also lies at SP-155. Velocities range from 3482-3948 m/sec for the given time of 1400-1800 milliseconds. Comparing them with the velocity window of its seismic section, velocities vary between 3400-3900 m/sec recorded for SP140 and SP160. Porosity estimation in the reservoir zone of seismic line PDK-104 via Seismic inversion has shown good limestone porosities (total porosity≈19%). The average porosity (Φav) is 6% calculated via Seismic inversion. While well log analysis yield average porosity of 4.3%.

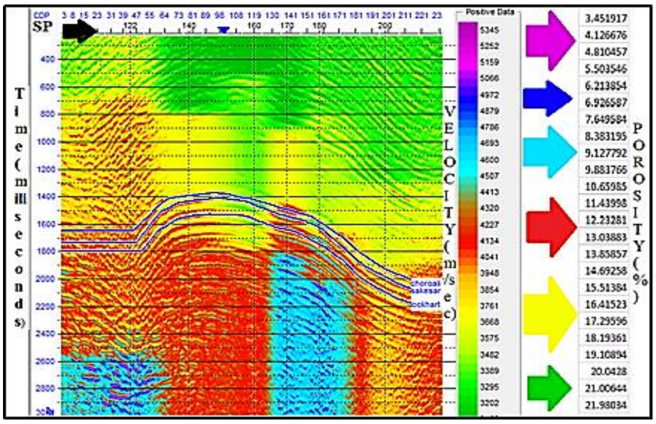

Fig. 15: Inverted velocity section of seismic line PDK-104. Porosity estimation from these velocities in terms of percentage is shown at the right corner. At the center of the anticline, is the best low velocity and high porosity zone. Well Dhulian-43, also drilled at this zone lies at SP-155. Below SP 165-195, and at bottom of marked reservoirs (Formation, Sakesar Limestone, and Lockhart Formation), very high velocity and high-density layers can be seen intruded. It may be some basement rock, observed to be intruded between 1900 milliseconds to 3000 milliseconds.

A quantitative geophysical approach is implemented to demarcate reservoir structure and petrophysical properties of tight carbonate gas reservoirs (of Eocene age) in Dhulian field, Upper Indus Basin, Pakistan. The applied technique is used for the detection of geological horizons, discontinuities at faults, reservoirs, and fluid saturation and thus generating their respective models. The generated models gave positive signs of hydrocarbon potential in carbonate reservoirs. Quantitative seismic reservoir-characterization methodology, integrated seismic attribute analysis, and post-stack seismic inversion ascribe (impedance, velocity, porosity), is supported with customized well-log and seismic data conditioning to achieve reliable results. It has highlighted hidden features of the subsurface, which are difficult to decipher otherwise. Research has shown good reciprocity with the conventional method applied to the study area. Thus proposed methodology can be considered useful to be applied elsewhere with similar geological settings, for reservoir characterization, particularly for tight carbonates.

5. Conclusions

Dhulian area deformation is mainly in the northeast to south-west direction with tight and occasionally overturned anticlines separated by broad syncline. South dipping trust fault is also being marked. This line is passing over the Dhulian anticline, east of the crustal part. Porosities are not very high indicating a tight reservoir in carbonates. However, the interrelationship of all available logs has served to mark a zone in Sakesar Limestone (Eocene), designated as a possible hydrocarbon-bearing zone. Localized lead or prospect is visible at the level of Eocene and Paleocene in the form of strong reflectors at seismic sections. Seismic attribute analysis also suggests the strongest amplitude anomaly at the level of Eocene and Paleocene, indicating it to be the most probable prospect zone. Based on the integrated study, Sakesar Limestone of Eocene is considered as a probable zone for hydrocarbon exploration in the region. A good correlation is observed between velocities and average porosities (Φav) from seismic data and well log interpretation and those calculated from seismic inversion and geo-statistical analysis.

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