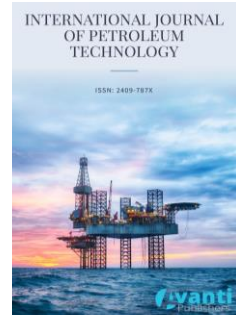
Published by Avanti Publishers

International Journal of Petroleum Technology

ISSN (online): 2409-787X



Geo-Body and Geostatistical Modelling of Carbonate Reservoir Facies Architecture and Characterization

Surajit Gorain*

Directorate General of Hydrocarbons under the Ministry of Petroleum and Natural Gas, Noida, Uttar Pradesh, India

ARTICLE INFO

Article Type: Research Article

Academic Editor: Ahmed Naseem Al-Dawood

Keywords:
Geo-body
RMS amplitude
Seismic attribute
Facies architecture
Carbonate reservoirs
Petrophysical properties

Timeline:
Received: April 27, 2023
Accepted: June 24, 2023
Published: August 02, 2023

Citation: Gorain S. Geo-body and geostatistical modelling of carbonate reservoir facies architecture and characterization. Int J Petrol Technol. 2023; 10: 26-38.

DOI: https://doi.org/10.15377/2409-787X.2023.10.3

ABSTRACT

Carbonate reservoirs present significant challenges in characterizing and extracting hydrocarbons due to their low permeability, matrix heterogeneities, fractures, and dissolution patterns. Accurately predicting the facies architecture and reservoir properties in such complex formations has been a persistent challenge for geoscientists.

This paper proposes an integrated approach that combines geo-body extraction and geostatistical modeling to accurately predict the facies architecture and reservoir properties in carbonate reservoirs. The methodology begins by generating 3D seismic root mean square amplitude (RMS) attributes, which are then used to extract geo-bodies along the pay sequences. The extracted geo-bodies are then subjected to geostatistical modeling to analyze reservoir properties to facilitate the optimization of drilling and production strategies.

To validate the effectiveness of the proposed approach, a small field in the Mumbai offshore basin is chosen as a case study. This field is located on the Mumbai High-Deep Continental Shelf and exhibits westerly dipping structures. Structural mapping confirms the presence of an antiformal structure, with one particular well (D-8) at the crest showing the absence of hydrocarbons.

The proposed approach mapped two seismic reflectors within the reservoir zones and generated window-based 3D seismic RMS attributes to extract three geo-bodies within the reservoir. Facies and property modeling revealed the presence of distinct non-reservoir facies with poor reservoir properties near dry wells (D-8, D-4, and D-7), which is in line with the production performance observed in the drilled wells.

The proposed integrated approach of geo-body extraction and geostatistical modeling is effective in delineating the facies architecture and reservoir heterogeneity of carbonate reservoirs. It enables the identification of favorable reservoir facies and facilitates a comprehensive assessment of the remaining potential.

*Corresponding Author

Email: dr.surajitgorain@gmail.com

Tel: +(91) 9999981246

1. Introduction

Manual interpretation of seismic data for delineating geological features is a subjective and time-consuming process, particularly when marking boundaries. This often relies on the interpreter's perception and their ability to visualize the data [1, 2]. However, with the advancement of data computation and visualization techniques, body modeling has become more routine [3]. The term "Geobody" refers to a distinct and physically defined three-dimensional unit or entity in the earth's subsurface, formed by various geological processes like erosion, faulting, deformation, etc. [4, 5]. Geobody modeling is a crucial tool for reservoir characterization in petroleum geology. It involves creating three-dimensional models of geological bodies within the subsurface using data from various sources like seismic surveys, well logs, and geological maps [6]. These models help in better understanding the spatial distribution and characteristics of reservoirs, such as porosity, fluid saturation, and other petrophysical properties which help in optimizing drilling and production strategies, reducing exploration risk, and improving reservoir management [7]. A common approach to body modeling is to use seismic data to create a structural framework of the subsurface, which is then refined by calibrating it with well-log and core data to build a more detailed model of the reservoir [8]. By analyzing the seismic attributes of the geobody, like amplitude, frequency, and phase, geoscientists can identify and map the location and properties of reservoir units and their associated features. Overall, geobody modeling is a powerful tool for reservoir characterization and helps in efficient and profitable hydrocarbon exploration and production [7].

On the other hand, carbonate reservoirs are believed to hold more than 60% of the world's oil reserves and 40% of the world's gas reserves, indicating their importance [9]. The effect of their complex features, however, causes major hurdles in predicting facies architecture and reservoir properties [10-12]. The study area is on the Mumbai High-Deep Continental Shelf [13], on a westerly dipping gentle homo-clinal region (Fig. **1**). The area has been extensively studied and has a full coverage of 3D seismic data (Fig. **2**). Eight exploration wells were drilled within the study area. The first discovery well (D-1) was drilled in 1985 to explore the hydrocarbon potential in reefoidal and mud mound facies within Paleogene and Miocene carbonate and confirmed the presence of hydrocarbon in Oligocene carbonate within the Panvel and Mukta Formations [10, 13]. Out of the eight drilled wells, five of them turned out to be oil-bearing, with three pays while well (D-7) was oil-bearing only at lower pay. These pays are found in Oligocene limestone. Although being drilled close to the top of the antiformal structure, the second most recent well (D-8) encountered no hydrocarbons. This unusual behavior of the well is examined to find out the logical explanation. A geological model based on geo-body modeling is built to distribute the reservoir properties and locate the remaining potential within the study area.

2. Geological Setting

The Mumbai Basin (Fig. **1a**) is situated within the larger Western Continental Margin of India, which extends along the west coast of the Indian subcontinent [10, 13]. It is part of the greater Arabian Sea Basin, which is primarily a passive continental margin characterized by sedimentary deposition. The basin is primarily filled with sediments of the Tertiary and Quaternary age. These sediments accumulated over millions of years due to the combined effects of fluvial (river) input, marine transgression, and subsidence of the basin floor [10,13]. The sediments consist of various types, including clays, silts, sands, and gravel. The basin is relatively tectonically stable compared to other nearby basins, such as the Cambay Basin. It is characterized by gentle folding and faulting. The basin floor has a relatively flat topography, with the sedimentary deposits being relatively undisturbed [10]. Oil and gas reserves have been discovered in the sedimentary rocks of the basin, particularly in the offshore areas. The oil and gas fields of Bombay High, Bassein, and Neelam are notable examples (Fig. **1b**). According to [10, 13], five distinct structural provinces with different tectonic and stratigraphic events are identified within the Mumbai offshore basin, namely Surat Depression (Tapti-Daman Block) in the north, Panna-Bassein-Heera Block in the east-central part, Ratnagiri in the southern part, Mumbai High/Platform-Deep Continental Shelf (DCS) (Fig. **1b**). The Mumbai High-DCS region, on the other hand, is made up of three major structural elements: the Mumbai High platform, the area of homoclinic dips including the Deep Continental Shelf, and the South Mumbai Depression (Fig. **1b**). The region is subjected to an extensional tectonic regime, which resulted in the formation of horsts and grabens trending from NW-SE to NNW-SSE [10].

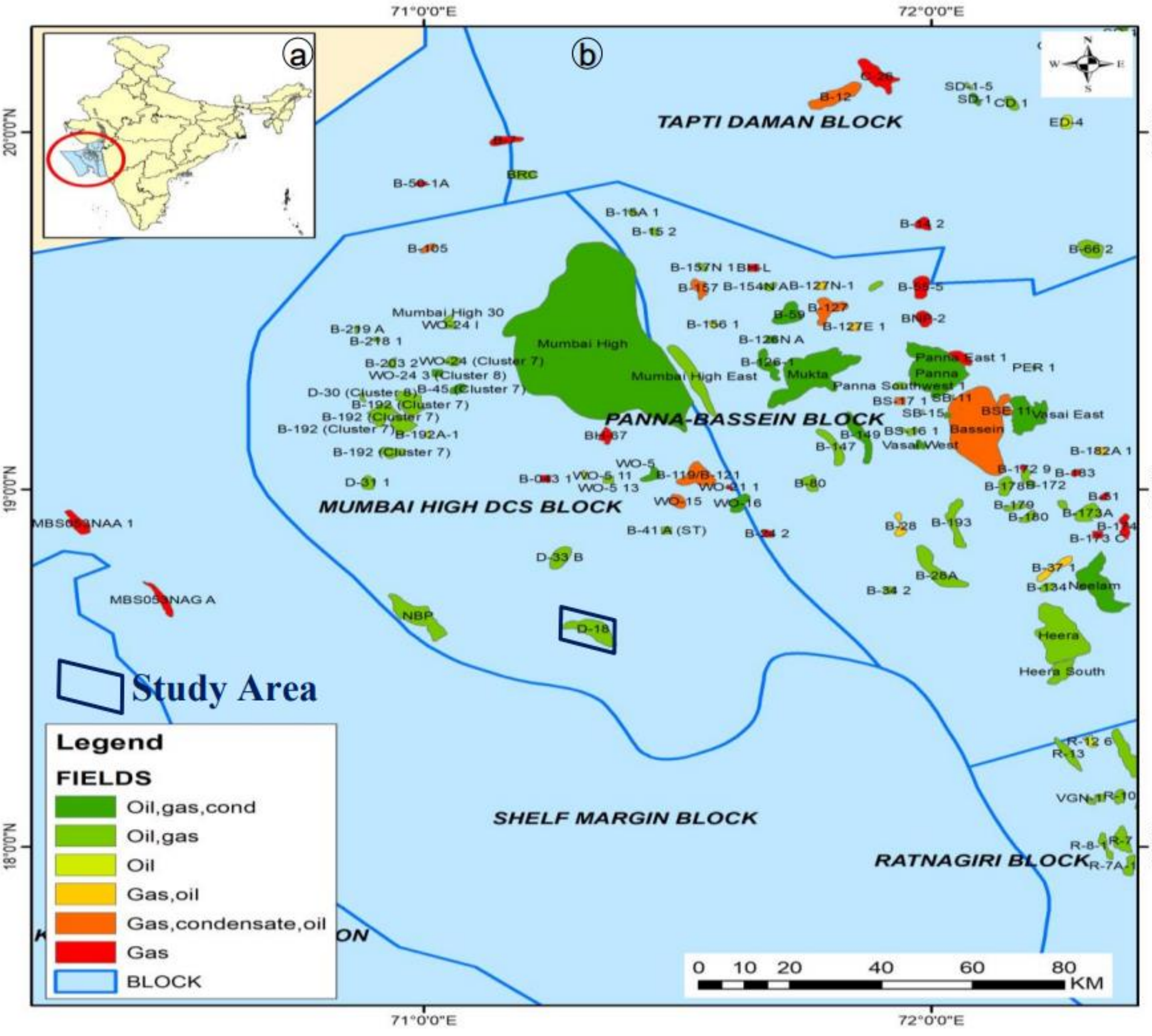


Figure 1: a) Represented the inset map of the study area within the Mumbai Basin, India whereas, b) Highlighted the major tectonic elements of the Bombay offshore basin with major discovered oil and gas fields modified after [10].

An antiformal structure within the early Oligocene is identified within the study area with hydrocarbon accumulations in three different layers, labeled as Lower, Middle, and Upper pay. According to [14] these limestones are composed of wackestone in the higher and lower pay, and packstone and occasional grainstone in the middle pay. The reservoirs exhibit low to high energy deposition in shallow open sea conditions to a restricted shallow marine environment [10]. The generalized stratigraphy (Fig. **3**) of the study area is added to highlight the lithological assemblage and its corresponding geological age.

3. Methodology

Geo-Body and Geostatistical Modelling is a powerful tool in the field of geology and reservoir characterization, as it helps in understanding the subsurface heterogeneity, improving geological modeling accuracy, and making informed decisions in exploration and production activities [11]. The general steps involved in this methodology are shown in Fig. (**4**).

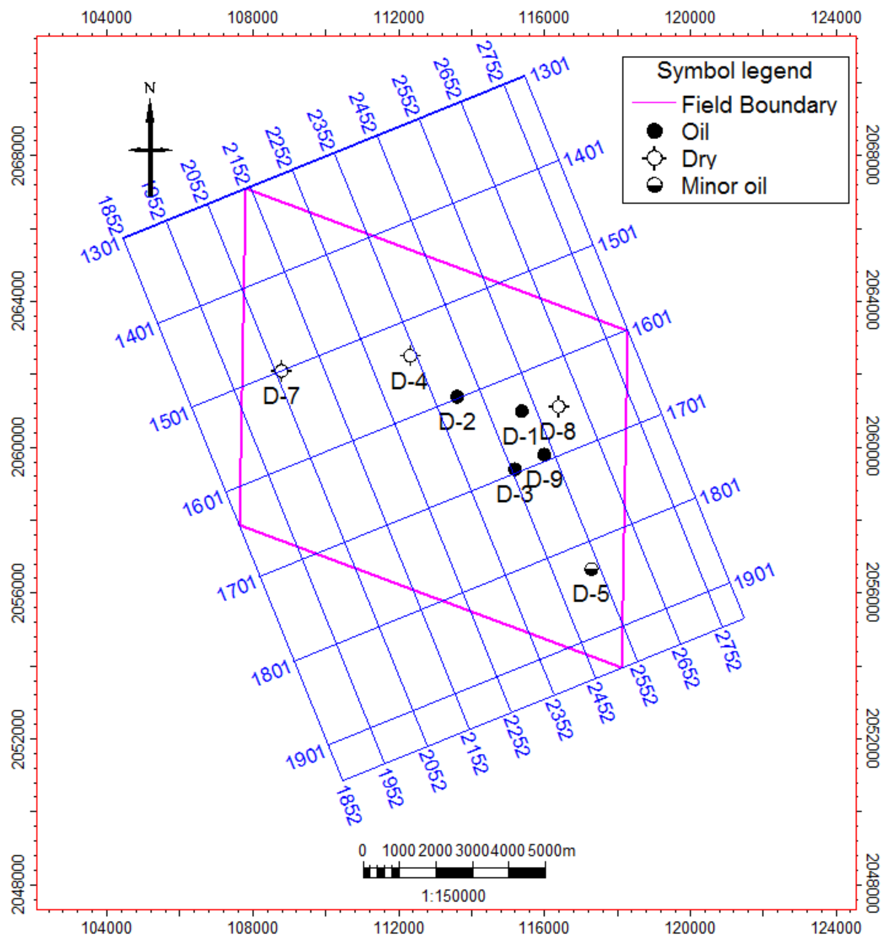


Figure 2: Base map of the study area with available data. Eight exploratory wells were already drilled within the study area, out of which five wells (D-1, D-2, D-3, D-9, and D-5) proved to be oil-bearing with multiple pays.

Age	Formation	Lithology
Late Miocene to Recent	Chinchini	Claystone, Shale
Middle Miocene	Bandra/Tapti	Claystone and shale at the upper part and lower part is mainly shale with minor limestone bands
Early Miocene	Mahim	Siltstone at the top part, limestone at middle part followed by shale at the bottom part
	Bombay	Dirty white, Greyish white, moderately hard to hard, fossiliferous limestone with thin shale bands.
Late Oligocene	Panvel	Mainly consists of limestone with minor shale
Early Oligocene	Mukta	Mainly consists of light to dark grey, argillaceous foraminiferal wackestone and mudstone
Middle to Early Eocene	Bassein	Grey, white, moderately hard and compact Limestone along with thin shale streaks.
	Devgarh	Light grey to dirty white to dark grey limestone/dolomite, moderate hard occasionally argillaceous in nature and fossiliferous with presence of pyrite.
Early Eocene to Paleocene	Panna	The formation consists of Siltstone and sandstone of calcareous nature along with thin bands of carbonaceous shale. Middle part mainly consists of limestone.

Figure 3: The generalized stratigraphy of the study area modified as per [10, 15].

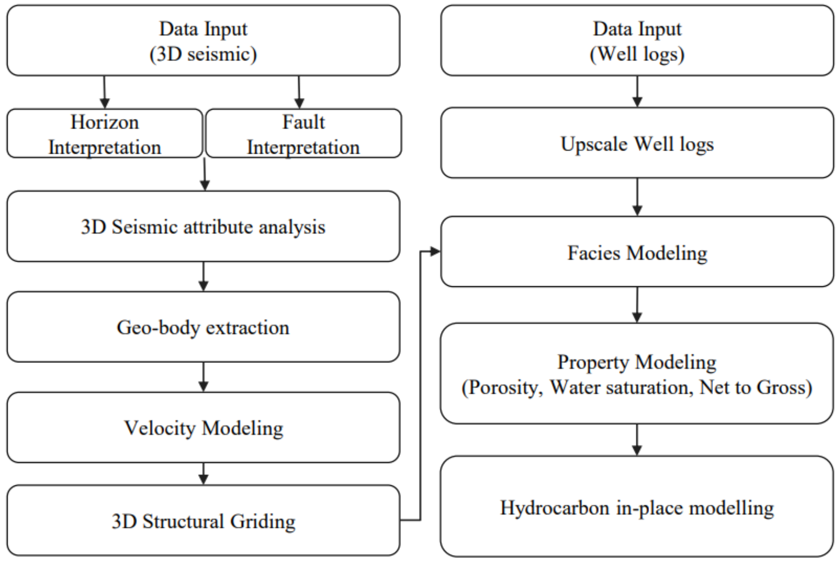


Figure 4: Proposed workflow with the critical process.

The first step is to collect various types of data, including well logs, seismic data, and any other available geological information relevant to the study area. These data sources provide essential information about the subsurface. The acquired data is then integrated and interpreted to identify the horizons and faults to build a structural model. This includes identifying key lithological units, facies variations, structural features, and other geological characteristics. The geostatistical analysis is applied to the interpreted data to quantify the spatial variability and relationships of the different geological parameters of interest. This involves analyzing statistical properties such as variograms, covariance, or correlation functions to model the spatial continuity and distribution patterns of the geological features [5, 15]. Based on the interpreted data and geostatistical analysis, geobodies are extracted or delineated from the data volume. This process involves defining appropriate thresholds or criteria to identify and differentiate the different geobodies of interest. This step aims to identify and isolate regions or volumes of the subsurface that exhibit similar geological characteristics [15]. Once the geobodies are extracted, they are characterized by assigning relevant properties such as lithology, porosity, fluid saturation, and other petrophysical properties. These properties can be estimated using various techniques, including interpolation methods or geostatistical simulations [3]. Finally, using the extracted and characterized geobodies, a 3D geobody model is constructed. This model represents the spatial distribution, geometry, and properties of the geological features within the study area. The model can be further analyzed and used for reservoir characterization, or to guide drilling and production strategies.

4. Results

To assess the effectiveness of the integrated approach involving geo-body extraction and geostatistical modeling, a small field located in the Mumbai offshore basin with a carbonate reservoir is chosen (Fig. **1**). The implemented methodology and achieved significant outcomes, are elaborated in the following sections.

4.1. Input Data

The study area is extensively covered by 2D as well as 3D seismic surveys. In the present study, only the 3D seismic data is used as it provides the full coverage (~100 km^2). Eight exploratory wells (D-1, 2, 3,4,5,7, 8 & 9) have been drilled wherein D-1, 2, 3, 5,7 & 9 proved to be oil bearing (Fig. **2**). All the basic logs like gamma ray (GR), later log deep resistivity (LLD), Neutron porosity (NPHI), Bulk density (RHOB), Sonic (DT), etc. are available in the wells but vertical seismic profile (VSP) data exists only in seven wells (D-1, 2, 3, 4, 5, 8 & 9). Petrophysical analysis logs, Porosity (PHI), and Water saturation (Sw) are also available in the wells. Using these basic logs and cutting information, a discrete facies log is generated for each well. The 3D seismic velocity data is not available. The seismic data quality is good and is found to be suitable for reservoir characterization. A geological cross-section of the field is prepared based on the drilling and testing results of the wells, as shown in Fig. (**5**).

4.2. Structural Mapping

Using the available VSP velocity, the time-depth relationship for the seven wells has been established and well tops are correlated with the seismic events at pay levels. Based on the well-to-seismic tie, seismic reflectors corresponding to (Upper pay and Lower pay) have been mapped throughout the study area. Faults are visible along the periphery of the structural high present within the study area.

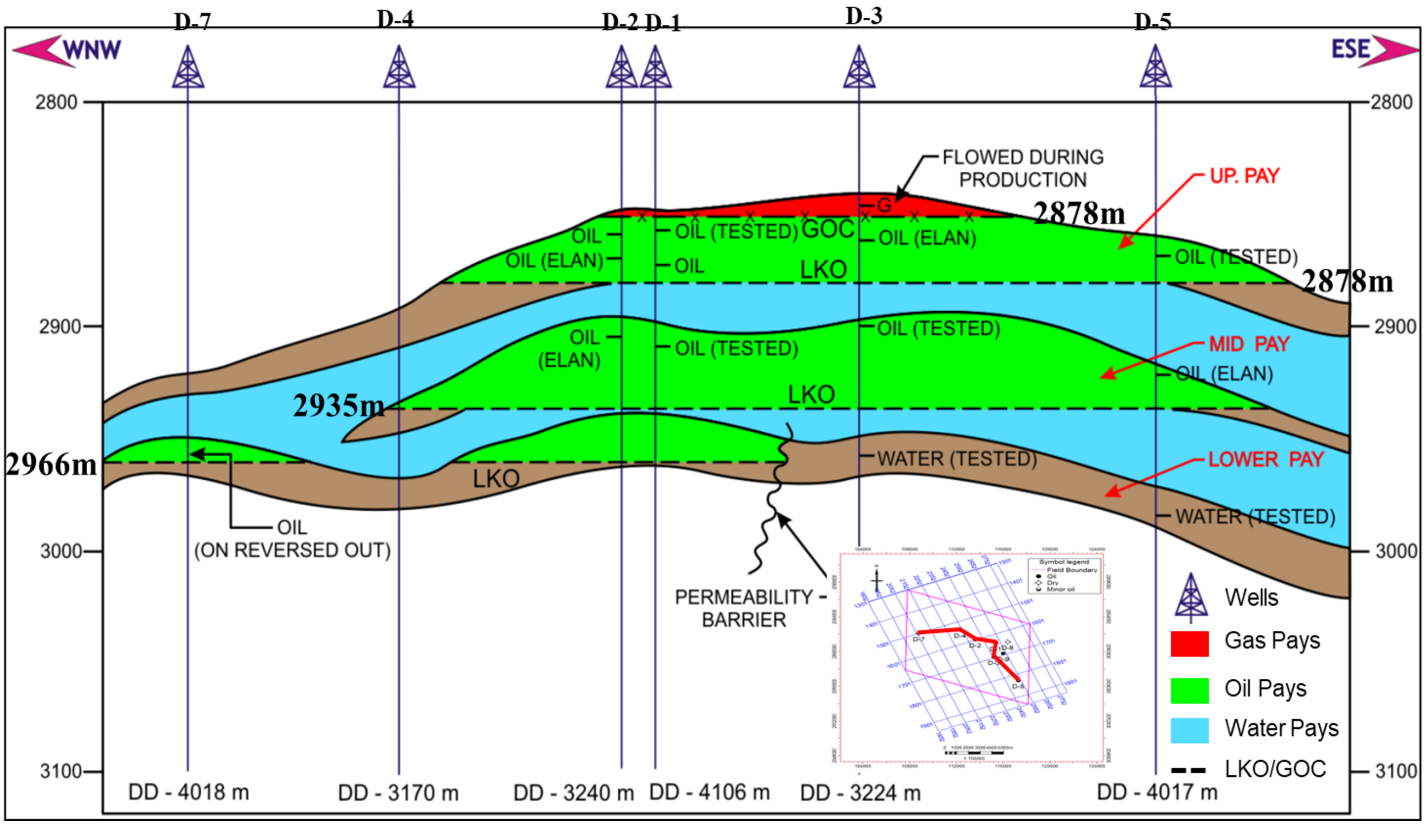


Figure 5: Geological cross section across the field showing fluid distribution pattern.

4.3. Seismic Attribute Analysis and Geobody Extraction

Window-based 3D RMS amplitude attribute is extracted within the proportionate slices in the time domain. Fig. (**6**) shows the RMS distribution along the Upper, Middle, and Lower sequence. It is noticed that the oil wells had higher RMS amplitude than the dry wells. Based on opacity control three, geo-bodies are extracted from the RMS cube by filtering out the low RMS (<1) using a surface probe taking sufficient thickness along the three pays. Fig. (**7**) shows the extracted geo-bodies along the Upper, Middle, and Lower sequence. Holes are noticed within the geo-bodies near the D-8 well which signify the absence of these geo-bodies/reservoir facies near D-8.

4.4. Velocity and Structural Modeling

As the 3D seismic velocity is not available in the study area, the time depth relationship is established using the available VSP velocity of seven wells that have been used for depth conversion. Fig. (**8**) depicted the structural configuration along the pay (Upper pay and Lower pay). Geo-bodies extracted in the time domain are converted to the depth domain using the velocity model derived from the VSP velocities.

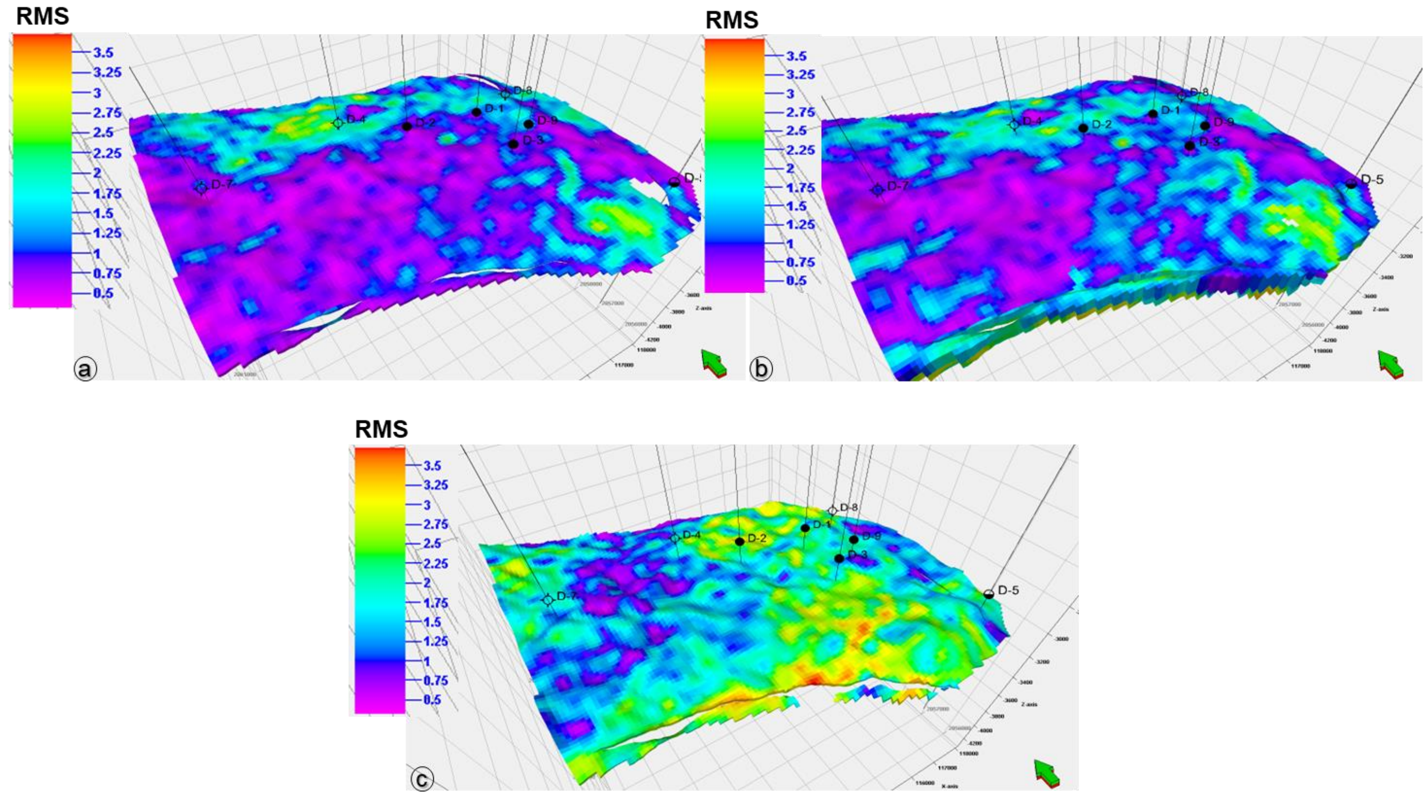


Figure 6: RMS distribution along the a) Upper pay level, b) Middle pay level, and c) Lower pay level.

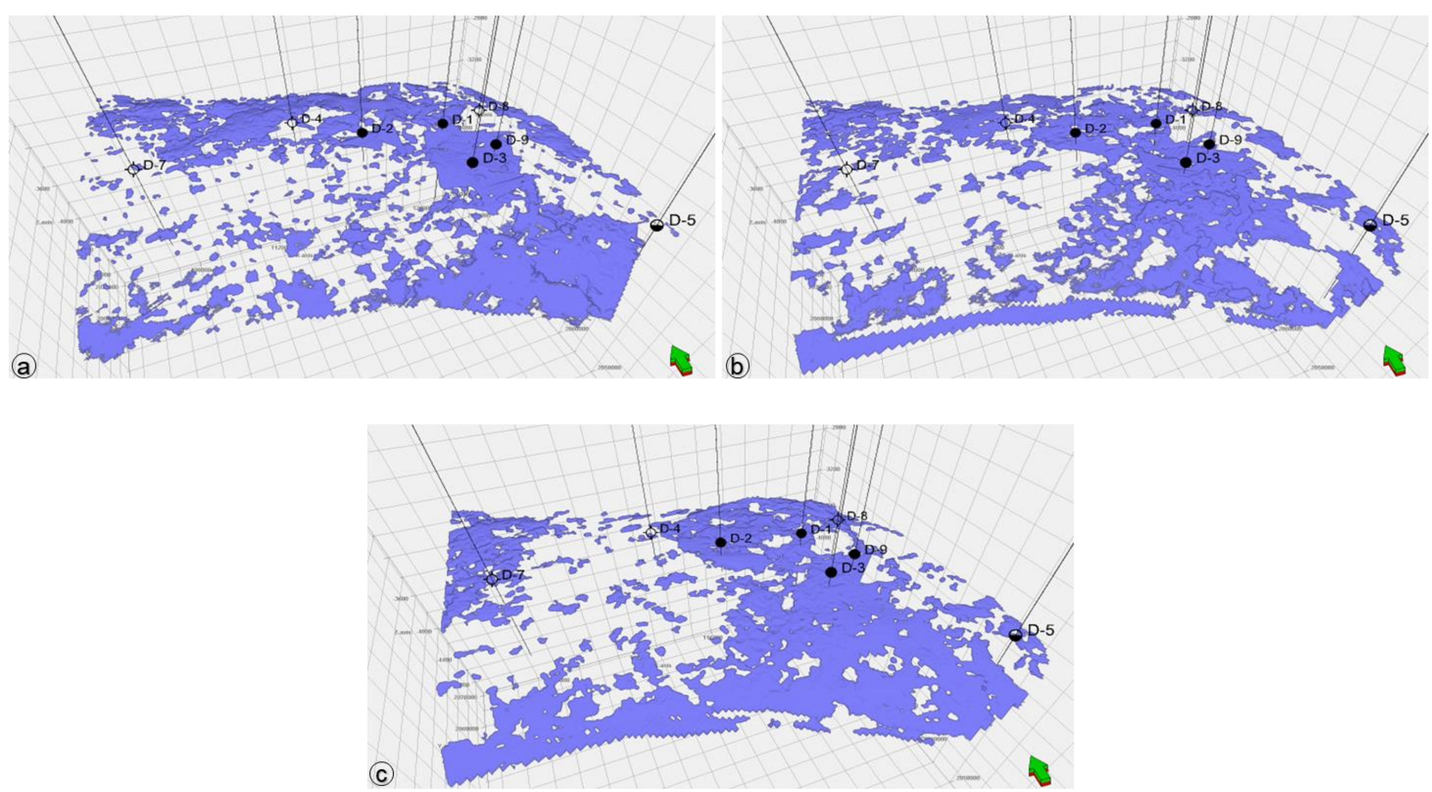


Figure 7: Extracted Geo-bodies along the a) Upper pay level, b) Middle pay level, and c) Lower pay level.

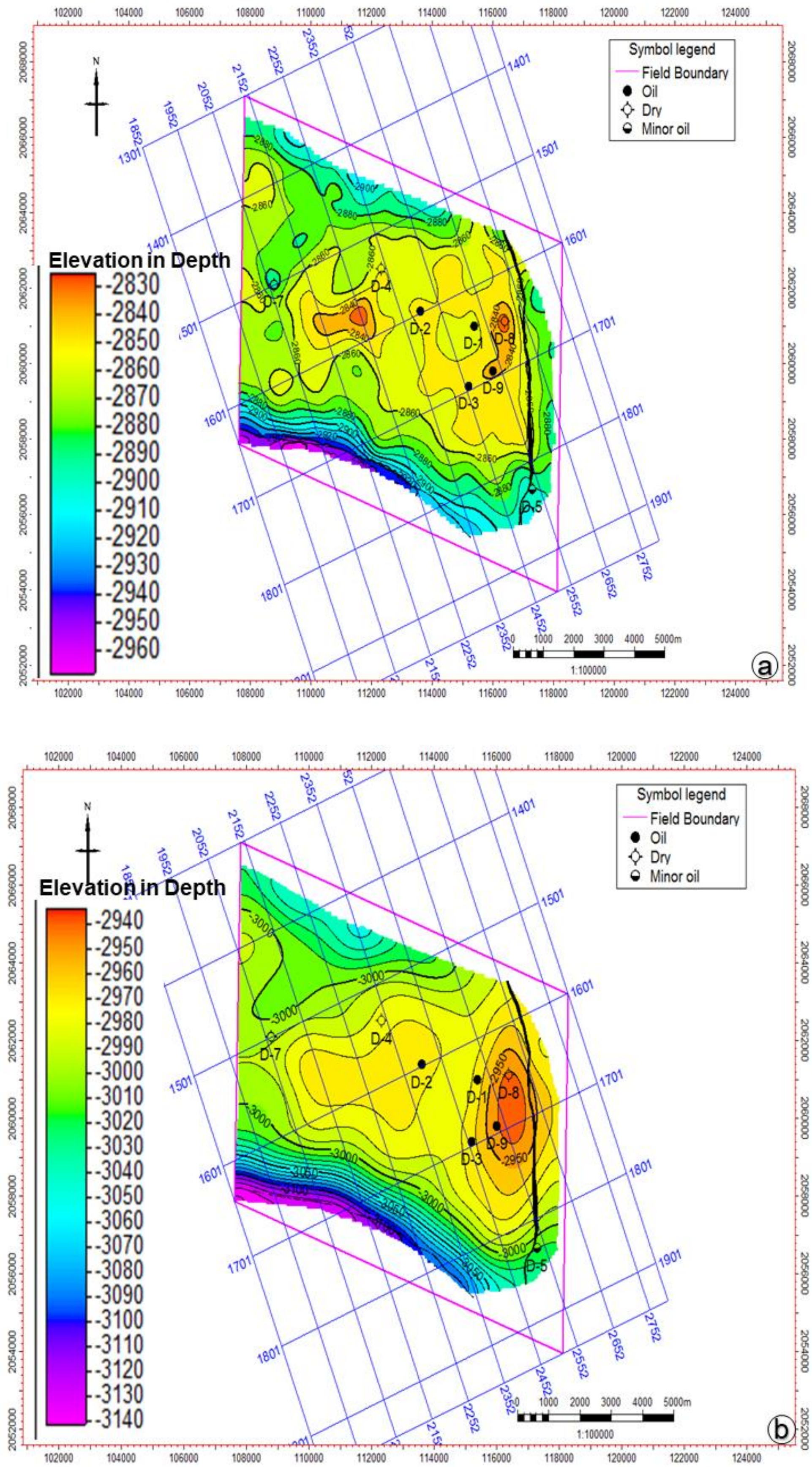


Figure 8: a) Structural configuration along the Upper pay level, b) Lower pay level.

4.5. Facies Modelling

A structural grid size of 100m x 100m x 5 m is considered for property modeling and grids are resampled. All the petrophysical analysis logs, PHI, and Sw logs are upscaled in the structural grid. In a similar approach, the discrete facies logs are also upscaled using 'most of' (a geostatistical algorithm) within the structural grid [16, 17]. It is observed that RMS greater than 1 corresponds to reservoir facies at the well location. Using this cut-off upscaled facies logs are populated geostatistically in the structural grid and facies modeling is performed considering the extracted geo-body as reservoir and rest areas as non-reservoir. Fig. (**9**) shows the facies distribution within the structural grid for the Upper, Middle, and Lower sequence and it depicts the areas near dry wells (D-8, and D-4) that have distinct non-reservoir facies.

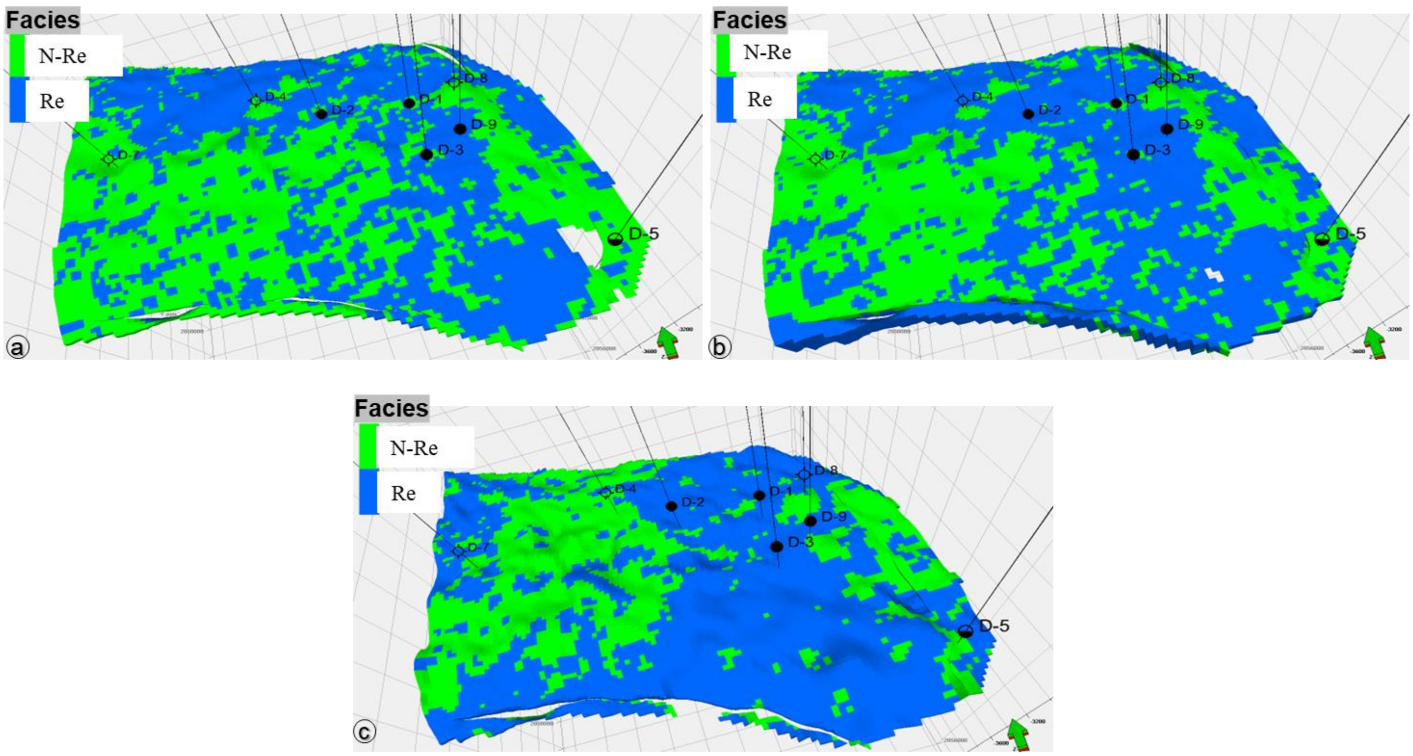


Figure 9: Facies distribution along the a) Upper pay level, b) Middle pay level, and c) Lower pay level.

4.6. Property Modeling

The upscaled porosity and water saturation logs are populated in the reservoir facies through geostatistical analysis (Kriging Interpolation). In the non-reservoir segment of the facies model, zero porosity and 100% water saturation are assigned during property distribution [16, 17]. Fig. (**10**-**11**) shows the porosity and water saturation distribution along the Upper, Middle, and Lower sequences. Instead of taking a cut off on porosities/water saturation net to gross (NTG) calculations across the geo-bodies are performed using the following relation-

NTG=Porosity value of the cell/Maximum porosity observed in the geo-bodies [16].

This normalization helps in reducing the weightage of poorer facies within each geo-body and volumetric estimates are more realistic.

4.7. Hydrocarbon in-Place Modeling

Grid base hydrocarbon in-place is estimated by taking inputs from porosity, water saturation, and NTG models as described above. The contacts and volume expansion factor (Bo) are considered based on the available information in the study area. Hydrocarbon in-place distribution along the Upper pay, Middle pay, and Lower pay are shown in Fig. (**12**). The composite hydrocarbon distribution for all the pay sequences is shown in Fig. (**12d**). It is

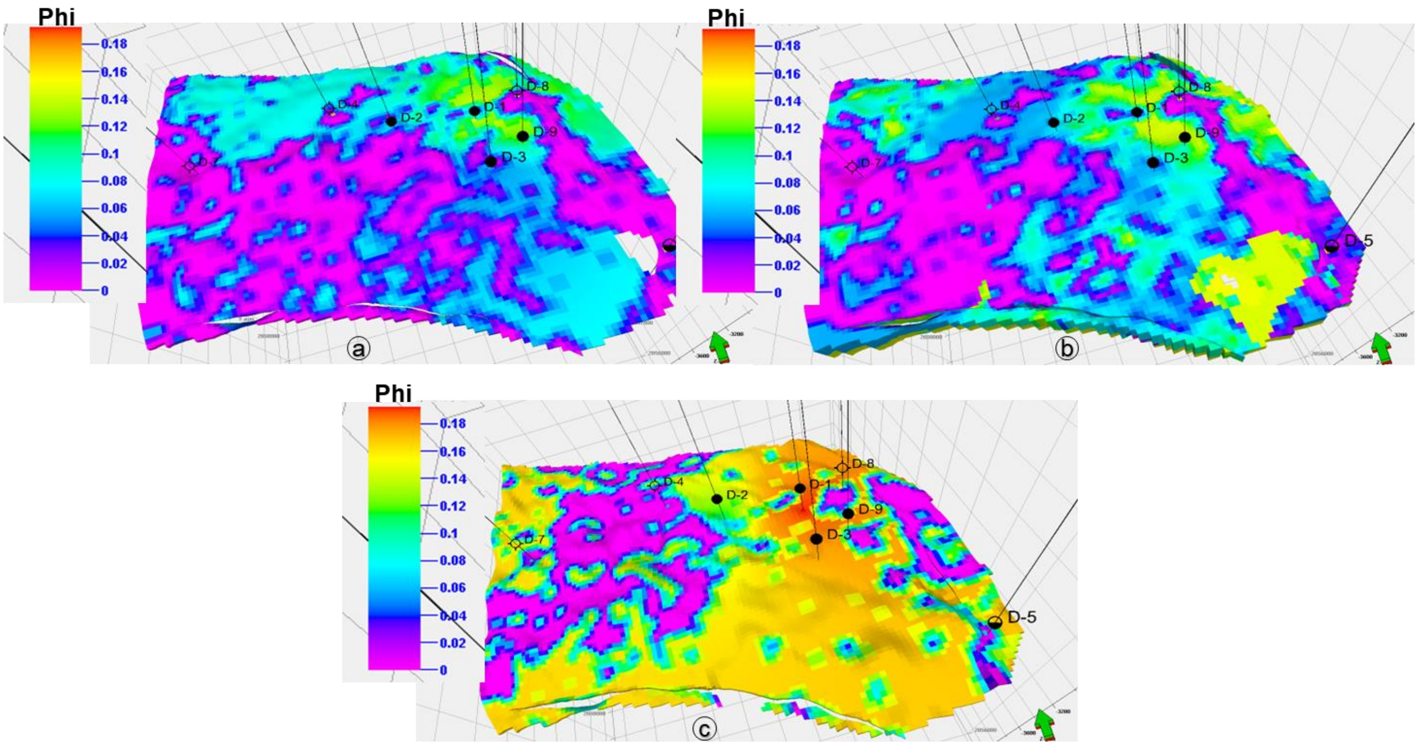


Figure 10: Porosity distribution along the a) Upper pay level, b) Middle pay level, and c) Lower pay level.

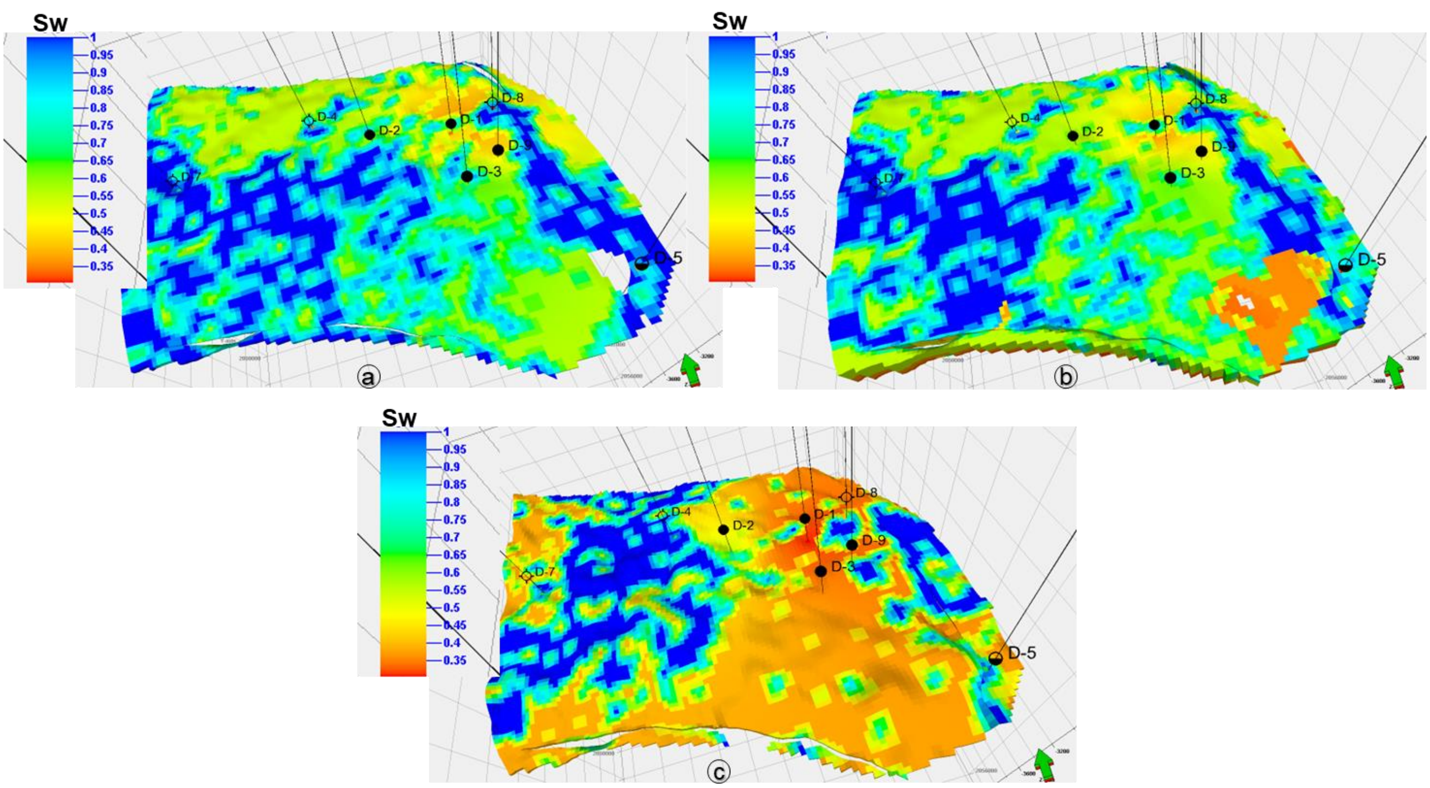


Figure 11: Water Saturation distribution along the a) Upper pay level, b) Middle pay level, and c) Lower pay level.

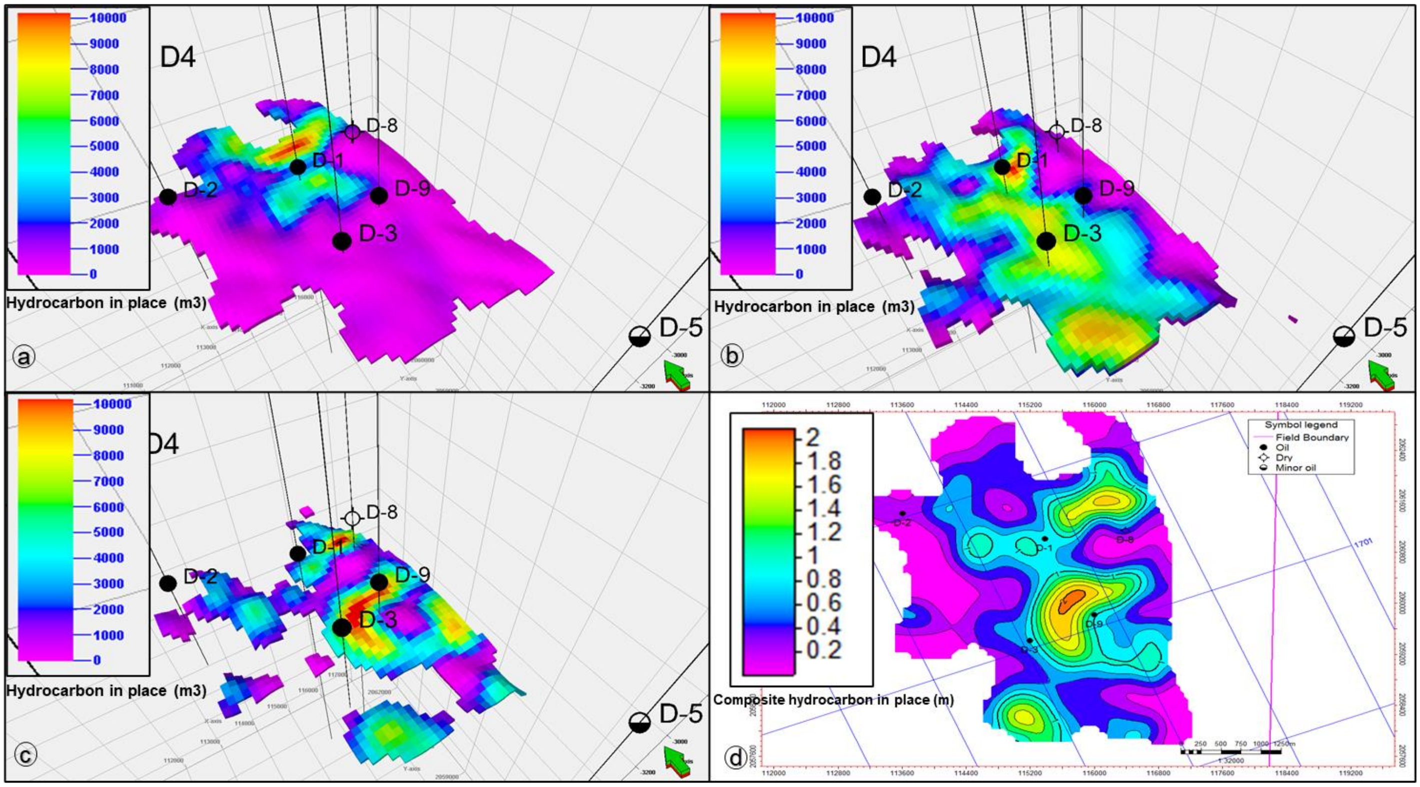


Figure 12: Hydrocarbon in-place distribution along the a) Upper pay level, b) Middle pay level, c) Lower pay level, and d) Composite plot for all the pay levels.

found that due to the absence of reservoir facies and good petrophysical properties, well D-8 is dry whereas wells D-2, D-4 and D-7 are below the contacts. It also indicates that though wells D-9 and D-3 are above the contacts at upper pay but due to poor petrophysical properties these wells have no hydrocarbon at this pay. The hydrocarbon distribution pattern within the study area indicates that the reservoir is highly heterogeneous and can have additional potential for future exploration.

5. Discussion

The structural modeling (Fig. **8**) reveals the existence of an antiformal structure with two distinct culminations at the reservoir level. The culmination is more noticeable at the lower pay than at the upper pay. The eastern culmination is targeted by wells (D-1, D-3, D-8, and D-9) whereas the western culmination is targeted by wells (D-2, D-4, and D-7). Well D-5 is drilled at the separate fault block of the structure (Fig. **8**). The study indicates that wells D-4 and D-7 are dry because they are below the contacts (Fig. **5**), however, well D-5 is on the eastern side of the N-S trending fault with a minor show (Fig. **8**). Even though the well D-8 is drilled close to the top of the structure, no hydrocarbon shows are identified which differs from conventional thinking. This peculiar behavior of the wells motivates to approach differently. To capture the facies variation, seismic attribute analysis is tried and all amplitude-based 3D seismic attributes are generated [15]. A good correlation is observed between RMS amplitude and reservoir facies, but it also noticed that three different pays have different amplitude cut off, which is why three separate geo-body are extracted corresponding to the three pays. Considering the limit of the seismic resolution only two broad categories (reservoir/non-reservoir) of seismic facies are extracted and facies modeling is performed. Taking this facies model as the base model the upscaled property logs (PHI and Sw) are distributed geostatistically taking the RMS amplitude as a secondary input. This geostatistical modeling captures the reservoir heterogeneity very well and the RMS attribute helps in providing the geological trends during the property modeling. Finally, the pay-wise, as well as the combined hydrocarbon in-place distribution maps, provides confidence in the proposed approach as they captured all the drilling and production data.

6. Conclusion

In conclusion, this paper addresses the challenges associated with characterizing and producing hydrocarbons from carbonate reservoirs, which are known for their low permeability, matrix heterogeneities, and complex fracture and dissolution patterns. The results demonstrate that the integrated approach of geo-body extraction and geostatistical modeling is effective in delineating the facies architecture and reservoir heterogeneity of carbonate reservoirs. It allows for the identification of favorable reservoir facies and provides a comprehensive assessment of the remaining potential.

In summary, the proposed integrated approach offers a promising solution to the challenges associated with carbonate reservoirs. By accurately predicting the facies architecture and reservoir properties, it enables informed decision-making in drilling and production operations. This, in turn, can lead to improved exploration success and optimized hydrocarbon recovery in carbonate reservoirs.

Acknowledgments

The author is indebted to Director General, DGH for providing permission to publish the paper.

Furthermore, heartfelt thanks are extended to Asit Kumar, Head of Department (NDR) National Data Repository, for his valuable guidance throughout this work.

References

[1] Branets LV, Ghai SS, Lyons SL, Wu XH. Challenges and technologies in reservoir modeling. Commun Comput Phys. 2009; 6(1): 1–23. https://doi.org/10.4208/cicp.2009.v6.p1

[2] Herron DA. First Steps in Seismic Interpretation. USA: Society of Exploration Geophysicists; 2011. https://doi.org/10.1190/1.9781560802938

[3] Ruan F, Yang S, Huang G. Seismic attributes blending analysis for structural interpretation and geobody delineation. International Geophysical Conference, Beijing, China: 24-27 April 2018, Society of Exploration Geophysicists and Chinese Petroleum Society; 2018, p. 840–3. https://doi.org/10.1190/IGC2018-205

[4] Babak O, Liu K. Facies trend modeling based on geo-body-based binning of seismic impedance. J Appl Geophys. 2018; 154: 37–49. https://doi.org/10.1016/j.jappgeo.2018.03.016

[5] ElBadry ME, Cunnell JC, Zdraveva O, Benson M. A workflow and case study for adaptive geobody imaging in the Nile Delta, 2012. https://doi.org/10.3997/2214-4609.20148736

[6] Haque A, Islam A, Shalaby MR. Three-dimensional facies analysis using object-based geo body modeling: A case study for the farewell formation, Maui gas field, Taranaki basin, New Zealand. Preprints 2018. https://doi.org/10.20944/preprints201801.0123.v1

[7] Purnomo EW, Abdul Latiff AH, Elsaadany MMAA. Predicting reservoir petrophysical geobodies from seismic data using enhanced extended elastic impedance inversion. Appl Sci. (Switzerland) 2023; 13(8): 4755. https://doi.org/10.3390/app13084755

[8] Amini H. A pragmatic approach to simulator-to-seismic modeling for 4d seismic interpretation. Thesis. Heriot-Watt University; September 2014.

[9] Amjad MR, Ehsan M, Hussain M, Al-Ansari N, Rehman A, Naseer Z, et al. Carbonate reservoir quality variations in basins with a variable sediment influx: a case study from the Balkassar Oil Field, Potwar, Pakistan. ACS Omega. 2023; 8(4): 4127-45. https://doi.org/10.1021/acsomega.2c06773

[10] Biswas SK. Regional tectonic framework, structure, and evolution of the western marginal basins of India. Tectonophysics. 1987; 135: 307–27. https://doi.org/10.1016/0040-1951(87)90115-6

[11] Amaru M, Li L, Tyshkanbayeva A. Integration of seismic data in reservoir modeling through seismically constrained facies models. The Leading Edge. 2022; 41: 815–23. https://doi.org/10.1190/tle41120815.1

[12] de Sousa A, Bizarro P, Ribeiro MT. Seismic attributes for channels identification and facies modeling application in a siliciclastic onshore reservoir, Kazakhstan, Central Asia. Abu Dhabi International Petroleum Exhibition & Conference November 9–12, 2020, Abu Dhabi, UAE: SPE; 2020. https://doi.org/10.2118/202978-MS

[13] Nair N, Pandey DK. Cenozoic sedimentation in the Mumbai Offshore Basin: Implications for the tectonic evolution of the western continental margin of India. J Asian Earth Sci. 2018; 152: 132–44. https://doi.org/10.1016/j.jseaes.2017.11.037

[14] Burnham BS, Hodgetts D. Geologic Modelling of Geobody Geometry and Architecture of the Huesca Distributive Fluvial System. 77th EAGE Conference and Exhibition, 1-4 Jun 2015, Madrid, Spain: European Association of Geoscientists & Engineers; 2015, p. 1-5. https://doi.org/10.3997/2214-4609.201412863

[15] Gorain S, Kumar A, Reddy L. Prediction of facies reservoir properties in carbonate reservoir through geo-body modeling: Mumbai Offshore case study. EAGE Workshop on Innovative Reservoir Modeling into Digital Proliferation, European Association of Geoscientists & Engineers; 2022, p. 1–3. https://doi.org/10.3997/2214-4609.202273004

[16] Gorain S, Shalivahan. Application of attribute-based inversion and spectral decomposition with red–green–blue color blending for visualization of geological features: a case study from the Kalol Field, Cambay Basin, India. Pet Geosci. 2018; 24: 102–11. https://doi.org/10.1144/petgeo2015-090

[17] Gorain S, Thakur P. "Attribute-based Inversion" a tool for reservoir characterization: a case study-Kalol Field, Cambay Basin, India. Acta Geodaetica et Geophysica. 2015; 50: 321–38. https://doi.org/10.1007/s40328-014-0088-y