Hydrocarbon Potential and Basin Analysis of the Southern Permian Basin, North Sea: Evaluating Key Plays in the Turonian and Carboniferous

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Abstract:- This research provides an in-depth basin analysis and evaluates the hydrocarbon potential in the Southern Permian Basin, North Sea, Netherlands. It employs a thorough approach, including interpreting well logs, analysing petrophysical data, mapping faults and horizons, converting time to depth, and calculating reserves. The study highlights two key plays: the Turonian play (Barremian Formation) and the Carboniferous play (Rotliegend Formation). Petrophysical analysis of the Turonian Formation shows porosity values between 8.9% and 16% and net-to-gross ratios ranging from 0.6 to 1.0, indicating variable reservoir quality with a 45% geological chance of success. In contrast, the Carboniferous play, which includes Rotliegend marine sandstones, has a 45% chance of success but benefits from better porosity and permeability than the Turonian Formation. The research produced time and depth structure maps, clarifying trap mechanisms and identifying potential leads. With its promising results, the Southern Permian Basin presents a significant opportunity for future exploration and development. However, the study notes several limitations, such as issues with power stability, the need for more 3D seismic data and missing logs like neutron and density for some wells. Addressing these issues by improving data collection and operational conditions is crucial, as it could enhance exploration accuracy and increase the chances of success in the Southern Permian Basin. It also highlights the potential for further research in this area.

Keywords:- *Southern Permian Basin, North Sea, Basin Analysis, Rotliegend Formation, Petrophysics, Petroleum System.*

I. INTRODUCTION

The study area, which encompasses the Southern Permian Basin, North Sea, and Netherlands, is home to a geologically significant structure. This structure, classified as a failed rift extensional basin, has origins that can be traced back from the Devonian to the Tertiary periods. The Southern Permian Basin, the larger of the two basins, extends approximately 1,700 kilometres (Figure 1). It stretches from the eastern coast of England across the southern North Sea, traversing Northern Germany and reaching into Poland and the Baltic states. This extensive reach underscores its significance within the European geological framework and potential for future petroleum exploration.

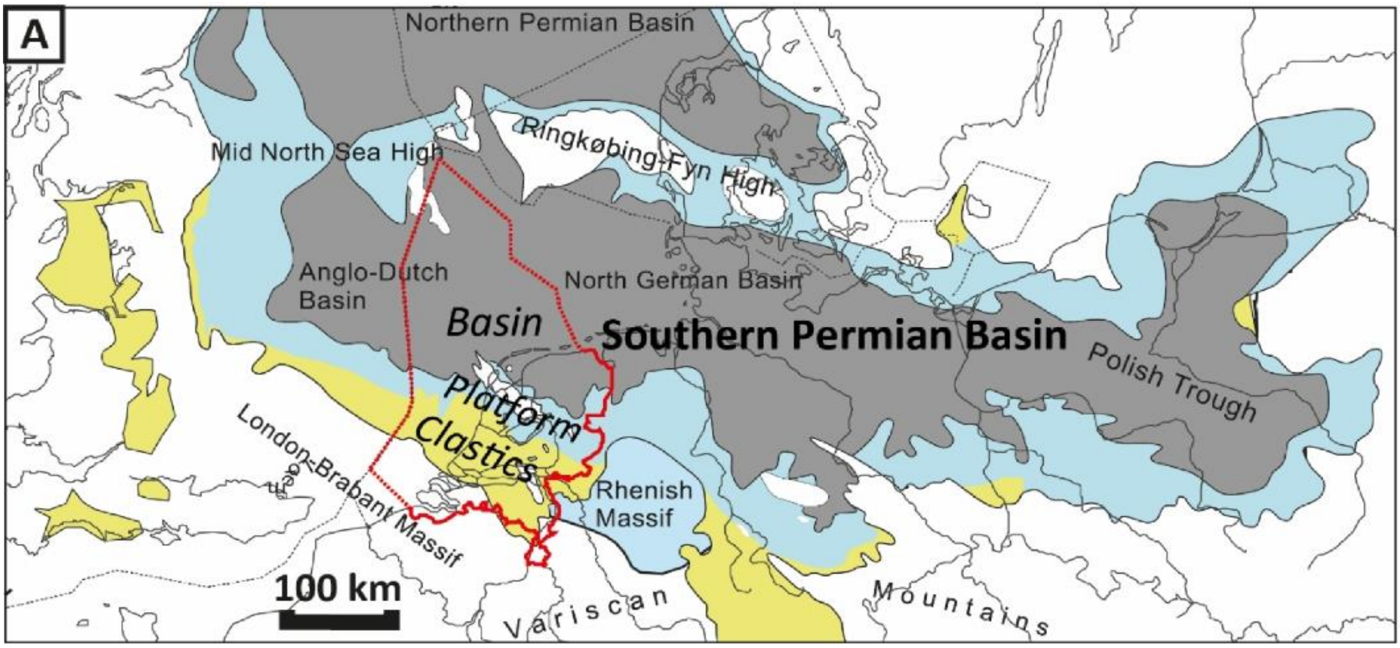

Fig 1 Location of the Southern Permian Basin.

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In the Southern Permian Basin, Rotliegend sandstones and Zechstein carbonates reserve most of the hydrocarbon accumulations. Since 1994, over 1,000 wells have been drilled to a maximum depth of 5,000m, and companies exploring hydrocarbons beneath the southern North Sea have acquired many hundred thousand kilometres of digitally recorded seismic reflection data.

SPE (2015) defines a basin's maturity by the underlying number of discoveries and the declining production rate of mature fields. As the Southern Permian Basin's gas (Figure 2) and oil province continue to mature, and with field sizes inevitably decreasing, more careful data integration and geoscientific effort will be required to discover new reserves (Ken Glennie et al., 2010).

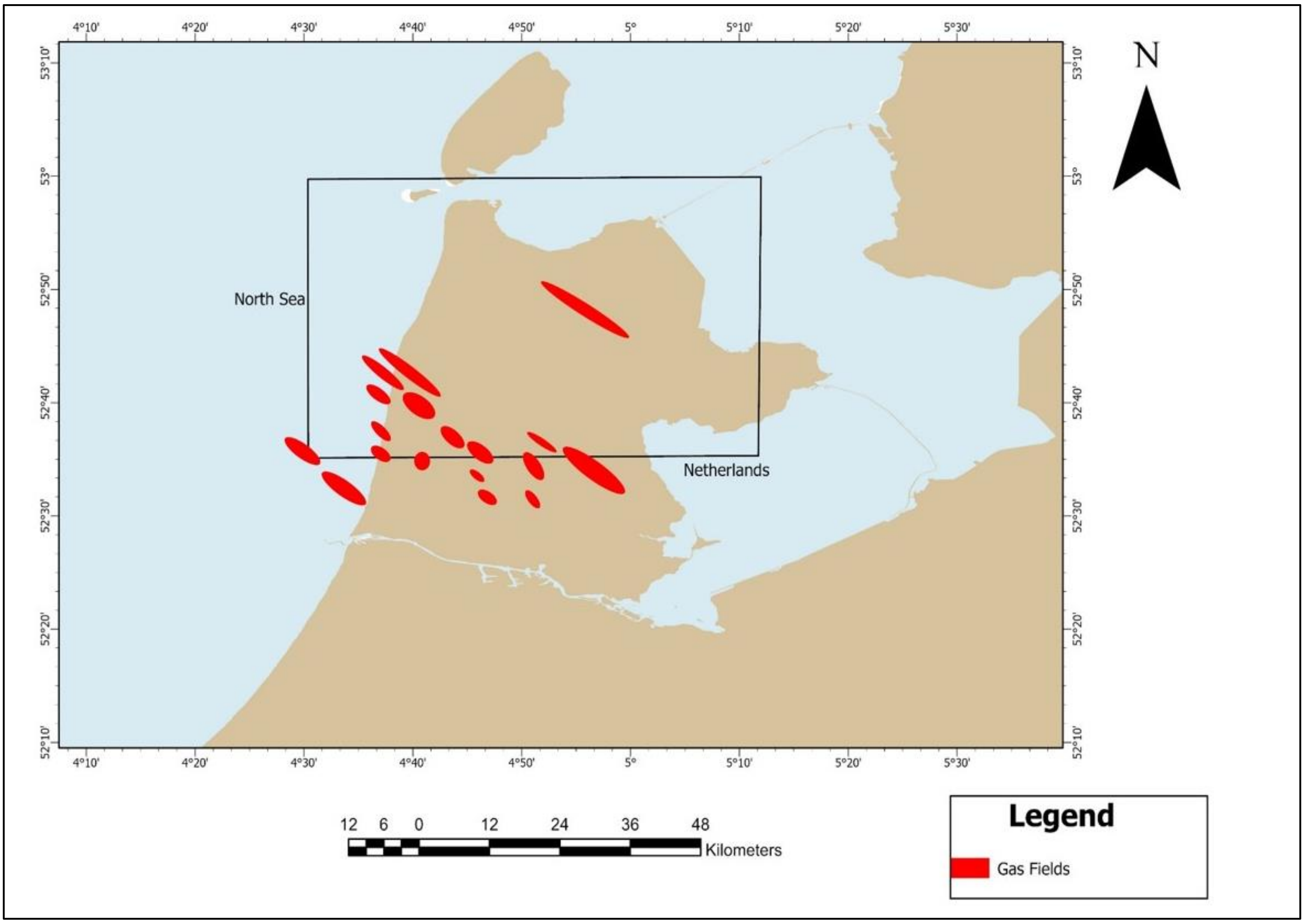

Fig 2 The Southern Permian Basin map showing the Gas Fields.

This study aims to better understand the Southern Permian Basin and its hydrocarbon potential within the Turonian and Carboniferous plays.

II. GEOLOGY

The North Sea covers the offshore part of a significant Permian basin, extending from Norway, Scotland, and Denmark across northern Germany and the Netherlands into eastern England. This paper will focus mainly on the Southern Permian Basin. The basin is divided into several structural sub-basins with different tectonostratigraphic evolutions. The Rotliegend sedimentation history of the southern North Sea and adjacent countries is characterised by a sequence of aeolian, fluvial, and lacustrine deposits deposited in a semi-arid to arid environment (Figure 3). The Zechstein Supergroup, including the Hauptdolomit Formation, is a prominent unit in the basin known for its potential as a petroleum play.

The Southern Permian Basin is also home to several key geological formations, including the Halibut Carbonate Formation, which consists of dolostones, limestones, anhydrite, and conglomerates and is equivalent to the Z1 and Z2 cycles of the Zechstein Supergroup, the Triassic Fluvial Sandstones, the Lower Cretaceous Paralic-Shallow-Marine Sandstones which is known for its oil discoveries, the Westphalian Fluvial Sandstones known for its gas production (Figure 4).

Generally, the geological and structural setting of the Southern Permian Basin is influenced by the interrelation of tectonic and depositional processes. An example of this interrelation is the presence of salt structures. The salt structures in the basin have been analysed using 3D seismic data and time-thickness variations, which have provided insights into their evolution across the diverse structural sub-basins.

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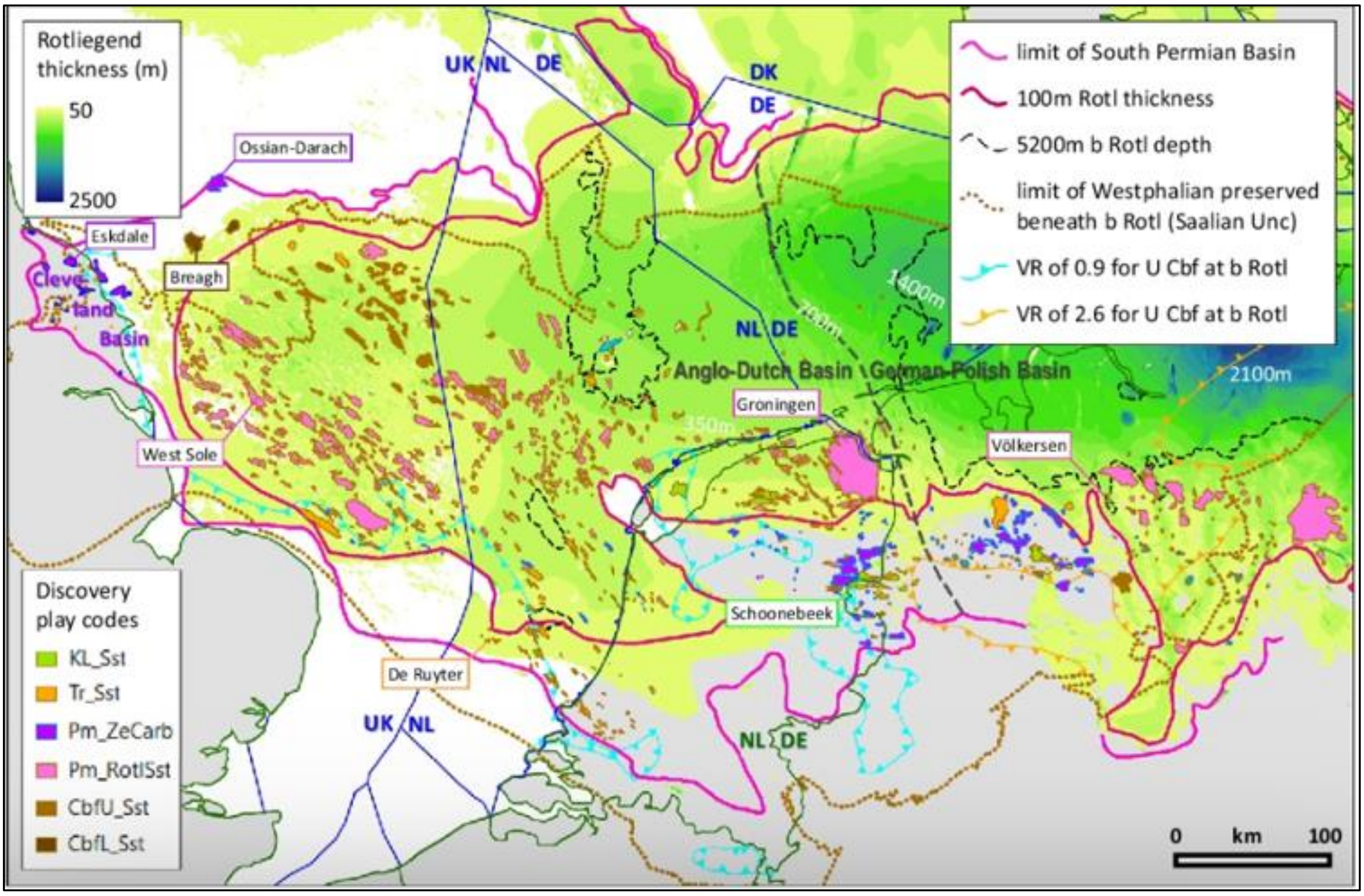

Fig 3 Outline of the Southern Permian Basin showing the Play-Coded Discoveries within it and the Rotliegend Thickness.

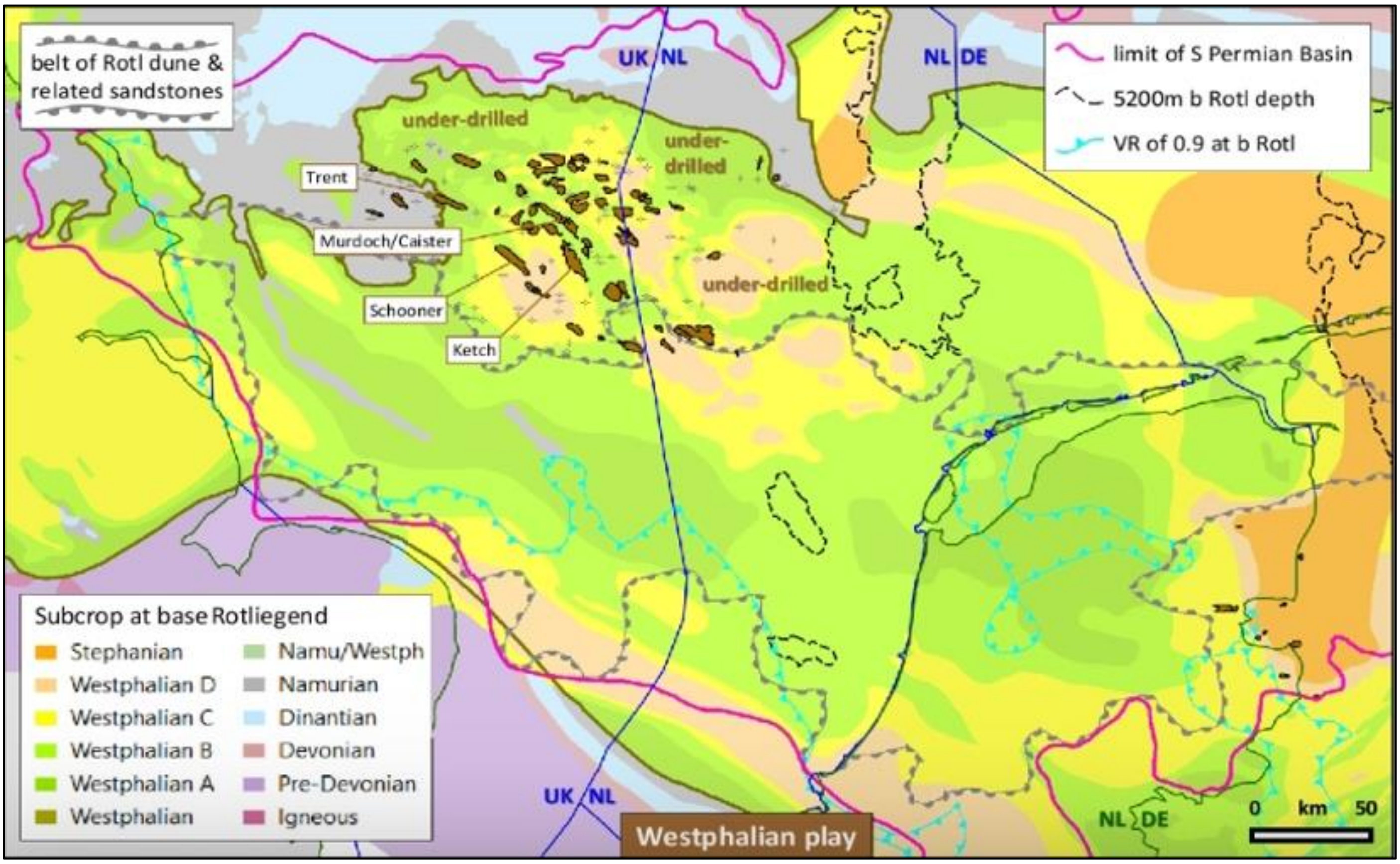

Fig 4 Westphalian Gas Discoveries Highlighted in Brown.

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III. DATA AND METHODOLOGY

The data used for this study include one 3D Seismic reflection volume, nine 2D Seismic reflection lines, 17 wells (Figure 5) with incomplete log suites (4 digital and 13 composite logs), a check-shot survey for two wells and one deviation data (Table 1), surface geologic maps, and geopolitical and geologic posters.

➢ *Datasets*

The study of the Southern Permian Basin utilised various geological and geophysical data to gain a comprehensive understanding of the region. The American Association of Petroleum Geologists (AAPG) provided the dataset for this study. The dataset included:

- *3D Seismic Reflection Volume:*

This provided a detailed three-dimensional view of the subsurface, essential for mapping geological structures and stratigraphy. The high-resolution data from these surveys helped identify structural traps, faults, and stratigraphic features.

- *2D Seismic Reflection Lines:*

These provided cross-sectional images of the subsurface along specific lines. Although less detailed than 3D data, 2D seismic lines were helpful in regional mapping and understanding broader geological trends.

- *17 Wells with Incomplete Log Suites:*

Well logs from 17 wells, including four digital and thirteen composite logs, were used to gather a continuous record of rock properties. Digital logs offer precise data, while composite logs integrate various tools to view subsurface conditions comprehensively.

- *Check-shot Surveys for 2 Wells:*

These surveys measured the travel time of seismic waves from the surface to specific depths, helping to calibrate seismic data with actual depths and align seismic interpretations with natural subsurface conditions.

- *1 Deviation Data:*

This recorded the trajectory of the wellbore, which is essential for correlating well logs with seismic data, especially in deviated or horizontal wells.

- *Surface Geologic Maps and Posters:*

These provided contextual information about the region's geology and the spatial distribution of geological units and structures.

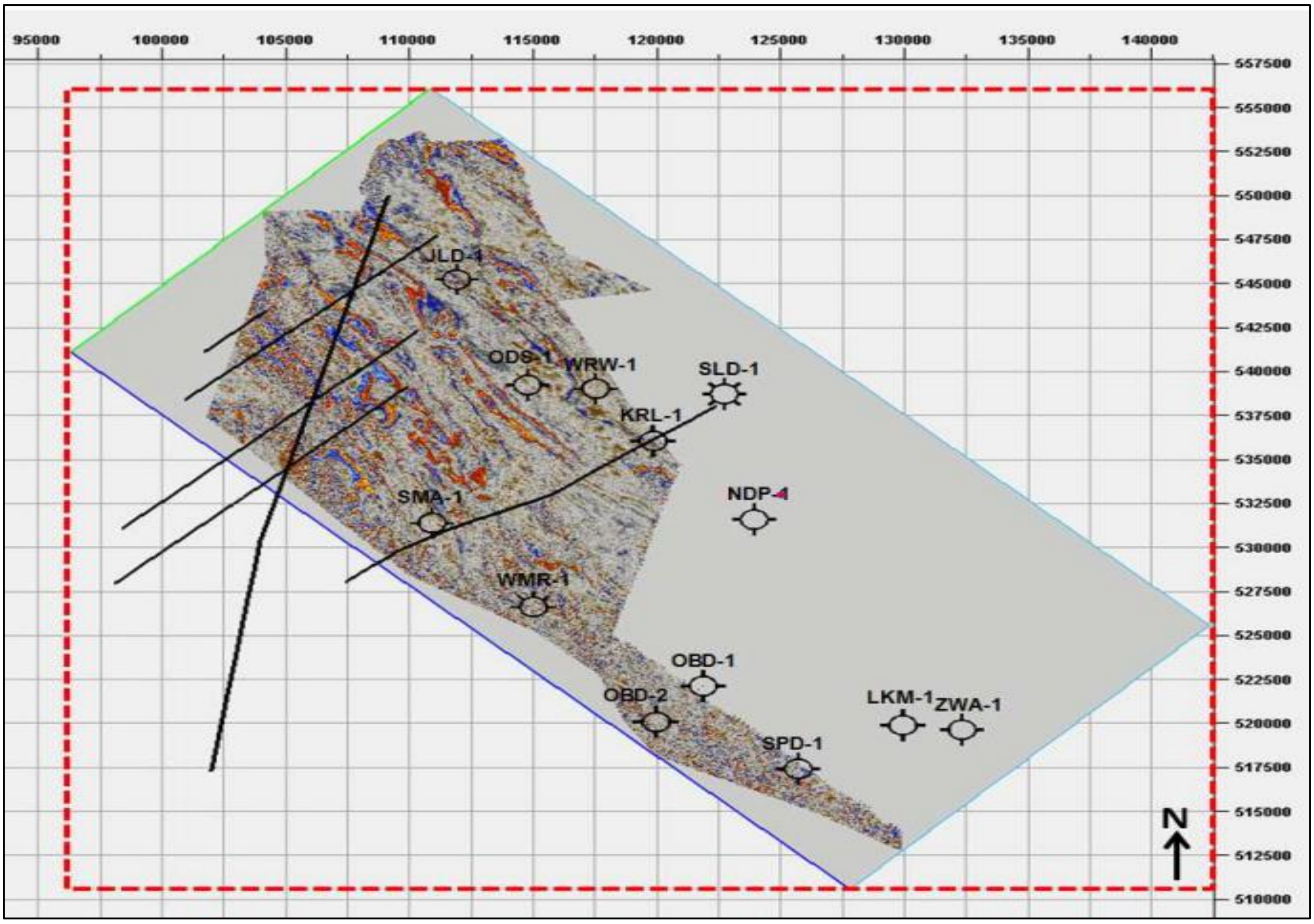

Fig 5 Base Map of the Study Area showing the 3D Seismic Reflection Coverage, 2D Seismic Reflection Lines and the Position of the Available wells.

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Table 1 Summary of the Available Logs for each well.

Well ID	Well Name	Strip Log	Deviation Survey	Checkshots	Caliper	Density	Sonic	Neutron	Gamma Ray	Resistivity
JLD-1	Juliandorp 1	X			X		X		X	X
KRL-1	Kreil 1	X	X	X	X	X	X	X	X	X
LKM-1	Lekkermeer 1	X		X	X	X	X		X	X
NDP-1	Niedorp 1	X			X		X		X	X
OBD-1	Obdam 1	X			X		X		X	X
OBD-2	Obdam 2	X					X		X	
ODS-1	Oudesluis 1	X			X				X	X
SMA-1	SintMaarten 1	X								X
SLD-1	Slootdorp 1	X					X			X
SPD-1	Spierdijk 1	X					X		X	X
WRW-1	Wieringerwaard 1	X			X		X		X	X
WMR-1	Woudmeer 1	X			X				X	X
ZWA-1	Zwaag 1	X					X		X	

The workflow adopted for the study is summarised in Figure 6. The well-log interpretation was carried out using the available well logs from which reservoir tops were mapped and correlated across the wells in the southeast-northwest direction. A synthetic seismogram was generated to tie the mapped reservoir tops to the seismic. Well-log sequence stratigraphic interpretation was made using the Galloway Sequence Model to identify genetic sequences and their corresponding system tracts. Seismic structural interpretation was also done on the seismic sections to generate a seismic time map, depth maps, fault planes and isochore maps. The petroleum play maps were generated and utilised to identify the play sweet spot of the leads and prospects. Based on this information, the volumetrics for the prospect identified were evaluated, as well as the risks involved in exploring the potential prospect and leads identified.

The data interpretation and analysis were done using the Petrel software, available in the Petroleum Workstation Geoscience lab at Nnamdi Azikiwe University.

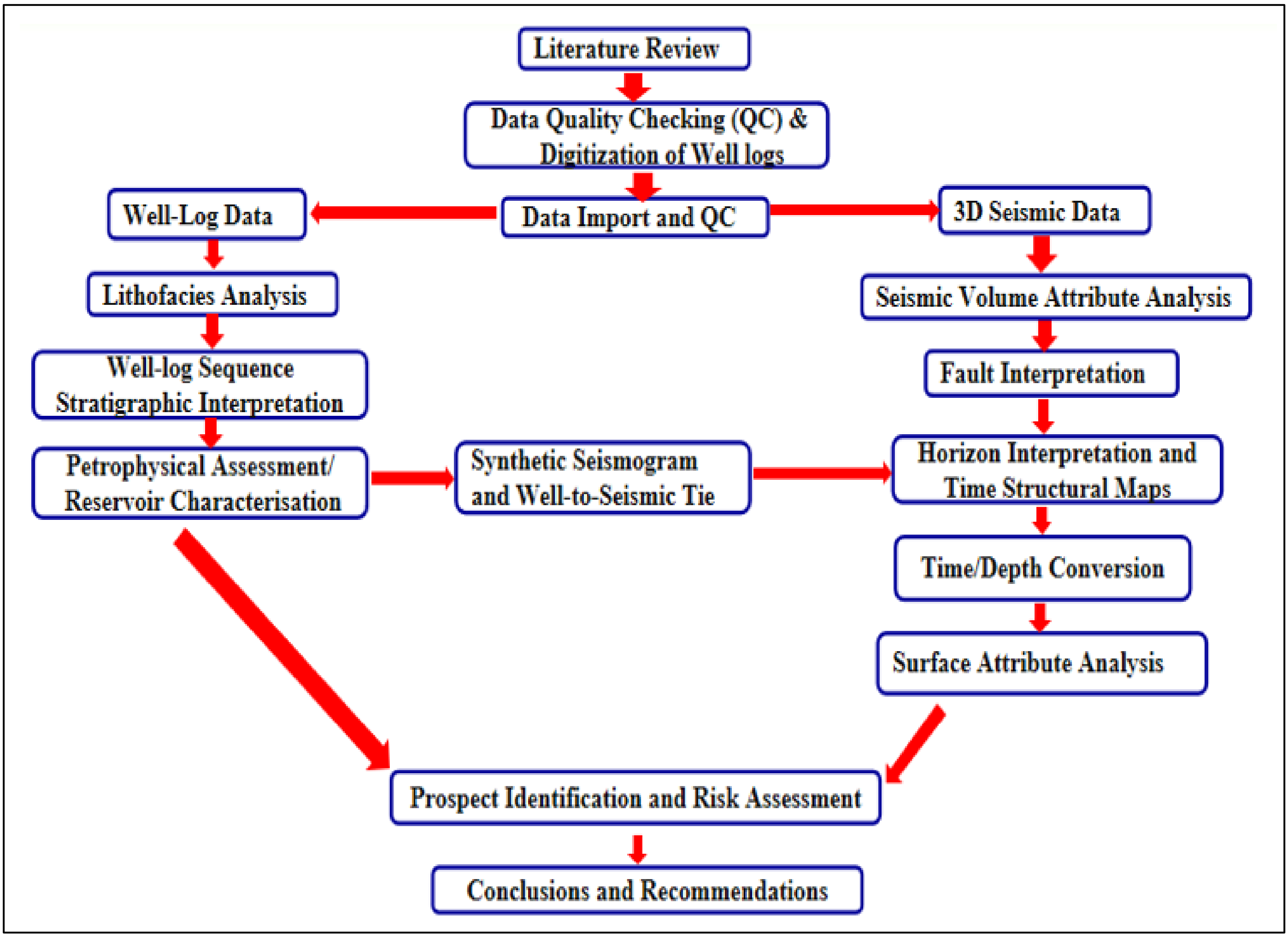

Fig 6 Workflow for Southern Permian Basin analysis

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IV. RESULTS AND DISCUSSION

➢ *This Section Documents the Various Findings of this Study.*

The seismic-well tie's seismic and well-log data are integrated in time and depth; this is done through a synthetic seismogram model. The synthetic seismogram generated before and after bulk shifting (figures 9a and 9b) reveals that all formation tops were tied to the WRW-1 well. Due to the absence of a density log, Sonic estimated the density log using Gardner's equation. Stretch and squeeze were applied to 3-Intervals, shallow, mid and deep, giving a good fit for the tie at WRW-1 well.

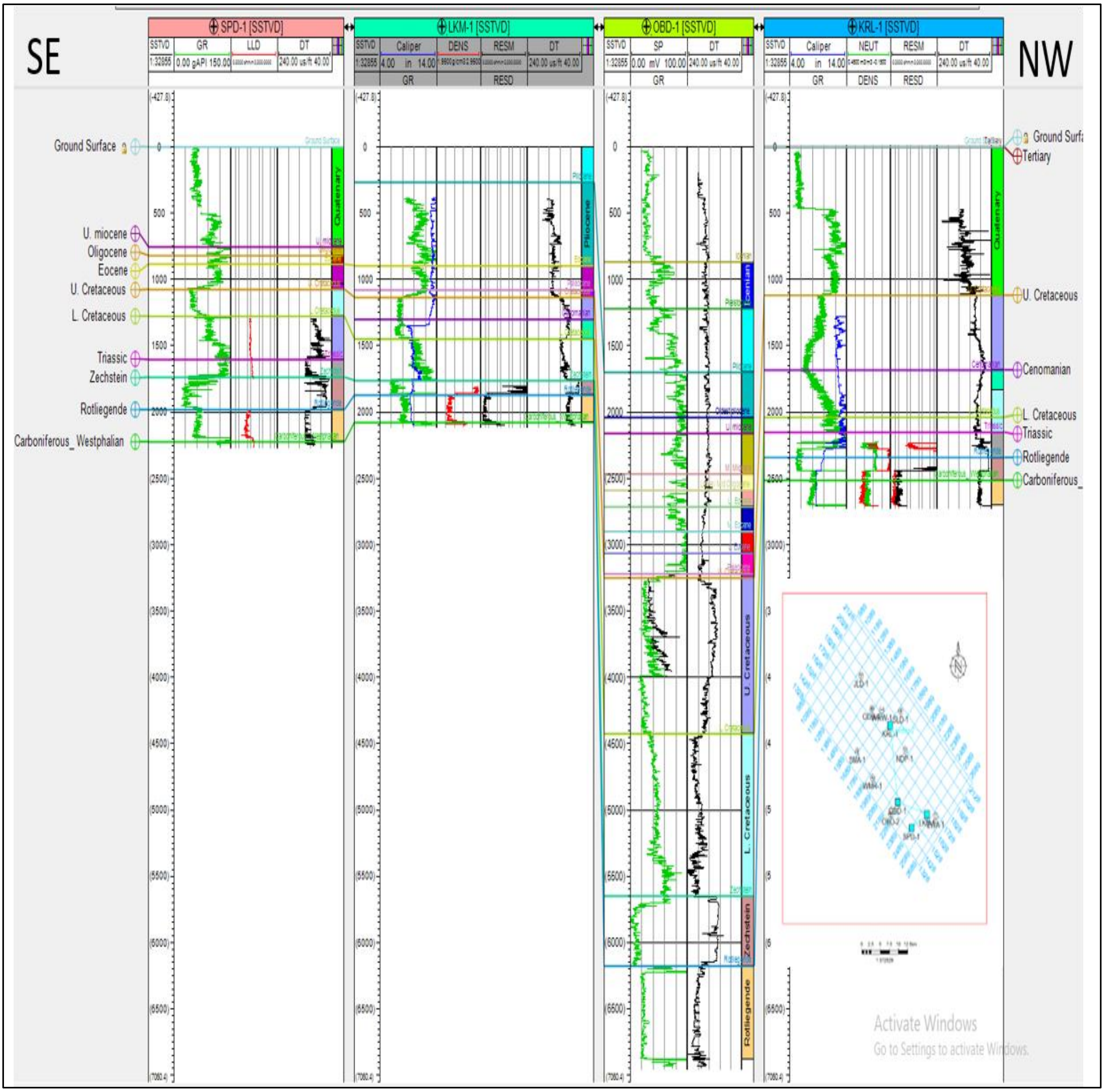

Fig 7a Lithostratigraphic Correlation between SPD-1, LKM-1, OBD-1 and KRL-1 wells.

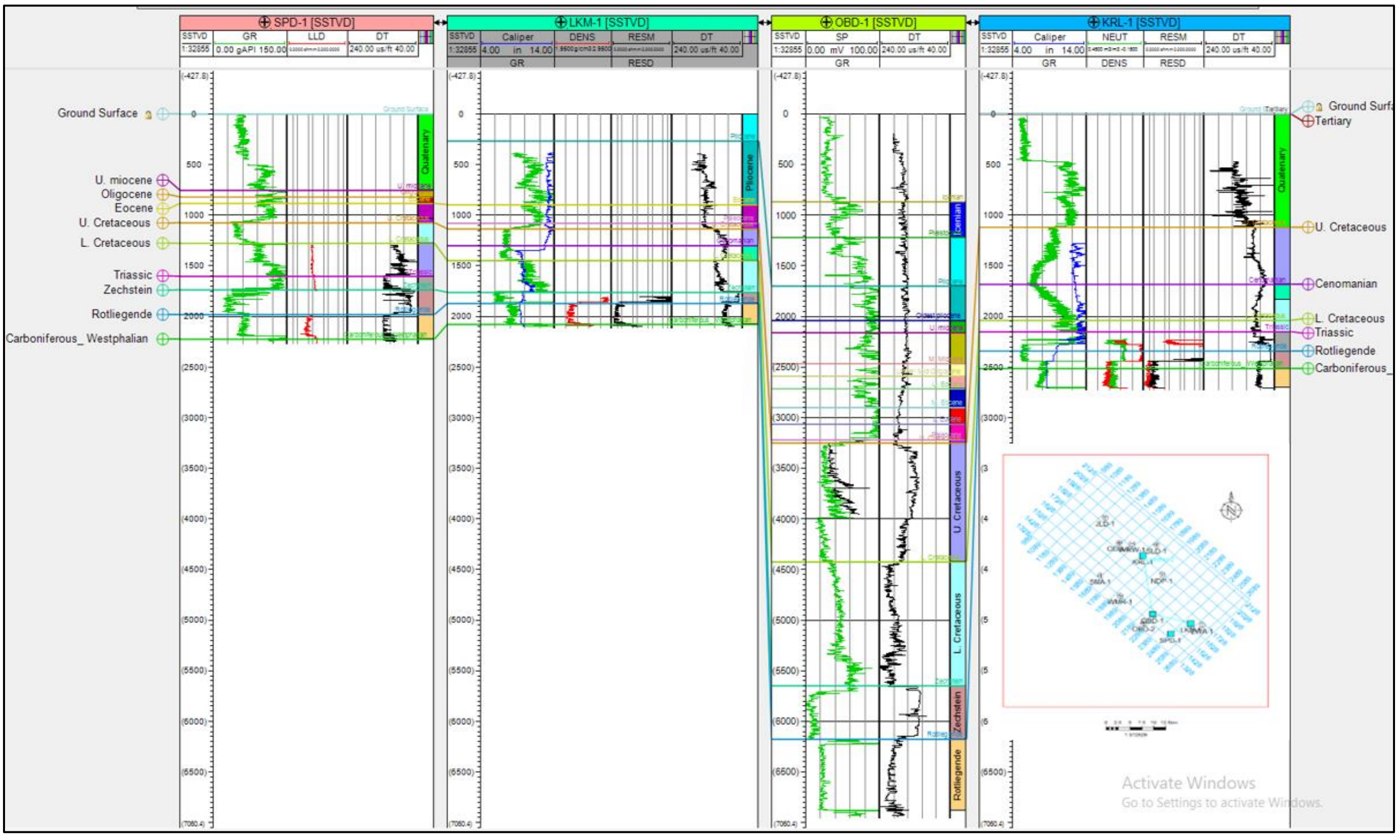

Fig 7b Sequence Stratigraphic Interpretation using the Galloway Model.

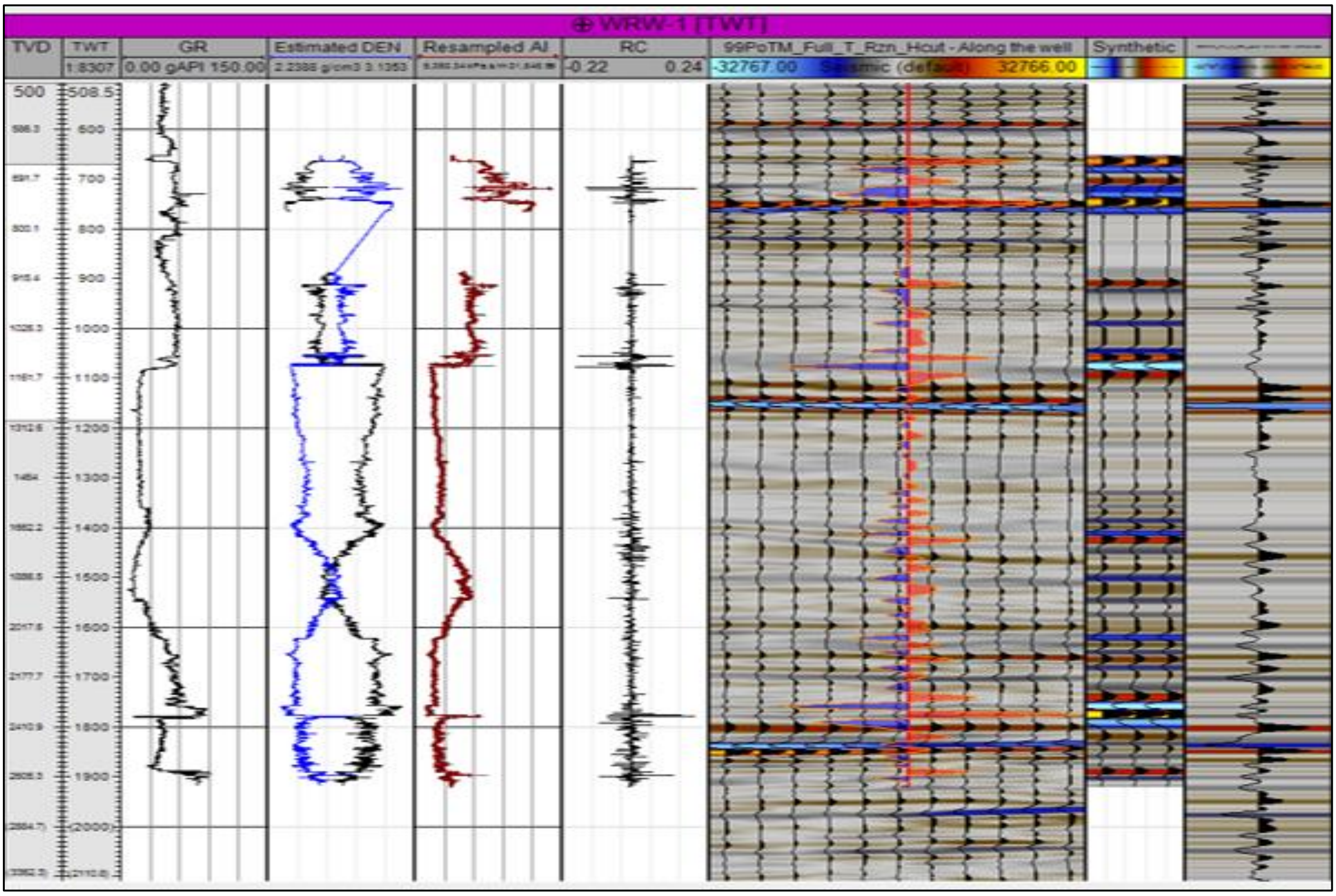

Fig 8a Synthetic Seismogram before Bulk Shifting.

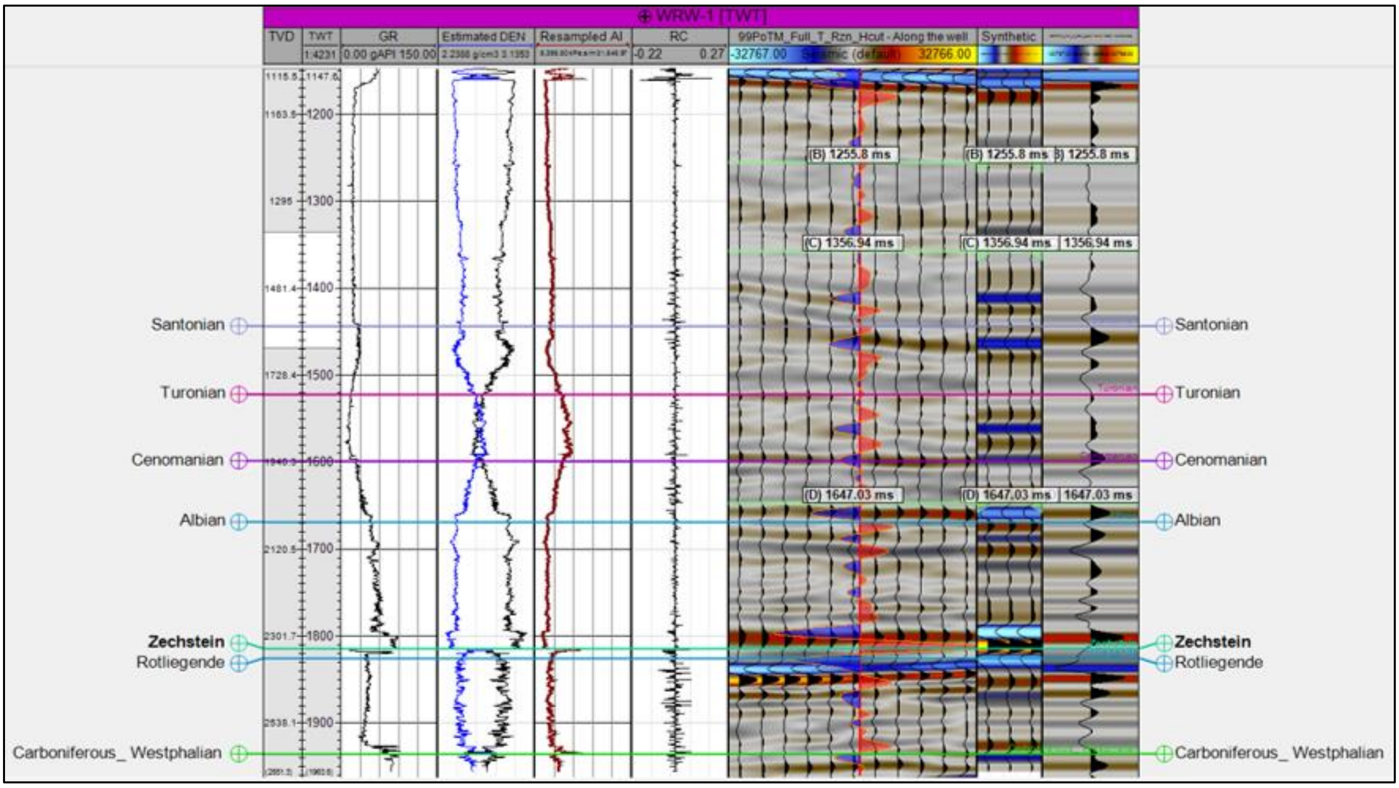

Fig 8b Synthetic Seismogram after Bulk Shifting.

➢ *Structural Framework Interpretation*

The structural framework of the study area reveals a complex system of normal faults characteristic of extensional tectonic settings. These normal faults are typically linear and define the structural boundaries of the basin, significantly influencing its overall architecture.

The analysis also identifies antithetic faults, which dip in the opposite direction to the primary normal faults. These antithetic faults intersect with the central fault system, marking the boundary between the transition zone and the adjacent ocean basin. This transition zone is crucial as it represents the continental to oceanic crust shift.

The linear geometry of these faults reflects the extensional forces that have shaped the basin over geological time. This alignment suggests a consistent stress regime during their formation, consistent with the rifting processes that created the basin.

The observed structural style is complex, reflecting the basin's multi-phase tectonic history. This complexity results from various tectonic events, including initial rifting, subsidence phases, and possible fault reactivation during later tectonic episodes. The interplay of these forces has created a layered and intricate structural fabric in the region.

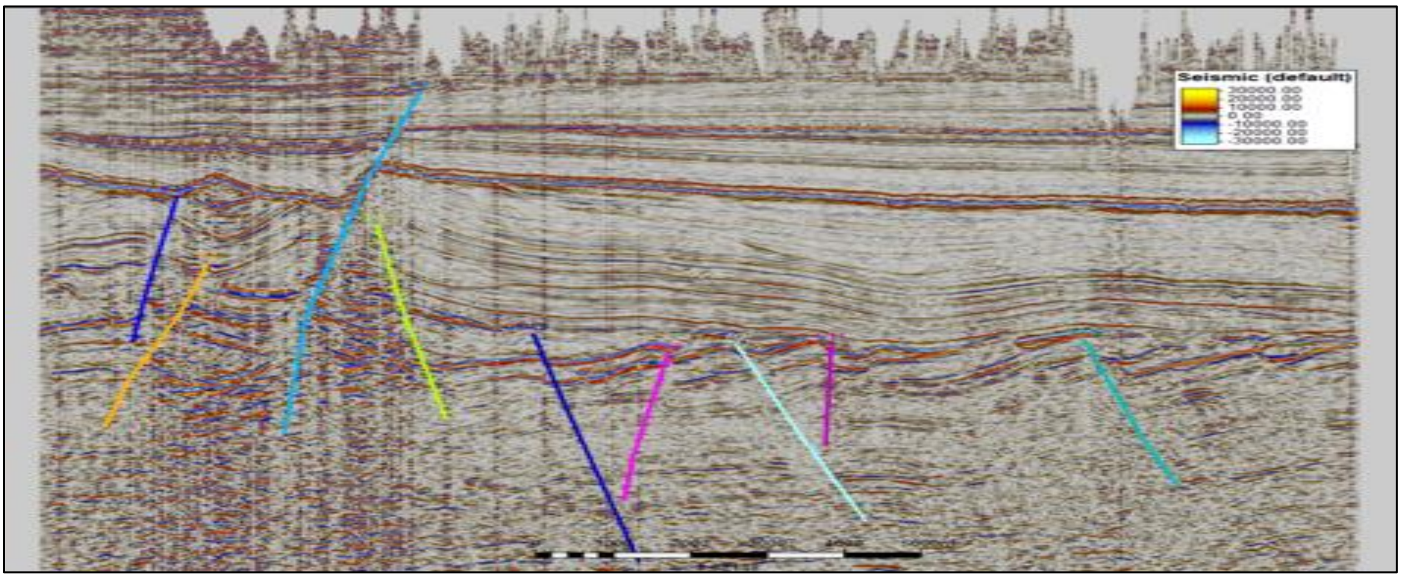

Fig 9 Seismic Line Interpretation showing the Faults and Horizons.

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➢ *Age Model and Structural Framework Interpretation*

An age model was developed using Petrel software to map the chronological sequence of geological events and formations in the basin. This model helps in understanding the basin's evolution and sedimentary history.

During the analysis of 2D seismic sections, a significant feature was identified: a suspected volcanic mound in the southwestern part of the basin. This mound is distinguished by its unique seismic reflection patterns, differing from the surrounding sedimentary layers. It likely has a volcanic origin, which could impact the basin's thermal history and hydrocarbon generation potential.

➢ *The Structural Framework Interpretation Uncovered Several Key Elements:*

- *Faults as Migration Pathways*:

The identified faults likely serve as pathways for hydrocarbons, enabling their movement from source rocks to reservoir rocks. Understanding the orientation and connectivity of these faults is crucial for determining hydrocarbon distribution within the basin.

- *Faults as Hydrocarbon Traps*:

Some faults are also potential hydrocarbon traps. These faults can create structural closures or barriers that accumulate hydrocarbons. Analysing their depth, orientation, and intersection points helps pinpoint promising areas for exploration and drilling.

The age model and structural framework offer a detailed view of the basin's geology. The age model clarifies the sequence of sedimentary and volcanic events, while the structural framework reveals features that affect hydrocarbon migration and trapping. This combined approach is essential for assessing the basin's hydrocarbon potential and guiding exploration efforts.

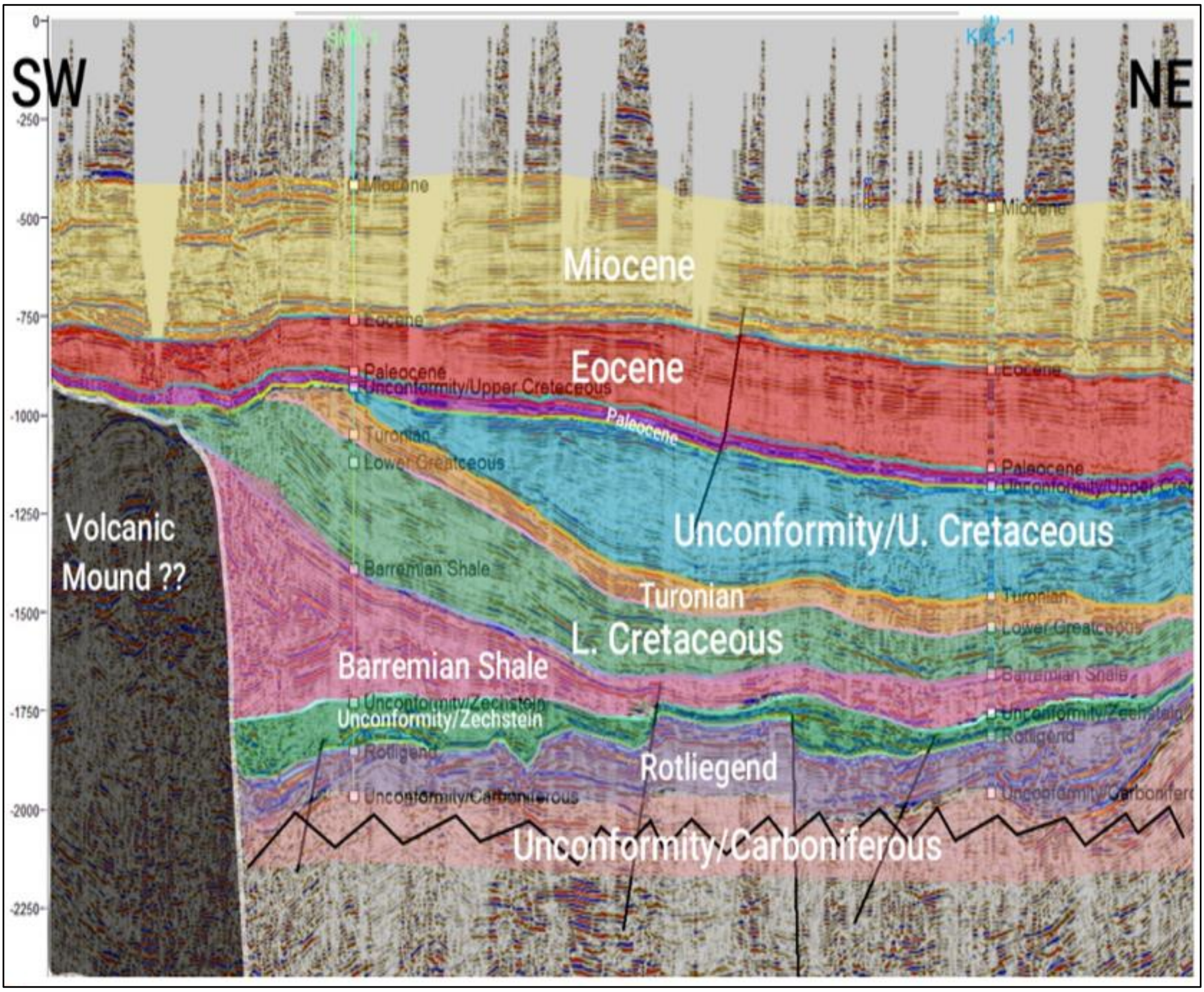

Fig 10 2D Seismic Line showing an Age-Modelled Section, Interpreted Faults and Horizons.

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➢ *Surface Map Generation and Interpretation*

The mapped horizons were used to generate both time-domain surface maps and depth-domain surface maps. The depth-domain surface maps were generated from the time-domain surface maps using the look-up function. The mapped horizons' time and depth structure maps highlight the closure and trap mechanism for the interpreted reservoirs. These depth surface maps reveal the present leads, prospects, and other petroleum system elements.

Surface maps were generated to represent the subsurface features in time and depth domains. Time-domain surface maps were initially created from the seismic data, showing subsurface features based on seismic two-way travel time. These maps offered a preliminary view of the geological structures and helped in understanding the general layout of the formations.

To get a more precise representation, depth-domain surface maps were derived from the time-domain maps. This conversion used a look-up function to translate seismic time data into true vertical depth, considering the velocity of seismic waves through different rock types.

The time and depth structure maps provided a detailed view of the subsurface, highlighting key features:

Closure Mechanisms: These maps show how geological formations close off or trap hydrocarbons, revealing structural features like anticlines and fault blocks that can hold hydrocarbon accumulations.

Trap Mechanisms: The maps also illustrate structural or stratigraphic features that create conditions favourable for hydrocarbon accumulation.

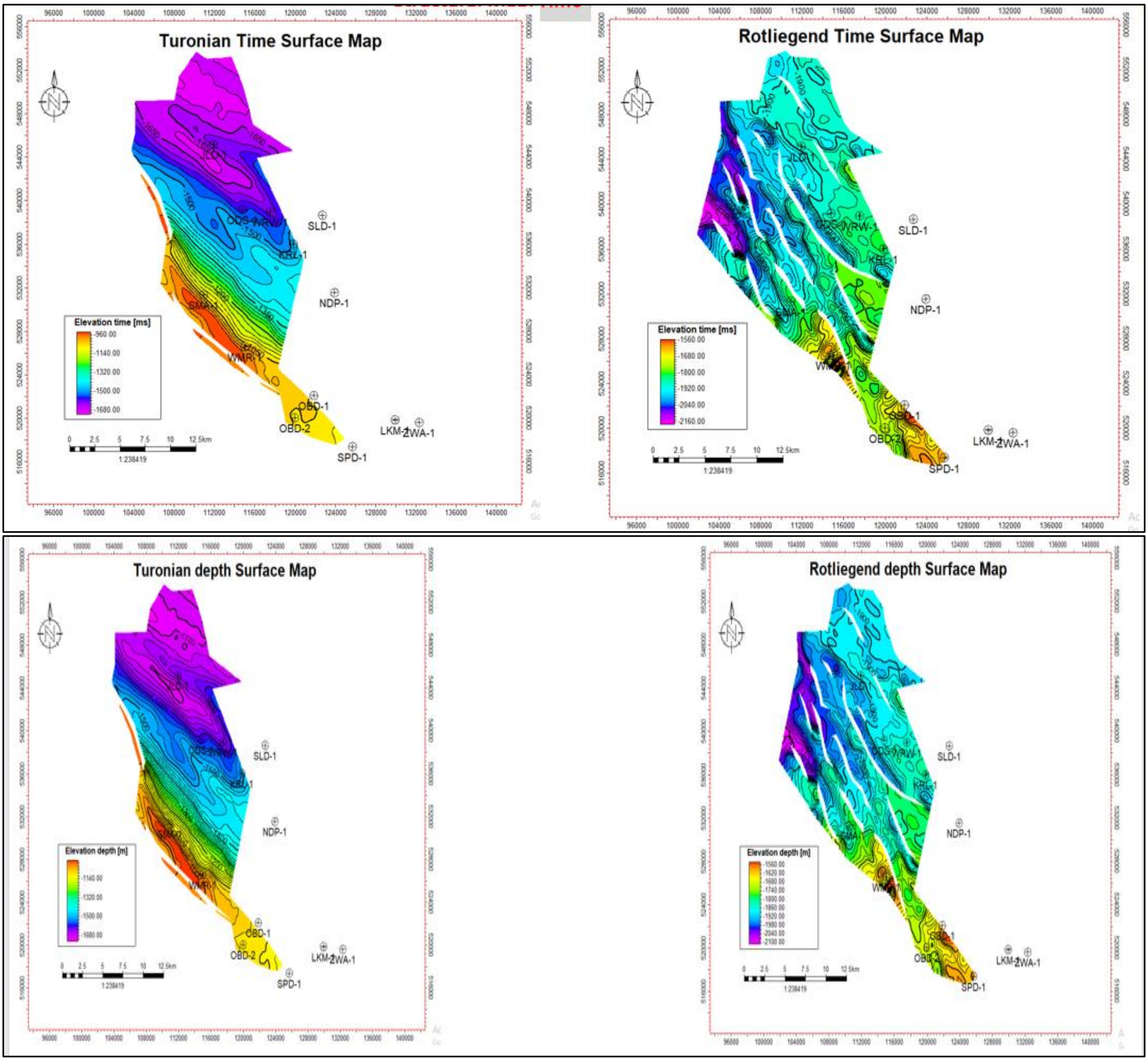

Fig 11 Time and Depth Surface Maps Generated for the Turonian Formation and Rotliegend Formation

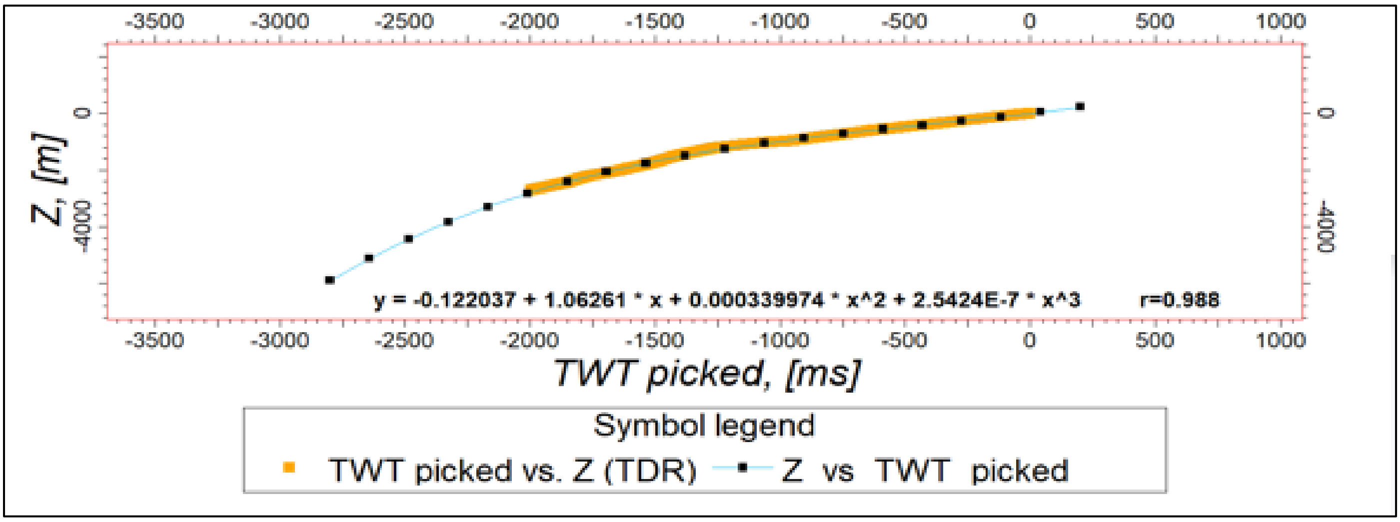

Fig 12 Time-Depth Relationship Generated from the Checkshot Formation and Rotliegend Formation.

One lead with no prospect was identified in the Turonian Formation, while four prospects with no lead were identified in the Rotliegend Formation.

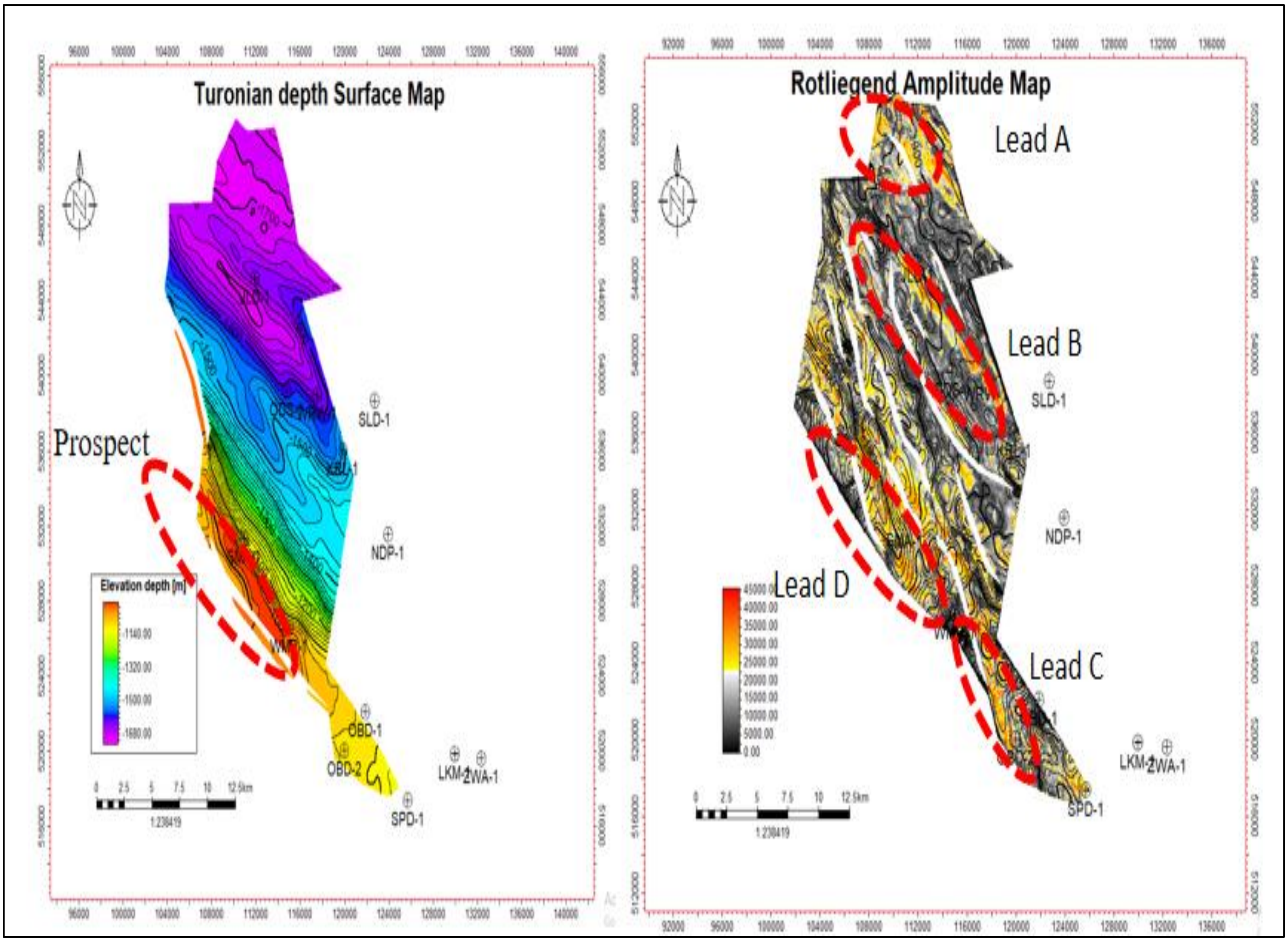

Fig 13 Prospect and Leads Identified in the Turonian and Rotliegend Formations, Respectively.

From the petroleum play fairway analysis of the Barremian and Carboniferous plays, two source rocks (Carboniferous coal and Barremian shale), two reservoir rocks (Rotliegend sandstone and Turonian carbonates) and two seal rocks (Zechstein evaporites and the upper Cretaceous unconformity) were discovered. The migration occurred laterally up-dip through faults and secondary migration pathways.

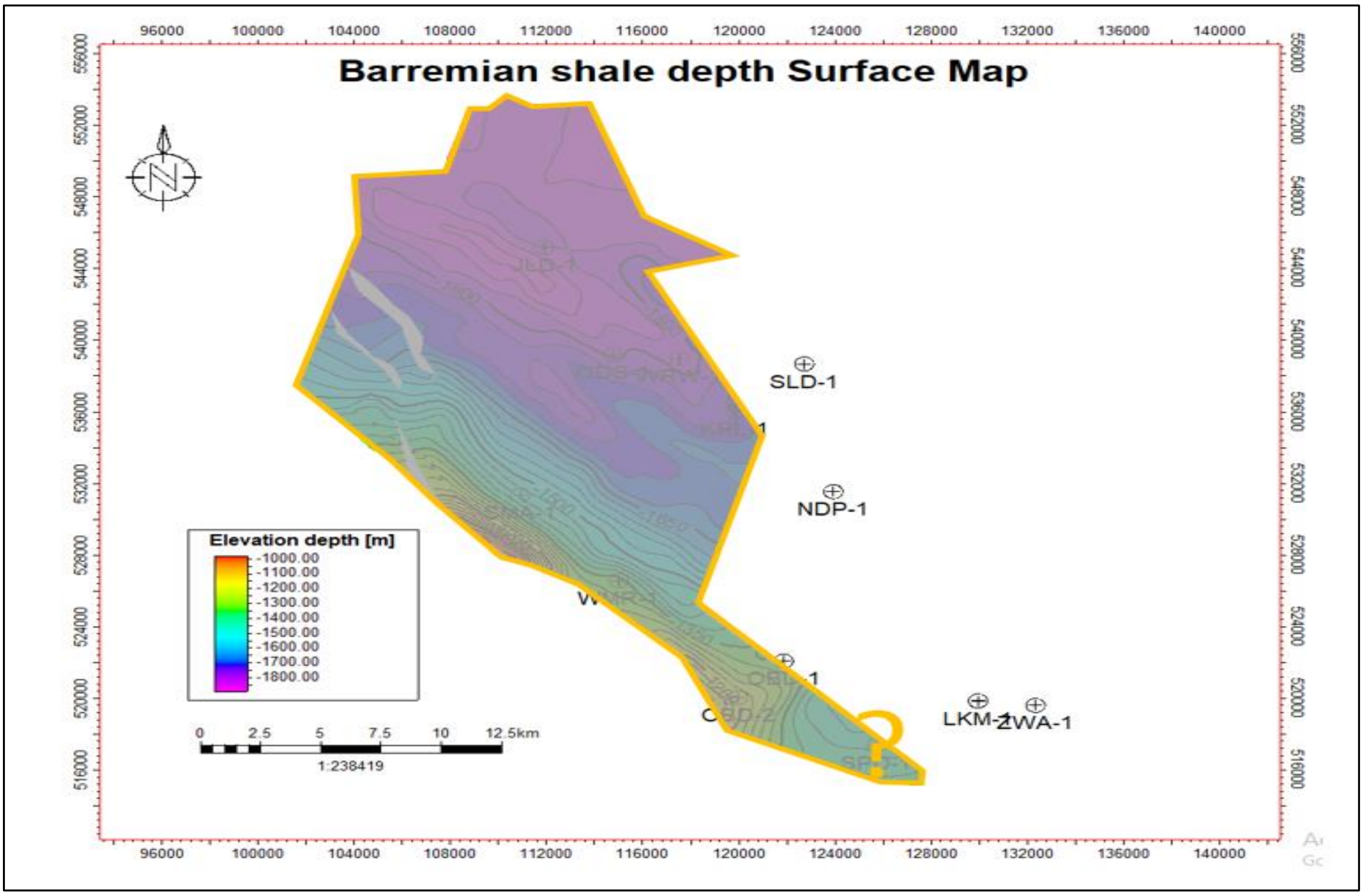

Fig 14a Laterally Extensive Barremian Source Rock.

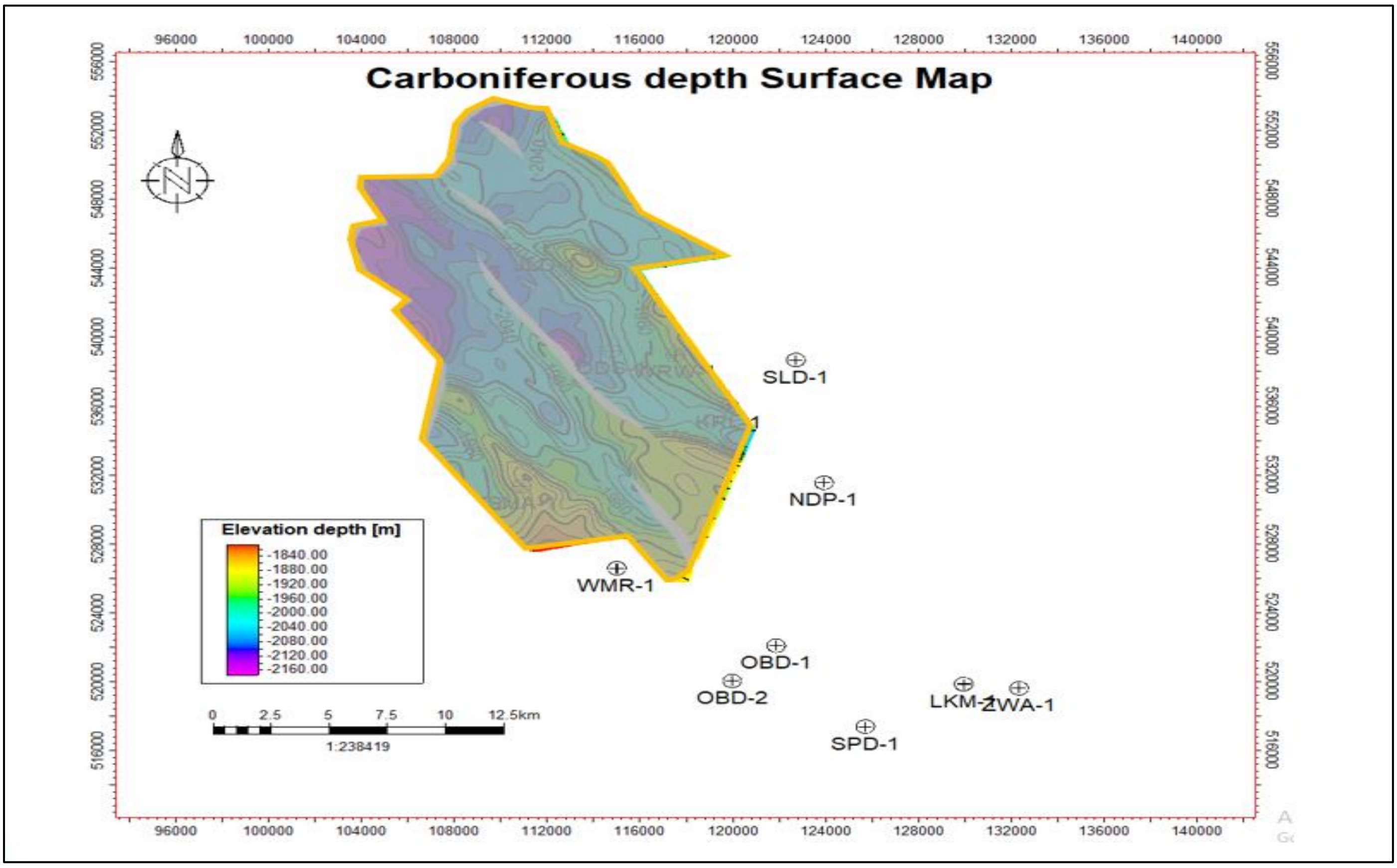

Fig 14b Laterally Extensive Carboniferous Source Rock.

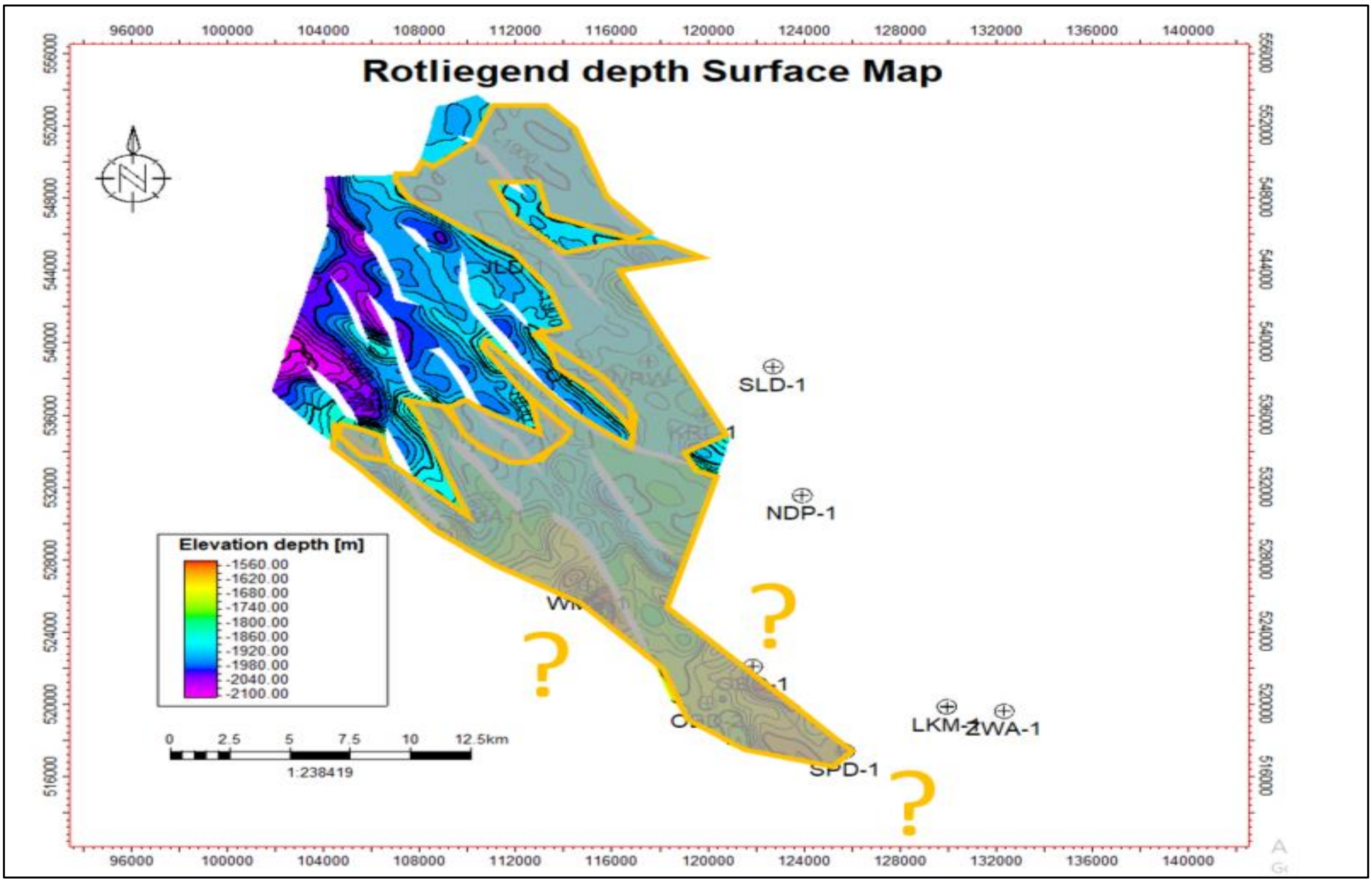

Fig 15a Extensive Rotliegend Sandstone Reservoir from the Carboniferous Play

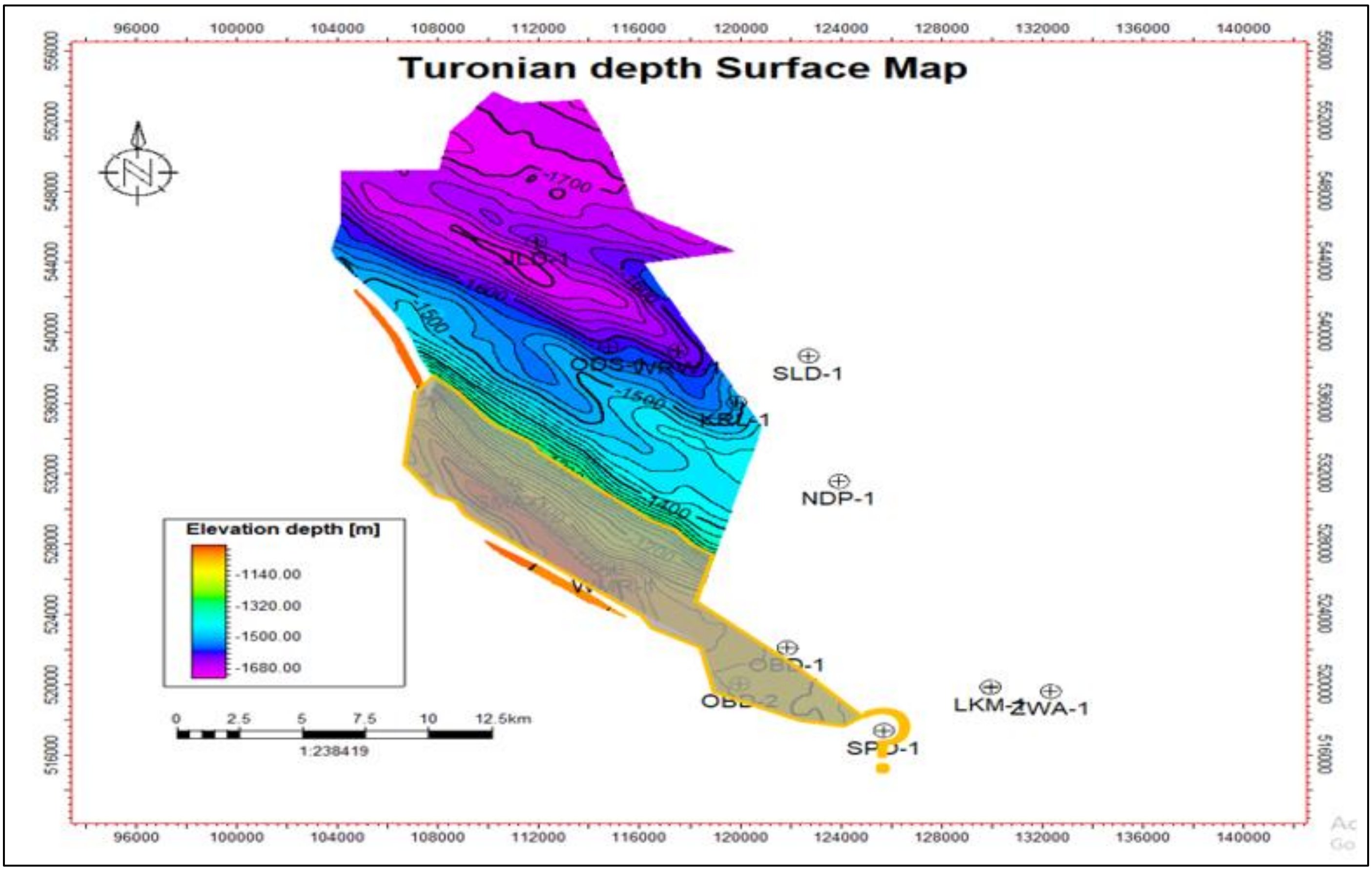

Fig 15b Extensive Silty Limestone Chalk Turonian Reservoir from the Barremian Play

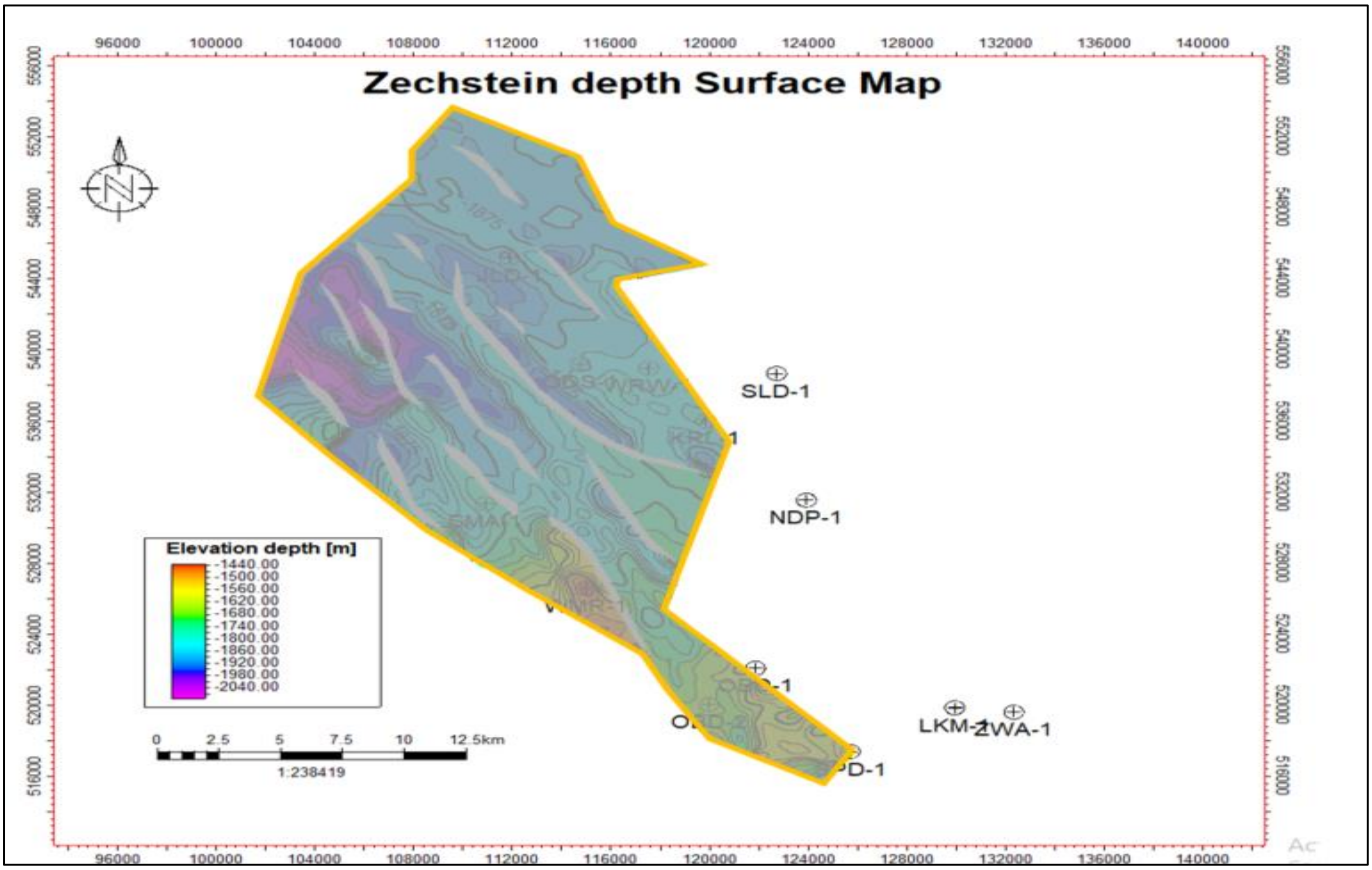

Fig 16a Extensive seal of the Zechstein Group from the Carboniferous Play.

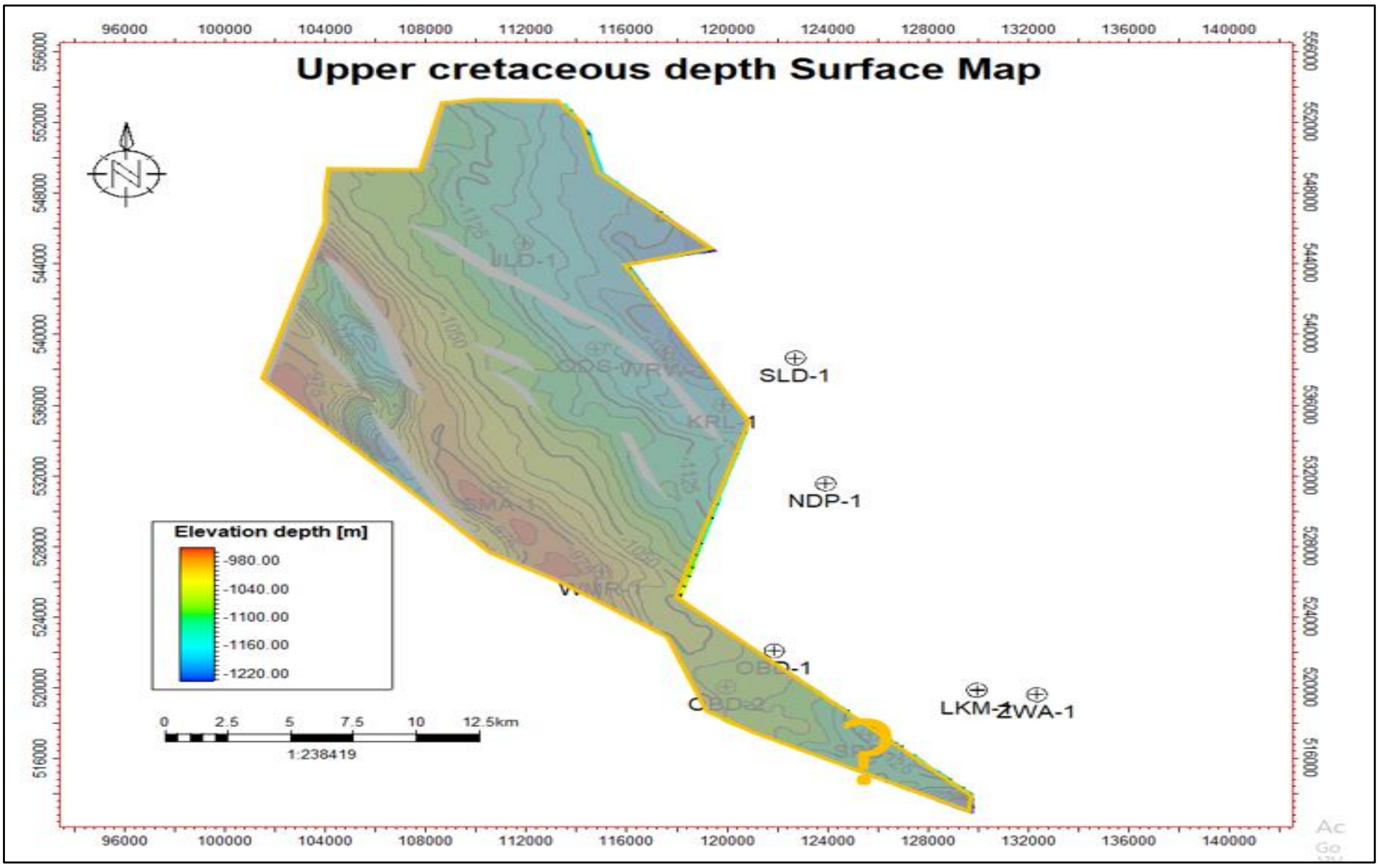

Fig 16b Extensive Seal of the Upper Cretaceous Conformity from the Barremian Play

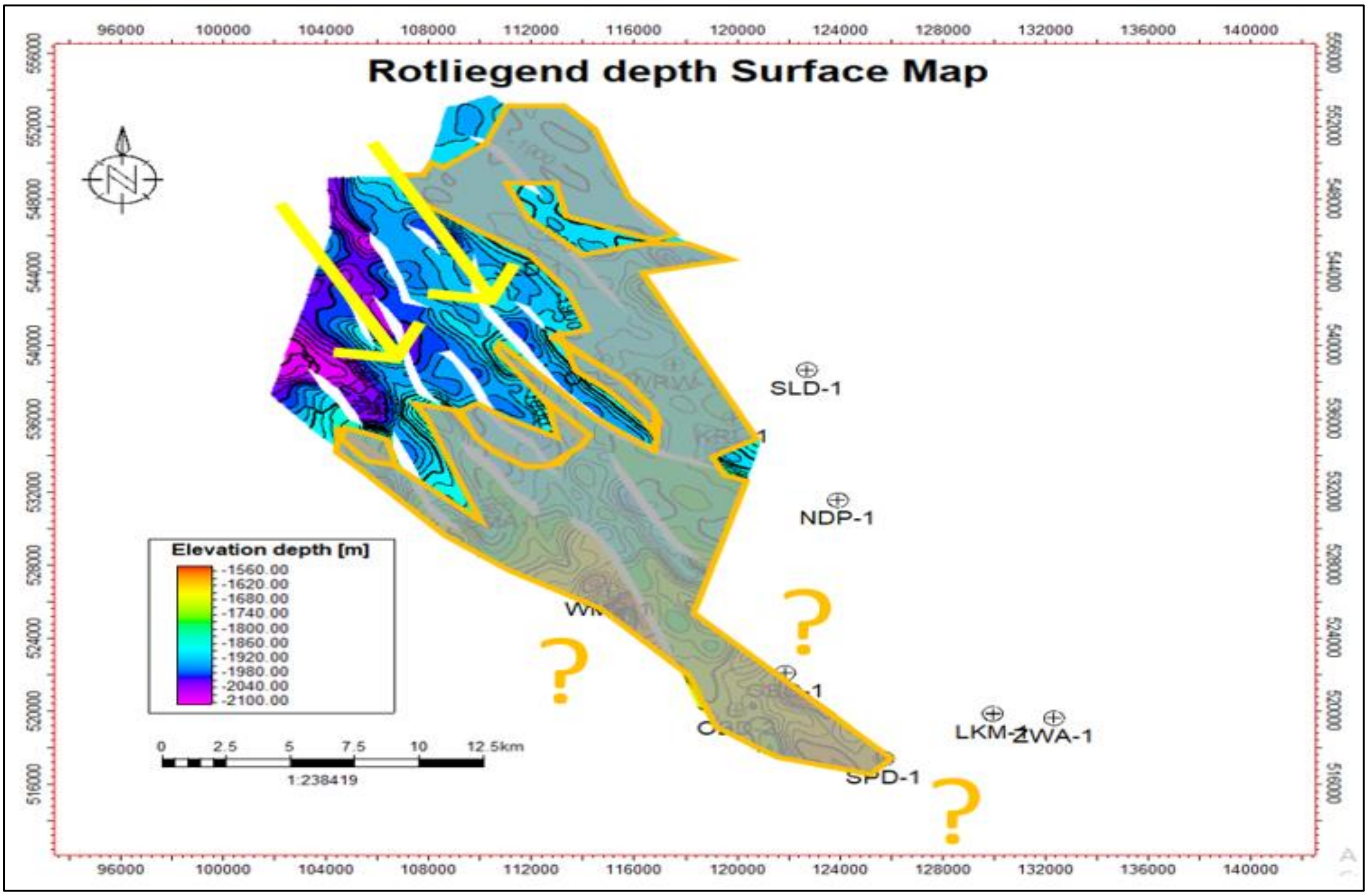

Fig 16c Extensive Seal of the Rotliegend Depth Surface Map

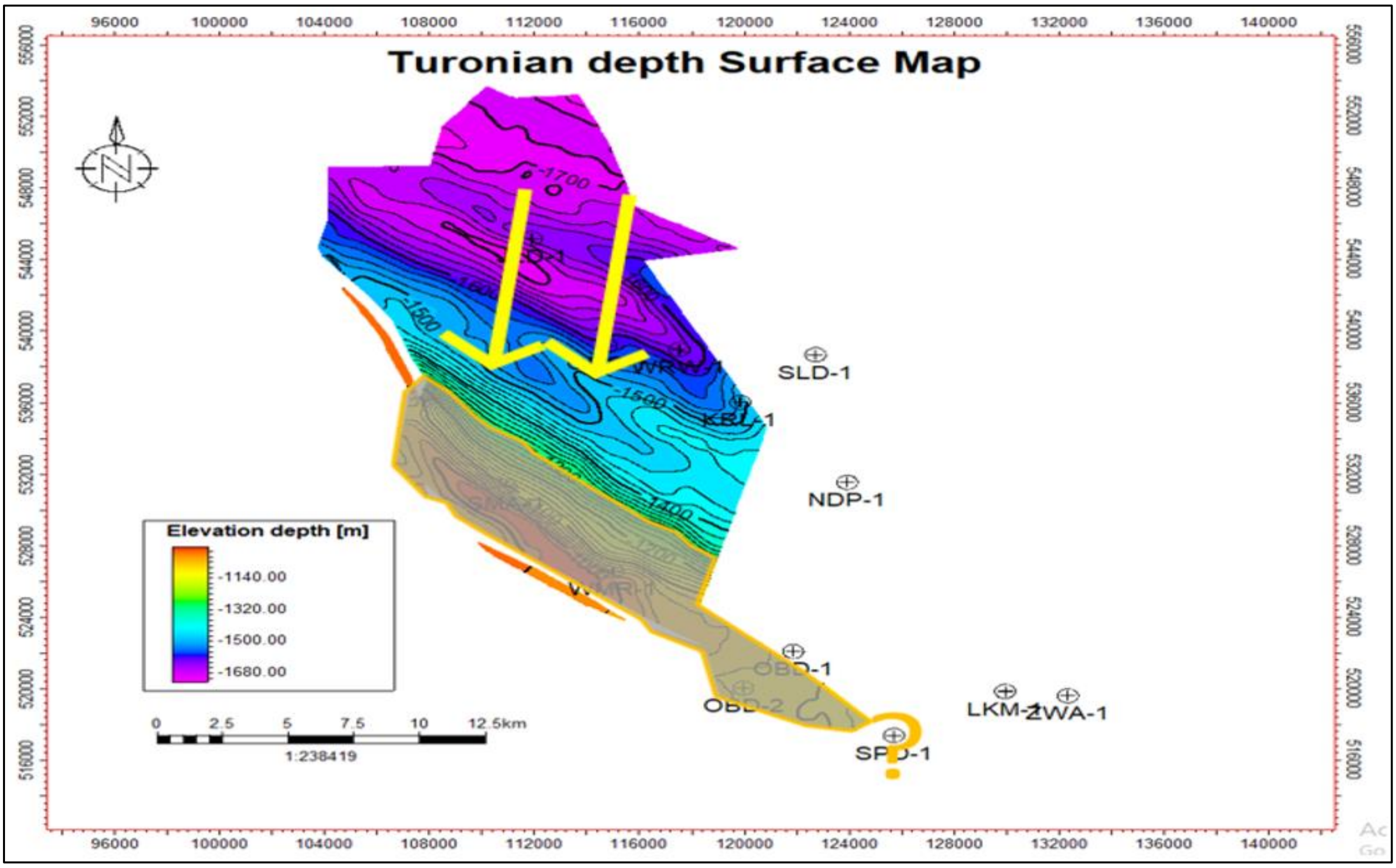

Fig 17 Up-Dip Lateral Migration Along Carrier Beds in both Barremian and Carboniferous Plays.

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- *Petrophysical Assessment of Reservoirs*

A petrophysical assessment was done for the two reservoirs, namely NAU Turonian Reservoir and NAU Rotliegend Reservoir. Poor porosity was noted in the NAU Turonian Reservoir. The reason for the poor porosity was tied to its lithology- the siltiness. The NAU Rotliegend Reservoir was made up of marine sandstone of the Rotliegend group.

- *NAU Turonian Reservoir*

The NAU Turonian Reservoir showed poor porosity, which indicates its limited capacity to store hydrocarbons. Low porosity suggests that the reservoir may not hold significant oil or gas. This poor porosity is due to the reservoir's silt-rich lithology. Silt-sized particles are smaller and more tightly packed than sand grains, reducing pore space and limiting the reservoir's ability to store and transmit hydrocarbons effectively.

- *NAU Rotliegend Reservoir*

In contrast, the NAU Rotliegend Reservoir is characterised by its marine sandstone composition. Sandstones generally have better porosity and permeability than siltstones due to their coarser grain size and well-developed pore spaces. Marine sandstones, which form from sand deposited in marine environments, typically offer good hydrocarbon storage and flow conditions. This suggests that the Rotliegend Reservoir is more promising for hydrocarbon production due to its likely higher porosity and permeability.

A petrophysical assessment was done for the two reservoirs, namely NAU Turonian Reservoir and NAU Rotliegend Reservoir. Poor porosity was noted in the NAU Turonian Reservoir. The reason for the poor porosity was tied to its lithology- the siltiness. The NAU Rotliegend Reservoir was made up of marine sandstone of the Rotliegend group.

Wells	Reservoir Parameters	Unit = m	HC Type
WRW-1	**NAU Turonian Reservoir**		GAS
	Gross Gas Thickness	358.169	
	Net Gas Thickness	358.02	
	N/G	1	
	Porosity	8.9%	
	SWT	0.6	
	Hydrocarbon Saturation	0.4	
	NAU Rotliegend Reservoir		
	Gross Gas Thickness	250.059	
	Net Gas Thickness	232.41	
	N/G	0.929	
	Porosity	16%	
	SWT	0.7	
	Hydrocarbon Saturation	0.3	

Fig 18 Petrophysical Analysis.

Reserve estimation was carried out on the identified prospect, taking into account the risks and uncertainties, which were expressed as P90 (low estimate), P50 (best estimate) and P10 (high estimate). The volumetrics evaluation for prospect yielded 14BSCF, 68BSCF, and 74BSCF for P90, P50 and P10, respectively.

Reservoir (Turonian)	P90	P50	P10
GRV (Acre)	3500	4168.02	4668.63
Net/Gross	0.60	0.80	1.00
Porosity (%)	6.0	7.2	8.9
Hydrocarbon Saturation	0.30	0.35	0.4
Formation Volume Factor	0.007	0.025	0.035
GIIP (BSCF)	**14**	**68**	**74**

Fig 19 Reserve Estimation of the Identified Prospect.

V. CONCLUSION

The research has effectively combined geophysical, geological, and petrophysical data to analyse the Southern Permian Basin comprehensively. This integration has pinpointed significant plays and prospects, clarified the structural framework, and revealed the petrophysical characteristics of the area, offering valuable insights for future exploration. Although the NAU Turonian Reservoir poses challenges due to its low porosity, the NAU Rotliegend Reservoir shows considerable promise with its favourable properties. These findings highlight the need for ongoing exploration and data integration to enhance hydrocarbon discovery and extraction in this complex and promising basin.

This study lays a strong foundation for further exploration and development, indicating potential hydrocarbon resources and providing a clear direction for future investigative and drilling efforts in the Southern Permian Basin.

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