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STUDY OF THE PETROPHYSICAL CHARACTERISTICS OF ROCKS FROM THE LIBWA FIELD IN THE PINDA RESERVOIR IN THE D.R. CONGO COASTAL BASIN

André Yelembangu Ngwey [1*]
Jean Iyolo Lungembo [1]
Dona Kampata Mbwelele [1,2]
Gustave Ngalamulume Bantu [1,4]
Néhémie Bikayi Tshiani [1, 3, 5]
Rachidi Opuluku [1]

[1] Exploration-Production Department, Faculty of Oil, Gas and Renewable Energies, University of Kinshasa, D.R. Congo
[2] General Inspectorate of Mines, D.R. Congo
[3] Petroleum Engineering Department, Polytechnic Institute of Advanced Sciences of Sfax, Tunisia
[4] DRC Ministry of Hydrocarbons
[5] Congolese Control Office, D.R. Congo
* email (corresponding author): andre.yelembangu@unikin.ac.cd

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ABSTRACT

The Libwa field, located offshore the Democratic Republic of Congo (DRC), has significant potential for hydrocarbon exploitation, particularly in the southern part, which remains unexploited. Previous studies have identified various hydrocarbon exploitation opportunities in place, as measured by the volumes of oil in place (STOIIP). However, recent analysis by Perenco DRC highlights the need for additional volumes to meet current production levels in the northern part of the field. The Pinda reservoir, which forms an essential part of the Libwa field, has a porosity of between 15% and 19%. However, it has a very low permeability, averaging less than 2 millidarcies (mD). This low permeability makes it difficult to accurately assess porosity using seismic data, due to minor variations in the geological structure. Ongoing research is aimed at gaining a better understanding of the geological structure of the Libwa field and determining whether additional volumes of hydrocarbons exist in the southern part or in other areas of the field. Understanding the petrophysical characteristics is crucial to optimizing extraction strategies and assessing the economic potential of the reservoir.

Keywords: Libwa field, reservoir engineering, reservoir interval, porosity, permeability.

INTRODUCTION

The Libwa oil field, located around 7 km off the coast of the Democratic Republic of Congo, was discovered in 1981 and began producing in 1990. Although the field covers an area of around 18 km² and contains a significant volumes of gas and oil, cumulative

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production is only 13 million barrels, or around 3% of the oil originally in place (OOIP) [1]. This low recovery efficiency is due to the heterogeneity of the reservoir and the lack of exploitation of the southern part of the field. This study aims to assess the potential of the unexplored southern part of the Libwa field using a prospective modeling approach based on rock physics and seismic data. The aim is to predict the expected seismic response as a function of reservoir quality and contained fluids, in order to inform the decision whether or not to exploit this part of the field [1,2].

The Libwa field reservoir is composed of platform carbonates of the Upper Albian Pinda formation. The trap is a rotated block fault, sealed by shales of the overlying Kinkasi formation. Field development has focused on the northern end, with 13 wells, including 4 verticals, 7 horizontals and 2 multilaterals. However, the two southernmost vertical wells, Libwa 2 and Libwa 5, have proven to have low permeability and are producing at low rates. [3]. The study involved a new seismic interpretation and depth conversion of the Libwa field. Data-driven rock physics calculations were used to predict the expected seismic response as a function of reservoir quality and fluids contained in the unexplored southern part. The results of the seismic inversion produced non-unique porosity and permeability models, making it difficult to assess reservoir quality in the southern part. However, forward modeling based on rock physics provides valuable information on the expected seismic response, helping to inform the decision on whether or not to exploit this part of the field [3,4].

The study focuses on assessing the petrophysical characteristics of rocks in the Libwa oilfield, particularly in the unexplored southern part of the Pinda reservoir, located in the coastal basin of the Democratic Republic of Congo (DRC). It aims to:

- Analysing reservoir quality: Use seismic data and models based on rock physics to assess the porosity and permeability of geological formations.
- Exploring untapped potential: Identifying exploitation opportunities in the southern part of the field, which has not yet been developed due to the heterogeneity of the reservoir and the low production rates observed to date.

The study addresses several significant gaps in our understanding and exploitation of the Libwa field:

- Low recovery efficiency: With cumulative production of only 13 million barrels, the study seeks to understand the reasons behind this poor performance, including reservoir heterogeneity and the limitations of existing wells.
- Limited exploration: The southern part of the field has not been sufficiently explored, representing a potential untapped opportunity. The study aims to fill this gap by providing data on reservoir quality in this area.

The originality of this study lies in several innovative aspects:

- Integrated approach: The joint use of forward modelling based on rock physics and in-depth seismic interpretation represents a step forward compared with traditional methods, which often focus on a single aspect.
- Focus on an unexplored area: By concentrating on the southern part of the Libwa field, this study sheds light on a hitherto neglected region, offering significant potential for future discoveries.

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Broadly speaking, this study aims to provide a rigorous scientific assessment that could transform the current approach to oil exploitation in the Libwa field, while contributing to a better geological and petrophysical understanding.

METHODS AND MATERIALS

Our research integrates the proprietary data from PERENCO-REP, followed with the available published studies. GIS based, ArcGis 10, Grapher 8 and WEX software were used to concatenate a comprehensive data base for our study. The coastal basin of the Democratic Republic of Congo is located in the province of Central Congo, precisely in the city of Muanda, and extends between 12°00' and 12°45' East longitude and 5°30' and 6°00' South latitude. It is 42 km wide and covers an area of 5,992 km². It is approximately 600 km from the city of Kinshasa. Figure 1 below shows the location of the field studied.

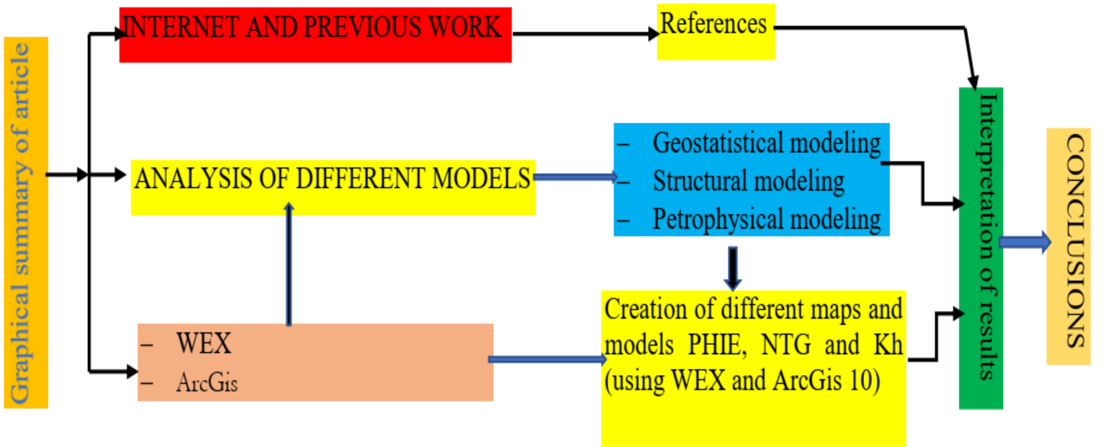

Figure 1*. Graphic synthesis of our study*

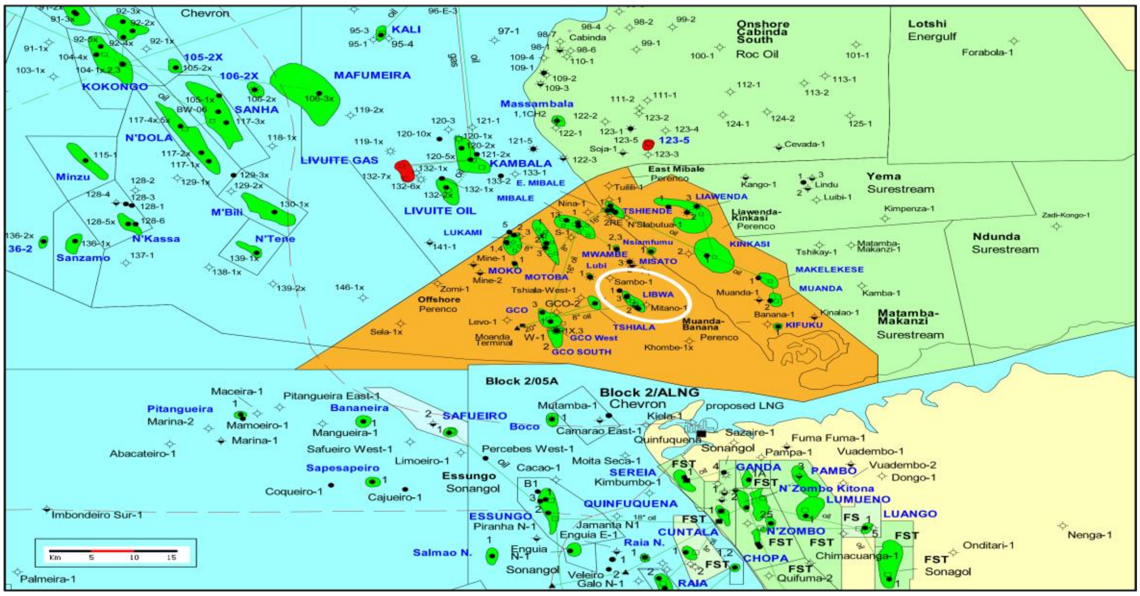

Figure 2*. Localization of the Libwa field.*

GEOLOGICAL AND STRATIGRAPHIC STRUCTURE OF THE FIELD

The Libwa field was formed in response to a growth deficit in the southeast of the country. The structure is an anticline of faulted blocks plunging northwest-southeast. The faults delineating the Libwa field from Aptian to Albian section formed in response to movement of the underlying salt. They extend upwards into the Lower Kinkasi, and are thought to extend downwards into the underlying Loeme salt layer. [5]

The Libwa Upper Pinda is characterized as a carbonate reservoir with about 240 feet of oil column and 310 feet of gas cap. This reservoir consists of very tight reservoir formation that can be subdivided into eight distinct facies recognized from the core data and are named from top to bottom: Transitional Layer (TL), Shelf (S), Skeletal Grainstone Complex (SGC), Skeletal Grainstone (SGF), Ooid Grainstone Complex (OGC), Lagoonal (L), Lagoonal Grainflat (LGF) and Dolomitic Sandstone (DS). Packstones and very fine- to medium-grained grainstones are the dominant rock type, Wackestone is subordinate. The overall depositional environment was probably a shallow carbonate plateau adjacent to a clastic-dominated shoreline. Fine-grained quartz is present in some facies. [8,9]

All facies have very similar petrophysical characteristics due to diagenetic overprinting phenomena that destroyed the original calcareous textures. Calcite ubiquitous; spar cement has filled much of the intergranular space and isolated much of the mole porosity, producing a consistently narrow range of pore throat radii from 0.3 to 0.9 m in all facies. Mouldy, uneven intergranular porosity is the dominant pore type and provides adequate reservoir pore volume of between 15% and 19%. Nevertheless, test data, baseline data and production performance all indicate low reservoir permeability, ranging from 0.1 to 12 millidarcies and averaging less than 2 millidarcies. The reservoir is currently considered unfractured [10].

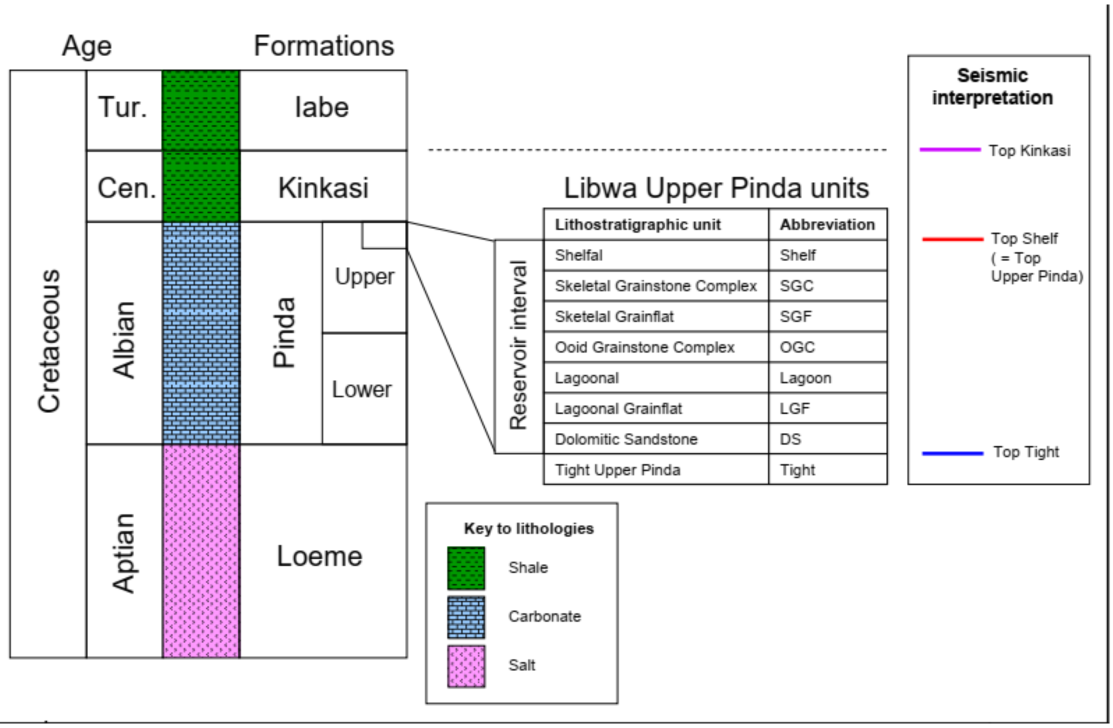

Figure 3. *Stratigraphic column of the upper Pinda reservoir in the Libwa field*

Previous work on the Libwa Upper Pinda reservoir shows that the field has interesting geological features. It consists mainly of a thick section of limestone underlain by a layer of dolomite, formed in a shallow marine platform environment. The reservoir has an estimated original oil in place (OOIP) of 408 million barrels (MMstb), contained in an oil rim measuring 265 feet under a gas cap of 310 feet, equivalent to 154 billion standard cubic feet (Bscf).

GEOLOGICAL FEATURES

- Stratification: The reservoir is vertically stratified, with great lateral continuity.
- Limestone zone UP1-7: This zone is tight with a permeability of around 1 millidarcy (mD).
- Dolomitic layer UP8: This layer, although unmeasured, has a permeability greater than 10 mD and acts as a relief zone.

These geological properties suggest significant potential for oil extraction, while also highlighting the importance of interactions between the different layers of the reservoir for the management of oil resources in this region. The field was discovered in 1981 and put in production in January 1990. The first development steps were focused on the northern and central part of the accumulation:

- 1st phase in 1990: vertical wells LIB-01X (800 bopd with UP8 dolomitic layer) and LIB-03 (200 bopd in limestone) and first horizontal well LIB-04 (800 bopd),
- 2nd phase in 1993-1994: horizontal wells LIB-07 (1000 bopd), LIB-06 and LIB-03R side track (500 bopd),
- 3rd phase in 2000-2001: dual lateral horizontal wells LIB-08 and LIB-09ST (~ 1800 bopd)
- 4th phase in 2003: horizontal wells LIB-10 and LIB-04ST side track (700 bopd), LIB-11(250 bopd with high water cut). [8,28,29]

PETROPHYSICAL CHARACTERISTICS OF THE UPPER PINDA RESERVOIR IN THE LIBWA FIELD

Core samples were taken from the LIB-03 and LIB-05 vertical wells covering: UP1 to UP7 in LIB-03, and UP1 to UP5 in LIB-05

Thus, only the limestone lithofacies was covered by this coring. The dolomitic UP8 aquifer in these two wells was not sampled, nor was the permeability of the voleuse layer matrix measured. The plugs were sampled at regular 1-foot spacing where possible (315 samples in LIB-03, 266 in LIB-05) and conventional core analysis carried out. The resulting porosity-permeability cloud is shown in the Figure 4, along with some limestone core data from other RDC fields:

- ✓ The Libwa limestone formation is tight with an average permeability of 1 to 2 mD
- ✓ The limestone porosity-permeability trend is relatively consistent across all DRC fields [6,7].

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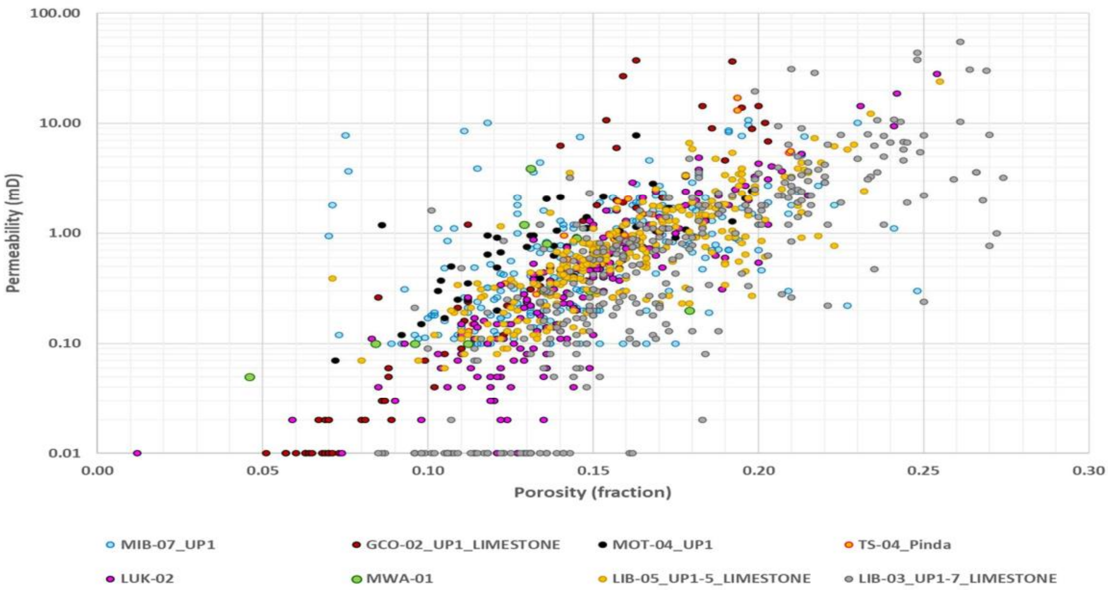

Figure 4*. Basic Libwa porosity-permeability data compared with other limestone data of DRC field.*

GEOSTATISTICAL MODELING

The Libwa static reservoir model was built using structural interpretation and conversion of reservoir interval top and base depth maps generated from seismic interpretation and physics of the most recent Libwa rocks. The generated CPIs were used as input data for the petrophysical models. Table 1 lists the input data used to generate the model. [11]

Table 1*. Input data*

Data type	Input
Wells	Lib-1X, Lib-2, Lib-3, Lib-3RD, Lib-4, Lib-5, Lib-6, Lib-7, Lib-8, Lib-8LT1, Lib-8LT2, Lib-9, Lib-9LT1, Lib-9LT2, Lib-10 and Lib-11
Logs	GR, DT, Resistivity, NPHIE, RHOB, Vsh and PHIE
Maps	Top Shelf and Top Libwa Tight structure maps
Faults	Upper Pinda fault polygons

STRUCTURAL MODELING

Fault modeling

Fault polygons converted to depth for Upper Pinda were imported into Petrel. Faults were modeled (Figure 5) using 3-point geometry to obtain a geometry suitable for capturing the listric nature of many faults [12].

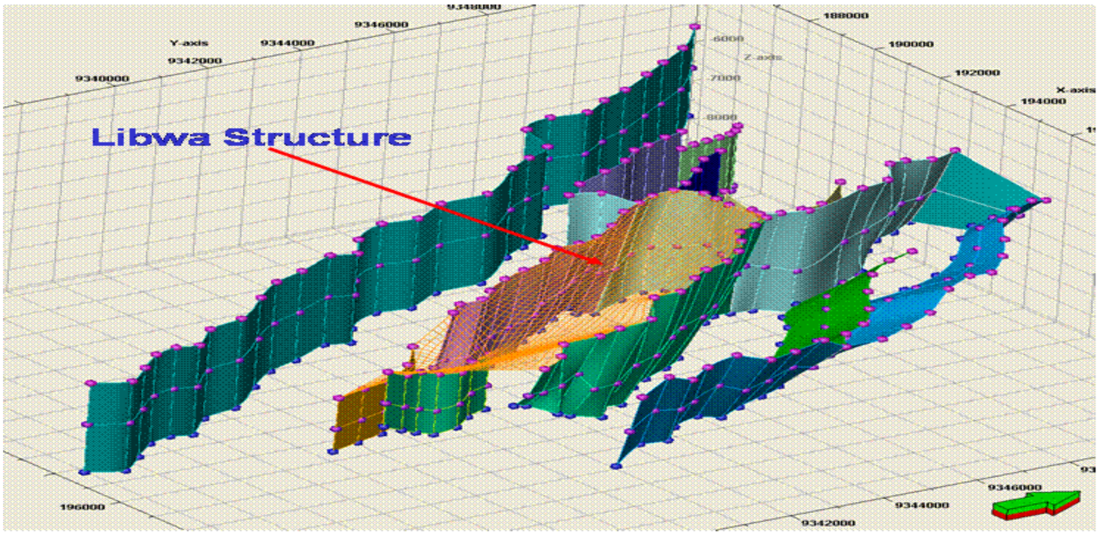

Figure 5. *Regional fault model based on new fault polygons converted to depth.*

3D Static grid modeling

Figure 6 shows the regional 3D static modeling grid generated with Petrel (In x Jn = 90 x 147). The Libwa segment of the 3D grid was calculated using the local interactive method; grid cells: 100 x 100 ft and cell size (nI x nJ x nK) for modeling: 25 x 101 x 33, giving an average of 83,325 3D cells [13].

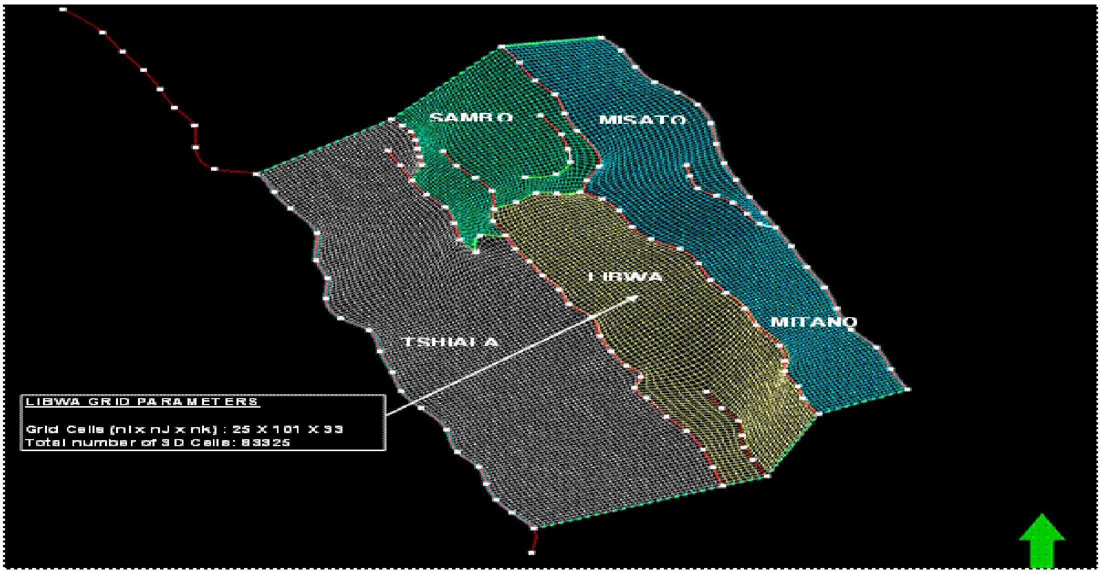

Figure 6. *Regional grid from the new conversion of the interpreted structural depth map*

Zones and overlay

The eight lithofacies recognized in the core correspond to eight zones named from top to bottom: UP-1, UP-2, UP-3, UP-4, UP-5, UP-6, UP-7 and UP-8. A total of 59 layers were defined, mainly using a stratigraphic sequence based on cored formations. As the Upper Pinda reservoir section is almost entirely limestone, many layers were defined and correlated using rather subtle variations in wireline logging characteristics. [14] The main logs used were the GR, DT, Resistivity, NPHI and RHOB curves, which can reflect variations in the clay content of the limestone. The layers are subdivided as follows: UP-1 (TL): 1-4 layers; UP-2 (S): 5-11 layers; UP-3 (SGC): 12-19 layers; UP-4 (SGF): 20-24 layers; UP-5 (OGC): 25-37 layers; UP-6 (L): 38-39 layers; UP-7 (LGF): 40-50 layers; UP-8 (DS): 51-59 layers [15, 29].

FACIES MODELLING

Core descriptions and sedimentological analyses have established a clear link between reservoir properties, porosity and permeability, and facies (geological studies). A prediction of facies distribution in the undrilled zone was attempted to support the result of petrophysical modelling based on logging data. The database is not good enough to model porosity and permeability from facies.

The facies model was built using the four main rocks identified from cores and lithologists. Facies logs were created for cored wells and scaled into the model. Sequential Gaussian simulation was used to inform the facies (Figure 7). A Gaussian variogram with an azimuth of 160 was used for all facies. The facies range of 8000 by 5000 m with a nugget of 0.01 was filled in. In order to obtain a truly geological approach, the facies model was somewhat manually corrected [16, 28].

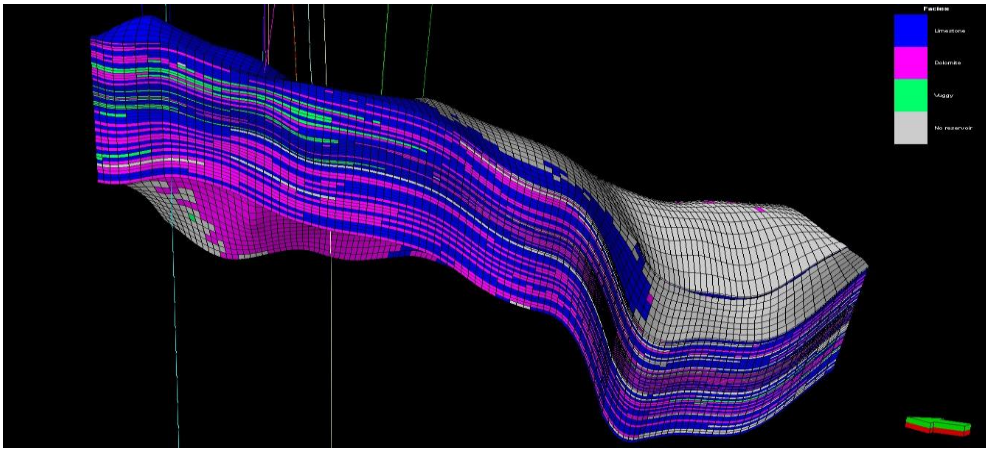

***Figure 7**. Libwa facies model*

PETROPHYSICAL MODELING

PHIE, NTG and core permeability logs were imported into Petrel, scaled using the arithmetic mean method and distributed using the Kriging methodology. Variograms were used to give anisotropy to the distributions in line with regional sedimentation. Due to the very low variation in reservoir quality, sequential Gaussian simulation was also used to capture property heterogeneities [17,18,19]. A Gaussian variogram with an azimuth of 160 was used for all properties. The range of 800 by 320 m with a nugget of 0.01 was used. The PHIE model was used as a trend for the NTG model and as a cokriging for the permeability model. The final model (P50) of PHIE, NTG and Kh is an arithmetic mean of 30 realizations. Quality control data for PHIE and NTG are shown in Table 2 and Table 3.

Table 2. *Porosity data*

Statistics for PHIE (U)			
Name	Min	Max	Mean
Property	0.02	0.30	0.15
Upsaled	0.02	0.30	0.15
Well logs	0	0.35	0.16
Statistics for PHIE 10 (U)			
Name	Min	Max	Mean
Property	0.10	0.30	0.16
Upsaled	0.10	0.30	0.16
Wells logs	0.10	0.35	0.17
Statistics for PHIE 12 (U)			
Name	Min	Max	Mean
Property	0.12	0.30	0.17
Upsaled	0.12	0.30	0.17
Wells logs	0.12	0.35	0.18
Statistics for PHIE 15 (U)			
Name	Min	Max	Mean
Property	0.15	0.30	0.17
Upsaled	0.15	0.30	0.17
Wells logs	0.15	0.35	0.18

Table 3*. NTG data*

Statistics for NTG 10 (U)			
Name	Min	Max	Mean
Property	0	1	0.85
Upsaled	0	1	0.85
Wells logs	0	1	0.87
Statistics for NTG 12 (U)			
Name	Min	Max	Mean
Property	0	1	0.77
Upsaled	0	1	0.77
Wells logs	0	1	0.80
Statistics for NTG 15 (U)			
Name	Min	Max	Mean
Property	0	1	0.57
Upsaled	0	1	0.57
Wells logs	0	1	0.62

WATER SATURATION MODELLING

Examination of the well logging data has led to the introduction of a Sw vs. Depth and Sw vs. PHIE relationship. The saturation points come from the logs of all the wells and are the average water saturations for the zone. They are color-coded according to the porosity ranges indicated. The height above free water level (HAFWL) and connected water saturation (Swc) of Sw vs. depth and Sw vs. PHIE respectively were modeled using the following assumptions:

- ✓ If $\Phi < 0.12\%$, Swc = 0.3
- ✓ If $\Phi > 0.20\%$, Swc = 0.05 [26, 27]

The water saturation model was calculated as a function of depth and Swc according to the following assumptions:

- ✓ If h >= 300, Sw = Swc
- ✓ If h <= 2, Sw = 1

VOLUMETRICS

Volumetric estimates for Libwa Upper Pinda are presented in Table 4 below. STOIIP was estimated on the basis of the PHIE12, NTG12 and Sw models. A Bg of 0.005269 and a Bo of 1.31 are fully consistent with reservoir conditions based on the Libwa Upper Pinda study. The GOC and OWC were set at -5400 ft and -5665 ft respectively.

Table 4. *STOIIP estimation.*

Zone	Bulk volume $^*10^6$ m^3	Net volume $^*10^6$ m^3	Pore volume $^*10^6$ m^3	HCPV Oil $^*10^6$ m^3	HCPV Gas $^*10^6$ m^3	HCPV Total $^*10^6$ m^3	STOIIP (in oil) MMstb	GIIP (in gas) Bcf
UP1	134	5.7	0.7	0.2	0.3	1	1	2
UP2	353	174.4	29.8	17	5.1	22	86	34
UP3	295	285.3	54.5	31.1	11.5	43	158	77
UP4	91	87.6	16.9	9.9	3	13	50	20
UP5	208	200.9	35.1	19.8	4.6	24	101	31
UP6	37	31.7	4.9	2.4	0.6	3	12	4
UP7	147	109.7	16.7	10.5	0.6	11	53	4
UP8	57	24.7	4.1	2.3	0	2	12	0
TOTAL	**1322**	**920**	**163**	**93**	**26**	**119**	**473.6**	**173**
Limestone	779	583.2	104	60.4	16.3	77	307	209
Dolomite	389	250.6	44.1	25.9	5.2	31	132	35
Vuggy	79	64	11	5	3.9	9	25	26
Reservoir	75	22.3	3.5	1.9	0.3	2	10	2

The main STOIIP is located in UP-3 (33%), UP-5 (21%) and UP-2 (18%). The STOIIP of UP-3 and UP-5 represents 54% of the total field. The limestone facies contain 65% of total STOIIP in the Libwa reservoir; 28% of STOIIP is concentrated in dolomite, while vacuolarian represents 5% of STOIIP. Using the arithmetic mean of 30 model PHIE and

NTG realizations, a probable STOIIP (P50) of 65 MMSTB was estimated in the undeveloped southern zone. [20,21,22]. P90 and P10 were calculated based on the assumption of a fixed NTG in the southern zone, so a minimum (0.15) and maximum (0.75) well NTG were used. Based on the NTG and STOIIP of P50, the estimated P10 and P90 were calculated as follows:

- ✓ P10: (65 / NTG (P50)) *0.75 = 84 MMSTB,
- ✓ P90: (65 / NTG (P50)) *0.15 = 17 MMSTB [30].

Development of the Libwa field from 1990 to October 2008 resulted in a production of 13 MMSTB oil, representing around 3% of the EEP. The heterogeneous nature of the reservoir and the undeveloped part of the field contribute to relatively low recovery yields. The Libwa field has the potential to deliver a significant volume of oil, which will have both short- and long-term impacts on the concession. A significant volume of oil exists in the southern zone where good HPV trends are mapped in UP-2, UP-3, UP-4 and UP-5. [23,24,25].

CONCLUSIONS

The study aims to assess the development potential of the southern Libwa areas by building a 3D geological model. This model aims to predict porosity and permeability distributions, parameters that are essential for understanding the capacity of a reservoir to contain and transmit fluids. The analysis identified four main types of lithofacies: limestone, dolomite and vacuolar. These lithofacies significantly influence the petrophysical properties of the Upper Pinda reservoir. The results indicate that there is a volume of oil in the southern zone, particularly in the zones mapped UP-2, UP-3, UP-4 and UP-5, which show favourable trends in terms of high pressure volume (HPV). However, the heterogeneous nature of the reservoir, combined with the underdeveloped state of the field, contributes to relatively low recovery yields. Despite this, the Libwa field is considered promising for significant oil production. This could have a significant impact on the concession's short- and long-term results.

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