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تحليل شامل لحقل غاز مكثفات ليبي – تقدير كمية الغاز الأصلية في المكنن وتحديد آلية الدفع في المكنن

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Comprehensive Analysis of the Libyan LGC Field: OGIP Estimation and Reservoir Drive Mechanism Identification

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Abstract

Accurate estimation of the Original Gas in Place (OGIP) and understanding reservoir drive mechanisms are essential for efficient gas field development and management. This study investigates the Libyan LGC gas-condensate reservoir using two well-established techniques: the volumetric method and the material balance equation (MBE).

The dual-method approach integrates static geological parameters and dynamic production data to reduce uncertainty and improve reservoir modeling. Stewart's mixing rules were applied for known gas compositions, while Sutton's correlations were used when compositions were unknown.

The Volumetric Method estimated OGIP at 8128 Bscf (known) and 8259 Bscf (unknown), while the MBE method estimated it at 8172 Bscf...

The identification of the reservoir drive mechanism was based on the analysis of p/z versus cumulative gas production behavior. The observed deviation from linearity, without a pronounced upward curvature, indicates the presence of aquifer support that is moderate rather than dominant, which is characteristic of a moderate water-drive gas reservoir.

This study underscores the value of methodological integration for reliable reserve estimation and effective reservoir management, and supports better reservoir modeling and development planning.

Keywords: Original Gas in Place, Gas Condensate, Water Drive, Material Balance, Stewart Mixing Rules, Sutton Correlations.

الملخص:

يُعدّ التقدير الدقيق لكمية الغاز الأصلية الموجودة في المكن (OGIP) وفهم آليات دفع المكن أمراً بالغ الأهمية لتطوير وإدارة حقول الغاز بكفاءة. تتناول هذه الدراسة مكن الغاز المكثف في حقل LGC الليبي باستخدام طريقتان رئيسيتان: الطريقة الحجمية ومعادلة توازن المواد (MBE).

يُدمج النهج المزدوج المعايير الجيولوجية الثابتة وبيانات الإنتاج الديناميكية لتقليل عدم اليقين وتحسين نمذجة المكن. طُبقت قواعد ستوارت للخلط على تركيبات الغاز المعروفة، بينما استُخدمت معادلات ساتون عندما كانت التركيبات غير معروفة.

قُدّرت الطريقة الحجمية كمية الغاز الأصلية الموجودة في المكن بـ 8128 مليار قدم مكعب قياسي (معروفة) و8259 مليار قدم مكعب قياسي (غير معروفة)، بينما قُدّرتها طريقة معادلة توازن المواد بـ 8172 مليار قدم مكعب قياسي...

استند تحديد آلية دفع المكن إلى تحليل نسبة الضغط إلى الشحنة (p/z) مقابل سلوك إنتاج الغاز التراكمي. يشير الانحراف الملحوظ عن الخطية، دون وجود انحناء تصاعدي واضح، إلى وجود دعم من طبقة المياه الجوفية متوسطة وليس مهيمناً، وهو ما يميز خزانات الغاز ذات الدفع المائي المتوسط.

تؤكد هذه الدراسة على أهمية التكامل المنهجي لتقدير الاحتياطيات بدقة وإدارة الخزانات بكفاءة، وتدعم تحسين نمذجة الخزانات وتخطيط تطويرها.

الكلمات الدالة: الكميات الغازية الأصلية في المكن، غاز/مكثفات الغاز، دفع الماء للمكن، ميزان المواد، قواعد خلط ستوارت، ارتباطات ساتون

1 Introduction

Natural gas reservoirs play a pivotal role in global energy systems due to their cleaner combustion characteristics and economic viability. Accurately estimating the Original Gas in Place (OGIP) is essential in evaluating reservoir capacity and planning optimal extraction strategies. This study focuses on the Libyan LGC field, a gas condensate reservoir, where two principal methods—the volumetric method and the material balance equation (MBE)—are applied to estimate OGIP. Identifying the reservoir drive mechanism is equally critical, as it affects production behavior and long-term recovery planning.

The goal of this research is to provide a comprehensive comparative analysis of these methods under varying assumptions of gas composition and to evaluate the degree of reservoir heterogeneity. Moreover, the study seeks to demonstrate the integration of gas property correlations—Stewart's mixing rules and Sutton's correlations—in OGIP estimation. These insights contribute to more robust reservoir models and enhanced decision-making in petroleum engineering.

Recent studies have demonstrated the importance of addressing gas–water two-phase flow conditions when analyzing production data, as ignoring moving water flow can bias reserve estimates. Research between 2023 and 2025 developed practical methods for selecting the optimal watershed model and using Monte-Carlo techniques to measure uncertainty.

Several studies have highlighted the strengths and limitations of different OGIP estimation techniques, particularly in reservoirs influenced by water drive. Peterson et al. (2011) and Taylor et al. (2013) demonstrated the reliability of material balance equations when adjusted for water influx. Zhang and Li (2015) refined these models to increase precision in gas-in-place estimation, while Havlena and Odeh (1963) established a straight-line approach that remains foundational in material balance analysis. More recent work by Kim et al. (2012) and Wang (2018) emphasized the need to incorporate accurate gas properties and water-drive dynamics for effective reserve prediction.

The results of Mohammed and Dmour (2023) also showed that using RMSE with Monte-Carlo is an effective tool for determining the most appropriate watershed model, such as Carter-Tracy or Hurst-Van Everdingen.”

This study builds upon these findings by applying both volumetric and MBE techniques to real field data from the LGC field and validating results through cross-method comparison.

Recent studies have emphasized the importance of integrating static and dynamic approaches for gas reserve estimation, particularly in water-drive reservoirs (Aliu et al., 2024; Shi et al., 2024; Yang et al., 2025). These studies highlight that neglecting aquifer behavior may lead to significant uncertainty in OGIP estimation.

2 Methodology

the methodology used to estimate the Original Gas in Place (OGIP) and determine the drive mechanism for the LGC gas condensate field in North Africa. The analysis is based on data collected from 31 wells and employs two widely recognized techniques: the volumetric method and the material balance method (P/z chart). These methods were applied to analyses geological and PVT data, core and pressure analysis data, and production history data. By using both methods, engineers can cross-check and validate their estimates, refining them as more data becomes available throughout the field's production life.

All parameters in the above equations were evaluated specifically for the LGC reservoir conditions.

In these calculations we assume that the retrograde condensation effect is minor at current field conditions; however, if the PVT data show significant condensation at pressure drop, the estimates will require modification using phase modeling or two-phase simulation in the future.

The study utilizes geological, PVT, production, and pressure data from the LGC field. In this study, we analyzed our data in two ways to evaluate the correlations reported in the literature. First, we used the known gas composition to validate existing correlations. Second, we treated the composition as unknown to compare the results with available correlations and assess their reliability.

This study did not consider the effect of relative permeability of water and gas due to the shortage of data available, which may affect the p/z analysis in the presence of actual water flow. The work of Yang et al. (2025) suggests the importance of including these effects in future studies.

Although relative permeability effects were highlighted as important in recent studies (Yang et al., 2025), this work focuses on OGIP estimation during early depletion stages where mobile water flow is limited. The inclusion of relative permeability effects is recommended for future studies involving advanced production forecasting.

The Volumetric Method involves estimating pore volume, gas formation volume factor (B_g), and compressibility factor (z) based on known and unknown gas compositions. Material Balance relies on historical production/pressure data and P/z vs. G_{pT} analysis. MATLAB was used for numerical evaluations using the Dranchuk-Abou-Kassem equation of state.

2.1 Volumetric Method:

The Volumetric OGIP estimation equation used in this study follows standard reservoir engineering formulations (McCain, 1990; Dake, 1994):

$$OGIP = \frac{7758 * A * h * \phi * (1 - S_{wi})}{B_{gi}} \quad \dots (1)$$

This method calculates OGIP from static geological parameters: porosity, thickness, area, initial water saturation, and gas formation volume factor (B_{gi}). It is suitable during early reservoir life and was applied using both known and unknown gas composition assumptions.

- *For known compositions,*

Stewart's mixing rules were used to determine gas properties, followed by z-factor estimation via the Dranchuk-Abou-Kassem equation of state.

- *For unknown compositions,*

Sutton's empirical correlations based on gas gravity were applied.

2.2 Material Balance Equation (MBE):

The material balance equation for gas reservoirs under water-drive was applied in p/z form:

$$\frac{p}{z} = \frac{\left(\frac{p_i}{z_i}\right) * \left(1 - \frac{G_p}{GIIP}\right)}{1 - \frac{1}{GIIP} * \left(\frac{P_i}{P_{sc}}\right) * \left(\frac{Z_{sc}}{Z_i}\right) * \left(\frac{T_{sc}}{T}\right) * (W_e - W_p * B_w)} \quad \dots (2)$$

This formulation follows the material balance approach for gas reservoirs with water influx (Havlena and Odeh, 1963; Dake, 1994).

This dynamic method uses the production and pressure history data to determine OGIP. It applies the p/z plot, where we can estimate the original gas in place (OGIP) and predict the dominant reservoir's drive mechanism from the plot's trend.

Havlena and Odeh (1963) expressed the material balance in terms of gas production, fluid expansion, and water influx as:

$$G_p B_g + W_p B_w = G(B_g - B_{gi}) + G B_{gi} * \frac{c_w S_{wi} + c_f}{(1 - S_{wi})} \Delta p + W_e B_w \quad \dots (3)$$

The material balance formulation follows the classical Havlena and Odeh straight-line approach for gas reservoirs with water influx (Havlena and Odeh, 1963; Dake, 1994). The calculated vapor equivalent (Veq), total produced gas (Gpt), average gas production (Gpa), gas-oil ratio (R), and water specific gravity (γ_w) were obtained from production and PVT data and are summarized for completeness.

3 Assumptions and Limitations

- Retrograde condensation effects were considered minimal at current field conditions
- Relative permeability effects were not included due to data limitations (acknowledged as important for future studies)
- Early depletion stages were analyzed where mobile water flow is limited

4 Data Collection

Tables 1 to 4 are illustrated the data obtained from 31 production wells in the LGC field, which include:

- ✓ Geological Data, and Core Analysis are shown in Table 1.
- ✓ PVT Data and Compositional data demonstrated in Tables 2 and 3.

- ✓ Production and Pressure History data found in Table 4.

This rich dataset allowed cross-validation of OGIP estimates under varying methodological assumptions.

- PVT Analysis.

Table 1: Core analysis and Geological data collected from LGC field.

Area (acre)	Avg Ø (%)	Avg K (md)	Avg h (ft)	Avg S _{wi} (%)
80123	11	250	130	9

- Core Analysis and Reservoir Data.

Table 2: PVT data Collected from LGC field.

P _i (psi)	T (°R)	API	P _d (psi)	γ _{c7+}	M _{c7+} (lb/lb-mole)	GOR (SCF/STB)
3102	703	65°	3100	0.797	123.1	15471

- Gas Composition From (LGF).

Table 3: Gas Composition Analysis Data Collected from LGC field.

Composition	L _i mol%	g _i mol%
N ₂	0	0.0038
CO ₂	0.01	0.034
H ₂ S	0	0
CH ₄	0.1219	0.8285
C ₂ H ₆	0.0673	0.0868
C ₃ H ₈	0.0988	0.301
i-C ₄ H ₁₀	0.0397	0.0044
n-C ₄ H ₁₀	0.1099	0.0073
i-C ₅ H ₁₂	0.071	0.0018
n-C ₅ H ₁₂	0.074	0.0014
Pseudo C ₆ H ₁₄	0.1021	0.0009
C ₇₊	0.3052	0.001

Table 4: *Pressure and production history Data.*

date	P(Psi)	G _P (M scf)	W _p (bbl/day)
Dec2005	2669	181280750	126390.0665
Dec2006	2547	336959530	632052.5255
Dec2007	2426	502825199.8	863046.5921
Dec2008	2313	676987173.5	1099302.592
Dec2009	2191	842488168.6	1326306.592
Dec2010	2072	1034423340	1581805.592
Dec2011	1946	1067061461	1603144.592
Dec2012	1824	1356129491	1836069.592
Dec2013	1703	1361276486	2004420.592
Dec2014	1579	1383566888	2216527.592
Dec2015	1457	1580950218	2458086.391
Dec2016	1335	1782072486	2677257.48
Dec2017	1209	1976521922	2908016.024
Dec2018	1086	2166179270	3097099.784
Dec2019	968	2378209986	3234861.8
Dec2020	946	2551557812	3438949.346
Dec2021	718	2710970134	3636738.63

5 Results and Discussion

All gas properties, z-factors, gas formation volume factors, and p/z relationships were calculated using MATLAB based on the Dranchuk–Abou-Kassem equation of state.

The alignment of results across methods confirms a homogeneous reservoir. Recombination and z-factor calculations showed consistency across both gas composition approaches. Gas properties were accurately derived through MATLAB-assisted correlation models.

The close agreement between OGIP values obtained using Stewart’s mixing rules and Sutton’s correlations confirms the consistency and reliability of the applied gas property correlations for the LGC gas-condensate reservoir.

5.1 Known composition.

Table 55: *pseudocritical properties for the reservoir gas.*

M _a lb/lb.mol	P _{pc} psi	γ _g	T _{pc} R
24.12	669	0.812	420

Table 6: Pseudoreduced properties and initial z_i factor and initial Gas FVF for the gas.

T_{pr}	P_{pr}	Z_i	B_{gi} (bbl/MMSCF)
1.67381	4.63677	0.84136	0.9952

5.2 Unknown composition.

Table 7: The vapor equivalent (V_{eq}), G_{pa} and γ_w .

V_{eq} (SCF/STB)	G_{pa} (MMSCF)	R (SCF/STB)	G_{pt} (MMSCF)	γ_w
2837.9	3343.01	37281	195079958	1.048

The hydrocarbon pseudocritical properties were calculated using Sutton's correlations, the results indicate that the hydrocarbon pseudocritical pressure (P_{pch}) is 615.5 psia, which is equal to the pseudocritical pressure (P_{pc}) because the non-hydrocarbons are below the allowable limits. Similarly, the pseudocritical temperature (T_{pch}) was estimated to be 454.2°F, which is the same as the pseudocritical temperature (T_{pc}) for the same reason mentioned above.

Table 8: The initial gas formation factor, the initial formation volume factor and the Original Gas In Place.

Z_i	B_{gi} (bbl/MMSCF)
0.86085	0.9794

5.3 Volumetric OGIP Estimates

By applying equation (1) the original gas in place was estimated for both cases of known and unknown gas composition as shown in the following table 9. The gas properties in case of Unknown gas composition were estimated based on Sutton's correlations.

Table 9: Original Gas In Place estimated by Volumetric Method

OGIP (Bscf)	
Known composition	Unknown composition
8126.8	8259.2

The reported OGIP values were obtained by substituting the calculated reservoir parameters into the volumetric equation and by extrapolating the p/z trend to zero cumulative production for the material balance analysis.

Figure 1 below illustrates the comparison between the two methods for both known and unknown compositions.

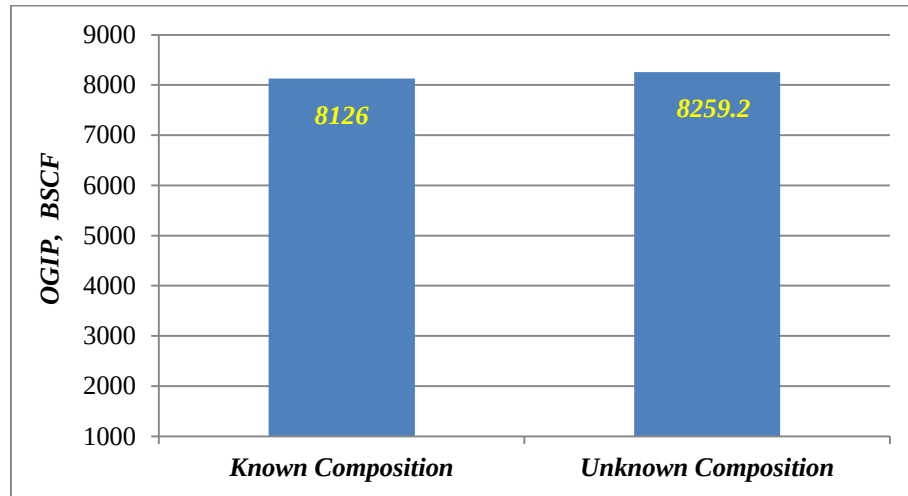


Figure 1: OGIP Calculated when the gas composition was known and unknown.

5.4 MBE OGIP Estimates

Based on p/z plot extrapolation shown in Figure 3 the OGIP for the Known composition can be estimated as 8195 Bscf, while in the case of Unknown composition (using Sutton's correlations), the OGIP was found to be 8172 Bscf.

For the predicting of the dominated reservoir Drive mechanism; the reservoir can be classified as moderate water drive, supported by material balance trend analysis when compared with figure 2 which shows the shapes of p/z plots for various drive mechanisms [2,4].

The Original Gas in Place (OGIP) for the LGC reservoir was estimated by extrapolating the curve in Figures 3 and 4 to its intersection with the x-axis when p/z = 0. Alternatively, OGIP was calculated using the following Equation, which represents the trend line of the data:

$$p/z = 2964.8e^{-6 \times 10^{-10} G_{pT}}$$

Rearranging the equation above

$$G = \ln \frac{p/z}{2964.8} \times \frac{1}{-6 \times 10^{-10}}$$

The results indicated that the OGIP is 8172 Bscf, at p/z = 22 psia which is very close to the OGIP calculated using the volumetric method which was 8126 Bscf. This suggests that the reservoir is a homogeneous formation.

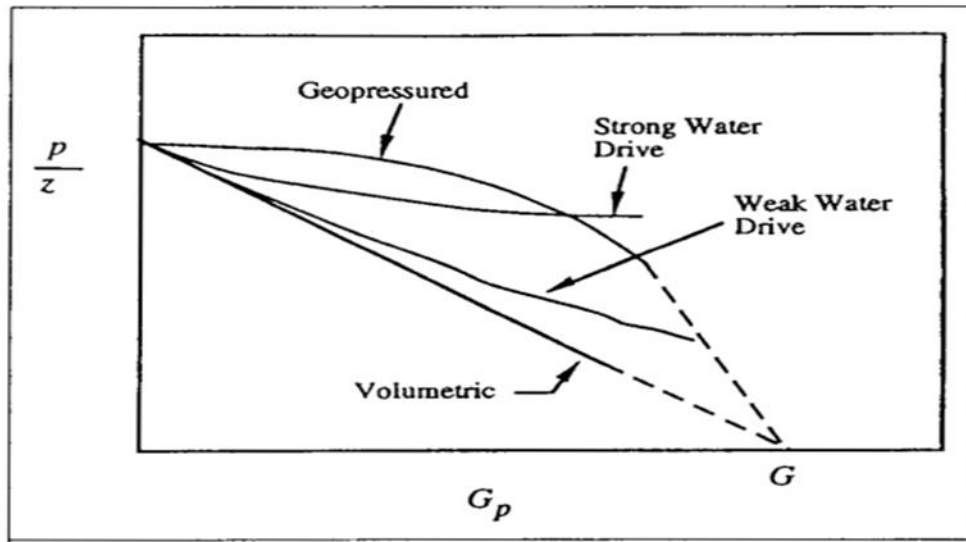


Figure 2: Shapes of p/z plots for various drive mechanisms (Source: Havlena and Odeh, 1963).[4].

Figures below illustrate P/z vs. G_{pT} trend lines for known and unknown compositions, confirming consistency and drive mechanism:

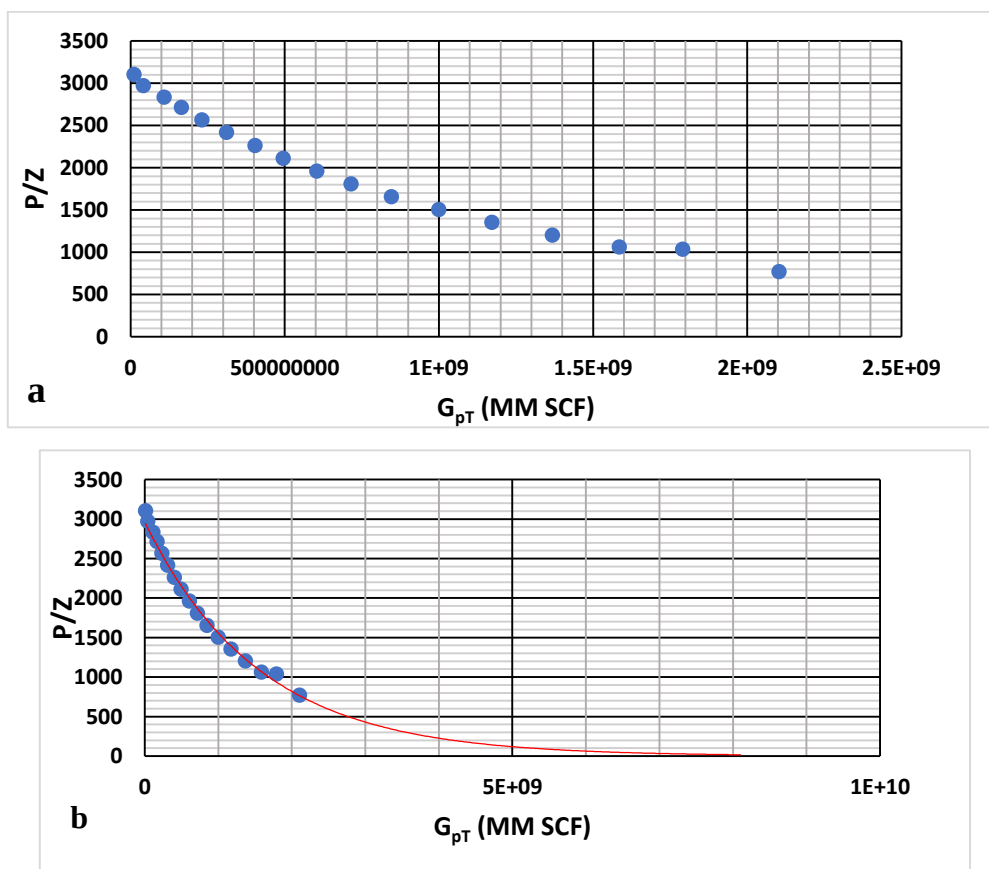


Figure 3: p/z plot for the LGC field.(known composition); a before extrapolation, and after extrapolation

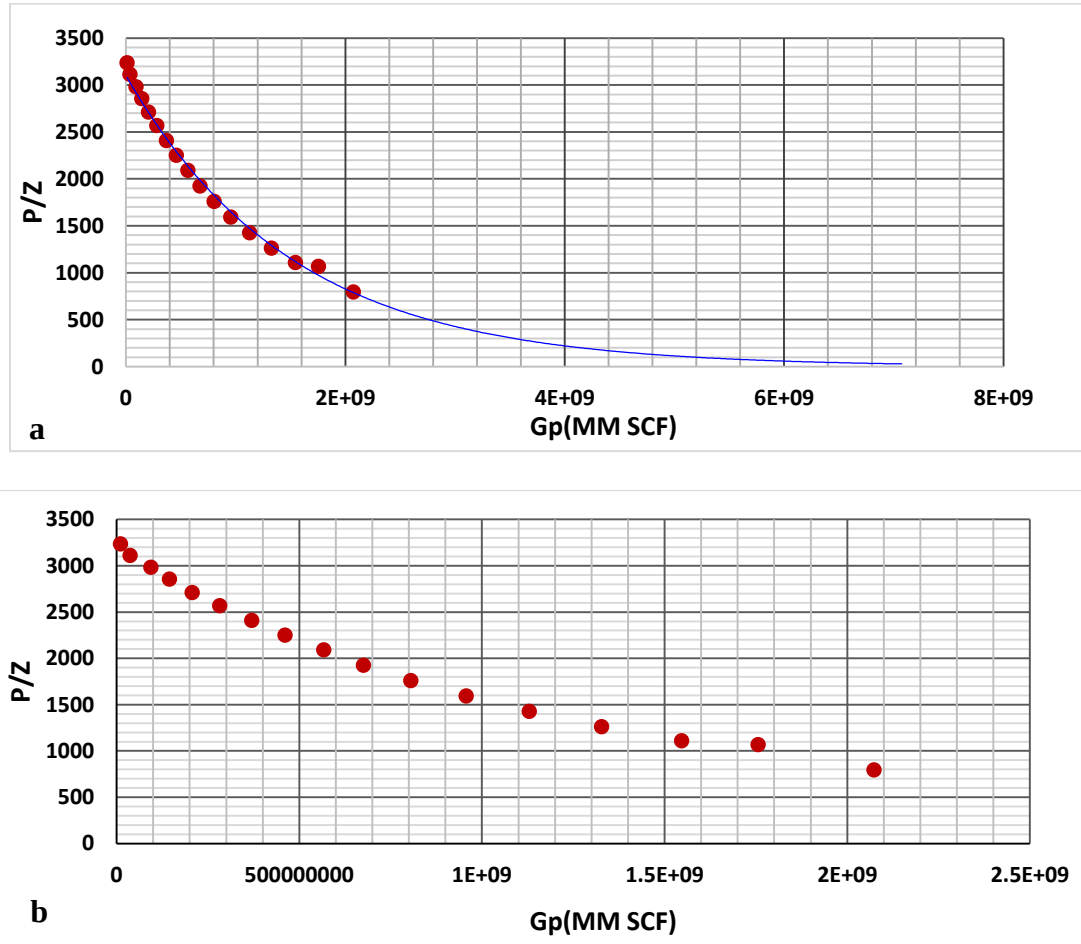


Figure 4: P/z Plot for LGC Field with (Unknown Gas Composition); a: before extrapolation, and b: after extrapolation

Due to the observed curvature caused by water influx, OGIP was estimated by extrapolating the early-time quasi-linear segment of the p/z plot, which represents reservoir behavior prior to significant aquifer influence.

A thorough p/z vs. G_p analysis identified a moderate water-drive mechanism. The close alignment between both static and dynamic methods confirms the reservoir's homogeneity.

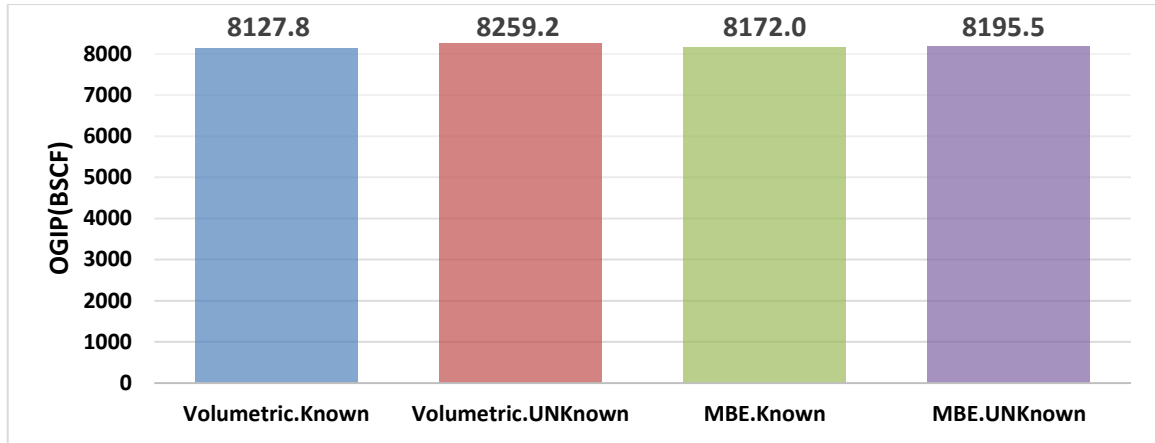


Figure 5: Comparison of OGIP Estimates Across Methods

5.5 Reservoir Characterization

The close agreement between volumetric and material balance estimates indicates that the LGC reservoir is laterally homogeneous and has not yet experienced strong aquifer dominance during the analyzed production period.

- Gas properties correlations (Stewart vs. Sutton) yielded consistent results, validating their applicability to Libyan gas condensate fields.

Table 10: z_i , z , B_g and P/z at different stages of the LGC reservoir depletion for known composition

Date	P (psi)	Z-factor	B_g (STB/MMscf)	P/Z
Dec2005	2669	0.859906857	1.137003707	3103.824534
Dec2006	2547	0.857606944	1.188278901	2969.891998
Dec2007	2426	0.856229917	1.245542766	2833.351127
Dec2008	2313	0.852085961	1.300070247	2714.514857
Dec2009	2191	0.854506685	1.376360275	2564.052497
Dec2010	2072	0.857276486	1.460125557	2416.95653
Dec2011	1946	0.860727523	1.560924498	2260.878091
Dec2012	1824	0.864639139	1.672896601	2109.550583
Dec2013	1703	0.869134522	1.801073328	1959.4205
Dec2014	1579	0.874424633	1.954336286	1805.758828
Dec2015	1457	0.880335713	2.132297564	1655.05043
Dec2016	1335	0.886975142	2.344710484	1505.115461
Dec2017	1209	0.894596297	2.61131845	1351.44758
Dec2018	1086	0.902781389	2.933673746	1202.949034
Dec2019	968	0.911298575	3.322342303	1062.220469

Dec2020	946	0.912951599	3.405772696	1036.19951
Dec2021	718	0.931331481	4.57761097	770.939257

Table 11: *Veq and GpT results.*

Date	T_{sep} °F	P_{sep} psi	API	R (SCF/STB)	G_p (MSCF)	V_{eq} (SCF/STB)	G_{pt} (MMSCF)
Dec2005	150	610	59	37282	181,280.750	2837.874638	19,510.799
Dec2006	152	612	57	33684	336,959.530	2679.129515	558,840.637
Dec2007	158	618	59	31532	502,825.2	2757.407199	110558.887
Dec2008	164	624	58	40164	676,987.174	2640.79976	192,709.235
Dec2009	164	624	57	42094	842,488.169	2556.085047	272,081.655
Dec2010	167	627	59	41793	1,034,423.34	2636.806956	382,060.342
Dec2011	168	628	58	42336	1,188,561.46	2637.354551	508,308.274
Dec2012	164	624	58	50633	1,356,129.49	2421.240278	650,400.339
Dec2013	156	616	59	40119	1,361,276.49	2335.714807	794,445.332
Dec2014	167	627	59	59135	1,383,566.89	2171.960253	937,889.829
Dec2015	162	622	58	51530	1,580,950.22	2056.401063	1,102,288.075
Dec2016	164	624	58	50444	1,782,072.49	1954.016218	1,287,411.089
Dec2017	154	614	58	74284	1,976,521.92	1656.582885	1,489,468.711
Dec2018	155	615	53	47183	2,166,179.27	1447.341583	1,712,735.712
Dec2019	149	609	51	88506	2,378,209.99	924.4843875	1,953,043.145
Dec2020	147	607	56	113663	2,55,1557.81	957.7113759	2,210,348.151
Dec2021	144	604	52	80075	2,710,970.13	882.4036039	2,484,433.114

Table 12: *zi, z and P/z results for unknown composition.*

Date	P(psi)	Z	Bg(STB/MMscf)	(P/Z)
Dec2005	2669	0.82459182	1.090308734	3236.75294
Dec2006	2547	0.81853661	1.134144009	3111.6507
Dec2007	2426	0.81377314	1.183781624	2981.17485
Dec2008	2313	0.81047277	1.236578912	2853.88985
Dec2009	2191	0.80812692	1.301656045	2711.20778
Dec2010	2072	0.80737854	1.37513866	2566.33029
Dec2011	1946	0.80825288	1.46576202	2407.66233
Dec2012	1824	0.81079578	1.568720919	2249.6417

Dec2013	1703	0.81507267	1.689043069	2089.38426
Dec2014	1579	0.82100082	1.834934224	1923.2624
Dec2015	1457	0.82855681	2.006881733	1758.47931
Dec2016	1335	0.83773642	2.214548393	1593.57999
Dec2017	1209	0.84828024	2.476122297	1425.23655
Dec2018	1086	0.86012763	2.795066324	1262.60331
Dec2019	968	0.87325108	3.183631673	1108.50135
Dec2020	946	0.88729861	3.310074045	1066.15742
Dec2021	718	0.9022365	4.434605501	795.800212

6 Conclusion.

This study demonstrates that a dual-method approach to OGIP estimation significantly enhances accuracy and reduces uncertainty. The consistency between volumetric and MBE methods affirms the homogeneous nature of the LGC reservoir. Identifying the water drive mechanism is crucial for production optimization. Utilizing both Stewart's and Sutton's models ensures flexibility and reliability in property estimation. If actual water flow occurs within the pores with the gas (not just stationary water) this may affect the production analysis and p/z derivation when exposed to water interference. Both Stewart's and Sutton's gas property estimation methods are suitable for North African gas fields. The insights gained from this work can guide future development strategies and support better reservoir management, and Reservoir Characterization.

- ✓ Strong agreement among all methods.
- ✓ Minimal deviation between the results obtained from both volumetric and MBE methods indicate reservoir homogeneity.
- ✓ Gas properties correlations (Stewart vs. Sutton) yielded consistent results, validating their applicability to Libyan gas condensate fields.

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