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Controls on Gas Storage and Pressure Preservation in a Deep Coalbed Methane Reservoir

Faktor Pengendali Penyimpanan Gas dan Preservasi Tekanan pada Reservoir Coalbed Methane Dalam

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Abstract

Understanding gas storage and pressure preservation is critical for evaluating deep coalbed methane (CBM) reservoirs. This study investigates the Patchawarra VC50 Deep Coal seam in the Cooper Basin, Australia, through an integrated analysis of gas desorption, methane sorption isotherms, formation pressure testing, and petrophysical characterization. Gas-content measurements indicate raw gas contents of 14.6–20.6 scf/g in coal-dominated intervals, while Langmuir volumes range from 421 to 491 scf/ton (DAF), reflecting strong methane storage capacity. Formation pressure data reveal the coexistence of pressure-preserved and depleted compartments within the Patchawarra Formation, suggesting the importance of reservoir connectivity and pressure compartmentalization. Geochemical analyses show high organic richness (TOC >80 wt%) and thermal maturity within the dry-gas window (mean Ro = 1.46%), whereas mineralogical data indicate contrasting coal- and shale-dominated lithologies. The results suggest that gas retention is influenced by the combined effects of organic richness, adsorption capacity, reservoir isolation, and seal characteristics. The study demonstrates the value of integrating pressure, sorption, geochemical, and mineralogical datasets for deep CBM reservoir evaluation and development planning.

Keywords: Coalbed Methane (CBM); Gas Storage; Formation Pressure; Reservoir Compartmentalization; Petrophysical Characterization

Abstrak

Pemahaman mengenai penyimpanan gas dan preservasi tekanan sangat penting dalam evaluasi reservoir coalbed methane (CBM) dalam. Penelitian ini mengkaji lapisan Patchawarra VC50 Deep Coal di Cekungan Cooper, Australia, melalui analisis terintegrasi desorpsi gas, isoterm sorpsi metana, pengujian tekanan formasi, dan karakterisasi petrofisika. Hasil pengukuran menunjukkan kandungan gas mentah sebesar 14,6–20,6 scf/g pada interval yang didominasi batubara, sedangkan nilai Langmuir volume berkisar antara 421–491 scf/ton (DAF), yang mencerminkan kapasitas penyimpanan metana yang tinggi. Data tekanan formasi menunjukkan keberadaan kompartemen yang mempertahankan tekanan dan kompartemen yang mengalami deplesi dalam Formasi Patchawarra, mengindikasikan pentingnya konektivitas reservoir dan kompartementalisasi tekanan. Analisis geokimia menunjukkan kekayaan organik yang tinggi (TOC >80 wt%) dan tingkat kematangan termal pada jendela gas kering (rata-rata Ro = 1,46%), sementara data mineralogi memperlihatkan perbedaan yang jelas antara litologi batubara dan serpih. Hasil penelitian menunjukkan bahwa retensi gas dipengaruhi oleh kombinasi kekayaan organik, kapasitas adsorpsi, isolasi reservoir, dan karakteristik seal. Studi ini menegaskan pentingnya integrasi data tekanan, sorpsi, geokimia, dan mineralogi dalam evaluasi serta perencanaan pengembangan reservoir CBM dalam.

Kata Kunci: Coalbed Methane (CBM); Penyimpanan Gas; Tekanan Formasi; Kompartementalisasi Reservoir; Karakterisasi Petrofisika



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INTRODUCTION

Global energy demand continues to drive exploration into unconventional gas resources, with coal seam gas (CBM) emerging as a critical component of the energy mix. Australia, now one of the world's largest LNG exporters, derives approximately 29 % of its LNG nameplate capacity from three east coast facilities supplied primarily by CBM. The Cooper Basin (northeastern South Australia and southwestern Queensland) is an upper Carboniferous Middle Triassic intracratonic basin that hosts Permian coal measures with significant deep CBM potential.¹ Over the past decade, industry trials in the basin have comprised more than 130 hydraulic fracture stimulation stages in vertical wells completed in deep Permian coals; while economic viability has been demonstrated, production rates exhibit considerable variability, suggesting that key controlling factors particularly pressure anomalies and their relationship to gas storage capacity remain inadequately characterized.

Deep CBM development presents unique technical challenges that distinguish it from shallower plays. As burial depth increases, temperature and pressure conditions elevate substantially, with methane entering the supercritical state. Fluid density increases while viscosity remains near gas-phase values, fundamentally altering gas storage and transport mechanisms.² In the Cooper Basin, optimum reservoir conditions for ultra-deep coals occur at depths beyond 9,000 ft (2,740 m), driven by dehydration, high gas content, gas oversaturation, overpressure, and a rigid host rock framework.³ However, current reservoir characterization workflows often fail to capture the complexity of deep coal systems. A particular knowledge gap exists in the integration of three critical parameters: desorption characteristics from canister testing, sorption behavior from high-pressure isotherms, and in-situ pressure anomalies measured during formation testing. This lack of integration leads to uncertainty in gas-in-place estimates and suboptimal fracture stimulation design.⁴

The phenomenon of “supercharging,” where measured formation pressures exceed expected hydrostatic gradients, has been documented in tight gas reservoirs and can significantly affect resource assessment.⁵ In CBM, overpressure can arise from continued gas generation in low-permeability coal after the coal has reached its adsorption capacity, combined with effective sealing by mineral cements. In the Cooper Basin, some deep Patchawarra coals are gas oversaturated and overpressured, as shown by formation pressure surveys that record pressures up to ~4,400 psi, well above the hydrostatic gradient.⁶

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- 1 Lisa Hall et al., “Cooper Basin Source Rock Geochemistry: Regional Hydrocarbon Prospectivity of the Cooper Basin, Part 2,” *Geoscience Australia Record* 2016/06 (Australia: Geoscience Australia, February 29, 2016), <https://doi.org/10.11636/Record.2016.006>.
 - 2 M. Chen, Y. C. Yortsos, and W. R. Rossen, “A Pore-Network Study of the Mechanisms of Foam Generation,” in *SPE Annual Technical Conference and Exhibition*, vol. 90939 (SPE, 2004), <https://doi.org/10.2118/90939-MS>.
 - 3 Erik C. Dunlop, “A New Concept for the Extraction of Gas from Permian Ultra-Deep Coal Seams of the Cooper Basin, Australia: Expanding Reservoir Boundary Theory,” *The APPEA Journal* 60, no. 1 (2020): 296–314, <https://doi.org/10.1071/aj19011>.
 - 4 Mingzhong Gao et al., “Evolutionary Pattern and a Calculation Method of in Situ Gas Pressure Based on Pressure-Retaining Coal Cores,” *Meitiandizhi Yu Kantan/Coal Geology and Exploration* 53, no. 4 (2025): 18–29, <https://doi.org/10.12363/issn.1001-1986.24.09.0613>.
 - 5 Martin K. Jensen and Malcolm A. Kelland, “A New Class of Hyperbranched Polymeric Scale Inhibitors,” *Journal of Petroleum Science and Engineering* 94–95 (September 2012): 66–72, <https://doi.org/10.1016/j.petrol.2012.06.025>.
 - 6 Hall et al., “Cooper Basin Source Rock Geochemistry: Regional Hydrocarbon Prospectivity of the Cooper Basin, Part 2.”

Recent advances in high-pressure sorption measurement under supercritical conditions have improved understanding of methane storage in deep coals. Optimised supercritical Langmuir (S-L-va) and supercritical Dubinin–Radushkevich (S-D-R) models have been shown to effectively characterise supercritical methane adsorption, with Langmuir volume (VL) correlating positively with vitrinite reflectance (Ro) and Langmuir pressure (PL) demonstrating an inverse relationship. Despite these advances, few studies have systematically integrated measured sorption parameters with pressure survey results and petrophysical data to diagnose supercharging and guide stimulation design.

Furthermore, the petrophysical and geochemical controls on supercharging remain poorly understood. Total organic carbon (TOC) content, thermal maturity indicators such as vitrinite reflectance (Ro), and mineral composition particularly the presence of quartz and siderite influence both gas generation potential and seal capacity.⁷ Hall and co-workers have comprehensively reviewed Cooper Basin source-rock geochemistry, documenting TOC, Rock-Eval pyrolysis, and vitrinite-reflectance data, but the integration of these data with pressure surveys to identify supercharging indicators has not been systematically attempted.

This study addresses these gaps by integrating three independent datasets from the Patchawarra VC50 coal seam in the Cooper Basin: (1) desorption measurements from ten core segments (9,155–9,212 ft) conducted according to Australian Standard AS 3980,⁸ (2) high-pressure methane adsorption isotherms performed at reservoir temperature (150°C) up to ~4,000 psi, and (3) formation pressure surveys from 24 FMT points across the Patchawarra interval, revealing both supercharged and depleted zones. The central hypothesis is that supercharging anomalies correlate with specific petrophysical characteristics (high quartz/siderite seal content and optimal thermal maturity) and that integrated characterization can reduce exploration risk in analogous deep CBM plays.

The objectives of this paper are therefore: (1) to present a comprehensive dataset of gas content, Langmuir parameters, and in-situ pressures for the Patchawarra VC50 coal; (2) to identify and characterise supercharging zones through pressure-survey analysis; (3) to evaluate the petrophysical controls on supercharging using TOC, vitrinite reflectance, and XRD mineral-composition data; and (4) to develop an integrated workflow for quantifying gas-in-place uncertainty and optimising fracture-stimulation design in deep CBM reservoirs.

Method

This study utilised core data obtained from Bobs Well 2, located within Petroleum Production Licence (PPL) 89, South Australia, targeting the VC50 Deep Coal seam of the Patchawarra Formation. The core was recovered from the 9,155–9,215 ft interval using conventional coring techniques, achieving a recovery rate of 98.5%, which indicates excellent sample quality for laboratory analysis.⁹ The recovered core was subsequently divided into several segments for gas-content determination and reservoir characterisation. Selected segments were used for gas desorption measurements, whereas the remaining samples were preserved for petrophysical and

7 Cunlei Li et al., “Occurrence and Transformation Mechanism of Deep Coalbed Methane in Medium and High Rank Coal under Temperature and Pressure Coupling Control,” *Fuel* 404 (January 2026): 136188, <https://doi.org/10.1016/j.fuel.2025.136188>.

8 Standards Australia, “AS 3980-2016: Determination of Gas Content of Coal and Carbonaceous Material – Direct Desorption Method” (Sydney: Standards Australia, 2016).

9 Roman Sidortsov, “A Perfect Moment during Imperfect Times: Arctic Energy Research in a Low-Carbon Era,” *Energy Research & Social Science* 16 (June 1, 2016): 1–7, <https://doi.org/10.1016/j.erss.2016.03.023>.

geochemical analyses.¹⁰ This integrated sampling strategy enabled a comprehensive evaluation of coal reservoir properties, gas-storage capacity, and the geological factors controlling *Coal Bed Methane* (CBM) accumulation and production potential within a deep coal-bearing succession.¹¹

Coal gas content was determined using the Direct Method in accordance with Australian Standard AS 3980. Immediately upon retrieval to the surface, core samples were placed into sealed desorption canisters to monitor gas release over time.¹² Following completion of the desorption process, the samples were crushed under controlled conditions to determine residual gas content. Total gas content was calculated using the following equation:

$$G_{total} = G_{lost} + G_{measured} + G_{residual}$$

where G_{lost} represents gas lost during coring and retrieval, $G_{measured}$ denotes gas released during desorption monitoring, and $G_{residual}$ refers to gas retained within the coal matrix and released during crushing. To eliminate the influence of moisture and ash content, gas-content values were normalised to a dry ash-free (DAF) basis using:

$$G_{DAF} = G_{raw} \times \frac{100}{100 - (Moisture + Ash)}$$

where *Moisture* and *Ash* represent the respective percentages of moisture and ash content in the analysed coal samples.

Methane sorption characteristics were evaluated through high-pressure adsorption isotherm experiments using a manometric technique at reservoir temperature conditions of approximately 150°C. Prepared coal samples were exposed to a series of controlled methane pressures until adsorption equilibrium was achieved. The resulting data were used to determine Langmuir parameters that describe the gas-storage capacity and adsorption behaviour of the coal. The relationship between adsorbed gas volume and pressure was modelled using the Langmuir equation:

$$V(P) = V_L \frac{P}{P + P_L}$$

where $V(P)$ is the adsorbed gas volume at pressure P , V_L is the maximum adsorption capacity, and P_L is the pressure at which adsorption reaches one-half of V_L . In addition to methane, a selected sample was subjected to carbon dioxide adsorption testing to evaluate the feasibility of *Enhanced Coal Bed Methane* (ECBM) recovery under deep reservoir conditions.¹³

Reservoir pressure conditions were assessed using a *Formation Micro Tester* (FMT) deployed across multiple measurement points within the Patchawarra Formation. The objective of the survey was to obtain reliable formation-pressure data and evaluate permeability characteristics within the coal-bearing interval. Measured pressures were compared with the calculated hydrostatic gradient to identify the occurrence of supercharging and depletion phenomena.

10 M J Mavor, L. B. Owen, and T. J. Pratt, "Measurement and Evaluation of Coal Sorption Isotherm Data," in SPE Annual Technical Conference and Exhibition, vol. 20728 (SPE, 1990), 157–69, <https://doi.org/10.2118/20728-MS>.

11 K E Peters, "Guidelines for Evaluating Petroleum Source Rock Using Programmed Pyrolysis," AAPG Bulletin 70, no. 3 (March 1, 1986): 318–29, <https://doi.org/10.1306/94885688-1704-11D7-8645000102C1865D>.

12 J. Espitalie et al., "Methode Rapide De Caracterisation Des Roches Meres De Leur Potentiel Petrolier Et De Leur Degre D'Evolution," Rev Inst Fr Pet 32, no. 1 (1977): 23–42, <https://doi.org/10.2516/ogst:1977002>.

13 E. Stach et al., Stach's Textbook of Coal Petrology, 3rd ed. (Berlin: Gebrüder Borntraeger, 1982), http://www.schweizerbart.de//publications/detail/isbn/9783443010188/Stach_Textbook_of_Coal_Petrology_3rd.

Pressure values exceeding the hydrostatic gradient were interpreted as evidence of supercharging, whereas pressures below the expected gradient were considered indicative of reservoir depletion associated with nearby production activities. These pressure data were integrated with gas-content and sorption results to improve understanding of gas accumulation mechanisms and the controls governing gas distribution within the coal reservoir.¹⁴

Geochemical and petrophysical characterisation was conducted through analyses of *Total Organic Carbon* (TOC), Rock-Eval pyrolysis, vitrinite reflectance, *X-ray Diffraction* (XRD), and *Shale Rock Properties* (SRP). TOC analysis was employed to quantify organic matter abundance, whereas Rock-Eval pyrolysis provided information regarding hydrocarbon-generating potential and thermal maturity. Vitrinite reflectance measurements were used to assess coal-rank evolution, while XRD analysis identified mineralogical composition. SRP analysis supplied additional information regarding bulk density, porosity, permeability, and fluid saturation. The resulting datasets were integrated through three analytical stages comprising reservoir characterisation, identification of supercharged intervals, and uncertainty assessment for reservoir development. This integrated workflow provided a comprehensive framework for evaluating CBM potential and optimising future reservoir-development strategies.

RESULTS AND DISCUSSION

Gas Content and Desorption Characteristics

Gas desorption measurements for the ten desorbed segments of the Patchawarra VC50 coal (9,155–9,212 ft) revealed significant variability in total gas content across the 60-foot interval. Table 2 summarizes the gas content data, expressed both as raw (as-received) values and normalized to dry, ash-free (DAF) basis.

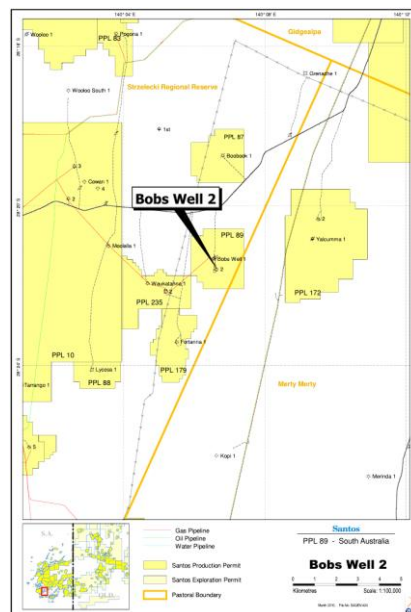


Figure 1. Location map of Bobs Well 2 within PPL 89, South Australia, showing nearby wells and infrastructure. The well is situated 0.49 km southeast of Bobs Well 1 and 29 km southwest of the Moomba Gas Plant.

Source: Author (2026)

14 Colin R. Ward, "Analysis and Significance of Mineral Matter in Coal Seams," *International Journal of Coal Geology* 50, no. 1–4 (2002): 135–68, [https://doi.org/10.1016/S0166-5162\(02\)00117-9](https://doi.org/10.1016/S0166-5162(02)00117-9).

Controls on Gas Storage and Pressure Preservation

As shown in Figure 1, Bobs Well 2 is located within PPL 89 in South Australia, approximately 0.49 km southeast of Bobs Well 1 and 29 km southwest of the Moomba Gas Plant. The well occupies a strategically important position within the regional gas development area and provides access to the deep coal-bearing interval of the Patchawarra Formation. Its location within an established production corridor allows reservoir characteristics to be evaluated in relation to nearby wells and existing infrastructure. Moreover, the availability of core, pressure, petrophysical, and geochemical data from Bobs Well 2 makes it a suitable case study for investigating gas storage mechanisms, reservoir pressure behaviour, and the overall *Coal Bed Methane* (CBM) potential of deep coal reservoirs in the Cooper Basin.

Table 1. Gas content data for Patchawarra VC50 Deep Coal (Core 2, desorbed segments).

| Sample ID | Top Depth (ft) | Bottom Depth (ft) | Lost Gas (cc/g) | Measured Gas (cc/g) | Residual Gas (cc/g) | Total Raw Gas (cc/g) | Total DAF Gas (cc/g) |
|-------------|----------------|-------------------|-----------------|---------------------|---------------------|----------------------|----------------------|
| 56169 8(1) | 9155 | 9158 | 5.77 | 8.58 | 0.70 | 14.55 | 15.79 |
| 56169 8(2) | 9161 | 9164 | 5.71 | 10.52 | 0.89 | 17.12 | 18.23 |
| 56169 8(3) | 9164 | 9167 | 8.21 | 10.62 | 0.77 | 19.60 | 23.76 |
| 56169 8(4) | 9173 | 9176 | 7.01 | 12.24 | 0.90 | 20.15 | 23.16 |
| 56169 8(5) | 9176 | 9179 | 6.50 | 10.94 | 0.78 | 18.21 | 20.37 |
| 56169 8(6) | 9182 | 9185 | 6.93 | 12.48 | 1.20 | 20.63 | 21.72 |
| 56169 8(7) | 9191 | 9194 | 6.50 | 12.21 | 0.76 | 19.47 | 20.67 |
| 56169 8(8) | 9197 | 9200 | 0.86 | 0.49 | 0.29 | 1.63 | 25.48 |
| 56169 8(9) | 9203 | 9206 | 0.92 | 0.25 | 0.46 | 1.64 | 36.48 |
| 56169 8(10) | 9209 | 9212 | 0.84 | 0.24 | 0.46 | 1.55 | 35.18 |

Source: Author (2026)

As shown in Table 1, gas-content measurements from Core 2 reveal considerable variation across the sampled interval of the VC50 Deep Coal seam. Total raw gas content generally ranges from approximately 14 to 21 cc/g within the main coal section, indicating a substantial capacity for methane storage. The highest gas contents are observed in samples collected between 9,164 and 9,185 ft, suggesting favourable conditions for gas generation and retention within these intervals. In contrast, samples recovered near the base of the cored section exhibit markedly lower raw gas values, which may reflect lithological changes associated with the transition from coal to shale. Overall, the gas-content distribution demonstrates that the Patchawarra VC50

Deep Coal seam possesses significant CBM potential and warrants further evaluation through pressure, sorption, and petrophysical analyses.

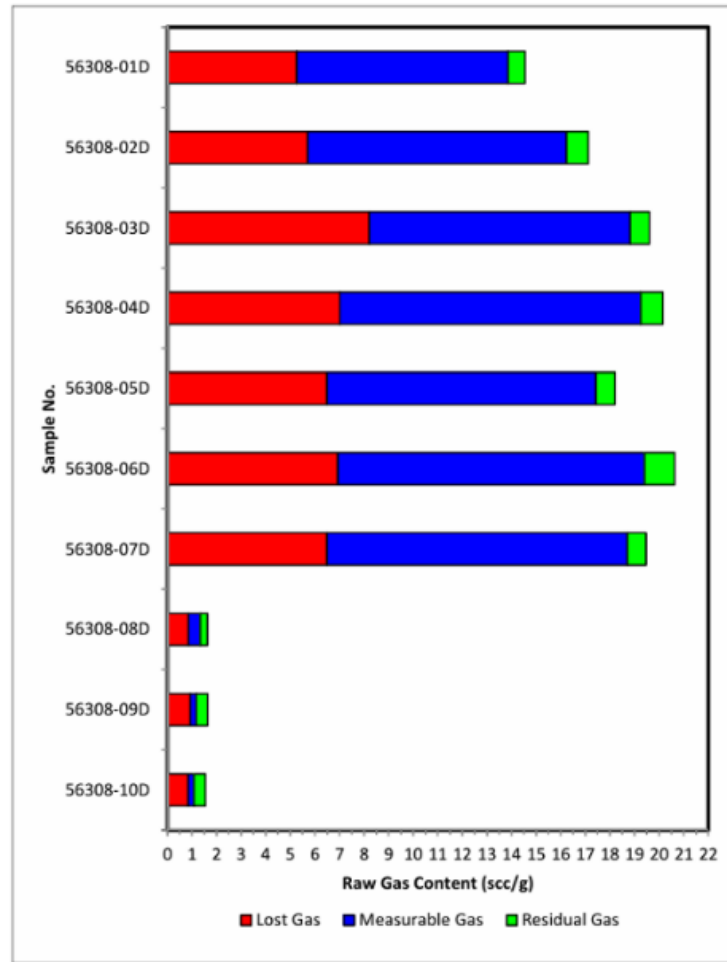


Figure 2. Raw and DAF gas content of desorbed samples (1D–10D) from the VC50 Deep Coal seam.

Source: Author (2026)

Figure 2 presents a bar chart of raw gas content distribution by sample, clearly delineating the transition from high-gas coal in the upper portion of the core (samples 1D–7D) to low-gas shale/siltstone in the lower portion (samples 8D–10D). The dramatic decrease in raw gas content below 9,197 ft reflects the lithological transition from massive coal to dominantly shale and siltstone, with ash content increasing from 4–17% in the coal interval to 93–95% in the lower section.

Table 2. Proximate analysis data (air-dry basis) for Patchawarra VC50 desorption samples.

| Sample ID | Top Depth (ft) | Bottom Depth (ft) | Moisture (wt%) | Ash (wt%) | Volatile Matter (wt%) | Fixed Carbon (wt%) |
|-----------|----------------|-------------------|----------------|-----------|-----------------------|--------------------|
| 56308-01D | 9155 | 9158 | 0.9 | 6.5 | 15.8 | 76.8 |
| 56308-02D | 9161 | 9164 | 1.5 | 21.5 | 15.7 | 78.1 |

Controls on Gas Storage and Pressure Preservation

| | | | | | | |
|-----------|------|------|-----|------|------|------|
| 56308-03D | 9167 | 9170 | 0.9 | 16.6 | 17.0 | 65.5 |
| 56308-04D | 9173 | 9176 | 0.9 | 12.1 | 15.9 | 71.1 |
| 56308-05D | 9179 | 9182 | 0.9 | 9.7 | 17.7 | 71.7 |
| 56308-06D | 9185 | 9188 | 0.8 | 4.2 | 16.2 | 78.8 |
| 56308-07D | 9191 | 9194 | 1.1 | 4.5 | 15.2 | 79.2 |
| 56308-08D | 9197 | 9200 | 0.4 | 93.2 | 4.5 | 1.9 |
| 56308-09D | 9203 | 9206 | 0.4 | 95.1 | 3.4 | 1.1 |
| 56308-10D | 9209 | 9212 | 0.4 | 95.2 | 3.6 | 0.8 |

Source: Author (2026)

A critical observation from Tables 1 and 2 is the inverse relationship between raw gas content and DAF gas content in samples 8D–10D. Despite raw gas contents of only 1.55–1.64 scc/g, DAF-normalized gas contents reach 25.5–36.5 scc/g, exceeding those of several coal samples. This pattern results from the extremely high ash contents of samples 8D–10D (93–95 wt%), which greatly reduce the proportion of organic matter in the bulk sample. Consequently, when gas content is normalized to a dry ash-free basis, the gas associated with the limited organic fraction is concentrated, producing elevated DAF values. These results indicate that the high DAF gas contents are primarily a mathematical consequence of normalization rather than evidence of exceptionally gas-rich intervals.

For the coal-dominated samples (1D–7D), raw gas content ranges from 14.55 to 20.63 scc/g (average 18.53 scc/g), with lost gas comprising 31.6–36.2% of total gas. Measurable gas dominates (54.2–62.7%), while residual gas represents only 3.9–5.9% of total gas, indicating efficient gas release during the desorption process. The lost gas content of 5.27–8.21 scc/g, determined by extrapolation of early-time desorption data, represents an important uncertainty component in total gas estimation.

Table 3. Air-corrected gas composition results (representative samples).

| Sample No. | Top Depth (ft) | Stage | N ₂ (mol%) | CH ₄ (mol%) | C ₂ H ₆ (mol%) | C ₃ H ₈ (mol%) | CO ₂ (mol%) |
|------------|----------------|-------|-----------------------|------------------------|--------------------------------------|--------------------------------------|------------------------|
| 56308_001D | 9155 | Early | 23.24 | 41.69 | 2.37 | 0.23 | 32.47 |
| 56308_002D | 9161 | Early | 23.76 | 42.21 | 2.57 | 0.23 | 31.19 |
| 56308_003D | 9167 | Early | 23.03 | 42.12 | 4.00 | 0.29 | 30.53 |
| 56308_008D | 9197 | Early | 23.40 | 42.07 | 3.14 | 0.22 | 31.13 |
| Average | — | — | 23.36 | 42.02 | 3.02 | 0.24 | 31.33 |

Source: Author (2026)

As shown in Table 3, the early desorption gas composition is dominated by methane (CH₄), which averages 42.02 mol%, followed by carbon dioxide (CO₂) at 31.33 mol% and nitrogen (N₂) at 23.36 mol%. Minor quantities of ethane (C₂H₆) and propane (C₃H₈) are also present, averaging 3.02 mol% and 0.24 mol%, respectively. The relatively consistent gas composition among the analysed samples indicates a homogeneous gas system within the sampled interval of the VC50 Deep Coal seam. The predominance of methane confirms the coal seam as a gas-bearing reservoir, while the substantial proportion of carbon dioxide suggests that non-hydrocarbon gases contribute significantly to the overall gas composition. The presence of measurable heavier hydrocarbons further indicates thermogenic influences associated with the deep burial and thermal evolution of the Patchawarra coal sequence.

Sorption Isotherms and Langmuir Parameters

High-pressure methane adsorption isotherms were conducted on preserved segments 1P through 10P (8P–10P are shales) at reservoir temperature (150°C). Table 5 summarizes the Langmuir parameters derived from these measurements.

Table 4. Summary of Langmuir parameters for methane adsorption at 302°F (150°C).

| Sample No. | Depth (ft) | TOC (wt%) | Ash (wt%) | VL Raw (scf/ton) | PL Raw (psia) | VL Dry (scf/ton) | VL DAF (scf/ton) |
|------------|-----------------|-----------|-----------|------------------|---------------|------------------|------------------|
| 1P | 9158.23–9159.75 | 79.75 | 10.76 | 431.7 | 1229.1 | 436.1 | 489.3 |
| 2P | 9164.24–9167.23 | 76.31 | 6.43 | 453.8 | 1187.0 | 459.3 | 491.3 |
| 3P | 9170.20–9173.19 | 83.09 | 3.72 | 403.6 | 1099.3 | 407.3 | 423.1 |
| 4P | 9176.20–9179.18 | 89.70 | 4.54 | 438.6 | 1140.3 | 442.3 | 463.6 |
| 5P | 9182.07–9185.07 | 79.30 | 5.17 | 396.3 | 1020.4 | 399.0 | 420.8 |
| 6P | 9188.09–9191.07 | 83.47 | 3.55 | 443.1 | 1108.3 | 446.6 | 463.2 |
| 7P | 9194.08–9195.98 | 27.52 | 37.60 | 268.4 | 1112.9 | 269.1 | 432.0 |
| 8P | 9200.12–9203.09 | 2.66 | 94.73 | 20.4 | 1256.5 | 20.5 | – |
| 9P | 9206.15–9209.11 | 1.37 | 95.38 | 11.4 | 1396.0 | 11.4 | – |
| 10P | 9212.13–9214.23 | 2.95 | 91.82 | 19.9 | 1050.0 | 19.9 | – |

Source: Author (2026)

As shown in Table 4, the coal-dominated samples (1P–6P) exhibit exceptionally high total organic carbon (TOC) contents ranging from 76.31 to 89.70 wt%, accompanied by low ash contents and high Langmuir volumes (VL DAF) of approximately 421–491 scf/ton. These

results indicate a strong capacity for methane adsorption and storage within the VC50 Deep Coal seam. Sample 7P represents a transitional interval, characterised by a lower TOC content (27.52 wt%) and higher ash content (37.60 wt%), resulting in a reduced adsorption capacity compared with the overlying coal samples. In contrast, samples 8P–10P display very low TOC values (1.37–2.95 wt%) and extremely high ash contents exceeding 91 wt%, reflecting shale-dominated lithologies with substantially lower methane storage capacities. The clear decline in Langmuir volume with decreasing organic content demonstrates that organic matter abundance is a primary control on gas adsorption potential within the studied interval.

Figure 3 presents a typical methane adsorption isotherm (Sample 6P), demonstrating the characteristic asymptotic approach to VL as pressure increases. The isotherm shape indicates Type I adsorption behavior (Langmuir model appropriate), with rapid initial adsorption at low pressures followed by gradual approach to saturation.

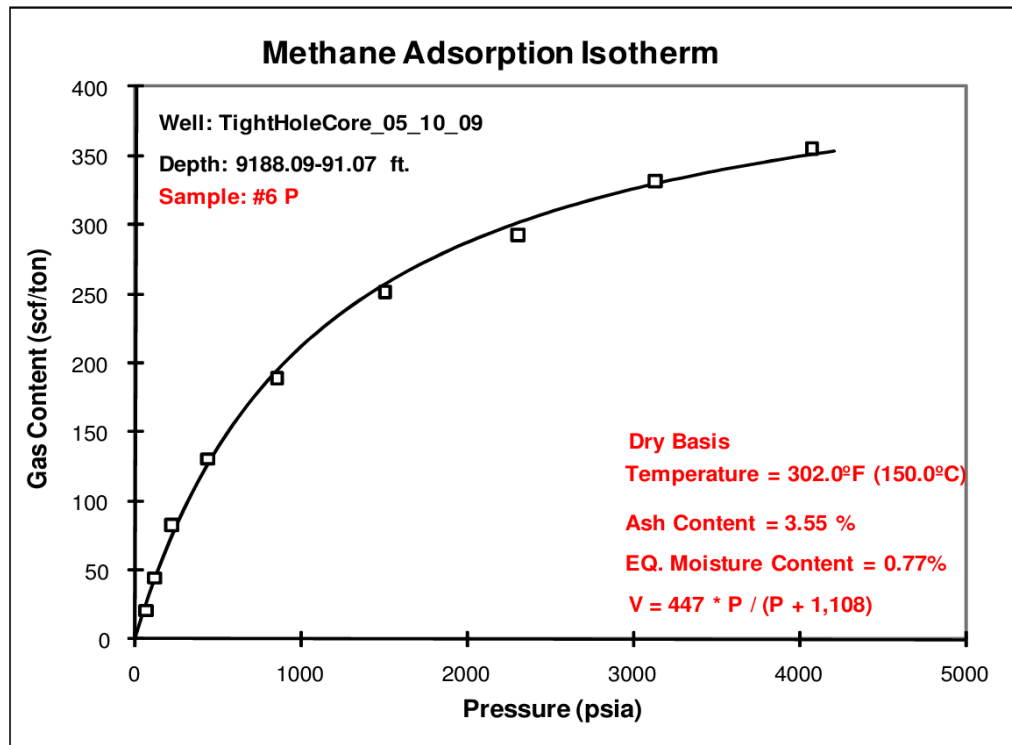


Figure 3. Methane adsorption isotherm for Sample 6P (Patchawarra coal, 9188.09–91.07 ft). Langmuir volume VL = 443.1 scf/ton, Langmuir pressure PL = 1108.3 psia at 150°C.

Source: Author (2026)

The CO₂ adsorption isotherm conducted on Sample 2P reveals significantly higher adsorption capacity for CO₂ compared to methane (Figure 4), with VL raw = 561.2 scf/ton and PL = 476.4 psia. The steeper initial slope and higher VL indicate that CO₂ is preferentially adsorbed over CH₄, consistent with the known competitive adsorption behavior in coals and supporting the potential for CO₂-ECBM applications.

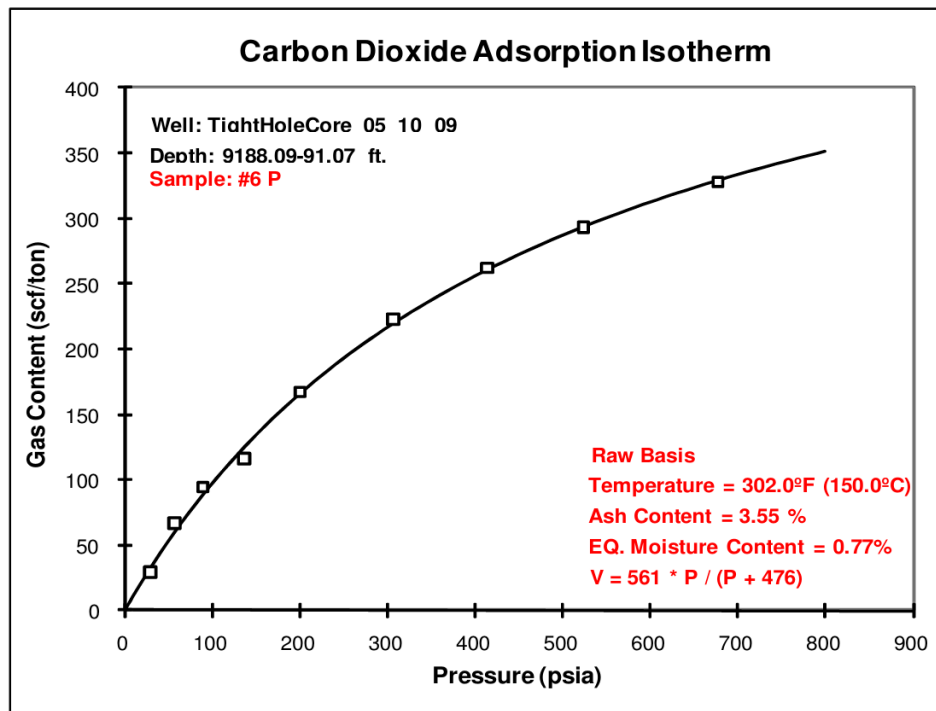


Figure 4. Carbon dioxide adsorption isotherm for Sample 2P (8309.12–10.85 ft). VL = 561.2 scf/ton, PL = 476.4 psia at 150°C.

Source: Author (2026)

Formation Pressure Survey and Supercharging Identification

A total of 24 FMT pressure points were attempted across the Patchawarra interval. Of these, 5 were classified as good tests, 14 curtailed, and 5 no seal. Table 6 presents the successful and curtailed tests with sufficient data for interpretation.

Table 5. Selected FMT pressure survey results (good tests and curtailed tests with interpretation).

| Test No. | Depth (ft) | Formation | Hydrostatic Pressure (psi) | Final Pressure (psi) | Mobility | Build-up Type | Interpretation |
|----------|------------|--------------------|----------------------------|----------------------|----------|---------------|----------------|
| 10 | 8697 | Patchawarra (VL22) | ~4,140 | 4,138.10 | 7.8 | Good | Supercharged |
| 12 | 8838 | Patchawarra (VL32) | ~4,201 | 3,779.10 | 0.7 | Good | Depleted (63%) |
| 15 | 8981 | Patchawarra (VL43) | ~4,262 | 4,257.60 | 0.6 | Good | Supercharged |
| 16 | 8985 | Patchawarra (VL43) | ~4,264 | 4,257.30 | 0.6 | Good | Supercharged |
| 23 | 9288 | Patchawarra (VC60) | ~4,405 | 4,394.90 | 0.5 | Good | Supercharged |

Source: Author (2026)

As shown in Table 5, formation pressure testing identified several distinct pressure compartments within the Patchawarra Formation. Supercharged conditions were recognised in the VL22, VL43, and VC60 intervals, where measured pressures closely approached or slightly

exceeded the expected hydrostatic gradient of 0.473 psi/ft. The VL22 sand at 8,697 ft exhibited the highest mobility (7.8 md/cP), indicating relatively favourable permeability compared with the deeper intervals. In contrast, the VL43 and VC60 sands displayed very low mobility values (0.5–0.6 md/cP), suggesting tight reservoir conditions despite maintaining elevated pressure. A notable exception is the VL32 sand at 8,838 ft, which recorded a pressure of 3,779 psia, significantly below the expected hydrostatic pressure, indicating approximately 63% depletion and probable hydraulic communication with nearby production activities. These results demonstrate the coexistence of supercharged and depleted compartments within the Patchawarra reservoir system.

Petrophysical Characterization: TOC, Vitrinite Reflectance, and Mineral Composition

To further evaluate the source-rock quality and thermal maturity of the studied interval, geochemical analyses were conducted using *Total Organic Carbon* (TOC) measurements and Rock-Eval pyrolysis. These analyses provide information on organic matter abundance, hydrocarbon-generating potential, kerogen characteristics, and thermal evolution. Key parameters obtained include TOC, free hydrocarbons (S1), remaining generative potential (S2), Hydrogen Index (HI), Oxygen Index (OI), maximum pyrolysis temperature (Tmax), and Production Index (PI). Together, these parameters enable assessment of both the quantity and quality of organic matter and provide insights into the gas-generation capacity of the VC50 Deep Coal seam and adjacent shale intervals.

Table 6. TOC and programmed pyrolysis data for selected Patchawarra VC50 samples.

| Sample ID | Top Depth (ft) | TOC (wt%) | S1 (mg/g) | S2 (mg/g) | HI (mg HC/g TOC) | OI (mg CO ₂ /g TOC) | T _{max} (°C) | PI |
|-----------|----------------|-----------|-----------|-----------|------------------|--------------------------------|-----------------------|------|
| 1D-1G | 9155.46 | 82.12 | 2.31 | 190.48 | 1101 | 4 | 479 | 0.02 |
| 2D-4G | 9161.48 | 83.65 | 2.81 | 161.35 | 973 | 4 | 479 | 0.04 |
| 4D-10G | 9173.48 | 82.25 | 2.21 | 144.52 | 542 | 4 | 492 | 0.05 |
| 6D-16G | 9185.50 | 85.96 | 2.31 | 172.08 | 842 | 4 | 483 | 0.03 |
| 8D-22G | 9197.56 | 15.15 | 0.62 | 16.85 | 111 | 2 | 487 | 0.04 |
| 9D-25G | 9203.52 | 1.05 | 0.17 | 0.43 | 41 | 50 | 505 | 0.28 |

Source: Author (2026)

As shown in Table 6, the geochemical results reveal a clear distinction between the coal-dominated and shale-dominated intervals. Coal samples are characterised by exceptionally high TOC values exceeding 82 wt%, indicating abundant organic matter and strong source-rock potential. These samples also display high S2 values and elevated Hydrogen Index (HI) values, reflecting substantial hydrocarbon-generating capacity despite their advanced thermal maturity. In contrast, the lower shale-dominated interval exhibits a pronounced decline in TOC, S2, and HI values, indicating significantly reduced organic richness and gas-generation potential. The consistently high Tmax values, ranging from 479°C to 505°C, suggest that the organic matter has reached a mature to overmature stage of thermal evolution.

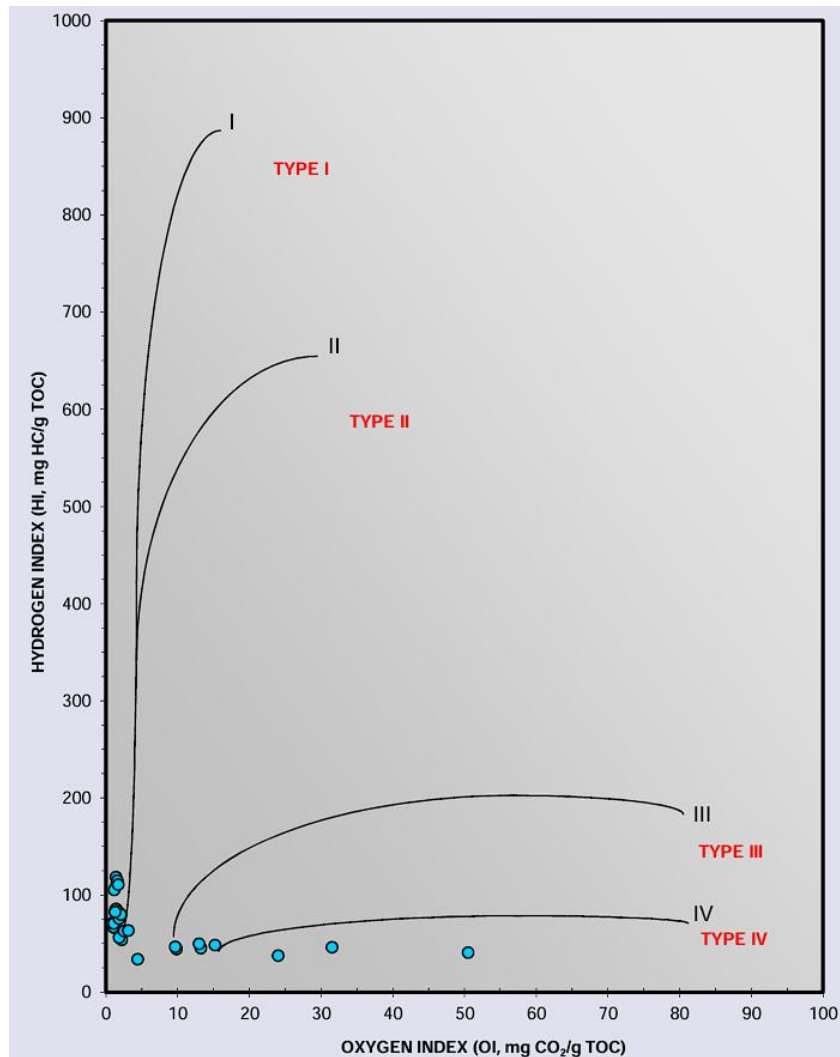


Figure 5. Modified van Krevelen diagram showing HI vs. OI. Patchawarra coal samples plot in Type III/Type IV region, consistent with gas-prone kerogen at advanced maturity.

Source: Author (2026)

Vitrinite Reflectance: Forty samples were analyzed for vitrinite reflectance thermal maturity (Ro). Ro values for the Patchawarra VC50 coal range from 1.37% to 1.53% (mean 1.46% Ro). These values place the coal in the dry gas window (1.4–4.0% Ro), indicating that thermal maturation has progressed beyond the wet gas/condensate window. This is consistent with the observed gas composition, which is methane-rich with minor ethane and propane but no significant liquid hydrocarbon content.

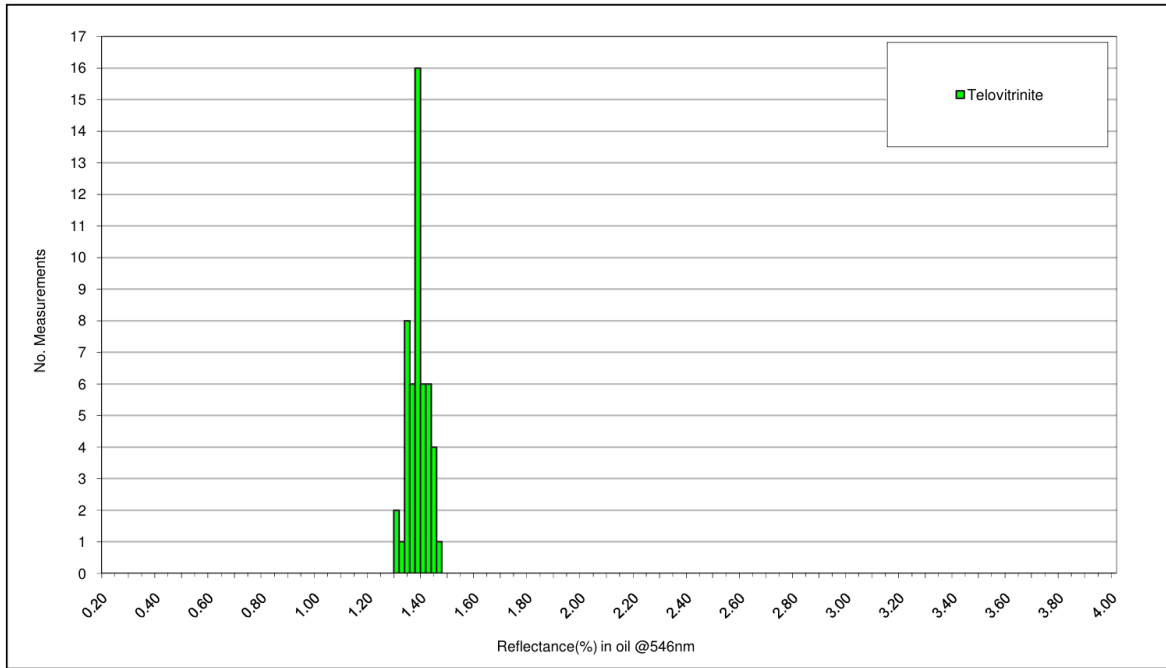


Figure 6. Vitrinite reflectance histogram for Sample 1D-1P (9155.40–9155.58 ft), showing mean Ro = 1.37% with narrow distribution, indicating homogeneous thermal maturity.

Source: Author (2026)

X-Ray Diffraction Mineral Composition: XRD analysis reveals distinct mineralogical differences between the coal-dominated upper interval and the shale-dominated lower interval. Figure 7 presents the mineral composition summary for selected samples.

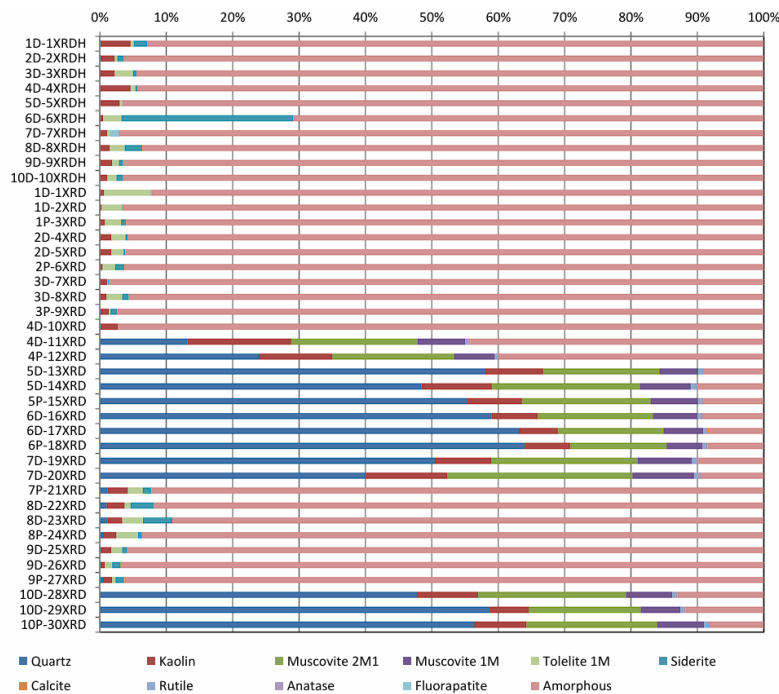


Figure 7. X-ray diffraction mineral composition summary for Patchawarra VC50 samples, showing dominant mineral phases including quartz, kaolin, muscovite, siderite, and amorphous (organic) content.

Source: Author (2026)

X-ray diffraction (XRD) analysis reveals substantial mineralogical variations across the studied interval, reflecting the transition from coal-dominated to shale-dominated lithologies. Coal samples (1D–7D) are characterised by high amorphous contents ranging from approximately 70% to 98%, indicating the predominance of organic matter and supporting the TOC results. Minor mineral constituents include quartz, kaolin, and siderite, with siderite concentrations reaching up to 25.9% in certain coal intervals. A distinct transitional zone is observed at sample 4D-11XRD (9,175.58 ft), where increased proportions of quartz, kaolin, muscovite, rutile, and anatase coincide with reduced amorphous content, indicating a shift from coal to shale or siltstone lithologies. In contrast, shale samples (8D–10D) contain significantly higher concentrations of quartz, kaolin, and muscovite, accompanied by much lower amorphous contents. The high quartz content, reaching up to 64.1%, suggests favourable brittleness and mechanical strength for hydraulic fracture propagation, whereas the occurrence of siderite may influence both reservoir mechanical properties and sealing capacity.

Integrated Analysis of Supercharging Controls and Implications for Deep CBM Development

The integrated dataset indicates that reservoir pressure behaviour within the Patchawarra Formation is controlled not by a single parameter but by the interaction among organic richness, thermal maturity, mineralogical composition, and reservoir permeability. Although the coal intervals consistently exhibit high TOC values exceeding 80 wt%, not all intervals display the same pressure characteristics. This observation suggests that organic matter abundance alone cannot explain the occurrence of supercharging. Instead, supercharging appears to result from the combined effect of substantial methane generation and the ability of the surrounding strata to retain that gas over geological timescales.¹⁵

The pressure data demonstrate that supercharged intervals are associated with extremely low mobility values and effective sealing lithologies. The VL43 and VC60 zones retain pressures close to hydrostatic conditions despite their very low mobility, indicating limited pressure dissipation. In contrast, the VL32 interval exhibits significant depletion despite occurring within the same regional stratigraphic framework. This contrast implies that reservoir connectivity exerts a stronger control on pressure preservation than gas-generation potential alone.¹⁶ The depleted condition of VL32 suggests hydraulic communication with adjacent production zones, whereas the supercharged intervals remain effectively isolated from pressure depletion.

Mineralogical evidence further supports this interpretation. XRD results show that shale intervals adjacent to the supercharged reservoirs contain elevated quartz and siderite contents. Rather than merely describing mineral composition, these minerals have important reservoir implications. Quartz-rich rocks generally possess greater mechanical strength and lower susceptibility to compaction, enabling them to function as competent sealing units.¹⁷ Similarly, siderite cementation may reduce permeability and restrict fluid migration. The coincidence of supercharged pressures with quartz- and siderite-bearing seals suggests that mineralogical controls play a significant role in preserving reservoir overpressure and preventing gas leakage.

15 C. D. Ruppel and W. F. Waite, “Timescales and Processes of Methane Hydrate Formation and Breakdown, With Application to Geologic Systems,” *Journal of Geophysical Research: Solid Earth* 125, no. 8 (August 10, 2020), <https://doi.org/10.1029/2018JB016459>.

16 Tenger Borjigin et al., “Formation, Preservation and Connectivity Control of Organic Pores in Shale,” *Petroleum Exploration and Development* 48, no. 4 (August 2021): 798–812, [https://doi.org/10.1016/S1876-3804\(21\)60067-8](https://doi.org/10.1016/S1876-3804(21)60067-8).

17 Yunjun Zhang et al., “Pore-Micro Fracture Structure, Porosity and Gas-Bearing Property of Deep Shale under Lithofacies-Formation Pressure Coupling,” *Scientific Reports* 16, no. 1 (February 4, 2026): 7303, <https://doi.org/10.1038/s41598-026-38352-7>.

Thermal maturity data provide additional insight into the origin of the gas accumulations. Vitrinite reflectance values around 1.46%Ro place the Patchawarra coals within the dry-gas generation window, indicating that methane generation has likely reached an advanced stage. Combined with the exceptionally high TOC values and strong methane adsorption capacities reflected by Langmuir volumes exceeding 400 scf/ton, these results suggest that the reservoir possesses both a substantial gas source and an efficient storage mechanism. Consequently, the supercharged intervals can be interpreted as zones where gas generation, adsorption capacity, and seal effectiveness have acted together to maximise gas retention.

These findings have direct implications for gas-in-place estimation and reservoir development. Conventional CBM assessments frequently assume hydrostatic reservoir conditions; however, the pressure data demonstrate that significant local deviations may occur even within the same formation. As a result, the use of measured reservoir pressures becomes essential for accurate resource estimation. The relationship between supercharging and favourable petrophysical characteristics also provides a practical exploration criterion.¹⁸ Intervals exhibiting high TOC, mature organic matter, low mobility, and quartz–siderite-rich seals are more likely to preserve economically significant gas accumulations than intervals lacking these characteristics.

From a development perspective, the integration of pressure, sorption, geochemical, and mineralogical data provides a framework for reducing uncertainty in deep CBM projects. Rather than selecting stimulation targets solely on the basis of gas content, operators can prioritise intervals where favourable adsorption capacity coincides with preserved reservoir pressure and competent seal lithologies. This integrated approach improves confidence in gas-in-place estimates, enhances completion design, and reduces exploration risk by identifying the geological conditions most strongly associated with supercharged gas accumulations.

CONCLUSION

This study investigated the Patchawarra VC50 Deep Coal seam in the Cooper Basin through an integrated evaluation of gas desorption, methane sorption, formation-pressure testing, and petrophysical characterization. The results demonstrate that the coal-dominated interval possesses favorable conditions for deep coalbed methane (CBM) accumulation and retention. Gas-content measurements indicate raw gas contents of 14.6–20.6 scc/g and Langmuir adsorption capacities of 421–491 scf/ton (DAF), confirming strong methane storage potential within the reservoir. Geochemical analyses reveal exceptionally high organic richness, with TOC values exceeding 80 wt%, while vitrinite reflectance values averaging 1.46% Ro indicate thermal maturity within the dry-gas generation window. Formation-pressure measurements further reveal the coexistence of pressure-preserved and depleted compartments within the Patchawarra Formation, highlighting the importance of reservoir connectivity and compartmentalization in controlling pressure distribution. Mineralogical analyses show distinct contrasts between coal-rich and shale-rich intervals, suggesting that lithological heterogeneity contributes to variations in reservoir behavior and gas preservation.

The principal contribution of this study lies in demonstrating the value of integrating gas-content measurements, adsorption behavior, formation-pressure data, and petrophysical characteristics within a single reservoir-evaluation framework. Rather than relying on any individual parameter, the findings show that gas retention in deep CBM systems is controlled by the interaction among organic richness, methane adsorption capacity, reservoir isolation, and seal effectiveness. This integrated perspective provides a more comprehensive understanding of gas accumulation processes than approaches based solely on desorption data or pressure

18 Nian Peng et al., “Pore Pressure Evaluation of Formation Testing While Drilling under Supercharged Conditions,” *Journal of Petroleum Science and Engineering* 203 (August 2021): 108689, <https://doi.org/10.1016/j.petrol.2021.108689>.

measurements. The study also highlights the significance of pressure compartmentalization in deep coal reservoirs and emphasizes the need to incorporate measured formation pressures into reservoir evaluation and resource assessment workflows. By combining geological, geochemical, and reservoir-engineering datasets, the proposed framework offers a practical basis for improving reservoir characterization and supporting more informed development decisions in deep CBM settings.

Several limitations should be acknowledged when interpreting the results. The analysis is based on data from a single well and a limited number of successful pressure measurements, which restricts the ability to generalize the findings across the broader Cooper Basin. In addition, the inferred relationships among pressure preservation, reservoir isolation, and mineralogical characteristics remain primarily interpretive and require further validation using larger datasets and independent geological evidence. Future research should therefore focus on multi-well investigations, expanded formation-pressure surveys, and three-dimensional geological modeling to evaluate the spatial continuity of pressure compartments and sealing lithologies. Additional studies incorporating geomechanical analysis, fracture characterization, and production-performance data would also improve understanding of the mechanisms controlling gas retention and pressure preservation in deep CBM systems. Such efforts would help refine predictive models of reservoir quality and contribute to more reliable assessment and development of deep coalbed methane resources in the Cooper Basin and other analogous basins worldwide.

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