Research Article

Three-Dimensional Modelling of Desorbed Gas Volume and Comparison to Gas Production Rate in the Montney Plays, Western Canadian Sedimentary Basin

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Shale reservoir has been focused among unconventional resources since the first extraction of free and adsorbed gas from the low-permeable Barnett Shale via horizontal drilling and hydraulic fracturing. In the beginning of production, free gas was rapidly recovered through an artificial fracture system, and then, desorbed gas followed at the final stage due to a decrease of reservoir pressure. This desorbed gas volume commonly occupies 10 to 40% of total gas production in shale gas play although it shows wide variety in cumulative gas volume and production time. The largest gas production in Canada is recovered from either tight sandstone or shale reservoirs. The Montney play in Western Canadian Sedimentary Basin (WCSB) has produced up to 80% of Canadian natural gas production. The desorbed gas production from this play has been reported up to 10% of total produced gas. The distribution and productivity of the desorbed gas have not been fully studied. Therefore, we focus to understand the distribution of the desorbed gas volume of eastern, middle, and northwestern areas in the Montney play. The desorbed gas volume within these areas was estimated from the relationship among canister, illite, and shale volumes in core samples and well logs. The average shale volume fraction in eastern area is 0.38 v/v, the average illite mineral volume fraction is 0.25 v/v, and the average desorbed gas volume refers to 8.52 scf/ton. In middle area, calculated volume represents 0.34 v/v, 0.216 v/v, and 8.15 scf/ton as listed above. The northwestern area also shows 0.65 v/v, 0.4 v/v, and 9.78 scf/ton, respectively. 3D models of each area indicated relatively rich and lack parts of desorbed gas volume. These estimated desorbed gas volume and gas production history were compared in order to understand when and how the desorbed gas would affect to gas production. It shows strong positive relationship, gradually increasing correlation to the later stage (from 24–44 months to 36–44 months) of gas production in the entire areas. This result implies that the estimation of later stage gas productivity is able from the estimated volume of desorbed gas, and also, the total gas production can be forecast in shale gas reservoir. Northwestern area in Montney play preserves relatively abundant desorbed gas volume, which will be dominant after 24 months of production.

1. Introduction

The shale gas production within Western Canadian Sedimentary Basin (WCSB), Alberta, and British Columbia province, occupies about 80 percent of Canadian natural gas production. The gas productions in Alberta and British Columbia provinces will increase until 2036 up to 14,000 and 9,000 mmcf/day, respectively [1]. Growing attention of

shale gas play in WCSB leads to understand characteristics of shale formation such as sedimentary features, petrophysical properties (porosity, permeability, saturation, brittleness, etc.), and gas production profile (free and desorbed) [2–10]. The production of the desorbed gas, also known as the residual gas, is dominant at the final stage after the most of free gas was already extracted. However, it is still unknown that when and how the production of in situ desorbed gas would affect

FIGURE 1: (a) Gas production profile of well 200/C-045-K/94-O-05/2 in British Columbia, Canada. (b) The schematic diagram of free and desorbed gas transport mechanism in shale reservoir. E^3m^3 : thousand cubic meter.

the overall gas production (Figure 1). Even though these gas volume commonly occupies 10 to 40% of total gas production in shale gas play [8, 11].

The residual gas volume was estimated from Langmuir volume and pressure. This residual gas mostly refers to adsorbed gas which was bounded in the surface of mineral layers of glass was firstly introduced by Langmuir [12]. Most of researchers generally treated the remaining gas volume as adsorption gas and conduct several experiments followed by Langmuir's research [3–8, 13, 14]. These

experiments, however, cannot measure the volume of gas which is trapped in micropore with ultralow permeability and have function to only measure the adsorption. It is because gas adsorption happens by the electrostatic attraction which is generally occurs between surface of various clay minerals and liquid and gas molecules [15, 16]. On the contrary, the canister volume measurement is capable to detect the actual volume of desorbed gas in shale core which have the characteristic of low permeability matrix and microfractures [15, 17]. Recently, estimation of

FIGURE 2: Distribution of the Lower Triassic Montney Formation in southwestern Alberta and northeastern British Columbia province representing its lithology pattern and study area (modified Yang and Lee [11]). Each well location was displayed. Eastern area data location is magnified to show clear location.

desorbed gas volume by using the conventional logs based on relationship between canister volume analysis data and XRD data was suggested [11]. It shows relatively high correlation with illite mineral to canister volume in shale reservoir [11].

The eastern area of Montney Formation, located in Alberta province, comprised with dolomitic siltstone and some sandstone. The middle area of Montney Formation in Alberta province is composed of siltstone and some sandstone. The northwestern area of Montney Formation in British Columbia is dominance of siltstone. This Montney Formation is generally thickening westward and deepening [16, 18–23]. Within these areas, the desorbed gas volume relatively increased westward, following the general distribution of the formation.

Yang and Lee [11] focused to understand which clay mineral has most relevant with desorbed gas in the Montney play using single well. They used the canister analysis data and XRD data to figure out the relationship, based on which the desorbed gas volume was calculated from conventional logs. This method is applied to three different areas in Montney Formation in WCSB to visualize three-dimensional distribution of desorbed gas. Furthermore, it is

compared to the gas production history which will provide a unique opportunity to quantify desorbed gas volume in gas production of Montney play.

2. Previous Works

The shale gas production within WCSB is very important for Canada, which occupies 80 percent of national gas production since 2016. Its production amount will keep increase and reach maximum at 2023. From the forecast [1], this maximized production will also be maintained until 2036 by the shale gas investment within WCSB, mainly in Alberta and British Columbia provinces. As a consequence, the shale gas production in Montney Formation is overviewed and evaluated intensively in regard to reservoir characteristic [8, 9]. Moreover, adsorbed gas, a part of residual gas, is reviewed as a control factor of shale gas production when the reservoir pressure decreases to a certain level [24]. Yang and Lee [11], recently, introduced the method by using the conventional logs, canister volume analysis, and mineral composition data to calculate the shale volume, illite mineral volume, and desorbed gas volume in shale reservoir. A linear equation was driven

FIGURE 3: Stratigraphic chart of the Montney Formation. In this study, Diaber group of Montney Formation has divided into upper and lower member based on lithological characters (modified Yang and Lee [11]).

to estimate the illite mineral volume which has certain relationship with desorbed gas in shale reservoir, found by the comparison between canister volume analysis and mineral composition data. They suggested to use a linear equation to estimate the desorbed gas volume in shale reservoir and imply that the desorbed gas volume can be calculated from conventional logs.

The Montney Formation was deposited during the lower Triassic time (during approximately 252 to 247 Ma; million years ago) within the Western Canada Sedimentary Basin (WCSB), ca 750,000 km² in areas, equivalent to present-day subsurface of northeastern British Columbia and western Alberta, of Peace River subbasin (Figure 2). Its average thickness is 100-300 m, and its burial depth reaches maximum up to 4 km in westward [18–23]. The Montney Formation is mainly composed of dolomitic siltstone, very fine to fine grain sandstone and silty shale [16, 18, 22, 23]. The formation is divided into lower and upper members

(Figure 3) [11, 18, 19, 25]. The lower member comprises of very fine sandstone and siltstone with rare of interbedded shale and overlies the carbonate-dominant Permian Belloy Formation. The upper member was composed of shale with interbedded mudstone and siltstone and is overlain by phosphate rich siltstone, Doig Formation. These diverse types of sediments in Montney Formation were influenced and characterized by their paleomorphology and paleoenvironment in which arid setting was prevail throughout the WCSB.

3. Data and Method

Three areas in the Montney play are studied to construct 3D models of desorbed gas volume: eastern (township range 72-71, region 26w500), middle (township range 65-64, region 06W600), and northwestern (township range 94, region 0400-1500). In eastern area, named Crook Creek,

TABLE 1: Basic well information used in this study. UWI: Unique Well Identifier; MNTY Fm: Montney Formation.

Area	UWI	Location	Interval for MNTY Fm (m)	Thickness (m)	Latitude	Longitude
Eastern	100060307226W500	AB	1557.5 ~ 1744.3	186.8	50°12'23.11"N	117°54'42.55"W
	100060407226W500	AB	1559.7 ~ 1750.0	190.3	55°12'23.91"N	117°56'31.75"W
	100090407226W500	AB	1548.0 ~ 1733.8	185.8	55°12'38.71"N	117°55'26.35"W
	100110307226W500	AB	1577.3 ~ 1741.5	184.2	55°12'38.16"N	117°54'53.81"W
	100110407226W500	AB	1554.0 ~ 1741.0	187	55°12'38.50"N	117°56'13.87"W
	100133307126W500	AB	1561.0 ~ 1752.0	191	55°11'55.41"N	117°56'38.92"W
	100160307226W500	AB	1557.0 ~ 1745.0	188	55°12'43.33"N	117°54'12.47"W
	100163207126W500	AB	1559.3 ~ 1752.8	193.5	55°11'57.22"N	117°56'58.91"W
Middle	102123307126W500	AB	1559.5 ~ 1749.9	190.4	55°11'44.73"N	117°56'35.95"W
	100030106506W600	AB	3066~3153.7	87.7	54°36'20.43"N	118°46'35.81"W
	100032306406W600	AB	3016.4 ~ 3074.9	58.5	54°32'48.46"N	118°49'53.28"W
Northwestern	100142506406W600	AB	3072~3278.1	206.1	54°34'23.32"N	118°46'11.44"W
	200C052H094B0902	BC	2063.0 ~ 2378.0	315	56°36'52.49"N	122°00'33.75"W
	200C004F094G0800	BC	1739.0 ~ 2012.0	273	57°20'22.49"N	122°17'48.75"W
	202C092G094G0800	BC	1621.0 ~ 1885.0	264	57°24'7.49"N	122°07'41.25"W
	100D078G094H0400	BC	1560.0 ~ 1674.0	114	57°08'52.50"N	121°42'56.25"W
	200C030I094B1500	BC	2450.0 ~ 2793.0	343	56°59'52.50"N	122°37'18.75"W

TABLE 2: Basic seismic profile information used in this study. The CRS (Coordinate Reference System) was set by UTM27-11 to use, and well to seismic calibrated profiles were KK-101 and KK-103.

Seismic name	CRS	Location	Length (m)
69_A2Z85	UTM27-11	Alberta	8800
69B_A2Z86	UTM27-11	Alberta	7800
71_A2Z87	UTM27-11	Alberta	9200
71B_A2S99	UTM27-11	Alberta	16000
79_AA	UTM27-11	Alberta	9900
KK-101	UTM27-11	Alberta	15100
KK-102	UTM27-11	Alberta	11000
KK-103	UTM27-11	Alberta	14200
SR-08	UTM27-11	Alberta	44200

closely located nine wells and nine seismic profiles were used (Figure 2, Tables 1 and 2). In middle area, named Kakwa, three wells were used, and five wells were used to estimate desorbed gas volume in northwestern area (Figure 2 and Table 1).

In eastern area, as the well to seismic calibration is prior step, it is conducted to check the relationship between well data (depth domain data) and seismic data (time domain data); sonic log was converted to velocity (check-shot) data from the well (100090407226W500) to calibrate with 2D seismic profile (KK-103) (Figure 4 and 1st step of right column, Figure 5).

Seismic interpretation (time domain) in eastern area was converted in depth domain to reflect structural morphology

of Montney Formation when building 3D model of log-based calculated desorbed gas volume (depth domain) in study area (2nd to 4th step of right column, Figure 5).

The desorbed gas volume is driven within 17 wells by conventional logs [11] (left column, Figure 5 and Table 1). These estimated volumes were divided into upper and lower member of Montney Formation, and log upscaling was applied to optimize the difference between upper and lower Montney member (5th step of right column, Figure 5). The same 3D model grid size, I, J, and K direction to 50 m, 50 m, and 4.4 m, respectively, is applied to three area of the play (6th step of right column, Figure 5). A moving average algorithm was applied to understand the three-dimension distribution pattern of the desorbed gas volume (Figure 5).

4. Results

4.1. Volume Calculation of Shale, Illite Mineral, and Desorbed Gas. The shale volume (V_{shale}) fraction is calculated from index gamma-ray (GR) [11, 26–29], I_{GR} :

$$V_{\text{shale}} = I_{\text{GR}} = \frac{(GR_{\log} - GR_{\min})}{(GR_{\max} - GR_{\min})}, \quad (1)$$

where $GR_{\log}$ refers to the conventional depth domain gamma-ray log, $GR_{\min}$ represents shale free clean sand formation, and $GR_{\max}$ appears to be thoroughly shale formation with free sand [28, 30]. These $GR_{\min}$ and $GR_{\max}$ were

FIGURE 4: Well to seismic calibration with Alberta dataset: (a) seismic profile KK-103 with well 100090407226; (b) seismic profile KK-101 which were perpendicular with KK-103. This seismic interpretation surface (upper, lower Montney, and Belloy Formation) was divided based on the well log (GR) interpretation.

FIGURE 5: The workflow of three-dimension modeling of desorbed gas volume applied in eastern area in which has seismic profile. In middle and northwestern area, however, the workflow of the calculation of shale volume, illite mineral volume, and desorbed gas volume and from well log upscaling to moving average is applied.

determined as 20 and 200 gAPI (the unit of gamma-ray defined by American Petroleum Institute), respectively, by multiwell histogram analysis of each Alberta and British Columbia province dataset that its lower and upper 10% of gamma-ray values were eliminated due to anomalies (Figure 6). From the equation (1), shale volume of each well was calculated, and its average shale volume fraction refers to 0.38 v/v , 0.34 v/v , and 0.65 v/v in eastern, middle, and northwestern areas, respectively (second column of Figures 6–8 and Table 3). The lower member of

the Montney Formation is abundant in shale than the upper member in Alberta, which is the opposite in British Columbia (Table 3).

The illite mineral volume (V_{ill}) fraction was calculated based on well logs [11].

$$\therefore V_{ill} = \frac{(V_{shale} \times \rho_{shale}) - (V_{shale} \times \rho_{clays})}{(\rho_{ill} - \rho_{clays})}. \quad (2)$$

FIGURE 6: Well-log stratigraphy cross section displaying the upper and lower zone of Montney Formation and Belloy Formation of nine wells of eastern area (Table 1). Upper Montney Formation is flattened. First column is gamma-ray log; second column is volume of shale drove from equation (1); third column is volume of illite mineral calculated from equation 6; fourth column is volume of desorbed gas drove from equation 7.

FIGURE 7: Well-log stratigraphy cross section showing the Montney Formation division of three wells of middle area. Belloy Formation and lower member of UWI 100030106506W600 and 100032306406W600 were not defined. Upper member Montney is flattened. Column display is equal to Figure 5.

Equation (2) was used to calculate illite mineral volume fraction in shale formation, and its average value refers to $0.25 v/v$, $0.216 v/v$, and $0.4 v/v$ in eastern, middle, and north-western area, respectively (third column of Figures 6–8 and Table 3). As similar to the calculated volume of shale in each plays, illite mineral volume also shows the greatest volume in the British Columbia. Unlike the shale volume separation of

upper and lower member, however, the volume of illite is greater in upper member of Montney Formation throughout the study plays.

Desorbed gas volume ($V_{\text{desorbed gas}}$) was estimated by using illite mineral volume fraction in shale reservoir [11].

$$V_{\text{desorbed gas}} = (6.317) + (8.534 + V_{\text{ill}}). \quad (3)$$

FIGURE 8: Well-log stratigraphy cross section representing the upper and lower zone of Montney Formation and Belloy Formation of five wells (WA 28232, 29010, 29375, 29655, 31401) of northwestern area. Upper Montney Formation is flattened. Column display is equal to Figure 5.

From equation (3), log-based desorbed gas volume was calculated throughout the studied wells, and its average volume shows 8.52 scf/ton, 8.15 scf/ton, and 9.78 scf/ton in eastern, middle, and northwestern area, respectively (fourth column of Figures 6–8 and Table 3). From the results, it shows the greatest volume in northwestern area and lowest in eastern and middle area. This reflects the introduced procedure that if the formation has great amount of shale and illite mineral, its desorbed gas volume may also have similar volume in formation.

4.2. Three-Dimensional Model of Desorbed Gas. Three-dimensional models were generated to understand the distribution pattern of desorbed gas volume (Figures 9–11). Calculated desorbed gas volume was upscaled, prior to modeling procedure, and grid size was decided as 50 m, 50 m, and 4.4 m in the I, J, and K direction which is same in three study areas. The method applied to build three-dimension modeling is moving average algorithm (Figure 5). The eastern area model, using 9 wells, separated by upper and lower member of Montney Formation, represents the highest desorbed gas volume around 100110407226W500 well (northern region) and lowest desorbed gas volume at 100163207126W500 well (eastern region) (Figure 9). The division of upper and lower members was obvious that the upper member's average

desorbed gas volume is 8.62 scf/ton, and the lower member's volume is 8.35 scf/ton (Figure 9 and Table 3). The model of middle area was generated from the upper member boundary, using 3 wells, due to the lack of lower boundary. The result of upper member surface, however, represents more distinctive than other 3D models that around 100142506406W500 well indicates the highest desorbed gas volume (9.28 scf/ton) whereas, nearby 100030106506W600 well shows the lowest desorbed gas volume (6.9 scf/ton) (Table 3). Likewise, eastern area result, the northwestern model, using 5 wells, was divided into upper and lower members of Montney Formation. The highest concentration of desorbed gas volume is northwestern region (Figure 11). Its result also indicates that upper member's average desorbed gas volume (10.82 scf/ton) is slightly greater than lower member's desorbed gas volume (9.43 scf/ton) (Figure 11 and Table 3). In short, the 3D model result generally represents that upper member of Montney Formation has higher concentration of desorbed gas volume than lower member. The distribution of desorbed gas, however, throughout the Montney Formation is not clear because the desorbed gas volume occurrence is not controlled by the burial depth of its play, rather it reflects each shale play mineral composition characteristic which were effected by their depositional environment.

TABLE 3: Shale volume, illite mineral volume, and estimated desorbed gas volume in each shale plays. First area refers to nine wells is located in eastern area of Montney Formation; second area wells were three well situated middle in Montney Formation; in third area, bottom five wells are located on northwestern part of Montney Formation. In most of well, Montney Formation is divided in to upper and lower member. Each volume was calculated within upper and lower member, by wells and by areas. AB: Alberta; BC: British Columbia.

Result	UWI	Eastern area (AB)					Middle area (AB)					Northwestern area (BC)				
		1000603	1000604	1000904	1001103	1001104	1001333	1001603	1001632	1021233	1000301	1000323	1001425	200C05	200C004	202C09
V_{shale}		07226	07226	07226	07226	07226	07126	07226	07126	07126	06506	06406	06406	2H094B	F094G	2G094G
		W500	W500	W500	W500	W500	W500	W500	W500	W500	W600	W600	W600	0902	0800	0800
	Upper (v/v)	0.35	0.35	0.37	0.36	0.37	0.35	0.34	0.27	0.35	—	—	—	0.95	0.84	0.65
	Lower (v/v)	0.45	0.45	0.47	0.45	0.47	0.45	0.42	0.36	0.45	—	—	—	0.76	0.75	0.57
V_{III}	Average by well (v/v)	0.39	0.39	0.4	0.39	0.4	0.38	0.37	0.3	0.39	0.12	0.41	0.5	0.81	0.79	0.58
	Average by area (v/v)				0.38						0.34					0.65
$V_{\text{desorbed gas}}$	Upper (v/v)	0.28	0.26	0.28	0.26	0.28	0.28	0.24	0.23	0.28	—	—	—	0.67	0.58	0.44
	Lower (v/v)	0.24	0.24	0.24	0.23	0.26	0.26	0.21	0.21	0.24	—	—	—	0.44	0.43	0.31
	Average by well (v/v)	0.26	0.25	0.26	0.25	0.28	0.27	0.23	0.22	0.27	0.07	0.23	0.30	0.49	0.46	0.33
	Average by area (v/v)				0.25						0.216					0.4
$V_{\text{desorbed gas}}$	Upper (v/v)	8.72	8.57	8.72	8.6	8.79	8.73	8.4	8.3	8.78	—	—	—	12.06	11.31	10.13
	Lower (v/v)	8.42	8.4	8.4	8.3	8.53	8.55	8.14	8.11	8.37	—	—	—	10.09	10.06	8.97
	Average by well (v/v)	8.6	8.51	8.6	8.5	8.71	8.67	8.29	8.24	8.63	6.9	8.28	9.28	10.56	10.23	9.16
	Average by area (v/v)				8.52						8.15					9.78

FIGURE 9: The three-dimensional model result of eastern area. It represents the division of upper and lower member of Montney Formation. The upper member has relatively higher value of desorbed gas volume than the lower member. Around the UWI 100110407226W500 have the highest and lowest in eastern area (nearby UWI 100163207126W500) of desorbed gas volume (the legend scale of Figures 9–11 set to be the same).

4.3. Comparison of Desorbed Gas Volume to Gas Production History. The estimated average desorbed gas volume of five wells was compared with gas production history data per well and fracture stage. The several cases of cumulative gas production by the month such as 12–44 months, 18–44 months,

24–44 months, 30–44 months, and 36–44 months were collected, using two types of cross-plot, desorbed gas versus cum gas production and desorbed gas *average stage spacing versus cum gas per stage, to look for the desorbed gas contribution to overall gas production (Figures 12 and 13,

FIGURE 10: The three-dimensional model of the middle area using three wells. The desorbed gas volume shows highest toward the central region (near the UWI 100142506406W600) and lowest in northwestern region (near the UWI 100030106506W600).

FIGURE 11: The three-dimensional model of northwestern area. It appears the separation of the upper and lower member of Montney Formation. The upper member represents higher volume of desorbed gas. In northwestern area shows the most concentrated and highest desorbed gas volume.

FIGURE 12: Desorbed gas versus cum gas production history cross-plots. From cum 12-44 to cum 36-44 represents to the cumulative gas production by month. The correlation coefficient increases toward the cum 36-44 indicates that estimated desorbed gas was more correlative at the end of gas production. Each mark represents the well use for the comparison and included in Table 4. R^2 represents correlation coefficient.

FIGURE 13: Desorbed gas * average stage spacing versus cum gas per fracture stage cross-plots. Horizontal length was divided into stages, and its average length was multiplied to estimated desorbed gas volume. The gas production amounts were divided by stages. The correlation coefficient slightly increased toward the end stage of gas production. Each mark represents the well use for the comparison and included in Tables 4 and 5. R^2 represents correlation coefficient.

Tables 4 and 5). The desorbed gas versus cum gas production cross-plot shows the gradual increase of correlation coefficient from cum 12-44 ($R^2 = 0.2323$) to cum 30-44 ($R^2 = 0.9681$), and also, it converges to $R^2 \approx 0.96$ at cum 36-44 (Figure 12). The other cross-plot result also shows the gradual increase of R^2 until cum 24-44/stage but it slightly decreases toward the cum 36-44/stage, and it converges to $R^2 = 0.8$ at cum 36-44 (Figure 13). Although fracture stage spacing and number of fracture stage influenced production

history, the relatively low R^2 of the desorbed gas volume to gas production history per fracture stage implies additional elements of reservoir design such as fracture system, stimulated rock volume, and dynamic reservoir pressure should be considered. Without these complicated approaches, the comparison result generally indicates that the earlier stage of gas production is mainly contributed by the free gas in fractured zone, and toward the later stage of gas production may be affected by the desorbed gas production.

TABLE 4: Five wells compared between the log-based estimated desorbed gas volume and gas production history data. From cum 12-44 to cum 35-44 refers to the sum of gas production month. Length refers to the horizontal length used for gas production of well. This length was divided into stages as a given standard, and its average length represents the average stage spacing. AB: Alberta; BC: British Columbia; E^3m^3 : thousand cubic meter.

UWI	Location	Average volume of desorbed gas (scf/ton)	Cum 12-44 (E^3m^3)	Cum 18-44 (E^3m^3)	Cum 24-44 (E^3m^3)	Cum 30-44 (E^3m^3)	Cum 36-44 (E^3m^3)	Length (m)	Average stage spacing (m)	Stage count	Marks
100110307226W500	AB	8.41	12024.7	8493.8	5771.3	3758.4	1959.8	1142.6	67.2	17
100142506406W600	AB	9.28	28629.9	23238.1	11312.3	4925	2396	2122.5	84.9	25
100030106506W600	AB	6.9	5712	3380.7	2347.8	1474.4	648.4	1443.5	96.2	15
200C052H094G0800	BC	10.56	13199.5	12844.9	10029.3	6170	3103.5	1723.1	191.5	9
202C092G094G0800	BC	9.16	13763.2	10382.1	7070.7	5151.7	2568.5	950.4	55.9	17

TABLE 5: Estimated desorbed gas volume and sum of gas production by month were modified to figure out the gas production amount by stage count and average stage spacing factors.

UWI	Location	Average volume of desorbed gas (scf/ton)	((Desorbed gas) * (Avg. spacing)) ((scf/ton) * m)	((Cum 12-44)/(stage)) (E^3m^3)	((Cum 18-44)/(stage)) (E^3m^3)	((Cum 24-44)/(stage)) (E^3m^3)	((Cum 30-44)/(stage)) (E^3m^3)	((Cum 36-44)/(stage)) (E^3m^3)	Marks
100110307226W500	AB	8.41	565.2508498	707.33	499.63	339.48	221.08	115.28
100142506406W600	AB	9.28	787.857146	1145.19	929.52	452.49	197	95.84
100030106506W600	AB	6.9	664.0284004	380.8	225.38	156.52	98.29	43.22
200C052H094G0800	BC	10.56	2020.77	1466.61	1427.21	1114.36	685.55	344.83
202C092G094G0800	BC	9.16	512.07	809.6	610.71	415.92	303.04	151.08

5. Discussion and Conclusion

The estimation of desorbed gas volume from canister volume and mineralogy can be very various in types of shale reservoir. The relationship between reservoir properties and desorbed gas volume should be constructed in each shale play. The method of this study is most likely valid only to Montney play. Desorbed gas volume is minor contributor in the Montney play, so the free gas volume has to be assessed for the exact evaluation. Despite of these limitations, the method in this study can predict the timing of desorbed gas contributing to total production in the Montney play. 3D models also can provide distribution of desorbed gas volume and high potential area without complex and time-consuming simulation.

The shale volume, illite mineral volume, and desorbed gas volume within three different shale gas areas in Montney Formation were calculated. These represents average V_{shale} is 0.38 v/v , 0.34 v/v , and 0.65 v/v ; average V_{ill} is

0.25 v/v , 0.216 v/v , and 0.4 v/v ; average $V_{\text{desorbed gas}}$ is 8.52 scf/ton, 8.15 scf/ton, and 9.78 scf/ton in eastern, middle, and northwestern area, respectively (Table 3). 3D models were built for each play to figure out the distribution and high potential place of desorbed gas volume. Estimated desorbed gas volume was compared with gas production history to understand the contribution of desorbed gas production period to the entire production. Each model displays the high potential place for desorbed gas in the Montney play. Furthermore, the models show that the desorbed gas volume gradually increases westward (Figures 9–11). The comparison between estimated desorbed gas volume and gas production history indicates that toward the later stage of production (from cum 12-44 to 36-44), the correlative coefficient increased. This implies that desorbed gas gradually increases its proportion and contributes to the gas production at the end of stage (Figures 12 and 13).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request and approval of the operator company.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

- [1] L. Johnson, P. Kralovic, and A. Romanjuk, "Canadian crude oil and natural gas production and supply costs outlook (2016–2036)," Canadian Energy Research Institute, 2016.
- [2] K. A. Bowker, "Development of the Barnett shale play, Fort Worth Basin," *Bulletin of American Association of Petroleum Geologist*, vol. 91, no. 4, pp. 1–13, 2007.
- [3] C. H. Sondergeld, K. E. Newsham, J. T. Comisky, M. C. Rice, and C. S. Rai, "Petrophysical considerations in evaluating and producing shale gas resources," in *SPE Unconventional Gas Conference*, Pittsburgh, PA, USA, January 2010.
- [4] T. Alexander, J. Baihly, C. Boyer et al., "Shale gas revolution," *Oilfield Review*, vol. 23, no. 4, pp. 40–55, 2011.
- [5] J. C. Glorioso and A. Rattia, "Unconventional reservoirs: basic petrophysical concepts for shale gas," in *SPE/EAGE European Unconventional Resources Conference & Exhibition-From Potential to Production European Association of Geoscientists & Engineers*, p. cp-285, Vienna, Austria, March 2012.
- [6] R. L. Kennedy, W. N. Knecht, and D. T. Georgi, "Comparisons and contrasts of shale gas and tight gas developments, North American experience and trends," in *SPE Saudi Arabia Section Technical Symposium and Exhibition. Society of Petroleum Engineers*, Al-Khobar, Saudi Arabia, April 2012.
- [7] X. Wei, L. Jun, G. G. Dong et al., "Global cross application of shale gas development work flows revealed," in *20th Formation Evaluation Symposium of Japan. Society of Petrophysicists and Well-Log Analysts*, Chiba, Japan, October 2014.
- [8] D. M. Jarvie, "Shale resource systems for oil and gas: part 1—shale-gas resource systems," in *Shale reservoirs—Giant resources for the 21st century*, J. A. Breyer, Ed., vol. 97, pp. 69–87, AAPG Memoir, 2012.
- [9] C. Rivard, D. Lavoie, R. Lefebvre, S. Séjourné, C. Lamontagne, and M. Duchesne, "An overview of Canadian shale gas production and environmental concerns," *International Journal of Coal Geology*, vol. 126, pp. 64–76, 2014.
- [10] G. Kim, H. Lee, Z. Chen, S. Athichanagorn, and H. Shin, "Effect of reservoir characteristics on the productivity and production forecasting of the Montney shale gas in Canada," *Journal of Petroleum Science and Engineering*, vol. 182, article 106276, 2019.
- [11] I. H. Yang and H. S. Lee, "Desorbed gas volume estimation using conventional well-log data for the Montney Formation, Deep Basin, Canada," *Journal of Petroleum Science and Engineering*, vol. 162, pp. 633–651, 2018.
- [12] I. Langmuir, "The adsorption of gases on plane surfaces of glass, mica and platinum," *Journal of the American Chemical Society*, vol. 40, no. 9, pp. 1361–1403, 1918.
- [13] M. Elsaig, K. Aminian, S. Ameri, and M. Zamirian, "Accurate evaluation of Marcellus Shale petrophysical properties," in *Paper presented at the SPE Eastern Regional Meeting*, Canton, OH, USA, September 2016.
- [14] A. Kakhodaie and R. Rezaee, "A new correlation for water saturation calculation in gas shale reservoirs based on compensation of kerogen-clay conductivity," *Journal of Petroleum Science and Engineering*, vol. 146, pp. 932–939, 2016.
- [15] C. D. Jenkins and C. M. Boyer, "Coalbed- and shale-gas reservoirs," *Journal of Petroleum Technology*, vol. 60, no. 2, pp. 92–99, 2008.
- [16] J. P. Zonneveld and T. F. Moslow, "Palaeogeographic evolution of the Montney in the Western Canada Sedimentary Basin," in *CSPG CSEG CWLS Joint Annual Convention*, pp. 15–19, Calgary, Canada, May 2017.
- [17] S. L. Montgomery, D. M. Jarvie, K. A. Bowker, and R. M. Polastro, "Mississippian Barnett Shale, Fort Worth basin, north-central Texas: gas-shale play with multi-trillion cubic foot potential," *Bulletin of American Association of Petroleum Geologist*, vol. 89, no. 2, pp. 155–175, 2005.
- [18] D. W. Gibson and D. E. Edward, "An overview of Triassic stratigraphy and depositional environments in the Rocky Mountain Foothills and western interior plains, Peace River Arch area, northeastern British Columbia," *Bulletin of Canadian Petroleum Geology*, vol. 38, no. 1, pp. 146–158, 1990.
- [19] G. R. Davies, "The Triassic of the Western Canada Sedimentary Basin: tectonic and stratigraphic framework, paleogeography, paleoclimate and biota," *Bulletin of Canadian Petroleum Geology*, vol. 45, no. 4, pp. 434–460, 1997.
- [20] G. R. Davies, T. F. Moslow, and M. D. Sherwin, "The lower Triassic Montney formation, west-central Alberta," *Bulletin of Canadian Petroleum Geology*, vol. 45, no. 4, pp. 470–505, 1997.
- [21] G. R. Davies, N. Waton, T. F. Moslow, and J. A. MacEachern, "Regional subdivisions, sequences, correlations and facies relationships of the Lower Triassic Montney Formation, west-central Alberta to northeastern British Columbia, Canada—with emphasis on role of paleostructure," *Bulletin of Canadian Petroleum Geology*, vol. 66, no. 1, pp. 23–92, 2018.
- [22] T. F. Moslow, B. Haverslew, and C. M. Henderson, "Sedimentary facies, petrology, reservoir characteristics, conodont biostratigraphy and sequence stratigraphic framework of a continuous (395 m) full diameter core of the Lower Triassic Montney Fm, northeastern British Columbia, Western Canada Sedimentary Basin," *Bulletin of Canadian Petroleum Geology*, vol. 66, no. 1, pp. 259–287, 2018.
- [23] J. P. Zonneveld and T. F. Moslow, "Palaeogeographic setting, lithostratigraphy, and sedimentary framework of the Lower Triassic Montney Formation of western Alberta and north-eastern British Columbia," *Bulletin of Canadian Petroleum Geology*, vol. 66, no. 1, pp. 93–127, 2018.

- [24] W. HanYi, "What factors control shale gas production and production decline trend in fractured systems: a comprehensive analysis and investigation," 2017, <http://arxiv.org/abs/1710.11464>.
- [25] D. E. Edwards, J. E. Barclay, D. W. Gibson, G. Kvill, and E. Halton, "Triassic strata of the Western Canada sedimentary basin," in *Geological Atlas of the Western Canada Sedimentary Basin*, G. D. Mossop and I. Shetsen, Eds., vol. 16, pp. 257–275, Canadian Society of Petroleum Geologist and Alberta Research Council, 1994.
- [26] G. B. Asquith and C. R. Gibson, "Basic well log analysis for geologists," *American Association of Petroleum Geologist*, vol. 3, 1983.
- [27] M. H. Rider, *The Geological Interpretation of Well Logs*, Rider-French Consulting Limited, 2nd edition, 1999.
- [28] N. P. Szabó, "Shale volume estimation based on the factor analysis of well-logging data," *Acta Geophysica*, vol. 59, no. 5, pp. 935–953, 2011.
- [29] S. Moradi, M. Moeini, M. K. G. Al-Askari, and E. H. Mahvelati, "Determination of shale volume and distribution patterns and effective porosity from well log data based on cross-plot approach for a shaly carbonate gas reservoir," *IOP Conference Series: Earth and Environmental Science*, vol. 44, article 042002, pp. 1315–1755, 2016.
- [30] Schlumberger, *Log Interpretation Principles/Applications*, Schlumberger Educational Services, 1991.