Results of Coalbed-Methane Drilling, Meadowfill Landfill, Harrison County, West Virginia

By Leslie F. Ruppert, Michael H. Trippi, Nick Fedorko,
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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
millimeter (mm)	0.03937	inch (in.)
	Volume	
cubic inch (in^3)	16.39	cubic centimeter (cm^3 or cc)
cubic inch (in^3)	16.39	milliliter (mL)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
milliliter (mL)	0.06102	cubic inch (in^3)
cubic centimeter (cm^3 or cc)	0.06102	cubic inch (in^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
	Pressure	
inch of mercury at 60°F (in Hg)	3.377	kilopascal (kPa)
pound per square inch (lb/in^2 or PSIA)	6.895	cubic foot per pound avoirdupois (ft^3/lb)
	Calorific value	
British thermal unit (Btu)	1,055.056	joule (J)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F–32)/1.8

Gas desorption volumes are provided in cubic centimeters, which is abbreviated using the standard industry abbreviation, cc, instead of cm^3.

Gas content measurements are provided in both standard cubic feet per ton (SCF/ton) and cubic centimeters per gram (cc/g). The abbreviations are those used by the oil and gas industry.

Hydrostatic pressure for coal is measured in pounds per square inch of area (PSIA, an industry abbreviation).

The Langmuir volume is the maximum gas capacity of the coal and is measured in standard cubic feet per ton (SCF/ton) or cubic centimers per gram (cc/g).

The Langmuir pressure is the pressure at which the coal absorbs half of its maximum gas capacity; it is measured in pounds per square inch of area (PSIA).

The isotopic composition of carbon (carbon 13, ^{13}C) in methane is reported as the deviation (expressed as $\delta^{13}C$) in units of parts per thousand (per mil) relative to the Vienna Peedee belemnite (VPDB) standard.

The isotopic composition of hydrogen (deuterium, ^{2}H) in methane is reported as the deviation (expressed as $\delta^{2}H$) in per mil relative to the Vienna standard mean ocean water (VSMOW).

Results of Coalbed-Methane Drilling, Meadowfill Landfill, Harrison County, West Virginia

By Leslie F. Ruppert,[1] Michael H. Trippi,[1] Nick Fedorko,[2] William C. Grady,[3] Cortland F. Eble,[4] and William A. Schuller[5]

Abstract

The U.S. Environmental Protection Agency funded drilling of a borehole (39.33889°N., 80.26542°W.) to evaluate the potential of enhanced coalbed-methane production from unminable Pennsylvanian coal beds at the Meadowfill Landfill near Bridgeport, Harrison County, W. Va. The drilling commenced on June 17, 2004, and was completed on July 1, 2004. The total depth of the borehole was 1,081 feet (ft) and contained 1,053.95 ft of Pennsylvanian coal-bearing strata, and 27.05 ft of Mississippian strata.

A total of 37.02 ft of high-volatile A and B bituminous Pennsylvanian coal was cored and desorbed from the Harlem, Brush Creek, Upper Freeport, Upper Kittanning upper split, and Upper Kittanning coal beds and the Clarion coal zone. Intact coal intervals were desorbed for a maximum period of 92 days before they were crushed to approximately 10-mesh to determine residual gas amounts. Crushed coal was desorbed for a period of 36 days. Measured gas content, on a dry, ash-free basis, ranged from 79.69 standard cubic feet per ton (SCF/ton), or 2.49 cubic centimeters per gram (cc/g), for the Harlem coal bed to 223.21 SCF/ton, or 6.98 cc/g, for the Clarion coal zone.

Methane contents of desorbed gas from coal samples in the Meadowfill Landfill study area ranged from 14.87 to 98.73 percent (corrected for air contamination) for the Harlem coal bed and Clarion coal zone, respectively. Proportions of methane to the sum of the higher molecular weight hydrocarbons ranged from about 40 to 340 as the desorbed gas contained only a small percentage of higher weight hydrocarbons. Coalbed methane from the Upper Kittanning upper split and the Upper Kittanning coal beds is thermogenic in origin with isotopic composition of carbon (carbon 13, ^{13}C) in methane (expressed as $\delta^{13}C$ in units of parts per thousand (per mil) relative to the Vienna Peedee belemnite (VPDB) standard) ranging from -46.6 to -48.7 per mil. Coalbed methane from the Brush Creek and Upper Freeport coal beds and the Clarion coal zone contains some biogenic methane with $\delta^{13}C$ values ranging from -51.05 to -51.56 per mil.

Introduction

In 2002, U.S. landfills emitted about 200 million tons of methane, accounting for about 3 percent of the total U.S. greenhouse-gas emissions (Panehal and Guzzone, 2004). The Meadowfill Landfill near Bridgeport, Harrison County, W. Va. (fig. 1), which is developed above the Pittsburgh coal bed, is one of the largest landfills in the State. The landfill is expected to produce nearly 426,000 tons of methane and 1 million tons of carbon dioxide over the next 40 years (The West Virginia High Technology Consortium Foundation, unpub. data, 2003). Concerned with the direct venting of these gases in the atmosphere, the U.S. Environmental Protection Agency (EPA) funded a demonstration project to evaluate the feasibility of separating the landfill gas (LFG) into methane and carbon dioxide streams and then using the methane for power generation and sequestering the carbon dioxide in unmined coal beds beneath the landfill. A test borehole was drilled adjacent to the landfill to verify (1) the presence of coal beds that could potentially be used to sequester the carbon dioxide, and (2) to obtain coal samples to evaluate the coalbed-methane (CBM) resource within those coal beds.

Drilling started on June 17, 2004, and was completed on July 1, 2004, running 5-day, 12-hour shifts per week with some downtime. The West Virginia Geological and Economic Survey (WVGES), in cooperation with EG&G Technical Services, Inc., Morgantown, W. Va., and the West Virginia High Technology Consortium Foundation, Fairmont, W. Va., coordinated the drilling, electric logging, and coalbed-methane desorption. The borehole was drilled by L.J. Hughes & Sons, Summersville, W. Va., and the geologist's log can be obtained

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[3]West Virginia Geological and Economic Survey, Morgantown, W. Va.
[4]Kentucky Geological Survey, Lexington, Ky.
[5]EG&G Technical Services, Inc., Morgantown, W. Va.

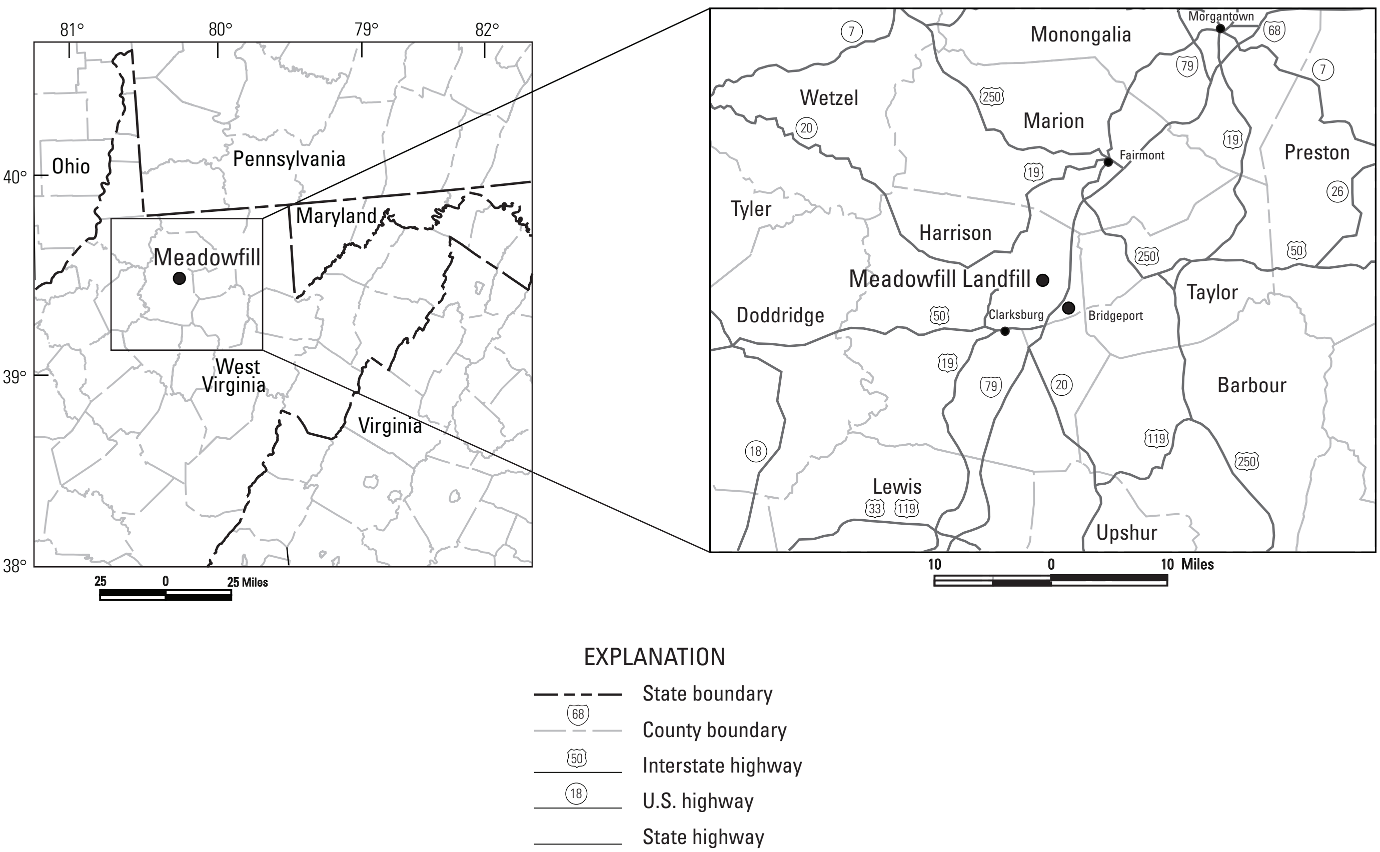

Figure 1. Generalized location map of the Meadowfill Landfill study area in Harrison County, W. Va.

through the West Virginia Geological and Economic Survey (2007). After desorption was completed, the coal was analyzed in the WVGES laboratory. The 1,081 feet (ft) of core contained 1,053.95 ft of Pennsylvanian coal-bearing strata and 27.05 ft of Mississippian strata. Six coal beds or zones were present and cored at the landfill site: the Harlem, Brush Creek, Upper Freeport, Upper Kittanning upper split, and Upper Kittanning coal beds, and the Clarion coal zone (fig. 2).

Methods

Desorption Methods

Procedures modified from Gas Research Institute (1995), Stricker and other (2000), and Barker and others (2002) were followed throughout the coring and desorption to measure gas contents of the coals. During coring, both the time that the coal was retrieved off the bottom (base of the borehole) and the temperature of the water circulating in the borehole were recorded in order to estimate the amount of lost gas (the volume of gas desorbed between the time the core was retrieved from the bottom and the time that the coal was sealed in a desorption canister) and the reservoir temperature, respectively. As soon as the core barrel was recovered at the surface, the core was extracted onto a wooden core holder, quickly described (coal versus rock), and measured. The coal was removed from the wooden core holder in a graduated curved polyvinyl-chloride (PVC) scoop to keep it intact, weighed, and placed in a thin (approximately 4-mm-thick) sheet-plastic sleeve with holes to maintain the stratigraphic integrity of the coal during desorption. Within 10 to 16 minutes of reaching the surface, the coal was placed in a thin (1-mm-thick), semi-rigid polyethylene tube and capped with a vinyl lid to maintain the stratigraphic integrity of the coal. Thickness and interval measurements were written on the tube, and then it was placed in either a 2-ft-long aluminum or a 1-ft-long PVC canister (table 1), depending on the coal interval thickness. Each canister was filled with distilled water in order to eliminate headspace (the volume of air left in the canister) and treated with a biocide (a benzalkonium chloride 1:750 aqueous solution) to prevent bacterial contamination (Faraj and Hatch, 2004). The canister was sealed and placed in a water bath kept at reservoir temperature (68°F–70°F) as estimated from the circulating borehole water. This temperature was roughly equivalent to measured reservoir temperatures in cores within northern West Virginia.

<table>
<tr><th colspan="2">System (and series)</th><th>Group or formation</th><th>Coal bed or zone</th></tr>
<tr><td rowspan="4">Pennsylvanian</td><td>Upper</td><td>Monongahela Group</td><td></td></tr>
<tr><td rowspan="2">Middle</td><td>Conemaugh Group</td><td>Harlem coal bed
Brush Creek coal bed</td></tr>
<tr><td>Allegheny Group</td><td>Upper Freeport coal bed
Upper Kittanning upper split coal bed
Upper Kittanning coal bed
Clarion coal zone</td></tr>
<tr><td>Lower</td><td>Pottsville Group</td><td></td></tr>
<tr><td>Mississippian</td><td>Upper</td><td>Mauch Chunk Group</td><td></td></tr>
</table>

Figure 2. Generalized stratigraphic column showing Pennsylvanian coal beds and coal zones from which samples were desorbed for coalbed-methane content in the Meadowfill Landfill study area, Harrison County, W. Va. (Based on Rice and others, 1994.)

Desorbed gas volumes (tables 2 and 3) were initially measured after 10 to 30 minutes from the time that the canisters were sealed. To obtain volumes, the canister valves were opened and the volumetric displacement of water in a graduated manometer was recorded. In addition, the ambient air and water-bath temperatures and the atmospheric pressure were recorded during each desorption measurement to correct desorbed gas volumes according to standard temperature and pressure (STP). Each canister was measured approximately every 10 minutes for the first half hour to hour, and then every 20 to 30 minutes for the first day. Canisters were not monitored overnight but were measured upon reaching the drill site in the morning. After a week, the canisters were moved to a laboratory at the U.S. Geological Survey (USGS) where they were measured once a day for 4 weeks. Over the course of the desorption, the canisters were measured less frequently because less gas was desorbed from the coals. Toward the end of the desorption tests, the canisters were measured bimonthly. See appendix A for desorption data for all of the coal samples.

Lost gas was estimated using the graphical methods found in Barker and others (2002). Diffusion rates of coal samples from the Meadowfill Landfill study area were relatively low; thus, lost gas volumes also were very low, ranging from approximately 25 cubic centimeters (cc, an abbreviation commonly used in oil and gas geochemical reports) in an interval from the Harlem coal bed (B3–1, canister 1) to a high of 200 cc in an interval from the Upper Kittanning coal bed (US4–30, canister 3). See appendix A for lost gas amounts for all canisters.

Table 1. Coal bed or coal zone name, depth of sample, and canister number for desorbed coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.

Coal bed or zone	Depth of sample (feet)	Canister number
Harlem coal bed	231.75–232.65	Canister 1: B3–1
	232.65–233.73	Canister 2: B3–3
Brush Creek coal bed	441.97–443.55	Canister 1: US4–5
Upper Freeport coal bed[1]	530.75–532.22	Canister 1: US4–6
Upper Kittanning upper split coal bed	632.40–634.25	Canister 1: US4–14
	634.25–635.16	Canister 2: B3–4
Upper Kittanning coal bed[2]	642.40–644.00	Canister 1: US4–8
	644.00–644.40	Canister 2: B3–5
	644.80–645.48	
	645.48–647.20	Canister 3: US4–30
Clarion coal zone	776.00–776.90	Canister 1: B3–6
	776.90–777.80	Canister 2: B3–7
	777.80–778.50	Canister 3: B3–8
	778.50–779.30	Canister 4: B3–9

[1]The depth interval for the Upper Freeport coal bed does not include 0.20 feet of canneloid coal from the overlying carbonaceous shale that was placed in canister US4–6 for desorption.

[2]For canister 2 (canister B3–5), the sample depth is broken into two sections with a 0.40-foot split: 644.00 to 644.40 feet and 644.80 to 645.48 feet.

On October 26, 2004, 126 days after the first coal was cored and recovered from the borehole, the canisters were moved from the USGS laboratory to a WVGES core facility in Morgantown, W. Va. The canisters were opened and the intact, polyethylene-sleeved coal interval was removed and sawed in half lengthwise. Both halves of the coal core were weighed, and one of the halves was resealed in its canister within a period of 5 minutes. The other half was transported to WVGES laboratories at West Virginia University for ultimate, proximate (table 4), and petrographic analyses.

The sealed canisters were immediately transported to a Kentucky Geological Survey laboratory in Lexington, Ky. The gas content of each canister was measured. Each canister was then opened, the coal was extracted and crushed in a hammer mill to approximately 10-mesh size. The coal was collected at the base of the hammer mill and resealed within its canister within 5 minutes. Residual-gas measurements were taken over a period of about 10 hours (appendix A) before the canisters were transported back to the USGS laboratories for additional residual-gas desorption measurements. Residual-gas measurements were halted after 34 days because initial results from the drilling program were due to funding organizations.

Table 2. Desorbed and residual gas volumes, on a measured raw-total-gas basis, by coal bed or zone and canister number, for the coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.

[Where there is more than one canister per coal bed or zone, a weighted average was calculated. Canister numbers beginning with US4 indicate 2-foot-long aluminum canisters; canister numbers beginning with B3 indicate 1-foot-long polyvinyl chloride canisters. Abbreviations are as follows: SCF/ton, standard cubic feet per ton; cc/g, cubic centimeter per gram]

Coal bed or zone	Canister number	Total thickness (feet)	Depth of sample (feet)
Harlem coal bed	B3–1	0.90	231.75–232.65
	B3–3	1.08	232.65–233.73
	weighted average	1.98	
Brush Creek coal bed	US4–5	1.58	441.97–443.55
Upper Freeport coal bed	US4–6	1.47	530.75–532.22
Upper Kittanning upper split coal bed	US4–14	1.85	632.40–634.25
	B3–4	0.91	634.25–635.16
	weighted average	2.76	
Upper Kittanning coal bed	US4–8	1.60	642.40–644.00
	B3–5	1.08	644.00–644.40
			644.80–645.48
	US4–30	1.72	645.48–647.20
	weighted average	4.40	
Clarion coal zone	B3–6	0.90	776.00–776.90
	B3–7	0.90	776.90–777.80
	B3–8	0.70	777.80–778.50
	B3–9	0.80	778.50–779.30
	weighted average	3.30	

Table 3. Desorbed and residual gas volumes, on a dry, ash-free basis, by coal bed or zone and canister number, for the coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.

[Where there is more than one canister per coal bed or zone, a weighted average was calculated. Canister numbers beginning with US4 indicate 2-foot-long aluminum canisters; canister numbers beginning with B3 indicate 1-foot-long polyvinyl chloride canisters. Abbreviations are as follows: SCF/ton, standard cubic feet per ton; cc/g, cubic centimeter per gram]

Coal bed or zone	Canister number	Total thickness (feet)	Depth of sample (feet)
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	weighted average	1.98	
Brush Creek coal bed	US4–5	1.58	441.97–443.55
Upper Freeport coal bed	US4–6	1.47	530.75–532.22
Upper Kittanning upper split coal bed	US4–14	1.85	632.40–634.25
	B3–4	0.91	634.25–635.16
	weighted average	2.76	
Upper Kittanning coal bed	US4–8	1.60	642.40–644.00
	B3–5	1.08	644.00–644.40
			644.80–645.48
	US4–30	1.72	645.48–647.20
	weighted average	4.40	
Clarion coal zone	B3–6	0.90	776.00–776.90
	B3–7	0.90	776.90–777.80
	B3–8	0.70	777.80–778.50
	B3–9	0.80	778.50–779.30
	weighted average	3.30	

Table 2. Desorbed and residual gas volumes, on a measured raw-total-gas basis, by coal bed or zone and canister number, for the coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.—Continued

Desorbed gas (intact core) (SCF/ton)	Residual gas (SCF/ton)	Total gas (SCF/ton)	Desorbed gas (intact core) (cc/g)	Residual gas (cc/g)	Total gas (cc/g)	Residual gas (percent)
38.87	28.79	67.66	1.21	0.90	2.11	43
45.82	25.68	71.50	1.43	0.80	2.23	36
42.69	27.06	69.75	1.33	0.84	2.17	39
69.68	49.56	119.24	2.18	1.55	3.73	42
61.12	16.50	77.62	1.91	0.52	2.43	21
89.18	56.49	145.67	2.79	1.77	4.56	39
87.62	24.73	112.35	2.74	0.77	3.51	22
88.61	44.51	133.12	2.77	1.39	4.16	33
96.77	30.30	127.07	3.02	0.95	3.97	24
80.80	35.92	116.72	2.53	1.12	3.65	31
90.77	16.19	106.96	2.84	0.51	3.35	15
90.74	26.68	117.42	2.84	0.84	3.67	23
112.71	46.32	159.03	3.52	1.45	4.97	29
137.83	43.82	181.65	4.31	1.37	5.68	24
150.00	36.77	186.77	4.69	1.15	5.84	20
152.80	34.15	186.95	4.78	1.07	5.85	18
137.06	40.63	177.69	4.28	1.27	5.55	23

Table 3. Desorbed and residual gas volumes, on a dry, ash-free basis, by coal bed or zone and canister number, for the coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.—Continued

Desorbed gas (intact core) (SCF/ton)	Residual gas (SCF/ton)	Total gas (SCF/ton)	Desorbed gas (intact core) (cc/g)	Residual gas (cc/g)	Total gas (cc/g)	Residual gas (percent)
45.28	33.53	78.81	1.41	1.05	2.46	43
51.56	28.88	80.44	1.61	0.90	2.51	36
48.78	30.91	79.69	1.52	0.97	2.49	39
83.07	59.10	142.17	2.60	1.85	4.45	42
116.02	31.31	147.33	3.63	0.98	4.61	21
112.35	71.21	183.56	3.51	2.23	5.74	39
127.97	37.56	165.53	4.00	1.17	5.17	23
117.91	59.18	177.09	3.68	1.85	5.54	33
135.13	42.28	177.36	4.22	1.32	5.54	24
119.56	53.47	173.03	3.74	1.67	5.41	31
172.72	30.83	203.55	5.40	0.96	6.36	15
143.44	41.83	185.27	4.48	1.31	5.79	23
142.40	58.56	200.96	4.45	1.83	6.28	29
174.29	55.41	229.70	5.45	1.73	7.18	24
176.81	43.38	220.19	5.53	1.36	6.89	20
200.61	44.85	245.46	6.27	1.40	7.67	18
172.20	51.02	223.21	5.38	1.59	6.98	23

Table 4. Selected proximate analyses for the coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.

Coal bed or zone	Depth of sample (feet)	Moisture (percent)	Volatile matter, dry basis (percent)	Volatile matter, as-received basis (percent)	Volatile matter, mineral-matter-free basis (percent)
Harlem coal bed	231.75–233.73	1.20	35.32	34.89	40.14
Brush Creek coal bed	441.97–443.55	0.91	33.28	32.98	39.70
Upper Freeport coal bed	530.75–532.22	1.11	22.36	22.11	42.44
Upper Kittanning upper split coal bed	632.40–635.16	1.24	28.45	28.09	41.01
Upper Kittanning coal bed	642.40–647.20	1.18	26.20	25.90	37.03
Clarion coal zone	776.00–779.30	1.36	26.20	25.84	33.38

Gas Analyses

Gas was sampled on August 5, 2004, which was 44 days after the first canister was sealed. Gas volumes were measured in the manometer and samples were collected directly from the manometer with a short (approximately 5-inch-long) piece of plastic tubing and bled into Tedlar bags. The bags were shipped to a commercial laboratory (Isotech Laboratories, Inc.) and analyzed for the following gas constituents (tables 5 and 6): He, H_2, Ar, O_2, CO_2, N_2, CO, methane (CH_4, also denoted as C_1), ethane (C_2H_6, also denoted as C_2), ethylene (C_2H_4), propane (C_3H_8, also denoted as C_3), *iso*-butene (iC_4H_{10}, also denoted as iC_4), *n*-butane (nC_4H_{10}, also denoted as nC_4), *iso*-pentane (iC_5H_{12}, also denoted as iC_5), *n*-pentane (nC_5H_{12}, also denoted as nC_5), and hexanes (denoted as C_{6+}). Results for hydrocarbon species were reported in parts per million (ppm) and converted to weight percent for this report.

In addition, the isotopic composition of carbon (carbon 13, ^{13}C) in methane (reported as the deviation (expressed as $\delta^{13}C$) in units of parts per thousand (per mil) relative to the Vienna Peedee belemnite (VPDB) standard) and the isotopic composition of hydrogen (deuterium, ^2H) in methane (reported as the deviation (expressed as δ^2H) in per mil relative to the Vienna standard mean ocean water (VSMOW)) were analyzed to determine gas origin (biogenic versus thermogenic) following the method in Bernard and others (1978). Gas samples from coal in the Brush Creek coal bed, Upper Freeport coal bed, and Clarion coal zone, and mixed intervals of the Upper Kittanning upper split and Upper Kittanning coal beds were analyzed (table 7).

The use of a short tube to collect gases from the manometer and evacuate it into gas collection bags did not preclude air contamination in the samples. To remove the air, we normalized all of the gas analyses (table 5) to an air-free basis (table 6).

Desorption Results and Gas Chemistry by Coal Bed and Coal Zone

Harlem Coal Bed

A 1.98-ft-long sample of coal from the Harlem coal bed was cored and retrieved to the surface from a depth of 231.75 to 233.73 ft at 17:50 hours[6] on June 22, 2004, and placed in two 1-ft-long PVC canisters for desorption. The overall moisture content of the coal was 1.20 percent and the ash yield was 12.02 weight percent on a dry basis (db) (table 4). The total gas content (using a weighted average) was 69.75 SCF/ton (2.17 cc/g), of which 42.69 SCF/ton (1.33 cc/g) was desorbed before crushing and 27.06 SCF/ton (0.84 cc/g) was residual, or desorbed from the crushed coal (table 2). A total of 39 percent of the measured total raw-gas-content was in the crushed, or residual, fraction. See tables A1, A2, A3, and A4 in appendix A for raw data.

- Canister 1 (B3–1; 231.75–232.65 ft)—A total of 96 desorption measurements was taken on the intact coal sample over 126 days (fig. 3) before it was crushed. The measured raw-total-gas content of the intact coal was 38.87 SCF/ton (1.21 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 4) and the measured residual raw-total-gas content was 28.79 SCF/ton (0.90 cc/g) (table 2). The measured raw-total-gas for the coal in the canister was 67.66 SCF/ton (2.11 cc/g), of which 43 percent was residual (table 2).

[6]For this study, a 24-hour clock was used for reporting time.

Table 4. Selected proximate analyses for the coal samples from the Meadowfill Landfill borehole, Harrison County, W. Va.—Continued

Ash, dry basis (percent)	Ash, as-received basis (percent)	Fixed carbon, dry basis (percent)	Fixed carbon, as-received basis (percent)	Fixed carbon, moist, mineral-matter free basis (percent)	Coal rank	Calorific value (British thermal units)
12.02	11.88	52.66	52.03	59.86	High-volatile B bituminous	13,112
16.15	16.01	50.56	50.10	60.30	High-volatile B bituminous	12,555
47.32	46.80	30.32	29.98	57.56	High-volatile C bituminous	7,776
30.40	30.02	41.16	40.65	58.99	High-volatile B bituminous	10,363
29.30	28.94	44.50	43.98	62.97	High-volatile A bituminous	10,648
21.50	21.21	52.30	51.59	66.62	High-volatile A bituminous	11,963

- Canister 2 (B3–3; 232.65–233.73 ft)—A total of 96 desorption measurements was taken on the intact coal sample over 126 days (fig. 3) before it was crushed. The measured raw-total-gas content of the intact coal was 45.82 SCF/ton (1.43 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 4) and the measured residual raw-total-gas content was 25.68 SCF/ton (0.80 cc/g) (table 2). The measured raw-total-gas for the coal in the canister was 71.50 SCF/ton (2.23 cc/g), of which 36 percent was residual (table 2).

Gas chemistry of the Harlem coal bed.—A composite gas sample was analyzed from the Harlem coal bed (table 5). The sample contained approximately 15 percent methane, even after correcting for air contamination (table 6). The low gas content is likely attributed to a significant migration of gas out of the Harlem coal bed due to its shallow depth (231.75–233.73 ft, table 1). In contrast, the nitrogen content of the Harlem coal bed is very high (83.12 percent, table 6). The origin of high nitrogen contents observed in this coal may be due to oxidation of the coal in the canisters (Morse and others, 2005). The proportion of methane to the higher molecular weight hydrocarbons (ethane, ethylene, propane, *iso*-butane, *n*-butane, *iso*-pentane, *n*-pentane, and hexanes) in the Harlem coal-bed gas is 39.70 (table 6). There was not enough of a sample for isotopic analysis.

Brush Creek Coal Bed

A 1.58-ft-long sample of coal from the Brush Creek coal bed was cored and retrieved to the surface from a depth of 441.97 to 443.55 ft at 8:10 hours on June 24, 2004, placed in a 2-ft-long aluminum canister (canister US4–5) for desorption for 124 days (fig. 5) before it was crushed. After crushing, the desorbed residual gas was measured for 35 days (fig. 6). The overall moisture content of the coal was 0.91 percent and the ash yield was 16.15 weight percent (db) (table 4). The total gas content was 119.24 SCF/ton (3.78 cc/g), of which 69.68 SCF/ton (2.18 cc/g) was desorbed before crushing and 49.56 SCF/ton (1.55 cc/g) was residual, or desorbed from the crushed coal (table 2). A total of 42 percent of the measured total raw-gas-content was in the crushed, or residual, fraction. See tables A5 and A6 in appendix A for raw data.

Gas chemistry of the Brush Creek coal bed.—A gas sample was analyzed from the Brush Creek coal bed. The sample contained 98 percent methane, 1.9 percent ethane, and small amounts of *iso*-butane (0.007 percent), and carbon dioxide (0.2 percent) (air-free basis). The ratio of methane to the higher molecular weight hydrocarbons was 52.29 (table 6). The value for $\delta^{13}C$ was -51.05 per mil and the value for $\delta^{2}H$ was -204.5 per mil (table 7).

Upper Freeport Coal Bed

A 1.27-ft-long sample of coal from the Upper Freeport coal bed was cored and retrieved to the surface from a depth of 530.95 to 532.22 ft at 16:22 hours on June 24, 2004, placed in a 2-ft-long aluminum canister (canister US4–6). In addition to the 1.27-ft-long coal sample, a 0.20-ft-long sample of canneloid coal from the overlying carbonaceous shale from 530.75 to 530.95 ft depth was inserted into the canister for desorption, bringing the total sampled thickness to 1.47 ft. The Upper Freeport coal and the canneloid coal were desorbed for 124 days (fig. 7) before they were crushed. After crushing, the desorbed residual gas was measured for 35 days (fig. 8). The overall moisture content of the coal was 1.11 percent and the ash yield was 47.32 weight percent (db) (table 4). The total gas content was 77.62 SCF/ton (2.43 cc/g), of which

Table 5. Raw gas geochemistry analyses for coal samples from core retrieved from the Meadowfill Landfill borehole, Harrison County, W. Va.

[These analyses are raw and uncorrected for air contamination. Abbreviations are as follows: SCF/ton, standard cubic feet per ton; He, helium; H_2, hydrogen; Ar, argon; O_2 oxygen; CO_2, carbon dioxide; N_2, nitrogen; CO, carbon monoxide; C_1, methane; C_2, ethane + ethylene; C_2H_4, ethylene; C_3, propane; *i*C_4, *iso*-butane; *n*C_4, *n*-butane; *i*C_5, *iso*-pentane; *n*C_5, *n*-pentane; C_{6+}, hexanes]

Coal bed or zone	Depth (feet)	Cumulative gas volume (SCF/ton)	He (percent)	H_2 (percent)	Ar (percent)	O_2 (percent)	CO_2 (percent)
Harlem coal bed	231.75–233.73	79.69	0.0033	0	0.864	20.02	0.07
Brush Creek coal bed	441.97–443.55	142.17	0.0026	0	0.623	15.94	0.075
Upper Freeport coal bed	530.75–532.22	147.33	0.0026	0	0.526	14.05	0.076
Upper Kittanning upper split coal bed and Upper Kittanning coal bed (part)	632.40–635.16	177.09	0.0028	0	0.382	10.01	0.71
Upper Kittanning coal bed (part)	642.40–647.20	185.27	0.0029	0	0.366	10.3	0.49
Clarion coal zone	776.00–779.30	223.21	0.0029	0.001	0.169	4.87	0.82

Table 6. Gas geochemistry analyses corrected for air contamination for coal samples from core retrieved from the Meadowfill Landfill borehole, Harrison County, W. Va.

[These analyses are corrected for air contamination and presented to two decimal points. Abbreviations are as follows: He, helium; H_2, hydrogen; Ar, argon; O_2, oxygen; CO_2, carbon dioxide; N_2, nitrogen; CO, carbon monoxide; C_1, methane; C_2, ethane + ethylene; C_2H_4, ethylene; C_3, propane; *i*C_4, *iso*-butane; *n*C_4, *n*-butane; *i*C_5, *iso*-pentane; *n*C_5, *n*-pentane; C_{6+}, hexanes; C_{2+}, methane + ethane + ethylene + propane + *iso*-butane + *n*-butane + *iso*-pentane + *n*-pentane + hexanes]

Coal bed or zone	Depth (feet)	Cumulative gas volume (SCF/ton)	He (percent)	H_2 (percent)	Ar (percent)	O_2 (percent)	CO_2 (percent)	N_2 (percent)
Harlem coal bed	231.75–233.73	79.69	0.0736	0	0	0	1.561	83.12
Brush Creek coal bed	441.97–443.55	142.17	0.0077	0	0	0	0.222	0
Upper Freeport coal bed	530.75–532.22	147.33	0.0057	0	0	0	0.166	0
Upper Kittanning upper split coal bed and Upper Kittanning coal bed (part)	632.40–635.16	177.09	0.0048	0	0	0	1.215	0
Upper Kittanning coal bed (part)	642.40–647.20	185.27	0.0046	0	0	0	0.784	0
Clarion coal zone	776.00–779.30	223.21	0.0034	0.001	0	0	0.972	0

Table 5. Raw gas geochemistry analyses for coal samples from core retrieved from the Meadowfill Landfill borehole, Harrison County, W. Va.—Continued

N_2 (percent)	CO (percent)	C_1 (percent)	C_2 (percent)	C_2H_4 (percent)	C_3 (percent)	iC_4 (percent)	nC_4 (percent)	iC_5 (percent)	nC_5 (percent)	C_{6+} (percent)
78.36	0	0.667	0.0168	0	0	0	0	0	0	0
49.67	0	33.06	0.63	0	0	0.0022	0	0	0	0
39.72	0	44.52	1.09	0	0.0091	0.0043	0.0023	0	0	0
31.15	0	56.88	0.856	0	0.0019	0.0028	0	0	0	0
26.81	0	61.05	0.943	0	0.0274	0.0064	0.0039	0	0	0
10.59	0	83.3	0.234	0	0.0074	0.0035	0	0	0	0

Table 6. Gas geochemistry analyses corrected for air contamination for coal samples from core retrieved from the Meadowfill Landfill borehole, Harrison County, W. Va.—Continued

CO (percent)	C_1 (percent)	C_2 (percent)	C_2H_4 (percent)	C_3 (percent)	iC_4 (percent)	nC_4 (percent)	iC_5 (percent)	nC_5 (percent)	C_{6+} (percent)	C_{2+} (percent)	C_1/C_{2+} (ratio)
0	14.871	0.3746	0	0	0	0	0	0	0	0.37	39.70
0	97.898	1.8656	0	0	0.0065	0	0	0	0	1.87	52.29
0	97.409	2.3849	0	0.0199	0.0094	0.0050	0	0	0	2.42	40.26
0	97.308	1.4644	0	0.0033	0.0048	0	0	0	0	1.47	66.09
0	97.643	1.5082	0	0.0438	0.0102	0.0062	0	0	0	1.57	62.25
0	98.733	0.2774	0	0.0088	0.0041	0	0	0	0	0.29	340.14

Table 7. Isotopic composition of carbon and hydrogen (deuterium) in methane in gas samples from coal beds from the Meadowfill Landfill borehole, Harrison County, W. Va.

[By convention, isotope compositions are reported as the deviation (δ) of values in units of parts per thousand (per mil) relative to a known reference standard. The reference standard for isotopes of carbon (carbon 13, ^{13}C) is the Vienna Peedee belemnite (VPDB) and the reference standard for hydrogen (deuterium, ^{2}H) is the Vienna standard mean ocean water (VSMOW). See Kendall and Caldwell (1998) for fundamental information on isotope analyses. Coal-bed gas in the Upper Kittanning upper split coal bed and the top interval of the Upper Kittanning coal bed (from canister US4–8 only) were combined due to a labeling error that occured in the field. This error resulted in (1) a composite sample of the Upper Kittanning upper split coal bed (canisters US4–14 and B3–4 and the Upper Kittanning coal bed (top interval, canister US4–8 and (2) a partial Upper Kittanning coal-bed-gas sample. n.d., no data]

Coal bed or zone	Canister number(s)	$\delta^{13}C_1$ (per mil)	$\delta^{2}H$ (per mil)
Harlem coal bed	B3–1, B3–3	n.d.	n.d.
Brush Creek coal bed	US4–5	-51.05	-204.5
Upper Freeport coal bed	US4–6	-51.25	-205.1
Upper Kittanning upper split coal bed and Upper Kittanning coal bed (part)	US4–14, B–3, US4–8	-48.7	-204.9
Upper Kittanning coal bed (part)	B3–5, US4–30	-46.6	-204.6
Clarion coal zone	B3–6, B3–7, B3–8, B3–9	-51.56	-207.0

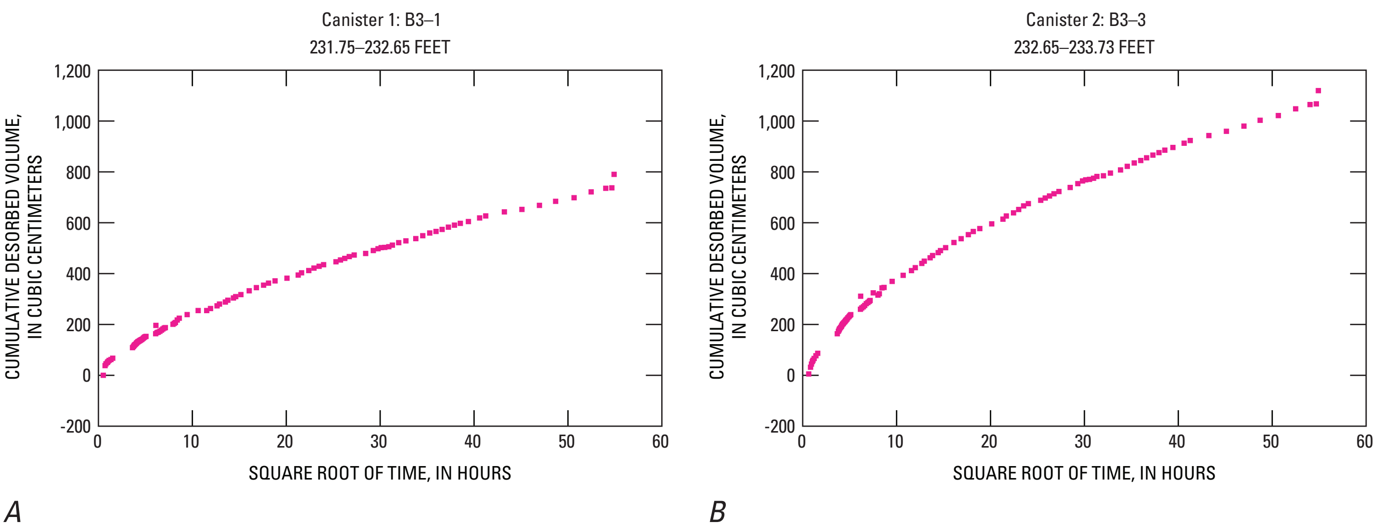


Figure 3. Graphs showing cumulative coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Harlem coal bed plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A1 and A2 in appendix A for the desorption data from which these graphs were derived.

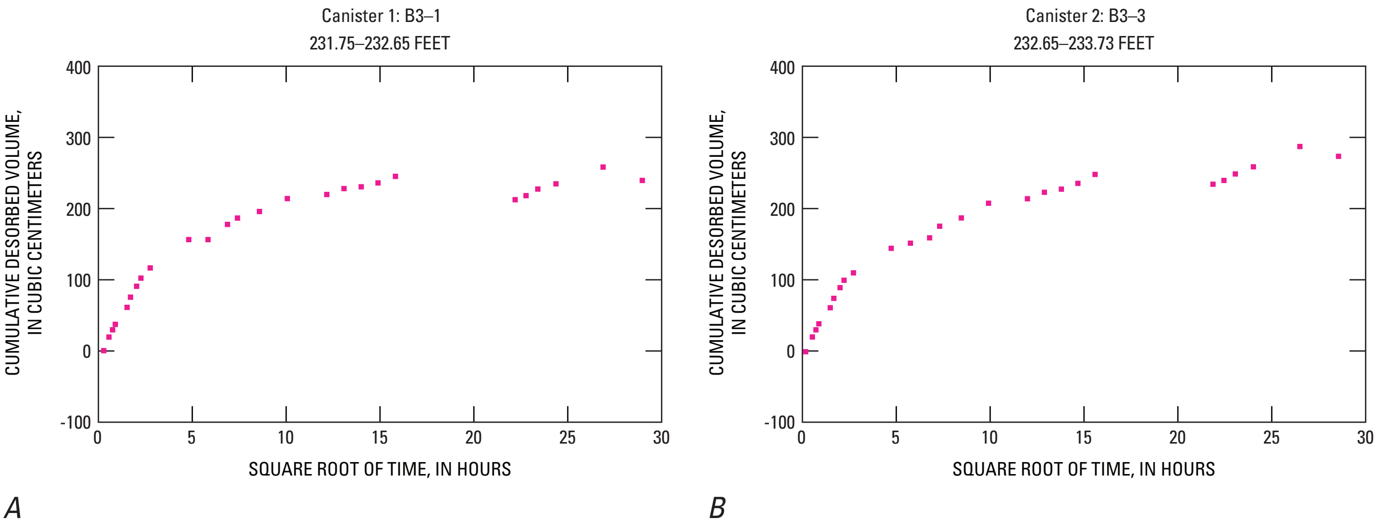


Figure 4. Graphs showing cumulative residual coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Harlem coal bed plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A3 and A4 in appendix A for the desorption data from which these graphs were derived.

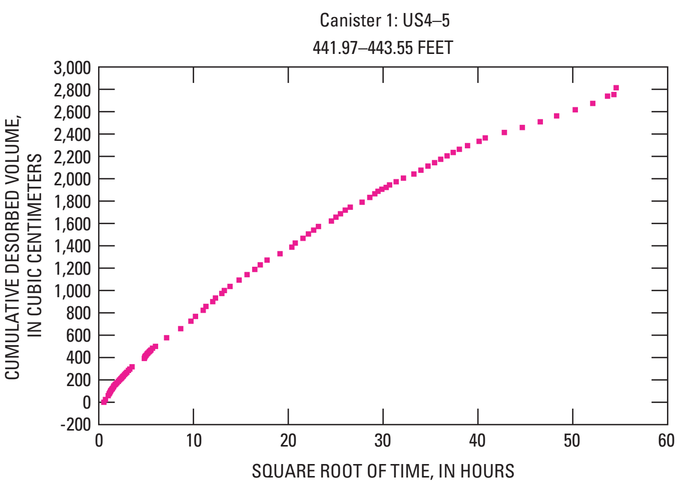


Figure 5. Graph showing cumulative coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal sample from the Brush Creek coal bed plotted against the square root of time (in hours). Canister number and coal sample depth are shown. See table A5 in appendix A for the desorption data from which this graph was derived.

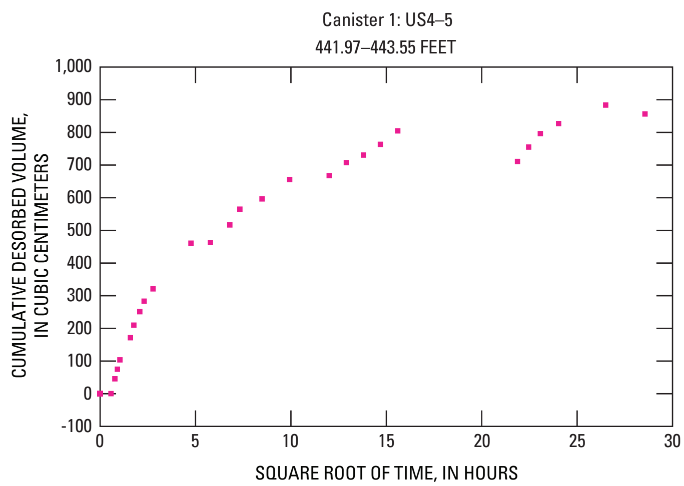


Figure 6. Graph showing cumulative residual coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal sample from the Brush Creek coal bed plotted against the square root of time (in hours). Canister number and coal sample depth are shown. See table A6 in appendix A for the desorption data from which this graph was derived.

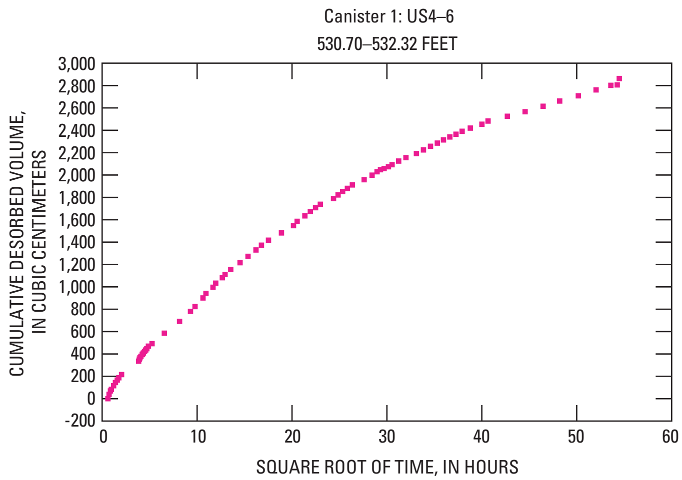


Figure 7. Graph showing cumulative coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal sample from the Upper Freeport coal bed plotted against the square root of time (in hours). Canister number and coal sample depth are shown. See table A7 in appendix A for the desorption data from which this graph was derived.

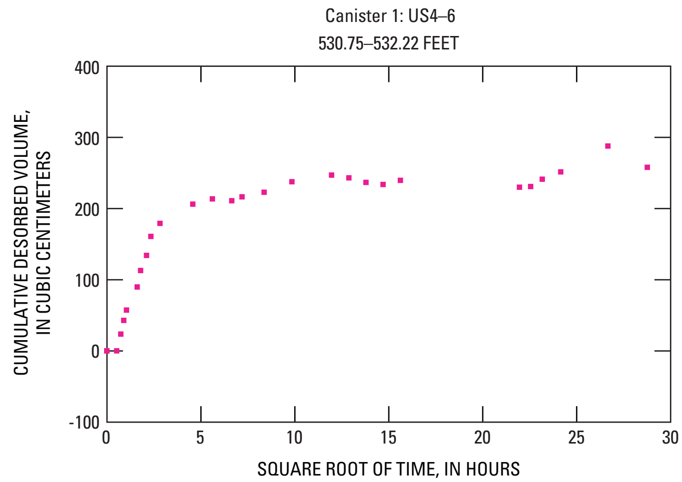


Figure 8. Graph showing cumulative residual coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal sample from the Upper Freeport coal bed plotted against the square root of time (in hours). Canister number and coal sample depth are shown. See table A8 in appendix A for the desorption data from which this graph was derived.

61.12 SCF/ton (1.91cc/g) was desorbed before crushing and 16.50 SCF/ton (0.52 cc/g) was residual, or desorbed from the crushed coal (table 2). A total of 21 percent of the total measured raw-gas-content was in the crushed, or residual, fraction. See tables A7 and A8 in appendix A for raw data.

Gas chemistry of the Upper Freeport coal bed.—A gas sample was analyzed from the Upper Freeport coal bed. The sample contained 97 percent methane, 2.4 percent ethane and ethylene, and small amounts of carbon dioxide (0.17 percent), propane (0.02 percent), *iso*-butane (0.009 percent), and *n*-butane (0.005 percent), on an air-free basis. The ratio of methane to the higher molecular weight hydrocarbons was 40.26 (table 6). The value for $\delta^{13}C$ was -51.25 per mil and the value for $\delta^{2}H$ was -205.1 per mil (table 7).

Upper Kittanning Upper Split Coal Bed

A 2.76-ft-long sample of coal from the Upper Kittanning upper split was cored and retrieved to the surface from a depth of 632.40 to 635.16 ft at 9:45 hours on June 25, 2004, and placed in one 2-ft-long aluminum canister and one 1-ft-long PVC canister. The overall moisture content of the coal was 1.24 percent and the ash yield was 30.40 weight percent (db) (table 4). The total gas content using a weighted average was 133.12 SCF/ton (4.16 cc/g), of which 88.61 SCF/ton (2.77 cc/g) was desorbed before crushing and 44.51 SCF/ton (1.39 cc/g) was residual, or desorbed from the crushed coal (table 2). Overall, 33 percent of the measured total raw-gas-content was in the crushed or residual fraction. See tables A9, A10, A11, and A12 in appendix A for raw data.

- Canister 1 (US4–14; 632.40–634.25 ft)—A total of 66 desorption measurements was taken on the intact coal sample over 123 days (fig. 9) before it was crushed. The measured raw-total-gas content of the intact coal was 89.18 SCF/ton (2.79 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 10) and the measured residual raw-total-gas content was 56.49 SCF/ton (1.77 cc/g). The total gas content was 145.67 SCF/ton (4.56 cc/g), of which 39 percent was residual (table 2).

- Canister 2 (B3–4; 634.25–635.16 ft)—A total of 66 desorption measurements was taken on the intact coal sample over 123 days (fig. 9) before it was crushed. The measured raw-total-gas content of the intact coal was 87.62 SCF/ton (2.74 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 10) and the measured residual raw-total-gas content was 24.73 SCF/ton (0.77 cc/g) (table 2). The total gas content was 112.35 SCF/ton (3.51 cc/g), of which 22 percent was residual (table 2).

Gas chemistry of the Upper Kittanning upper split coal bed.—Coal-bed-gas samples in the Upper Kittanning upper split coal bed and the top interval of the Upper Kittanning coal bed (canister US4–8) were combined due to a labeling error that occurred in the field, resulting in a composite Upper Kittanning upper split coal bed (canisters US4–14 and B3–4) and Upper Kittanning coal bed (top interval, canister US4–8) gas sample (see section on gas analyses, above). The mixed-gas sample contained approximately 97 percent methane, 1.5

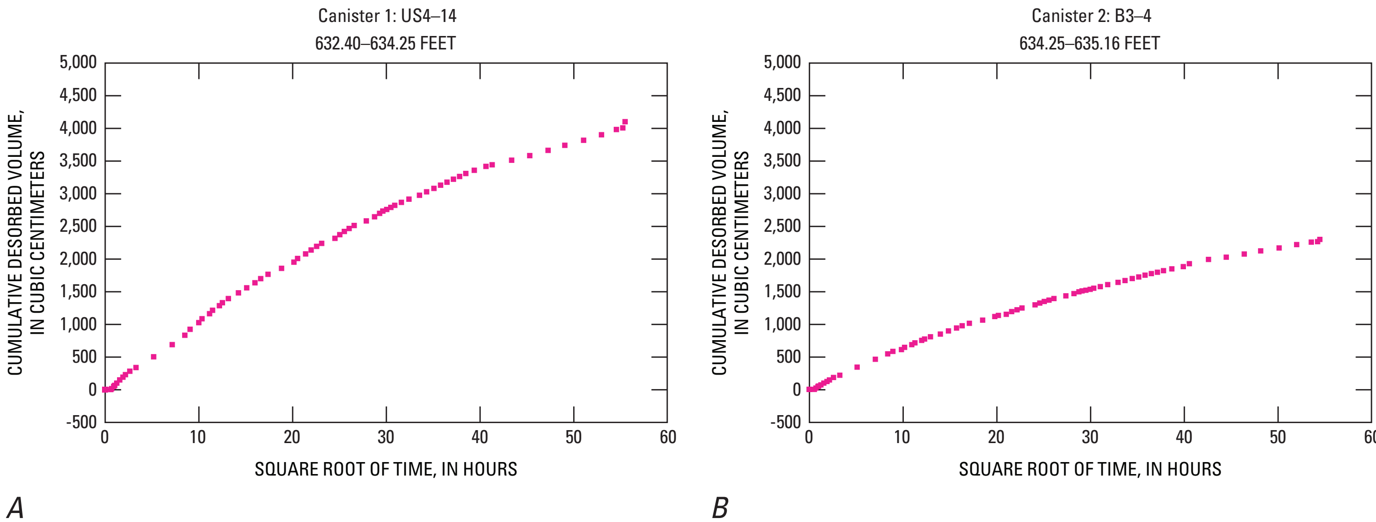


Figure 9. Graphs showing cumulative coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Upper Kittanning upper split coal bed plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A9 and A10 in appendix A for the desorption data from which these graphs were derived.

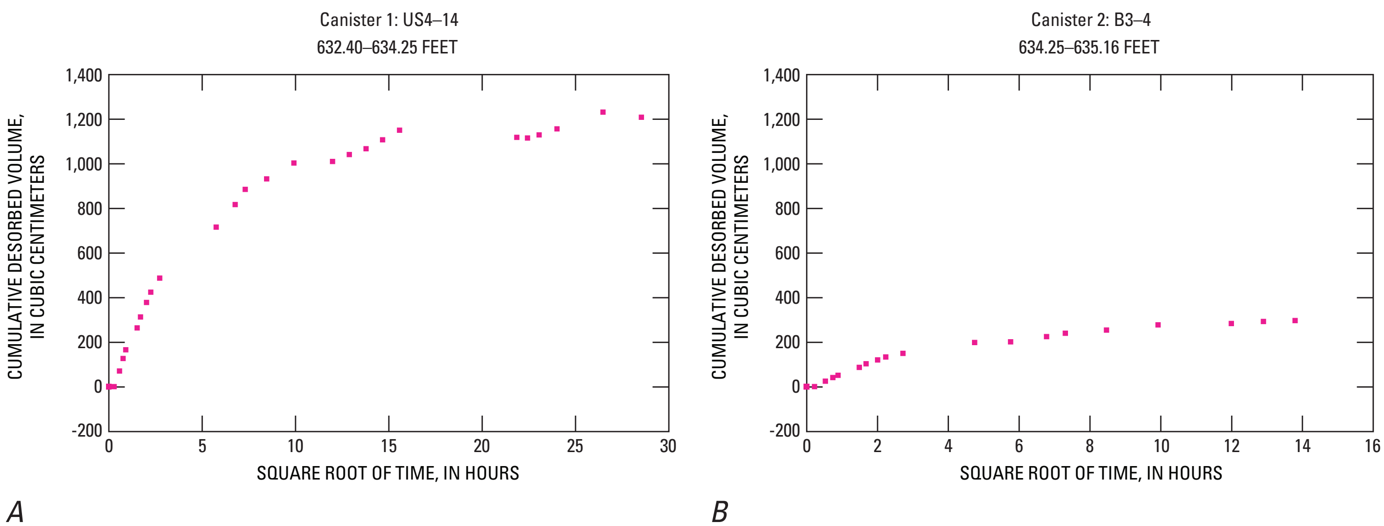


Figure 10. Graphs showing cumulative residual coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Upper Kittanning upper split coal bed plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A11 and A12 in appendix A for the desorption data from which these graphs were derived.

percent ethane and ethylene, and small amounts of carbon dioxide (1.2 percent), propane (0.003 percent), and *iso*-butane (0.005 percent), on an air-free basis. The ratio of methane to the higher molecular weight hydrocarbons was 66.09 (table 6). The value for $\delta^{13}C$ was -48.70 per mil and the value for $\delta^{2}H$ was -204.9 per mil (table 7).

Upper Kittanning Coal Bed

A 4.80-ft-long sample of coal and shale from the Upper Kittanning coal bed was cored and retrieved to the surface from a depth of 642.40 to 647.20 ft on June 25, 2004, and placed in two 2-ft-long aluminum canisters and one 1-ft-long PVC canister. Unlike the other coals that were cored in the Meadowfill Landfill, coal from the Upper Kittanning coal bed was retrieved in two separate runs, one at 9:45 and the other at 11:27. Core from the top 1.60 ft of Upper Kittanning coal bed was retrieved at 9:45 and placed in a 2-ft-long aluminum canister (canister 1, US4–8). At 11:27, 2.47 ft of coal and 0.40 ft of shale was retrieved and placed in two canisters (canisters 2 and 3; B3–5 and US4–30, respectively). The 0.40-ft-thick shale parting at 644.40 to 644.80 ft was removed and not desorbed; thus the total thickness of the material analyzed was 4.40 ft. The overall moisture content of the coal was 1.18 percent and the ash yield was 29.30 weight percent (db) (table 4). The total gas content (using a weighted average) was 117.42 SCF/ton (3.67 cc/g), of which 90.74 SCF/ton (2.84 cc/g) was desorbed before crushing and 26.68 SCF/ton (0.84 cc/g) was residual, or desorbed from the crushed coal (table 2). Overall, 23 percent of the measured total-raw-gas content was in the crushed, or residual, fraction. See tables A13, A14, A15, A16, A17, and A18 in appendix A for raw data.

- Canister 1 (US4–8; 642.40–644.00 ft)—A total of 66 measurements was taken on the intact coal sample (fig. 11) over 123 days. The measured raw-total-gas content of the intact coal was 96.77 SCF/ton (3.02 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 12) and the measured residual raw-total-gas content was 30.30 SCF/ton (0.95 cc/g). The total gas content was 127.07 SCF/ton (3.97 cc/g), of which 24 percent was residual (table 2).

- Canister 2 (B3–5; 644.00–644.40 and 644.80–645.48 ft)—A total of 66 measurements was taken on the intact coal sample over 12 days (fig. 11). The measured

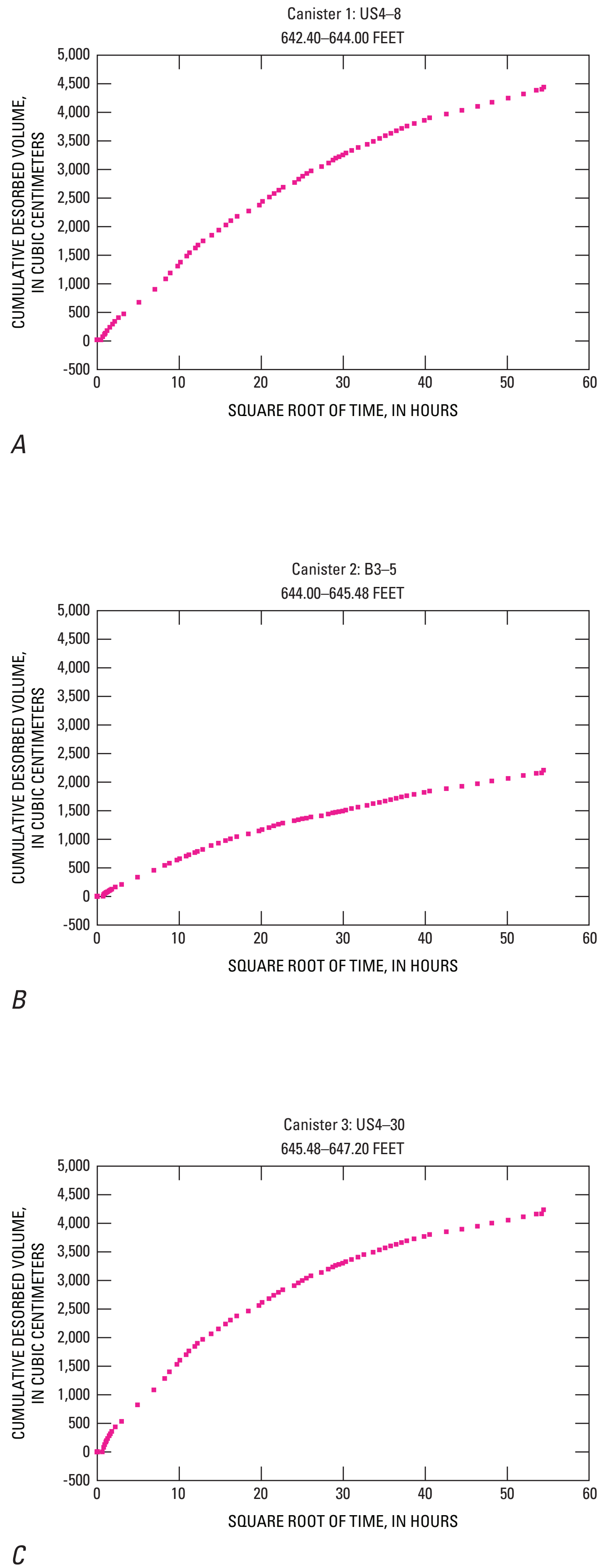


Figure 11. Graphs showing cumulative coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Upper Kittanning coal bed plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A13, A14, and A15 in appendix A for the desorption data from which these graphs were derived.

raw-total-gas content of the intact coal was 80.80 SCF/ton (2.53 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 12) and the measured residual raw-total-gas content was 35.92 SCF/ton (1.12 cc/g) (table 2). The total gas content was 116.72 SCF/ton (3.65 cc/g), of which 31 percent was residual (table 2).

- Canister 3 (US4–30; 645.48–647.20 ft)—A total of 66 desorption measurements was taken on the intact coal sample over 123 days (fig. 11). The measured raw-total-gas content of the intact coal was 90.77 SCF/ton (2.84 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 12) and the measured residual raw-total-gas content was 16.19 SCF/ton (0.51 cc/g) (table 2). The total gas content was 106.96 SCF/ton (3.35 cc/g), of which 15 percent was residual (table 2).

Gas chemistry of the Upper Kittanning coal bed.—As noted, the top interval of the Upper Kittanning coal bed (canister 1, US4–8) was analyzed with the Upper Kittanning upper split coal bed. The gas from canisters 2 and 3 (B3–5 and US4–30) was composed of approximately 97 percent methane, 1.5 percent ethane and ethylene, and small amounts of carbon dioxide (0.8 percent), propane (0.04 percent), *iso*-butane (0.01 percent), and *n*-butane (0.006 percent) on an air-free basis, and the ratio of methane to the higher molecular weight hydrocarbons was 62.25 (table 6). The value for $\delta^{13}C$ was -46.6 per mil and the value for $\delta^{2}H$ was -204.6 per mil (table 7).

Clarion Coal Zone

A 3.30-ft-long sample of coal from the Clarion coal zone was cored and retrieved to the surface from a depth of 776.00 to 779.30 ft at 15:45 hours on June 28, 2004, and placed in four 1-ft-long PVC canisters. The overall moisture content of the coal was 1.36 percent and the ash yield was 21.50 weight percent (db) (table 4). The total gas content (using a weighted average) was 177.69 SCF/ton (5.55 cc/g), of which 137.06 SCF/ton (4.28 cc/g) was desorbed before crushing and 40.63 SCF/ton (1.27 cc/g) was residual, or desorbed from the crushed coal (table 2). Overall, 23 percent of the measured total raw-gas content was in the crushed or residual fraction. See tables A19, A20, A21, A22, A23, A24, A25, and A26 in appendix A for raw data.

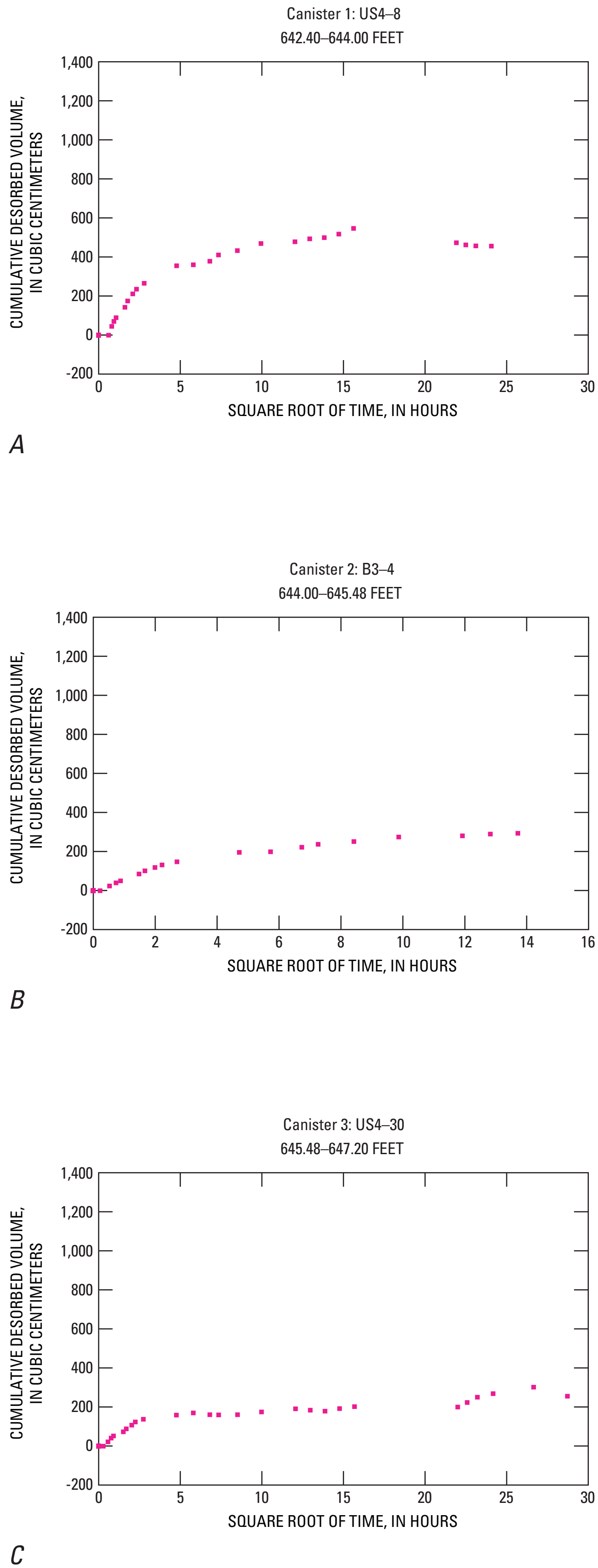


Figure 12. Graphs showing cumulative residual coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Upper Kittanning coal bed plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A16, A17, and A18 in appendix A for the desorption data from which these graphs were derived.

- Canister 1 (B3–6; 776.00–776.90 ft)—A total of 91 desorption measurements was taken on the intact coal sample over 120 days (fig. 13). The measured raw-total-gas content of the intact coal was 112.71 SCF/ton (3.52 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 14) and the measured residual raw-total-gas content was 46.32 SCF/ton (1.45 cc/g). The total gas content was 159.03 SCF/ton (4.97 cc/g), of which 29 percent was residual (table 2).
- Canister 2 (B3–7; 776.90–777.80 ft)—A total of 91 desorption measurements was taken on the intact coal sample over 120 days (fig. 13). The measured raw-total-gas content of the intact coal was 137.83 SCF/ton (4.31 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 14) and the measured residual raw-total-gas content was 43.82 SCF/ton (1.37 cc/g) (table 2). The total gas content was 181.65 SCF/ton (5.68 cc/g), of which 24 percent was residual (table 2).
- Canister 3 (B3–8; 777.80–778.50 ft)—A total of 91 desorption measurements was taken on the intact coal sample over 120 days (fig. 13). The measured raw-total-gas content of the intact coal was 150.00 SCF/ton (4.69 cc/g) (table 2). Desorbed residual-gas

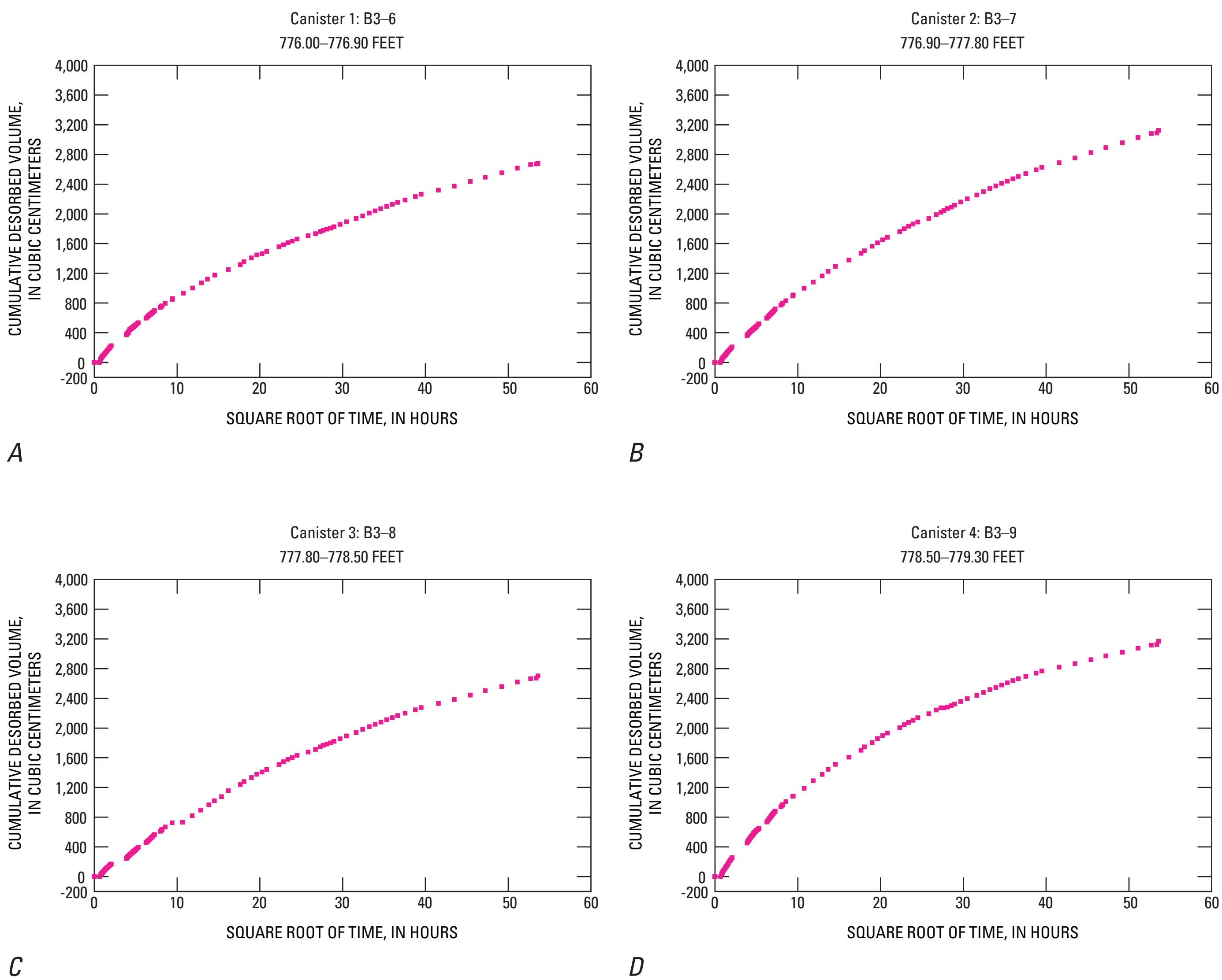


Figure 13. Graphs showing cumulative coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Clarion coal zone plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A19, A20, A21 and A22 in appendix A for the desorption data from which these graphs were derived.

measurements were taken over 35 days (fig. 14) and the measured residual raw-total-gas content was 36.77 SCF/ton (1.15 cc/g) (table 2). The total gas content was 186.77 SCF/ton (5.84 cc/g), of which 20 percent was residual (table 2).

- Canister 4 (B3–9; 778.50–779.30 ft)—A total of 91 desorption measurements was taken on the intact coal sample over 120 days (fig. 13). The measured raw-total-gas content of the intact coal was 152.80 SCF/ton (4.78 cc/g) (table 2). Desorbed residual-gas measurements were taken over 35 days (fig. 14) and the measured residual raw-total-gas content was 34.15 SCF/ton (1.07 cc/g) (table 2). The total gas content was 152.80 SCF/ton (5.85 cc/g), of which 18 percent was residual (table 2).

Gas chemistry of the Clarion coal zone.—Coal-bed gas in the Clarion coal zone was composed of approximately 99 percent methane, 0.3 percent ethane and ethylene, and small amounts of carbon dioxide (1.0 percent), propane (0.01 percent), and *iso*-butane (0.004 percent), on an air-free basis. The ratio of methane to the higher molecular weight hydrocarbons was 340.14 (table 6). The value for $\delta^{13}C$ was -51.56 per mil and the value for $\delta^{2}H$ was -207.0 per mil (table 7).

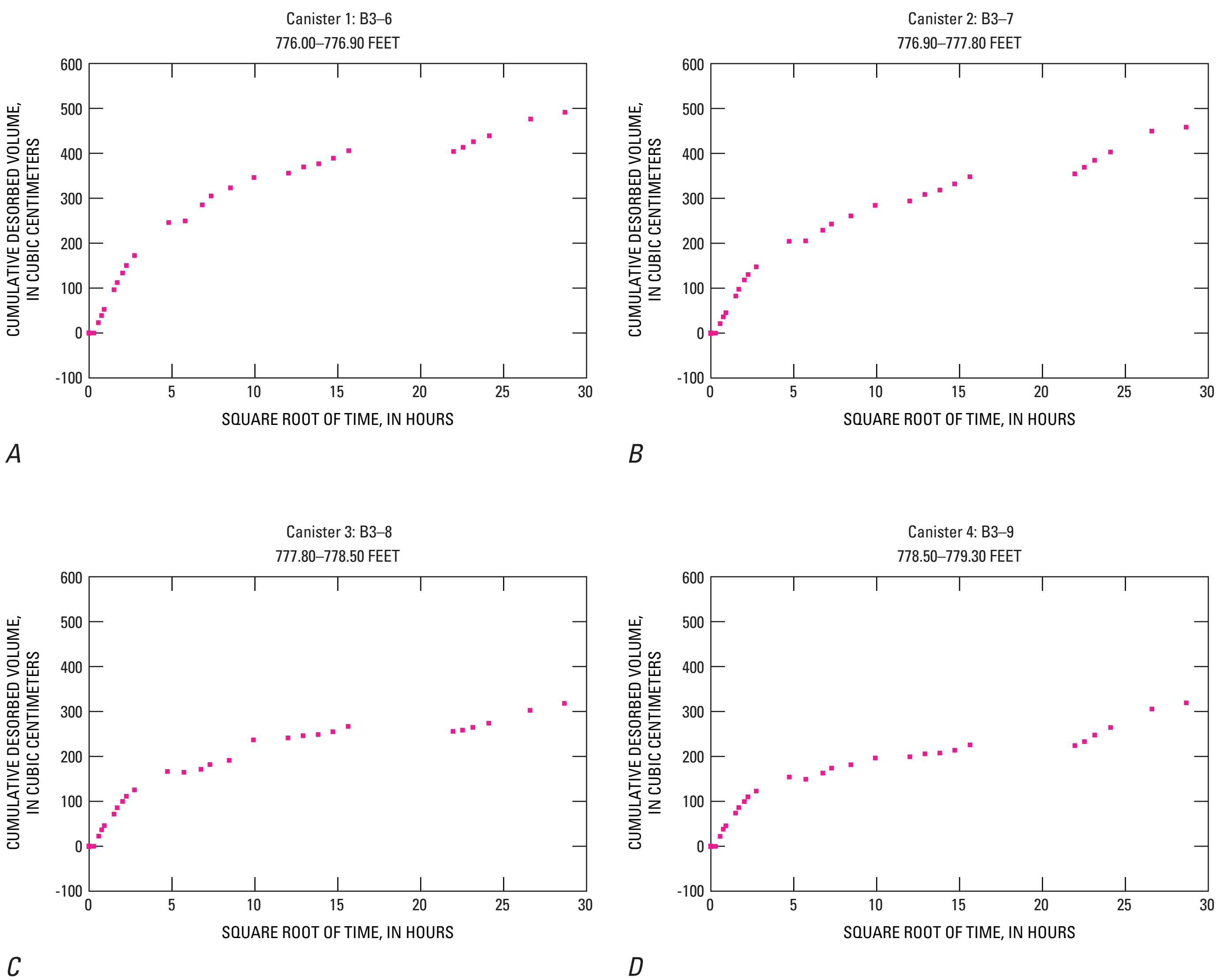


Figure 14. Graphs showing cumulative residual coal-bed-gas desorption volumes (in cubic centimeters, cc) of the coal samples from the Clarion coal zone plotted against the square root of time (in hours). Canister numbers and coal sample depths are shown. See tables A23, A24, A25, and A26 in appendix A for the desorption data from which these graphs were derived.

Discussion

A total of 37.02 ft of coal was drilled and desorbed for coal-bed gas at Meadowfill Landfill, Harrison County, W. Va. Measured coal-bed-gas content (using a weighted average, raw basis) was 69.75 SCF/ton (2.17 cc/g) for the Harlem coal bed, 119.24 SCF/ton (3.73 cc/g) for the Brush Creek coal bed, 77.62 SCF/ton (2.43 cc/g) for the Upper Freeport coal bed, 133.12 SCF/ton (4.16 cc/g) for the Upper Kittanning upper split coal bed, 117.42 SCF/ton (3.67 cc/g) for the Upper Kittanning coal bed, and 177.69 SCF/ton (5.55 cc/g) for the Clarion coal zone (table 2). The majority of the coal-bed gas was methane (table 6), and methane contents ranged from about 15 percent in the shallow (231.75–233.73 ft) Harlem coal bed to 99 percent in the deepest (776.00 0–779.30 ft) Clarion coal zone (table 6). Migration of methane out of the Harlem coal bed is probably due to its shallow depth.

The values for $\delta^{13}C$ of methane from the five coal beds sampled at the Meadowfill Landfill study area range from -46.60 per mil for the Upper Kittanning coal bed (part) to -51.56 per mil for the Clarion coal zone. The values for $\delta^{2}H$ range from -204.5 per mil for the Harlem coal bed to -207.0 per mil for the Clarion coal zone (table 7). Ratios of methane to the higher molecular weight hydrocarbons range from 39.70 in the Harlem coal bed to 340.14 in the Clarion coal zone (table 6).

A plot of the isotopic composition of carbon in methane against the ratio of methane to the sum of higher molecular weight gases (fig. 15) provides information on the origin of methane in coal beds (Whiticar, 1994) at the Meadowfill Landfill. The coal-bed-gas samples from the mixed Upper Kittanning upper split coal bed and Upper Kittanning coal bed and from the Upper Kittanning coal bed alone plot in the thermogenic field (fig. 15). However, the Brush Creek and the Upper Freeport coal-bed-gas samples appear to have been minimally oxidized by microbial activity, as they plot just outside of the boundary of pure thermogenic gas (fig. 15). The Clarion coal zone gas appears to have a bacterial component and is more clearly a mixed gas, containing a mixture of gases that are thermogenic and bacterial in origin.

However, a plot of the isotopic composition of hydrogen (deuterium) in methane against the isotopic compositions of carbon in methane (modified from Whiticar, 1994) shows that all of the methane from coal beds at the Meadowfill Landfill (fig. 16) fall within the thermogenic field. Methane from the Clarion coal zone and the Brush Creek and Upper Freeport

Table 8. Calculated coal-bed gas in place for coal beds underlying the Meadowfill Landfill borehole, Harrison County, W. Va.

Coal bed or zone	Canister number or weighted average	Total thickness (feet)	Top depth (feet)	Bottom depth (feet)	Total gas (SCF/ton)
Harlem coal bed	Weighted average	1.98	231.75	233.73	69.75
Brush Creek coal bed	US4–5	1.58	441.97	443.55	119.24
Upper Freeport coal bed	US4–6	1.47	535.70	532.32	77.62
Upper Kittanning upper split coal bed	Weighted average	2.76	632.40	635.16	133.12
Upper Kittanning coal bed	Weighted average	4.40	642.40	647.20	117.42
Clarion coal zone	Weighted average	3.30	776.00	779.30	177.69
Total gas in-place					

coal beds plots close to the transition area, which may suggest minimal mixing with biogenic gas. The values for $\delta^{13}C$ range -46.60 per mil to -51.56 per mil and the values for $\delta^{2}H$ range from -204.5 per mil to -207.0 per mil.

A gross estimate (*G*) for gas in place for coal beds directly underlying the Meadowfill Landfill is about 1.2 billion cubic feet (ft^3) (36.7 million cc/g), as estimated by the equation

$$G = 1,3597.7\, A h \bar{\rho} \bar{G}_{ct}$$

where

A = is the Meadowfill Landfill area (300 acres);
h = is the thickness, in feet, using a weighted average;
$\bar{\rho}$ = is the average density of coal (g/cm^3); and
$\bar{G}_{ct}$ = is the average gas content of the coal, using a weighted average (Gas Research Institute, 1995).

Coal density was estimated from measured ash content (Smith, 1991) and ranged from approximately 1.39 g/cm^3 for the Harlem coal bed to 1.72 g/cm^3 for the Upper Freeport coal bed (table 8).

Total gas-in-place estimates do not represent amounts of coal-bed gas that might actually be produced because coalbed methane plays only account for about 10 to 15 percent of the calculated gas-in-place resource estimates. This is particularly true for coals at the Meadowfill Landfill, which have very high percentages of residual gas (a mean of about 30 percent for the Harlem, Upper Freeport, Brush Creek, Upper Kittanning upper split, and Upper Kittanning coal beds, and the Clarion coal zone combined (table 2). The percentages of residual gas ranged from 21 percent for the Upper Freeport coal bed to about 42 percent in the Brush Creek coal bed (table 2). These values, and the relatively slow release of gas over the desorption experiment (appendix A), suggest that gas production rates probably will be low but continuous for a relatively long time interval. However, if it becomes economically feasible to separate the landfill gas into methane and carbon-dioxide streams, the carbon dioxide could be used to enhance methane desorption and presumably more quickly displace some of the tightly held residual gas in the coal beds underlying the Meadowfill Landfill.

Table 8. Calculated coal-bed gas in place for coal beds underlying the Meadowfill Landfill borehole, Harrison County, W. Va.—Continued

Total gas (cc/g)	Meadowfill Landfill (acres)	Estimated density (g/cm^3)	Ash content (percent)	Coal rank	Estimated gas in-place (SCF)	Estimated gas in-place (cc)
2.17	300	1.39	12.02	High-volatile B bituminous	78,304,831	2,436,150
3.73	300	1.45	16.15	High-volatile B bituminous	111,432,381	3,485,766
2.43	300	1.72	47.32	High-volatile C bituminous	80,054,136	2,506,204
4.16	300	1.54	30.40	High-volatile B bituminous	230,800,882	7,212,528
3.67	300	1.54	29.30	High-volatile A bituminous	324,548,664	10,143,873
5.55	300	1.46	21.50	High-volatile A bituminous	349,216,001	10,907,473
					1,174,356,894	**36,691,994**

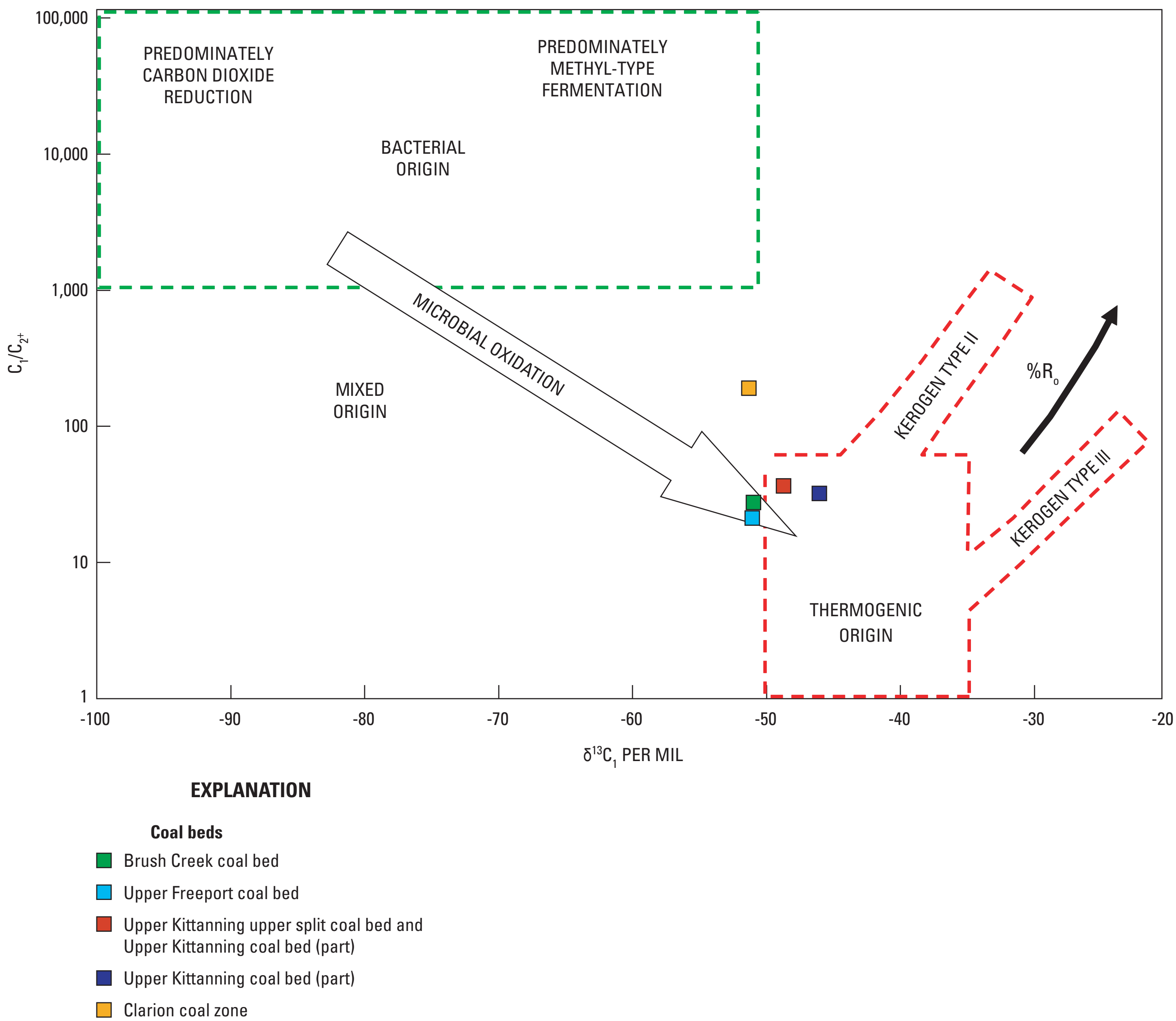
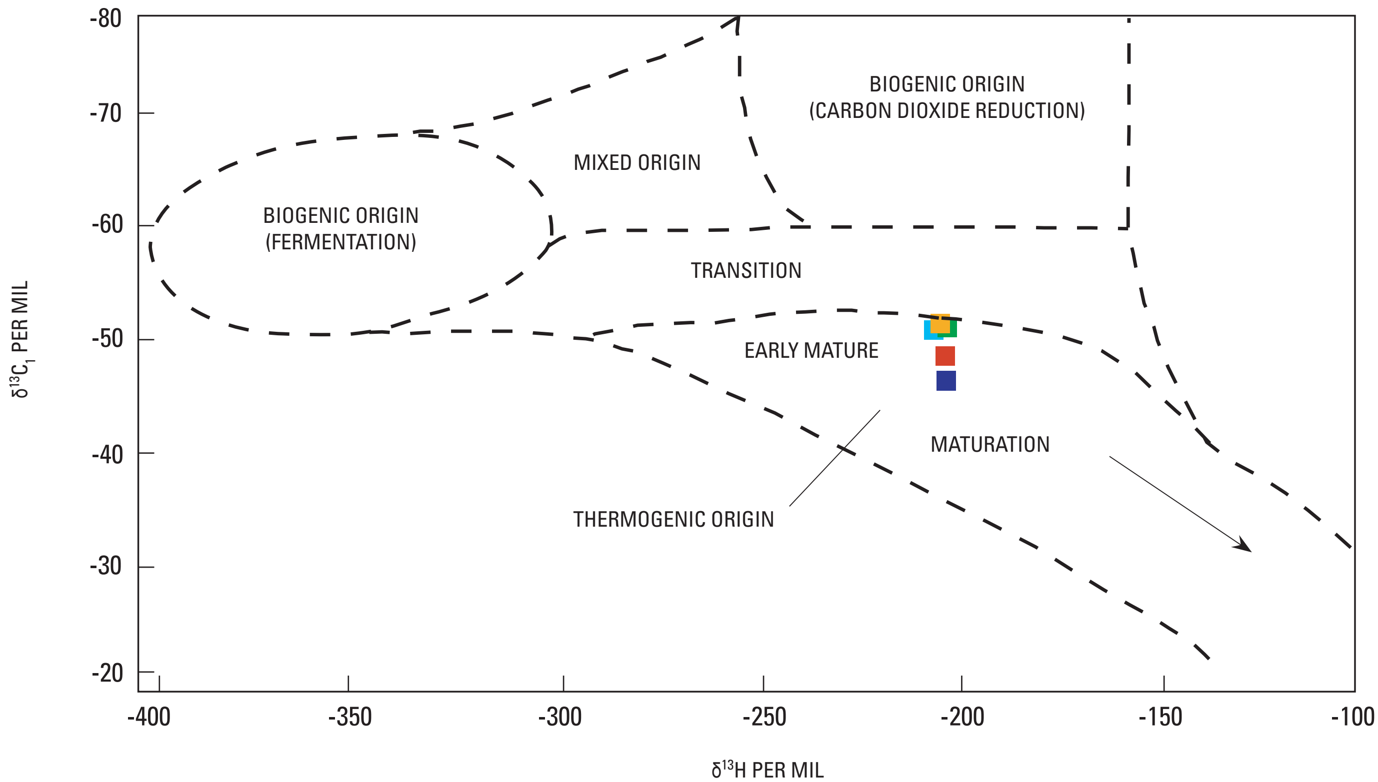


Figure 15. Bernard diagram for Meadowfill Landfill coal-bed-gas samples (modified from Bernard and others, 1978; Faber and Stahl, 1984; and Whiticar, 1994). This diagram plots the isotopic composition of carbon (carbon 13, ^{13}C) in methane reported as the deviation in units ($\delta^{13}C$) of parts per thousand (per mil) relative to the Vienna Peedee belemnite (VPDB) standard against the ratio of methane (C_1) to the sum of the higher molecular gases (C_{2+}, which includes ethane, propane, *iso*-butane, *n*-butane, *iso*-pentane, 2-methylbutane, *n*-pentane, and hexane). Note that the sample from the Clarion coal zone falls in the mixing zone, suggesting a mixed thermal and biogenic origin of the Clarion coal-bed gas. All of the other samples are primarily thermogenic in origin. Abbreviations are as follows: %R_o, percent vitrinite reflectance.



EXPLANATION

Coal beds

- Brush Creek coal bed
- Upper Freeport coal bed
- Upper Kittanning upper split coal bed and Upper Kittanning coal bed (part)
- Upper Kittanning coal bed (part)
- Clarion coal zone

Figure 16. Graph showing the isotopic composition of hydrogen (deuterium, ^2H) in methane (reported as the deviation in units (δ^2H) of parts per thousand (per mil) relative to the Vienna standard mean ocean water (VSMOW) plotted against the isotopic composition of carbon in methane (reported as the deviation in units ($\delta^{13}C$) of parts per thousand (per mil) relative to the Vienna Peedee belemnite (VPDB) standard). Methane from the Harlem, Brush Creek, Upper Freeport, Upper Kittanning upper split, and Upper Kittanning coal beds at the Meadowfill Landfill study area is predominately thermogenic in origin, but methane from the Clarion coal zone falls in the transition zone.

Conclusions

1. The measured raw-total-gas contents for coal samples from the Meadowfill Landfill, Harrison County, W. Va., study area range from 69.75 SCF/ton (2.17 cc/g) for the Harlem coal bed to 177.69 SCF/ton (5.55 cc/g) for the Clarion coal zone.

2. Residual gas from the coal samples was significant, ranging from 21 percent in the Upper Freeport coal bed to about 42 percent in the Brush Creek coal bed.

3. Coal-bed-gas contents of the coal-bed samples from the Meadowfill Landfill increase systematically with depth when compared on a dry, ash-free basis.

4. Gas contents of the coal-bed samples had to be normalized to an air-free basis, despite efforts to prevent air contamination during gas sampling. The mean methane content of all of the samples from the Meadowfill Landfill study area was 83.98 percent (air-free basis) (table 6).

5. Carbon isotopic analyses of methane indicated that the coal-bed gas is primarily thermogenic in origin, but some degree of mixing with gas of a biogenic origin may have occurred within the Clarion coal zone.

6. Samples from the coal beds at the Meadowfill Landfill study area desorbed gas slowly, which may result in slow production rates. However, if carbon dioxide is successfully separated from other landfill gases, it could be injected into the coal beds underlying the landfill and could potentially result in enhanced coalbed-methane recovery.

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Appendix A. Desorption Data for Coal Samples Retrieved From a Borehole at Meadowfill Landfill, Harrison County, W. Va.

The original data for each canister in this study may be accessed by clicking the link below. The tables follow the terminology, abbreviations, and format of the data spreadsheets found in Barker and others (2002), which also contains a detailed discussion of their use; therefore, the terminology may not be identical to that found in the text of this report. See table headnotes for an explanation of abbreviations.

CLICK HERE TO ACCESS APPENDIX A DATA