OPEN FILE REPORT 94-02

Coalbed Gas Composition, Upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico

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DOI: https://doi.org/10.58783/cgs.of9402.gvjy7818

Colorado Geological Survey
Division of Minerals and Geology
Department of Natural Resources
Denver, Colorado
1994

TABLES

PLATES (in pocket)

ACKNOWLEDGMENTS

I want to thank the many individuals, operators, and companies who provided most of the gas compositional data used in this study. This research could not have been performed without their cooperation. I thank Naijiang Zhou for organizing the gas compositional data base, performing all of the statistical analyses, and assisting with plate preparation. Joseph Yeh assisted in locating wells with gas compositional data. Reviews by W. R. Kaiser, R. A. Levey, and C. M. Tremain improved the manuscript. Technical editing was by T. F. Hentz, and word processing and layout were by Susan Lloyd and Margaret L. Evans, respectively. This publication was authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin. This research was funded by the Gas Research Institute under contact number 5087-214-1544.

ABSTRACT

Coalbed gas composition is highly variable across the San Juan Basin and is controlled primarily by coal rank and basin hydrodynamics. Although gas composition is affected by coal rank, the correlation of dry to very dry, carbon-dioxide-rich gases in the north-central part of the basin with artesian overpressure indicates that basin hydrogeology affects gas composition in that part of the basin.

Chemically wet coalbed gases in the central part of the basin were formed during the early thermogenic stage of gas generation and are characterized by C_1/C_{1-5} values of less than 0.94 and ethane contents of nearly 12 percent. Carbon dioxide contents are generally less than 1 percent, and negative (less than -25 °/oo) isotopic values indicate that the carbon dioxide is thermogenic. In contrast, coalbed gases in the northern, overpressured part of the basin are characterized by C_1/C_{1-5} values greater than 0.97 and carbon dioxide contents commonly more than 10 percent. The abrupt change in coalbed gas composition across a structural hingeline, consistency of methane isotopic values throughout the basin, and presence of isotopically heavy carbon dioxide and bicarbonate in coalbed gases and formation waters, respectively, indicate that coalbed gases in the northern part of the basin are a mixture of thermogenic and biogenic gases. Chemically dry (C_1/C_{1-5} values greater than 0.97) coalbed gases in the southern and southwestern parts of the basin probably represent a mixture of early thermogenic and secondary biogenic gases.

INTRODUCTION

The San Juan Basin of northwestern New Mexico and southwestern Colorado is the most prolific coalbed gas basin in the world; production in 1992 exceeded 440 Bcf (12.4 Bm^3), resources of approximately 50 Tcf (1.4 Tm^3), and proved reserves of over 6 Tcf (170 Bm^3). Nearly 80 percent of the 1992 U.S. coalbed gas production (550 Bcf, 15.5 Bm^3, total U.S.) came from Upper Cretaceous Fruitland coal beds in the San Juan Basin. Coalbed gas production in 1993 is estimated to approach 600 Bcf (17.0 Bm^3; R. Schraufnagel, personal comm., 1993). San Juan Basin cumulative production through 1992 was about 1 Tcf (28.3 Bm^3) from more than 2,100 wells (Petroleum Information, 1993).

Coalbed methane reservoirs differ from conventional gas reservoirs in that coal beds act as both the source rock and the reservoir for natural gases. Large quantities of methane, carbon dioxide, and other gases are generated from coal beds during progressive burial and thermal maturation (coalification). Gases are sorbed onto a coal structure that consists of a network of micropores having diameters on the order of nanometers. Coal surface area, as measured by carbon dioxide, ranges from 50 m^2/g to 250 m^2/g for high-volatile A and C bituminous coals, respectively (Thomas and Damberger, 1976). The density of methane molecules retained on the coal surface may approach that of liquid methane (Creedy, 1988) and gas contents of greater than 800 scf/ton have been reported. Although several thousand cubic feet of methane is produced from coal beds during coalification, most coals have gas contents of less than 400 to 500 scf/ton (Scott and Ambrose, 1992) and are often undersaturated with respect to that predicted from the sorption isotherms, indicating that most of the gases generated during coalification migrate out of the coal beds.

The objectives of this study are to (1) describe the major components in coalbed gases and the timing of their generation during coalification, (2) assess factors affecting the coalbed gas composition of coalbed gases, (3) evaluate the variability of Fruitland coalbed gas composition across the basin, and (4) discuss the origins of Fruitland coalbed gases. Gas compositional data from more than 750 Fruitland coalbed gas wells were used to make gas-composition maps and evaluate factors controlling gas origin. Operators and pipeline companies provided compositional data on produced coalbed gases obtained from individual coalbed methane wells. Gas samples collected from the meter run, tubing head, or casing head were run through a standard volume loop into a gas chromatograph. Individual gas samples, carried through appropriate columns by helium, were separated into various components prior to reaching a thermal conductivity detector (TCD). Quantitative analysis was performed by integrating chromatograph peak areas of each gas component; all values are reported in mole percent. The gas data were divided into overpressured, underpressured, and transitional categories on the basis of the regional pressure regime.

MAJOR COALBED GAS COMPONENTS

The process of coalification encompasses physical and chemical changes that occur in a coal beginning shortly after deposition and continuing throughout the burial history. During coalification, natural gases are generated from organic matter through biogenic, early thermogenic, and late thermogenic processes. Although methane is the major gas component in coalbed gases, water, carbon dioxide, wet gases (ethane, propane butane, etc.), nitrogen, and liquid hydrocarbons are also generated (table 1). In general, gases produced from lower rank coals (vitrinite reflectance [R_m] values less than 0.5 percent) are biogenic, whereas gases produced from higher rank coals are predominantly thermogenic; however, biogenic gases are also present in higher rank coals (Scott and others, 1991a, b; Scott and Kaiser, 1991; Scott, 1993; Rice, 1993).

Table 1. Gas volumes generated during coalification up to vitrinite reflectance values of 2.0 percent (from Scott, 1993).
scf = standard cubic feet.

Methane	2,000 to 5,000+ scf/ton (63 to 157+ cm^3/g)
Carbon dioxide	6,000+ scf/ton (188+ cm^3/g)
Wet gases*	100 to 1,000+ scf/ton (3 to 31+ cm^3/g)
Nitrogen	250 to 500 scf/ton (8 to 16 cm^3/g)

* ethane, propane, butane, and pentane.

Once the threshold of thermogenic methane-generation is attained between vitrinite reflectance values of 0.8 and 1.0 percent, significant quantities of methane can be generated from coal beds. Total methane production between vitrinite reflectance values of 0.5 and 2.0 probably ranges between 2,000 to 5,000 scf/ton (63 to 156 cm^3/g), depending upon maceral composition, types of gases generated, and hydrocarbon expulsion efficiency (table 1). Gas contents in western United States coal basins are generally less than 400 scf/ton (13 cm^3/g) (Scott and Ambrose, 1992), suggesting that large quantities of thermogenic methane generated during coalification are lost from the system.

Carbon dioxide is released from the coal structure during coalification and/or is generated through the metabolic activity of bacteria during primary or secondary bacterial gas generation. According to data from Levine (1992), over 6,000 scf/ton (128 cm^3/g) of carbon dioxide can be generated from coal during coalification over the peat-through-semianthracite range under the right conditions. Carbon dioxide generation decreases with increasing coal rank, and only 5 percent of the total carbon dioxide generated is produced during the semianthracite stage (R_m of 2.0 to 2.5).

Ethane, propane, butane, pentane, and heavier n-alkanes are generated from hydrogen-rich coals during coalification. Over 215 scf/ton (7 cm^3/g) of ethane alone is estimated to be sorbed on some Fruitland coals (Scott, 1993). Total wet gas generation from hydrogen-rich coals during coalification is estimated to range from less than 100 to more than 1,000 scf/ton (3 to 31 cm^3/g) in hydrogen-rich coals (table 1). Wet gases and n-alkanes generated during coalification remain sorbed to the coal surface, where they are subsequently cracked with increasing temperatures or migrate out of the system once a certain saturation threshold is reached. The proportion of wet gases decreases during coalification due to migration, thermal cracking, and/or dilution through additional methane generation.

The loss of nitrogen-bearing functional groups linked to the molecular structure of the coal results from bacterial metabolism and/or occurs during thermal maturation of the coal. The total amount of nitrogen released from a coal may depend on how much nitrogen is in the coal, how it is chemically bonded to the coal structure, and the types and distribution of oxygen-bearing functional groups in the coal. Kneuper and Huckel (1972) estimated that approximately 320 scf/ton (100 cm^3/g) of nitrogen are released from carboniferous coals over the coal rank range of subbituminous to semianthracite.

FACTORS AFFECTING GAS COMPOSITION

Coalbed gas composition is controlled by the maceral composition of the coal, particularly the abundance of hydrogen-rich components, reservoir pressure, which affects the sorptive capacity of the coal, thermal maturation (coal rank), which controls the timing of major coalbed gas component generation, and hydrogeology, which influences gas composition through the introduction of bacteria and generation of biogenic coalbed gases (fig.1). Although more carbon dioxide and wet gas components are released from coals at elevated temperatures, suggesting that reservoir temperature could affect coalbed gas composition, insufficient gas desorption data have been collected at reservoir temperatures and pressures to fully evaluate the effects of temperature differences on coalbed gas composition.

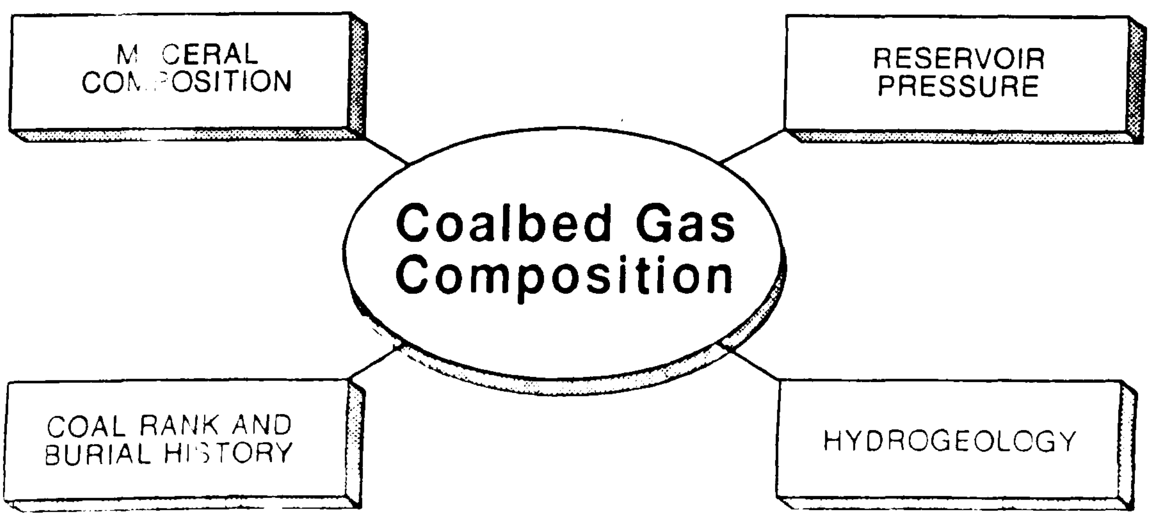

Figure 1. Factors affecting the composition of coalbed gases.

Coalbed gases can be characterized using the gas dryness index, which is the ratio of methane to heavier hydrocarbons (C_1/C_{1-5} value), and carbon dioxide content. Very dry gases have C_1/C_{1-5} values greater than 0.99; dry gases have C_1/C_{1-5} values between 0.94 and 0.99; wet gases have values between 0.86 to 0.94; and very wet gases have a gas dryness index less than 0.86 (Scott and others, 1991a). Carbon dioxide in coalbed gases is considered to be very high (>10 percent), high (6 to 10 percent), moderate (2 to 6 percent), or low, if less than 2 percent (Hanson, 1990).

Chemical Composition of Coal

Coal has traditionally been thought of as a source of chemically dry gases with little or no potential for generating liquid hydrocarbons. However, geochemical studies indicate that con[illegible] [illegible]e produced from Fruitland coals is indigenous to the coal beds (Rice and others, 1989; Cla[illegible]ton a[illegible] [illegible], 1991; Michael and others, 1993). Hydrogen-poor coals cannot generate [illegible]es of wet gases and liquid hydrocarbons, indicating that coalbed gases associ-[illegible]ed w[illegible] th[illegible]e [illegible]als would be composed almost entirely of methane.

[illegible]pe III or terrestrial organic matter composed predominantly of vitrinite, but [illegible]hey commonly c[illegible]ntain lesser amounts of exinite (liptinite) and inertinite macerals. Vitrinites originate from lignin and cellulose of cell walls, whereas hydrogen-rich liptinite is from pollens, resins, waxes, and fats (Stach and others, 1982). Vitrinite, the dominant maceral of most coals from the Western U.S., is composed of two main genetic types: structured humic material and matrix gels (Rice and others, 1992). Structured humic material is oxygen-rich and generates chemically dry gases (C_1/C_{1-5} values greater than 0.98), whereas matrix gels are more hydrogen rich and can produce wet gases (C_1/C_{1-5} values less than 0.90) and liquid hydrocarbons (Rice and others, 1992). Therefore, the available evidence indicates that maceral composition can affect coalbed gas composition. Significant compositional variations in coalbed gases may [illegible]epresent a combination of m[illegible]jor ch[illegible]nges in macer[illegible]l [illegible]omposition, which is ultim[illegible]tely controlled b[illegible] [illegible]

Reservoir Pressure

At constant temperature, the sorptive capacity of coal for methane and other gases is proportional to reservoir pressure (Arri and others, 1991). As reservoir pressures decrease during production, the sorption capacity of the coal also decreases, resulting in desorption and subsequent migration of methane and other gases from the coal to the well bore. However, each gas component has different sorption characteristics, indicating that some gas components remain more strongly sorbed and others less strongly sorbed (Rupple and others, 1972; Arri and others, 1992; fig. 2). Carbon dioxide, ethane, and other heavier hydrocarbon gases are strongly sorbed onto coal surfaces, whereas methane and nitrogen are less strongly sorbed. Much more carbon dioxide is sorbed to the coal surface than is present in produced coalbed gases (fig. 2). The variability of coalbed gas composition with decreasing reservoir pressure will depend on the individual desorption isotherms of methane, carbon dioxide, nitrogen, and wet gas components that are specific to each coal sample. The composition of coalbed gases has not changed significantly with time of production (Hale and Firth, 1988). As reservoir pressure decreases over time, coalbed gas composition will

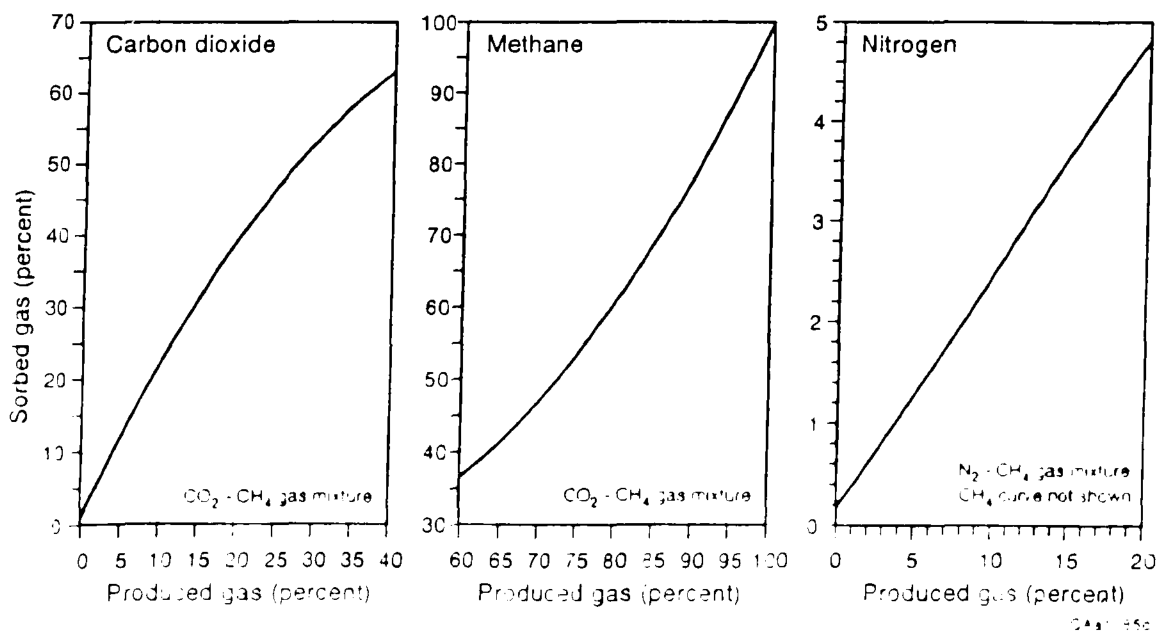

Figure 2. Fraction of gas sorbed on the coal surface relative to fraction in produced gas. The quantity of a gas component sorbed on the coal surface is disproportional to the component [illegible] Modified from Arri and [illegible]

gradually change. Relatively minor changes in gas chemistry occur at high reservoir pressures, whereas large increases in carbon dioxide and wet gases generally occur when reservoir pressures decrease to below approximately 500 psi (3,447 kPa). The exact pressure at which the carbon dioxide and/or wet gas desorption rates significantly increase depends on the shape of the desorption isotherm of each coalbed gas component. Therefore, reservoir pressure and the sorptive characteristics and capacity of coal can affect the composition of coalbed gases.

Coal Rank and Burial History

Relatively minor quantities of thermogenic gases are formed at low coal ranks (R_m less than approximately 0.8 percent). The first early thermogenic gases generated at vitrinite reflectance values of less than 0.5 percent are composed predominantly of methane but probably contain minor amounts of the wet gas components. With increasing maturation, hydrogen-rich coals are capable of generating wet gases, n-alkanes, condensate, and waxes as they pass through the oil-generating stage (R_m values between 0.5 and 1.3 percent). Maximum wet gas generation at vitrinite reflectance values between 0.6 and 0.8 percent generally occurs before the main stage of thermogenic methane generation (table 2; fig. 3). Significant quantities of methane are not generated until a certain threshold of thermal maturity is reached, at which time main-stage thermogenic gases are generated. Although main-stage thermogenic methane generation occurs up to vitrinite reflectance values of 3.0 percent, maximum methane generation occurs during the medium- and low-volatile bituminous ranks over R_m values of approximately 1.1 to 2.0 percent. The proportion of wet gases in coal beds decreases with increasing burial and thermal maturation (fig. 3). This decrease is probably due to a combination of dilution effects as more methane is generated from the coal and/or thermal cracking of heavier hydrocarbons into methane.

Carbon dioxide and nitrogen are also generated during coalification. On the basis of data from Levine (1992), and assuming that only methane and carbon dioxide are produced from the coals, most of the carbon dioxide generation (approximately 50 percent) occurs during early

Table 2. Stages of biogenic and thermogenic coalbed gas generation (from Scott, 1993, after Russell, 1990).

COALBED GAS GENERATION STAGE	VITRINITE REFLECTANCE (percent)
Primary biogenic methane	<0.30
Early thermogenic	0.50 to 0.80
Maximum wet gas generation	0.60 to 0.80
Onset of intense thermogenic methane generation	0.80 to 1.00
Onset of secondary cracking of condensate to methane	1.00 to 1.35
Maximum thermogenic methane generation	1.20 to 2.00
Deadline for significant wet gas generation	1.80
Deadline for significant thermogenic methane generation	3.00
Secondary biogenic methane	0.30 to 1.50+

coalification at R_m values less than 0.65 percent (lignite to high-volatile B bituminous ranks). Only 5 percent of the total carbon dioxide generation occurs at R_m values above 2.5 percent. Carbon dioxide generation corresponds to moisture loss in coal, suggesting that a large portion of the carbon dioxide generated at lower coal ranks is dissolved in water and subsequently transported out of the system. The total amount of nitrogen generated from a coal may depend on how much nitrogen is in the coal, how it is bonded in the coal structure, and the types and distribution of oxygen-bearing functional groups in the coal. Atomic nitrogen and/or ammonia are released through the thermal decomposition of amines (Klein and Jüntgen, 1972) as n-alkanes are generated and released during the early gas-generating stage. Ammonia participates in redox reaction during coalification and is subsequently converted into atomic nitrogen (Rohrback and others, 1983). Therefore, coals in the maximum wet-gas-generation stage between vitrinite reflectance values of 0.5 and 0.8 percent can contain appreciable quantities of nitrogen (fig. 4).

Migration and diffusion of gases through coal beds during active gas generation and/or [illegible] uplift and erosion may also affect [illegible] gas composition. [illegible]rption [illegible] may reduce

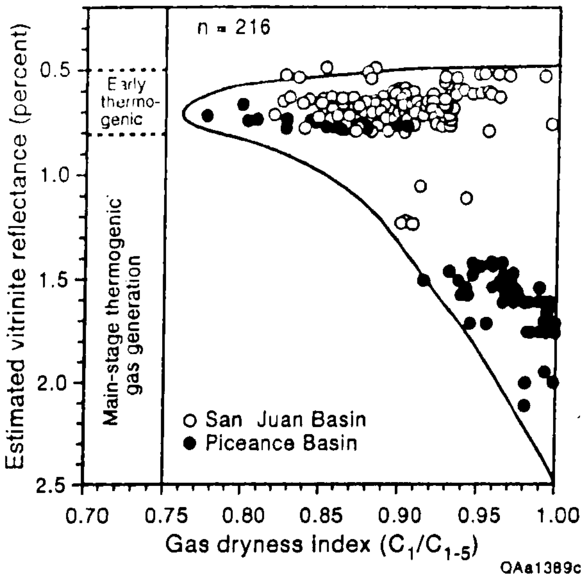

Figure 3. Changes in gas dryness index with increasing coal rank. Wet gases are generated from hydrogen-rich coals during the early thermogenic stage above vitrinite reflectance values of 0.5 percent. The wet gas generation stage corresponds to maximum wet gas generation (R_m between 0.5 and 0.8 percent). Gas dryness indices increase toward unity as the amount of wet gas components are thermally cracked and/or diluted by additional methane formation. From Scott (1993).

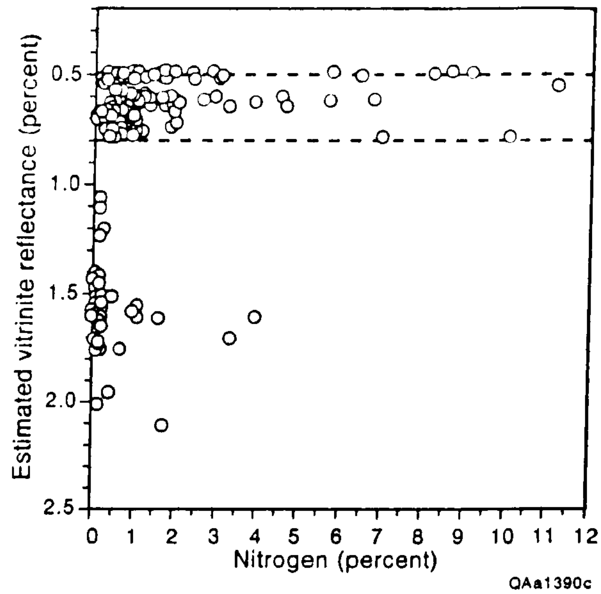

Figure 4. Variation of nitrogen content in coalbed gas with increasing rank. The generation of wet gases (R_m between 0.5 and 0.8 percent) also results in the release of nitrogen contained in amines. Ammonia involved in redox reactions is subsequently reduced to atomic nitrogen during coalification. From Scott (1993).

the effective rate of diffusion, suggesting that strongly sorbed gases, such as ethane and carbon dioxide, diffuse through the coal much more slowly than methane and nitrogen. Therefore, gases diffusing through coal beds may become enriched in methane or nitrogen. However, methane enrichment may not occur if gas migration occurs primarily through the fracture or cleat system according to Darcy's law. As coal beds are elevated during uplift, reservoir pressures decrease, resulting in a possible increase in the ethane and carbon dioxide content in coalbed gases.

Hydrogeology

The importance of hydrology to coalbed methane production was first documented in the San Juan Basin (Kaiser and others, 1993 [illegible]). [illegible] potentiometric surface, pressure regime, hydrochemistry, and numerical ground-water modeling were used to evaluate the relation between hydrogeology and coalbed methane producibility. Coal beds are commonly aquifers with permeabilities that are orders of magnitude higher than those of associated sandstones and mudstones. Coal bed continuity and permeability, basin structural configuration, topography, and annual precipitation all affect recharge to coal beds.

Hydrogeology affects coalbed gas composition in several ways. Artesian overpressure increases reservoir pressure, thus affecting the relative sorption of different gas components, whereas preferential migration of methane may occur in water. The high sorption capacity of ethane, propane, and the other wet gases on the coal surface and the lower solubility of these gases in water relative to methane suggest that methane is more likely to migrate in water moving through coal beds than the heavier hydrocarbon gas components. Bacteria transported through permeable coal beds can metabolize wet gas components, n-alkanes (generated from hydrogen-rich coal beds during coalification), and organic compounds on the coal to generate chemically dry secondary biogenic gases. Bacterial alteration of chemically wet gas components can remove nearly all of the heavier gas components, resulting in chemically dry gases that resemble mature thermogenic gases (James and Burns, 1984). Water washing (Hanson, 1990) and biodegradation of n-alkanes can result in the complete removal of n-alkanes from coal extracts.

FRUITLAND COALBED GAS COMPOSITION

Among U.S. coalbed gases, San Juan Basin gases show the largest gas compositional variations (Scott, 1993). The Fruitland Formation is abnormally pressured relative to freshwater hydrostatic gradient (0.433 psi/ft; 9.80 kPa/m) and is divided into overpressured and underpressured areas separated by a narrow transition zone (fig. 5). On that basis, gas compositional data were divided into overpressured, underpressured, and transitional categories (fig. 5; table 3).

There are significant differences in coalbed gas composition between overpressured and underpressured parts of the basin. Hydrologic analyses indicate that overpressure in the Fruitland Formation is artesian in origin and [illegible] a reg[illegible] event that [illegible] during the

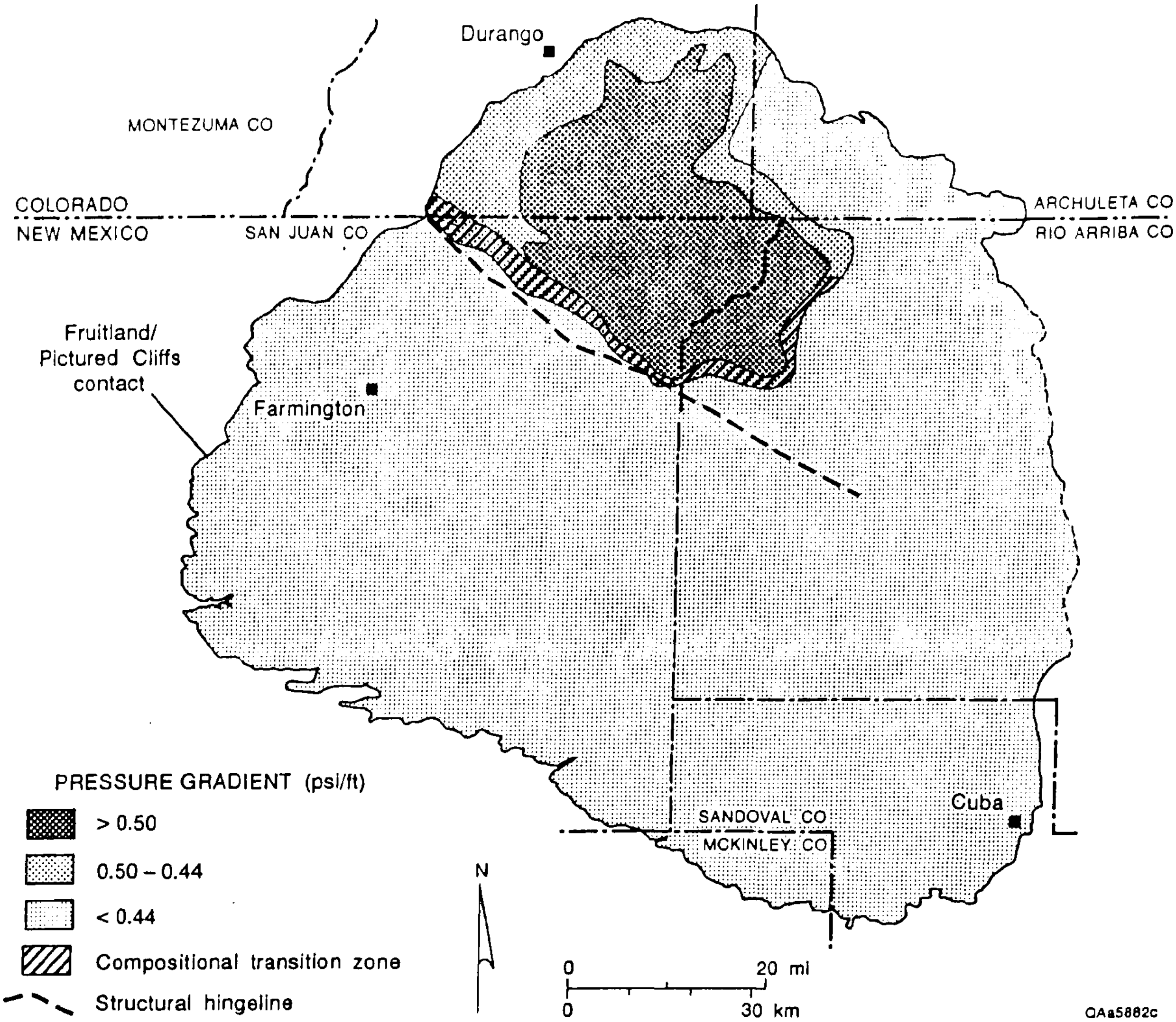

Figure 5. Regional overpressure and underpressure in the San Juan Basin. Overpressure (pressure gradients [pressure-depth quotients] more than 0.44 psi/ft) is artesian in origin and is coincident with southwestward pinch-out and/or offset of aquifer coal beds along a structural hingeline. Modified from Kaiser and others (1991).

middle Pliocene (Kaiser and others, 1991). Highly permeable, laterally continuous coal beds override abandoned shoreline Pictured Cliffs sandstone tongues and extend to the elevated recharge area in the northern basin to form a dynamic, regionally interconnected aquifer system. Pinch-out of coal beds and/or their offset by faults along a structural hingeline serve as a permeability barrier

Table 3. Gas compositional statistics for produced Fruitland coalbed gases.

		C_1/C_{1-5}	Ethane (percent)	Carbon dioxide (percent)	Nitrogen (percent)	Heating value (Btu/ft^3)
SAN JUAN BASIN						
Upper Cretaceous Fruitland Formation	min	0.77	0.0	0.0	0.0	634
	max	1.00	11.9	42.0	11.2	1266
	X	0.96	2.3	4.4	0.8	1015
	S	0.05	2.6	4.4	1.3	97
	C	0.05	1.1	1.0	1.8	0.10
	n	759	759	769	759	759
Overpressured	min	0.85	0.0	0.0	0.0	748
	max	1.00	8.4	26.4	9.2	1196
	X	0.99	0.6	6.5	0.5	953
	S	0.02	0.9	3.9	1.0	49
	C	0.02	1.5	0.6	1.9	0.1
	n	395	395	399	395	395
Underpressured	min	0.80	0.1	0.0	0.0	879
	max	1.00	11.3	5.5	11.2	1266
	X	0.92	4.8	0.9	1.1	1109
	S	0.04	2.2	0.7	1.6	66
	C	0.05	0.5	0.8	1.4	0.1
	n	278	278	280	278	278
Transition	min	0.77	0.0	0.1	0.0	634
	max	1.00	1.19	42.0	9.8	1231
	X	0.96	2.4	6.3	0.5	996
	S	0.05	2.7	5.7	1.3	106
	C	0.00	0.0	0.1	0.0	1.1
	n	86	86	90	86	86

X = mean
S = standard deviation
C = coefficient of variation

to basinward flow of meteoric water that separates overpressure from underpressure (Ayers and others, 1991; Kaiser and others, 1991). This dynamic, hydrogeologic system has a major influence on coalbed gas composition.

Basinwide, gas dryness indices of produced coalbed gases range from 0.77 to 1.00 and average 0.96 (table 3), whereas ethane content ranges from zero to nearly 12 percent. Carbon dioxide and nitrogen range from zero to more than 40 and 11 percent, respectively. Coalbed gases with the highest carbon dioxide values ($>$ 20%) are located along the northwest margin of the basin near the Colorado and New Mexico border. Chemically dry to very dry coalbed gases, located in both the overpressured, north-central and the underpressured, southern part of the basin, are separated by a northwest-trending band of relatively wet coalbed gases (plate 1). Overpressured coalbed gases are chemically drier (mean C_1/C_{1-5} value of 0.99) than underpressured gases, which have a mean C_1/C_{1-5} value of 0.92 (table 3). Ethane content of Fruitland coalbed gases ranges from zero to more than 11 percent. The wet gases from underpressured coal beds have a significantly higher mean ethane content (4.8 percent) than gases from overpressured coal beds [illegible] of 0.6 percent).

Carbon dioxide content in Fruitland coalbed gases ranges from less than 1 percent to more [illegible] cent (table 3). Coalbed gases with the highest carbon dioxide content (greater than 10 p[illegible]) are from the north-central part of the basin. This area is characterized by very dry [illegible] C_1/C_{1-5} value of 1.00) from highly productive coalbed gas wells. From this area, carbon di[illegible] content o[illegible] bed gases decreases gradually northeastward and very abruptly southward [illegible] content of Fruitland coalbed gases is generally less than [illegible] of the basin. The ranges of carbon dioxide values for underpressured [illegible] bed gases are similar (table 3); however, the mean carbon dioxide of [illegible] gases (6.5 percent) is significantly higher than that of underpressured [illegible] percent).

Underpressured and overpressured coalbed gases have similar ranges of nitrogen content. Nitrogen content in Fruitland coalbed gases is generally low (mean of 0.8 percent), and fewer than 5 percent of the samples contain more than 3 percent nitrogen, indicating that gas sample contamination by air was probably not a major problem. Some wells in the southern part of the basin, where the lowest rank coals are located, contained more than 5 percent nitrogen, which may be related to biogenic activity. Heating value ranges from 634 Btu/ft^3 in the northern, overpressured part of the basin to 1,266 Btu/ft^3 in the underpressured part of the basin, reflecting relative abundance of inert and wet gas components

ORIGINS OF FRUITLAND COALBED GASES

Thermogenic gases

Wet Fruitland coalbed gases (C_1/C_{1-5} values less than 0.94) occur in high-volatile C and B bituminous coal range between vitrinite reflectance values of 0.49 and 0.75 percent (fig. 5). This range of vitrinite reflectance values corresponds to the early stages of hydrocarbon generation; vitrinite reflectance values for the principal zone of oil generation, or the oil window, range from approximately 0.5 to 1.3 percent (Tissot and Welte, 1978). This relation between chemically wet coalbed gas distribution and vitrinite reflectance values suggests that Fruitland coal beds are capable of producing wet gases and that the presence of wet gases in the southern part of the basin is directly related to coal rank and maceral composition.

Thermogenic gases become progressively drier (higher C_1/C_{1-5} values) with increasing thermal maturity as additional methane is generated from the coal and from thermal cracking of wet gases and condensate generated during the wet gas generation stage. Predictably, coalbed gases from the thermally more mature northern part of the basin are chemically dry to very dry. However, the regional distribution of these gases (plate 1) suggests that coal rank is not the only factor controlling the chemical composition of the gas. The eastern boundary of chemically dry coalbed gases does not coincide with coal-rank trends (fig. 6 and plate 1). Furthermore, a gradational change in C_1/C_{1-5} values that parallel vitrinite reflectance trends would be expected if coal rank alone controlled gas composition. Instead, there is an abrupt transition from very dry (C_1/C_{1-5} value of 1.00), carbon-dioxide rich, to wet (C_1/C_{1-5} value of 0.87), carbon-dioxide poor coalbed gases over distances of less than 1.5 mi (2 km) along some parts of the overpressured/underpressured transition (plate 1). In fact, gas composition correlates better with the pressure regime in the Fruitland Formation than with coal rank (figs. 5 and 7), suggesting that basin hydrology is a major factor controlling coalbed gas composition (Scott and Kaiser, 1991). The convoluted transition zone that separates chemically dry to very dry, carbon dioxide-rich gases and chemically wet carbon dioxide-poor gases (fig. 7, plates 1 and 2) reflects the pinch-out of coal beds (fig. 8) or their offset by faulting along the structural hinge line.

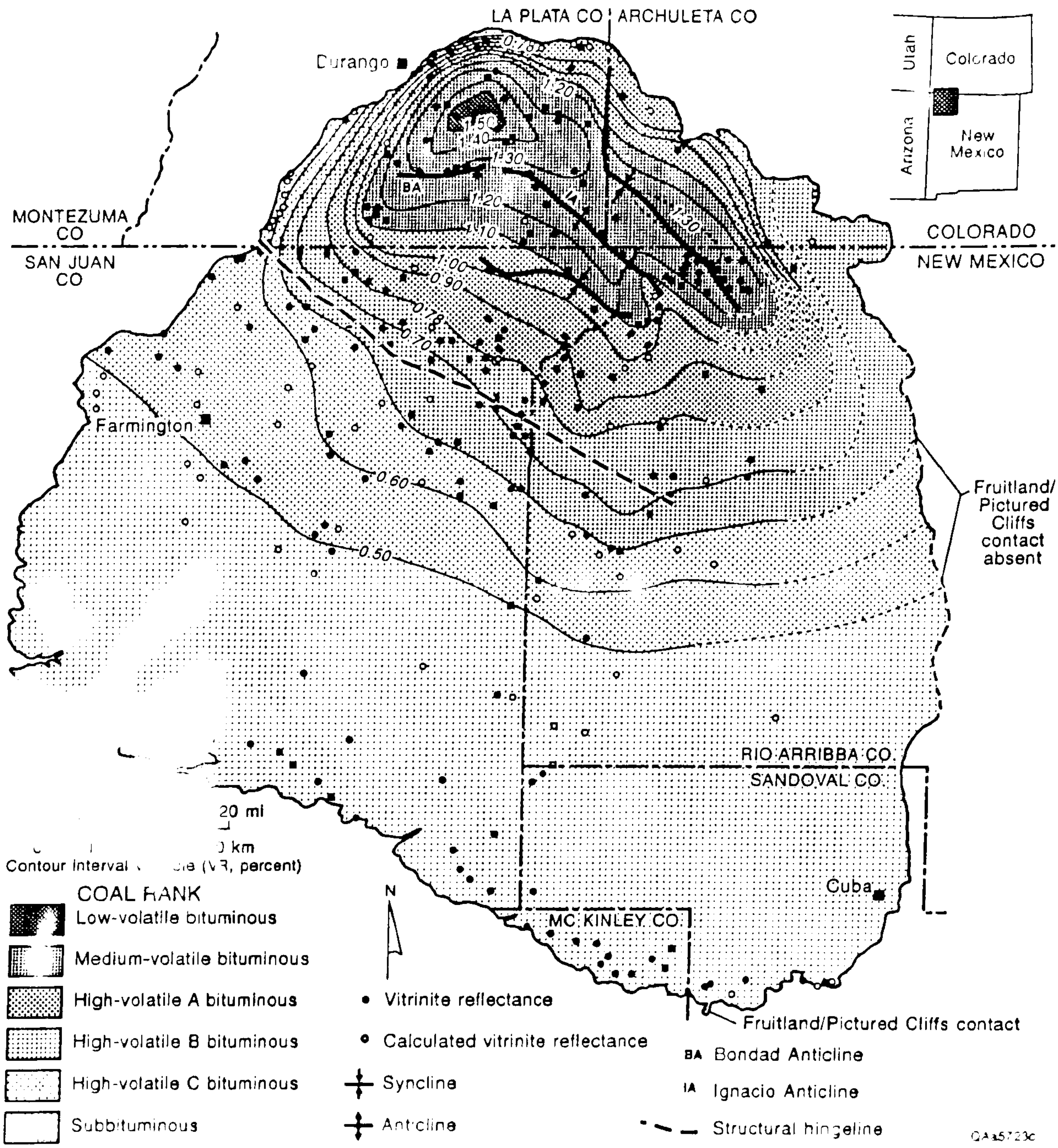

Figure 6. Fruitland coal-rank map. Coal rank generally corresponds to the structural configuration of the basin, indicating that major structural features probably formed syntectonically with coalification. Modified from Scott and others (in press).

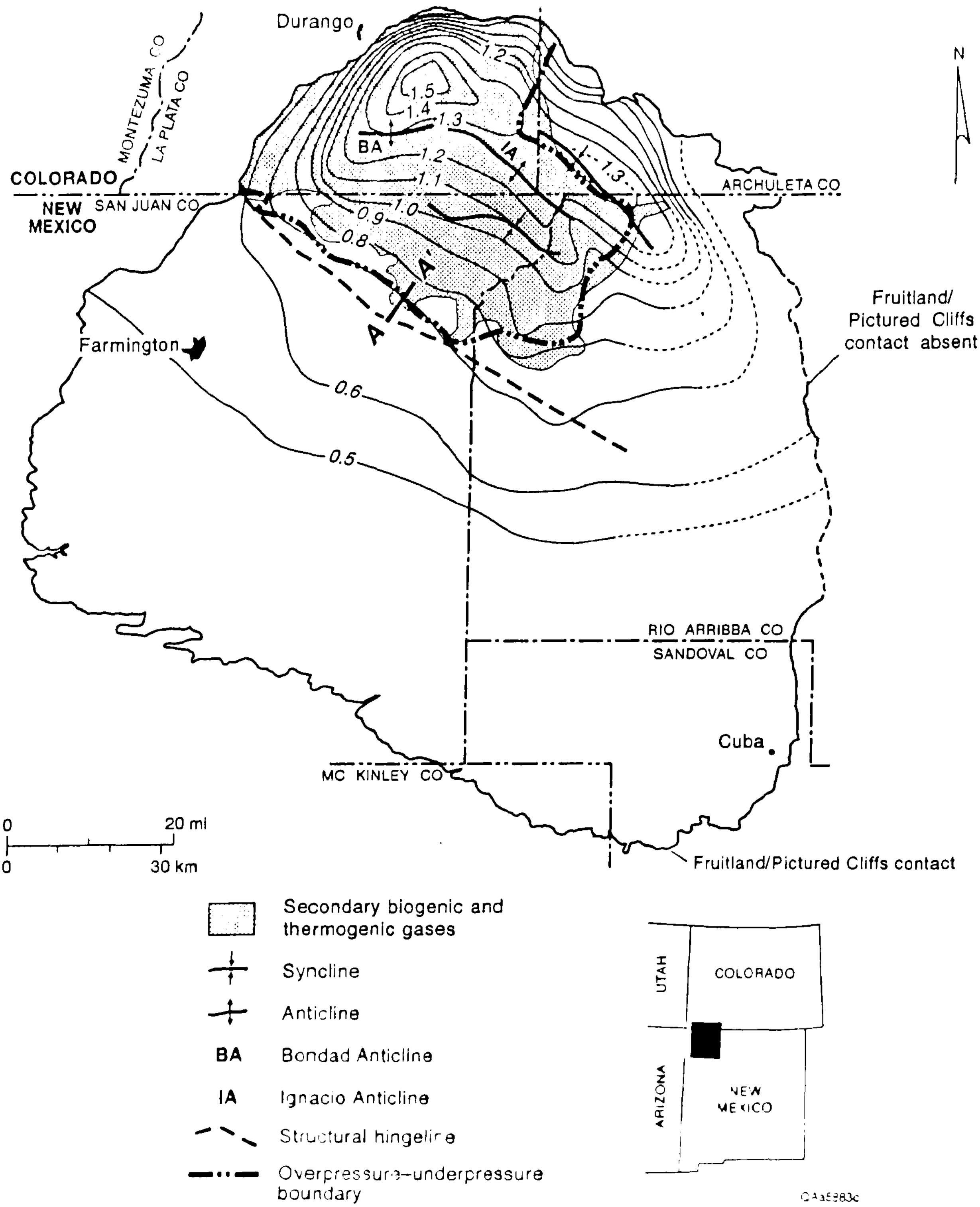

Figure 7. Relation between the distribution of chemically dry to very dry coalbed gases and coal rank. Chemically dry gases in the northern part of the basin correspond better to artesian overpressure (fig. 4) than to coal rank, indicating that gas composition is controlled by basin hydrodynamics in the northern part of the basin. From Scott ([illegible]).

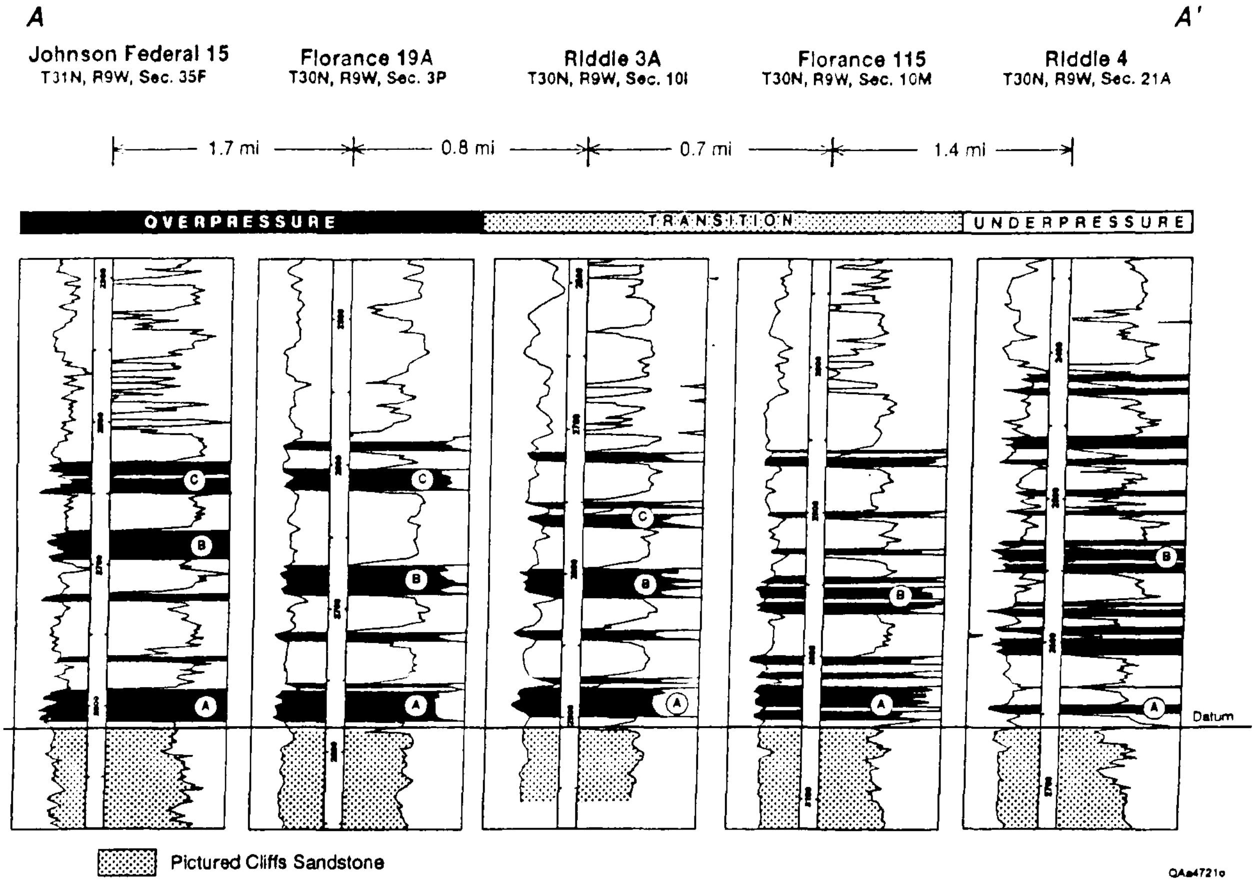

Figure 8. Northeast-to-southwest cross section across the overpressure-to-underpressure transition zone. In this part of the basin, thinning and pinch-out of the basal coal bed (A) may serve as a permeability barrier to regional flow. Offset of coal beds by faulting along the structural hingeline may also impede flow across the southern boundary of overpressure. Line of section A–A′ is shown in figure 7.

Much of the total carbon dioxide generated from coal beds is produced during early coalification, and the carbon dioxide content of coalbed gases generally decreases with increasing rank. Gases from low- and medium-volatile bituminous coals from the northern basin and high-volatile B bituminous to subbituminous coals in the southern part of the basin generally have low to moderate carbon dioxide content (less than 3 percent). Carbon dioxide content is highest in the high volatile A bituminous range (plate 2). However, carbon dioxide content of gases from high-volatile A bituminous coal varies from less than 1 to more than 10 percent, indicating that [illegible] is [illegible] the [illegible] factor [illegible] carbon dioxide cont[illegible] high [illegible] bon dioxide content in coalbed gases coincides with the overpressured part of the basin and with highest bottom-hole pressures (Kaiser and others, 1991; Scott and others, 1991b), indicating that the carbon dioxide content is partly controlled by basin hydrology, that is, by regional artesian overpressure. The low carbon dioxide content (less than 1 percent) of low-volatile bituminous coals in the northern part of the basin may be due to a combination of rank, solution, and subsequent transportation of carbon dioxide in ground water flowing basinward.

Slightly higher carbon dioxide content (1 to 3 percent) in coal beds from dip-elongate bands extending south of the overpressured area (plate 2) may represent diffusion of carbon dioxide and/or southwestward flow of bicarbonate from the overpressured part of the basin. These higher carbon-dioxide-content trends correspond to dip-elongate coal deposits, regional hydraulic gradient, and northeast-oriented productivity trends. The relatively high carbon-dioxide-content bands terminate in northern San Juan County near the San Juan River valley, a regional flow boundary (Kaiser and others, 1991; Scott and others, 1991a, b).

Chemically dry gases with low carbon dioxide contents are associated with higher rank coal in the northern part of the basin, whereas chemically wet, low-carbon-dioxide-content coalbed gases occur in the underpressured, southern region. The coincidence between regional overpressure and the occurrence of chemically dry to very dry, carbon dioxide-rich gases, and the abrupt transition between these gases and wetter gases with low carbon dioxide contents in the underpressured, southern part of the basin indicate that coalbed gas composition is controlled by hydrodynamics as well as coal rank.

In general, methane $\delta^{13}C$ values will become progressively more positive with increasing coal rank if the gases are strictly thermogenic. For example, methane isotopic values in the Piceance Basin of Colorado range from -60.2 to -29.1 ‰ and become isotopically heavier with increasing coal rank over the range of high-volatile C bituminous to semianthracite (vitrinite reflectance values of 0.48 to 2.10 percent; Tyler and others, 1991, and references therein). The range of methane $\delta^{13}C$ from Fruitland coals in the San Juan Basin is -41.0 to -54.3 ‰ over a [illegible] rank range of high-volatile C bituminous to low-volatile bituminous (Rice and others, 1989; Scott, 1993). These coalbed gases are unusual because there is no significant change in methane $\delta^{13}C$ with increasing rank. More than 90 percent of the samples have $\delta^{13}C$ values between −43.9 to −41.0 °/oo over vitrinite reflectance values of 0.5 to 1.5 percent. The isotopically lightest methane (-46.5 to −54.8 °/oo) is restricted to a relatively small area in the southern basin. The consistency of methane isotopic values across the basin is attributed to mixing of thermogenic, secondary biogenic, and migrated gases.

Biogenic gases

Previous studies on the origin of coalbed gases have generally assumed that coalbed gases are p[illegible]minantly thermogenic and that biogenic gases, when recognized, in coal beds were gen[illegible]ed during the early stages of coalification (peatification) (DeLaune and others, 1986; Law and oth[illegible]1; Rice, 1992; Whiticar, 1992). Although the presence of biogenic methane in coal [illegible] known for some time, only recently has the origin of these gases become clear. [illegible]c methane generated during early coalification is probably not retained by the coal [illegible]es, suggesting that most of the biogenic gases found in coal beds are actually [illegible]ondary bio[illegible] gases related to meteoric recharge and basin hydrodynamics. These secondary biogenic gases are more abundant than was previously recognized.

Primary biogenic methane is generated from peat at relatively low temperatures and burial depths (vitrinite reflectance [R_m] less than 0.30 percent). The fate of primary biogenic methane remains controversial. Some researchers believe that primary biogenic methane, retained by the coal in a sorbed or free state, is preserved to become part of the coal structure (Rice, 1992; Whiticar, 1992). However, no obvious mechanism for retaining the primary biogenic gases exists at low ranks, suggesting that primary biogenic gases readily escape from the system (Levine, 1993; Scott, 1993). The high moisture content of peat suggests that many of the potential sorption sites for [illegible]ogenic gases are occupied by water molecules. Therefore, biogenic gases cannot be sorbed to the coal surface, and large amounts of the biogenic methane and carbon dioxide are probably dissolved in water and/or subsequently removed from the system during compaction and coalification. Although some of the anaerobic bacteria in the peat stage could continue to metabolize organic compounds into the lignite to subbituminous ranks, the generation of primary biogenic gases into the lignite and subbituminous ranks has not been fully documented in the context of basin hydrodynamics; biogenic gases in low-rank coals along wet basin margins, such as in the Powder River Basin in Wyoming, may actually be secondary biogenic gases associated with meteoric recharge.

The generation of secondary biogenic gases is directly related to basin hydrodynamics. Until recently, relatively few studies of the importance of hydrogeology to coalbed methane production have been performed (Kaiser and others, 1989; Kaiser and Ayers, 1991; Kaiser and others, 1991; Stevens and others, 1992; Kaiser, 1993; Scott and Kaiser, 1993). These studies demonstrate that coal beds commonly act as regional aquifers and that long-term high water production indicates high permeability, probable continuity of coal beds, and likely meteoric recharge from elevated, wet basin margins. The importance of secondary biogenic gas generation to coalbed gas exploration and production was first recognized in the San Juan Basin (Kaiser and others, 1991; Scott and Kaiser, 1991; Scott and others, 1991a, b). Other researchers subsequently recognized the presence of secondary biogenic gases in other basins (Tyler and others, 1991; Smith and others, 1992; Rice, 1993; Scott, 1993). Secondary biogenic gases are generated through the metabolic activity of bacteria, which are introduced into the coal beds by meteoric waters flowing basinward through them (fig. 9). Thus, secondary biogenic gases differ from primary biogenic gases in that the bacteria are introduced into the coal beds after coalification and subsequent uplift of the basin margins. The bacteria metabolize wet-gas components, n-alkanes, and other organic compounds on the coal to generate methane and carbon dioxide. Secondary biogenic gases are known to occur over subbituminous to low-volatile bituminous coal ranks (Scott and others, 1991a, b) and probably occur over the lignite to anthracite range (Rice, 1993; Scott, 1993). These gases are

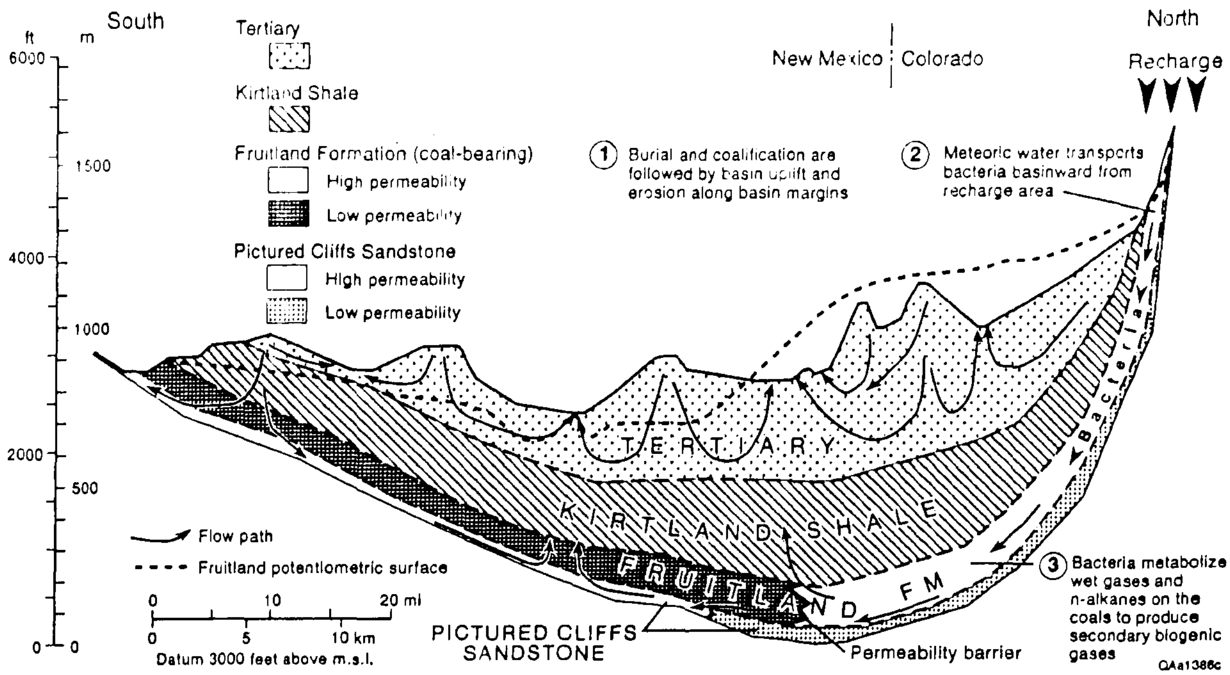

Figure 9. Schematic cross section showing ground-water flow and generation of secondary biogenic gases in the San Juan Basin. Bacteria transported basinward in meteoric waters moving basinward from a northern recharge area metabolize wet gases (ethane, propane, etc.), n-alkanes, and organic compounds on the coal to produce secondary biogenic methane and carbon dioxide. From Kaiser and others (1991) and Scott (1993).

usually restricted to low-rank coals near basin margins but are also found more than 35 mi (56 km) from the northern recharge area of the San Juan Basin.

The isotopic composition of coalbed carbon dioxide produced with methane from coal beds can provide valuable information about gas origin when used in conjunction with coal rank, gas chemistry, and basin hydrodynamics data (Scott and others, 1991a, b; Scott and Kaiser, 1991). The isotopic values of carbon dioxide derived from decarboxylation reactions during thermal maturation are estimated to range from -25 to -10 ^{o}/oo (Irwin and others, 1977; Chung and Sackett, 1979). Therefore, carbon dioxide released during coalification should be isotopically negative (light). However, the isotopic composition of carbon dioxide in Fruitland coal beds is highly variable, ranging from -32.0 to +13.2 ^{o}/oo. Isotopically light carbon dioxide is associated [illegible] the central part of the basin, whereas isotopically heavy carbon dioxide

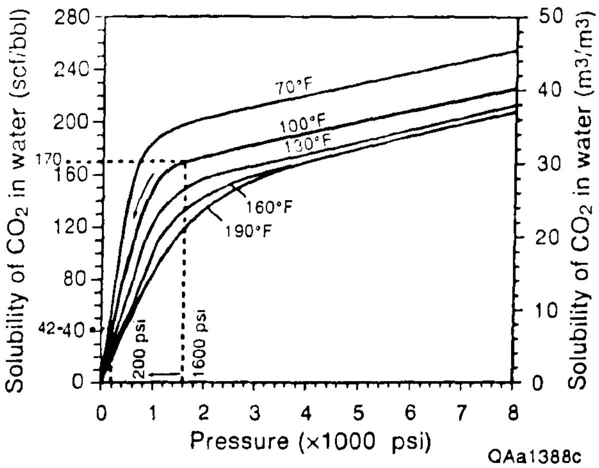

Figure 10. Variation in carbon dioxide solubility in pure water with decreasing reservoir pressure. As bicarbonate-rich coalbed waters are produced, pressure reduction results in the exsolution of carbon dioxide from the water. This carbon dioxide is then produced along with other coalbed gases. Modified from Crawford and others (1963).

is restricted to the northern, overpressured part of the basin. Therefore, carbon dioxide in the central part of the basin is thermogenic, whereas carbon dioxide in the northern part of the basin is predominantly biogenic. The direct correlation of carbon dioxide $\delta^{13}C$ values and carbon dioxide content further supports secondary biogenic gas generation in the overpressured part of the basin, where the highest carbon dioxide contents occurs.

Carbon dioxide in Fruitland coalbed gases is derived through desorption from coal surfaces and/or exsolution from formation water with pressure reduction during production. Secondary biogenic carbon dioxide generated by bacteria in Fruitland coal beds was subsequently dissolved in formation waters; as pressure increased basinward, progressively more carbon dioxide was dissolved. However, as reservoir pressure decreases during production, carbon dioxide is exsolved from the formation water and desorbed from the coals to be produced along with other coalbed gases. A pressure decrease from 1,600 to 200 psi (11,032 to 1,379 kPa) would exsolve approximately 132 scf/bbl (23.4 m^3/m^3) of carbon dioxide from the water, which is then produced along with other coalbed gases (fig. 10). This indicates that a well producing 1,000 bbl/d (160 m^3/d) of bicarbonate-rich water could also produce 132 Mcf/d (3,738 m^3/d) of carbon dioxide.

CONCLUSIONS

(1) Fruitland coalbed gas composition is highly variable across the basin. Gas dryness indices (C_1/C_{1-5} values) range from 0.77 to 1.00, indicating that coalbed gases range from chemically very wet to very dry. Ethane content in coalbed gases ranges from 0 to nearly 12 percent. Gases with the highest ethane content occur in coals in the wet-gas-generating stage, between vitrinite reflectance values of 0.5 and 0.8 percent. The carbon dioxide content of coalbed gases is variable, ranging from 0 to more than 40 percent, and is derived from thermal decarboxylation reactions that occur during coalification and from bacterial activity in coals of all ranks.

(2) The composition of produced coalbed gases is controlled by maceral composition of the coal, particularly the abundance of hydrogen-rich components, reservoir pressure, which affects the sorptive capacity of the coal, burial history and coal rank, which control the timing of major coalbed gas component generation, and hydrogeology, which influences gas composition through the introduction of bacteria and generation of biogenic coalbed gases and migration of gases.

(3) Chemically wet gases, located in the central part of the basin between vitrinite reflectance value of 0.5 to 0.8 percent, were formed during the early thermogenic stage of gas generation. Carbon dioxide produced from these coal beds is isotopically negative (less than $-25\ ^{\circ}/oo$), indicating a thermogenic origin.

(4) Gases in the northern part of the basin are a mixture of thermogenic and secondary biogenic gases, as evidenced by abrupt changes in gas chemistry, consistency of methane isotopic values across the basin, and the presence of isotopically heavy carbon dioxide in coalbed gases and bicarbonate in formation water. Carbon dioxide and bicarbonate isotopic values range up to +18 and +26 $^{\circ}/oo$, respectively.

(5) Coal beds in the southern and southwestern part of the basin are subbituminous rank and have not reached the thermal maturity level required to generate significant quantities of methane. Therefore, coalbed gases in the southern part of the basin are probably a mixture of early thermogenic and predominantly secondary biogenic gases.

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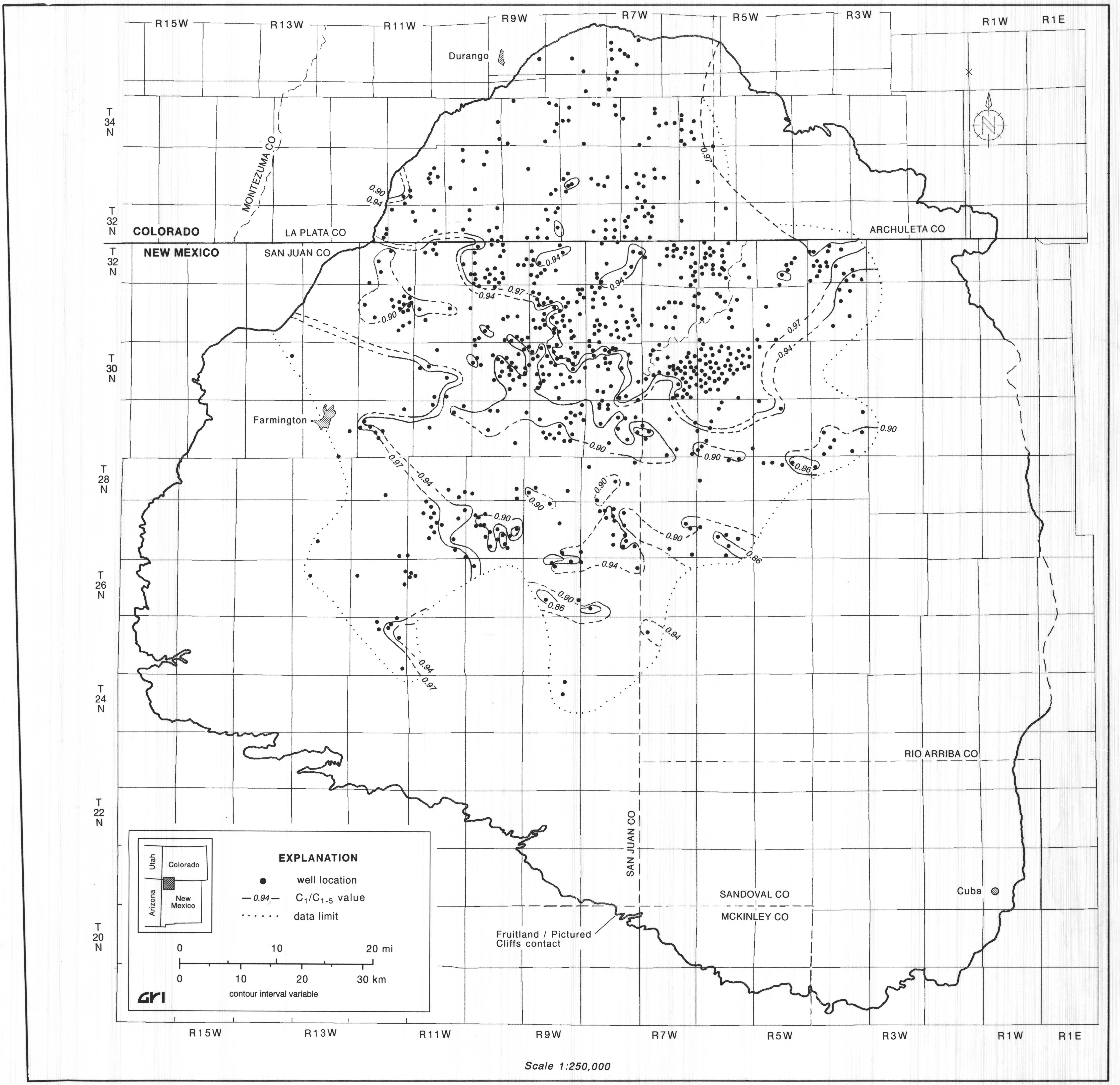

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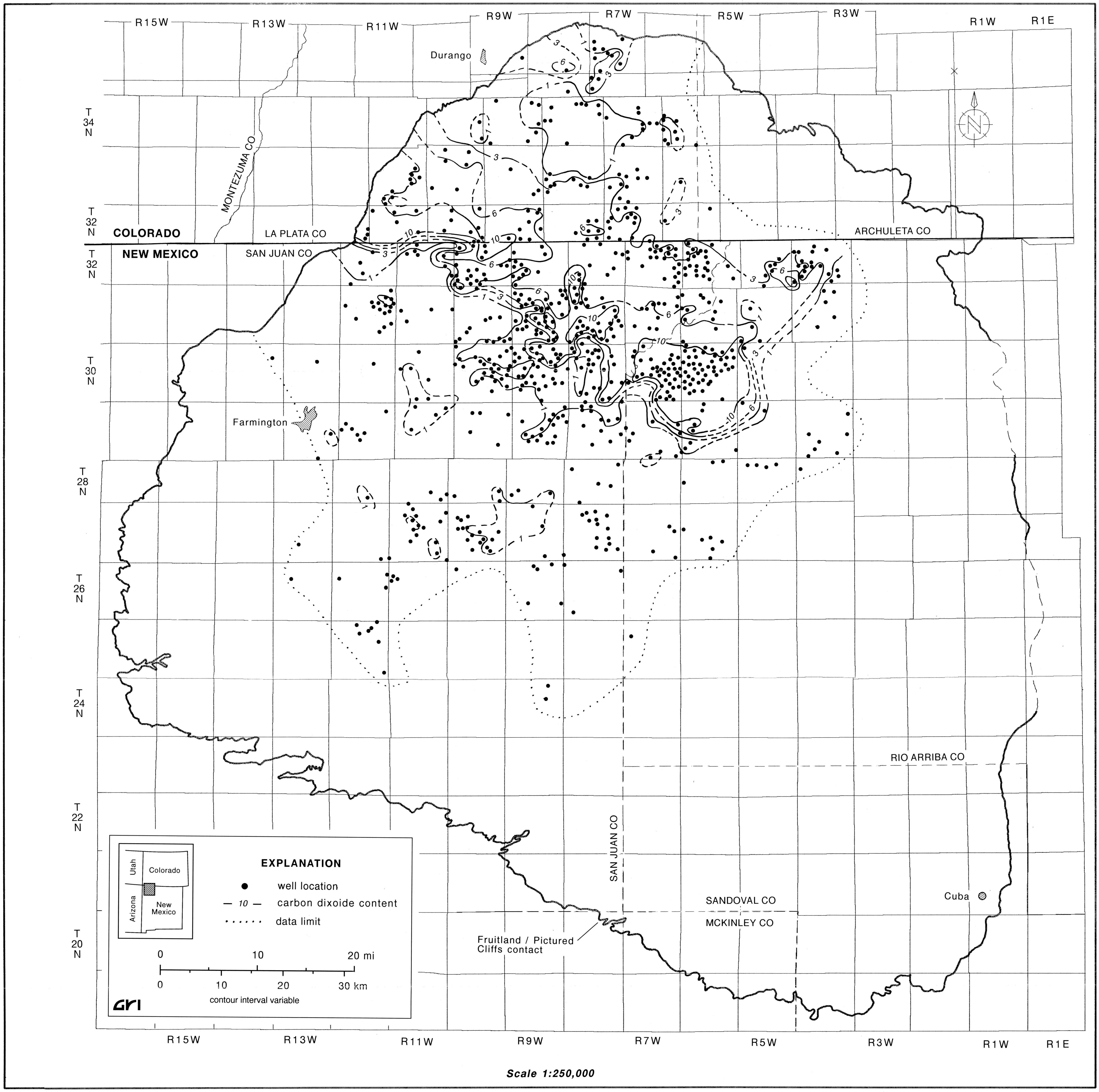

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