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# Variations in Composition and Origins of Gases from Coal Bed and Conventional Reservoirs, Wind River Basin, Wyoming

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## ABSTRACT

*Variations in the chemical and isotopic compositions ($\partial^{13}C_1$ or methane) of gases from the Wind River Basin, central Wyoming, were studied in order to better understand the origins of the gases. Gases from all producing intervals in conventional reservoirs at depths ranging from 2,321 to 18,050 ft are predominantly thermal in origin ($C_1/C_{1-5}$ of 0.82 to 1.0, $\partial^{13}C_1$ of -31.12 to -47.40‰). Most gases sampled from conventional reservoirs appear to have migrated from deeper, more mature source rocks. Gases were collected from three fields where reservoirs from several stratigraphic levels are productive, the Madden field along the deep basin trough, and the Pavillion and East Riverton Dome fields in the western part of the basin. Considerable vertical migration has occurred at all of these fields. At Madden, for example, gases become only slightly heavier isotopically ($\partial^{13}C_1$ of -34.81 to -31.82‰) and chemically drier ($C_1/C_{1-5}$ of 0.95 to 1.0 ) through more than 12,000 ft of section (5,556 to 18,050 ft). At Pavillion, gases from the shallow (3,437 to 3,564 ft), immature reservoirs ($R_m$ 0.5 percent) in the lower Eocene Wind River Formation are isotopically heavy ($\partial^{13}C_1$ of -39.24 to -40.20‰) and were generated by mature to post-mature source rocks.*

*The lacustrine Waltman Shale Member of the Paleocene Fort Union Formation, which is present throughout much of the eastern two-thirds of the basin, appears to inhibit the vertical migration of gas from deeper sources. Few gas fields produce from the marginally mature reservoirs above the Waltman Shale Member, and the gas that is produced from this interval appears to have been generated in the Waltman. At Fuller Reservoir field, in the central part of the basin, gas from shallow (2,500-3500 ft ), marginally mature ($R_m$ 0.60 to 0.65 percent) reservoirs in the Fort Union Formation above the Waltman Shale Member is associated with waxy oil, is wet chemically ($C_1/C_{1-5}$ of 0.84) and is isotopically light ($\partial^{13}C_1$ of -46.99‰). This gas and oil appears to have been generated in the Waltman Shale Member deeper in the basin. Gases from below the Waltman Shale Member are chemically dry ($C_1/C_{1-5}$ of 0.94 to 0.95) and isotopically heavy ($\partial^{13}C_1$ of -34.79 to -36.19‰) and probably migrated from underlying Upper Cretaceous source rocks. In contrast, at Pavillion field, west of the pinchout of the Waltman Shale Member, mature gases from probable Upper Cretaceous source rocks were able to migrate into the shallow marginally mature reservoirs of the lower Eocene Wind River Formation.*

*A single coalbed methane well is producing in the western part of the basin, at Riverton Dome in the southeast corner of the Wind River Reservation. Gas from this well, which is completed in Upper Cretaceous Mesaverde Formation coals at depths of 3,270 to 3,839 ft., appears to be of thermogenic origin ($\partial^{13}C_1$ -46.15‰, $C_1/C_{1-5}$ 0.98). Shallow coalbed gases (307 to 818 ft) desorbed from cores of the thermally immature ($R_m$ 0.40 to 0.54 percent) Mesaverde Formation in the Wind River Reservation have highly varied chemical and isotopic compositions and appear to have complex and varied origins. Coalbed gases from the Hudson area in the southeastern corner of the Reservation have the isotopic compositions of a thermally generated gas ($\partial^{13}C_1$ -47.0 to -55.91‰). Coalbed gases from the Pilot Butte area about 25 miles to the northwest appear to be a mixture of biogenic and thermogenic gas. The methane fraction is isotopically light ($\partial^{13}C_1$ -61.85 to -66.21‰) and is probably largely biogenic, but the gases contain as much as 5.6 percent $C_{2+}$ and this fraction is probably of thermogenic origin. These coals appear to be too thermally immature to have generated significant quantities of thermogenic gas, and it is suggested that the thermogenic component of these gases migrated into the coals from a deeper, more thermally mature source.*


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## INTRODUCTION

The Wind River Basin of central Wyoming has produced significant amounts of oil and gas from a large number of different geologic formations ranging in age from Paleozoic to early Eocene. This paper discusses the geochemistry and origin of natural gases in the Wind River Basin. Gases were collected and analyzed for variations in chemical and isotopic compositions from several of the Mesozoic and Tertiary-age formations. Paleozoic-age reservoirs produce mainly sour gas and were not sampled. The thermal maturity of gases are compared with the approximate thermal maturity of the reservoirs in order to better understand distances of migration and possible migration pathways. The objectives of the study are to (1) study variations in chemical and isotopic compositions of natural gases, and (2) interpret the origins of these gases as an aid to future exploration in the Wind River Basin.

## GEOLOGIC SETTING AND HYDROCARBON OCCURRENCE

The Wind River Basin is a complex structural and sedimentary basin formed during the Laramide orogeny in latest Cretaceous, Paleocene, and early Eocene time (Fig. 1). It is bounded on the north by the Absaroka Range, Owl Creek Mountains, and Bighorn Mountains; on the east by the Casper Arch; on the south by the the Granite Mountains; and on the west by the Wind River Range. The Wind River Basin is asymmetrical, with the deep trough adjacent to the east-west trending Owl Creek Mountains which were uplifted and faulted southward over the sedimentary basin. The west and southwest margins dip fairly gently away from the Wind River Range and the south margin dips away from the Granite Mountains. Numerous northwest-trending anticlines, many of which are bounded by reverse faults, occur along the basin margins (see Plate 1, structure contour map in paper by Keefer and Johnson, this volume).

Oil and gas fields are scattered throughout much of the Wind River Basin (Fig. 2). Hydrocarbons are produced from formations ranging in age from the Mississippian Madison Limestone to the lower Eocene Wind River Formation. Major Paleozoic-age reservoirs include the Mississippian Madison Limestone, the Middle and Upper Pennsylvanian Tensleep Sandstone and the Lower Permian Phosphoria Formation. These reservoirs produce mainly oil and sour gas. Major Mesozoic reservoirs are the Triassic Chugwater Formation and Lower Jurassic Nugget Sandstone, the Lower Cretaceous Cloverly Formation and Muddy Sandstone, and the Upper Cretaceous Frontier Formation, Cody Shale,

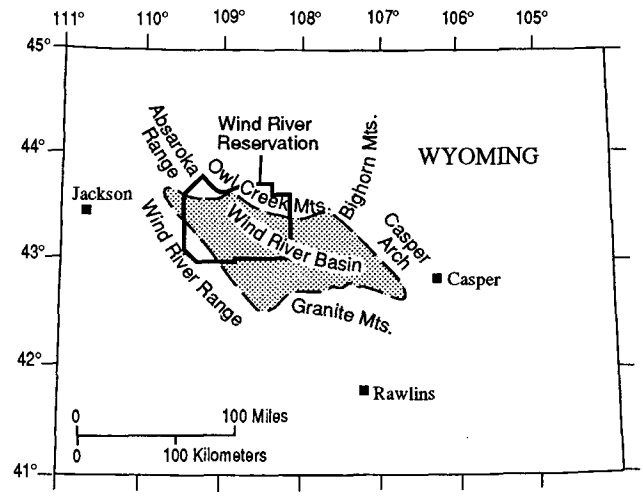


**Figure 1. Index map showing location of Wind River Basin and surrounding uplifts. Location of Wind River Reservation is also shown.**

Mesaverde Formation, Meeteetse Formation, and Lance Formation. These formations produce mainly sweet gas and condensate, and minor amounts of oil; an exception is the Nugget Sandstone which has produced significant amounts of oil. Cenozoic reservoirs include the Paleocene Fort Union Formation and the lower Eocene Wind River Formation. These formations produce mainly sweet gas and condensate, with minor amounts of oil. The Mesozoic and Cenozoic reservoirs that were sampled for this study are shown on Figure 3.

### Origin of Natural Gas

Natural gas can be of either biogenic or thermogenic origin. Biogenic gas is generated by the breakdown of organic matter by bacteria at temperatures less than 75° C by either $CO_2$ reduction (Kim and Douglas, 1972; Rice and Claypool, 1981) or, less commonly, by fermentation (Whiticar and Faber, 1986b). Isotopic compositions of methane are expressed as $\partial^{13}C_1$ (‰) [1]. Biogenic gas consists mainly of methane ($C_1/C_{1-5} > 0.99$) that is usually isotopically light, with $\partial^{13}C_1$ values lighter than -60 ‰ (Fig. 4) (Rice and Claypool, 1981; Schoell, 1983; Whiticar and Faber, 1986). Thermogenic gas is generated at higher temperatures by thermal cracking and degradation processes. During early catagenesis, both liquid and gaseous hydrocarbons are generated. Hydrogen-rich type I and type II organic matter generate mainly liquid hydrocarbons and wet gas whereas mainly gas is generated from oxygen-rich type III organic matter. During the mature stage of hydrocarbon gen-

[1] $\partial 13C_1$ (‰) = ([$^{13}C/1^2C$ sample / $^{13}C/1^2C$ standard - 1]) X 1000

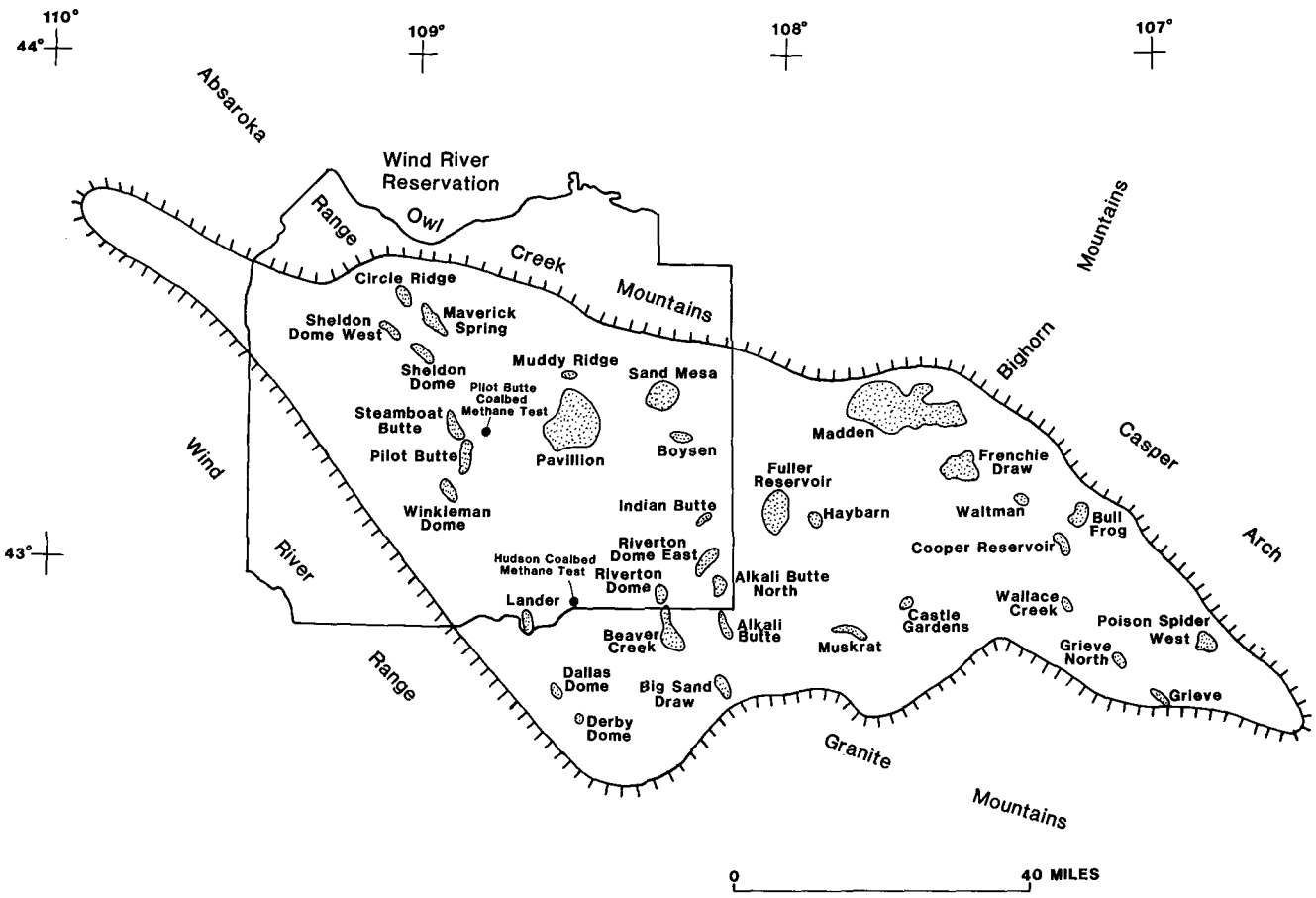


**Figure 2. Map showing locations of oil and gas fields in Wind River Basin and locations of U. S. Geological Survey coalbed gas tests in the Wind River Reservation. Approximate outline of Wind River Basin is shown by hachured line.**

eration (vitrinite reflectance 0.60-1.30 percent), thermogenic gases are chemically wet ($C_1/C_{1-5}$ values less than 0.95) and generally have $\partial^{13}C_1$ values ranging from about -50 to -40‰ (Fig. 3). With increasing levels of thermal maturity during the late stages of catagenesis, gas is formed by the thermal cracking of previously formed liquid hydrocarbons while type III organic matter continues to generate mainly gas. A $\partial^{13}C_1$ value of -40‰ commonly corresponds to the lower preservation limit of liquid hydrocarbons, either oil or condensate, and a vitrinite reflectance ($R_m$) value of 1.30 percent (Tissot and Welte, 1984). Gases generated at higher levels of thermal maturity are generally dry ($C_1/C_{1-5}$>0.95) and were generated during the post mature stage (Fig. 4).

In the Wind River Basin, biogenic gas was probably generated in shallower areas of the basin during basin subsidence, whereas thermogenic gas was generated later, under deeper burial conditions and higher levels of thermal maturity. The quantity of biogenic gas formed is usually small when compared with the quantity of thermogenic gas, and the presence of an early biogenic component in natural gas is commonly difficult to detect. Gases having $\partial^{13}C_1$ values in the -60 to -50 ‰ range are usually interpreted to be mixtures of biogenic gas and early thermogenic gas (Schoell, 1983).

The Wind River Basin was uplifted along with much of the Rocky Mountain region starting about 10 Ma and from 3,000 to 5,000 ft of erosion has occurred basinwide (Keefer, 1970, p. D29). This erosion has caused a marked decrease in formation temperatures and pressures throughout the basin and has significantly changed the hydrodynamics of the basin as well. These changes have allowed groundwater and microorganisms to reinvade formations that were too deep and too hot for bacteria to flourish prior to erosion. For example, oils in the Pennsylvanian Tensleep Sandstone reservoirs in the Wind River Basin which are at depths of less than 3,000 ft are commonly in contact with meteoric waters (Hunt 1979, p. 371). This contact has led to a degradation of the oil by a combination of abiological oxidation, microbial oxidation, and the solution of the lighter components. All of the coalbed gas tests by the U.S. Geological Survey were at depths of less than 1,000 ft in

areas where the hydrodynamics could have changed significantly because of uplift and erosion. The possibility that these coals might have been affected by the relatively recent introduction of meteoric water, and renewed microbial activity, will be discussed later.

### Gas Storage In Coal Beds

While some free gas and dissolved gas may occur in coal, as much as 98 percent of the gas is sorbed in the coal (Gray, 1977). The free and dissolved gas in the coal occurs within the fractures (cleats) and pores, whereas the sorbed gas occurs as a monomolecular layer on the internal surfaces of coal (Seldon, 1934; Kim, 1977). Because coal is a microporous solid with large internal surface areas (10's to 100's of $m^2/gm$), it has the ability to sorb very large amounts of gas and can hold much more gas in place than the same volume of a conventional reservoir. In addition, the microstructure of coal has been described as a molecular sieve or cage (van Krevelan, 1981) within which the methane molecule can be stored. Micropore capillary pressure keeps the methane bonded to the structure.

Desorption of coalbed gas occurs if the micropore capillary pressure is decreased because of uplift and erosion or dewatering (Close and Erwin, 1989). If the coal is overlain by a permeable layer, free gas in the fracture system may escape upward and out of the coal (Ulery, 1988). Because the free gas in the fracture system is thought to be in equilibrium with gas adsorbed within the microstructure of the coal, the loss of free gas from the coal bed will cause desorption to begin. A coal bed may lose part or all of its methane if this process continues. Several thousand feet of erosion has occurred in the area of the Wind River Reservation since middle or late Pliocene (Keefer, 1970), reducing capillary pressures in the coals and undoubtedly causing some methane to be lost. The circulation of near-surface waters through porous sandstones adjacent to coal beds may have caused a further loss of methane, particularly at shallow depths.

### Potential Source Rocks

The source for the heavy black oils and sour gas found in Paleozoic formations is generally believed to be the phosphatic shale of the Retort Phosphatic Shale Member of the Phosphoria Formation (Maughan, 1984). Potential source rocks are generally absent from Triassic and Jurassic formations, and the source of hydrocarbons found in these strata is problematical. Potential source rocks in the Cretaceous sequence include dark marine shale beds in the Mowry Shale (Schrayer and Zarrella, 1963; 1966; 1968; Burtner and Warner, 1984), the Frontier Formation, and the Cody Shale (Hagen and Surdam, 1984), and coals and carbonaceous shales found in the largely nonmarine Mesaverde, Meeteetse, and Lance Formations. The Cody Shale is divided into two informal members throughout much of the Wind River Basin, the upper sandy member, and the lower shaly member (Thompson and White, 1954; Yenne and Pipiringos, 1954; Keefer and Troyer, 1964; Keefer, 1972; Keefer and Johnson, this volume: Finn, this volume; Szmajter, this volume). The sandy member, which is approximately the upper half of the Cody Shale, grades to the east into a less sandy interval, and is not recognized in about the eastern one-fourth of the Wind River Basin (Finn, this volume; Szmajter, this volume). Potential source rocks Cody Shale appear to be largely confined to the shaly member (Keefer and Johnson, this volume).

The Paleocene Fort Union Formation contains abundant potential source rocks. The Fort Union Formation is divided into three members in ascending order, the lower member, the Waltman Shale Member, and the Shotgun Member. The lower member contains some coal and carbonaceous shale which are potential source rocks for gas. The Waltman Shale Member of the Fort Union Formation, a lacustrine unit which is found throughout much of the eastern two-thirds of the basin, contains significant amounts of organic matter. Keefer (1965, p. A28) analyzed four samples of the Waltman and found them to contain from 2.5 to 6.5 percent organic matter. About 25 percent of this organic matter was converted to oil upon retorting. The Waltman Shale Member grades westward into the Shotgun Member of the Fort Union Formation, which locally contains as much as 100 ft total coal thickness (Johnson and Flores, this volume). Some coal beds and carbonaceous shale are found locally in the overlying lower Eocene Wind River Formation.

### Thermal Maturity of Potential Source Rocks

Thermal maturities, estimated from vitrinite reflectance ($R_m$), of Cretaceous and younger rocks in the Wind River Basin were briefly described by Johnson and others (1991), and are more completely discussed by Pawlewicz (this volume), and Nuccio and others (this volume). In outcrops (or shallow drillholes), the marine shales of the Frontier Formation and Cody Shale, and the carbonaceous shales and coals of the Mesaverde, Meeteetse, and Fort Union Formations are immature ($R_m$ 0.40 to 0.50 percent). In wells in the deep basin, the potential sources rocks listed above are mature (Fort Union- $R_m$ 1.28 percent), to overmature (Frontier- $R_m$ 2.12 to 2.42 percent; Cody- $R_m$ 2.53 percent; Mesaverde- $R_m$ 2.08 percent; Meeteetse- $R_m$ 2.11 percent). An $R_m$ of 0.76 percent was measured for the Waltman Shale Member in Madden field, but this value probably in-

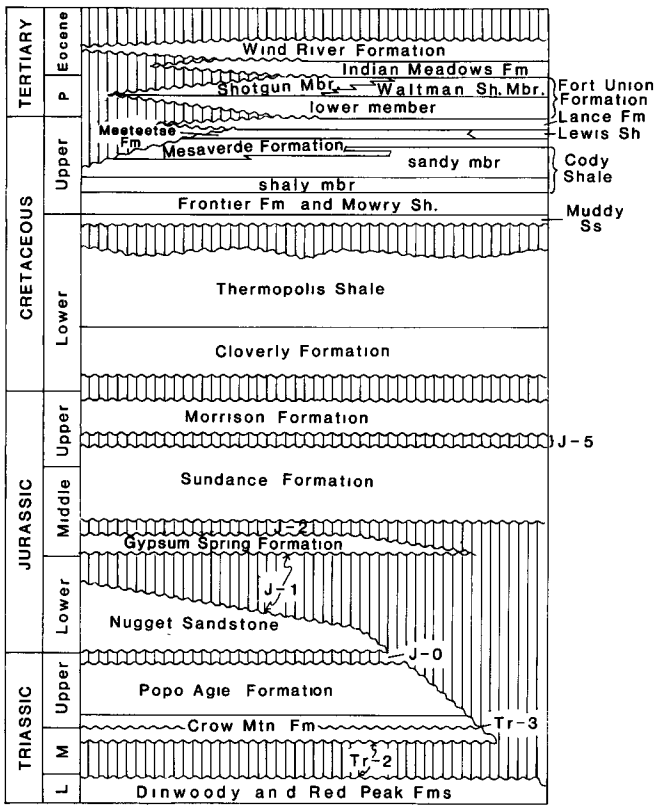


**Figure 3. Generalized stratigraphic chart of Mesozoic age and Cenozoic age rocks, Wind River Basin, Wyoming. Patterns of vertical lines indicate hiatuses. Locations of Triassic unconformities (Tr-2, Tr-3) and Jurassic unconformities (J-0, J-1, J-2, J-5) from Pipiringos and O'Sullivan (1978).**

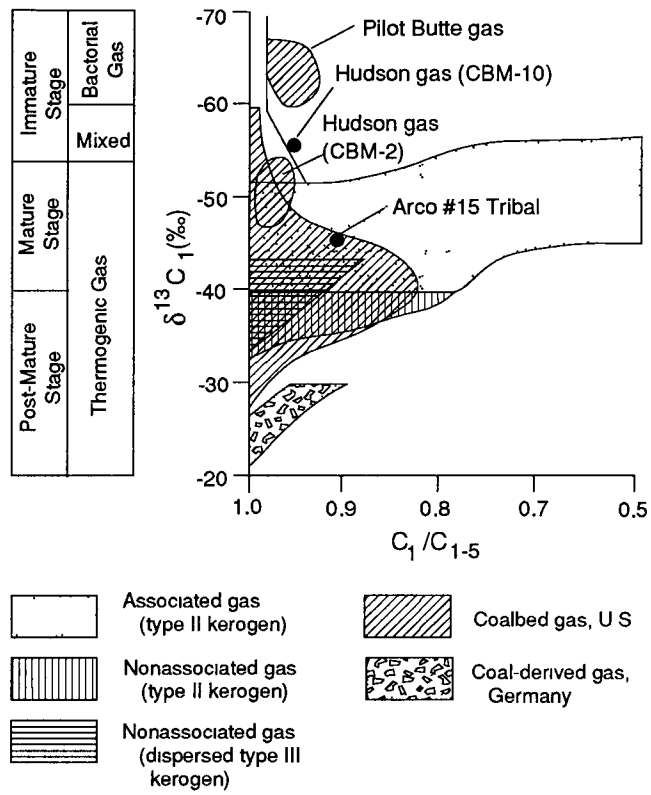


**Figure 4. Methane $\partial^{13}C$ versus chemical composition ($C_1/C_{1-5}$) of gas from various source rocks during stages of hydrocarbon generation. Modified from Schoell (1983).**

creases toward the west. The lower part of the laterally equivalent Shotgun Member in the east-central part of the Wind River Reservation attains an $R_m$ of 1.18 percent.

### Chemical and Isotopic Results From Conventional Gas Fields

Pavillion field is in the east-central part of the Wind River Reservation about 20 miles northwest of Riverton (Fig. 2). The field produces gas from the Paleocene Fort Union Formation and lower Eocene Wind River Formation. Gas is localized by stratigraphic pinchouts on the crest and along the flanks of a broad dome (Mueller, 1989; Keefer and Johnson, this volume). Three gas samples from the Fort Union Formation at depths of from 4,830-5,097 ft are isotopically heavy ($\partial^{13}C_1$ -38.04 to -39.24‰) and chemically dry ($C_1/C_{1-5}$ 0.95 to 0.96) (Table 1). Two gas samples from the Wind River Formation at depths of from 3,437 to 3,564 ft are also isotopically heavy ($\partial^{13}C_1$ -39.24 to -40.20‰) and chemically dry ($C_1/C_{1-5}$ 0.95 to 0.96) (Table 1).

Muddy Ridge field, located directly north of Pavillion field (Fig. 2), produces from the Fort Union, Lance, Meeteetse, and Mesaverde Formations. Trapping appears to be both structural and stratigraphic on the crest and along the flanks of a broad dome (Mueller, 1989). The Muddy Ridge gases are similar in isotopic composition but significantly wetter than those produced from shallower reservoirs at Pavillion field. Three Mesaverde gas samples from depths of 11,860 to 12,504 ft are isotopically heavy ($\partial^{13}C_1$ -34.49 to -36.05‰) and contain as much as 14.5 percent $C_{2+}$ gases ($C_1/C_{1-5}$ 0.86 to 0.90) (Table 1). One Meeteetse gas sample from depths of 9,668 to 9,871 ft is isotopically heavy ($\partial^{13}C_1$ -35.76‰) and chemically dry ($C_1/C_{1-5}$ 0.95) (Table 1). One Lance gas sample in the Muddy Ridge field is also isotopically heavy ($\partial^{13}C_1$ -35.76‰) and chemically dry ($C_1/C_{1-5}$ 0.95) (Table 1).

One Lance gas sample was collected at a depth of 13,175 to 15,055 ft from the Sand Mesa field about 10 miles east of the Pavillion and Muddy Ridge fields (Fig. 2). This sample is similar both isotopically ($\partial^{13}C_1$ -35.72‰) and chemically ($C_1/C_{1-5}$ 0.95) to Upper Cretaceous gases from Muddy Ridge field (Table 1).

**Table 1. Chemical and isotopic analysis of gases from conventional gas fields in the Wind River Basin, Wyoming.**

| Field | I.D. No. | Well Name | Location | Depth of Sample (ft) | Local Nomenclature | Age of Reservoir |
|---|---|---|---|---|---|---|
| Fuller Reservoir | 1 | Eron 7-19 Fed. | Sec. 19-36N.-93W. | 4,866-6530 | Lower mbr. Fort Union Fm. | Paleocene |
| Fuller Reservoir | 2 | Enron 12-19 Fed. | Sec. 19-36N.-93W. | 5,317-6,590 | Lower mbr. Fort Union Fm. | Paleocene |
| Fuller Reservoir | 3 | Eron 12-18 Fed. | Sec. 18-36N.-93W. | 2,982-3,113 | Shotgun Mbr. Fort Union Fm. | Paleocene |
| Madden | 4 | BHP 1-34 Quincy | Sec. 34-39N.-91W. | 16,098-16,151 | Mesaverde Fm. | Cretaceous |
| Madden | 5 | BHP 2-34 Quincy | Sec. 34-39N.-91W. | 17,632-17,662 | "2nd." Shannon Ss. Mbr. Cody Sh. | Cretaceous |
| Madden | 6 | Monsanto 1-32 Lester | Sec. 32-39N.-90W. | 17,198-18,050 | Shannon Ss. Mbr Cody Sh. | Cretaceous |
| Madden | 7 | BHP 1-5 Megg | Sec. 5-38N.-90W. | 16,410-16,714 | Cody Sh. | Cretaceous |
| Madden | 8 | BHP 1-35 Fed. Energy | Sec. 35-39N.-90W. | 11,090-12,830 | Lance Fm. | Cretaceous |
| Madden | 9 | BHP 1 Madden Deep | Sec. 2-38N.-90W. | 7,462-7,476 | Lower mbr. Fort Union Fm. | Paleocene |
| Madden | 10 | BHP 6 Maddon Deep | Sec. 1-38N.-90W. | 5,556-9,764 | Lower mbr. Fort Union Fm. | Paleocene |
| Madden | 11 | BHP 10 Madden Deep | Sec. 11-38N.-90W. | 8,606-8,640 | Lower mbr. Fort Union Fm. | Paleocene |
| Frenchie Draw | 12 | Exxon 1 Grahm | Sec. 21-37N.-89W. | 9,101-9,891 | Lower mbr.. Fort Union Fm | Paleocene |
| Frenchie Draw | 13 | Exxon 19 Grahm | Sec. 16-37N.-89W. | 7,083-9,480 | Lower mbr. Fort Union Fm | Paleocene |
| Frenchie Draw | 14 | Exxon 3 Grahm | Sec. 22-37N.-89W. | 8,578-9,647 | Lower mbr. Fort Union Fm | Paleocene |
| Waltman | 15 | Chevron 13 Waltman | Sec. 13-36N.-87W. | 4,457-4,485 | Lower mbr. Fort Union Fm | Paleocene |
| Waltman | 16 | Chevron 5 Waltman | Sec. 13-36N.-87W. | 4,402-4,508 | Lower mbr. Fort Union Fm | Paleocene |
| Waltman | 17 | Chevron 4 Waltman | Sec. 24-36N.-87W. | 4,278-4,305 | Lower mbr. Fort Union Fm | Paleocene |
| Pavillion | 18 | Tom Brown 14-6 Shoshone-Arapahoe | Sec. 6-3N.-3E. | 3,437-3,479 | Wind River Fm. | Eocene |
| Pavillion | 19 | Tom Brown 41-09 Shoshone-Araphahoe | Sec. 9-3N.-2E. | 4,830-5,097 | Fort Union Fm. | Paleocene |
| Pavillion | 20 | Quinaco 4-8 Blankenship | Sec. 4-3N.-2E. | 4,870-5,094 | Fort Union Fm. | Paleocene |
| Pavillion | 21 | Tom Brown 21-5 Govt. | Sec. 5-3N.-3E. | 3,540-3,564 | Wind River Fm. | Eocene |
| Muddy Ridge | 22 | Tom Brown 30-11 Tribal | Sec. 30-4N.-3E. | 11,877-11,913 | Mesaverde Fm. | Cretaceous |
| Muddy Ridge | 23 | Tom Brown 30-11 Tribal | Sec. 30-4N.-3E. | 12,045-12,463 | Mesaverde Fm. | Cretaceous |
| Sand mesa | 24 | ANR Production 1-13 Boyson-Amoca | Sec. 13-4N.-4E. | 13,175-15,055 | Lance Fm. | Cretaceous |
| East Riverton | 25 | Conoco 1 -1 Tribal | Sec. 1-1S,-5E. | 9,770-10,263 | Frontier Fm. | Cretaceous |
| East Riverton | 26 | Conoco 1-11 Tribal | Sec. 11, 1S., 5E. | 3,300 | Lower mbr. Fort Union | Paleocene |
| East Riverton | 27 | Conoco 6-4 Tribal | Sec. 6, 1S., 6E. | 11,091-11,099 | Muddy Ss. | Cretaceous |
| East Riverton | 28 | Conoco 12-5 Tribal | Sec. 12, 1S., 5E., | 11,745-11,952 | Nugget Ss. | Jurassic |
| Riverton | 29 | Arco 15 Tribal | Sec. 25, 1S., 4E. | 3,270-3,869 | Mesaverde Fm.coals | Cretaceous |
| Riverton | 30 | Arco 41 Trinbal | Sec. 30, 1S., 5E. | 8,070-9,770 | Frontier and Muddy Fms | Cretaceous |
| Beaver Creek | 31 | Amoco 4 Beaver Cr. | Sec. 10-33N.-96W. | 8,210-8,212 | Cloverly Fm. | Cretaceous |
| Beaver Creek | 32 | Amoco 4 Beaver Cr. | Sec. 10-33N.-96W. | 6,787-7,210 | Frontier Fm. | Cretaceous |
| Beaver Creek | 33 | Amoco 2 Beaver Cr. | Sec. 11-33N.-96W. | | Frontier Fm. | Cretaceous |
| Beaver Creek | 34 | Amoco 2 Beaver Cr. | Sec. 11-33N.-96W. | | Cloverly Fm. | Cretaceous |
| Muddy Ridge | 35 | Tom Brown 25-41 Tribal | Sec. 25-4N.-2E. | 9,668-9,871 | Meeteetse Fm. | Cretaceous |
| Muddy Rıdge | 36 | Tom Brown 25-41 Tribal | Sec. 25-4N.-2E. | | Lance Fm. | Cretaceous |
| Pavillion | | Tom Brown 14-11 Tribal | Sec. 11-3N.-2E. | | Fort Union Fm. | Paleocene |

**Table 1. Continued.**

| Type of Gas | $Nr_2$ and (or) air (vol%) | $CH_4$ (vol.%) | $CO_2$ (vol.%) | $C_2H_6$ (vol.%) | $C_3H_8$ (vol.%) | i-$C_4H_{10}$ (vol.%) | n-$C_4H_{10}$ (vol.%) | j-$C_5H_{12}$ (vol.% | n-$C_5H_{12}$ (vol.%) | $C_1/C_{1-5}$ (vol.%) | $\delta^{13}C_1$ (‰) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Associated | 1.23 | 91.99 | 1.24 | 4.46 | 0.70 | 0.26 | 0.12 | - | - | 0.9432 | -36.19 |
| Nonassociated | 0.93 | 92.90 | 1.06 | 3.65 | 0.91 | 0.23 | 0.21 | 0.06 | 0.03 | 0.9479 | -34.79 |
| Associated | 0.98 | 82.53 | 0.40 | 5.97 | 5.42 | 1.26 | 1.98 | 0.80 | 0.67 | 0.8368 | -49.99 |
| Nonassociated | 1.27 | 92.93 | 5.14 | 0.18 | 0.19 | 0.29 | - | - | - | 0.9929 | -31.82 |
| " | 0.82 | 96.21 | 2.97 | - | - | - | - | - | - | 1.00 | -31.12 |
| " | 1.16 | 96.02 | 2.82 | - | - | - | - | - | - | 1.00 | -34.42 |
| " | 0.81 | 96.27 | 2.92 | - | - | - | - | - | - | 1.00 | -32.17 |
| " | 1.60 | 91.60 | 4.03 | 2.61 | 0.17 | - | - | - | - | 0.9706 | -34.57 |
| " | 1.13 | 92.83 | 1.98 | 2.96 | 0.89 | 0.11 | 0.10 | - | - | 0.9581 | -34.08 |
| " | 0.91 | 91.92 | 2.12 | 3.26 | 1.06 | 0.25 | 0.27 | 0.11 | 0.10 | 0.9479 | -34.72 |
| " | 0.85 | 90.47 | 1.85 | 3.98 | 1.57 | 0.46 | 0.42 | 0.25 | 0.17 | 0.9298 | -34.81 |
| " | 1.08 | 86.07 | 2.76 | 7.01 | 1.86 | 0.53 | 0.35 | 0.22 | 0.12 | 0.8951 | -37.93 |
| " | 3.41 | 78.03 | 2.09 | 9.84 | 4.07 | 1.19 | 1.09 | 0.17 | 0.10 | 0.8257 | -41.85 |
| " | 1.67 | 85.74 | 2.25 | 6.18 | 2.32 | 0.81 | 0.76 | 0.18 | 0.10 | 0.8924 | -37.50 |
| " | 1.72 | 88.68 | 0.40 | 3.74 | 3.33 | 0.92 | 0.85 | 0.23 | 0.13 | 0.9060 | -47.40 |
| " | 1.20 | 90.48 | 0.62 | 3.40 | 2.35 | 0.92 | 0.69 | 0.22 | 0.11 | 0.9216 | -45.12 |
| " | 1.09 | 93.59 | 1.48 | 2.50 | 0.51 | 0.48 | 0.23 | 0.08 | 0.05 | 0.9606 | -44.42 |
| " | 1.22 | 95.28 | - | 2.83 | 0.30 | 0.11 | 0.18 | 0.05 | 0.02 | 0.9646 | -39.24 |
| " | 7.61 | 88.17 | 0.29 | 3.35 | 0.36 | 0.14 | 0.09 | - | - | 0.9573 | -38.04 |
| " | 1.57 | 93.38 | 0.36 | 4.00 | 0.41 | 0.05 | 0.06 | 0.07 | 0.01 | 0.9522 | -38.08 |
| " | 1.39 | 93.24 | 0.09 | 3.75 | 0.73 | 0.33 | 0.22 | 0.16 | 0.09 | 0.9464 | -40.20 |
| " | 0.84 | 84.83 | 1.08 | 8.31 | 3.15 | 0.61 | 0.68 | 0.26 | 0.24 | 0.8649 | -36.05 |
| " | 1.19 | 87.80 | 1.62 | 6.34 | 1.80 | 0.48 | 0.51 | 0.13 | 0.12 | 0.9034 | -34.49 |
| " | 3.60 | 90.23 | 1.33 | 4.06 | 0.48 | 0.18 | 0.12 | - | - | 0.9491 | -35.72 |
| | 4.98 | 89.17 | 0.41 | 3.80 | 1.18 | 0.17 | 0.30 | 0.00 | 0.00 | 0.9383 | -37.63 |
| | 16.24 | 79.18 | 0.41 | 2.92 | 0.89 | 0.14 | 0.22 | 0.00 | 0.00 | 0.9453 | -36.74 |
| | 17.19 | 79.76 | 0.51 | 1.96 | 0.48 | 0.05 | 0.06 | 0.00 | 0.00 | 0.9631 | -36.18 |
| | 17.00 | 80.43 | 0.28 | 1.71 | 0.45 | o.o5 | 0.06 | 0.00 | 0.00 | 0.9693 | -35.71 |
| | 2.35 | 91.22 | 4.12 | 2.11 | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.9342 | -46.15 |
| | 1.61 | 91.93 | 0.42 | 4.33 | 1.25 | 0.18 | 0.29 | 0.00 | 0.00 | 0.9193 | -39.02 |
| " | 3.66 | 87.71 | 1.35 | 4.81 | 1.89 | 0.20 | 0.26 | 0.08 | 0.03 | 0.9234 | -38.01 |
| " | 2.98 | 87.86 | 1.39 | 4.71 | 1.89 | 0.50 | 0.45 | 0.14 | 0.09 | 0.9187 | -38.43 |
| " | 3.21 | 86.70 | 0.48 | 5.86 | 2.16 | 0.58 | 0.56 | 0.20 | 0.12 | 0.9002 | -39.05 |
| " | 5.69 | 86.78 | 0.42 | 4.89 | 1.62 | 0.27 | 0.25 | 0.06 | 0.02 | 0.9243 | -38.41 |
| " | 12.93 | 82.3 | 0.41 | 3.47 | 0.67 | 0.14 | 0.074 | 0.022 | 0.003 | 0.950 | -35.21 |
| " | 16.42 | 78.8 | 0.13 | 3.63 | 0.73 | 0.15 | 0.070 | 0.018 | 0.003 | 0.945 | -35.76 |
| " | 31.89 | 66.0 | 0.054 | 1.96 | 0.060 | 0.054 | 0.006 | 0.006 | 0.002 | 0.969 | -38.40 |

Riverton Dome field is in the southeast corner of the Wind River Reservation (Fig. 2). It was discovered more than 40 years ago and, during its lifetime, has produced oil and sour gas from the Tensleep Sandstone and Phosphoria Formation, gas and condensate from the Muddy Sandstone and Cloverly Formation, gas and condensate from the Frontier Formation, gas and oil from sandstones in the Cody Shale, coalbed gas from the Mesaverde Formation, and gas and oil from the Fort Union Formation. One gas sample analyzed from the Muddy Sandstone and the Frontier is fairly heavy isotopically ($\partial^{13}C_1$ -39.02‰) and contains about 9 percent $C_2$+ gases ($C_1/C_{1-5}$ 0.92) (Table 1). A gas sample was analyzed from the only producing coalbed methane well in the Wind River Basin, and the results of this analysis are discussed later under the discussion of coalbed gases.

Riverton Dome East field is a small anticline about 6 miles northeast of Riverton Dome in the southeast corner of the Wind River Reservation (Fig. 2). It has produced sour gas from the Phosphoria Formation, gas from the Nugget Sandstone, gas and condensate from the Cloverly Formation and Muddy Sandstone, gas from the Frontier Formation, and gas from the Fort Union Formation. Gas samples were analyzed from the Nugget Sandstone, Muddy Sandstone, Frontier Formation and Fort Union Formation (Table 1). The gases are all similar in that they are isotopically heavy ($\partial^{13}C_1$ -35.71 to -37.63‰) and contain about 4 to 5 percent C2+ gases ($C_1/C_{1-5}$ 0.95 to 0.96) at depths ranging from 3,300 to 11,952 ft (Table 1). The deepest gas sampled from the Nugget Sandstone is slightly heavier isotopically ($\partial^{13}C_1$ -35.71) and chemically drier($C_1/C_{1-5}$ 0.97) than gases in the shallower reservoirs.

Fuller Reservoir field is in the central part of the Wind River Basin, a few miles east of the east margin of the Wind River Reservation (Fig. 2). Trapping is by multiple local stratigraphic traps on a large, northeast plunging structural nose (Specht, 1989). This actively developing field produces from the Lance Formation, both the lower member and the Shotgun Member of the Fort Union Formation, and the Wind River Formation. The two gas samples from the lower member of the Fort Union are significantly different from the gas in the Shotgun Member (Table 1). The gas from the latter is associated with a waxy oil indicating generation from a nonmarine source. Gases from the lower member of the Fort Union are isotopically heavier ($\partial^{13}C_1$ -34.79 to -36.19‰ versus $\partial^{13}C_1$ -49.99‰) and chemically drier ($C_1/C_{1-5}$ 0.94 to 0.95 versus $C_1/C_{1-5}$ 0.84) than gas in the Shotgun Member above the Waltman Shale Member (Table 1).

Beaver Creek field was discovered in 1938 and is developed on an asymmetrical anticline with about 100 ft of closure in the western part of the Wind River Basin, just south of the southeast corner of the Wind River Reservation (Fig. 2). The field has produced oil and sour gas from the Madison Limestone, the Tensleep Sandstone, and the Phosphoria Formation, sweet gas from the Frontier Formation and Cloverly Formation, oil and sweet gas from the Muddy Sandstone and Cody Shale, and oil and sweet gas from the Fort Union Formation. The two Frontier and two Cloverly gas samples analyzed are all quite similar with $\partial^{13}C_1$ values ranging from -38.01 to -39.05‰ and $C_1/C_{1-5}$ of from 0.90 to 0.92 (Table 1).

The Madden field is developed on a large anticlinal structure in the north-central part of the Wind River Basin. It produces sour gas from the Madison Limestone, and sweet gas from the Cody Shale (sandstones in the upper part), the Mesaverde Formation, the Lance Formation, and the lower member and Shotgun Member of the Fort Union Formation. Three gas samples from the lower member of the Fort Union Formation at depths of 5,556 to 9,764 ft are isotopically heavy ($\partial^{13}C_1$ -34.08 to -34.81‰) and contain 4 to 7 percent $C_{2+}$ hydrocarbons ($C_1/C_{1-5}$ 0.93 to 0.96) (Table 1). One sample from the Lance Formation in the depth interval 11,090 to 12,830 ft is very similar in composition with a $\partial^{13}C_1$ of -34.58‰ and a $C_1/C_{1-5}$ of 0.97 (Table 1). Four samples from the Mesaverde Formation and Cody Shale at depths ranging from 16,098 to 18,050 ft are somewhat heavier isotopically ($\partial^{13}C_1$ -31-21 to -34.42‰) and chemically drier ($C_1/C_{1-5}$ 0.99 to 1.00) than gases in the Fort Union Formation. These gases were the driest encountered in our study.

Frenchie Draw field is in the east-central part of the Wind River Basin (Fig. 2). The field is on the gently dipping south flank of the basin about 6 miles southeast of Madden anticline and produces gas and some condensate from the lower member of the Fort Union Formation below the Waltman Shale Member. Three gas samples have moderately heavy $\partial^{13}C_1$ values of -37.50 to -41.85‰ and are relatively wet chemically ($C_1/C_{1-5}$ 0.83 to 0.89 (Table 1).

Waltman field, in the eastern part of the Wind River Basin (Fig. 2), is a complex structural and stratigraphic trap feature which produces gas, condensate, and small amounts of oil from the lower member of the Fort Union Formation below the Waltman Shale Member and from the Lance Formation. Three gas samples from the lower member of the Fort Union Formation are isotopically light ($\partial^{13}C_1$ -44.42 to -47.40‰) and contain from about 4 to 9% C2+ gases ($C_1/C_{1-5}$ 0.91 to 0.92) (Table 1).

Figure 5 is a plot of hydrocarbons ($C_1/C_{1-5}$) versus methane $\partial^{13}C_1$ for gases from various fields in the basin. Results from coalbed gases are also shown and will be discussed later. All gases except those from coal beds

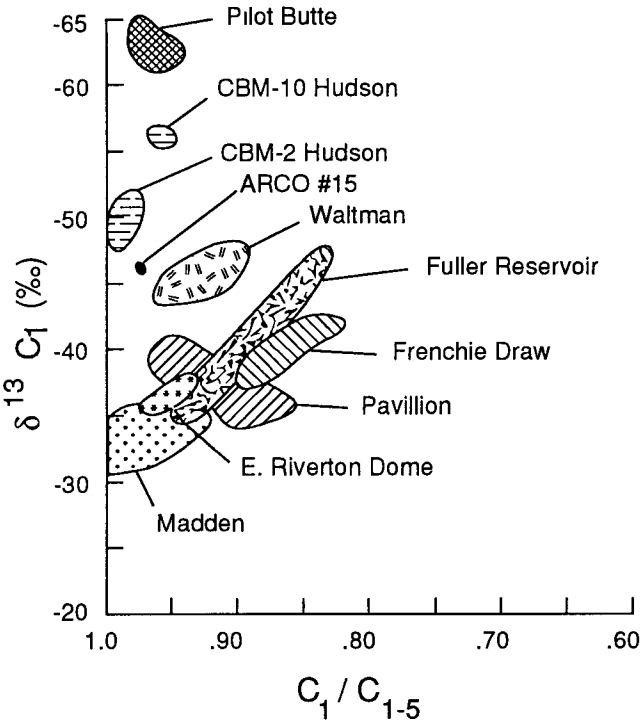


**Figure 5. Methane carbon isotopic composition ($\partial^{13}C_1$) versus hydrocarbon composition ($C_1/C_{1-5}$) for gases from oil and gas fields in the Wind River Basin, Wyoming. Coalbed methane gases are also shown.**

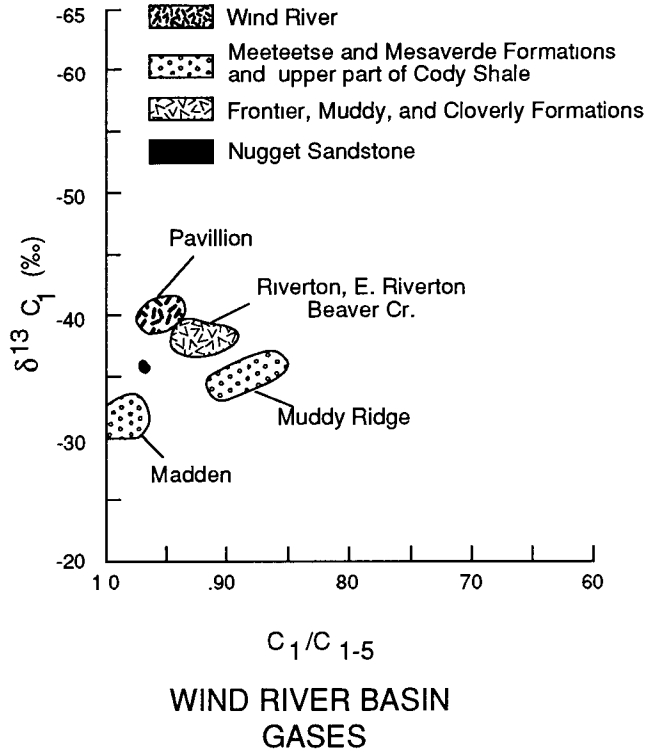


**Figure 6. Methane carbon isotopic composition ($\partial^{13}C_1$) versus hydrocarbon composition ($C_1/C_{1-5}$) for gases from producing formations excluding the Fort Union Formation, Wind River Basin, Wyoming. Fields where samples were collected are labeled.**

appear to be predominantly thermogenic in origin and were produced in the mature to post-mature stages of hydrocarbon generation (Fig. 4). In each field, there is relatively little variation in chemical and isotopic compositions for all produced gases with the exception of Fuller Reservoir field. There, the chemical and isotopic compositions of gas produced above the Waltman Shale Member of the Fort Union Formation are distinctly different from gases below the Waltman. Figure 6 is a plot $C_1/C_{1-5}$ versus $\partial^{13}C_1$ for all of the producing formations sampled, except the Fort Union Formation; the fields where the gases were collected are also shown. All of these gases are isotopically heavy, and, with the exception of Wind River Formation gases from Pavillion field, fall in the post-mature range of hydrocarbon generation (Fig. 4). Wind River Formation gases straddle the boundary between mature and post-mature gases. Gases from the Frontier Formation, Muddy Sandstone, and Cloverly Formations are relatively dry and isotopically heavy ($C_1/C_{1-5}$ of 0.90 to 0.96, $\partial^{13}C_1$ of -36.18 to -39.05), and vary little between the three fields sampled. Gases from the Wind River Formation are relatively dry and isotopically heavy ($C_1/C_{1-5}$ of 0.95 to 0.96, $\partial^{13}C_1$ of -39.24 to -40.20) at Pavillion field, the only field where Wind River gases were sampled. A single gas sample from the Nugget Sandstone at East Riverton field is also relatively dry and isotopically heavy ($C_1/C_{1-5}$ of 0.97, $\partial^{13}C_1$ of -35.71). The chemical and isotopic compositions of Fort Union and Lance gases are plotted separately on Figure 7. These gases have highly varying chemical and isotopic compositions ($C_1/C_{1-5}$ of 0.84 to 0.97, $\partial^{13}C_1$ of -49.99 to -34.08). In any given field, however, variations are relatively minor except at Fuller Reservoir field where a Fort Union gas sample from above the Waltman Shale Member of the Fort Union is chemically much wetter and isotopically lighter than gases from below the Waltman.

Figure 8 shows depth versus $\partial^{13}C_1$ for all gases sampled, including coalbed gases. There is a very general relationship between depth and thermal maturity as measured by vitrinite reflectance ($R_m$) in the basin (Johnson and others, 1991; Pawlewicz, this volume), and this relationship is used to convert reservoir depths to approximate $R_m$ on Figure 8. In general, gases become isotopically heavier and hence more mature with increasing depth but the gases appear to have formed at significantly higher levels of thermal maturity than the reservoir rocks in which they occur. A reference line showing where $\partial^{13}C_1$ of gases would generally fall if no vertical migration has occurred is plotted

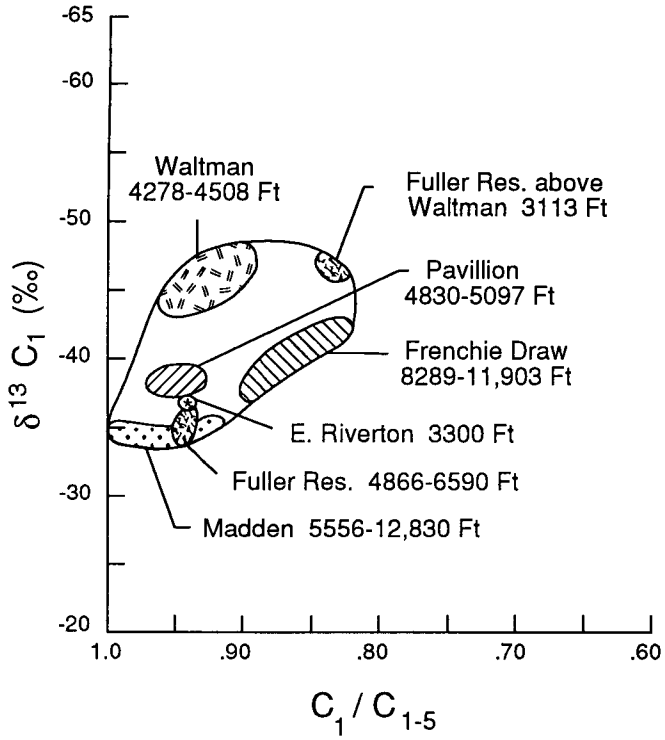


**Figure 7. Methane carbon isotopic composition ($\partial^{13}C_1$) versus hydrocarbon composition ($C_1/C_{1-5}$) for gases from the Fort Union and Lance Formations, Wind River Basin, Wyoming. Field names and depths of producing intervals are shown.**

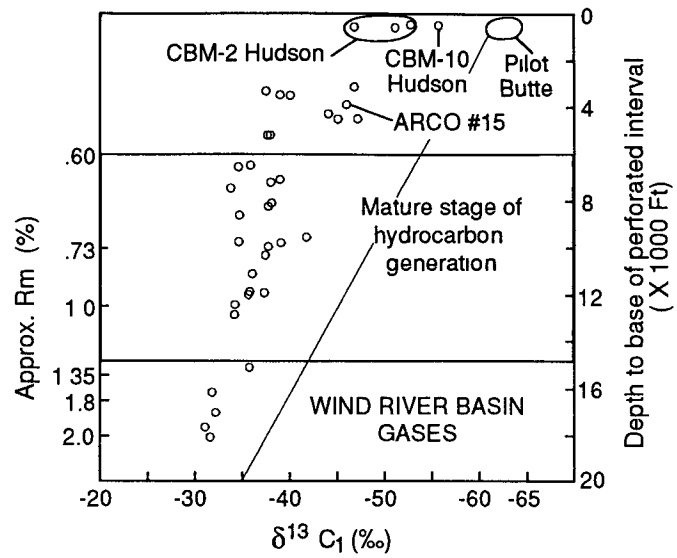


**Figure 8. Depth to base of producing interval versus methane carbon isotopic composition ($\partial^{13}C_1$) for gases, Wind River Basin, Wyoming. Approximate vitrinite reflectance (Rm) is also shown. Gases from coalbed methane reservoirs are labeled. Locations of coalbed methane tests are shown on Figure 2. A line showing changes in $\partial^{13}C_1$ with increasing thermal maturity is shown. Gases which plot to the left of the line have probably migrated from deeper, more mature source rocks.**

on the figure. Any significant shift to the left indicates that vertical migration has occurred. All Wind River Basin gases fall significantly to the left of the line indicating that at least a significant component of the methane in these gases has migrated from deeper, more mature source rocks. The amount of shift from the reference line is greatest for the shallowest samples, indicating that the shallower gas samples have migrated much further vertically than the deeper samples. The deepest samples, in the 16,000 to 18,000 ft depth range, fall very close to the reference thermal maturity line, suggesting that these samples may have migrated vertically very little from their source rocks. Figure 9 shows depths and approximate Rm versus $\partial^{13}C_1$ for all producing intervals sampled in this study, including coalbed gases. The highly variable isotopic compositions for Fort Union gases is readily apparent in this figure. Fort Union gases at higher levels of thermal maturity are relatively uniform isotopically while a broad range of compositions occur at lower levels of thermal maturity.

### Results From Coalbed Gases

Coalbed gases were collected from coals cored by the U. S. Geological Survey for a coalbed gas assessment of the Wind River Reservation. A total of 10 sites were drilled where coals in the Mesaverde and Meeteetse Formations occur at shallow depths along the southwest and western margins of the Wind River Basin. For a summary of this drilling program see Johnson and others (this volume). Coals at several of these sites contain little or no methane and hence were not sampled for analysis, however, coals from two areas, the Hudson area (CBM-2 and CBM-10) and the Pilot Butte area (CBM-7 and CBM-8), were found to contain significant methane, and these gases were sampled and analyzed for chemical and isotopic compositions (Fig. 2; Table 2). Gas was also collected from the ARCO Tribal no. 15 well in the Riverton Dome Field (Fig. 2, Table 1), the only known coalbed methane well in the basin.

Five gas samples were collected at the Hudson CBM-2 site, three from desorption cannisters and two from well surface casings. Casing gas was collected in 1990 after the first Hudson hole had been drilled to total depth. This gas was interpreted as coming from a sandstone in the Mesaverde Formation because gas began bubbling vigorously from the surface casing when the top of the formation was penetrated, and the gas volume did not noticeably increase after penetrating the first coal. Because of the possibility that this gas

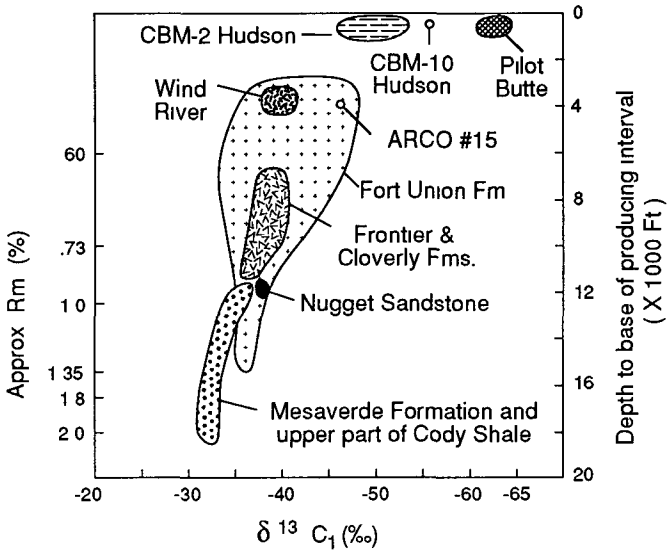


**Figure 9. Depth to base of producing interval versus methane carbon isotopic composition ($\partial^{13}C_1$) for gases from various producing formations, Wind River Basin, Wyoming. Approximate vitrinite reflectance ($R_m$) of reservoir is also shown.**

was contaminated with coalbed gas, a second casing gas sample was taken while drilling a water test hole at Hudson in 1991. This second sample was collected after penetrating the upper part of the Mesaverde Formation but prior to penetrating the Mesaverde coals, hence the gas is interpreted as coming from sandstone rather than coal. The chemical and isotopic compositions of all five samples are essentially the same (Table 2), being chemically dry ($C_1/C_{1-5}$ of 0.97 to 1.0) and low in $CO_2$ (0.57 to 1.00 percent). Carbon isotopes of the methane fraction are isotopically light ($\partial^{13}C_1$ of -47.00 to -53.00‰), but fall in the thermogenic or mixed biogenic and thermogenic range rather than biogenic range (Fig. 4). Coal ranks at Hudson are low ($R_m$ 0.40 to 0.50 percent) (Johnson and others, 1991; Pawlewicz, this volume), and the coals have probably not generated thermal gas. Biogenic gases, which were degraded in an oxygenated environment, can resemble thermogenic gases isotopically (Whiticar and Farber, 1986a) but the Hudson gases contain 0.3 to 2.7 percent $C_{2+}$ gas. Although minute amounts of $C_{2+}$ gas can be generated by bacteria (Oremland ant others, 1982) the significant percentages found in the Hudson gases can only result from thermogenic processes.

Gas was analyzed from the coal cored and desorbed at the CBM-10 site about 2 1/2 miles northwest of CBM-2 (Table 1, Fig. 2). The CBM-10 gas is similar to the gases from CBM-2 except that it is isotopically lighter ($\partial^{13}C_1$ value of -55.9‰). Two samples were taken , the first early in the desorption process and the second at the end of the desorption process. The percentage of $C_{2+}$ gases should increase, if they are present, during the desorption process inasmuch as the $C_{2+}$ molecules are larger than the methane molecule and take longer to escape from the structure of the coal (Wyman, 1984). The percentage of $C_{2+}$ gases did increase with time, as expected (from 0 percent to 4.1percent).

Twenty-four gas samples were analyzed from the Pilot Butte site (Table 1), and a large number of these were analyzed to better understand the complex processes that can affect coalbed gases at shallow depths. Gases at these depths can be partially degraded by aerobic bacteria which preferentially feed on isotopically light methane. This causes the remaining methane to become isotopically heavier (Whiticar and Farber, 1986a). Anaerobic bacteria can generate late stage biogenic gas, and this gas may have a different isotopic composition from the gas that was originally in the coal (Rice, in press). All of the coalbed gases analyzed from the Pilot Butte area are chemically and isotopically similar to each other, but distinctly different from the gases from the Hudson area. The gases at Pilot Butte are somewhat wetter than Hudson ($C_1/C_{1-5}$ of 0.94 to 1.0) and contain variable amounts of $CO_2$ (0 to 9.09 percent). Carbon isotopes of the methane fraction are much lighter at Pilot Butte than the Hudson gases ($\partial^{13}C_1$ -61.85 to -66.21‰) and fall within the range of biogenic gases (Fig. 4). As with the Hudson gases, the Pilot Butte gases contain significant amounts of $C_{2+}$ gases which result from thermogenic processes, suggesting that the Pilot Butte gases may be a mixture of biogenic gas generated in the coals and thermogenic gas generated in deeper, more mature source rocks. The chemical composition of six Pilot Butte samples were rerun using gas samples collected at the end of the desorption experiment, and the percentage of $C_{2+}$ gases was found to be higher for all gases collected near the end of the desorption experiment than for gases collected shortly after the coals were placed in desorption cannisters.

The single coalbed methane well on the Wind River Reservation is the ARCO no. 15 Tribal well at Riverton Dome (Fig. 2). Gas from this well, which is completed in Mesaverde coals at depths of 3,270 to 3,839 ft., appears to be of thermogenic origin (∂13C1 -46.15‰) and is similar to the Hudson coalbed gases (Tables 1 and 2, Figs. 3 and 4).

### Origin of Gases in Conventional Reservoirs

Gases from the Fort Union Formation vary the most in chemical and isotopic composition (Table 1, Figs. 7 and 9). At Fuller Reservoir field in the central part of the basin, shallow (2,982-3,113 ft ) gas in the Shotgun Member, which is associated with a waxy oil, is chemically wetter ($C_1/C_{1-5}$ of 0.84) and isotopically lighter

**Table 2. Chemical and isotopic analysis of gases from the USGS CBM-2, CBM-7, CBM-8, and CBM-10 drillholes, Wind River Reservation.**

| Well name | Sample Depth ft and meters | $N_2$ and (or) air | $\%C_1$ | $\%CO_2$ | $\%C_2H_6$ | $\%C_3H_8$ | $\%iC_4H_{10}$ | $\%nC_4H_{10}$ | $\%iC_5H_{10}$ | $\%nC_5H_{12}$ | $C_1/C_{1-5}$ | $\delta^{13}C_1$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CBM-2 | 483.83-484.75' 147.47-147.75 m | 44.58 | 53.30 | 0.61 | 0.63 | 0.58 | 0.10 | 0.20 | 0. | 0. | 0.973 | -53.00 |
| | 583.25-584.25' 177.77-178.08 m | 50.38 | 48.90 | 0.57 | 0.14 | 0. | 0. | 0. | 0. | 0. | 0.9971 | -47.00 |
| | 590.67-591.67' 180.04-180.34 m | 28.66 | 70.30 | 0.83 | 0.21 | 0. | 0. | 0. | 0. | 0. | 0.9970 | -51.30 |
| | 1990 casing gas | 8.64 | 90.11 | 1.00 | 0.24 | 0. | 0. | 0. | 0. | 0. | 0.9864 | -52.10 |
| | 1991 casing gas | 11.59 | 87.79 | 0.30 | 0.32 | 0. | 0. | 0. | 0. | 0. | 0.9930 | -51.23 |
| CBM-7 | 573-575' 174.65-175.26 m | 65.25 | 33.97 | 0. | 0.77 | 0. | 0. | 0. | 0. | 0. | 0.978 | -64.15 |
| | 536-537' 163.37-163.68 m | 69.92 | 29.28 | 0.23 | 0.56 | 0. | 0. | 0. | 0. | 0. | 0.981 | -63.73 |
| | 313.9-314.9' 95.68-95.98 m | 51.46 | 46.56 | 0.84 | 1.14 | 0. | 0. | 0. | 0. | 0. | 0.976 | -63.29 |
| | 313.9-314.9 (end of desorption) | 33.92 | 63.50 | 0.35 | 2.22 | 0. | 0. | 0. | 0. | 0. | 0.9611 | - |
| | 438.3-439.2' 133.59-133.87 m | 35.62 | 60.65 | 1.94 | 1.78 | 0. | 0. | 0. | 0. | 0. | 0.972 | -61.85 |
| | 438.3-439.2' (end of desorption) | 37.23 | 59.57 | 0.80 | 2.40 | 0. | 0. | 0. | 0. | 0. | 0.949 | - |
| CBM-7 | 460.7-461.7' 140.42-140.73 m | 40.52 | 51.2 | 6.55 | 1.75 | 0. | 0. | 0. | 0. | 0. | 0.967 | -63.30 |
| | 474.6-475.4' 144.05-144.90 m | 54.61 | 42.18 | 1.84 | 1.36 | 0. | 0. | 0. | 0. | 0. | 0.969 | -63.08 |
| | 479.3-480.3' 146.09-146.40 m | 41.95 | 54.81 | 1.53 | 1.71 | 0. | 0. | 0. | 0. | 0. | 0.970 | -64.01 |
| | 577-578' 175.87-176.17 m | 71.81 | 25.62 | 1.98 | 0.59 | 0. | 0. | 0. | 0. | 0. | 0.978 | -62.85 |
| CBM-8 | 465-468' 141.73-142.65 | 26.66 | 71.07 | 0.41 | 1.86 | 0. | 0. | 0. | 0. | 0. | 0.975 | -63.69 |
| | 473-475' 144.17-144.78 m | 34.17 | 63.7 | 0.4 | 1.73 | 0. | 0. | 0. | 0. | 0. | 0.974 | -64.26 |
| | 563-566' 171.60-172.52 m | 50.28 | 48.69 | 0.16 | 0.88 | 0. | 0. | 0. | 0. | 0. | 0.982 | -63.65 |
| | 658-662' 200.56-201.78 m | 67.85 | 31.01 | 0.26 | 0.89 | 0. | 0. | 0. | 0. | 0. | 0.972 | -64.15 |
| | 706-710' 215.19-216.41 m | 88.11 | 11.62 | 0. | 0.27 | 0. | 0. | 0. | 0. | 0. | 0.977 | -63.76 |
| | 381-391.3' 116.13-119.27 m | 100. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | | INSUF |
| | 402-403.4' 122.53-122.96 m | 63.8 | 33.41 | 0.76 | 1.46 | 0.41 | 0.16 | 0. | 0. | 0. | 0.943 | -62.66 |

**Table 2. Continued.**

| Well name | Sample Depth ft and meters | $N_2$ and (or) air | $\%C_1$ | $\%CO_2$ | $\%C_2H_6$ | $\%C_3H_8$ | $\%iC_4H_{10}$ | $\%nC_4H_{10}$ | $\%iC_5H_{10}$ | $\%nC_5H_{12}$ | $C_1/C_{1\text{-}5}$ | $\delta^{13}C_1$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CBM-8 | 455.5-457.95' 138.84-139.58 m | 33.49 | 64.57 | 0.46 | 1.47 | 0. | 0. | 0. | 0. | 0. | 0.978 | -63.73 |
| | 455.5-457.95' (end of desorption) | 33.58 | 63.47 | 0.75 | 2.21 | 0. | 0. | 0. | 0. | 0. | 0.955 | - |
| | 460.3-462.2' 140.30-140.88 | 50.72 | 46.97 | 1.11 | 1.20 | 0. | 0. | 0. | 0. | 0. | 0.975 | -63.99 |
| | 551.5-560.6' 168.10-170.87 m | 60.97 | 36.81 | 1.42 | 0.79 | 0. | 0. | 0. | 0. | 0. | 0.979 | -64.73 |
| | 565.75-568.25' 172.44-173.20 m | 53.51 | 44.92 | 0.69 | 0.87 | 0. | 0. | 0. | 0. | 0. | 0.981 | -64.34 |
| | 565.75-568.25 ' (end of desorption) | 35.27 | 62.44 | 0.69 | 1.60 | 0. | 0. | 0. | 0. | 0. | 0.965 | - |
| | 572-575' 174.35-275.26 m | 53.73 | 45.2 | 0.27 | 0.8 | 0. | 0. | 0. | 0. | 0. | 0.983 | -64.11 |
| | 649.5-653.6' 197.97-199.22 m | 83.0 | 16.0 | 1.0 | 0. | 0. | 0. | 0. | 0. | 0. | 1.0 | -64.02 |
| | 666.8-667.6' 203.24-203.48 m | 86.12 | 12.58 | 0.95 | 0.34 | 0. | 0. | 0. | 0. | 0. | 0.974 | -64.48 |
| | 675.3-676.4' 205.83-206.17 m | 77.22 | 21.17 | 1.04 | 0.56 | 0. | 0. | 0. | 0. | 0. | 0.974 | -64.48 |
| | 678.7-679.5' 206.87-207.11 m | 80.86 | 17.62 | 1.01 | 0.5 | 0. | 0. | 0. | 0. | 0. | 0.972 | -63.79 |
| | 698.1-700.4' 212.73-213.48 m | 89.0 | 10.0 | 1.0 | 0.3 | 0. | 0. | 0. | 0. | 0. | 0.971 | -63.61 |
| | 717.5-718.6' 218.69-219.03 m | 78.31 | 20.04 | 1.24 | 0.41 | 0. | 0. | 0. | 0. | 0. | 0.980 | -64.90 |
| | 765.35-766-85' 233.28-233.74 m | 77.06 | 23.0 | 1.49 | 0.45 | 0. | 0. | 0. | 0. | 0. | 0.981 | -65.21 |
| | 773.25-774.25' 235.69-235.99 m | 65.31 | 32.58 | 1.39 | 0.72 | 0. | 0. | 0. | 0. | 0. | 0.978 | -65.08 |
| | 779.3-781' 237.53-238.05 m | 44.05 | 54.3 | 0.28 | 1.36 | 0. | 0. | 0. | 0. | 0. | 0.976 | -65.12 |
| | 779.3-781" (end of desorption) | 47.94 | 50.32 | 0.53 | 1.21 | 0. | 0. | 0. | 0. | 0. | .967 | - |
| | 833-835' 253.90-254.51 m | 54.27 | 44.25 | 0.3 | 1.18 | 0. | 0. | 0. | 0. | 0. | 0.974 | -66.21 |
| | 833-835' (end of desorption) | 39.96 | 58.37 | 0.46 | 1.20 | 0. | 0. | 0. | 0. | 0. | 0.9723 | - |
| CBM-10 | 590.3-593.8' 179.92-180.99 m | 86.64 | 12.83 | 0.32 | 0.20 | 0. | 0. | 0. | 0. | 0. | - | -55.91 |
| | 590.3-593.8' (end of desorption) | 66.97 | 31.67 | 0.57 | 0.79 | 0. | 0. | 0. | 0. | 0. | 0.959 | - |

($\partial^{13}C_1$ of -46.99‰) than gases from the lower member of the Fort Union at depths of 4,500-7000 ft ($C_1/C_{1-5}$ of 0.94 to 0.95, $\partial^{13}C_1$ of -34.79 to -36.19‰). A likely source for the gas in the Shotgun Member is the underlying Waltman Shale Member but from deeper in the basin. The Waltman is probably too immature at Fuller Reservoir field ($R_m$ of 0.50 to 0.60 percent) to have generated the gas and waxy oil found in the Shotgun Member, suggesting that both vertical and lateral migration has occurred. The mature to post-mature gases from the lower member at Fuller Reservoir, probably migrated both vertically and laterally from deeper, mature source rocks. Fort Union gases from Waltman field in the eastern part of the basin (Fig. 2) are isotopically light ($\partial^{13}C_1$ of -44.42 to -47.40‰) and chemically wet ($C_1/C_{1-5}$ of 0.91 to 0.96). The reservoir rocks appear to be marginally mature ($R_m$ of 0.6 and 0.7 percent) and the gases probably originated in deeper strata. The Waltman Shale Member is an unlikely source since the gas reservoirs are beneath the Waltman.

Figure 8 suggests that all gases sampled from conventional reservoirs have migrated from deeper, more mature source rocks. In general, the difference between the thermal maturity of the reservoir rock and the thermal maturity of the gas increases at shallower depths. This suggests that most of the gas that was sampled, regardless of depth, migrated from deep, mature to overmature source rocks, and that the amount of vertical migration is greater for the shallower gases than it is for the deeper ones. Figure 10 shows depth and approximate $R_m$ versus $\partial^{13}C_1$ of reservoirs at three fields that produce gas from several stratigraphic levels (Pavillion-Muddy Ridge, Madden, and East Riverton Dome). Figure 11 shows depth and approximate $R_m$ versus wetness for the same fields, as well as Frenchie Draw, Fuller Reservoir, and the results obtained from coalbed gases. At Pavillion field, gases change very little isotopically from shallow (4,830-5,097 ft), marginally mature reservoirs ($R_m$ 0.5 percent) of the lower Eocene Wind River Formation to the deepest reservoirs in the Mesaverde Formation. Another indication of possible vertical migration in this field is the trend toward drier gases in the younger strata. Vertical migration can explain this trend since the rates of migration for C2+ gases is considerably less than that for methane (Coleman, 1977; Schoell, 1983).

Results from the East Riverton Dome field are similar to those of Pavillion (Figs. 10 and 11), except that gases are chemically dry at all stratigraphic levels (Fig. 11). Gases from the Madden field along the deep trough of the basin become only slightly heavier isotopically and chemically drier over 12,000 ft of section (5,556 to 18,050 ft, $R_m$ 0.63 to 2.2), again suggesting considerable vertical migration. Gases in the lower member of the Fort Union Formation appear to be much too thermally mature to have been generated in situ; they are found in reservoirs that have thermal maturities of about $R_m$ 0.60-0.70 percent.

### Origin of Coalbed Gases

The coalbed gases analyzed in the Wind River Reservation are highly variable in isotopic composition and appear to be mixtures of biogenic and thermal gases which probably formed at different times. The origins of these gases are complex and related to the geologic history of the southwest flank of the Wind River Basin, where these gases occur. During the Laramide orogeny (Late Cretaceous to early Eocene), the southwest flank of the Wind River Basin alternated between periods of deposition and erosion. At least three unconformities can be identified on the southwest flank of the basin: 1) at the base of the Lance Formation, 2) at the base of the Fort Union Formation, and 3) at the base of the Wind River Formation. (Fig. 3). The original thickness of the Mesaverde Formation in the Reservation was about 2,000 ft but it has been partially to completely truncated over a 2 1/2 to 15 mile wide area along the southwest margin of the basin (Keefer and Johnson, this volume). The Meeteetse Formation is also missing from this area. Its original thickness, based on data from wells farther basinward, was about 1,000 ft. Most of the beveling occurred prior to deposition of the Fort Union Formation inasmuch as the Fort Union overlies the Mesaverde throughout most of this area. The Lance Formation overlies the Mesaverde near Alkali Butte, and the Wind River Formation overlies the Mesaverde locally along outcrop. The Mesaverde Formation is completely absent in outcrop in many places along the southwest margin of the basin. The Fort Union and Wind River Formations directly overly the Cody Shale in these areas.

The Mesaverde coaly interval was exposed on the surface prior to deposition of the Fort Union Formation along the entire southwest margin of the Wind River Basin. At Hudson and at Pilot Butte these coals were exposed on the surface a short distance from the drillsites prior to deposition of the Fort Union Formation (see Johnson and others, this volume). Any methane that was present in the coals at that time escaped to the atmosphere. Any $CO_2$ present should have escaped as well, since it is very soluble in water. It is possible that a small residue of $C_{2+}$ gases could have remained in the coals, however, since these gases escape at much slower rates. The small amounts of $C_{2+}$ gases found in these coals could therefore be older than the time of deposition of the Fort Union Formation.

The methane, which appears to be a mixture of biogenic and thermogenic gas, must have accumulated

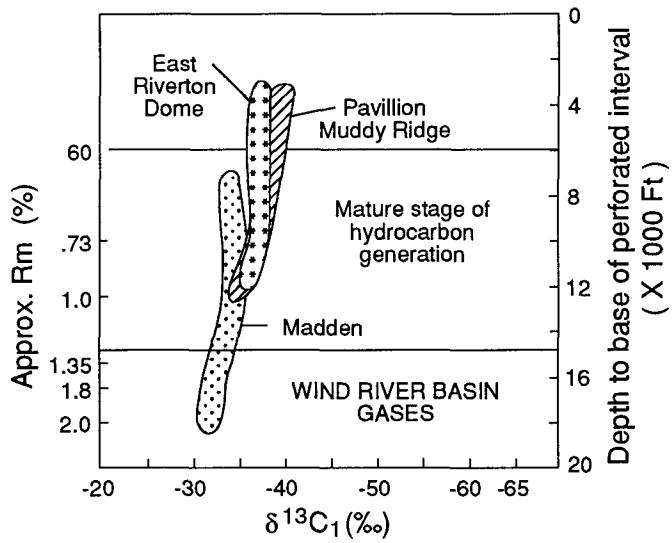


**Figure 10. Depth to base of producing interval versus methane carbon isotopic composition ($\partial^{13}C_1$) for gases from over wide depth ranges at Pavillion-Muddy Ridge, East Riverton Dome, and Madden fields.**

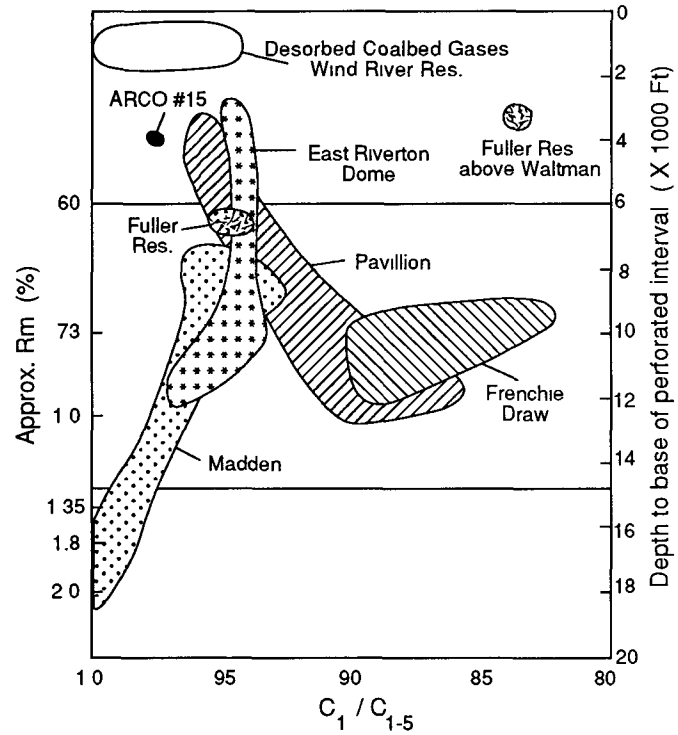


**Figure 11. Depth to base of producing interval versus hydrocarbon composition ($C_1/C_{1-5}$) for gases from various oil and gas fields in the Wind River Basin, Wyoming. Coalbed methane gases are also shown. Approximate vitrinite reflectance ($R_m$) of reservoir is also shown.**

in the coals after deposition of the Paleocene Fort Union Formation. One interesting characteristic of this methane is the thorough mixing of bacterial and thermogenic components at Pilot Butte. Little variation occurs in the methane $\partial^{13}C$ ‰ for all 24 gas samples collected from many different coals at the two drill sites which are about 800 ft apart. Little variation in the methane $\partial^{13}C$ was found at the Hudson site as well, but far fewer samples were analyzed. Any explanation for the origin of these gases must account for this lack of variation in the methane $\partial^{13}C$ ‰ between all Mesaverde coals in a given area despite wide variations in the quantity of gas stored in various coal beds.

Maximum formation temperatures and depth of burial at the Hudson and Pilot Butte sites could have been reached during either one of two times: 1) prior to truncation of the Meeteetse and Mesaverde Formations and before deposition of the Fort Union Formation, or 2) during maximum basin aggradation sometime after basin subsidence ceased during the Eocene. Approximately 1,000 ft of Meeteetse Formation, 1,500 ft of Mesaverde Formation and an unknown thickness of Lance Formation were removed from the Hudson and Pilot Butte sites prior to deposition of the Fort Union Formation. The Lance appears to have been 500 ft thick or less at the two sites based on extrapolating thicknesses shown on stratigraphic cross sections constructed by Keefer and Johnson (this volume). The maximum thickness of strata removed prior to deposition of the Fort Union Formation at the two sites was therefore approximately 3,000 ft.

Calculating the thickness of strata removed since maximum basin aggradation is more difficult. Maximum aggradation occurred sometime after Laramide subsidence ceased during the Eocene and prior to regional uplift and downcutting during the late Tertiary. Keefer (1970, p. D29) suggests that fairly reliable estimates of strata removed could be made by extrapolating between the high plateau surface at an elevation of 11,000 ft in the Absaroka Range northwest of the basin, and Beaver Divide at an elevation of 7,000 ft south of the basin. Using Keefer's projection, approximately 3,000 ft of section has been eroded from the Hudson site and about 3,500 ft has been eroded from the Pilot Butte site since uplift and erosion began during the late Tertiary. Depth to the base of the coaly interval today at Pilot Butte is about 800 ft and at Hudson is about 600 ft. Maximum burial of coal beds at Pilot Butte was therefore about 4,300 ft and at Hudson about 3,600 ft.

It appears that coals at the Hudson and Pilot Butte sites were under approximately the same thickness of strata at two different time periods, prior to deposition

of the Fort Union Formation, and during maximum basin aggradation. Using a thermal gradient of 1.4° F/100 ft (Geothermal Gradient Map of North America, AAPG, USGS, 1976), a mean annual surface temperature of 55°, and the somewhat higher burial depths during maximum basin aggradation, formation temperatures for the Mesaverde coaly interval under maximum burial were approximately 115° F at the Pilot Butte site and 105° F at the Hudson site. Even assuming a higher gradient of 2.0° F/100 ft results in formation temperatures of only 141° F at Pilot Butte and 127° F at Hudson. These temperatures were probably too low for significant thermogenic gas generation; the low coal ranks of $R_m$ 0.40 to 0.50% for these two sites supports the conclusion that the coals have generated little thermogenic methane. Temperatures at maximum burial at the two sites, however, are still well within the range of temperatures where biogenic gas can form (Rice and Claypool, 1981).

The bacterial gas component of these gases could have begun to accumulate in these coals any time after the coals were buried beneath the Paleocene Fort Union Formation, and indeed, bacterial gas could still be forming in the coals today. The thermogenic component is highly problematical, and it does not appear that this component could have been generated within the coals. It appears, therefore, that the thermogenic component of these gases migrated into the coals from a deeper, more mature source.

## CONCLUSIONS

Gases in conventional sandstone and limestone reservoirs in the Wind River Basin appear to be largely of thermogenic origin. Fort Union gases are the most variable chemically and isotopically, and it appears that these gases were generated in the Waltman Shale Member in some instances and in deeper strata below the Fort Union in others. Considerable vertical and lateral migration has occurred in fields such as Pavillion, East Riverton Dome, and Madden. Chemically and isotopically similar thermally mature gases occur at all stratigraphic levels in these fields.

Maximum measured thermal maturity for the Waltman Shale Member is an $R_m$ of only 0.76 percent or marginally mature for hydrocarbon generation. The Waltman probably attains higher levels of maturity in the deep trough of the basin. Therefore, although the Waltman Shale Member and the overlying strata contain significant amounts of potential source rocks, because of relativity low thermal maturities, the quantities of hydrocarbons generated in these rocks might not be great.

There is evidence that the Waltman Shale Member acts as a fairly good seal. At Madden field, formation pressures increase to above hydrostatic just below the base of the Waltman. At Fuller Reservoir field, reservoirs above the Waltman appear to be charged with hydrocarbons from different sources. Isotopically light gas and waxy oil, which appear to be derived mainly from the Waltman, are in reservoirs above the Waltman, whereas isotopically much heavier, more mature gas is in older reservoirs. Only in the western part of the basin, where the Waltman Shale Member is absent, has gas from deep, thermally mature to overmature Cretaceous source rocks migrated into shallow reservoirs such as the lower Eocene Wind River Formation .

Coalbed gases found in the structurally shallow areas of the basin within the Wind River Reservation are mixtures of biogenic and thermogenic gases. The biogenic component could have formed any time since the coals were buried by the Fort Union Formation in Paleocene time, but it is likely that some of this gas also formed since uplift and erosion of the basin area began during the late Tertiary. The coals are immature and were never buried to depths great enough to have generated significant quantities of thermogenic gas. The thermogenic component of these gases must have migrated into the coals from a deeper, more thermally mature source sometime after the coals were buried in Paleocene time.

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