

Coalbed gas systems, resources, and production and a review of contrasting cases from the San Juan and Powder River basins

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ABSTRACT

Coalbed gas has been produced commercially from the northern Appalachian basin since the 1930s and from the San Juan basin since the early 1950s. However, the magnitude and economic significance of coalbed gas resources were realized only in the 1970s and early 1980s when the U.S. Bureau of Mines, U.S. Department of Energy, the Gas Research Institute, and oil and gas operators made a concerted effort to demonstrate commercial production of coalbed gas from vertical wells. Exploration and development expanded in the late 1980s and early 1990s, due partly to an unconventional fuels tax credit. By 2000, coalbed gas accounted for 8.8% of the reserves (15.7 tcf [0.44 Tm³]) and 9.2% of the annual production (1.38 tcf [40 Gm³]) of dry gas in the United States. From 1989 through 2000, cumulative United States coalbed gas production was 9.63 tcf (272 Gm³). Today, coalbed gas development has spread to about a dozen basins in the United States, and exploration is progressing worldwide.

Coal beds are self-sourcing reservoirs that can contain thermogenic, migrated thermogenic, biogenic, or mixed gas. Coalbed gas is stored primarily within micropores of the coal matrix in an adsorbed state and secondarily in micropores and fractures as free gas or solution gas in water. The key parameters that control gas resources and producibility are thermal maturity, maceral composition, gas content, coal thickness, fracture density, in-situ stress, permeability, burial history, and hydrologic setting. These parameters vary greatly in the producing fields of the United States and the world.

In 2000, the San Juan basin accounted for more than 80% of the United States coalbed gas production. This basin contains a giant coalbed gas play, the Fruitland fairway, which has produced more than 7 tcf (0.2 Tm³) of gas. The Fruitland coalbed gas system and its key elements contrast with the Fort Union coalbed gas play in the Powder River basin. The Fort Union coalbed play is one of

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the fastest developing gas plays in the United States. Its production escalated from 14 bcf (0.4 Gm³) in 1997 to 147.3 bcf (4.1 Gm³) in 2000, when it accounted for 10.7% of the United States coalbed gas production. By 2001, annual production was 244.7 bcf (6.9 Gm³).

Differences between the Fruitland and Fort Union petroleum systems make them ideal for elucidating the key elements of contrasting coalbed gas petroleum systems.

INTRODUCTION, HISTORIC PERSPECTIVE, AND OBJECTIVES

Coalbed gas is rapidly reaching maturity as an energy source. What are noteworthy are its expansion to many basins, its increasing economic impact, and its significance to future United States energy supplies. The objectives of this article are to (1) briefly review the history of coalbed gas production; (2) describe the key elements of coalbed gas systems; (3) review geologic settings and operational practices of two disparate coalbed gas systems, the Fruitland and Fort Union formations; and (4) summarize the international coalbed gas resources and activity and the United States coalbed gas production, reserves, and resources.

Small volumes of coalbed gas have been produced commercially in the eastern United States for more than 70 yr (Price and Headlee, 1943; Patchen et al., 1991). In fact, with prescience and great detail, Price and Headlee (1943) described the potential for a commercial coalbed gas industry 60 yr ago. Coalbed gas production in the western United States began nearly 40 yr ago, in the San Juan basin (Dugan and Williams, 1988; Hale and Firth, 1988; Harr, 1988). In both the eastern and western United States, early coalbed completions were shallow contingency targets following unsuccessful testing or depletion of deeper strata. Production rates and volumes from most early wells were unimpressive, because little or no reservoir stimulation was performed.

The development of a robust coalbed gas industry in the United States over the past two decades is an outgrowth of both technical and nontechnical issues that include (1) the U.S. Bureau of Mines interest in coal degasification in advance of underground mining to prevent explosions; (2) the 1970s OPEC oil embargo that led to a federal tax incentive (the 1980 Crude Oil Windfall Profits Tax Act, Section 29) to encourage development of unconventional gas resources;

(3) public sector research and technology development by the U.S. Department of Energy, the Gas Research Institute (GRI; now the Gas Technology Institute [GTI]), and others; and (4) research by operating companies, especially Amoco (now BP Amoco). As a result of these research and testing programs, coalbed gas exploration began in earnest in the late 1970s, and the historic Amoco 1 Cahn well was drilled in the San Juan basin in 1977. Also in 1977, a successful vertical-well coal degasification project was initiated at Oak Grove field in the Black Warrior basin by USX Corporation in conjunction with the U.S. Bureau of Mines. By the middle to late 1980s there was exploration in several United States basins and established production and development in the San Juan and Black Warrior basins (Ayers et al., 1991a, 1994; Pashin et al., 1991).

Early coalbed methane exploration models emphasized the importance of thermogenic gas (e.g., San Juan and Black Warrior basins). In the past 5 yr, however, successful economic development of biogenic coalbed gas in the low-rank Fort Union coals of the Powder River basin has led to modification of coalbed gas exploration and development concepts within the petroleum systems framework.

Additional coalbed gas models, coupled with the escalating gas prices, triggered a resurgence of coalbed gas exploration and acquisitions beginning in 1999. Today, coalbed gas is produced from more than 20,000 wells in more than a dozen basins throughout the conterminous United States (Figure 1). Eastern and mid-continent production is from Upper Carboniferous rocks, whereas production from the western basins is from Cretaceous and Lower Tertiary rocks.

DEFINITION OF COALBED GAS SYSTEMS

Descriptions of petroleum systems (Magoon and Dow, 1994) provide an orderly method of evaluating the potential for commercial hydrocarbon accumulations. A petroleum system is "a natural system that encompasses a pod of active source rock and all related oil and gas and which includes all the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist" (Magoon and Dow, 1994, p. 10). Key elements of a conventional petroleum system are source, reservoir, and seal rocks. Equally important are the geologic processes and the time frame in which these processes act upon the rocks. These processes include hydrocarbon generation and migration (including formation of migration pathways), trap formation,

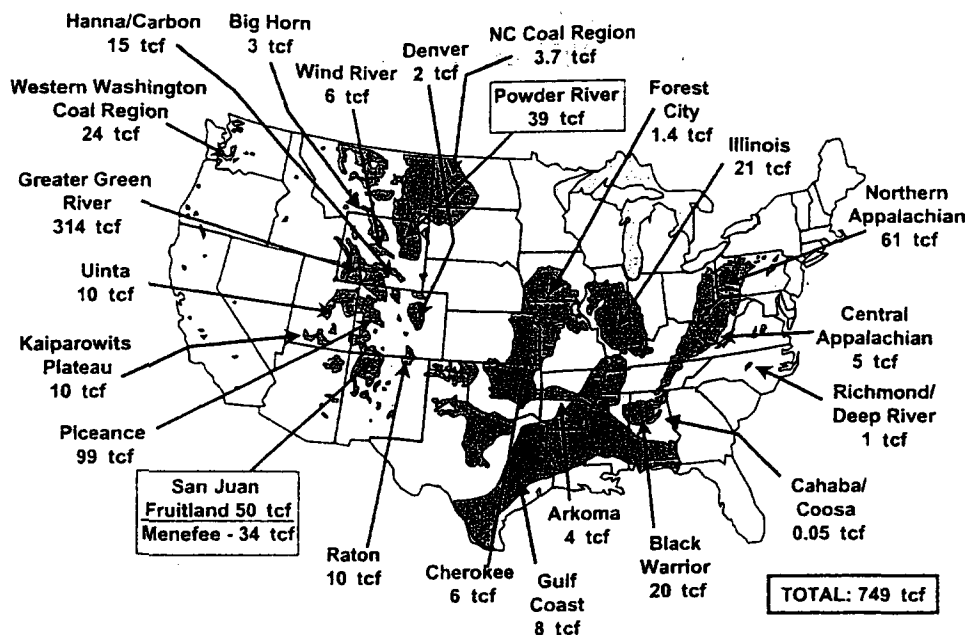


Figure 1. United States coal basins and coalbed gas resources (modified from GTI, 2001).

and hydrocarbon accumulation. Coalbed petroleum systems may differ from conventional systems in several ways, including source rock and gas origin, migration paths, and storage and trapping mechanisms.

Hydrocarbon Source and Migration

Most coal beds are self-sourcing reservoirs. However, coalbed reservoirs may contain self-sourced or migrated thermogenic gas, or biogenic gas, or some mixtures of these (D. D. Rice, 1993; Scott et al., 1994a, b;). In cases where coal beds are self-sourcing reservoirs for thermogenic gas, migration does not occur. In other cases, however, coal beds trap (adsorb) gas migrating from other source rocks, or they may adsorb gas generated by microbes (secondary biogenic gas) at the coal cleat-water interface.

The chemical composition and volume of thermogenic gas depend on maceral composition, thermal maturity, ash content, and seal integrity. The term "coalbed methane" has become entrenched in usage, and it aptly describes coalbed gas composition in many regions, where the gas is more than 98% methane. In other areas, however, coalbed gas contains significant quantities of heavier hydrocarbons (mainly ethane), carbon dioxide, and/or nitrogen; thus, it is more appropriate to use the generic term "coalbed gas" (Scott, 1993).

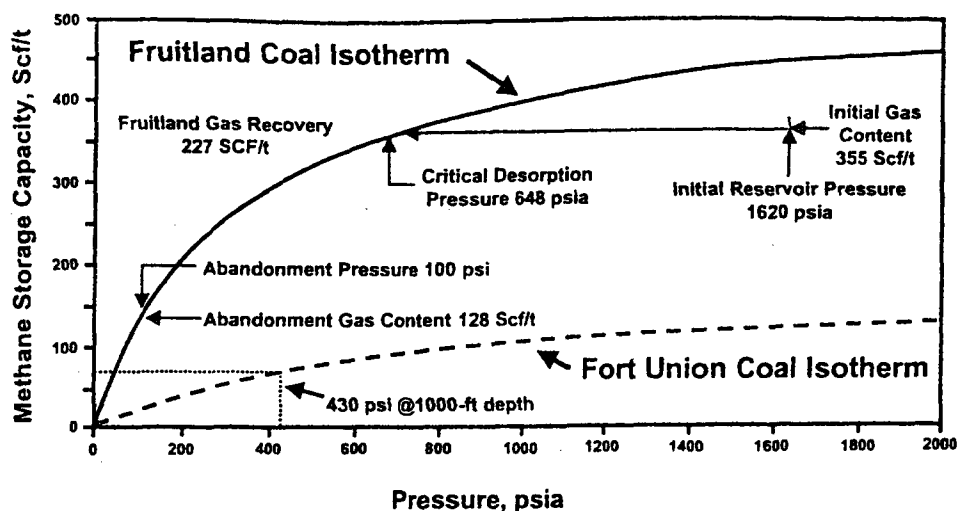
Because coalbed gas may contain self-sourced thermogenic, migrated thermogenic, or biogenic gas, a more complex events chart (e.g., Magoon and Dow,

1994, figure 1.5) may be necessary to capture key events. Some additional events common in coalbed gas systems are erosional unroofing and cooling that may lead to undersaturated reservoirs and development of hydrologic systems that may maintain fluid pressure and provide microbes and biogenic gas.

Gas Storage and Reservoir Behavior

Although some coalbed gas is stored as free gas in natural fractures, called cleats, or as solution gas in water occupying the cleats and pores, the majority of coalbed gas is adsorbed on the surface of organic matter of the coal matrix. Among the factors that affect the gas storage capacity of coal are thermal maturity (coal rank), moisture content, chemical composition of the gases, and pressure (see Levine, 1993; Yee et al., 1993). Coalbed reservoirs may be normally (hydrostatically) or abnormally pressured. At the usual pressures encountered in producing coalbed reservoirs (<4000 ft [1200 m] deep), coal can store more adsorbed gas than typical sandstone can store in primary pores. Gas-saturated coal yields gas upon initial production. To initiate gas desorption and production from coals that are not gas saturated, formation pressure must be reduced below the saturation point (Figure 2). Therefore, where coal cleats are water saturated, it is necessary to dewater (depressurize) the coal bed to allow desorption and gas production (Figure 3). Such reservoirs initially produce water and little or no commercial gas. As the depressurization occurs, gas desorbs from the coal matrix

Figure 2. Sorption isotherm for a Fruitland coal sample, Blackwood and Nichols 403 Northeast Blanco Unit well, San Juan basin (modified from Mavor, 1990), with superposed Fort Union coal isotherm (data from Pratt et al., 1999).



adjacent to the cleat and moves by darcy flow (two-phase flow where water is present) to the wellbore. Desorption of coalbed gas from the coal matrix adja-

cent to the cleat creates a concentration gradient, and gas within the matrix diffuses to the cleat, hence depleting the matrix gas. Over time, water production declines and gas production increases, which is commonly referred to as negative decline (Figure 3a). Generally, production decline rates of coalbed gas wells are much lower than those of conventional reservoirs. Therefore, coalbed reservoirs may provide long-term, stable production and reserves to balance more rapidly depleted reservoirs in an energy portfolio.

Seals and Traps

Seals are necessary in coalbed gas systems to maintain formation pressure and prevent gas desorption and escape. Although conventional traps may be present in coalbed gas systems, their presence is unnecessary, because gravity separation of gas and water are greatly subordinate to sorption on micropore surfaces. The most productive coalbed gas wells in the world, those in the San Juan basin Fruitland coalbed gas fairway, are located in a syncline where adsorbed gas is held by fluid (water) pressure. However, some structural, stratigraphic, or combination trapping probably enhances the Fruitland fairway production, as described in a subsequent section. A similar synclinal sweet spot was mapped in the Black Warrior basin (Ellard et al., 1992; Pashin and Groshong, 1998).

Fractures, Permeability, and In-Situ Stress

Coal permeability is even more important than coalbed gas content. The matrix permeability of coal is too low for commercial gas production. Fluid flow in coalbeds is through the natural fractures, or cleats (Figure 4).

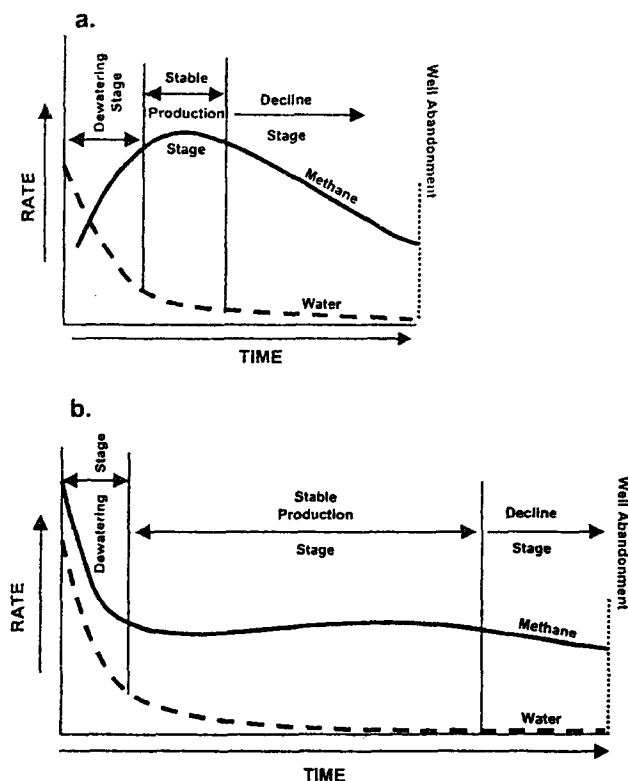


Figure 3. Schematic diagrams of hypothetical gas and water production profiles for coalbed methane wells. (a) Negative decline example commonly cited as characteristic of coalbed gas wells (modified from Schraufnagel, 1993). (b) Production curves characteristic of high in-situ stress (low-permeability) areas. Similar reserves may be recovered from the two wells, but reserves are recovered more quickly from example a, with the added cost of greater water handling.

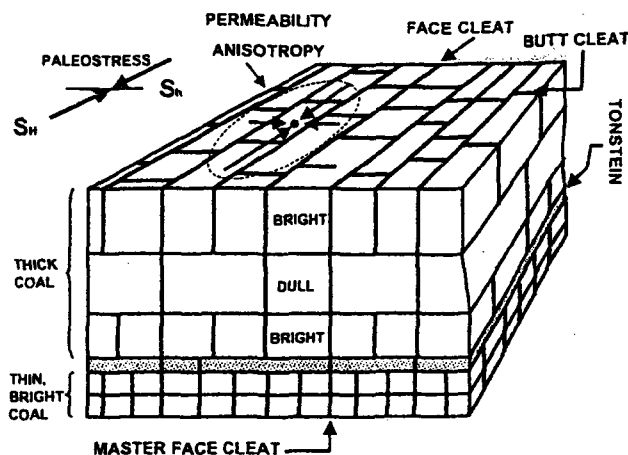


Figure 4. Schematic showing cleat terminology, controls on cleat characteristics, and cleat effects on coalbed permeability. Generally, cleat (fracture) density is greatest in thin, bright, low-ash coal.

Cleats are systematic, orthogonal fracture systems that commonly are perpendicular to bedding. They commonly form during coalification, and the face (dominant) cleat orientation reflects the far-field stress present during their formation (Nickelsen and van Hough, 1967; Laubach et al., 1998). Tectonic, postcoalification fractures also may be present. Cleat permeability is controlled by fracture density (spacing), aperture width and openness, extent, and connectivity. These factors, in turn, are controlled by coal rank, coal quality (ash content), maceral composition, bed thickness, tectonic deformation, mineralization, and in-situ stress (see Ammosov and Eremin, 1963; Close, 1993; Laubach et al., 1998). Where biogenic gas is present, cleats may serve multiple purposes of conveying microbes to the coal-water interface, sweeping microbial gas along the groundwater flow paths, and, during production, transporting water and gas to the wellbore. The face cleat is more continuous than the subordinate butt cleat, which may lead to permeability anisotropy and elliptical reservoir drainage patterns (Figure 4) (Koenig, 1989, 1991).

Because coal beds are highly compressible, in-situ stress may affect reservoir permeability and production characteristics (Figures 3b, 5) (Enever, 1987; McKee et al., 1988; Ellard et al., 1992; Sparks et al., 1993; Enever and Hennig, 1997). Generally, permeability decreases with depth owing to overburden stress. As a result, most coalbed gas production in the United States is from depths less than 4000 ft (1200 m) deep. In reservoirs having high in-situ stress, decline behavior of coalbed gas wells may differ from the typical negative curves, owing to increased effective stress as cleats

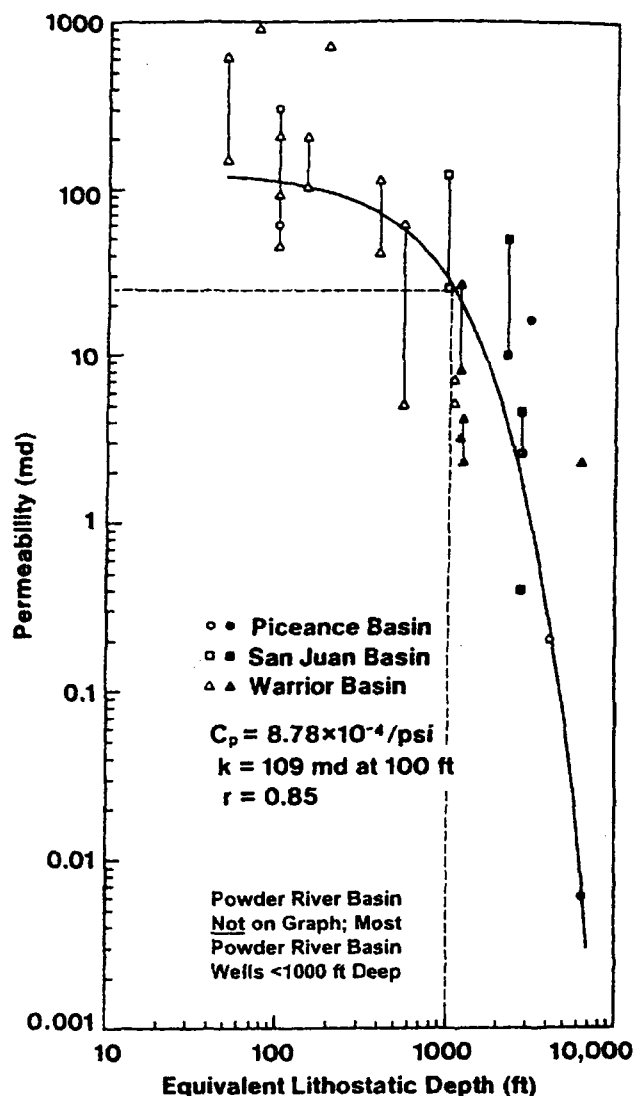


Figure 5. Effects of stress (expressed as lithostatic depth) on coalbed permeability (modified from McKee et al., 1988). Coalbed permeability is highly stress dependent.

are dewatered (Figure 3b) (Ellard et al., 1992). The wells having decline behaviors shown in Figure 3 may produce equal volumes of gas over their lives, but the reservoir in Figure 3a will produce this gas in a shorter time. Where present, artesian overpressure may reduce the effective stress and enhance coalbed permeability. Theoretically, however, dewatering coal beds should increase the effective stress, allowing cleats to close, but this appears to be an issue only in high-stress areas (Ellard et al., 1992; Sparks et al., 1993). In fact, laboratory studies have shown that the coal matrix can shrink as result of methane and CO₂ desorption, thus widening the cleat aperture (Levine, 1993, 1996; Palmer and Mansoori, 1996; Mavor, 1997). In some basins, tectonic stress is a significant factor in coalbed

permeability and/or the orientation and plane (vertical, horizontal, or complex) of induced fractures.

Reservoir Compartments

Coalbed reservoir quality varies across all basins, and fairways or sweet spots comprise less than 10% of the area of producing basins. An economic coalbed project requires convergence of several geologic factors in a favorable time frame, as well as in acceptable operational and environmental settings. The key to exploring for and developing coalbed gas is to recognize compartments within which reservoirs have similar properties, including gas content, permeability, water, and gas composition. Also, it is necessary to confirm sufficient reserves and production rates adequate to support the project infrastructure (e.g., water handling, gas treatment, if necessary). Among the key factors controlling coalbed gas project economics are coal thickness and extent, thermal maturity permeability, permeability-thickness product, coal depth, stratigraphic occurrence of coal, amount and quality of water to be handled, costs for water handling and disposal, geographical setting, and market access.

This article reviews the Fruitland and Fort Union coalbed gas plays, which represent end members for coalbed gas systems in the United States and, possibly, the world. The Fruitland Formation play in the San Juan basin (Figure 1) is charged with thermogenic and biogenic gas of highly variable chemical composition. The Fruitland Formation hosts the only giant coalbed gas field in the world, the well-publicized Fruitland fairway. The Fort Union Formation in the Powder River basin is one of the most active gas plays in the United States. Despite the fact that the coal is thermally immature and has low concentrations of biogenic gas, it has immense gas volumes stored in thick, high-permeability coal beds.

FRUITLAND COALBED GAS SYSTEM, SAN JUAN BASIN

Fruitland Coalbed Gas Development History

The San Juan basin has abundant coalbed gas in the Cretaceous Fruitland and Menefee formations, but coalbed gas production is entirely from the Fruitland Formation (Figures 1, 6). Coalbed gas production began in the early 1950s, when wells along the Ignacio anticline (Figure 7) in the northern San Juan basin were

completed open hole in Fruitland sandstones, mudstones, and coal beds and in the underlying Pictured Cliffs Sandstone. These wells were later abandoned upon water encroachment (Harr, 1988). The Phillips San Juan Unit 32-7 Fruitland 6-17 well was drilled south of the Ignacio anticline in 1953. By 1988, it had produced 1.36 bcf (38.5 Mm³) gas from an open-hole completion in the Fruitland Formation, with no decline in production rate or reservoir pressure (Hale and Firth, 1988). In the early 1970s, numerous shallow wells in the southwestern San Juan basin were completed open hole in the Fruitland Formation and Pictured Cliffs Sandstone; production was commingled (Dugan and Williams, 1988). The most significant advance for the San Juan basin coalbed gas industry occurred in the middle 1970s. After reviewing U.S. Bureau of Mines coal degasification tests throughout the United States, Amoco began an extensive coalbed gas exploration program that included the San Juan basin (Waller, 1992). When Amoco drilled and tested the Amoco 1 Cahn Fruitland coalbed gas well in the Cedar Hill field in 1979, production tests met or exceeded company expectations, and they initiated a development program (Decker et al., 1988; Waller, 1992). Encouraged by Amoco's results and the Section 29 tax credit, major and independent operators began leasing and testing coalbed gas throughout the basin, and a play was started.

In the late 1980s, the GRI funded studies to determine controls on coalbed gas occurrence and production in the San Juan, Black Warrior, and northern Appalachian basins (Ayers et al., 1990, 1991a; Pashin et al., 1991; Ayers and Kaiser, 1994). The San Juan basin study defined three major trends and several sub-trends that have markedly different coalbed gas compositions and production characteristics (Figure 8). Among these trends was the highly productive coalbed gas fairway. By the time the Section 29 tax credit deadline arrived (midnight, December 31, 1992), thousands of coalbed gas wells had been drilled in the San Juan basin. The Fruitland fairway had been delineated, exploration models had been developed, and operators were exploring for analogs to the Fruitland fairway throughout the United States and the world.

The Fruitland Formation (Upper Cretaceous) is the world's leading producer of coalbed gas. In 1999, the San Juan basin produced approximately 1006 bcf, or 2.75 bcf gas/day (28.7 Gm³ or 78.6 Mm³/day), of coalbed gas, and it accounted for 80% of the United States total coalbed gas production; cumulative coalbed gas production from the basin surpassed 7 tcf (200

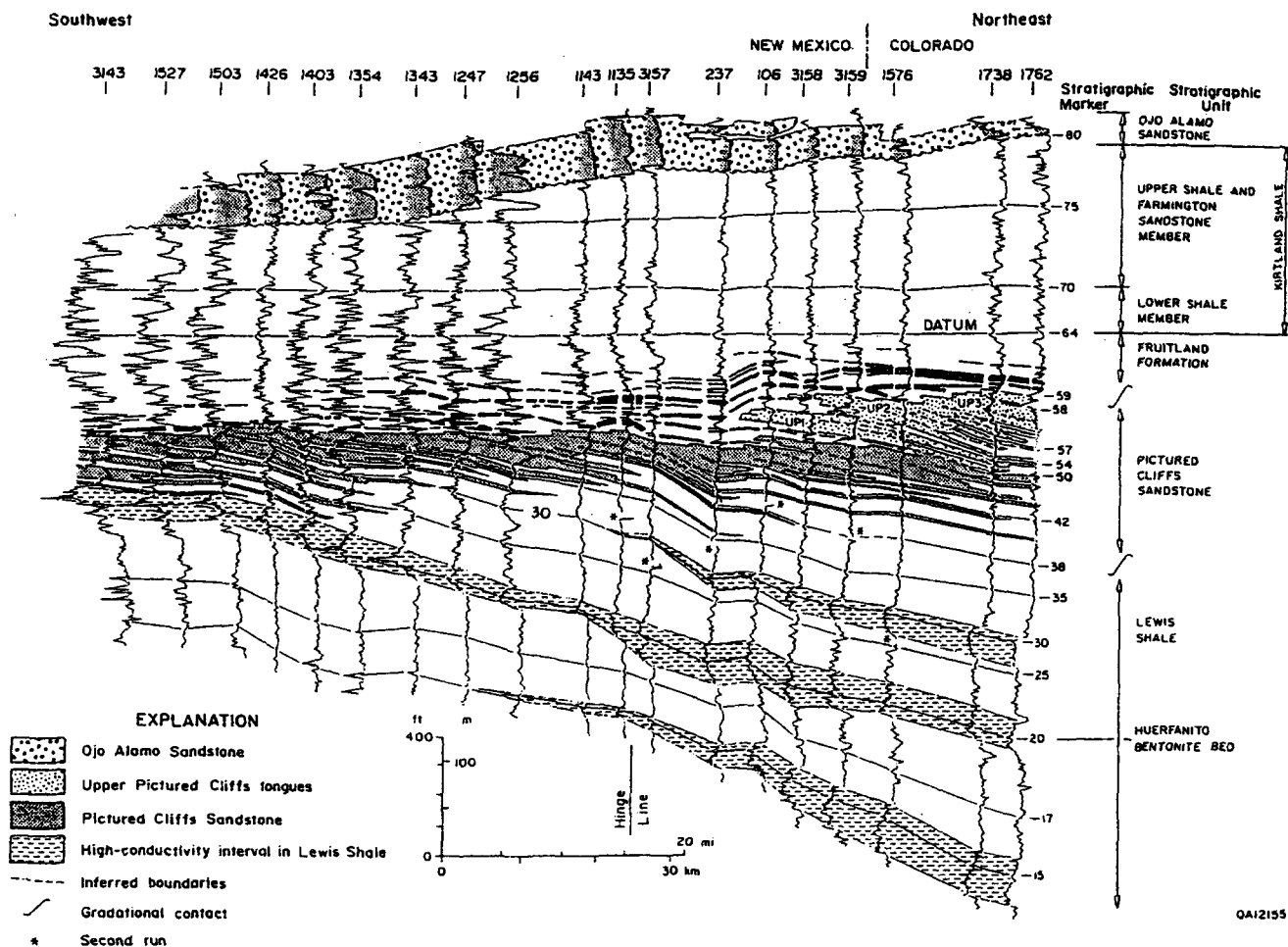


Figure 6. Paleodip stratigraphic cross section showing Upper Cretaceous stratigraphy and Fruitland coal occurrence, San Juan basin (modified from Ayers and Ambrose, 1990). Conductivity curves are shown. See Figure 7 for location.

Gm³). Coalbed gas reserves were 7.8 tcf (221 Gm³) at the beginning of 1998 (Kuuskraa, 1999). The Fruitland coalbed gas fairway qualifies as a giant, continuous-type gas play (Ayers, in press). By definition, a domestic giant field has reserves greater than 1 tcf (28 Gm³) (Halbouty, 1992).

Geologic Framework, Stratigraphy, and Depositional Systems

During the Late Cretaceous, the present San Juan basin area was located along the west margin of the Western Interior seaway. The Cretaceous coastline prograded northeastward, depositing shelf (Lewis Shale), coastal (Pictured Cliffs Sandstone), and continental (Fruitland Formation) sediment (Figure 6). Pictured Cliffs shoreface units are single-story or amalgamated, multistory sandstone bodies that were deposited by prograding or aggrading barrier-strand plain and wave-

dominated deltaic depositional systems (Figure 9) (Fassett and Hinds, 1971; Ayers and Ambrose, 1990; Ayers et al., 1991b, 1994).

The Fruitland coal beds formed as peats in coastal plain settings landward of, and overlying, Pictured Cliffs coastal sandstones. Northeastward, individual coal beds interfinger with and terminate behind coeval, backbarrier deposits. Along paleostrike (northwest-southeast), coal beds interfinger with northeast-trending fluvial channel-fill sandstones and overbank deposits of the Fruitland Formation (Ayers and Zellers, 1991; Ayers et al., 1991b, 1994). The Fruitland Formation is overlain by the Kirtland Shale, which is a seal, except in the southeastern part of the basin where the Ojo Alamo Sandstone unconformably overlies the Fruitland Formation (Ayers et al., 1994).

Fruitland net-coal thickness is greatest (50–70 ft [15–21 m]) in a northwest-trending belt of extensive, backbarrier coal bodies in the northern third of the

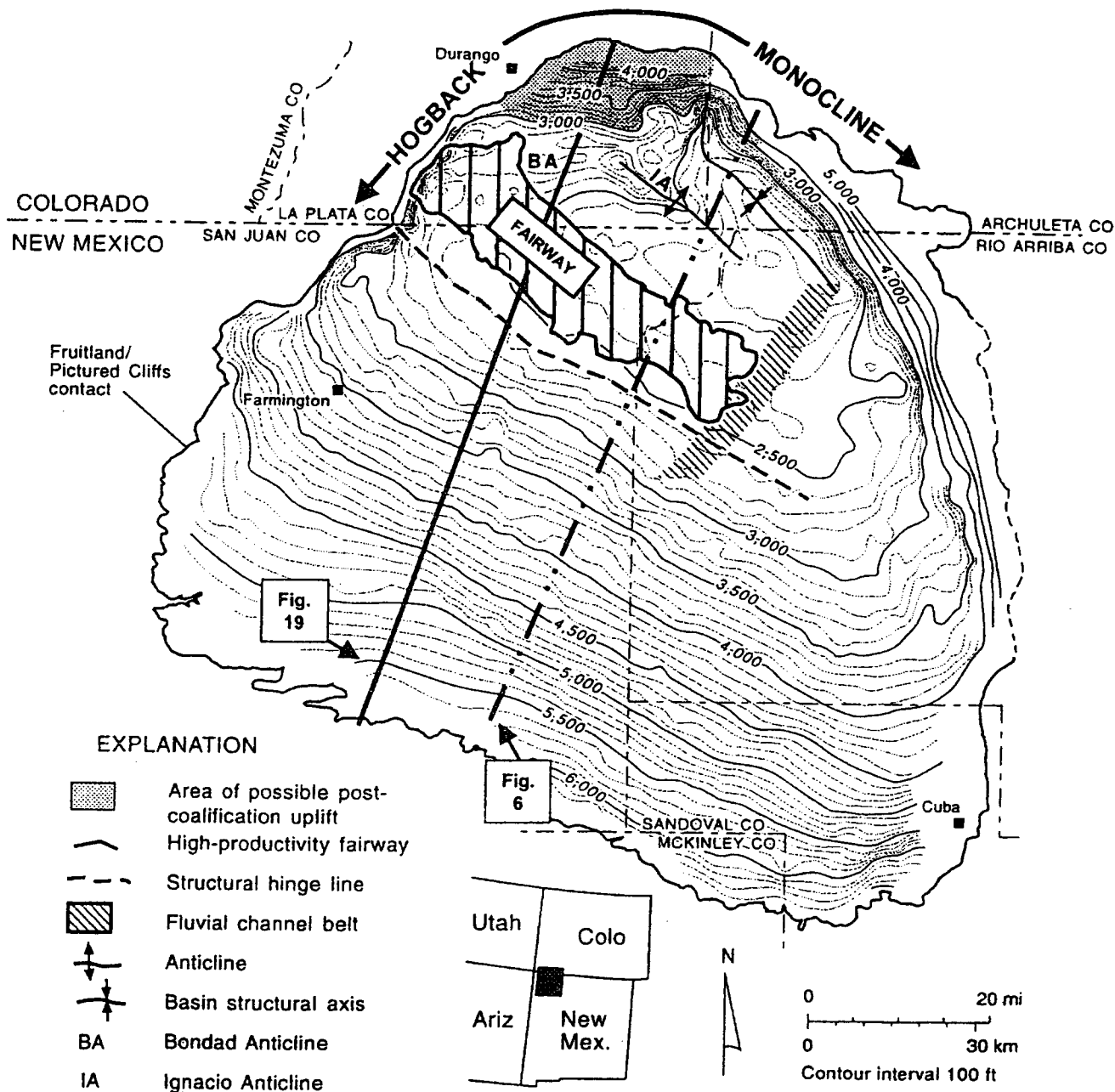


Figure 7. Structure map of the Huerfano Bentonite Bed, San Juan basin and location of the Fruitland fairway (modified from Scott et al., 1994b, after Ayers et al., 1991b and Palmer et al., 1992). Dip is steep around the north margin of the basin (Hogback monocline) and gentle on the south flank. Structural hinge line at 2600 ft (790 m) coincides with numerous geologic boundaries.

basin (Figure 10). Typically, a wellbore in this area encounters 6–12 coal beds, and the thickest individual bed is 20–30 ft (6–9 m) thick. In the northern part of the basin, dip-elongate interfluvial coal deposits extend southwestward, up the paleoslope toward the southwestern Fruitland outcrop. Interfluvial coal beds average 6 ft (1.8 m) thick, and maximum individual coal thickness may be as great as 10 ft (3 m) (Ayers et al., 1994).

Structural Setting

The San Juan basin is an asymmetrical Laramide structural basin that formed in the Late Cretaceous and early Eocene (~80 to 40 Ma) (Figure 7) (Kelley, 1955; Berry, 1959). Regional extension during the Oligocene was accompanied by volcanic eruptions that formed the San Juan volcanic field and emplaced batholiths and igneous dikes north of the San Juan basin (T. A.

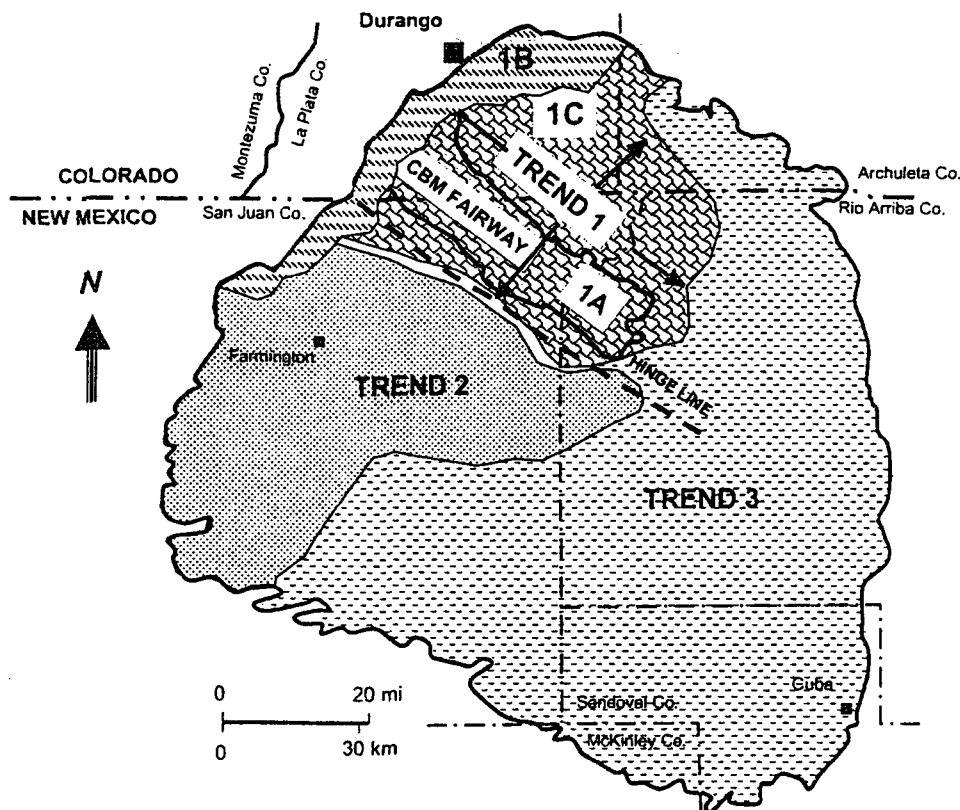


Figure 8. Fruitland coalbed methane reservoir productivity trends (modified from Kaiser et al., 1991b). The major productivity areas are trend 1 in the overpressured, north-central part of the basin and trend 2 in the underpressured, regional discharge area. The Fruitland fairway occurs primarily in trend 1A. Trend 3 is underpressured, and coal is outside the regional discharge area; it has few producing coalbed gas wells.

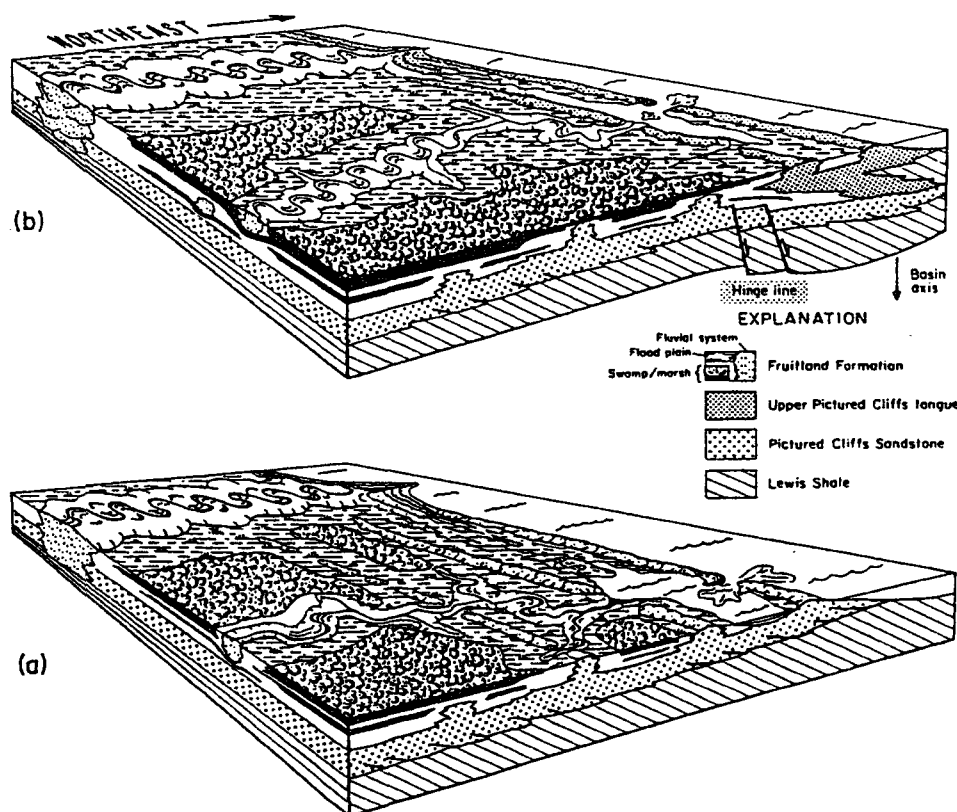


Figure 9. Depositional model for Fruitland Formation coal seams in the San Juan basin (modified from Ayers et al., 1994, after Ayers et al., 1991b). Swamps are bounded by abandoned shoreline sands at the northeast and fluvial channel-fill sands at the northwest. (a) Peat is deposited behind abandoned and foundered Pictured Cliffs shoreline sandstones, as well as in flood basins between Fruitland rivers. (b) Intermittently high subsidence rates north of the structural hinge line result in shoreline stillstands, allowing aggradation of the coastal plain. Peat swamps overspread abandoned shoreline and fluvial channel-fill sandstone complexes south of the active shoreline to form extensive deposits.

Stevens, 1975; Lipman et al., 1978; Laubach and Tre-main, 1994a). Higher heat flux associated with the igneous event, or heat advection associated with ground-water movement, caused anomalously high thermal

maturity in the northern San Juan basin (Figure 11) (Bond, 1984; Meissner, 1984; Clarkson and Reiter, 1988; Scott et al., 1994a). Regional uplift, which began in the Miocene and continues today, caused erosion

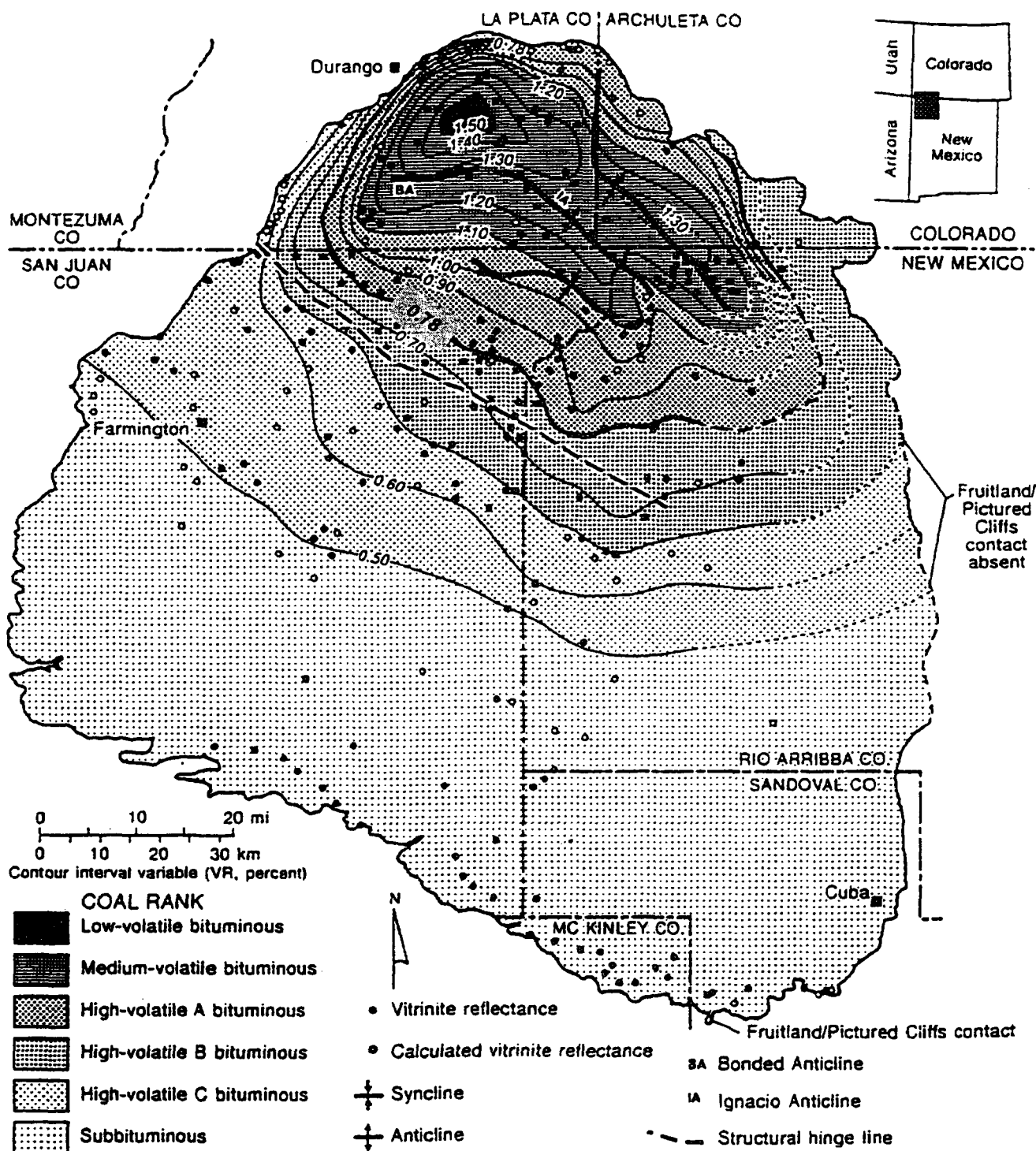


Figure 11. Vitrinite reflectance map for the Fruitland Formation, San Juan basin (modified from Scott et al., 1994a). Coal rank is greatest in the northwest part of the basin.

that stripped the Oligocene volcanic and volcanoclastic strata and exposed the upturned Pictured Cliffs Sandstone and Fruitland Formation, allowing meteoric recharge along the basin's northern Hogback monocline (Figure 7) (Kaiser et al., 1991a, 1994). A structural hinge line (and coincident flow barrier) occurs where the southern monocline meets the basin floor, approximately coincident with the 2500 ft (762 m) contour (Figure 7).

Coal and Coalbed Gas Origins, Composition, and Resources

In the south-central San Juan basin, Fruitland coals are composed of vitrinite (80%), liptinite (5.2%), and inertinite (14.1%) (Close et al., 1997). Ash content of Fruitland coal ranges from 10 to 30% and commonly exceeds 20%, and moisture content averages 10% in the southern part of the basin and 2% in the northern area (Roybal et al., 1985; Fassett, 1988). In much of the northern third of the San Juan basin, Fruitland coal rank is high-volatile A bituminous, or higher (Figure 11) (Kelso et al., 1988; Scott et al., 1991, 1994a), and thus, it is in the thermogenic gas window. Relations between the structural configuration and the coalification pattern indicate that thermal maturation was mainly synorogenic. However, the northern part of the basin may have later undergone structural inversion (compare Figures 7, 11) (Scott et al., 1994a).

In the northern area of thermally mature coal (vitrinite reflectance > 0.78%), ash-free gas content is generally greater than 300 scf/t (9 cm³/g), and, in the fairway area, it commonly exceeds 500 scf/t (15.6 cm³/g) (Kelso et al., 1988; Dhir et al., 1991; Meek and Bowser, 1993). Gas content of Fruitland coals is generally 150 scf/t (4.79 cm³/g) or less in the southern two-thirds of the San Juan basin, where thermal maturity is low (vitrinite reflectance < 0.65%).

After thermogenic gas charged the coal, the basin was uplifted and several thousand feet of overburden were stripped, allowing the Fruitland coal to cool. Because the sorptive capacity of coal is inversely related to temperature, this cooling event has caused the coal beds to be undersaturated (Scott et al., 1994b). Where the upturned coal beds crop out along the north margin of the basin, incursion of fresh water repressured the coal and supplied microbes that generated carbon dioxide and secondary biogenic methane that in places resaturated the coal. Isotopic studies demonstrated that this secondary biogenic methane is of great importance and may comprise 15–30% of Fruitland coal-

bed gas (see trend 1A, in a subsequent section) (Scott et al., 1991, 1994b).

Fruitland coalbed gas in place is 43–50 tcf (1.22–1.39 Tm³) in 245 billion tons (223 billion t) of coal from 400 to 4200 ft (122 to 1280 m) deep (Kelso et al., 1988; Ayers and Ambrose, 1990; Ayers et al., 1994). Both reserves and resources are greatest in the northern part of the basin, coincident with high coalbed gas in place and with thick, northwest-trending, thermally mature overpressure coal beds. In this area, coalbed gas resources are 15–30 bcf/mi² (Figure 12) (Ayers and Ambrose, 1990; Ayers et al., 1994).

Gas Producibility and Coalbed Permeability

Two face-cleat systems are present in Fruitland coal beds, one striking north-northeastward and the other striking northwestward (Figure 13) (Tremain et al., 1994). Along the northwestern margin of the basin, on strike with the coalbed methane fairway, both face-cleat sets are present, which may contribute to high permeability and production rates (Laubach and Tremain, 1994b; Tremain et al., 1994). Modern tectonic stress in the Colorado Plateau is extensional and does not appear to adversely impact coal permeability (Zoback and Zoback, 1980, 1989; Wong and Humphrey, 1989; Laubach and Tremain, 1994a). Fruitland coal permeability in the producing regions of the San Juan basin is typically 5–60 md; it is greatest in the fairway area.

Hydrologic Setting

Fruitland recharge occurs mainly at the elevated northern margin of the San Juan basin. Low rainfall, poor aquifer quality, erosional truncation, and topographically low outcrops limit recharge along other margins of the basin (Kaiser et al., 1991a, 1994). The Fruitland Formation is abnormally pressured relative to a freshwater hydrostatic gradient (0.433 psi/ft [9.80 kPa/m]). It is overpressured in the north-central part of the basin, coincident with the thick, northwest-trending coal beds, and underpressured in much of the rest of the basin (Figure 14). Overpressuring in the Fruitland Formation is hydrodynamic in origin, as is evidenced by artesian coalbed wells near the northern basin rim. The transition from overpressure to underpressure occurs along the hinge line of the basin, coincident with marked steepening of the potentiometric surface (Figure 14) and southwestward pinch-out of coal beds (Figure 10) (Kaiser et al., 1994).

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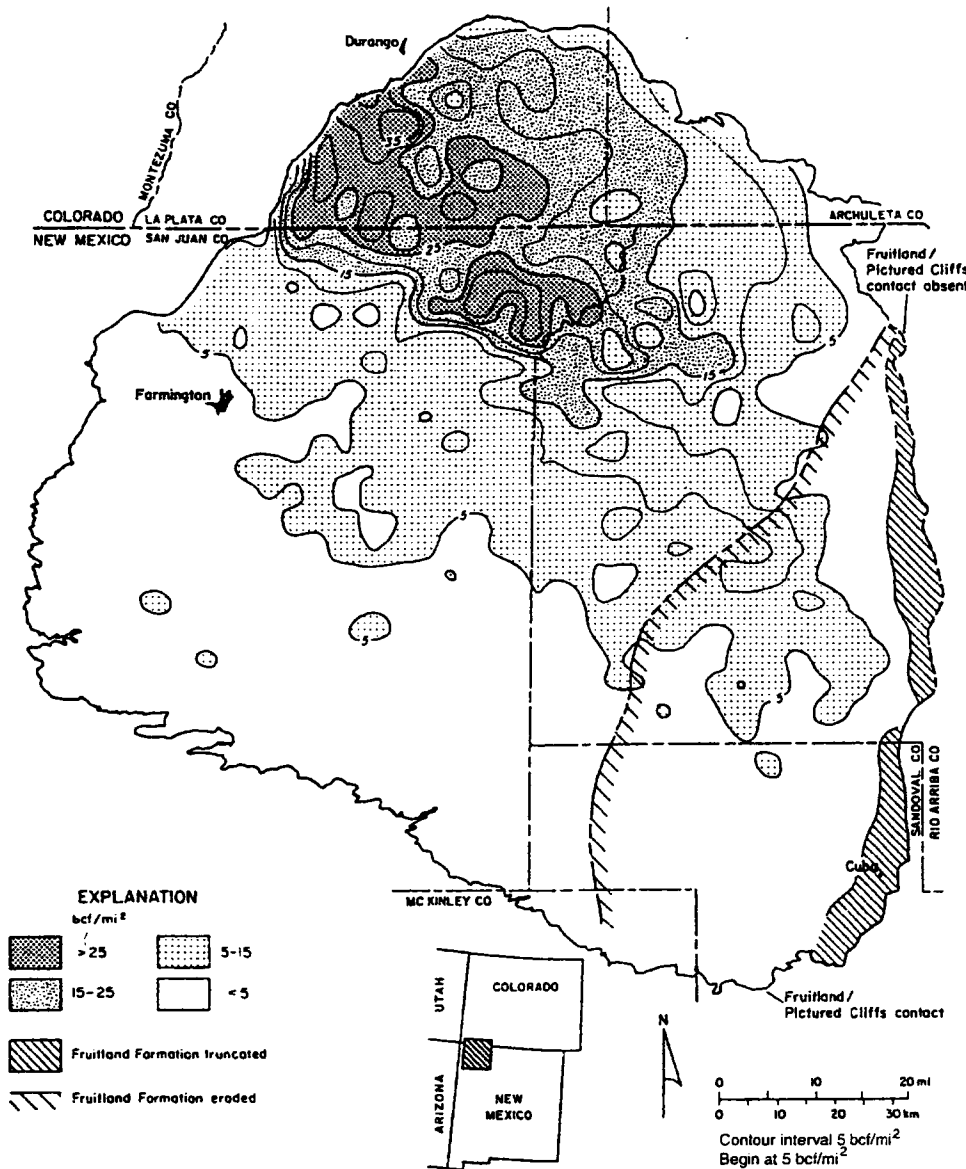


Figure 12. Coalbed gas in place for the Fruitland Formation, San Juan basin (modified from Ayers et al., 1994, after Ayers and Ambrose, 1990). Amounts calculated on the basis of 20% average ash content in coal. High gas in place values (>15 bcf/mi²) coincide with thick, northwest-trending, high-rank coal deposits in the northern part of the basin.

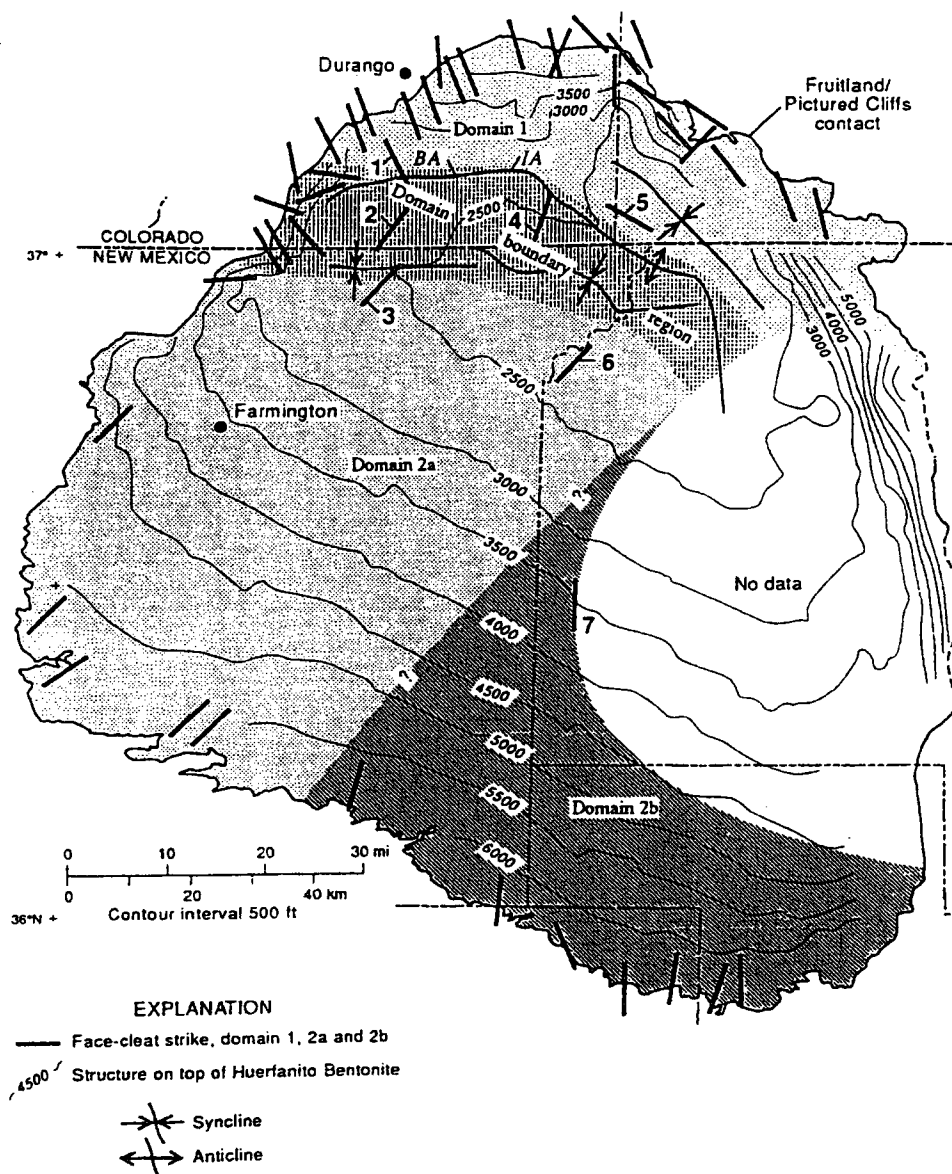
Fresh, low-chloride water occurs in the recharge area along the northwest margin of the basin and penetrates far into the basin, indicating a dynamic flow system (Figure 15) (Kaiser et al., 1991a, 1994). A hydrochemical boundary between low-chloride, Na-HCO₃-type and high-chloride, Na-Cl-type waters (1600 mg/L contour in Figure 15) coincides with regional pressure, potentiometric, and depositional facies boundaries, all of which occur along the hinge line of the basin (Kaiser et al., 1994).

Production Analysis/Reservoir Characteristics

Coal zones commonly appear to be continuous in well log and seismic cross sections in the San Juan basin, but

faults, pinch-outs, and erosional truncations commonly result in flow boundaries that compartmentalize coal reservoirs. Interplays among Fruitland geologic and hydrologic elements result in three regional coalbed gas production trends (Figure 8; Table 1). Trend 1 is the regionally overpressured, north-central part of the basin, and trend 2 is the underpressured, regional discharge area in the west-central part of the basin. Trend 3 is the underpressured, south and east part of the basin, for which there is little reservoir data owing to low-permeability coal and limited coalbed gas production (Figure 8; Table 1). There are more than 3100 Fruitland wells in the San Juan basin, but the greatest production is from approximately 600 wells in the fairway subtrend of trend 1 (Figure 8).

Figure 13. Generalized structure map of the San Juan basin (top of Huerfanito Bentonite Bed) with superposed face-cleat strikes and cleat domains (from Tremain et al., 1994, reprinted with permission from the Bureau of Economic Geology). Cleat domain boundaries are imprecise and gradational. Boldface numbers indicate data from oriented core. BA-IA = Bondad-Ignacio anticline.



Trend 1

Coalbed methane resources and production are greatest in trend 1 (Figure 8; Table 1), where thick, laterally extensive, high-rank coal deposits have high formation pressure and high gas content. Trend 1 coalbed gas is chemically dry ($C_1/C_1-C_5 > 0.97$) and generally contains 3–12% CO_2 (Figures 16, 17), which lowers the heating value. Isotopic analyses of coalbed gas and produced water indicate that gas in the northern part of the basin is a mixture of in-situ thermogenic, migrated thermogenic, and biogenic gas (D. D. Rice et al., 1988; Hanson, 1990; Scott et al., 1991, 1994b). Trend 1 is subdivided into trends 1A, 1B, and 1C (Figure 8). Owing to regional artesian overpressure, trend 1 wells generally produce 100–

300 bbl/day (16–48 m^3 /day) of water on initial completion. Generally, water production is greatest near the recharge area at the northwest margin of the basin (trend 1B) and in the Fruitland fairway (trend 1A) (Figure 18) (Cox et al., 1993; Scott et al., 1997). Fruitland coalbed waters in trend 1 are predominantly sodium bicarbonate, low-chloride waters that have moderate to high total dissolved solids (TDS) content (Kaiser et al., 1994). In 1992, after 10–12 yr of coalbed gas development, wells along the northern margin of the basin were averaging more than 250 bbl (40 m^3) of water daily. Average daily water production decreased basinward, and water production trends are similar to flow trends inferred from potentiometric and chloride maps (Figures 14, 15).

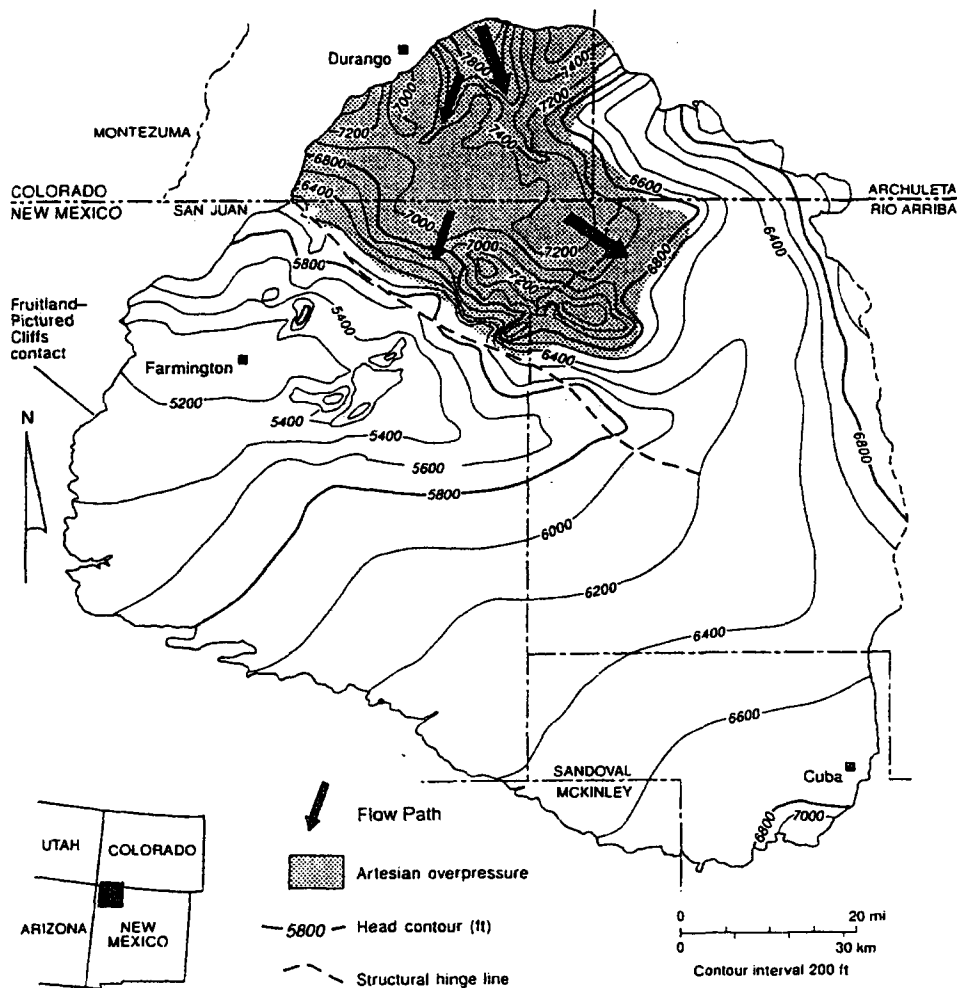


Figure 14. Potentiometric surface map and area of overpressure (shaded) in the northern San Juan basin (modified from Scott et al., 1994b, after Kaiser et al., 1991a.). Fruitland potentiometric surface is highest in the northern San Juan basin where recharge occurs. The northwest-trending, steep potentiometric surface in the center of the basin coincides with southwestward pinch-out of aquifer coal beds and/or their offset by faults along the structural hinge line. From near the northern outcrop where recharge occurs, artesian overpressuring extends basinward and is nearly coincident with thick, aquifer coal beds and freshest formation waters (Figures 10, 15). In much of the remainder of the basin, the Fruitland Formation is underpressured; transition from overpressure to underpressure is at the structural hinge line (Figure 7).

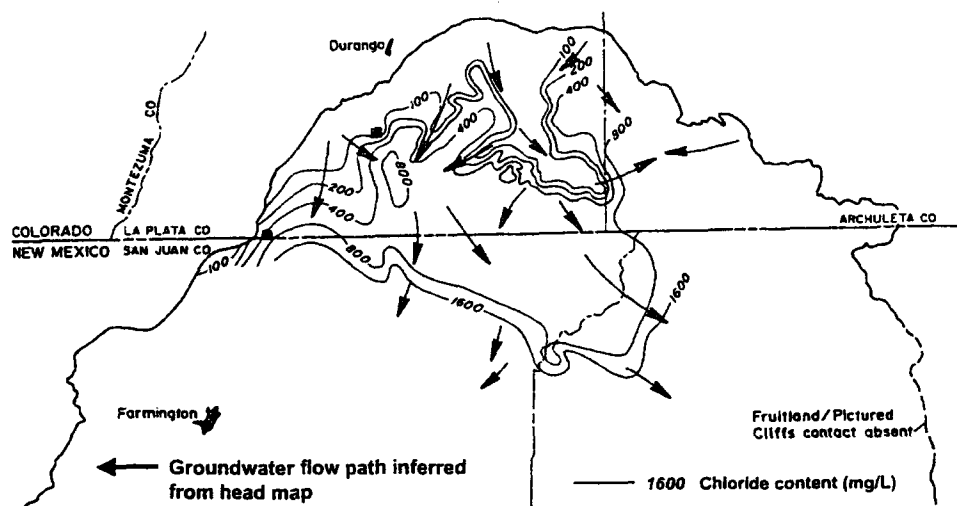


Figure 15. Chlorinity map, Fruitland Formation water (modified from Kaiser et al., 1991a). The chlorinity gradient suggests that flow is in the directions inferred from the potentiometric surface map (Figure 14). Low-chloride water coincides with greatest net coal values and overpressure (Figures 10, 14).

Trend 1A, the fairway, is approximately 9 mi (14 km) wide and 40 mi (64 km) long (Figures 7, 8, 19; Table 1). It contains more than 600 of the most productive coalbed gas wells of the basin. Peak produc-

tion of individual fairway wells is commonly 1–6 mmcf gas/day (>28–168 km³/day) (Kaiser et al., 1991b; Palmer et al., 1993). After 5 yr, cumulative gas production from the overpressured fairway ranges

Table 1. Comparison of Coalbed Gas Reservoir Parameters and Production Characteristics, San Juan and Powder River Basins

Properties/Characteristics	Fruitland Coalbed Gas System, San Juan Basin			Fort Union	
	Trend 1a	Trends 1b and 1c	Trend 2	Trend 3	Coalbed Gas System, Powder River Basin East and North Rims
Net coal thickness in belts	50–70 ft (15–21 m)	30–60 ft (10–20 m)	30–50 ft (9–15 m)	30–50 ft (9–15 m)	50 to >215 ft (15 to >65 m)
Coal thermal maturity and gas origin	High-volatile A to medium-volatile bituminous; thermogenic gas with high biogenic component	High-volatile B to low-volatile bituminous; thermogenic gas with high biogenic component	High-volatile B bituminous or lower; early stage and migrated thermogenic gas?	Mostly high-volatile B bituminous or lower; some high volatile A in north; early stage and migrated thermogenic gas	Subbituminous C-B; biogenic gas
Gas content (saturation)	Commonly >500 scf/t (mostly saturated; some undersaturated)	200–400 scf/t (undersaturated)	Mostly <150 scf/t (undersaturated)	Mostly <150 scf/t; higher in north (undersaturated)	16–76 scf/t; increase with depth (undersaturated)
Gas resources (original gas in place)	15–30 (bcf/mi ²)	15–25 (bcf/mi ²)	3–15 (bcf/mi ²)	3–15 (bcf/mi ²)	1.6–19.8 (bcf/mi ²)
Gas dryness	$C_1/C_1-C_5 > 0.97$	$C_1/C_1-C_5 > 0.97$	$C_1/C_1-C_5 > 0.89-0.98$	$C_1/C_1-C_5 > 0.89-0.95?$ (limited data)	$C_1/C_1-C_5 > 0.98$
CO ₂ content	3–13%	1–6%	<1.5%	<1.5%	Desorbed from core = 8%; production stream <2%?
Hydrologic setting	Artesian overpressure; potential for upward flow	Artesian overpressure; potential for downward flow	Underpressured	Underpressured	Normal to artesian overpressure
Water quality and disposal (San Juan basin water disposal is by injection or evaporation)	Predominantly sodium bicarbonate, low chloride, moderate to high TDS	Sodium bicarbonate type water; fresh-to-brackish; low chloride near outcrop, TDS chloride increase basinward	Sodium chloride type water; similar to seawater; TDS 14,400–42,000 mg/L	Sodium chloride type water; similar to seawater; TDS 14,400–42,000 mg/L	Fresh water; TDS 370–1940 mg/L; surface application and ranch use
Face cleat orientation	Northwest and northeast?	Northwest, into basin	Northeast, into basin	North and northeast, into basin	East-northeast on east rim; into the basin
Permeability (md)	15–60 md	10–35 md	5–25 md	< 5 md (limited data)	10 to >1000 md

permeability (md)	15-60 md	10-35 md	5-25 md	basin < 5 md (limited data)	rim; into sin 10 to >1000 md
Typical peak gas production rates (mcf/ day); (range and median cumulative production after 5 yr)	1-6 mmcf/day (.04-8 bcf; 2.4 bcf)	50-500 mcf/day (50-700 mmcf; 200 mmcf)	30-500 mcf/day (50-700 mmcf; 200 mmcf)	<50 mcf/day? (limited data?)	130-350 mcf/day EUR 300-400 mmcf/well on 80 ac spacing
Typical peak water production rates (bbl/ day)	100-300 bbl/day; higher locally	100-300 bbl/day; higher locally	0-100 bbl/day	0-25 bbl/day?	200-500 bbl/day; >1000 bbl/day in deep, thick coal
Well completions	Average depth 2600 ft Highest rate wells are open-hole cavity completions; some fracture stimulation; 320 ac spacing	750-2500 ft deep Fracture stimulation is most effective; some open-hole cavity completions; 320 ac spacing; down spacing to 160 ac	1100-1800 ft deep Fracture stimulation; 320 ac spacing	Few wells; fracture stimulation; tight; horizontal wells will be tried along southeastern margin	200-2000 ft deep; most <750 ft deep; open hole; light water fracture stimulation; no additives or proppant; most commonly 80 ac spacing; some 40 ac spacing

from 0.4 to 8.0 bcf (11.4 to 228 Mm³) per well, and median cumulative production is 2.4 bcf (68.6 Mm³) (Boyer et al., 2000; Boyer and Zuber, 2001). Some Fruitland wells have 7-12 bcf (198-340 Mm³) of reserves (Williams, 2001). Fairway coalbed gas wells are located at depths between 2500 and 3600 ft (762 and 1098 m), along the southwest part of a flat-bottomed syncline and adjacent to the fold hinge (Figure 7). Fruitland fairway coalbed gas is a mixture of in-situ thermogenic gas (self-sourcing), secondary biogenic gas, and migrated thermogenic gas (Scott et al., 1994b). Resaturation of the coal beds by biogenic and migrated thermogenic gas impacts the gas volume, and, importantly, it affects the amount of depressurization required to initiate gas production (Figure 20).

Typically, trend 1B and 1C wells produce 50-500 mcf gas/day (1.4-14.3 km³/day) (Figure 8; Table 1) (Palmer et al., 1993). For all San Juan basin nonfairway wells (trends 1B, 1C, 2, and 3), 5 yr cumulative production ranges from 50 to 700 mmcf (1.4 to 20 Mm³), with a median of 200 mmcf (5.7 Mm³) (Boyer et al., 2000). Trend 1B is located along the northern and northwestern flanks of the basin on the Hogback monocline (Figures 7, 8). Water production decreases with distance from outcrop (Figure 18). Fracture permeability may be high owing to local folds and flexure at the boundary between the Hogback monocline and the basin floor (Figure 7). Trend 1C (Figure 8) is defined by a flat potentiometric surface, which suggests the hydraulic interconnection facilitates uniform reservoir pressure in this area.

Trend 2

Trend 2 coalbed wells (Figure 8; Table 1) typically produce between 30 and 500 mcf gas/day (0.85 and 14.1 km³/day), similar to many wells in trends 1B and 1C, but trend 2 wells produce little or no water (Kaiser et al., 1991b; Kaiser and Ayers, 1994). Water is Na-Cl-type that has TDS of 14,000-42,000 mg/L. Cumulative gas production over 5 yr ranges from 50 to 700 mmcf (1.4 to 19.8 Mm³) per well, with a median of 200 mmcf (5.7 Mm³/day) (Boyer et al., 2000). Cumulative production of some wells in trend 2 exceeds 1 bcf (0.03 Gm³). Fruitland coalbed reservoirs in trend 2 are regionally underpressured, with the exception of local areas. Coalbed gas in trend 2 ranges from chemically wet to dry ($C_1/C_1-C_5 = 0.89$ to 0.98) (Figure 16) and contains less than 1.5% CO₂ (Figure 17) (Scott et al., 1991, 1994b).

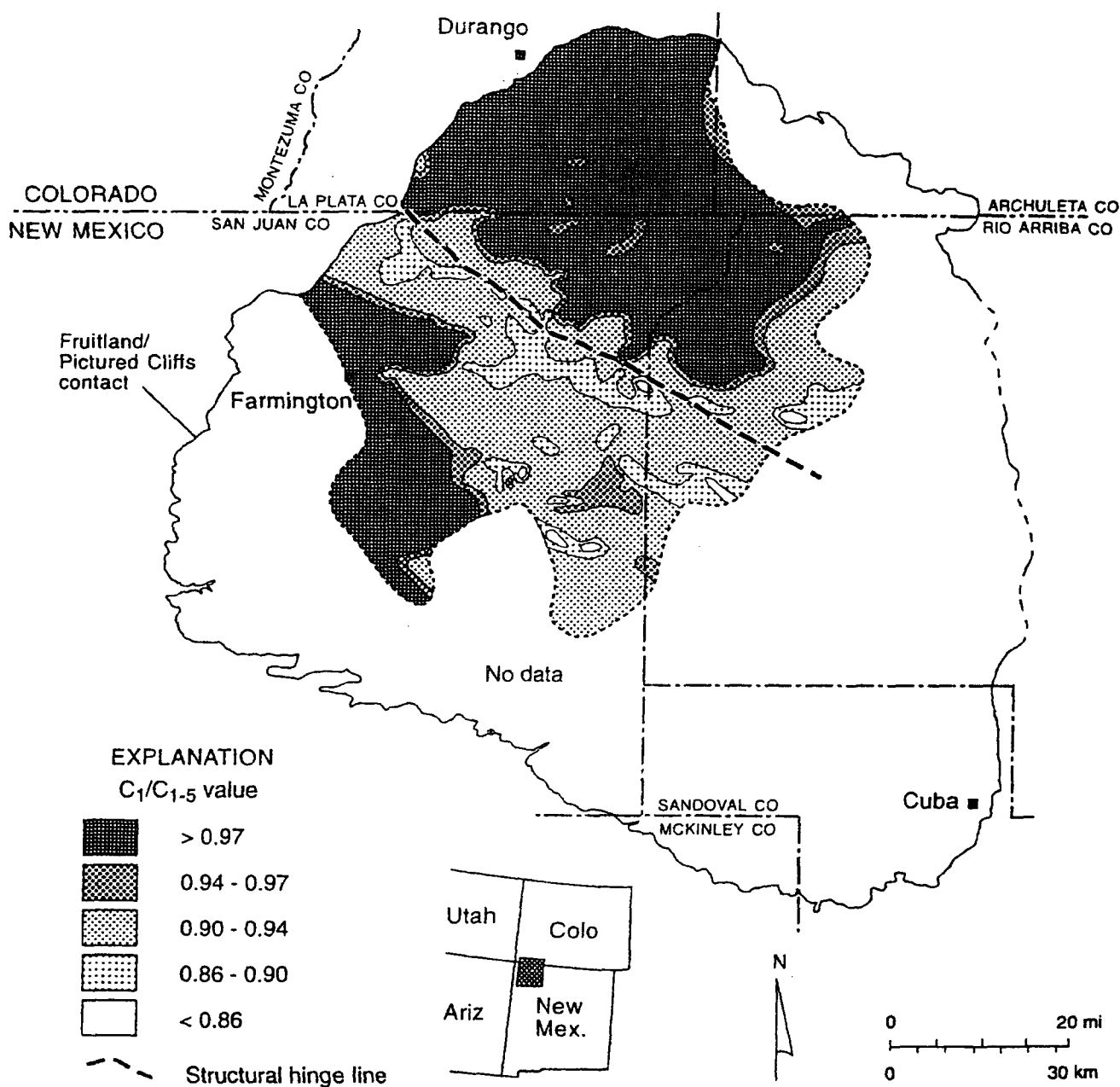


Figure 16. C_1/C_{1-5} values, Fruitland coalbed gases (from Scott et al., 1994b, reprinted by permission of the AAPG whose permission is required for further use). In the northern San Juan basin, coincident with overpressure (Figure 14), coalbed gas is chemically dry to very dry ($C_1/C_{1-5} > 0.97$) and has a sharp southwestern contact near the hinge line.

Trend 3

Trend 3 is the underpressured, southern and eastern part of the basin (Figure 8; Table 1). Coal is mostly high-volatile B bituminous rank, and gas content is generally less than 150 scf/t ($4.7 \text{ cm}^3/\text{g}$). Coalbed gas activity in this area has been limited, and reservoir data are meager because early tests yielded poor results. For example, in a GRI research project, drillstem testing in the Mesa FC Federal 12 well yielded a permeability of 0.004 (Pratt et al., 1992).

Completions and Operations

Fruitland coalbed completions are generally between 750 and 3600 ft (229 and 1098 m) deep. Typically, Fruitland coalbed reservoirs exhibit negative decline behavior (Figure 3a). Coalbed drilling and completion methods vary with well vintage, operator, and, especially, geologic and hydrologic settings in the basin (Clark and Hemler, 1988; Logan, 1993; Palmer et al., 1993; Schraufnagel, 1993). Early wells were com-

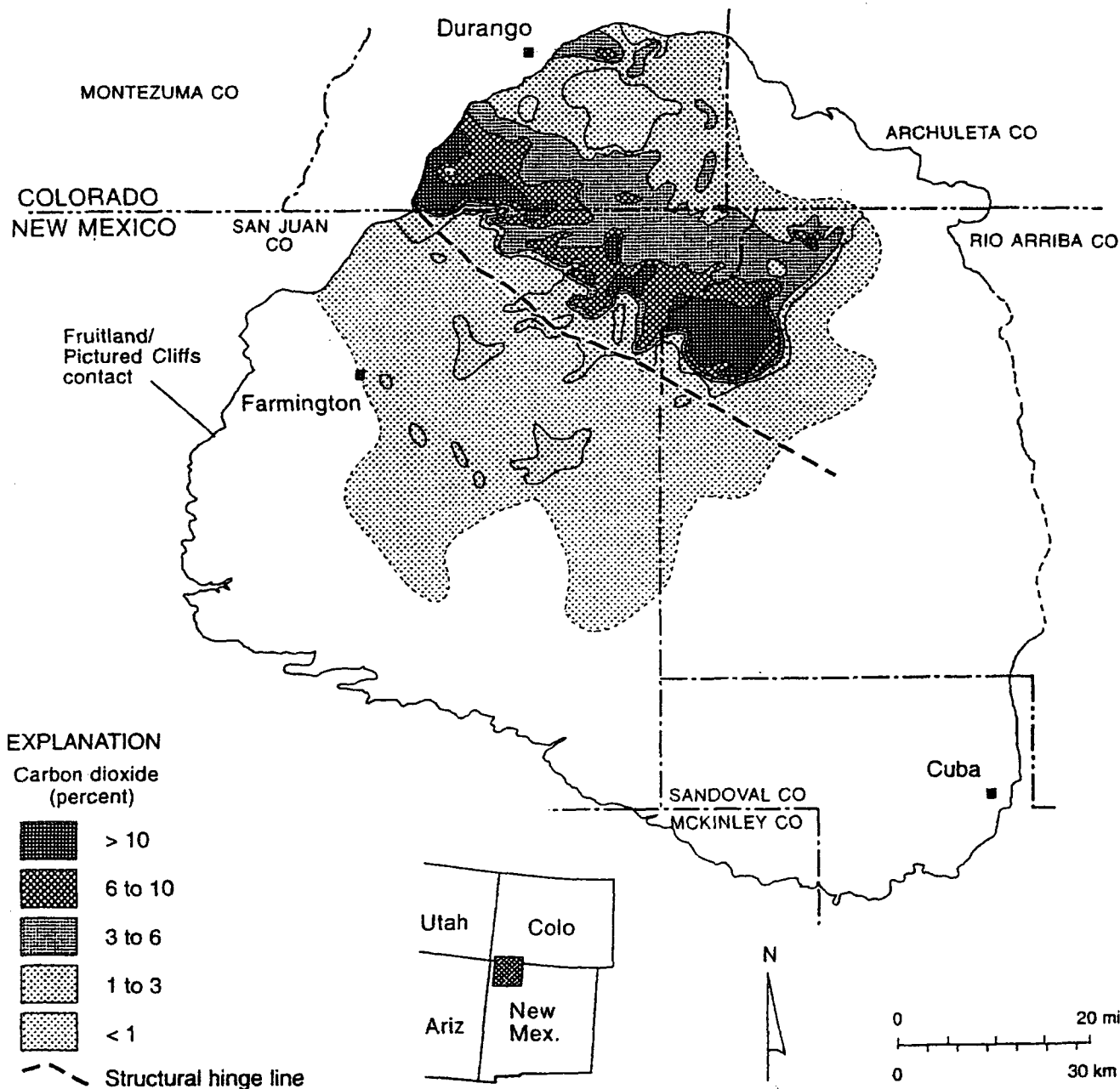
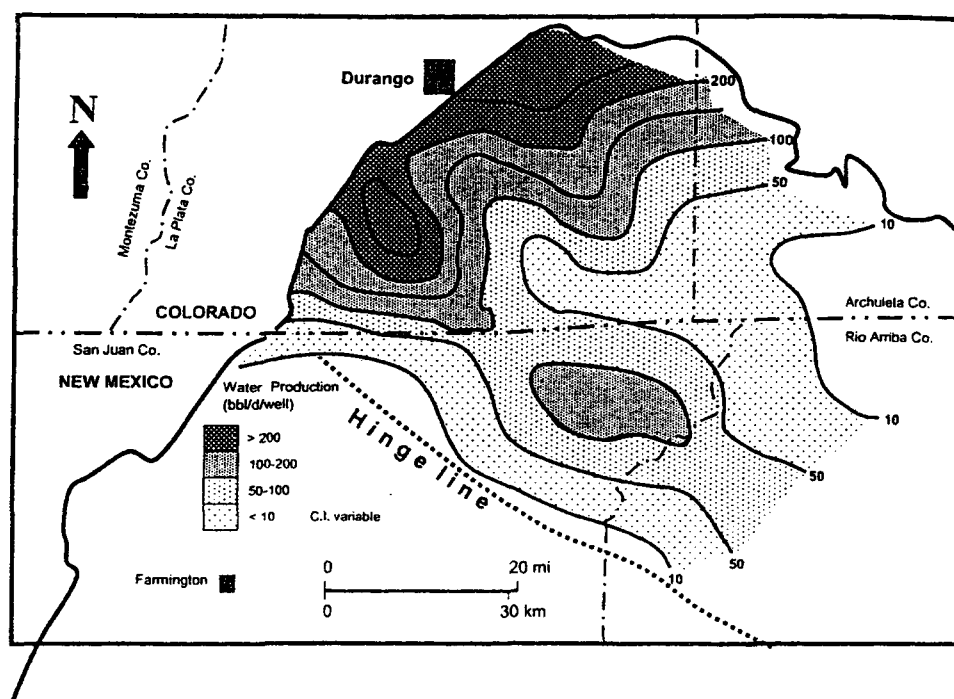


Figure 17. CO₂ values, Fruitland coalbed gases (from Scott et al., 1994b, reprinted by permission of the AAPG whose permission is required for further use). Gases containing high carbon dioxide content (>6%) coincide with the highly productive coalbed gas fairway (Figure 7).

pleted open hole, and production from Fruitland coal and underlying Pictured Cliffs sandstone reservoirs was commingled (Dugan and Williams, 1988). Today, depending on the geologic and hydrologic setting, most Fruitland coalbed wells are completed either as open-hole cavities or by being cased through the coal and fracture stimulated in 1–3 coal intervals (Figure 21). The open-hole cavity completion, developed by Meridian (Burlington Resources) in 1985, is the most ef-

fective fairway (trend 1A) completion. By contrast, fracture stimulation may be more effective in other parts of the basin (Palmer et al., 1993; Kelso, 1994; Logan, 1994; Young et al., 1994; Khodaverdian et al., 1996). Fairway wells with open-hole cavity completions produce 1–6 mmcf gas/day (28–168 km³), whereas nonfairway wells with fracture stimulations typically produce 50–500 mcf gas/day (1.4–14.3 km³) (Palmer et al., 1993). At least two operators drilled

Figure 18. Average water production per well, by township, northern San Juan basin, first half of 1992, 5–10 yr after intense coalbed gas development began (modified from Cox et al., 1993). Simplified contours result from mapping average water production by township. Water production rates are greatest near outcrop recharge areas and in the highly productive fairway.



horizontal Fruitland coalbed wells (Logan, 1988; Palmer et al., 1993). Although technically successful, these horizontal wells apparently did not provide the increased production necessary to justify added costs (Palmer et al., 1993). The numerous types of completions used in coal beds, including sandless water stimulation and underreaming, are well documented, as are concerns with the fluid sensitivity of coal (Palmer et al., 1993; Conway and Schraufnagel, 1995; Robinson and Holditch, 1999; Lavalle, 1999).

Gas Compression and Treatment

Coalbed gas requires compression and some treatment. Coalbed gas wells are produced at low pressure to facilitate gas desorption. Therefore, depending on the pipeline pressures, one or more stages of gas compression are required. Coalbed gas treatment may range from dehydration to CO₂ stripping. The CO₂ is a corrosive that lowers the heating value and increases processing costs of coalbed gas. Over much of the northern San Juan basin, the CO₂ content of Fruitland coalbed gas exceeds 3%, and in the fairway, it is commonly 6–13% or greater (Figure 17). Modeling of multicomponent gas suggests that the percentage of CO₂ in Fruitland coalbed gas may increase as the formation is depressurized and production matures (Scott, 1993). Typically, CO₂ is stripped at central gas-processing facilities and vented to the atmosphere. However, pilot

programs by Burlington Resources and the Alberta Research Council are testing the viability of enhanced recovery by injecting CO₂ to displace methane and maintain reservoir pressure (S. H. Stevens et al., 1999; ARC, 2002).

FORT UNION FORMATION COALBED GAS SYSTEM

Fort Union Coalbed Gas Production History

The Fort Union Formation (Paleocene) in the Powder River basin contains vast energy resources in thick, extensive coal beds (Figures 1, 22). Presence of Fort Union gas has been known for decades. Ranchers in the Powder River basin encountered gas in shallow water wells nearly a century ago, especially in water wells located in regional discharge areas along streams (Olive, 1957; Choate et al., 1984). In the 1970s, shallow drilling to evaluate coal resources encountered overpressure and blowouts from coal beds and adjacent sand units (Hobbs, 1978). Additionally, several small gas fields were discovered in sandstones adjacent to the coal beds in the middle 1980s (Randall, 1989; Peck, 1999). Thus encouraged, and with incentive provided by the Section 29 tax credit, several small independents developed coalbed gas projects near the eastern margin of the basin in the late 1980s and early 1990s,

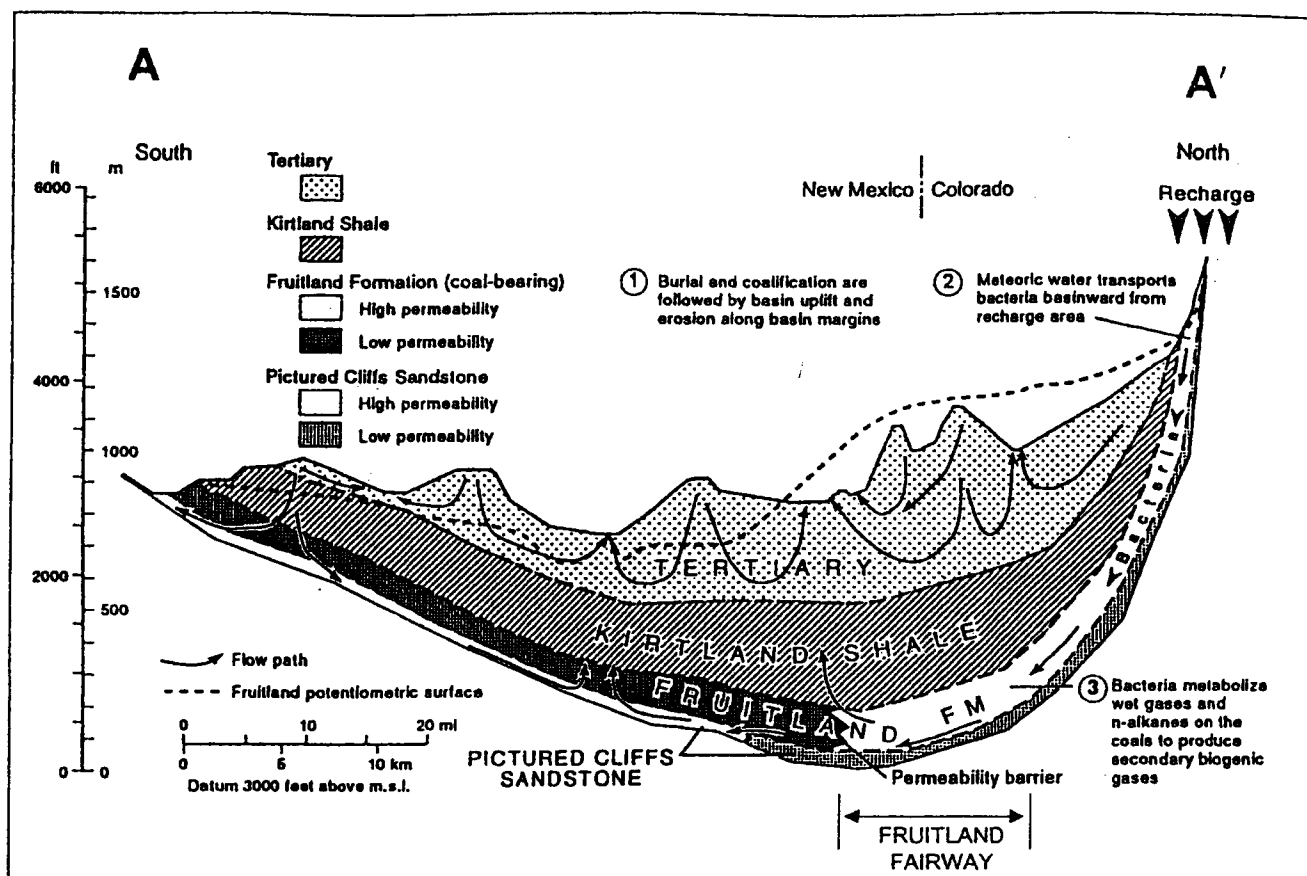


Figure 19. Hydrostratigraphic cross section, San Juan basin (see Figure 7 for location) (modified from Scott, 1993, after Kaiser et al., 1991a). Following thermogenic gas generation, the basin margin was upturned and eroded. From outcrops at the north rim, ground water recharged and repressured aquifer coal beds, causing artesian overpressure; introduced gas-generating microbes that resaturated coals with gas; and swept basinward to be trapped in the fairway, immediately north of the hinge line.

with mixed results. Moreover, wells that tested the deeper coal beds produced abundant water and little or no gas. Many companies decided that the coal had little potential for commercial gas production because it is shallow, thermally immature, contains low concentrations of methane (<70 scf/t; <2.2 cm³/g), is highly permeable and thick, and is a major aquifer that could be difficult to depressurize (Peck, 1999). Indeed, the early projects had difficulty dewatering the coal and developing optimal completions for the geologic setting. Successful early projects were those in depressurized areas adjacent to surface mines and those with free gas caps developed on small structural highs (Figure 23). However, by 1997, the effects of prolonged dewatering by mine and coalbed gas operators were realized in increased gas production rates and reserves, and the potential of the play was recognized.

Today, the Fort Union coalbed gas play is the most active natural gas play in the United States in terms of

the number of wells being drilled. The number of coalbed gas wells in the Powder River basin has increased from 54 to 8167 in the past decade, and 3655 wells were drilled in 2001 (WOGCC, 2002). There are many active operators and projects in the current play, which covers more than 2 million ac (807,716 ha). Development initiated around the eastern and northern margins of the basin (Figure 24) is expanding into the basin as coal beds are dewatered. The keys to success of this play appear to have been persistence in dewatering coal beds, developing the right completion methods, and confidence to invest in facilities and pipelines to provide market access (Peck, 1999).

Structural and Depositional Settings

The Powder River basin is an asymmetric Laramide foreland basin (Figure 25). Strata on the east flank of the basin dip 1–2° westward, whereas strata in the west

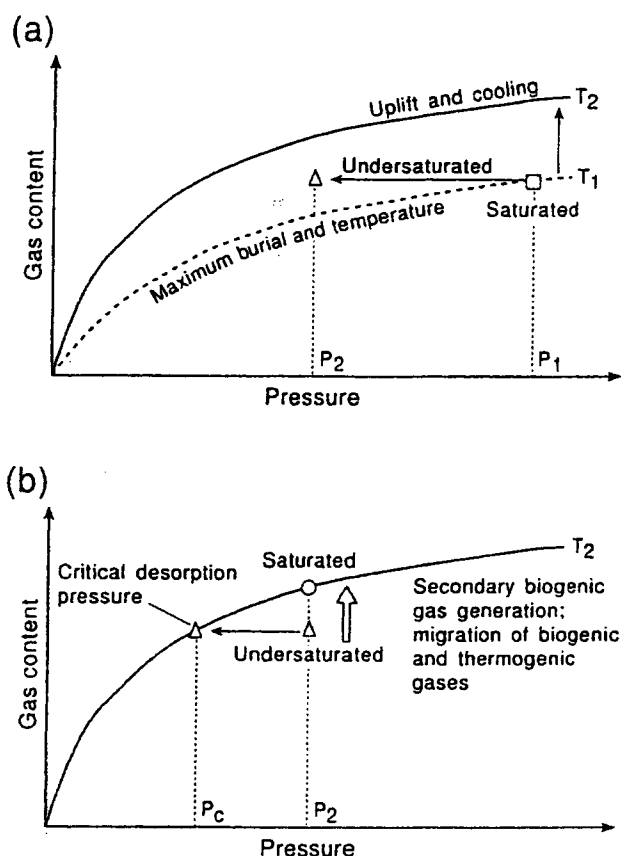


Figure 20. Fruitland coalbed gas sorption isotherms (from Scott et al., 1994b, reprinted by permission of the AAPG whose permission is required for further use). (a) Gas migrates from coal when gas generation exceeds storage capacity (saturation). Coal can store less gas at high temperature (dashed line, T_1) than at low temperature (T_2). Therefore, uplift and erosional unroofing may cause coals to be undersaturated. (b) If the coal is undersaturated, significant depressurization (dewatering) may be required to attain the critical desorption pressure and initiate gas production. However, secondary biogenic and migrated thermogenic gas may resaturate the coal, thus increasing the gas content and requiring less depressurization.

flank dip 5–25° eastward. The basin covers more than 25,800 mi² (66,822 km²) (GTI, 2001). The coal-bearing Fort Union Formation crops out around the margins of the basin and is overlain by the coal-bearing Wasatch Formation (Eocene) in the center of the basin.

Two depositional models have been proposed for the thick, extensive Fort Union coals. The lacustrine-deltaic model (Ayers and Kaiser, 1984; Ayers, 1986a) proposes that a lake (Lebo Shale Member in Figure 22) occupied the center of the Powder River basin during the Paleocene Epoch. The basin was filled from the margins by fluvial-deltaic systems of the Tongue River Member, which intertongue with the Lebo Shale

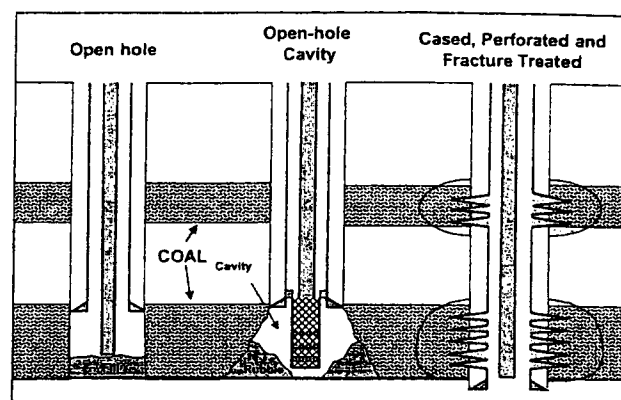


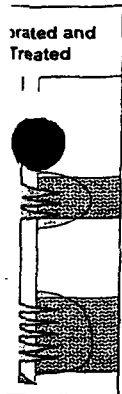
Figure 21. Coalbed well completion types commonly used in the San Juan basin (modified from Logan, 1993). The open-hole cavity completion contributes to high production rates in fairway wells, whereas fracture stimulation appears to give better results in most other parts of the San Juan basin.

Member. Thick, extensive peat (coal) deposits developed on broad interdeltic plains that were isolated from clastic influx. These thick coal beds extend as much as 30 mi (48 km) along paleostrike (north-south) and split and pinch out into deltaic depocenters. In the paleodip (west) direction, they extend as far as 15 mi (24 km) before splitting and pinching out where the fluvial-deltaic facies intertongue with Lebo lacustrine mudstone.

According to the fluvial model (Flores and Hanley, 1984; Flores, 1986), thick Tongue River coals were deposited in a backswamp setting marginal to northeast-flowing, meandering fluvial systems. Splits in the coal were attributed to channel-levee facies.

Coal and Coalbed Gas Origin, Resources, and Composition

Tongue River coal occurs in 2 to more than 24 laterally extensive (tens of kilometers) beds that range up to greater than 100 ft (30 m) thick; in places, total coal thickness is as great as 300 ft (91 m) (Figure 26). Individual thick (>60 ft [18 m]) coal beds occur in two north-trending areas, one along the eastern margin of the basin and the other in the center of the basin (Figure 27). Within these two coal belts, individual coal beds commonly extend more than 30 mi (48 km) (Ayers and Kaiser, 1984; Ayers, 1986b). Distinct coal zones are present from outcrop to depths greater than 2000 ft (610 m). Coal resources in the Fort Union Formation are 1.1 trillion tons (1 trillion t) at depths less than 3000 ft (915 m) (Table 1) (Ayers, 1986b). In 2001, Wyoming led the United States in coal produc-



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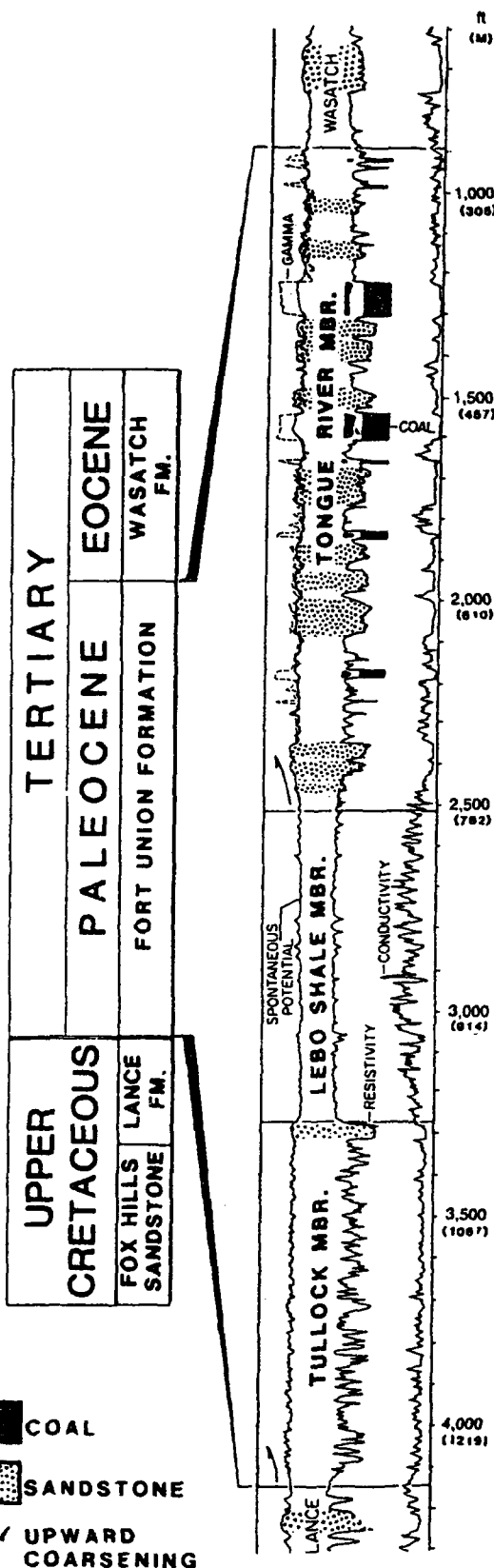


Figure 22. Fort Union Formation stratigraphy and coal occurrence, Powder River basin (modified from Ayers and Kaiser, 1984).

tion when it produced 352 million tons (319 million t), primarily from the Powder River basin.

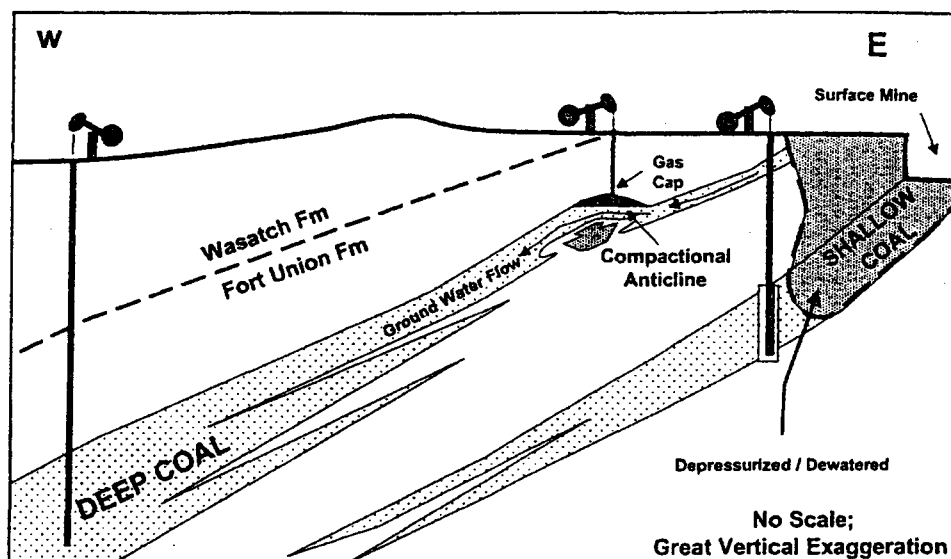
Fort Union coal is thermally immature (vitrinite reflectance < 0.4%). Coal rank ranges from subbituminous C to B. Fort Union coal has low ash (generally <5%; range 4–10%) and sulfur (0.4–0.6%) content (Glass, 1981). Moisture content ranges between 22 and 30%. Coal macerals are dominantly vitrinite (69–78%) with subordinate amounts of inertinite (19–26%; limited number of samples) (Pratt et al., 1999). Formation pressure is low, owing to shallow depths; therefore, sorbed gas content is low (Figure 2). Coalbed gas content is reported to be between 22 and 74 scf/t (0.7–2.3 cm³/g); the sorbed gas is approximately 90% methane, 8% carbon dioxide, and 1.4–2.3% nitrogen (Boreck and Weaver, 1984; Choate et al., 1984; Pratt et al., 1999). Gas composition and isotherm data suggest that produced gas should be approximately 99% methane and 1% carbon dioxide (Pratt et al., 1999). The methane is isotopically light ($\delta^{13}\text{C} = -57$) (Boreck and Weaver, 1984), which suggests a biogenic origin consistent with the low thermal maturity and aquifer characteristics of the coal. Estimates of coalbed gas in place in the Powder River basin range between 15 and 39 tcf (0.4–1.1 Tm³) (Choate et al., 1984; Tyler et al., 1992; GTI, 2001). Recoverable coalbed gas resources are approximately 25 tcf (0.7 Tm³) in the Powder River basin (PGC, 2000; De Bruin et al., 2001). Although some sources indicate that Fort Union coalbed gas reserves are between 6 and 9 tcf (0.2–0.3 Tm³) (Montgomery, 1999; Shirley, 2000), the methods for determining these reserves are unclear.

Coalbed Permeability, Hydrologic Setting, and Gas Producibility

Limited studies indicate that cleat orientations are variable in Fort Union coals, but, along the eastern margin of basin, cleats generally trend east-northeastward, nearly perpendicular to the basin axis (Figure 25) (Glass, 1975; Law et al., 1991; Tyler et al., 1992, 1995; Tyler, 1995). Although they are thermally immature, Fort Union coals are fairly well cleated, most likely because of their low ash and relatively high vitrinite content. There have been few studies of Fort Union coal cleat characteristics. At Eagle Butte mine along the eastern margin of the basin, face-cleat spacing averages 3.3 in. (8.4 cm) in the lower bench and 4.9 in. (12.5 cm) in the upper bench (Law et al., 1991).

Fort Union coal beds and the interbedded sand units are aquifers. The coals are thick, extensive

Figure 23. Coalbed gas exploration strategies in the Powder River basin. Early wells were located in depressurized strata adjacent to surface mines or on small anticlines where gas caps occurred in thick coal beds. As the industry expands and Fort Union coals are depressurized, development is advancing basinward.



aquifers that have permeabilities ranging between 10 md and several darcys (USBLM, 1990; Pratt et al., 1999). Owing to their high permeability and thickness, the coal beds are the major Fort Union aquifer elements. Along the eastern margin of the basin, face cleats trend into the basin, which facilitates ground-water recharge of the coals. The TDS content of Fort Union coalbed water samples from 47 wells in the eastern and central part of the basin ranged between 370 and 1940 mg/L, with a mean of 840 mg/L; water appears to be fresher near the eastern margin of the basin where primary recharge occurs (C. S. Rice et al., 2000). Fort Union groundwater quality is adequate for ranch use and for surface discharge by coalbed gas operating companies. The dynamic aquifer system accounts for the presence of biogenic gas, as well as the fresh character of the water.

Groundwater recharge occurs primarily along the eastern outcrop. From the eastern outcrop, ground water flows basinward (westward) (Figure 28). Flow is directed northward, and artesian conditions develop where the aquifer coal beds are confined by pinch-out in the Lebo shale (Lowery and Cummings, 1960; Whitcomb et al., 1966; Martin et al., 1988; Tyler et al., 1992). Sites of anomalously high sorbed gas content may occur where migrating gas is trapped adjacent to pinch-outs or in structural traps (Figures 23, 29). In some cases, Fort Union coalbed gas wells have produced more than 100% of the estimated gas in place (Pratt et al., 1999). These cases may be explained by real-time addition of migrated gas or by active generation of gas in the vast water legs of anticlinal folds.

Other explanations are offered by Pratt et al. (1999). Potential for ongoing biogenic gas generation (biogenerators) exists where basinward-moving ground water sweeps below compactional folds (Figures 23, 29). However, it is unknown whether the rates of biogenic gas formation are sufficient to provide real-time reservoir charge.

Drilling and Completion

Early Fort Union coalbed gas projects were concentrated near Gillette along the eastern margin of the Powder River basin, where the coal beds were depressurized/dewatered in association with surface mines. Other projects were sited to test thick coals that had gas caps in small anticlines that were primarily compactional structures (Figure 23). Over time, projects spread basinward as coalbed wells accomplished further depressurization. With success in this region, new projects developed along the north and northwest margins of the basin. Typical drilling depths of the early wells were 300–700 ft (91–213 m). Today, companies are expanding operations basinward, and a few companies are testing subbituminous coal beds as deep as 2000 ft (610 m).

Early Powder River basin coalbed gas wells were drilled on 40 ac (16 ha) spacing. Later, 80 ac (32 ha) spacing became the standard, and now, many operators consider 160 ac (65 ha) spacing to be optimal (Coal Seam Gas International, 1999; Pratt et al., 1999; B. Kelso, 2002, personal communication). Average drilling, completion, and facility costs for the wells range



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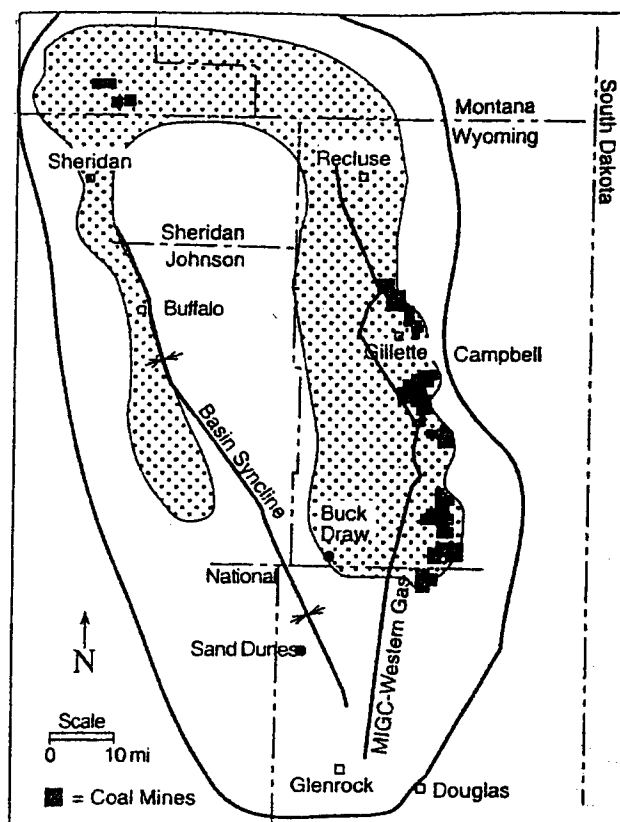


Figure 24. Fort Union coalbed gas development, Powder River basin (from Montgomery, 1999, reprinted by permission of the AAPG whose permission is required for further use). Robust development began along the eastern margin of the basin and has spread to the north and northwest margins. Thick coal beds in the center of the basin are being tested, but thus far they have been difficult to dewater.

between \$65,000 and \$95,000. For the deeper wells that target the thick (up to 180 ft [55 m] thick) Big George coal at depths of 1500 ft (457 m) and deeper, wells typically cost \$130,000 (Williams, 2001).

Over the years, operators have developed a completion method that appears to work well in the thick, high-permeability Fort Union coal beds. Wells generally penetrate 40–100 ft (12–30 m) of net coal in a well, in several seams (Shirley, 2000). Although some operators perform cased-hole completions in multiple coal beds, most complete wells open hole in a single, thick seam. In open-hole completions, operators drill 2–3 ft (0.6–0.9 m) into the top of the coal and set and cement 5 1/2 or 7 in. (13.97 or 17.78 cm) casing. Next, coal is drilled and underreamed, after which it is fracture stimulated with 160 bbl (25 m³) of water, with no proppant or additives, at rates between 12 and 50 bbl/min. (1.9–7.9 m³/min.) (Coal Seam Gas International, 1999; Peck, 1999; Pratt et al., 1999).

A submersible pump is used to depressurize the coal beds. Reportedly, some operators use a variable speed pump and keep some water on coal to minimize effective stress and keep cleats open. This practice differs from that used in many other basins, where the pump is set in a rat hole below the coal to minimize formation pressure.

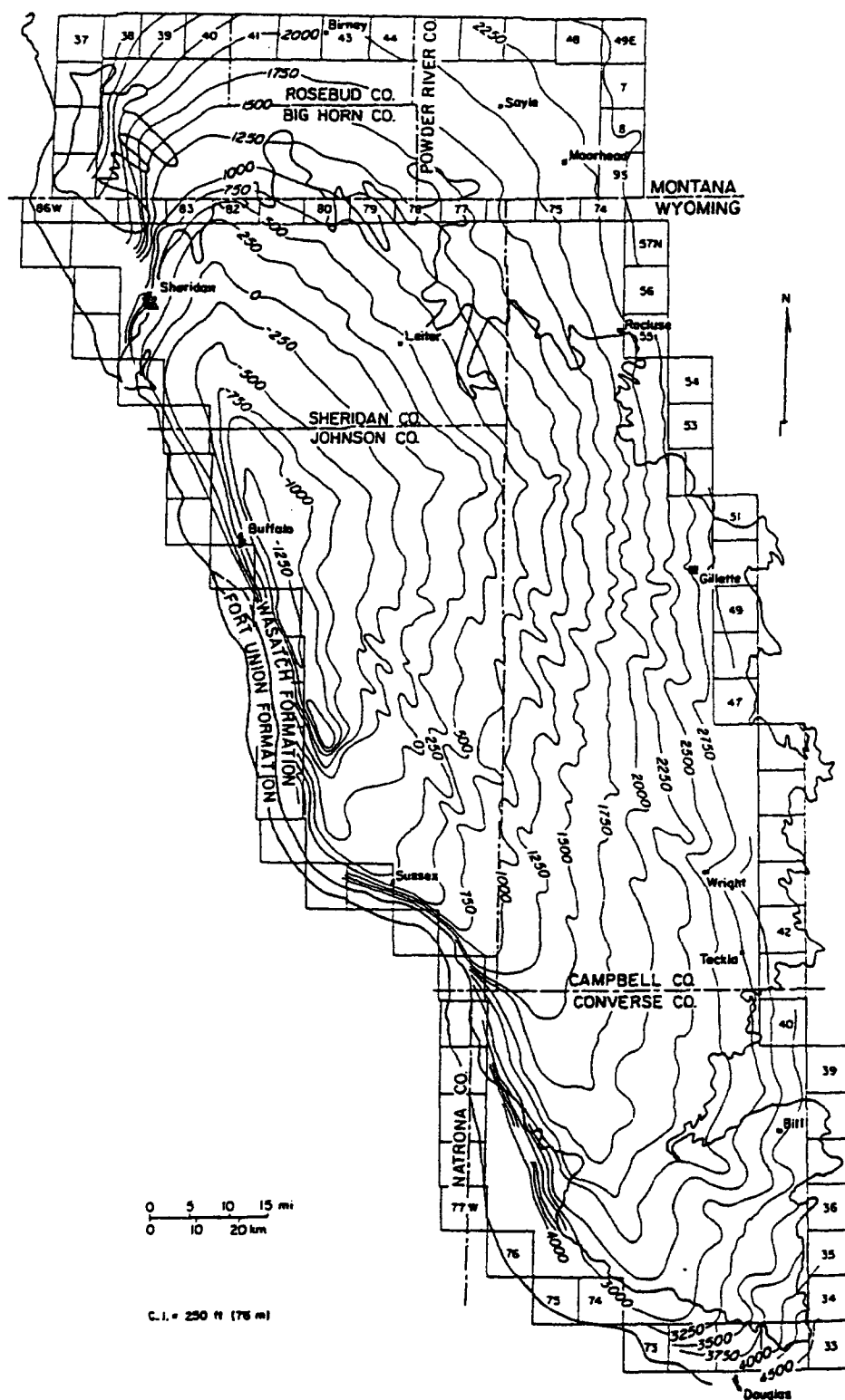
The Fort Union water quality is good, which allows Powder River basin operators a greater variety of water disposal methods that are less expensive than options available to operators in many other basins. Among the methods used or tested are outflow into surface drainage and streams; containment in surface ponds where it infiltrates, evaporates, or is used for ranch and stock watering needs; and atomization. Typical operating costs are \$0.15/mcf (Coal Seam Gas International, 1999; Peck, 1999; Pratt et al., 1999; Shirley, 2000).

Production Characteristics and Reserves

Annual coalbed gas production in the Powder River basin has increased from 0.9 bcf (25 Mm³) in 1991, with 54 producing wells, to 245 bcf (6.9 Gm³) in 2001, when there were 8167 wells in the basin (Figure 30) (WOGCC, 2002). The basin now ranks second in the nation in annual coalbed gas production. Cumulative production was 511 bcf (14.5 Gm³) over this period; 77% of this gas was produced in 2000 and 2001. After several months of depressurization, Fort Union coalbed gas wells typically reach peak production rates between 130 and 350 mcf gas/day (3.7–9.9 km³/day), depending on the location in the basin (Montgomery, 1999; Williams, 2001). Some exceptional wells have peak production greater than 1 mmcf gas/day (28 km³/day) (Coal Seam Gas International, 1999). Average gas recovery is estimated to be 300–400 mmcf (8–11 km³) per well on 80 ac (32 ha) spacing, payout is typically 1.5 yr (Coal Seam Gas International, 1999; Montgomery, 1999), and average economic life is approximately 7 yr (Shirley, 2000), which is relatively low for coalbed gas wells.

Annual water production has increased from 3,441,000 bbl (547 km³) in 1991 to 515,814,000 (82 Mm³) in 2001 (Figure 30). Cumulative water production over this period was 1,229,672,000 bbl (196 Mm³) (WOGCC, 2002). Initial water production from individual wells varies with project location; typical wells initially produce 200–500 bbl/day (32–79 m³/day). Deep wells completed in the thick Big George seam are more difficult to dewater and may initially produce greater than 1000 bbl/day

Figure 25. Structure map, top of the Tullock Member, Fort Union Formation, Powder River basin (from Ayers, 1986a, reprinted by permission of the AAPG whose permission is required for further use).



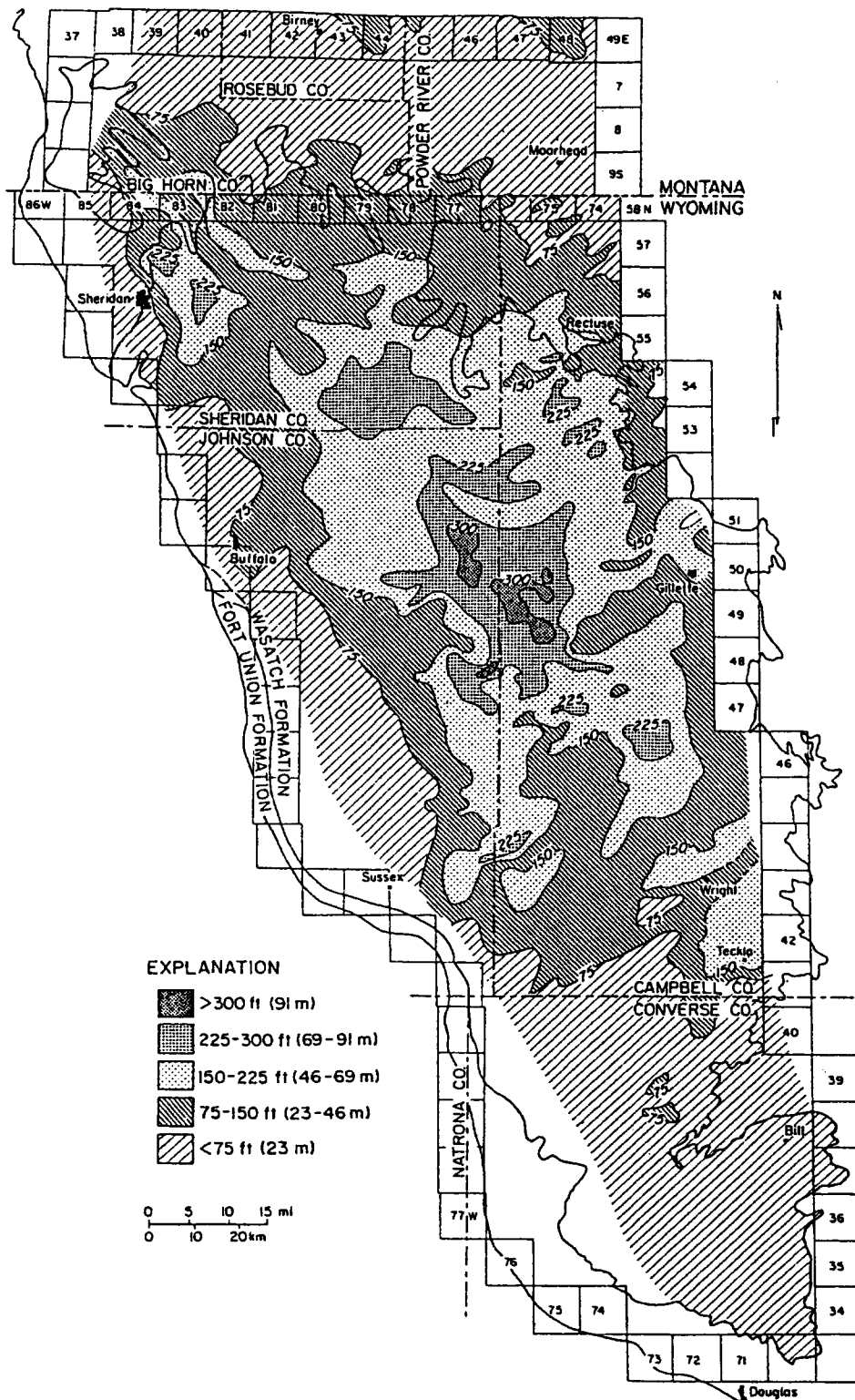
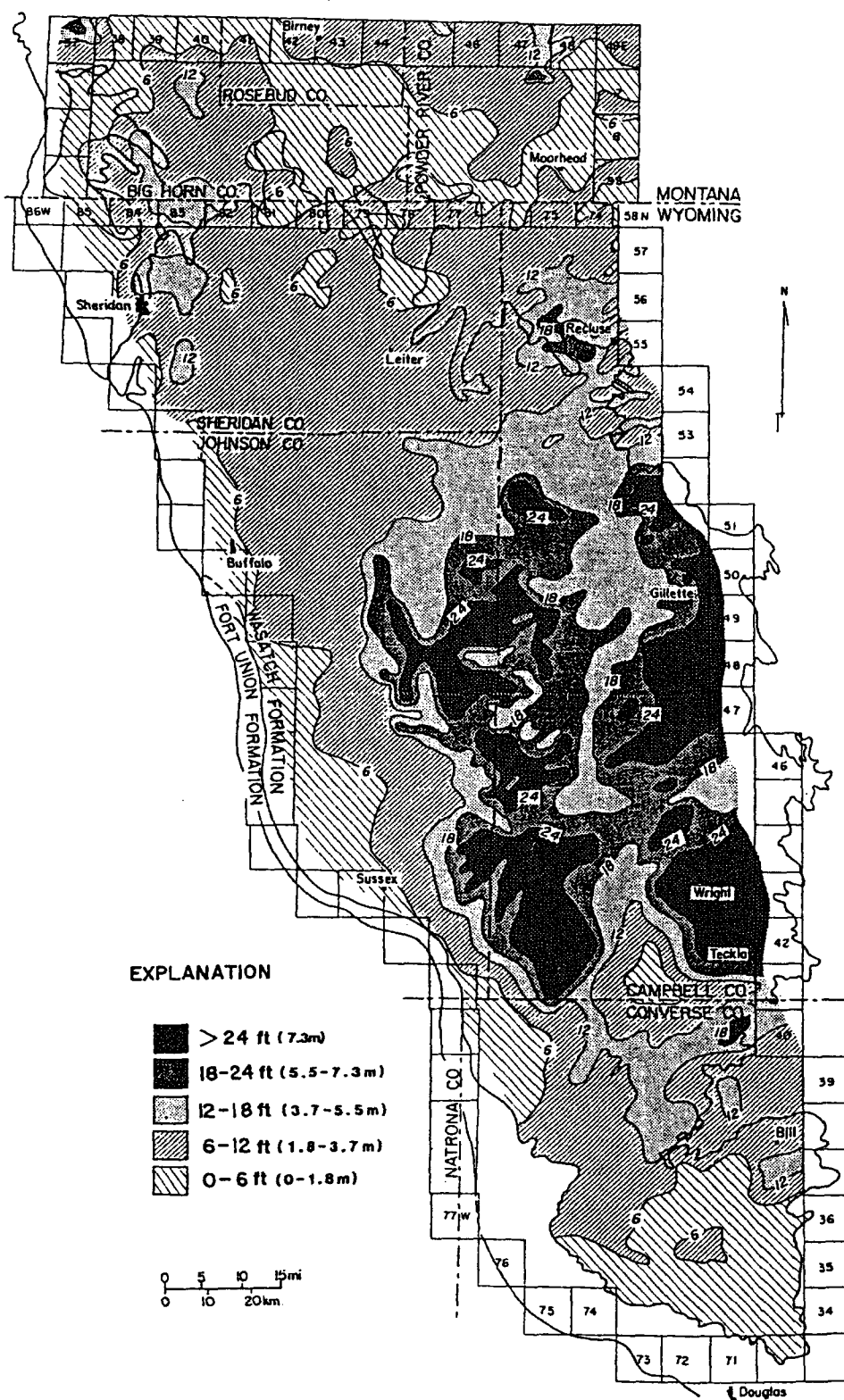


Figure 26. Net thickness of Fort Union coal, Powder River basin (from Ayers, 1986b). Net coal thickness exceeds 225 ft (69 m) in the center of the basin.

Figure 27. Maximum coal map, Fort Union Formation, Powder River basin (from Ayers, 1986b). Map shows the thickest individual coal in each borehole, regardless of stratigraphic position. The north-trending area of thick (thicker than 100 ft [30 m]) coal in the central part of the basin is approximately 2000 ft (610 m) deep. The band of thick (thicker than 60 ft [18 m]) coal at the eastern margin of the basin is surface mined at outcrop.



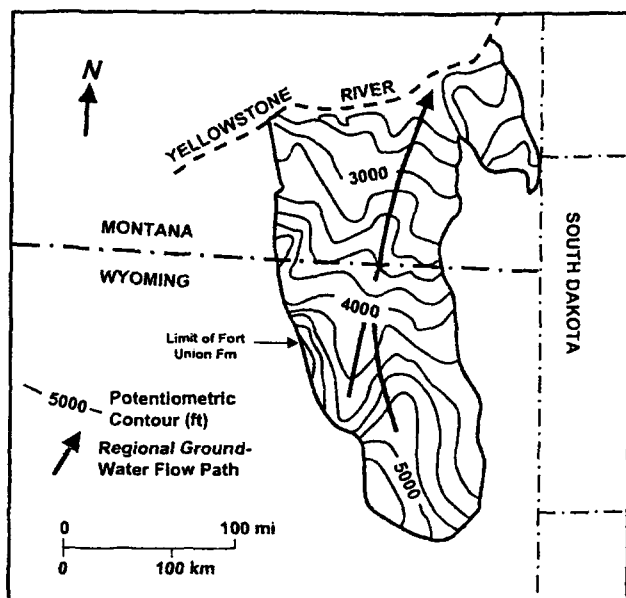


Figure 28. Potentiometric surface map for Tertiary strata, Powder River basin (modified from Lobmeyer, 1985).

(160 m³/day). However, if successfully dewatered, this coal should provide greater reserves than basin-margin wells, owing to greater reservoir thickness and higher pressure (greater adsorbed gas content).

The Fort Union coalbed gas play is flourishing in the post-tax-credit era. Reasons for this success include (1) new pipelines in 1999 that more than doubled the takeaway capacity; (2) permeability is high and coal beds are thick and continuous (high kH product); (3) wells are shallow (low drilling costs); (4) completions and stimulations are simple and inexpensive; (5) produced water is fresh, and water handling and disposal are inexpensive; (6) resources are great; and (7) gas prices have improved in recent years.

COALBED FORMATION EVALUATION ISSUES

The most important and difficult coalbed gas parameters to assess are gas content and permeability during the early project stages. Coalbed gas resources are difficult to assess, because conventional well logs are unable to measure methane content in coals, despite attempts by some service companies. Instead, gas content of coal must be measured by desorbing samples in the laboratory. Core samples provide the most accurate results, but gas content can be measured from drill cutting, with a large error margin (Nelson, 1998). Similarly, coalbed permeability cannot be determined

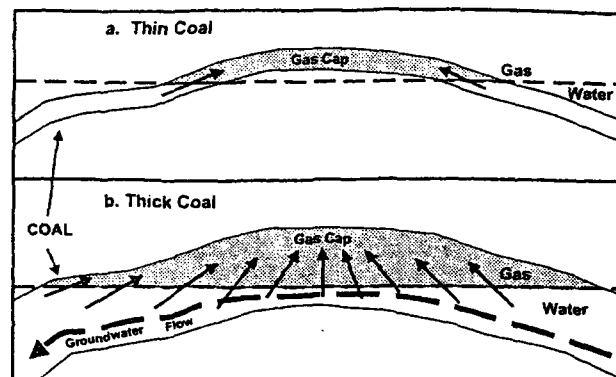


Figure 29. Schematic of hypothetical biogenic coalbed gas generators associated with anticlines having a gas cap. Thick coal (b) provides much greater substrate for microbes to generate biogenic gas, and it has a broader surface than thin coal (a) for migration into the gas cap. Rates of biogenic gas generation are unknown. Can these rates be effective in real time, resulting in a biogenic gas engine that continually recharges the gas cap?

by logging methods; instead, it requires field tests or production analysis.

COALBED COMPLETION, STIMULATION, AND OPERATIONAL ISSUES

The design and costs of coalbed wells vary considerably and are affected by the completion method. The selection of completion type depends on geologic and hydrologic factors, including the thickness, number, and vertical distribution of coal beds; hydrologic setting; and coal characteristics, such as cleat development. The vertical distribution of coal reservoirs (e.g., 1 thick or several thin beds) determines the number of fracture treatments and, thus, can greatly impact well costs. Many types of coalbed gas well completions have been developed for different geologic settings and project types (e.g., Figure 21) (Logan, 1993; Palmer et al., 1993). Early vertical coalbed gas completions were commonly open hole in coal beds and adjacent strata. The open-hole completions developed for the Fort Union coalbed gas play are among the least expensive completions. Since the 1980s, most coalbed completions have been single- or multiseam cased-hole completions that were fracture-stimulated with various fluids and proppants. In the late 1980s, the open-hole cavity completion method was developed in the Fruitland fairway. Because it resulted in wells that produced at rates substantially greater than wells completed by

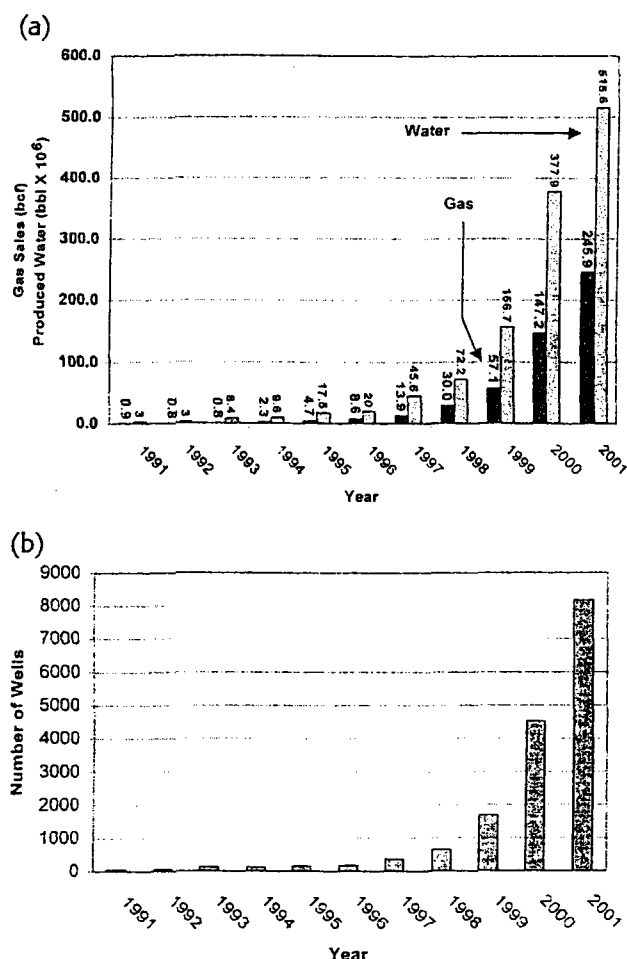


Figure 30. Annual production statistics for Fort Union coalbed gas wells, Powder River basin, showing (a) coalbed gas and water production volumes and (b) the number of coalbed gas wells (data from WOGCC, 2002).

other methods, the open-hole cavity completion was successfully used through the Fruitland fairway. However, when the open-hole cavity completion was used in other parts of the San Juan basin and in other United States and international basins, the technique was either unsuccessful or showed no production advantage. The Fruitland Fairway conditions favorable for the open-hole cavity completion apparently are well fractured, gas-saturated coals located in an area of artesian overpressure. Horizontal coalbed gas wells drilled in the San Juan basin in the 1980s and 1990s showed no economic advantages (Palmer et al., 1993). Therefore, the technique was not vigorously pursued until the late 1990s, when it was successfully applied to thin, Carboniferous coal beds in eastern Oklahoma.

Coalmine methane is methane released during mining. Some of the earliest coalbed gas research was conducted to address methane hazards in underground

mining and in-mine degasification by horizontal, in-seam, GOB (gas overburden), and cross-measure wells that have been practiced for decades in gassy mines. In many cases, this gas was vented to the atmosphere, but today, recognizing the impact of methane as a greenhouse gas and in view of the economic value of the methane, many mining operations have mechanisms to capture methane in advance of, during, and after mining. These activities have been encouraged through programs sponsored by the U.S. Environmental Protection Agency. More recently, projects have targeted commercial methane production from abandoned underground mines.

Coalbed gas projects may face operational burdens not encountered in conventional gas operations. These include handling and disposal of significant volumes of water, treatment of gas where CO₂ content is high, and gas compression. Coalbed gas wells are commonly operated with low bottom-hole pressures to facilitate gas desorption and migration to the wellbore. Therefore, one or more stages of compression are commonly required, depending on the pressure in the sales pipeline. These operational burdens may vary markedly among and within basins. In the gas-rich, northern San Juan basin, for example, coalbed gas wells incur CO₂ stripping costs that are not a major issue in the southern San Juan basin or in most coalbed gas projects. Although coalbed gas reserves of individual Fort Union coalbed gas wells are a fraction of those of San Juan basin wells, Fort Union well completions are shallower and less expensive, and water surface disposal costs are much less than the cost of water injection practiced in the San Juan basin.

RESOURCES, RESERVES, AND PRODUCTION

Worldwide, coalbed gas resources (gas in place) are estimated to be 2980–9260 tcf (85–265 Tm³) (Table 2) (Kuuskraa et al., 1992). Discovery of the Fruitland coalbed gas fairway sparked international exploration in the 1980s and early 1990s. Although no fields comparable to the Fruitland fairway have resulted from this exploration, many economic, if modest, coalbed projects developed in the United States during this period, and the international search continues. In Australia, there are commercial coalbed gas projects in the Bowen basin of Queensland and pilot projects in several other basins. Exploration, test wells, or pilot projects are ongoing in several other countries, including

the United Kingdom, Canada, China, Colombia, and India. Canada announced coalbed gas sales in 2002.

The United States has 749 tcf (21.2 Tm³) of coalbed gas resources in the lower 48 states and leads the world in coalbed gas activity with commercial production in more than a dozen basins (Figure 1) (GTI, 2001). Recoverable coalbed gas resources in the United States are estimated to be 96 tcf (2.7 Tm³) (PGC, 2000; GTI, 2001). Among the major producing areas are the San Juan, Powder River, Black Warrior, Raton, central Appalachian, and Uinta basins. Other areas in the United States with significant exploration or production projects are the Arkoma, Cahaba, Cherokee, Greater Green River, Illinois, Maverick, northern Appalachian, and Piceance basins.

United States Coalbed Gas Reserves

In 2000, United States coalbed gas reserves were approximately 15.7 tcf (0.44 Tm³), or 8.8% of the United States dry natural gas reserves of 177.4 tcf (5 Tm³) (Table 3; Figure 31). This is an 18.9% increase over 1999 coalbed gas reserves (13.2 tcf [0.37 Tm³]) and more than a fourfold increase over 1989 coalbed gas reserves (3.7 tcf [0.1 Tm³]). The greatest gains in coalbed gas reserves in 2000 were in Colorado and other areas (Table 3), which reflects coalbed gas development in the Raton, Powder River, Uinta, Appalachian, and mid-continent areas. Approximately 63% of the 2000 coalbed gas reserves are in the San Juan, Raton, and Piceance basins of Colorado and New Mexico, and 20% of the reserves are in Utah and Wyoming (EIA, 2001). The Appalachian basin has 9% of the United States Reserves, and the Warrior basin has 8%.

United States Coalbed Gas Production

In 2000, United States coalbed gas production was 1.38 tcf (40 Gm³) (Table 4; Figures 31, 32), or 7.2% of the dry natural gas production of 19.2 tcf (0.54 Tm³) in the lower 48 states. This represents a 10.4% increase over 1999 production of approximately 1.25 tcf (35.4 Gm³) and a 15-fold increase over 1989 production of 91 bcf (2.8 Gm³). In 2000, the San Juan, Raton, and Piceance basins of Colorado and New Mexico accounted for 73% of the domestic coalbed gas production. In 2000, Fort Union coalbed gas production was 147 bcf (4.2 Gm³), and, for the first time, the Powder River basin surpassed coalbed gas production from the Black Warrior basin, which produced 109 bcf (3.1 Gm³) that year (Table 4). At the present rate of

Table 2. Major Coalbed Gas Resources of the World*

Country	Gas Resources (tcf)
Russia	600–4000
China	1060–1240
United States**	400
Canada	200–2700
Australia	300–500
Germany	100
United Kingdom	60
Kazakhstan	40
Poland	100
India	30
Southern Africa (South Africa, Zimbabwe, and Botswana)	30
Ukraine	60
Total	2980–9260

*Modified from Kuuskraa et al. (1992).

**Resources stated for the United States do not match current estimates.

annual production (1.38 tcf [0.04 Tm³]), and considering the gas reserves (15.7 tcf [0.44 Tm³] in 2000), the United States has an 11 yr supply of coalbed gas.

DISCUSSION: DOMESTIC AND INTERNATIONAL OUTLOOK

The Energy Information Agency predicts 2% average annual increases in United States natural gas demand to 2020, primarily for electricity generation (EIA, 2001). As conventional gas resources decline, coal beds and other unconventional gas reservoirs (i.e., tight sands and fractured shales) will be increasingly important to the natural gas supply. Early coalbed gas development in the United States was motivated by an unconventional fuels tax credit, which has now expired. However, the United States coalbed gas industry is robust in the post-tax-credit qualification era, owing to several factors. First, operators demonstrated the economic production in existing plays, as well as new regions, even before recent gas price increases. Second, recent gas prices more than offset the absence of the tax credit. Third, coalbed gas development in the Powder River basin showed that economic production can be achieved from low-rank coal beds, and it has stimulated exploration in low-rank coals in other areas.

The United States coalbed gas industry is maturing, as is indicated by a production milestone that

Table 3. United States Coalbed Gas Proved Reserves, 1989–2000*

Year	Alabama	Colorado	New Mexico	Others**	Total
1989	537	1117	2022	0	3676
1990	1224	1320	2510	33	5087
1991	1714	2076	4206	167	8163
1992	1968	2716	4724	626	10034
1993	1237	3107	4775	1065	10184
1994	976	2913	4137	1686	9712
1995	972	3461	4299	1767	10499
1996	823	3711	4180	1852	10566
1997	1077	3890	4351	2144	11462
1998	1029	4211	4232	2707	12179
1999	1060	4826	4080	3263	13229
2000	1241	5617	4278	4572	15708

*Data from EIA (2001); values in bcf.

**Includes Pennsylvania, West Virginia, Virginia, Utah, Wyoming, Kansas, Oklahoma, and Montana.

occurred when annual production from the San Juan basin peaked at slightly more than 1 tcf (28 Gm³) in 1999 (Figure 32). However, approval to downsize from 320 to 160 ac (130 to 65 ha) well spacing in Colorado allows approximately 600 additional wells in the northern San Juan basin, which, if drilled, may account for a future production surge in the basin. Clearly, coalbed gas is poised to be an important factor in meeting future gas demand in the United States and worldwide. Worldwide coalbed gas resources are enormous (Table 2). United States coalbed gas in place is estimated to be 749 tcf (21.2 Tm³), and recoverable coalbed gas resources in these basins are estimated to be 96 tcf (2.7 Tm³) (PGC, 2000; GTI, 2001). However, booked coalbed gas reserves are only 15.7 tcf (0.44 Tm³) (EIA, 2001).

The challenge is to convert the vast resources to reserves by increased understanding of diverse coalbed gas systems, better reservoir characterization, and improved technology. Enhanced coalbed gas recovery by nitrogen or CO₂ injection is being tested (S. H. Stevens et al., 1999), and ongoing research is evaluating the potential for sequestering industrial CO₂ in coal beds while enhancing methane recovery (Gentzis, 2000; Pashin et al., 2002).

CONCLUSIONS

1. The diverse origins, character, and reservoir properties of coalbed gas systems are demonstrated by the Fruitland and Fort Union systems. This diversity

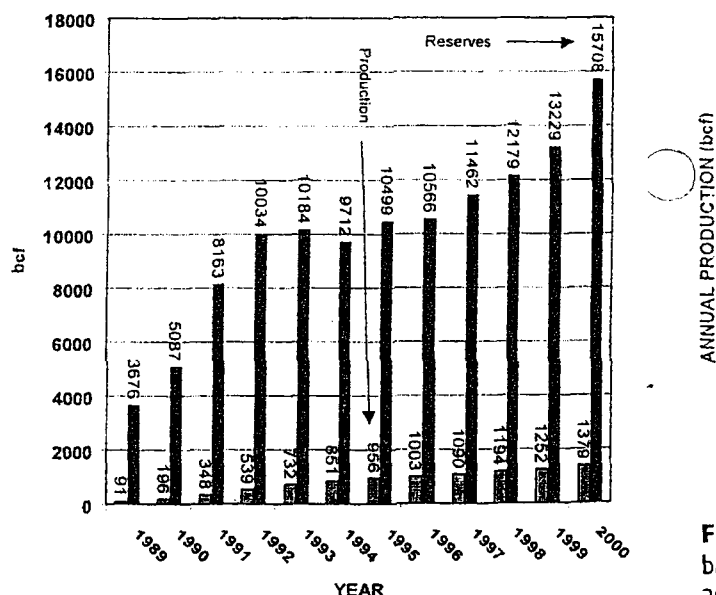


Figure 31. United States coalbed methane production and reserves, 1989–2000 (data from EIA, 2001).

is reflected in production behavior, gas reserves, and gas composition, as well as in completions and operations. The Fruitland coalbed gas system is dominated by self-sourced and migrated thermogenic gas with a significant biogenic gas and hydrodynamic overprint. Conversely, the Fort Union coalbed gas system is dominated by biogenic gas and hydrodynamics.

2. Coal beds are aquifers, source rocks, and reservoirs whose vertical and aerial distributions, thicknesses, and trends are determined by depositional systems.

Table 4. United States Coalbed Gas Production, 1989–2000*

Year	Alabama	Colorado	New Mexico	Others**	Total
1989	23	12	56	0	91
1990	36	26	133	1	196
1991	68	48	229	3	348
1992	89	82	358	10	539
1993	103	125	486	18	732
1994	108	179	530	34	851
1995	109	226	574	47	956
1996	98	274	575	56	1003
1997	111	312	597	70	1090
1998	123	401	571	99	1194
1999	108	432	582	130	1252
2000	109	451	550	269	1379
Total	1085	2568	5241	737	9631

*Data from EIA (2001); values in bcf.

**Includes Pennsylvania, West Virginia, Virginia, Utah, Wyoming, Kansas, Oklahoma, and Montana.

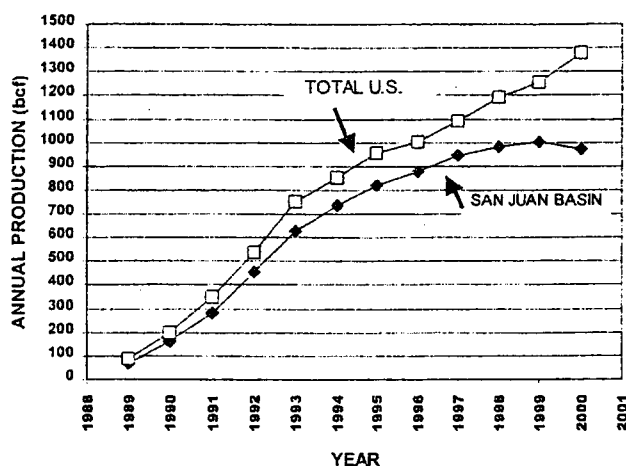


Figure 32. Annual coalbed gas production from the San Juan basin and total United States coalbed gas production, 1988–2000 (data from EIA, 2001 and PTTC 2001). Annual production from the San Juan basin appears to have peaked in 1999, whereas United States total coalbed gas production is increasing.

- Integration of geologic and hydrologic assessments with production analysis identifies key elements of coalbed gas systems, as well as controls on coalbed gas occurrence, producibility, and composition.
- Structural history determines thermal maturation patterns and cleat characteristics and greatly affects hydrology.
- Hydrologic setting controls the fluid pressure regime, water production rates, and the gas and water composition; aquifers may provide microbes that generate biogenic methane and carbon dioxide.

- The Fruitland coalbed gas play has produced more than 7 tcf (0.2 Tm³) gas in the past 20 yr. The Fruitland coalbed gas system is primarily a self-sourcing, thermogenic system with supplemental gas supplied to the fairway by migrated thermogenic and biogenic gas. High production rates in the fairway result from coincidence of artesian overpressure and hydrodynamic trapping of migrated thermogenic and biogenic gas that resaturated coal beds.
- The Fort Union coalbed gas play is the most active area of gas drilling in the United States. Groundwater movement through thick, high-permeability coal beds has supplied low concentrations of biogenic gas that are driving a new gas play in a low-pressure system.
- The Fort Union play has led to new concepts of commercial coalbed gas systems, and it opens the door for gas exploration in low-rank coal deposits worldwide.

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