Coalbed methane characteristics in the foreland of the Cordilleran Thrust Belt, Western United States

by

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ABSTRACT

Five basins in the foreland of the Cordilleran thrust belt contain approximately 63 percent of the total coalbed methane resource (11.09 Tm^3) in the United States. The San Juan, Piceance, Greater Green River, Powder River, and Raton Basins could make a significant contribution to the methane gas supply of the United States. Within these basins similar structural, depositional, hydrodynamic, and thermal maturity characteristics are controls on the occurrence and producibility of coalbed methane. In coal-bearing strata, areas of change in structural attitude and fracture orientation may be zones of enhanced permeability or sites of conventional methane trapping. Regionally, uniformly oriented systematic fractures in coal are oriented parallel to tectonic shortening directions and normal to thrust fronts. Areas of uniform fracture strike are separated by domains that contain varying fracture sets. The overlapping or smoothly varying fracture domains occur adjacent to recesses or salients in the Cordilleran thrust belt and may be zones of enhanced permeability and thus sites for enhanced methane production.

These basins contain thick (maximum coal thickness 46 m), laterally continuous Upper Cretaceous lower-coastal-plain coal beds and less continuous lower Tertiary fluvial coal beds, offering numerous methane targets. The San Juan, Piceance, and Greater Green River Basins contain coals of high rank (vitrinite reflectance [R_o] > 0.73 percent) and high gas content (4.7-14.0 m^3/t). The hydrology of the San Juan, Greater Green River, and Powder River Basins suggests overall good reservoir conditions; coal-seam permeabilities are high (~ 10 md or greater). Moreover, the San Juan and Greater Green River Basins have large areas of pressure transition and convergent, upward flow, which are regions hydrologically favorable for coalbed methane exploration. Low coalbed permeability (< 1 md) may limit the methane potential of the Piceance Basin. In contrast, the Powder River Basin has thermally immature coals of low rank (R_o < 0.50 percent) and low gas content (< 3 m^3/t), and the Raton Basin has high-rank coals (R_o> 0.73 percent) but in thin (< 3 m), discontinuous beds, resulting in limited coalbed methane potential. These structural, depositional, hydrologic, and thermal maturity characteristics are some of the controls on the producibility of coalbed methane in the foreland of the Cordilleran thrust belt that occur in similar coal basins throughout the world.

INTRODUCTION

Five intermontane basins of the western United States--San Juan, Piceance, Greater Green River, Powder River, and Raton (fig. 1 -- contain, by virtue of their tremendous coal tonnage (2,200x10^9 tonne), an estimated 7.04 Tm^3 methane, or 63 percent of the nations total coalbed methane resource of 11.09 Tm^3 (Tyler *et al.*,1992a). Because of their sizes and net-coal thicknesses, the San Juan (19,425 km^2), Piceance (18,722 km^2), Greater Green River (53,381 km^2), and Powder River (66,800 km^2) Basins have large coal resources: 265 x 10^9 tonne; 419 x 10^9 tonne; 333 x 10^9 tonne; and 1,137 x 10^9 tonne, respectively. Gas resources are therefore estimated to be large in the San Juan (2.49 Tm^3), Piceance (2.38 Tm^3), Greater Green River (0.82 Tm^3), and Powder River (0.85 Tm^3) Basins (Tyler *et al.*, 1991a). However, only in the San Juan Basin are these methane resources being extensively exploited to meet the demand for natural gas in the western United States. The Raton Basin is smaller

(5,564 km^2) and has limited coal (19 x 10^9 tonne) and coalbed methane resources (0.35 Tm^3).

Using the San Juan Basin as a test, Ayers *et al.*, (1991) investigated the controls on production of coalbed methane. In the San Juan Basin, the complex interplay between tectonic and structural evolution, depositional setting, hydrology, and thermal maturity emerged as the most important controls on the producibility of methane from fractured coalbed reservoirs. The insight and technological advances gained from the San Juan Basin study were applied to other similar basins in the foreland of the Cordilleran thrust belt. This paper characterizes the structural and depositional setting, hydrology, and thermal maturity of the Greater Green River, Piceance, Powder River, and Raton Basins and confirms the fundamental importance of geologic and hydrologic controls on the occurrence and producibility of coalbed methane in intermontane basins.

STRUCTURAL SETTING

The structure of the San Juan, Piceance, Greater Green River, Powder River, and Raton Basins is the result of roughly similar tectonic histories. These basins lie in the foreland of the Cordilleran thrust belt (fig. 1). During the Laramide Orogeny, in Late Cretaceous and early Tertiary time, the foreland was broken into several smaller basins by basement-involved thrusting and folding, which elevated highlands and resulted in sediment being shed into the newly formed basins. Tectonism was followed by erosion, a period of widespread magmatism and volcanism in the Oligocene, and finally an episode of renewed tectonic uplift about 10 Ma. By the end of the Pliocene, the basins present structural configurations, topographies, surface drainages, and hydrodynamics were largely established.

Within the foreland, coal is pervasively fractured (cleated) and commonly contains systematic fracture sets (face cleats) that are uniformly oriented or gradually variable over wide areas or domains. Systematic fractures are an important control on permeability in coal, and face cleats commonly impart permeability anisotropy to coal beds. Preliminary mapping of fracture attributes show that face cleats strike normal to traces of regional thrusts and folds. Fractures having variable cleat domains occur adjacent to recesses or salients in the Cordilleran thrust belt (Tyler *et al.*,1991a; Laubach *et al.*, 1992). In the San Juan Basin, regional changes in structural dip are also sites of structural discontinuities (hingelines) and thus are zones of coalbed methane production (Kaiser *et al.*, 1991a). Describing variations in structural configurations is, therefore, important in predicting the associated fracture permeability.

DEPOSITIONAL SETTING

Upper Cretaceous and/or lower Tertiary coal-bearing strata are the major coalbed methane targets in intermontane basins. Upper Cretaceous depositional systems were predominantly wave-dominated deltas and barrier/strandplains, which formed linear clastic shorelines. The thickest coal seams were preserved landward and parallel to these ancient shorelines. Commonly, thickest coal beds (individual seams 3 to 8 m thick) directly overlie marine shoreline sandstones. In contrast, lower Tertiary coals are hosted by fluvial-lacustrine sediments where interchannel floodplains and foundered lacustrine delta platforms were sites of peat accumulation. These lower Tertiary fluviolacustrine coals vary greatly in thickness; individual coal seams in the San Juan, Piceance, Greater Green River, and Raton Basins are locally 9 m thick and form dip-elongate belts between fluvial depositional axes, whereas thick Tertiary coal beds (locally exceeding 30 m in thickness) in the Powder River Basin occur in strike-elongate pods that directly overlie abandoned lacustrine-delta sandstone platforms.

HYDROLOGY

Basin hydrology reflects present-day structural configuration (attitude of aquifers and aquitards), topography, climate (precipitation and infiltration), and permeability. Recharge occurs over the wet, elevated basin margins, and ground water flows basinward, down regional topographic gradient and structural dip, converging on the basins topographically lowest point, where discharge occurs. Reservoir conditions are inferred from the hydrology. Because hydraulic gradient, pressure regime, and hydrochemistry can reflect an aquifers ability to accept and transmit fluid, they reflect regional permeability contrasts. In the San Juan Basin, higher permeability in the Upper Cretaceous Fruitland Formation coincides with gentle hydraulic gradients, artesian overpressure, and low-chloride formation waters (Kaiser *et al.*, 1991b). High permeability is inferred from gentle gradients. Artesian overpressure requires high permeability, confinement, and recharge at an elevated outcrop, whereas underpressure reflects low permeability and insulation from recharge. The presence of low-chloride water indicates active recharge and basinward flow along permeable pathways. However, in some basins, overpressure may reflect active hydrocarbon generation (Spencer, 1987) and low permeability, whereas underpressure may reflect high permeability downflow of an elevated recharge area (Belitz and Bredehoeft, 1988).

THERMAL MATURITY

A coal beds gas content is dependent on its rank, pressure, ash content, maceral composition, and burial history. The volume of methane generated is directly related to coal rank, which in turn reflects burial history. Rapid subsidence through high geothermal gradients produces coal of subbituminous to semianthracite rank. The higher the rank, the more gas generated. The minimum vitrinite reflectance value for significant gas generation is 0.73 percent (Meissner, 1984). Although most coalbed methane is thought to be predominantly thermogenic, at least some gas produced from coal beds is biogenic. In the San Juan Basin, the presence of biogenic methane, generated after the main stage of coalification, is inferred from similar $\delta^{13}C$ values of methane over a wide range of coal rank (subbituminous to low-volatile bituminous) and isotopically heavy carbon dioxide and bicarbonate (Kaiser, *et al.*, 1991a; Scott *et al.*, 1991). If the gases are biogenic or migrated from deeper, higher rank coals or marine shales, gas content could be much higher than predicted from rank alone. Gas content is directly related to pressure and is commonly more dependent on pressure than on rank. The pressure/burial history, presence of biogenic gases, migration of thermogenic and/or biogenic gases, or a combination thereof may result in unusually high gas content in relatively low rank coals. Much of the methane present in high-volatile C bituminous and subbituminous coal is probably biogenic and early thermogenic. Ash content influences the volume of gas stored--low-ash coals having higher gas content. Maceral composition influences gas composition, wherein higher exinite or liptinite (hydrogen) content correlates with wetter gases.

PRODUCTION

In an analysis of gas and water production from Fruitland coal beds in the San Juan Basin, initial potential (IP) for gas was found to be a predictor of long-term productivity (Kaiser *et al.*, 1991a). There was a correlation between IP for gas and average daily production during a wells most productive year. Initial water potential increases with permeability (Oldaker, 1991), and high water potentials (several hundred m^3/d) are indicative of high permeability. Coalbed methane wells are low-yield water wells; that is, they produce less than 450 L/min (< 545 m^3/d). Because initial potentials for gas and water reflect productivity and permeability, respectively, and were readily available from Petroleum Information (1990a-k; 1991a-e) and Gas Research Institute (1986a-b; 1987a-d; 1988a-d; 1989a-d; 1990a-b; 1991a-c), these data were used for production analysis.

PICEANCE BASIN

The Piceance Basin in northwestern Colorado (fig. 1) is an asymmetric, northwest-trending, elongate basin of Late Cretaceous to early Tertiary age (Johnson, 1987). The basin, which covers an area of 18,722 km^2, is separated from the Uinta Basin to the west by the Douglas Creek Arch (fig. 2). The structural axis is on the northeast side of the basin, adjacent to the Grand Hogback, where it extends northwestward from the Divide Creek Anticline (fig. 2). Dip is steep along the sharply upturned east flank, adjacent to the Grand Hogback, but gentle on the west and southwest flanks of the basin (fig. 3). Depth to the Upper Cretaceous coal-bearing

Iles and Williams Fork Formations varies from outcrop along the basin margin to more than 3,660 m along the structural axis (figs. 3 and 4).

Face cleats in Upper Cretaceous and Tertiary coal beds may have been influenced by evolving folds in the Piceance Basin (Grout, 1991). Face cleats can be correlated with systematic fractures in clastic rocks on the basis of orientation, relative age, and style (Grout, 1991). In some coal beds, two, and rarely three, face-cleat sets are present. Generally, along the south margin of the basin most face-cleat strikes are east-northeast and east (050° to 086°), normal to the trace of the synclinal basin-margin fold (fig. 2). A few poorly exposed face cleats from the northwest margin of the basin also strike northeastward. Northwesterly face-cleat strikes (280° to 310°) occur in the north and east Piceance Basin (fig. 2). These patterns suggest several regional face-cleat domains.

The major coalbed methane target in the Piceance Basin is the Cameo coal group (fig. 4). The Cameo coal group ranges from 91 to 183 m in thickness and occurs at an average depth of approximately 1,525 m (McFall *et al.*, 1986). Maximum thickness of individual Cameo coal beds is 6 to 11 m, and net-coal thickness ranges from less than 6 to more than 18 m. The most continuous Cameo coal beds formed landward (northwestward) of the Rollins shoreline sandstone and extend northeastward along depositional strike for 8 to 16 km. Less continuous, fluvial Mesaverde coal beds occur up paleoslope to the northwest.

The coal-bearing hydrostratigraphic unit in the Piceance Basin is the Mesaverde Group, which is confined below by marine shale and unconfined above (fig. 4). Recharge is mainly at the basins southeast margin, and regional ground-water flow is convergent on the Colorado River valley from the basin margin (fig. 3). Mesaverde coals are overpressured, underpressured, and normally pressured. Overpressure is found in the east-central part of the basin. It extends from outcrop in the southeast part of the basin northwestward along the Divide Creek Anticline to just beyond the Colorado River (fig. 2). Both artesian and hydrocarbon-related overpressures are present. The absence of an upper confining layer and the presence of low permeability and limited recharge restrict artesian overpressure. The overpressure area is surrounded by an underpressured area that coincides with high coal rank and high gas content. Underpressure extends to the basins east margin along the Grand Hogback (fig. 2), where some repressuring should have occurred because the Mesaverde Group is exposed to recharge. The presence of underpressure near the outcrop means low permeability or limited recharge, or both. Low-permeability strata are too tight to receive and transmit appreciable recharge basinward, and thus they remain underpressured. Only from the southeast margin of the basin does repressuring appear to have occurred.

Vitrinite reflectance values for Cameo coal seams range from 0.48 percent (high-volatile C bituminous) along the basin margin to 2.10 percent (semianthracite) at the basin axis (fig. 5). The threshold of thermogenic gas generation is reached between 610 and 1,982 m (fig. 6b), indicating that the Cameo zone has reached the gas-generating stage over much of the basin. Coal rank changes abruptly with depth, generally paralleling structure of the Rollins and Trout Creek Sandstones in the southern two-thirds of the basin but cuts across structure in the north part of the basin (Johnson and Nuccio, 1986). The highest rank coal does not coincide with the present-day deepest part of the basin. Gas content increases with depth and generally ranges from 6.2 to more than 14.0 m^3/tonne in the south part of the basin but is less than 3.1 m^3/tonne in the north part. Produced Cameo coalbed gases range from very dry to very wet ($C_1/C_{1\text{-}5}$ values of 0.90 to 0.78) and have carbon dioxide contents ranging from 1.3 to 14.3 percent. The $\delta^{13}C$ values of methane generally increase with coal rank, indicating that the gases are predominantly thermogenic. However, isotopically light methane in the north and west parts of the basin suggests that some of the gases may be biogenic.

The Piceance Basin contains an estimated 2.38 Tm^3 of coalbed methane resources, 1.84 Tm^3 of which is contained in the Cameo coal group. Cumulative production of gas is 222 MMm^3 from Mesaverde coal beds and sandstones. The average depth of coalbed methane wells is 1,808 m. Gas IPs typically range from 2,830 to 14,150 m^3/d in coal beds and are as high as 73,580 m^3/d in wells dually completed in Mesaverde coal beds and sandstones. Decline analysis of these wells indicates that much of the gas is from low-permeability sandstones. Significant gas production occurs along the Colorado River valley in the north-central part of the basin where convergent, regional ground-water flow may favor hydrocarbon accumulation. Although water IPs from coal beds are low (< 16 m^3/d), indicating low permeability, coalbed methane wells along the Divide Creek Anticline have IPs of more than 80 m^3/d from artesian overpressured coal seams.

GREATER GREEN RIVER BASIN

The Greater Green River Basin is Wyomings largest coal-bearing area, covering approximately 38,870 km^2 of southwestern Wyoming and 14,511 km^2 of northwestern Colorado (fig. 7). Fragmentation of the basin during the Laramide Orogeny resulted in four intrabasin uplifts (the north-trending Moxa Arch and Rock Springs Uplift and the east-trending Wamsutter and Cherokee Arches) and four subbasins (Green River, Great Divide, Washakie, and Sand Wash) (fig. 7). Sedimentary rocks in the basin, ranging from Cambrian through Tertiary in age, have a maximum thickness of 9,750 m. About 7,012 m of these rocks are Upper Cretaceous, Paleocene, and Eocene in age (fig. 8) (Dickinson, 1989). Depth to the Cretaceous coal-bearing strata varies from outcrop to over 3,960 m (fig. 9).

Face-cleat strikes in Cretaceous and Tertiary coal beds along the west margin of the basin and along the east part of the Rock Springs Uplift have east and east-northeast strikes (060° to 085°) (fig. 7). These face-cleat strikes are normal to the Wyoming-Idaho segment of the thrust belt and the basement-cored thrust sheet associated with the Rock Springs Uplift, respectively (fig. 7). On the southeast margin of the basin, face-cleat strikes are west (275° to 280°) and northwest (320° to 350°), parallel to faults associated with the eastern Uinta Uplift and the Axial Arch. The boundary between the dominantly northeast face-cleat strikes at the north and the west-to-northwest strikes at the south is an area where cleat trends have not been documented.

Coal-bearing intervals in the Greater Green River Basin are collectively hundreds of meters thick, and they extend from the Upper Cretaceous Mesaverde Group through the lower Tertiary Wasatch Formation. The thickest and most continuous Cretaceous coal beds occur in the lower part of coal-bearing intervals in the Mesaverde Group (Williams Fork, Almond, and Rock Springs Formations) and the Lance Formation (fig. 8). These coal beds are individually as much as 11 m thick and extend along depositional strike for as much as 16 to 32 km (Glass, 1981). In contrast, lower Tertiary coal beds (Fort Union and Wasatch Formations) are generally less continuous and typically have lateral extents of less than 8 km, reflecting accumulation on floodplains of limited size and temporal stability. However, some Fort Union coal units have continuities of tens of kilometers (Hettinger *et al.*, 1991). Cretaceous coal seams less than 1,830 m deep occur along the southeast margin of the basin (Sand Wash Basin), in the center of the basin at the Rock Springs Uplift, and along the northwest margin of the basin on the north end of the Moxa Arch (Lickus and Law, 1988).

Coal-bearing hydrostratigraphic units in the Greater Green River Basin are the Mesaverde Group and Lance-Wasatch Formations (fig. 8). Both units are confined regionally by marine or lacustrine shales. Recharge is mainly at the basins southeast margin over the Sierra Madre and Park Uplifts and Williams Fork Mountains (fig. 7). Recharge also occurs over the Rock Springs Uplift, which is rimmed by strata containing low-chloride waters. Eastward flow off the Rock Springs Uplift into the Great Divide and Washakie Basins is probably promoted by the northeast-trending face cleat and fractures. Westward flow is promoted along the Cherokee Arch by east-west faults, and northwest flow from the south margin of the Sand Wash Basin is promoted by northwest-trending fractures (fig. 7) (Tyler *et al.*, 1992a). Basinward, ground-water flow paths turn upward upon aquifer pinch-out, convergence from the basin margins, and at the top of regional overpressure (fig. 9). Permeable, water-productive, normally pressured, and artesian coal seams occur at depths of 2,135 m or less above regional overpressure, which is predicated on the basis of low permeability (< 0.1 md) and active generation of gas (Law and Dickinson, 1985; Law *et al.*, 1986). Regional overpressure cuts across structural and stratigraphic boundaries and is not restricted to any particular stratigraphic unit (fig. 9), as is common in artesian overpressure. Consequently, the pressure transition between hydropressure updip and hydrocarbon-related overpressure downdip is basinwide, occurring further basinward in progressively younger strata (fig. 9). Higher pressure and confinement associated with artesian conditions preserve high gas content. Because of low permeability and great depth, the top of regional overpressure is a floor for coalbed methane exploration.

Coal rank in the Greater Green River Basin ranges from subbituminous in the Fort Union Formation to semianthracite in the Almond Formation in the deep Washakie Basin (Law, 1984). Vitrinite reflectance profiles suggest that coal rank is higher at equivalent depths in the east relative to the west (fig. 6a). The threshold of significant thermogenic gas generation (R_o values of 0.73 percent; Meissner, 1984) is not reached until depths of 2,439 to 2,744 m. However, local vitrinite reflectance anomalies are present northeast and east of the Rock Springs Uplift and in the southeast part of the basin (Merewether *et al.*, 1987), indicating that coal in these areas may have approached the threshold of thermogenic gas generation. North and east of the Rock Springs Uplift, gas content in coal beds less than 915 m deep is generally less than 3.1 m^3/tonne but increases abruptly between 915 to 1,220 m and then decreases with depth. The reasons for decreasing gas content with depth are unknown. However, the relatively high gas content over a narrow interval may reflect migrated thermogenic and/or biogenic gas, and could be related to basin hydrodynamics. Limited coalbed gas compositional data indicate that coalbed gases generally have C_1/C_{1-5} values greater than 0.97 and carbon dioxide content ranging from 1 to greater than 26 percent (Tremain and Toomey, 1983). Coalbed gases are probably thermogenic, migrated thermogenic, and/or biogenic.

The Greater Green River Basin contains an estimated 821 Bm^3 of coalbed methane resources and has produced 7.2 MMm^3 of coalbed methane. Coalbed methane production has been established in the Sand Wash Basin and on the east flank of the Rock Springs Uplift from Mesaverde coal seams. The average completion depth is 814 m. In the Sand Wash Basin, initial gas production ranges from 280 to 2,300 m^3/d and water production from 80 to 350 m^3/d. High water production from wells along the east and south margins of the basin reflects proximity to recharge at the Park Uplift and Williams Fork Mountains, respectively, and it also reflects basinward flow of ground water (fig. 7) and high coalbed permeability.

POWDER RIVER BASIN

The Powder River Basin of northeastern Wyoming and southeastern Montana covers an area of 66,800 km^2 and is the largest intermontane basin east of the thrust belt (fig. 1). Structural relief on the top of the Tullock Member of the Fort Union Formation is approximately 1,555 m (Ayers, 1984) (fig. 10). Because the synclinal axis lies close to the west margin of the basin, dips of the sedimentary rocks on the shallow eastern limb are gentle, averaging 1° to 2° westward (Ayers, 1984). The north and northeast flanks of the Powder River Basin have homoclinal dips of about 1° west-southwestward (Slack, 1981), whereas dips on the west flank, adjacent to the Bighorn Uplift, average 5° to 25° eastward (fig. 10).

The thickest, most laterally continuous coal seams in the Powder River Basin occur in the Tongue River Member of the Paleocene Fort Union Formation (fig. 11). These coal seams locally exceed 91 m in net thickness in the center of the basin (Ayers, 1984). Individual coal beds exceed 30 m in thickness, extend along depositional strike (northwest) for tens of kilometers, and occur in two separate northwest-trending belts in the east and central parts of the basin. These belts reflect westward progradation of a lacustrine-delta system, followed by abandonment, foundering, and subsequent peat (coal) accumulation on a deltaic platform (Ayers and Kaiser, 1984).

East- and east-northeast-striking face cleats occur in the southern and west-central Powder River Basin in Tertiary coal beds (fig. 10). In the northwestern part of the basin, face cleats have northeast strikes, but east of this area face cleats strike eastward. On the eastern margin of the basin, face-cleat strikes are variable (Tyler *et al.*, 1991a; Law *et al.*, 1991). Near Gillette, several exposures have equally prominent east- and north-striking cleat sets that have highly variable patterns. These coal beds lack distinct face-cleat sets. Tyler *et al.* (1991b) and Law *et al.* (1991) related these variations in cleat strike to differences in sandstone thickness and compaction of coal over and under sandstone bodies.

Coal seams of the Tongue River Member of the Fort Union Formation in the Powder River Basin are major aquifers (fig. 11). The Wyodak coal aquifer in the upper Tongue River is the most continuous geohydrologic unit in the basin; its permeability ranges from 10 md to several darcys (U.S. Department of Interior, Bureau of Land Management, 1990). Regionally, ground water flows northward, recharged mainly from the east margin of the basin, with a westward component toward the Tongue River (Davis, 1976; Daddow, 1986), which probably reflects west-dipping strata and east-west face cleats (fig. 10). Artesian conditions develop basinward where coal seams pinch out and are confined by lacustrine shales. Flowing wells are common in the Powder and Tongue River valleys and attest to artesian conditions (Lowry and Cummings, 1966; Whitcomb *et al.*, 1966).

In the Powder River Basin, Fort Union and Wasatch coal beds are lignite and subbituminous rank (R_o percent). Coal rank in the north and central parts of the basin does not reach the high-volatile C bituminous stage until approximately 2,744 m, much deeper than the Fort Union Formation and the threshold of significant gas generation (high-volatile B bituminous) is not reached until 3,963 m (fig. 6c). In the south part of the basin the high-volatile C bituminous stage is reached at approximately 1,829 m, which is also much deeper than the Fort Union Formation. The low coal rank and great depth to the threshold of thermogenic methane generation suggest that gases present in the coal beds are biogenic and/or early thermogenic. This conclusion is supported by methane ,$\delta^{13}C$ values of less than -55 $^{o}/oo$, which indicate that these gases are biogenic (Boreck, 1984; Rice and Flores, 1991). Coalbed gases are dry (C_1/C_{1-5} values greater than 0.97) and have carbon dioxide content ranging from 4 to 11 percent. The presence of heavier hydrocarbons (C_{2+}) in coalbed gases suggests that minor amounts of early thermogenic gases may have been generated from the coal in addition to biogenic gases. Gas contents in the Fort Union and Wasatch coal beds are less than 3.1 m^3/tonne but could be greater locally owing to the migration of gases to structural highs.

Coalbed methane resources in the Powder River Basin are estimated to range from 453 to 849 Bm^3. The basin has produced only 24 MMm^3 of coalbed methane. Initial testing of coalbed wells produced less than 2,830 to 8,490 m^3/d methane. Conventional structural trapping, partial confinement, and dewatering by nearby surface mines probably explain local low-water gas production on the east basin margin. Water IPs typically range from 32 to 160 m^3/d and are highest basinward, reflecting artesian conditions and high permeability.

RATON BASIN

The Raton Basin of southern Colorado and northeastern New Mexico extends about 129 km north-south and is 80 km wide along the New Mexico!Colorado border, encompassing an area of 5,564 km^2 (fig. 12). To the west, the basin is bounded by a frontal thrust, defined by the Sangre de Cristo Mountains (fig. 12). The asymmetric axial trace of the Raton Basin, which is approximately 8 to 16 km east of, and parallel to, the Sangre de Cristo thrust front (fig. 12), results in a steep eastward dip of the sedimentary rocks on the west limb adjacent to the Sangre de Cristo Mountains and a gentle westward dip on the wider east limb (fig. 13) (Close, 1988). Sedimentary rocks along the west edge of the Raton Basin are extensively deformed by steeply dipping thrust and reverse faults. The east flank is only mildly deformed by open folds and faults having small displacements (Merin *et al.*, 1988). At least 4,726 m of structural relief is present between the deepest part of the Raton Basin and the adjacent Sangre de Cristo Mountains. Depths to the Upper Cretaceous-Paleocene coal-bearing horizons range from outcrop along the basin perimeter to more than 1,220 m near the structural axis of the basin.

In the Raton Basin face cleats strike northwest in the south (090° to 110°) and northeast in the north (070° to 080°) (Close, 1988). Cleat strikes are nearly constant along east-west transects. Face-cleat strikes are at right angles to the trace of the basin axis and remain normal to the trace of the salient defined by the Sangre de Cristo thrust front.

The Raton Basin contains a nearly complete Cretaceous and Tertiary stratigraphic succession (Close and Dutcher, 1990), which includes the coal-bearing Vermejo and Raton Formations (fig. 14). The basins thickest coal beds (maximum thickness ranges from 3 to 4 m) occur in the lower Vermejo Formation, where they formed landward (westward) of Trinidad shoreline sandstones. Fluvial coal beds in the Raton Formation are thinner (maximum thickness 2 m) and less continuous (Flores, 1984).

The coal-bearing hydrostratigraphic unit in the Raton Basin is composed of the Vermejo and Raton Formations (fig. 14). The unit is regionally confined below by the Trinidad Sandstone and Pierre Shale. Above, it is unconfined because the Raton Formation crops out throughout much of the basin. Regional ground-water flow is from west to east, converging on the Purgatoire River and eastern outcrop belt (fig. 13). Basinal pressure regime is poorly known, but regional underpressure is postulated from hydraulic head data (Howard, 1982; Geldon, 1990). Although artesian conditions may be present along the elevated western outcrop belt (recharge area) flanking the Sangre de Cristo Mountains and in the Purgatoire River valley, coal-seam lenticularity, low equivalent permeability, insulation from recharge, and a topographically low discharge area maintain underpressuring over much of the basin. Development of overpressuring is most likely in the thicker, more laterally extensive and presumably better interconnected lower Vermejo coal seams near the western recharge area.

Coal rank in the Vermejo Formation ranges from high-volatile C bituminous along the basin margins to low-volatile bituminous rank in the central part of the basin (R_o values from 0.57 to 1.57 percent). Vitrinite reflectance profiles indicate that the threshold of thermogenic gas generation occurs at depths of less than 305 m (fig. 6d). The highest rank coals are located in an area parallel to the Purgatoire River (fig. 15). The higher vitrinite reflectance values paralleling the river valley may be due to hot fluids ascending to an ancestral Purgatoire River. These hot fluids were derived from nearby Tertiary intrusives and a localized, deep heat source, or both. Gas content generally increases with depth and increasing coal rank. Low rank coal beds having low gas content are present along the basin margins. Also, some high-rank coals at shallow depths have low gas content. High gas content (6.2 to 12.5 m^3/tonne) at shallow burial depths (< 915m) indicates commercial coalbed potential. Gas compositional data indicate that Vermejo coalbed gases are dry to very dry, having C_1/C_{1-5} values that range from 0.97 to 1.00 in coals of high-volatile A bituminous to low-volatile bituminous rank (Tremain and Toomey, 1983: Close, 1988). The low carbon dioxide content of coalbed gases (< 2 percent) reflects the high coal rank; carbon dioxide content generally decreases with increasing rank. Carbon dioxide generated through coalification and/or the emplacement of sills probably remains adsorbed onto coal surfaces. However, some carbon dioxide may have escaped from the system through fractures and may have been precipitated and/or assimilated as carbonate or calcsilicate minerals in adjacent sandstones, coal beds, and/or magma. Methane $\delta^{13}C$ values suggest that most of the coalbed gases are thermogenic, although biogenic gases may be present in the northern part of the basin.

The Raton Basin contains an estimated 340 to 509 Bm^3 of coalbed methane resources. However, cumulative production is a miniscule 331 Mm^3 because most coalbed methane wells are shut in pending construction of pipelines. The average completion depth is 457 m. Maximum gas IP's of coalbed wells typically range from less than 2,830 to 8,490 m^3/d; values of less than 4,245 m^3/d are common and may reflect incomplete dewatering. Wells located in the west part of the basin, close to the recharge area, and in the Purgatoire River valley have IP's of several hundred barrels per day, indicating good permeability. Possible artesian conditions and attendant higher reservoir pressures may contribute to higher gas content in those areas.

CONCLUSIONS

Regionally, the structural elements of intermontane basins in the foreland of the Cordilleran thrust belt are the result of Laramide and post-Laramide tectonism. The importance of these regional structural elements is mainly in the potential for conventional methane trapping and in the prediction of fracture permeability. Where structural complexity and dip changes result in fracture-enhanced permeability and conventional trapping of gas along structural hingelines, previously underexplored basins have the potential for coalbed methane production. Regionally, as in the San Juan Basin, structural discontinuities and/or changes in structural dip constitute zones of fracture-enhanced permeability and thus sites for conventional trapping of gas. Within these zones, face cleats commonly strike parallel to tectonic shortening directions and are typically oriented normal to traces of orogenic thrust belts.

Coalbed methane reservoirs are thickest and most continuous in Upper Cretaceous and/or lower Tertiary strata in all basins. Maximum-coal thickness, or thickness of the single thickest seam, exceeds 6 m, and typicla net-coal thickness exceeds 30 m, except in the Raton Basin. Thus, potential coalbed methane targets are numerous in all basins.

Hydrologically, in the San Juan Basin, the pressure transition fairway, characterized by upward flow, hosts the basin's most productive coalbed. methane wells (Kaiser *et al.*, 1991a). In the Greater Green River Basin, normally pressured or artesian coal seams above regional overpressure yield large volumes of low-chloride water, indicating high permeability. Areas of pressure transition and convergent, upward flow may be extensive and, by analogy to the San Juan Basin, potentially very productive. In the Piceance Basin, underpressure and hydrocarbon-related overpressure indicate low permeability, and low permeability may limit the basin's commercial coalbed methane potential. Very low permeabilities (microdarcys) occur in the underpressured parts of the basin, whereas the higher permeabilities (~ 10 md) occur in artesian overpressured coal seams. Paradoxically, high permeability may ultimately limit coalbed methane development in the Greater Green River and Powder River Basins; coal seams are major aquifers and will be difficult to dewater and depressure economically. Large volumes of produced water will create disposal problems and add to production costs, depending on disposal methods -- discharge to surface, injection, or osmotic treatment. In the Raton Basin, coal seams along the west margin are under higher pressure and are water productive, indicating good permeability. Regional underpressure is thought to reflect eastward decrease in permeability, insulation from recharge, and coal seam lenticularity. Predictably, reservoir pressure (gas content) decreases eastward.

Coals in the Powder River Basin have not reached the main stage of thermogenic methane generation (0.73 percent R_o). These subbituminous coals have gas content less than 3.1 m^3/tonne, reflecting the presence of biogenic gases. The maximum rank for coals in the Greater Green River, Piceance, and Raton Basins exceeds the threshold of significant methane generation. Gas content associated with higher-rank coals can exceed 12.5 m^3/tonne. Significantly, lower-rank coals in these basins (depths < 1,800 m) have not reached the thermogenic threshold, yet they can have gas content in excesss of 9.4 m^3/tonne, suggesting the presence of only migrated thermogenic and/or biogenic gases. Because gas content is not entirely rank related, its distribution is difficult to predict. Ash content in all basins ranges from 8 to 13 percent and should have little or no impact on coalbed methane potential. In the San Juan Basin, coal seams with two to three times that ash content are highly productive.

Cumulative production of coalbed methane is highest in the Piceance Basin, followed by the Powder River, Greater Green River, and Raton Basins. Gas IP's are highest in the Piceance Basin (2,830 to 14,150 m^3/d), where they reflect gas-saturated coal seams. The highest gas IP's are from wells dually completed in the Mesaverde coal beds and sandstones. The dual completions may indicate low coalbed permeability low gas content coal seams, or economic benefit from accessing both types of reservoirs in one borehole.

Gas IP's are lowest in the Great Green River and Raton Basins (mostly < 2,264 m^3/d), reflecting low gas content and/or incompete dewatering. Water IP's are high in all basins, except the Piceance, where they are mostly less than 16 m^3/d, indicating low overall permeability. Highest water IP's (~ 160 m^3/d), indicating high permeability, are from artesian Fort Union coal seams in the Powder River Basin and Wiliams Fork coal seams in the Sand Wash Basin. Dewatering and disposal costs will adversely affect the economics of coalbed methane development in these basins. Awareness of these geologic and hydrologic characteristics as the fundamental controls on the producibility of methane in intermontane basins has obvious applications to coalbed exploration and development in similar coal basins throughout the world.

ACKNOWLEDGMENTS

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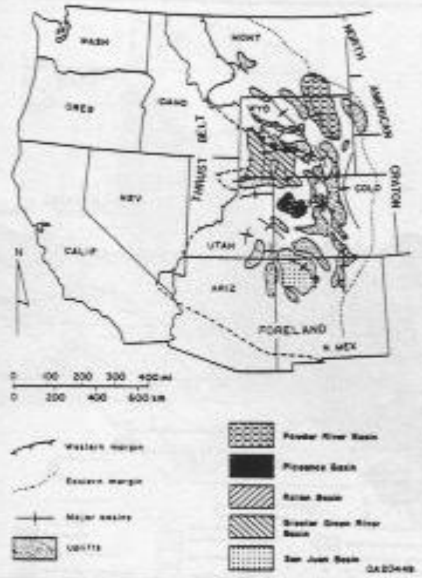

Figure 1. Coal basins and uplifts in the foreland area of the Cordilleran thrust belt. Modified from Wood and Bour (1988).

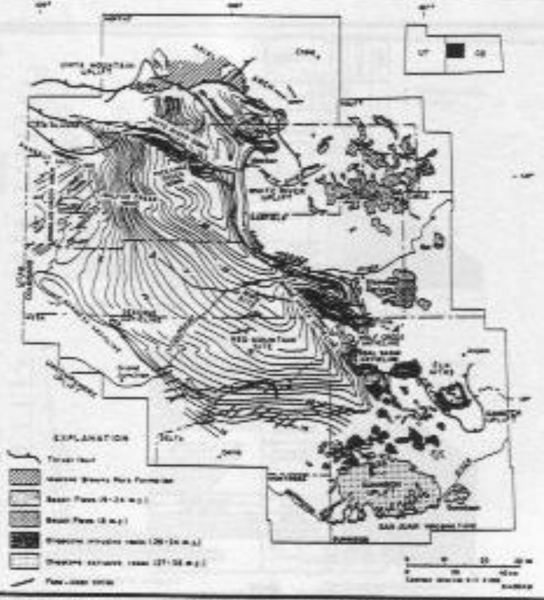

Figure 2. Structure-contour map on top of the Rollins and Trout Creek Sandstone Members, Iles Formation, Piceance Basin, showing face-cleat strikes. Structure contour interval is 500 ft (152 m), relative to mean sea level. Cross section A-A shown in Figure 3. Modified from Johnson and Nuccio (1986).

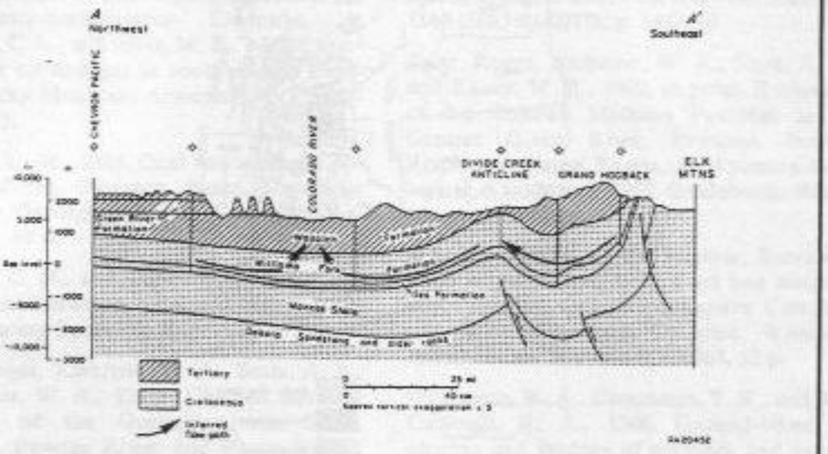

Figure 3. Northwest-southeast cross section A-A through Piceance Basin including the Multi-well (MWX) site. Modified from Law and Johnson (1989)

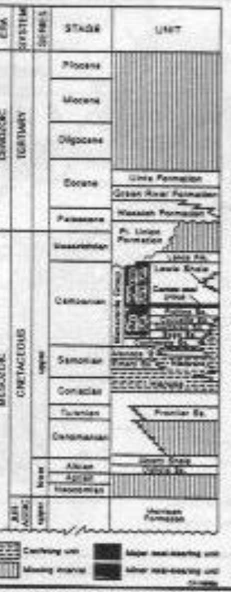

Figure 4. Stratigraphic column showing coal-bearing and confining units in the Piceance Basin. Modified from Tayler, *et al.*, (1992 in press).

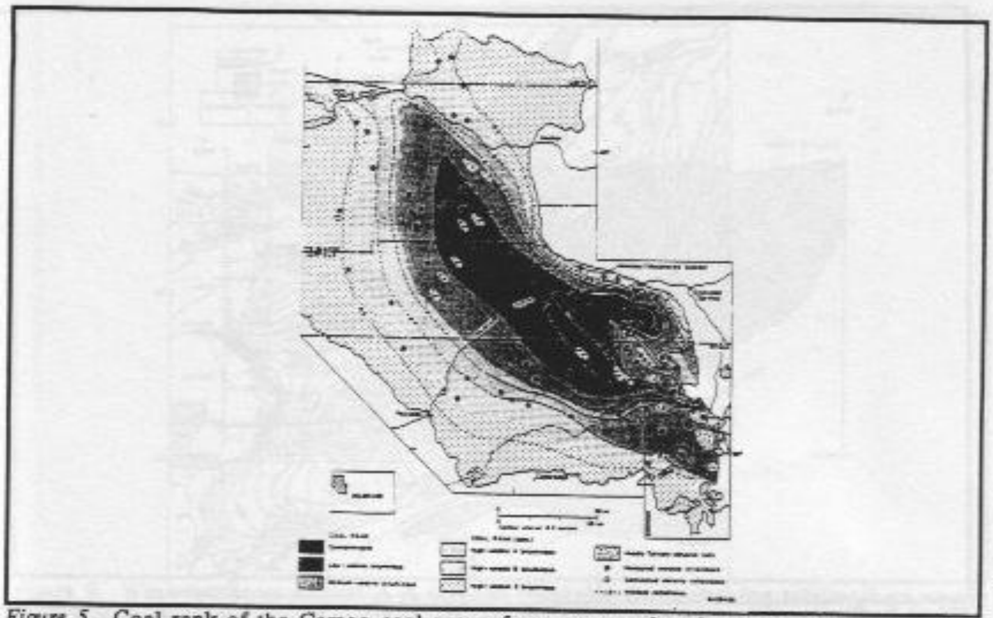

Figure 5. Coal rank of the Cameo coal group from measured and calculated vitrinite reflectance values. Map based on data from Tremain (1983), Tremain and Toomey (1983), Bostick and Freeman (1984), Johnson and Nuccio (1986), and Decker and Horner (1987).

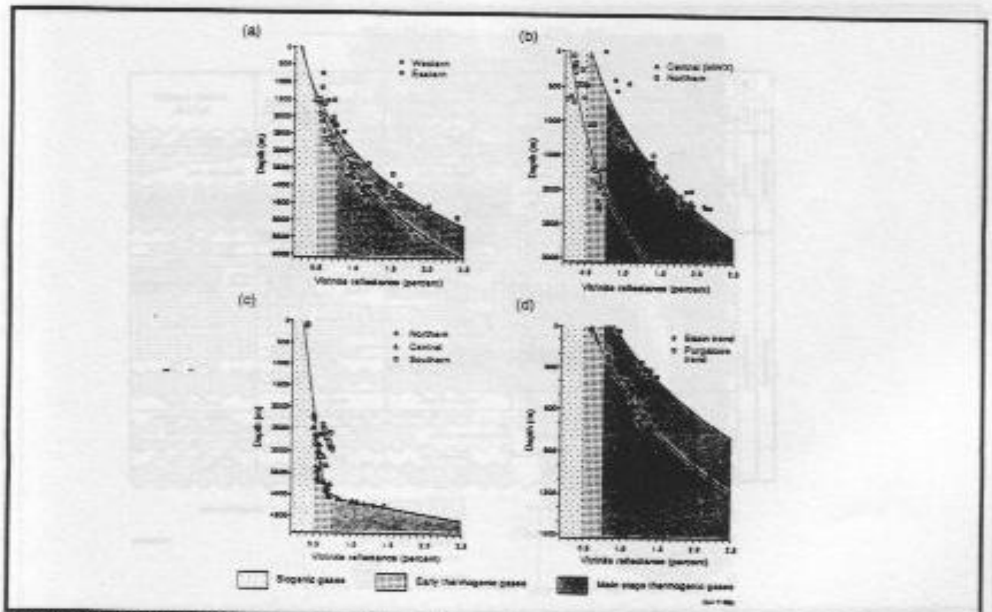

Figure 6. Vitrinite reflectance profiles and gas generation thresholds for the (a) Greater Green River, (b) Piceance, (c) Powder River, and (d) Raton Basins. Data from Law (1984), Johnson and Nuccio (1986), Nuccio (1990), and ARI, Inc. (1991).

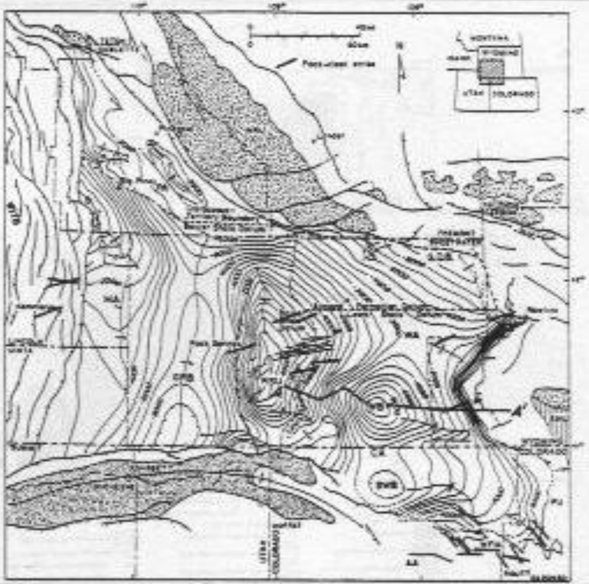

Figure 7. Structure-contour map of the Greater Green River Basin showing face-cleat strikes. Modified from Lickus and Law (1988) and Tyler *et al.*, (1991a).

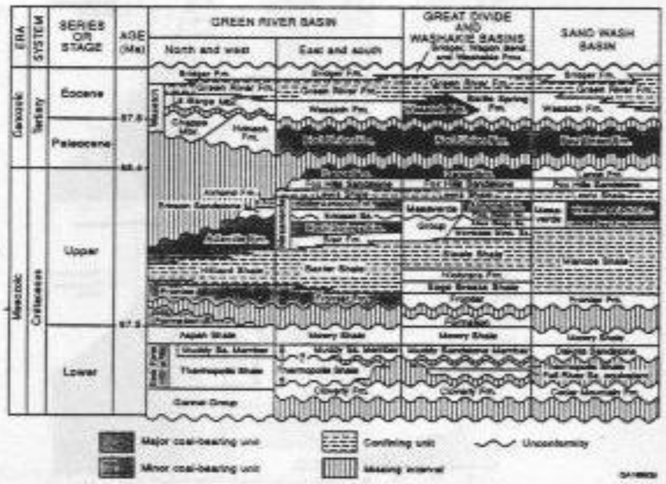

Figure 8. Stratigraphic column showing coal-bearing and confining units in the Greater Green River Basin. Modified from Tyler, *et al.*, (1991a) and Baars, *et al.*, (1988)

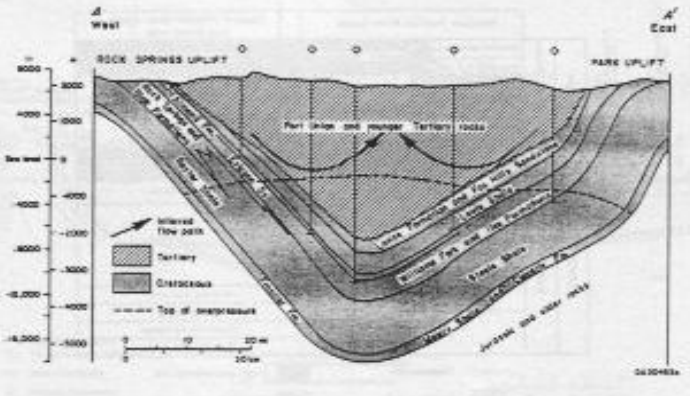

Figure 9. West-east cross section A-A through Washakie Basin showing relationships among structure, stratigraphy, top of regional geopressure, and ground-water flow. Modified from Law, *et al.*, (1989). Groundwater recharge occurs at the Sierra Madre and Rock Springs Uplifts, flows basinward, and turns upward when the aquifers pinch out, where flow paths converge from basin margins, and at the top of regional overpressure. Line of section shown in Figure 7.

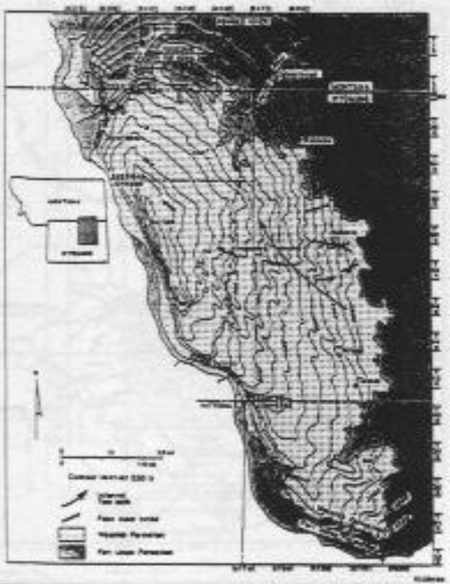

Figure 10. Structure-contour map of the top of the Tullock Member, Fort Union Formation, Powder River Basin, showing face-cleat strikes.

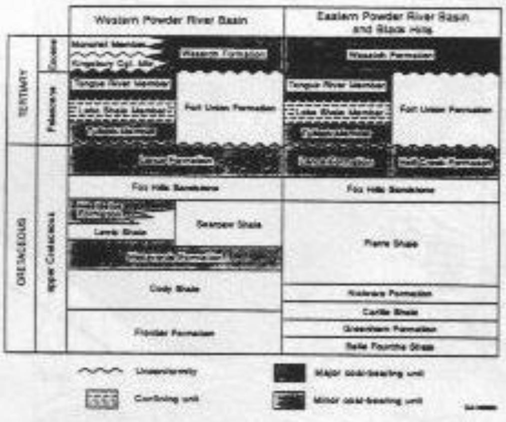

Figure 11. Stratigraphic column showing coal-bearing and confining units in the Powder River Basin. Modified from Jones (1990).

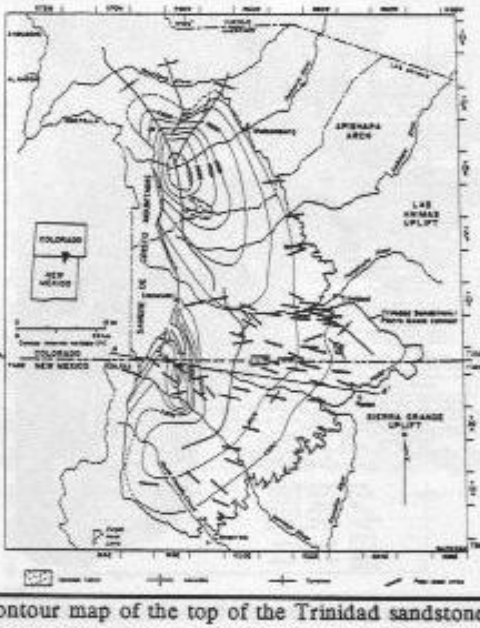

Figure 12. Structure-contour map of the top of the Trinidad sandstone, Raton Basin, showing face-cleat strike. Structure contours, in feet (0.31 m), relative to mean sea level. Cross sections A-A shown in Figure 13. Modified from ARI, Inc. (1991).

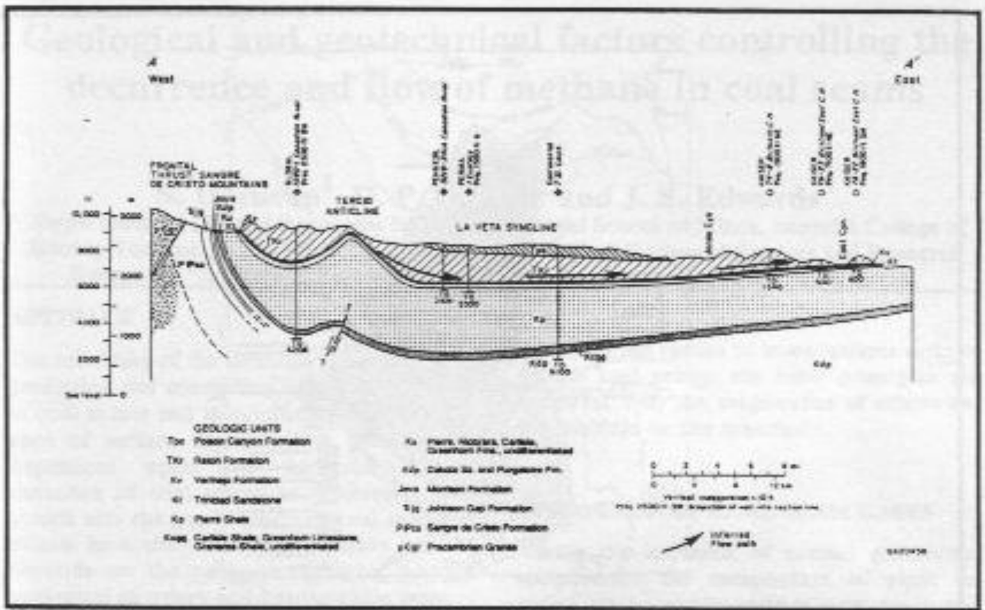

Figure 13. West-east cross section A-A through the Raton Basin showing relations between structure and stratigraphy. Total depth (TD) in feet (0.31 m). Modified from ARI, Inc. (1991).

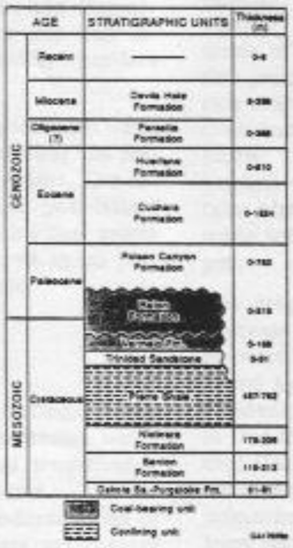

Figure 14. Stratigraphic column showing coal-bearing and confining units in the Raton Basin. Modified from Dolly and Meissner (1977)

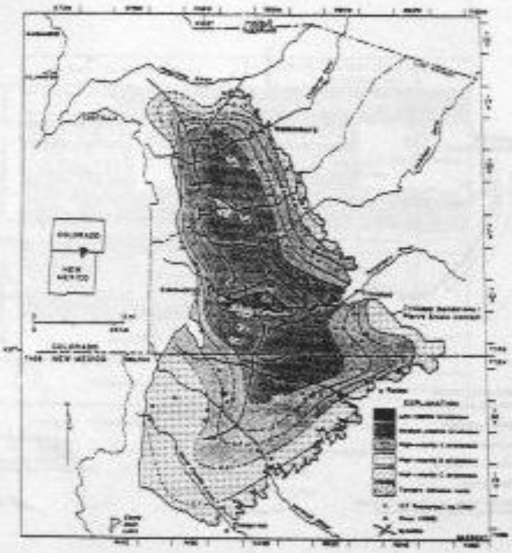

Figure 15. Coal-rank map to the base of the Vermejo Formation. The highest rank coals are located in an east-west band along the Purgatoire River valley. This area of higher coal rank may be due to a deeply buried heat source and/or heat advection by groundwater. Modified from ARI, Inc. (1991).