COAL BED GAS PLAYS

Overpressured Play

(USGS 2250)

Underpressured Discharge Play

(USGS 2252)

Underpressured Play

(USGS 2253)

General Characteristics

On the basis of hydrology, pressure regime, reservoir properties, and hydrocarbon composition, three plays are identified for the Fruitland coal-bed gas: (1) San Juan-Overpressured Play, (2) San Juan-Underpressured Discharge Play, and (3) San Juan-Underpressured Play (Gautier et al., 1996).

The San Juan-Overpressured Play (2250) is in the north-central part of the basin and north of the structural hingeline where recharge of relatively fresh water takes place. The coals are generally thick (greater than 10 feet) and laterally extensive in northwest-trending bands. The coals are generally of high rank (as much as medium-volatile bituminous), have high gas contents, and are characterized by high formation pressures (greater than 0.5 psi/ft). The coal-bed gases are relatively dry (heavier hydrocarbons less than 3 percent) and contain significant amounts of CO_2 (3-12 percent). Although depths of burial extend to 4,200 feet, the Fruitland Coal in a large part of the play is at depths of less than 3,000 feet. Within this play is the very productive "Fairway" Trend. The average daily gas production for wells in this play during their most productive year ranges from less than 30 MCF/D to more than 3,000 MCF/D, and the highest rates were in the "Fairway" Trend. Because of recharge of fresh water on the north margin, most wells produce water at rates as high as 2,000 bbl/D and must be dewatered to initiate desorption and production. Because of the high productive capacity of wells in this play, the prime areas have been explored and developed (Cedar Hills, Ignacio-Blanco, and Basin Fruitland Coal Fields). The potential for additional reserves from this play is considered to be good; however, the areal extent of this potential is limited because of previous development.

The San Juan-Underpressured Discharge Play (2252) is south of the structural hingeline in the southwest part of the basin where the coal beds are underpressured (0.3 to 0.4 psi/ft). The area is characterized by regional groundwater convergence and discharge. The groundwater is a NaCl type and has a higher chloride content than that of the overpressured play. Coals may be as thick as 10 feet and the thickest coals are in northeast trends. Compared to the Overpressured Play, coal rank is lower (high-volatile B bituminous and lower) and gas contents are lower. The gas is chemically wet (heavier hydrocarbons generally more than 5 percent) and contains less than 1.5 percent CO_2. During early months of production, the coals of high-volatile B bituminous rank produce some waxy oil. Depths of burial are less than 3,000 feet, and production is commonly water free. The average daily production of wells in this play during their most productive year ranges from 30 to 300 MCFPD. The potential for undiscovered coal-bed gas in this play is good to fair. Similar to the Overpressured Play, extensive drilling and production (Basin Fruitland Coal-Bed Gas Field) have taken place in this play, and the remaining potential for reserves is mainly at shallower depths (less than 1,500 feet) in the southwestern part of the play.

The San Juan-Underpressured play (2253) is in the eastern part of the basin where groundwater flow is sluggish. The produced waters are a NaCl type and similar to seawater. Coal beds are generally thin and gas content is low, particularly in the eastern part. Minor production has been established and rates are low (average annual production in the range of 1 to 3 MMCF) with little or no water production. Depths of burial (500-4,000 feet) and coal rank (subbituminous to medium-volatile bituminous) are variable and generally increase to the north. The potential for additional reserves from this play is only fair because of underpressuring and low permeability.

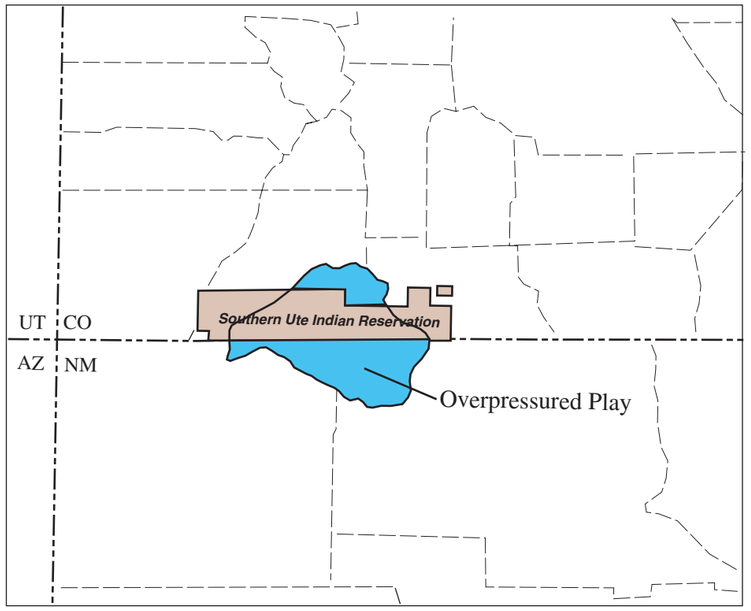

Figure SU-65. Location of the Overpressured Play (modified after Gautier et al., 1996).

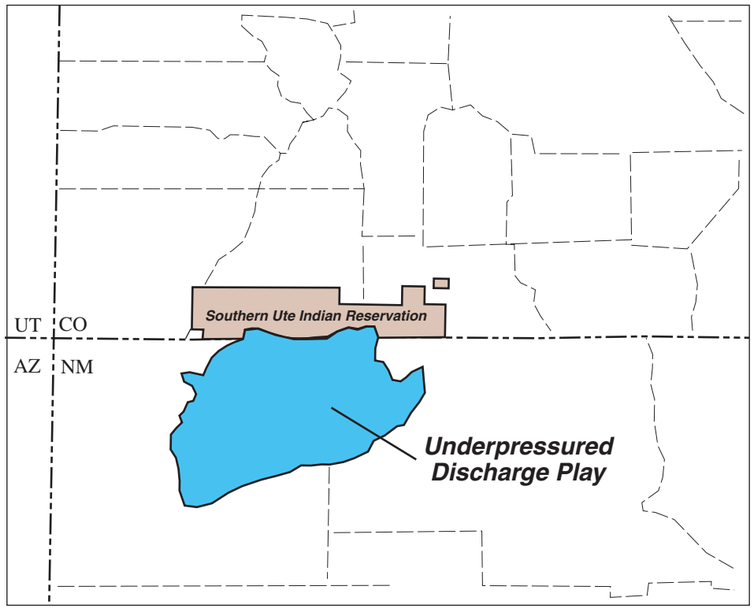

Figure SU-66. Location of the Underpressured Discharge Play (modified after Gautier et al., 1996).

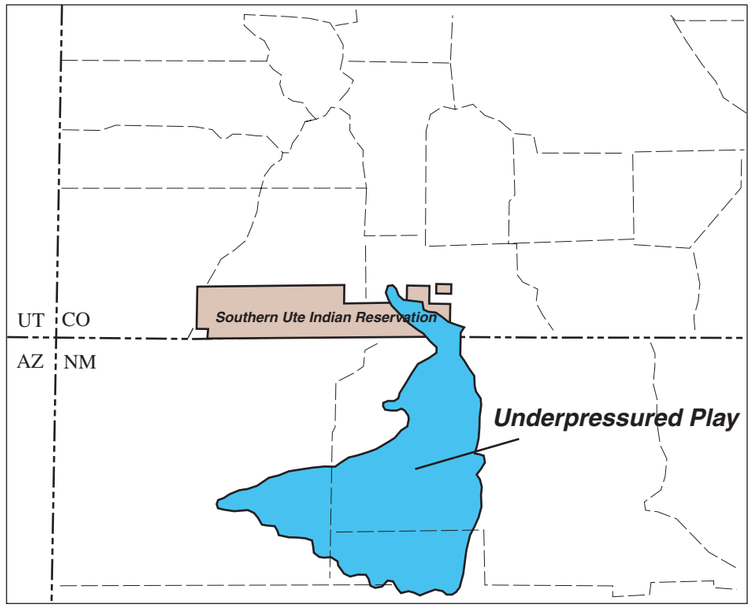

Figure SU-67. Location of the Underpressured Play (modified after Gautier et al., 1996).

Coal-Bed Gas Plays

In the San Juan Basin, significant resources of both coal and coalbed gas are in the Upper Cretaceous Fruitland Formation (Rice and Finn, 1996) . The occurrence, thickness, and geometry of Fruitland coal deposits are strongly influenced by depositional environment. Coal deposits resulted from peat that accumulated on sandstone platforms of the underlying Pictured Cliffs Sandstone, which were deposited along the coast of a northeast-prograding shoreline. Individual coal beds are as much as 40 ft thick. The greatest net coal thickness, up to 100 ft, is in a northwest-trending belt in the northern part of the basin where thick coal deposits occur in both northwest- and northeast-trending deposits, with the thickest deposits in the northwest-trend. In the northwest-trend, individual coal beds average more than 9 ft in thickness, which resulted from standstills in the Pictured Cliffs Sandstone shoreline. Average thickness of coal beds in the northeast-trend is 6 ft. They occur in floodplain facies between channel-fill sandstone deposits. Depths of burial for the Fruitland coal beds are as much as 4,200 ft in the northeastern part of the basin.

Coal beds in the Upper Cretaceous Menefee Formation are an additional target for gas. The Menefee is older and deeper than the Fruitland and is in the middle part of the Mesaverde Group. Although as much as 35 net ft of coal occur in the Menefee, the coals are generally thinner, more discontinuous, and dispersed over a greater stratigraphic interval than those of the overlying Fruitland Formation. The Menefee coals are as deep as 6,500 ft.

Across the central basin, the rank of Fruitland coal increases northeastward from subbituminous C to medium-volatile bituminous. Coal rank generally conforms with the structural configuration of the basin and abruptly decreases along the steeply dipping north flank. Rank trends for Menefee coals are similar, but somewhat higher because of greater burial depth. Present-day depths of burial do not coincide with the maximum levels of thermal maturity in the northern part of the basin. This is partly the result of significant uplift and erosion that has taken place since about 10 Ma. However, maximum depth of burial and present-day heat flow cannot account for the high rank present at the north end of the basin. In addition to maximum burial depths, this high rank is interpreted to be the result of (1) convective heat transfer associated with a deeply buried heat source located directly below the northern part of the basin, and (or) (2) the circulation of relatively hot fluids into the basin from a heat source located in the vicinity of the San Juan Mountains to the north. Thermogenic gases were probably generated in the coals during time of maximum heat flow and (or) depth of burial in Tertiary time.

Produced Fruitland coalbed gases are variable in their composition. Although methane is the major component, significant amounts of heavier hydrocarbon gases (as much as 23 percent), CO_2 (as much as 13 percent), and nitrogen (as much as 11 percent) are also present. The producing part of the basin can be divided into two areas based on coalbed gas composition. The boundary between the two areas is rather abrupt and coincides with the structural hingeline. In the southern part, the gases are generally wet (heavier hydrocarbons generally greater than 6 percent) with minor amounts of CO_2 (generally less than 1 percent). Waxy oil is produced in association with wet gases in this part. In contrast, gases in the north part are dry (heavier hydrocarbons generally less than 3 percent) but contain significant amounts of CO_2 (generally greater than 6 percent). On the basis of chemical and isotopic composition, the hydrocarbon gases are interpreted to be mainly thermogenic in origin. The heavier hydrocarbon gases and oils, which are restricted to coals of high-volatile B bituminous and lower ranks, were probably generated from hydrogen-rich coals. In the northern part of the basin, active groundwater flow has probably led, relatively recently, to intensified microbial activity resulting in aerobic consumption of the heavier hydrocarbons and mixing of biogenic methane-rich gas. Isotopic data suggest that the large amounts of CO_2 in the north part of the basin are also the result of recent bacterial activity

The San Juan Basin is a strongly asymmetric basin with a gently dipping southern flank and steeply dipping northern flank. It has two axes in the northeastern part of the basin, which are separated by the Ignacio Anticline. A structural hingeline has been interpreted to occur where the gently dipping southern monocline meets the basin floor. This hingeline is probably a zone of northwest trending, en-echelon normal faults and divides the basin into two distinct areas relative to coalbed gas productivity.

The Colorado-New Mexico border roughly marks the division of the basin into two areas of distinctly different face-cleat orientations. North of the border the cleats are oriented northwestward; however, south of the border they are oriented northward or northeastward. Along the State border, interference of the two sets may result in increased permeability, which has led to the success of vertical open-hole cavity completions. Increased permeability may also result from compaction-induced fractures in areas where the Fruitland coal beds overlie upper Pictured Cliffs sandstone tongues. In addition, compaction-induced fractures may be present where coal beds split and interfinger with fluvial channel-sandstones. In the Cedar Hill coal field area of northern New Mexico, multicomponent 3D seismic surveys indicate that movement on basement-controlled faults with strike-slip displacement has opened natural fractures in the coal.

Fruitland coal beds are major aquifers in the San Juan Basin. In the northern part of the basin, they are commonly thick, well cleated, and more permeable than the adjacent sandstones that serve as aquitards. Recharge is mainly along the wet, northern margin of the basin in the foothills of the San Juan Mountains with limited recharge along the other margins. A sharp steepening of the potentiometric surface occurs along the structural hingeline and divides the basin into two hydrologic provinces. This steepening indicates an area of reduced permeability and is a no-flow boundary.

Groundwater movement and associated reservoir characteristics can be tracked by water composition, in particular the chloride content. Lobes of relatively fresh, low-chloride water extend into the basin from the northern margin. The hydrochemical boundary between low chloride, $NaHCO_3$-type water and high chloride NaCl-type water coincides with the structural hingeline. Water production rates for individual wells are highly variable and range from essentially nothing to more than 2,000 barrels per day. The production rates are strongly controlled by hydrodynamics, and the highest rates are north of the hingeline and along the northern margin. Most of the water is currently being injected into deep wells. However, the disposal capacity is rapidly being approached and alternate, cost-effective methods of disposal will be required.

The Fruitland coal beds are both abnormally pressured and underpressured relative to fresh-water hydrostatic pressure. Overpressuring occurs in the north-central part of the basin and coincides with the area of relatively fresh water. The overpressuring is interpreted to be artesian in origin as evidenced by the flowing artesian coalbed gas wells. However, most of the basin is underpressured. The transition from overpressured to underpressured is abrupt and takes place along the structural hingeline.

Gas contents in the San Juan Basin are highly variable and range from less than 100 to more than 800 Scf/t. As expected, there is a general relation between gas content, depth, and rank. However, the gas content also strongly correlates with the pressure regime. In dealing with coals of similar rank, the highest gas contents are usually reported from the overpressured north-central part of the basin.

On the basis of resources and a range of gas contents, in-place coalbed gas resources of the Fruitland Formation are estimated to be about 50 TCF. An additional 38 TCF have been estimated for the Menefee coal beds resulting in a total of 88 TCF for the basin.

New Mexico ranked 14th among the States in 1991 for the production of coal. Most of this coal was mined on the surface from the Fruitland along the western flank of the basin. The New Mexico counties of San Juan and McKinley, located on the west flank of the basin, were ranked 7th and 10th in the nation in terms of production from surface mining. Some coal is also mined in the Colorado part of the basin. Because the coal in the basin is mostly mined on the surface, methane emissions are minor.

The San Juan Basin has been the most productive coalbed gas basin in the United States since 1988. In 1992, more than 436 BCF of coalbed gas were produced from about 2,000 wells. In 1993, more than 480 BCF were produced from about 1980 wells in only the New Mexico part of the basin. Most of the coalbed gas wells in the basin have been drilled since 1987 and the largest number was completed in 1990. Although the Black Warrior Basin has the largest number of producing wells, more than four times as much coalbed gas was produced in the San Juan Basin in 1992 (436 BCF versus 92 BCF). Production rates for individual wells are highly variable and range from 50 to 15,000 MCFGPD. About one-third of the total producing wells are vertical open-hole cavity wells, which accounted for about 75 percent of the gas production in 1992. These cavity wells commonly produce 10 times more gas than those completed by hydraulic fracturing. However, successful, open-hole cavity completions are generally restricted to a northwest-trending area referred to as the "Fairway," located north of the structural hingeline. Cavity wells in the "Fairway" are successful because of artesian overpressuring and high permeability; open-hole cavity completions have not been successful in other basins.

The first coalbed gas well (Cahn No. 1) was drilled in the New Mexico part of the basin in the late 1970's. The well is part of the Cedar Hills coal field. Most of the production in New Mexico is assigned to the Basin Fruitland coal field, and all the production in Colorado is assigned to the Ignacio-Blanco coal field. The reserves in the basin as of 1993 are about 7.8 TCF, which represents about 70 percent of the coalbed gas reserves in the country.

The San Juan Basin has had major gas pipelines to southern California since the 1950's, when gas was first produced from Cretaceous sandstones. With the rapid development of coalbed gas, pipeline capacity was insufficient in the late 1980's. Since 1990, major expansion projects have resulted in increased capacity for transmitting the gas to interstate markets.

REFERENCES

Anderson, R., ed., 1995, Southern Ute Indian Reservation, in Anderson, R., ed., The Oil and Gas Opportunity on Indian Lands: Exploration Policies and Procedures, 1995 edition, Bureau of Indian Affairs, p. 78-92.

Aubrey, W.M., 1992, New interpretations of the stratigraphy and sedimentology of uppermost Jurassic to lowermost Cretaceous strata in the San Juan Basin of northwestern New Mexico: U.S. Geological Survey Bulletin 1808-J.

Aubrey, W.M., 1991, Geologic framework of Cretaceous and Tertiary Rocks in the Southern Ute Indian Reservation and adjacent areas in the northern San Juan Basin, Southwestern Colorado, in Zech, R.S., Geology and Mineral Resources of the Southern Ute Indian Reservation: U.S. Geological Survey Professional Paper 1505-B.

Aubrey, W.M., 1991, Stratigraphic architecture and deformational history of Early Cretaceous foreland basin, eastern Utah and southwestern Colorado, in Huffman, Jr., A.C., Lund, R.W., Godwin, L.H., eds., Geology and Resources of the Paradox Basin, 1996 Special Symposium, Utah Geological Association and Four Corners Geological Society, p. 211-220.

Ayers, W.B., Jr., W.A. Ambrose, and J.S. Yeh, 1994, Coalbed methane in the Fruitland Formation, San Juan basin: depositional and structural controls on occurrence and resources, in W.B. Ayers, Jr., and W.R. Kaiser, eds., Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Bulletin 146, Socorro, p. 13-61.

Ayers, W.B., and S.D. Zellers, 1994, Coalbed methane in the Fruitland Formation, Navajo Lake area: geologic controls on occurrence and producibility, in W.B. Ayers, Jr., and W.R. Kaiser, eds., Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Bulletin 146, Socorro, p. 63-85.

Baumgardner, R.W., Jr., 1994, Use of lineament attributes to predict coalbed methane production in the northern San Juan Basin, in W.B. Ayers, Jr., and W.R. Kaiser, eds., Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Bulletin 146, Socorro, p. 119-132.

Bell, G.J., 1989, Pressurized Coal Core Desorption Measurement Southern Ute Mobil 36-1 Well, San Juan Basin, Colorado: Resource Enterprises, INC., Grand Junction, Colorado.

Bevacqua, L.J., 1983, Wildwater, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 907-908.

Bland, D.M., 1992, Coalbed methane from the Fruitland Formation, San Juan Basin, New Mexico, in Lucas, S.G., et al., eds., San Juan Basin IV, New Mexico Geological Society forty-third annual field conference, p. 373-383

Bowman, K.C., 1978, Ignacio Blanco Dakota, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 131, 137, 390, 393.

Boyce, B.C., and L.C. Burch, 1988, The Southern Utes: An economically and socially successful Indian nation building upon its history and challenging the future, in Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico, Rocky Mountain Association of Geologists, Denver, Colorado, p. 11-18.

Bircher, J.E., 1978, Glades Fruitland, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 966.

Broadhead, R.F., 1989, Petroleum production and frontier exploration in New Mexico, in Lorenz, J.C, Lucas, S.G. eds., Energy Frontiers in the Rockies, AAPG-SEPM-IMD Rocky Mountain Section, p. 35-46.

Brown, C.F., 1978, Aztec Pictured Cliffs, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 192.

Brown, C.F., 1978, Blanco Pictured Cliffs, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 225.

Brown, C.F., 1978, Blanco Pictured Cliffs, East, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 228.

Chidsey, T.C., D.E. Eby, and D.M. Lorenz, 1996, Geological reservoir characterization of small shallow-shelf carbonate fields, southern Paradox Basin, in Huffman, Jr., A.C., Lund, R.W., Godwin, L.H., eds., Geology and Resources of the Paradox Basin, 1996 Special Symposium, Utah Geological Association and Four Corners Geological Society, p. 39-56.

Clark, W.R., et. al, 1989, Frontier Exploration Plays in Colorado, in Lorenz, J.C, Lucas, S.G. eds., Energy Frontiers in the Rockies, AAPG-SEPM-IMD Rocky Mountain Section, p. 57-68.

Close, J.C., et al., 1991, Western Cretaceous Coal Seam Project, Measurement and Analysis of Sorption Isotherm Data: Gas Research Institute Topical Report GRI-91/0335, Chicago Illinois.

Close, J.C., T.J. Pratt, M.J. Mavor, 1991, Western Cretaceous Coal Seam Project, Preliminary Evaluation of the Co-operative Research Well Valencia Canyon 32-1: Gas Research Institute Topical Report GRI-92/0129, Chicago, Illinois.

Condon, S.M., 1992, Geologic and Structure Contour Map of the Southern Ute Indian Reservation and Adjacent Areas, Southwestern Colorado and Northeastern New Mexico, U.S. Department of the Interior, U.S. Geological Survey, scale 1:100,000.

Condon, S.M., 1992, Geologic framework of Pre-Cretaceous rocks in the Southern Ute Indian Reservation and adjacent areas, southwestern Colorado and Northwestern New Mexico, in Zech ed., Geology and Mineral Resources of the Southern Ute Indian Reservation: U.S. Geological Survey Professional Paper 1505-A.

Condon, S.M., and A.C. Huffman Jr., 1994, Northwest-southeast-oriented stratigraphic cross sections of Jurassic through Paleozoic rocks, San Juan Basin and vicinity, Colorado, Arizona, and New Mexico: Oil and Gas Investigations Chart, U.S. Geological Survey.

Conway, M.W., 1994, Is it time to put the final nail in the fraccing coffin?: Methane from Coal Seams Technology, April, 1994, p. 7-12.

Craney, D.L., 1978, Ignacio Blanco Fruitland-Pictured Cliffs, East, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 134.

Cross, T.A., and M.A. Lessenger, 1997, Correlation strategies for clastic wedges, in RMAG special publication.

Davis, T.L., and G.M. Jackson, 1988, Seismic stratigraphy study of algal mound reservoirs, Patterson and Nancy fields, Paradox Basin, San Juan County, Utah: Geophysics, V. 53, No. 7, p. 875-880.

Doneselaar, M. E., 1989, The Cliff House Sandstone, San Juan Basin, New Mexico: Model for the stacking of 'transgressive' barrier complexes: Journal of Sedimentary Petrology, Vol. 59, No. 1, p. 13-27.

Donovan, W., 1978, Price Gramps, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 157.

DuChene, H.R., 1989, Fractured Reservoirs in the San Juan Basin, Colorado and New Mexico, in Lorenz, J.C, Lucas, S.G. eds., Energy Frontiers in the Rockies, AAPG-SEPM-IMD Rocky Mountain Section, p. 101-109.

Dunbar, R.W., et al., 1992, Strandplain and deltaic depositional models for the Point Lookout Sandstone, San Juan basin and Four corners platform, New Mexico and Colorado, in Lucas, S.G., et al., eds., San Juan Basin IV, New Mexico Geological Society forty-third annual field conference, p. 199-206.

Edmister, J.A., 1983, Cottonwood Fruitland, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 946.

Fassett, J.E., 1988, Geometry and depositional environment of Fruitland Formation coal beds, San Juan basin, New Mexico and Colorado: Anatomy of a giant coal-bed methane deposit, in Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico, Rocky Mountain Association of Geologists, Denver, Colorado, p. 23-38.

Fassett, J.E. ed., 1983, Oil and gas fields of the Four Corners area, Volume III, Four Corners Geological Society, 727 p.

Fassett, J.E. ed., 1978, Oil and gas fields of the Four Corners area, Volumes I and II, Four Corners Geological Society, 727 p.

Gautier, D.L., G.L. Dolton, K.I. Takahashi, and K.L. Varnes, eds., 1996, 1995 National Assessment of United States Oil and Gas Resources-Results, Methodology, and Supporting Data: U.S. Geological Survey Digital Data Series DDS-30, Release 2.

Gorhman, Jr., F.D., et al., 1979, Fractures in Cretaceous rocks from selected areas of San Juan Basin, New Mexico-Exploration Implications: AAPG Bulletin V. 63, No. 4, P. 598-607.

Gorhman, Jr., F.D., and L.A. Woodward, J.F. Callender, and A.R. Greer, 1977, Fracture permeability in Cretaceous rocks of the San Juan Basin, in Fasset, J.E., James, H.L., and Hodgson, H.E., eds., San Juan Basin III, New Mexico Geological Survey, p. 235-241.

Greer, A.R., 1978, La Plata Gallup, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 371.

Hamilton, D.P, 1983, Twin Mounds Pictured Cliffs, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 540.

Harr, C.L., 1996, Paradox Oil and Gas Potential of the Ute Mountain Ute Indian Reservation, in Huffman, Jr., A.C., Lund, R.W., Godwin, L.H., eds., Geology and Resources of the Paradox Basin, 1996 Special Symposium, Utah Geological Association and Four Corners Geological Society, p. 13-28.

Harr, C.L., 1988, The Ignacio Blanco gas field northern San Juan basin, Colorado, in Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico, Rocky Mountain Association of Geologists, Denver, Colorado, p. 205-219.

Hart, A.W., and E.G. Mickel, 1983, Wickiup, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 904.

Hoppe, W.F., 1992, Hydrocarbon potential and stratigraphy of the Pictured Cliffs, Fruitland, and Ojo Alamo Formations in the northeastern San Juan basin, New Mexico, in Lucas, S.G., et al., eds., San Juan Basin IV, New Mexico Geological Society forty-third annual field conference, p. 359-371.

Hoppe, W.F., 1978, Animas Chacra, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 184.

Hornbeck, J. M., 1978, Flora Vista Gallup, in Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 294.

Huffman, Jr., A.C., 1996, San Juan Basin Province (022), in Gautier, D.L., et al., 1995 National assessment of United States oil and gas resources-results, methodology, and supporting data, U.S Geological Survey Digital Data Series DDS-30 Release 2.

Huffman, Jr., A.C., and S.M. Condon, 1993, Stratigraphy, Structure, and Paleography of Pennsylvanian and Permian rocks, San Juan Basin and adjacent areas, Utah, Colorado, Arizona, and New Mexico: U.S. Geological Survey Bulletin 1808-O, plates, p. 9.

Huffman, Jr., A.C., and S.M. Condon, 1994, Southwest-northeast-oriented stratigraphic cross sections of Jurassic through Paleozoic rocks, San Juan Basin and vicinity, Colorado, Arizona, and New Mexico: Oil and Gas Investigations Chart, U.S. Geological Survey.

Hunt, A.P., and L.G. Spencer, 1992, Stratigraphy, paleontology and age of the Fruitland and Kirtland Formations (Upper Cretaceous), San Juan basin, New Mexico, in Lucas, S.G., et al., eds., San Juan Basin IV, New Mexico Geological Society forty-third annual field conference, p. 217-239.

Indian Land Areas: U. S. Department of the Interior Bureau of Indian Affairs, 1993.

Jennette, D.C., and C.R. Jones, 1995, Sequence stratigraphy of the Upper Cretaceous Tocito Sandstone: A model for tidally influenced incised valleys, Sand Juan Basin, New Mexico, in Van Wagoner, J.C., Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits, Outcrop and subsurface examples from the Cretaceous of North America, AAPG Memoir 64, p. 311-348.

Kaiser, W.R., and W.B. Ayers, Jr., 1994, Coalbed methane production, Fruitland Formation, San Juan basin: Geologic and hydrologic controls, in W.B. Ayers, Jr., and W.R. Kaiser, eds., Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Bulletin 146, Socorro, p. 187-207.

Katzman, D., and R. Write-Dunbar, 1992, Parasequence geometry and facies architecture in the upper Cretaceous Point Lookout Sandstone, Four Corners Platform, southwestern Colorado, in Lucas, S.G., et al., eds., San Juan Basin IV, New Mexico Geological Society forty-third annual field conference, p. 187-197.

Keighin, C.W., 1996, Petroleum geology and hydrocarbon potential of pre-Dakota strata, western portion of the Southern Ute Indian Reservation, Colorado, *in* Huffman, Jr., A.C., Lund, R.W., Godwin, L.H., eds., Ge-Malone, T.L., 1978, La Jara Fruitland, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 369.

Marvin, L, and J.P. Matheny, 1978, Cha Cha Gallup, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 256.

Matheny, M.L., 1983, Cinder Buttes, *in* Fassett, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 873.

Matheny, M.L., 1978, Barker Creek Dakota, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 198.

Matheny, M.L., 1978, Barker Creek Paradox, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 201.

Matheny, M.L., and C.J. Little, 1978, Many Rocks Gallup, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 398.

Matheny, M.L., and C.J. Little, 1978, Many Rocks Gallup, North, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 403.

Mavor, M.J., 1994, Well testing for San Juan Basin open-hole completion evaluation: Methane from Coal Seams Technology, April, 1994, p. 19-26.

Mavor, M.J., et al., 1992, Western Cretaceous Coal Seam Project Summary of the Vertical COAL Site, San Juan Basin: Gas Research Topical Report GRI-92/0504, Chicago Illinois.

Mavor, M.J., et al., 1990, Western Cretaceous Coal Seam Project, Preliminary Evaluation of the Co-operative Research Well FC Federal #12, Gas Research Institute Topical Report, Chicago Illinois.

McEachin, W.D., and R.M. Royce, 1978, Horseshoe Gallup, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 335.

Meibos, L.C., 1983, Navajo City Chacra, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 989.

Meibos, L.C., 1983, Nenahnezad Mesaverde, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 992.

Middleman, A.A., 1983, Albino Gallup, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 924.

Middleman, A.A., 1983, Albino Pictured Cliffs, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 927.

Molenaar, C.M., D. Nummedal, and W.A. Cobban, 1996, Regional stratigraphic cross sections of the Gallup Sandstone and associated strata around the Sand Juan Basin, New Mexico, and parts of adjoining Arizona and Colorado: Oil and Gas Investigations Chart, U. S. Geological Survey.

Molenaar, C.M., and J.K. Baird, 1991, Stratigraphic cross sections of Upper Cretaceous rocks in the Northern San Juan Basin, Southern Ute Indian Reservation, southwestern Colorado, *in* Zech ed., Geology and Mineral Resources of the Southern Ute Indian Reservation: U.S. Geological Survey Professional Paper 1505-C

Molenaar, C.M., and J.K. Baird, 1989, North-south stratigraphic cross sections of Upper Cretaceous rocks, northern San Juan Basin, southwestern Colorado: Miscellaneous Field Studies Map, U.S. Geological Survey.

Molenaar, C.M., 1988, Stratigraphic cross section showing upper Cretaceous rocks across the San Juan basin, New Mexico and Colorado, *in* Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico, Rocky Mountain Association of Geologists, Denver, Colorado, p. 21.

Nuccio, V.R., and S.M. Condon, 1996, Burial and thermal history of the Paradox Basin, Utah and Colorado, and petroleum potential of the middle Pennsylvanian Paradox Formation, *in* Huffman, Jr., A.C., Lund, R.W., Godwin, L.H., eds., Geology and Resources of the Paradox Basin, 1996 Special Symposium, Utah Geological Association and Four Corners Geological Society, p. 57-76.

Nummedal, D., 1992, Sequence stratigraphy in ramp settings-with application to upper Cretaceous rocks in the San Juan basin, *in* Lucas, S.G., et al., eds., San Juan Basin IV, New Mexico Geological Society forty-third annual field conference, p. 185-186.

Nummedal, D., and C.M. Molenaar, 1995, Sequence stratigraphy of ramp-setting strand plain successions: the Gallup Sandstone, New Mexico, *in* Van Wagner, J.C., Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits, Outcrop and subsurface examples from the Cretaceous of North America, AAPG Memoir 64, p. 277-310.

Olszewski, A.J., and R.A. Schraufnagel, 1993, Development of formation evaluation technology for coalbed methane development: Methane from Coal Seams Technology, February 1993, P. 32-36.

Olszewski, A.J., and J.D. McLennan, 1992, Development of formation evaluation technology for coalbed methane development: Methane from Coal Seams Technology, July 1992, P. 25-29.

Osterhoudt, W., 1978, Chromo, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 111.

Pritchard, R.L., 1987, Flora Vista Mesaverde, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 131.

Raup, O.B, and R.J. Hite, 1992, Lithology of evaporite cycles and cycle boundaries in the upper part of the Paradox Formation of the Hermosa Group of Pennsylvanian Age in the Paradox Basin, Utah and Colorado: U.S. Geological Survey Bulletin 2000-B.

Rice, D.R., and T.M. Finn, 1996, Coal-bed gas plays, *in* Gautier, D.L., et al., eds., 1995 National assessment of United States oil and gas resources-results, methodology, and supporting data, U.S. Geological Survey Digital Data Series DDS-30 Release 2.

Rice, D.D., et al., 1988, Identification and significance of coal-bed gas, San Juan basin, northwestern New Mexico and southwestern Colorado, *in* Fassett, J.E., ed., Geology and coal-bed methane resources of the northern San Juan basin, Colorado and New Mexico, Rocky Mountain Association of Geologists, Denver, Colorado, p. 51-59.

Riggs, E.A., 1983, Wyper Farmington, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 1059.

Riggs, E.A., 1978, Verde Gallup, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 550.

Roth, G., and R.E. Lauth, 1983, Alkali Gulch, West, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 867.

Roth, G., and R.E. Lauth, 1983, Menefee Mountain, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 884.

Rueger, B.F., 1996, Palynology and its relationship to climatically induced depositional cycles in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of southeastern Utah: U.S. Geological Survey Bulletin 2000-K.

Sandberg, D.T., 1990, Coal resources of Upper Cretaceous Fruitland Formation in the Southern Ute Indian Reservation, Southwestern Colorado *in* Zech R.S. ed., Geology and Mineral Resources of the Southern Ute Indian Reservation, U.S. Geological Survey Professional Paper 1505-D.

Scott, A.R., W.R. Kaiser, and W.B. Ayers, Jr., 1994, Thermal maturity of Fruitland coal and composition of Fruitland Formation and Pictured Cliffs Sandstone gases, *in* W.B. Ayers, Jr., and W.R. Kaiser, eds., Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Bulletin 146, Socorro, p. 165-186.

Sperandio, R.J., 1983, Sedro Canyon Fruitland, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volume III, Four Corners Geological Survey, p. 1029.

Stevenson, G.M., 1989, Petroleum Exploration in southwestern Colorado: Paradox Basin, *in* Lorenz, J.C, Lucas, S.G. eds., Energy Frontiers in the Rockies, AAPG-SEPM-IMD Rocky Mountain Section, p. 85-89.

Stevenson, G.M., 1978, Middle Canyon Dakota, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 421.

Tezak, M.A., 1978, Ute Dome Dakota, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 543.

Tezak, M.A., 1978, Ute Dome Paradox, *in* Fasset, J.E., ed., Oil and Gas Fields of the Four Corners Area, Volumes I and II, Four Corners Geological Survey, p. 546.

Tremain, C.M., S.E. Laubach, and N.H. Whitehead III, 1994, Fracture (cleat) patterns in Upper Cretaceous Fruitland Formation coal seams, San Juan basin, *in* W.B. Ayers, Jr., and W.R. Kaiser, eds., Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, New Mexico Bureau of Mines and Mineral Resources, Bulletin 146, Socorro, p. 87-102.

Turner-Peterson, C.E. 1989, Recent geologic studies in the San Juan Basin: Highlights and new directions, *in* Lorenz, J.C, Lucas, S.G. eds., Energy Frontiers in the Rockies, AAPG-SEPM-IMD Rocky Mountain Section, p. 177-188.

Valasek, D. 1995, The Tocito Sandstone in a sequence stratigraphic framework: An example of landward-stepping small-scale genetic sequences, *in* Van Wagner, J.C., Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits, Outcrop and subsurface examples from the Cretaceous of North America, AAPG Memoir 64, p. 349-370.

White, J.V., and B.L. Kirkland, 1996, Diagenesis and porosity distribution of Pennsylvanian Paradox Formation Carbonates (Upper Ismay), Southeastern Utah, *in* Huffman, Jr., A.C., Lund, R.W., Godwin, L.H., eds., Geology and Resources of the Paradox Basin, 1996 Special Symposium, Utah Geological Association and Four Corners Geological Society, p. 151-160.

Whitehead III, N.H. 1993, San Juan Basin Plays-Overview, *in* Hjellming C.A. ed., Atlas of Major Rocky Mountain Gas Reserviors: available from New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 878801

Young, G.B.C., 1994, Parametric study of open-hole cavity performance: Methane from Coal Seams Technology, April, 1994, p. 35-38