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**GEOHYDROLOGIC FEASIBILITY STUDY OF THE PICEANCE BASIN OF COLORADO
FOR THE POTENTIAL APPLICABILITY OF JACK W. MCINTYRE'S PATENTED
GAS/PRODUCED WATER SEPARATION PROCESS**

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**For
Jack W. McIntyre
Fort Stockton, Texas**

And

**U.S. Department of Energy
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**By
Geraghty & Miller, Inc.
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GEOHYDROLOGIC FEASIBILITY STUDY OF THE PICEANCE BASIN OF COLORADO FOR THE POTENTIAL APPLICABILITY OF JACK W. MCINTYRE'S PATENTED GAS/PRODUCED WATER SEPARATION TOOL

ABSTRACT

Geraghty & Miller, Inc. of Midland, Texas conducted geologic and hydrologic feasibility studies of the potential applicability of Jack McIntyre's patented process for the recovery of natural gas from coalbed/sand formations in the Piceance Basin through literature surveys. Jack McIntyre's tool separates produced water from gas and disposes of the water downhole into aquifers unused because of poor water quality, uneconomic lifting costs or poor aquifer deliverability. The beneficial aspects of this technology are two fold. The process increases the potential for recovering previously uneconomic gas resources by reducing produced water lifting, treatment and disposal costs. Of greater importance is the advantage of lessening the environmental impact of produced water by downhole disposal. Results from the survey indicate that research in the Piceance Basin includes studies of the geologic, hydrogeologic, conventional and unconventional recovery oil and gas technologies. Available information is mostly found centered upon the geology and hydrology for the Paleozoic and Mesozoic sediments. Lesser information is available on production technology because of the limited number of wells currently producing in the basin. Limited information is available on the baseline geochemistry of the coal/sand formation waters and that of the potential disposal zones. No determination was made of the compatibility of these waters. The study also indicates that water is often produced in variable quantities with gas from several gas productive formations which would indicate that there are potential applications for Jack McIntyre's patented tool in the Piceance Basin.

INTRODUCTION

The Piceance Basin has a significant potential for the production of coalbed methane and is one of the prime target coalbed methane area in the western United States. Coals and associated sandstones of the Cretaceous-age Mesaverde Formation have total gas in-

place reserves estimated from 30 to as much as 110 TCF of methane (GRI 1986). In 1980 the National Petroleum Council estimated that 32 TCF of gas was recoverable from the basin (Johnson 1987). Because of these estimates, extensive investigations have been undertaken through grants from the Department of Energy and efforts made by gas producers to optimize the recovery of this resource.

Historically from areas of coalbed methane resources such as the San Juan Basin of New Mexico, most of the completed wells produce methane and wastewater (brine). The produced water is usually treated and released to a surface body of water in conformance with a NPDES permit. Treatment facilities are expensive to construct and operation and maintenance costs can be high especially when large volumes of water are produced. Also, environmental regulations pertaining to the release of wastewater to surface waters of the United States is presently under governmental investigation.

A new process patented by Jack W. McIntyre has both economic and environmental advantages over the conventional surface treatment and disposal. This process has been tested in the Michigan Basin and reported to be successful. The process is based on utilizing a single well for both production and water disposal. During production, fluids enter the wellbore, gas rises to the surface and water moves down into the disposal zone either by gravity or mechanical pumping. This method allows separation of gas with simultaneous disposal of the water without the economic and environmental obstacles of bringing the water to the surface. A description and discussion of Jack W. McIntyre's process is summarized in the compendium of the seven basins studied under this contract.

The objective of this investigation was to identify the geologic and hydrologic parameters associated with the production of coalbed methane and associated sandstone gas reservoirs in the Piceance Basin for the potential use of Jack McIntyre's patented tool. The investigation includes the description of pertinent geologic formations in ascending order, the present-day structure of each formation, the stratigraphy of each formation as it applies to potential methane gas production and water disposal, hydrologic conditions (formation

pressure, fluid chemistry, etc.) and reservoir and production history. Published papers and reports were the primary sources of information utilized for this investigation. No field acquisition of data was performed during this investigation, and Jack McIntyre's process was not tested in the Piceance Basin.

GEOLOGICAL SETTING

The Piceance Basin is an northwest-southeast trending structural basin located in the northwestern quarter of Colorado (Figure 1). It covers major portions of Rio Blanco, Garfield and Mesa Counties and parts of Moffatt, Gunnison, Delta and Pitkin Counties. The basin was formed during the Larimide Orogeny. The basin is 150 miles long. At its widest point on the north the basin is about 90 miles wide but the basin narrows gradually to less than 20 miles in width at its southeastern extremity. The total surface area of the basin is slightly more than 7,000 square miles. The form of the basin is evident at the surface by viewing the outcrop of the resistant beds of the Mesaverde Formation (Mesozoic rocks). At depth the shape of the basin is more complex. In general the basin can be described as an asymmetrical syncline with several anastomosing synclinal axes. Structural the basin is bounded by the White River Uplift on the east, the Umcompahgre-Gunnison Uplift on the south, and the Douglas Creek Arch and Axial Basin Arch on the west and north, respectively (Murray & Haun 1974) (Figure 2). The basin has a steeply dipping eastern limb and a gently dipping western limb with nearly horizontal beds in the center (TRW 1979). The main axis of the basin lies parallel to the steep eastern limb. The surface expression of the eastern limb structure is the Hogback Monocline which is considered part of the White River Uplift (Murray & Haun 1974).

EXPLANATION

TERTIARY
VOLCANIC
ROCKS

TERTIARY
SEDIMENTARY
ROCKS

MESOZOIC
ROCKS

PALEOZOIC
ROCKS

PRECAMBRIAN
ROCKS

Figure 1. General geologic map of northwestern Colorado.
(Maclachlan 1987).

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Figure 2. Structural basins and uplifts. (MacLachlan 1987).

Surface drainage in the basin is divided between the tributaries of the Colorado River and the White River. The Colorado River is the primary drainage system for the southern two-thirds of the basin. In the northern part of the basin where Piceance Creek is located, the White River is the primary river system. The divide between these two river systems is called the Roan Plateau. (Choate 1984)

The topography of the basin is characterized by wide variations in elevations, high plateaus and deep canyons. While the average elevations are approximately 5,000 to 8,000 feet, elevations along the Colorado River are 4,500 feet and those in the Elk Mountains in the southeastern part of the basin area approach 12,000 feet.

Variations in climate follow variations in topography. In general the basinal area can be classified as having a semiarid climate. Precipitation averages about 8-20 inches per year over much of the basin although there are important topographic effects increasing precipitation in mountainous areas with winter snows (NWS, 1985). Sixty percent of annual precipitation occurs as winter snows. Other significant precipitation events occur as thunderstorms in early and late summer.

A generalized stratigraphic chart is found on the following page (Figure 3). The chart indicates the age of deposition, formation name and, in some cases, indicates general lithologic information for the formation. The stratigraphic sequence in the basin begins with

GEOLOGIC COLUMN: PICEANCE BASIN			
ERA	SYSTEM	SERIES	GEOLOGY FORMATION
CENOZOIC	Tertiary	Pliocene	
			Browns Park
		Miocene	
		Oligocene	
		Eocene	Uinta Formation
		Paleocene	Green River Formation
MESOZOIC	Cretaceous		Ft. Union Formation
			Lance Formation
		Upper	Mesaverde Group
			Williams Fork Fm. Hles Fm.
			Mancos Shale
		Lower	Mowry Shale
	Jurassic		Dakota Sandstone
			Morrison Fm.
			Salt Wash Mem.
			Curtis Formation
	Triassic		Entrada Sandstone
			Chinle Formation
			Shinarump Fm.
			Moenkopi Fm.
PALEOZOIC	Permian		Park City Fm.
	Penn-sylvanian		Maroon Fm.
			Weber Sandstone
	Missis-sippian		Morgan Fm.
			Leadville Limestone
	Devonian		Chaffee Group
	Silurian		
	Ordo-vician		Manitou Fm.
	Cambrian		Lodore Sandstone
	Pre-Cambrian		Uinta Mountain Group

Figure 3. General geologic column for the Piceance Basin. (after McMillian 1986).

rocks of pre-Cambrian age and includes representative formations from the Paleozoic, Mesozoic and Cenozoic Eras (Maclachlan 1987).

The following is a brief geologic history of the basin. During early and middle paleozoic time, the basin was a part of the Cordilleran miogeosyncline eastern foreland shelf. Sediments accumulating on the shelf were primarily carbonates, sandstones and minor amounts of shale. The first significant change in deposition occurred in the early Pennsylvanian when orogenic activity caused the shelf areas of the geosyncline to be segmented into smaller elongated basins separated by emerging elements of the Ancestral Rockies. Erosion of these Ancestral Rockies highland areas created thick fans of coarse red clastics emptying into the restricted environments which over time formed in these smaller basins. These terrestrial sediments from the east interfinger on the western side of the basin with the marine sediments of the Cordilleran geosyncline. As the highlands were reduced by erosion through Permian time, the sediments became finer and some minor amounts of carbonate deposition occurred in the deeper part of the basin. By the end of the Paleozoic, open shelf conditions had returned, however, fine red clastics sedimentation continued into the Mesozoic Era through to mid-Jurassic time. Paleozoic sedimentary rocks present in northwest Colorado comprise 27 geologic units with a total thickness varying from 5,250 to 22,400 feet (A.L. Gordon, 1986).

The second profound change in the geologic history of the basin occurred in the Cretaceous when a broad marine transgression occurred. This transgression proceeded from

the north and caused the development of thick wedges of time-transgressive sedimentation. For the Cretaceous this means that while marine shales were being deposited in the north and east, coarser clastics representing shoreline deposits were being deposited in the south and west. As time progressed, these rock units prograded to the north, more or less, so that an individual rock unit, i.e. a shoreline sand deposit, can represent a deposit which began in the early Cretaceous in one area and continuing through to the late Cretaceous in other locations (McGookey et al 1972). The Cretaceous shoreline deposits are important hydrocarbon targets in the Piceance Basin.

The lower part of the Cretaceous section is composed primarily of marine shales representing the marine transgression across a broad shelf. The upper part of the Cretaceous section indicates the general but sometimes interrupted regression following that transgression. The regressive phase is represented by complex deltaic and coastal plain sedimentation composed of intercalated sandstones, shales and coals.

Regional tilting at the end of the Cretaceous associated with the Laramide orogeny caused the structural axis of the basin to move toward the east. The axis deepened rapidly as the opposing White River Uplift was rising. Cenozoic sedimentation into the Piceance Basin includes Eocene and Paleocene sandstones deposited on the eastern side of the basin and derived from the rising White River uplift. On the western side of the basin highly organic lacustrine shales and marlstones were deposited and interfingered with the sandstones derived from the White River uplift. These Eocene and Paleocene deposits are

related to Lake Uinta and the Uinta Basin located to the west of the Piceance Basin. After a period of nondeposition during the early Oligocene, late Oligocene and Miocene volcanism and uplift led to the sculpting of the basin as we see it today. (Dunn 1972) Figure 4 is a map of the major structural features of the present Piceance Basin.

STRUCTURE AND STRATIGRAPHY

Gas production in the Piceance Basin is confined to a few formations. These units are the Jurassic aged Morrison and Entrada formations, the Cretaceous-aged rocks (Dakota sandstone, Mancos Shale and Mesaverde Group), the Eocene-aged Green River and Wasatch formations and the Paleocene Uinta formation. The reconstruction of the geologic history of these units will be discussed because of their potential applicability for the use of the McIntyre process in recovering these gas reserves. This historical geologic reconstruction is beneficial because it helps define the conditions under which the potential reservoir and source rocks evolved. The elements of this study disclose the depositional and diagenetic changes caused by tectonics, weathering and hydraulics factors in the formation of gas and the trapping mechanisms both proven and inferable from the reconstruction. In addition the study helps determine the potential for hydrocarbon generation and the potential magnitude of that resource.

EXPLANATION

OUTCROP SYMBOLS

Miocene(?) and Pliocene volcanic rocks

Base of Eocene Green River Formation

Base of Eocene and Paleocene Wasatch Formation

Mesozoic and Paleozoic rocks
(locally includes Tertiary Browns Park Formation)

Precambrian rocks

STRUCTURE SYMBOLS

FOLDS

Anticline
showing direction of plunge

Syncline
showing direction of plunge

Monocline

FAULTS

Normal fault
bar and ball on downthrown side

Reverse fault
dotted where concealed or inferred

KEY TO NUMBERED SELECTED STRUCTURES

1. Red Wash syncline (structurally deepest part of Piceance Creek basin on troughline near number)	16. Massadona anticline
2. Piceance Creek dome	17. Pinyon Ridge anticline
3. South Rangely syncline	18. Skull Creek anticline
4. Sulphur Creek anticlinal nose	19. Yampa fault
5. Hunter Creek syncline	20. Cross Mountain uplift
6. Douglas Creek anticline	21. Axial Basin anticline
7. Crystal Creek anticlinal nose	22. Juniper Mountain uplift
8. Clear Creek syncline	23. Bell Rock anticline
9. DeBeque anticline	24. Moffat anticline
10. Asbury Creek anticline	25. Axial Basin anticline
11. Highline Canal anticline	26. Danforth Hills anticline
12. Garmesa anticline	27. Maudlin Gulch anticline
13. South Douglas Creek anticline	28. Wilson Creek anticline
14. Rangely anticline	29. Ninemile anticline
15. White River dome	30. Yellowjacket anticline
	31. Grand Hogback monocline
	32. Meeker dome
	33. Divide Creek anticline

Compiled for the 1974 Field Conference of the Rocky Mountain Association of Geologists
by M. W. Reynolds from available published sources

Figure 4. Major structural features. (Murray & Haun 1974).

Figure 4 (continued). Major structural features. (Murray & Haun 1974).

JURASSIC PERIOD

During the Jurassic Period, the ancestral Rocky Mountains were being rejuvenated. In particular the Central Colorado Uplift controlled significant clastic deposition into the Piceance Basin. In the Colorado Plateau area, rocks of Jurassic age are generally divided into four transgressive-regressive cycles. Only three of the cycles are significantly represented by rock units in the basin. Early Jurassic rocks have not been identified; however rocks of middle- and late-Jurassic age representing the three remaining cycles are present. During these cycles, the basin was mainly a depositional shelf area. The prominent formations representing Jurassic deposition in descending age are the Entrada, Summerville and Morrison. (Peterson 1974)

In general, the Jurassic sequence thins toward the southeastern part of the basin. In fact the Entrada and Summerville may be missing in the subsurface in the very southern portion and parts of the eastern section of the basin, respectively. Due to the non-deposition of some of the Jurassic section, it is about 250 feet thick in the south but more than 800 feet thick in the northern part of the basin.

During Entrada time the climate was apparently quite dry and non marine deposition was probably mainly eolian. The Entrada formation is almost 100 percent non-marine sandstone on the eastern side of the basin but grades to a partly marine section on the west side. Along with this gradation to more marine rocks is a decrease in the sandstone content

of the formation and increases in mudstones and siltstones (Peterson 1974). The thickness of the Entrada is about 150 feet near Grand Junction, Colorado (Johnson 1965).

The Summerville-Curtis section is relatively thin and represents marine deposition. The lithology of the unit is alternating thin bed of sandstone with siltstones, bentonitic clays and shales. The thickness of the Summerville formation near Grand Junction is approximately 50 feet (PP451).

The single largest unit of the Jurassic section is the Morrison formation which represents the last regression of the Jurassic Sea. The Morrison section typifies fluvial and lacustrine dominated deposition on the emerging sea floor plain which consisted of the earlier Jurassic sedimentation (Peterson 1972). This formation has been subdivided by lithologic characteristics into four members, being the Salt Wash member (the base), the Recapture member, the Westwater Canyon member and Brushy Canyon member (the uppermost). In general, the Morrison can be described as composed of channel and overbank sandstones and siltstones and varicolored red, green and tan mudstones (Peterson 1972). The distribution of these rock components in the basin can best be described is that most of the Piceance Basin area contains Morrison-aged rocks having 20 to 50 percent sandstone sections. However in the northwestern quarter of the basin the Morrison is at least 80 percent varicolored shale while in the extreme northeastern corner of the basin the formation is predominately (i.e. more than 50%) sandstone.

The thickness of the Morrison Formation near Grand Junction is approximately 600 feet (Johnson 1965).

CRETACEOUS PERIOD

The Cretaceous rocks are a complex assemblage of marine and near shore marine sediments (McGookey, etal 1972). A confusing nomenclature for the rock units in the Piceance Basin has been used in the literature in part because of the time transgressive nature of these rock units and the consequential variation in the stratigraphic sequence in different locations. The variations can be characterized as eastward prograding tongues of shallow water continental deposits (McGookey, etal 1972). This report will use the most common names for Cretaceous aged units. Nonetheless the complexity of Cretaceous stratigraphy and the prevalence of fossil fuel production both in the subsurface and coal deposits at the surface has caused the assignment of local rock names. This situation has historically caused difficulty in the discussions of the stratigraphy.

The total thickness of Cretaceous-aged rocks in the Piceance Basin exceeds 10,000 feet. The greatest part of Cretaceous deposition occurred in the upper Cretaceous time interval. The common theme of late Cretaceous deposition in the Piceance Basin is the transgression of a Cretaceous sea to the south and west followed by a pulsating regression of that sea to the north and east. The marine transgression resulted in the deposition of dark marine shales. These shales have been given different names but they represent one

really large lithosome. This lithosome will be called the Mancos shale in this paper. The regressive facies inter-tonguing with the Mancos shale are more varied. They represent near shore and nonmarine rocks which are not only much smaller in areal and stratigraphic extent than the marine facie but also intercalate with each other in complex ways. These clastics were supplied from the west from the Cordilleran Mountain Range of western Utah (McGookey etal 1972). A major part of the hydrocarbon resources of the Piceance Basin are found in the near shore marine facies of coals and sandstones.

The lower Cretaceous is thin and, in most cases, non-existent in the Piceance Basin area. Evidence of widespread deposition did not occur until the late Cretaceous when the Dakota group, 200 feet of transgressive beds, were deposited under diverse marine and non-marine conditions.

Early (lower) cretaceous rocks are not well represented in the Piceance Basin. However, in some locales the earliest Cretaceous rocks, the Burro Canyon Formation, overlies the Jurassic rocks with some indications of unconformity. The Burro Canyon is a continental deposit of sandstone and shale which is less than 200 feet thick. The Dakota sandstone section is immediately above the Burro Canyon rocks but there are indications of unconformity between the two units, although in some areas the Burro Canyon has been assigned to the Dakota (Johnson 1965). A more major incursion of a shallow sea from the north covered the basin in middle Cretaceous time. This spreading of the sea was the result of the broad regional subsidence of the Rocky Mountain foreland basin.

The Dakota group can in some places be divided into three zones known as the upper, middle and the lower Dakota. The total thickness of the Dakota sandstone in the Piceance Basin is about 225 feet (Taylor 1987). The upper Dakota is characterized by fine grained sandstone, the middle Dakota by a shale and coal series and the lower by a coarse conglomerate (Beaumont et al. 1950). The age of the Dakota section varies because of its transgressive nature.

The marine section time stratigraphic equivalent to the Dakota is the Mowry shale. Although in the outcrop the Mowry is distinct from the overlying Mancos shale because the Mowry has alternating bands of light colors, it is essentially no more than a distinctive part of the very lowest part of the Mancos lithosome (RMAG Atlas 1972). The Mancos shale has a thickness of about 6,000 feet along the Grand Hogback (Taylor 1987). The Mancos represents continuous shale deposition through most of upper Cretaceous time. For probably two-thirds of the upper Cretaceous time, only Mancos shale was deposited in the Piceance Basin.

Following the deposition of the main body of the Mancos, an uplift occurred to the west and southwest of the Piceance Basin. The uplift caused the transportation of detritus into the basin which accumulated to form floodplains, deltas, swamps and barrier islands composed of deposits of alternating beds of sandstone, carbonaceous shale, siltstone and coalbeds. The coalbeds found within the Mesaverde group are the result of the Paludal

environment created by several advances and retreats of the strand line associated with this influx of detrital sediments.

The Mesaverde group in the Piceance Basin is generally divided into two formations. The lower formation is called the Illes and the upper formation is known as the Williams Fork. This report will use the nomenclature of Young 1982 (Figure 5). The Illes Formation contains three main sandstone bodies. These three are, in oldest to youngest order, the Corcoran, Cozzette and Trout Creek-Rollins sandstone members. Each of these members is separated from one another by shales, coaly shales or coalbeds (GRI Nov 86). Overlying the Illes is the Williams Fork Formation. The lower Williams Fork contains in its lower section primarily coals, coaly shales and shales. In the middle section of the Williams Fork, the marine Twentymile sandstone underlies the Paonia shale. The Paonia contains shales with interbedded coals. The upper part of the Williams Fork Formation is primarily fluvial sandstones with occasional coalbeds. In the Piceance Basin, the Williams Fork extends to the Cretaceous-Tertiary unconformity (Johnson 1987).

The thickness of the Mesaverde Group at the Grand Hogback is approximately 6,000 feet thick; the Illes formation being approximately 1,500 feet thick and the Williams Fork about 4,500 feet thick (Taylor 1987).

The end of the Cretaceous, i.e. Mesozoic time, was marked by tectonic activity. This tectonic activity is called the Laramide Orogeny and a significant paleo-environmental shift

Lee (1909, 1912), Cameo coal field; Hanks (1962), Somerset coal field; Collins (1970), Coal Basin		Johnson (1948) Wellborn (1962) Somerset		Warner (1964) Thompson Creek South Rifle Gap North		Young (1962) Southern Piceance Creek basin West East		Madden (1969) Eastern Piceance Creek basin New Castle South Rifle Gap North	
Wasatch Formation		Wasatch Formation		Not studied		Not studied		Not studied	
Ohio Creek Conglomerate		Ohio Creek Conglomerate							
Mesaverde Formation	Upper part	Mesaverde Formation	Barren member	Mesaverde Formation	Williams Fork Formation	Mesaverde Group	Williams Fork Formation	Mesaverde Group	Williams Fork Formation
	Paoia Shale Member		Upper coal member						
	Bowie Shale Member		Lower coal member						
	Rollins Sandstone Member		Rollins Sandstone Member						
Mancos Shale		Mancos Shale		Mancos Shale	Mancos Shale	Mancos Shale	Mancos Shale	Mancos Shale	Mancos Shale

Figure 5. Nomenclature of Upper Cretaceous rocks in southern and eastern Piceance basin. (modified from Ellis and Kelso 1987).

occurred during this Orogeny. Most of the present day structural features of the basin were formed at this time (Taylor 1987).

CENOZOIC ERA

Laramide orogenic activity caused the rise of the boundary structures which today define the extent of the Piceance Basin (Dunn 1972, 1974). The Douglas Creek Arch is known to be the oldest of the Piceance Basin boundary structures because both the Mesaverde and Wasatch formations thin over the arch (Taylor 1987). The White River Uplift is the most pronounced of the boundary features. Coincident with this White River Uplift and as a result of it, there was an eastward shift of the basinal axis, and the axis was severely steepened. Thick clastic sediments from the White River Uplift filled the eastern part of the basin as erosion of Cretaceous sediments occurred primarily on the western flank of the basin. This chain of events created the following stratigraphic sequence. From the eastern side of the basin, thick wedges of Paleocene and Eocene rocks thin westward and interfinger with lacustrine shales and marlstones deposited from the west. Filling of the basin was essentially accomplished by Eocene time.

Paleocene sediments in the Piceance Basin include the lower portion of the Wasatch Formation; the upper part of the Wasatch formation being of Eocene age. The Wasatch formation consists of 5,000 feet of varicolored claystones and shales with lenticular sands and conglomerate beds. Eocene environments include alluvial, fluvial, swamp, shoreline and

freshwater and saline water lacustrine sedimentation (RMAG 74, Roehler). The axial Basin Arch played a major role in the definition of these environments in the early and middle Eocene by forming a barrier which separated two ancient lakes. The lake present in the area of the Piceance Basin and extending a great distance to the west was called Lake Uinta (Taylor 1987). The younger Eocene rocks are the Green River Formation and the overlying Uinta Formation. The Green River Formation contains oil shales and other shales, mudstones and siltstones with deposits of evaporitic minerals amounting to about 3,500 feet of section. The Uinta consists of 1,000 feet of marlstones, siltstones, sandstones and tuff. These sediments were deposited primarily in Lake Uinta. Oligocene and Pliocene age deposits are represented only by intrusive and extrusive rocks. Oligocene rocks are mostly granodiorites. Miocene volcanism is represented as extensive basalt flows which are up to 200 feet thick on Grand Mesa (Taylor 1987). In some circumstances the intrusive rocks have altered existing rocks. In particular, Mesaverde coal rank has been altered in some parts of the southern Piceance Basin by this activity.

COAL AND COALBED METHANE - OCCURRENCE, QUANTITY IN-PLACE AND CHEMICAL CHARACTERISTICS

COAL OCCURRENCE

Important factors determining the regional character of the Piceance Basin is its depositional environment, the mainly fresh water swamps and flood plains along the migrating margins of a shallow continental sea that repeatedly encroached on and retreated (transgressed and regressed) from a broad southwestern land mass (Choate et al. 1984). It is because of these transgression and regression cycles and a relatively stable climate along

with constant shoreline trends and a uniform source of sediment supply that coalbeds are present in the Piceance Basin. Coal in the basin varies from semi-anthracite to subbituminous rank; the higher rank coals correlate with a high thermal gradient owing to depth anomalous heat sources (Johnson 1987).

Coals are present and productive of methane in the Mesaverde, Fort Union and Green River formations. This report will focus on the Mesaverde formation for which the greatest amount of production information is available. These are the significant coalbeds and associated gaseous low permeability sandstone reservoirs in the Mesaverde section. Production of coalbed methane will be discussed in detail from the coals of the Mesaverde Group.

Estimated Coal in Place and Chemical Characteristics

Mesaverde Formation

There are approximately 18 coal seams in the Mesaverde Formation with an aggregate thickness of between 30 and 80 feet (Figure 6). The individual seams may be lenticular and discontinuous or they may be thick and continuous with lateral extent in excess of 2,000 square miles (TRW 1979). The primary coal zones of the Mesaverde Group are known as the Black Diamond Coal Group (oldest), the Cameo Coal Group (middle) and the Coal Ridge Coal Group (youngest). The Black Diamond coals are found within the Illes Formation. These coals are 50 to 300 feet below the Trout Creek-Rollins sandstone. The Cameo and Coal Ridge Group are located within the Williams Fork Formation and are separated by the Twentymile sandstone (GRI 1986). The Cameo coals are found in the interval above the Trout Creek-Rollins sandstone and below the Twentymile sandstone. A structure map of the Rollins sandstone in the Piceance Basin is shown as Figure 7 (Pitman et al 1987).

Figure 6. Total coal thickness (Johnson 1987) Piceance basin.

Figure 7. Structure map, Rollins-Trout Creek Sandstone Reservoir Formation, Piceance basin. (Pitman et al 1989).

Based upon the location, rank and thickness of coal seams, the total drillable basin area for coalbed methane has been estimated to be approximately 6,500 square miles. The total gas in place (GIP) reserves for this area is 84 trillion cubic feet (TCF) (GRI 1986).

The rank of coals found within the Mesaverde deposits varies from semianthracite to High Volatile C Bituminous (Figure 8). For Piceance Basin coals the gas per ton of coal varies from about 5 cubic feet per ton for semianthracite up to 130 cubic feet per ton for High Volatile C Bituminous coals. The distribution of the total natural gas in place indicates that the east-central portion of the basin (from just north of the Colorado River and along the Grand Hogback south to the Mesa-Delta County line) contains the most gas in place per square mile. This area has approximately 30 billion cubic feet (BCF) per square mile. From this center, gas in place per square mile decreases outwardly to the north, south and west. Figure 9 shows the interpreted GIP per square mile (GRI 1986).

The greatest reserves of gas as estimated based upon the distribution of thick, high rank coals is in the east-central portion of the basin. In addition, within this east-central area, the density of structural deformation and associated fracturing make this area the more attractive for economic coalbed methane recovery because of the necessity of cleat porosity for the economic recovery of the gas in place.

The largest estimated gas reserves are found in the Cameo coals. Cameo coals account for more than 77 percent of the natural gas in place. GIP reserves in the Coal Ridge and Black Diamond coals are very similar and account for 11.8% and 10.5% of the total estimated natural gas in place, respectively (GRI 1985).

Figure 8. Coal rank, base of the Cameo coal zone. From Freeman (1979) and Nuccio and Johnson (1983) and Johnson (1987).

Figure 9. GRI 1986.

Black Diamond Coal Group

Black Diamond coals are found in lenticular deposits which are located primarily in the northern one-half of the basin. The southern edge of the coalbeds pinches out along a line roughly following the present course of the Colorado River. The Black Diamond coals also stratigraphically pinch out along the western flank of the basin. The coals are found as deep as 12,000 feet below the surface near the basin axis and as shallow as 2,000 feet on the southwestern side of the basin. The total thickness of the Black Diamond coals varies from 10 to 30 feet but the average coal thickness for most of the basin is about 10 feet. Thicker areas are found on the west and far northeastern corners of the basin. The rank of Black Diamond coals varies from semianthracite to High Volatile C Bituminous. The highest rank coals are found at the greatest depths and become progressively lower rank concentrically from the basin center. Total gas in place has been estimated to be 8.8 TCF for the approximately 3,400 square mile drillable area of these coal deposits. (GRI 1986)

Cameo Coal Group

Cameo coals are essentially found throughout the entire basinal area in more or less persistent seams. They average a total of approximately 30 feet in thickness although the deposits thicken towards the center of the basin where 40 feet of coal is common and in some areas 60 feet of coal is found. The depth to the Cameo coals is up to 10,000 feet in the north-central part of the basin but can be found at depths less than 2,000 feet on the western side of the basin. Coal rank is similarly distributed as that of the Black Diamond Group with semianthracites found in the area just south of the Colorado River and lower ranks of coals distributed radially from this center (Figure 10). The lowest rank of coals in the Cameo Group is a High Volatile C Bituminous. Total gas in place estimates for Cameo coals has been estimated to be approximately 65 TCF within its 6,500 square mile drillable area. (GRI 1986)

Coal Ridge Coal Group

The Coal Ridge Coal Group coals are confined to an elliptical area of approximately 1,500 square miles comprising the southeastern part of the basin. Most of this coal in the Piceance Basin is found south of the Colorado River. Average total coal thickness is approximately 20 feet of coal. The Coal Ridge Coal Group stratigraphically pinches out on the western side of the basin but reaches a thickness of 40 to 60 feet in the center of the coal field. The coal field thins radially from this center. Average depth to these coals is 8,000 feet near the Colorado River to less than 2,000 feet in the very southeastern corner of the basin. Coal rank varies from high volatile B bituminous to the low volatile bituminous found along the Garfield-Mesa County line. Total gas in place for Coal Ridge coals has been estimated at about 9.9 TCF. (GRI 1986)

COALBED METHANE OCCURRENCE

The Piceance Basin of northwestern Colorado is an active area of coalbed methane development in the western United States. Although many geologic factors act in concert to determine the availability and producibility of coalbed methane, the sedimentary depositional system that hosts the coal seams, structural features, igneous activity and fractures and faults within the coal are of primary importance in determining resources and recoverability of these natural gas reserves (Ayers et al. 1988).

Biogenic and Thermogenic Coalbed Methane Generation

During the early stages of coalification of buried peat, biogenic methane is generated as a by-product of bacterial respiration (Jones et al. 1990). Organic material which developed from the swamps and marshes of the marine environments is the source material for coalbeds and coalbed methane. After burial, if any sulfate is present in the coal formation, anaerobic bacteria consume all of the sulfate before methane generation can dominate. In environments of low sulfate content, methane production begins immediately

after the oxygen has been depleted (Rice and Claypool 1981). Aerobic bacteria metabolizes the oxygen present in both the organic material comprising the coalbeds and in the non-marine strata associated with the coalbeds. The aerobic bacteria produces carbon dioxide as a by-product which is consumed by anaerobic bacteria which in turn, produce biogenic methane gas. Given an appropriate amount of time and temperatures exceeding 50 degrees centigrade, most of the biogenic methane are produced (Jones et al. 1990).

As the depth of burial increases or the geothermal gradient increases, the temperatures exceed 50 degrees Centigrade. At this temperature additional water along with carbon dioxide and nitrogen is generated. Once the temperatures exceed 120 degrees C, thermogenic methane is produced. The maximum generation of thermogenic methane from coal occurs at approximately 150 degrees Centigrade. Methane is still generated at higher temperatures but at lower rates and volumes (Jones et al. 1990).

Coalbed Methane Generation

The generation of coalbed methane during the coalification process in the Piceance Basin is primarily due to three heating processes, although the generation and trapping of biogenic methane is likely to some extent. The first of the heating processes is the heat of burial (i.e., increasing temperatures at increasing depths). The total heat exposure is dependent upon the time of heat exposure and the depth of burial (i.e., temperature). The second heating process involves plutonism (i.e., the introduction of large igneous bodies into the sedimentary section). This process causes a unique scenario of heating on a regional scale and cooling at a very slow rate over a long period of time. The third process involves heating associated with smaller scale volcanic heat sources such as sills and stocks or by geothermal sources such as the circulation of both heated juvenile and meteoric waters along deep-seated fault zones (Choate et al. 1984).

In the Piceance Basin, two ages of magmatism in the Oligocene and Miocene to Holocene epochs, altered the rank of coals in the southern part of the basin. Calculations

indicate that the temperature of coals in the Mesaverde may have been as high as 350 degrees F. During these time of magmatism, the elevated temperature was beyond the stability range of oil and probably resulted in the breakdown of existing oils within the Mesaverde section into methane and other gaseous hydrocarbons. This may have significantly increased the gas in place within the Mesaverde. There is a noted lack of oil production from the Mesaverde in the southern part of the Piceance Basin which may indicate that higher temperatures have broken down oils into gaseous hydrocarbons. (Johnson 1987)

Magmatism and tectonism have effected the pressure regime in the Piceance Basin. Figure 11 shows that the areas around the Divide Creek Anticline has overpressured coals. Coals surround this overpressured area are underpressured. Coals along the broad flanks of the basin and around the underpressured area are normally underpressured.

Other major factors involved in the study of the methane producing formations of the Piceance Basin are the history of the sedimentation processes and the source material for deposition in the basin, interstratification of the marine and non-marine depositional environments and their relationships to each other and, as mentioned above, the heat, time and maturation cycle of deposition (Choate et al. 1984).

Cleat Porosity and Permeability of the Mesaverde Formation

In order to better understand the production rates of coalbed methane, it is necessary to have an understanding of cleat fractures and cleat porosity of the formations. Natural fractures or cleats enhance the flow of both methane gases and fluids through formations. Cleats are systematic natural fractures in coal that are analogous to joints in other sedimentary rocks (Raistrick and Marshall 1939; Ver Steeg 1942; McCulloch et al. 1974).

Figure 11. GRI 1986.

Cleats are subdivided into two groups, face cleats and butt cleats. Face cleats are natural fractures in coals. They are the straightest, and the longest, most persistent of the fractures in the coal. Butt Cleats are shorter and perpendicular to face cleats, they are often curvilinear and terminate against the older face cleats. The tectonic forces controlling cleating is generally the same as that controlling jointing/fracturing in the surrounding rocks. However, due to differences in the time of induration of various sediments, i.e. coals versus sandstone, variations in the orientation of coal cleats and those of fractures in the surrounding rocks may be different if the tectonic stresses have varied throughout time (Grout 1991).

Cleats are important conduits for the production of natural gas. In many areas, the cleats are initially filled with high percentages of connate waters and have a minimum gas saturation. Gas is held adsorbed onto the small interstitial surfaces within the matrix of the coal and is only released when the hydrostatic pressure on the coal is lowered sufficiently to allow the desorption and mobilization of the majority of the sorped gas through the cleat porosity. The rate of gas desorption is an important factor in the production of gas from the formation and in particular for the earliest stages of gas production during which high rates of water production occur as the cleats release the connate waters held within them first. (Johnson 1991)

Coals of different ranks contain different amounts of free space. This free space consists of cleats, fractures, pore space and other microscopic surface areas. The amount of natural gas which can be held within a seam is dependent upon the amount of this free space (Johnston 1991).

The spacing of cleats is dependent on the thickness of the coal seam, cleat height and the rank of the coal. A direct relationship exists between cleat spacing to bed thickness and to cleat height. However, there is an inverse relationship between cleat spacing and coal rank.

The formation of cleats found in the coals of the Mesaverde do not appear to always agree with the general hypothesis that face cleats are perpendicular to the axial trace of folding and that butt cleats are parallel to it (Grout 1991). Rather, cleating is related to a certain age of deformation which may or may not be directly related to folding. However, cleats are features derived from extension.

For the southern Piceance Basin, the primary cleat orientations are east-northeast (N50-90 degrees E) and the correlative set at a north-northwest (N10-30 degrees W) trend and dip at steep angles (Figure 12). Further to the north these joints are not so abundant (Verbeek/Grout 1986). In the northern part of the basin joints striking west-northwest predominate (Verbeek/Grout 1986). Measurement of cleat widths in the southern Piceance Basin indicates that face cleats are spaced 0.04 to 9 inches apart.

Taylor (Taylor 1987) reports that for the Green River Formation the most abundant fractures are oriented west-northwest. The dip on these fractures is vertical. Joint sets in the Green River Formation which are parallel with the strike of Mesaverde coal face cleats (as discussed by Grout for the southern Piceance Basin) are found only in the southern part of the basin. Taylor indicates that these large joints in the Green River are oriented east-northeast. These joints are large enough that they cause serious slope stability problems at the outcrop. Of added interest is that these joints occur almost exclusively in only the richest oil shale zones of the Green River Formation but do not appear in the lean zones.

Mesaverde Formation Methane Production

Methane that is produced from the coalification process can either escape to the surface, be absorbed within the coalbed formation or migrate to adjacent reservoir rocks. Gas which is generated in the coalbeds not only migrates upward to the surface but can also migrate downward into other reservoir rocks such as the Corcoran or Cozzette sandstone following available pressure gradients.

Figure 12. Distribution and average strike of joints of the F₃ (above) and F₄ (below) sets in southern Piceance basin (Grout 1991).

Although the Piceance Basin contains large estimates of coalbed methane and gas in low permeability sands, the development of these resources has been slowed by the historically erratic production results. The cause of these variable results appears to be the low permeability of the coal gas reservoirs due to the depth of burial and high rank of most of the coal. Two-thirds of the coals are found at depths exceeding 5,000 feet. Natural fracturing of the coalbed appears to be a major factor in better gas production from wells. (GRI Quarterly Review August 1993)

Viable commercial development of the coalbed methane resources began only in 1989 with the completion of gas wells in the Grand Valley and Parachute fields from Cameo coal seams. Additional production in these fields comes from associated sandstone reservoirs (GRI Quarterly Review August 1993). Figure 13 shows the location of the fields. Currently 95 wells produce from the Mesaverde coals and associated sandstones in four major fields which include those previously mentioned fields as well as White River field and South Shale Ridge field. Average daily production is 9.2 MMCFPD from all wells. Figure 14 shows some statistical production information for these fields.

At the Grand Valley field two major gas reservoirs are present in the depth interval 5,700 to 8,500 feet. Production of gas comes from both the lenticular, fluvial sandstones and from about 80 net feet of coal seams associated with the primary sandstone reservoirs. These low volatility bituminous coals are part of the Cameo group of coals. The compositions of produced gas varies between that produced from the sands and the coals. In general, coal gases are chemically drier and contain more carbon dioxide than the gas from the sandstone. However, much of the productions seem to be a mixture of the two gases indicating mixed sources for the gas. In general, the wells produce low volumes of sodium chloride type waters. Since in general sodium bicarbonate waters are considered to be diagnostic of coal waters, the production of sodium chloride water indicates further communication between the coal and the sandstone reservoirs. Reservoir pressures appear to be normal and the gas content of the coal is about 554 SCF/T.

Figure 13. Coalbed methane gas fields, Piceance basin, Rollins structure map (modified from Johnson and Rice 1990).

Coalbed methane production from four fields in Piceance basin, 1990 to 1993 (compiled from Petroleum Information and various operators).

Average per-well gas productivity in four coalbed methane fields in Piceance basin (compiled from Petroleum Information and various operators).

Average gas and water production for A-30-2-96-N Federal well in White River field, Rio Blanco County, Colorado (compiled from Petroleum Information).

Figure 14. Coalbed methane production information. (GRI 1993).

Core data indicates that the development of cleat porosity is limited. Face cleat spacing appears to be 0.1 to 0.3 inches. Butt cleats were often poorly developed. Although no oriented cores were collected, the asymmetry of the boreholes indicated that the likely cleat direction were approximately north 78 degrees east and north 30 degrees west.

For the coal reservoirs, low rates of gas and associated water production indicates poor cleat development probably due to depth of burial and minimal extensional forces as evidence by the lack of faulting in the area.

Production from sandstone reservoirs above the coals is erratic in nature and requires at least 160 acre spacing for economic recoveries of gas, however, the reserves contributed by the sandstone are necessary to make many of the wells commercially successful.

Completions from the Cameo coals in the Grand Valley field initially produce 300 to 400 MCFD after hydraulic fracturing. Production declines to about 100 MCFD after the first year (GRI Quarterly Review August 93). Water production is generally low about 2 barrels per day.

White River Field appears to be a more typical coalbed methane production reservoir. Wells show the reverse-decline curve normally associated with these reservoirs. In addition, water production for some wells have higher stabilized rates up to 100 barrels of water per day. However, the best well in the field produces 600 MCD with only 1 to 2 BPD and there does not appear to be a correlation between declining water production and increasing gas production.

HYDROLOGY OF THE PICEANCE BASIN

General information available on the hydrology of the Piceance Basin has been prepared by the United States Geological Survey in Regional Aquifer systems Analysis (RSA). The available hydrologic information on the basin includes general geohydrology

and reservoir characteristics for the area of the Upper Colorado River Basin. This area encompasses data from parts of Colorado, Arizona, Utah and Wyoming. Specific hydrogeologic information was reviewed on the pre-Tertiary aquifers on this regional basis but only on a limited basis for the area of the Piceance Basin. Other sources of hydrogeologic information were utilized for the Tertiary aquifers and as a supplement to the RASA and included the 1984 and 1985 National Water Summary and other sources.

AQUIFER AND RESERVOIR DISTRIBUTION

Groundwater in the Piceance Basin ranges in quality from fresh to brine. Fresh water is known to occur primarily in the upper alluvium and shallow Tertiary rocks and near the outcrop of any of the deeper aquifers. These outcrops are found in the uplifted area surrounding the basin and this fresher water represents meteoric recharge to these aquifers. In general, within the basin area connate waters of the deeper aquifers are not fresh.

Most communities in the Piceance Basin rely on surface water sources for their domestic water supply. However, groundwater is commonly used for irrigation. The source of most of the groundwater is either the Uinta/Green River aquifer above the Mahogany Zone or the Parachute member of the Green River Formation below the Mahogany zone. Figure 15 is a table of the principal and other aquifers of the Piceance Basin area.

Paleozoic Aquifers

The approximately 8,400 foot thick Paleozoic section contains 27 rock units. (Geldon 1986). These 27 rock units have been divided into 11 hydrostratigraphic units. The term hydrostatic unit includes aquifers and confining zones. Aquifers have been subdivided into those which are of a regional nature and those which appear to be more localized. The regional aquifers include the Mississippian-Devonian carbonates and the Permopennsylvanian sandstones. Local aquifers include the basal Cambrian sandstones, Cambro-ordovician rocks, Mississippian carbonate and clastic rocks and Permo-

National Water Summary—Ground-Water Resources

Aquifer and well characteristics in Colorado

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Principal Aquifers					
Piceance basin aquifer system:					
Upper aquifer: Coarse- to fine-grained silty sandstone and siltstone of the Uinta Formation and fractured dolomite marlstone of the Parachute Creek Member of the Green River Formation above the Mahogany zone. Generally confined.	500 – 1,000	1,400	10 – 500	2,000	Potential of aquifer not developed. Water almost exclusively in fractures. Transmissivity ranges from 10 to 600 ft ² /d. Dissolved-solids concentration generally ranges from 400 to 2,000 mg/L.
Lower aquifer: Fractured dolomitic marlstone of the Parachute Creek Member of the Green River Formation below the Mahogany zone. Generally confined.	600 – 2,000	2,800	2 – 50	100	Potential of aquifer not developed. Transmissivity ranges from 10 to 600 ft ² /d. Water commonly contains dissolved gas. Dissolved-solids concentration ranges from about 500 to 40,000 mg/L.
Leadville limestone aquifer: Gray dolomitic limestone with some sandstone and chert. Confined.	-	2,000	-	500	Potential of aquifer not developed. Some exploratory wells drilled in Eagle County. Spring on Rifle Creek, north of Rifle, Colorado, discharges 11 ft ³ /s.
Other Aquifers					
Western Colorado alluvial aquifers: Boulders, cobbles, gravel, sand, silt, and clay; unconsolidated and only moderately sorted. Generally unconfined.	20 – 40	140	5 – 100	500	Alluvial aquifers along Yampa, White, Colorado, and Uncompahgre Rivers provide some water for irrigation, public supply, and industrial use. Capability of aquifer in terms of yield and quality not determined. Measured transmissivity values as much as 75,000 ft ² /d.

Figure 15. Aquifers of the Piceance basin. (NWS 1984)

pennsylvanian redbeds and carbonates. The five confining zones consist of Cambrian shales, Devonian carbonates and clastics, Mississippian and Pennsylvanian shales, and Pennsylvanian evaporites. All of the Paleozoic section is capped by another confining zone of Triassic age, the Moenkopi formation. Figure 16 is a full description of all of the hydrostatic units. Only the regional aquifers will be discussed in this document.

Mississippian-Devonian Carbonate Aquifer

The Mississippian-Devonian aquifer is the most productive of the paleozoic aquifers and has yielded the largest flows of groundwater to wells and springs in the area. The unit consists of the Devonian-aged Dyer Dolomite and the Mississippian-aged Leadville limestone. Core measurements of porosity from this unit show values from 0.1 to 21 %. Hydraulic conductivities from well tests indicate values of 0.0001 to 0.1 feet/day (fpd) in the basin area. Hydraulic conductivities are much higher in the uplift areas and where the units are exposed owing to secondary porosity from tectonic deformations and the release of overburden pressure. Transmissivity for the Mississippian-Devonian carbonate aquifer in the basin area ranges from 0.1 to 1000 feet squared per day (ft²pd). (Figure 17) (Geldon 1986)

Permopennsylvanian Sandstone Aquifer

The Permopennsylvanian sandstone aquifer is comprised entirely of the Weber sandstone. The Weber is a 400 foot thick lens of tan to orange sandstone. This is the second most productive Paleozoic aquifer for the area. There are many springs in the Weber sandstone at the outcrop. Springs in the area have yields of 10 to 270 gallons per minute. Drillstem test data indicate that flows of 1.4 to 89 gpm can be expected from the Weber in the subsurface. From a total of 2,482 cores on the upper Colorado River Basin the porosity of the Weber varies from less than 0.10 to 27% with a median value of 8%.

GEOGRAPHIC AREAS														
System	Hydrologic unit (Lindner-Lunsford and others, in press)	Hydrostratigraphic unit in this report	Ute Mountains and Tropic Plateau Unit	Thickness	Piñon Basin and Douglas Creek Arch Unit	Thickness	White River Plateau and Anasazi Basin Arch Unit	Thickness	Sawatch Range and Elk Mountains Unit	Thickness	Sand Wash Basin and Park Range Unit	Thickness	Burns Basin and Gore Range Unit	Thickness
Triassic	Lower Mesozoic confining layers	Triassic confining layer	Moenshopi Formation		Wingate, Chinle, State Bridge ¹ , and Moenshopi Formations		State Bridge ¹ and Moenshopi Formations		Absent		Goose Egg ¹ and Moenshopi Formations		State Bridge Formation ¹	
Permian	Upper Paleozoic aquifers	Permian shale and carbonate rocks	Park City Formation	150	State Bridge and Park City Formations	200	State Bridge and Park City Formations	300	State Bridge Formation	200	Goose Egg and Park City Formations	500	State Bridge Formation	300
Permian and Pennsylvanian	Upper Paleozoic aquifers	Pennsylvanian and Permian sandstone	Weber Sandstone	1,400	Weber Sandstone	1,400	Weber Sandstone	1,000	Weber Sandstone	400	Weber Sandstone	700	Weber Sandstone	400
Pennsylvanian	Upper Paleozoic aquifers	Pennsylvanian and Permian redbeds and carbonate rocks	Hergen Formation	900	Hargrove and Hargrove Formations	2,500	Hargrove, Hargrove, and Hargrove Formations	7,000	Hargrove, Hargrove, and Hargrove Formations	16,000	Hargrove and Hargrove Formations	900	Hargrove and Hargrove Formations	10,000
Pennsylvanian	Upper Paleozoic aquifers	Pennsylvanian carbonate rocks and evaporites	Round Valley Limestone	100	Eagle Valley Formation	1,500	Eagle Valley Evaporite (Formation)	4,700	Eagle Valley Evaporite	3,800	Round Valley Limestone and Eagle Valley Evaporite	300	Eagle Valley Evaporite	4,700
Pennsylvanian and Mississippian	Upper Paleozoic aquifers	Mississippian and Pennsylvanian shale and carbonate rocks	Doughnut Shale		Belden Formation and Manning Canyon Shale		Belden Formation		Belden Formation		Belden Formation		Belden Formation	
				400	Molas Formation	600	Molas Formation	4,000	Molas Formation	1,800	Molas Formation	900	Molas Formation	4,000
GEOGRAPHIC AREAS														
System	Hydrologic unit (Lindner-Lunsford and others, in press)	Hydrostratigraphic unit in this report	Ute Mountains and Tropic Plateau Unit	Thickness	Piñon Basin and Douglas Creek Arch Unit	Thickness	White River Plateau and Anasazi Basin Arch Unit	Thickness	Sawatch Range and Elk Mountains Unit	Thickness	Sand Wash Basin and Park Range Unit	Thickness	Burns Basin and Gore Range Unit	Thickness
Mississippian		Mississippian carbonate and clastic rocks	Humboldt Formation	200	Humboldt Formation	50	Absent	0	Absent	0	Humboldt Formation	200	Absent	0
Mississippian and Devonian	Middle Paleozoic aquifers	Devonian and Mississippian carbonate rocks	Madison Limestone	800	Leadville Limestone and Dyer Dolomite	750	Leadville Limestone and Dyer Dolomite	600	Leadville Limestone and Dyer Dolomite	300	Madison Limestone	800	Leadville Limestone and Dyer Dolomite	500
Devonian	Middle Paleozoic aquifers	Devonian carbonate and clastic rocks	Parting Formation	50	Parting Formation	150	Parting Formation	150	Parting Formation	100	Parting Formation	100	Parting Formation	200
Ordovician and Cambrian	Lower Paleozoic aquifers	Cambrian and Ordovician rocks	Absent		Absent		Absent		Fremont Limestone and Harding Sandstone	300	Absent		Absent	
				0		200		300						
	Lower Paleozoic aquifers	Cambrian and Ordovician rocks	Absent		Hamilton Dolomite and Dotsero Formation	200	Hamilton Dolomite and Dotsero Formation	200	Hamilton Dolomite and Dotsero Formation	180	Dotsero Formation	300	Hamilton Dolomite and Dotsero Formation	100
				50										
Cambrian	Basal Paleozoic aquifer	Cambrian shale	Unnamed shale	150	Unnamed shale	150	Unnamed shale	100	Absent	0	Unnamed shale	350	Unnamed shale	50
			Lodere Formation	850	Sawatch Quartzite and Lodere Formation	700	Sawatch Quartzite	600	Sawatch Quartzite	500	Lodere Formation	700	Sawatch Quartzite	500
GEOGRAPHIC AREAS														
System	Hydrologic unit (Lindner-Lunsford and others, in press)	Hydrostratigraphic unit in this report	Ute Mountains and Tropic Plateau Unit	Thickness	Piñon Basin and Douglas Creek Arch Unit	Thickness	White River Plateau and Anasazi Basin Arch Unit	Thickness	Sawatch Range and Elk Mountains Unit	Thickness	Sand Wash Basin and Park Range Unit	Thickness	Burns Basin and Gore Range Unit	Thickness
		Precambrian confining layer	Ute Mountain Group (quartzite, sandstone, and shale)	24,000	Ute Mountain Group, granitic rocks, and metasedimentary rocks		Ute Mountain Group, granitic rocks, metasedimentary rocks, and metavolcanic rocks		Granitic rocks, metasedimentary rocks, and metavolcanic rocks		Ute Mountain Group, granitic rocks, and metavolcanic rocks		Granitic rocks, metasedimentary rocks, and metavolcanic rocks	
Aggregate thickness of Paleozoic formations				5,250		8,400		18,950		22,400		5,750		20,850

¹Above stratigraphically highest carbonate layer.

²Of Langenheim (1952).

Figure 16. Hydrostratigraphic units of northwestern Colorado. (Geldon 1986).

Thickness and distribution of Devonian and Mississippian carbonate rocks hydrostratigraphic unit.

- EXPLANATION
- AREA IN WHICH UNIT CONSISTS MOSTLY OF LIMESTONE WITH 10 PERCENT SANDSTONE AND SHALE
 - AREA IN WHICH UNIT CONSISTS MOSTLY OF LIMESTONE WITH 20 PERCENT SANDSTONE AND SHALE
 - AREA IN WHICH UNIT CONSISTS OF LIMESTONE AND SHALE
 - AREA IN WHICH UNIT IS MISSING BECAUSE OF EROSION OR NON-DEPOSITION
 - LINE OF EQUAL THICKNESS—INTERVAL 100 FEET
 - APPROXIMATE BOUNDARY BETWEEN GEOLOGIC UNITS THAT COMPOSE THE HYDROSTRATIGRAPHIC UNIT
 - BOREHOLE
 - ✦ MEASURED STRATIGRAPHIC SECTION

Estimated transmissivity in Devonian and Mississippian carbonate rocks hydrostratigraphic unit.

- EXPLANATION
- RELATIVE TRANSMISSIVITY
 - High
 - Medium
 - Low
 - AREA IN WHICH UNIT IS MISSING BECAUSE OF EROSION OR NON-DEPOSITION
 - LINE OF EQUAL TRANSMISSIVITY—INTERVAL 10 FEET
 - DATA SITES
 - ▲ Transmissivity determined from aquifer test. Number shown is transmissivity in feet squared per day.
 - ✕ Transmissivity calculated from measured hydraulic conductivity and thickness.
 - Transmissivity estimated from estimated hydraulic conductivity and measured thickness. Hydraulic conductivity estimated from structural setting.

Figure 17.

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Based on the thickness of the Weber, the likely storage coefficient for the hydrostatic unit is 1×10^{-4} to 5×10^{-4} .

Hydraulic conductivities in the basinal area are expected to be 0.0001 to 0.01 ft/day. Transmissivities for the Weber sandstone in the basin are expected to be 0.1 to 1.0 ft²/day (Figure 18) (Geldon 1986).

MESOZOIC AQUIFERS

The USGS regional aquifer systems analysis for the Mesozoic rock of the Upper Colorado River Basin was used extensively for the characterization of these aquifers.

The Mesozoic has been divided into ten geohydraulic units. These ten units represent five aquifers and five confining zones. (Figure 19) The five aquifers in stratigraphic order of oldest to youngest are the Navajo-Nugget aquifer, Entrada-Preuss aquifer, Morrison aquifer, Dakota aquifer and Mesaverde aquifer (Freethy et al 1991).

NAVAJO-NUGGET AQUIFER

The Navajo-Nugget was deposited under arid and terrestrial conditions and, therefore, are primarily of eolian or fluvial in origin. These rocks are primarily sandstones. The Navajo-Nugget sandstone aquifer is absent in the eastern portions of the Piceance Basin. It thickens to the west and has a saturated thickness of up to 500 feet. The Navajo-Nugget aquifer is found beneath the Carmel-Twin Creek confining unit.

The average hydraulic properties of this aquifer are an air permeability of 900 millidarcies, hydraulic conductivity of 1 ft/day, storativity of 0.0008 and effective porosity of 19%.

Estimated transmissivity in Pennsylvanian and Permian sandstone hydrostratigraphic unit.

Thickness and distribution of Permian shale and carbonate rocks hydrostratigraphic unit.

Figure 18.

REGIONAL AQUIFER-SYSTEM ANALYSIS—UPPER COLORADO RIVER BASIN, EXCLUDING SAN JUAN BASIN

Geohydrologic units of Mesozoic age in the Upper Colorado River Basin

Name	Principal formations represented	Principal lithologic character	Average thickness of unit, in feet (and as percent of total section), at representative sections				
			South-western Wyoming	Northwestern Colorado and northeastern Utah	East-central Utah	South-central Utah and north-central Arizona	Southwestern Colorado
Mesaverde aquifer	Mesaverde Group; Lance, Kaiparowits, Mesaverde, and Adaville Formations; Fox Hilla, Wahweap, and Straight Cliffs Sandstones	Sandstone; Shale	4,000 (36)	3,000 (26)	Missing	Missing	Missing
Mancos confining unit	Mancos, Hilliard, Baxter, Aspen, Mowry, Thermopolis, Tropic, Steele, and Cody Shales; Frontier, Niobrara, and Blind Bull Formations	Shale; Sandstone	4,500 (40)	4,000 (37)	2,000 (31)	Missing	Missing
Dakota aquifer	Dakota Sandstone; Cedar Mountain, Bear River, Burro Canyon, and Cloverly Formations; Gannett Group	Sandstone; Conglomerate; Mudstone	200 (2)	200 (2)	300 (5)	Missing	200 (7)
Morrison confining unit	Brushy Basin Member of the Morrison Formation; undifferentiated Morrison Formation	Siltstone; Mudstone; Claystone		400 (4)	250 (4)	Missing	300 (11)
Morrison aquifer	Tidwell, Salt Wash, Recapture, Westwater Canyon, and Bluff Sandstone Members of the Morrison Formation; Cow Springs and Junction Creek Sandstones	Sandstone; Conglomeratic sandstone; Siltstone	Not divided 450 (4)	300 (3)	400 (6)	Missing	450 (16)
Curtis-Stump confining unit	Summerville, Curtis, Stump, Sundance, and Wanakah Formations	Siltstone; Shale; Sandstone	150 (1)	250 (2)	400 (6)	Missing	150 (5)
Entrada-Preuss aquifer	Entrada, Preuss, and Romana Sandstones; Sundance Formation	Sandstone; Siltstone	80 (1)	500 (5)	550 (9)	600 (15)	150 (5)
Carmel-Twin Creek confining unit	Carmel and Gypsum Springs Formations; Twin Creek Limestone	Limestone; Siltstone; Shale	150 (1)	500 (5)	350 (5)	160 (4)	Missing
Navajo-Nugget aquifer	Nugget, Glen Canyon, Navajo, Wingate, and Page Sandstones; Kayenta Formation	Sandstone	500 (5)	750 (7)	1,100 (17)	2,100 (50)	600 (21)
Chinle-Moenkopi confining unit	Moenkopi, Thaynes, State Bridge, Dinwoody, Chinle, Ankareh, and Dolores Formations; Chugwater Group	Siltstone; Claystone; Limestone	1,100 (10)	1,000 (9)	1,100 (17)	1,300 (31)	1,000 (35)

Figure 19.

Water quality of the Navajo-Nugget in the Piceance Basin is likely to be of a sodium chloride type. Based on 289 analyses of the unit across the Upper Colorado River basin area the total dissolved solids concentration is approximately 11,800 ppm. Seventy-nine percent of the total dissolved solids is sodium chloride (see Figure 20A and 20B) (Freethy et al 1991).

ENTRADA-PREUSS AQUIFER

In the area of the Piceance Basin, this aquifer is primarily the Entrada Sandstone. The unit is found mostly throughout the basin and is composed of 75 to 100% cross-bedded eolian sandstone. The saturated thickness of the Entrada varies from less than 100 feet to up to 500 feet on the southwestern side of the basin. The Entrada aquifer is found beneath the Curtis-Stump confining unit although in a large portion of the Piceance Basin the confining unit is absent.

The average hydraulic characteristics of the Entrada aquifer are an air permeability of 600 md, hydraulic conductivity of 1 ft/day, storativity of 0.00004 and effective porosity of 13%.

The water quality of the Entrada is based on 64 analyses throughout the upper Colorado River Basin. The total dissolved solids concentration of the water averages 13,500 ppm (Figure 20A and 20B).

MORRISON AQUIFER

The Morrison aquifer consists of a number of sandstones within the Morrison formation. The sands represent fluvial processes of deposition under moderate climatic conditions. The saturated thickness of the aquifer is between 100 to 500 feet throughout most of the Piceance Basin. The aquifer is topped by the Morrison confining unit which contains undifferentiated Morrison formational zones.

FACTORS AFFECTING GROUND-WATER DEVELOPMENT IN MESOZOIC ROCKS

Comparison of major chemical constituents in water from four aquifers in Mesozoic rocks.

Figure 20A.

REGIONAL AQUIFER-SYSTEM ANALYSIS—UPPER COLORADO RIVER BASIN, EXCLUDING SAN JUAN BASIN

DISSOLVED-SOLIDS
CONCENTRATION, IN
MILLIGRAMS PER LITER

LESS THAN 3,000
FRESH TO SLIGHTLY
SALINE

3,000 TO 10,000
MODERATELY SALINE

MORE THAN 10,000
VERY SALINE
TO BRINY

EXPLANATION

MAJOR CHEMICAL CONSTITUENTS

Pie-slice numbers are percent of total. Number below the pie is the mean dissolved-solids concentration, in milligrams per liter

Comparison of average concentration of major chemical constituents in fresh to briny water from confining units and aquifers.

Figure 20B.

The average hydraulic characteristics of the Morrison aquifer in the upper Colorado River Basin are an air permeability of 300 md, hydraulic conductivity of 1.6 ft/day, storage coefficient of 1×10^{-4} and an effective porosity of 13%.

The water quality in the Morrison aquifer based upon the analysis of 105 samples is a total dissolved solids content of approximately 10,000 ppm (Figure 20A and 20B) (Freethy et al 1991).

MESAVERDE AQUIFER

The Mesaverde aquifer consists of a large number of stratigraphic units encompassing all of the Mesaverde Group, the upper part of the underlying Mancos and were present in the overlying Lance formation. The rocks represent transgressive-regressive sequences in complex vertical and lateral patterns of fluvial, deltaic, lagoonal, swampy and shallow marine deposition. The saturated thickness of the total Mesaverde aquifer is large due to the great number of units involved. The general saturated thickness of the Mesaverde aquifer throughout most of the Piceance Basin is more than 2,000 feet and reaches upward to 7,000 feet total.

The average hydraulic characteristics of the Mesaverde aquifer are an air permeability of 15 md, hydraulic conductivity of 0.30 ft/day, storativity of 4×10^{-5} and an effective porosity of 11%.

Based upon 528 analyses of Mesaverde water in the upper Colorado River Basin the total dissolved solids concentration is about 7,500 ppm (Figure 20A and 20B) (Freethy et al 1991).

CENOZOIC AQUIFERS

Cenozoic aquifers are the primary aquifers within the Piceance Basin. The Green River Formation and the Uinta Formation are the principal aquifers of Cenozoic age. These two aquifers are separated by a confining interval known as the Mahogany zone. The upper aquifer consists of the Parachute Creek member of the Green River Formation and lower part of the Uinta Formation. The Parachute Creek lithology is one of fracture oil shale and marlstones. The Uinta Formation part of the upper aquifer consists of fractured marlstones and permeable sandstones (Weeks 1974) (Weekes et al 1974).

Water quality in the upper aquifer generally degrades downgradient and with depth. The water is a sodium bicarbonate type containing moderate amounts of sulfate and low concentrations of chloride and fluoride. The total dissolved solids concentration varies from 250 to more than 2,000 mg/L.

Wells completed in the Green River Formation produce as much as 1,000 gpm.

The Cenozoic-aged lower aquifer consists of fractured oil shales and marlstones of the Parachute Creek member below the Mahogany zone. The Mahogany zone is only a partially (confining zone) effective barrier between the two aquifers. The Mahogany zone retards the movement of groundwater because of its low permeability but water movement between the upper and lower aquifers does take place (Taylor 1987).

Water quality in the lower aquifer is much poorer. High concentrations of easily dissolved evaporitic rock matrix minerals cause the water to commonly have a total dissolved solids concentration of 30,000 mg/L.

Recharge of the aquifers can occur under a variety of conditions. It can occur from the percolation of precipitation at the outcrops, recharge of the groundwater via streams and rivers that intersect outcrops and leaking from confined rocks through natural fractures. All

of these recharge methods are important in the Piceance Basin (Weekes 1974, Weekes et al 1974).

Research Limitations

Limited information was available in the literature for the specific objectives for which the research was conducted. Data limitations include the following:

- Formation hydrology
- Formation water qualities
- Field completion and production data

SUMMARY

The Piceance is dominated by a geosyncline in the central portion of the basin into which detritus material from surrounding mountains and ridges was deposited. Tilting, subsidence and uplift caused periodic transgressive and regressive cycles which produced a variety of both marine and non-marine depositional environments. Pressures, temperatures and time acted on these depositional sequences to produce coal and coalbed methane. The basin has significant reserves of gas in place estimated to be as much as 84 TCF. Development of this resource is limited by unpredictable reserves and often low rates of gas production per well. Associated sandstone production often finds limited reservoirs or water producing sands laterally to gas productive sands. Enhanced stimulation and production technology will need to be applied to bring about the successful development of these resources. (Johnson 1987)

Production will be enhanced in areas of natural fracturing. These fractures will most likely be structurally induced both in anticlinal and synclinal situations. The synclinal areas will possibly contain greater amounts of water than those found on the anticlines. (Johnson 1987)

Groundwater is known to occur in many of the coalbed producing formations of the basin. Because of a limited amount of field tests and published material, generalizations were made about the quality and quantity of groundwater present in the basin.

The quality of the water from aquifers in the basin appears to be best in the upper formations and decreases in quality with depth. However, some fresh water aquifers are known to occur at depths where typically brackish and brine waters are usually found. There is a direct relationship between the rate at which groundwater can be produced from these formations and the thickness of the aquifer, its porosity, permeability, grain size, presence or lack of fractures and hydraulic continuity.

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DISCLAIMER

Mention of specific brand names or models of equipment is for information only and does not imply endorsement of any particular brand.

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