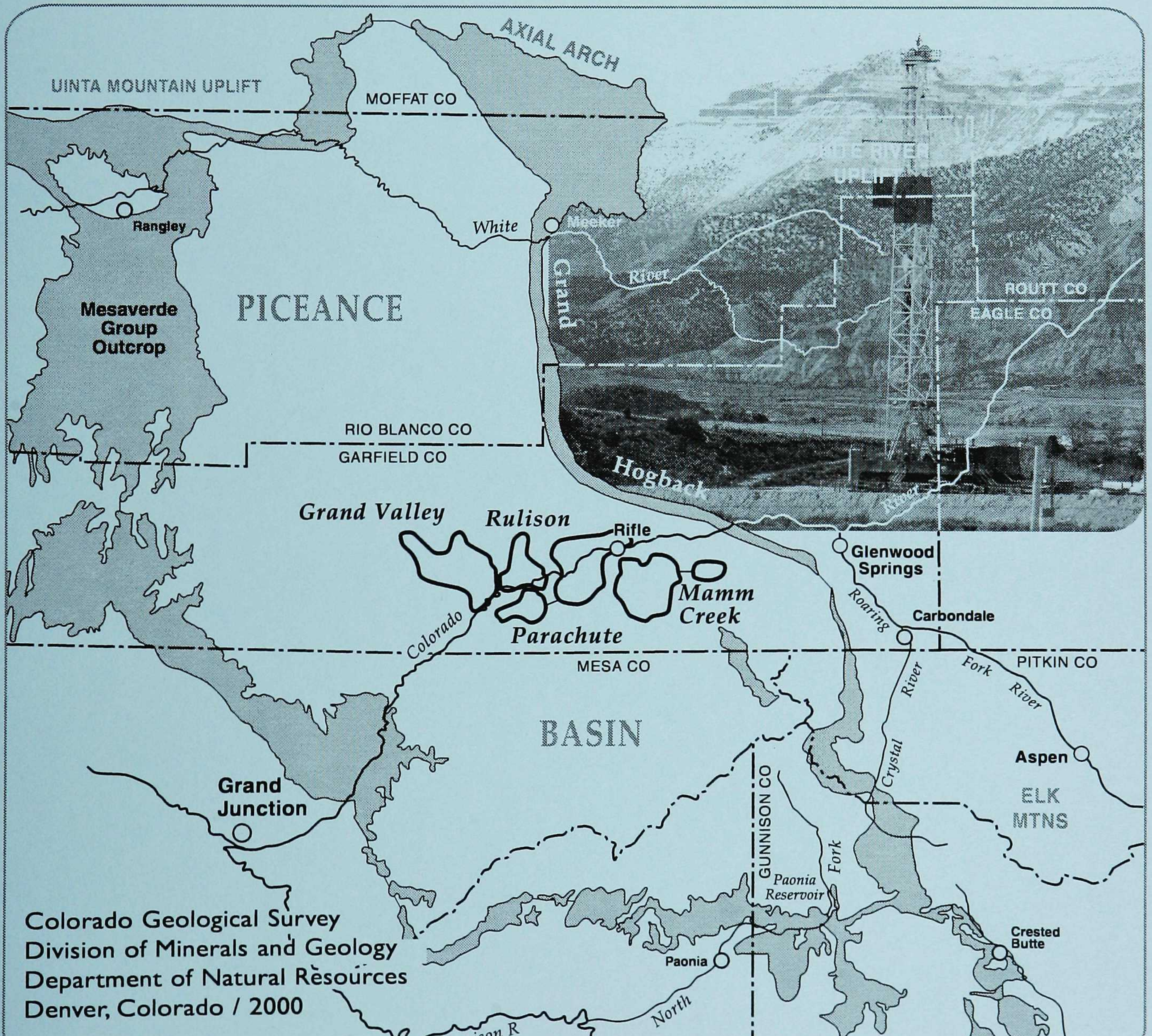
Resource Series 39

Gas Production Characteristics of the Rulison, Grand Valley, Mamm Creek, and Parachute Fields, Garfield County, Colorado:

Turning Marginally Economic Basin-Centered Tight-Gas Sands into Profitable Reservoirs in the Southern Piceance Basin

By H. Thomas Hemborg



Colorado Geological Survey
Division of Minerals and Geology
Department of Natural Resources
Denver, Colorado / 2000

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FOREWORD

The purpose of Colorado Geological Survey Resource Series 39, Rulison, Grand Valley, Mamm Creek, and Parachute Fields, Garfield County, Colorado is to describe exploration, development, and production activities in these fields. The report discusses the application of new technologies and the resultant near tripling of gas production in the ten years from 1989 to 1999. Tom Hemborg of the Mineral Resources Section of the Colorado Geological Survey wrote this report in 1999 and early 2000. The objective of this publication is to provide geological information to resource developers, government planners, and interested citizens.

Funding for this project came from the Colorado Department of Natural Resources Severance Tax Operational Fund. Severance taxes are derived from the production of gas, oil, coal, and minerals.

James A. Cappa
Chief, Mineral Resources and Geological Mapping Section

Vicki Cowart
State Geologist and Director

Acknowledgements

I would like to express my gratitude to Jim Cappa, Richard Castle, Harry TerBest, and Laura Wray for their critical reading of this manuscript and numerous helpful comments. Larry Scott produced the illustrations.

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INTRODUCTION

Rulison, Grand Valley, Mamm Creek and Parachute gas fields currently (December 1999) incorporate approximately 40,000 proven productive acres in the south central portion of the Piceance Basin in Garfield County, Colorado (Figure 1). The four fields include approximately 560 active wells with a cumulative production of nearly 320 billion cubic feet (bcf) of natural gas and 400,000 barrels of oil (bo). Production is derived from three reservoir intervals ranging in depth from approximately 1,250 ft to 8,500 ft and in stratigraphic level from the lower Tertiary through Upper Cretaceous (Figure 2). The reservoir sequences include the lower Tertiary, Wasatch Formation (Eocene–Paleocene) and the Upper Cretaceous Mesaverde Group, Williams Fork (Maestrichtian–Campanian) and Iles (Campanian) Formations.

The four fields are clustered in a 35 mi by 15 mi "fairway" (a zone of increased favorability for hydrocarbon production) which more-or-less straddles the Colorado River valley between Silt on the east and Grand Valley on the west. Substantial reserves of gas have been known to reside in the tight sands of the Mesaverde Group, particularly in the Williams Fork Formation, in this general area since at least the late

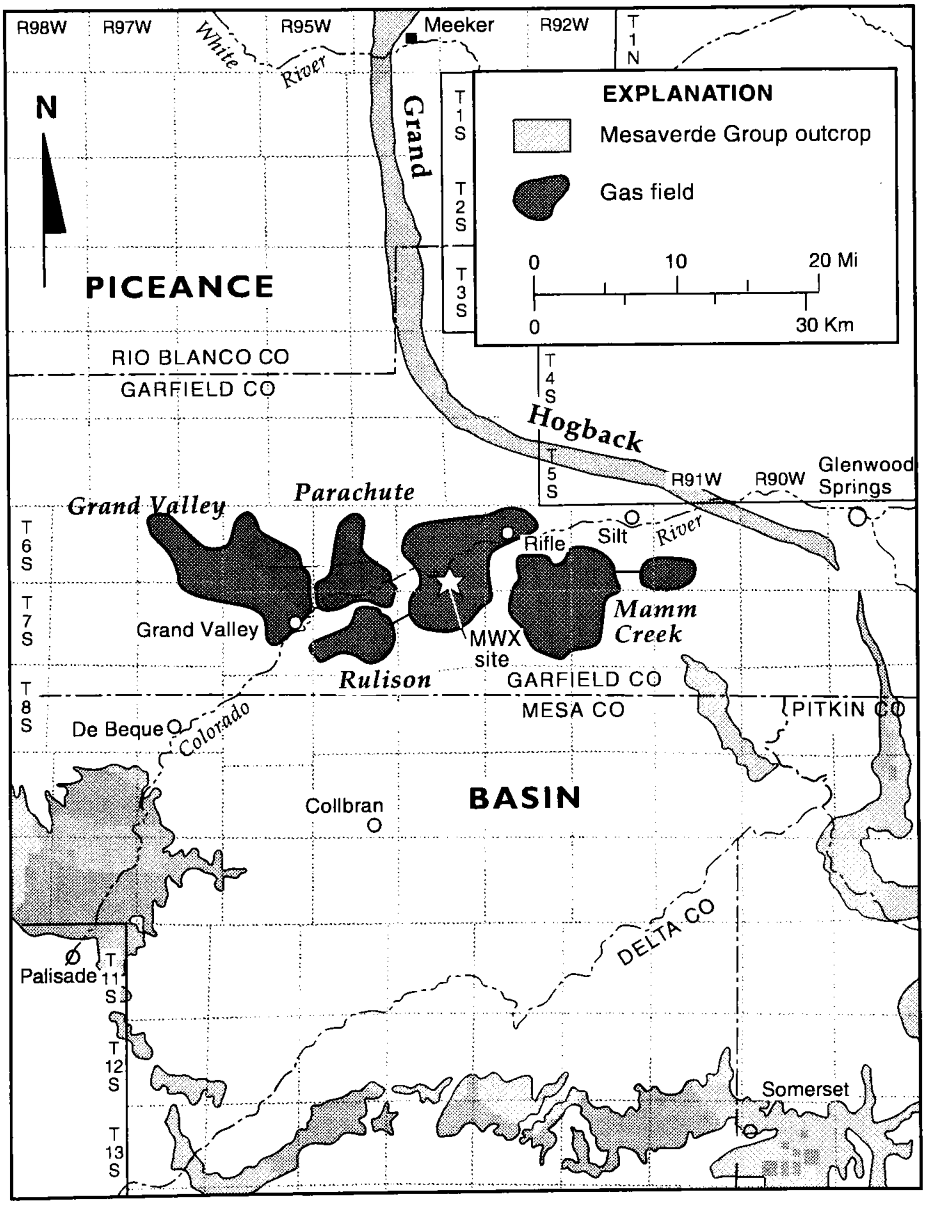


Figure 1. Location within the Piceance Basin of the Rulison, Grand Valley, Mamm Creek, and Parachute gas fields. The four fields lie within the Colorado River Valley between the towns of Grand Valley and Silt, Colorado.

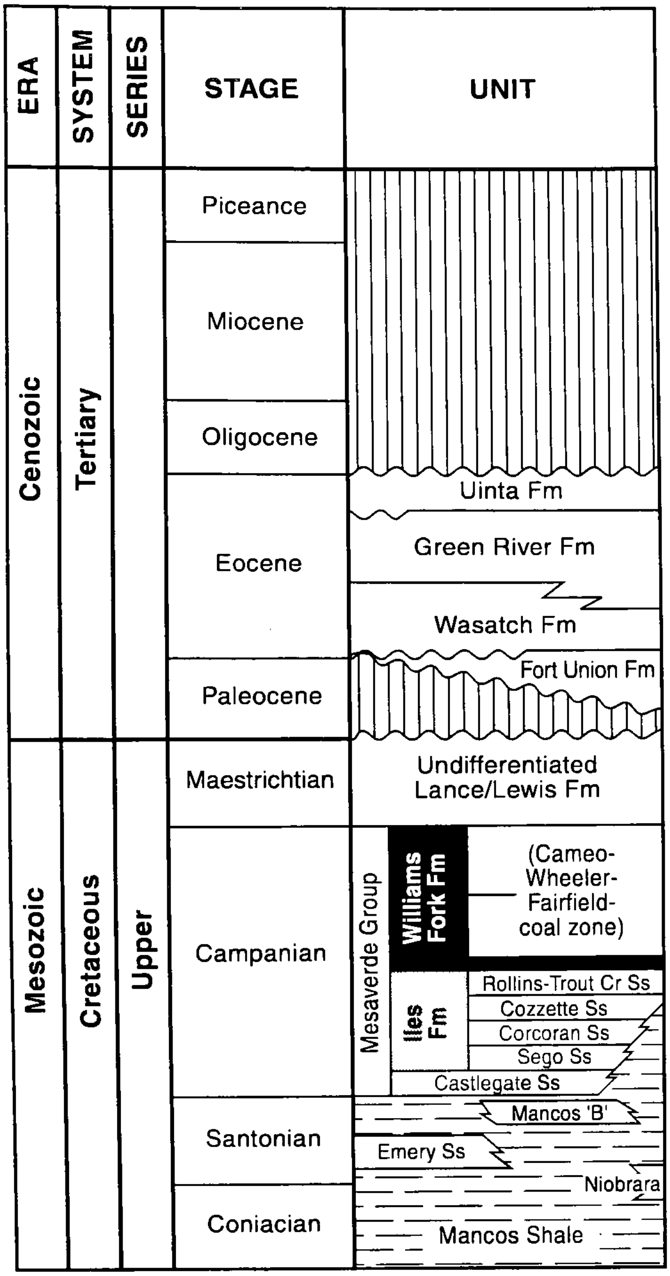


Figure 2. Generalized Upper Cretaceous and lower Tertiary stratigraphic units in the Piceance Basin (modified from Kuuskraa 1997).

1950s. These reserves are located in a "continuous-type" accumulation, which is defined as gas resources that exist as geographically extensive accumulations in deeper basin-centered areas and that lack well-defined gas-water contacts. Common geological characteristics of these accumulations include: a location down-dip from water-bearing reservoirs, absence of a conventional seal or trap, large areal extent, low reservoir matrix permeability, lack of relationship to lithologic contacts, and vertical relationship to source rocks. Commonly, these reservoirs are either abnormally overpressured or underpressured (Johnson, 1989). In the central core of these gas accumulations, all rocks including sandstones, siltstones, shales, and coals, appear to be gas saturated (Masters, 1979).

Kuuskraa (1997) made a gas-in-place estimate for the Piceance Basin's Williams Fork Formation "continuous-type" basin-centered gas resource based on: a) a recent stratigraphic study of the southern Piceance Basin (Lorenz, 1990), b) advanced well-log analysis on 12 key wells, and c) reservoir data from field operators. He concluded that 311 trillion cubic ft (tcf) of gas exists in Williams Fork reservoirs including 75 tcf of gas in associated coal seams. He estimated that the southern portion of the basin contains 106 tcf of this total 311 tcf gas resource. The four fields under discussion in this review (Rulison, Grand Valley, Mamm Creek, and Parachute) are more-or-less centered geographically in this southern Piceance Basin resource area.

The Williams Fork Formation in the Rulison, Grand Valley, Mamm Creek, and Parachute "fairway" is a 3,000 to 3,500 ft thick sequence of tight sands, shales and coals. Field operators divide this unit into two reservoir zones. The lower 550 ft to 800 ft portion of the Williams Fork Formation (locally referred to as the Cameo Coal zone) includes wells that have been completed in both the numerous coal seams and lenticular paludal sands. Wells completed in the 2,450 ft to 2,700 ft section of the Williams Fork Formation just above the Cameo zone (locally referred to by operators as either the Mesaverde Formation and/or Williams Fork Formation) have been almost exclusively perforated in the massively stacked, lenticular coastal plain and fluvial point bar sandstones that prevail within the interval.

Attempts by industry, starting from the late 1950s to the early 1990s, to exploit these very large in-place Williams Fork Formation gas resources in the Piceance Basin can best be characterized as disappointing. The principal difficulty was developing well completion techniques that provided sufficient sustained flows of natural gas and ultimate per well gas recoveries that were economically viable to operators. The main obstacles in this economic pursuit were developing drilling and logging techniques that would result in improved zone selection in the massively stacked tight-sandstone units and development of effective well stimulation procedures.

From the mid 1950s to the late 1980s, a number of oil and gas producers ranging in size from major multinational organizations to small independents collectively invested considerable monetary and staff resources in attempts to economically exploit the gas-saturated, tight gas sands of the Williams Fork Formation. Individual company staying power varied in terms of time and capital expended over this three decade period, but the end result was that nearly all these companies became pessimistic about the viability of the play and finally abandoned it to pursue other opportunities.

In tandem with private sector enterprises over this same time period, branches of the United States Government (Atomic Energy Commission and Department of Energy), in consort with the Gas Resource Institute (GRI), funded programs directed toward increasing deliverability and ultimate recovery from the Williams Fork Formation tight gas sands. These research programs included the detonation of nuclear devices in 1969 and 1973 in two separate bore holes for Williams Fork Formation fracture stimulation and a massive hydraulic fracturing project from 1974 to 1977.

Since 1977, the U. S. Department of Energy (DOE) has supported several additional Piceance Basin tight-gas sand research efforts. This research includes regional studies of stratigraphy, structure, sedimentary environments, thermal maturity, petrography, X-ray mineralogy, hydrocarbon source rocks, fractures, and drill-stem test and perforation results (Johnson and Nuccio, 1984). These regional studies were complemented by detailed core analysis. In 1981, DOE began a comprehensive study at the Multi-well Experiment (MWX) site located in the Rulison gas field west of Rifle, Colorado (see Figure 4, p. 6). At this site, three closely spaced wells were drilled in a triangular pattern. Nearly all of the Mesaverde Group rocks were cored and studied in detail. A U.S. Geological Survey (USGS) open-file report (Spencer and Keighin, 1984) summarizes much of the USGS work conducted at the MWX site for DOE.

Starting in 1990, these various efforts began to bear fruit, particularly beginning in 1995. The trend is demonstrated in Figure 3 which is a graph of annual production volumes and well counts from the Piceance Basin's Colorado River tight gas sand "fairway" from 1970 through 1999. From 1980 to 1989, annual production from the "fairway" averaged 2.3 bcf of gas. From 1990 to 1994, annual production from the "fairway" rose to 13.9 bcf. From 1995 through 1999, average annual production jumped to 41.5 bcf. More importantly, average annual gas production per well during 1980 through 1989 averaged 32 million cubic ft (MMcf). During 1990 through 1994 average annual per well volumes rose to nearly 55 MMcf, then from 1995 through 1999, average annual per well volumes climbed to 84 MMcf.

According to Kuuskraa (1997), technology advances in five areas brought forth by the research efforts of GRI and the Department of Energy are the key factors responsible for this growth in production. These areas include:

- ▲ Detection of naturally fractured "sweet spots"
- ▲ Well log analysis
- ▲ Completion and stimulation procedures
- ▲ Infill development design
- ▲ Recompletion of older wells

This report attempts to integrate some of these detailed GRI and DOE-sponsored studies. This synthesis relies primarily on published material, but new data is included, particularly well-performance data on selected Williams Fork completions within the "fairway". This study of Rulison, Grand Valley, Mamm Creek, and Parachute fields is significant in the following respects: (1) documents how the integrated application of new technologies has turned a non-economic gas play into a profitable active field development program; (2) provides

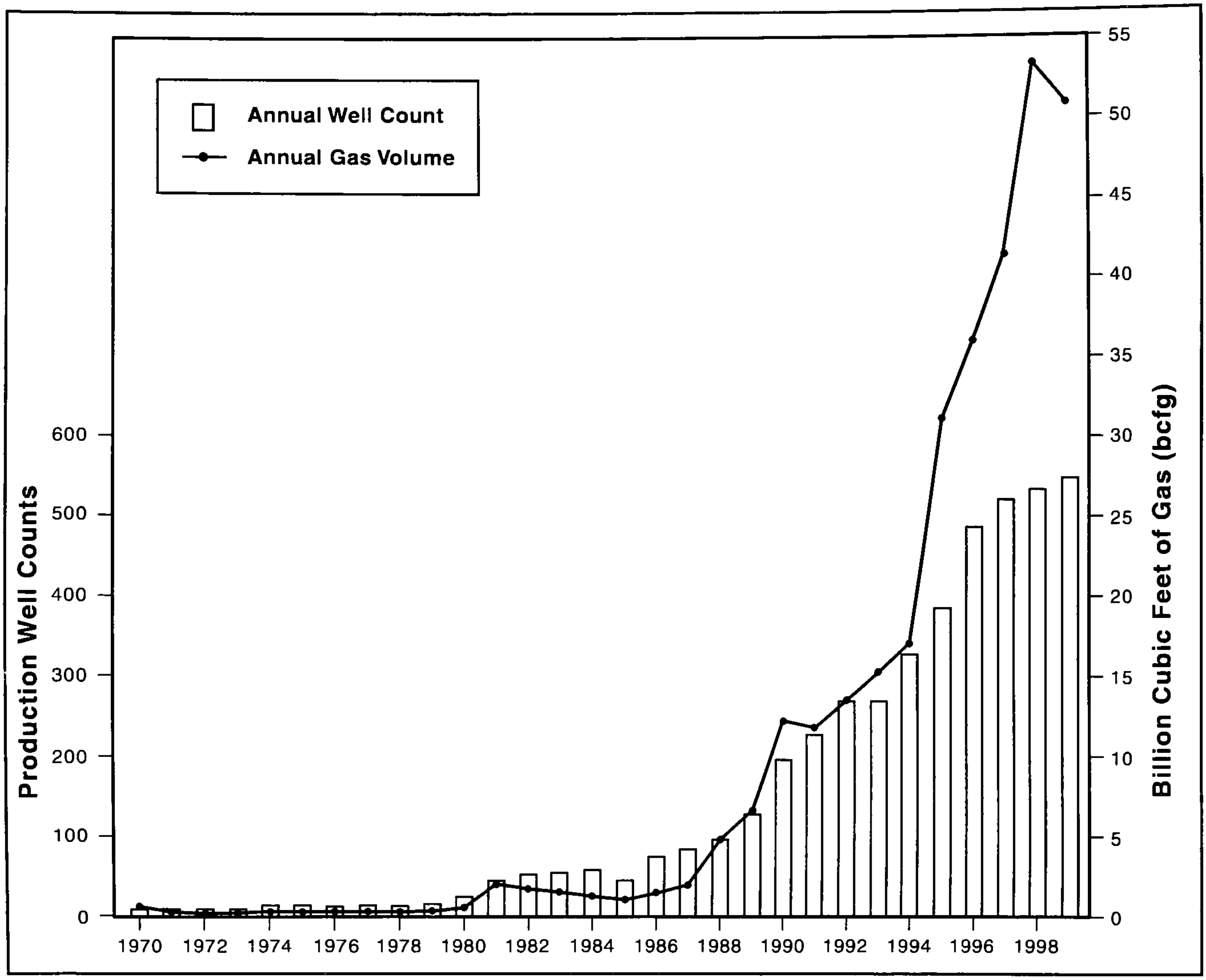


Figure 3. Rulison, Grand Valley, Mamm Creek, and Parachute gas field annual production volumes and annual count of productive wells from 1970 to 1999. 1999 annual well count and production volumes extrapolated from January 1999 through September 1999 data.

incentive for development of the Williams Fork Formation gas reserves over a much larger area of the Piceance Basin both north and northwest of the "fairway area"; and (3) includes strategies that operators can apply in other tight sandstone basin settings.

Tectonic and Stratigraphic Overview

The Piceance Basin of Colorado is an elongate northwest-southeast trending structural basin (Figure 4). The basin is highly asymmetrical and deepest along its east side near the White River Uplift, where more than 20,000 ft of Phanerozoic sedimentary rocks are present (Spencer, 1996). The basin is bounded on the north by the Uinta Mountain Uplift and the Axial Arch, on the east by the sinuous "S" -shaped Grand Hogback Monocline lying along the west flank of the White River Uplift, on the southeast by the West Elk Mountains, Sawatch Uplift, and the Gunnison Uplift, and on the southwest by the Uncompahgre Uplift. The western boundary, formed by the Douglas Creek Arch, separates the Piceance Basin from the northeastern Utah's Uinta Basin. Most of these bounding tectonic features have undergone multiple periods of deformation from Precambrian through Neogene time.

The present Piceance Basin, however, is primarily a structural and sedimentary basin that formed during the Late Cretaceous through Eocene Laramide Orogeny. The region of the structural basin down-warped as surrounding regions were uplifted in the Laramide Orogeny (Tweto, 1980). The down-warped region was a depositional basin for Tertiary sediments eroded off the higher, newly-uplifted surrounding regions. Present structural relief between the White River Uplift and the trough of the Piceance Basin is about 30,000 ft. Perhaps about 2,000 ft of this relief is due to Neogene elevation of the White River Uplift (Tweto, 1980).

Generally flat-lying sedimentary rocks of Cambrian through Cretaceous age (Figure 5) have an approximate thickness of 25,600 ft and were deposited on Precambrian crystalline rock in the general area of the Piceance Basin prior to basin development (Maclachlan and Welder, 1987). During the Paleocene and Eocene, an additional 11,000 ft of sediment was deposited in the Piceance Basin (Figure 6). This study concentrates on the Late Cretaceous Mesaverde Group reservoirs although some discussion of the Paleocene–Eocene, Wasatch Formation reservoir sequence is also included.

Sediments of the Mesaverde Group were deposited in the Cretaceous Rocky Mountain Foreland Basin, a large inland basin that covered central North America from northern Canada to southern Mexico (Figure 7). The western boundary of this basin bordered the Sevier Orogenic Belt, an area of active uplift and eastward thrusting from Late Jurassic through the early Tertiary. Subsidence in the foreland basin during this time resulted in major marine flooding. Throughout much of the Cretaceous, a shallow epeiric seaway covered the foreland basin including the area of the Piceance Basin. During this time the western shoreline of the seaway was generally restricted to a rather narrow strip west of the present Piceance Basin that paralleled the Sevier Orogenic Belt, the major source of sediment supply to the basin.

Prior to Mesaverde deposition, several thousand feet of Mancos Shale were deposited in the Piceance Basin during this marine incursion. During Late Cretaceous Campanian time, pulses of clastic sediment, related to stronger episodes of orogenic activity in the Sevier Orogenic Belt (Fouch and others, 1983), began to push the shoreline of the epeiric seaway farther and farther to the east. The shoreline regressed and transgressed across the Piceance Basin throughout much of Campanian time. Beginning in Late Cretaceous Maestrichtian time, the shoreline was east of the present day eastern margin of the basin. The resulting shoreline, lower delta plain, and upper flood plain

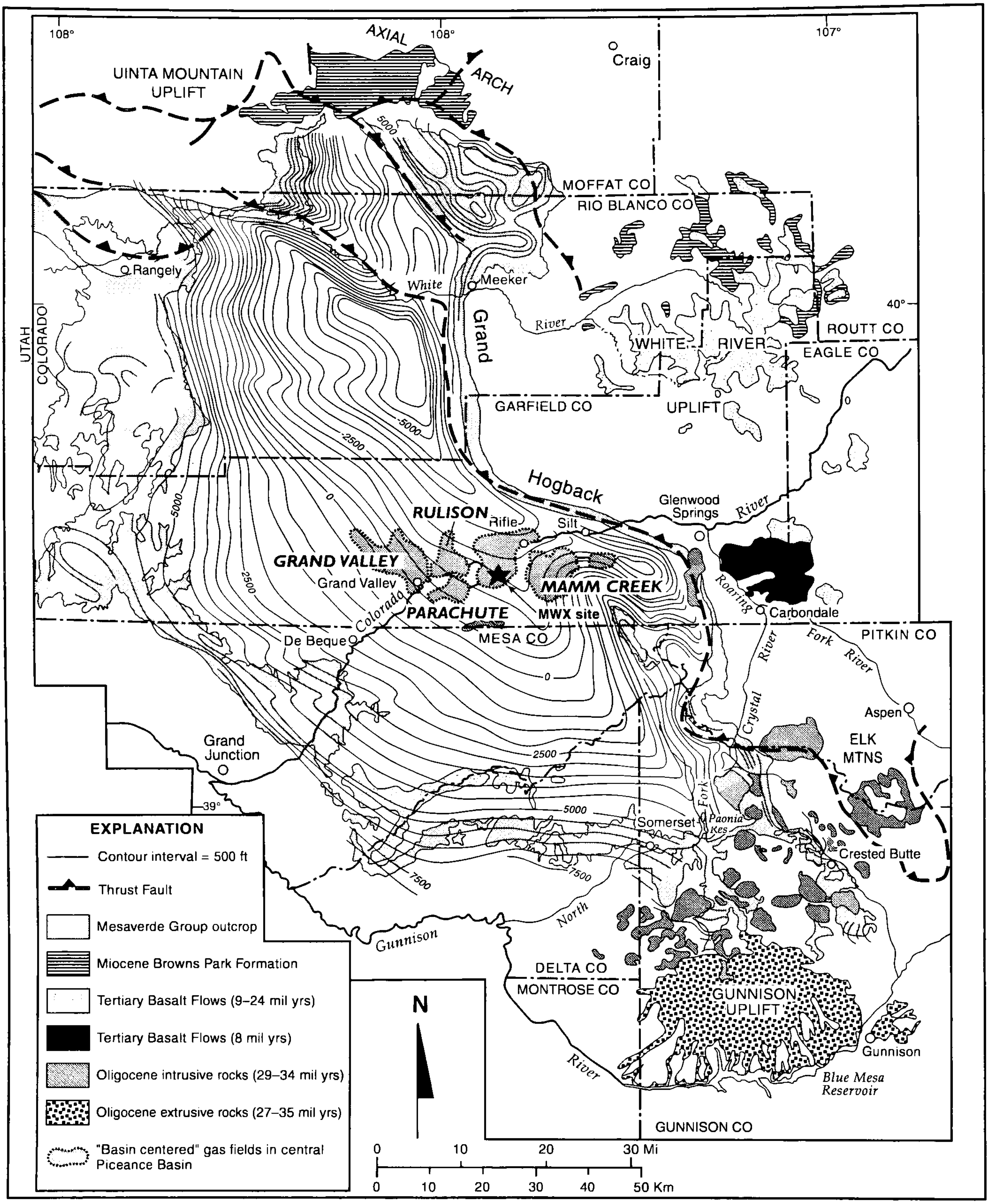


Figure 4. Index map of Piceance Basin showing surrounding tectonic features, structural configuration of basin on top of the Late Cretaceous Mesaverde Group Iles Formation, and location of the "basin centered" Rulison, Grand Valley, Mamm Creek, and Parachute gas fields. Contour interval 500 ft (modified from Tyler and others, 1995).

ERA	PERIOD	EPOCH	FORMATION North → South	LITHOLOGY	THICKNESS (Feet)
Mesozoic	Cretaceous	Upper	Mesaverde Group: Williams Fork Fm	Brown/white sandstone; gray/black shale; coal	1,350
			Mesaverde Group: Iles Fm	Brown/white sandstone; gray shale; coal	300 to 400
			Mancos Shale	Gray shale; gray sandstone	1,500 to 1,800
		?	Dakota Sandstone	Gray/tan sandstone	40 to 70
		Lower	Burro Canyon Fm	Yellow sandstone; green claystone	70
	Jurassic	Upper	Morrison Fm	Variegated shale and mudstone; gray sandstone; local gray limestone	150
		Middle	Curtis Fm	Variegated shale and mudstone; gray sandstone; local gray limestone	30
			Entrada Sandstone	Gray/orange, crossbedded sandstone	25 to 30
		Lower	Navajo Sandstone	Gray/orange, crossbedded sandstone	0 to 30
	?	?			
	Triassic	Upper	Chinle Fm	Red/mottled sandstone, siltstone, shale; gray/brown conglomeratic sandstone	70 to 170+
		Lower	State Bridge Fm	Red-brown, brown-buff shale/siltstone; gray dolomite/limestone	30 to 150+
Paleozoic	Permian				
	Pennsylvanian	Upper	Maroon Fm; Weber Ss	Weber: gray sandstone	5 to 75+
				Maroon: maroon arkosic sandstone shale, siltstone, conglomerate	450 to 2,100
		Middle	Eagle Valley Fm; Minturn Fm	Eagle Valley, gray siltstone, shale, sandstone, carbonate rocks, gypsum lenses. Minturn, gray-red sandstone, conglomerate, shale, carbonates	Eagle Valley + Minturn to 580
			Belden Fm	Gray limestone/shale	175 to 200+
		Lower	Molas Fm	Red-brown shale/siltstone; gray chert	5 to 10
	Missis-sippian	Upper			
		Lower	Leadville Limestone	Gray limestone	30 to 80+
	?	?			
	Devonian	Upper	Chaffee Fm	Gray limestone, dolomitic limestone, and shale; white quartzite	40 to 80+
		Mid/Lower			
	Silurian				
	Ordovician	Upper		Gray/white limestone and dolomitic limestone	20
		Middle			
		Lower	Manitou Dolomite	Brown dolomite; gray shale; limestone pebble conglomerate	25 to 50
	Cambrian	Upper	Dotsero Fm	Gray dolomite; limestone/dolomite conglomerate; gray shale	30
				Gray shale; orange/brown sandstone and dolomite	20
			Sawatch Sandstone	Brown sandstone	75 to 150
		Mid/Lower			

Figure 5. Generalized stratigraphy of Paleozoic and Mesozoic units on eastern side of the Piceance Basin (after Maclachlan and Welder, 1987; Hemborg and Tremain, 1993).

fluvial sediments deposited in the Piceance Basin during this time (Tyler and McMurry, 1995) make up the Mesaverde Group tight gas sand, reservoir sequence which is the focus of this report.

ERA	SYSTEM	SERIES	UNIT	GENERAL LITHOLOGY (Maximum Thickness in Feet)
Cenozoic	Tertiary	Pliocene		
		Miocene		Basalt on Grand Mesa, 9.7±0.5 million years old (200–500)
		Oligocene		Granodiorite and related rocks of West Elk Mountains, 29 to 34 million years old
		Eocene	Uinta Fm	Gray and yellow-brown, marlstone, siltstone, sandstone, and tuff. Intertongues with Green River Formation (1,000+)
		Eocene	Green River Fm: Parachute Creek Mbr; Garden Gulch Mbr; Douglas Cr Mbr; Anvil Points Mbr	Only four major members shown. Gray sandstone, green to gray siltstone, claystone, mudstone, shale, marlstone, oolitic algal limestone, and dark brown oil shale. Complexly intertongued sequence of stream, swamp, nearshore, lake , mudflat, and evaporite origin (3,500)
		Eocene	Wasatch Fm	Wasatch: Varicolored clay and clay shale, lenticular sandstone, and conglomerate. Intertongues with Green River Formation. (5,000+)
		Paleocene	Fort Union Fm (north and northeast)	Fort Union: Gray, brown lenticular to crossbedded sandstone; brown, gray shale; claystone; siltstone; mudstone; carbonaceous shale; coaly shale; and coal (1,400+)

Figure 6. Generalized stratigraphy of Cenozoic units in the central Piceance Basin, (after Maclachlan and Welder, 1987).

The Laramide Orogeny in Colorado and Wyoming changed the general flat-lying structural fabric of the mid-continent Cretaceous Foreland Basin into a melange of mountain uplifts and deep structural basins (Tweto, 1980). Each basin received Laramide orogenic sediments that constitute the principal record of events in the uplifts (In the Piceance Basin area the Sawatch Uplift began to rise prior to the end of Mesaverde deposition in the basin (Johnson, 1989). The onset of the Laramide Orogeny is recorded within the basin by an unconformity at the top of the Mesaverde Group. Although local relief on top of the unconformity is slight, thousands of feet of sediment may have been removed (Johnson and Nuccio, 1986). The unconformity produced by this regional event separates the Mesaverde Group from the lower

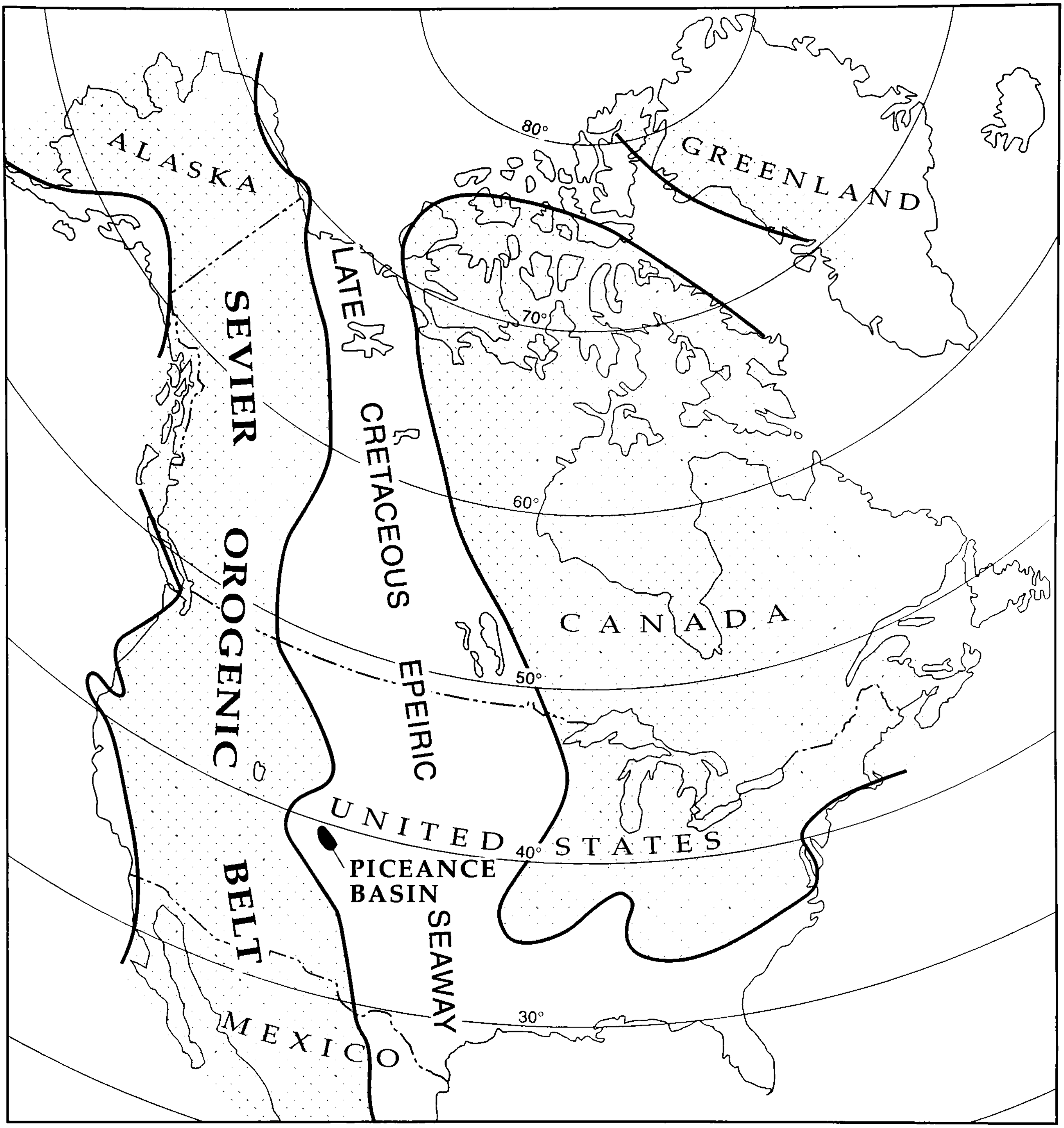
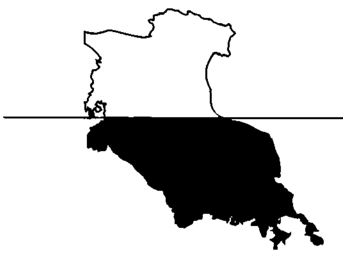


Figure 7. Relationship of Piceance Basin to Sevier Orogenic Belt and North American Cretaceous epeiric seaway (modified from Johnson, 1989).

Cenozoic rocks throughout the basin. Piceance Basin subsidence caused by the Laramide Orogeny began during the Paleocene and ended near the end of the Eocene (Johnson and Nuccio, 1984). The resulting stack of non-marine fluvial and lacustrine sediment reached a maximum thickness of 11,000 ft in the deepest part of the Piceance Basin and provided the thermal blanket that led to the generation of large quantities of gas by source rocks in the Mesaverde Group.



MESAVERDE GROUP STRATIGRAPHY

Figure 8 summarizes the stratigraphy, depositional environments, and sandstone reservoir characteristics of the Mesaverde Group in the central Piceance Basin. The shoreline-marine sandstones of the Iles Formation were deposited during transgressive-regressive cycles along northeast-southwest trending shorelines. Figure 7 locates the shoreline trends of the Mesaverde Group. During the majority of Williams Fork time the shoreline of this eastern-most regressive cycle of the Mesaverde group was located east of the eastern basin margin (Zapp and Cobban, 1960; Warner, 1964; Johnson, 1989).

The Iles Formation members have a combined thickness ranging from approximately 700- to 900-ft west to east across the study area. The Williams Fork Formation in the study area has a thickness ranging from approximately 3,500 to 3,850 ft west to east. The sandstones and coalbeds of the Iles Formation were deposited in a wave-dominated coastal setting (Johnson 1989, Lorenz, 1989). The marine units are composed of shelf, delta front, barrier-island, bay-lagoon, and strand plain deposits. The non-marine units include fluvial floodplain, coastal plain marsh and swamp environments.

The lower Williams Fork Formation was deposited in a delta plain setting that included delta front, distributary channel, strandplain, lacustrine and swamp environments.

The upper Williams Fork Formation was deposited in a fluvial setting and includes fluvial point bar, floodplain, and swamp deposits. The Iles Formation and lower Williams Fork Formation include numerous coal seams that have been extensively mined along present-day basin margin outcrops. The Rulison, Grand Valley, Mamm Creek, and Parachute gas fields include a minor component of coalbed methane production in cumulative field production volumes from these same coals.

The net sandstone thickness of the three Iles Formation Members varies from 100 to 150 ft (Tyler and others, 1991; 1994; Tyler and McMurry, 1995). Individual sands in these units average from 30 to 50 ft. The number of coal seams in individual members can vary from two to four. Average thickness of individual coal seams can vary from 5 to 10 ft. Net coal thickness in individual members varies from 15 to 30 ft. Net sandstone thickness in the lower Williams Fork Formation Cameo zone can vary between 70 and 110 ft. Maximum thickness is approximately 35 ft. The number of individual coals seams in this interval can be as high as 12. Net coal thickness for the interval can vary from 30 to 60 ft. Average seam thickness is about 7 to 10 ft. In places a few seams exceed 30 ft in thickness.

The Upper Williams Fork Formation sandstones, which provide the majority of the Rulison and other gas field production volumes are arcuate point bar deposits stacked into composite meander belt reservoirs 20–40 ft thick and 1,000–2,000 ft wide with considerable internal discontinuity and compartmentalization (Lorenz, 1989). The net interval thickness of these massively stacked lenticular sands varies from 2,800 to 3,300 ft.

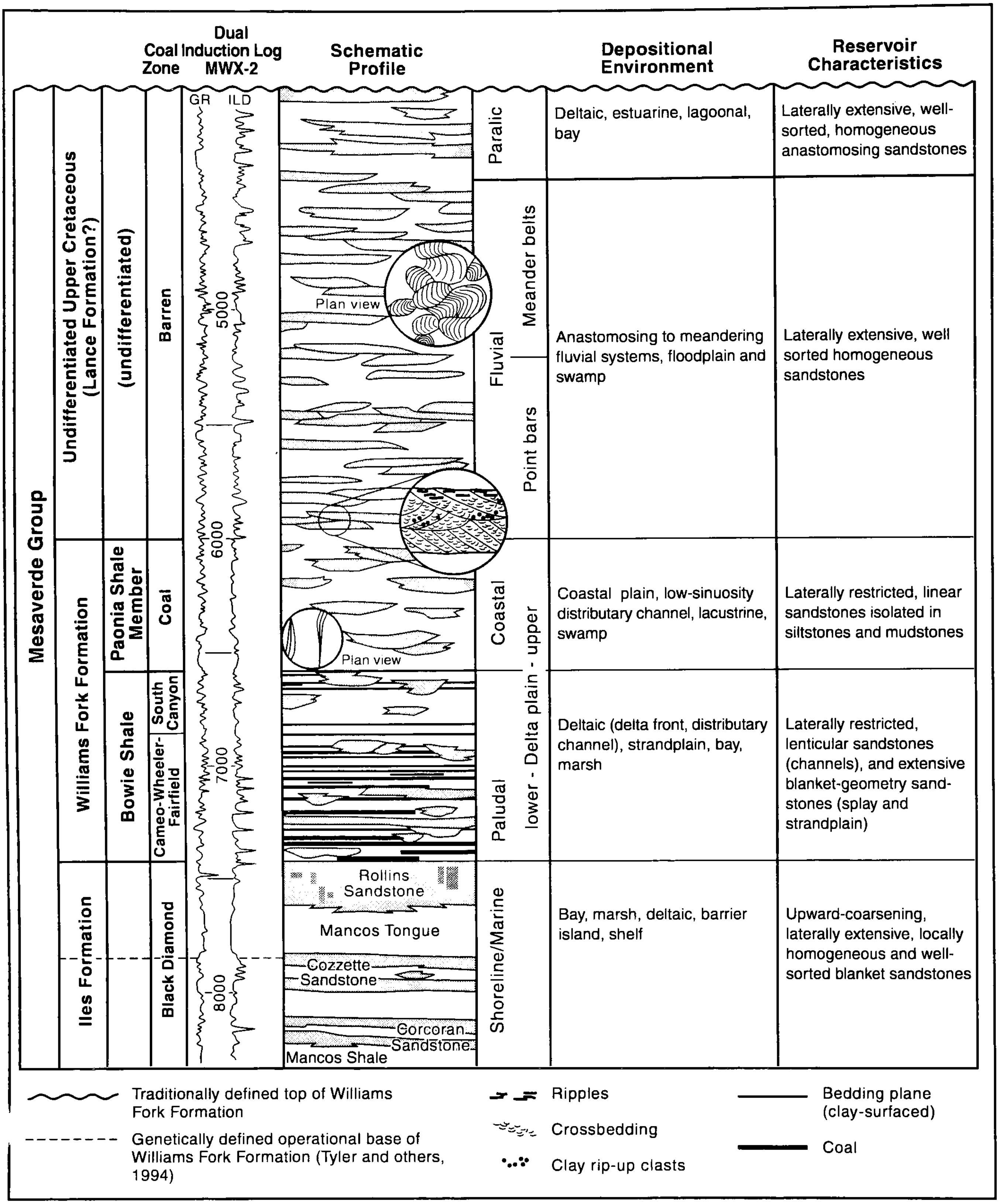


Figure 8. Schematic profile of stratigraphic column showing principal coal-bearing zones, depositional environments, and sandstone reservoir characteristics in the Rulison, Grand Valley, Mamm Creek, and Parachute gas fields of the central Piceance Basin (Lorenz, 1983).

Discovery History and Field Development

According to the Colorado Oil and Gas Conservation Commission the official discovery well in the central Piceance Basin "fairway" area was spudded by the Southern Union Gas Company on October 24, 1955. This well, Southern Union Gas Company-Juhan Fee #1, located approximately 4 mi southwest of Rifle, Colorado in the NW¼SE¼SE¼ of sec. 26, T. 6 S., R. 94 W., was the discovery well for the Rulison field. The well was drilled to a total depth of 6,545 ft and completed from perforations at 5,600–5,625 ft, 6,227– 6,255 ft, 6,283–6,303 ft, and 6,417–6,440 ft for an initial production rate of 1,937 million cubic ft (MMcf) of gas per day. At total depth the well was in the South Canyon coal zone of the Williams Fork Formation. The perforated intervals were interpreted to be in point bar sands in the lower middle portion of the 3,800 ft thick Williams Fork Formation. The well was completed on June 4, 1958 and the first gas was sold in 1959.

A precursor of the discovery well for Rulison field was drilled in 1946 approximately 2 mi to the northwest of the Juhan-Fee #1 in the NW¼NE¼ of sec. 22, T. 6 S., R. 94 W. This well, Wasatch Oil-Clough #1, was drilled to a total depth of 3,685 ft. Formation at total depth was the basal Wasatch Formation. The operator ran casing to 2,007 ft and then production tested Wasatch Formation sands through casing above that depth. The well flowed gas to surface at rates the operator judged to be uneconomic (Martinez and Duey, 1980) and as a result the well was abandoned. The Clough #1 was not properly plugged and flowed gas with water to surface for many years until it was re-plugged by the Colorado Oil and Gas Conservation Commission.

Mamm Creek field was discovered by the California Company in 1959. Their Shaffer #1 was drilled to a total depth of 8,733 ft in the SW¼NW¼NW¼ of sec. 12, T. 7 S., R. 93 W. The formation at total depth was the upper Mancos Shale. The well was completed in the Corcoran Sandstone Member of the Iles Formation from perforations at 8,444 to 8,588 ft and flowed gas at rates of up to 1,420 MMcf per day during production testing.

Barrett Resources Corporation opened the Grand Valley field in 1984 when they completed the Crystal #23-1 A2 located in the NW¼NW¼NW¼ of sec. 23, T. 6 S., R. 97 W. for 1,500 MMcf of gas per day from Cameo, South Canyon, and Coal Ridge coal zone sands of the Williams Fork Formation. Perforated intervals were selected zones from 6,905 to 8,800 ft. Subsequent Grand Valley field development wells were placed on production in 1986 before the Crystal #23-1 A2 was placed on production in 1987. This delay in placing the discovery well on line was because the well was 7 or 8 mi from the nearest gas transmission sales line, whereas, the development wells were located much closer to this line. Barrett opted to production test the development wells before extending a gathering line to the more remote field discovery location. Barrett also opened the Parachute field in 1986 when they completed their Grand Valley #2 located in the SE¼NW¼SW¼ of sec. 33, T. 6 S., R. 95 W. for 3,270 MMcf of gas per day from Wasatch Formation perforations from 1,258 to 1,633 ft.

Figures 9 through 12 report on the annual gas production volumes for these four Colorado River "fairway" fields from date of first production through 1998 for the combined Iles and Williams Fork reservoirs and the Wasatch Formation reservoir. These figures also show the annual well counts for these reservoirs. It would have been preferable to separate out Iles

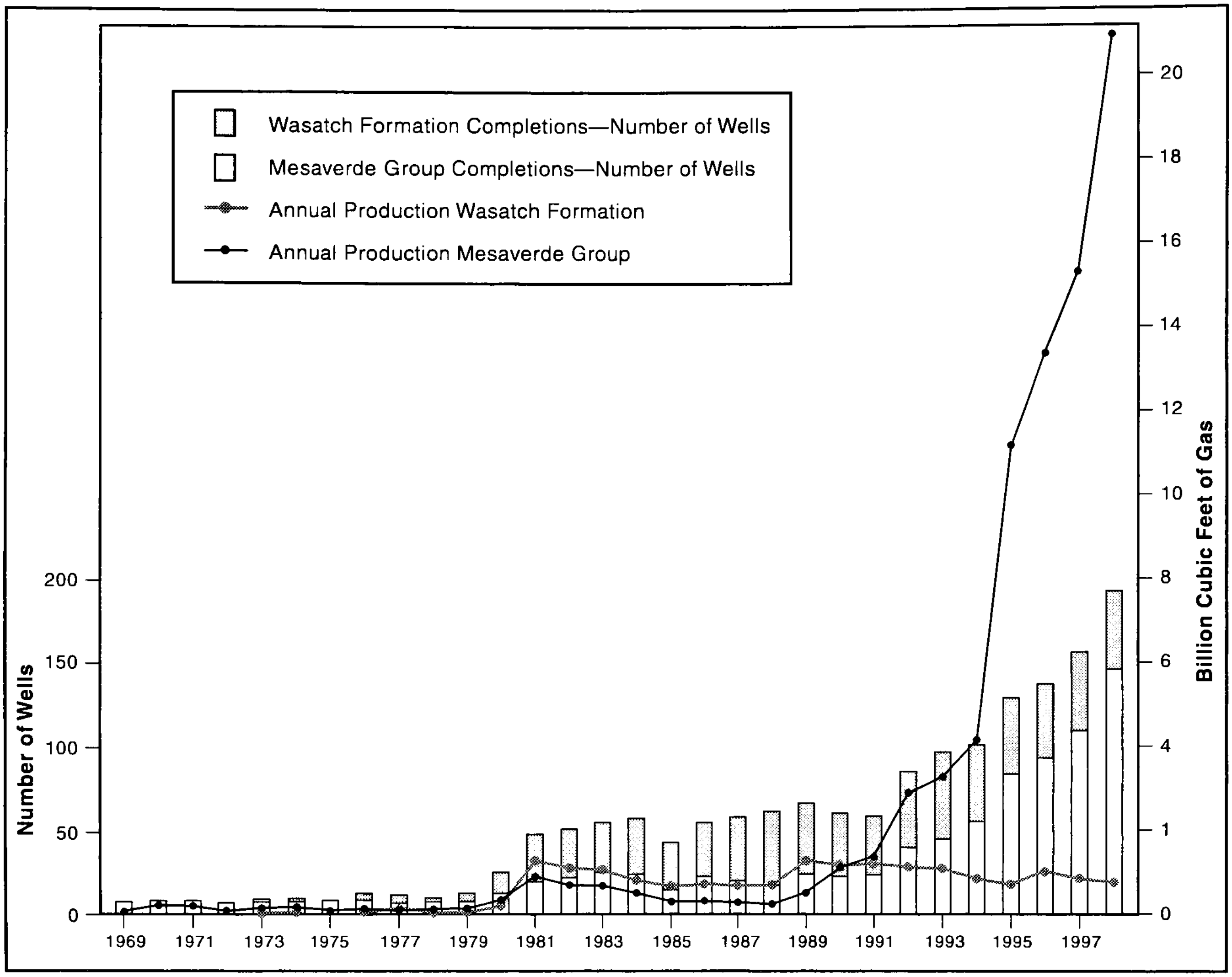


Figure 9. Rulison field annual production volumes for Wasatch Formation and Mesaverde Group reservoirs and annual well counts for the same reservoirs from 1969 to the end of 1998.

Formation sandstone production, Williams Fork Formation coalbed methane production and Williams Fork sandstone production into separate groupings but because of commingling, lack of detailed perforation data on the majority of publicly available well completion records, and extensive re-completion activity, it was not possible to accurately make these distinctions from the production data reported by the Colorado Oil and Gas Conservation Commission. Despite this resulting homogenization of the data, four important production trends emerge from these graphs:

- ▲ Wasatch Formation annual gas production, the bulk of which is derived from Rulison (Figure 9) and Parachute (Figure 12) fields, after ramping up collectively to about 4.9 billion cubic ft (bcf) in the early 1990s has been in slow decline from then to the present. Both pools have undergone little additional development drilling since 1991. Annual gas production from the two pools dropped to approximately 2.4 bcf by 1999.
- ▲ For 27 years after the first gas sales in 1959, annual gas production volumes for the Mesaverde Group reservoirs in the Rulison (Figure 9) and Mamm Creek (Figure 10) fields exhibited little growth. Starting in 1986, when Grand Valley (Figure 11) and Parachute (Figure 12) fields were brought on line, development activity in the four

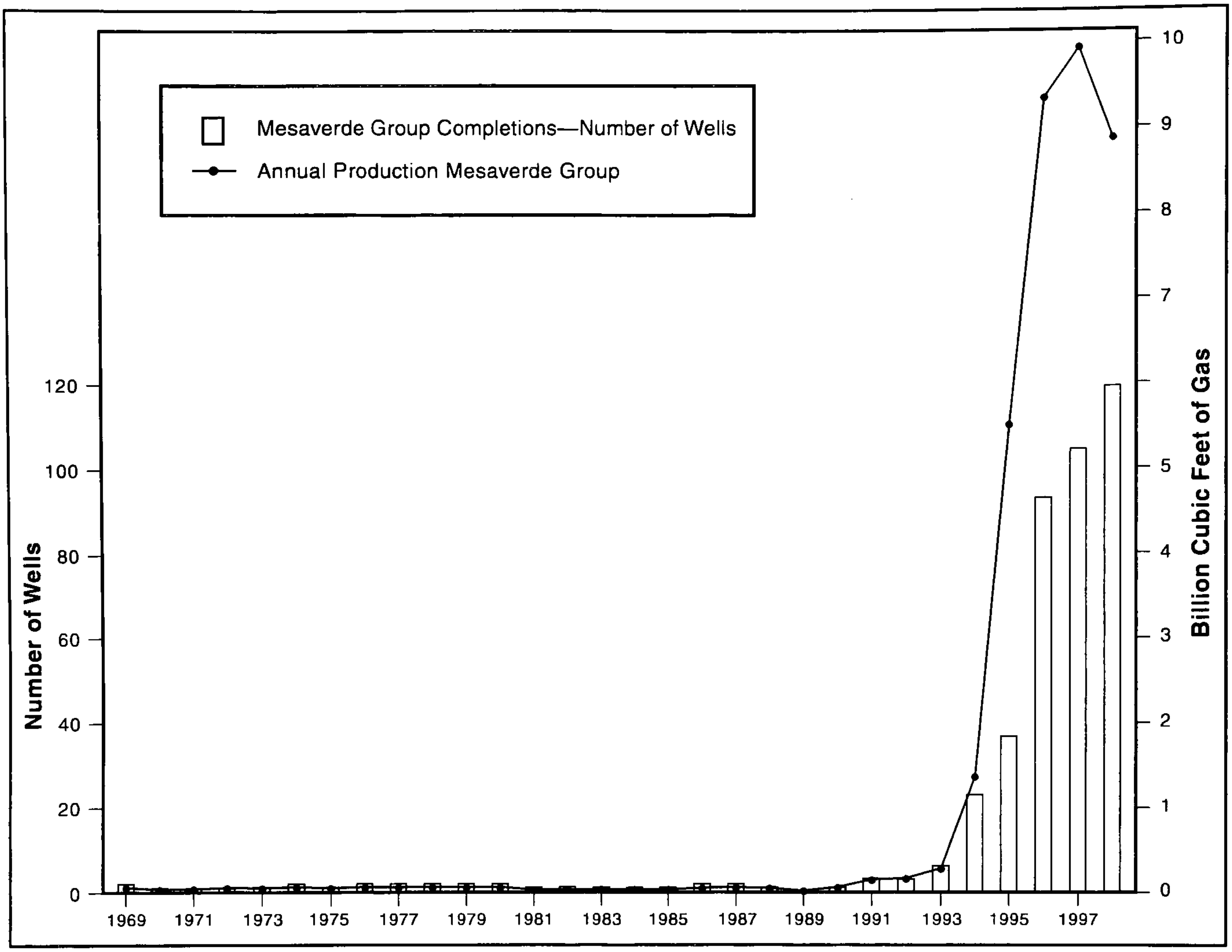


Figure 10. Mamm Creek field annual production volumes and well counts for Mesaverde Group reservoirs from 1969 to the end of 1998. Mamm Creek is not productive from the Tertiary Wasatch Formation.

fields showed a strong growth that mushroomed in the last half of the 1990s. The resulting activity translated into ever-increasing annual gas production volumes. By 1990, annual Mesaverde Group production for the four fields stood at approximately 7.2 bcf. By 1995, annual Mesaverde Group production had risen nearly 450 percent to 32.3 bcf. In 1999 the annual production volume climbed to over 51.8 bcf.

- Average-annual-per-well gas volumes for Wasatch completions in 1990 within the four fields were 57 MMcf. By 1999, average per well gas volume for these Wasatch completions had dropped to 26.5 MMcf.
- Average-annual-per-well gas volumes for Mesaverde Group completions in 1990 within the Colorado River fairway was 75 MMcf. By 1999 average per well gas volumes for these Mesaverde Group completions was approaching 113 MMcf.

Clearly, the Mesaverde Group reservoir sequence has come to dominate the production stream in Rulison, Grand Valley, Mamm Creek, and Parachute fields during the 1990s. The principal source of this expanding gas flow is the massively-stacked, lenticular sands of the Williams Fork Formation overlying the Williams Fork Formation Cameo Coal zone. Most of the pre-1989 Mesaverde Group gas stream was

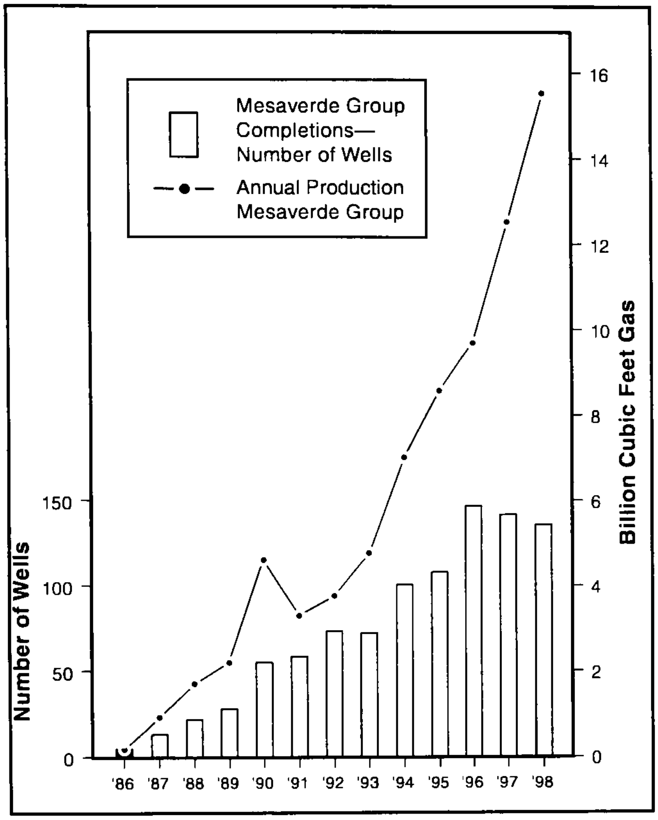


Figure 11. Grand Valley field annual production volumes and well counts for Mesaverde group reservoirs from date of first production to 1998. Only 3 wells have been completed in the Tertiary Wasatch formation within the Grand Valley field area. The resulting Wasatch Formation cumulative production volume of 51 MMcf of gas at the end of 1998 is only 0.001 percent of the Mesaverde Group end of 1998 cumulative production of 50.2 bcf of gas. This very minor Grand Valley field Wasatch Formation production component is not included in this figure.

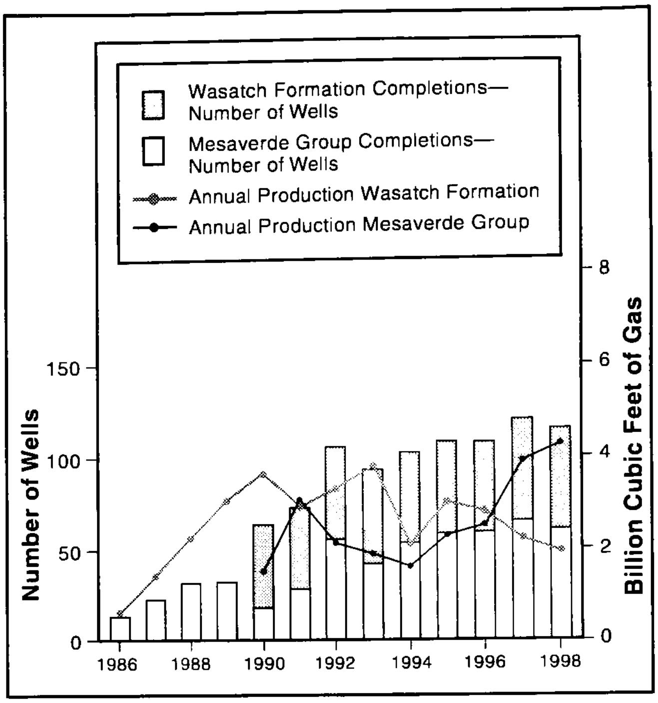


Figure 12. Parachute field annual production volumes for Wasatch Formation and Mesaverde Group reservoirs and annual well counts for the same reservoirs from date of first production to the end of 1998.

derived from either the Corcoran or Cozzette Members of the Iles Formation or coal seams in the Cameo zone. The accelerated pace of drilling activity since 1992 and 1993 has considerably expanded field sizes to the point that the four fields have more-or-less coalesced into one large gas field.

MESAVERDE RESERVOIR PROPERTIES

Tight gas reservoirs generally are defined as gas-bearing rocks with an in-situ permeability to gas of less than 0.1 millidarcy (md). Tight reservoirs can be subdivided into two main types based on characteristics of porosity (Spencer, 1983): high porosity (HP) and low porosity (LP). The Mesaverde Group reservoirs in the southern Piceance are a typical example of LP gas reservoirs (Spencer, 1989).

LP reservoirs have low porosity (3–12 percent) and less than 0.1 md in-situ permeability to gas. Many LP reservoirs have in-situ permeabilities in the nannodarcy range. Capillary pressures are relatively high, and water saturations are quite variable (45 percent to > 70 percent). These rocks are tight because the pore space consists of small microvugs scattered throughout the reservoir rock. The pores are poorly connected by short to relatively long, flat or ribbon like tortuous capillaries through which the gas must flow or diffuse during production. Because of their small size (commonly < 1.0 (micron), the capillaries are probably almost always water filled. Reservoir pressures vary from subnormal to abnormally high These reservoirs are found at intermediate to deeper burial depths (>6,000 to <15,000 ft). This reservoir category contains very large volumes of gas in the Uinta Basin of northeast Utah, Green River Basin of southwestern Wyoming, and the Piceance Basin.

Under simulated in-situ conditions, matrix permeabilities of both fluvial and marine Mesaverde Group reservoirs are tight, to near tight, throughout most of the Piceance Basin, and in general become tighter with depth of burial (Spencer, 1983). Conventional dry gas permeabilities were measured in both marine regressive cycles and the fluvial intervals of Rulison field MWX core, and most are 0.01–0.10 md (Pitman and Sprunt, 1984). According to Pitman and Sprunt (1984) permeabilities to gas would be much less at in-place confining pressures. In the deepest part of the Piceance Basin located some 35 to 40 mi northwest of the MWX wells, the fluvial part of the Mesaverde Group has permeabilities of 0.0006–0.055 md (Rio Blanco Natural Gas Company, 1980).

Sandstones of the Mesaverde Group have low permeabilities because intense regional diagenesis has filled the pore spaces with quartz, authigenic feldspar, dolomite, calcite, illite, mixed-layer illite/smectite, kaolinite, and iron-rich chlorite (Pitman and Sprunt, 1984). The diagenetic mineral suite varies widely between different areas of the basin and between different parts of the section at any given locality.

Source and Trapping of Mesaverde Basin Centered Gas

Limited data in the Piceance Basin suggest that both the underlying Mancos Shale and the interbedded Mesaverde Group coals and carbonaceous shales were the source for Mesaverde Group gas (D. Rice, written commun. to Allan Sattler, Sandia National Laboratories, 1982). According to Rice the gas in the coal beds originated in the coal beds themselves, whereas gas in the Corcoran and Cozzette Members of the Iles Formation was derived in part from thermal cracking of oil that originated in the underlying Mancos Shale.

LP gas accumulations are normally pressured to moderately underpressured except in the central areas of structurally deeper basins such as the Piceance where highly overpressured conditions have been encountered (Spencer, 1989). A normal pressure gradient in a reservoir in which saline water is the pressuring fluid is about 0.43 psi/ft. Mud weights of 8.3–10.2 lb/gal are needed to counterbalance normal hydrostatic pressures of formation waters and hydrocarbon-bearing intervals during drilling to prevent these compounds from flowing into the wellbore during the drilling process. Increased mud weights are required to prevent blowout in overpressured intervals. In one of the MWX wells, mud weights as heavy as 15.3 lb/gal were needed to maintain well control in the Corcoran interval (Mann, 1984). This indicates a pressure gradient as high as 0.8 psi/ft at the Corcoran interval in the Rulison field area.

Tremendous amounts of water must have been driven out of structurally deep areas of the Piceance Basin while gas was accumulating. The expulsion of water was aided by thermogenic gas generation that created pore pressures greater than hydrostatic pressures (Meissn 1984; Law and Dickinson, 1985). Berry (1 suggested that the Middle Cretaceous Dakota Sandstone field in the San Juan Basin of northwest New Mexico and southwest Colorado is a "basin centered" gas deposit trapped hydrodynamically by downdip water movement. Meissner (1984), however, suggested that downdip water movement could not have trapped gas while the gas resource was being created. Masters (1979) believed that gas in basin centered geological settings was trapped by a relative permeability barrier. He pointed out that in extremely tight rocks like the Mesaverde Group in the Piceance Basin the permeability of gas is only about 30 percent of water at a water saturation of 40 percent. This permeability difference would tend to trap gas and allow water to pass through (Spencer, 1989). This phenomenon has been experimentally demonstrated by Geis (1984) and could well explain the gas entrapment in the Mesaverde Group in the Rulison, Grand Valley, Mamm Creek, and Parachute field area.

Key Factors Driving Recent Successful Exploitation of the Williams Fork Formation Fluvial Sands

Over the last decade, and particularly within the last few years, the integrated application of new technologies has turned the non-economic exploitation of Williams Fork Formation tight gas sands in the Rulison field and Grand Valley field area into an active, profitable play, Kuuskraa (1997). With well costs estimated at approximately $750,000 (including four large hydraulic stimulations) and reserves of 2 bcf per well, the reserve replacement costs for the area are in the range of 50 cents per Mcf. This resulting profitability is significantly better than past estimates of replacement costs of $3.87 per Mcf. Barrett Resource Corporation, which operates approximately 350 wells in the Rulison and Grand Valley field area, stated in a recent Annual Report that the company has entered into financial hedges for much of their Piceance Basin production to lock in a sales price of $1.73 per Mcf for five years. The technology advances being used by Barrett Resource Corporation, the major player in the Piceance Basin Williams Fork Formation gas development, and the other operators with smaller acreage positions is the subject for the remainder of this review.

Role of Natural Fracture Detection

Considerable evidence indicates that natural fractures are the primary conduits for fluid movement in the Piceance Basin and that these fractures play a significant role in Mesaverde Group gas production. A well-developed fracture system in an otherwise tight sandstone would seem to be the major cause of much higher-than-expected productivity in some wells.

Work carried out in the Rulison and Grand Valley field area by Advanced Resources International, Inc. for the DOE indicated a close relationship between basement structure and fracture controlled production trends in the Williams Fork Formation. The focus of this research was to develop of an integrated methodology for locating these basement structural trends. The methodology combined detailed aeromagnetic data, 2D seismic data, well data, remote-sensing imagery, and regional syntheses. Figure 13 shows an anticline with related faulting identified by high-resolution aeromagnetics (Hoak and Decker, 1995). Figure 14 shows a seismic line across the same area imaging basement structure (Hoak and Decker, 1995).

Hoak and Klawitter (1999) presented additional data that showed this integrated approach located fracture production trends in the Grand Valley, Parachute, and Rulison fields. Figure 15 is a structure map on top of the Williams Fork Formation in the Grand Valley field area showing little more than regional northeast dip. This indicates the importance of using the integrated approach to locate production "sweet spots".

Role of Well Completion

Until the early 1990s, operators believed that the hydraulic fracturing of the lenticular sands would not be very effective (Kuuskraa, 1997) Operators bypassed these sands and completed wells in the deeper Cozzette and Corcoran sands. Because of questions about quality of pay and post stimulation performance resulting from attempted completions in the Williams Fork Formations, a variety of stimulation types were used, ranging from small, single-zone fracs to multiple-perforation, massive-frac designs.

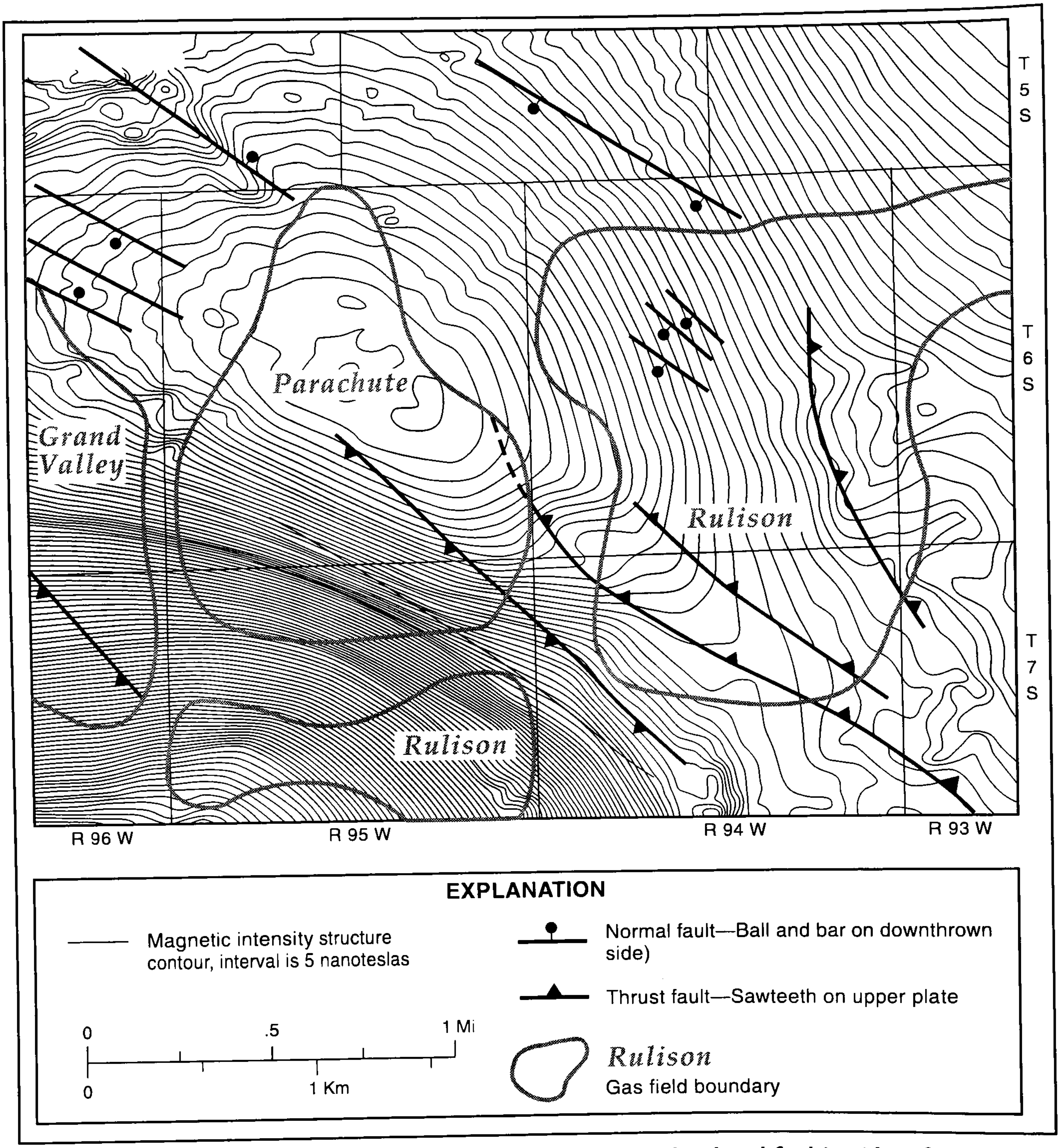


Figure 13. Areomagnetic structure in the Rulison field area with related faulting identified by high-resolution seismic data (modified from Hoak and Decker, 1995).

Beginning in late 1993, Piceance Basin operators, drawing on GRI research and experienced in other tight gas sand basins, initiated aggressive programs to complete wells in the massively stacked, lenticular Williams Fork Formation fluvial sands. The new technique generally involved perforating multiple zones and using very large propant loads with gels or nitrogen

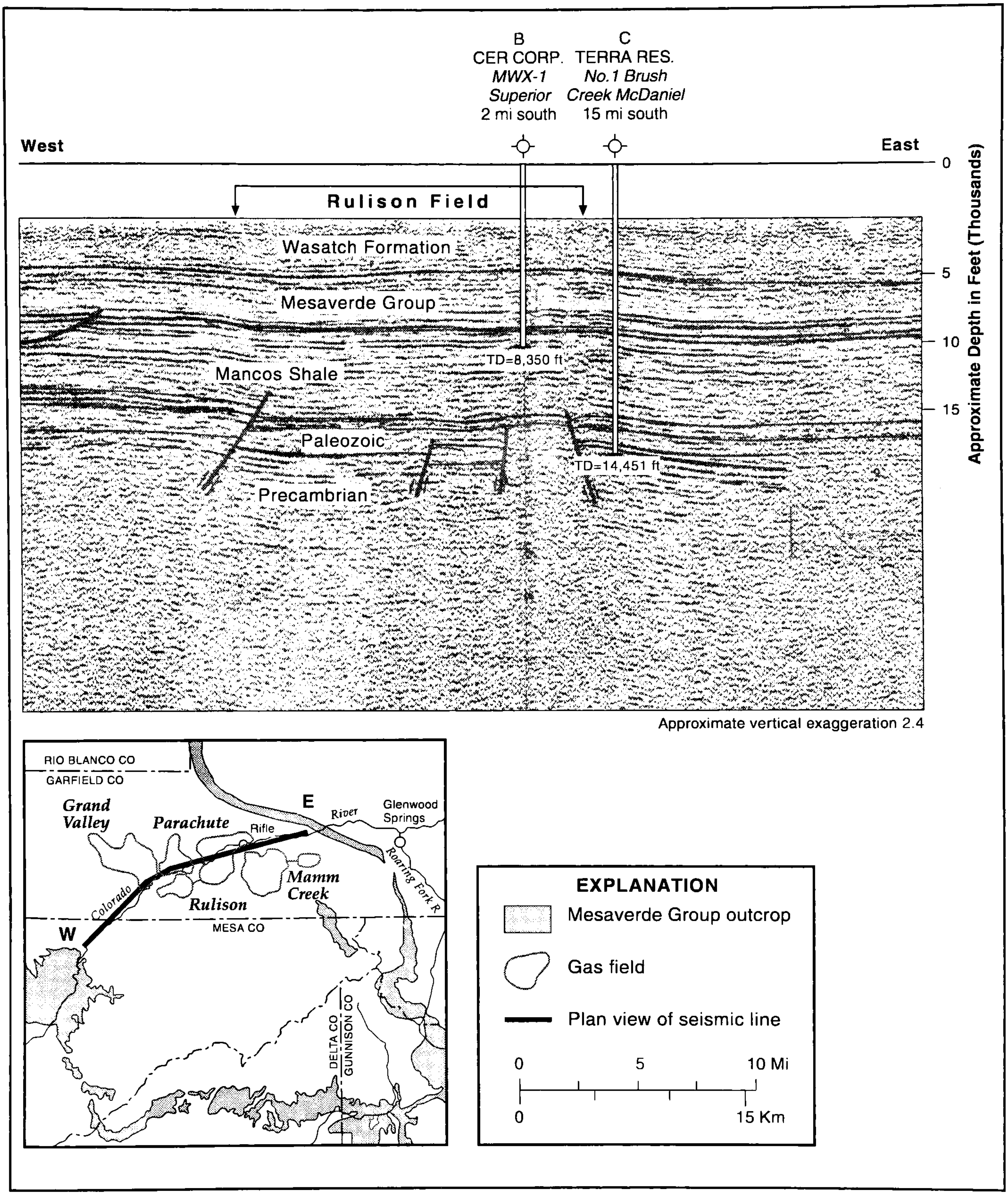


Figure 14. Celsius Energy Company seismic line recorded along Colorado River. Segment shown crosses over Rulison Field. Note pronounced basement-involved, structural movement on the east side of field (modified from Waechter and Johnson, 1986).

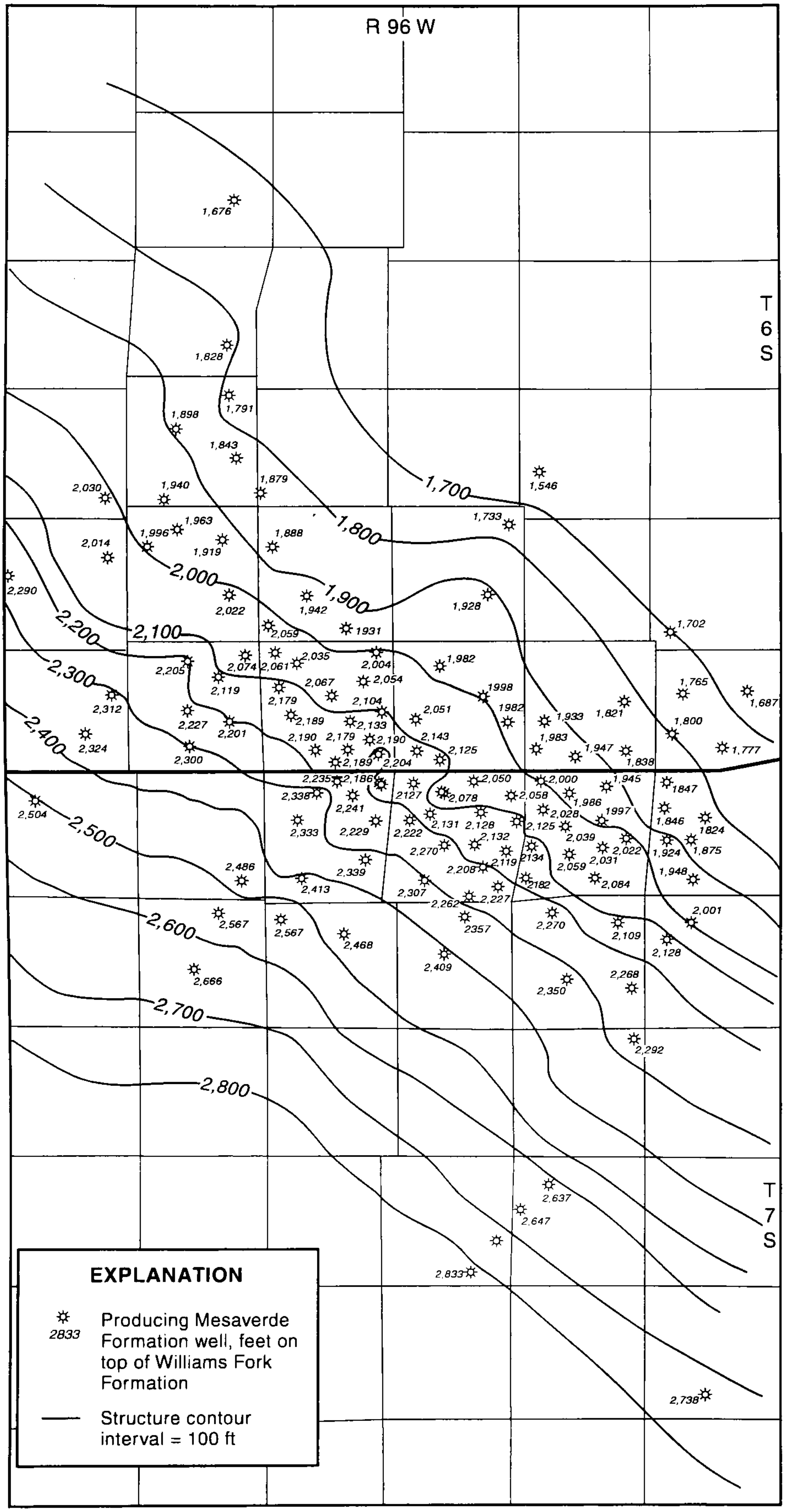


Figure 15. Structure contours on top of Williams Fork Formation, Grand Valley field.

mixed with water, as a carrying agent.

Current Rulison field completion practice is to separate the lenticular sands into a series of packages containing 400 to 500 ft of gross interval. Each zone is stimulated separately. Most wells have three to five such intervals in a +2,000 ft gas saturated zone.

Figure 16 compares an older and more recent completion in the Williams Fork Formation fluvial sequence and demonstrates the success of the new technology. The two wells are located approximately 1,300 ft apart near the current western boundary of Rulison field. The Northwest Exploration-Clough #19 was completed in 1981 over an interval 6,352 to 7,138 ft. The well was given a single stimulation treatment of 65,000 gallons of frac fluid and 150,000 pounds of sand. The Barrett-Clough #RMV was completed in 1997 over an interval 5,230 to 7,058 ft. The Kelly Bushing elevation of the Northwestern Exploration well was 105 ft higher than the Barrett well. Barrett gave their well four separate hydraulic fracture treatments. Each job averaged 105,300 gallons of gelled fluid and 531,700 pounds of sand.

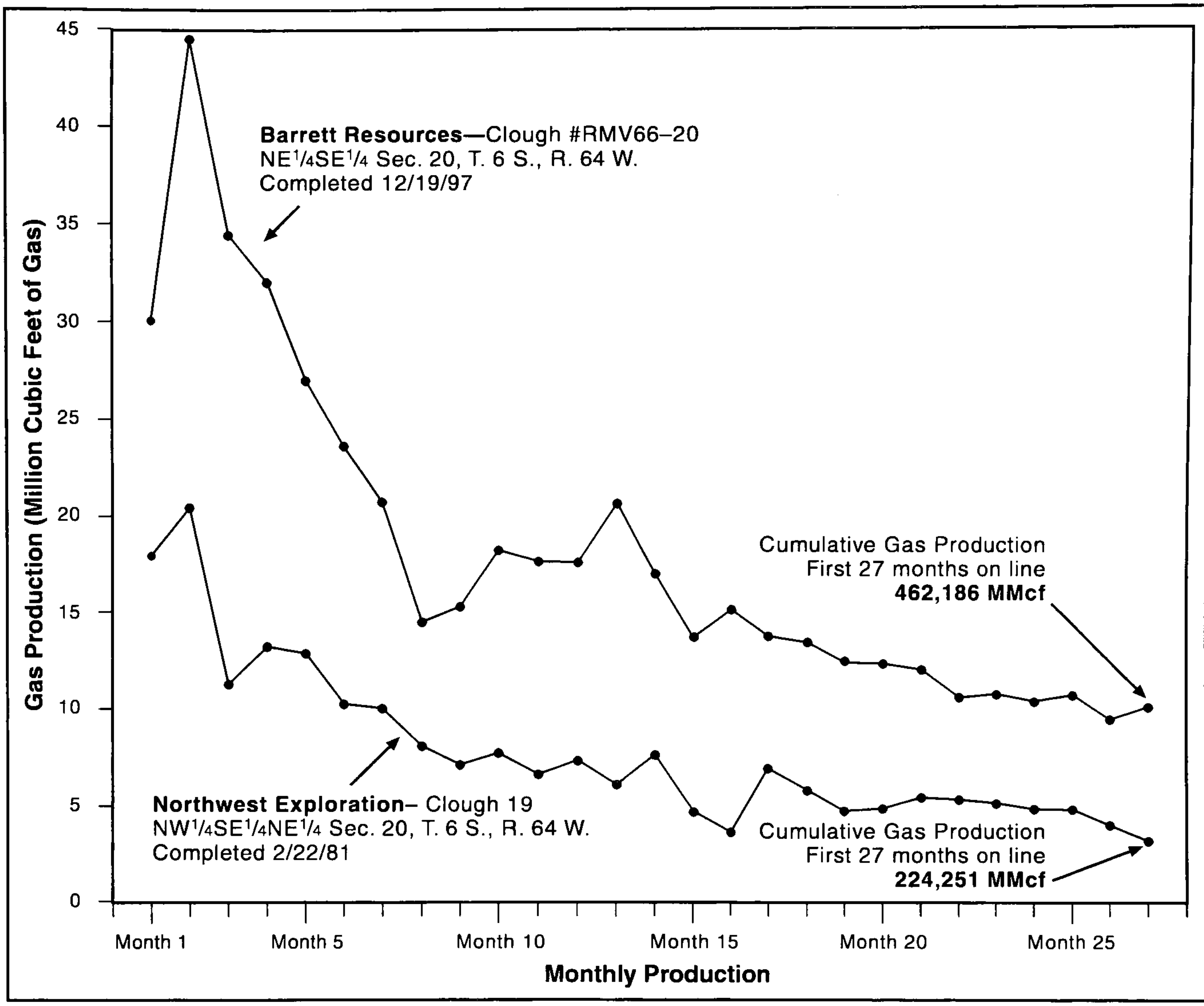


Figure 16. Gas production performance comparison of the first 27 months on line of an older and recent Williams Fork Formation completion in the Rulison gas field.

Role of Advanced Log Analysis

Operators in the Piceance Basin have relied heavily on using mudlog gas shows to pick pay intervals. Wireline log analysis in tight-gas-sand settings has always been difficult because of variable formation water resistivity, bound water in shaley sands, and the heterogeneous nature of sandstone types and cements of the reservoirs.

Research indicates that using a shaley-sand water saturation model and variable water resistivity values are essential for properly determining net pay in the Williams Fork Formation. According to Kuuskaa (1997), "using representative Mesaverde reservoir properties to compare Archie (Archie, 1942) and Waxman-Smits (Waxman-Smits, 1968) models illustrates the errors that can occur when one does not include clay activity in the water saturation model." Some recent studies in the Piceance Basin have continued to use the Archie model leading to erroneously high, calculated water saturations and pessimistically low, estimates of gas resource stored in these low resisitivity sands (Kukal et al., 1983; Scotia Group, 1993). A true resisitivity of 10 ohm-m would give an Archie water saturation of 66 percent, and a more accurate Waxman-Smits based water saturation of 36

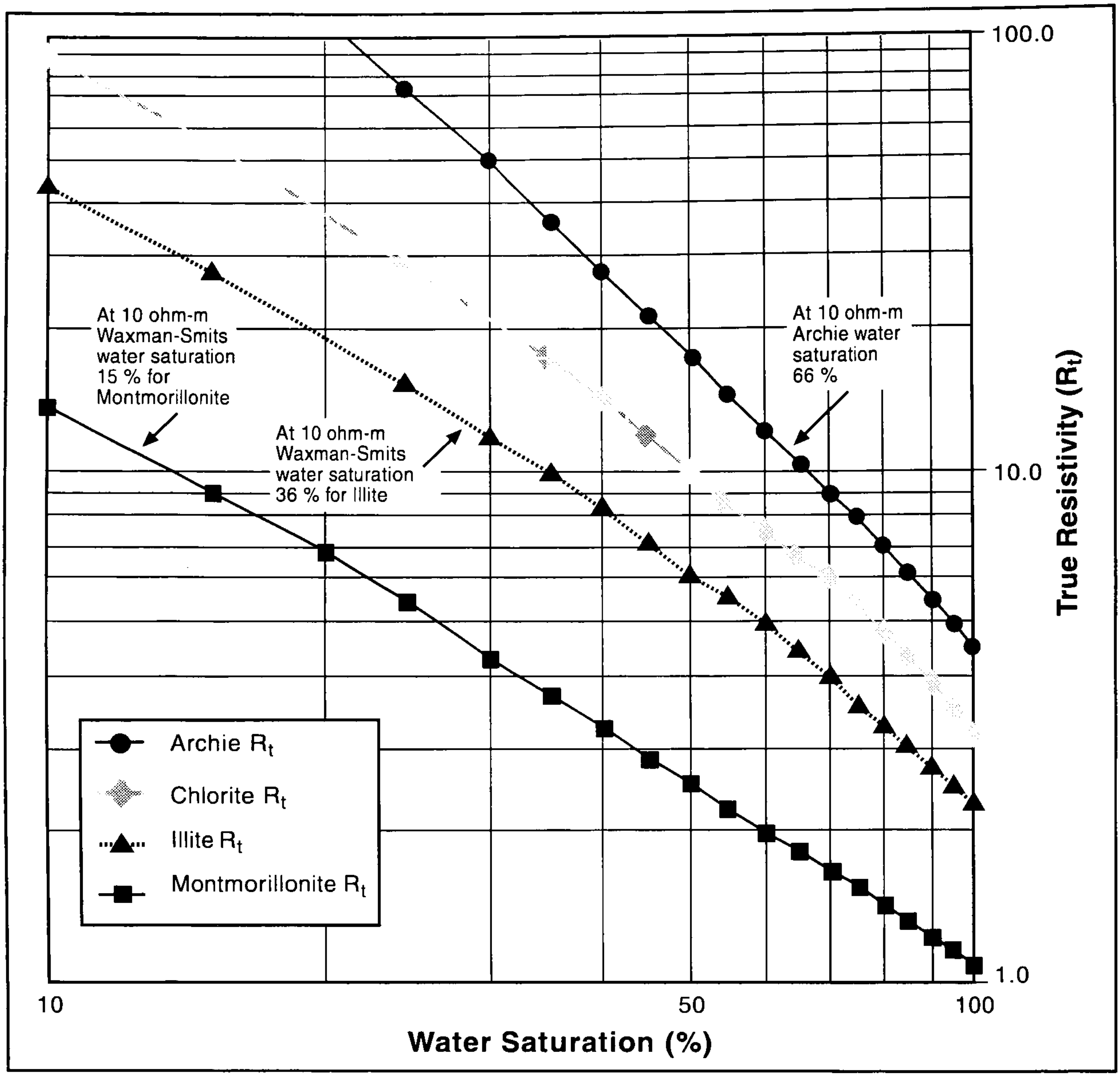


Figure 17. Comparison Water Saturation versus Rt for Waxman-Smits and Archie models (modified after Kuuskraa, 1997).

percent for a formation containing illite clay (Figure 17). At a 10 ohm-m resistivity with montmorillonite clay, the reservoir would have a 15 percent water saturation., based on Waxman-Smits, but would still show 66 percent using the Archie model."

The Waxman-Smits model in a test case of 30 Piceance Basin wells was used to pick the top of gas in the Williams Fork Formation. This was compared to earlier work using vitrinite reflectance data, mud logs, and log analysis with porosity tools corrected for flushed zone effects (Kukal, 1983). The Waxman-Smits technique picked the top of gas higher, indicating the possibility of unidentified pay. Some recent recompletions have confirmed the existence of these previously bypassed, gas pay zones.

Role of Recompletion

The Rulison–Grand Valley field area contains a large number of pre-1993 wells that were completed in a number of pay zones with small stimulations. Thus, operators have the option of improving reserves per well through recomple-

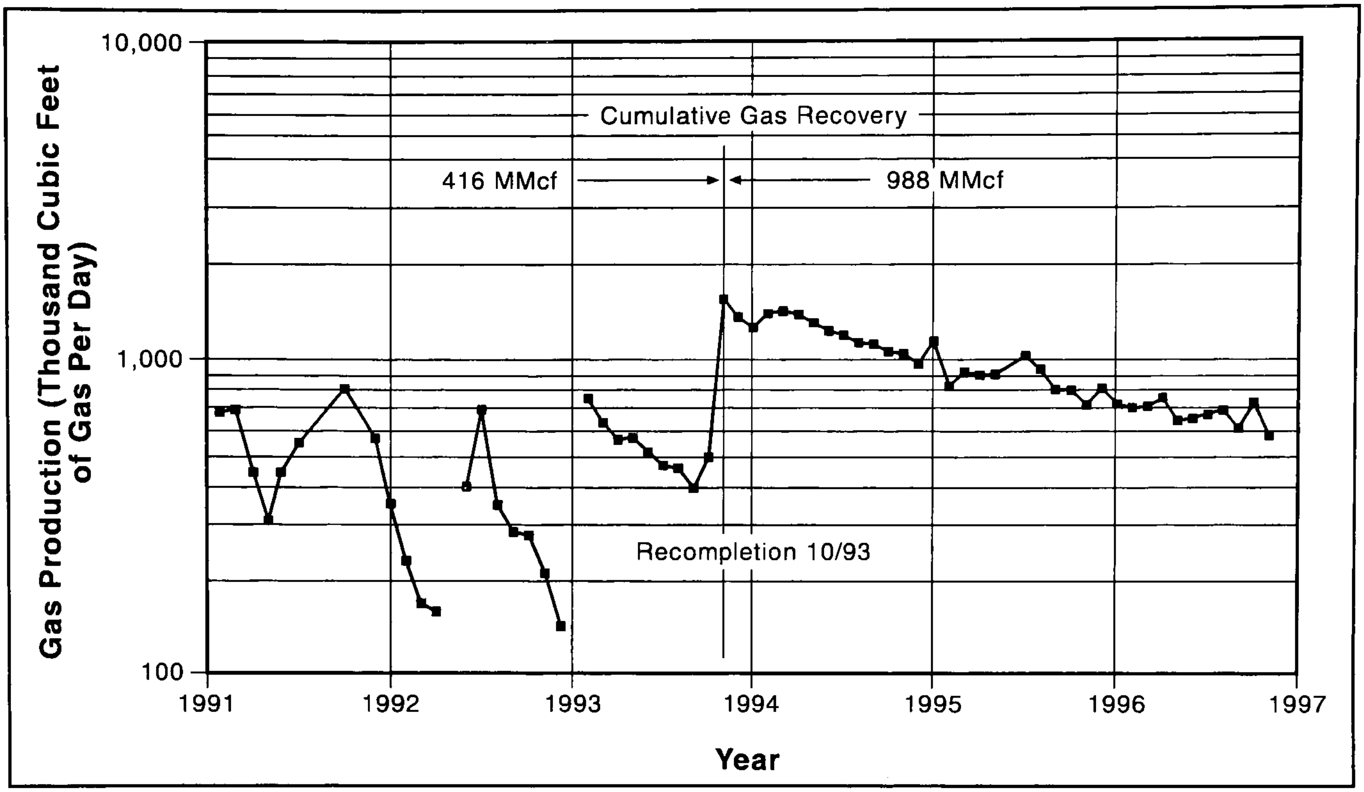


Figure 18. Pre- and post-recompletion gas production from a Rulison field gas well (from Kuuskraa, 1997).

tion. This strategy can add more zones via application of Waxman-Smits log analysis techniques and restimulation with much larger proppant loads. Figure 18 is an example of such a recompletion. The pre- and post-re-completion performance for well RMV 2-27 shows the improvement achieved.

An independent example of a recent recompletion at Rulison by the US DOE is well DOE Federal 9-17 MV. The well was originally completed in two Cameo coal and sand intervals in 1990 with a stimulation treatment of 100,000 gallons of gelled fluid and 270,000 pounds of sand per zone. Estimated ultimate recovery from the original completion was 516 MMcf. The well was recompleted in Williams Fork Formation lenticular sand intervals with 130,000 gallons of gelled fluid and 670,000 pounds of sand per zone (two zones). The estimated additional volume of gas added for the recompletion based on initial production rates is 1.2 bcf, more than doubling the wells original 0.5 bcf of reserves. Barrett Resource Corporation has been particularly active in pursing this strategy.

Role of Spacing

Barrett Resource Corporation initially developed this area with one well per 640 acres. Over time, it became apparent that one well would not drain all the gas that was recoverable under each 640 acre section. Eventually the company was authorized to drill one well per 40 acres (16 wells per section). Barrett indicates that the company has seen no communication between wells at that density.

In 1996 and into 1997 Barrett conducted two pilot programs evaluating 20-acre well densities, which confirmed there was little or no depletion or communication between wells. Approval was received in January 1998 from the Colorado Oil and Gas Conservation Commission to allow 20 acre spacing on a selected 2,830 net acres. According to Barrett the approval added 107 additional locations and 79 bcf of reserves to the company.

The approximate 14 township area with both proven-developed and proven-undeveloped tight Mesaverde Group gas contains 50 tcf of gas in-place reserves (Kuuskaa, 1997). Development at 160 acres would recover 5 percent of this resource. At 40-acre spacing, recovery is estimated to be 26 percent. Development at this spacing could add another 7,000 new wells. Twenty-acre-spacing could theoretically add another 7,000 wells and lead perhaps to an ultimate gas recovery approaching 40 percent, or 20 tcf.

There is considerable room for expansion of this play to the north in the topographically rugged Roan Cliff area. Clearly the south-central, Mesaverde tight-gas-sand area is a 1990s oil and gas industry success story. This will remain an important area of gas resource for the nation well into the twenty-first century.

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