COALBED METHANE POTENTIAL OF THE GREATER GREEN RIVER, PICEANCE, POWDER RIVER, AND RATON BASINS

TOPICAL REPORT
(January 1991–July 1991)

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16. Abstract (Limit: 200 words)

Coalbed methane potential of the Greater Green River, Piceance, Powder River, and Raton Basins was evaluated in the context of geologic and hydrologic characteristics identified in the San Juan Basin, the nation's leading coalbed methane producing basin. The major comparative criteria were (1) coalbed methane resources, (2) geologic and hydrologic factors that predict areas of high gas producibility and high coalbed reservoir permeability, and (3) coalbed thermal maturity. These technical criteria were expanded to include structure, depositional systems, and data base and then combined with economic criteria (production, industry activity, and pipeline availability) to evaluate the coalbed methane potential of the basins.

The Greater Green River and Piceance Basins have primary potential to make a significant near-term contribution to the nation's gas supply. These basins have large gas resources, high-rank coals, high gas contents, and established coalbed methane production. The Greater Green River Basin has numerous coalbed methane targets, good coal-seam permeability, and extensive hydrologic areas favorable for production. The Powder River and Raton Basins were judged to have secondary potential. Coal beds in the Powder River Basin are thermally immature and produce large volumes of water; the Raton Basin has a poor data base and has no gas pipeline infrastructure. Low production and minimal industry activity further limit the near-term potential of the Raton Basin. However, if economic criteria are discounted and only major technical criteria are considered, the Greater Green River and Raton Basins are assigned primary potential. The Raton Basin's shallow, thermally mature coal beds of good permeability are attractive coalbed methane targets, but low coal-seam permeability limits the coalbed methane potential of the Piceance Basin.

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Coalbed methane potential, Upper Cretaceous-lower Tertiary, western intermontane basins, structural setting, cleat, depositional systems, coal occurrence, hydrology, coal rank, thermal maturity, gas composition, coalbed methane production, coalbed methane resources, bibliography

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Methane from coal seams, potential, occurrence and resources, bibliography of four western United States coalbed methane basins

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RESEARCH SUMMARY

Title	Coalbed methane potential of the Greater Green River, Piceance, Powder River, and Raton Basins
Contractor	Bureau of Economic Geology, The University of Texas at Austin, GRI Contract No. 5087-214-1544, entitled "Geological Evaluation of Critical Production Parameters for Coalbed Methane Resources, San Juan Basin."
Principal Investigator	W. R. Kaiser
Report Period	January 1991–July 1991
Objectives	To identify technical and economic criteria useful for evaluating the potential of coalbed methane in western United States coal basins and to compile data and describe each basin in terms of the criteria.
Technical Perspective	Eight western basins contain coalbed methane resources of 280 Tcf (7.92 Tm^3), or 71 percent of the nation's total of 392 Tcf (11.09 Tm^3). Recent GRI reports characterized the geologic and hydrologic controls on coalbed methane producibility in the San Juan Basin (88 Tcf). The initial phase of this study eliminated Western Washington (24 Tcf), Uinta (5 Tcf), and Wind River (2 Tcf) Basins from further consideration owing to their small coalbed methane resources and/or lack of sizable data base. This report reviews the coalbed methane potential of the Greater Green River (29 Tcf), Piceance (84 Tcf), Powder River (30 Tcf), and Raton (18 Tcf) Basins on the basis of current literature and available production data.
Results	The Greater Green River Basin is divided into four subbasins (Green River, Great Divide, Washakie, and Sand Wash Basins) by the Rock Springs Uplift and Wamsutter and Cherokee Arches. Upper Cretaceous and lower Tertiary strata offer numerous coalbed methane targets. Permeable, normally pressured and artesian coal seams occur at depths to 7,000 ft (2,135 m) above regional overpressure. Coal rank ranges from subbituminous to semianthracite, and gas contents range from 150 to 375 Scf/ton (4.3 to 10.9 m^3/t). Vitrinite reflectance profiles indicate that the eastern Greater Green River Basin has greatest coalbed methane potential. Coalbed methane resource is 29 Tcf (821 Bm^3), with a cumulative production of 4,651 MMcf (131 MMm^3) mostly from Mesaverde and Fort Union coal beds in the Sand Wash Basin.

The Piceance Basin is bounded by the Uinta Mountain Uplift, Axial Arch, White River Uplift, and Elk Mountains. Coals in the Cameo coal group (Mesaverde Group) are the major coalbed methane targets, the basin being dominated by underpressure and hydrocarbon-related overpressure, indicating low overall permeability. Coal rank ranges from high-volatile C bituminous to semianthracite, and gas contents range from 200 to 450 Scf/ton (5.8 to 13.12 m^3/t). The Cameo coal group contains 65 Tcf (1.84 Tm^3) of coalbed methane resources of the total of 84 Tcf (2.38 Tm^3). Cumulative coalbed methane production is 7,854 MMcf (222.3 MMm^3).

The Powder River Basin is bounded by the Big Horn, Laramie, and Black Hills Uplifts. The main coalbed methane target is the Tongue River Member of the Fort Union Formation, where coal seams are major aquifers that will be difficult to dewater. Coal rank is lignite to subbituminous and locally to high-volatile C bituminous. Gas contents are less than 100 ft^3/ton (<2.9 m^3/t), and coalbed methane resource estimates range from 16 to 30 Tcf (453 to 849 Bm^3), but cumulative coalbed methane production is only 850 MMcf (24.1 MMm^3). Shallow drilling depths (average completion depth 500 ft [152 m]) are attractive to small operators.

The Raton Basin is bounded by the Sangre de Cristo Mountains, the Apishapa and Las Animas Arches, and the Sierra Grande Uplift. Tertiary intrusives cause additional structural complexity. The main coal-bearing units are the Vermejo and Raton Formations. The basin is regionally underpressured, reflecting insulation from recharge and coal-seam lenticularity. Coals of high gas content (200 to 400 Scf/ton [5.8 to 11.6 m^3/t]) ranging from high-volatile C bituminous to low-volatile bituminous in rank, occur at shallow depths. The coalbed methane resource is estimated at between 12.4 Tcf (350.9 Bm^3) and 18.4 Tcf (520.7 Bm^3). Only 11.7 MMcf (331,110 m^3) of coalbed methane has been produced because most of the basin's wells are currently shut-in, pending construction of a gas pipeline.

Technical Approach

The basins were compared in terms of structure, stratigraphy, hydrology, and thermal maturity. Tectonic and stratigraphic settings were described to document areas where coalbed methane production may be favored. Coalbed cleats and stress orientations were recorded to determine possible permeability anisotropy. Coalbed methane exploration fairways were based on coalbed and sandstone characteristics and regional coalbed-occurrence trends. Topographic, precipitation, stratigraphic, and structure data were combined with available hydraulic head and hydrochemical data to identify basinal ground-water flow patterns. The pressure regime was evaluated from pressure gradients, relation between head and land surface, flowing wells, hydrostratigraphy, and surface geology. Vitrinite reflectance and proximate analyses were used to construct coal-rank maps and to evaluate the thermal maturation history, and vitrinite reflectance profiles were used to evaluate the relationship between depth and coal rank. The isotopic and compositional data for coalbed gases were used to determine coalbed gas origin, explore the possibility of gas migration, and evaluate the relation between coal rank and gas composition. Production data from coalbed methane wells were tabulated. The major coalbed methane fields were described and completion and drilling activity summarized. On the basis of technical and economic criteria, basins were assigned primary and secondary coalbed methane potential.

Implications

This report will help producers identify potential targets for development in the Greater Green River, Piceance, Powder River, and Raton Basins of the western United States. It describes the factors found to be important for high productivity from coal seams in the San Juan Basin, such as structural setting, coal thickness, rank, distribution, and hydrology. These insights advance the understanding of the controls and occurrences of areas having high coalbed methane potential and will also be used to help guide future GRI research efforts.

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EXECUTIVE SUMMARY

Introduction

Eight western basins—San Juan, Greater Green River, Piceance, Powder River, Raton, Western Washington, Uinta, and Wind River (fig. ES-1)—contain, by virtue of their tremendous coal tonnage, coalbed methane resources of 280 Tcf (7.92 Tm^3), or 71 percent of the nation's total of 392 Tcf (11.09 Tm^3). However, only in the San Juan Basin are these western coalbed resources being extensively exploited to meet the nation's demand for natural gas. In a recently completed comprehensive study integrating geology and hydrology, the Bureau of Economic Geology (BEG) identified geologic and hydrologic controls on the production of coalbed methane in the San Juan Basin (Ayers and others, 1991). As part of the GRI's assessment of natural gas supply, the BEG is currently reviewing the geology and hydrology of other western basins. In a preliminary screening, Western Washington, Uinta, and Wind River Basins were eliminated from further review because of small coalbed methane resources and/or data bases, judged too small for a full analysis of the controls on coalbed methane production. On the basis of available data, this report reviews the coalbed methane potential of the four remaining basins: Greater Green River, Piceance, Powder River, and Raton. Coal and coalbed methane resources, structure, depositional setting, hydrology, thermal maturity, production, industry activity, and infrastructure are reviewed in each basin in order to identify geologic and hydrologic controls on the occurrence and producibility of coalbed methane (table ES-1). Their relative importance is discussed in the context of lessons learned in the San Juan Basin.

Resources

Estimated coal and coalbed methane resources are large in all four basins and each basin is an attractive coalbed methane target (table ES-1). These reported estimates were arrived at under a variety of assumptions and criteria that were not the same for each basin. Although the estimates are not strictly comparable, they are not significantly different except in the Raton Basin, where coal resources are one or two orders of magnitude less than those of the other basins (table ES-1). Small coal resources limit the Raton Basin's coalbed methane potential. The Greater Green River and Powder River Basins, because of their sizes and great net-coal thicknesses, have the largest coal resources (table ES-1). Not all of the area of the Greater Green River and Piceance Basin is underlain by coals that are accessible by shallow (<6,000 ft [<1,830 m]) drilling. However, the great overall thickness of the coal-bearing stratigraphic interval in the Greater Green River Basin partly compensates for the greater depths of part of the basin. All the area of the Powder River and Raton Basins is underlain by shallow coals. Gas resources are largest in the Piceance and Greater Green River Basins, 84 Tcf (2.38 Tm^3) and 29 Tcf (0.82 Tm^3), respectively

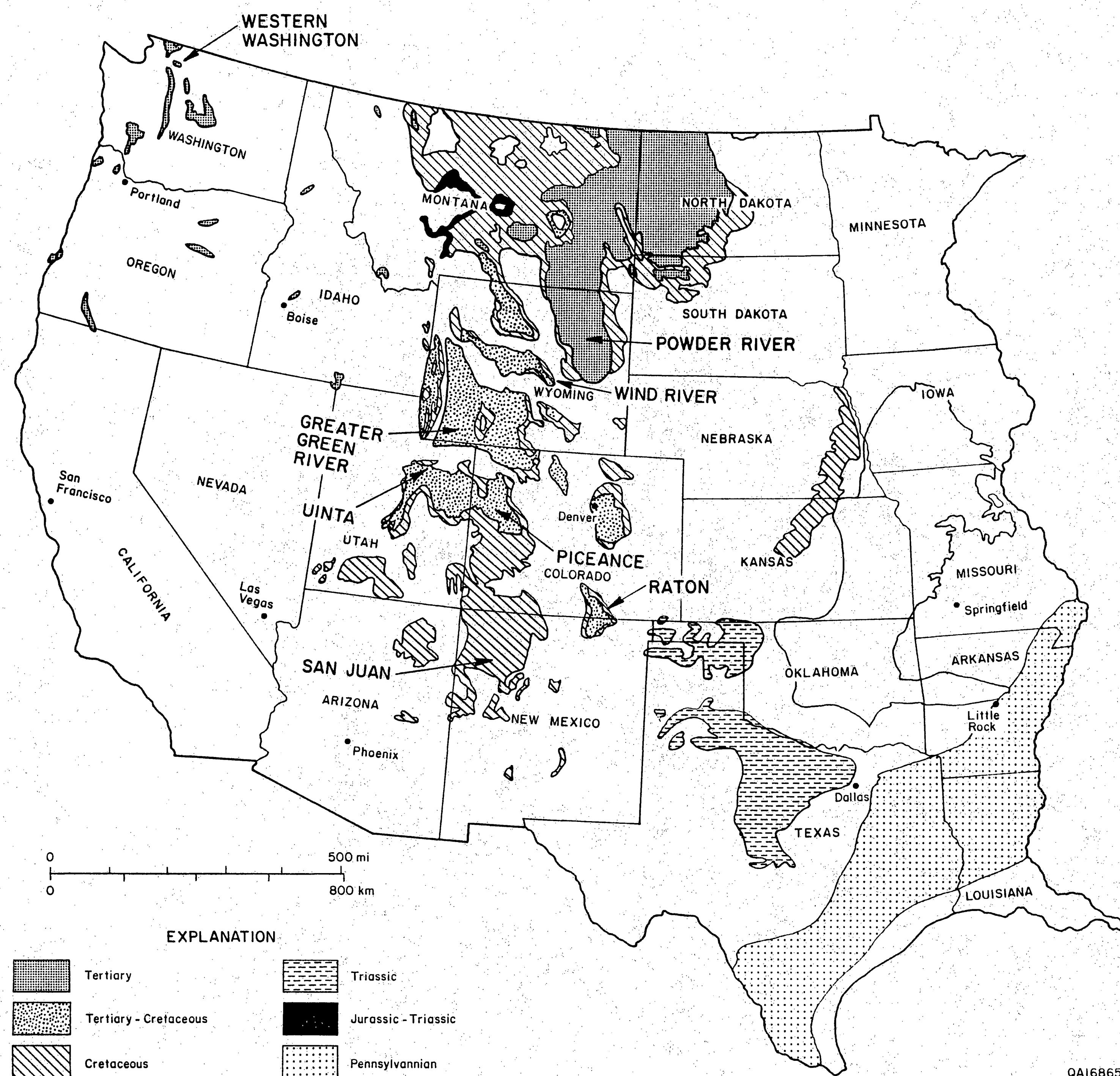

Figure ES-1. Western United States coal basins. Modified from Wood and Bour (1988).

Table ES-1. Coalbed methane characteristics of western United States coal basins.

CRITERIA	San Juan	Greater Green River	Piceance	Powder River	Raton
RESOURCES					
Area (mi²)	7,500	21,000	6,700	25,800	2,200
Typ. thick. of maj. coal-bearing int. (ft)	300–400	4,000–9,000	500–1,500	1,500–2,500	500–1,500
Coal resource (billion tons)	240	>302	380	1,031	17
Coal rank (R_o percent)	>0.73	>0.73	>0.73	<0.50	>0.73
Typical gas content (Scf/ton)	100–500	150–375	200–450	<100	200–400
Published max. gas-in-place (Tcf)	88	29	84	16 – 30	12–18
STRUCTURE					
Structural relations	Simple	Complex	Complex	Locally complex	Locally complex
Thrusted/elevated margins (sides)	Steep (3)	Steep (4)	Very steep (2)	Gentle (1)	Steep (1)
Intrabasin uplifts	Absent	Numerous	Several	Absent	Few
Face-cleat orientation	NW; NE	ENE; WNW	NNE; ENE	NNE; E	ENE;WNW
Overlapping face-cleat domains	Yes	No	Possible	Yes	No
Structural dip changes	Few	Numerous	Several	Few	Few
DEPOSITIONAL SETTING					
Maximum-coal thickness (ft)	25–40	25–35	20–35	100–150	<10
Typical net-coal thickness (ft)	40–60	150–200	100–150	250–350	40–70
Coal seam continuity	Good	Good	Good	Excellent	Poor
Coal seam orientation	NW	N-NE	NE (shoreline) / NW (floodplain)	NW	NE (south basin) / NW (north basin)
Typ. thick. of maj. coal-bearing int. (ft)	300–400	4,000–9,000	500–1,500	1,500–2,500	500–1,500
HYDROLOGY					
Artesian overpressure	Extensive	Present	Present	Present	Probable
Hydrocarbon overpressure	Absent	Extensive	Present	Absent	Absent
Normal pressure	Present	Extensive	Present	Present	Present
Underpressure	Extensive	Present	Extensive	Absent	Extensive
Chlorinity (mg/L)	10's–100's	100's–1,000's	100's–1,000's	100's	100's
Permeability (md)	~10	~10	<1/ locally ~10	10's – 100's	~5
Pressure transition	Extensive	Extensive	Present	Absent	Absent
Convergent flow	Extensive	Extensive	Present	Minimal	Present
Flow direction	Southwest	East and west	Northwest	North	East
THERMAL MATURITY					
Coal rank, avg R_o (%) at 6000 ft	0.65 – 2.35	0.55 – 0.60	0.70 – 1.50	<0.50	>2.0
Typical gas content (Scf/ton)	100–500	150–375	200–450	<100	200–400
Gas composition	Very wet-very dry	Dry – very dry (?)	Very wet - very dry	Dry - very dry	Very dry
CO_2 content	Low - very high	Low – high (?)	Low - very high	Low - very high	Low
Dominant gas origin	Thermogenic and biogenic	Biogenic, migrated thermogenic	Thermogenic	Biogenic	Thermogenic
DATA BASE					
Geophysical logs	19,000	19,294	6,860	33,283	189
DST's (coal intervals)	50	1,803	150	10	4
DST's (coalbed)	10	11	19	3	0
PRODUCTION					
Cumulative gas (MMcf)	165,000	4,651	7,810	791	12
Cumulative water (MMbbl)	>3	2	1	3	1
IP gas (Mcf/d)	100–400	50–>200	100–500	<100–300	<100–300
IP water (bbl/d)	40–400	<200–600	<100–400	200–1000	100–400
Avg. depth of CBM completion (ft)	~2,600	2,671	5,048	478	1,512
INDUSTRY ACTIVITY					
Companies active	>50	22	13	32	7
Coalbed completions	>1,200	20	49	55	17
Relative interest	Very high	High	Very high	High	Low
INFRASTRUCTURE					
Pipelines	Interstate	Interstate	Intrastate	Interstate	None

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(table ES-1). Gas resources in the Greater Green River Basin are potentially larger than reported because of the basin's large size and net-coal thickness of more than 200 ft (>61 m).

Structure

The configuration of the Greater Green River, Piceance, Powder River, and Raton Basins is the result of similar tectonic and structural histories. These basins lie in the Rocky Mountain Foreland, a major tectonic element between the Overthrust Belt and the North American Craton (fig. ES-2). During the Laramide Orogeny, in Late Cretaceous and early Tertiary time, the Foreland was broken into a number of smaller basins by basement-involved thrusting, which elevated highlands and resulted in sediment being shed into the newly formed intermontane basins. Tectonism was followed by an episode of erosion, a period of widespread magmatism and volcanism in the Oligocene, and finally an episode of renewed tectonic uplift about 10 mya. By the end of the Pliocene, the basins' present structural configuration, topography, surface drainage, and hydrodynamics were largely established.

Regional structural elements are the result of Laramide and post-Laramide tectonism. Their abundance is a measure of structural complexity. The Greater Green River and Piceance Basins are structurally complex, whereas the Powder River and Raton Basins have relatively simple structures (table ES-1), as does the San Juan Basin, the nation's most productive coalbed methane basin. The importance of regional structural elements is mainly in the associated fracture-enhanced permeability. Regional changes in structural dip may be sites of fracture-enhanced permeability or structural discontinuities (hingelines), and thus sites for coalbed methane production, as in the San Juan Basin where the basin's most productive wells occur. If structural complexity and dip changes translate into fracture-enhanced permeability and conventional trapping of gas along structural hingelines, the more complex Greater Green River Basin is given an advantage over the other basins.

Fractures are the primary control on coalbed permeability. Coal is pervasively fractured (cleated) and commonly has one or more dominant sets (face cleat) that impart permeability anisotropy, which may be predictable from the regional cleat patterns. The face cleats are extension fractures that strike parallel to tectonic shortening directions, and they are typically oriented at right angles to orogenic thrust faults.

Depositional Setting

Major depositional controls on the producibility of coalbed methane are the size, thickness, orientation, and stratigraphic complexity of the coal reservoirs. Maximum-coal thickness is a critical parameter for the production of coalbed methane and is inferred to be an indicator of productivity, whereas net-coal thickness indicates gas resources. In the San Juan Basin, the correlation of maximum-coal thickness with productivity trends is superior to that of average- and net-coal thickness with such trends. Sandstones, which are depositional platforms for coal accumulation, ultimately bound coal

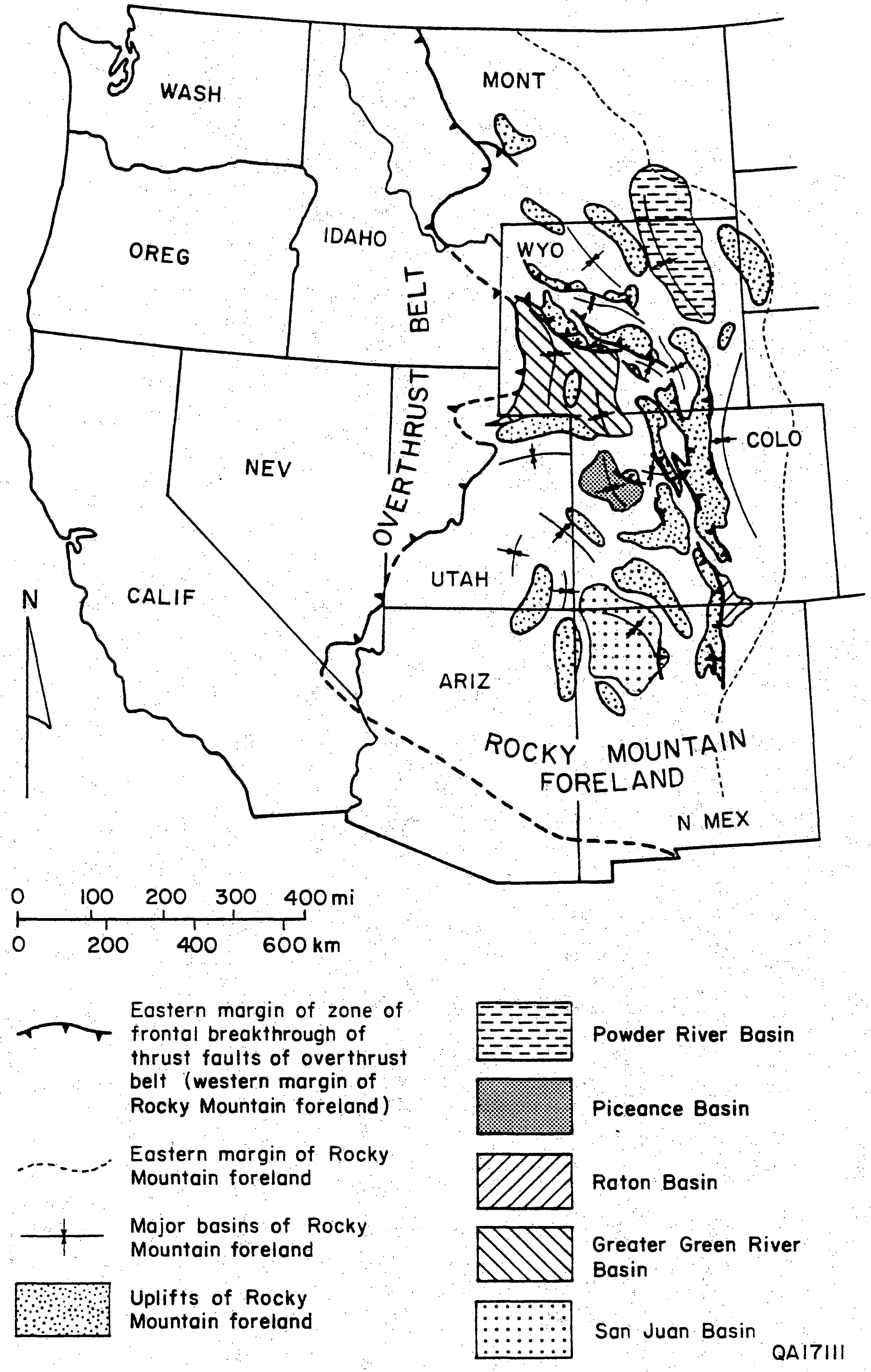


Figure ES-2. Basins and uplifts of the Rocky Mountain Foreland.

seams and therefore determine their size. Therefore, sand-body geometry and coal/sandstone relations cannot be ignored.

Upper Cretaceous and/or lower Tertiary coal-bearing strata are the potential coalbed methane targets in all basins. Upper Cretaceous depositional systems were predominantly wave-dominated deltas and barrier/strandplains, which formed linear clastic shorelines. The thickest coal seams were preserved landward and parallel to these ancient shorelines. Commonly, thick coals rest directly on marine shoreline sandstones. In contrast, lower Tertiary coals are hosted by fluvial-lacustrine sediments where interchannel floodplains and foundered lacustrine deltas were sites of organic accumulation.

Greater Green River Basin

In the Greater Green River Basin, the coal-bearing stratigraphic interval is thousands of feet thick and extends from the Upper Cretaceous Mesaverde Group through the lower Tertiary Wasatch Formation. The thickest and most continuous Cretaceous coal beds occur in the lower part of coal-bearing intervals in the Mesaverde Group (Williams Fork, Almond, and Rock Springs Formations) and the Lance Formation. These coal beds are individually as thick as 35 ft (11 m) and extend for as much as 10 to 20 mi (16 to 32 km). In contrast, lower Tertiary coal beds (Fort Union and Wasatch Formations) are less continuous and typically have lateral extents of less than 5 mi (<8 km), reflecting accumulation on floodplains of limited size and temporal stability. Most of the Cretaceous coal seams are less than 6,000 ft (<1,830 m) deep only along the southeast margin of the basin (Sand Wash and Washakie Basins), in the center of the basin at the Rock Springs Uplift, and along the northwest basin margin on the north end of the Moxa Arch. However, because of the thick coal-bearing interval, multiple targets are present, and basinward progressively younger intervals can be tested at exploitable depths. For example, at the center of the Washakie and Sand Wash Basins, Mesaverde coal seams are certainly too deep for economic exploitation, but lower Tertiary coals may be present at exploitable depths.

Piceance Basin

The Piceance Basin has a single major coalbed methane target—the Cameo coal group in the lower part of the Mesaverde Group. The Cameo interval ranges from 300 to 600 ft (91 to 183 m) thick and occurs at an average depth of approximately 5,000 ft (1,525 m). Maximum thickness of individual Cameo coal beds is 20 to 35 ft (6 to 11 m), and net-coal thickness ranges from less than 20 ft (<6 m) to more than 60 ft (>18 m). The most continuous Cameo coal beds formed landward (northwestward) of the Rollins shoreline sandstone and extend northeastward along depositional strike for 5 to 10 mi (8 to 16 km). Less continuous, fluvial Mesaverde coal beds occur up the paleoslope to the northwest.

Powder River Basin

The thickest, most laterally continuous coal seams are found in the Powder River Basin in the Tongue River Member of the Paleocene Fort Union Formation. These coal seams locally exceed 300 ft (91 m) in net thickness in the center of the basin. Individual coal beds exceed 100 ft (30 m) in thickness, extend along depositional strike (northwest) for tens of miles, and occur in two separate northwest-trending belts in the east and central parts of the basin. These belts reflect westward progradation of a lacustrine-delta system, followed by abandonment, foundering, and subsequent peat (coal) accumulation.

Raton Basin

The coal-bearing stratigraphic units in the Raton Basin are the Upper Cretaceous Vermejo and Upper Cretaceous–Paleocene Raton Formations. The basin's thickest coals (maximum thickness ranges from 10 to 14 ft [3 to 4.3 m]) are found in the lower Vermejo Formation, where they formed landward (westward) of the Trinidad shoreline sandstone. Fluvial coal beds in the Raton Formation are thinner (maximum thickness 6 ft [1.8 m]) and less continuous.

Basin Comparison

Coalbed methane targets occur in Upper Cretaceous and/or lower Tertiary strata. The thickest and most continuous coal seams are in the Powder River Basin, the thinnest and least continuous, in the Raton Basin (table ES-1). Maximum-coal thickness, or thickness of the single thickest seam, exceeds 20 ft (6 m) in all basins, except the Raton. In the San Juan Basin, maximum-coal thickness is inferred to be an indicator of gas productivity, whereas net-coal thickness indicates gas resources. In all basins, typical net-coal thickness exceeds 100 ft (30 m) except in the Raton. However, the thickest coal-bearing stratigraphic interval (thousands of feet) is in the Greater Green River Basin. Thus, potential coalbed methane targets are numerous in all basins but most numerous in the Greater Green River Basin, where progressively younger intervals can be tested basinward at exploitable depths.

Hydrology

Basin hydrology reflects present-day structural configuration (attitude of aquifers and aquitards), topography, climate (precipitation and infiltration), and permeability. Reservoir conditions are inferred from basin hydrology. Because hydraulic gradient, pressure regime, and hydrochemistry reflect an aquifer's ability to accept and transmit fluid, they reflect regional permeability contrasts. In the San Juan Basin, higher permeability in the Upper Cretaceous Fruitland Formation was correlated with gentle hydraulic gradients, artesian overpressure, and low-chloride formation waters (Kaiser and others, 1991b). Regionally, artesian overpressure requires high permeability, confinement, and recharge at an elevated outcrop. Underpressure reflects low permeability and insulation from recharge. The presence of low-chloride water indicates active recharge and basinward flow along permeable pathways. In other basins, overpressure may reflect active hydrocarbon generation, whereas underpressure may reflect high permeability downflow of an elevated recharge area. Explanation of local pressure anomalies requires detailed data unavailable for this study.

Greater Green River Basin

In the Greater Green River Basin, the Mesaverde Group and Lance–Wasatch Formations are the coal-bearing hydrostratigraphic units. Both units are confined regionally by marine or lacustrine shales. Recharge is mainly at the basin's southeast margin and over the Rock Springs Uplift, which is rimmed by low-chloride waters. Ground-water flow is convergent on the basin center. Permeable, normally pressured, and artesian coal seams occur at depths of 7,000 ft (2,135 m) or less above regional overpressure that is predicated on low permeability (<0.1 md) and active generation of gas. Overpressure is not restricted to any particular stratigraphic unit. Consequently, the pressure transition is basinwide, occurring basinward in progressively younger strata. Because of low permeability and great depth, the top of regional overpressure is a floor for coalbed methane exploration.

Piceance Basin

In the Piceance Basin, the Mesaverde Group is the coal-bearing hydrostratigraphic unit, confined below by marine shale and unconfined above. Recharge is mainly at the basin's southeast margin, and regional ground-water flow is convergent on the Colorado River valley from the basin margin. Mesaverde coals are overpressured, underpressured, and normally pressured. Overpressure is found in the east-central part of the basin and covers about 11 townships. It extends from outcrop in the southeast part of the basin northwestward along the Divide Creek Anticline to just beyond the Colorado River. Both artesian and hydrocarbon-related overpressures are present. The absence of an upper confining layer, low permeability, and limited recharge restricts artesian overpressure to a relatively small part of the basin. Overpressure is surrounded by a very large underpressured area that coincides with high coal rank and gas content.

Powder River Basin

In the Powder River Basin, coal seams of the Tongue River Member of the Fort Union Formation are major aquifers. The Wyodak coal aquifer in the Upper Tongue River is the most continuous geohydrologic unit in the basin; its permeability ranges from 10 md to darcys. Recharge is mainly along the east margin of the basin. Regional ground-water flow is northward toward the Tongue River. Artesian conditions develop basinward as coal seams pinch out and become confined by lacustrine shales.

Raton Basin

In the Raton Basin, the coal-bearing hydrostratigraphic unit is composed of the Vermejo and Raton Formations. The unit is regionally confined below by the Trinidad Sandstone and Pierre Shale. Above, it is unconfined because the Raton crops out throughout much of the basin. Regional ground-water flow is from west to east, converging on the Purgatoire River and eastern outcrop belt. Basinal pressure regime is poorly known, but regional underpressure is postulated from hydraulic head data. Although artesian conditions may be present along the elevated western outcrop belt, or recharge area, coal-seam lenticularity, low equivalent permeability, insulation from recharge, and a topographically low discharge area maintain underpressuring.

Basin Comparison

In the Greater Green River Basin, normally pressured or artesian coal seams above regional overpressure yield large volumes of low-chloride water upon production, indicating high permeability (table ES-1). Areas of pressure transition and convergent, upward flow may be extensive and are favorable sites for coalbed methane production. The transitional pressure fairway is large and, if at exploitable depths (by analogy to the San Juan Basin) very productive. In the San Juan Basin, the pressure transition fairway, accompanied by upward flow, hosts the basin's most productive coalbed methane wells. In the Raton Basin, coal seams along the west margin are water productive, indicating good permeability. Regional underpressure is thought to reflect eastward decrease in permeability, insulation from recharge, and coal-seam lenticularity.

The Piceance Basin is dominated by underpressure and hydrocarbon-related overpressure, indicating low permeability (table ES-1). Very low permeabilities (microdarcys) have been reported from the underpressured parts of the basin, whereas the highest permeabilities (~10 md) come from artesian overpressured coal seams. Low permeability may ultimately limit the basin's coalbed methane potential. Paradoxically, high permeability may ultimately limit development in the Powder River Basin. Coal seams are major aquifers and will be difficult to dewater and depressure economically. Large volumes of produced water will create disposal problems and add to production costs.

Thermal Maturity

A coal bed's capacity to generate and store natural gases is dependent on its rank, ash content, and maceral composition. The volume of methane generated is directly related to coal rank, which in turn reflects basin tectonics and structural evolution. Rapid subsidence through high geothermal gradients produces coals of subbituminous to semianthracite rank. The higher the rank, the more gas generated. The minimum vitrinite reflectance value for significant gas generation is greater than 0.73 percent. Although most coalbed methane is believed to be predominantly thermogenic, at least some produced from coal beds is biogenic in origin. In the San Juan Basin, the presence of biogenic methane is supported by relatively constant $\delta^{13}C$ values of methane throughout the basin. If the gases are biogenic or sourced from deeper, higher-rank coals or marine shales, gas content can be much higher than predicted from rank alone. Thus, gas content may depend on methanogenesis and migration as much as thermal maturity of the coal. Much of the methane produced from high-volatile C and subbituminous coal is probably biogenic and early thermogenic. Ash content influences the volume of gas stored, with low-ash coals having higher gas contents. Maceral composition influences gas composition, wherein higher exinite or liptinite (hydrogen) content correlates with wetter gases.

Basin Review

In the Greater Green River Basin, coal rank ranges from subbituminous in the Fort Union Formation to semianthracite in the Almond Formation in the deep Washakie Basin. Vitrinite reflectance profiles suggest that coal rank is higher in the east part of the greater basin (fig. ES-3); there are no published reports on the composition of coalbed gases. Locally, north of the Rock Springs Uplift and in the Sand Wash Basin, gas content exceeds 400 ft^3/ton (>12.5 m^3/t) in Mesaverde coal beds. In the Piceance Basin, coal rank changes abruptly with depth; vitrinite reflectance values for Cameo coal seams range from 0.48 percent (high-volatile C) along the basin margin to 2.10 percent (semianthracite) at the basin axis. Gas contents typically range from 200 to 450 ft^3/ton (6.2 to 14.0 m^3/t) in the south part of the basin. Produced Cameo coalbed gases range from very dry to very wet (C_1/C_{1-5} 0.90 to 0.78) and have CO_2 contents ranging from 1.3 to 14.3 percent. The $\delta^{13}C$ values of methane indicate that the coalbed gases are mainly thermogenic and secondarily biogenic in origin. In the Powder River Basin, Fort Union and Wasatch coals have only reached lignite and subbituminous rank. The threshold of significant methane generation (high-volatile B bituminous) is not reached until 13,000 ft (3,965 m) (fig. ES-3). The $\delta^{13}C$ values of methane indicate that Fort Union coalbed gases are biogenic in origin. In the Raton Basin, coals of the Vermejo Formation range from high-volatile C to low-volatile bituminous rank (R_o values from 0.57 to 1.57 percent). Gas contents of 200 to 400 ft^3/ton (6.2 to 12.5 m^3/t) at shallow depths (<3,000 ft [<915 m]) indicate excellent coalbed methane potential. Coal rank is distinctly higher in an area parallel to the Purgatoire River (fig. ES-3). Hot fluids, heated by nearby Tertiary intrusives and ascending to an ancestral Purgatoire River, may account for high vitrinite reflectance values paralleling the river valley. Vermejo coalbed gases are very dry (C_1/C_{1-5} ~1.00) and very low in CO_2 (usually <1 percent). The $\delta^{13}C$ values of methane indicate that coalbed gases are mainly thermogenic in origin.

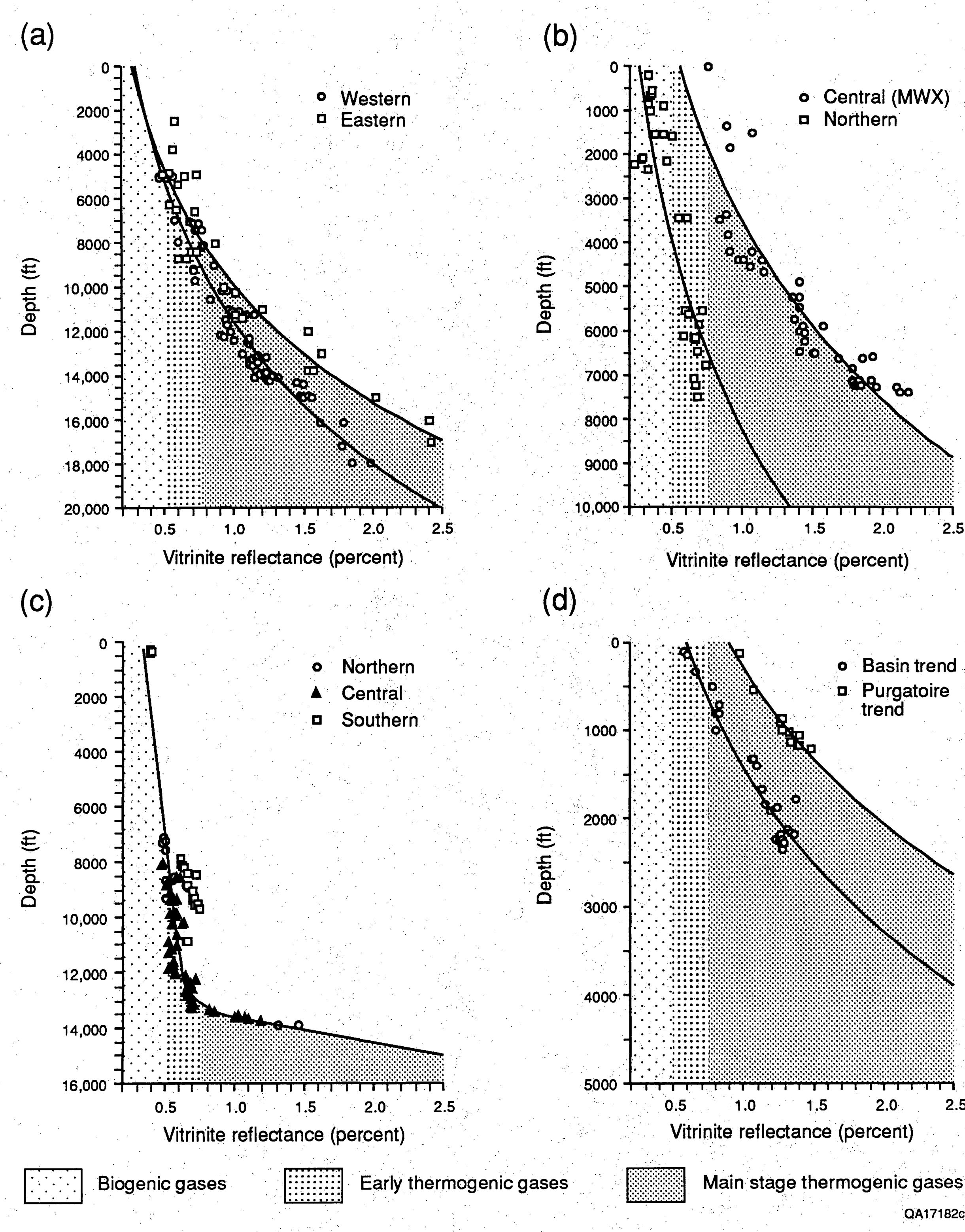


Figure ES-3. Vitrinite reflectance profiles and gas generation thresholds. Data from Law (1984), Johnson and Nuccio (1986), Nuccio (1990), and ARI, Inc. (1991).

Basin Comparison

The minimum vitrinite reflectance value for significant gas generation (0.73 percent) has been attained by coals in all basins, except the Powder River Basin (table ES-1). Coal rank is higher in the east part of the Greater Green River Basin than in the west. Significantly, Cretaceous coal seams at exploitable depths have not reached the thermogenic threshold, yet they have high gas contents (>300 ft^3/ton [9.4 m^3/t]) (fig. ES-3 and table ES-1), suggesting the presence of mainly biogenic and/or migrated thermogenic gas. Because gas content is not rank related, its distribution will be more difficult to predict. In the Piceance Basin, coal seams at depths of less than 6,000 ft (<1,830 m) range from high-volatile C bituminous to medium-volatile bituminous in rank, indicating good coalbed methane potential. However, the best potential, based on rank and depth, is in the Raton Basin, and the poorest is in the Powder River Basin (fig. ES-3). Gas contents are hundreds of cubic feet per ton in all basins, except the Powder River Basin, where they are less than 100 ft^3/ton (<3.1 m^3/t). Ash content in all basins ranges from 8 to 13 percent and should have little or no impact on coalbed methane potential. In the San Juan Basin, coal seams with two to three times that ash content are highly productive.

Production

In an analysis of gas and water production from Fruitland coal beds in the San Juan Basin, initial potential (IP) for gas was found to be a predictor of long-term productivity (Kaiser and others, 1991a). There was a positive correlation between IP gas and average daily production of a well's most productive year. Initial water potential increases with permeability (Oldaker, 1991) and high water potentials (several hundred bbl/d) are indicative of high permeability. By water-well standards, coalbed methane wells are low-yield water wells; that is, they produce less than 100 gal/min (<3,430 bbl/d [<545 m^3/d]). Because IP gas and water reflect productivity and permeability, respectively, and were readily available, production analysis was done here with emphasis on initial test data.

Greater Green River Basin

The Greater Green River Basin contains an estimated 29 Tcf (821 Bm^3) of coalbed methane resources and cumulatively has produced 4,651 MMcf (131 MMm^3) of coalbed methane as of January 1991 (table ES-1). In the past 18 months, 22 companies have been active at one time or another in the basin, where drilling activity is greatest in the Sand Wash Basin and north flank of the Rock Springs Uplift. Coal seams of the Fort Union Formation and Mesaverde Group (Williams Fork, Almond, and Rock Springs Formations) are being targeted. The Lance and Wasatch Formations are potential targets in other parts of the basin. Coalbed wells typically have IP's of 50 to more than 200 Mcf/d (1,415 to >5,660 m^3/d) (table ES-1), whereas wells dually completed in Fort Union coal beds and sandstones have IP's as high as

2,500 to 5,690 Mcf/d (70,750 to 161,030 m^3/d). The average completion depth is 2,671 ft (814 m), although deeper coal beds are common. Highest water IP's (>500 bbl/d [80 m^3/d]), indicating good permeability, are from wells along the east and south margins of the Sand Wash Basin. They reflect recharge over the Park Uplift and ground-water flow to the west.

Piceance Basin

The Piceance Basin contains an estimated 84 Tcf (2.38 Tm^3) of coalbed methane resources, of which 65 Tcf (1.84 Tm^3) is contained in the Cameo coal group (table ES-1). Cumulative production of gas is 7,854 MMcf (222.3 MMm^3) from Mesaverde coal beds and sandstones as of January 1991. Thirteen companies have been or are active in the basin, and drilling activity is concentrated in the south part of the basin and is mainly targeted in the Cameo coal group of the Williams Fork Formation. The average depth of coalbed methane wells is 5,930 ft (1,808 m). Gas IP's typically range from 100 to 500 Mcf/d (2,830 to 14,150 m^3/d) in coal beds and are as high as 2,600 Mcf/d (73,580 m^3/d) in wells dually completed in Mesaverde coal beds and sandstones. Decline analysis of these wells indicates that much of the gas is from low-permeability sandstones. Significant gas production occurs along the Colorado River Valley in the north-central part of the basin, where convergent, regional ground-water flow may favor hydrocarbon accumulation. Although water IP's from coal beds are low (<100 bbl/d [<16 m^3/d]), indicating low permeability, coalbed methane wells along the Divide Creek Anticline have IP's of more than 500 bbl/d (80 m^3/d) from artesian overpressured coal seams.

Powder River Basin

Coalbed methane resources in the Powder River Basin are estimated to range from 16 to 30 Tcf (453 to 849 Bm^3). Cumulatively the basin has produced only 850 MMcf (24.1 MMm^3) of coalbed methane as of January 1, 1991. As many as 32 companies have been or are active in the basin (table ES-1) because drilling depths are shallow (average completion depth is 478 ft [146 m]). Drilling activity centers on the basin's eastern margin and is targeted in Tongue River coal seams of the upper Fort Union Formation. On initial test the most productive coalbed wells produce less than 100 to 300 Mcf/d (<2,830 to 8,490 m^3/d). Conventional structural trapping, partial confinement, and dewatering by nearby surface mines probably explain local low-water gas production. Water IP's typically range from 200 to 1000 bbl/d (32 to 160 m^3/d) and are highest basinward in Johnson County, reflecting artesian conditions and high permeability.

Raton Basin

The Raton Basin contains an estimated 12 to 18 Tcf (340 to 509 Bm^3) of coalbed methane resources. However, its cumulative production, as of January 1, 1991, is a minuscule 11.7 MMcf (331,110 m^3) because most coalbed methane wells are shut-in pending construction of pipelines (table ES-1). Seven companies have been active in the basin. Drilling activity is along the west margin of the basin and is targeted in coal seams in the Vermejo and Raton Formations. The average completion depth is 1,500 ft (457 m). Maximum gas IP's of coalbed wells typically range from less than 100 to 300 Mcf/d (<2,830 to 8,490 m^3/d); values of less than 150 Mcf/d (<4,245 m^3/d) are common. Wells located in the western part of the basin, close to the recharge area, and in the Purgatoire River valley, have water IP's of several hundred barrels per day, indicating good permeability. Possible artesian conditions and attendant higher reservoir pressures may contribute to higher gas contents in those areas.

Basin Comparison

Cumulative production of coalbed methane is highest in the Piceance Basin, followed by the Greater Green River Basin (table ES-1). In the Raton Basin, most coalbed wells are shut-in for lack of pipelines, accounting for the basin's insignificant cumulative production. Gas IP's are highest in the Piceance Basin (100 to 500 Mcf/d [2,830 to 14,150 m^3/d]), where they reflect gas-saturated coal seams, except at Divide Creek field, where low IP's (<100 Mcf/d [<2,830 m^3/d]) complement high water IP's of more than 500 bbl/d (80 m^3/d). In the Piceance and Greater Green River Basins, highest gas IP's are, respectively, from wells dually completed in Mesaverde and Fort Union coal beds and sandstones. The need for dual completions may indicate low permeability or low-gas-content coal seams, or both. Gas IP's are lowest in the Powder River Basin (mostly <100 Mcf/d [<2,830 m^3/d]), reflecting low gas content and high water production. Industry activity is highest in the Powder River Basin because shallow drilling depths are attractive to small companies. Water IP's are high in all basins, except the Piceance, where they are mostly less than 100 bbl/d (<16 m^3/d), indicating low overall permeability. Highest water IP's (~ 1,000 bbl/d [~ 160 m^3/d]), indicating high permeability, are from artesian Fort Union coal seams in the Powder River Basin (table ES-1). Dewatering and disposal costs will adversely affect the economics of coalbed methane development.

Conclusion

This report compares the Greater Green River, Piceance, Powder River, and Raton Basins on the basis of lessons learned in the San Juan Basin. The Greater Green River and Piceance Basins have primary potential to make a significant near-term contribution to the nation's gas supply. These basins have large gas resources (29 and 84 Tcf [0.82 and 2.38 Tm^3], respectively), coals of high rank (R_o >0.73 percent) and high gas content (150 to 450 ft^3/ton [4.7 to 14.0 m^3/t]), and established coalbed methane production (table ES-1). The Powder River and Raton Basins are judged to have secondary potential. The Powder River Basin has coals of low rank (R_o <0.50 percent) and low gas content (<100 ft^3/ton [<3.1 m^3/t]). The Raton Basin has thin, discontinuous coal beds, small coal resources, a poor data base (<250 geophysical logs), and lacks gas transmission pipelines. Low production and minimal industry activity further limit the basin's near-term potential (table ES-1). However, if economic aspects are discounted and aspects of depositional setting, hydrology, and thermal maturity are compared, the Greater Green River and Raton Basins are judged to have primary potential. The Greater Green River Basin has several coal-bearing intervals offering numerous coalbed methane targets, good coal-seam permeability, and extensive hydrologic areas (pressure transition and convergent flow) where exceptional production could occur. The Raton Basin's shallow, high-rank coals of good permeability and high gas content are attractive coalbed methane targets. Low coal-seam permeability limits the coalbed methane potential of the Piceance Basin. A discussion of each basin and a reference list of more than 1,000 papers compose the body of the report, which follows this summary.

GREATER GREEN RIVER BASIN

Geologic Overview

The Greater Green River Basin is Wyoming's largest coal-bearing area, covering approximately 15,000 mi^2 (38,870 km^2) of southwestern Wyoming and 5,600 mi^2 (14,511 mi^2) of northwestern Colorado (fig. 1). Fragmentation of the Rocky Mountain foreland basin resulted in the Greater Green River Basin being bounded on three sides by basement-cored thrust sheets. The thrust sheets are now exposed in, or adjacent to, the Gros Ventre, Wind River, and Granite Mountains in the north; the Lost Soldier and Wertz Anticlines, Rawlins Uplift, and Hatfield and Miller Hill Anticlines in the east; the Sierra Madre and Park Uplifts in the southeast; and the Wind River, Axial Arch, and Uinta Uplifts in the south (fig. 2) (Armstrong and Oriel, 1965; Berg, 1961, 1962, 1983; Royse and others, 1975; Smithson and others, 1978; Gries, 1981, 1983a; Garing and Tainter, 1985). The emplacement of uplifts along thrust sheets has implications for fracture patterns in buried and less deformed parts of the Greater Green River Basin. East-west compression along salients in the thrust belt of the Tertiary uplifts could have caused east-west-striking fractures and faults. Such fractures and faults may play a role in fluid-flow patterns within the basin.

The Greater Green River Basin encompasses four intrabasin uplifts (the north-trending Moxa Arch and Rock Springs Uplift and the east-trending Wamsutter and Cherokee Arches) and four subbasins (Green River, Great Divide, Washakie and Sand Wash) (fig. 2). Sedimentary rocks ranging from Cambrian through Tertiary in the basin reach a maximum thickness of 32,000 ft (9,750 m). About 23,000 ft (7,012 m) of these rocks are Upper Cretaceous, Paleocene and Eocene in age (fig. 3) (Dickinson, 1989). Depth to the Cretaceous coal-bearing strata varies from outcrop to more than 12,000 ft (3,600 m) in the east basin and from outcrop to over 13,000 ft (3,960 m) deep in the west. Lower Tertiary coal-bearing strata range from outcrop to 9,500 ft (2,900 m) deep.

Tectonic and Stratigraphic Setting

The Overthrust Belt (Sevier Orogenic Belt) (fig. 1), is a region of north-trending folds and thin-skinned, generally west-dipping imbricate thrust faults that moved eastward in the Late Cretaceous to early Tertiary times (fig. 4). The Greater Green River Basin, to the east of the Overthrust Belt, is a structurally complex intermontane basin. The basin records three major progradational cycles in Upper Cretaceous, pre-Laramide sequences (fig. 3). The cycles were initiated by tectonic uplift and loading of the Overthrust Belt but sedimentation patterns are also thought to be influenced by eustatic sea-level fluctuations. Each cycle extended deltaic and coastal-plain deposits farther basinward than did the preceding cycle, indicating an overall filling of the Western Interior Seaway. Progradation extended coal-bearing strata (Frontier Formation) (fig. 3) as far east as the Rock Springs Uplift during the first cycle.

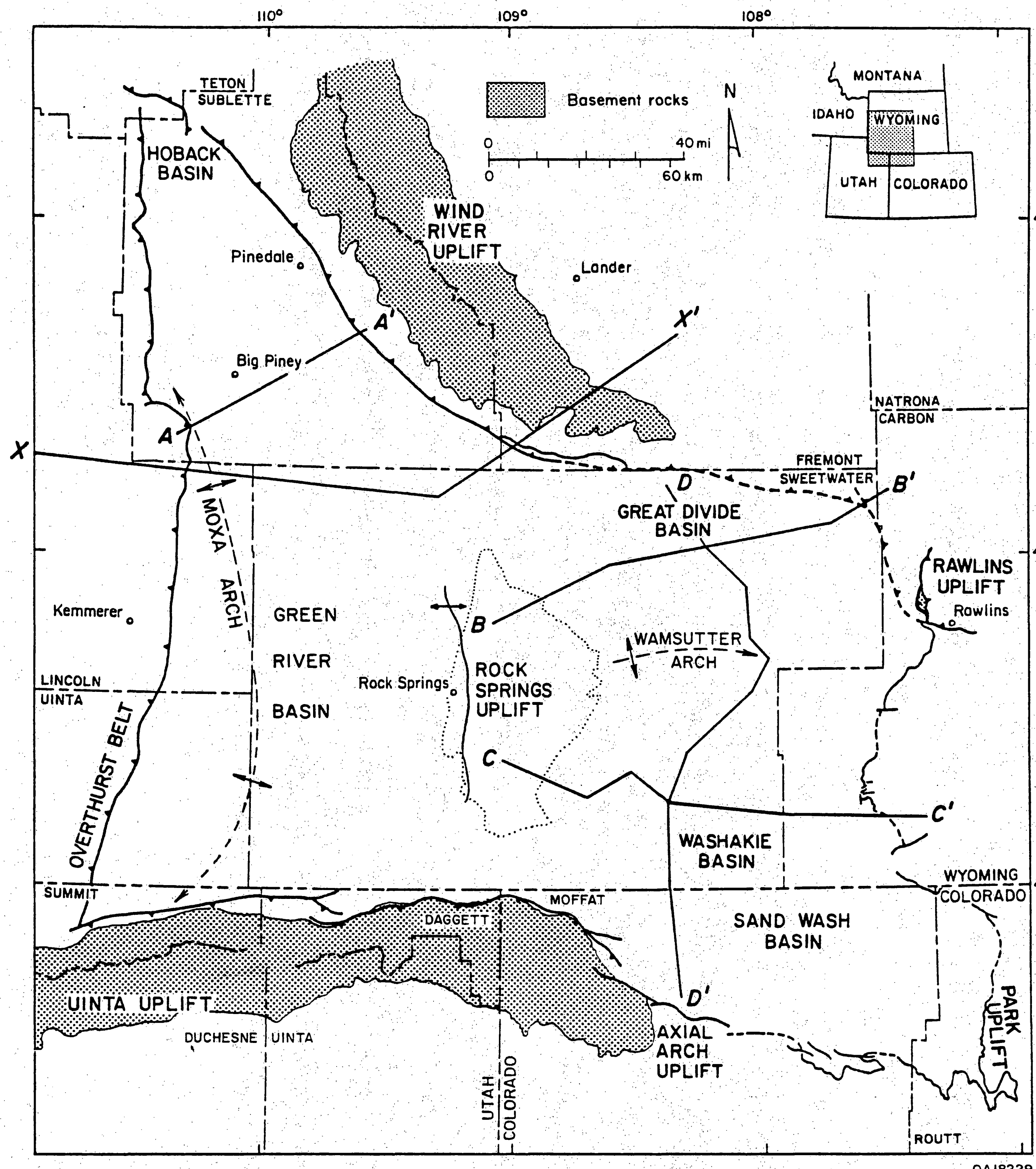


Figure 1. Areal extent of the Greater Green River Basin. Modified from Law and others (1989). Cross sections X–X′ and A–A′ through D–D′ are shown in figures 4 through 8.

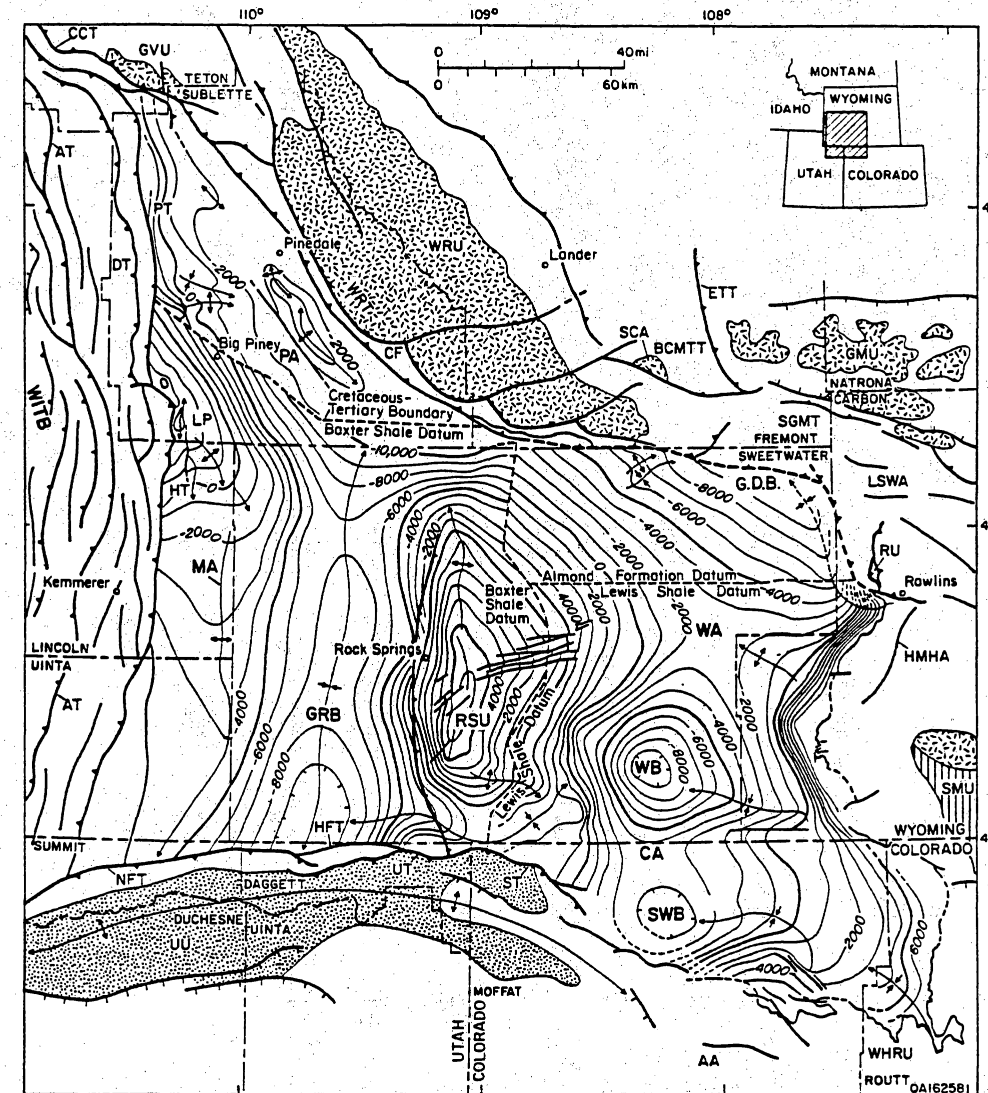


Figure 2. Tectonic map of southwestern Wyoming and adjacent states showing the major tectonic elements of the Greater Green River Basin. The map is taken from King (1969) with modifications from Reynolds (1968), Blackstone (1979), Love and Christiansen (1985), and Lickus and Law (1988). Structure contours, in feet relative to mean sea level, are drawn on a bentonite marker in the Upper Cretaceous Lewis Shale in the Washakie and Sand Wash Basins. Contours in the Great Divide Basin are drawn on top of the Upper Cretaceous Almond Formation. Contours in the Green River Basin are drawn on a bentonite marker in the Upper Cretaceous Baxter Shale. Contours in the north part of the Green River Basin are drawn on the Cretaceous–Tertiary boundary. Hachures show closed depressions. Major tectonic features are identified as follows: AA, Axial Arch; AT, Absaroka thrust fault; BCMTT, Beaver Creek and Mormon Trail thrust faults; CA, Cherokee Arch; CCT, Cache Creek thrust fault; CF, Continental Fault; DT, Darby thrust fault; ETT, Emigrant Trail thrust fault; GDB, Great Divide Basin; GMU, Granite Mountain Uplift; GRB, Green River Basin; GVU, Gros Ventre Uplift; HFT, Henry's Fork thrust fault; HMHA, Hatfield and Miller Hill Anticlines; HT, Hogsback thrust fault; LSWA, Lost Soldier and Wertz Anticlines; MA, Moxa Arch; LP, La Barge Platform; NFT, North Flank thrust fault; PA, Pinedale Anticline; PU, Park Uplift; RSU, Rock Springs Uplift; RU, Rawlins Uplift; SCA, Sweetwater Crossing Anticline; SGMT, South Granite Mountains thrust fault; SMU, Sierra Madre Uplift; ST, Sparks thrust fault; SWB, Sand Wash Basin; UT, Uinta thrust fault; UU, Uinta Uplift; WA, Wamsutter Arch; WB, Washakie Basin; WHRU, White River Uplift; WITB, Wyoming–Idaho Overthrust Belt; WRT, Wind River thrust fault; and WRU, Wind River Uplift. Basement rocks are identified as follows: random-dash pattern, basement rocks of Archean age; vertical-line pattern, basement rocks of early Proterozoic age; stippled pattern, basement rocks of middle Proterozoic age.

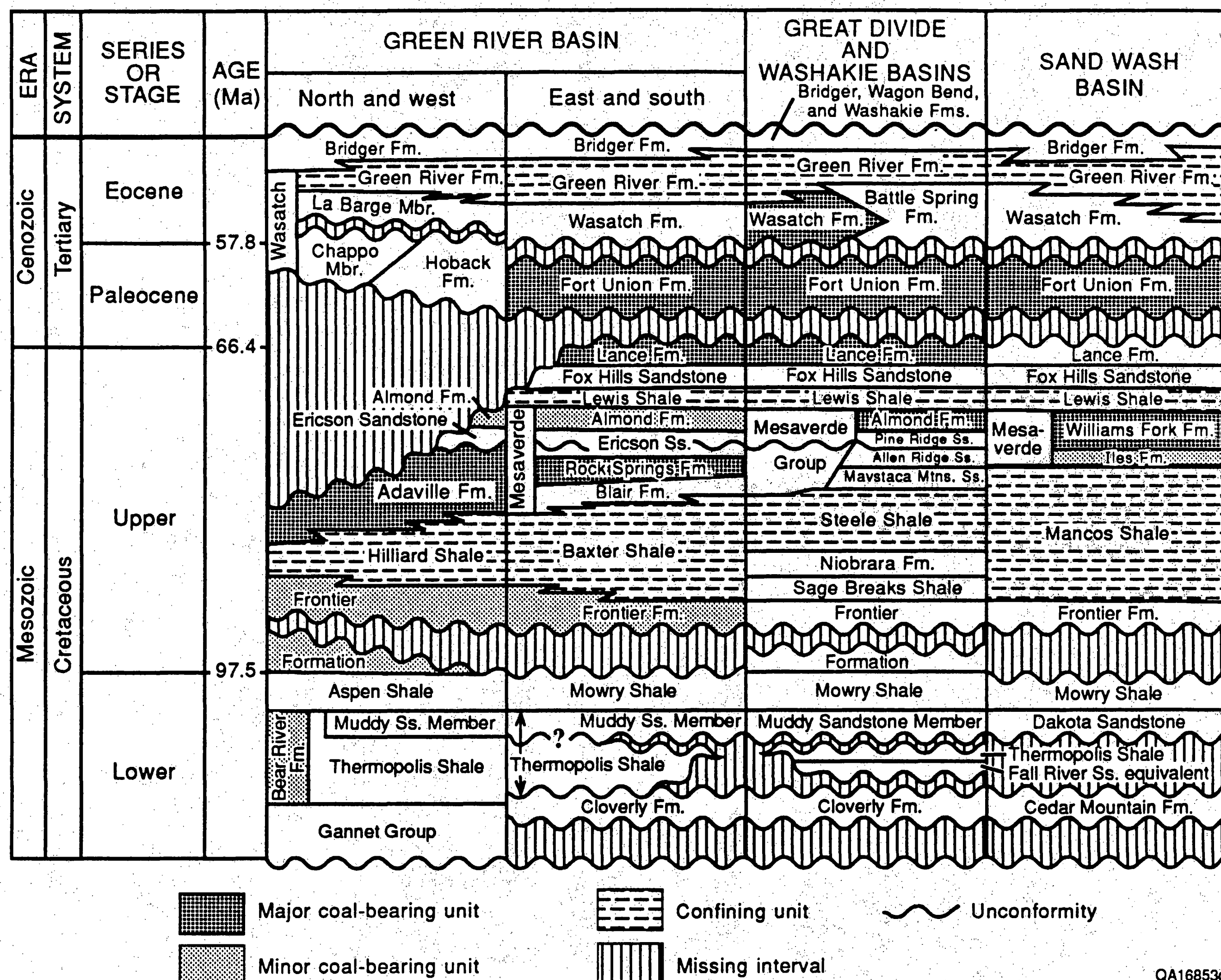


Figure 3. Coal-bearing stratigraphic and confining units in the Greater Green River Basin. Modified from Baars and others (1988).

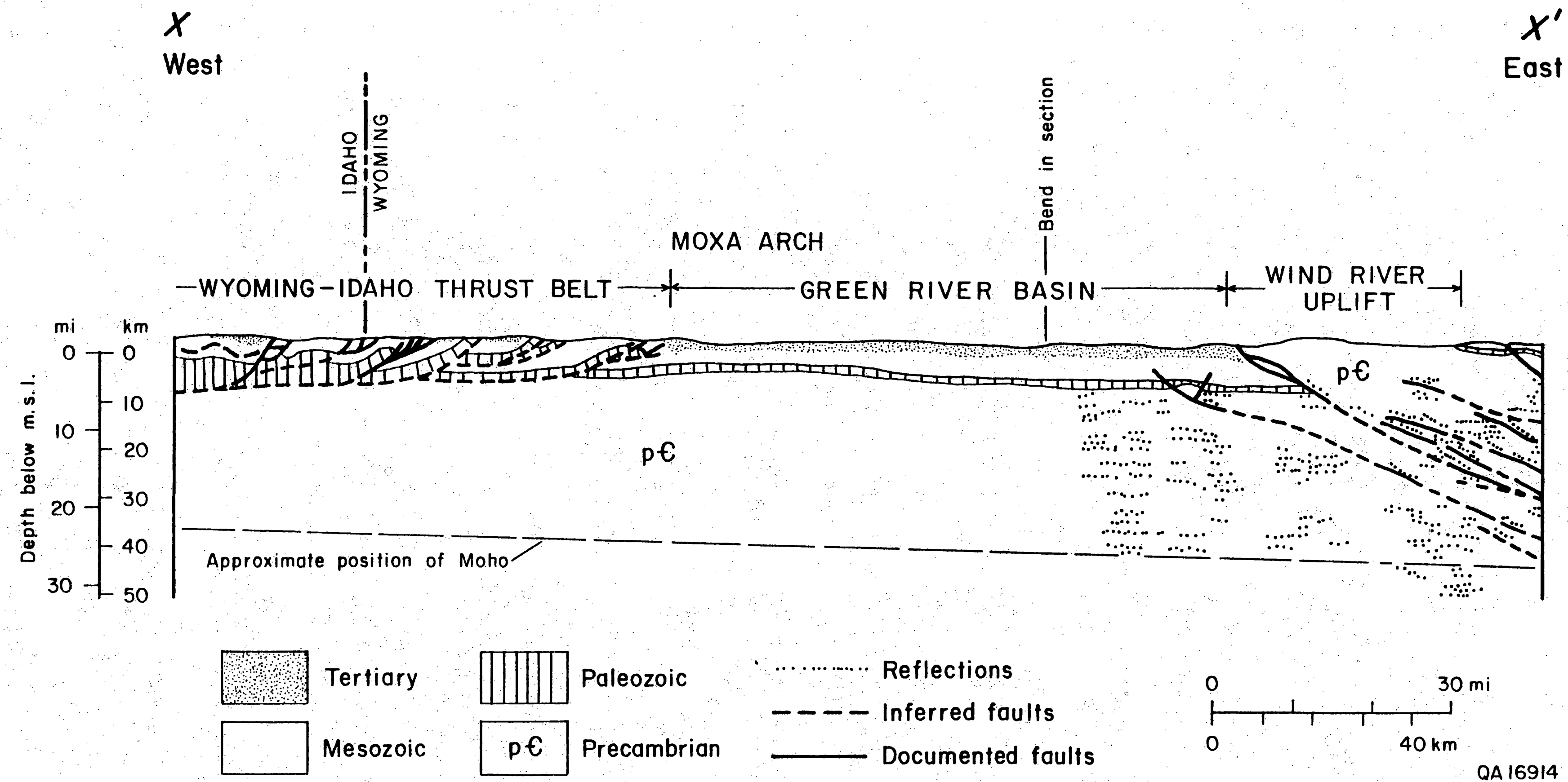


Figure 4. West-east cross section X–X′ through the Wyoming–Idaho Overthrust Belt, the Green River Basin, and the Wind River Uplift. Line of section shown in figure 1. The section is from Bally and Snelson (1980); modified from Baars and others (1988).

Equivalent strata basinward are mud-rich prodelta and delta-front facies. The second major cycle established coal-forming conditions in deltaic and back-barrier settings (Mesaverde Group) beyond the present-day eastern limit of the Greater Green River Basin. Minor regressive and transgressive cycles are recognized within the major Mesaverde Group cycle. The Fox Hills Sandstone represents the last Cretaceous progradational event in the Rocky Mountain Foreland basin and is the platform upon which Lance Formation coals accumulated (fig. 3).

Basement uplifts subsequently broke the foreland basin into smaller structural and depositional basins during Laramide deformation (mainly Tertiary in age, between 70 and 40 mya). Activation of the late Campanian phase of uplift and erosion across the north margin of the present-day Greater Green River Basin in Paleocene time produced the nonmarine beds of the Fort Union Formation (Ryder, 1988). Fluvial sandstone and conglomeratic sandstone, floodplain sandstone, siltstone, and gray-green shale, as well as paludal coal and carbonaceous shale are the major lithologic components of the Fort Union Formation (Love, 1970; McDonald, 1972, 1975) (fig. 3).

Early Eocene time brought an even greater period of crustal instability to the region. The Fort Union Formation was uplifted throughout the region, tilted and truncated along the margins of the basement uplift, and covered by sandstone and variegated shale of the Wasatch Formation (Love, 1970; McDonald, 1972, 1975; Reynolds, 1976). Sediments of the Wasatch Formation in the northern Green River Basin and in the Great Divide, Washakie, and Sand Wash Basins are derived from a granitic terrane (Ryder, 1988). In contrast, the Wasatch of the south and west Green River Basin was derived from a sedimentary terrane (Oriel, 1962; Hansen, 1965).

By middle Eocene time, structural and topographic relief had developed to the extent that the Greater Green River Basin probably became a closed topographic basin and contained an extensive lacustrine system. Following the Laramide Orogeny (Miocene to Pliocene) an extensional stress regime, characterized by basin filling, faulting, and partial to complete collapse of several basement uplifts, further modified the structural configuration of the basin (Hansen, 1965; Love, 1970; Reynolds, 1976; Sales, 1983; Ryder, 1988).

Geometry and Age of Intrabasin Uplifts and Subbasins

Intrabasin Uplifts

The doubly plunging Rock Springs Uplift, having rocks as old as Santonian (Upper Cretaceous) exposed in its core, is the most conspicuous uplift within the Greater Green River Basin (fig. 2; Ryder, 1988). This 60-mi (97-km) long and 35-mi (56-km) wide, north-trending anticline extends from the southeastern part of the Wind River Uplift to near the east end of the Uinta Uplift, and separates the Green River Basin on the west side from the Great Divide, Washakie, and Sand Wash Basins on the east.

Westward-facing asymmetry and curvature of the uplift was probably caused by east-west-oriented compression and by east-dipping thrust faults that occur along the west margin of the uplift (Garing and Tainter, 1985). The thrust fault along the west flank of the uplift formed in latest Cretaceous time because its subcrop trace is buried beneath Paleocene rocks (Love and Christiansen, 1985). Intermittent growth of the Rock Springs Uplift must have continued at least through the middle Eocene to Early Oligocene, because lacustrine rocks of that age are gently tilted by the uplift and are cut by northeast and east-northeast normal faults (Roehler, 1978a; Ryder, 1988).

To the west of the Rock Springs Uplift, the Moxa Arch is a broad, gently folded basement uplift in the Green River Basin (Stockton and Hawkins, 1985) (fig. 2). This uplift is buried beneath uppermost Cretaceous and lower Tertiary rocks along its entire length (Ryder, 1988). The north end of the arch, commonly referred to as the La Barge Platform, is a prominent structural feature that projects eastwards approximately 6 mi (9.7 km) into the basin (Krueger, 1968). This structure is associated with large accumulations of oil and gas in the Big Piney–La Barge area. Drill-hole data indicates that the arch plunges to the south and is convex eastward in plan view (Ryder, 1988). Angular unconformities, recognized in subsurface stratigraphic studies, indicate that the arch experienced initial uplift and truncation in early to middle Turonian (Baxter/Hilliard shale) time and then a second period of major uplift and truncation in late Campanian time (Merewether and others, 1984; Roehler, 1965b). Stratigraphic studies by Wach (1977) indicate that the Moxa Arch was only mildly active in latest Cretaceous and early Tertiary time.

Two subtle east-west-trending uplifts, the Wamsutter and Cherokee Arches, divide the east half of the Greater Green River Basin into three subbasins (fig. 2). The Wamsutter Arch, a broad easterly projection of the Rock Springs Uplift, is the larger of the two uplifts, separating the Great Divide Basin on the north from the Washakie Basin on the south. The Cherokee Arch separates the Washakie Basin on the north from the Sand Wash Basin on the south. Judging from isopach maps of Lower Tertiary rocks across the uplifts and the age of the youngest rocks in the uplifts, the Wamsutter and Cherokee Arches probably developed in Eocene time (McDonald, 1975). However, Weimer (1966) suggested that the west part of the Wamsutter Arch had a history of tectonic growth going back to early Late Cretaceous time.

Subbasins

The Green River Basin, covering approximately 10,000 mi^2 (25,913 km^2) is a broad synclinal basin that is covered almost entirely by rocks of Eocene age. The Eocene rocks dip south from 0.5° to 6°, except along the margins of the basin where beds are nearly horizontal or dip at angles generally less than 1.5° (Bradley, 1964). The principal synclinal axis of the basin trends north-south and lies approximately 20 mi (32 km) west of the axis of the Rock Springs Uplift (fig. 2). To the north and northeast of the axis, the basin is bounded by the Wind River Uplift forming a deep syncline (fig. 5). Within this zone, the Pinedale Anticline is an asymmetric, thrust-rooted detachment structure that probably formed in response

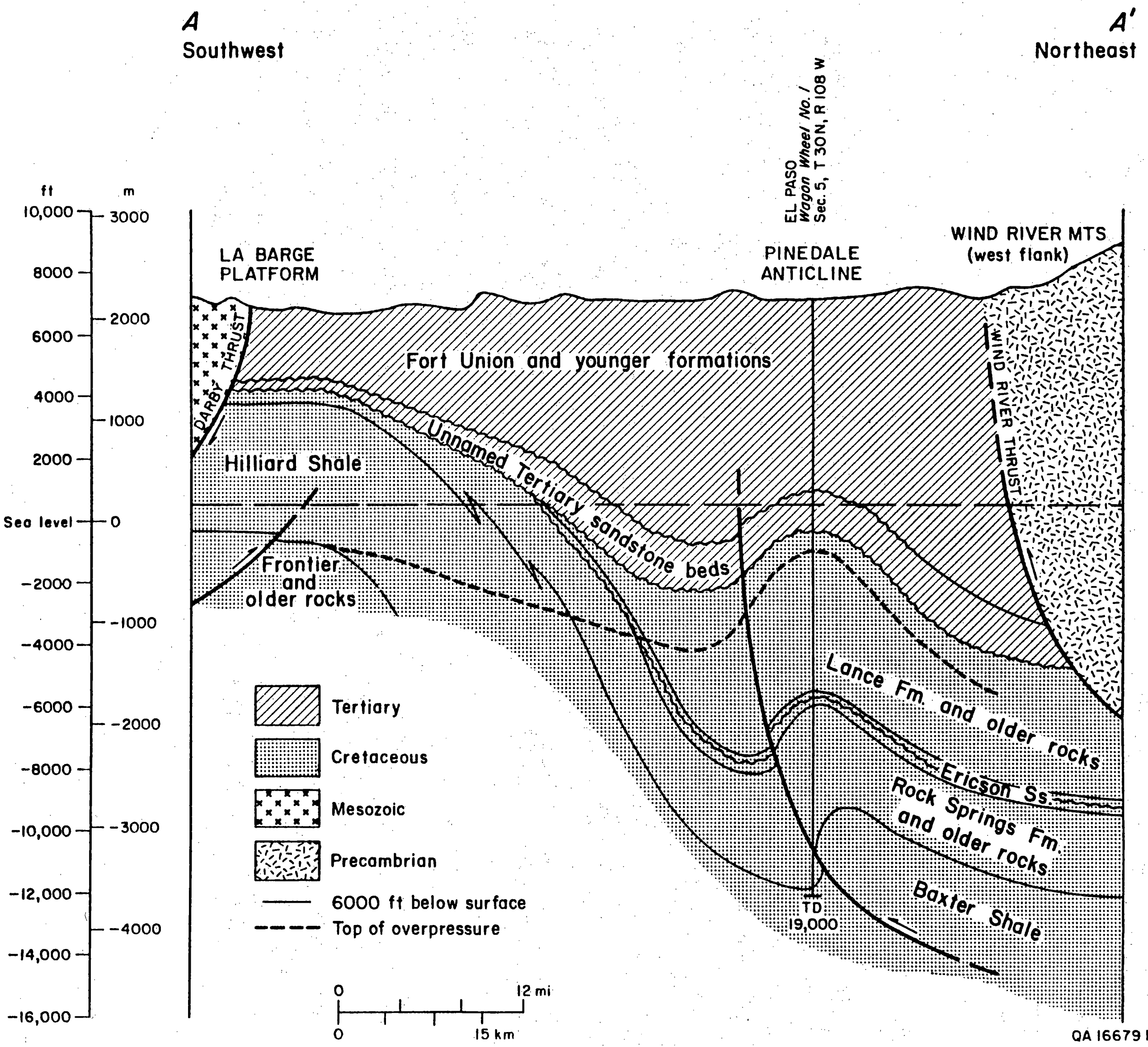


Figure 5. Southwest-northeast cross section A–A′ showing relationship between structure and top of regional overpressure. From Law and Dickinson (1985). Thrust faults may limit recharge to coal-bearing units. Line of section shown in figure 1.

to southwest-directed compression associated with structural deformation of the Wind River Uplift (Law and Johnson, 1989). Sedimentary rocks attain a thickness of approximately 30,000 ft (9,144 m) in the trough of the Green River Basin Syncline (Krueger, 1960). To the east, where the basin is bounded by the Rock Springs Uplift, the Upper Cretaceous rocks dip 3° to 12° to the west (McCord, 1984) (fig. 2), and on the west where the basin is bounded by the Overthrust Belt, rocks dip at 2° to 8° to the east.

The Great Divide Basin, also known as the Red Desert and Shoshone Basin, is a large topographic and structural basin having interior drainage (fig. 6). The basin is a simple synclinal basin modified by broad shallow folds and widespread small-scale faults (Mroz and others, 1983). The synclinal axis trends north-south in the southeast part of the basin and curves around to approximately N60°W in the northeast. In the west and southwest part of the basin, the strata dip from 2° to 3° toward the east and northeast. In the east, the strata as much as 20° west on the west flank of the Rawlins Uplift (McCord, 1984).

The Washakie Basin is a deep synclinal basin that covers an area of about 3,000 mi^2 (7,774 km^2; fig. 7). Along the basin margins the Eocene beds dip from 3° to 5° toward the center of the basin. Away from the edges of the basin, these strata are essentially horizontal (McCord, 1984). Upper Cretaceous sediments dip steeply toward the center of the basin (fig. 2). This basin is the deepest part of the eastern Greater Green River Basin, and depths to the coal-bearing Mesaverde Group can exceed 18,000 ft (5,486 m) (fig. 7).

The Sand Wash Basin is a southeast-trending synclinal prong of the Washakie Basin (fig. 8). Haun and Weimer (1960) estimated as much as 11,000 ft (3,354 m) of clastic sediments were deposited in the Sand Wash Basin during the Late Cretaceous. In the deepest part of the basin (T10N, R49W and T11N, R94W) the top of the Mesaverde Group is at 9,000 to 9,500 ft (2,744 to 2,896 m; Siepman, 1985). Therefore, basal Mesaverde sandstones probably attain maximum depths of 15,000 to 16,000 ft (4,570 to 4,800 m) in the Sand Wash Basin, with the total amount of Cambrian through Tertiary sedimentary rocks being approximately 30,000 ft thick (9,144 m; Irwin, 1986).

Fracture Systems and Cleat in Coal

A survey of outcrops and mine highwalls of interbedded lenticular, channel-fill sandstone and coal in several locations of the Greater Green River Basin shows that subbituminous coal seams have uniformly developed, vertical to subvertical opening-mode extension fractures (face and butt cleats) arranged in orthogonal map patterns that generally show little variation in orientation, dip, spacing, or frequency over wide areas, (for example, Bridger and Black Butte coal mines, Fort Union Formation, east of Rock Springs; Tyler and others, 1991). In the west and central parts of the basin, average face-cleat strikes are east to northeast (fig. 9; N60°E to N90°E) and butt-cleat strikes are north to northwest (N to N30°W) in Cretaceous and Tertiary coals. In the southeastern Greater Green River Basin, face-cleat strikes are generally

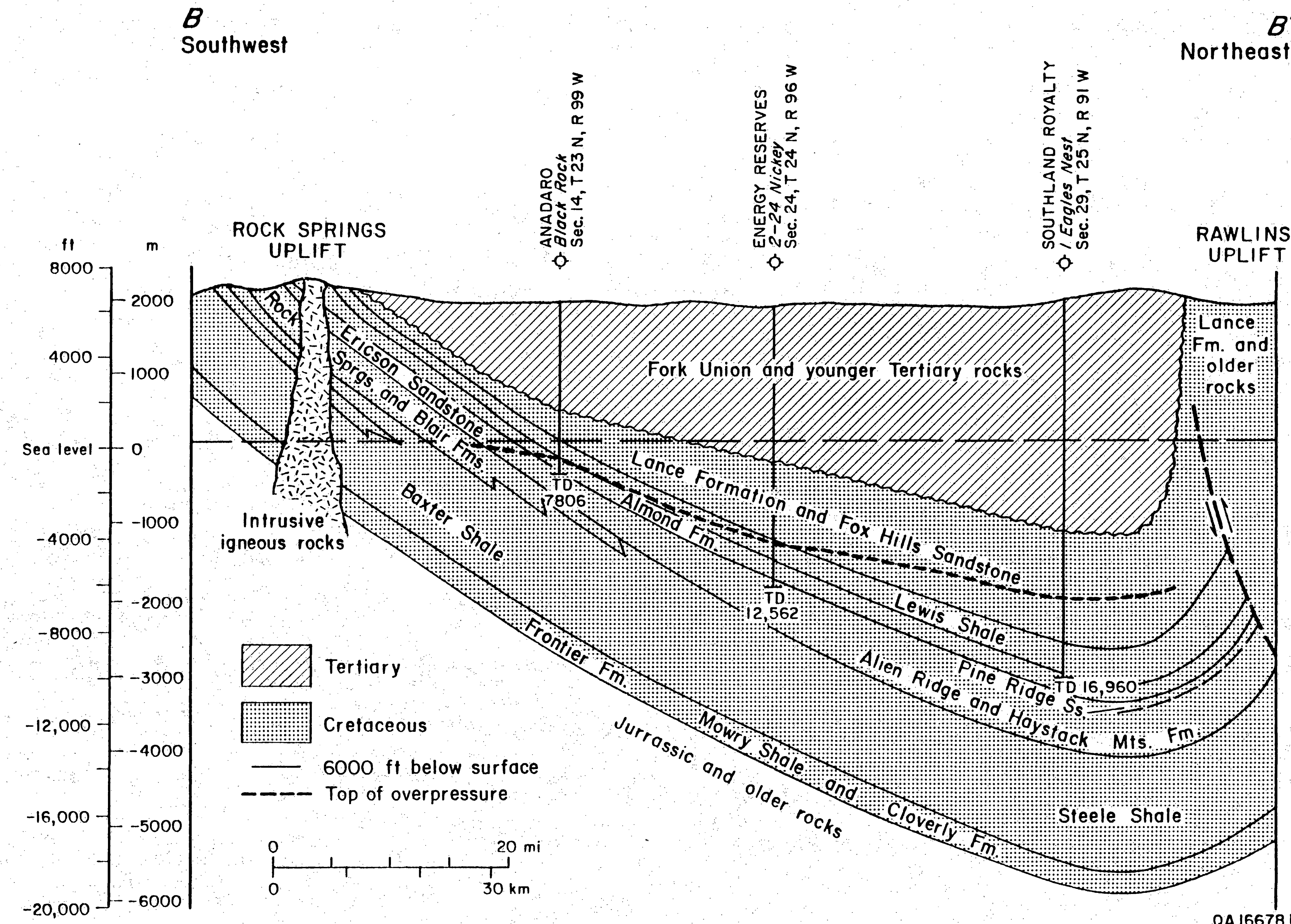


Figure 6. Southwest-northeast cross section B–B′ through Great Divide Basin showing relationships among structure, stratigraphy, and top of regional overpressure. Modified from Law and others (1989). Recharge occurs over Rock Springs Uplift. Line of section shown in figure 1.

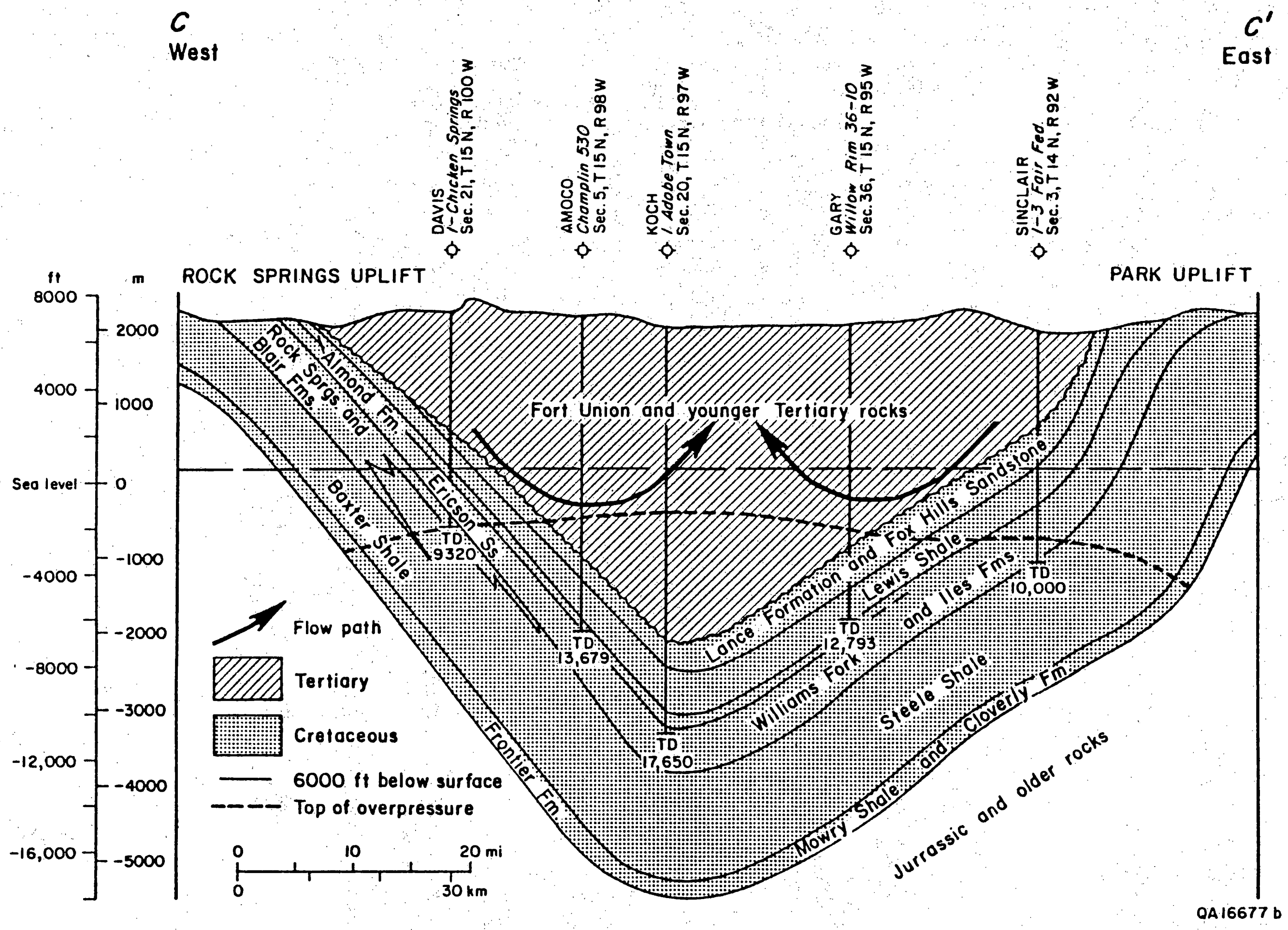


Figure 7. West-east cross section C–C′ through Washakie Basin showing relationships among structure, stratigraphy, top of regional geopressure, and ground-water flow. Modified from Law and others (1989). Recharge over Park Uplift and Rock Springs Uplift. Ground water flows basinward, turning upward upon aquifer pinch-out or convergence from the basin margins, or both. Top of regional overpressure is a no-flow boundary. Line of section shown in figure 1.

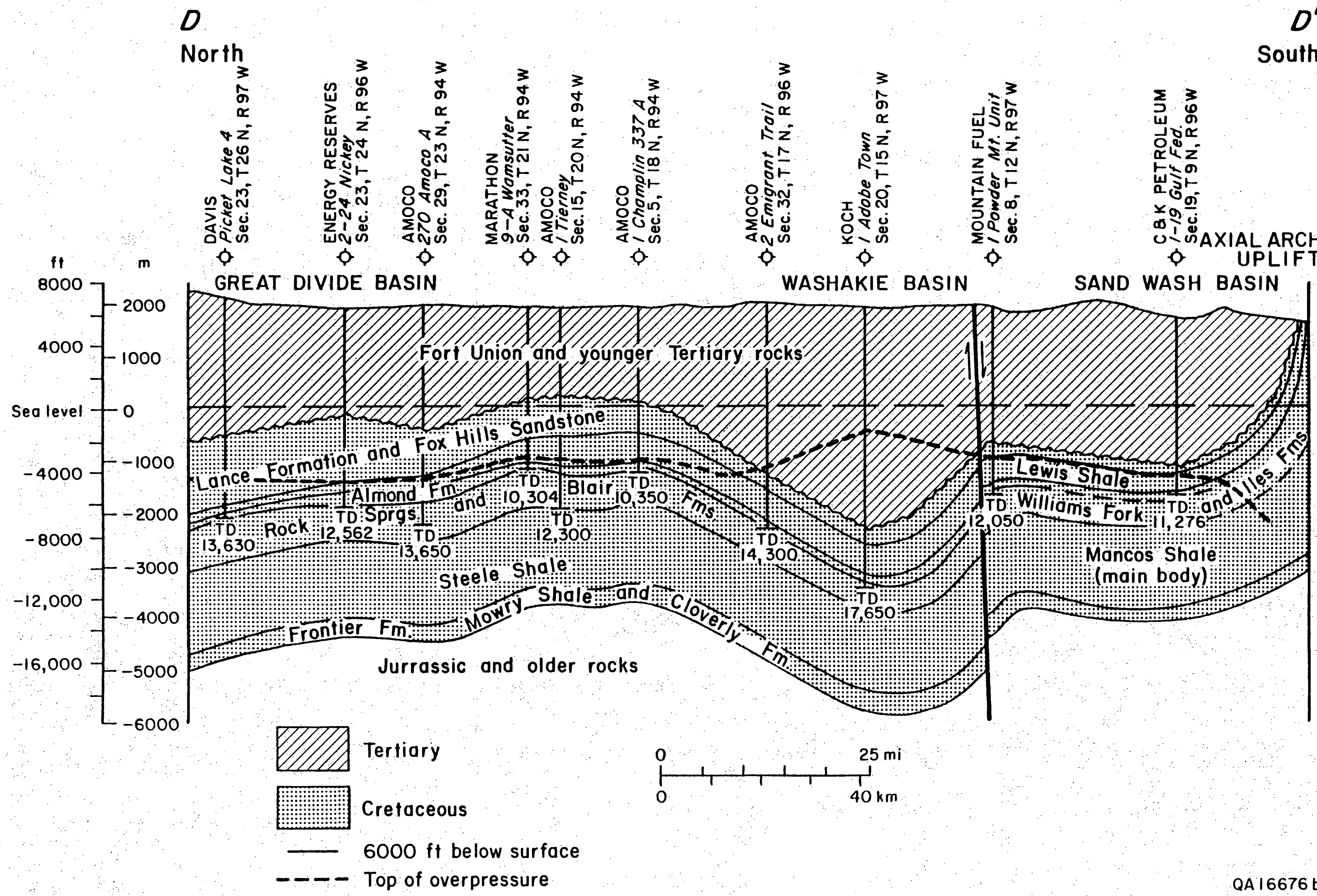


Figure 8. North-south cross section D–D′ through Great Divide, Washakie, and Sand Wash Basins showing relationships among structure, stratigraphy, and top of regional overpressure. Modified from Law and others (1989). Depth to pressure transition unknown. Line of section shown in figure 1.

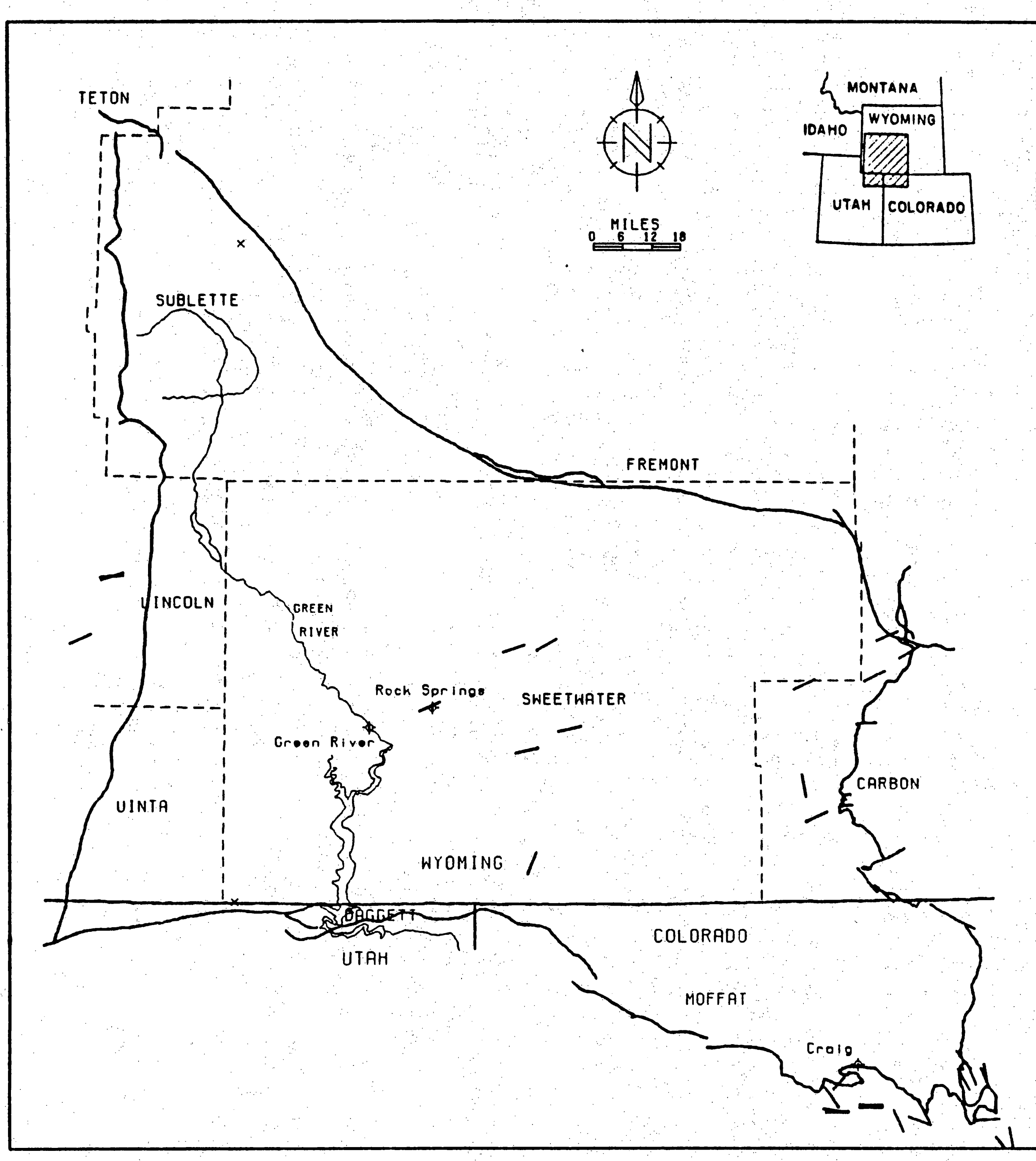


Figure 9. Face-cleat strike, Greater Green River Basin.

northwesterly. Generally, face-cleat strikes in the basin are parallel to tectonic shortening directions, and they are typically oriented at right angles to orogenic thrust fronts.

Cleat spacing ranges from 0.5 inch (1.3 cm) to greater than 12 inches (>30.5 cm) for fractures of different sizes. Cleat spacing is less than 0.5 inch (<1.3 cm) for the smallest microfracture, 0.5 to 2 inches (1.3 to 5 cm) for cleat within coal layers, greater than 2 inches (>5 cm) for primary cleats that terminate vertically against bed boundaries, and greater than 12 inches (>30 cm) for master cleats that may extend across coal seams. Cleat frequency, the inverse of spacing, ranges from less than 1 cleat per inch (2.5 cm) to greater than 5 cleats per inch (2.5 cm).

Local variations in cleat strike are associated with low-amplitude folds caused by differential compaction (Tyler and others, 1991). The effect of compaction on fracture systems has not been determined. Studies of folded subbituminous coal beds at Kemmerer and Rock Springs mines suggest that cleat strike, dip, spacing, frequency, and type can vary on the flanks and under fluvial-deltaic channel-fill sandstones (Tyler and others, 1991). No typical regional face cleats are evident; instead, closely spaced normal faults replace face cleats. These faults have slip surfaces that are mineralized, striated in a downdip orientation, and curviplanar. The curviplanar slip surfaces are concave and convex, forming sigmoidal patterns. The spacing of the faults, from 1 to 6 inches (2.5 to 15 cm), is similar to regional face-cleat spacing. Cutoff angles of 45° to 60° between coal bedding and fault cleats indicate that they are not simply reactivated face cleats, but closely spaced mode-II fault cleat sets that formed instead of opening mode (mode-I) cleats during coalification (Tyler and others, 1991). These fault cleats occurring together with localized zones of opening-mode face cleat systems, could enhance coalbed permeability. Any ability to predict these cleat characteristics would be useful for methane exploration because areas for degasification could then be identified using structural and lithofacies maps.

Stress Orientations

The Greater Green River Basin is within the Cordilleran Extension stress province, north of the Colorado stress province and west and southwest of the Mid-Plate stress province, (fig. 10; Zoback and Zoback, 1989). Sparse stress-direction measurements suggest that the maximum horizontal compressive stress orientation is north-northwest in the southeast parts of the Greater Green River Basin, northeast near Pinedale and north-south in the area northwest of the basin (fig. 10). Zoback and Zoback (1989) tentatively included southwestern Wyoming in this province because their data indicated horizontal stress orientations consistent with nearby regions of the Basin and Range and because available focal mechanisms suggest normal faulting. In addition, this area (as well as the rest of the Cordilleran Extension stress province) coincides with a broad zone of high regional elevation and heat flow.

Results of hydraulic fracture experiments in the Greater Green River Basin confirm northeast maximum horizontal stress in the Pinedale area and suggest that locally, hydraulic fractures may have

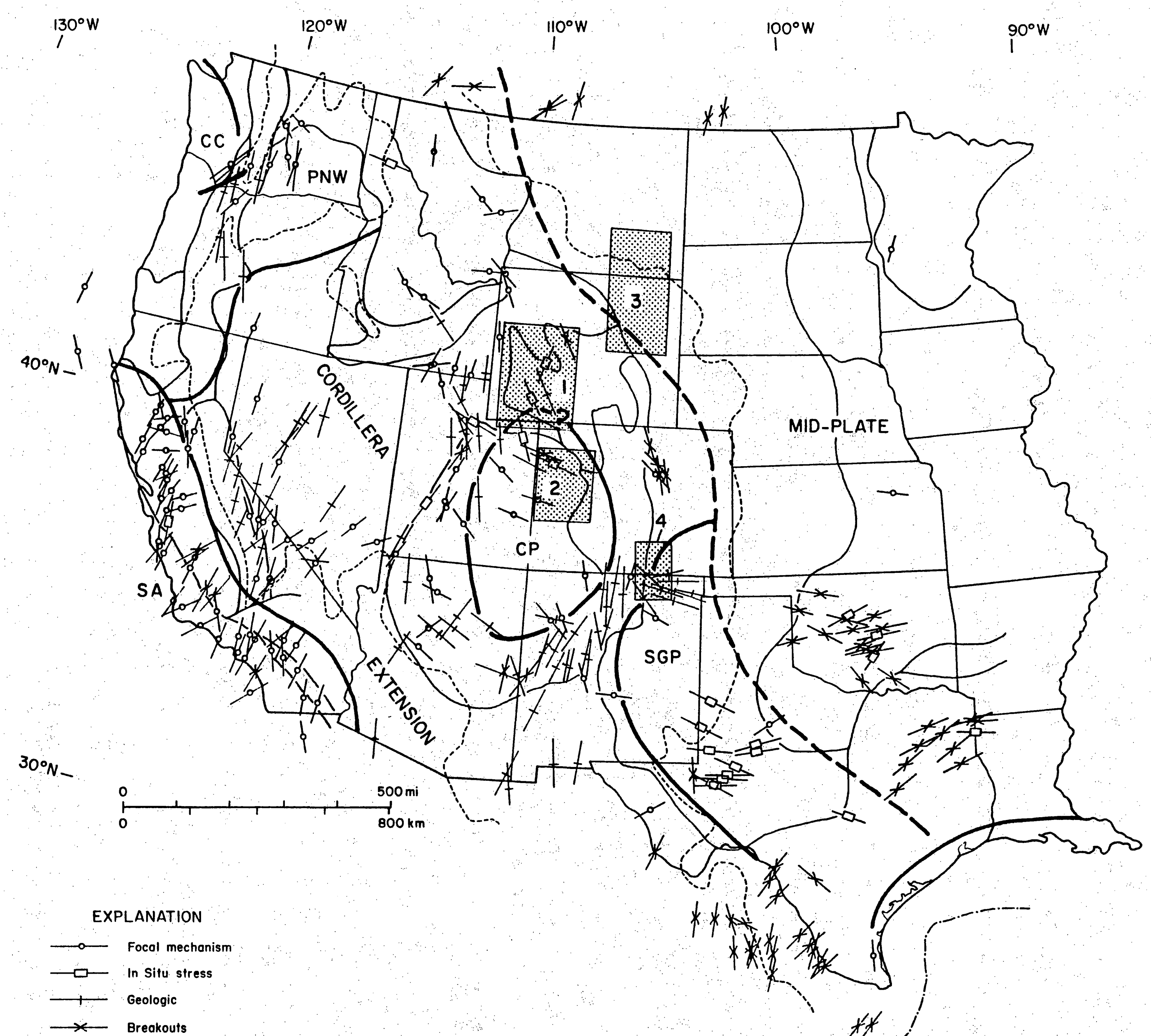


Figure 10. Maximum horizontal compressive stress orientations of the western United States. Stress provinces are delineated by thick solid and dashed lines: CC = Cascade convergent province; PNW = Pacific Northwest; SA = San Andreas province; CP = Colorado Plateau interior; SGP = Southern Great Plains. Thin dashed lines mark the 3,609-ft (1,100-m) elevation contour based on 1° average elevations. Small boxes correspond to four selected basins: 1 = Greater Green River Basin; 2 = Piceance Basin; 3 = Powder River Basin; and 4 = Raton Basin. Modified from Zoback and Zoback (1989).

multiple, nonparallel wings (Power and others, 1976). Passive surface seismic detection of hydrofracture hypocenters in the Pinedale area indicated that hydraulically induced fractures grew northeast (030° to 045°) (Power and others, 1976). The fracture also showed predominant growth of one wing, a curved fracture trajectory, and possible growth of a third fracture wing at right angles to the principal northeast-trending fracture. This pattern may be due to the induced fracture intersecting with a natural fracture zone or fault and possible reactivation of the fracture zone or fault.

Stratigraphic and Depositional Setting of Coal-Bearing Formations

The primary coal-bearing formations in the Greater Green River Basin occur in Upper Cretaceous and lower Tertiary strata (fig. 3; Baars and others, 1988). The Upper Cretaceous contains several coal-bearing, nonmarine stratigraphic units (Rock Springs, Iles, Williams Fork, Almond, and Lance Formations) deposited in delta-plain and back-barrier settings, landward of delta-front and barrier-island systems (Haun, 1961; Asquith, 1970; Roehler, 1990). In the Sand Wash Basin, the Almond Formation is equivalent to the Williams Fork Formation (Roehler, 1990). Lower Tertiary coal-bearing units in the Greater Green River Basin include the Fort Union (Paleocene), Wasatch (Eocene) and Green River (Eocene) Formations (fig. 3). Correlation of subunits in these formations is difficult because of the considerable thickness of nonmarine rocks lacking consistent marker beds. Additionally, the Fort Union Formation is separated from underlying Upper Cretaceous strata by a regional unconformity. Laramide deformation and uplift created source areas for coarse-grained fluvial systems in the Fort Union and Wasatch Formations.

The complicated stratigraphy of the Greater Green River Basin reflects a complex structural and depositional history. Regional correlation of stratigraphic units across the basin is difficult because of sandstone pinch-outs, multiple unconformities, and deposition in separate subbasins. Stratigraphic units are difficult to correlate across the Greater Green River Basin because the Rock Springs Uplift separates the basin into east and west halves. The east half of the basin includes the Great Divide, Washakie, and Sand Wash Basins; the west half contains the Green River and Pinedale Basins (fig. 2).

Eastern Greater Green River Basin

Cretaceous coal-bearing strata in the east part of the Greater Green River Basin include the Mesaverde Group (Rock Springs, Iles, Williams Fork, and Almond Formations) and the Lance Formation, which is separated from the Mesaverde Group by the Lewis Shale and Fox Hills Sandstone. Tertiary coal-bearing strata include the Fort Union, Wasatch, and Green River Formations. Cretaceous coal-bearing strata are less than 5,000 ft (1,500 m) deep on the flanks of the Rock Springs Uplift, on the east margin of the Greater Green River Basin, and in the Sand Wash Basin. However, these strata are more than 12,000 ft (3,660 m) deep in the Washakie and Great Divide Basins (fig. 11). Tertiary coal-bearing strata are

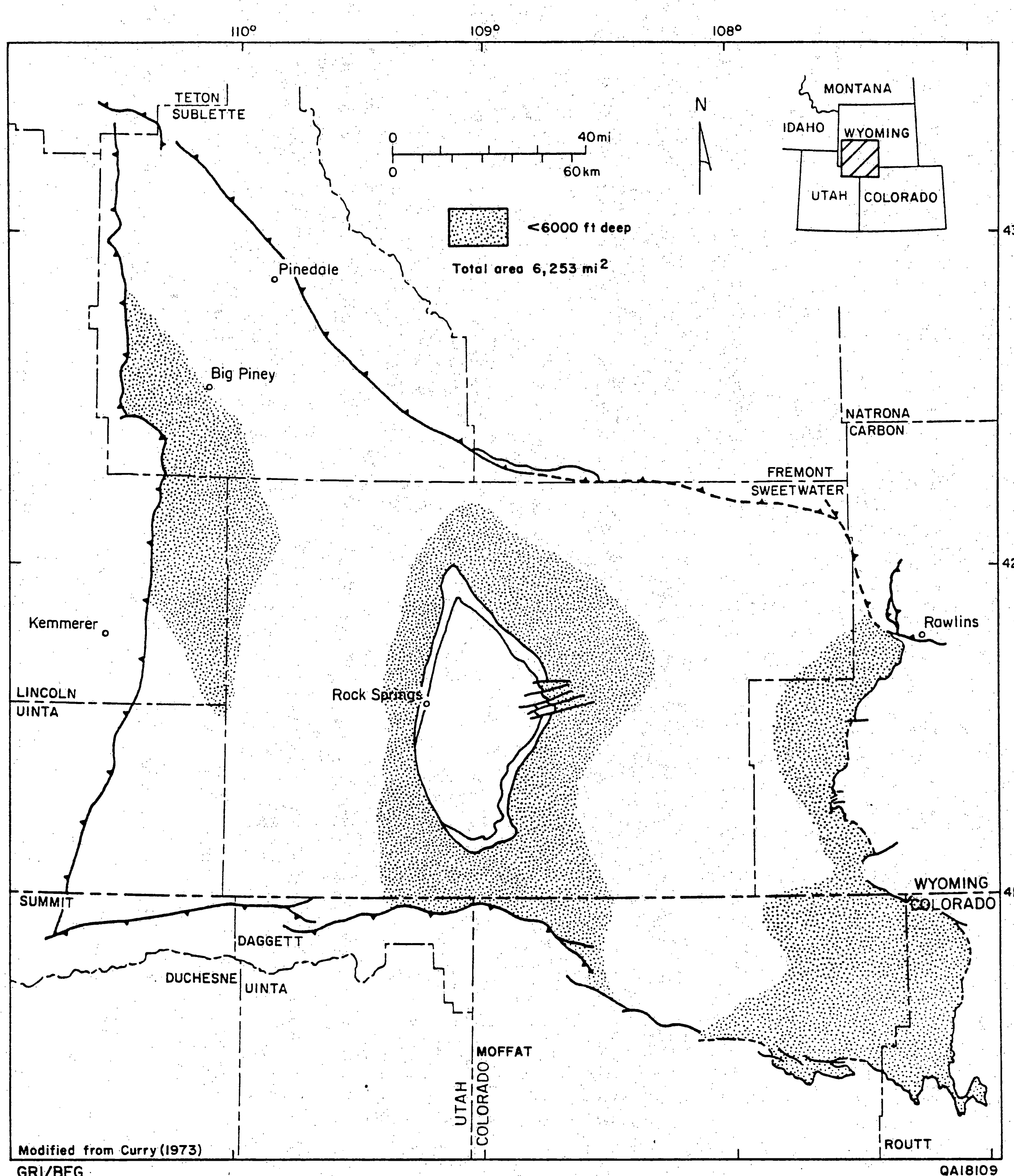


Figure 11. Depth to top of the Mesaverde Group in the Greater Green River Basin. Modified from Curry (1973) and Lickus and Law (1988).

buried at depths ranging from 7,000 to 9,500 ft (2,130 to 2,900 m) in the Washakie and Great Divide Basins (McDonald, 1975).

Rock Springs Formation

The Rock Springs Formation is the principal coal-bearing unit in the Mesaverde Group and rises stratigraphically eastward, where it is lithologically equivalent to the Allen Ridge Formation (Roehler, 1990). In the deepest part of the Washakie Basin, the Rock Springs and Allen Ridge Formations are at a structural elevation of more than 9,000 ft (2,740 m) subsea (Lickus and Law, 1988) or more than 12,000 ft (3,660 m) below surface.

In the east part of the Greater Green River Basin, the Rock Springs Formation is best exposed on the east flank of the Rock Springs Uplift, where it consists of wave-dominated deltaic deposits (Levey, 1985). Peats (coal beds) formed in delta-plain environments, landward of Rock Springs delta-front deposits. Rock Springs sandstones vary greatly in thickness and lateral continuity. Delta-front (shoreline) sandstones, which extend northeastward in the basin (fig. 12) are 50 to 140 ft (15 to 43 m) thick at the Rock Springs Uplift, whereas distributary-channel sandstones are 200 to 800 ft (61 to 240 m) wide and 20 to 55 ft (6 to 17 m) thick (fig. 13). Rock Springs distributary-channel sandstones are flanked by thin (2 to 15 ft [0.6 to 4.5 m] thick) crevasse-splay sandstones, which were platforms for local peat accumulation and which partly controlled coalbed continuity.

The Rock Springs Formation contains at least 12 coal beds, which average 6 ft (1.8 m) in thickness (McCord, 1984). These coal beds are grouped into three types (A, B, and C) that are associated with specific depositional environments (fig. 14) (Levey, 1985). Type-A coal beds, thickest in the Rock Springs Formation and as much as 22 ft (6.7 m) thick, have areas of more than 500 mi^2 (1,300 km^2); they overlie delta-front sandstones and formed in a lower delta-plain setting. Type-B coal beds are more variable in thickness and less continuous than type-A, having an area of 50 to 200 mi^2 (130 to 520 km^2). These coal beds formed in an upper delta-plain setting. Type-C coal beds, which formed on abandoned-delta lobes, are the thinnest in the Rock Springs Formation; they are less than 10 ft (3 m) thick and have an area of only 50 mi^2 (130 km^2).

Iles and Williams Fork Formations

The Iles and Williams Fork Formations in the Sand Wash Basin are equivalent to the Allen Ridge and Almond Formations, respectively (fig. 3) (Law and others, 1989). The Iles Formation consists of shelf and coal-bearing deltaic deposits (fig. 15) (Boyles and Scott, 1981). The thickest seams (individual seams as much as 10 ft [3 m] thick) trend northeastward, parallel to the paleoshoreline. Other Iles coal beds, 3 to 6 ft (0.9 to 1.8 m) thick, overlie thin (<5 ft [<1.5 m] thick) crevasse-splay sandstones that were local platforms for peat accumulation in interchannel swamps.

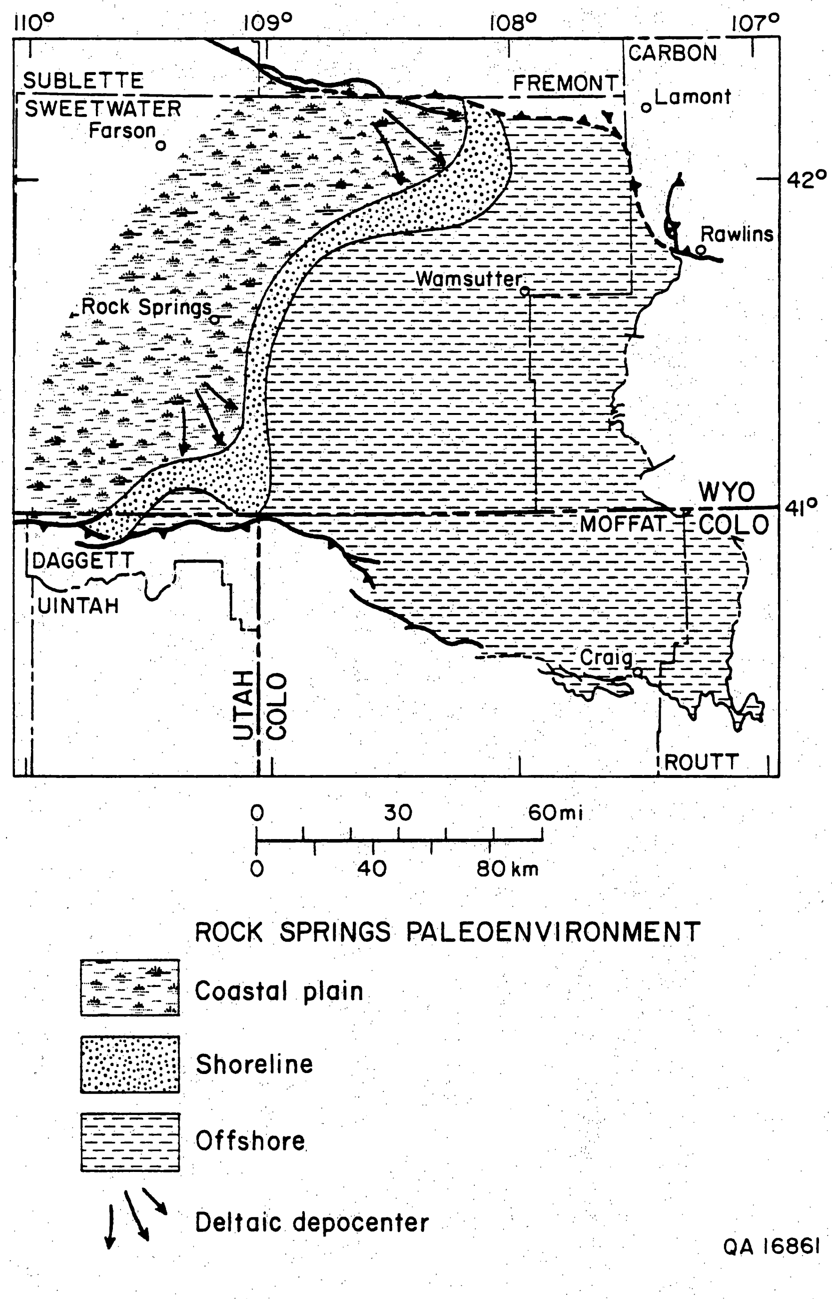
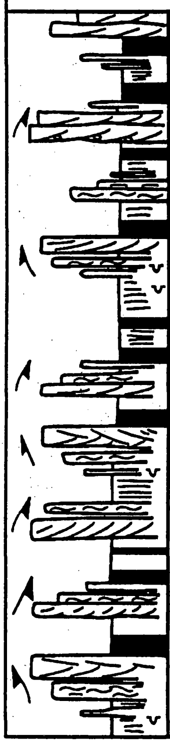


Figure 12. Paleogeography of the middle Rock Springs Formation in the east half of the Greater Green River Basin. Modified from Roehler (1990).

SCHEMATIC SECTION	FORMATION (Depositional system)	COAL BEDS: Thickness (ft)			COAL BEDS	COAL BEDS	SANDSTONES: Thickness (ft)		SANDSTONES	COAL-SANDSTONE RELATIONS
		Average	Maximum	Net	Number	Continuity	Maximum	Net	Continuity	
	FORT UNION FORMATION (Fluvial)	10-15	30	>50	5-10	Moderate: most continuous coal beds between channel ss.	20-40	>60	Fair: numerous lenticular channel-fill sandstones	Thickest, most continuous coal beds between channel-fill ss.; coal beds split and pinch out at margin of fluvial depositional axes
	LANCE FORMATION (Delta plain)	5	8-22	—	5 main	Poor: discontinuous coal beds have 100's to 1000's of ft of continuity	40 ?	—	Fair: lenticular delta-plain sandstones	Many discontinuous coal beds pinch out at channel ss. margins, grading laterally into carbonaceous shale
Fox Hills Sandstone *Lewis Shale*										
	ALMOND FORMATION (Coastal plain, wave-dominated shoreline)	3 upper 10 lower	8-12	Up to 35	Up to 18	Good along strike (north-northeast) Moderate along dip (northwest-southeast)	50-60 (underlying ss.)	100 (underlying ss.)	Underlying barrier ss., excellent continuity along strike; distrib.-channel ss., fair continuity	Thickest and most continuous coal beds directly overlie barrier ss. and interfinger with tidal-inlet and distrib.-channel sandstones.
Ericson Sandstone										
	ROCK SPRINGS FORMATION (Wave-modified deltaic)	10	14-22	Up to 90	Up to 12	Continuous, north-northeast trending delta-front coal beds; delta-plain coal beds pinch out over 1000's of ft	140	—	Delta-front ss. continuous for tens of miles along strike; lenticular distributary-channel ss. pinch out laterally	Thickest and most continuous coal beds directly overlie delta-front ss.; thinner and less continuous coal beds override and pinch out against fluvial and distributary-channel sandstones

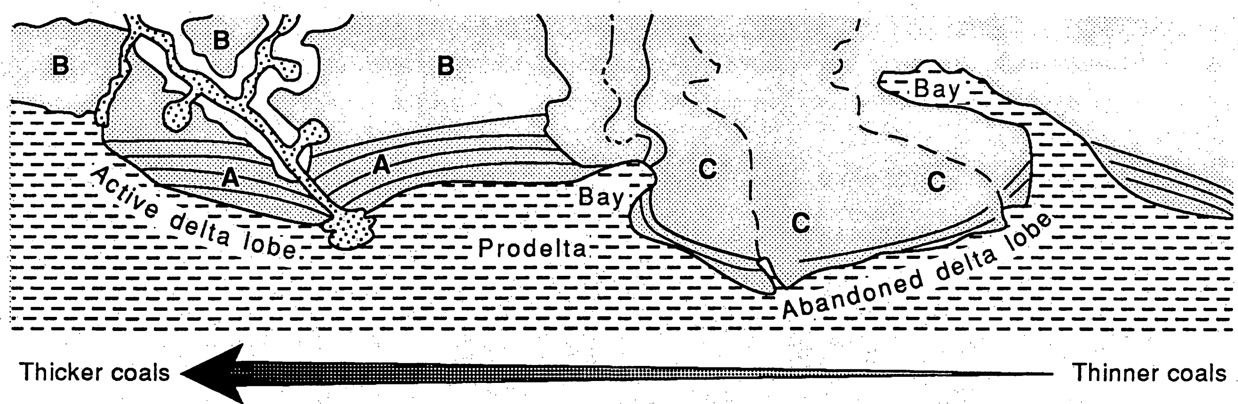
SEDIMENTARY STRUCTURES AND ROCK TYPES

∘∘ Clasts — Upward-coarsening — Planar bedding — Ripples

v Burrows — Upward-fining — Cross bedding — Coal

QA16954c

Figure 13. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units at the Rock Springs Uplift in the Greater Green River Basin.



Characteristics	Type A	Type B	Type C
Coal thickness	Thick coal seams 3 – 22 ft (0.9 – 6.7 m)	Variable coal seam thickness 1 – 17.5 ft (0.3 – 5.3 m)	Thin coal seams 1 – 8 ft (0.3 – 2.4 m)
Areal extent	Large areal extent >500 mi^2 (1300 km^2)	Variable areal extent 50 – 250 mi^2 (130 – 650 km^2)	Medium areal extent 50 mi^2 (130 km^2)
Generalized depositional setting	Coals associated with active deltaic progradation on lower delta plain. Coals developed on top of delta-front foreshore environment.	Coals developed in upper delta plain. Landward of delta-front sandstones, in interchannel areas.	Coals associated with abandoned delta lobes.

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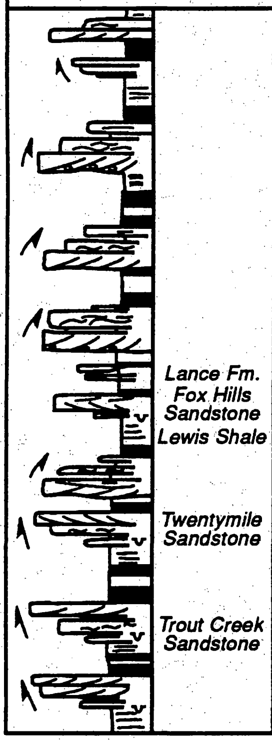
Figure 14. Depositional setting of three types of coal beds in the Rock Springs Formation at the Rock Springs Uplift. Modified from Levey (1985).



FORMATION (Depositional system)	COAL BEDS Thickness (ft) Average	COAL BEDS Thickness (ft) Maximum	COAL BEDS Thickness (ft) Net	COAL BEDS Number	COAL BEDS Continuity	SANDSTONES Thickness (ft) Maximum	SANDSTONES Thickness (ft) Net	SANDSTONES Continuity	COAL-SANDSTONE RELATIONS
WASATCH FORMATION (Fluvial, lacustrine)	10	25-35	—	>10	Moderate: coal beds extend 2–5 miles between fluvial complexes	50?	—	Discontinuous, lenticular channel-fill sandstone	Similar to Fort Union Formation
FORT UNION FORMATION (Fluvial)	10	15-30	Up to 90	Up to 12	Moderate: coal beds continuous along dip (north); discontinuous along strike	35-70	—	Discontinuous; channel-fill sandstone 1000-2000 ft wide	Coal beds split and interfinger with lenticular channel-fill sandstones; upper Fort Union coal beds not commonly eroded.
WILLIAMS FORK FORMATION (Fluvial-dominated, wave-modified deltaic)	<10	8-12	Up to 60	Up to 10	Coal beds continuous along strike (northeast); discontinuous along dip (northwest)	50	—	Moderately continuous delta-front sandstone; discontinuous distributary channel sandstone	Thickest coal beds overlie delta-front sandstone; thinner, discontinuous coal beds split and interfinger with distrib.- channel sandstones.
ILES FORMATION (Wave-dominated shoreline)	<5	5-10	—	—	Continuous along strike (northeast)	20-40	Up to 90	Blanket shoreline sandstone; thin, discontinuous crevasse-splay sandstone	Thin coal beds overlie shoreface and crevasse-splay sandstones

SEDIMENTARY STRUCTURES AND ROCK TYPES

•• Clasts — Upward-coarsening — Planar bedding — Ripples

Burrows — Upward-fining — Cross bedding — Coal

QA16955c

Figure 15. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in the Sand Wash and Washakie Basins in the Greater Green River Basin.

The Williams Fork Formation consists of deltaic and fluvial deposits (Boyles and Scott, 1981; Siepman, 1985). Coal beds occur in two zones in the Williams Fork Formation; the lower zone overlies the Trout Creek Sandstone Member of the Iles Formation and the upper zone overlies the Twentymile Sandstone Member of the Williams Fork Formation (Siepman, 1985; Roehler, 1990). Both of these sandstone members consist of wave-dominated deltaic deposits that served as platforms for peat accumulation (Siepman, 1985).

Williams Fork coal beds occur in as many as 10 seams, with a net-coal thickness of as much as 60 ft (18 m) and maximum-coal thickness of 12 ft (3.7 m) (fig. 15). Net-coal thickness trends are dominantly strike-elongate (northeast-oriented, parallel to the paleoshoreline), with minor dip-elongate (northwest-oriented) components (Siepman, 1985). Upper Williams Fork fluvial coal beds are discontinuous and are eroded by fluvial channel-fill sandstone deposits that are 30 to 50 ft (9 to 15 m) thick.

Almond Formation

The Almond Formation is equivalent to the Williams Fork Formation in the Sand Wash Basin (Law and others, 1989). In the Washakie Basin, the Almond Formation is more than 10,000 ft (3,049 m) deep (fig. 2). In outcrop along the Rock Springs Uplift, the Almond Formation ranges from 500 to 800 ft (150 to 240 m) in thickness (Jacka, 1965). The Almond Formation contains as much as 35 ft (11 m) of coal in beds thicker than 2 ft (0.6 m) (fig. 13). Average coalbed thickness in the lower part of the Almond Formation is 8 to 12 ft (2.4 to 3.7 m) (Glass, 1981), whereas average coalbed thickness in the upper part of the Almond Formation is only 2 to 4 ft (0.6 to 1.2 m) (Roehler, 1988).

At the Rock Springs Uplift, the Almond Formation grades seaward (eastward) into north-trending barrier-island sandstones (fig. 16) (Weimer, 1965; Roehler, 1988; Roehler, 1990). Upper Almond barrier-island complexes are more than 60 mi (96 km) long and approximately 4 mi (6.4 km) wide; sandstones in these complexes are as much as 100 ft (30 m) thick (McCubbin and Brady, 1969) (fig. 13). East of the Rock Springs Uplift, coal beds have an average thickness of 3 ft (0.9 m) and are present at the top of at least four barrier-island sandstones. These coal beds split where they override tidal-inlet sandstones (Roehler, 1988). Upper Almond net-coal thickness ranges from 6 to 12 ft (1.8 to 3.6 m) in three to four seams (fig. 13). Many Upper Almond coal seams extend for 12 mi (19.2 km) along depositional strike (Roehler, 1988), whereas they extend only 5 to 10 mi (8 to 16 km) eastward along depositional dip (McCubbin and Brady, 1969).

Lance Formation

The Lance Formation, the youngest Cretaceous stratigraphic unit in the Greater Green River Basin, overlies and intertongues with nearshore-marine deposits of the Fox Hills Sandstone and consists of brackish and nonmarine shales, lenticular sandstones, and coal beds (Land, 1972). The Lance Formation

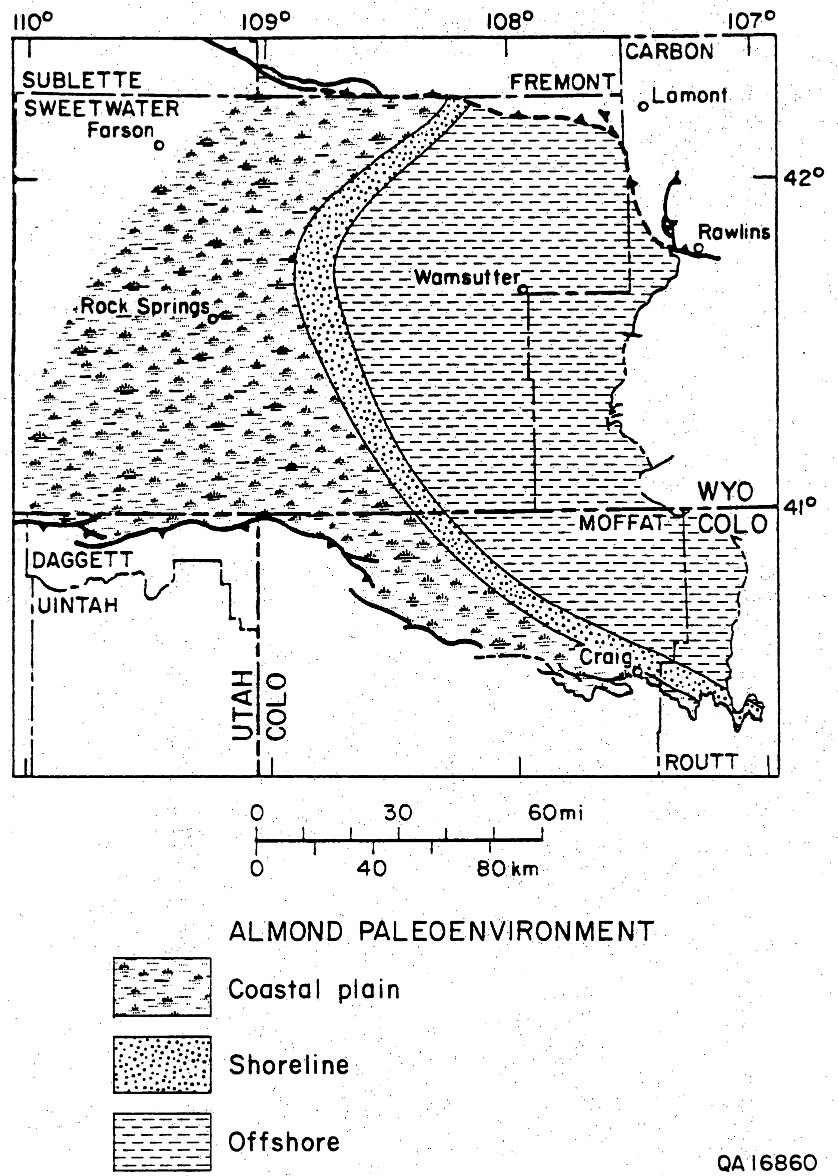


Figure 16. Paleogeography of the upper Almond Formation and lower Lewis Shale in the east half of the Greater Green River Basin. Modified from Roehler (1990).

is approximately 900 ft (274 m) thick in the east part of the Greater Green River Basin (Masters, 1961) and is separated from the overlying Fort Union Formation by a regional unconformity.

Coal beds are thicker and more abundant in the lower part of the Lance Formation above the platform Fox Hills sandstone and range from a few inches to 8 ft (2.4 m) in thickness at the Rock Springs Uplift (fig. 13) (Schultz, 1910). Locally, these coal beds merge into single seams that are 16 to 22 ft (4.9 to 6.7 m) thick (Glass, 1981). However, these coal beds have a limited lateral extent and can be traced for only a few hundred to several thousand feet in outcrop, where they grade into carbonaceous shales (Land, 1972). Sandstones in the coal-bearing part of the Lance Formation are thin (<10 ft [<3 m]) and also pinch out over a few hundred feet (fig. 13).

Fort Union Formation

The Fort Union Formation (Paleocene) is present throughout the Greater Green River Basin and consists of fluvial, lacustrine, and paludal deposits (Ritzma, 1955; Masters, 1961; Colson, 1969). The Fort Union Formation is sand-rich on the east margin of the Greater Green River Basin and at the Rock Springs Uplift but grades into shales in the Washakie Basin, where it is approximately 9,500 ft (2,900 m) deep (McDonald, 1975). At the Rock Springs Uplift, Fort Union coal beds are some of the thickest (individual coal beds as much as 30 ft [9 m] thick) (fig. 13) in the Greater Green River Basin (Glass, 1981). At least five Fort Union coal beds are thicker than 5 ft (1.5 m) at the Rock Springs Uplift (Roehler, 1979).

In the Sand Wash Basin, the Fort Union Formation contains dip-elongate (north- and northeast-trending) fluvial sandstones and floodplain coal beds (Beaumont, 1979). Fort Union sandstones are lenticular and discontinuous, pinching out over distances of less than 1,000 ft (305 m). Coal beds are thicker (net-coal thickness as much as 90 ft [27.4 m]) in floodplain areas but more numerous adjacent to channel-fill sandstones, where they split and override and underlie sandstones. Net-coal thickness in the Fort Union Formation ranges from 0 to 90 ft (0 to 27.4 m) in as many as 12 seams (fig. 17) at depths as much as 8,000 ft (2,400 m); average depth of Fort Union coal beds in the Sand Wash Basin is slightly less than 4,000 ft (1,200 m). Net-coal thickness and coal-seam continuity in the upper Fort Union Formation are greater than that in the lower Fort Union Formation, as a result of coal beds having formed in stabilized floodplains.

Wasatch Formation

The Wasatch Formation is the youngest stratigraphic unit in the Greater Green River Basin that contains thick coal beds (individual coal beds locally 30 ft [9 m] thick) (Glass, 1981). The Wasatch Formation exhibits similar net-sandstone trends and depositional systems to the underlying Fort Union Formation (McDonald, 1975). However, the main body of the Wasatch Formation near the Rock Springs Uplift consists of 1,500 to 2,500 ft (450 to 760 m) of conglomeratic fan-delta deposits that grade laterally

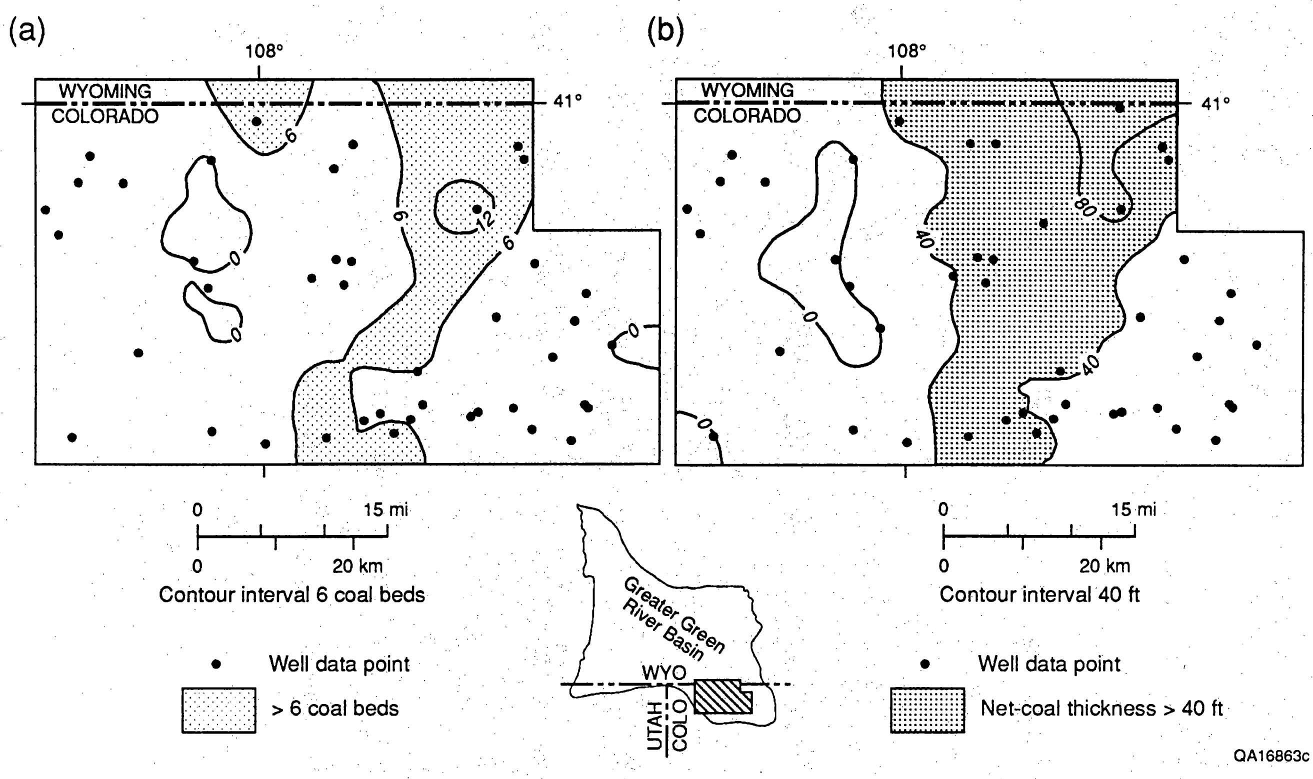


Figure 17. Maps of (a) number of coal beds and (b) net-coal thickness of the Fort Union Formation in the Sand Wash Basin, showing coal occurrence trends. Modified from Beaumont (1979).

into fluvial sandstones, floodplain and lacustrine shales, and coal-bearing paludal deposits (Roehler, 1965a; Sklenar and Anderson, 1985) that are 8,000 ft (2,400 m) deep in the Washakie Basin (McDonald, 1975).

In the east part of the Greater Green River Basin, Wasatch coal beds vary greatly in thickness, with individual coalbed thickness as great as 35 ft (11 m) (fig. 15). The thickest coal beds formed in stable swamps that were widespread in the Great Divide Basin, where the Wasatch Formation is the major coal-bearing unit. Two Wasatch coal beds in the Washakie Basin range in thickness from 10 to 32 ft (3 to 10 m) (McCord, 1984). Most Wasatch coal beds are moderately continuous and pinch out at sandy fluvial complexes over distances ranging from 2 to 10 mi (3.2 to 16 km) (Sklenar, 1982).

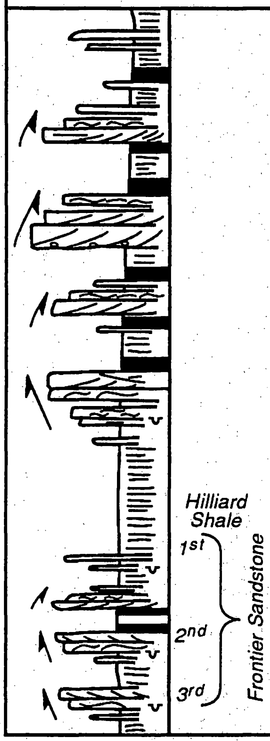
Green River Formation

The Green River Formation (Eocene) is the youngest coal-bearing formation in the Greater Green River Basin. It intertongues with the underlying Wasatch Formation and consists of fluvial, paludal, floodplain, and lacustrine deposits. However, Green River lacustrine deposits are much more extensive than in the Wasatch Formation (Surdam and Stanley, 1980). During deposition of the Green River Formation, a widespread lake complex evolved in the basin; short-lived swamps were reflected by numerous, thin (<5 ft [<1.5 m] thick) and discontinuous peats (coal beds) grading laterally into carbonaceous shales. Because coal beds in the Green River Formation are thin and discontinuous, they probably represent the poorest coalbed methane targets in the basin.

Western Greater Green River Basin

The west half of the Greater Green River Basin is bounded on the west by the Wyoming Overthrust Belt and on the east by the Rock Springs Uplift (figs. 1 and 2). During the Late Cretaceous, there was complex interfingering of coarse clastic sediments from the west with finer grained marine sediments to the east (Boyd and others, 1989). Late Cretaceous thrusting and Tertiary extension produced additional structural and stratigraphic complexity; as a result, strata in the west half of the Greater Green River Basin are discontinuous and difficult to correlate.

The major coal-bearing units in the western Greater Green River Basin are the Upper Cretaceous Frontier and Adaville Formations (fig. 18) (Mesaverde Group) and the Fort Union Formation. Depths of coal-bearing rocks in the western Greater Green River Basin vary greatly. The Mesaverde Group is less than 2,000 ft (600 m) deep on the La Barge Platform near the edge of the Wyoming Overthrust Belt (Asquith, 1966). However, it is more than 13,000 ft (3,960 m) deep in the Pinedale Basin in the extreme northwest part of the basin, and more than 9,000 ft (2,740 m) deep in the Green River Basin, 15 mi (24 km) west of the Rock Springs Uplift (fig. 11). Lower Tertiary coal-bearing strata are more than 7,500 ft (2,290 m) deep in the Pinedale Basin (Law and Spencer, 1989).

SCHEMATIC SECTION	FORMATION (Depositional system)	COAL BEDS Thickness (ft) Average					SANDSTONES Thickness (ft) Maximum			COAL-SANDSTONE RELATIONS
		Average	Maximum	Net	Number	Continuity	Maximum	Net	Continuity	
	FORT UNION FORMATION (Fluvial)	<10	10	—	—	Poor: coal beds pinch out near channel-fill sandstones	20-40	—	Poor: lenticular channel-fill sandstones common	Coal beds commonly pinch out against channel-fill sandstones
	ADAVILLE FORMATION (Wave-dominated deltaic)	10	20	—	5-10	Moderate to poor: most continuous coal beds are north-trending; others pinch out or are truncated by Tertiary unconformity	50-100	>100	Similar to Frontier Formation	Similar to Frontier Formation
	FRONTIER FORMATION (Wave-dominated deltaic)	5-10	10-20	—	5-10	Moderate continuity along strike (north-trending)	~100	>200	Good: parallel to depositional strike (north-trending)	Thickest coal beds overlie delta-front and barrier-island sandstones; other coal beds overlie thin crevasse-splay sandstones and pinch out at fluvial-sandstone complexes

SEDIMENTARY STRUCTURES AND ROCK TYPES

- Clasts
- Burrows
- Upward-coarsening
- Upward-fining
- Planar bedding
- Cross bedding
- Ripples
- Coal

QA16956c

Figure 18. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in the west half of the Greater Green River Basin.

Frontier Formation

The Frontier Formation, separated from the overlying Mesaverde Group by the marine Hilliard Shale (equivalent to the Mancos Shale in the east half of the Greater Green River Basin), consists of north- to northeast-trending, eastward-thinning wedges of deltaic and shoreline sandstones that intertongue with marine shales. Individual progradational Frontier wedges contain more than 200 ft (60 m) of net sandstone along the basin axis near the Overthrust Belt (Hamlin, 1991). Thin coal beds (individual seams commonly less than 10 ft [<3 m] thick) formed in coastal-plain environments landward (westward) of the paleoshoreline. Thickest Frontier coal beds (individual seams as much as 20 ft [6 m] thick) are exposed on the west margin of the basin (McCord, 1984). However, Frontier coal beds are thin (<5 ft [<1.5 m] thick) and are more than 14,000 ft (4,270 m) deep along the south end of the Moxa Arch, only 25 mi (40 km) eastward from outcrop. Along the north end of the Moxa Arch, Frontier coal beds are 6,000 to 7,000 ft (1,830 to 2,130 m) deep (Hamlin, 1991).

Mesaverde Group

The Adaville Formation in the Mesaverde Group is equivalent to the Rock Springs Formation (fig. 3). The Almond Formation, which is part of the Mesaverde Group at the Rock Springs Uplift, is not differentiated from the Rock Springs Formation in the western Greater Green River Basin (Law and others, 1989). In the western Greater Green River Basin, the Mesaverde Group overlies and intertongues with the marine Hilliard Shale (fig. 3) and consists of thick (locally more than 100 ft [30 m]) shoreface sandstones overlain by coal-bearing siltstone and sandstone (Roehler, 1990). The Mesaverde shoreline and peats (coal beds), which formed in swamps landward of the shoreline, trend northeastward (Asquith, 1966). Mesaverde coal beds have limited extent, because of pinch-outs at fluvial and distributary-channel sandstones, from offset by complex Laramide faults, and from truncation due to a post-Cretaceous unconformity.

In outcrops along the Wyoming Overthrust Belt in southwestern Wyoming, the Adaville Formation contains as much as 32 coal beds, with one structurally thickened coal seam as much as 118 ft (36 m) thick (McCord, 1984). However, in the Green River Basin these coal beds are much thinner and are deeply buried (more than 12,000 ft [3,660 m]) only 20 to 30 mi (32 to 48 km) eastward along the Moxa Arch where average-coal thickness is approximately 10 ft (3 m) and maximum-coal thickness is 20 ft (6 m) (fig. 18). In the Pinedale Basin, Mesaverde coal beds are more than 13,000 ft (3,960 m) deep (Law and Johnson, 1989).

Fort Union Formation

Thin Fort Union coal beds (<10 ft [<3 m] thick) exist at the north end of the Moxa Arch (fig. 18), buried at depths of less than 2,000 ft (600 m) (Asquith, 1966). These coal beds are discontinuous and pinch out near lenticular, channel-fill sandstones. Fort Union coal beds are absent at the Pinedale Anticline in the northwest part of the basin (Curry, 1973; Law and Johnson, 1989). In the Paleocene, coal beds did not form in this part of the basin because floodplain environments were unstable; coarse clastics were deposited in alluvial fans near source areas in the Wind River Basin (Law and Johnson, 1989).

Hydrology

In the Greater Green River Basin, the Mesaverde Group and Lance-Wasatch interval are the coal-bearing hydrostratigraphic units. The Mesaverde Group is confined below by the Hilliard, Baxter, Steele, and Mancos Shale from west to east, respectively, and above by the Lewis Shale (fig. 3). Above the Lewis Shale is the Fox Hills Sandstone/Lance Formation couplet. The Lance Formation is unconformably overlain by the Fort Union Formation, which is unconformably overlain by the Wasatch Formation (fig. 3). The Wasatch is overlain by the Green River Formation, a regional confining layer.

The Mesaverde Group crops out along the east margin of the Great Divide, Washakie, and Sand Wash Basins and on the Rock Springs Uplift (Tweto, 1979; Love and Christiansen, 1985), where it receives recharge. Most of the recharge is to the Sand Wash Basin, where mean annual precipitation exceeds 16 inches (40 cm) to the east over the Park Uplift (figs. 7 and 19). Recharge is also accepted over the Rock Springs Uplift (figs. 6 and 7). Low-chloride waters (<600 mg/L) are reported in the Rock Springs Formation about 6 mi (9.6 km) basinward of the outcrop (Leel and Wickstrom, 1990). This relatively narrow band of low-chloride water reflects lower precipitation and less recharge on the drier uplift. Mesaverde recharge from the north, south, and west margins of the greater basin is limited by low precipitation (fig. 19) and possibly by thrust faults (figs. 2, 5, and 6).

The Lance–Wasatch coal-bearing hydrostratigraphic unit has an outcrop distribution similar to that of the Mesaverde unit with some exceptions. The Fort Union Formation is present on the south margin of the Sand Wash and north margin of the Great Divide Basins and may receive some recharge from those margins (fig. 8). The Wasatch crops out over much of the Great Divide Basin, and the Lance Formation is absent on the west flank of the Rock Springs Uplift (Love and Christiansen, 1985).

Regional ground water flows basinward mainly from the high-precipitation outcrop (recharge area) along the east margin of the basin, down the regional topographic gradient and structural dip (figs. 2 and 19). Moreover, fracture flow may be favored parallel to the northeast-trending face cleat (fig. 9), promoting flow eastward off the Rock Springs Uplift into the Great Divide and Washakie Basins. Topographic and structural control of flow is affirmed in the San Juan Basin, where ground water in the Fruitland Formation

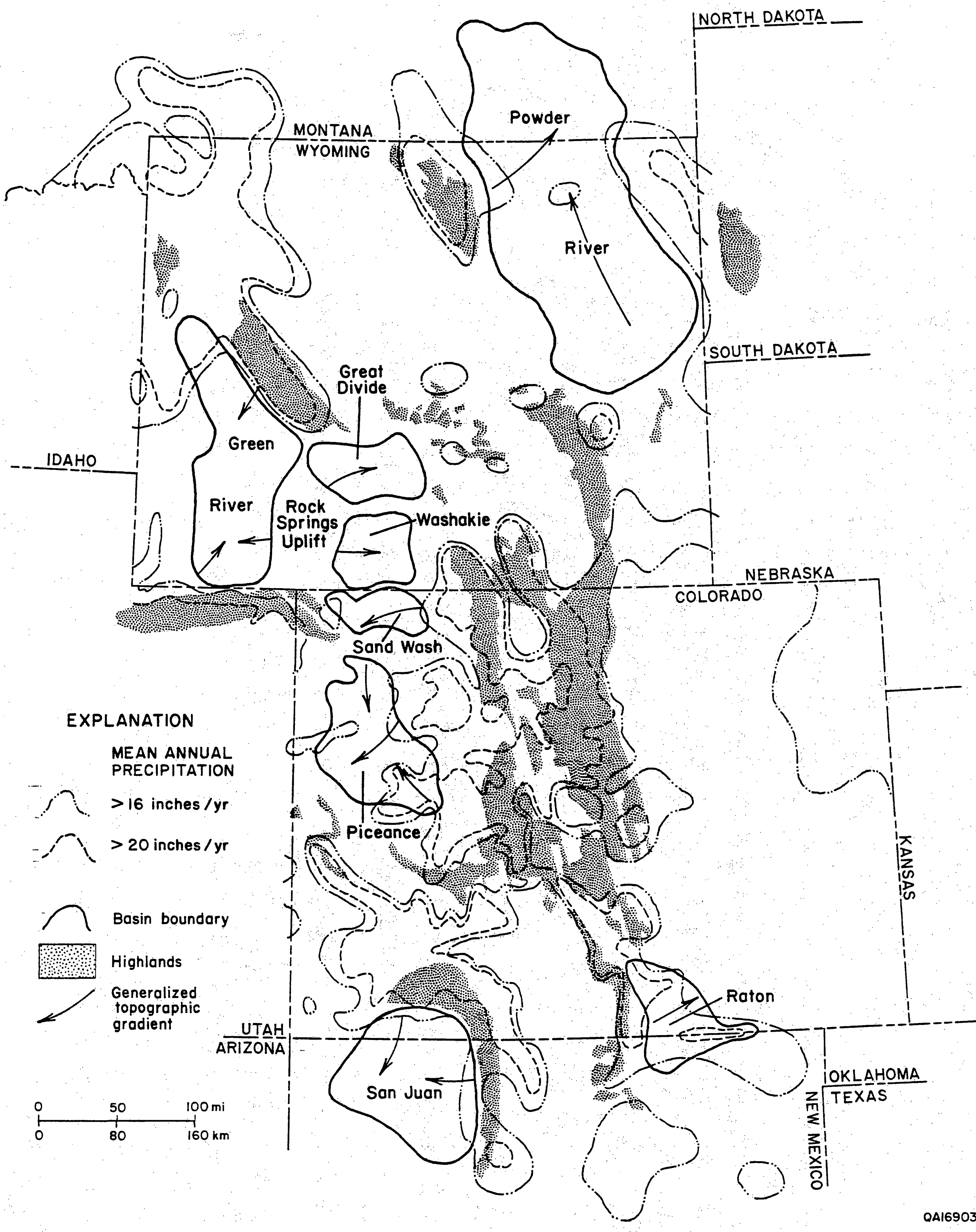


Figure 19. Annual precipitation and topographic gradients, western basins. Precipitation data from NOAA (1974). Regionally, ground water flows basinward, down regional topographic gradient from the wet, elevated basin margin or recharge area.

flows southward down topographic gradient and structural dip from an elevated area of high precipitation (Kaiser and others, 1991b). On the east the Fruitland is thin or absent and accepts little recharge.

Because potentiometric-surface maps are unavailable for the Greater Green River Basin, very little can be said about regional discharge areas. Flow must eventually turn upward basinward. Presumably this occurs upon aquifer pinch-out or convergence from the basin margins, or both, and upon encountering the top of regional overpressure (fig. 7). Because internal drainage characterizes the basins east of the Rock Springs Uplift, convergence probably occurs in the center of those basins. West of the Rock Springs Uplift, regional flow probably converges on the Green River and its major tributaries. Discharge areas are important hydrodynamically because hydrocarbon accumulation is favored in areas of upward flow (Tóth, 1980). For example, in the San Juan Basin the most prolific coalbed methane wells are in an area of upward flow (Kaiser and others, 1991b).

In the Greater Green River Basin, coal-bearing strata are normally pressured near the outcrop (McCord, 1984; Young and others, 1991). Upon confinement basinward, artesian conditions may develop to locally overpressure coal seams. Permeable coal seams in the Mesaverde Group (Young and others, 1991) are elevated at outcrop and confined basinward by thick marine shales of regional extent (fig. 3). Confinement of the Lance–Wasatch unit is most likely in the Green River and Washakie Basins, where the Wasatch Formation is overlain by the Green River Formation.

Normally pressured and slightly overpressured coal-bearing strata occur above regional overpressure that is predicated on low permeability (<0.1 md) and active generation of gas (Law and Dickinson, 1985; Law and others, 1986). Because of low-permeability and high pressure, the top of geopressure is a no-flow boundary. Pressure gradients exceed 0.5 psi/ft (11.31 kPa/m)and locally are greater than 0.8 psi/ft (18.10 kPa/m). Gas accumulates at rates faster than it is lost to become the pressuring fluid (Law, 1984). The top of overpressure, at depths of 7,000 ft (2,135 m) or more, cuts across structural and stratigraphic boundaries and is not restricted to any particular stratigraphic unit (figs. 5–8). Consequently, the transition between gas-bearing strata downdip and water-bearing strata updip is basinwide, occurring in progressively younger strata basinward.

In the Greater Green River Basin, the top of regional overpressure, because of low permeability, is a floor for coalbed methane exploration. Normally pressured or artesian coal seams above regional overpressure yield large volumes of low-chloride water upon production, indicating good permeability. Basinward areas of upward flow, where flow converges from the basin margins or encounters top of overpressure, may be extensive at exploitable depths, particularly in the Fort Union and Wasatch Formations. The potential for artesian overpressuring exists and may be extensive. Higher pressures and confinement will serve to preserve high gas contents at exploitable depths. Finally, the transitional pressure fairway between hydrostatic normal pressure updip and hydrocarbon-related overpressure downdip is large and potentially very productive (fig. 20); whether the fairway is at exploitable depths is

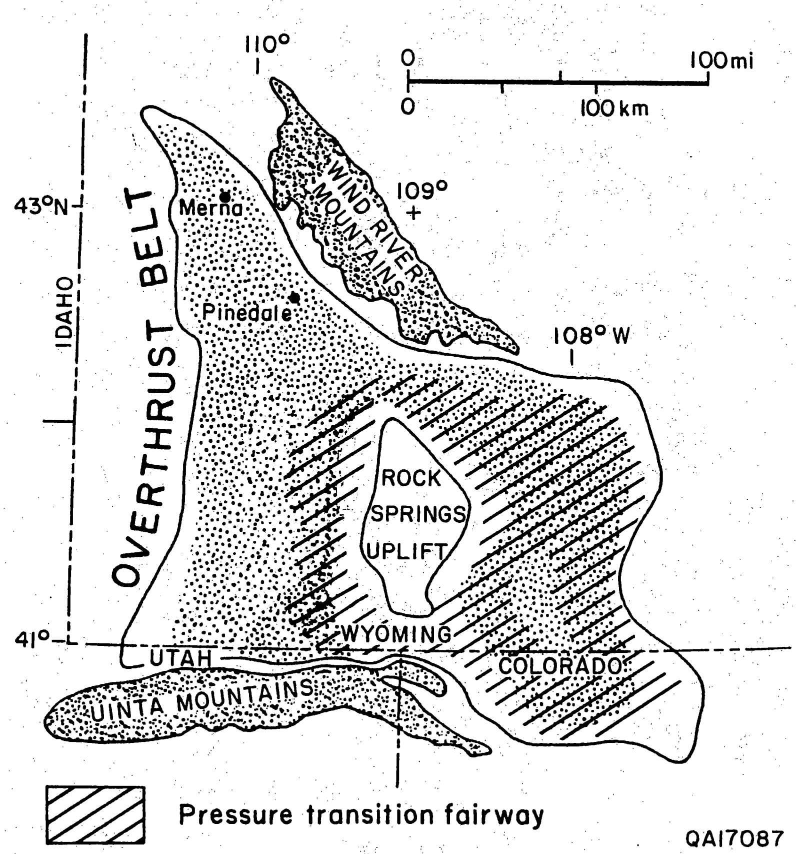


Figure 20. Distribution of regional overpressure in the Greater Green River Basin. Modified from Spencer (1987) and Law and others (1989). Pressure transition fairway is schematic, occurring in progressively younger strata basinward.

unknown (fig. 8). In the San Juan Basin, the pressure-transition fairway hosts the most productive coalbed methane wells (Kaiser and others, 1991a).

Coal Rank and Gas Composition

The amount of methane generated from coal beds is primarily a function of coal rank. The onset of significant methane generation from coal occurs at vitrinite reflectance values (R_m) of approximately 0.73 percent (high-volatile A bituminous) (Meissner, 1984), although significant amounts of early thermogenic methane can be derived from terrestrial organic matter at much lower levels of thermal maturity (R_m of approximately 0.40 percent; Galimov, 1988). Determination of coal-rank trends and burial history of coal-bearing units in the Greater Green River Basin becomes complicated by insufficient vitrinite reflectance and proximate data. Most of the published vitrinite reflectance data are from shales and sandstones within the coal-bearing formations. However, thermal maturation studies by Law and others (1980), Law (1984), Pawlewicz and others (1986), Merewether and others (1987), Dickinson (1989), and Lickus and others (1989) provide the basis for estimating coal rank in the Greater Green River Basin.

Coal Rank

Vitrinite reflectance data (Law, 1984) from individual wells were grouped into four regional subdivisions (fig. 21). Area I covers the Pinedale Basin including the Pinedale Anticline; Area II includes the northern Green River Basin and the Pacific Creek Area; Area III represents the Great Divide Basin; and Area IV includes the Washakie and Sand Wash Basins. Vitrinite reflectance values for the coal-bearing Fort Union Formation range from 0.40 to 1.53 percent (subbituminous to low-volatile bituminous) at Wells 25 and 8, respectively (fig. 21). Measured vitrinite reflectance values from the Lance Formation ranged from 0.42 to 1.63 percent, corresponding to the high-volatile C bituminous to low-volatile bituminous coal ranks (Wells 32 and 8, respectively; fig. 21). Vitrinite reflectance values in the Almond Formation range from 0.42 percent (subbituminous; Well 32, fig. 21) to 2.41 percent (semianthracite; Well 8, fig. 21). Measured vitrinite reflectance values from the Rock Springs Formation range from 0.60 percent (high-volatile C bituminous; Wells 10 and 19, fig. 21) to 1.20 percent (medium-volatile bituminous; Well 5, fig. 21). However, Rock Springs coals have probably reached the semianthracite rank in the Washakie Basin.

Regression analyses were performed on vitrinite reflectance profiles for each area (fig. 22). The equations calculated by regression analysis (table 1) were subsequently used to estimate vitrinite reflectance values for the top of the Cretaceous using data from the Fort Union, Lance, and Almond Formations. A coal-rank map was made for the top of the Cretaceous because calculated vitrinite reflectance data could easily be extrapolated from other coal-bearing formations. Vitrinite reflectance values and coal-rank data were obtained from Boreck and others (1981), Tremain and Toomey (1983), Law (1984), and Roehler (1988). Thermal maturity maps (Pawlewicz and others, 1986; Merewether and

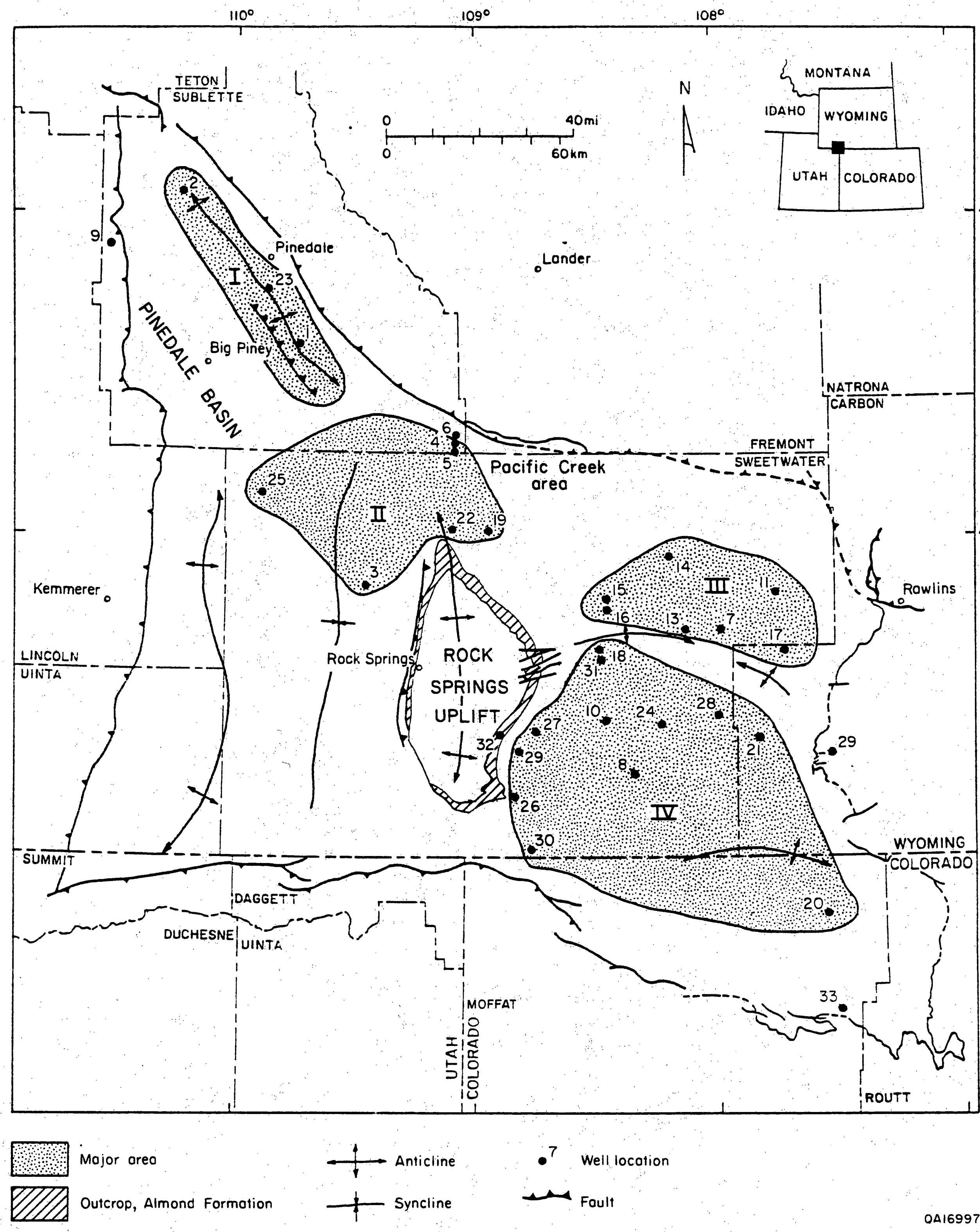


Figure 21. Map of Greater Green River Basin showing vitrinite reflectance well locations and the major subdivisions used to make vitrinite reflectance profiles. Data from Law (1984) and Roehler (1988).

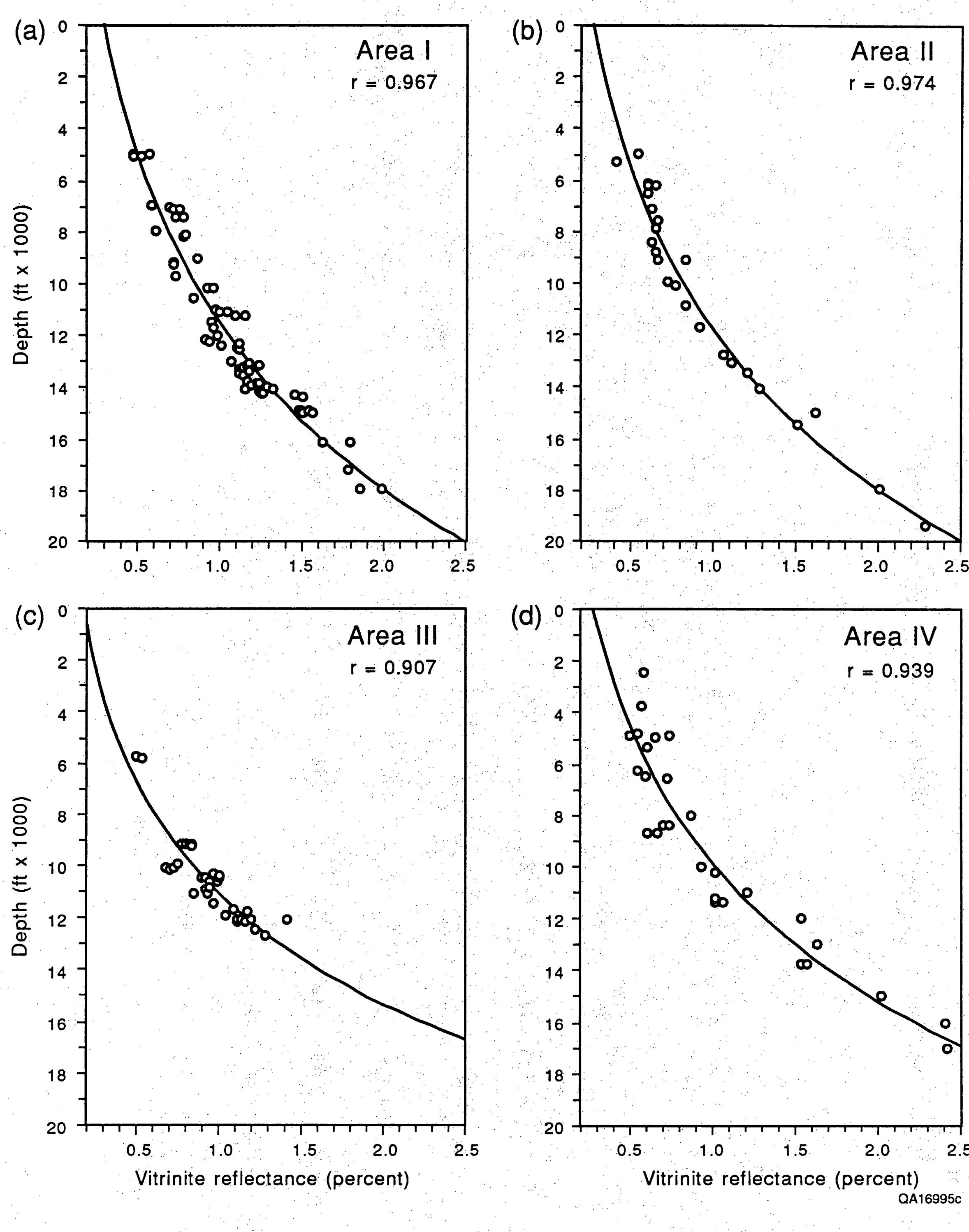


Figure 22. Vitrinite reflectance profiles showing depth versus vitrinite reflectance values for each of the subdivisions in the Greater Green River Basin shown in figure 21. Wells 6, 9, 16, 29, and 33 were excluded from these plots. Data from Law (1984).

others, 1987) showing the depths to vitrinite reflectance values of 0.3, 0.6, and 1.3 percent, and post-Mesaverde isopach and structural contour maps (Curry, 1973 [fig. 11]; Lickus and Law, 1988 [fig. 2]) were used to supplement the vitrinite reflectance data.

Table 1. Equations determined from vitrinite reflectance profiles were used to estimate some of the vitrinite reflectance values shown in figure 23. The location of each subdivision is shown in figure 21. R_m = vitrinite reflectance value.

Area I	Pinedale Basin	$LOG(R_m)$ = (Depth - 11,599 ft)/21,300 ft
Area II	Green River Basin	$LOG(R_m)$ = (Depth - 11,829 ft)/20,495 ft
Area III	Great Divide Basin	$LOG(R_m)$ = (Depth - 11,095 ft)/14,101 ft
Area IV	Washakie and Sand Wash Basins	$LOG(R_m)$ = (Depth - 9,938 ft)/17,590 ft

High-volatile C bituminous coals are located around the Rock Springs Uplift (fig. 23). Coal rank increases away from the uplift toward the Pinedale Anticline and Pacific Creek Area to the northwest and eastward toward the Great Divide, Washakie, and Sand Wash Basins. The presence of lower-rank coal around the Rock Springs Uplift suggests that this structure was formed before or during the main stage of coalification. Vitrinite reflectance trends in the northwestern Green River Basin (Area I; fig. 21) generally follow Tertiary structures (Lickus and others, 1989), suggesting that structural deformation occurred after the main stage of coalification. However, possible vertical migration of hot fluids could make the relation between coalification and structural events difficult to interpret in this area (Lickus and others, 1989). Coal rank at the top of the Cretaceous probably does not increase beyond the high-volatile B bituminous stage in the central and south parts of the Green River Basin, judging from vitrinite reflectance contour maps (Merewether and others, 1987) and vitrinite reflectance data (Area II).

Coal in the eastern Greater Green River Basin is generally of higher rank than coal in the western Greater Green River Basin (fig. 23). Tertiary coals (Fort Union and Wasatch) in the Great Divide Basin (Area III; fig. 21) are mostly subbituminous, whereas Almond and Rock Springs coals range in rank from subbituminous to high-volatile C bituminous (McCord, 1984). However, vitrinite reflectance values in the Lewis Shale for Well 11 (fig. 21) are approximately 1.19 (medium-volatile bituminous; Law, 1984), suggesting that coal rank in the Lance and Rock Springs Formations may approach the high-volatile A bituminous or higher stages (fig. 23). The highest-rank coal (low-volatile bituminous) in the Lance Formation is located near the center of the Washakie Basin (Area IV, Well 8; figs. 21 and 23), which is also the deepest part of the Greater Green River Basin. Vitrinite reflectance values in the overlying Fort Union Formation have reached the medium- to low-volatile bituminous coal rank (vitrinite reflectance values of 1.53 percent), whereas coal rank in the Almond Formation has reached the semianthracite to anthracite

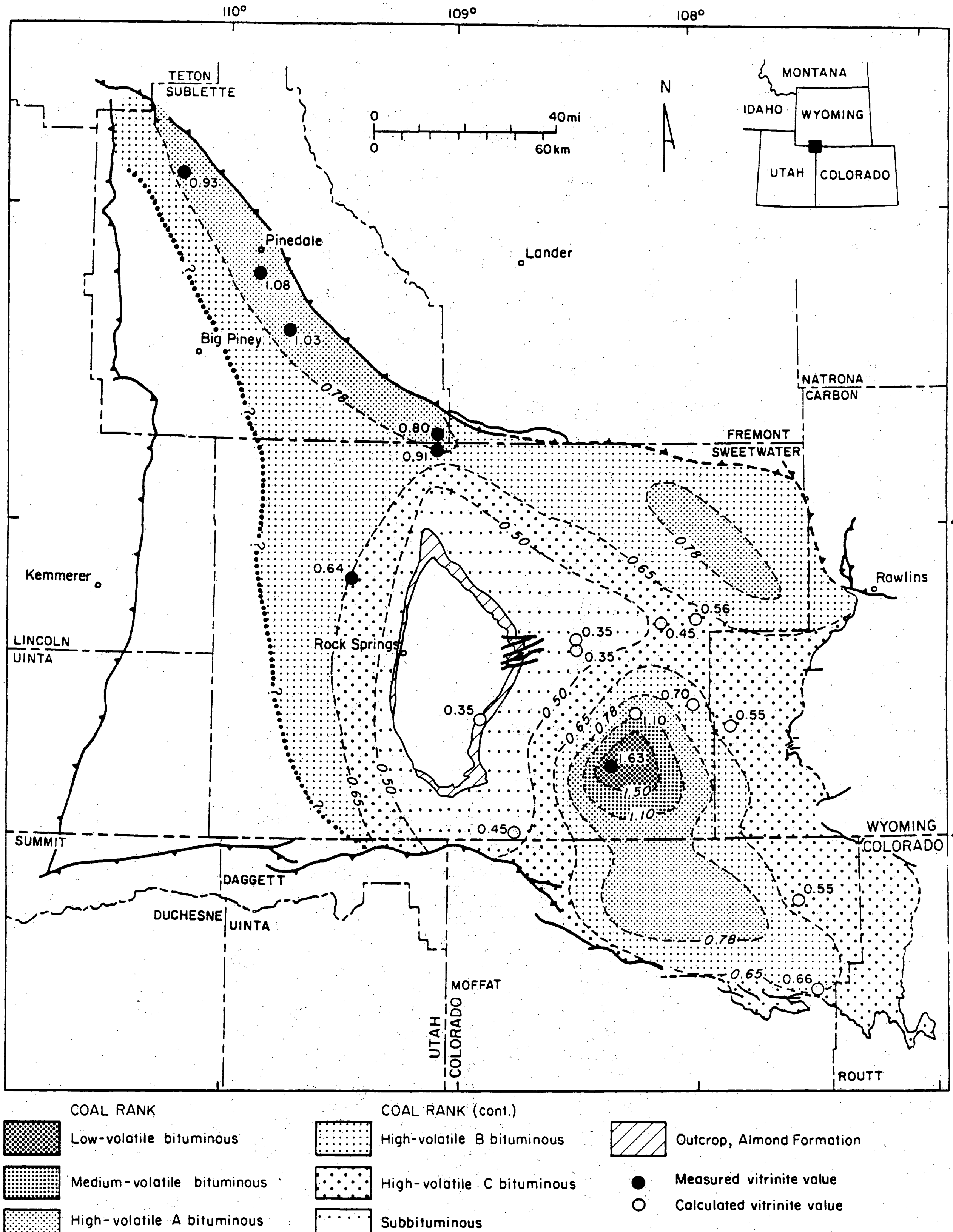


Figure 23. Coal-rank map for the top of the Cretaceous made from actual and calculated vitrinite reflectance values from Law (1984) and thermal maturity maps from Pawlewicz and others (1986) and Merewether and others (1987). Coal rank decreases away from the Rock Springs Uplift towards individual subbasins. The highest-rank coals (low-volatile bituminous) are in the Washakie Basin.

stage (vitrinite reflectance values of 2.41 percent) in the Washakie Basin (Law, 1984). Cretaceous coal rank in the Sand Wash Basin (Area IV; fig. 21) probably ranges from high-volatile C bituminous to high-volatile A bituminous (fig. 23). Although Mesaverde coal rank ranges from high-volatile C bituminous to semianthracite and anthracite locally have been reported (Gas Research Institute, 1990b).

Whereas maximum burial depth was undoubtedly an important factor in determining coal rank, the eastern Greater Green River Basin may also have had a different thermal maturation history than did the western Greater Green River Basin. Vitrinite reflectance profiles are similar for all parts of the Greater Green River Basin for depths of less than approximately 9,000 ft (2,744 m) (fig. 24). However, vitrinite reflectance values increase more with depth in the east part of the basin than in the west part (fig. 24), suggesting that the east part of the Greater Green River Basin may have been covered by more overburden or may have experienced a higher geothermal gradient in the past, resulting in higher-rank coal and a greater coalbed methane potential. Vertical movement of hot fluids at depth could have contributed to the higher vitrinite reflectance values in the Washakie Basin. According to McPeek (1981), the CIC Haystack well (Sec. 28, T14N, R96W) had a temperature gradient of 1.6°F per 100 ft (23.6°C/km) to a depth of 14,910 ft (4,545 m) and a gradient of 3.9°F per 100 ft (70.9°C/km) between the depths of 14,910 and 16,250 ft (4,545 and 4,953 m). The geothermal gradients for the Pinedale Basin, northeast part of the Rock Springs Uplift, and west part of the Wamsutter Arch are 2.4°, 2.1°, and 2.0°F per 100 ft (28°, 25°, and 25°C/km) (Heasler and others,1983). The relatively high temperature gradient below 14,910 ft (4,545 m) in the Haystack well may indicate vertical movement of fluids from deeper sediments, although more evidence is required to confirm this.

Gas Composition

Limited coalbed gas compositional data are available in the Greater Green River Basin (Tremain and Toomey, 1983). Although much of the coalbed methane produced from Upper Cretaceous coal beds may be thermogenic in origin, some coalbed gases could be biogenic as well. Significant quantities of methane produced from lower-rank coal vitrinite reflectance values of less than 0.73 percent) at relatively shallow depths (<6,000 ft [<1,829 m]) will indicate the presence of biogenic gases and/or the migration of thermogenic gases from deeper parts of the basin. Young and others (1991) reported that gas contents of coal from the Rock Springs Formation northeast of the Rock Springs Uplift uncharacteristically decrease with increasing depth and coal rank. This inverse relation between depth and gas content, including the scattering of data points, could be related to mixing of biogenic and thermogenic gases, variability in maceral content, pressure regime between coal beds, or a combination of several factors.

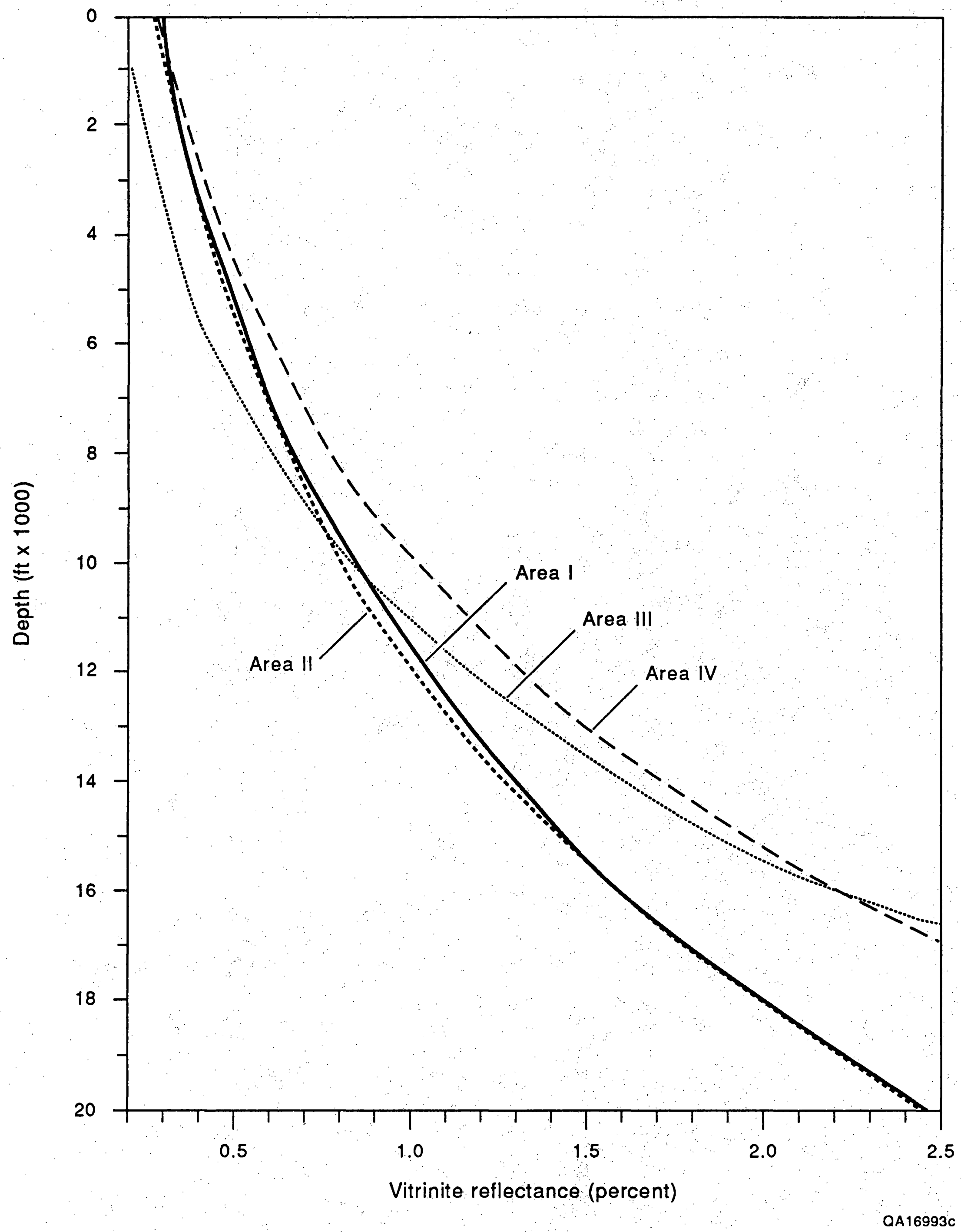


Figure 24. Vitrinite reflectance profiles for major subdivisions in the Greater Green River Basin. Vitrinite reflectance profiles for all subdivisions generally parallel each other for depth less than approximately 9,000 feet (2,744 m). However, vitrinite reflectance values increase more with depth in the east part of the Greater Green River Basin (Areas III and IV) than in the west (Areas I and II) (fig. 21). This suggests that the east part of the basin had a different thermal maturation history than did the west.

Coalbed Methane Production

Production Targets

The Greater Green River Basin contains a wide variety of Upper Cretaceous and lower Tertiary coalbed methane targets that occur in several subbasins. Most of these targets are less than 6,000 ft (1,800 m) deep only along the southeast perimeter of the basin (Sand Wash and Washakie Basins) and at the Rock Springs Uplift. Drilling activity is greatest in the Sand Wash and Washakie Basins and on the north flank of the Rock Springs Uplift. The Fort Union and Almond (equivalent to Williams Fork) Formations are the main drilling targets in the Sand Wash and Washakie Basins, where 81 coalbed methane wells were drilled from February 1990 to May 1991, of which 56 were wildcat wells (fig. 25). There were 31 potential coalbed methane wells at the Rock Springs Uplift, where the Almond, Rock Springs, and Fort Union Formations are the main coalbed methane targets.

Gas and Water Production

Cumulative production in the Greater Green River Basin is approximately 4,654 MMcf (131.7 MM m^3) of coalbed gas, 31,744 bbl (5,044 m^3) of liquid hydrocarbons, and approximately 1.97 MMbbl (313,033 m^3) of water. From October 1989 to January 1991, production from coalbed methane wells in the basin was approximately 97 MMcf (2.75 MM m^3) of gas (fig. 26a), 1,170 bbl (186 m^3) of liquid hydrocarbons (fig. 26b), and approximately 1.28 MMbbl (203,392 m^3) of water (fig. 26c) A maximum of 20 out of a possible reported 27 coalbed methane wells were producing in January 1991 (fig. 27). Of the 14 named fields in the Greater Green River Basin, coalbed methane is produced in 9 fields, all of which are in the Sand Wash and Washakie Basins (fig. 28).

Indications of gas contents in Williams Fork, Lance, and Fort Union coal beds in the Sand Wash Basin are encouraging. High-volatile B to high-volatile A coal beds at depths of 3,600 to 4,700 ft (1,100 to 1,430 m) display gas contents ranging from 120 to 376 ft^3/ton (3.7 to 11.7 m^3/t) (Tremain, 1990). Gas-desorption values in coal beds in the Rock Springs Formation at the Rock Springs Uplift range from 143 to 527 ft^3/ton (4.5 to 16.4 m^3/t) at depths of 3,342 to 4,399 ft (1,019 to 1,341 m) (fig. 29; Leel and Wickstrom, 1990).

An extremely wide range in methane content has been reported in coal seams in other parts of the Greater Green River Basin (2.9 to 539 ft^3/ton [0.09 to 16.8 m^3/t] in bituminous coal beds at depths of 3,000 ft [915 m] or less) (McCord, 1984). Although most reported gas-content values are low (<200 ft^3/ton [6.2m^3/t]), high gas-content values have been reported by Belco Petroleum in the Green River Basin in Sublette County, where Mesaverde coal samples from depths ranging from 3,478 to 3,528 ft (1,060 to 1,076 m) have gas contents ranging from 436 to 539 ft^3/ton (13.6 to 16.8 m^3/t) (Gas Research Institute, 1990a).

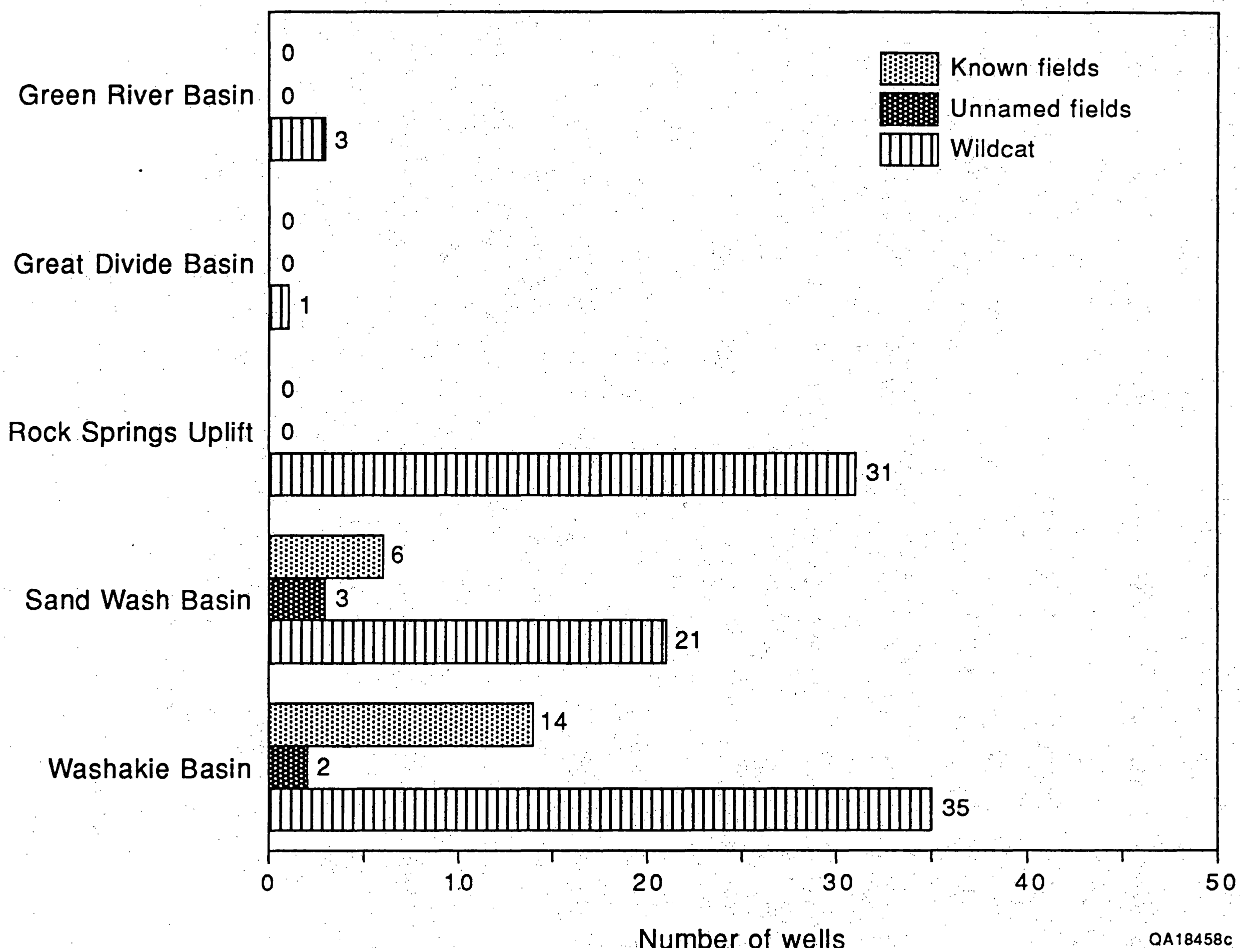


Figure 25. Distribution of coalbed methane wells in the Greater Green River Basin from February 1990 to May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

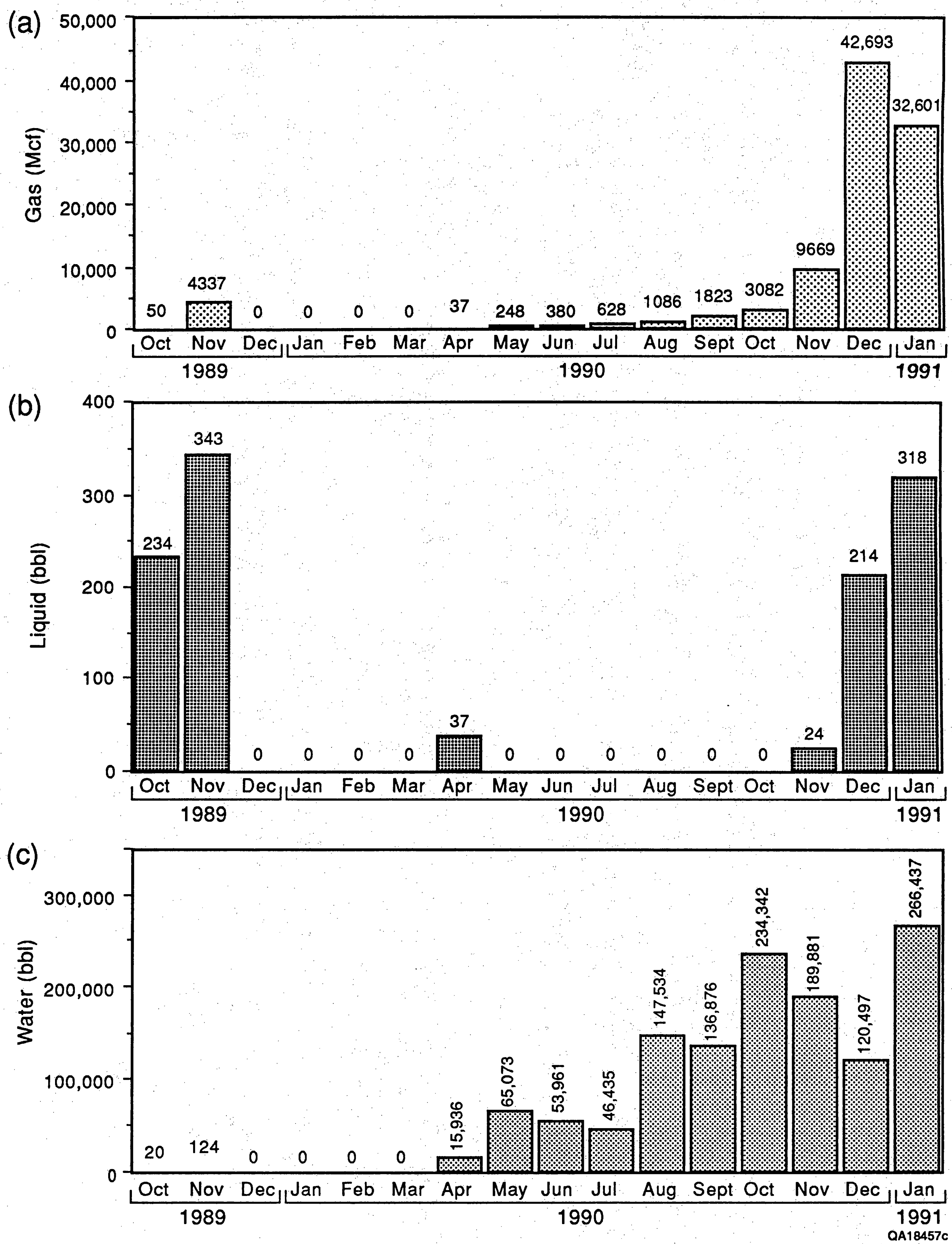


Figure 26. (a) Gas, (b) liquid hydrocarbon, and (c) water production from coalbed methane wells in the Greater Green River Basin from October 1989 to January 1991. Data from Petroleum Information (1990a–k; 1991b–f).

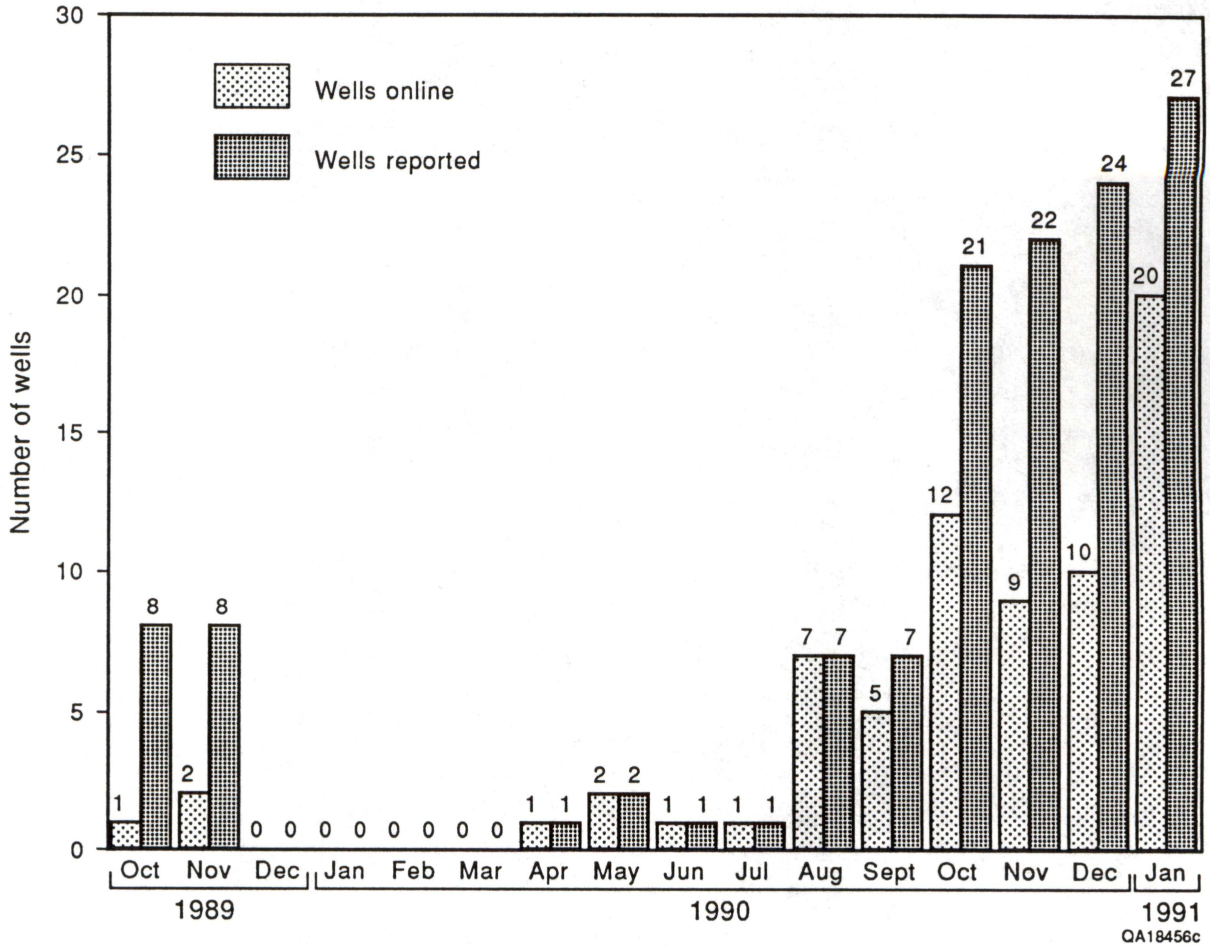


Figure 27. Number of coalbed methane wells online (reported by Petroleum Information [1990a–k; 1991b–f]) in the Greater Green River Basin from October 1989 to January 1991.

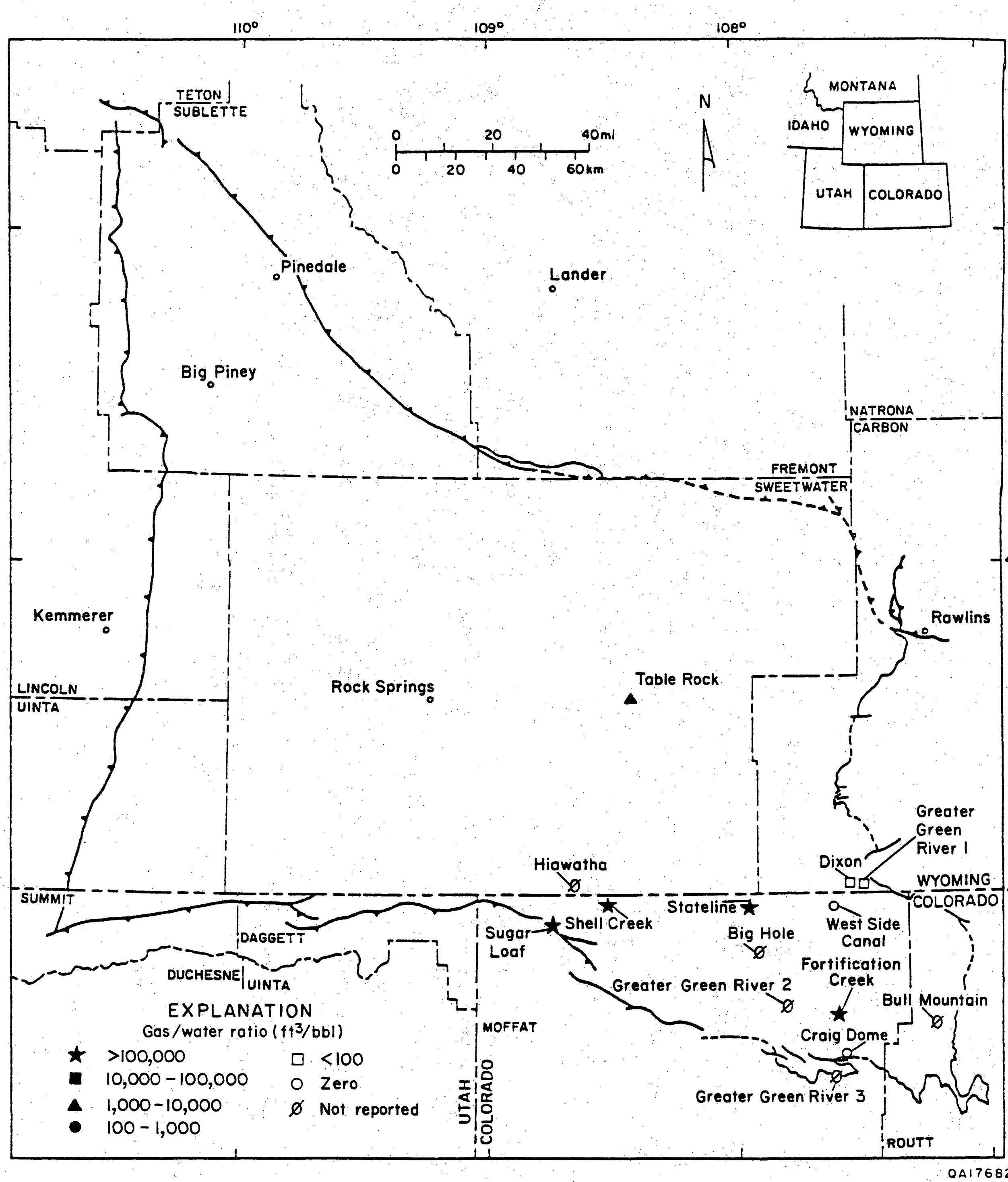


Figure 28. Cumulative gas/water ratio in coalbed methane fields in the Greater Green River Basin. Low ratios along the south and east margins of the basin reflect proximity to the recharge area and high inferred coal-seam permeability, and westward flow of ground water. Data from Petroleum Information (1990a–k; 1991b–f).

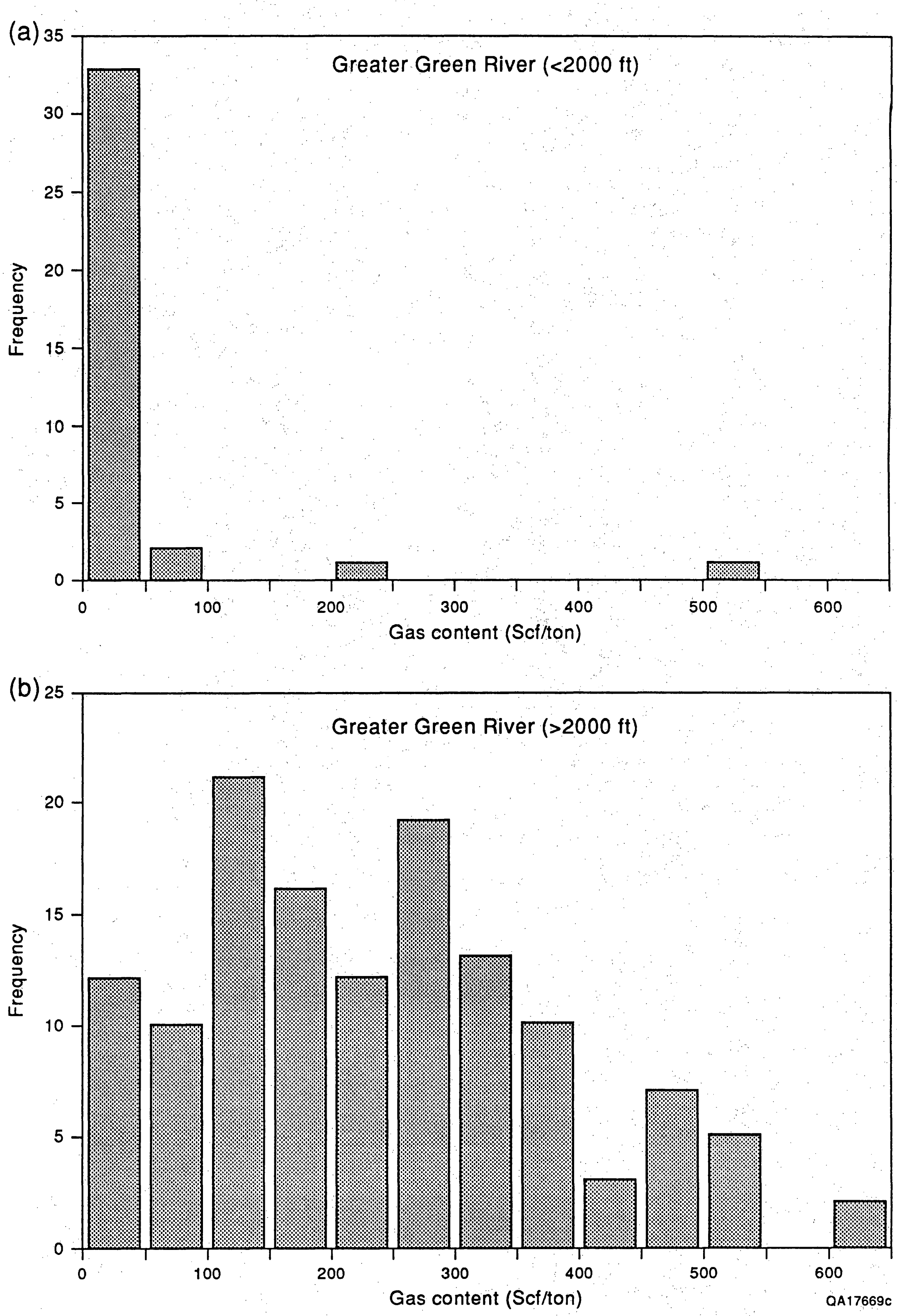


Figure 29. Gas content of coal beds in the Greater Green River Basin, mainly north of the Rock Springs Uplift, (a) less than 2,000 ft (610 m) deep and (b) more than 2,000 ft (610 m) deep. Data from Leel and Wickstrom (1990) and the Gas Research Institute (1990a, b; 1991a).

Production tests from coal- and sandstone-bearing zones in the Fort Union Formation indicate initial potentials as high as 2,500 to 5,690 Mcf/d (70,750 to 161,027 m^3/d) of gas (fig. 30) and 144 bbl/d (22.9 m^3/d) of liquid hydrocarbons (Boreck and others, 1981). However, some initial potentials are as low as 5 Mcf/d (141.5 m^3/d) of gas and 6 bbl/d (1.0 m^3/d) of water from 15-ft (4.6-m) Williams Fork coal beds (4,863 to 4,873 ft [1,483 to 1,486 m] deep) after stimulation (Gas Research Institute, 1989a).

Almost all coalbed methane production in the Greater Green River Basin is from Sugar Loaf field (Sand Wash Basin) (fig. 28), which has produced approximately 4,290 MMcf (121.4 MM m^3) of coalbed gas (92 percent of all coalbed gas in the basin) and 29,748 bbl (4,727 m^3) of liquid hydrocarbons (94 percent of all liquid hydrocarbons from coalbed methane wells in the basin) (table 2). The second most productive coalbed gas field is Shell Creek, also in the Sand Wash Basin, which has produced approximately 207 MMcf (5.86 MM m^3) of gas. The leading water-producing field is an unnamed field, referred to as Greater Green River 1, which produced 901 Mbbl (143,169 m^3) of water. The second most water-producing field is Craig Dome (Sand Wash Basin), which has produced approximately 650 Mbbl (103,285 m^3) of water and no gas from Mesaverde coal beds at depths of 1,900 to 4,200 ft (580 to 1,280 m) in T6N, R91W and in downdip areas at depths of 4,400 to 6,400 ft (1,340 to 1,950 m) in T7N, R91W. Coalbed methane fields with low gas/water ratios (less than 100 ft^3/bbl) occur on the southeastern margin of the basin near the Park Uplift, whereas those with highest gas/water ratios (more than 100,000 ft^3/bbl) occur westward (fig. 28). High meteoric recharge over the Park Uplift may explain high water production at Craig Dome and West Side Canal fields (figs. 7, 19, and 28).

Completions and Drilling Activity

Coalbed methane drilling in the Greater Green River Basin has mainly occurred in the Sand Wash Basin and at the Rock Springs Uplift (fig. 31). In the Sand Wash Basin, completions are either in the Mesaverde Group or Fort Union Formation, whereas at the Rock Springs Uplift they are in the Mesaverde Group. Of 116 coalbed methane wells reported for all companies from February 1990 to May 1991 in the Greater Green River Basin, 15 are listed as single-completion, 4 as commingled, 6 as temporarily abandoned, 4 as abandoned, and 1 as dry and abandoned, and 85 are without information (fig. 32a). The single completions are nearly evenly distributed among coal beds in the Mesaverde Group and Fort Union Formations. Depths to top of gas well completions range from 810 to 6,960 ft (247 to 2,122 m) deep, with an average depth of 2,671 ft (814 m) (fig. 32b). Total depths are less than 8,000 ft (2,400 m).

Among the 18 companies that were active in the Greater Green River Basin in 1990 and 1991, Fuel Resources Development (Fuelco) drilled the most coalbed methane wells (43), followed by Triton (26 wells) and Cockrell (14 wells, mostly at Craig Dome field) (fig. 33). In 1990, Fuelco reported 30 new wildcat coalbed methane wells in the Sand Wash Basin (Gas Research Institute, 1991a) and recently tested the coalbed methane potential of the Darling and Pioneer coal beds (Almond Formation) in the southern

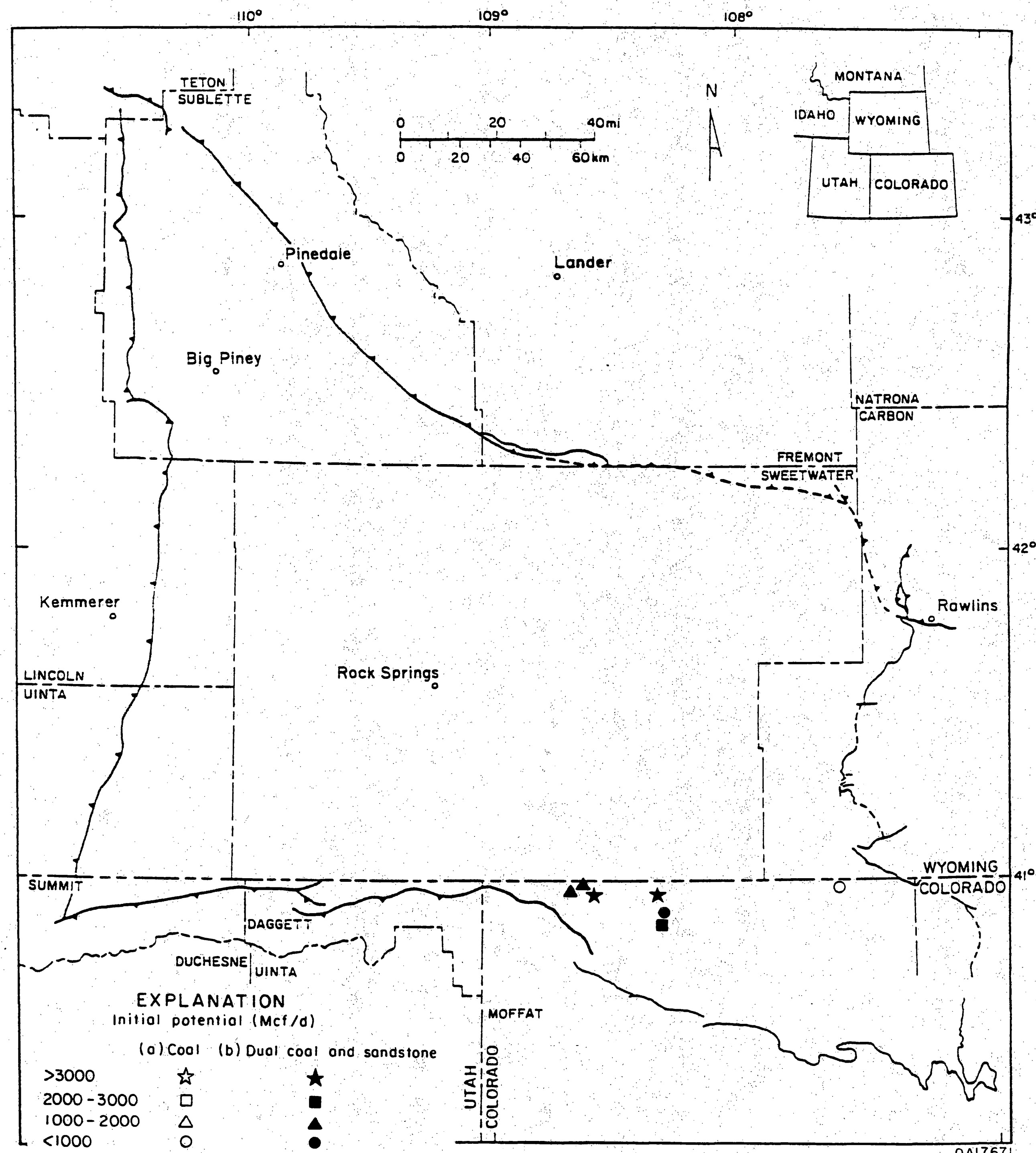


Figure 30. Initial potential of gas from (a) coal beds and (b) dually completed sandstones and coal beds from the Fort Union Formation in the Greater Green River Basin. Data from Boreck and others (1981), Petroleum Information (1990a–k; 1991 b–f), and the Gas Research Institute (1989a; 1990a, b; 1991a). Gas IP's are highest from dually completed wells.

Table 2. Liquid hydrocarbon, coalbed gas, and water production from fields in the Greater Green River Basin as of January 1991. Data from Petroleum Information, Inc. (1990a–k, 1991b–f).

Greater Green River Basin fields	Oct 89–Jan 91			Cumulative to Jan 91		
	Liquid (bbl)	Gas (Mcf)	Water (bbl)	Liquid (bbl)	Gas (Mcf)	Water (bbl)
Washakie Basin:						
Dixon	0	776	90,231	0	4,951	395,866
Hiawatha	*	*	*	*	*	*
Table Rock	218	6,093	110	218	6,280	2,343
Greater Green River 1	0	11,851	889,654	0	11,851	901,934
Washakie Basin Total	**218**	**18,720**	**979,995**	**218**	**23,082**	**1,300,143**
Sand Wash Basin:						
Big Hole	*	*	*	*	*	*
Bull Mountain	*	*	*	*	*	*
Craig Dome	0	0	287,070	0	0	649,929
Fortification Creek	338	73,490	0	338	73,490	0
Shell Creek	0	0	0	1,440	206,994	0
Stateline	0	0	0	0	60,995	0
Sugar Loaf	614	4,424	236	29,748	4,290,301	8,857
West Side Canal	0	0	9,815	0	0	9,815
Greater Green River 2	*	*	*	*	*	*
Greater Green River 3	*	*	*	*	*	*
Sand Wash Basin Total	**952**	**77,914**	**297,121**	**31,526**	**4,631,780**	**668,601**
Greater Green River Basin Total	**1,170**	**96,634**	**1,277,116**	**31,744**	**4,654,862**	**1,968,744**

* = No production reported

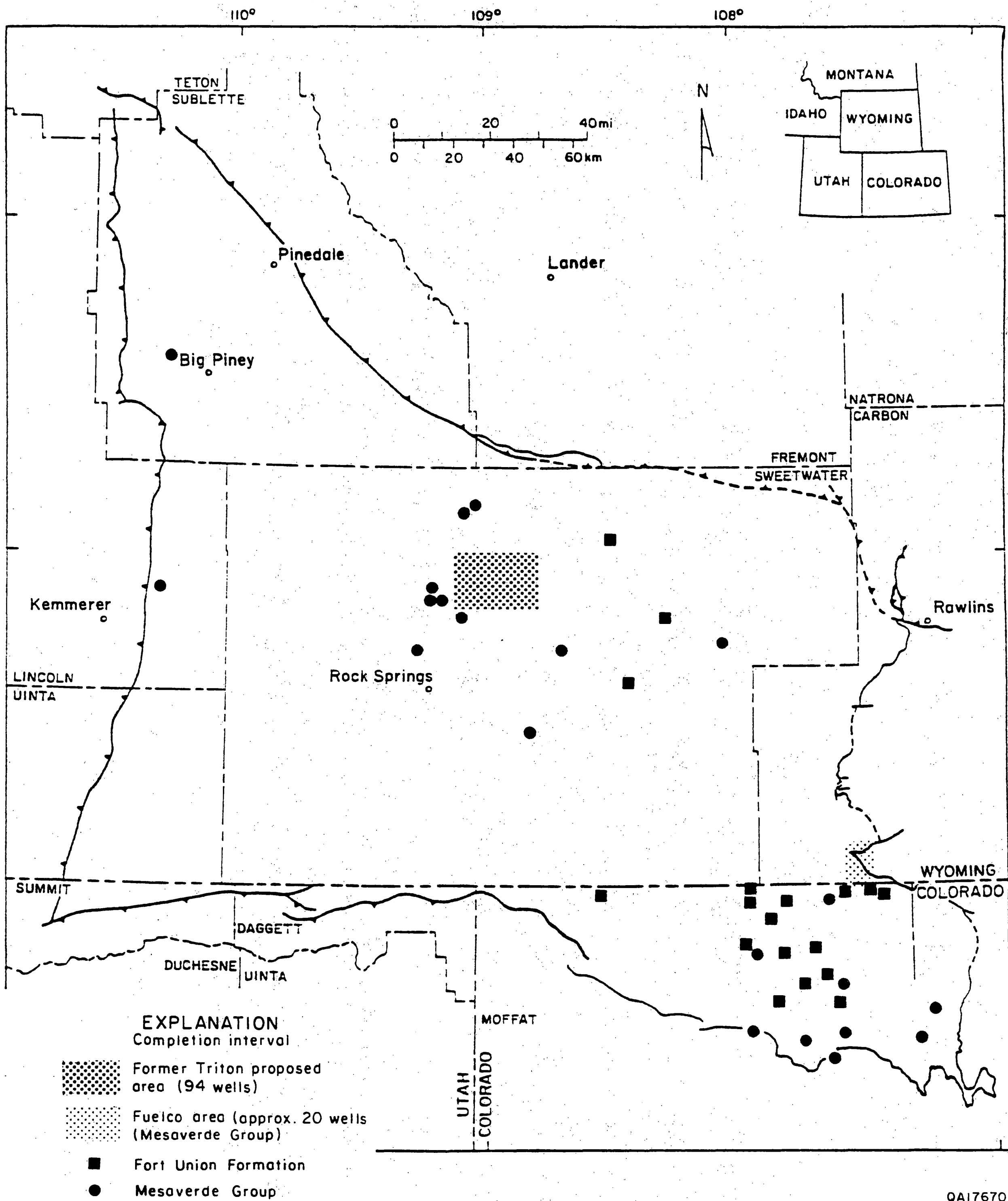


Figure 31. Recent (1990 and 1991) coalbed methane wells in the Greater Green River Basin. Data from Petroleum Information (1990a–k; 1991b–f) and the Gas Research Institute (1990a, b; 1991a).

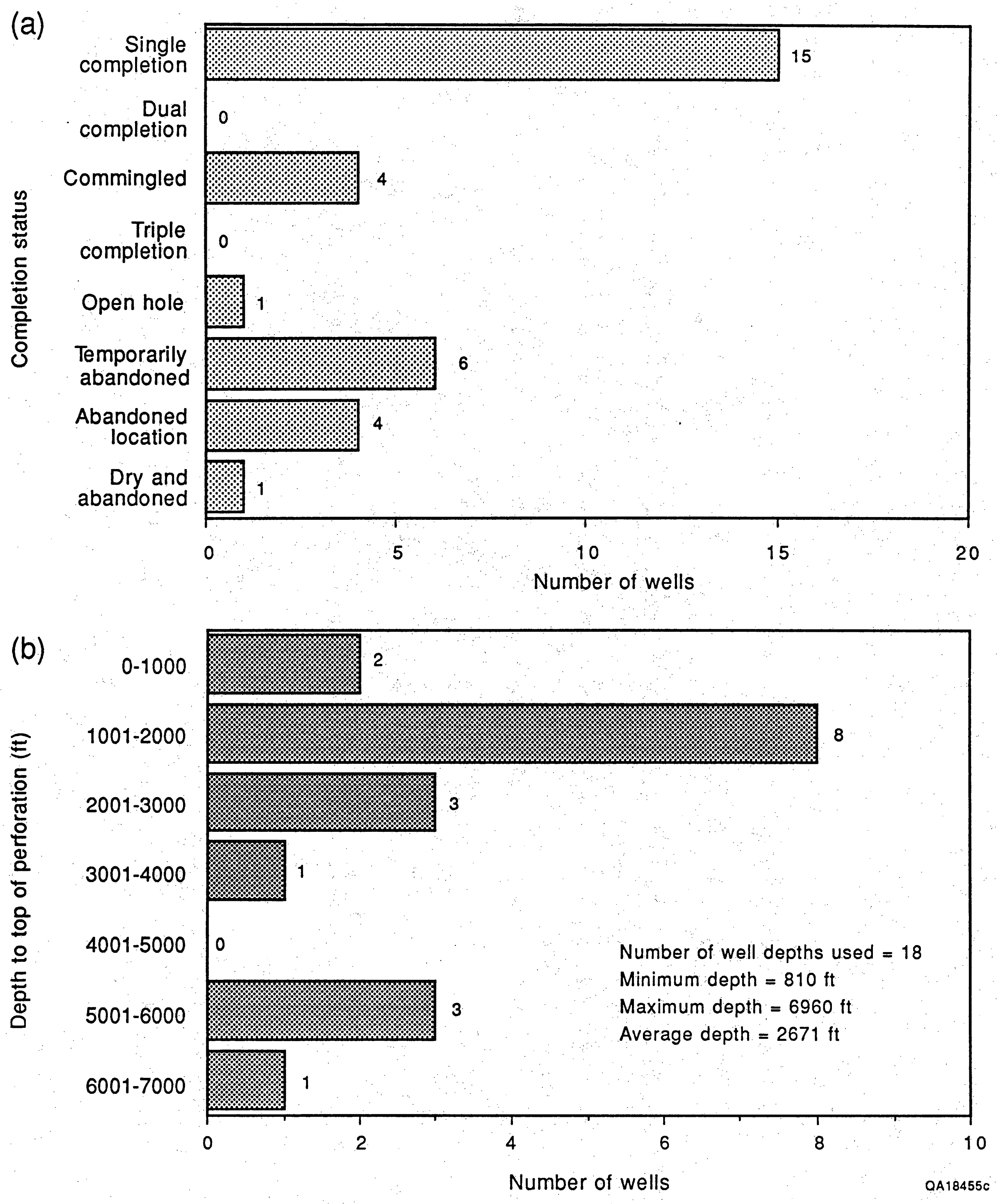


Figure 32. (a) Completion status and (b) depth to top of perforation of coalbed methane wells in the Greater Green River Basin from February 1990 to May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

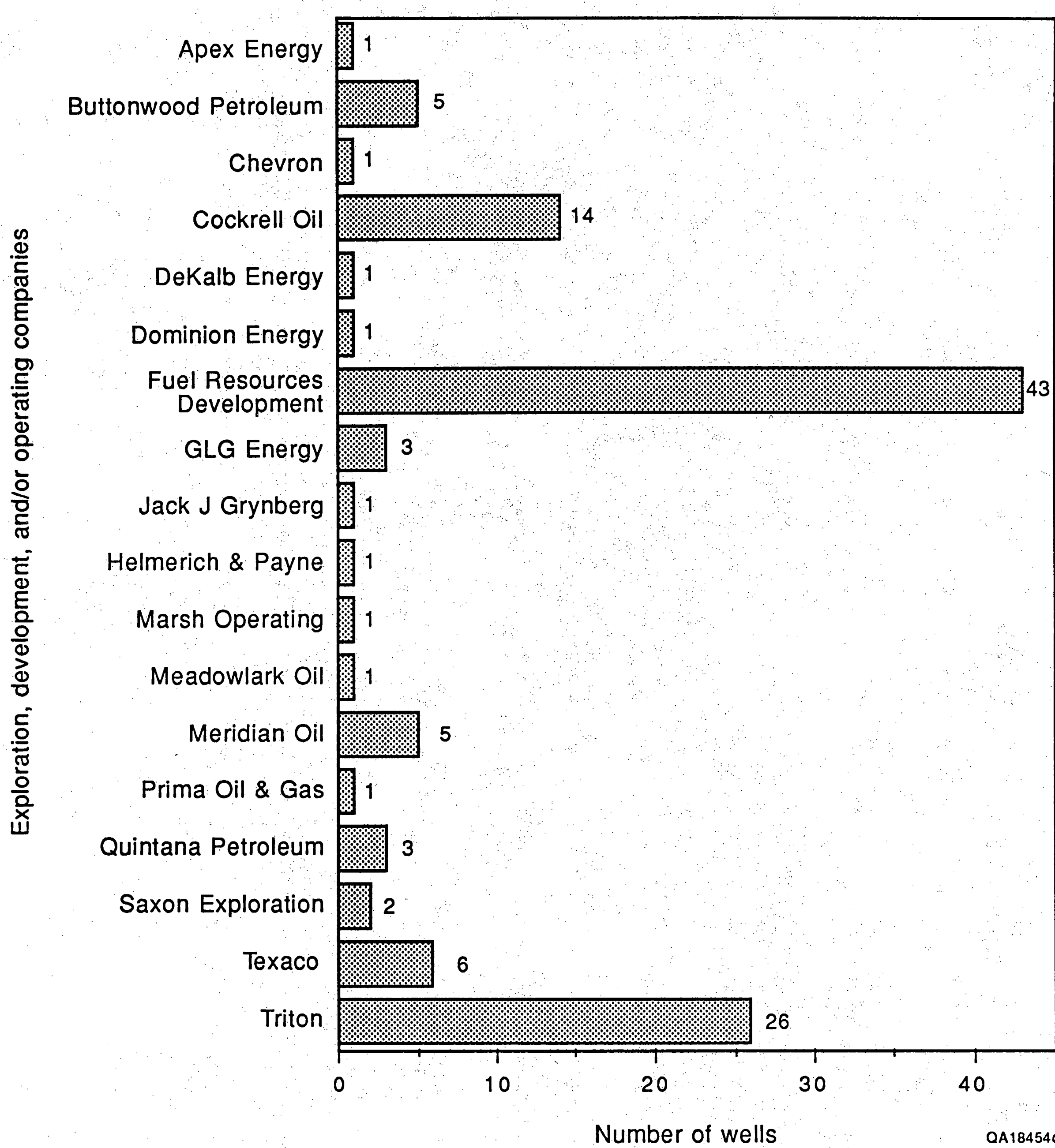


Figure 33. Number of coalbed methane wells drilled by exploration, development, and/or operating companies in the Greater Green River Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Washakie Basin, 9 mi (14.4 km) east of Baggs, Wyoming. One Almond test (total depth of 2,318 ft [707 m]) had an initial potential of 12.7 Mcf/d (359 m^3/d) of gas and 1,799 bbl/d (286 m^3/d) of water (Petroleum Information, 1990i).

Triton had planned to drill 94 wells approximately 30 mi (48 km) northeast of Rock Springs, Wyoming, to test and develop coalbed methane from the Rock Springs Formation at depths of 2,000 to 4,000 ft (600 to 1,200 m). On the basis of tests of Rock Springs coal beds at depths of 3,387 to 3,895 ft (1,033 to 1,188 m) in one well, Triton estimated the initial potential of water to range from 1,200 to 1,600 bbl/d (191 to 254 m^3/d) and then to decline sharply to 200 bbl/d (32 m^3/d) after dewatering (Gas Research Institute, 1991a). However, these wells were not approved because of environmental concerns over surface disposal of produced brines.

Meridian Oil, Inc., is actively drilling for coalbed methane in the Greater Green River Basin; in 1990, the company drilled seven coalbed methane wells in the center of the Sand Wash Basin, 28 mi (44.8 km) northwest of Craig, Colorado. One Mesaverde well, completed at 5,317 ft (1,621 m), had an initial potential of only 5 Mcf/d (141.5 m^3/d) of gas and no water. All five of Meridian's Fort Union wells in the same area were temporarily abandoned after producing "extremely variable" volumes of water but no gas (Gas Research Institute, 1991a). However, completions in Fort Union coal beds at depths of 1,647 to 1,671 ft (502 to 509 m) in Meridian wells just west of Baggs, Wyoming, in the southern Washakie Basin had initial potentials of 550 Mcf/d (15,565 m^3/d) of gas and 330 bbl/d (52 m^3/d) of water (Gas Research Institute, 1989a).

Other noteworthy coalbed methane drilling activity in the Greater Green River Basin includes Fort Union completions (1,831 to 1,865 ft [558 to 569 m]) by Quintana Petroleum Corporation in West Side Canal field, 31 mi (49.6 km) northwest of Craig, Colorado. Initial potentials of these coal beds are 228 bbl/d (36 m^3/d) of water but no gas (Gas Research Institute, 1991a). Dekalb Energy has scheduled a 5,300-ft (1,616-m) test in coal beds in the Adaville Formation, 5 mi (8 km) northwest of Kemmerer, Wyoming, in the overthrust belt. Eagle Oil and Gas, Saxon Exploration, and Buttonwood Petroleum are scheduling exploratory tests in Fort Union and Rock Springs coal beds on the north flanks of the Rock Springs Uplift.

Pipeline Availability

The Greater Green River Basin, serviced by 10 major pipeline companies (table 3), probably has one of the best pipeline infrastructures of all the basins studied in this report. Most of these pipelines are in the Sand Wash Basin, Washakie Basin, Rock Springs Uplift, and the south part of the Green River Basin (fig. 34). Of the 14 coalbed methane fields in the Greater Green River Basin (fig. 28), 5 of the fields produced methane between October 1989 and January 1991 (table 2). All of this methane is assumed to have been collected by the existing pipelines, most likely the Questar pipeline. Because fewer than half of these fields had any production, most of the existing pipelines probably carry the natural gas produced

Table 3. Pipeline companies of the Greater Green River Basin (Tonnsen, 1989).

Pipeline system	Affiliate	Basin or area service
Questar	Mountain Fuel	Green River Basin, Rock Springs Uplift, Washakie Basin, and Sand Wash Basin
NW Central Pipeline Corp.	Williams	Washakie Basin
Trailblazer System	Natural Gas Pipeline Corp. of America, Enrol, and Questar	Green River Basin, Rock Springs Uplift, and Washakie Basin
Stauffer Pipeline	Stauffer Chemical	Rock Springs Uplift
FMC Pipeline	FMC Corp.	Green River Basin and Rock Springs Uplift
Western Gas Processors	McCulloch Interstate Gas Corp. and Midwestern Gas Transmission Co.	Green River Basin
Green River Pipeline	Presidio	Green River Basin
Northwest Pipeline Corp.	Williams	Green River Basin, Rock Springs Uplift, and Sand Wash Basin
Wy-Cal Pipeline Co.	Coastal	Green River Basin
Kern River Gas Transmission Co.	Williams and Tenneco	Green River Basin

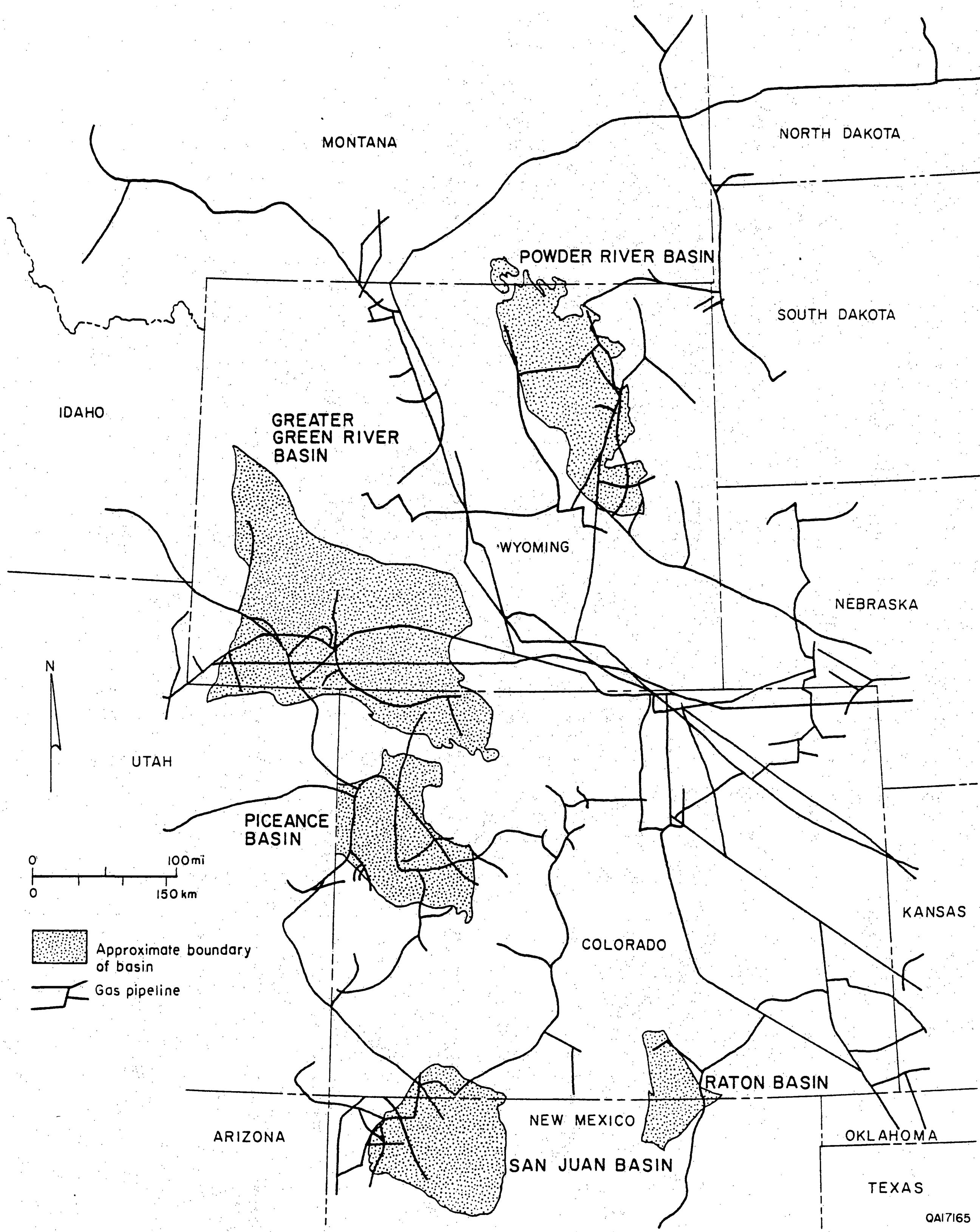


Figure 34. Gas transmission pipelines in the Greater Green River, Piceance, Powder River, and Raton Basins. Revised from Federal Energy Regulatory Commission (1977a, b; 1982), Kent and Porter (1980), and Tonnsen (1989).

from conventional gas reservoirs. Therefore, the coalbed methane fields would need to be connected to existing transmission lines.

Several new pipeline systems are proposed for future construction in the Greater Green River Basin. These pipelines will carry gas to other parts of Wyoming, as well as to Utah, Montana, Colorado, and California. Colorado Interstate Gas Company (CIG) has asked for approval from the Federal Energy Regulatory Commission (FERC) to construct a 223-mi (359-km), $85-million pipeline from eastern Utah, south of Vernal, Utah, through the north part of the Piceance Basin and the center of the Sand Wash Basin, to connect to the main CIG pipeline at Wamsutter, Wyoming (Western Oil World, 1991). FERC gave approval to Trans-Colorado Gas Transmission for a 300-MMcf/d (8.5-MMm^3/d) pipeline to connect the Western Slope gas fields to a pipeline system in northwestern New Mexico (Western Oil World, 1991). The Kern River system, connecting southwestern Wyoming to Bakersfield, California, was begun in January 1991 by Kern River Transmission Company (Petroleum Information, 1991a; Western Oil World, 1991). By early 1992 this $934-million project will transport 700 MMcf/d (19.8 MMm^3/d) through a 904-mi (1,455-km) pipeline. At Opal, Wyoming, this pipeline will connect to the proposed Altamont pipeline, a joint venture by Tenneco Gas, Amoco Canada, Petro-Canada, and Montana Power Company's Entech subsidiary (Petroleum Information, 1991a). This system will carry gas from Canada, Montana, and Wyoming to California markets (Petroleum Information, 1991a).

Coal and Coalbed Methane Resources and Potential

Estimates of coal resources in the basin vary greatly; they range from 77 billion tons (69.9 billion t) of coal at depths of 3,000 ft (915 m) or less (except for the Sand Wash Basin, with coal beds at depths of 6,000 ft [1,800 m] or less) (McCord, 1984) to as much as 302 billion tons (274 billion t). This does not include the Hams Fork Coal field along the Wyoming Overthrust Belt, which is west of the Green River Basin. Estimates of methane content of coal beds in the Greater Green River Basin are inexact because of scarce gas-content data. On the basis of the extremely wide range in reported methane content of coal beds in the Greater Green River Basin (2.9 to 539 ft^3/ton [0.09 to 17.1 m^3/t] in bituminous coal beds and 0 to 100 ft^3/ton [0 to 3.1 m^3/t] in subbituminous coal beds at these depths), McCord (1984) suggested a range of only 150 Bcf (4.25 Bm^3) to more than 30 Tcf (849 Bm^3) of coalbed methane resources. Jones and DeBruin (1990) estimated that the Greater Green River Basin, including the Hams Fork Coal field, contains 1.435 to 28.7 Tcf (40.6 to 812 Bm^3) of coalbed methane resources.

The coal-rank data for the Greater Green River Basin suggest that the east part of the basin (including the Great Divide, Washakie, and Sand Wash Basins) probably has the highest coalbed methane potential based on coal rank alone. Tertiary coal-bearing units (Wasatch and Fort Union) may have good coalbed methane potential in the Washakie Basin and, possibly, the Sand Wash Basin; however, these younger units probably have less coalbed methane potential in the Great Divide Basin because of the lower coal rank in this area. The deeper, Upper Cretaceous coal-bearing units (Lance Formation and Mesaverde Group) probably have a better coalbed methane potential in both the Great Divide and Sand Wash Basins than in the Washakie Basin. Although these Upper Cretaceous coal-bearing formations in the Washakie Basin have reached the semianthracite to anthracite coal ranks and have undoubtedly generated significant volumes of methane, the depth of these formations makes them unacceptable exploration targets.

Coalbed methane potential in the Green River Basin is less than other parts of the basin, judging from the available coal-rank data. Vitrinite reflectance and coal-rank data from this area suggest that only the deepest coal-bearing formations have reached the thermal maturity level to generate significant volumes of methane, although at least some methane has probably been generated from these lower-rank coals. Upper Cretaceous formations in the northwest part of the Greater Green River Basin (Pinedale Basin and the northernmost part of the Green River Basin) may have a better coalbed methane potential because of higher thermal maturity levels. Tertiary coal-bearing formations have reached only the subbituminous stage in these areas. The lower-rank coals around the Rock Springs Uplift have not reached the level of thermal maturity to generate significant quantities of methane; however, high gas content in this area suggests that some early thermogenic and possibly biogenic and/or migrated thermogenic methane may be associated with coal beds within these formations.

A major factor in controlling prospective areas for coalbed methane in the Greater Green River Basin is depth of the coalbed methane reservoir. Judging only from burial depth of coal beds in the basin, the most favorable areas for coalbed methane exploration are limited to relatively shallow fairways (most coal beds are less than 6,000 ft [1,800 m] deep) on the east margin of the basin, the periphery of the Rock Springs Uplift, and the relatively shallow, north end of the Moxa Arch in the northwest part of the basin (fig. 11). Additionally, many parts of the Sand Wash Basin (not shown in fig. 11) contain coal-bearing units (Iles, Williams Fork, Fort Union, and Wasatch Formations) that are less than 6,000 ft (1,800 m) deep.

The second phase of delineating prospective areas for coalbed methane exploration in the Greater Green River Basin is to overlay trends of greatest net thickness and maximum thickness of coal beds onto coalbed depth maps. Although these maps are nonexistent for most of the coal-bearing units in the basin, generalized areas in the basin contain both thick and shallow coal beds with documented thickness trends. For example, thick, north- and northeast-trending coal beds in the Rock Springs and Almond Formations are present on the east margin of the Rock Springs Uplift (figs. 12 and 16). Shallow parts of the Sand Wash Basin contain thick, northeast-trending Williams Fork coal beds, as well as thick, north-trending Fort Union coal beds (fig. 17). In the northwest part of the Greater Green River Basin along the basin margin (north end of the Moxa Arch), thickest Mesaverde coal beds are north-trending and less than 6,000 ft (1,829 m) deep.

PICEANCE BASIN

Geologic Overview

The Piceance Basin in northwestern Colorado (figs. ES-1 and ES-2) is an asymmetric, northwest-trending elongate structural basin of Late Cretaceous to early Tertiary age. The basin is bounded by Uinta Mountain Uplift on the northwest, Axial Arch on the north, White River Uplift on the east, Elk Mountains and Sawatch Uplift to the southeast, Gunnison Uplift and San Juan volcanic field to the south, and Uncompahgre Uplift to the southwest (fig. 35). It is separated from the Uinta Basin to the west by the Douglas Creek Arch. The structural axis is on the northeast side of the basin, adjacent to the Grand Hogback, where it extends for about 150 mi (241 km) northwestward (fig. 35). Width of the basin ranges from 90 mi (145 km) in the north to 20 mi (32 km) in the south. Dips of the strata are gentle on the west and southwest flanks of the basin, but steep along the sharply upturned east flank, adjacent to the Grand Hogback (figs. 35 and 36). The potential coalbed methane reservoirs are contained in Upper Cretaceous (Mesaverde Group) deposits, which cover an area of about 7,225 mi^2 (18,722 km^2). Depth of the coal-bearing Iles and Williams Fork Formations varies from surface outcrop along the basin margin to more than 12,000 ft (3,660 m) along the structural axis of the basin (fig. 35). Approximately 60 percent of the surface area within the Piceance Basin is underlain by Cameo coal (fig. 35) that is less than 6,000 ft (<1,830 m) deep.

Tectonic and Stratigraphic Setting

The following review of the regional structural and stratigraphic setting of the Piceance Basin is adapted from Johnson (1987). In the northeast part of the Colorado Plateau, the Sevier Orogeny (160 to 72 mya) caused east-west horizontal compression during deposition of the Upper Cretaceous and lower Tertiary sediments. East-west folding, contemporary with the orogeny, is marked by a low-amplitude north-south-trending flexure in the area of the Douglas Creek Arch (Quigley, 1965) (fig. 35). Intermittently during the early Cenozoic, the Douglas Creek Arch divided the Uinta and Piceance Basins into two separate basins; at other times (Cretaceous), there was little relief on the Douglas Creek Arch and sediments buried the arch, creating one large basin (Johnson, 1985a, 1986, 1987; Johnson and Finn, 1986). Rapid subsidence at the beginning of the Late Cretaceous caused a major marine incursion (Mancos Shale) (fig. 37), and the Western Interior Seaway covered much of the Rocky Mountain foreland basin. Pulses of orogenic activity in the Overthrust Belt throughout much of the Late Cretaceous caused sediment to be shed eastward into the epeiric sea, resulting in episodic transgression and regression along a fairly narrow area adjacent to the Orogenic Belt (Frontier and Emery Sandstones and Niobrara Formation) (fig. 37). By Campanian time, tectonically induced pulses of clastic sediment had begun to

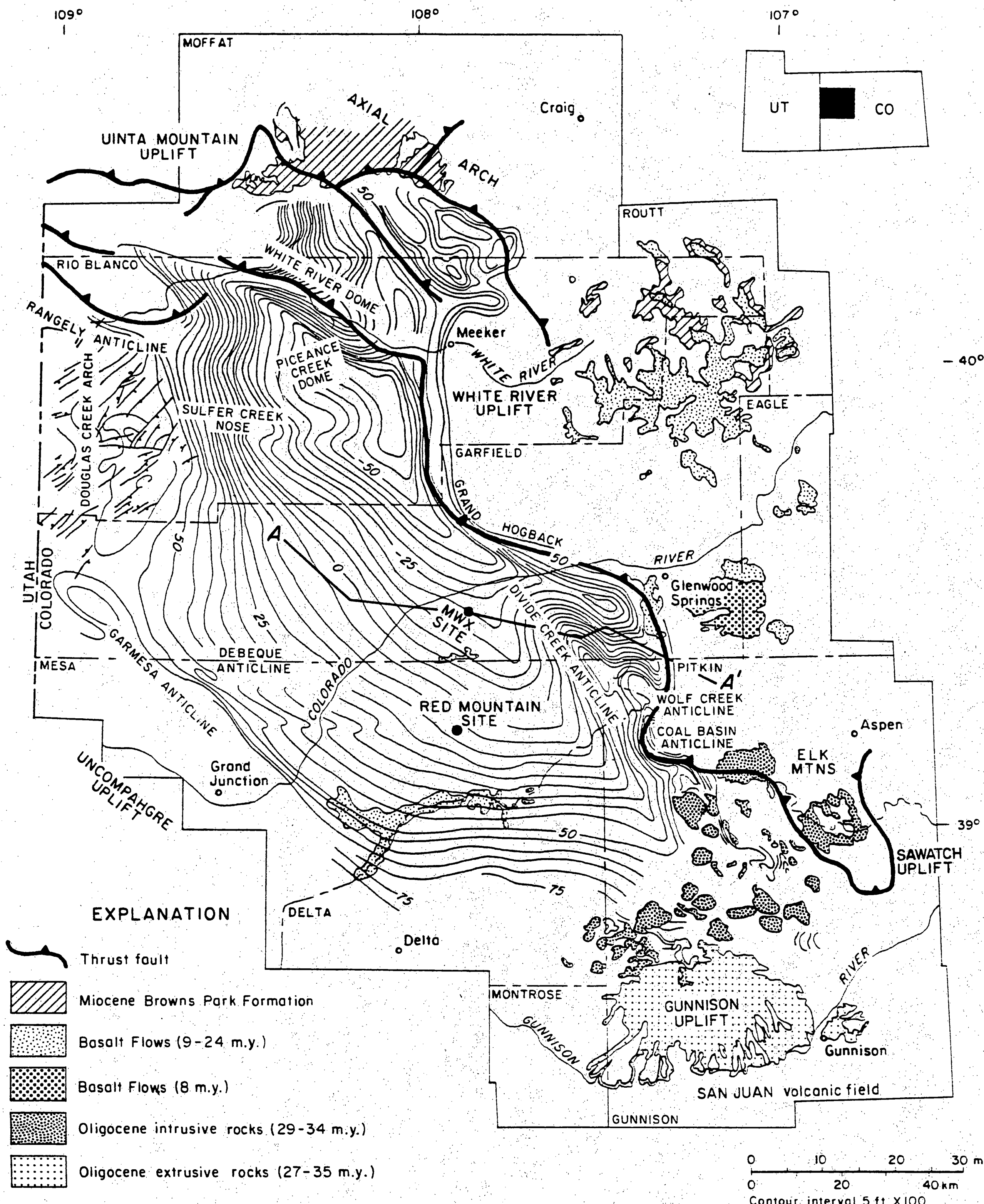


Figure 35. Structure map contoured on top of the Rollins and Trout Creek Sandstone Members, Piceance Basin. Contour interval 500 ft (152 m). Cross section A–A′ shown in figure 36. Modified from Johnson and Nuccio (1986).

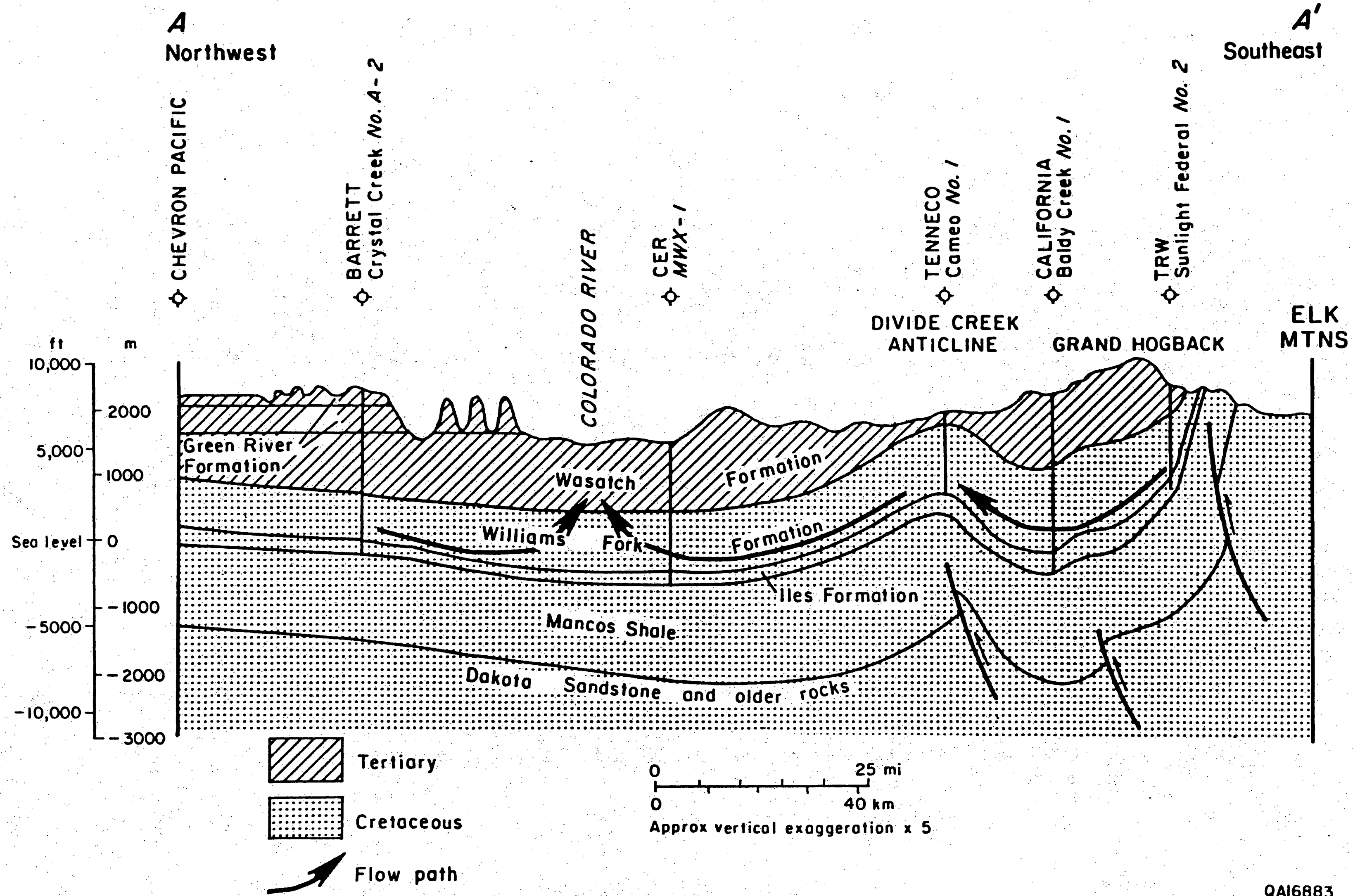


Figure 36. Northwest-southeast cross section A–A′ through Piceance Basin including MWX site. Modified from Law and Johnson (1989). The Fort Union Formation is undifferentiated. Mesaverde Group receives recharge along wet, elevated Grand Hogback. Ground water flows northwest, down hydraulic gradient, converging on the Colorado River valley. Line of section shown in figure 35.

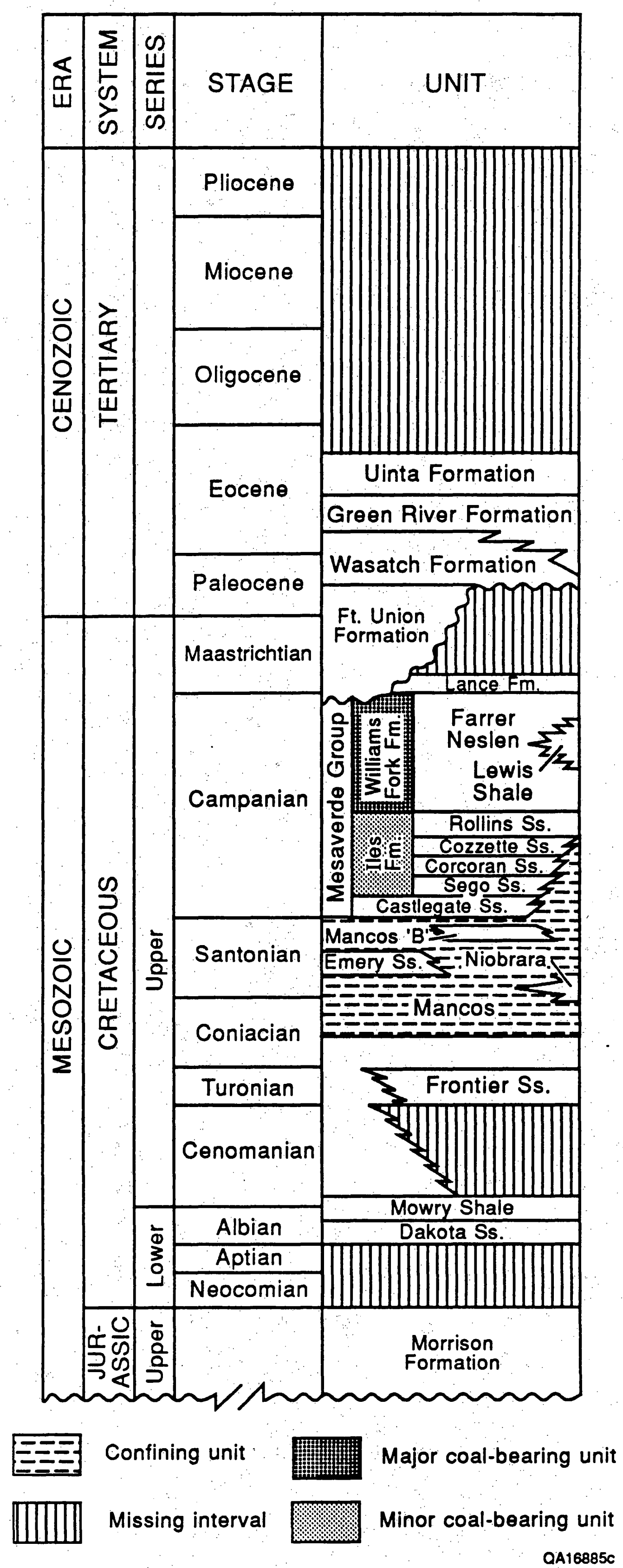


Figure 37. Coal-bearing stratigraphic and confining units in the Piceance Basin. After Rocky Mountain Association of Geologists (1977) and modified from Finley (1984).

advance the shoreline of the epeiric seaway farther to the east (Mesaverde Group; Fouch and others, 1983), and by the beginning of the Maestrichtian, the shoreline had prograded beyond the present-day east margin of the basin, and the Piceance Basin was the site of coastal-plain sedimentation (Lance Formation) (fig. 37).

The Piceance Basin was subsequently bounded by uplifts that formed in the Rocky Mountain foreland region during the Laramide Orogeny approximately 72 to 40 mya (Dickinson and Snyder, 1978; Tweto, 1980a). The onset of the Laramide Orogeny is recorded by an unconformity at the top of the Mesaverde Group and Lance Formation (Johnson and Nuccio, 1986) (fig. 37). Local relief on the unconformity is slight, but thousands of feet of Mesaverde and Lance rocks may have been removed (Johnson and Nuccio, 1986). Subsidence continued through the Paleocene to near the end of the Eocene in the Piceance Basin, during which time, as much as 12,000 ft (3,658 m) of Paleocene and Eocene sediments were deposited. During late Eocene to early Oligocene time, an erosion surface developed across the basin. This surface is similar to late Eocene erosion surfaces that developed in other parts of the Rocky Mountain foreland basins (Epis and Chapin, 1975). In the Piceance Basin, remnants of this surface are still preserved beneath 9.7-million-year-old basalts at a present-day elevation of about 10,000 ft (3,048 m) (Marvin and others, 1966). The amount of section removed is clearly a function of basin subsidence trends and varies from little or no section removed in the basin center, to 2,000–3,000 ft (610–914 m) removed along the slowly subsiding margins of the basin. The erosional surface probably started to develop around the margins of the basin during the latest stages of basin subsidence (late Eocene) and then spread to cover the entire basin after subsidence ceased (Johnson and Nuccio,1986). Below the erosional surface, the thick sequence of lower Cenozoic rocks provided the thermal blanket that led to large quantities of methane generating from source rocks in the Mesaverde.

At the end of the Laramide Orogeny, about 40 mya, basin subsidence ceased and little structural movement or sedimentation occurred in the basin until the Colorado River system began to cut deep canyons, about 10 mya. The late Cenozoic tectonism that affected many areas in Colorado and Utah apparently did not greatly affect the Piceance Basin. Probably the most significant post-Laramide tectonism in the basin was faulting on the Douglas Creek Arch and along the White River Dome (Johnson and Nuccio, 1986).

By 24 mya, the White River Uplift east of the basin was beveled to about the same level as the erosion surface in the Piceance Basin surface. The erosion surface on the uplift is covered by basalts that are from 24 to 8 mya (Larsen and others, 1975). Because basalts probably intercepted recharge, the artesian system that existed earlier along the flank of the uplift was probably destroyed, and Mesaverde outcrops along the Uncompahgre, Uinta, and Sawatch Uplifts were probably reduced to about the same elevation as that of the adjacent basin (Johnson and Nuccio 1986). Only along the south margin of the basin is there evidence that during this period Mesaverde outcrops were significantly higher than the erosion surface beneath the basalts in the Piceance Basin. Even today the Mesaverde is exposed at elevations of almost 12,000 ft (3,658 m) adjacent to Oligocene-age plutons, and even higher outcrops were present before the Recent period of erosion, and an artesian system may have been maintained.

Basin Margin and Intrabasin Uplifts

The northernmost part of the Piceance Basin is almost isolated from the rest of the basin by the White River Dome, a southeast-plunging anticline (fig. 35). Another southeast-plunging anticline, the Rangely Anticline, to the south and west of the White River Dome, forms the northern terminus of the Douglas Creek Arch. Both the Rangely Anticline and the White River Dome are probably subsidiary anticlines related to the eastern terminus of the Uinta Mountain Uplift (Johnson, 1987). These uplifts and anticlines are underlain by west- and southwest-vergent thrust faults (Gries, 1983a; Lorenz, 1985b). The regional stress regime during the Laramide Orogeny was primarily one of east-west compression, but the northwest trend of the White River Dome, Rangely Anticline, and some folds in the Piceance Basin suggest that either an episode of northeast-oriented compression occurred during part of the Laramide Orogeny, such as the late Laramide reorientation of stresses proposed by Chapin and Cather (1981), or the fold trends resulted from reactivation of northwest-trending anisotropy in the crystalline Precambrian basement (Tweto, 1980a; Lorenz, 1985b).

In the southeast part of the basin, three large closed anticlines, the Divide Creek, Wolf Creek and Coal Basin Anticlines, are underlain by deep-seated west- and southwest-vergent thrust faults, extending beneath the Grand Hogback (Grout and others, 1991). The Divide Creek Anticline is cut by several normal faults transverse to the fold trend (Berry, 1959; Grout and others, 1991). The geometry of the Coal Basin Anticline may also have been altered by intrusions of plutons during the Oligocene (Johnson, 1987). Several relatively minor east- and southeast-trending anticlines within the central and north-central Piceance Basin include the Piceance Creek Dome–Sulfur Creek Nose, the De Beque Anticline, and the Garmesa Anticline (fig. 35). These anticlines may have formed as a result of reactivation of faults during the Laramide Orogeny (Stone, 1977). The north part and center of the basin were apparently not intruded by Oligocene plutons (Larsen and others, 1975). The asymmetry of the Rangely and Piceance Creek domes suggests that reverse and thrust faults also underlie these anticlines at depth (Gries, 1983a; Lorenz, 1985b). With the exception of faults that have minor displacement (100 ft [30.5 m]) along the Grand Hogback, thrust faults do not cut the Upper Cretaceous through Eocene rocks (Johnson and Nuccio, 1983, 1986).

Fracture Systems and Cleat in Coal

Two types of natural fracture systems are present in the Piceance Basin: regional fracture sets and fracture sets associated with specific folds or faults (Kelley and Clinton, 1960; Lorenz and Finley, 1987a). Regional fracture sets can be caused by small regional strains in conjunction with high fluid pressures

(Warpinski, 1986), and they can occur in flat-lying, unfaulted rocks (Hancock, 1985). Fractures associated with folds and faults may have regular geometric patterns, but they commonly cut across lithologic boundaries (Hancock, 1985). Several regional fracture sets of different ages are present in the Piceance Basin (Murray, 1967; Amuedo and Ivey, 1978; Smith and Whitney, 1979; Smith, 1980; Jamison and Stearns, 1982; Grout and Verbeek, 1983; Verbeek and Grout, 1983, 1984a, 1984b; and Grout, 1991). The sequentially developed regional joint sets, termed F_1 (oldest) through F_5 (youngest), show consistent style in similar lithologies throughout the basin. Early-formed F_1 (north-northwest-striking) and F_2 (west-northwest-striking) joint sets are present chiefly in the northern two-thirds of the basin, whereas the intermediate-age F_3 (east-northeast-striking) joint set dominates the fracture network in the south half of the basin (Grout, 1991). The F_4 joints (north-northwest-striking) are abundant throughout the basin, but the F_5 joints are sparse, occurring only in Eocene oil shales.

A correlation exists between the orientation of these joints in clastic beds and the orientation of face and butt cleats in coal beds in the Piceance Basin. Cleats occur in the Upper Cretaceous and lower Tertiary coal beds, and most of the cleats are similar in orientation, relative age, and fracture style to the intermediate-age F_3 and F_4 joint sets (Grout, 1991). In the southeast part of the basin, the face cleats trend east-northeastward and are correlated in age and orientation with the F_3 joint set that is both prominent and abundant in the sandstones in this area (fig. 38; Grout, 1991). In the De Beque Canyon and Grand Mesa areas most of the face cleats strike from N60°E to N66°E, and at the Red Mountain site and along the south rim of the basin from N50°E to N86°E (fig. 38). In the center of the basin, however, some cleats are correlated with the older F_1 and F_2 sets (Grout, 1991). Vertical and lateral extrapolation and lateral correlation of joints and face cleats, therefore, cannot be randomly applied throughout the Piceance Basin because differences in lithology, age, and burial and thermal histories may cause fractures of different orientation to form in adjacent and overlying strata (Grout and Verbeek, 1985, 1987; Grout, 1991). However, in this preliminary study, the dominant fracture orientation (F_3 or face-cleat strike) appears to parallel tectonic shortening directions and to remain orthogonal to the Hogback thrust front.

In field-related studies Grout (1991) found that most of the face cleats are unmineralized, orthogonal to bedding and spaced from 0.5 inch (1.27 cm) to more than 12 inches (>30.5 cm) apart, depending on the thickness of the coal layer and the coal rank. The butt cleats are smaller, irregular, curviplanar fractures that commonly abut the face cleats at right angles. Butt cleats strike north-northwestward and are similar in relative age, orientation, and joint style to the regional F_4 fractures in the enclosing host rock (Grout, 1991). Spacing between the butt cleats ranges from less than 0.5 inch (<1.27 cm) to more than 8 inches (>20.3 cm), depending on the coal thickness and rank.

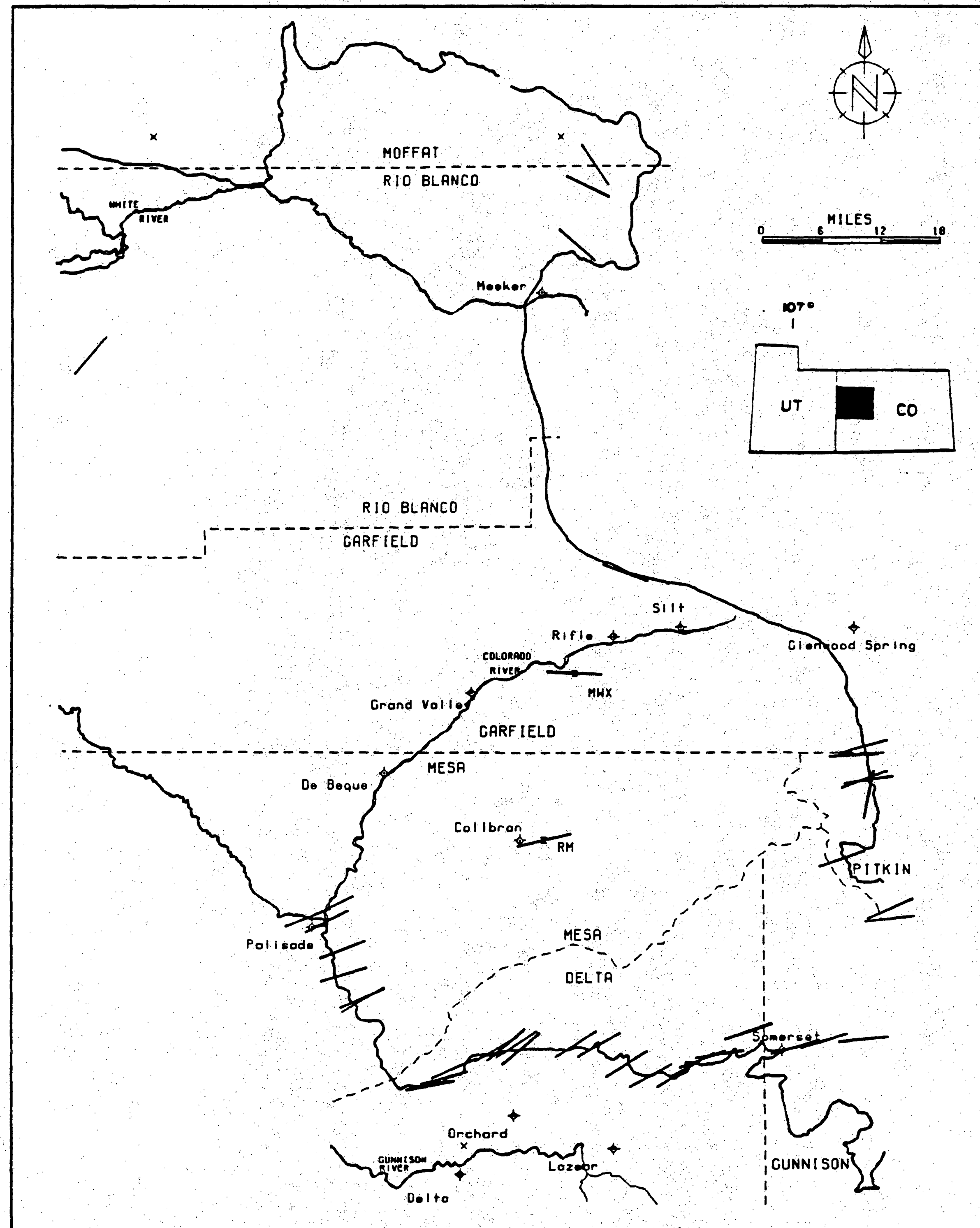


Figure 38. Face-cleat strike, Piceance Basin. Modified from Grout (1991).

Stress Orientation

The Piceance Basin is in the Colorado Plateau stress province (Zoback and Zoback, 1980; 1989), which is surrounded by the Cordilleran Extension stress province (fig. 10). The other stress provinces near the Piceance Basin are the Southern Great Plains stress province and the Mid-Plate stress province. The Colorado Plateau stress province is characterized by west-northwest-trending regional maximum horizontal compressive stress orientations—nearly perpendicular to the surrounding stress direction in the Cordilleran Extension stress province (Zoback and Zoback, 1989; fig. 10). However, focal mechanisms (normal and strike-slip faults) from the Colorado Plateau interior suggest that the stress regime is extensional. The difficulty in interpreting the tectonic stress fields in this region and understanding their apparent variations may be related to low differential horizontal stresses, as suggested by the absence of major thrust faulting within the Colorado Plateau interior (Zoback and Zoback, 1980). This interpretation is consistent with in situ stress measurements in the Piceance Basin that indicate all three principal stresses are approximately equal to lithostatic pressure (Wolff and others, 1974; Bredehoeft and others, 1976). The significance of this for cleats in coal beds is that prediction of fluid flow pathways and anisotropy may be complicated.

Local data, however, demonstrate that the maximum horizontal stress in the Piceance Basin is west-northwest, approximately orthogonal to that in surrounding regions (Zoback and Zoback, 1989). Horizontal stress orientations have been determined at the Multiwell (MWX) site where the maximum horizontal stress (S_{hmax}) and high-permeability anisotropy is west-northwestward (Clark, 1983; Towse and Heuze, 1983; Johnson, 1985a; Lorenz and others, 1986; Branagan and others, 1987; Lin and Heuze, 1987; Lorenz and Finley, 1987a and b; Lorenz, 1991), consistent with the regional stress pattern. However, local deviations of minifrac strike from the expected average regional fracture azimuth have been reported from the Piceance Basin (Towse and Heuze, 1983; Lorenz, 1991). Lorenz (1991) documented mean strike and dip of measured fractures in Mesaverde sediments between N81°W and N84°W, from oriented cores at the Slant Hole Completion Test site (SHCT-1; located about 600 ft [185 m] south of the MWX site). Warpinski (1986), who modeled the stress history of the Piceance Basin, had results that compare favorably with present-day stress data at the MWX site. These results suggest that the geologic history of the basin had an influence on current stress magnitude and orientation. It is therefore speculated that these variations in present-day in situ stress anisotropy may reflect remnant strains from the Sevier and Laramide east-west compressive stress fields (Wolff and others, 1974; Warpinski and Teufel, 1987).

Stratigraphic and Depositional Setting of Coal-Bearing Formations

More than 5,000 ft (>1,520 m) of intertonguing marine (shoreface and shelf) and nonmarine (deltaic and fluvial) sediments were deposited in the Piceance Basin during the Late Cretaceous. Intertonguing of these deposits resulted from southeastward progradation of the shoreline, which was interrupted by northwestward shoreline retreat during periods of relative sea-level rise (Spieker, 1949; Young, 1955; Weimer, 1960; Gunter, 1962; Warner, 1964). The coal-bearing sequences have been interpreted as wave-dominated linear clastic shoreline (Young, 1966) or as deltaic (Collins, 1970, 1976).

The principal coal-bearing units are associated with regressive sequences in the Mesaverde Group (fig. 39). Thin coal beds in the Black Diamond Group overlie the regressive Cozzette and Corcoran Sandstones of the Iles Formation. The thickest coal beds in the basin occur in the Cameo Coal Group (Bowie Shale Member, Williams Fork Formation), which overlies the regressive Rollins Sandstone. Other thin coal beds occur in the Coal Ridge Group (Paonia Shale Member, Williams Fork Formation) and in the upper, undifferentiated part of the Williams Fork Formation (McFall and others, 1986; Lorenz, 1989).

Black Diamond Coal Group (Iles Formation)

Coal beds in the Black Diamond Coal Group overlie multiple sandstones in the Iles Formation in the Piceance Basin (fig. 39). These sandstones (Corcoran and Cozzette Members) are each 0 to 220 ft (0 to 67 m) thick and contain individual sandstone units that range from less than 20 to 100 ft (<6 to 30 m) thick (fig. 40) Iles sandstones exhibit excellent continuity (50 by 75 mi [80 by 120 km]) and are described as blanket sandstones (Lorenz, 1983a). They trend northeastward and intertongue to the southeast with the marine Mancos Shale and to the northwest with coal-bearing deposits (Young, 1955; Warner, 1964; Finley, 1985). Iles paleoshorelines advanced to the southeast; the greatest advance of the shoreline was approximately 30 mi (48 km) from the southeast margin of the basin (Warner, 1964; Lorenz, 1983a).

Black Diamond coal beds are interbedded with carbonaceous mudstones or thin sandstones (Madden, 1985). Two to four Black Diamond coal beds typically occur in the 300-ft (90-m) thick interval (McFall and others, 1986). Although individual coal beds are commonly less than 10 ft (<3 m) thick, some are as thick as 20 ft (6 m) (fig. 40) (Madden, 1985). Net-coal thickness is also commonly less than 10 ft (<3 m), but in the northeast part of the basin it is more than 30 ft (>9 m). Black Diamond coal beds are absent in the west and southeast parts of the basin (fig. 41a) (McFall and others, 1986). Black Diamond net-coal thickness trends contain both strike- and dip-parallel elements (McFall and others,1986). The Black Diamond Coal Group contains the most deeply buried Mesaverde coal beds in the Piceance Basin; in Rio Blanco and Garfield Counties, these coal beds are more than 12,000 ft (>3,660 m) deep (fig. 41b).

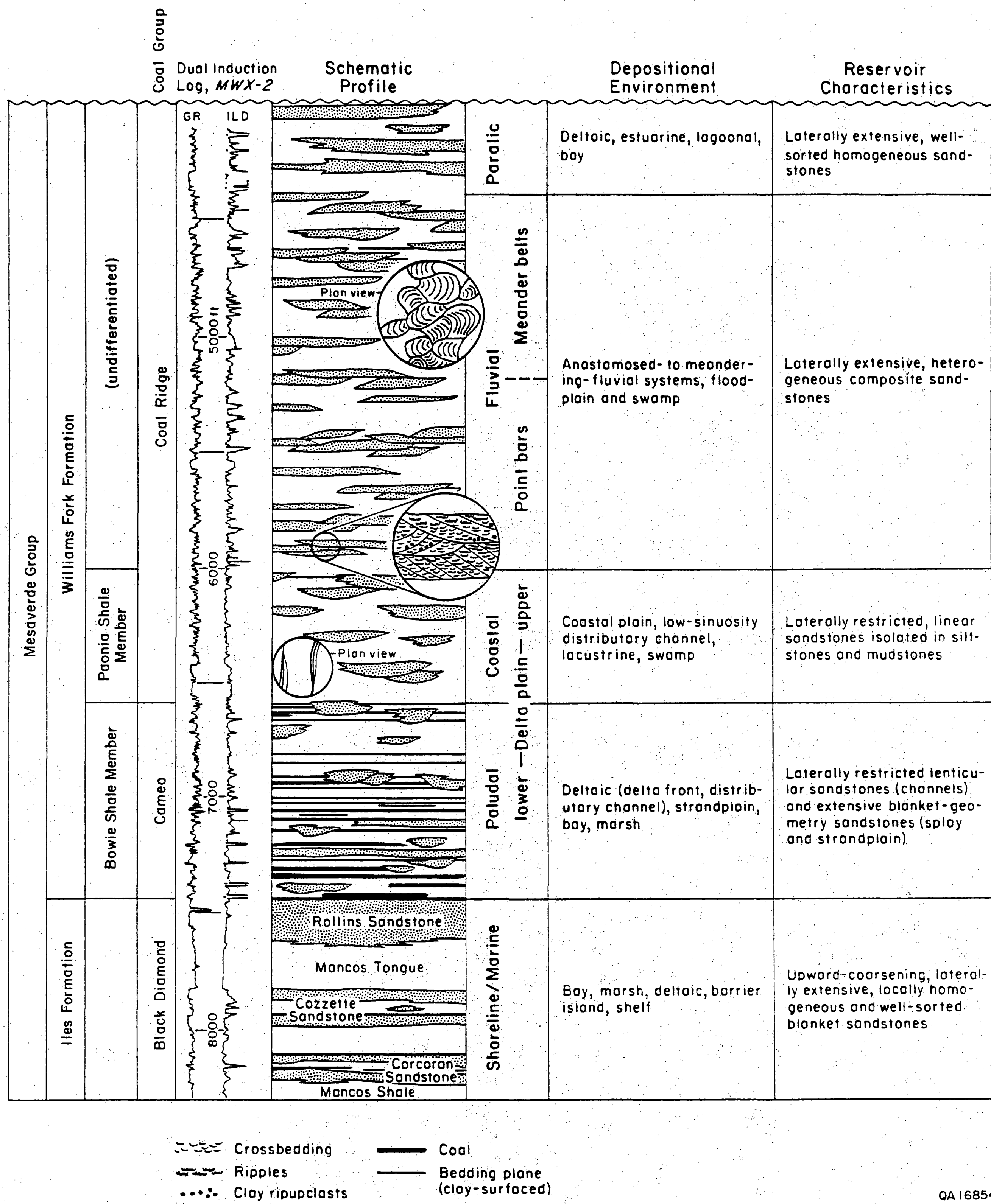
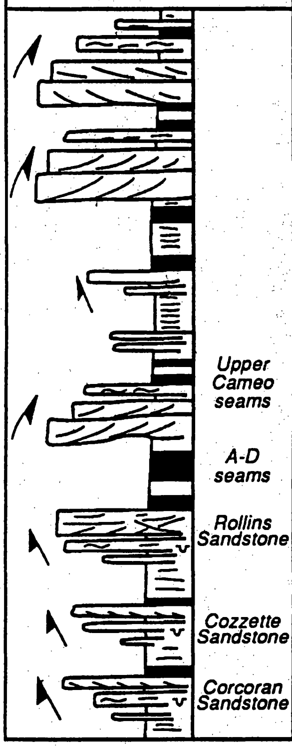


Figure 39. Stratigraphic column of principal coal-bearing units in the Piceance Basin. Modified from Lorenz (1983b).

SCHEMATIC SECTION



COAL GROUP	FORMATION (Depositional system)	COAL BEDS: Thickness (ft) Average	COAL BEDS: Thickness (ft) Maximum	COAL BEDS: Thickness (ft) Net	COAL BEDS: Number	COAL BEDS: Continuity	SANDSTONES: Thickness (ft) Maximum	SANDSTONES: Thickness (ft) Net	SANDSTONES: Continuity	COAL-SANDSTONE RELATIONS
Coal Ridge	UPPER WILLIAMS FORK FORMATION (Fluvial)	<5	3	<20 ?	2-5	Very discon-tinuous	50-70	—	Discontiuous, lenticular sandstones	Most coal beds eroded by channels; coal bed pinchouts common
	MIDDLE WILLIAMS FORK FORMATION (Coastal plain)	<10	5-10	20-40	Up to 10	Moderate	20-30	—	Isolated lenticular sandstones	Poorly documented: coal beds probably dip-elongate and split or pinch out against channel ss.
Cameo	LOWER WILLIAMS FORK FORMATION (Delta plain)	10	20-35	30-60	Up to 12	Most continuous in basin	35	70-110 at Rifle Gap, Co.	Good, parallel to depositional dip	Continuous coal beds directly overlie marine Rollins Ss.; some coal beds split and override lenticular, distributary-channel ss.
Black Diamond	ILES FORMATION (Wave-dominated shoreline)	5-10	10-20	15-30	2-4	Continuous, parallel to depositional strike	>50	100-150	Excellent, parallel to depositional strike	Major coal beds directly overlie marine, blanket sandstones; minor coal beds overlie crevasse-splay sandstones

SEDIMENTARY STRUCTURES AND ROCK TYPES

- v Burrows
- Upward-coarsening
- Upward-fining
- Planar bedding
- Ripples
- Cross bedding
- Coal

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Figure 40. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in the Piceance Basin.

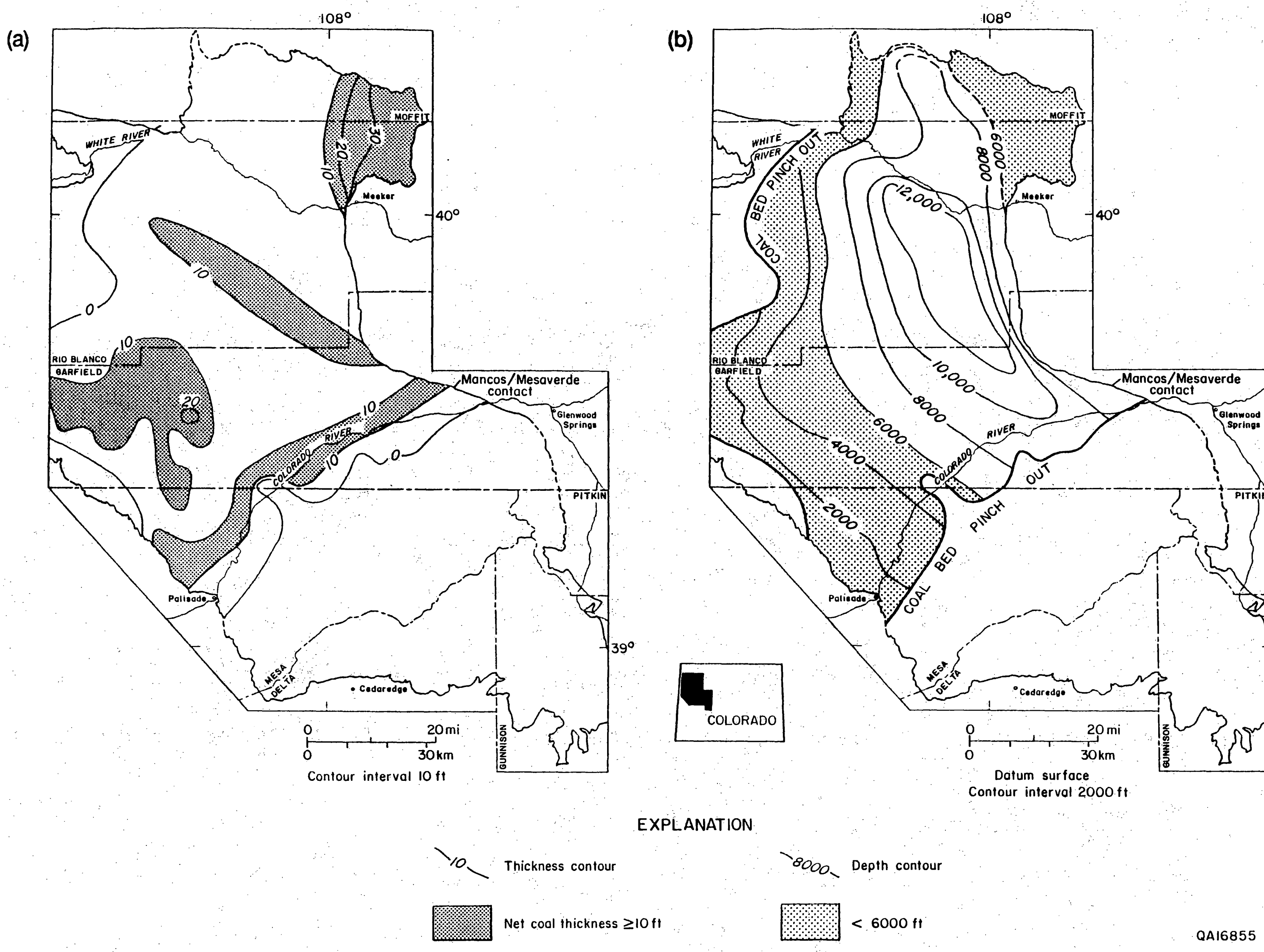


Figure 41. (a) Net-coal thickness of the Black Diamond Coal Group. (b) Depth to base of the Black Diamond Coal Group. Modified from McFall and others (1986).

Sandstones of the Iles Formation and coal beds in the Black Diamond Group were deposited in a regressive, wave-dominated coastal setting (Young, 1966; Collins, 1976; Finley and Ladwig, 1985; Madden, 1985; Johnson, 1987; Lorenz, 1989). Marine deposits (shelf, shoreface, barrier-island, strandplain, delta-front, bay-lagoon, and tidal-inlet) in the Iles Formation grade northwestward (updip) into nonmarine deposits (coastal-plain marsh and swamp, fluvial, and floodplain). Thickest Black Diamond coal beds occur landward (northwest) of thick, northeast-trending barrier-strandplain sequences (Finley and others, 1983) (fig. 42). These coal beds override the barrier-strandplain sandstones and pinch out seaward (southeastward) into transgressive mudstones (Finley, 1985).

Cameo and Coal Ridge Coal Groups (Williams Fork Formation)

The Williams Fork Formation overlies the Iles Formation and contains two coal groups (Cameo and Coal Ridge). The Cameo Coal Group, which contains the thickest and most continuous Williams Fork coal beds, corresponds to the Bowie Shale Member of the Williams Fork Formation, whereas the Coal Ridge Coal Group includes the Paonia Shale Member and an upper, undifferentiated member of the Williams Fork Formation (fig. 39).

Cameo Coal Group (Bowie Shale Member)

The Cameo Coal Group (Bowie Shale Member) overlies the Rollins Sandstone (upper Iles Formation) and consists mostly of shale, interbedded with sandstone and coal beds. Fresh-water swamps in the Cameo Coal Group formed landward of wave-dominated shoreline deposits of the Rollins Sandstone (Lorenz, 1983b, 1989). These swamp deposits were superimposed over the Rollins Sandstone with continued progradation of the shoreline, resulting in thick, continuous coal beds forming directly over the Rollins Sandstone (Collins, 1976). Peat formation was periodically interrupted by transgressions; some lower Cameo coal beds are overlain by nearshore-marine and distributary-mouth bar sandstones that formed the platform for subsequent peat swamps (Bell and Wiman, 1985). These sandstones in the Cameo Coal Group are thin, averaging less than 20 ft (<6 m) and occur in strike-elongate sheets crosscut by lenticular sandstone pods, 370 to 520 ft (113 to 159 m) wide (fig. 40) (Lorenz, 1989). Maximum-sandstone thickness is 35 ft (11 m) and net-sandstone thickness is 70 to 110 ft (21 to 34 m) in the eastern part of the Piceance Basin (Madden, 1985; Lorenz, 1989).

Coal beds in the Cameo Coal Group comprise 10 to 15 percent of the Bowie Shale Member (Lorenz, 1989). Thickness of individual seams is as great as 35 ft (11 m) on the eastern margin of the basin (Collins, 1976). Net-coal thickness ranges from less than 20 ft (<6 m) in the southeast part of the basin to more than 60 ft (>18 m) in the east-central part of the basin (fig. 43a) (McFall and others, 1986). At the Red Mountain site in northeastern Mesa County at least five Cameo coal beds have a net thickness of more than 50 ft (>15 m). The thickest coal bed (D coal seam, 16 to 20 ft [4.9 to 6.1 m] thick) at the

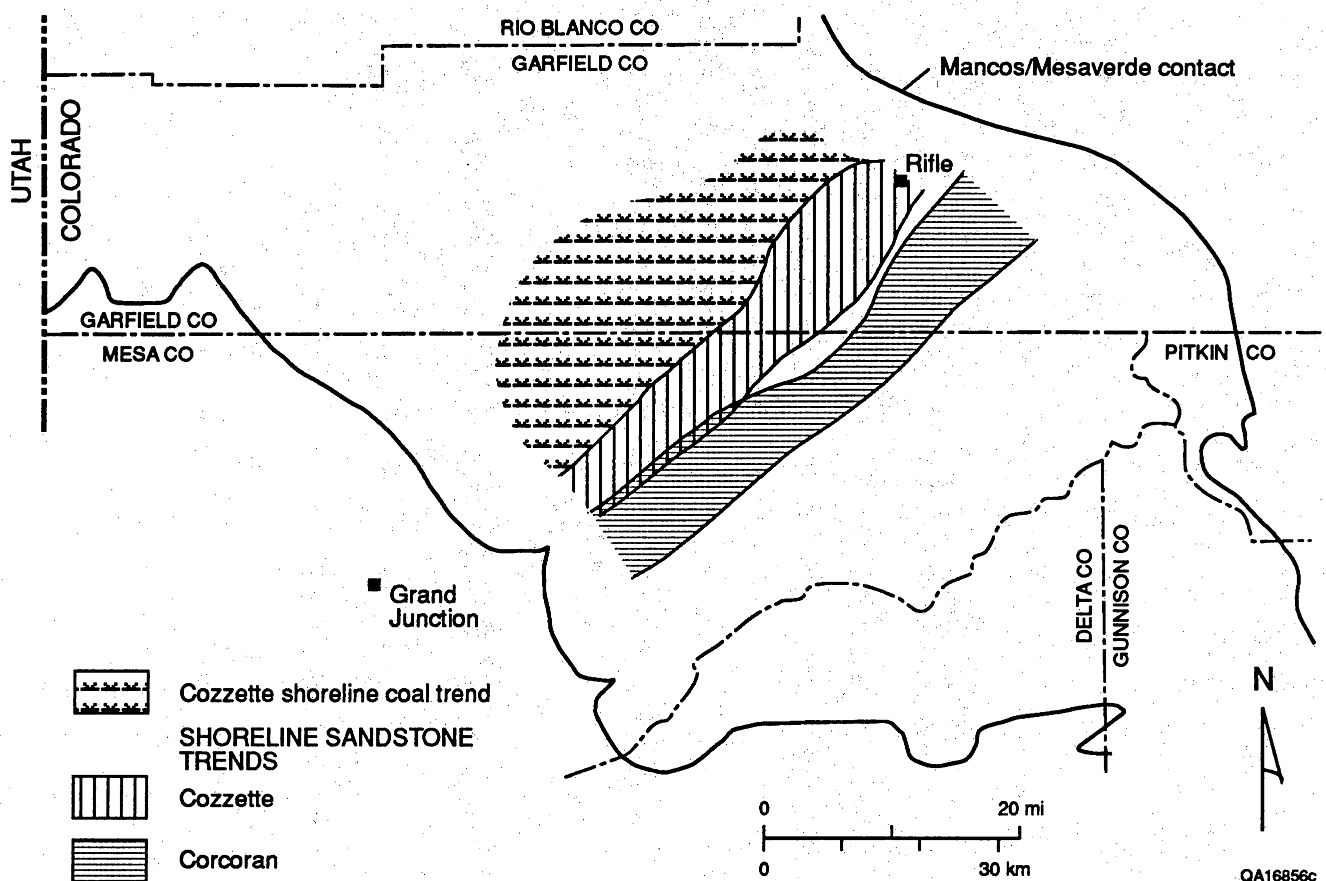


Figure 42. Shoreline trends of the Corcoran and Cozzette Sandstones in the southeast part of the Piceance Basin. Thick northeast-trending coal beds formed landward (northwest) of these shoreline trends. Modified from Finley and others (1983).

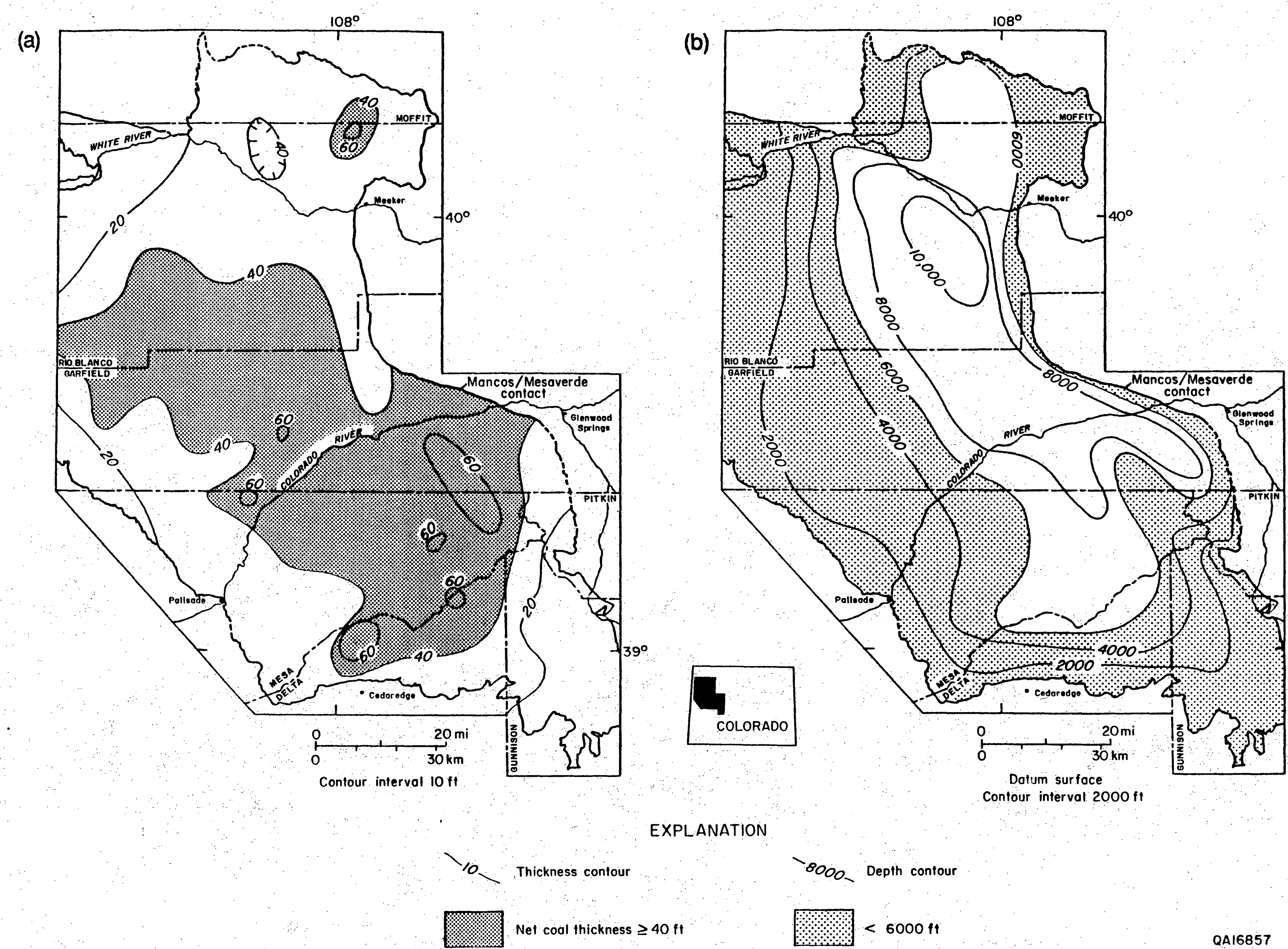


Figure 43. (a) Net-coal thickness of the Cameo Coal Group. (b) Depth to the base of the Cameo Coal Group. Modified from McFall and others (1986).

Red Mountain site is in the lower part of the Bowie Shale Member, 50 to 150 ft (15 to 46 m) above the A coal seam (12 ft [3.7 m] thick) that directly overlies the Rollins Sandstone (Bell and Wiman, 1985). Lower Cameo coal beds at the Red Mountain site extend for more than 4 mi (>6.4 km) parallel to depositional strike (Bell and Wiman, 1985). However, these coal beds are locally truncated by cross-cutting channel-sandstone deposits (Lorenz, 1983b). Coal-seam splits also occur along margins of channel sandstones. Collins (1976), for example, reports a 35-ft (11-m) thick coal seam in the east part of the basin splitting into four thinner coal seams over a distance of less than 3,000 ft (<1,200 m). Cameo net-coal thickness decreases to less than 20 ft (<6 m) in the southeast part of the Piceance Basin because of seaward (southeastward) pinch-out of the underlying Rollins Sandstone platform into the marine Mancos Shale (Murray and others, 1977).

Although coal beds in the Cameo Coal Group are thickest and most continuous in the Piceance Basin, they are more than 6,000 ft (>1,800 m) deep throughout much of the basin, and as much as 10,000 ft (3,048 m) deep in the northeast part of the basin (fig. 43b). However, Cameo net-coal thickness of more than 40 ft (>12 m) is present in the center and southeast part of the basin, where these coal beds are less than 6,000 ft (<1,800 m) deep (McFall and others, 1986).

Lower Coal Ridge Coal Group (Paonia Shale Member)

The Paonia Shale Member, in the lower part of the Coal Ridge Coal Group and approximately 600 ft (180 m) thick in the east part of the Piceance Basin (Collins, 1976), overlies the Bowie Shale Member (fig. 39). The Paonia Shale Member consists of continuous shales interbedded with isolated, lenticular sandstones and thin, discontinuous coal beds (fig. 39) (Lorenz, 1983a). The sandstones are 12 to 60 ft (3.7 to 18 m) thick, 400 to 600 ft (120 to 180 m) wide, and linear in plan view (fig. 40) (Lorenz, 1989).

Coal beds in the Paonia Shale Member vary greatly in thickness over relatively small distances (Collins, 1976). Individual coal beds are commonly less than 5 ft (<1.5 m) thick (Lorenz, 1983b) and occur only in the southeast part of the basin, where as many as 10 coal seams have a net thickness as much as 40 ft (12 m) (McFall and others, 1986). The coal beds are also discontinuous, as a result of having formed in restricted swamps between low-sinuosity distributaries on a low-gradient coastal plain (Lorenz, 1989). These coal beds commonly contain siltstone partings of overbank (levee and splay) origin.

Upper Coal Ridge Coal Group (Upper Williams Fork Formation)

Thin, minor coal beds of the Upper Coal Ridge Coal Group are present in the upper, undifferentiated member of the Williams Fork Formation. Upper Coal Ridge coal beds are discontinuous and commonly grade into carbonaceous shales interbedded with mudstones and lenticular sandstones (figs. 39 and 40). These limited coal beds contain insignificant methane resources. Upper Williams Fork coal beds were deposited in stable floodplains between laterally restricted, anastomosing rivers (Payne and Scott, 1982) or in unstable, restricted floodplains between meandering streams (Lorenz, 1983a). Thickest coal beds (as much as 3 ft [1 m] thick) occur locally in the middle of the undifferentiated Williams Fork Formation near Rifle Gap, Colorado, in the east part of the basin (Horn and Gere, 1959).

Hydrology

In the Piceance Basin, the Mesaverde Group is the coal-bearing hydrostratigraphic unit and is confined below by the marine Mancos Shale. The Rollins Sandstone, a tight-gas sandstone, is an aquitard and confines the Williams Fork Formation below (fig. 37). A major regional unconformity separates the Mesaverde Group from the overlying lower Tertiary Fort Union and Wasatch Formations. The Mesaverde Group is exposed on the north, south, and east margins of the basin (Tweto, 1979); on the west it extends into the Uinta Basin. Annual precipitation is highest along the elevated southeast and east margins, and presumably recharge enters the basin mainly along those margins (fig. 19). Lesser amounts of recharge are thought to enter the basin along the drier southwest and north margins. Relatively fresh water may extend 5 to 10 mi (8 to 16 km) from the outcrop in the marine regressive cycles and 10 to 15 mi (16 to 24 km) in the fluvial part of the Mesaverde Group (Johnson, 1987). However, except for the Coal Basin Mine on the southeast and the Roadside Mine in the Colorado River valley, dry underground mines further indicate that the basinward extent of fresh water is limited (Merry and Larsen, 1982; Kuhn, 1990; C. M. Tremain, personal communication, 1991). The Mesaverde Group probably contains some water near the basin's margin, except for the lowermost part of the Mesaverde (Johnson, 1987). Numerous wells have recovered minor volumes of water from drill-stem tests throughout the basin (Nuccio and Johnson, 1981). The Mesaverde Group is water-bearing on the White River Dome (Johnson, 1987).

Regional ground water flows basinward down the regional topographic gradient and structural dip (figs. 19 and 35). In the south part of the basin, the potentiometric surface slopes to the northwest toward the Colorado River (Treckman and others, 1962). Presumably the topographically low Colorado River valley is a regional discharge area where Mesaverde ground water converges and turns upward (fig. 36). Grand Valley, the basin's most productive coalbed methane field, and five other fields are located in this area of ground-water convergence and upward flow. Such areas in other basins favor the accumulation of hydrocarbons (Tóth, 1980).

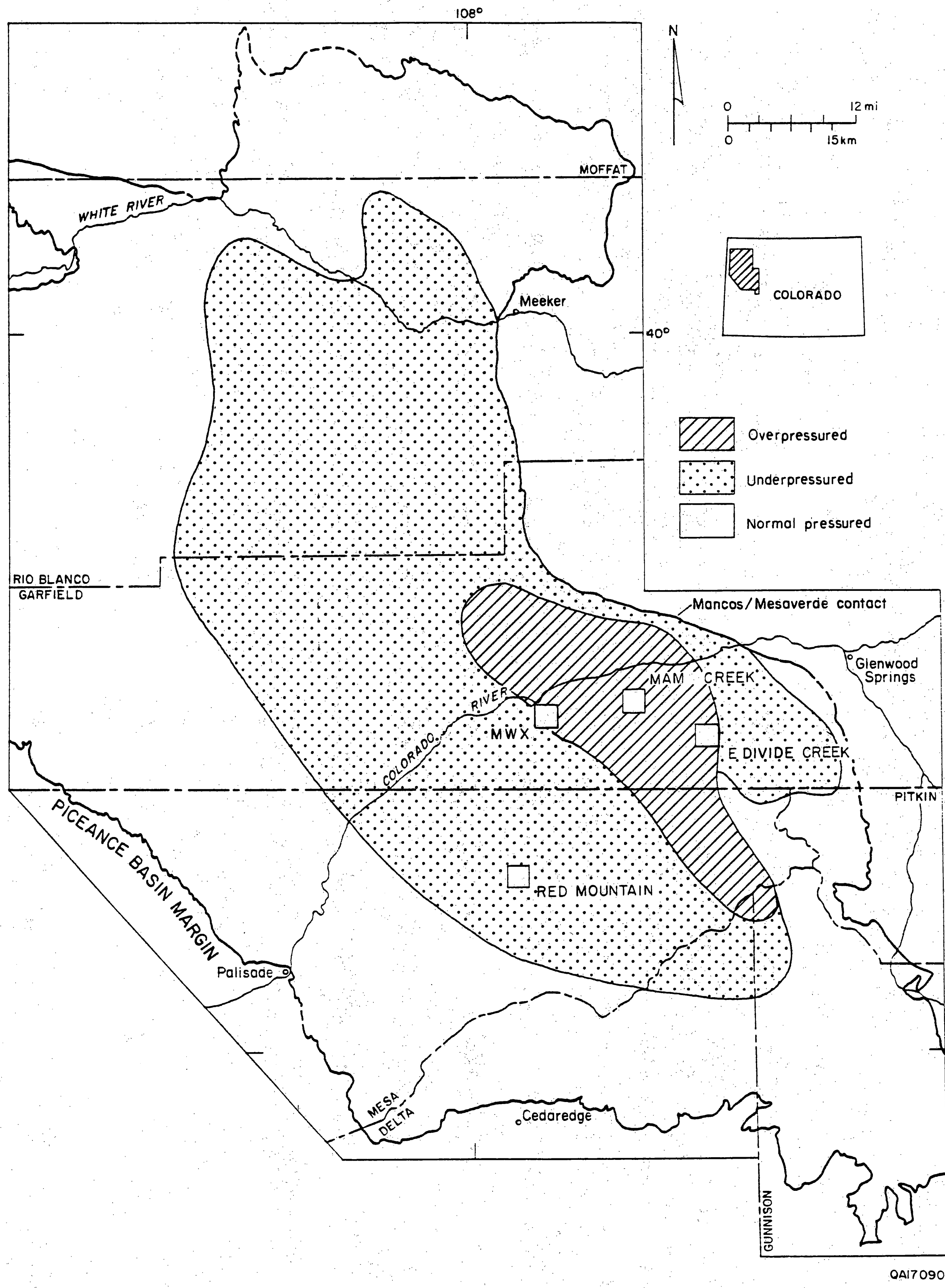


Figure 44. Map of pressure regime in the Mesaverde coals. Modified from McFall and others (1986). Mesaverde coals are overpressured, underpressured, and normally pressured. Highest coal permeabilities from artesian overpressured coal seams; lowest from underpressured and hydrocarbon overpressured coal seams.

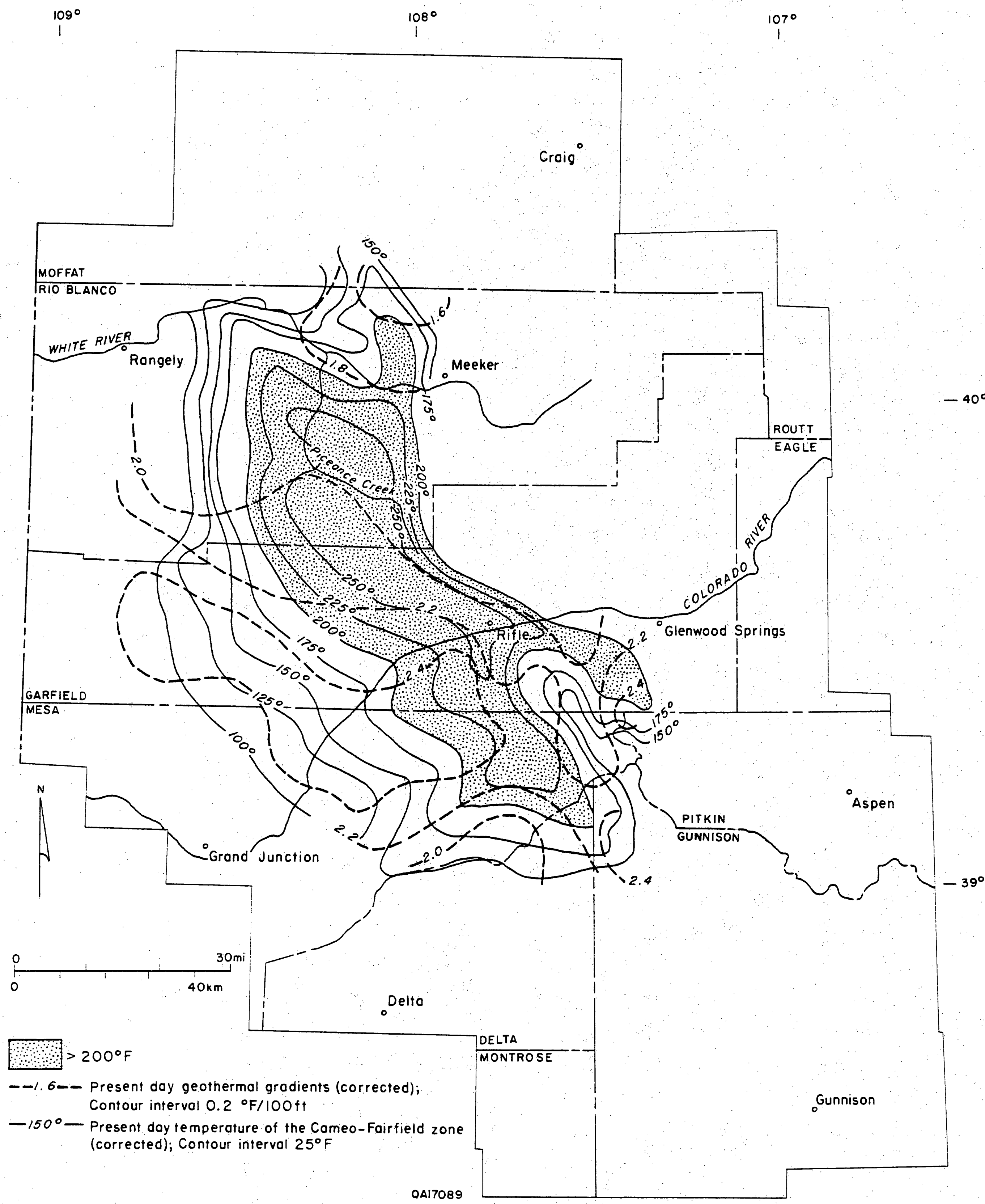


Figure 45. Present-day Mesaverde temperatures on top of the Rollins and Trout Creek Sandstones. Modified from Johnson and Nuccio (1986).

In the Piceance Basin, the pressure regime is complicated. Mesaverde coals are overpressured, underpressured, and normally pressured (fig. 44). Overpressure reflects either artesian conditions (Kaiser and others, 1991b) or basin subsidence and active gas generation (Law and Dickinson, 1985; Spencer, 1987). Artesian aquifers commonly have high permeability; they require confinement and are recharged over their wet, elevated outcrop areas. The aquifers may or may not contain hydrocarbons, and the pressure gradients rarely exceed 0.6 psi/ft (13.57 kPa/m) (Spencer, 1987). Hydrocarbon-related overpressuring is predicated on low-permeability (<0.1 md) and active generation of gas. Moreover, most reservoirs and source beds capable of hydrocarbon generation have minimum present-day temperatures of approximately 200°F (93°C). The top of geopressure has a minimum vitrinite reflectance of 0.5 to 0.7 percent (Spencer, 1987).

The overpressured area is located in the east-central part of the basin and covers about 11 townships (~400 mi^2 [~1,036 km^2]). It extends from outcrop on the southeast, northwest along the Divide Creek Anticline to just beyond the Colorado River (figs. 35 and 44). Pressure gradients in Cameo coal beds exceed 0.5 psi/ft (11.3 kPa/m). At East Divide Creek structurally enhanced permeability is 16 md. Coalbed wells flowed low-chloride (<200 mg/L), Na-HCO_3 type water at rates as high as 1,200 bbl/d (191 m^3/d) (Jeu and others, 1988). Artesian overpressuring is supported by low-chloride waters, flowing wells, direct connection with a topographically high recharge area on the southeast, and formation temperatures of less than 200°F (<93°C). Confinement is provided locally by shales and low-permeability sandstones. The absence of a regional confining layer and/or low permeability serves to limit artesian overpressuring to a relatively small part of the basin. Moreover, recharge from the basin's wettest margin on the southeast (figs. 19 and 36) may be limited by flow perpendicular to the face cleat (fig. 38).

Overpressuring at the MWX site is probably hydrocarbon related, where gas is the pressuring fluid rather than water, as is the case at Divide Creek. Formation temperatures exceed 250°F (121°C) (fig. 45), and active gas generation is inferred. At Mam Creek, very low permeability, gas-saturated coal seams are also overpressured. The Rollins Sandstone at MWX has a fresh-water equivalent head of approximately 12,000 ft (3,660 m) (Spencer, 1989), which is equivalent to the highest elevation of Mesaverde outcrops (~12,000 ft [~3,660 m]) at the southeast basin margin. However, oxygen-isotope data suggest the presence of modified meteoric water and possible hydraulic communication with the artesian system up hydraulic gradient to the southeast. Formation water from the coal zone in one MWX well has a $\delta^{18}O$ value of −7.5‰ (Pitman and Dickinson, 1989).

Overpressure is surrounded by an extensive underpressured region that almost coincides with an area of formation temperatures that exceed 200°F (93°C) (figs. 44 and 45). According to the hydrocarbon model of overpressure, this area should be overpressured. Presumably, it was previously overpressured and deteriorated to an underpressured state upon cooling, as the result of uplift and erosion after the Eocene gas-generating event (Johnson and Nuccio, 1986). Moreover, the gas-generative potential of the organic matter quite possibly was destroyed by higher temperatures of the earlier thermal event (Law and Dickinson, 1985). Significant quantities of gas are probably not being generated today.

Underpressure extends to the basin's east margin along the Grand Hogback, where some repressuring should have occurred. The Mesaverde is exposed along that margin positioned to receive recharge (fig. 19), and the face cleat is oriented basinward to promote recharge (fig. 38). The presence of underpressure near the outcrop means low permeability or limited recharge, or both. Low-permeability strata are too tight to receive and transmit appreciable recharge basinward and thus they remain underpressured. Underpressured coal seams at Red Mountain had permeabilities of a few microdarcys. Although thrust faults do not cut Upper Cretaceous rocks along the Grand Hogback, thrust faulting on the east may limit the area of Mesaverde outcrop available for recharge or may offset coal seams to block the flow of water basinward (figs. 35 and 36). Only from the southeast margin of the basin does repressuring appear to have occurred.

In summary, very low permeabilities have been reported from the underpressured parts of the basin, whereas the highest permeabilities come from overpressured coal seams, where artesian overpressuring is postulated. The area of artesian overpressuring is small and so is the area of high permeability. The basin is dominated by underpressure and hydrocarbon-related overpressure, indicative of low permeability. Thus, low permeability may ultimately limit the coalbed methane potential of the Piceance Basin.

Coal Rank and Gas Composition

Coal Rank

A coal-rank map for the Cameo Coal Zone that used over 60 measured and 25 calculated vitrinite reflectance values (R_m) was prepared using data from Tremain and Toomey (1983), Bostick and Freeman (1984), Johnson and Nuccio (1986), Decker and Horner (1987), and Johnson and Rice (1990), along with proximate analysis data from Murray and others (1977), Tremain (1983), and Tremain and Toomey (1983). Coal-rank maps for the Coal Ridge and Black Diamond Coal Groups were modified from McFall and others (1986) from Cameo coal-rank trends. Data on volatile-matter content (dry ash-free basis; VM_{daf}) were converted to equivalent vitrinite reflectance values using an equation determined from a cross plot of vitrinite reflectance and volatile matter data from the Mesaverde Group (fig. 46a). Although the high correlation coefficient (r=0.978) is due partly to sample distribution, the good relation between volatile matter and vitrinite reflectance has been demonstrated in previous studies (Teichmüller, 1971; van Gijzel, 1982; Meissner, 1984; Scott and others, 1991a). Calculated vitrinite reflectance values fall within 0.1 percent of the measured vitrinite reflectance values (fig. 46b) and provide the basis for using this equation to convert proximate data into equivalent vitrinite reflectance values.

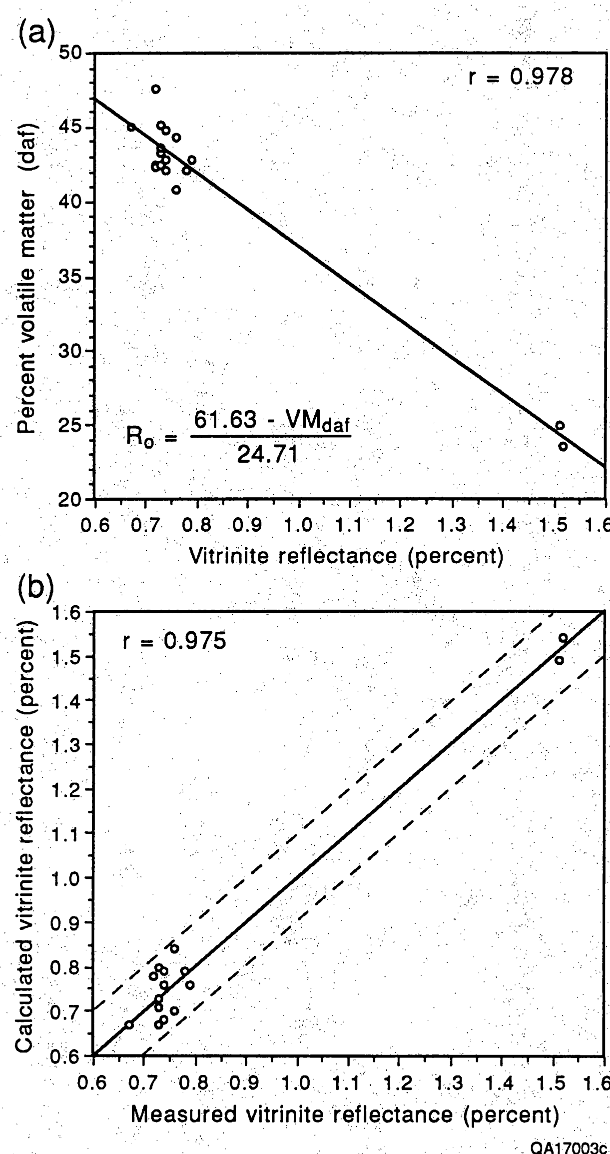


Figure 46. (a) Relation between vitrinite reflectance and volatile matter content of Mesaverde coal beds in the Piceance Basin; the equation determined by linear regression analysis was used to calculate vitrinite reflectance values from proximate data. (b) Calculated vitrinite reflectance values fall within 0.1 percent of the measured values.

Coal rank in the Cameo Zone ranges from high-volatile C bituminous in the northeast, west, and south margins of the basin to semianthracite in the east part of the basin, along synclinal axes (fig. 47). Coals adjacent to Tertiary intrusives have reached the anthracite stage, and some graphite has been reported locally (Collins, 1976). Coal rank generally parallels the structure of the Rollins and Trout Creek Sandstones in the southern two-thirds of the basin but cuts across structure in the north part of the basin (Johnson and Nuccio, 1986). The highest-rank coal does not coincide with the present-day deepest part of the basin (figs. 35 and 47). High rank coincides with regional underpressure and overpressure (fig. 44). Changes in coal rank and vitrinite reflectance contour spacing are abrupt in the Piceance Basin. The significance of these abrupt changes for coalbed methane producibility is unknown.

High-volatile A and B bituminous coals are located along the Grand Hogback Monocline and in the northeast, west, and south parts of the basin. Coal rank increases abruptly away from the Grand Hogback into low-volatile bituminous and semianthracite along the synclinal low between the basin margin and the Divide Creek Anticline. High-volatile B bituminous coals are located on the crest of the Divide Creek and Wolf Creek Anticlines in the east part of the basin (figs. 35 and 47). The presence of lower-rank coals on the Divide Creek and Wolf Creek Anticlines suggests that these structures either formed or were forming before the main stage of coalification and are related to Laramide Orogenic events and not to Tertiary volcanic activity (Johnson and Nuccio, 1986). Medium-volatile bituminous to high-volatile B bituminous coals are located on the Coal Basin Anticline (figs. 35 and 47). The presence of higher-rank coals along the west part of the anticline suggests that these coals may have been buried deeper and were subsequently uplifted after the main coalification stage. Quartz monzonite at a depth of 4,300 ft (1,311 m) below the Coal Basin Anticline was reported by Johnson and Nuccio (1986), suggesting that the anticline may have formed in response to the emplacement of an Oligocene pluton. Igneous rocks were not encountered in deep tests (more than 11,000 ft [>3,354 m]) on the Divide Creek and Wolf Creek Anticlines (Johnson and Nuccio, 1986). Coal rank increases southwestward from the Divide Creek Anticline into semianthracite in the inferred position of a northwest-trending syncline. Coal rank gradually decreases away from the synclinal axis to high-volatile C bituminous along the west and south margins of the basin (fig. 47).

High-volatile C and B bituminous coals are also located north of the White River Dome (figs. 35 and 47). Isoreflectance lines in this part of the basin plunge in a direction opposite to that of the sharply upturned structure on the underlying Rollins (Trout Creek) Sandstone (fig. 17 of Johnson and Nuccio, 1986). This is the only location in the basin where this relationship occurs. Uplift of the White River Dome began before the end of the Cretaceous and continued to rise through the Eocene (Johnson and Nuccio, 1986). Uplift and thrusting of Cameo coals before and during coalification resulted in lower-rank coals north of the thrust zone (figs. 35 and 47).

The Coal Ridge Group is confined to the southeast quarter of the basin. Coal rank ranges from high-volatile B bituminous to low-volatile bituminous (fig. 48). The lowest rank coals are located along the

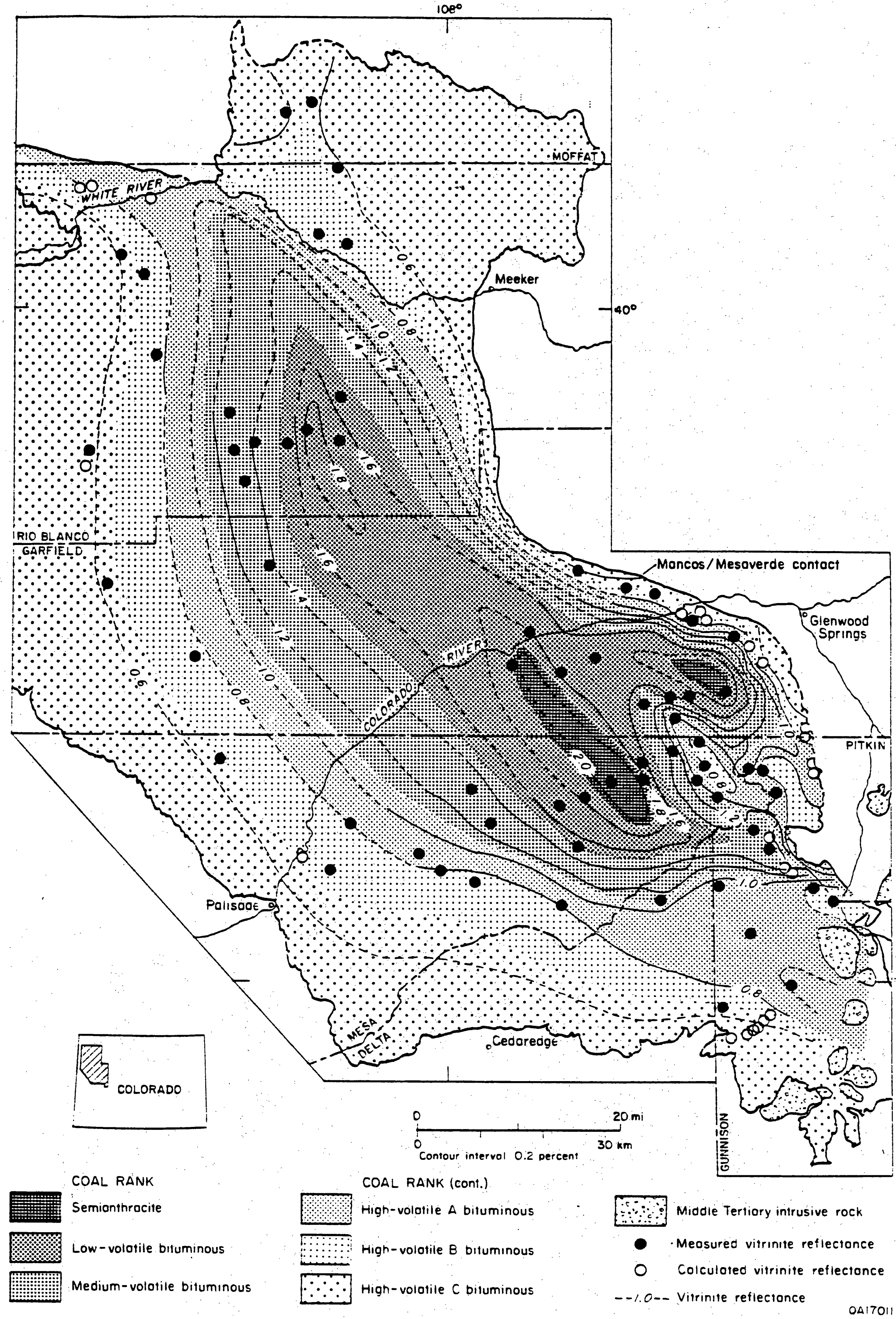


Figure 47. Coal rank of the Cameo Coal Group from measured and calculated vitrinite data. Map based on data from Tremain (1983), Tremain and Toomey (1983), Bostick and Freeman (1984), Nuccio and Johnson (1986), and Decker and Horner (1987).

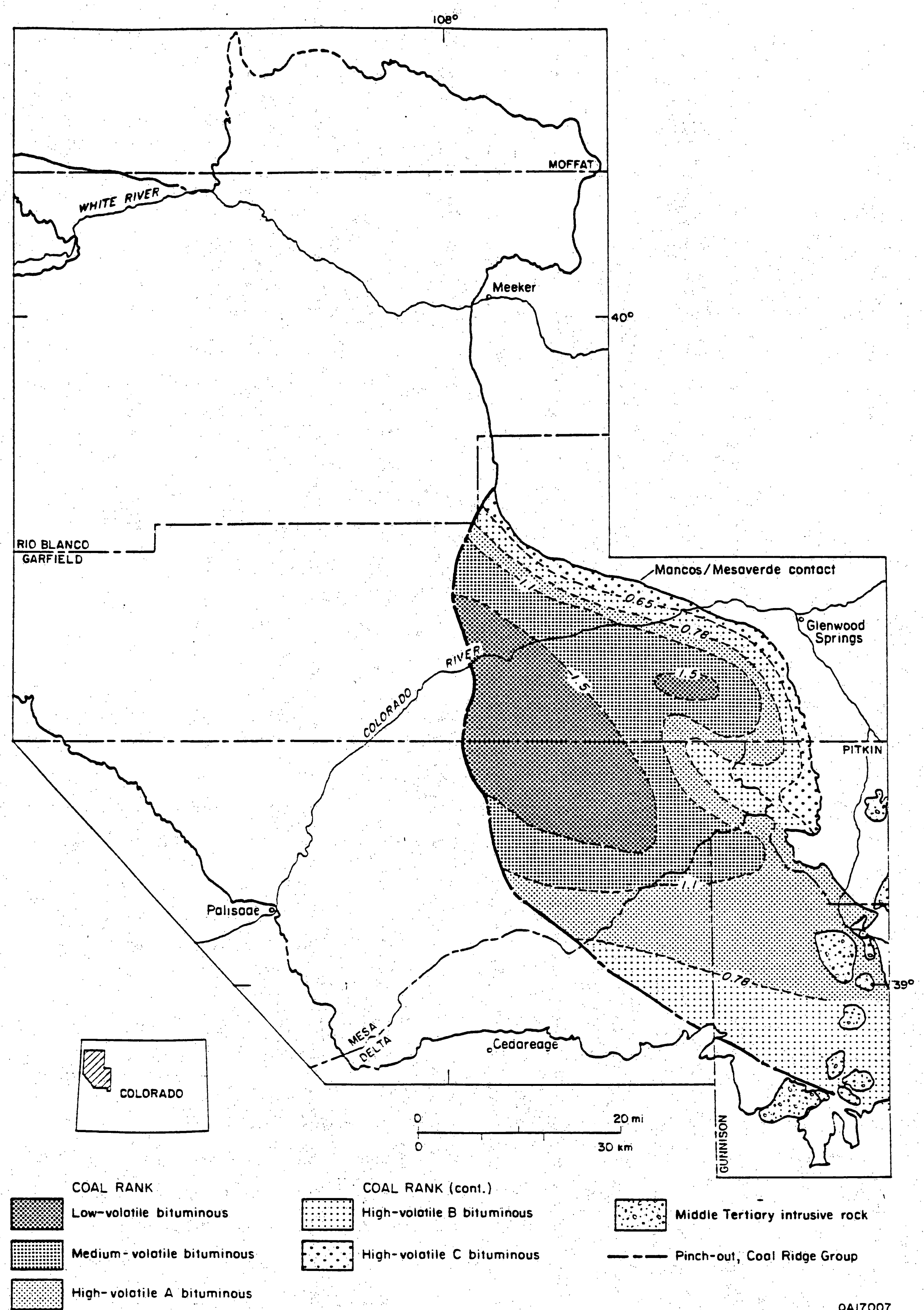


Figure 48. Coal-rank map of the Coal Ridge Group. Modified from McFall and others (1986).

Grand Hogback Monocline and on the Divide Creek and Coal Basin Anticlines. The highest-rank coals are associated with northwest-trending synclinal axes. Coal rank in the Black Diamond Coal Group ranges from semianthracite, near the southern pinch-out of the coal beds, to high-volatile C bituminous in the northeast and south parts of the basin (fig. 49). A northwest-trending band of low-volatile bituminous coals covers a large part of the basin. Coal rank decreases gradually westward and northward and abruptly eastward toward the Grand Hogback Anticline. The highest-rank coals occur in the deeper parts of the basin (McFall and others, 1986). Coal-rank trends in both the Coal Ridge and Black Diamond Groups parallel rank trends observed in the Cameo Coal Group.

Johnson and Nuccio (1986) summarized the timing of coalification on the basis of geologic relationships. Coal rank along the south margin of the basin was established before Oligocene volcanic activity began and probably before the Eocene ended. Lower-rank coal along the Grand Hogback and the Divide Creek and Coal Basin Anticlines indicates that these structures formed or were forming before the main stage of coalification and that coal rank has probably not increased significantly since the late Eocene because of erosion and, subsequently, less overburden. The high rank of coals in the southeast part of the basin suggests that coals throughout the basin attained their present-day rank from burial heating before the end of the Eocene. According to Johnson and Nuccio (1986), the effects of Tertiary thermal events, such as Oligocene-age plutonism, in the south part of the basin have not significantly affected coal rank. However, Rice and Johnson (1989) suggested that increased coal rank in the south part of the basin may be due to higher paleotemperatures.

Gas Composition

Terrestrially derived organic matter has been traditionally thought of as a source of chemically dry gases with little or no potential to generate liquid hydrocarbons or chemically wet gases. However, recent studies on coalbed gas composition have shown that coalbed gases may contain a significant proportion of wet gas components (Hanson, 1990; Scott and others, 1991a, b and c). The ratio of methane (C_1) to methane through pentane gas components (C_1–C_5) can be used to characterize coalbed gases (table 4). Although many coalbed gases are chemically dry to very dry, coalbed gases range from chemically very dry to chemically very wet, having C_1/C_{1-5} values of less than 0.80 (Scott and others, 1991a, b, and c). Relatively few studies have been performed on the composition of coalbed gases from the Cameo, Coal Ridge, and Black Diamond Coal Groups in the Piceance Basin. The following discussion on gas geochemistry is based on isotopic and gas compositional data from Tremain and Toomey (1983), Choate and others (1984), and Johnson and Rice (1990). All gas data from the Cameo Coal Group are from coal beds, whereas the data from the Williams Fork and Black Diamond Coal Groups are predominantly from sandstones.

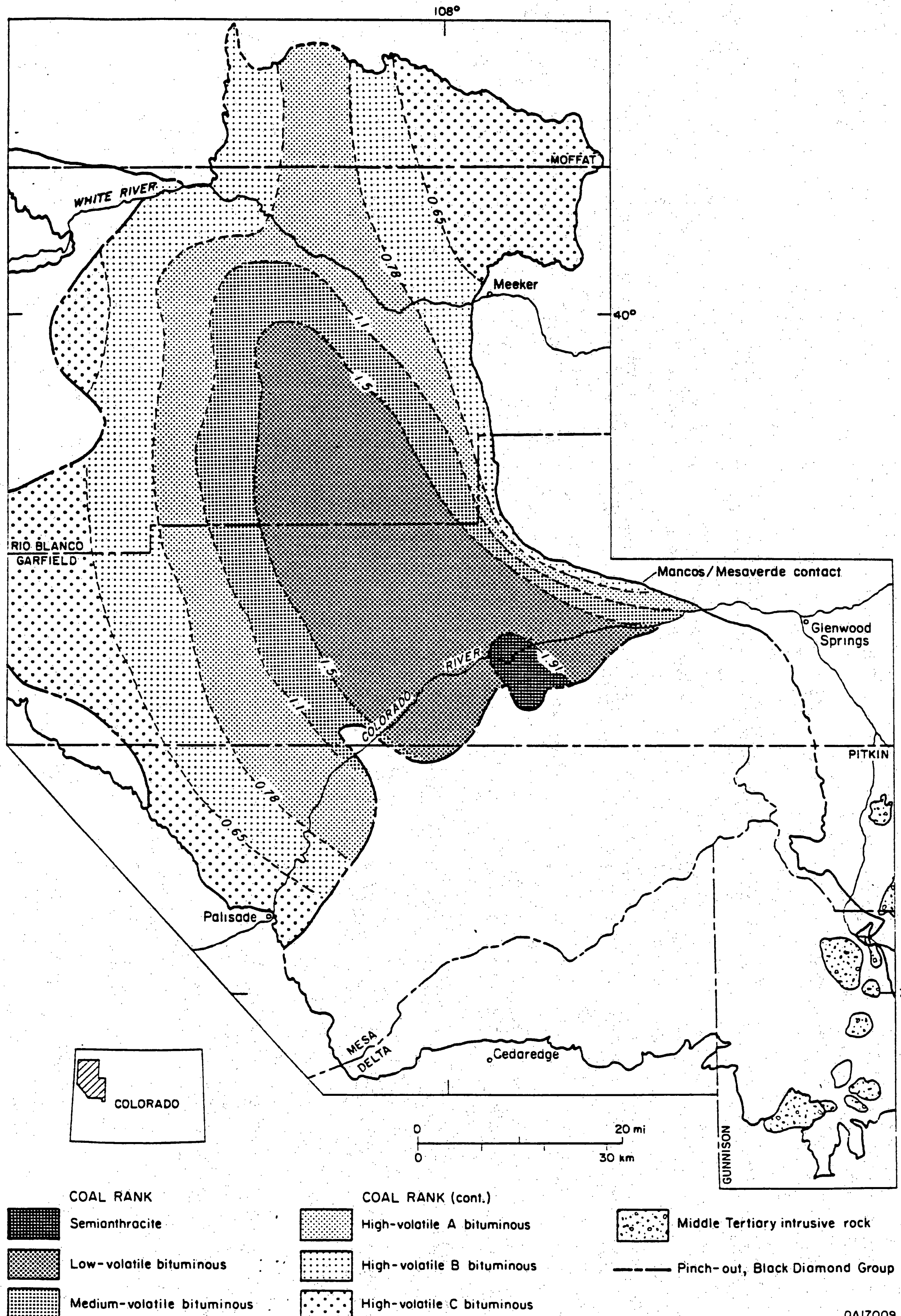


Figure 49. Coal-rank map of the Black Diamond Group. Modified from McFall and others (1986).

Table 4. The gas dryness index is the ratio of methane (C_1) to methane, ethane, propane, butane, and pentane (C_{1-5}).

C_1 / C_{1-5} value	Gas classification
> 0.99	Very dry
0.99–0.94	Dry
0.94–0.86	Wet
< 0.86	Very wet

Gas compositional and isotopic data were available for 20 Cameo coalbed gas samples. C_1/C_{1-5} values range between 0.99 (very dry) and 0.78 (very wet) and average 0.94 (fig. 50a). Minor differences of C_1/C_{1-5} values and carbon dioxide content between individual coal seams in the Walck 23-2 well (Sec. 23, T10S, R95W) may be due to variations in maceral composition between seams. Carbon dioxide content ranges from 1.3 to 14.3 percent and averages 5.3 percent (fig. 51). Coalbed gases with the highest carbon dioxide content are located near the Divide Creek Anticline (Sec. 20, T7S, R91W) and the south part of the basin (Sec. 23, T10S, R95W). Methane isotope values range from –60.3 to –29.1‰ (fig. 51) and become progressively more positive with increasing coal rank; the heaviest methane isotopic values are associated with semianthracite coals in the east part of the basin. Expulsion and migration of methane from deeper, high-rank coals to shallower, low-rank coals may have occurred. Higher-than-normal gas contents in low-rank coals are indicative of gas migration from more mature source rocks and/or biogenic activity. Coalbed gases in the northwest part of the basin (T2S, R101W and T3N, R101W) have methane isotope values ranging from –60.2 to –53.5‰ and are probably biogenic in origin.

Gases from the Williams Fork Formation (excluding Cameo coals) are generally chemically wetter than Cameo coalbed gases, having C_1/C_{1-5} values ranging from 0.79 to 1.00 and averaging 0.90 (fig. 50b). Carbon dioxide content ranges from less than 1 percent to more than 20 percent and averages 5 percent (fig. 51). A significant part of this carbon dioxide probably resulted from the decomposition of oxygen-bearing functional groups in Type III kerogen (Johnson and Rice, 1983; Rice and Johnson, 1989). However, the highest carbon dioxide values (13.7 to 22.4 percent) are found in the north part of the basin (SW/4, Sec. 31, T2N, R96W) adjacent to thrust faults along the White River Dome and may represent migrated gas.

The $\delta^{13}C$ of methane ranges from –43.6‰ in the north part of the basin to –34.8‰ in the southeast part of the basin and generally becomes more positive with increasing thermal maturity. Rice and Johnson (1989) suggested that Cameo coalbed gases are chemically distinct from gases produced from marine and nonmarine sandstones in the Williams Fork and Iles Formations and that coalbed gases have not migrated to adjacent reservoirs. However, mapping of gas compositional trends and detailed gas isotopic analyses are required to confirm the origin and migration pathways of these gases.

Limited gas compositional data suggest that gases from the Iles Formation are generally chemically dry to very dry (fig. 50c), although some samples associated with oil are chemically very wet. Iles gases have C_1/C_{1-5} values ranging from 0.26 to 1.00 and averaging 0.87. Johnson and Rice (1990) divided Iles gases into two groups on the basis of C_1/C_{1-5} values. The first group from the north part of the basin is characterized by very wet gases (C_1/C_{1-5} values of 0.26 and 0.41) associated with oil. The second group of gases are nonassociated and have C_1/C_{1-5} values ranging from 0.87 to 1.00 and averaging 0.97. Carbon dioxide content of Iles gases is usually less than 2 percent (fig. 51). The $\delta^{13}C$ of methane ranges from –48.7‰ in the north part of the basin (T102W, R2S) to less than –36.0‰ in the center of the basin (T94W, R6S). The isotopic values for Iles gases are generally more positive than they are for Cameo

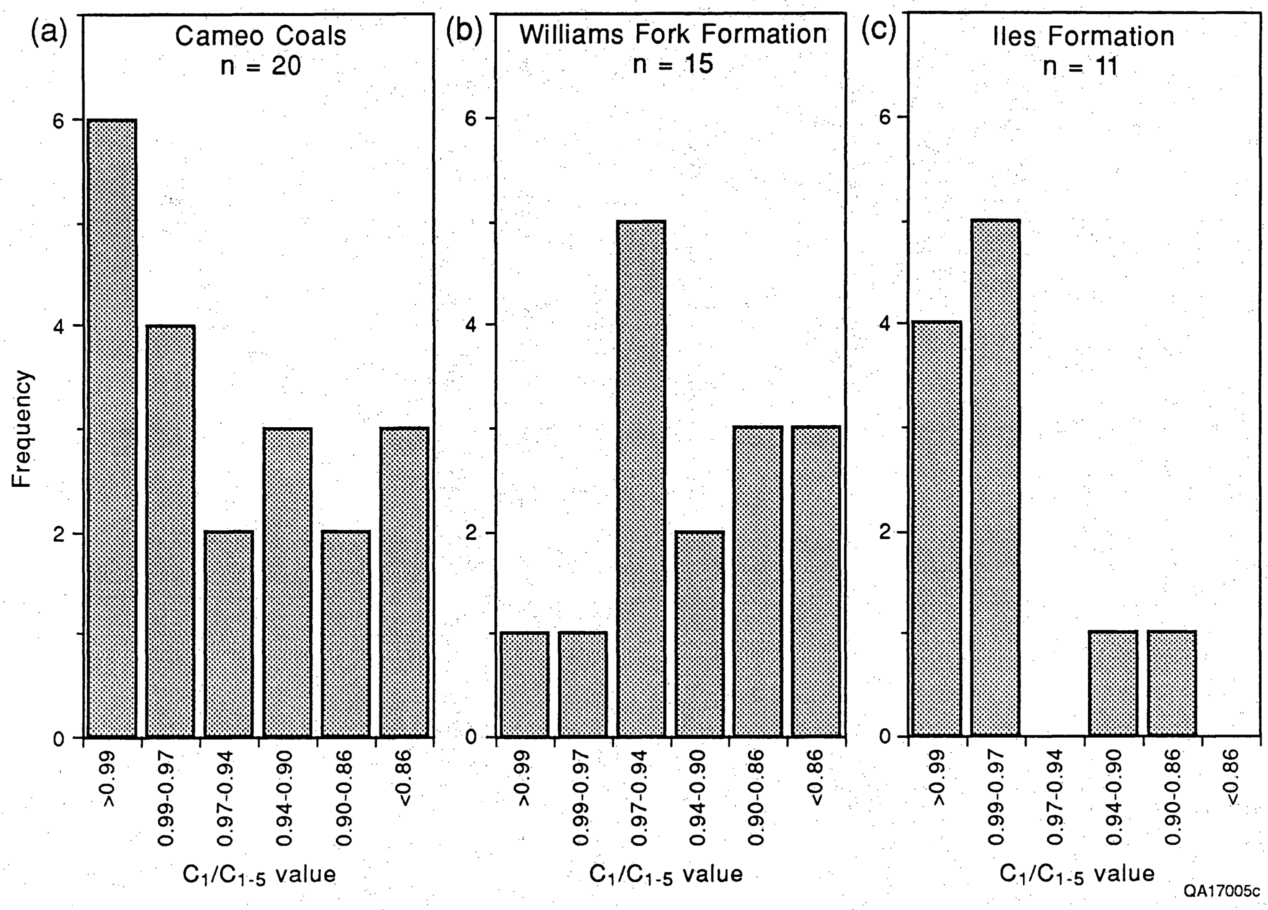


Figure 50. (a) Cameo coalbed gases range from very dry to very wet. (b) Gases produced from tight sandstones in the Williams Fork Formation are generally chemically wetter than Cameo coalbed gases. (c) Gases from the Iles Formation generally have C_1/C_{1-5} values greater than 0.97. Associated gases having C_1/C_{1-5} values of less than 0.41 are not shown in this figure.

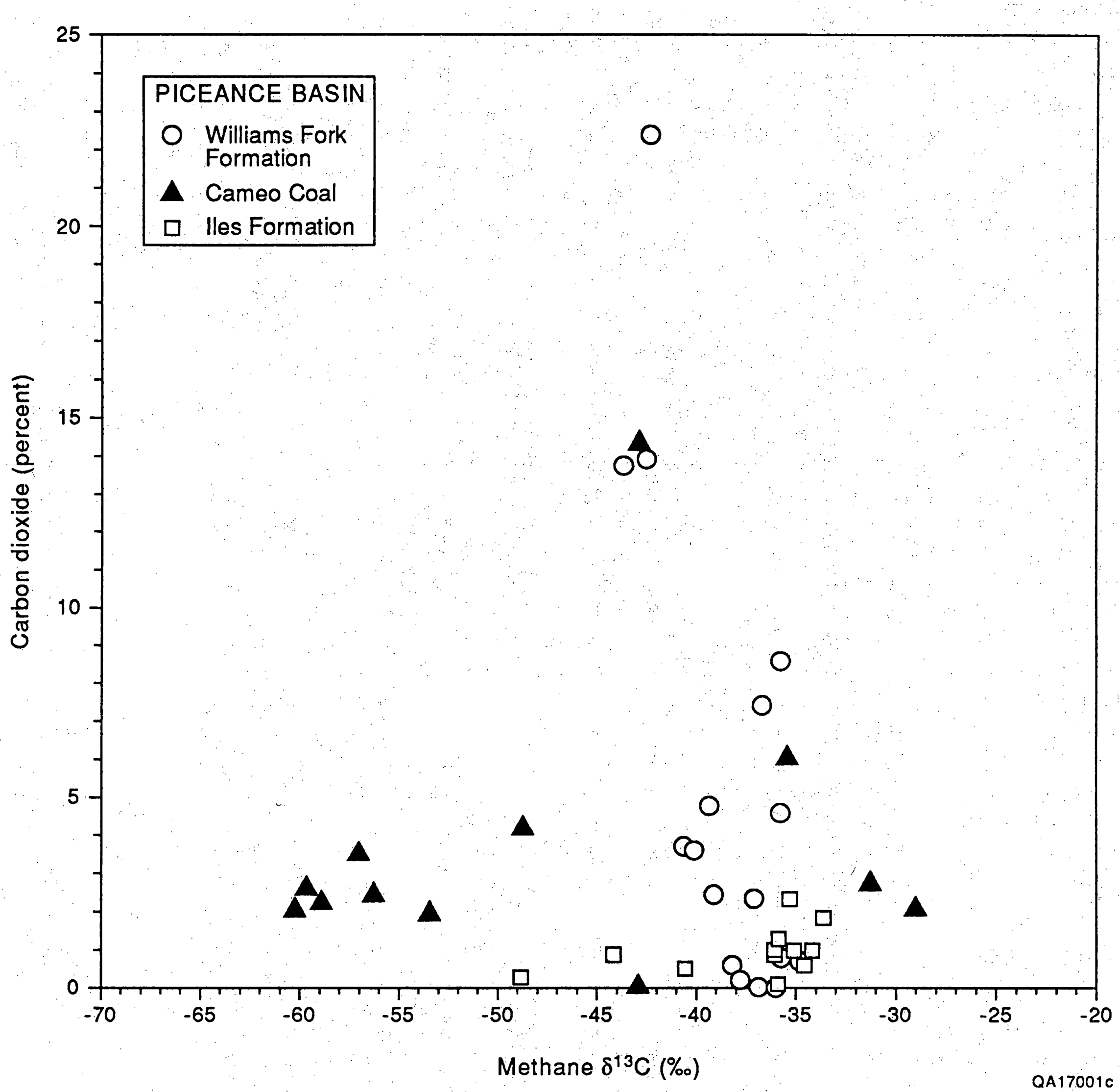


Figure 51. The $\delta^{13}C$ of methane and carbon dioxide content for Cameo coalbed, Williams Fork Formation, and Iles Formation gases. Methane $\delta^{13}C$ values for coalbed and sandstone gases generally become more positive as coal rank increases. Biogenic methane ($\delta^{13}C$ less than −55‰) is present in some coal beds. Williams Fork Formation gases near thrust faults along the White River Dome have very high carbon dioxide contents.

coalbed gases at the same level of thermal maturity (high-volatile bituminous) in the east part of the basin. This difference may be due to the difference in source material between the two formations; Cameo coalbed gases derived from terrestrial Type III kerogen, whereas Iles gases are believed to have derived from a mixture of Types II and III kerogen (Johnson and Rice, 1990).

Coalbed Methane Production

Production Targets

Most coalbed methane drilling activity in the Piceance Basin is in Garfield and Mesa Counties, in the south-central and southeast parts of the basin. The main production targets are thick coal beds (individual seams 20 to 35 ft [6 to 11 m] thick) in the Cameo Coal Group. Thickest coalbed reservoirs in the Cameo Coal Group commonly overlie the Rollins Sandstone directly. Cameo net-coal thickness locally exceeds 60 ft (18 m) in the south-central part of the basin (fig. 43a) at depths ranging from 4,000 to 9,000 ft (1,200 to 2,740 m) (fig. 43b). In the Cameo Coal Group, coalbed methane resources locally exceed 20 Bcf/mi^2 (218.5 MMm^3/km^2) along the Garfield/Mesa county line in the southeast part of the basin and along the Rio Blanco/Garfield county line in the center of the basin (fig. 52). However, the base of the Cameo Coal Group is more than 6,000 ft (>1,800 m) deep in the Garfield/Mesa area and more than 8,000 ft (>2,400 m) deep in the Rio Blanco/Garfield area (fig. 43b). Although the Cameo Coal Group is less than 4,000 ft (<1,200 m) deep in the extreme southeast part of the basin, it contains fewer coalbed methane resources because net-coal thickness decreases to less than 20 ft (<6 m) where the underlying Rollins Sandstone (the platform for Cameo peat deposition) pinches out into the Mancos Shale.

Gas and Water Production

The Piceance Basin has produced approximately 7,810 MMcf (221 MMm^3) of coalbed gas, 3,180 bbl (505 m^3) of liquid hydrocarbons, and approximately 1.31 MMbbl (208,159 m^3)of water from coalbed methane wells (table 5). During the period from October 1989 to January 1991, production from coalbed methane wells was approximately 5,001 MMcf (141.5 MMm^3) of coalbed gas (fig. 53a), 2,283 bbl (363 m^3) of liquid hydrocarbons (fig. 53b), and approximately 1.16 MMbbl (184,324 m^3) of water (fig. 53c) from 94 wells.

Maximum gas contents from coal beds in the basin range from 438 to 569 ft^3/ton (13.7 to 17.7 m^3/t) (Tremain, 1990). Highest gas contents occur in the northern part of the basin (fig. 54). Initial production rates in Piceance coalbed methane wells range from 14 to 1,500 Mcf/d (396 to 42,450 m^3/d) with water production from 0 to 2,500 bbl/d (0 to 397 m^3/d) (Tremain, 1990). Highest gas potentials of coalbed methane wells (more than 300 Mcf/d [8,490 m^3/d]) mainly occur along the Colorado River in the central part of the basin (fig. 55a). The lowest gas potentials (less than 100 Mcf/d [2,830 m^3/d]) are at the Divide

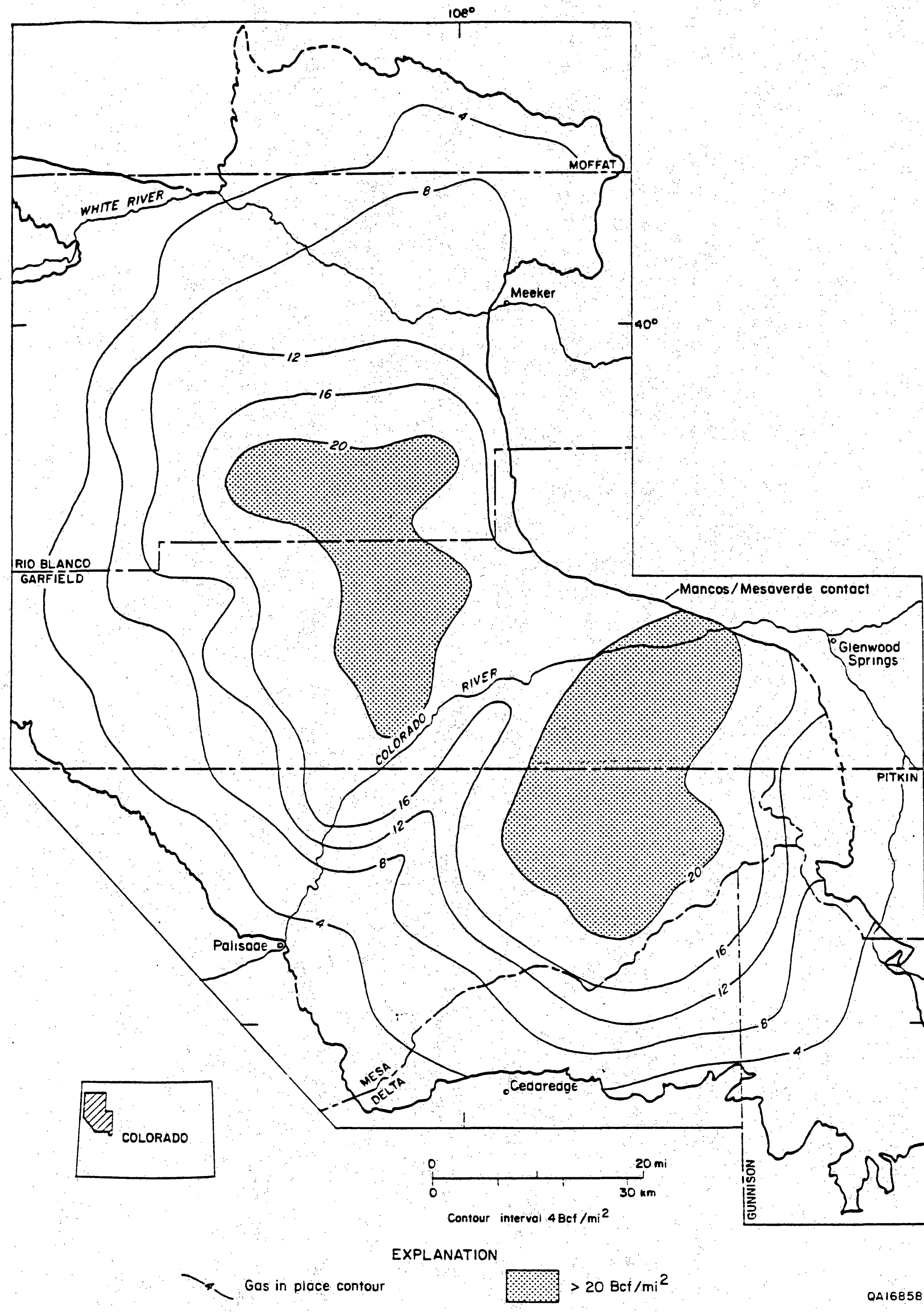


Figure 52. Gas in place in the Cameo Coal Group. Modified from McFall and others (1986).

Table 5. Cumulative liquid hydrocarbon, coalbed gas, and water production from fields in the Piceance Basin and production from October 1989 to January 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Piceance Basin fields	Oct 89–Jan 91			Cumulative to Jan 91		
	Liquid (bbl)	Gas (Mcf)	Water (bbl)	Liquid (bbl)	Gas (Mcf)	Water (bbl)
Bronco Flats	0	5,723	3,982	0	17,801	18,144
Buzzard	0	12,873	0	0	38,907	0
Divide Creek	0	516,274	1,131,214	0	472,668	1,252,124
Grand Valley	295	3,059,549	15,940	959	5,623,444	29,689
Hancock Gulch	0	0	0	0	4,022	156
Parachute	0	807,022	4,936	0	889,610	5,017
Rulison	0	347,194	812	0	416,347	1,075
Skinner Ridge	0	68,303	0	0	110,107	0
South Shale Ridge	0	50,149	6,683	0	68,982	7,215
White River	1,988	134,246	147	2,221	168,480	171
Piceance Basin Total	2,283	5,001,333	1,163,714	3,180	7,810,368	1,313,591

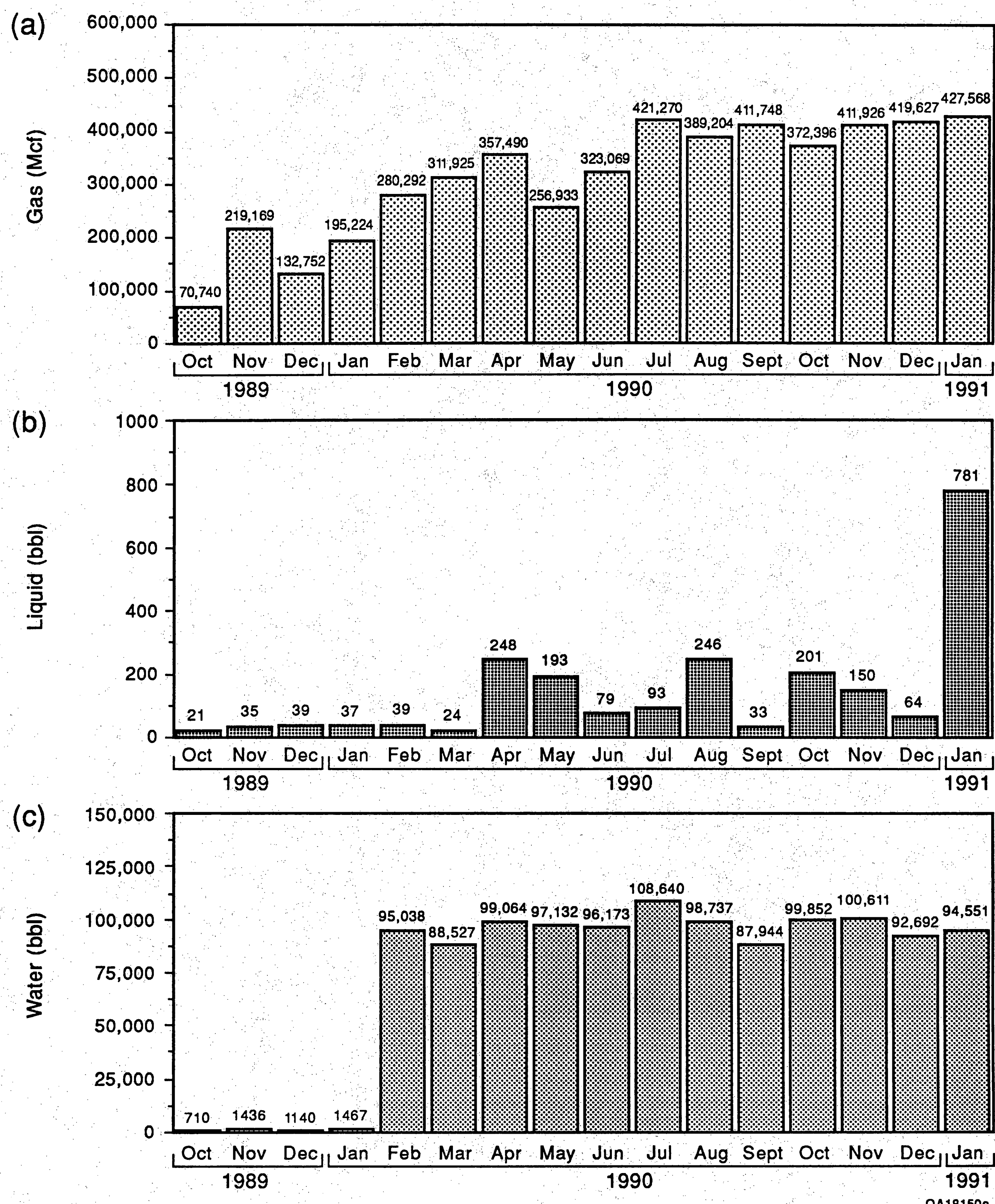


Figure 53. (a) Gas, (b) liquid hydrocarbon, and (c) water production from coalbed methane wells in the Piceance Basin from October 1989 through January 1991.

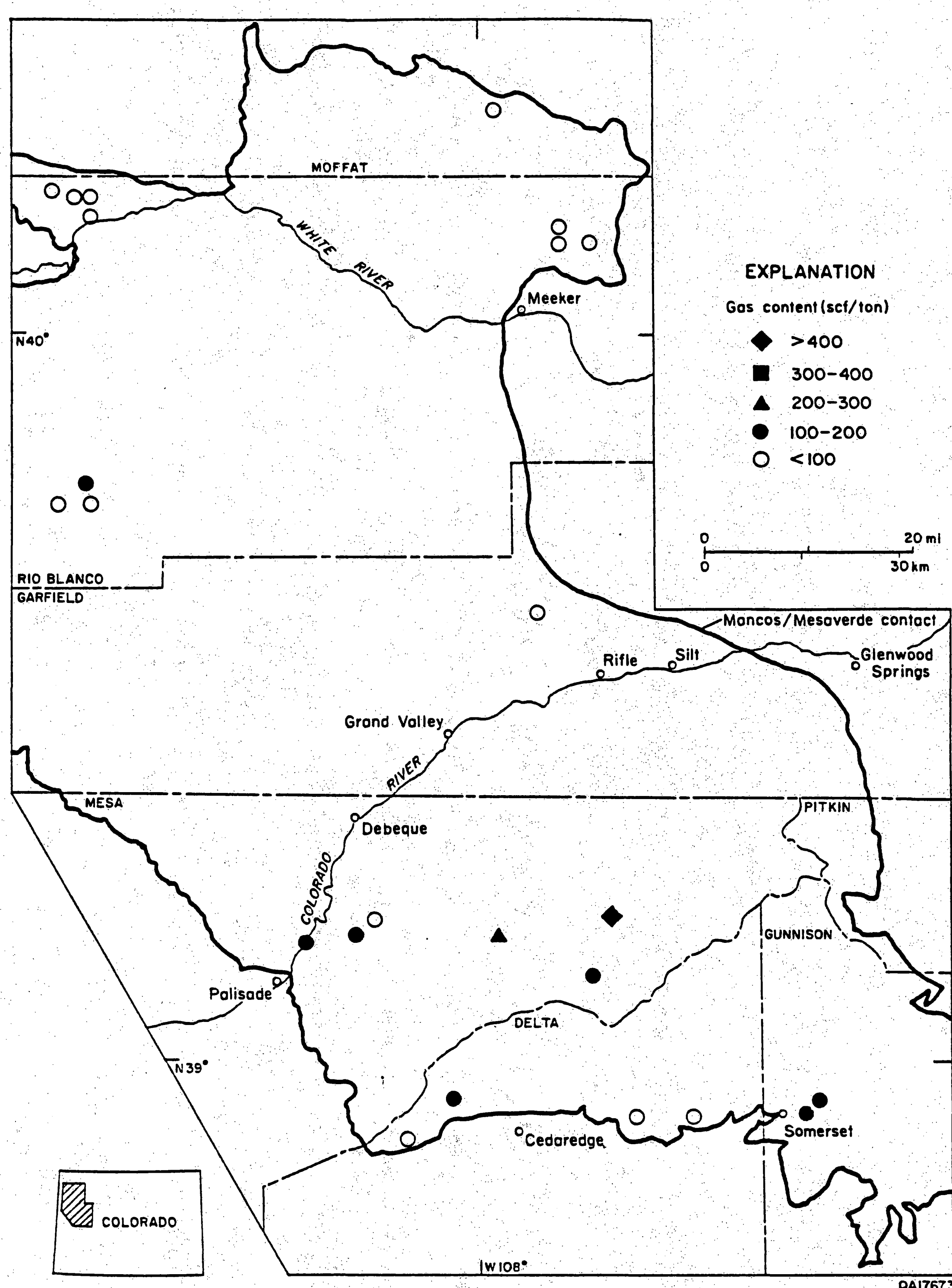


Figure 54. Gas content of Mesaverde coal beds in the Piceance Basin. Data from Tremain and Toomey (1983) and Choate and others (1984a).

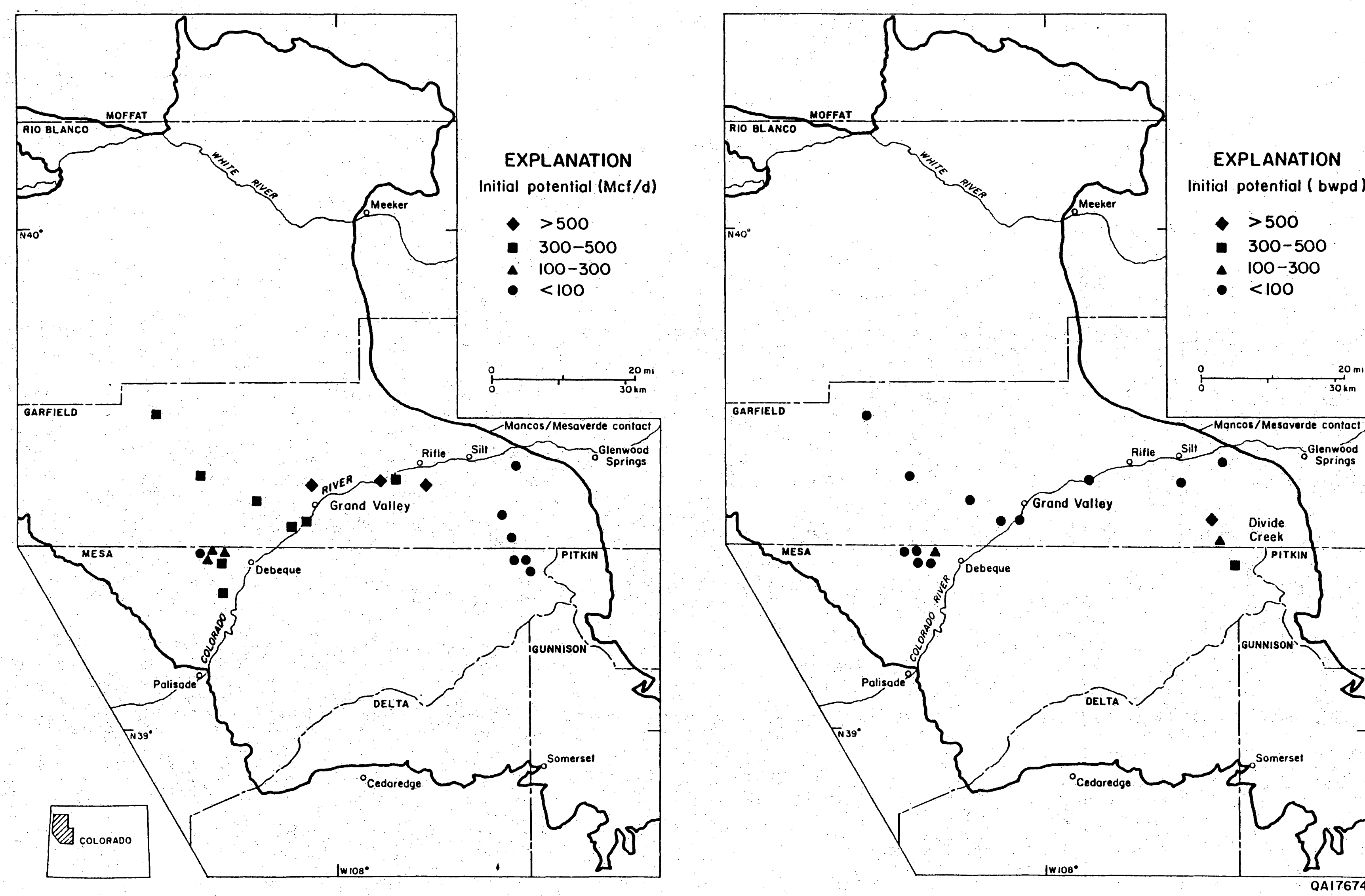


Figure 55. (a) Initial potential of gas from Cameo coal beds in the Piceance Basin. Production is greatest at Grand Valley field in the Colorado River valley, where convergent, regional ground-water flow may favor hydrocarbon accumulation. (b) Initial potential of water from Cameo coal beds. Low water IP's in the basin reflect low coal-seam permeability, except at Divide Creek field, where high water IP's reflect artesian, overpressured coal beds. Data from Petroleum Information (1990a–k; 1991b–f) and the Gas Research Institute (1991b–c).

Creek Anticline in the eastern part of the basin, where water potentials are highest (more than 300 bbl/d [47.7 m^3/d]) (fig. 55b). Except for this area, water potentials in the Piceance Basin are low (less than 100 bbl/d [15.9 m^3/d]), reflecting low permeability of coal beds. Mesaverde sandstones are also productive. For example, Coon Hollow field, located in northern Mesa County in T9–10S, R94–96W, has produced more than 670 MMcf (>18.96 MMm^3) of gas from Cozzette, Corcoran, Mesaverde, and Rollins Sandstones (Petroleum Information, 1990h). Wells dually completed in sandstones and coal beds in the Piceance Basin have production rates as high as 2,600 Mcf/d (73,580 m^3/d). Most gas-potential data are from wells completed in Mesaverde sandstones in fields along the Colorado River (fig. 56).

The Piceance Basin produces coalbed methane from 11 fields (fig. 57), with greatest cumulative production through January 1991 of approximately 5,623 MMcf (159.1 MMm^3) in Grand Valley field (table 5). Gas production in Grand Valley field is from the Rollins Sandstone, Cameo coal beds, Mesaverde sandstones, or dually completed Mesaverde sandstones and Cameo coal beds. Initial potentials of Cameo coal beds at Grand Valley field range from 125 to 1,500 Mcf/d (3,538 to 42,450 m^3/d) (Gas Research Institute, 1991b; Petroleum Information, 1991f). Mesaverde sandstones, at depths of 4,100 to 4,750 ft (1,250 to 1,450 m), typically have initial potentials of 200 to 1,250 Mcf/d (5,660 to 35,375 m^3/d). Water production in Grand Valley field is low, ranging from 0 to 20 bbl/d (0 to 3.2 m^3/d) per well.

Most gas/water ratios in coalbed methane fields in the basin are high (more than 100,000 ft^3/bbl), especially in the south-central part of the basin along the Colorado River (fig. 57). However, low gas/water ratios (less than 1,000 ft^3/bbl) occur along the Divide Creek Anticline and at Bronco Flats field, near the Mesaverde outcrop in the southwestern part of the basin. Other important coalbed methane fields are Parachute and Divide Creek fields, which have produced approximately 890 MMcf (25.2 MMm^3) and 473 MMcf (13.4 MMm^3) of coalbed gas, respectively, and White River field (fig. 57), which has produced approximately 2,200 bbl (350 m^3) of liquid hydrocarbons—two-thirds of all liquid hydrocarbons from coalbed methane wells in the basin. White River field produces from Williams Fork coal beds at depths ranging from 5,384 to 6,397 ft (1,641 to 1,950 m), and initial potentials of oil are typically 8 bbl/d (1.3 m^3/d) after fracture stimulation (Gas Research Institute, 1991c).

Divide Creek field (fig. 57), where Cameo coal beds occur at depths ranging from 4,910 to 6,000 ft (1,495 to 1,800 m), accounts for almost all of the water production from coal seams in the Piceance Basin between October 1989 and January 1991 (approximately 1.13 MMbbl [179,557 m^3]). Wells drilled by Oryx in Divide Creek field produce from 34 to 115 Mcf/d (962 to 3,255 m^3/d) of gas (Petroleum Information, 1990a) and average 353 bbl/d (56 m^3/d) of water, with a range of 1 to 694 bbl/d (0.2 to 110 m^3/d) (Gas Research Institute, 1991b).

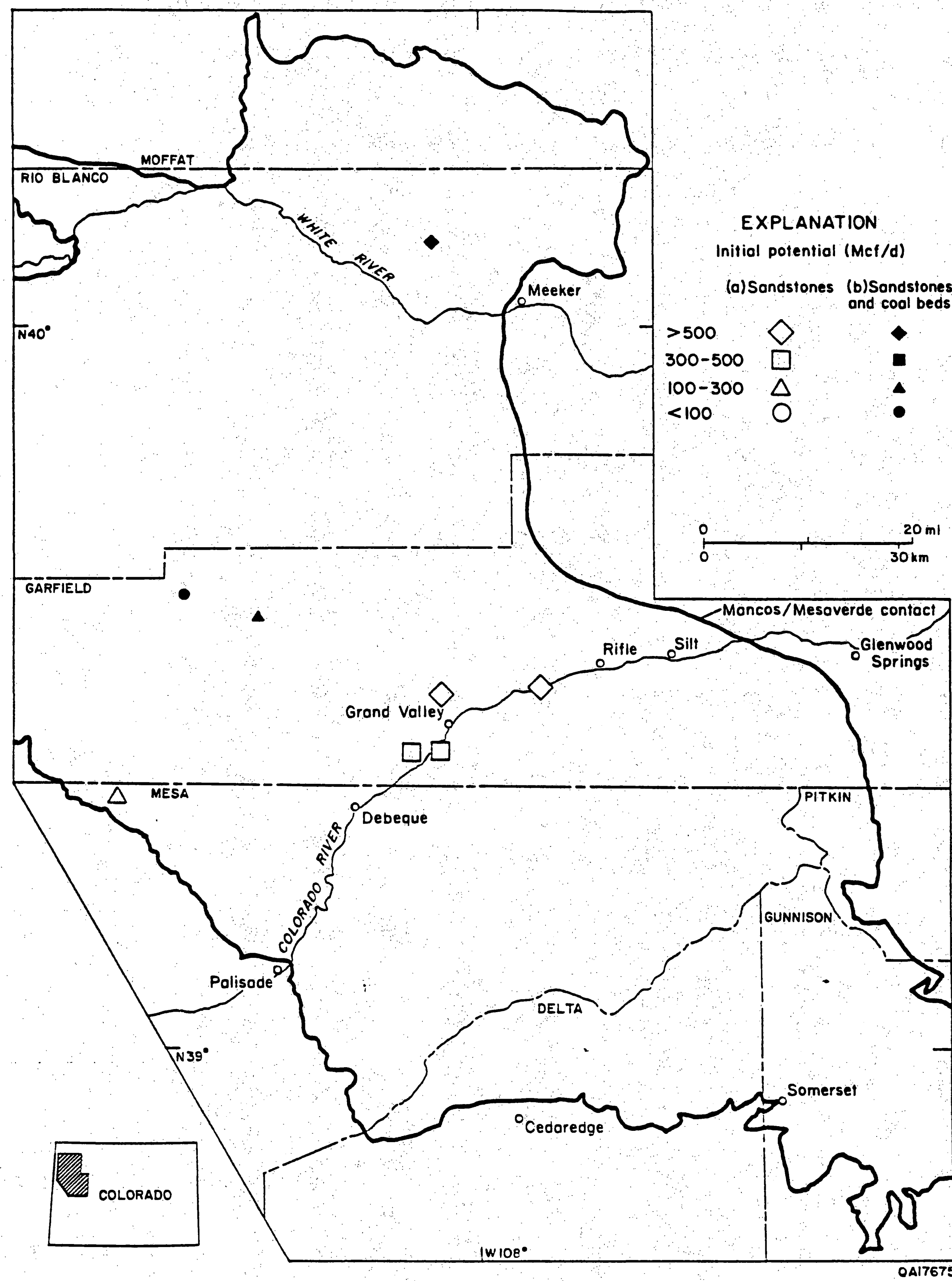


Figure 56. Initial potential of gas from (a) sandstone and (b) dually completed sandstone and coal beds in the Mesaverde Group in the Piceance Basin. Data from Petroleum Information (1990a–k; 1991b–f), and the Gas Research Institute (1991b, c). Gas IP's are highest from dually completed wells.

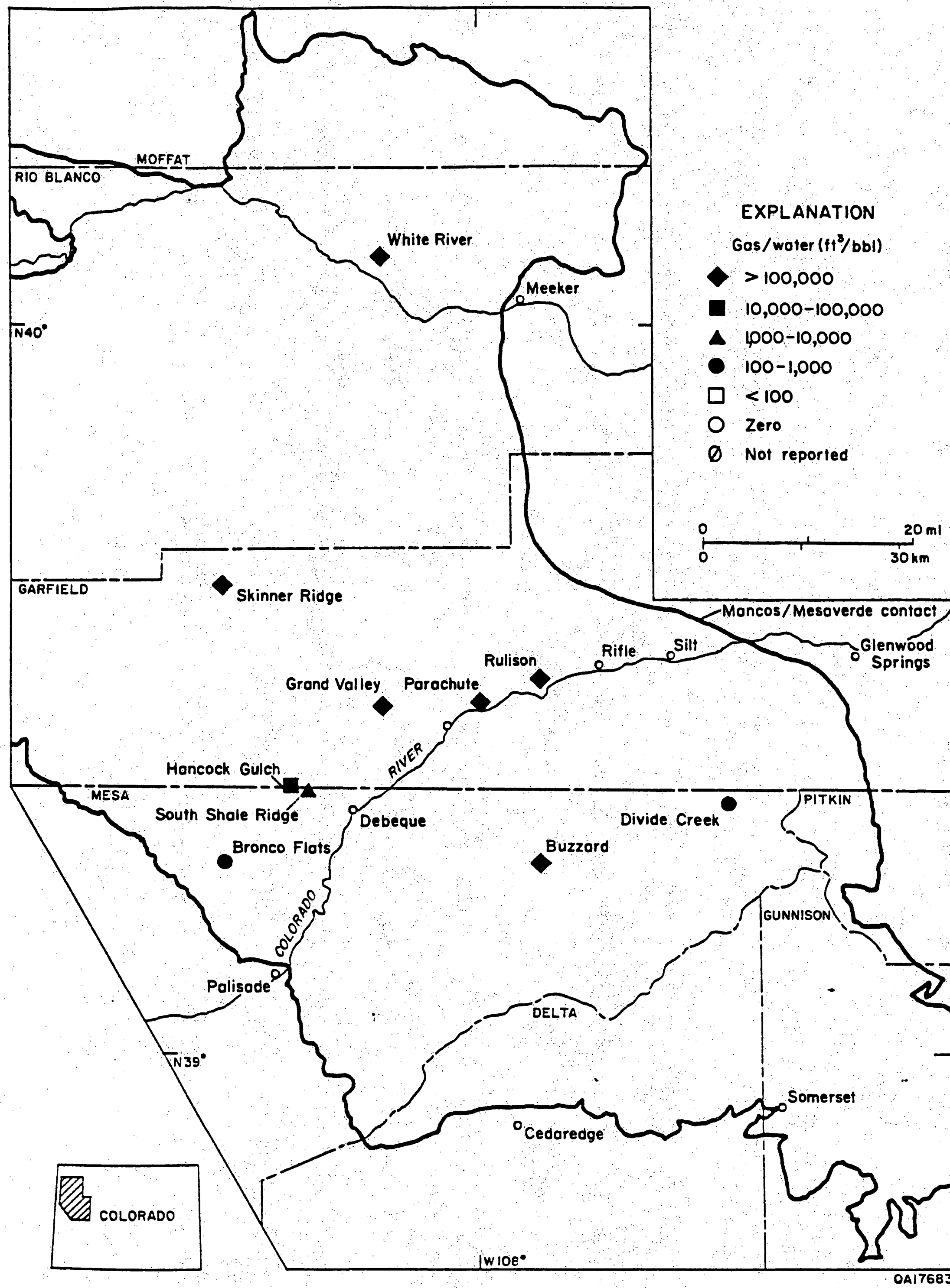


Figure 57. Cumulative gas/water ratio in coalbed methane fields in the Piceance Basin. Data from Petroleum Information (1990a–k; 1991b–f).

Completions and Drilling Activity

Coalbed methane drilling activity occurs mainly in the southern part of the Piceance Basin (fig. 58). Most completions are in the Cameo coal group, especially on the eastern margin of the basin, although there are dually completed wells in Mesaverde coal beds and sandstones along the Colorado River and along the southwestern margin of the basin. Nineteen drill-stem tests have been run in Piceance coal beds, although 14 of these were conducted in 4 wells. Completions are nearly evenly distributed between 25 single completions in the Cameo Coal Group and 21 dual completions in Cameo and Mesaverde sandstones (fig. 59a), with average depth of top of completions at 5,048 ft (1,537 m) in a range from 2,777 to 8,196 ft (847 to 2,499 m) (fig. 59b). Average total depth of wells is approximately 5,930 ft (1,808 m) in a range from 3,470 to 8,560 ft (725 to 2,610 m) (fig. 60).

Thirteen companies were active as of January 1991 in drilling for coalbed methane in the Piceance Basin (fig. 61). Barrett Energy is currently the most active and has drilled 24 coalbed methane wells, most of which are in Parachute and Grand Valley fields (fig. 57). Barrett Energy has also drilled extensively on the southwest margin of Parachute field; in late 1990, the company drilled a pair of Cameo Coal/Mesaverde sandstone wells 3 mi (4.8 km) to the southwest, in T7S, R96W. One well produced 490 Mcf/d (13,867 m^3/d) of gas and 5 bbl/d (0.8 m^3/d) of water from Cameo coal beds at depths of 5,011 to 5,319 ft (1,528 to 1,622 m) and 455 Mcf/d (12,877 m^3/d) of gas and 5 bbl/d (0.8 m^3/d) of water in the shallow Mesaverde at depths of 4,132 to 4,769 ft (1,260 to 1,454 m). Barrett Energy is also active in Rulison field; one well was completed in Cameo coal seams at depths of 6,989 to 7,339 ft (2,131 to 2,238 m) and tested at 500 Mcf/d of gas (14,150 m^3/d) and no water. The Corcoran Sandstone tested at 2,000 Mcf/d (56,600 m^3/d) of gas and no water (Gas Research Institute, 1991b).

Conquest/Bataa is the second most active coalbed methane operator in the basin (15 coalbed methane wells) and is currently drilling in South Shale Ridge and Hancock Gulch fields. In August 1990, Conquest/Bataa completed the discovery well (1-15 CBM Hancock Gulch Unit) in sec. 15, T8S, R98W in South Shale Ridge field. The well produced 4,022 Mcf (161 Mcf/d [4,556 m^3/d]) of gas and 156 bbl (25 m^3) (6 bbl/d [1m^3/d]) of water in a 25-day period in August 1990 (Petroleum Information, 1991b). Conquest/Bataa plans to drill as many as 45 Cameo tests in South Shale Ridge field, which produced approximately 38.4 MMcf (1.09 MMm^3)of gas and 4,600 bbl (731 m^3) of water in the first four months of production (Petroleum Information, 1991d).

Oryx is the third most active coalbed methane operator in the Piceance Basin (10 coalbed methane wells) and continues to develop Divide Creek and South Shale Ridge fields. Oryx plans to recomplete the No. 31 Divide Creek Unit well, which produces 68 Mcf/d (1,924 m^3/d) of coalbed gas and 188 bbl/d (30 m^3/d) of water in the basal Cameo coal seam in Divide Creek field. The recompleted well will be drilled for 100 ft (30 m) horizontally in the basal Cameo coal seam to intersect fractures. Oryx also plans to drill another horizontal coalbed methane well in Divide Creek field (Petroleum Information, 1990g).

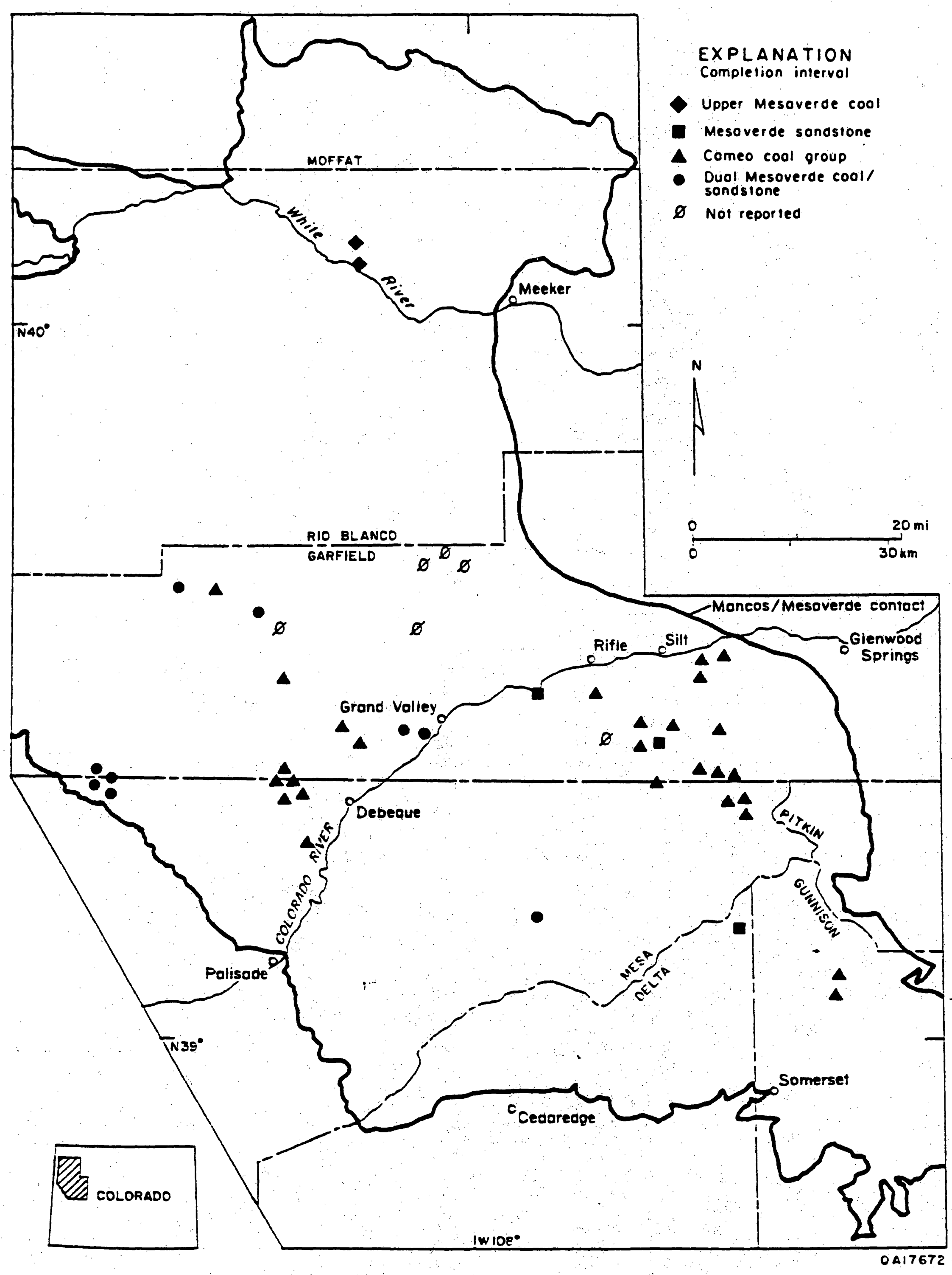


Figure 58. Recent (1990 and 1991) coalbed methane wells in the Piceance Basin. Data from Petroleum Information (1990a–k; 1991b–f), and the Gas Research Institute (1991b, c).

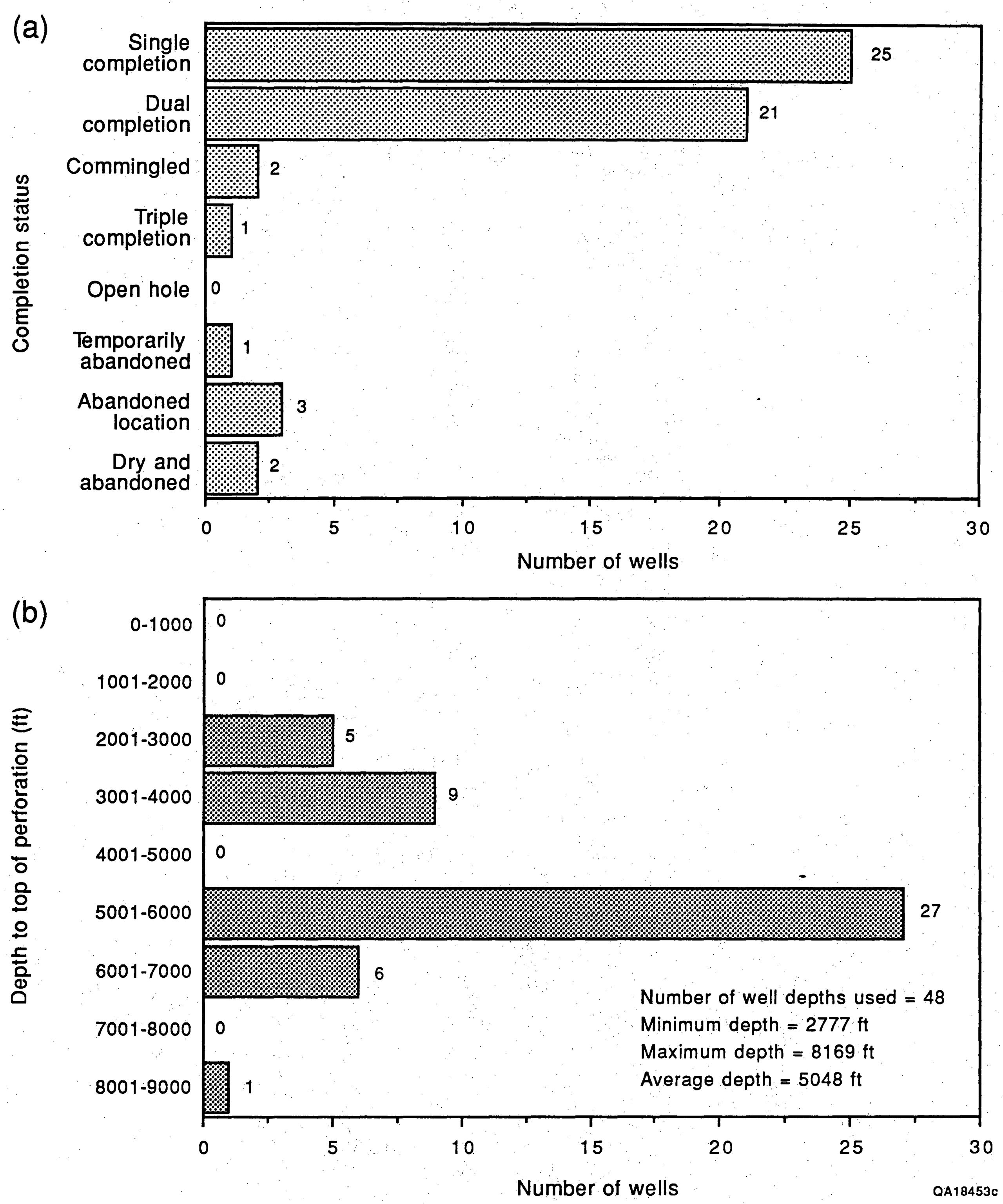


Figure 59. (a) Completion status and (b) depth to top of perforation of coalbed methane wells in the Piceance Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

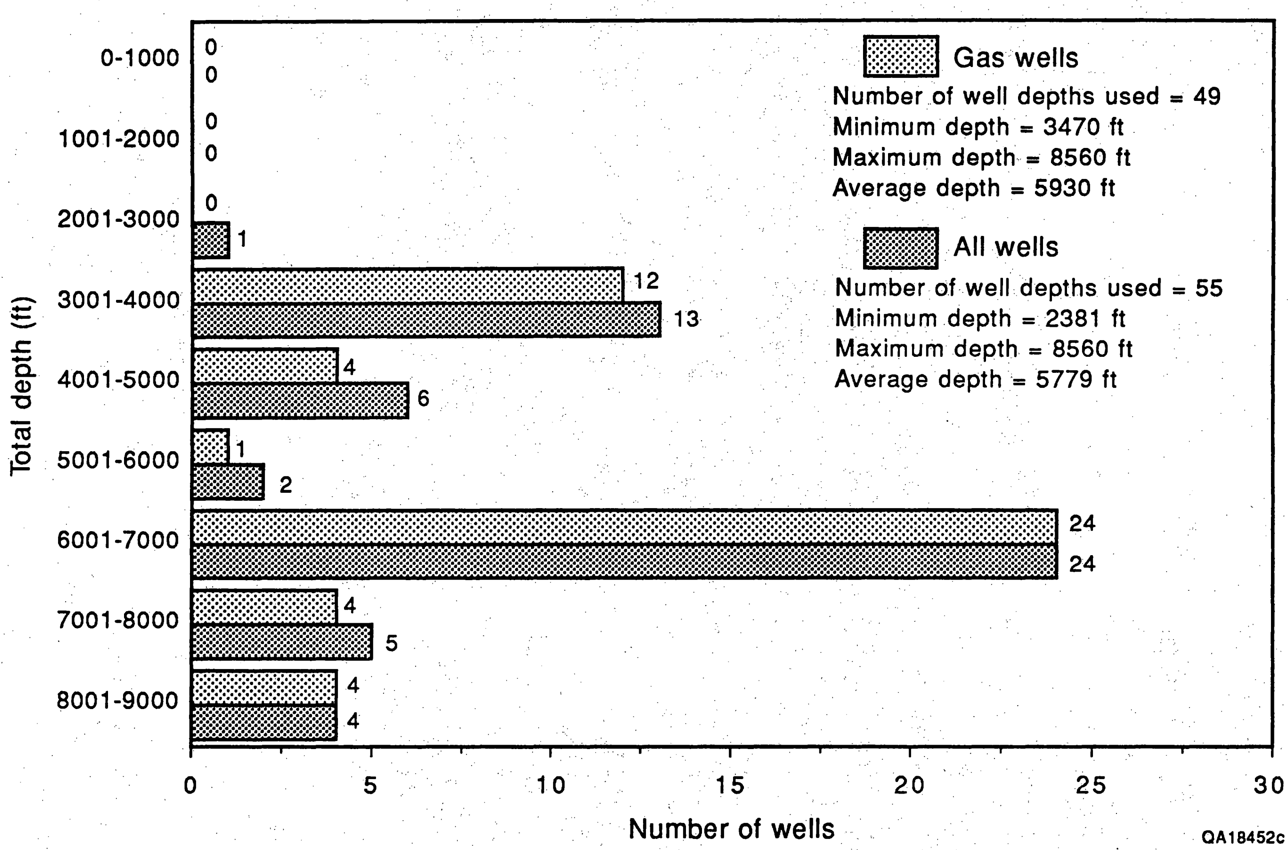


Figure 60. Range of total depth of coalbed methane wells in the Piceance Basin from February 1990 through May 1991. Light bars represent completed gas wells. Dark bars represent all wells, completed or not. See figure 59 for types of completions. Data from Petroleum Information (1990a–k; 1991b–f).

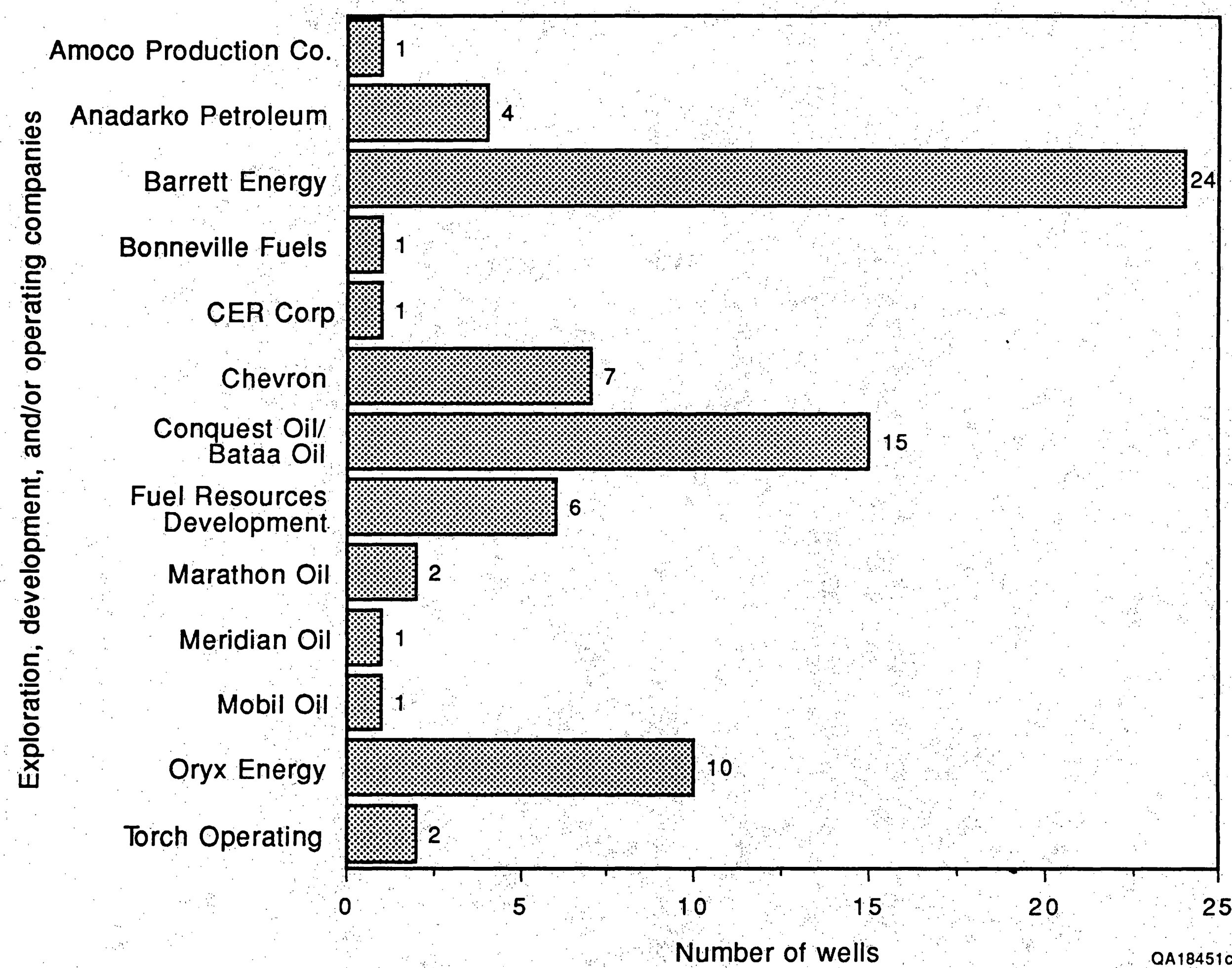


Figure 61. Number of coalbed methane wells drilled by exploration, development, and/or operating companies in the Piceance Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Fuel Resources Development (Fuelco) has drilled extensively in Plateau, Rulison, and White River fields. Fuelco recently recompleted the No. 1 Lad well in White River field in Williams Fork coal horizons at depths of 5,619 to 6,295 ft (1,713 to 1,919 m). After stimulation with sandstone and sand-gel treatments, the well flowed at 1,000 Mcf/d (28,300 m^3/d) of gas, 38 bbl/d (6 m^3/d) of water, and 2 bbl/d (0.3 m^3/d) of oil (Gas Research Institute, 1991b). Fuelco has also staked five new locations in Rulison field, and four will target the Cameo Coal at depths of 8,190 to 9,800 ft (2,497 to 2,988 m) (Gas Research Institute, 1991c).

Chevron is active in the area of Parachute field. In 1989, Chevron completed three coalbed methane wells northwest of the field and completed the Cameo Coal in one well and dually completed the Cameo Coal and Mesaverde sandstones in two other wells. The well with the single completion in the Cameo Coal at depths of 6,818 to 6,990 ft (2,079 to 2,131 m) had an initial potential of 381 Mcf/d (10,782 m^3/d) of gas and 28 bbl/d (4.4 m^3/d) of water. The other two wells with the dual completions tested at 30 to 152 Mcf/d (849 to 4,302 m^3/d) of gas and 8 to 28 bbl/d (1.3 to 4.4 m^3/d) of water from the combined Cameo Coal/Mesaverde sandstone horizons (Petroleum Information, 1991a).

Other coalbed methane operators in the Piceance Basin include Marathon Oil, Inc. (South Shale Ridge field), Nassau Resources, Inc. (5 mi [8 km] east of Silt, Colorado, only 3 mi [4.8 km] from the Grand Hogback monocline), Petro Energy Exploration, Inc. (24 mi [38.4 km] southwest of Carbondale, Colorado), Mobil Exploration and Production (Divide Creek field), Dekalb Energy Co. (3 mi [4.8 km] south of Coon Hollow field), Anadarko Petroleum, Inc. (Bronco Flats field in T9S, R99W), Fina Oil and Chemical Co. (Rulison field), and Torch Operating Co. (Garfield County, in T7S, R91W). The U.S. Department of Energy (DOE) drilled a horizontal well at the MWX site 5 mi (8 km) southwest of Rifle, Colorado. The well, the Slant Hole Completion Test (SHCT-1) was drilled vertically to 6,365 ft (1,941 m), and then at an inclination of 60° to 7,771 ft (2,369 m). Finally, the well was drilled horizontally for approximately 500 ft (150 m). Lenticular Upper Mesaverde sandstones were penetrated in the curved section of the well, whereas coal seams and the blanket Rollins Sandstone were penetrated in the horizontal section (Petroleum Information, 1990d).

Pipeline Availability

As of February 1977, six companies had pipeline systems in and through the Piceance Basin: Cascade Natural Gas Corporation, Northwest Pipeline Corporation, Public Service Company of Colorado, Rocky Mountain Natural Gas Company, Inc., Mountain Fuel Resources, Inc., and Western Slope Gas Company (Federal Energy Regulatory Commission, 1977a; Federal Energy Regulatory Commission, 1982). The pipelines owned by these companies cover most of the Piceance Basin (fig. 34). Of the 11 coalbed methane fields (fig. 57), 9 have produced methane between October 1989 and January 1991 (table 5). All of this methane was probably transported by the existing pipelines. Only one field had production as of January 1991, whereas another field produced before October 1989, an indication that the coalbed methane fields are well-connected to existing gas-transmission lines.

Pipeline availability and marketing, in which the existing pipeline system was predominantly intrastate, have been major problems for the Piceance Basin. However, several new pipelines are planned for the basin. A 310-mi (499-km) pipeline project is proposed to connect Grand Junction, Colorado, to a pipeline near Blanco, New Mexico (Western Oil World, 1990; Petroleum Information, 1991a). This 300-MMcf/d (8.5-MMm^3/d), $152-million construction project will begin in late 1991 with operations starting in mid-1992. The pipeline has preliminary approval from the FERC and is co-sponsored by West Gas, KN Energy, Inc., and Questar Pipeline Company. Another project is proposed to connect eastern Utah through the northern portion of the Piceance Basin and the center of the Sand Wash Basin to end at the Colorado Interstate Gas Company (CIG) pipeline at Wamsutter, Wyoming (Western Oil World, 1991). This 223-mi (359-km) $85-million pipeline will be constructed by CIG.

Coal and Coalbed Methane Resources and Potential

The Piceance Basin contains approximately 84 Tcf (2.38 Tm^3) of coalbed methane in the Black Diamond, Cameo, and Coal Ridge Coal Groups (McFall and others, 1986). Most of these resources (65.2 Tcf [1.85 Tm^3]) are in the Cameo Coal Group. More than 20 Bcf/mi^2 (>218.5 MMm^3/km^3) of coalbed methane in the Cameo Coal Group occurs in two large areas in the center of the basin (fig. 52). Areas of greatest Cameo coalbed-methane resources are partly controlled by (1) net-coal thickness, which is greatest in the southeast part of the basin and (2) coal rank, which is highest (semianthracite and low volatile bituminous) in the deep, east-central part of the basin (fig. 47) (McFall and others, 1986).

Black Diamond coalbed methane resources in the Piceance Basin are 8.8 Tcf (249 Bm^3) (McFall and others, 1986). These resources locally exceed 4 Bcf/mi^2 (43.7 MMm^3/km^2) in deeper (more than 8,000 ft [>2,400 m]) east-central and northeast parts of the basin. However, in the southeast part of the basin, no Black Diamond coalbed methane resources exist because the coal beds are absent. Rank of these coal beds is semianthracite in the east, deep part of the basin (fig. 49); lowest rank (high-volatile C bituminous) is present in the west part of the basin, where thick (net-coal thickness greater than 10 ft [3 m]) coal beds are less than 4,000 ft (<1,200 m) deep (McFall and others, 1986).

The Coal Ridge Group contains 9.9 Tcf (280.2 Bm^3) of coalbed methane resources, present only in the southeast part of the basin. Although the Coal Ridge Coal Group contains more coalbed methane resources than does the Black Diamond Coal Group, these coal beds are thin, lenticular, and discontinuous. Coalbed methane resources in the Coal Ridge Coal Group are mainly controlled by net-coal thickness, which locally exceeds 40 ft (12 m) in a northwest-trending belt, approximately 15 mi (24 km) west of Glenwood Springs. The area of greatest Coal Ridge coalbed methane resource is from 4,000 to 8,000 ft (1,200 to 2,400 m) deep.

POWDER RIVER BASIN

Geologic Overview

The Powder River Basin of northeastern Wyoming and southeastern Montana covers an area of 25,800 mi^2 (66,800 km^2) and is the largest intermontane structural basin east of the Overthrust Belt (fig. ES-2). The Powder River Basin is bounded by the Black Hills Uplift in the east, the Big Horn Uplift in the west, the Laramie and Hartville Uplifts in the south, and the Miles City Arch and Porcupine Dome in the north, which separates the Powder River Basin from the Williston Basin (fig. 62). The synclinal axis of the basin is along the southwest side, where the difference in altitude on the Precambrian surface and the adjacent Bighorn Uplift to the west is about 4 mi (6.4 km; Love, 1988a). The Powder River Basin is filled by Paleozoic and early Mesozoic rocks, mostly of marine origin, and a younger sequence of Upper Cretaceous and lower Tertiary coal-bearing rocks, of continental origin (fig. 63). Nearby orogenic uplifts provided the source areas for coal-bearing Upper Cretaceous (Mesaverde, Meeteetse, and Lance Formations), Paleocene (Fort Union Formation) and Lower Eocene (Wasatch Formation) rocks (fig. 63). Subsurface structure of the coal-bearing formations in the Powder River Basin is relatively simple (Ayers, 1984). Structural relief on the top of the Tullock Member of the Fort Union Formation, is approximately 5,100 ft (1,555 m) (fig. 64; Ayers, 1984). Folds and faults are apparently absent in the basin center (Pratsch, 1986). Because the synclinal axis lies close to the west margin of the basin, dips of the sedimentary rocks on the shallow eastern limb are quite low, averaging 1° to 2° westward (Ayers, 1984). The north and northeast flanks of the Powder River Basin have homoclinal dips of about 1° west-southwestward (Slack, 1981), whereas dips on the west flank, adjacent to the Bighorn Uplift, average 5° to 25° eastward (fig. 64). Sedimentary rocks older than Late Cretaceous have relatively steep dips on both margins of the basin (fig. 65; Choate and others, 1984a). Upper Cretaceous rocks are exposed only on the east and southwest sides of the basin (Love, 1988a). The Paleocene lacustrine and fluvial-deltaic Fort Union sediments are exposed around the periphery of the basin, whereas the predominantly Eocene fluvial Wasatch sediments are exposed at the surface throughout most of the center of the basin. These genetically related fluvial, deltaic, and lacustrine deposits (Ayers, 1984), contain some of the most economic coal deposits in the United States (1.031 trillion tons [935.3 billion t]; Jones and De Bruin, 1990) and are targets for coalbed methane exploration.

Tectonic and Stratigraphic Setting

The sequence of events that occurred within the Powder River Basin during the Laramide Orogeny includes subsidence during the Late Cretaceous (Lance Formation) through Paleocene (Lebo) time (fig. 63). The first evidence for the development and erosion of structural highlands surrounding the

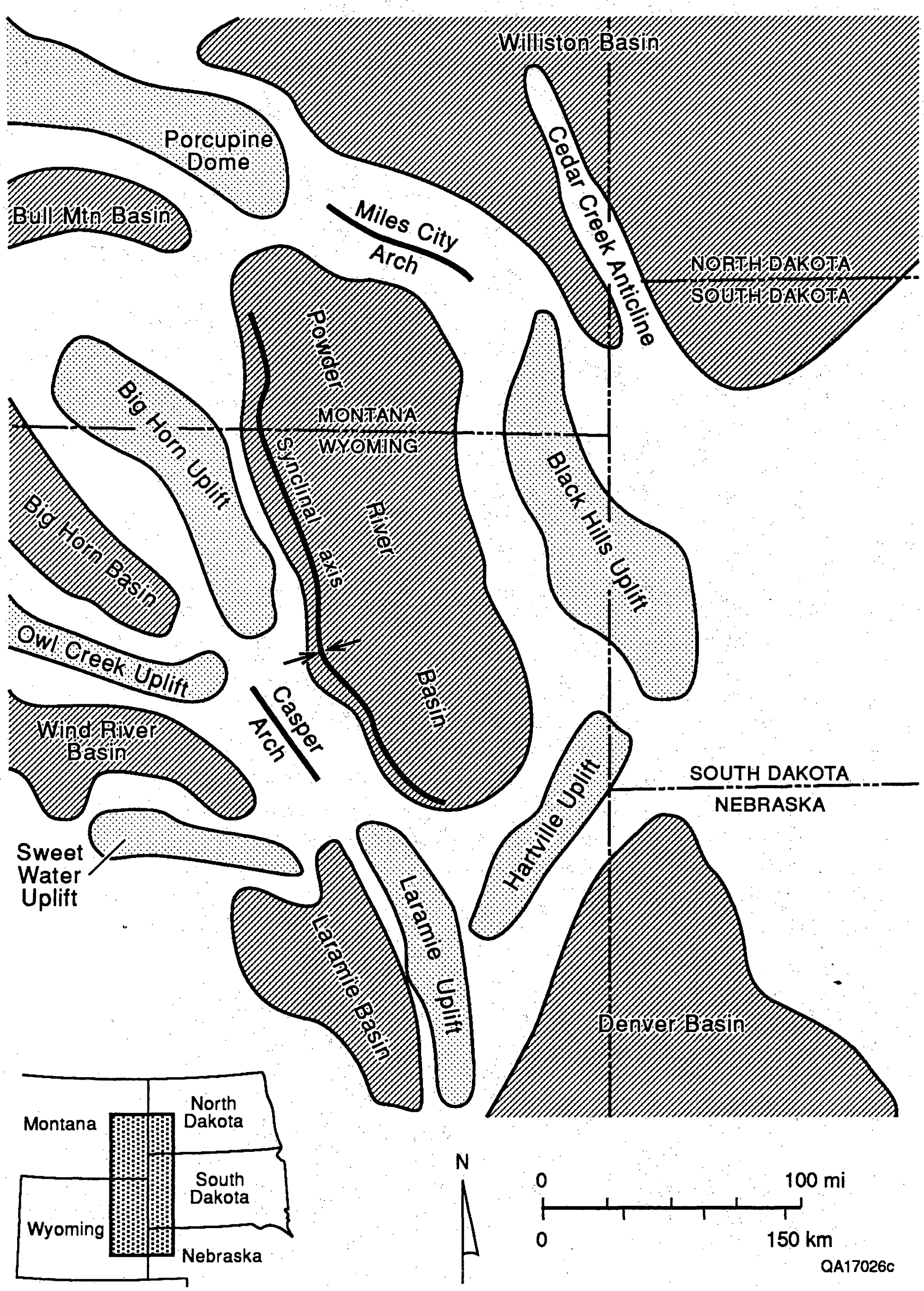


Figure 62. Powder River Basin index map. Modified from Ayers (1984).

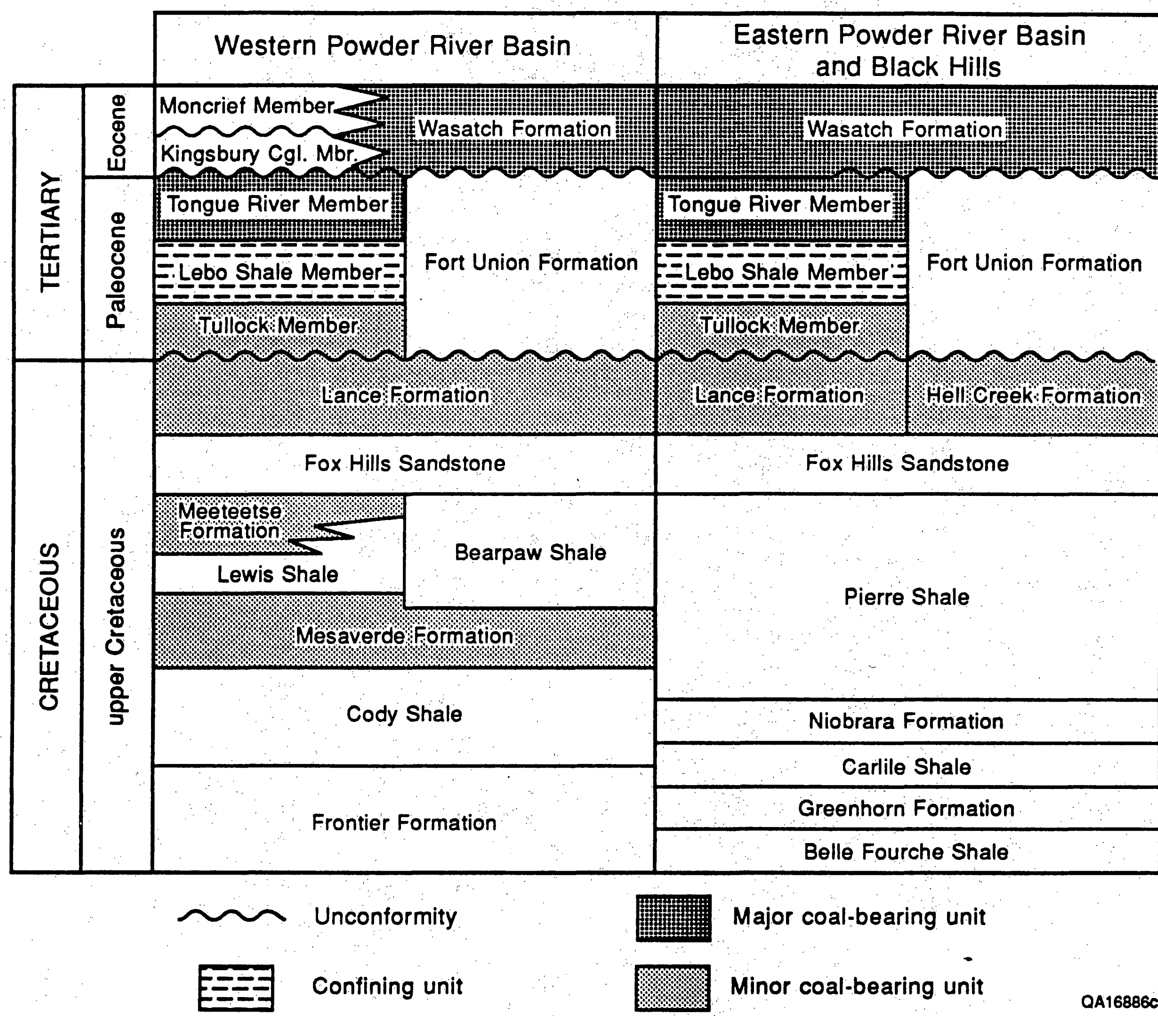


Figure 63. Coal-bearing stratigraphic and confining units in the Powder River Basin. Modified from Jones (1990).

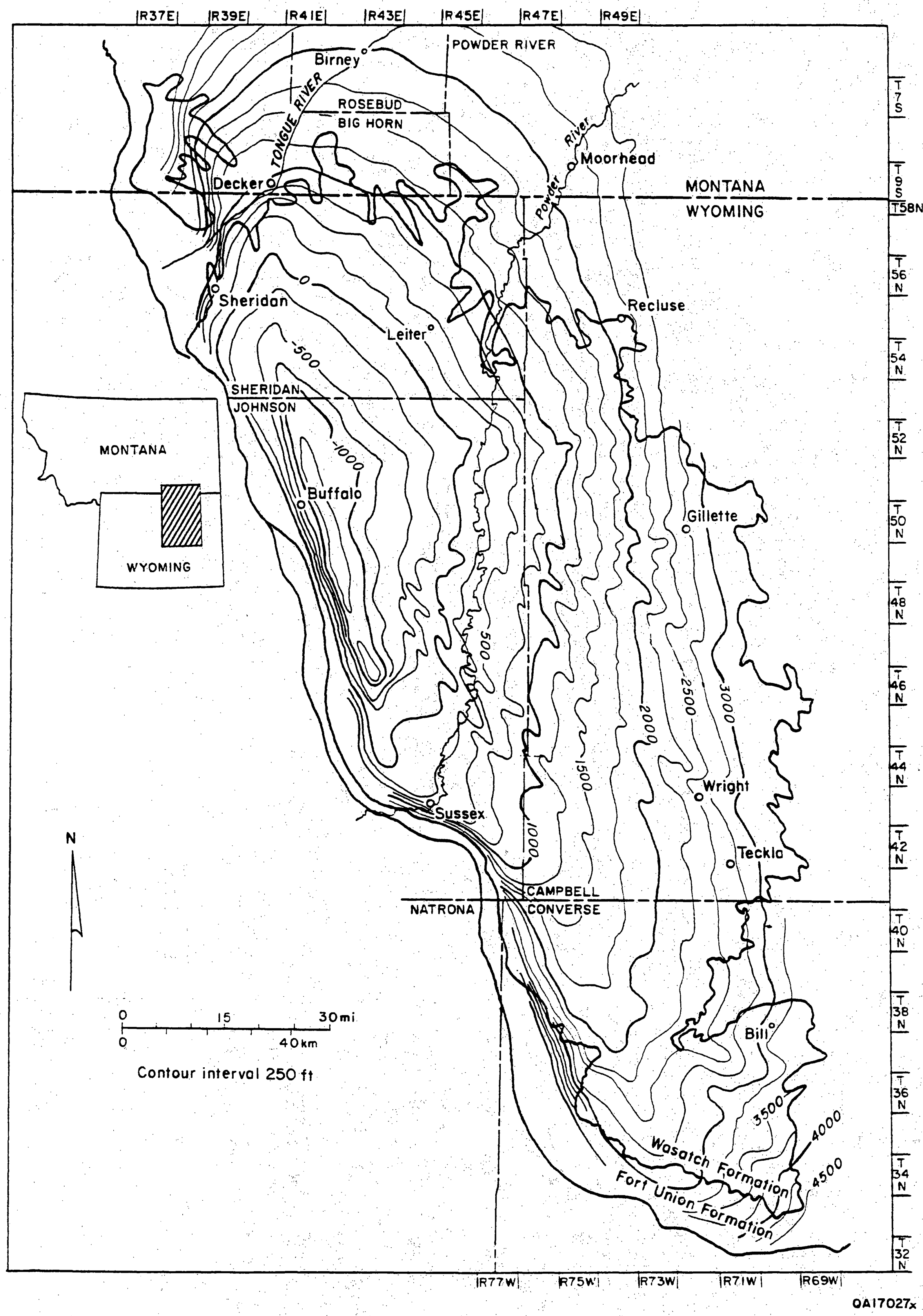


Figure 64. Structure map drawn on the top of the Tullock Member, Fort Union Formation. Datum is sea level. Pronounced asymmetry of the basin is apparent. The structural axis is 6 to 10 mi (10 to 16 km) from the west margin. Modified from Ayers (1984).

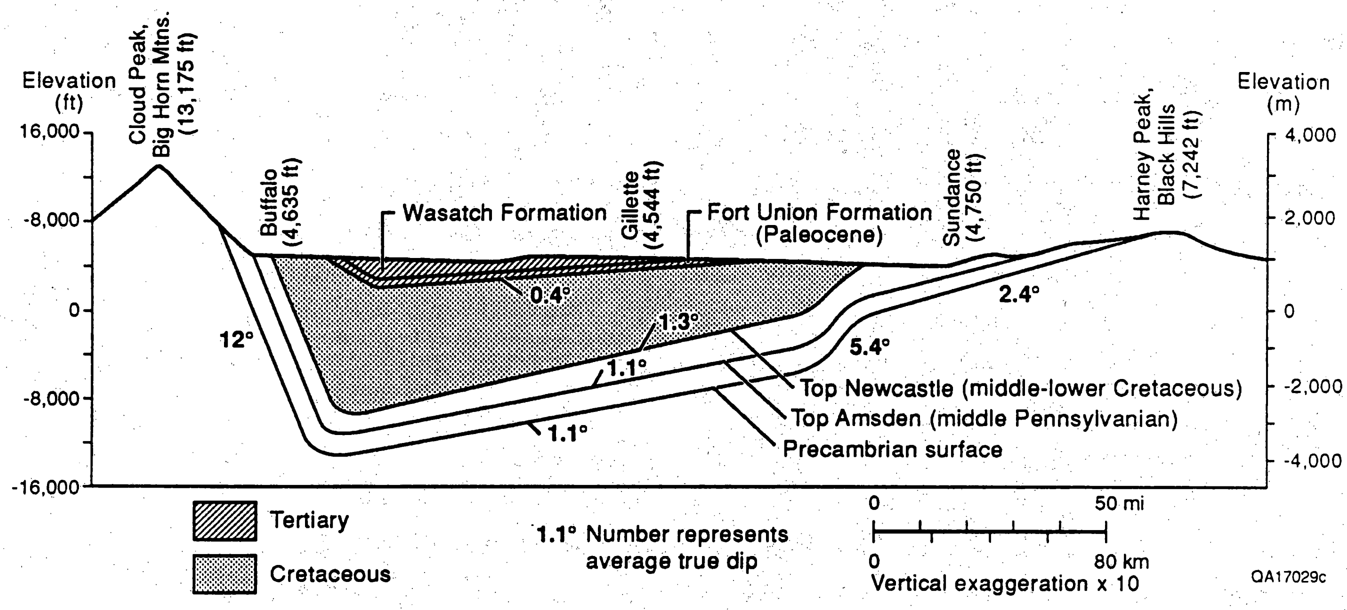


Figure 65. East-west section across Powder River Basin showing slightly tilted, troughlike structure in older sedimentary rocks. Modified from Choate and others (1984a).

Powder River Basin is marked by the deposition of the Tullock Member of the Fort Union Formation (Curry, 1971; fig. 63). Lacustrine conditions were established by the middle Paleocene (Lebo) after continued subsidence along the axis of the Powder River Basin. Further uplift and erosion shed coarse sediments mainly from the east into the basin in late Paleocene (Tongue River). During the Eocene (Wasatch) uplift continued, and conglomeratic alluvial fans were deposited along the flank of the Big Horn Mountains. In post-Oligocene time, the basin was further modified by additional tilting, warping, extensive and rapid basin excavation (Love, 1988a). Basin filling continued through at least the early part of the Miocene and possibly through middle Miocene time. This was followed by regional uplift, northward tilting of most of the Powder River Basin, and the establishment of the north-flowing Powder River and northeastward-flowing Belle Fourche River. The latter was superimposed across the north part of the Black Hills Uplift. At about the same time, normal faulting occurred near the south and southeast margins of the basin. Regional uplift and perhaps the more localized faulting started the reexcavation of the Powder River Basin and the exhumation of the adjacent mountains (Love, 1988a). This process has continued to the present time.

Geometry and Age of Basin Margin Uplifts

Although the overall structural pattern of the Powder River Basin appears simple relative to other intermontane basins of Colorado, Wyoming, and New Mexico that are closer to the Overthrust Belt, complex thrust structures are present along the flanks of the bounding uplifts (Blackstone 1981, 1988; Marrs and Raines, 1984). These thrust-related uplifts that developed during the Laramide Orogeny have strongly influenced depositional patterns in the Powder River Basin (Flores, 1981; Slack, 1981; Marrs and Raines, 1984; Weimer, 1986) and play a role in governing cleat patterns.

The Black Hills Uplift on the east side of the Powder River Basin was emplaced along a series of reverse and thrust faults in the Paleocene (Lisenbee, 1988). The uplift is a major source terrane for sediments entering the basin, as evidenced by (1) lithofacies maps of the Tullock Member that indicate sand percentage increasing towards the uplift (Ayers, 1984) and (2) westward paleocurrent directions (Flores and Ethridge, 1985). On the west side of the Black Hills Uplift, monoclines that dip westward as much as 45° (Slack, 1981) have an overall trend of N15°W, a structural relief of as much as 6,000 ft (1,800 m), and separate gently west-dipping strata of the basin from the uplift for a strike length of 150 mi (241 km).

The west and southwest parts of the Powder River Basin were affected by the Laramide Orogeny in Late Cretaceous time (Lisenbee, 1988). The Bighorn, Laramie, and Hartville Uplifts rose on the west, southwest, and south sides of the basin, respectively (fig. 62), became eroded to their Precambrian cores, and contributed coarse clastic debris to the basin (Love, 1988a). Uplift in this part of the basin is typified by the Bighorn Uplift, which was emplaced along a series of imbricate thrust faults (Blackstone, 1981). The Laramie Mountains and Hartville Uplifts are similarly bounded by a series of thrust-fault systems, which extend from Lance Creek field around the south end of the basin to the flank of the Laramie Mountains south of Glenrock, Wyoming, changing orientation from northeast to east-west to southwest in an arcuate pattern while dipping to the south beneath the adjacent highlands (fig. 66; Blackstone, 1988). The anticlinal nature of these uplifts in the Powder River Basin form by the draping of the Phanerozoic sections over upthrust basement blocks (Lisenbee, 1988). The orientation of maximum compressive stresses that cause these features is inferred to be northeasterly (Gries, 1983a), but reliable paleostress direction indicators have not yet been documented in the basin.

Fracture Systems and Cleat in Coal

Face- and butt-cleat sets are present in subbituminous coals of the Powder River Basin. Cleat spacing within these coal beds tends to decrease as the rank and purity of the coal increase (Stoner, 1981). In subbituminous coals in the Tongue River Member of the Fort Union Formation, Stoner (1981) recorded a cleat spacing ranging from 0.8 to 2.8 inches (2 to 7 cm). Cleat sets are, however, not uniformly developed throughout the basin. In the western and southwestern Powder River Basin, in areas where cleat polarity can be recognized and where mutually crosscutting cleat patterns are prevalent, the face-cleat set is oriented approximately perpendicular to the basin axis (N70°E to N90°E) (fig. 67); the butt-cleat set parallels the northwest-trending (N35°W) basin axis. In the eastern Powder River Basin, cleat polarities are not uniformly developed. In Buckskin and Wyodak Coal Mines near Gillette, cleat orientations are quite variable, and several cleat-strike domains can be recognized. The dominant cleat-strike domains are N40°E–N70°E and N20°W–N40°W, with variations including N70°E–N80°E, N50°W–N60°W, and N70°W–N90°W. No distinction could be made between face- and butt-cleat sets because the dominant cleat polarity could not be recognized. Similarly, cleat sets in oriented core in the Roland and Smith coal field (Fort Union Formation) in this area are highly variable, ranging from N75°–90°W; N35°–45°W; to N5°E–N35°E (Henkle and others, 1977; Stoner, 1981). Lee and others (1976) reported similar variable cleat orientations in the Tongue River Member in the Sheridan-Decker coal field, in the northwest part of the Powder River Basin. Because cleat sets are a manifestation of some combination of tectonic strain and volume compaction resulting from coal maturation during coalification, variable cleat domains in the east part of the Powder River Basin are probably the effects of being too far from the stress field associated with the Overthrust Belt or stress associated with compaction has played a dominant role in rotating the face-cleat strike. Additional documentation of cleat characteristics is needed in the Powder River Basin because these cleat sets are important conduits for methane migration.

Other Faults and Reactivated Basement Structures

The west part of the Powder River Basin is transected by northeastward-striking faults, breccia zones, and mineralized fracture zones. The largest, the Buffalo Deep Fault, which lies west of the basin

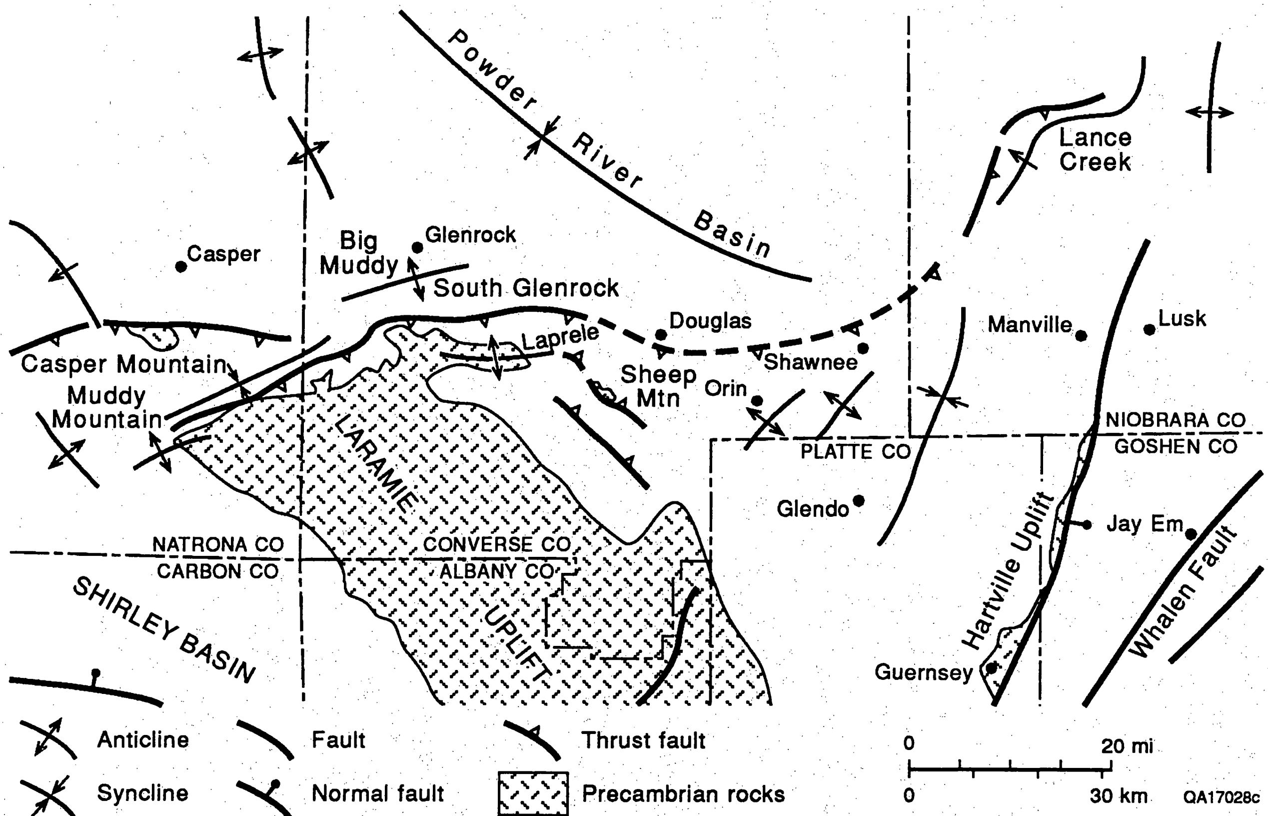


Figure 66. Tectonic index map, south end of Powder River Basin. Precambrian rocks indicated by pattern. Modified from Blackstone (1988).

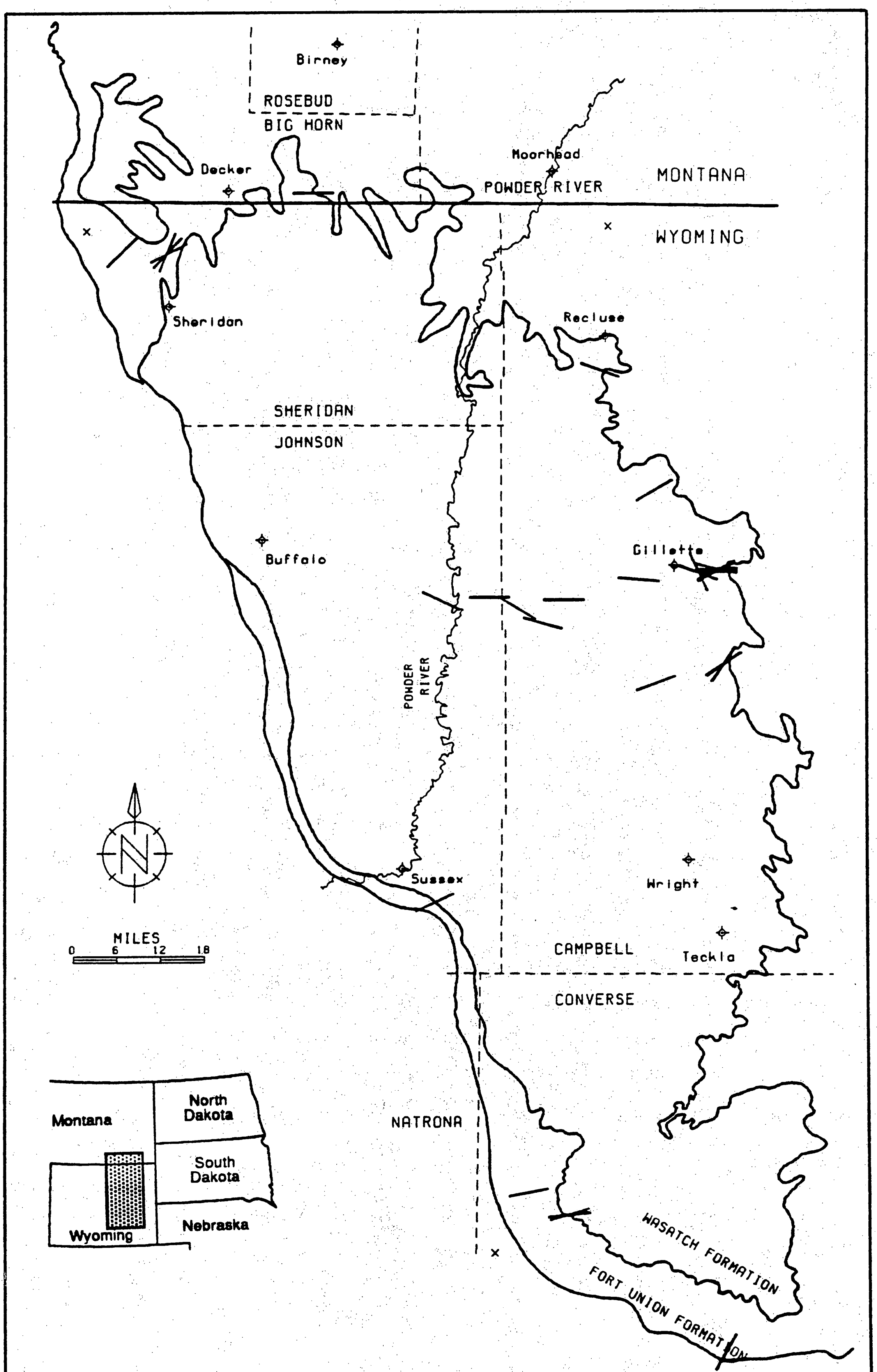


Figure 67. Face-cleat strike, Powder River Basin.

axis, dips westward and has an estimated throw of 1,300 ft (396 m) (Blackstone, 1981). Recurrent movement of these northeastward-trending faults has offset thrust faults in the Tertiary rocks in the west part of the basin. Within the Powder River Basin these northeastward- and northwestward-trending lineaments may control hydrocarbon accumulation in some Cretaceous and older sedimentary rocks (Slack, 1981; Marrs and Raines, 1984).

In the eastern Powder River Basin, thickness variation of strata (Upper Cretaceous, Belle Fourche Shale to Niobrara Formation; fig. 63) have been controlled by paleotectonic movement (Weimer and Flexer, 1985). Topographic highs are interpreted to be localized along structural lineaments corresponding to Precambrian (Hudsonian 1.7 bya) shear zones (Slack, 1981). Comparisons of lineaments with mapped folds, faults, facies changes, and geophysical data indicate that they represent reactivation zones along boundaries of basement blocks (Marrs and Raines, 1984). These block boundaries form systematic, rectilinear patterns. Facies changes, transport patterns, and contrasts in depositional environment parallel the block boundaries. Movement along lineaments is expressed primarily by stratigraphic variation in unit thickness, facies distribution, and changes in depositional strike. These linear features fall generally within two populations, one trending N30°E–N85°E, the other trending N12°W–N53°W (Marrs and Raines, 1984). The northeastward-trending lineaments are dominant and have been susceptible to repeated rejuvenation throughout Phanerozoic time. Because these lineaments have been reactivated through time, they controlled patterns of sedimentation in Cretaceous and other sedimentary units in the east parts of the basin (Slack, 1981; Marrs and Raines, 1984).

Roughly concordant with the two dominant fracture trends is a system of local, small, low-amplitude folds that are confined stratigraphically to the Fort Union and Wasatch coal-bearing horizons. These folds are drapes over depositional surfaces and may be partly caused by differential compaction of water-saturated sediments in shallow basins before lithification (Choate and others, 1984a). Such small but numerous compaction-induced folds have been noted as potential exploration targets for methane in other western coalbed methane basins (Ayers and Zellers, 1991; Tyler and others, 1991).

Stress Orientation

No stress orientation determinations have been published for coal-bearing units in the Powder River Basin. Stress patterns have been extrapolated from adjacent areas to make regional stress maps (Zoback and Zoback, 1980; Zoback and Zoback, 1989) According to these, the Powder River Basin is on the west edge of the Mid-Plate stress province, east of the Cordilleran Extension stress province (fig. 10; Zoback and Zoback, 1989). The Mid-Plate stress province is a large, tectonically quiescent region characterized by east-northeastward-striking maximum horizontal compressive stresses. The northwestward-trending boundary between the Mid-Plate stress province and the Cordilleran Extension stress province is southwest of the Powder River Basin. The maximum horizontal compressive stress in the Cordilleran

Extension stress province is north-northeast, oblique to that of the Mid-Plate stress province. In this poorly defined transition zone between the two provinces (fig. 10), stress orientations may rotate (Zoback and Zoback, 1980). Although stress direction determinations in the basin are sparse, the overall regional stress pattern predicts relatively uniform stress directions throughout the basin (Zoback and Zoback, 1989). If this is the case, predictions of fluid-flow patterns and anisotropy would be simplified. However, areas of contrasting face-cleat orientation in the north-central and -east parts of the basin may have different production characteristics, depending on the orientation of cleat in relation to current stress direction.

Stratigraphic and Depositional Setting of Coal-Bearing Formations

Mesaverde, Meeteetse, and Lance Formations

Upper Cretaceous coal-bearing stratigraphic units in the Powder River Basin include the Mesaverde, Meeteetse, and Lance Formations (fig. 63). Thin coal beds (1.8 to 3 ft [0.5 to 0.9 m] thick) (Glass, 1981) and carbonaceous shales of the Mesaverde and Meeteetse Formations formed in low-relief, delta-plain and coastal-plain environments landward (westward) of wave-dominated shoreline deposits in the Western Interior Seaway (Hubert and others, 1972). Both of these units interfinger with marine shales to the east and are absent in the eastern Powder River Basin (Jones, 1990).

The Lance Formation is separated from the underlying Mesaverde and Meeteetse Formations by the Bearpaw (Lewis) Shale and Fox Hills Sandstone (fig. 63). Coal beds in the Lance Formation are discontinuous and average 3 to 6 ft (0.9 to 1.8 m) in thickness in the southwest part of the Powder River Basin (Mapel, 1958; Curry, 1971; Glass, 1981). Thickest Lance coal beds overlie the Fox Hills Sandstone (Choate and others, 1984a) and formed landward of the north-trending Fox Hills paleoshoreline. In the Powder River Basin, Upper Cretaceous coal beds are 1,500 to 3,000 ft (457 to 915 m) below the base of the Fort Union Formation (Breckenridge and others, 1974) and are more than 5,000 ft (>1,524 m) deep in the center of the basin. Because these coal beds are also thin and discontinuous, they are poor targets for coalbed methane in the Powder River Basin.

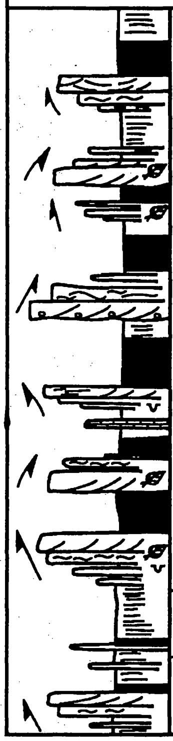
Fort Union Formation

The Fort Union Formation, approximately 3,000 ft (915 m) thick (Glass, 1981) and unconformably overlying the Lance Formation (fig. 63), contains the thickest coal beds in the Powder River Basin. Thickest Fort Union coal beds are present in the 1,500- to 1,800-ft (457- to 549-m) thick Tongue River Member that overlies the Lebo and Tullock Members (fig. 63). Tongue River coal beds are best exposed in the north and east parts of the basin, where there are 8 to 12 continuous subbituminous seams (Denson and Keefer, 1974). The thickest of these coal beds is the Wyodak-Anderson seam, exposed on the east margin of the basin. The Wyodak-Anderson seam is commonly 50 to 100 ft (15 to 30 m) thick, although it is locally as much as 150 ft (46 m) thick, and is estimated to contain at least 100 billion short tons (90.7 billion t) of coal to a depth of 2,000 ft (610 m) (Choate and others, 1984a). The Wyodak-Anderson seam splits into two to four thinner seams (each 10 to 50 ft [3 to 15 m] thick) southward, westward, and northward of the Gillette area (Glass, 1981).

Fort Union net-coal thickness, determined from geophysical logs, is greatest (locally exceeding 300 ft [91 m]) (fig. 68) in the center of the Powder River Basin, approximately 30 mi (48 km) southwest of Gillette (fig. 69a) (Ayers, 1984). Two northwest-trending, irregular belts of more than 100 ft (>30 m) of maximum coal in the east and central parts of the basin (fig. 69b) correspond to two offlapping coal depocenters in the upper Tongue River Member (Ayers and Kaiser, 1984). Individual coal beds in these depocenters are northwest trending, and extend for more than 40 mi (>64 km) and have an areal extent of as much as 1,200 mi^2 (3,107 km^2) at depths of less than 3,000 ft (<915 m) (Ayers and Kaiser, 1984). The greatest number of Fort Union coal beds (17 to 32) occurs in the north-central part of the basin in a broad area 10 to 45 mi (16 to 72 km) east and southeast of Sheridan, Wyoming (fig. 69c).

The depositional setting of the Fort Union Formation has been vigorously debated, and the alternate interpretations are either (1) accumulation of sediments in an alluvial sequence (Flores, 1979, 1980a, 1981) deposited by a northward-flowing axial fluvial system (Ethridge and others, 1981; Flores and others, 1982; Flores, 1983; Flores and Ethridge, 1985) or (2) a lacustrine system infilled by fluvial-dominated deltas that emanated from several point sources around the lake margin but mainly from the east (Ayers and Kaiser, 1984; Ayers, 1986a). The fundamental difference lies in whether the basin center is sand rich (northward-flowing fluvial system) or sand poor (lacustrine sedimentation). These disparate depositional interpretations have important implications for the prediction of coal distribution, quality, and thickness in the basin, as well as for the hydrologic setting of the coal.

Flores (1981), Flores and Hanley (1984), and Warwick and Stanton (1988) have postulated peat accumulation in floodbasin swamps adjacent to anastomosed and transitional meandering fluvial channel complexes associated with a major trunk stream in the center of the basin. Here, thick coal beds flank alluvial belts at the basin center. The lacustrine depositional model of Ayers and Kaiser (1984) and Ayers (1986a) identified multiple, digitate sand-rich axes sourced from the east, northwest, and southwest that pinch out in the muddy center of the basin (fig. 70) at the position of the fluvial system that was postulated by Flores (1984b). Peat accumulation commenced in broad interdeltaic and interdistributary areas at the loci of regional ground-water discharge (Ayers and Kaiser, 1984). Upon delta abandonment, peat growth spread over abandoned delta lobes. Regional coal geometry is therefore strike parallel (fig. 69a and b) and the interdeltaic coals are bounded basinward by lacustrine muds and updip by the framework fluvial-deltaic facies. Two broad, strike-parallel zones of thick coal are apparent in figure 69b. The more westerly zone (Big George Coal) is stratigraphically higher than the older, easterly zone (Wyodak-Anderson), which Ayers and Kaiser (1984) attributed to basinward Tongue River progradation.



SCHEMATIC SECTION	FORMATION (Depositional system)	COAL BEDS: Thickness (ft) Average	COAL BEDS: Thickness (ft) Maximum	COAL BEDS: Thickness (ft) Net	COAL BEDS: Number	COAL BEDS: Continuity	SANDSTONES: Thickness (ft) Maximum	SANDSTONES: Thickness (ft) Net	SANDSTONES: Continuity	COAL-SANDSTONE RELATIONS
	WASATCH FORMATION (Fluvial, lacustrine)	10-20	30-52; one 220-ft coal bed known near Sheridan, Wyoming	100-200 common	≥8	Good continuity in northwest- and north-trending belts between fluvial depositional axes	50-100	—	Fair: lenticular point-bar deposits; lobate lacustrine-delta-front and crevasse-splay sandstones	Thickest coal beds lie between north-trending belts of channel-fill sandstone; thinner coal beds overlie crevasse-splay ss. and split or pinch out near channel-fill sandstones.
Tongue River Member; *Lebo Member*; *Tullock Member*	FORT UNION FORMATION* (Lacustrine-delta, fluvial)	>20 in east-central basin	50-150	>300	10-20	Excellent: most continuous coal beds in northwest-trending pods in Johnson and Campbell Counties, Wyoming	100-170	300-700	Fair: lenticular distributary-channel ss.; thin, lobate crevasse-splay sandstone; lobate, moderately continuous lacustrine-delta-front sandstone.	Thickest coal beds overlie abandoned-delta lobes, down-dip (southwest) of major dip-elongate belts of fluvial channel-ss. in the east part of the basin.

*Tongue River Member only

SEDIMENTARY STRUCTURES AND ROCK TYPES

- Clasts
- Burrows
- Organic fragments
- Upward-coarsening
- Upward-fining
- Planar bedding
- Cross bedding
- Ripples
- Coal
- Limestone

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Figure 68. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in Powder River Basin.

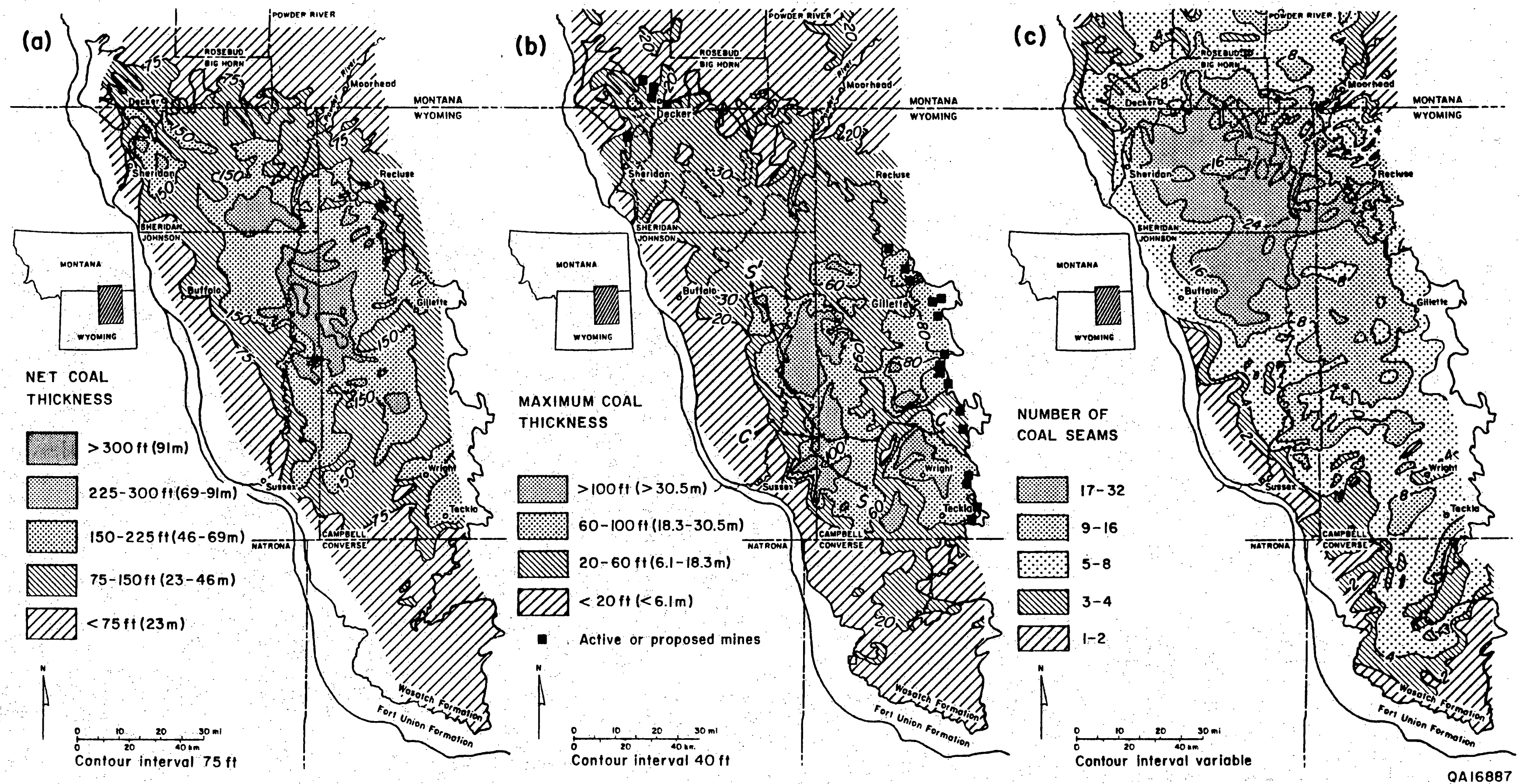


Figure 69. (a) Net-coal thickness, (b) maximum-coal thickness, and (c) coal-isopleth map of the Tongue River Member of the Fort Union Formation in Powder River Basin. Modified from Ayers (1984).

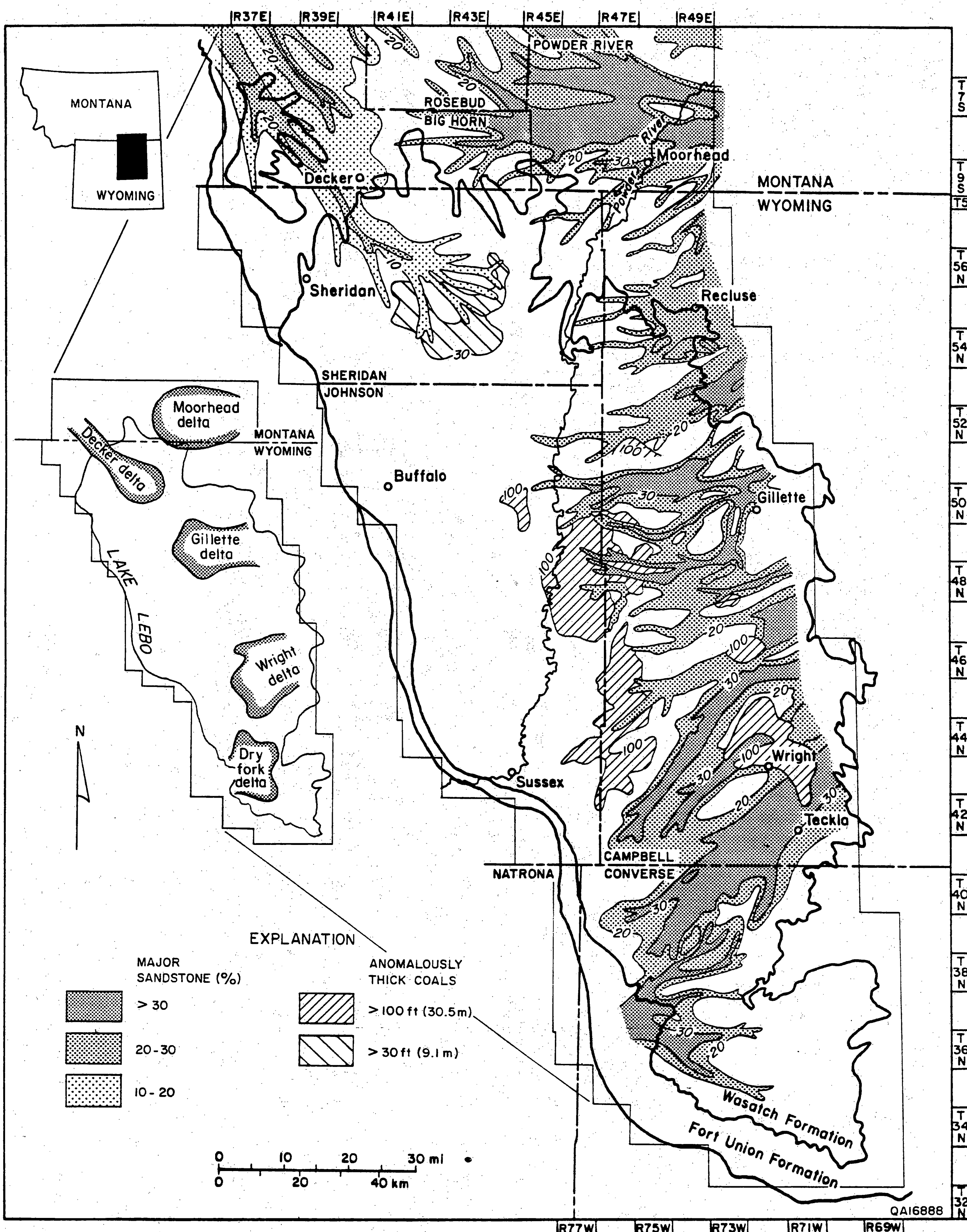


Figure 70. Lacustrine deltas and coal depocenters in the Tongue River Member of the Fort Union Formation in Powder River Basin. Peat-forming environments in coal depocenters (areas of anomalously thick coals) overspread abandoned deltas. Modified from Ayers (1984).

Wasatch Formation

Other important coal beds in the Powder River Basin occur in the 1,000- to 2,000-ft (305- to 610-m) thick Wasatch Formation that unconformably overlies the Fort Union Formation (fig. 63). The Wasatch Formation contains as many as eight thick, continuous coal beds that are thickest and most continuous in the west and central parts of the basin (Glass, 1981). Wasatch coal beds are thinner than those of the Fort Union Formation; maximum thickness of Wasatch coal beds ranges from 30 to 52 ft (9 to 16 m) (fig. 68), although the Lake De Smet coal bed near Sheridan is locally 220 ft (67 m) thick (Mapel, 1959)—the thickest coal bed in the United States. In many areas of the Powder River Basin, Wasatch coal beds have less than 200 ft (61 m) of overburden (Choate and others, 1984a) and are therefore poor targets for coalbed methane.

Regional subsurface maps showing distribution and thickness of Wasatch coal beds and sandstones in the Powder River Basin have not been published, although local outcrops and mine exposures were described by Sharp and others (1964), Seeland (1976), Obernyer (1978), Jackson and Ethridge (1979), and Ethridge and others (1981). A survey of Wasatch grain-size facies by Sharp and others (1964) indicates that coarse-sandstone facies are on the south margin of the basin along the basin axis and grade northward into interbedded sandstone and silty clay facies. Locally occurring conglomeratic facies in the northwest part of the basin near Buffalo were noted by Obernyer (1978). Grain-size trends were integrated with paleocurrent data around the basin by Seeland (1976), who interpreted the Wasatch Formation to have been deposited by a system of northward-flowing rivers with a trunk stream along the basin axis (fig. 71). Areas lateral to the trunk stream and between tributaries were dominated by floodbasin (crevasse-splay, swamp, and lake) environments and were sites of relatively thick peat accumulation. Thickest Wasatch coal beds (individual seams thicker than 30 ft [9 m]) formed in a belt on the west margin of the major basin-axis alluvial facies (Sharp and others, 1964) and appear to pinch out and split toward the basin axis (Ethridge and others, 1981).

Hydrology

In the Powder River Basin, the Fort Union and Wasatch Formations are combined to form the coal-bearing hydrostratigraphic unit. The Lebo Shale Member (Fort Union Formation), a leaky confining layer (U.S. Department of the Interior, Bureau of Land Management, 1990), separates the sandstone-rich Tullock Member from the coal-rich Tongue River Member (figs. 63 and 72). Thus, the Tongue River–Wasatch interval is the hydrostratigraphic unit relevant to coalbed methane, where coal seams are the major aquifers. The Wyodak coal aquifer is in the upper part of the Tongue River and is the most continuous geohydrologic unit in the Powder River Basin (U.S. Department of the Interior, Bureau of Land Management, 1990). Wells completed in the coal generally yield from 343 to 1,714 bwpd (55 to

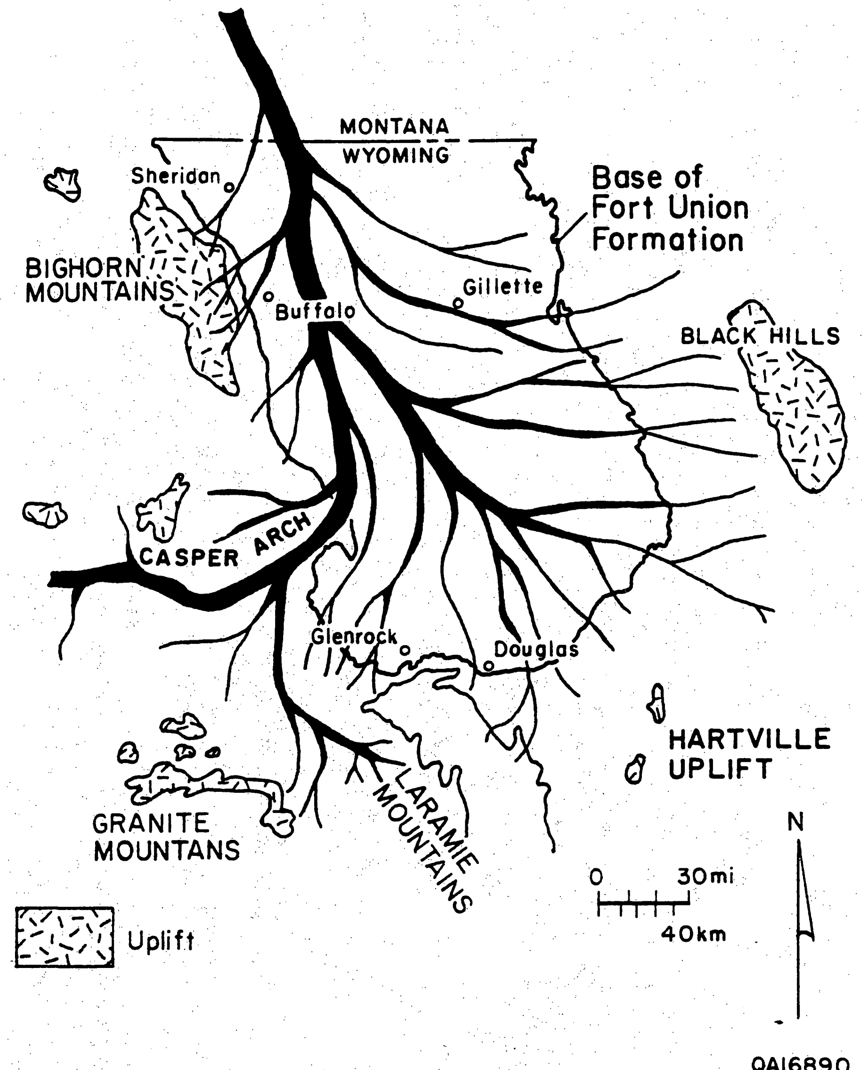


Figure 71. Paleogeographic reconstruction and inferred fluvial depositional axes of the Wasatch Formation in the Powder River Basin. Modified from Seeland (1976).

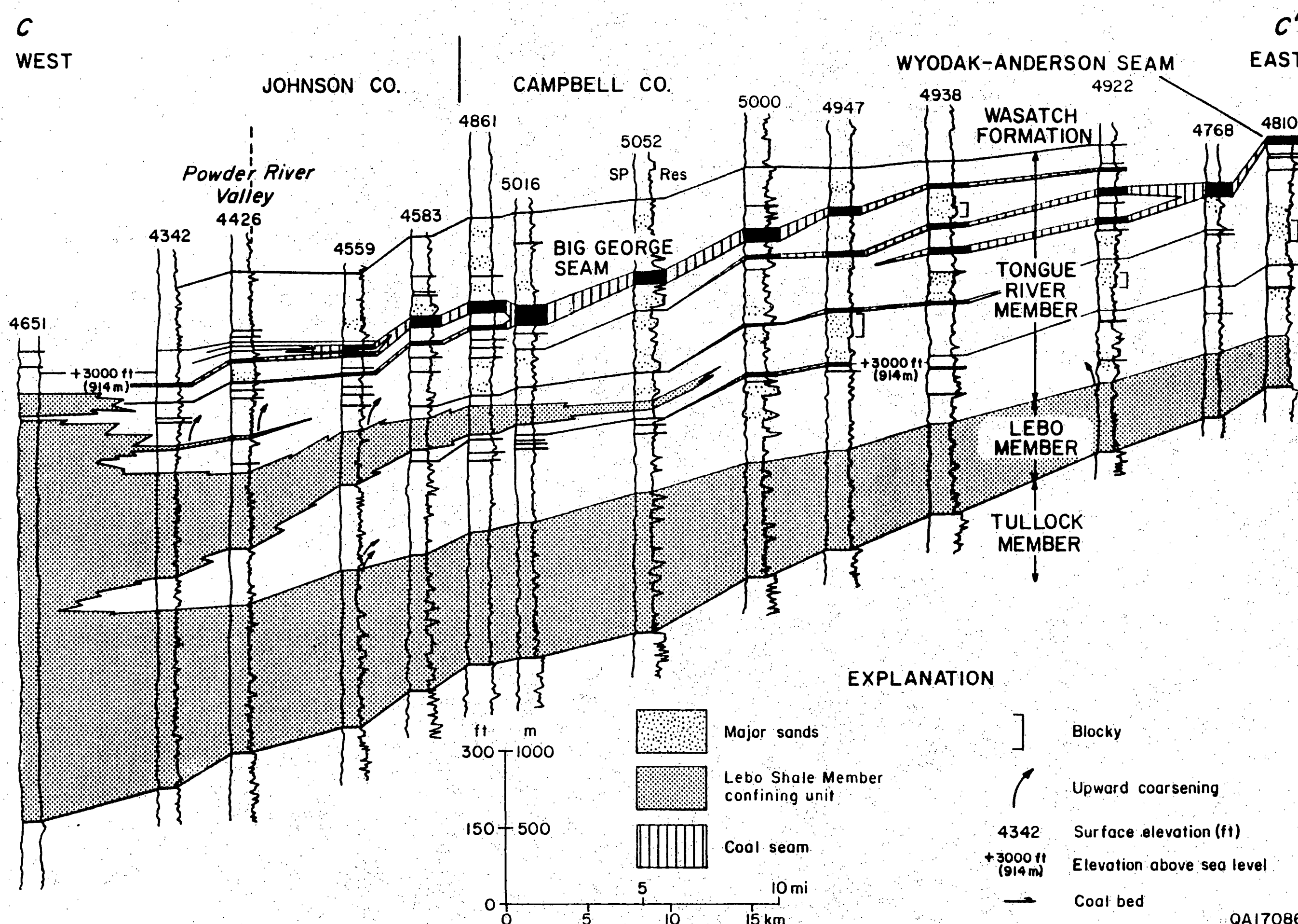


Figure 72. West-east dip cross section through the Powder River Basin at T45N. Modified from Ayers (1984). Lebo confining unit separates Tullock from Tongue River. Tongue River coal seams are normally pressured and artesian. Upon confinement and pinch-out basinward, artesian conditions develop. Wells flow at rates as high as 2,000 bbl/d.

272 m^3/d). Wyodak permeabilities range from 10 md to darcys (U.S. Department of the Interior, Bureau of Land Management, 1990).

The Fort Union Formation crops out around the basin margin (Love and Christiansen, 1985) and receives most of its recharge along the wet east margin of the basin (fig. 19). Recharge is also received on the east flank of the Big Horn Mountains (fig. 65). The Wasatch Formation crops out over much of the basin and receives recharge directly from infiltration of precipitation. Stream valleys may also provide recharge in areas where alluvium and coal seams are in contact (Davis, 1976).

Regional ground-water flow is northward (figs. 19 and 73). Ground water in the Fort Union coal seams has a westward component (Daddow, 1986) and appears to be moving toward the Tongue River (Davis, 1976). Westward flow probably reflects east dipping strata and/or an east-west face-cleat strike (fig. 74). The Tongue River Member is confined basinward, whereas the Wasatch Formation is mainly unconfined. Consequently, lower gas contents are predicted for Wasatch coal beds. Artesian conditions develop basinward as coal seams become confined by shale beds and pinch-out (fig. 72). Flowing wells attest to artesian conditions and are common in the Powder and Tongue River valleys (Lowry and Cummings, 1966; Whitcomb and others, 1966). Flowing wells discharge at rates ranging from 34 to 583 bbl/d (5.4 to 93 m^3/d) to as high as 2,207 bbl/d (351 m^3/d) (Whitcomb and others, 1966). Produced water is commonly accompanied by dissolved gas (mainly methane) at gas/water ratios of 1.7 to 12.4 ft^3 (0.05 to 0.35 m^3) of gas per bbl of water or 0.3 to 2.2 liters of gas per liter of water (Lowry and Cummings, 1966).

Fort Union (Tongue River) coal seams are major aquifers and will be difficult to dewater for economic exploitation, especially basinward as the seams become better confined. This is certainly true of the Big George seam in Johnson County (fig. 72). Because flowlines converge on discharge areas, dewatering and depressuring will be more difficult in the valleys of major rivers such as the Powder and the Tongue. Attendant large volumes of produced water will create disposal problems and add to production costs.

Coal Rank

Previous studies of coal rank in the Wasatch and Fort Union Formation have been limited to outcrop (Cooley and Ellman, 1975; Glass, 1975; Matson, 1975; Matson and Pinchock, 1976; Glass, 1980b; Pawlewicz and Barker, 1989). Coal rank of Wasatch and Fort Union coals ranges from lignite to subbituminous and locally to high-volatile C bituminous (Wold and Woodward, 1968), indicating that these coals have not reached the thermal maturity level required to generate significant quantities of thermogenic methane. Vitrinite reflectance profiles indicate that coal rank in the Powder River Basin does not increase significantly with depth (fig. 75). Coal rank in the north and central parts of the basin does not reach the high-volatile C bituminous stage until approximately 9,000 ft (2,744 m), and the threshold of significant methane generation (vitrinite reflectance value of 0.74 percent) is not reached until 13,000 ft (3,963 m). The high-volatile C bituminous stage is reached at approximately 6,000 ft (1,829 m) in the

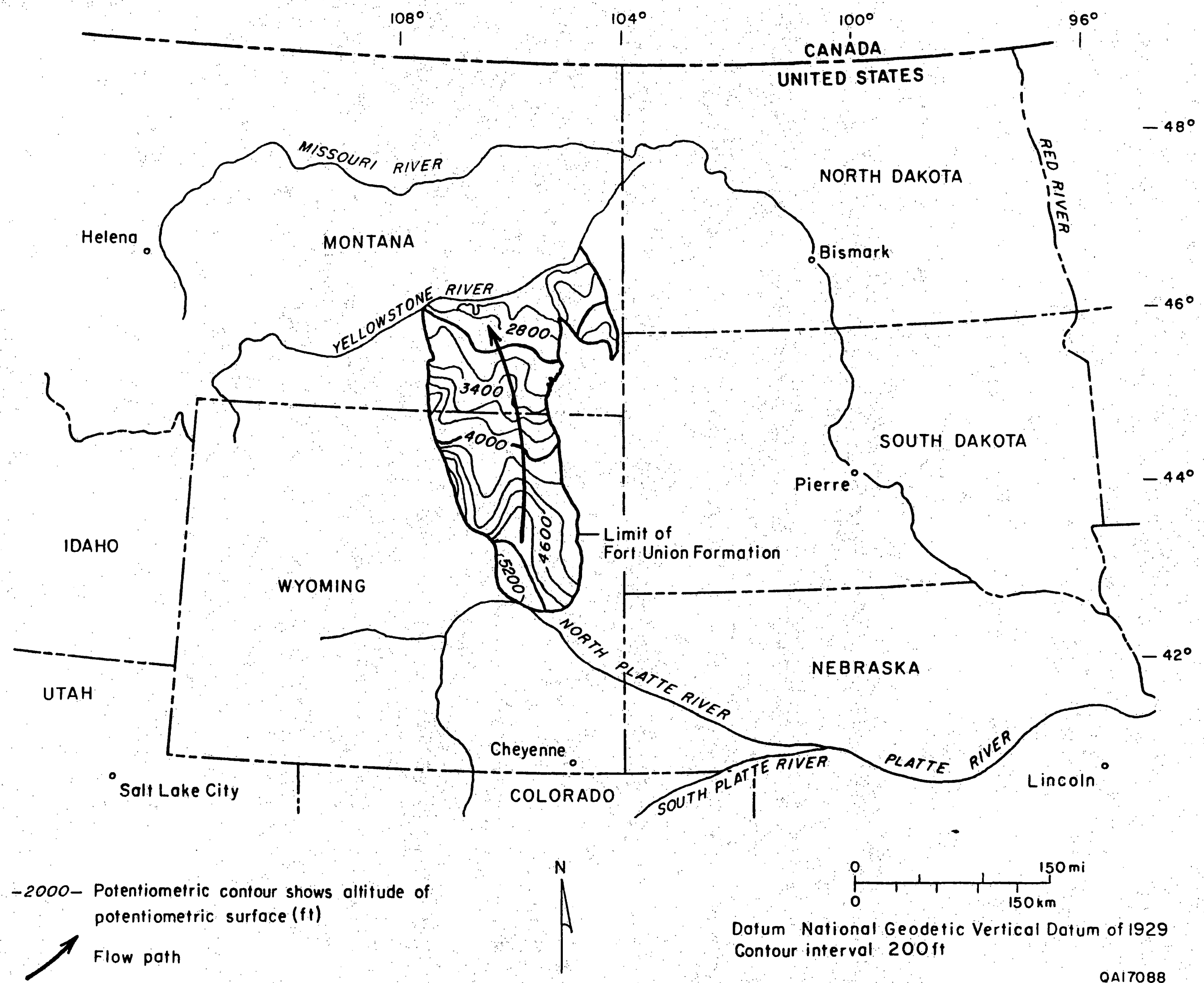


Figure 73. Potentiometric-surface map of the Tertiary (Fort Union/Wasatch) aquifer in Powder River Basin. Modified from Lobmeyer (1985). Ground water flows northward as predicted from regional topographic gradient.

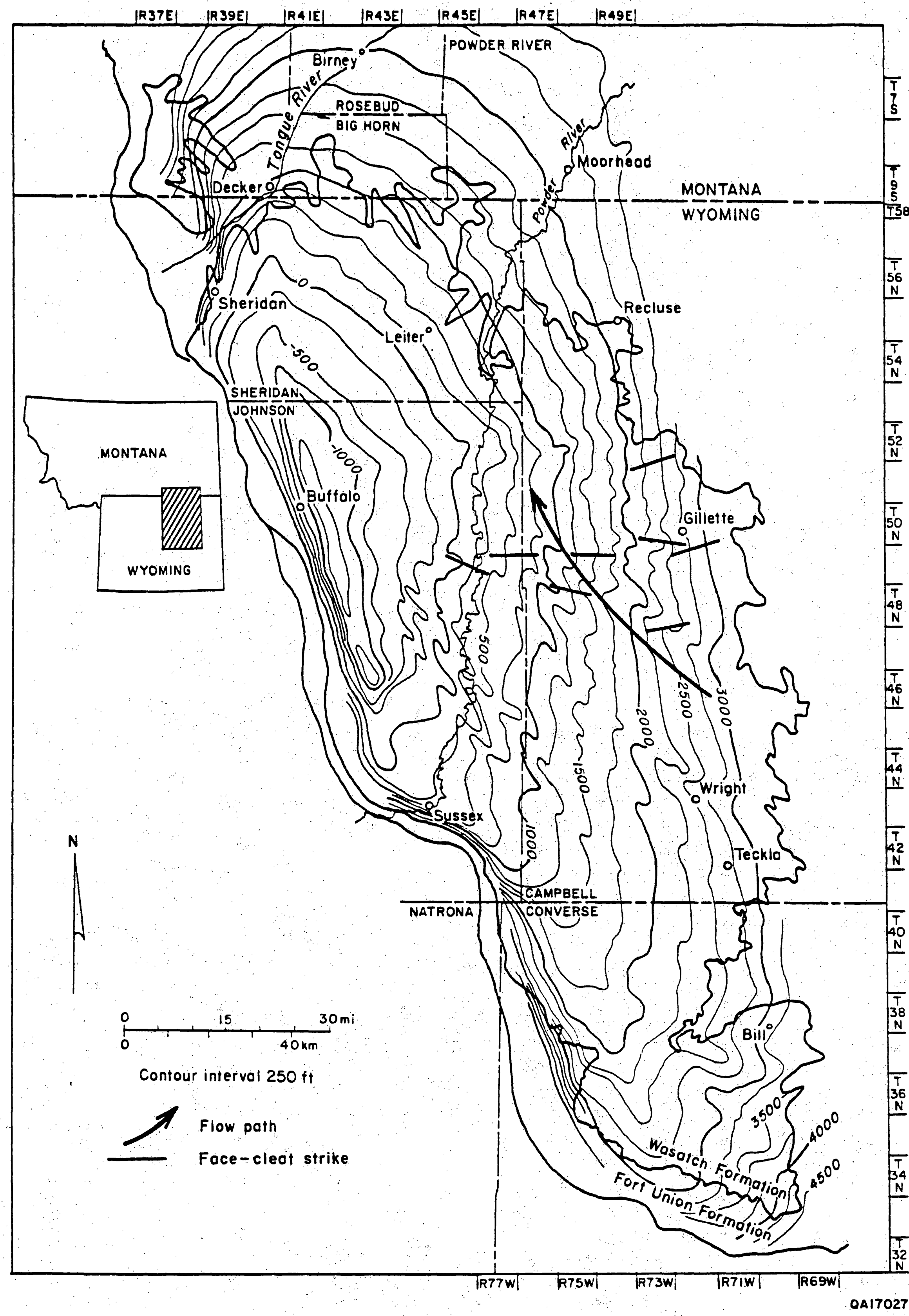


Figure 74. Ground-water flow in Fort Union coal seams. Flow has a westward component toward the Tongue River. Structure map modified from Ayers (1984).

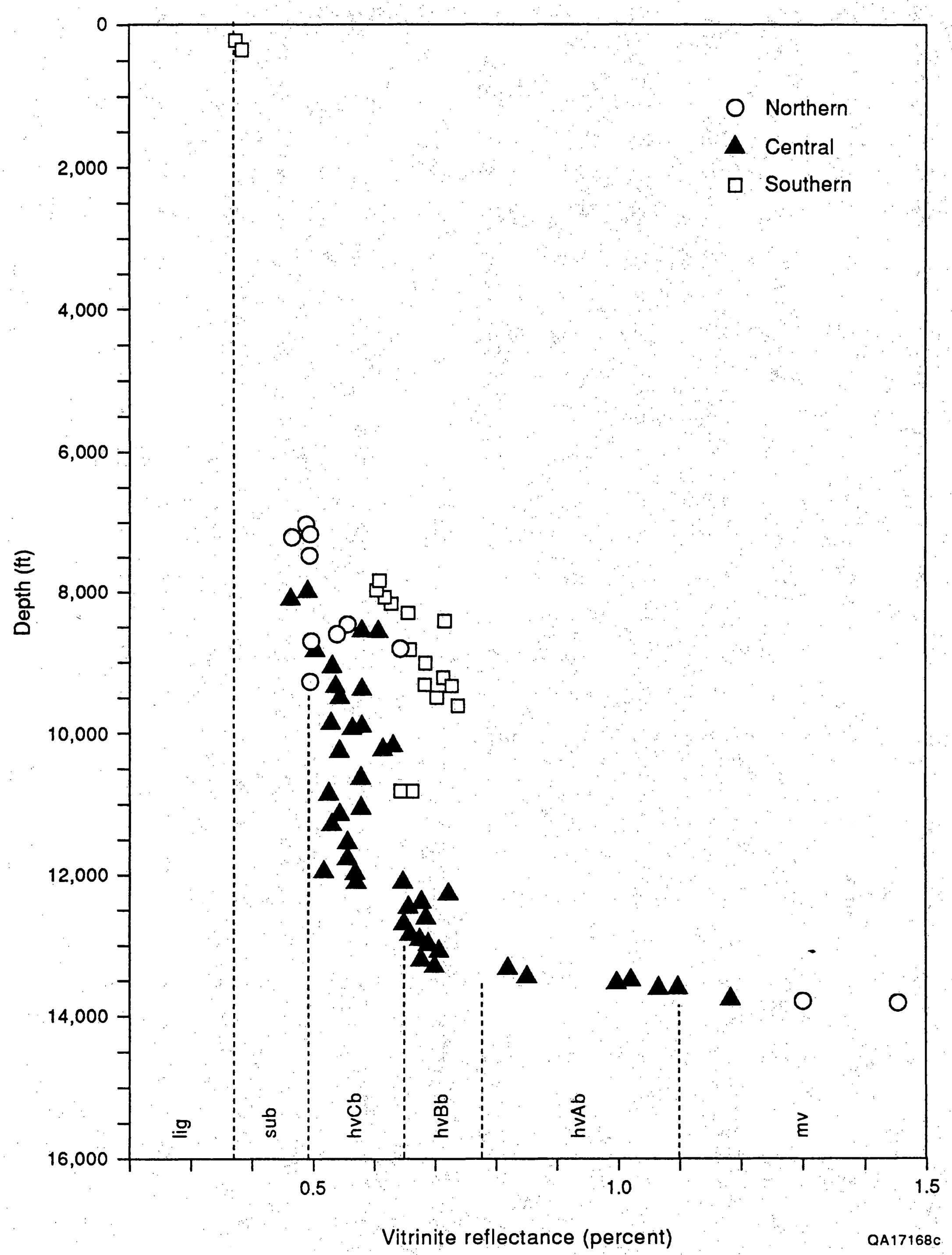


Figure 75. Vitrinite reflectance profiles for Powder River Basin. Vitrinite reflectance values increase gradually as depth increases. Data from Nuccio (1990). Note great depth required to exceed R_o of 0.73 percent.

south part of the basin (fig. 75). Burial and thermal maturity models developed by Nuccio (1990) for the Upper Cretaceous Steele Member of the Cody Shale (fig. 63) indicate that the thermally most mature source rocks are found along the structural axis of the basin. However, Fort Union coal beds are shallow (less than 3,000 ft [914 m])(Ayers and Kaiser, 1984), indicating that coal beds located along the basin axis probably have not reached the high-volatile C bituminous stage.

Wasatch and Fort Union coals are thermally immature and have not reached the main gas generating stage, although some early thermogenic coalbed gases may have been generated. Coal beds along the basin synclinal axis could contain slightly more thermogenic methane owing to deeper burial depths. The contribution of thermogenic gases, either early thermogenic indigenous to the coal beds or thermally mature gases that have migrated from deeper source rocks, to total coalbed methane production is currently unknown. However, coalbed gases produced from the Fort Union Formation have been found to be predominantly biogenic in origin on the basis of methane isotopic analyses. The quantity and distribution of biogenic methane will depend in part on the timing of gas generation; biogenic gases related to basin hydrology may show a different distribution than biogenic gases originating in the peat before coalification. Oils from Lower Cretaceous reservoirs along the east margin of the Powder River Basin have undergone biodegradation and water washing (Momper and Williams, 1984) in response to basinward movement of formation waters. Fort Union coal beds are laterally continuous (Ayers and Kaiser, 1984) and bacteria could also be transported downdip from the basin margins by formation waters under conditions similar to those in the San Juan Basin (Kaiser and others, 1991b; Scott and others, 1991a and c).

Devolatilization reactions in low-rank coal and biogenic activity are both possible sources of carbon dioxide in coal beds. Carbon dioxide is corrosive and noncombustible (which lowers the gas heating value). Therefore, carbon dioxide must be removed from the coalbed gases before the gases enter the pipeline system where carbon dioxide content exceeds 3 percent (Kaiser and others, 1991a). If the carbon dioxide content ranges reported by Boreck (1984) for Fort Union coalbed gases are representative for the basin (4 to 11 percent), then the expense of carbon dioxide removal ($0.14/Mcf [$3.96/m^3]; Kaiser and others, 1991a) must also be considered.

Gas Composition

The low rank of Wasatch and Fort Union coals suggests that methane produced from these formations either migrated from thermally more mature source rocks in the basin or were produced by the metabolic activity of bacteria in the coal. Fort Union methane $\delta^{13}C$ values range from –60.0 to –56.7‰ (Boreck, 1984: Rice and Flores, 1991) indicating that these coalbed gases are biogenic in origin rather than thermogenic. According to Rice and Flores (1991), δD of methane ranges from –307 to –315 indicating that the biogenic gases were generated via the fermentation metabolic pathway rather than by bacterial carbonate reduction. A biogenic origin for the gases is also indicated by the relatively low methane content of the coal, which is generally less than 74 scf/ton (<2.308 m^3/t) (Boreck, 1984; Rice and Flores, 1991). Therefore, most of the coalbed gases in the Powder River Basin are probably biogenic in origin, although more extensive isotopic studies are required to determine whether thermogenic gases have migrated into the coal beds.

Fort Union coalbed gases are composed of 88 to 94 percent methane, 0.4 to 3 percent heavier hydrocarbons, and 4 to 11 percent carbon dioxide (Boreck, 1984). Although gas-dryness indices were not reported, most of the gases are probably dry to very dry, having C_1/C_{1-5} values greater than 0.97. The presence of heavier hydrocarbons (C_{2+}) in these coalbed gases suggests that minor amounts of early thermogenic gases may have been generated from the coal in addition to biogenic gases. The relatively large amount of carbon dioxide associated with these coalbed gases is probably derived from devolatilization reactions that occur in lower-rank coal before the main stage of thermogenic methane generation, and/or is a byproduct of bacterial activity.

Boreck (1984) suggested that biogenic gases in Sec. 7, T48N, R77W have been retained in the coal beds because of several possible factors, including: (1) structural control, which limited the updip migration of the gases, (2) trapping of gases by shaley beds overlying the coal beds, and (3) the absence of a well-defined cleat system in the upper part of the coal bed, resulting in low permeability and limited vertical migration. However, Rice and Flores (1991) suggested that some of the coalbed gases may have migrated to adjacent sandstones. The extent and distance of vertical and horizontal migration of biogenic gases in Wasatch and Fort Union coal beds is unknown.

Coalbed Methane Production

Production Targets

The main coalbed methane targets in the Powder River Basin are thick, continuous coal beds in the upper part of the Tongue River Member of the Fort Union Formation. Almost all current drilling activity is in Wyoming (Campbell and Johnson Counties), in two northwest-trending Fort Union coal depocenters. The eastern coal depocenter in Campbell County contains the Wyodak-Anderson Coal, whereas the western coal depocenter in western Campbell and eastern Johnson Counties contains the younger and stratigraphically higher Big George Coal (fig. 72).

The Wyodak-Anderson Coal, south and southeast of Gillette in the eastern coal depocenter, ranges in thickness from 80 to 150 ft (24 to 46 m) and is 250 to 1,500 ft (76 to 457 m) deep. Drilling, completion, and production costs of typical coalbed methane wells in the eastern coal depocenter range from $45,000 to $60,000. Operation costs are low because drilling depths are shallow and water production is relatively low (Gas Research Institute, 1991e). In the eastern coal depocenter, the Wyodak-Anderson Coal trends northwestward and continues into the Recluse area, approximately 30 mi

(48 km) north of Gillette, where it splits into several thinner coal beds in Rawhide Butte and Oedekoven fields. An estimated 150 Bcf (4.245 Bm^3) of Fort Union coalbed methane resource is in the Recluse area (Larsen, 1989).

The Big George Coal in the western coal depocenter contains as much as 300 ft (91 m) of net coal in individual seams as much as 100 ft (30 m) thick. These water-charged coal beds are between 1,000 and 2,000 ft (305 and 610 m) deep. Big George coalbed methane wells are expensive and average $110,000 because the great volumes of water require disposal. For example, four Coastal Oil and Gas wells in the Big George Coal in Johnson County were recently shut in and abandoned because although they were collectively producing as much as 6,000 bbl/d (953 m^3/d) of water, only negligible amounts of gas were produced (Gas Research Institute, 1991e).

Gas and Water Production

Shallow gas production in the Powder River Basin was initially from methane-charged sandstones (250 to 2,500 ft [76 to 762 m] deep) interbedded with Fort Union coal beds in the Gillette and Recluse areas. Fort Union sandstones, which individually are locally more than 50 ft (>15 m) thick in the Gillette and Recluse areas, served as the reservoirs for gas desorbed from the adjacent coal beds (Randall, 1989). Shallow gas exploration in the Powder River Basin is now shifting to coal beds. Coalbed-methane resource estimates and gas-content values in Powder River coal beds vary widely because data are scarce. Measured desorbed-gas values from cores and chip samples range from 1 to 71 ft^3/ton (0.031 to 2.214 m^3/t) (Choate and others, 1984a). Boreck and Weaver (1984) desorbed seven samples from the Big George coal seam 35 mi (56 km) southwest of Gillette and measured 56 to 74 standard ft^3/ton (1.747 to 2.308 m^3/t) of coalbed gas. Although Powder River coal beds have low specific-gas contents (fig. 76), they may collectively contain as much as 30 Tcf (849 Bm^3) of gas in place in the Powder River Basin (Gas Research Institute, 1990d).

The Powder River Basin has produced approximately 791 MMcf (22.39 MMm^3) of coalbed gas, 76 bbl (12.1 m^3) of liquid hydrocarbons, and approximately 2.56 MMbbl (406,784 m^3) of water from coalbed methane wells (table 6). From October 1989 to January 1991, coalbed methane wells in the basin produced approximately 454 MMcf (12.85 MMm^3) of gas (fig. 77a), 76 bbl (12.1 m^3) of liquid hydrocarbons (fig. 77b), and approximately 1.44 MMbbl (228,816 m^3) of water (fig. 77c) from 164 on-line wells out of 256 wells reported by Petroleum Information, (1990a–k; 1991b–f). Some of the highest initial potentials in the basin have been reported from the Recluse area (fig. 78a), where four unstimulated wells in shallow (380 to 580 ft [116 to 177 m]) Fort Union coal beds each produced 473 to 550 Mcf/d (13,386 to 15,565 m^3/d) of gas and no water (Larsen, 1989). The basin's highest water potentials (more than 500 bbl/d [79.5m^3/d]) in coalbed methane wells occur in the central part of the basin (fig. 78b). These

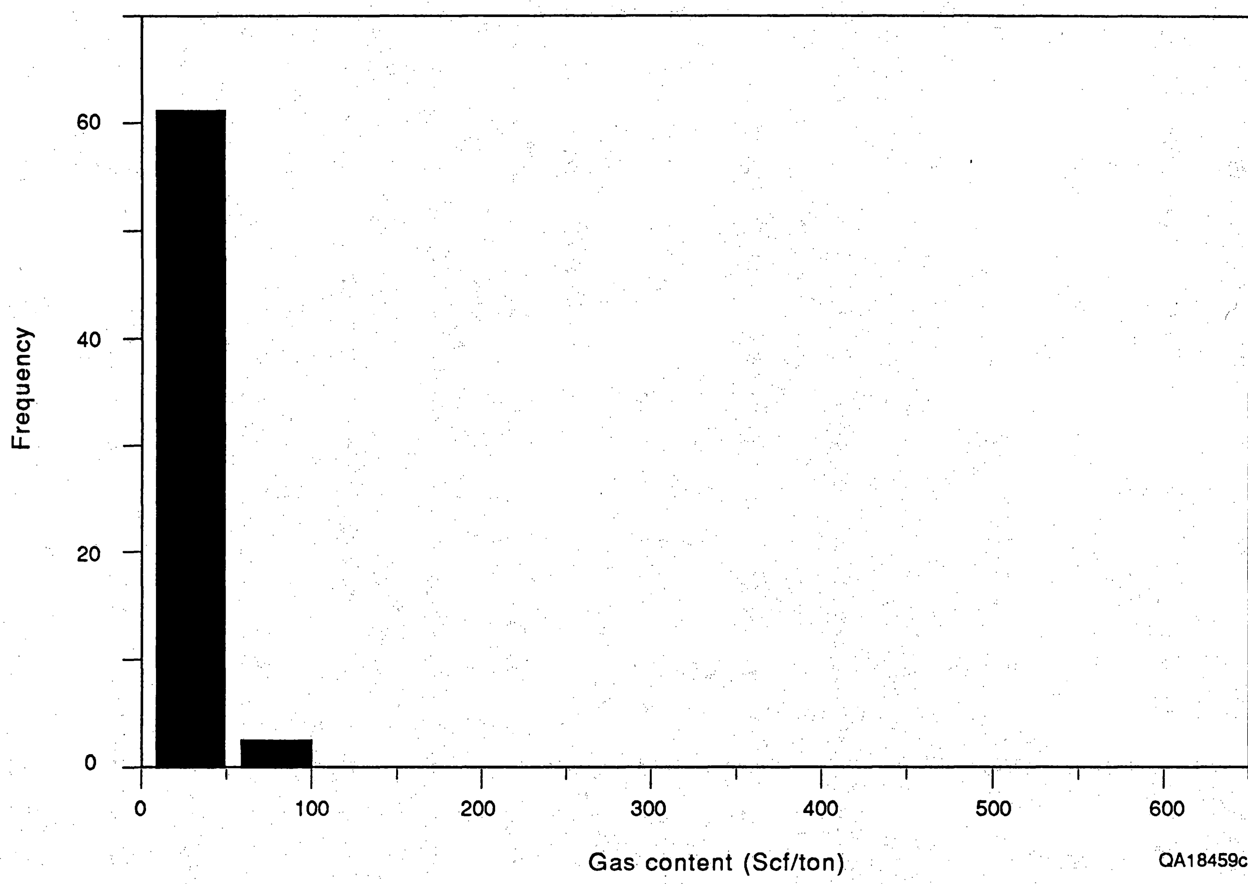


Figure 76. Gas content of Tertiary coal beds in the Powder River Basin. Data from Choate and others (1984a) and Boreck and Weaver (1984).

Table 6. Liquid hydrocarbon, coalbed gas, and water production from fields in Powder River Basin from October 1989 to January 1991 and cumulative to January 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Powder River Basin fields	Oct 89–Jan 91 Liquid (bbl)	Oct 89–Jan 91 Gas (Mcf)	Oct 89–Jan 91 Water (bbl)	Cumulative to Jan 91 Liquid (bbl)	Cumulative to Jan 91 Gas (Mcf)	Cumulative to Jan 91 Water (bbl)
Big Hand	*	*	*	*	*	*
Carson	*	*	*	*	*	*
Carson West	*	*	*	*	*	*
Chan	*	*	*	*	*	*
Collums	*	*	*	*	*	*
Dead Horse	0	1,208	786,319	0	1,208	786,319
Kingsbury	0	47	4,825	0	77	7,275
Kitty	*	*	*	*	*	*
L-X Bar	*	*	*	*	*	*
Maysdorf	*	*	*	*	*	*
Oedekoven	0	94,855	0	0	168,315	0
Poison Draw	*	*	*	*	*	*
Railroad Bend	*	*	*	*	*	*
Rawhide Butte	0	233,545	505,269	0	458,712	931,652
Recluse	*	*	*	*	*	*
Squaw Creek	*	*	*	*	*	*
Store	*	*	*	*	*	*
T-T Road	*	*	*	*	*	*
Powder River 1	0	12,505	19,559	0	70,103	122,991
Powder River 2	0	257	39,117	0	2,777	444,782
Powder River 3	0	87,341	75,155	0	28,621	1,845
Powder River 4	0	23,773	1,554	0	59,492	1,554
Powder River 5	76	0	2,192	76	0	2,192
Powder River 6	0	0	9,069	0	0	22,787
Powder River 7	0	0	300	0	1,863	233,946
Powder River 8	*	*	*	*	*	*
Powder River 9	*	*	*	*	*	*
Powder River 10	*	*	*	*	*	*
Powder River Basin Total	**76**	**453,531**	**1,443,359**	**76**	**791,168**	**2,555,343**

* = No production reported

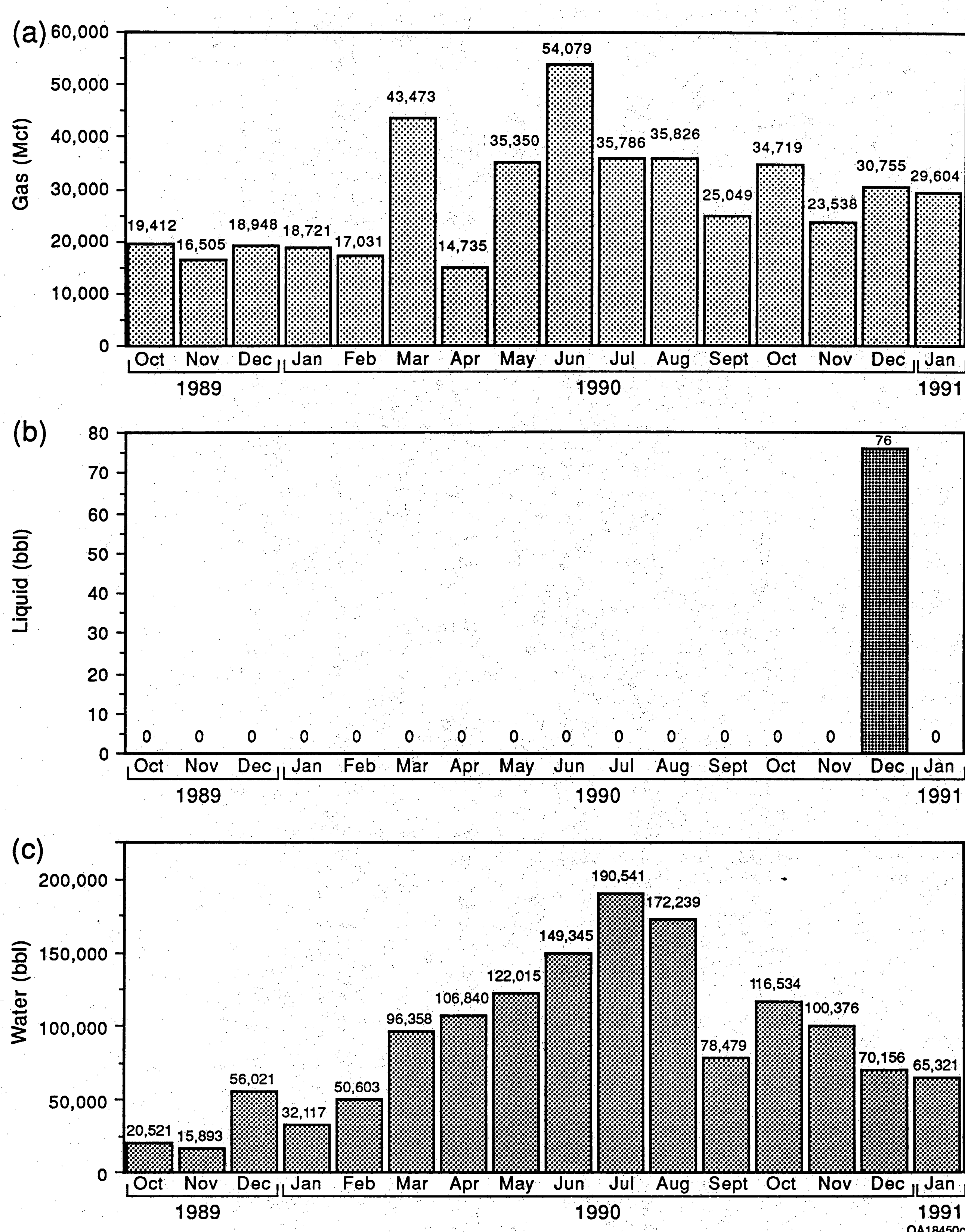


Figure 77. (a) Gas, (b) liquid hydrocarbon, and (c) water production from coalbed methane wells in Powder River Basin from October 1989 to January 1991. Data from Petroleum Information (1990a–k; 1991b–f).

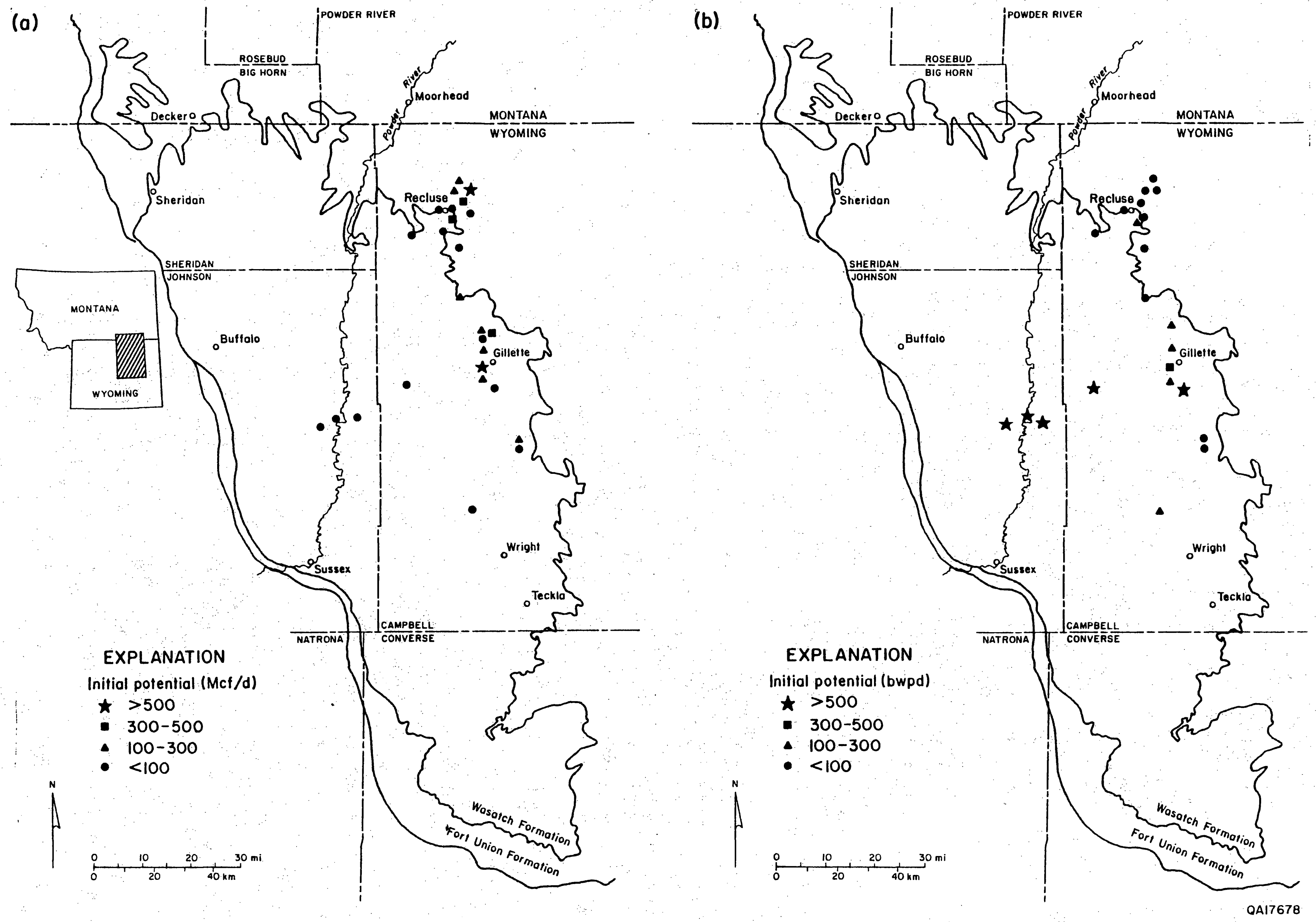


Figure 78. (a) Initial potential of gas from Fort Union coal beds in the Powder River Basin. Activity is greatest on the east margin of the basin. (b) Initial potential of water from Fort Union coal beds. Conventional structural trapping, partial confinement, and dewatering by nearby surface coal mines account for low water production on the east. High water production in the Powder River valley reflects artesian conditions in coal beds, where IP's may reach 1,500 bwpd. Data from Petroleum Information (1990a–k; 1991b–f) and the Gas Research Institute (1989b; 1991d, e).

fields also have low cumulative gas/water ratios (less than 100 ft^3/bbl) (fig. 79). Fields along the eastern rim of the basin have a wide range of gas/water ratios.

Rawhide Butte field, approximately 5 mi (8 km) northwest of Gillette (fig. 79), came on-line in 1989 and is now the most productive coalbed methane field in the basin, having produced approximately 459 MMcf (12.99 MMm^3) of gas (54 percent of the basin's coalbed methane production) and 932 Mbbl (148,095 m^3) of water (35 percent of the basin's coalbed-methane related production) (table 6). Coalbed methane production from Rawhide Butte field is from shallow (less than 500 ft [152 m] deep) Fort Union coal beds. The main operators in the field are Betop and Martens and Peck. In March 1990, five Betop coalbed methane wells in Rawhide Butte field had a combined gas production of 638 Mcf/d (18,055 m^3/d) and produced 1,115 bbl/d (177 m^3/d) of water (Petroleum Information, 1990f). Martens and Peck recently reported 691 Mcf/d (19,555 m^3/d) of gas and 2 bbl/d (0.3 m^3/d) of water in its Walls DC-10 well, perforated in the Wyodak Coal at depths between 344 and 360 ft (105 and 110 m) (Gas Research Institute, 1991e).

Oedekoven field, located approximately 30 mi (48 km) northwest of Gillette in the Recluse area (fig. 79), is the second most productive field, with approximately 168 MMcf (4.75 MMm^3) of gas and little or no water production. Oedekoven field produces from thick, Upper Fort Union coal beds and interbedded sandstones at depths of 100 to 750 ft (30 to 229 m). DCD and REI are the most active companies in the field. Although gas-production rates from individual wells in the field have been reported as high as 1,488 Mcf/d (42,110 m^3/d), most wells test at 200 to 400 Mcf/d (5,660 to 11,320 m^3/d) (Larsen, 1989).

Dead Horse Creek field, located in the western coal depocenter in western Campbell County (fig. 79), has produced almost as much water as has Rawhide Butte field (approximately 786 Mbbl [124,895 m^3]), but has produced only 1.2 MMcf (33,960 m^3) of coalbed gas (table 6). Betop wells in the field typically produce negligible amounts of gas after sand-water fracture treatment and average 853 bbl/d (136 m^3/d) of water (Gas Research Institute, 1991d).

Completions and Drilling Activity

Most coalbed methane drilling activity in the Powder River Basin has occurred in shallow Fort Union coal beds on the northeast rim of the basin (fig. 80). A minor number of coalbed methane completions have been made in deeper Fort Union coal beds in the downdip, central part of the basin in the Big George coal bed. The Wasatch well on the northwestern margin has been abandoned. As of January 1991, there have been 36 single and 19 open-hole Fort Union coalbed completions, as well as three drill-stem tests from two wells. Seventy-one wells were reported as dry and abandoned (fig. 81a), although 50 of these wells were stratigraphic tests possibly unintended as producing wells. The status of an additional 101 wells of the 256 total wells is unknown. Fort Union coalbed methane wells are shallow

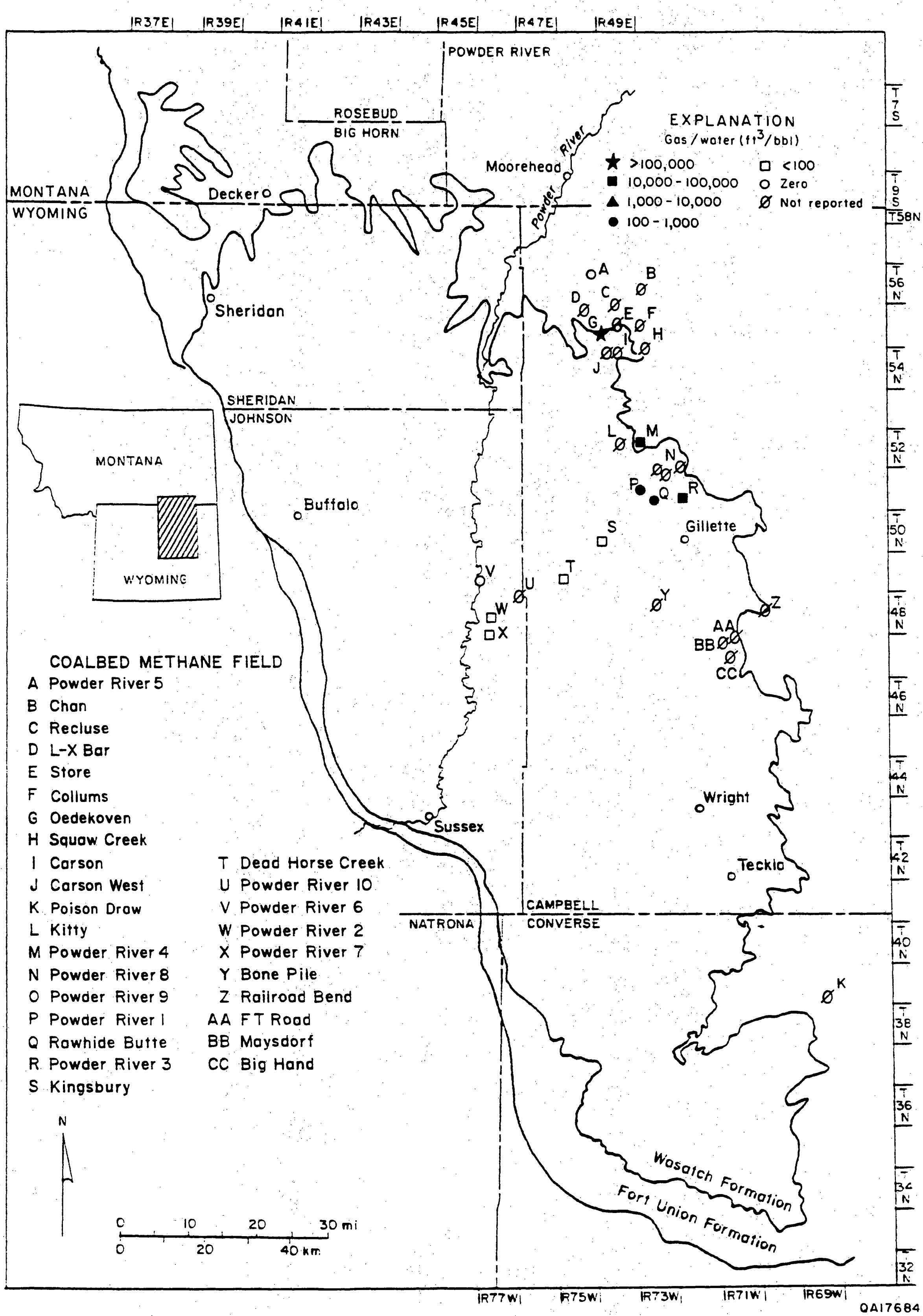


Figure 79. Cumulative gas/water ratio in coalbed methane fields in the Powder River Basin. Data from Petroleum Information (1990 a–k; 1991 b–f).

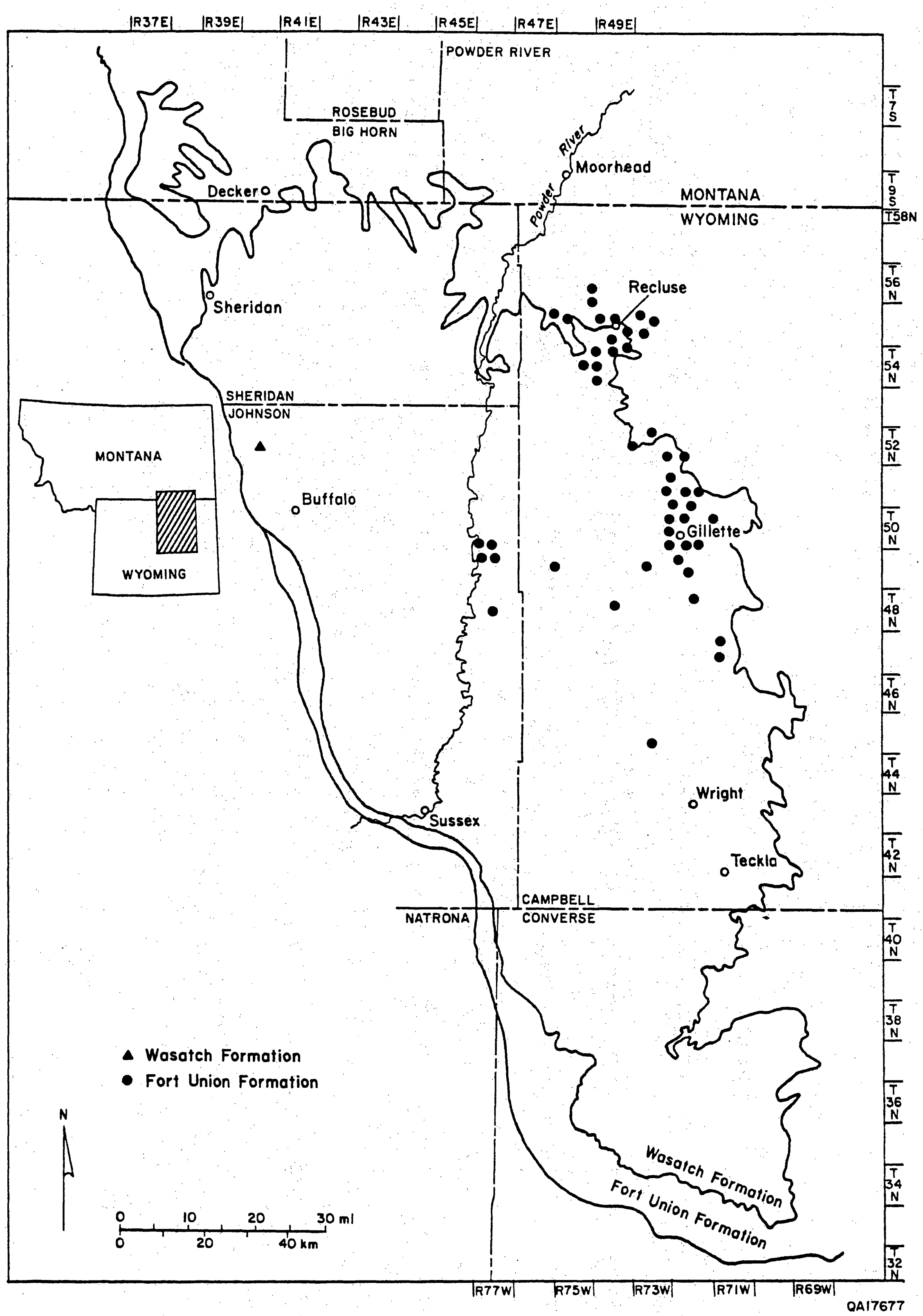


Figure 80. Recent (1990 and 1991) coalbed methane wells in the Powder River Basin. Data from Petroleum Information (1990a–k; 1991b–f), and the Gas Research Institute (1991d, e).

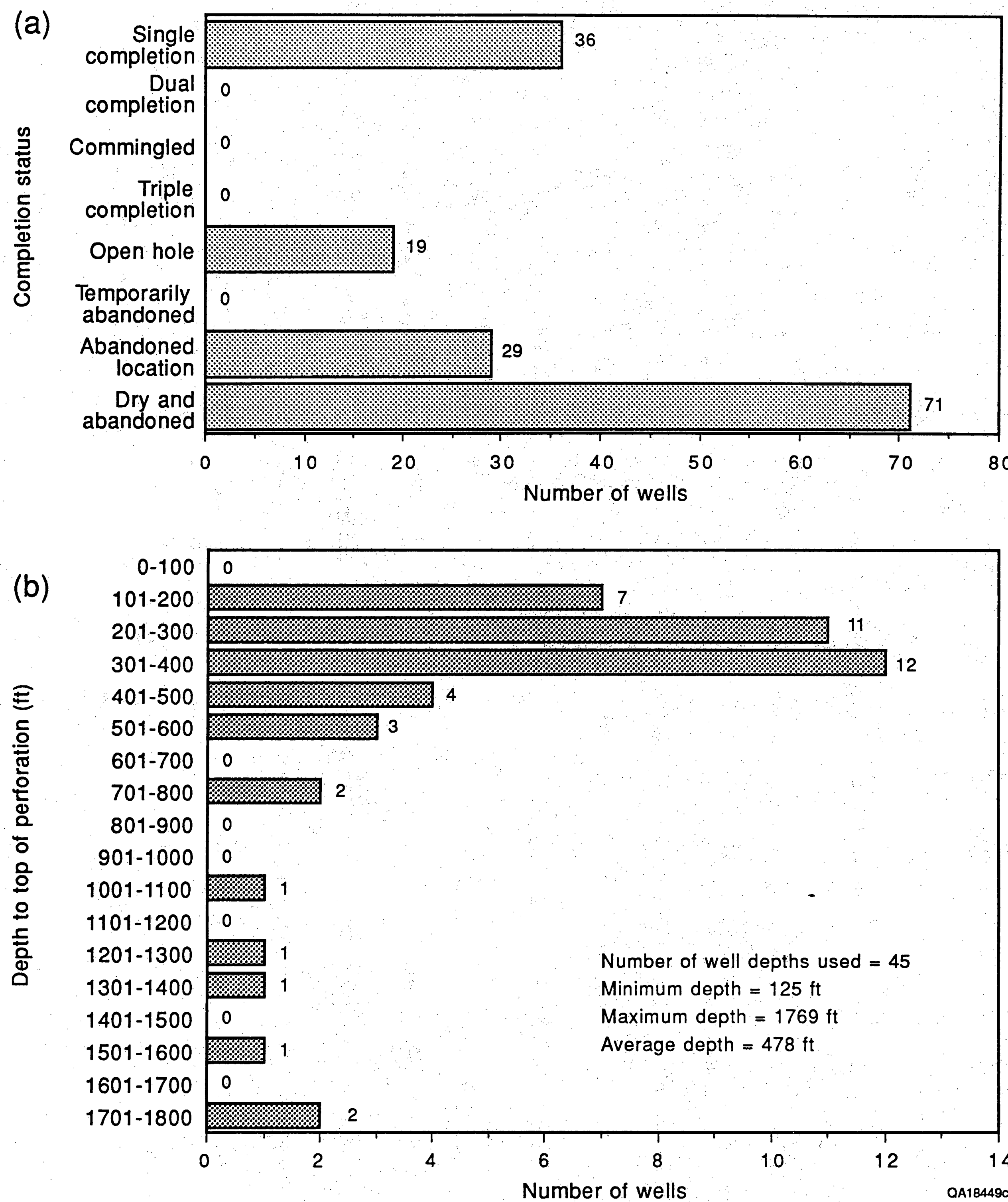


Figure 81. (a) Completion status and (b) depth to top of perforation of coalbed methane wells in the Powder River Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

and average only 500 ft (150 m) in depth in a range from 125 to 1,800 ft (38 to 549 m) (fig. 81b). Total depths of 55 reported gas wells average approximately 680 ft (207 m) in a range from 220 to 2,417 ft (67 to 737 m) (fig. 82).

The Powder River Basin is being actively explored for coalbed methane by 32 companies (fig. 83). The four most active companies, which are drilling coalbed methane wells mainly in Campbell and Johnson Counties in Wyoming, are Martens and Peck (82 wells), Betop (51 wells), Wasatch Energy (24 wells), and DCD (20 wells). However, several other operators, including the Northern Cheyenne Tribe, Powers Energy, and Florentine Exploration and Production, are now looking at the methane potential of vast coal resources in the Montana side of the basin.

Martens and Peck is most active in the Gillette area. In addition to its Rawhide Butte activity, Martens and Peck has recently discovered a new gas pool in the Wyodak-Anderson Coal approximately 3 mi (4.8 km) southwest of Gillette. Initial potentials range from 104 to 202 Mcf/d (2,943 to 5,717 m^3/d) of gas and 130 to 150 bbl/d (21 to 24 m^3/d) of water at depths of 368 to 480 ft (112 to 146 m) (Petroleum Information, 1991e). Martens and Peck has also conducted eight new tests approximately 9 mi (14.5 km) southeast of Gillette in Fort Union coal beds at depths of 600 to 650 ft (183 to 198 m) (Petroleum Information, 1990e).

Betop continues to be one of the most active companies at Rawhide Butte and Dead Horse Creek fields (see previous section, Gas and Water Production). Wasatch Energy is mainly active in Rawhide Butte field, L-X Bar field (approximately 4 mi [6.4 km] north of Spotted Horse, Wyoming), and Kitty field (T52N, R74W, near Gillette). Wasatch Energy is currently developing Fort Union coal beds as deep as 1,360 ft (415 m) in Kitty field (Petroleum Information, 1990k). Production information from the field is currently unavailable.

Although DCD is primarily active at Oedekoven field, the company has recently completed two Fort Union coalbed methane wells approximately 16 mi (25.8 km) south of Gillette. In these wells, DCD is producing 30 to 108 Mcf/d (849 to 3,056 m^3/d) of gas and no water through open-hole completions at depths of 169 to 340 ft (52 to 104 m) (Petroleum Information, 1990i).

Numerous other companies are also involved in coalbed methane operations in the Powder River Basin. National Cooperative Refining Association (NCRA) has tested six wells in the 450-ft (137-m) deep Wyodak Coal, 5 mi (8 km) south of Gillette. Gas production is only 3.9 Mcf/d (110 m^3/d) per well, whereas water production is 514 bbl/d (82 m^3/d) per well (Gas Research Institute, 1991d). REI is a major player in Oedekoven field and produces gas from the Anderson, Canyon, Cook, and Creche Coals (Upper Fort Union Formation) in several zones from 400 to 1,000 ft (122 to 305 m) deep. These wells individually average 30 Mcf/d (849 m^3/d) of gas and 150 bbl/d (24 m^3/d) of water. Dekalb Energy recently drilled for gas in 840-ft (256-m) deep Fort Union coal beds, approximately 6 mi (9.6 km) north of Reno Junction in the western coal depocenter in Johnson County, Wyoming. They reported 180 bbl/d (29 m^3/d) of water but no gas and soon abandoned the well (Gas Research Institute, 1991d). Wyatt

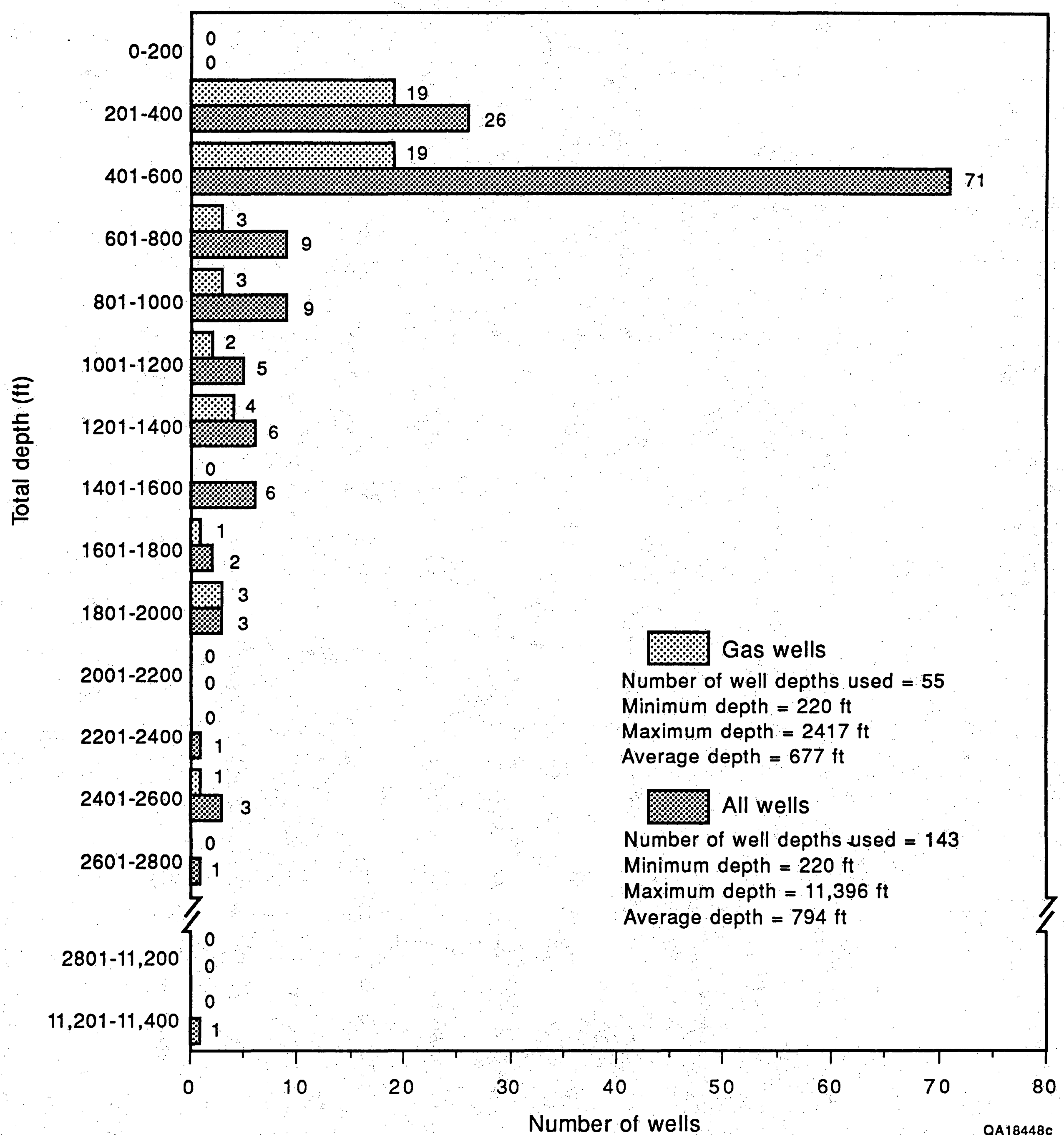


Figure 82. Range of total depths of coalbed methane wells drilled by exploration, development, and/or operating companies in Powder River Basin from February 1990 through May 1991. Light bars represent completed gas wells. Dark bars represent all wells, completed or not. See figure 81 for types of these completions. Data from Petroleum Information (1990a–k; 1991b–f).

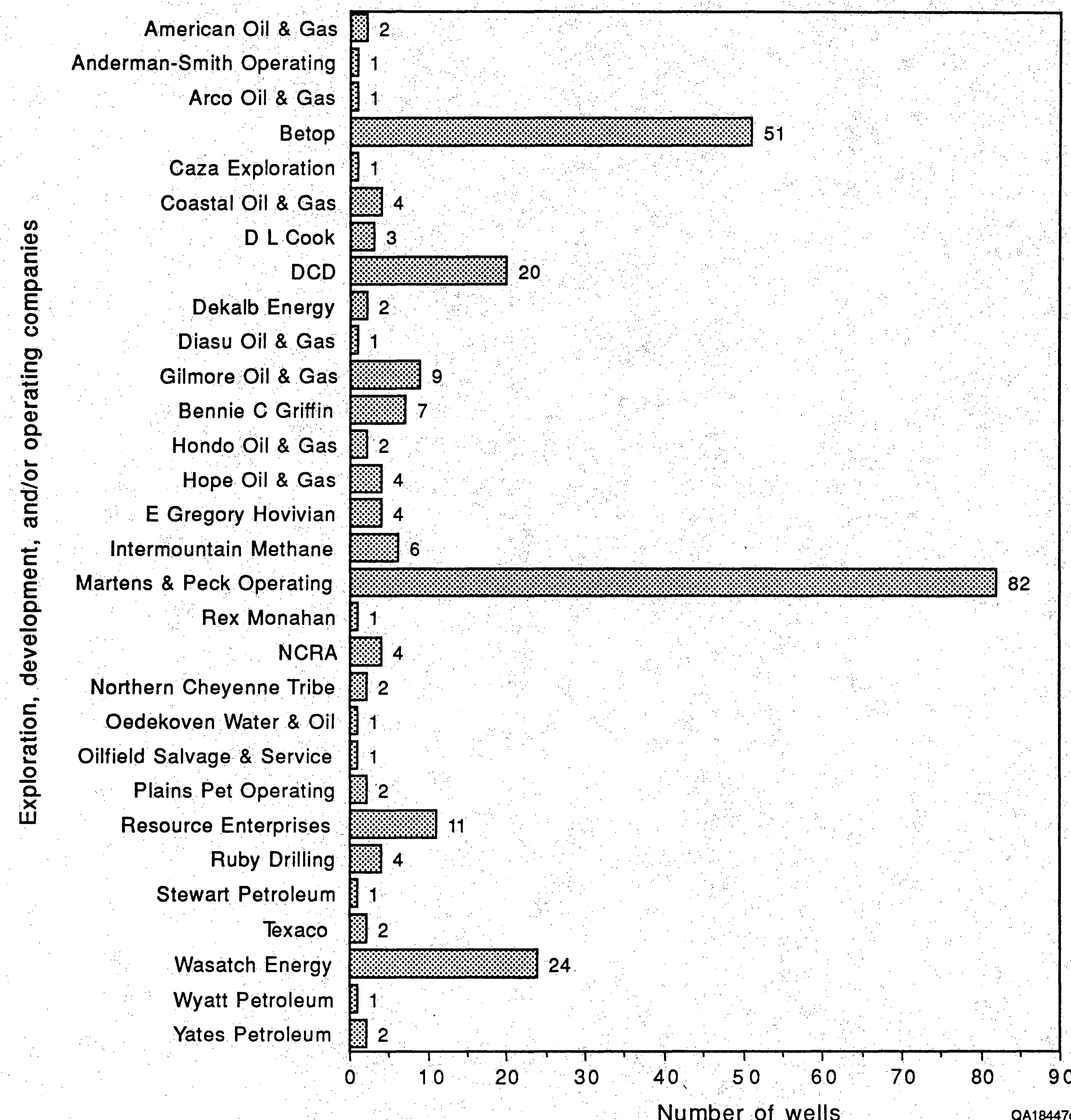


Figure 83. Number of coalbed methane wells drilled by exploration, development, and/or operating companies in the Powder River Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Petroleum is active in the Recluse area; in 1989 the company completed five Fort Union sandstone wells at depths of 175 to 540 ft (53 to 165 m) and produced 104 to 825 Mcf/d (2,943 to 23,348 m^3/d) of gas per well and no water (Gas Research Institute, 1989b).

Pipeline Availability

The Powder River Basin has no proposed pipeline construction projects. However, five companies have existing pipeline infrastructures (Tonnsen, 1989). The companies include Northern Utilities, McCulloch Interstate Gas Corporation, Panhandle Eastern Pipeline Company, Phillips 66 Natural Gas Company, and KN Energy, Inc. Eight coalbed methane fields of the twenty-nine fields (fig. 79) produced methane between October 1989 and January 1991 (table 6). This coalbed methane was probably carried by existing pipelines (fig. 34). Coalbed methane wells are very shallow in the Powder River Basin; therefore, coalbed gases must be compressed to pipeline pressures before they enter the system.

Coal and Coalbed Methane Resources and Potential

Estimates of total coal resources in the Powder River Basin range from 788 billion tons (714.9 billion t) (Mapel and Swanson, 1977; Glass, 1981) to 1.3 trillion tons (1.18 trillion t) (Choate and others, 1984, based on personal communication with E. M. Schell, 1976). Ayers (1986b), using data from 1,790 geophysical logs in the basin, estimated a coal resource of 1.16 trillion tons (1.05 trillion t) in just the Tongue River Member of the Fort Union Formation to a depth of 3,000 ft (915 m). Jones and DeBruin (1990) estimated 1.031 trillion tons (935.3 billion t) of total coal resources, a modification of Wood and Bour's (1988) estimate of 1.231 trillion tons (1.117 trillion t) in the Powder River Basin south of the Miles City Arch.

Coalbed-methane resource estimates for the Powder River Basin are inexact because gas-desorption data for Wyoming coal beds are scarce. Jones and DeBruin (1990), using Wood and Bour's (1988) estimate of coal resources, provided a very preliminary estimate of 5.155 to 103.1 Tcf (145.9 B m^3 to 2.92 T m^3) of coalbed methane in the Powder River Basin, on the basis of gas-content values of 5 ft^3/ton (0.16 m^3/t) and 100 ft^3/ton (3.1 m^3/t), respectively. Choate and others (1984a) assumed that roughly one-half of Schell's USGS coal-resource estimate (1.3 trillion tons [1.18 trillion t]) contains recoverable methane. Assuming a gas-content range of 15 to 100 ft^3/ton (0.47 to 3.1 m^3/t), Choate and others (1984a) provided a coalbed methane resource estimate ranging from 9.75 to 65 Tcf (275.9 B m^3 to 1.84 T m^3), with 30 Tcf (849 B m^3) as the most probable figure.

Thick Fort Union coal beds in the deep (approximately 2,500 ft [762 m]) Powder River Basin should be relatively good targets for coalbed methane exploration. These coal beds contain more than 25 ft^3/ton (>0.78 m^3/t) of gas (Choate and others, 1984a) and are the thickest (net-coal thickness >300 ft [>91 m] and maximum-coal thickness >100 ft [>30 m]) (Ayers and Kaiser, 1984) in the Powder River Basin. Other

RATON BASIN

Geologic Overview

The Raton Basin of southern Colorado and northeastern New Mexico is the southeasternmost structural basin associated with the Rocky Mountain Foreland region (fig. ES-2). It extends about 80 mi (129 km) in a north-south direction and is 50 mi (80 km) wide along the New Mexico–Colorado border, encompassing an area of 2,150 mi^2 (5,564 km^2) (fig. 84). The basin is bounded by the Sangre de Cristo Mountains to the west, the south edge of the Wet Mountains to the north, the Apishapa Arch to the northeast, the Las Animas Arch to the east, and the Sierra Grande Uplift to the southeast and south (fig. 84). The asymmetric axial trace of the Raton Basin (La Veta Syncline), which is approximately 5 to 10 mi (8 to 16 km) east of, and parallel to, the Sangre de Cristo Mountains (fig. 84), results in a steep eastward dip of the sedimentary rocks on the west limb, adjacent to the Sangre de Cristo Mountains, and gentle westward dip on the wider east limb (figs. 85, 86, and 87). Sedimentary rocks along the west edge of the Raton Basin are extensively deformed by steeply dipping thrust faults (figs. 86 and 87). The east flank is only mildly deformed by open folds and faults having small displacement (Merin and others, 1988). At least 15,500 ft (4,726 m) of structural relief is present between the deepest part of the Raton Basin and the adjacent Sangre de Cristo Uplift.

In the north part of the Raton Basin, the La Veta Syncline turns northwestward and passes into Huerfano Park. North of the Spanish Peaks, the La Veta Syncline bifurcates around a south-plunging spur of the Wet Mountains Uplift (Greenhorn Anticline) (fig. 88). The northwestern bifurcation is termed the Huerfano Park Syncline, whereas the eastern bifurcation is called the Del Carbon Syncline (fig. 88). The principal coal-bearing formations of the Raton Basin are absent in this area (Dolly and Meissner, 1977).

The Raton Basin contains a nearly complete Cretaceous and Tertiary stratigraphic succession (Close and Dutcher, 1990a), that includes the coal-bearing Vermejo and Raton Formations (fig. 89). Depths to the Upper Cretaceous-Paleocene coal-bearing horizons range from surface outcrop along the basin perimeter to more than 4,000 ft (>1,220 m) near the structural axis of the basin.

Intrusive rocks, injected during mid- to late Tertiary time, form the Spanish Peaks stocks and radiating dikes in the northwest part of the Raton Basin (fig. 88). Thinner dikes and sills, of composition similar to that of the Spanish Peaks stocks, are scattered throughout the basin.

Tectonic and Stratigraphic Setting

The area of the present Raton Basin, part of the larger Rocky Mountain foreland basin during the Late Cretaceous, evolved into an intermontane basin during the early Tertiary. Early orogenic activity (Late Cretaceous) resulted in at least 5,250 ft (1,600 m) of clastic sediment (Pierre Shale, Trinidad Sandstone prospective areas for coalbed methane are in the Gillette area where the Wyodak-Anderson coal seam is best developed or where it splits into several seams. For example, thick Fort Union coal seams (individual seams 20 to 60 ft [6 to 18 m] thick [Ayers and Kaiser, 1984]) that split off from the Wyodak-Anderson coal bed in Spotted Horse field in the Recluse area, approximately 30 mi (48 km) north of Gillette, are thought to contain 150 Bcf (4.245 B m^3) of coalbed methane (Larsen, 1989).

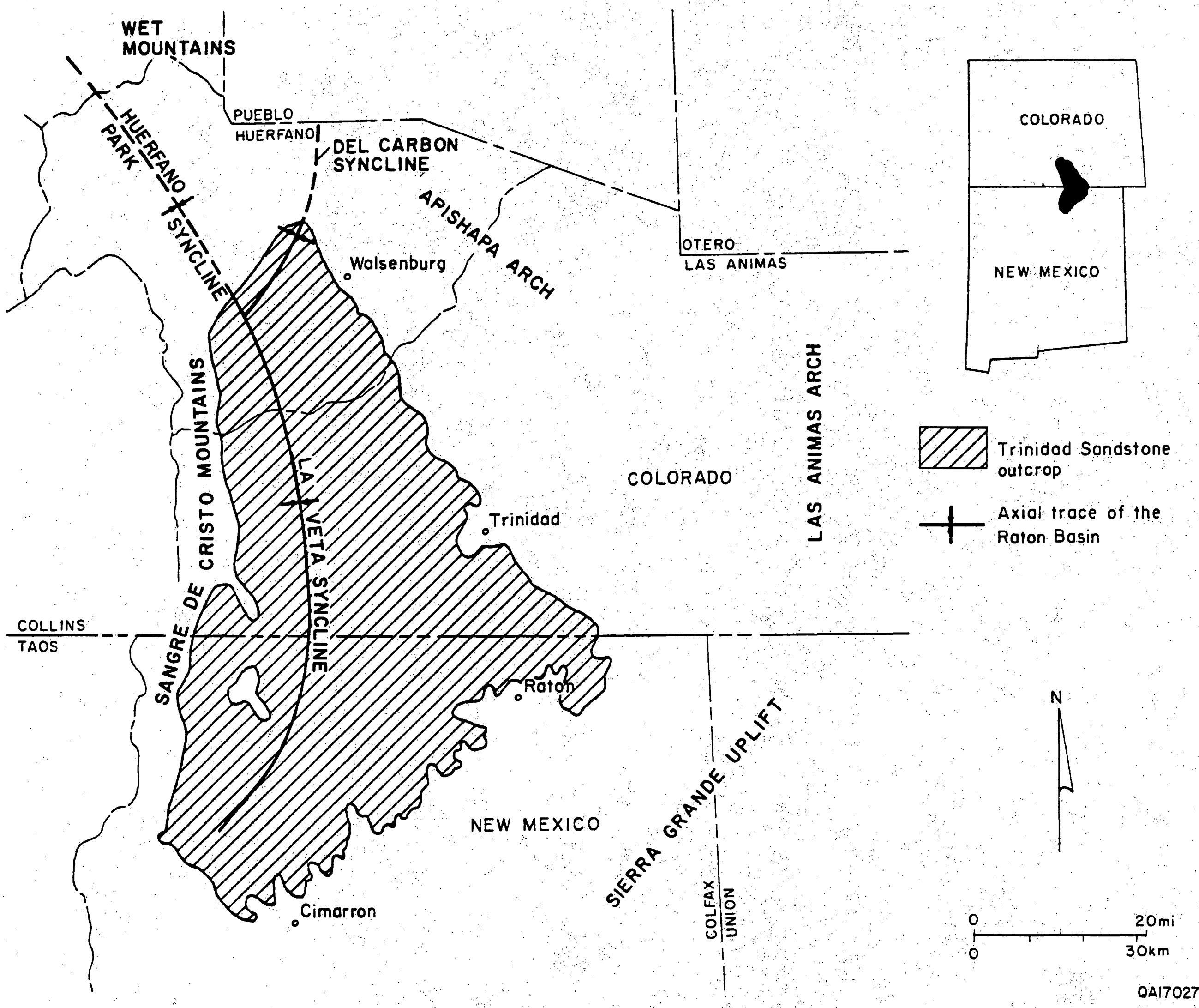


Figure 84. Tectonic map of the Raton Basin and surrounding area. Modified from ARI, Inc. (1991).

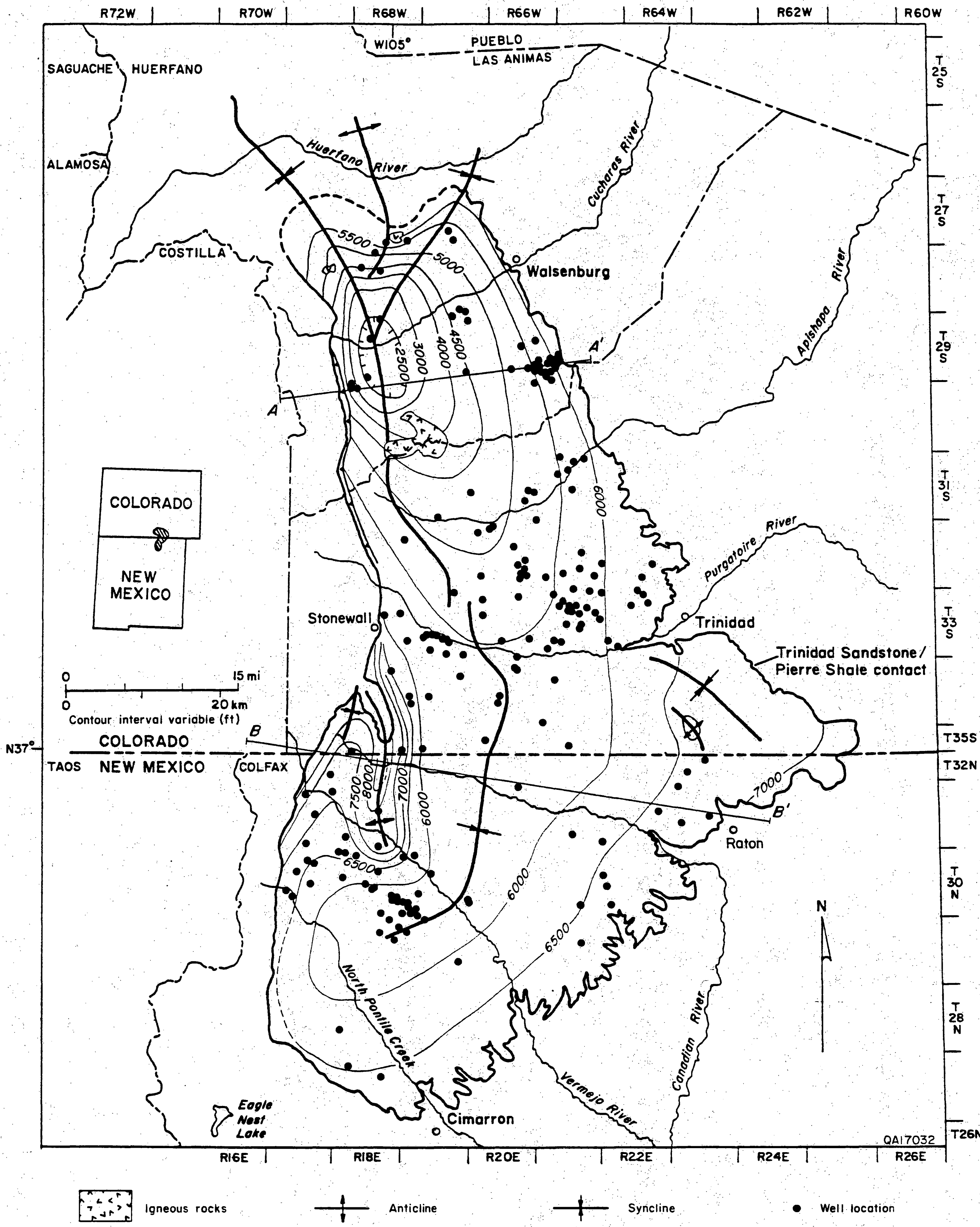
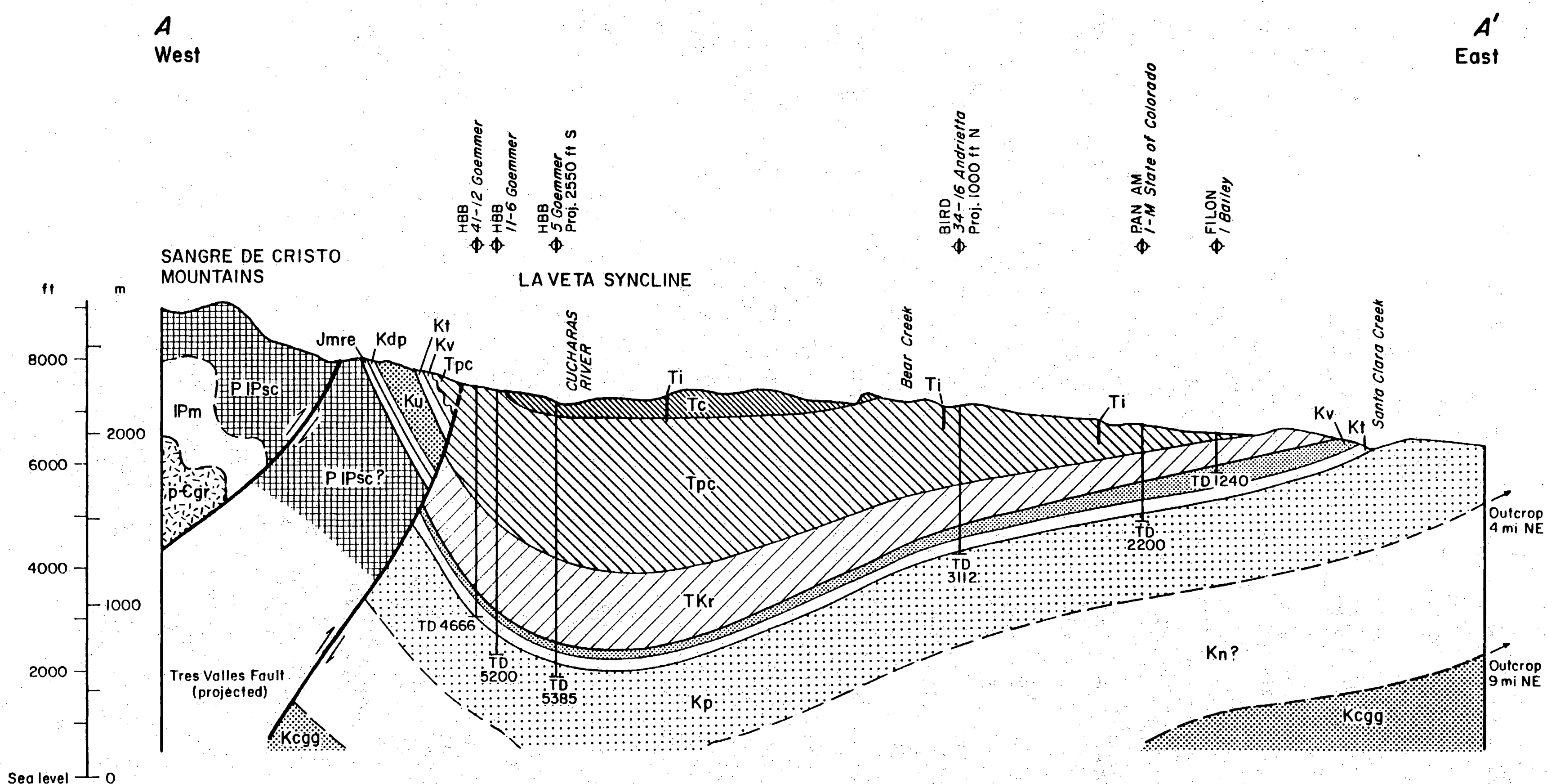


Figure 85. Structure-contour map on top of the Trinidad sandstone. Cross sections A–A′ and B–B′ shown in figures 86 and 87, respectively. Prepared by ARI, Inc. (1991).



GEOLOGIC UNITS

Ti	Igneous intrusives
Tc	Cuchara Formation
Tcp	Poison Canyon Formation
TKr	Raton Formation
Kv	Vermejo Formation
Kt	Trinidad Sandstone
Kp	Pierre Shale
Kn	Niobrara Formation
Kcgg	Carlisle Shale, Greenhorn Limestone, Graneros Shale, undifferentiated
Ku	Pierre, Niobrara, Carlisle, Greenhorn Fms., undifferentiated
Kdp	Dakota Ss. and Purgatoire Fm.
Jmre	Morrison Formation
PIPsc	Sangre de Cristo Formation
IPm	Minturn Formation
pЄgr	Precambrian Granite

0 2 4 6 mi
0 3 6 9 km

Vertical exaggeration x 10.4
Proj. 2500 ft SW projection of well into section line

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Figure 86. West-east cross section A–A′ through the Raton Basin showing relationships between structure and stratigraphy. Prepared by ARI, Inc. (1991). Ground-water recharge along upturned west margin. Line of section shown in figure 85.

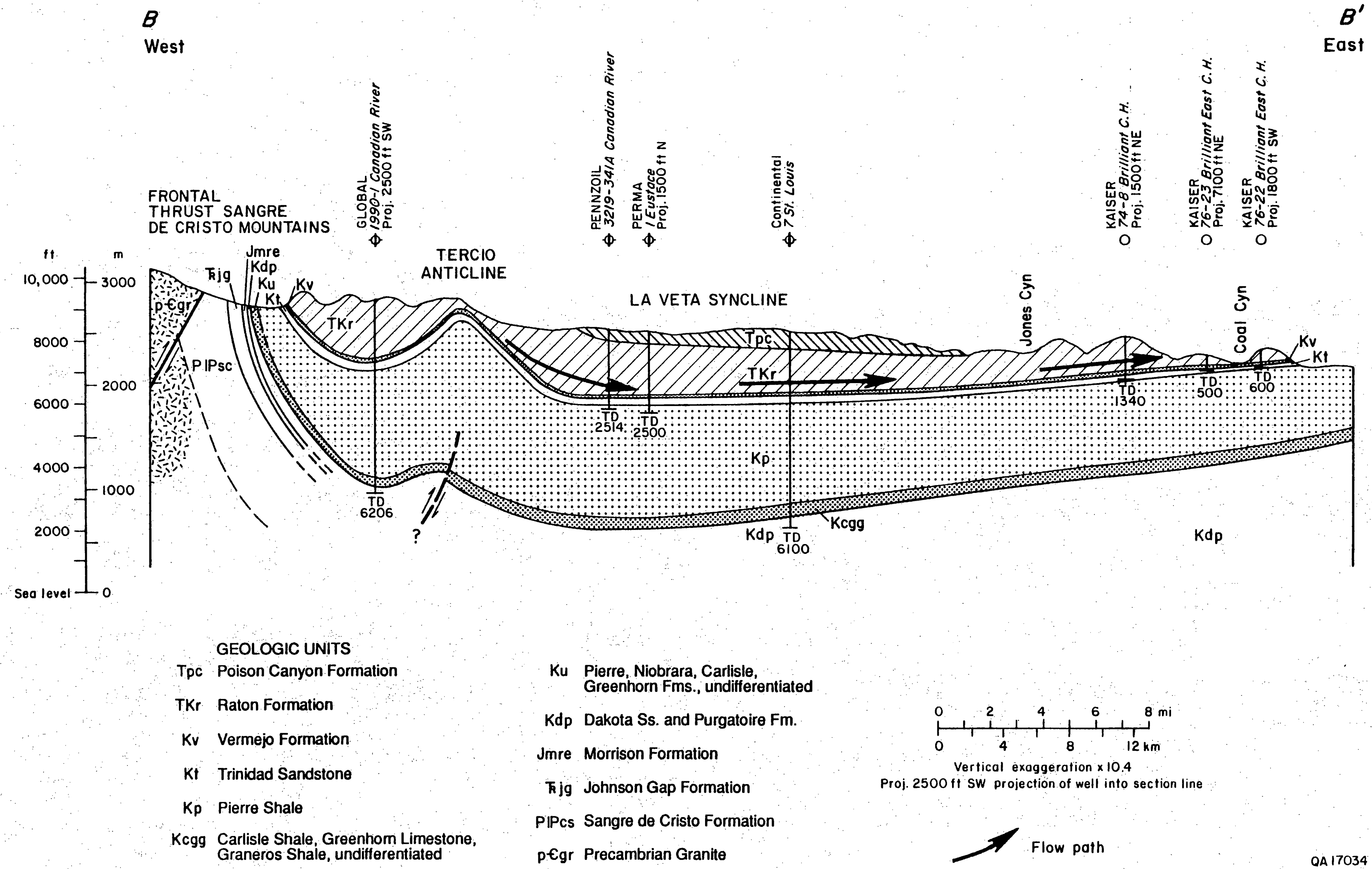


Figure 87. West-east cross section B–B′ through the Raton Basin showing relations between structure and stratigraphy. Modified from ARI, Inc. (1991). Recharge is over the flank of the Sangre de Cristo Mountains. Ground water flows westward and discharges to the eastern outcrop belt and Purgatoire River valley. Artesian conditions may develop along the wet, elevated western outcrop belt. Line of section shown in figure 85.

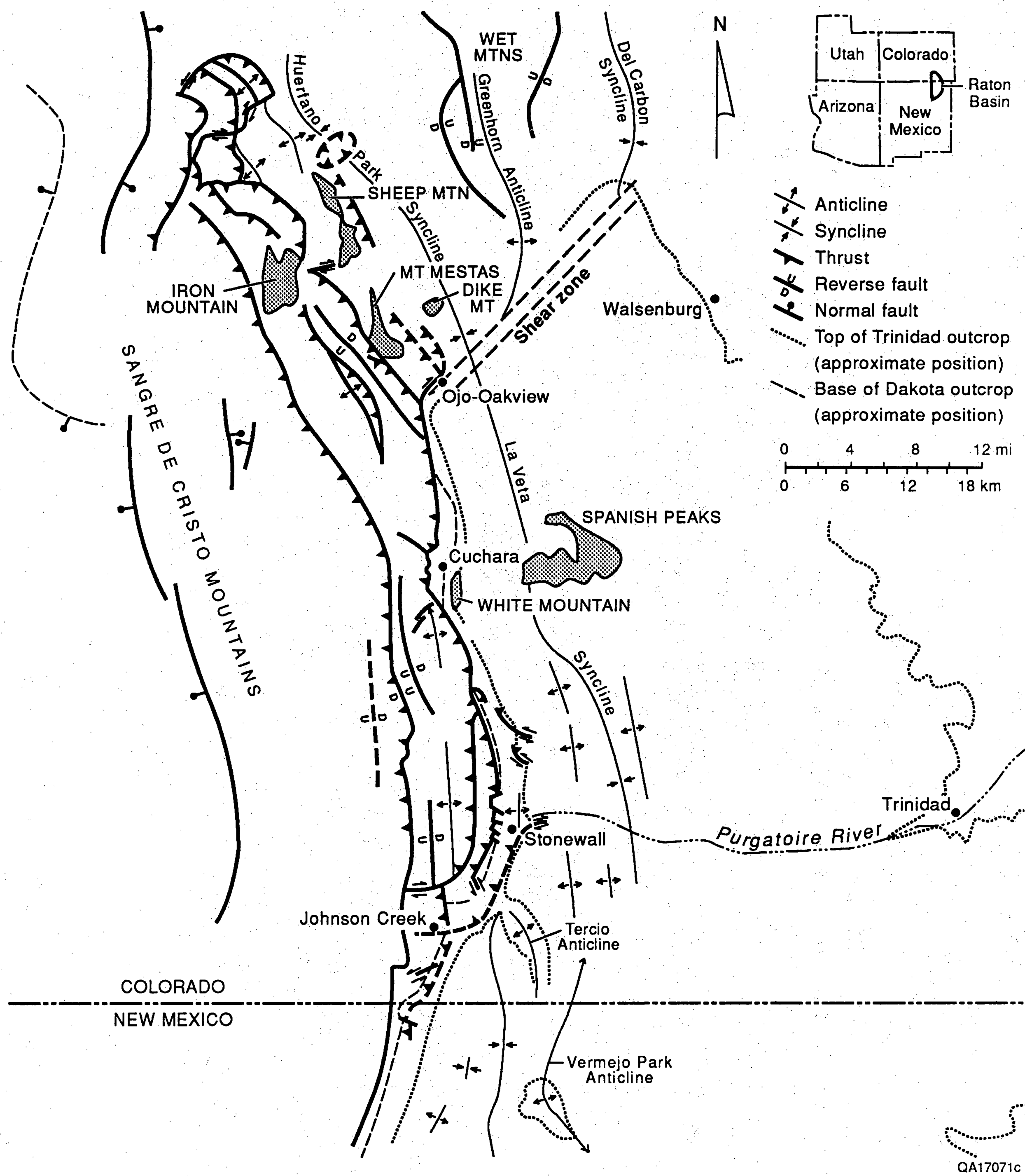


Figure 88. Generalized tectonic map of northern Raton Basin and Huerfano Park. Modified from Merin and others (1988).

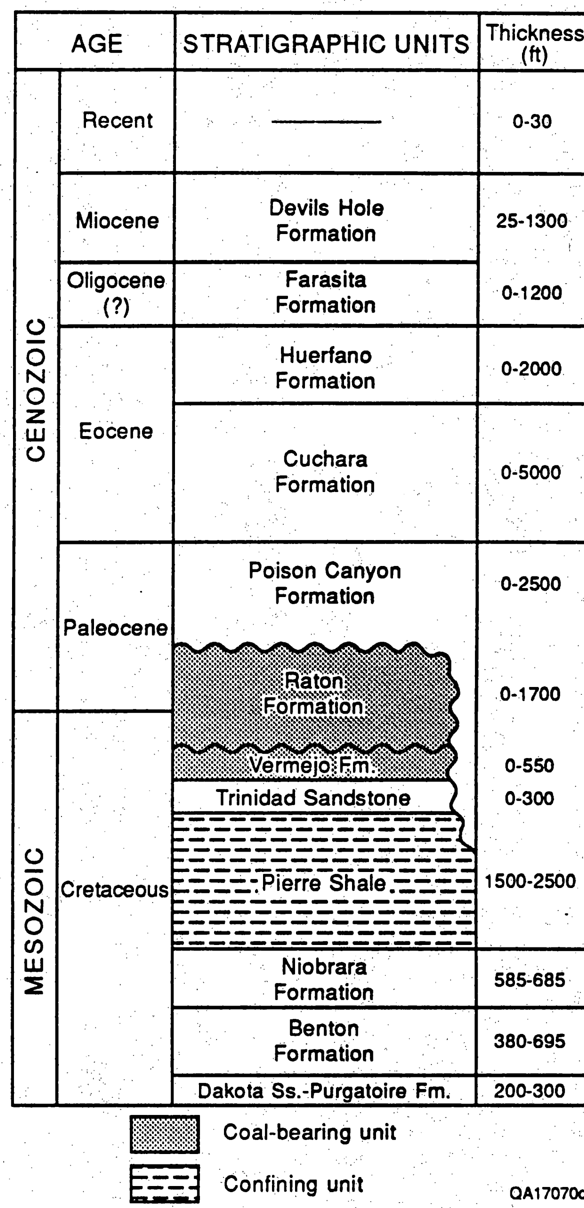


Figure 89. Coal-bearing stratigraphic and confining units in the Raton Basin. Modified from Dolly and Meissner (1977).

and Vermejo Formations; fig. 89) being deposited along the east coast of the Western Interior Seaway. During the Laramide Orogeny, east-directed reverse faulting, thrusting, and associated open to tight kilometer-scale folds created the asymmetric, intermontane Raton Basin and surrounding basement uplifts. The first evidence that the Raton Basin was a separate, isolated depositional basin is in the Maastrichtian, when arkose and conglomerates of the Raton Formation were deposited (fig. 89). This activity continued into and intensified during the Paleocene, being recorded by the coarse arkose and conglomerate-bearing pebbles of granite and gneiss in the Poison Canyon Formation (fig. 89). The composition, facies changes, and unconformable relations of the Raton and Poison Canyon Formations indicate sediment source areas southwest and northwest of the Raton Basin (Tweto, 1975). The northwest source was evidently the Wet Mountains, a rejuvenated element of the late Paleozoic Ancestral Front Range (Merin and others, 1988). The southwest source was the Laramide-age San Luis Uplift (west of the present Sangre de Cristo Uplift), now buried beneath the San Luis Valley. The Sangre de Cristo Mountains did not become a source of sediment until Eocene time (Merin and others, 1988), when late Laramide activity resulted in the deposition of at least 8,530 ft (2,600 m) of sedimentary rocks (Cuchara, Huerfano, and Farasita Formations) (fig. 89). Thrusting and folding during this time resulted in the present structural outlines of the Raton Basin and Sangre de Cristo Mountains.

Although general homoclinal dips characterize both east and west limbs of the Raton Basin, several anticlinal closures are present both within and marginal to the area containing the Trinidad Sandstone and younger formations. The Vermejo Park, Tercio, and Morley Anticlines (fig. 88) range in size from small domes to elongate folds 15 mi (24 km) in length (Woodward, 1984). Different types of anticlines occur in the Raton Basin. Some anticlines are caused by compression of strata, arching of Precambrian rocks, or draping of strata over basement faults, whereas others are formed by injection of laccolithic igneous bodies (Woodward, 1984). Distinguishing between structures of laccolithic and nonlaccolithic origin may be difficult, but the difference has important implications—laccolithic domes are younger (late Tertiary) and less likely to be conventional traps for methane, whereas the nonigneous-related folds are generally older (early Tertiary) and more likely to trap methane (Woodward, 1984). However, areas of igneous intrusion should not be totally discounted as exploration targets because methane in a fractured igneous sill has been reported in the north part of the Raton Basin.

Major intrusive events during the middle Tertiary are recorded by the Spanish Peaks stocks, which were intruded into the La Veta Syncline in the north part of the basin and are accompanied by a swarm of dikes that occur as a broad east-west band extending across the basin north of the Purgatoire River. This intrusive activity appears to be concordant with the regional structure of the Raton Basin (Close, 1988). Dikes bifurcate along primary fractures perpendicular to the axis of the La Veta Syncline or cross to an adjacent parallel east-trending joint along north-trending joints, suggesting emplacement of dike magmas along preexisting east- and north-trending fractures. No dikes are cut by local or regional joints, further suggesting that dikes are younger than the regional fractures (Close, 1988). Although high heat flow was associated with the intrusions, the areas affected by high temperatures are confined to the vicinity of the intrusions, and they did not significantly elevate geothermal levels of the sedimentary rocks in the Raton Basin.

On the basis of the orientation of dikes and the orientation of compressional structures, Chapin and Cather (1981) showed that the Cenozoic Raton Basin was a two-phase orogenic event. Middle Tertiary syenite and syenodiorite dikes of West Spanish Peaks in the northwestern Raton Basin show that the regional orientation of maximum principal horizontal stress during magmatic invasion was approximately N80°E (Johnson, 1968). This trend is essentially perpendicular to the trend of the Sangre de Cristo thrust-fault system along the west margin of the basin (Close and Dutcher, 1990a). Postsyenite monzonite dikes (late Miocene) of West Spanish Peaks indicate that the polarity of the stress field rotated 90° in the late Oligocene, owing to the inception of active Rio Grande rift extension just west of the Raton Basin. North-trending Laramide compressional release fractures may have been further enhanced by Oligocene–Recent extensional forces (Close and Dutcher, 1990b). In effect these north-trending fractures now probably represent a significant trend of permeability anisotropy in coalbed methane reservoirs, along with east-trending primary fracture permeability (Close and Dutcher, 1990b).

Fracture Systems and Cleat in Coal

Fracture data indicate that primary local and regional vertical systematic joints and corresponding face cleats south of the Spanish Peaks have trends between N80°E to N90°E and N70°W to N90°W (fig. 90; Close, 1988). Local face-cleat trends are perpendicular to the respective trend of both the Sangre de Cristo Mountains thrust front and the La Veta Syncline, which are regionally arcuate and slightly convex toward the east (Close, 1988). The east-trending face cleats are formed parallel to east-directed maximum shortening directions implied by the trends of the Laramide Sangre de Cristo thrust faults and are the primary paths of permeability (Close and Dutcher, 1990b). Butt cleats are orthogonal to face-cleat trends, ranging from N10°W to N20°E. These northward-trending butt cleats may cause secondary permeability trends (Close and Dutcher, 1990b).

Merry and Larsen (1982) and Close (1988) found that in the area surrounding the Spanish Peaks, joints in sandstone are generally parallel to face cleats. Where coal is not exposed, the joints can be used to estimate cleat orientation (Close, 1988). However, vertical and lateral extrapolation and lateral correlation of joints and face cleats cannot be randomly applied throughout the Raton Basin because differences in lithology, age, and burial and thermal histories can cause fractures of different orientation to form in adjacent and overlying strata (Grout and Verbeek, 1985, 1987; Grout, 1991, in press).

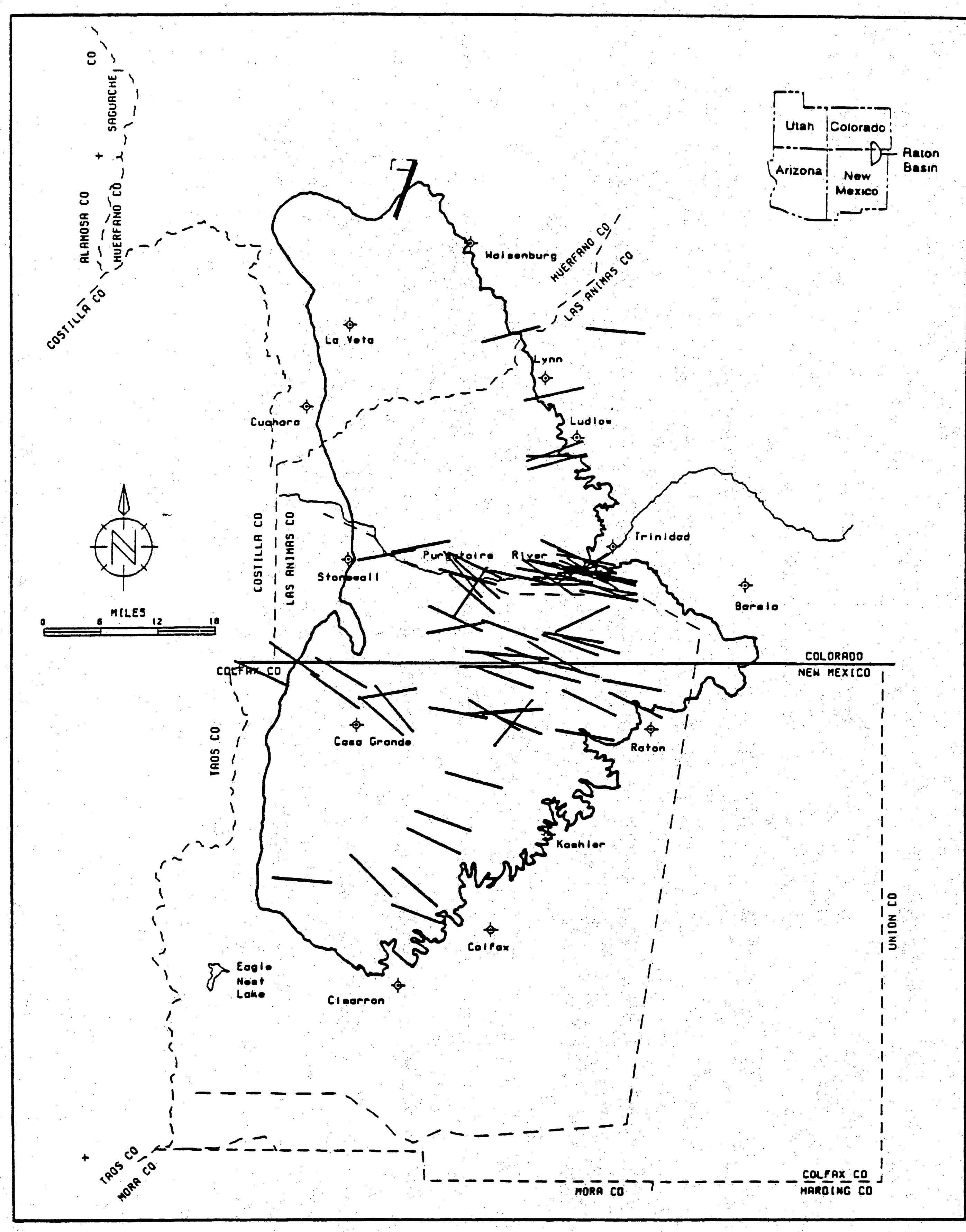


Figure 90. Face-cleat strike, Raton Basin. Modified from Close (1988).

Stress Orientation

The Raton Basin is in the Southern Great Plains stress province, which forms the boundary zone between active extensional tectonism of the western Cordillera and the relatively stable Mid-Plate stress province of the central United States (fig. 10) (Zoback and Zoback, 1989). Contrasts in stress orientations and a consistent indication of extensional tectonism distinguish the Southern Great Plains stress province from the relatively stable Mid-Plate region to the east (Zoback and Zoback, 1989). Maximum principal horizontal stress directions (west-northwest) are oblique to stress direction (east-northeast) in the adjacent Mid-Plate stress province and orthogonal to stress direction (north) in the Cordilleran Extension stress province (fig. 10).

Evidence for stress directions comes from hydraulically fractured wells in the Permian Basin of West Texas (Zemanek and others, 1970) and from alignment of post-5-mya volcanic feeders in northern New Mexico (Zoback and Zoback, 1980). The extensional regime is inferred from earthquake focal mechanisms and post-5-mya basaltic volcanism. Epicenters of sparse earthquakes on the High Plains of southeastern New Mexico are on the west edge of a region of seismic activity that extends southward and eastward into Texas; most earthquakes are centered on the Central Basin Platform (Rogers and Malkeil, 1979; Sanford and others, 1981), a fault-bounded Early Permian structure. Seismicity is spatially associated with faults, but because the old buried faults show no evidence of recent movement at the surface, Sanford and others (1981) suggested that hydrocarbon recovery practices, such as water injection for secondary recovery, may be responsible for some seismic activity.

Stratigraphic and Depositional Setting of Coal-Bearing Formations

The two main coal-bearing stratigraphic units in the Raton Basin are the Vermejo (Upper Cretaceous) and Raton (Upper Cretaceous–Paleocene) Formations. The Vermejo Formation conformably overlies the Trinidad Sandstone (fig. 89), which represents the final eastward regression of the Western Interior Seaway during the Late Cretaceous (Pillmore and Maberry, 1976). The Trinidad/Vermejo couplet is equivalent to the Pictured Cliffs/Fruitland couplet in the San Juan Basin. The Trinidad Sandstone has been variously interpreted as wave-dominated barrier-island deposits (Pillmore, 1969b; Pillmore and Maberry, 1976; Speer, 1976) or as fluvial-dominated deltaic deposits (Close, 1988), who interpreted the Trinidad shoreline to have prograded northeastward in the north part of the basin and southeastward in the south part of the basin, reflecting progradation of separate delta lobes. Flores (1987) interpreted both strike-elongate, barred coastal environments and dip-elongate, nonbarred deltaic environments in the Trinidad Sandstone. The nonbarred coastline consisted of prodelta (Pierre Shale) (fig. 89), delta-front (Trinidad Sandstone), and coal-bearing, delta-plain (Vermejo Formation) deposits, which formed in a deltaic complex and which served as a local source for reworked sediments along nearby barrier-island coastlines. They are northeast-trending in the south part of the basin (fig. 91).

The Raton Formation is divided into coarse alluvial-fan and braided-stream deposits of the Lower Raton Formation (McGookey and others, 1972) and fluvial, floodplain, and paludal (swamp) deposits of the Middle and Upper Raton Formation (Pillmore and Flores, 1987). The Pierre Shale, Trinidad Sandstone, and the Vermejo and Raton Formations are erosionally truncated in the north and southwest parts of the basin and unconformably overlain by the Paleocene Poison Canyon Formation (fig. 89). This unit consists of lenticular, coarse sandstones and conglomerates, shales, and thin, irregular coal beds (Hills, 1888; Lee, 1917). The underlying erosional surface resulted from uplift in the north and west parts of the basin during the middle Paleocene.

The Vermejo and Raton Formations are intruded by middle Tertiary sills and dikes associated with the Spanish Peaks Igneous Complex (Knopf, 1936; Harbour and Dixon, 1959; Johnson, 1968). These sills and dikes have thermally altered Vermejo and Raton coal beds over short distances (several inches to feet) (Podwysocki and Dutcher, 1971), locally affecting coalbed permeability and continuity.

Vermejo Formation

Although Vermejo coal beds are the thickest in the Raton Basin (maximum thickness of individual coal beds ranges from 10 to 14 ft [3 to 4.3 m]) (fig. 92), most are only inches to 11 ft (3.4 m) thick and pinch out or split over distances not exceeding 3 mi (4.8 km), where they encounter lenticular channel-fill sandstones (Flores, 1980a). The coal beds are locally 4,000 ft (1,220 m) deep near La Veta in the north part of the Raton Basin (fig. 93). In the south part of the basin, most of these coal beds are less than 2,000 ft (<610 m) deep.

Vermejo coal beds are interpreted to have formed in coastal swamps landward of wave-modified, delta-front and barrier-island sandstones (Flores, 1987) and between distributary- and fluvial-channel sandstones (Close, 1988). In the southeast part of the basin, Vermejo net-coal thickness trends are dominantly northeast-trending (fig. 94). Net coal is greatest (more than 20 ft [>6 m]) landward (northwestward) of thickest Trinidad net sandstone (more than 150 ft [>46 m]) (fig. 91). In the north part of the basin, Vermejo net-coal thickness trends of 20 ft (6 m) or more are dominantly northwest-trending (fig. 94) and coincide with three northwest-trending pods of more than 150 ft (>46 m) of Trinidad Sandstone (fig. 91). Similar northwest-trending Vermejo net-coal thickness trends have been mapped in the north part of the basin by Tremain (1990) and Johnson and Wood (1956a).

Raton Formation

Coal beds in the Raton Formation are thinner than those of the underlying Vermejo Formation. Maximum-coal bed thickness in the Raton Formation is only 6 ft (1.8 m) (fig. 92), although net-coal

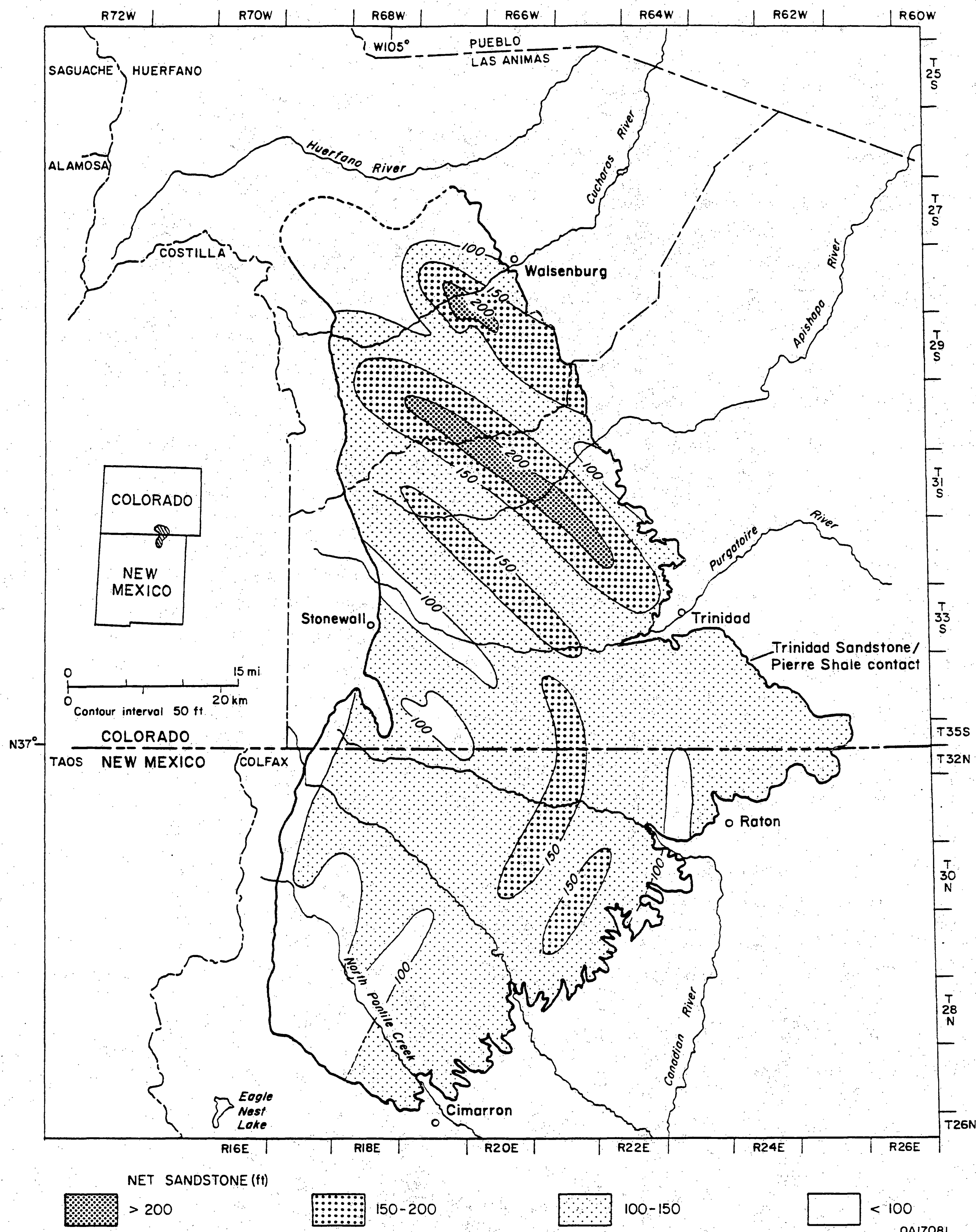
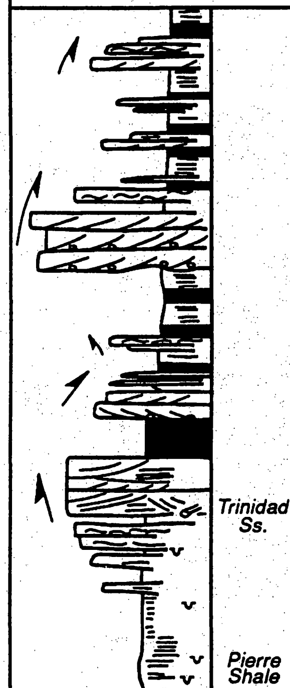


Figure 91. Net-sandstone thickness map of the Trinidad Sandstone. Modified from ARI, Inc. (1991).



SCHEMATIC SECTION	FORMATION	COAL BEDS					SANDSTONES			COAL-SANDSTONE RELATIONS
		Thickness (ft)					Thickness (ft)			
		Average	Maximum	Net	Number	Continuity	Maximum	Net	Continuity	
	RATON FORMATION	2-3	6	Locally >80	~10	Poor: coal beds commonly pinch out against fluvial sandstone	50; thicker ss. on western basin margin	Locally 100's of feet on western basin margin	Poor; many lenticular point-bar and crevasse-splay sandstones	Most coal beds pinch out at channel-sandstone margins
	VERMEJO FORMATION	6	10-14	Locally >50	5-10	Good continuity landward of thickest Trinidad Shoreline Sandstones	20-30	—	Lenticular, east- and northeast-trending distributary- and fluvial-channel sandstone	Thickest and most continuous coal beds directly overlie Trinidad Ss.; other coal beds pinch out or split at margins of distrib.- channel ss. or locally overlie crevasse-splay ss.
Trinidad Ss. / Pierre Shale										

Clasts; Burrows; Organic fragments; Upward-coarsening; Upward-fining

SEDIMENTARY STRUCTURES AND ROCK TYPES

Planar bedding; Cross bedding; Ripples; Coal

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Figure 92. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in the Raton Basin.

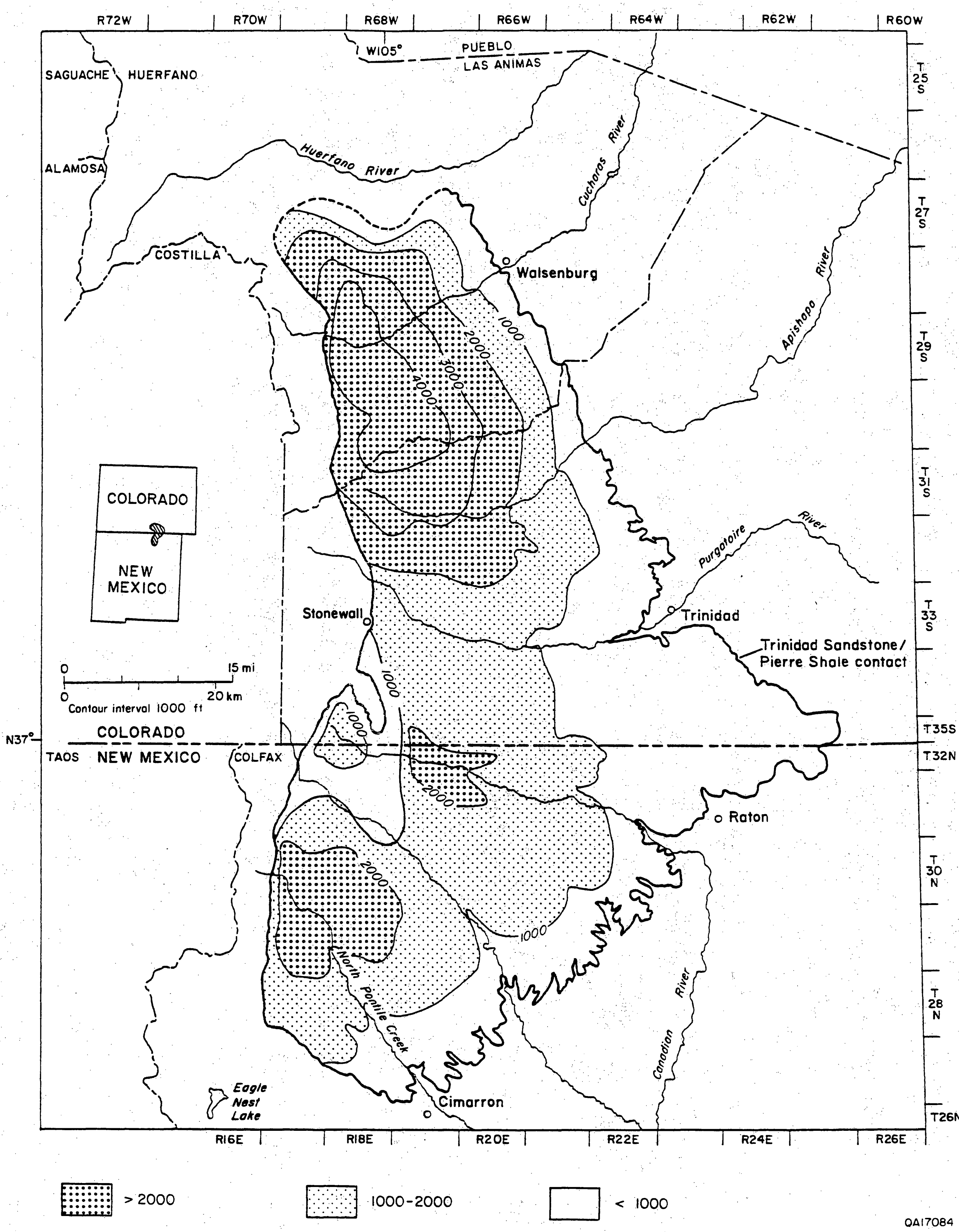


Figure 93. Depth to midpoint of the coal-bearing section in the Vermejo Formation. Modified from ARI, Inc. (1991).

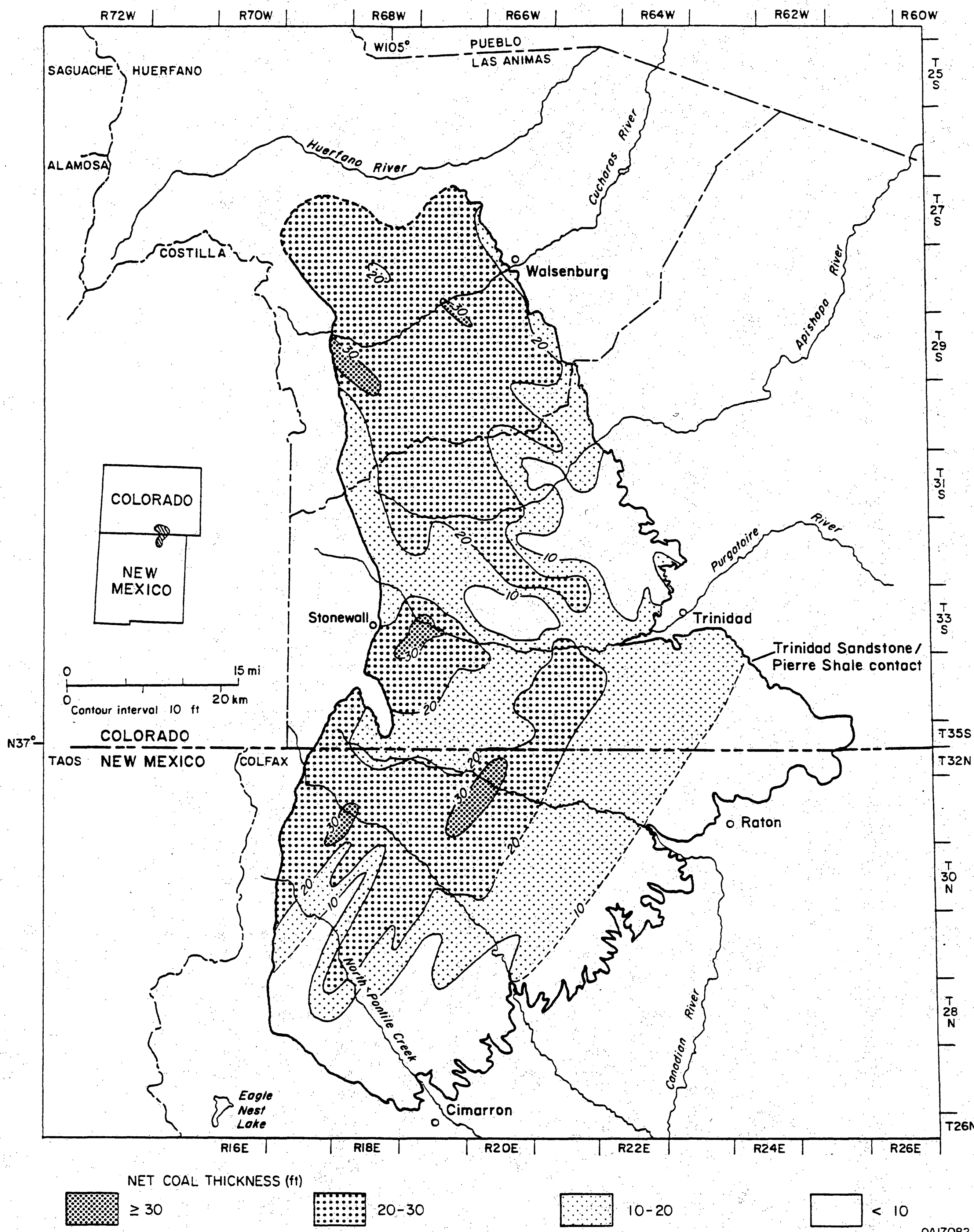


Figure 94. Net-coal thickness map of the Vermejo Formation. Modified from ARI, Inc. (1991).

thickness is locally more than 60 ft (>18 m) in a coal depocenter approximately 15 mi (24 km) northwest of Trinidad, Colorado, and more than 40 ft (>12 m) in another coal depocenter in the New Mexico part of the basin (fig. 95). These coal beds are shallow and have an average depth of less than 1,000 ft (<305 m) in the south part of the basin and an average depth of approximately 1,500 ft (457 m) in the north part of the basin (fig. 96).

Raton peats accumulated in floodplains adjacent to meandering and distal braided fluvial channels (Flores, 1984a). The thickest and most continuous Raton coal beds exist in elongate zones parallel to coeval channel-sandstone deposits (Close, 1988). Because Raton coal beds pinch out over a few hundreds to thousands of feet against fluvial channel-fill sandstones, prediction of coalbed thickness and extent of coalbed methane reservoirs between nearby wells is difficult. Coalbed splits resulted from channel avulsion into abandoned floodbasins, interrupting peat deposition, and migration of peat-forming environments over abandoned-channel deposits (Flores, 1984a).

Hydrology

In the Raton Basin, the coal-bearing hydrostratigraphic unit is composed of the Vermejo and Raton Formations (fig. 89). The Vermejo Formation is underlain by the Trinidad Sandstone, which is underlain by the Pierre Shale, a regional confining layer. Throughout much of the basin the Raton Formation crops out (Tweto, 1979) and therefore is unconfined. Consequently, lower gas contents are predicted for Raton coal beds. The Trinidad/Vermejo couplet crops out around the basin margin (Tweto, 1979) and accepts recharge at its upturned, west margin on the flank of the Sangre de Cristo Mountains (figs. 86 and 87). Regional ground-water flow is from west to east (figs. 19 and 87) with convergence on the Purgatoire River and eastern outcrop belt (Howard, 1982; Geldon, 1990), the regional discharge areas (fig. 97). Westward flow is supported by the presence of low-chloride formation waters on the west and high-chloride waters on the east (Close and Dutcher, 1990b; Geldon, 1990). Westward flow is favored by the east-trending face cleat (fig. 90) and igneous dikes of the same trend (Tweto, 1979). Dikes and sills are conduits for ground-water flow.

The basinal pressure regime is poorly understood. Close and Dutcher (1990b) reported pressure gradients of 0.433 psi/ft (9.80 kPa/m) or less, indicative of underpressured conditions. Heads below land surface support regional underpressure (Howard, 1982; Geldon, 1990) of unexplained origin. In the absence of a regional confining layer (fig. 89) and basinwide high rainfall (fig. 19) normal pressure is expected. Insulation from the water table or from recharge over the elevated outcrop by low-permeability rocks is implied by underpressure. Internal aquifer heterogeneity and disconnectedness are the likely causes of underpressure. Low-permeability sandstones and coal-seam lenticularity probably limit hydraulic connection with the water table and recharge area. Underpressure can be explained hydrodynamically by high-permeability rocks downflow of an elevated, low-permeability recharge area (Belitz and Bredehoft,

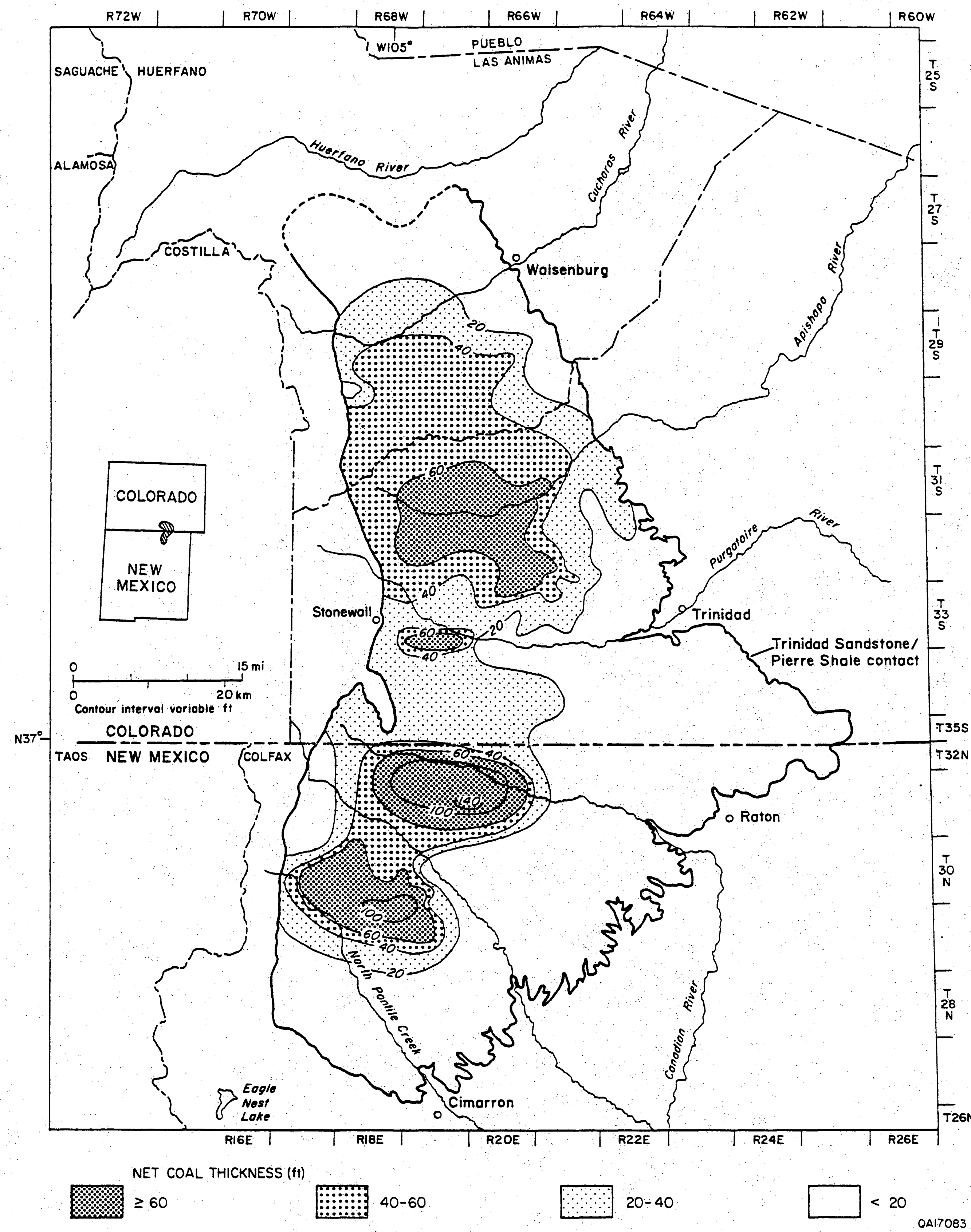


Figure 95. Net-coal thickness map of the Raton Formation. Modified from ARI, Inc. (1991).

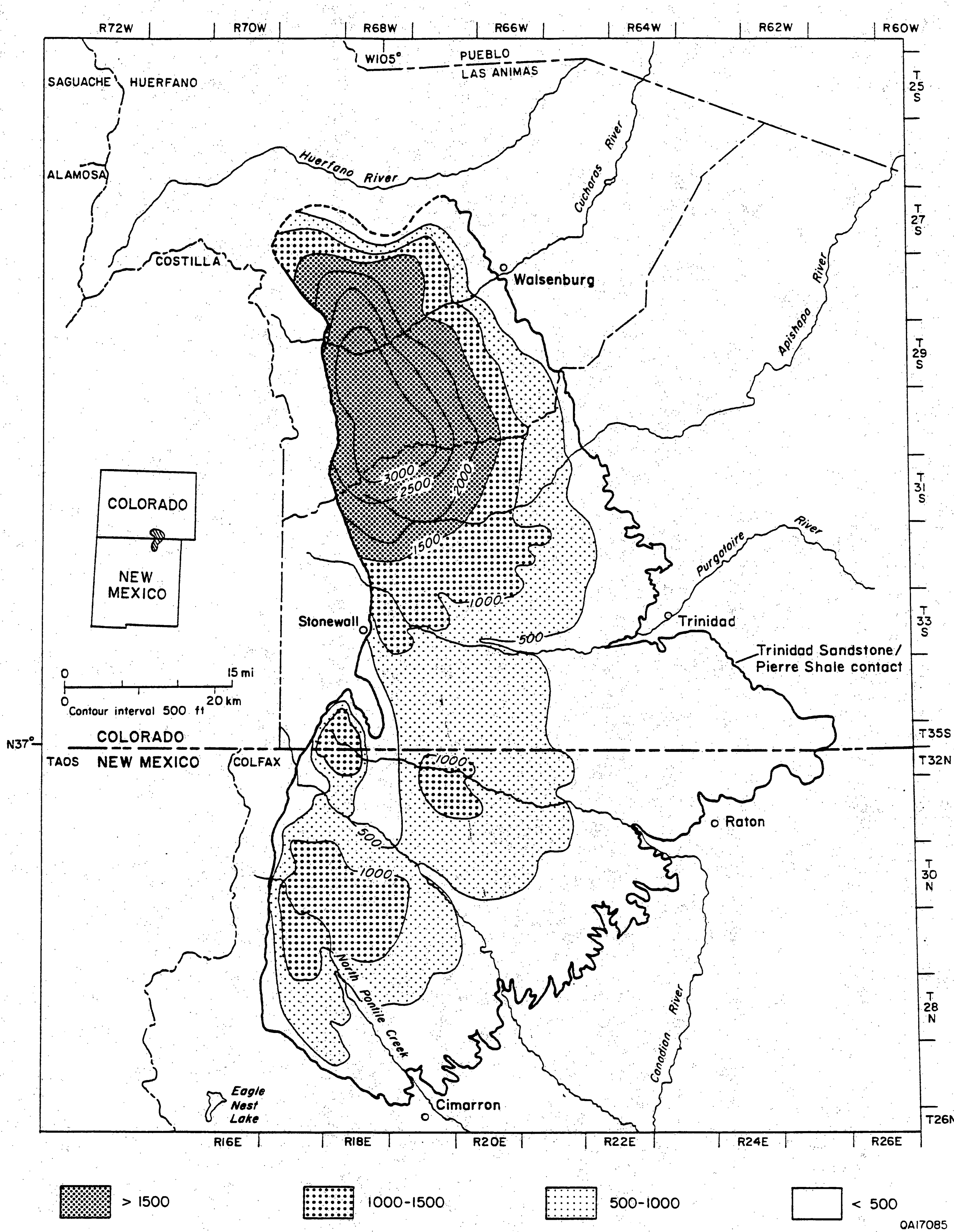


Figure 96. Depth to midpoint of the coal-bearing section in the Raton Formation. Modified from ARI, Inc. (1991).

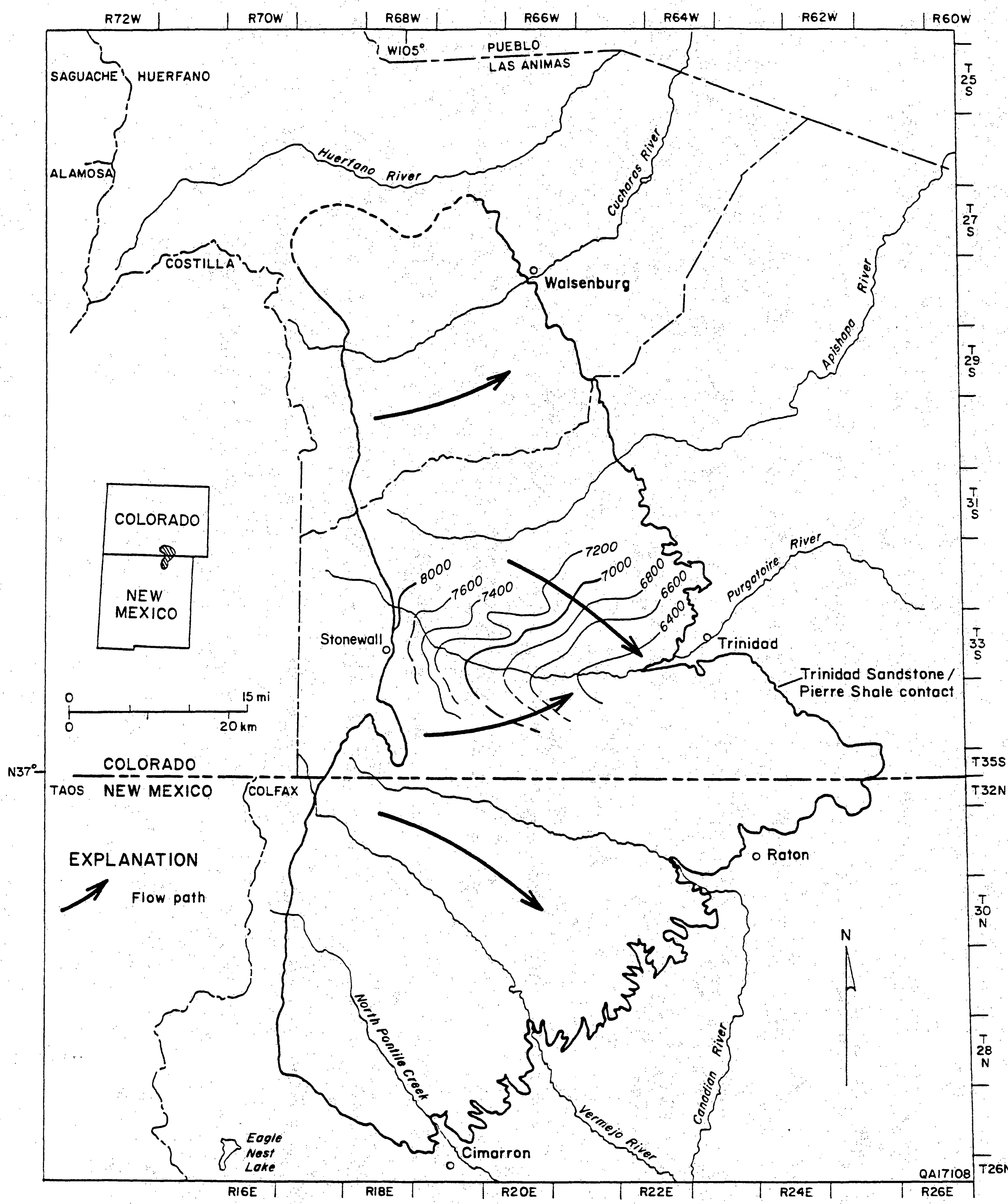


Figure 97. Potentiometric surface, Trinidad-Vermejo-Raton aquifer, central Raton Basin. Modified from Geldon (1990) and Howard (1982). Ground water flows toward the eastern outcrop belt and Purgatoire River valley.

1988) or by a basinward permeability barrier, low-permeability rocks downflow of the barrier, and insulation from water-table aquifers (Kaiser and others, 1991b). Initial water production (fig. 98) and operator comment indicate an eastward decrease in permeability, suggesting that underpressure reflects low equivalent permeability downflow in the Raton and Vermejo Formations.

Although artesian conditions may develop along the elevated western outcrop belt (or recharge area), coal-seam discontinuity precludes development of a regional, interconnected aquifer system and subsequent regional artesian overpressuring extending eastward from the western recharge area. Development of overpressuring is most likely in the thicker, more laterally extensive lower Vermejo coal seams (fig. 92), which are confined below by the low-permeability Trinidad Sandstone and above by shales and low-permeability sandstones. Artesian conditions may also be encountered along the Purgatoire River valley, where upward flow occurs. The possibility of artesian overpressuring on the western basin margin would favor higher gas contents in that area and in the Purgatoire River valley.

Coal Rank

A coal-rank map of the Vermejo Formation was prepared with depth-corrected vitrinite reflectance values (base of the Vermejo) determined by ARI, Inc. (1991). Vitrinite reflectance values (R_m) for both the Raton and Vermejo Formations are from Khalsa and Ladwig (1981), Merry and Larsen (1982), Tremain and Toomey (1983), and Close (1988). Additionally, proximate analytical data from Pillmore and Hatch (1976) and Goolsby and others (1979) were converted to equivalent vitrinite reflectance values for an equation determined by ARI, Inc. (1991). The measured and calculated vitrinite reflectance data were used to supplement the depth-corrected coal-rank data and to verify coal-rank trends. Coal rank in the Vermejo Formation ranges from high-volatile C bituminous (vitrinite reflectance value of 0.57) in the north part of the basin to medium- to low-volatile bituminous (measured vitrinite reflectance of 1.31; depth corrected vitrinite reflectance of 1.58). Coal rank approaches anthracite to graphite adjacent to igneous intrusives (Jurich and Adams, 1984b).

The highest-rank coals occur in an east-west-trending band parallel to the Purgatoire River. Coal rank decreases gradually north and south to high-volatile B and C rank coals along the basin margins. Isoreflectance contours generally parallel the basin margin (fig. 99) and follow basin structural trends (Merry and Larsen, 1982). These contours are closely spaced along the northwest margin of the basin adjacent to the deepest part of the basin near La Veta. The presence of lower-rank coals along the basin margin suggests that uplift along the basin margins occurred before the main stage of coalification. The relation between coal rank and the Tercio and Vermejo Domes (fig. 88) along the west margin of the basin is unknown. Coal rank may decrease over these structures if the structures were formed before the main stage of coalification or rank may remain constant if the structures are underlain by, and formed in response to, Tertiary intrusives.

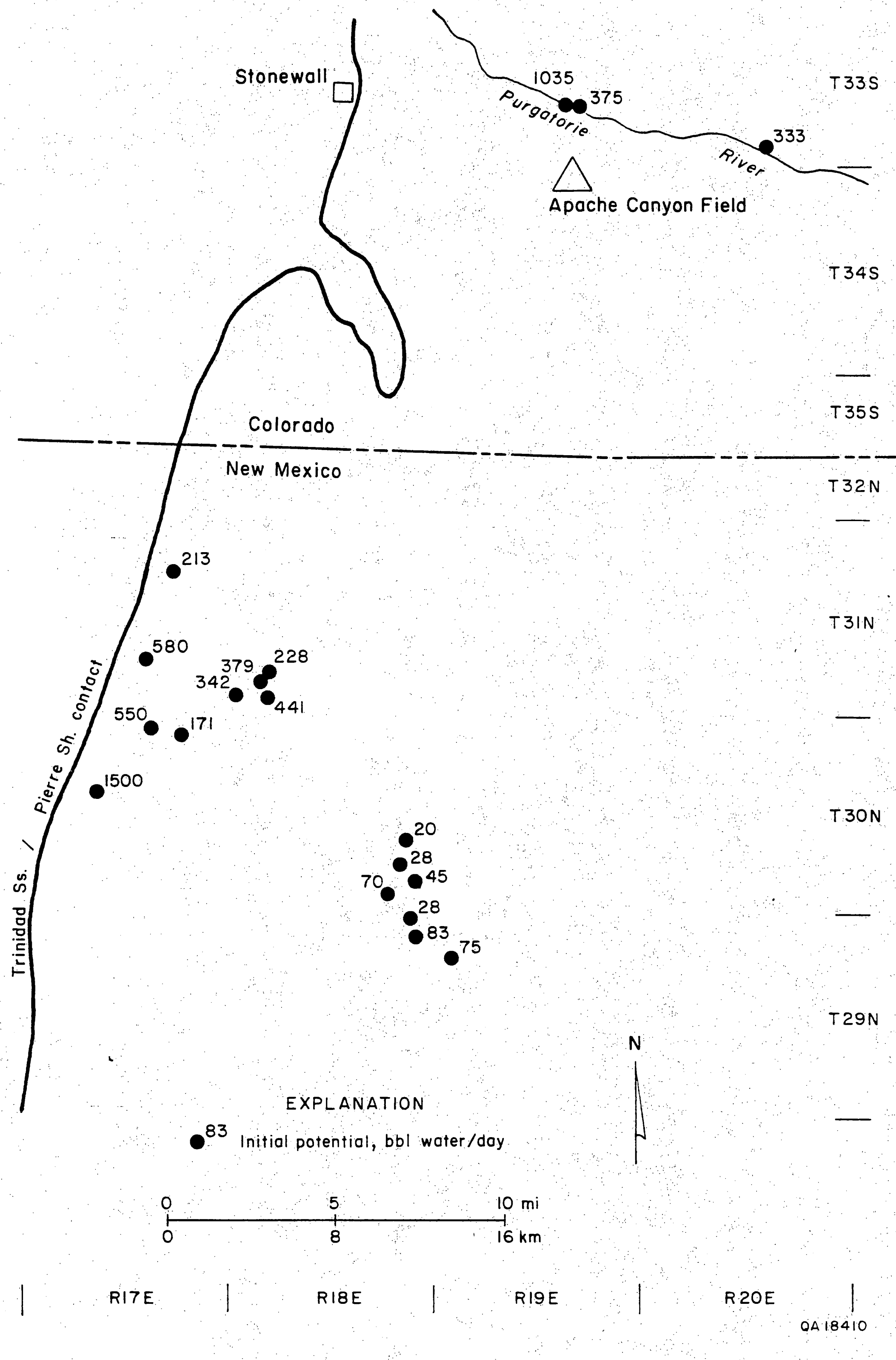


Figure 98. Initial potential of water from coal beds in the southern Raton Basin. Data from Petroleum Information (1990a–k; 1991a–f). IP's are high in the west and decrease eastward.

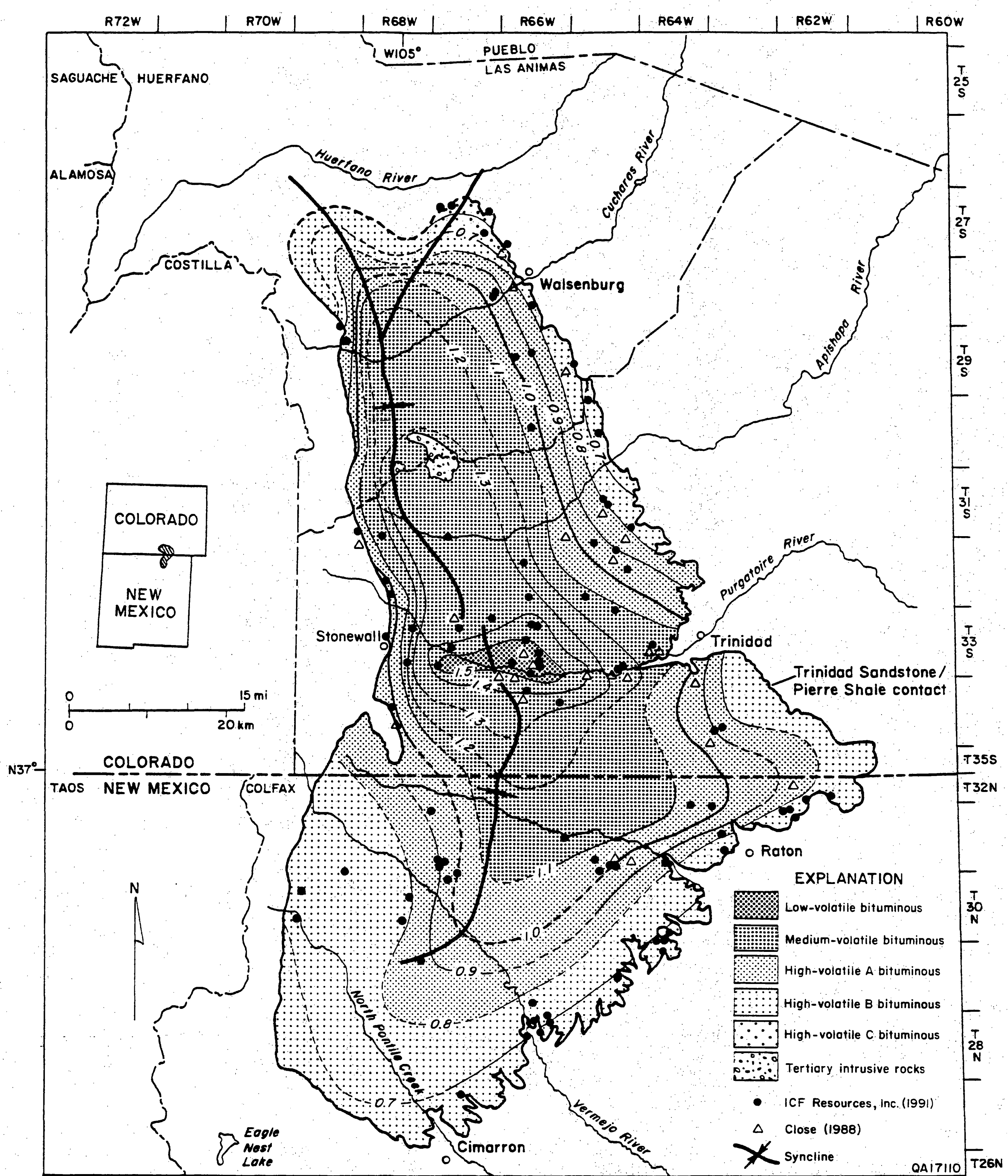


Figure 99. Coal-rank map to the base of the Vermejo Formation. The highest-rank coals are located in an east-west band along the Purgatoire River valley. This area of higher coal rank may be due to a deeply buried heat source and/or heat advection by ground water. Modified from ARI, Inc. (1991).

The effect of igneous intrusives on coal rank was discussed by Carter (1956), Dolly and Meissner, (1977), Merry and Larsen, (1982), Jurich and Adams, (1984b), and Close, (1988). Dikes that crosscut coal beds have affected coal rank in a zone about one dike thickness in width, whereas sills emplaced parallel to coal beds affected and/or removed large volumes of coal in the north part of the basin (Carter, 1956). Coal-rank trends do not appear to increase toward the Spanish Peak Igneous Complex; however, well control is scarce in that area. Furthermore, the local alteration of coal and other source rocks by igneous intrusives generally does not extend for more than one-half the thickness of the intrusive (Close, 1988 and references therein). Therefore, the direct effects of igneous intrusives (contact metamorphism) on coal rank is probably limited. However, secondary effects, such as regional heat flow and advection by ground water, may have significantly influenced coal rank in the Raton Basin.

The distribution of vitrinite reflectance values relative to present-day depths of burial indicate that burial depth alone cannot account for the distribution of higher-rank coals in the Raton Basin. Vitrinite reflectance profiles (fig. 100) indicate that a significant amount of overburden must have been removed after coalification in order to explain the relatively high surface vitrinite reflectance values. This is consistent with Close (1988) who estimated that at least 6,560 ft (2,000 m) of strata was removed along the eastern Purgatoire River valley in the last 18 million years. An elongate band of higher-rank coal parallel to the Purgatoire River and perpendicular to the basin axis indicates that factors other than burial depth must be considered to explain the coal-rank trends. Merry and Larsen (1982) suggested that the anomalously high ranks of Vermejo and Raton coals along the Purgatoire River resulted from a combination of deep burial during Pliocene time and proximity to Tertiary intrusives. The general east-west orientation of the higher-rank coal along the Purgatoire River follows the same trend as many dikes in the north-central part of the basin, suggesting that emplacement may have occurred along structurally weakened zones. A recent study by ARI, Inc. (1991) indicates that the area of higher-rank coal has a higher vitrinite reflectance gradient (0.46 percent per 1,000 ft [305 m]) than the vitrinite reflectance gradient throughout the basin (0.34 percent per 1,000 ft [305 m]) (fig. 100), which could indicate a deep igneous source. However, no magnetic anomaly is associated with this part of the basin that would indicate a deeply buried intrusive (Zietz and Kirby, 1972). Regional ground-water flow converges on the Purgatoire River (fig. 97), and hot fluids ascending to an ancestral Purgatoire River may account for the high vitrinite reflectance values paralleling the river valley (fig. 99). However, coal rank is not high along the entire length of the Purgatoire River, suggesting that something is unique about the coal rank along the river (Close, 1988). The emplacement of intrusive sills in Raton and Vermejo coal beds would heat fluids moving through coal beds, which would then move toward the Purgatoire River valley. Wells drilled near the river have encountered sills (ARI, Inc., 1991). Therefore, the distribution of higher-rank coals may be a function of basin hydrology and proximity of the coal beds to the river valley and to Tertiary intrusives, which would serve to heat fluids passing through the rocks. Alternatively, higher coal ranks along the

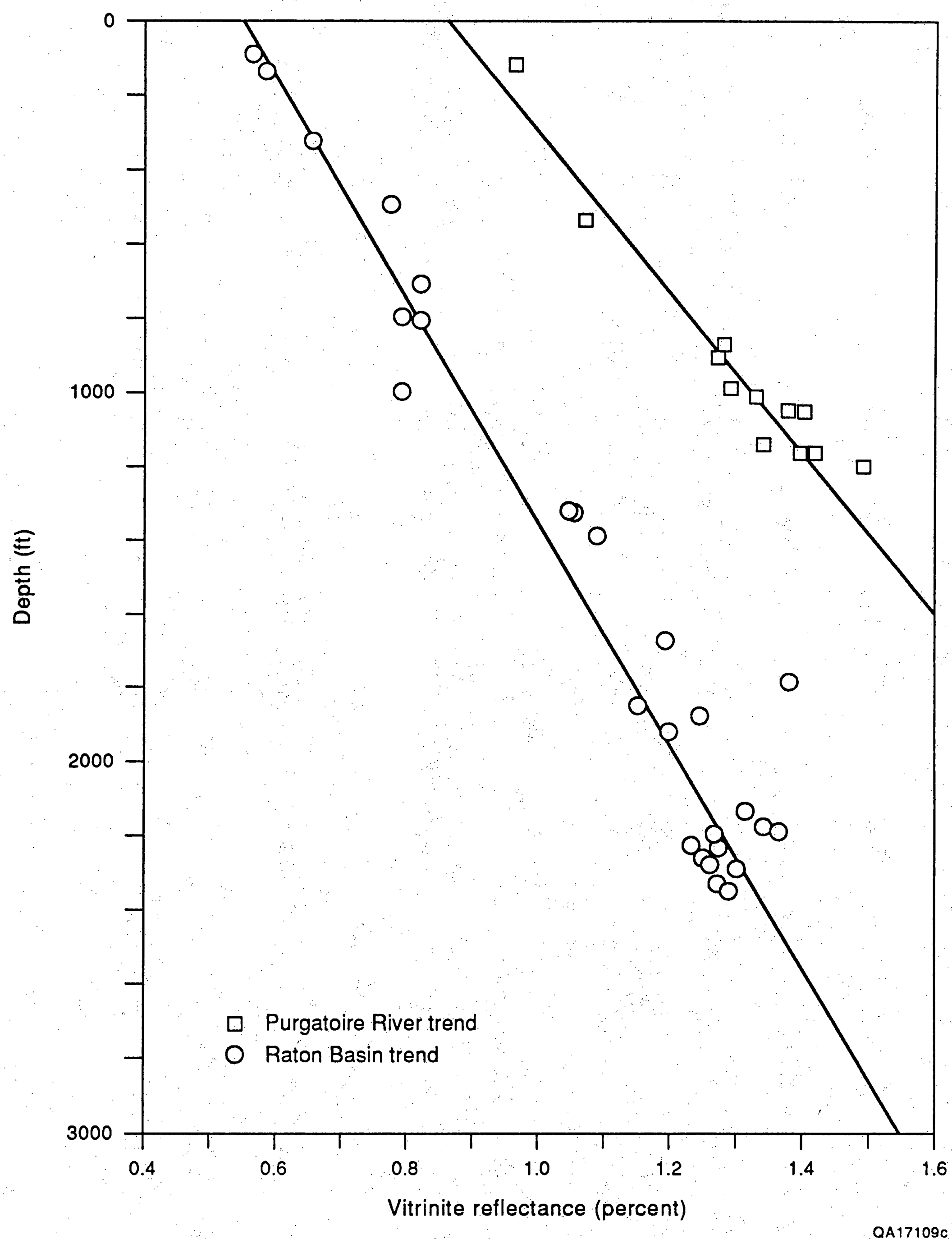


Figure 100. Vitrinite reflectance profiles for the Raton Basin. Vitrinite reflectance gradients along the Purgatoire River are significantly higher (0.46 percent/1,000 ft [305 m]) than vitrinite reflectance gradients elsewhere in the basin (0.34 percent/1,000 ft [305 m]). Modified from ARI, Inc. (1991).

Purgatoire River may be due to a deep localized source of higher heat flow associated with advective heat transfer from vertical fluid flow along deep-seated fractures.

Gas Composition

Gas compositional data for 15 Vermejo Formation coalbed gases indicate that Vermejo coalbed gases are chemically dry to very dry, having C_1/C_{1-5} values that range from 0.97 to 1.00 in coals of high-volatile A bituminous to low-volatile bituminous rank (Tremain and Toomey, 1983; Close, 1988). Large amounts of carbon dioxide were probably generated through the volatilization of the coal beds during the emplacement of sills and dikes; additional carbon dioxide may have an igneous source. However, carbon dioxide content of Vermejo coalbed gases ranges from 0.1 to 1.7 percent and averages 0.7 percent. The carbon dioxide generated during the emplacement of the intrusives may have absorbed onto coal surfaces and has not been completely desorbed yet, escaped from the system through fractures, precipitated as carbonate or calcsilicate minerals in adjacent sandstones or coal beds, assimilated into the intrusives, or a combination of the above processes. The low carbon dioxide content of gases from coal beds not associated with the igneous intrusives is due to the relatively high coal rank; carbon dioxide content generally decreases with increasing coal rank. Vermejo Formation coal beds contain some of the chemically driest gases and have the lowest carbon dioxide content of any of the western basins evaluated in this study. Methane $\delta^{13}C$ values range from –51.3 to –42.4‰ and average –44.8‰. Isotopically light methane (–51.3‰) in the north part of the basin (Sec. 24, T28S, R67W) may be biogenic in origin, whereas the isotopically heaviest coalbed methane is associated with higher-rank coals near the Purgatoire River (Sec. 8, T33S, R65W) is thermogenic.

Coalbed Methane Production

Production Targets

Most coalbed methane drilling activity in the Raton Basin occurs on the west margin, approximately 24 mi (39 km) west of Trinidad, Colorado, and 25 to 30 mi (40 to 48 km) northwest of Cimarron, New Mexico. Production targets in the Raton Formation occur at depths of 400 to 1,800 ft (122 to 549 m) and in the Vermejo Formation at depths of 1,400 to 2,500 ft (427 to 762 m). Individual Vermejo and Raton coal beds (reservoirs) are thin (typically 5 to 10 ft [1.5 to 3 m] thick) and pinch out over a few hundreds or thousands of feet. However, coal beds in the Raton and Vermejo Formations have a combined thickness of more than 100 ft (30 m) in a southern coal depocenter that coincides with the area of current drilling activity northwest of Cimarron. Because wells drilled in this southern coal depocenter intersect a great net thickness of coal beds, this area may locally contain some of the best coalbed methane targets and resources in the basin. Additionally, the northern (Colorado) area of current drilling activity coincides with highest-rank coal beds in the basin, where vitrinite reflectance values in the Vermejo Formation exceed 1.3 percent (ARI, Inc., 1990). Other coalbed methane targets in the southeast part of the Raton Basin may exist in thick (net-coal thickness greater than 25 ft [>7.6 m]), northeast-trending Vermejo coal beds that formed landward (northwestward) of shoreline deposits of the Trinidad Sandstone. However, little or no coalbed methane activity has been in this part of the basin, possibly because of relatively low coal rank (vitrinite reflectance of Vermejo coal beds less than 1.1 percent) (ARI, Inc., 1990) and corresponding lower gas content.

Gas and Water Production

The Raton Basin has the lowest coalbed methane production (11.7 MMcf [331,110 m^3]) among the basins described in this report. Almost all coalbed methane wells in the Raton Basin are shut in, pending installation of gas pipelines. However, coal beds in the basin have good gas contents; Vermejo coal beds typically contain from 115 to 492 ft^3/ton (3.6 to 15.3 m^3/t) of gas (fig. 101), whereas Raton coal beds contain 23 to 193 ft^3/ton (0.7 to 6.0 m^3/t) of gas (Bench, 1979). Some coalbed methane initial potentials in the Raton Basin compare favorably with those of other basins (fig. 102a) (Gas Research Institute, 1989c). Water production of coalbed methane wells in the Raton Basin can be as high as 1,200 bbl/d (191 m^3/d), especially on the west margin near areas of regional ground-water recharge (fig. 102b).

Coalbed methane production in the Raton Basin has been reported from only Three Bridges and Apache Canyon fields (fig. 103). Three Bridges field, located in the northwest part of the Raton Basin in Colorado, has produced approximately 8.3 MMcf (234,890 m^3) of coalbed gas and no water, whereas Apache Canyon field, located approximately 24 mi (39 km) west of Trinidad, Colorado, has produced approximately 3.4 MMcf (96,220 m^3) of gas and virtually all of the basin's water (821,710 bbl [130,570 m^3]) (table 7). Note its location in the Purgatoire River valley and near the western recharge area (fig. 103). Production from Apache Canyon field, which is operated mainly by Meridian Oil, Inc., is from the Vermejo Formation at depths of 2,000 to 3,000 ft (610 to 915 m). Average combined daily water production in November 1990, from four active wells out of the 25 wells drilled in the field, was 392 bbl (62.3 m^3) (Petroleum Information, 1991d). Most of the wells in Apache Canyon field are shut-in due to the lack of gas pipelines.

Completions and Drilling Activity

Most coalbed methane drilling activity has occurred in the central part of the basin along the Purgatoire River and along the western edge of the basin between Casa Grande, New Mexico and Stonewall, Colorado (fig. 104). In 1990, there were 50 shut-in and 16 dry and abandoned coalbed methane wells in the Colorado part of the basin (Tremain, 1990). Reasons for dry holes include low gas content or high water production. Of the 27 coalbed methane wells in the Raton Basin with reported

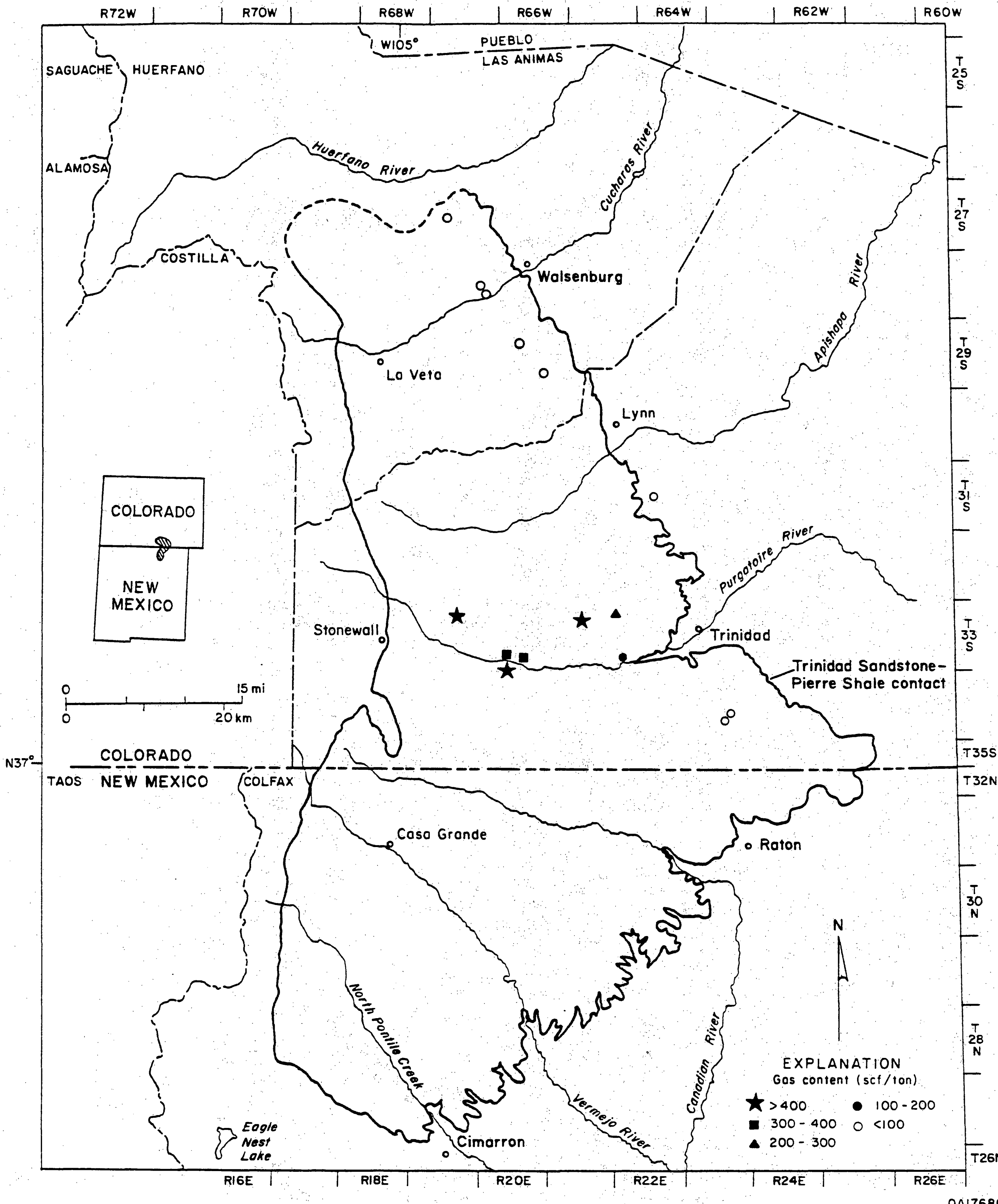


Figure 101. Gas content of Vermejo coal beds in the Raton Basin. Data from Tremain and Toomey (1983).

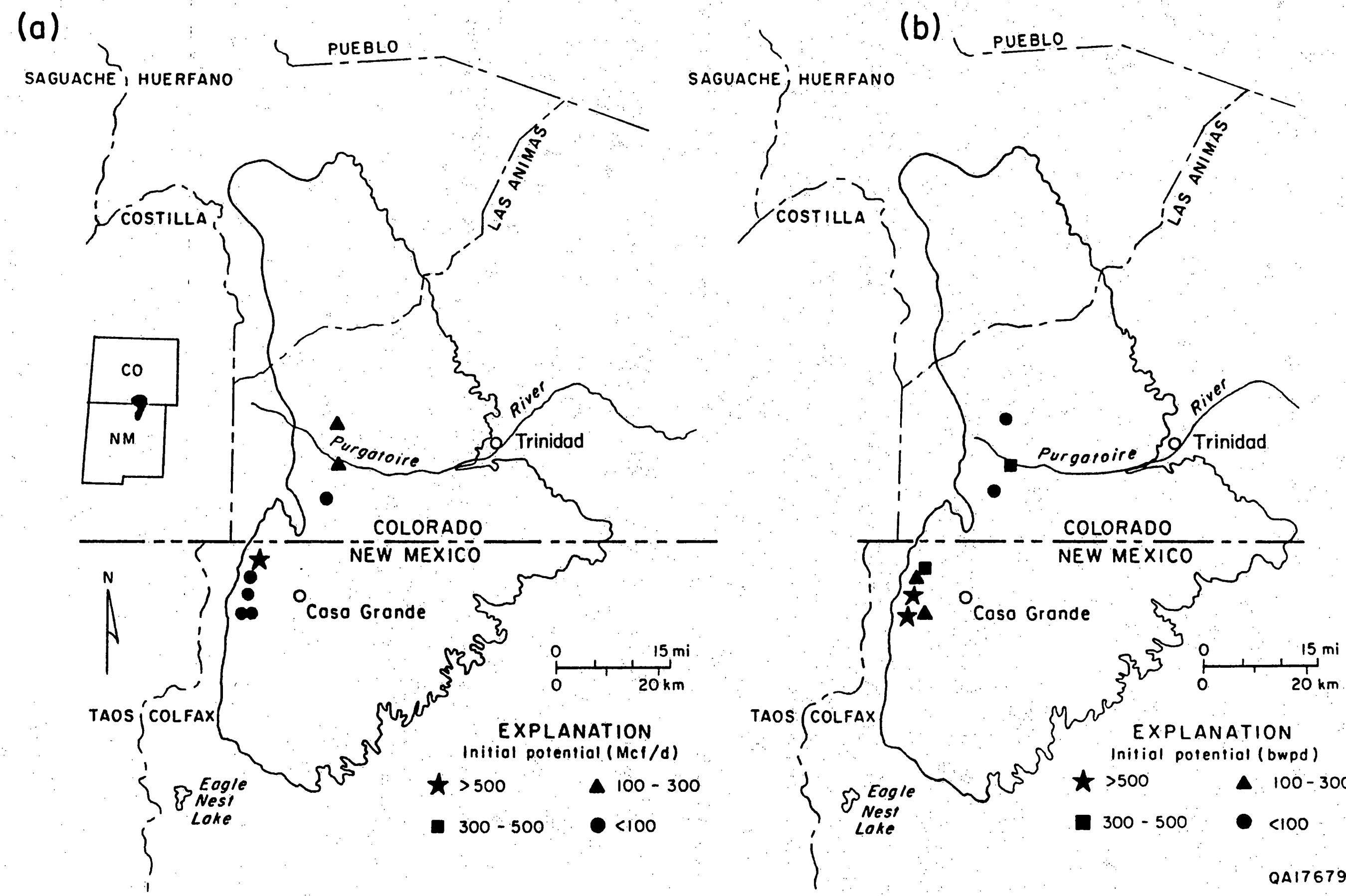


Figure 102. (a) Initial potential of gas from Vermejo coal beds in the Raton Basin. Most activity is along the west margin of the basin. (b) Initial potential of water from Vermejo coal beds. Highest water IP's (> 300 bbl/d) reflect proximity to the recharge area and inferred high coal-seam permeability. Data from Petroleum Information (1990a–k; 1991b–f) and the Gas Research Institute (1988; 1989c; 1990c).

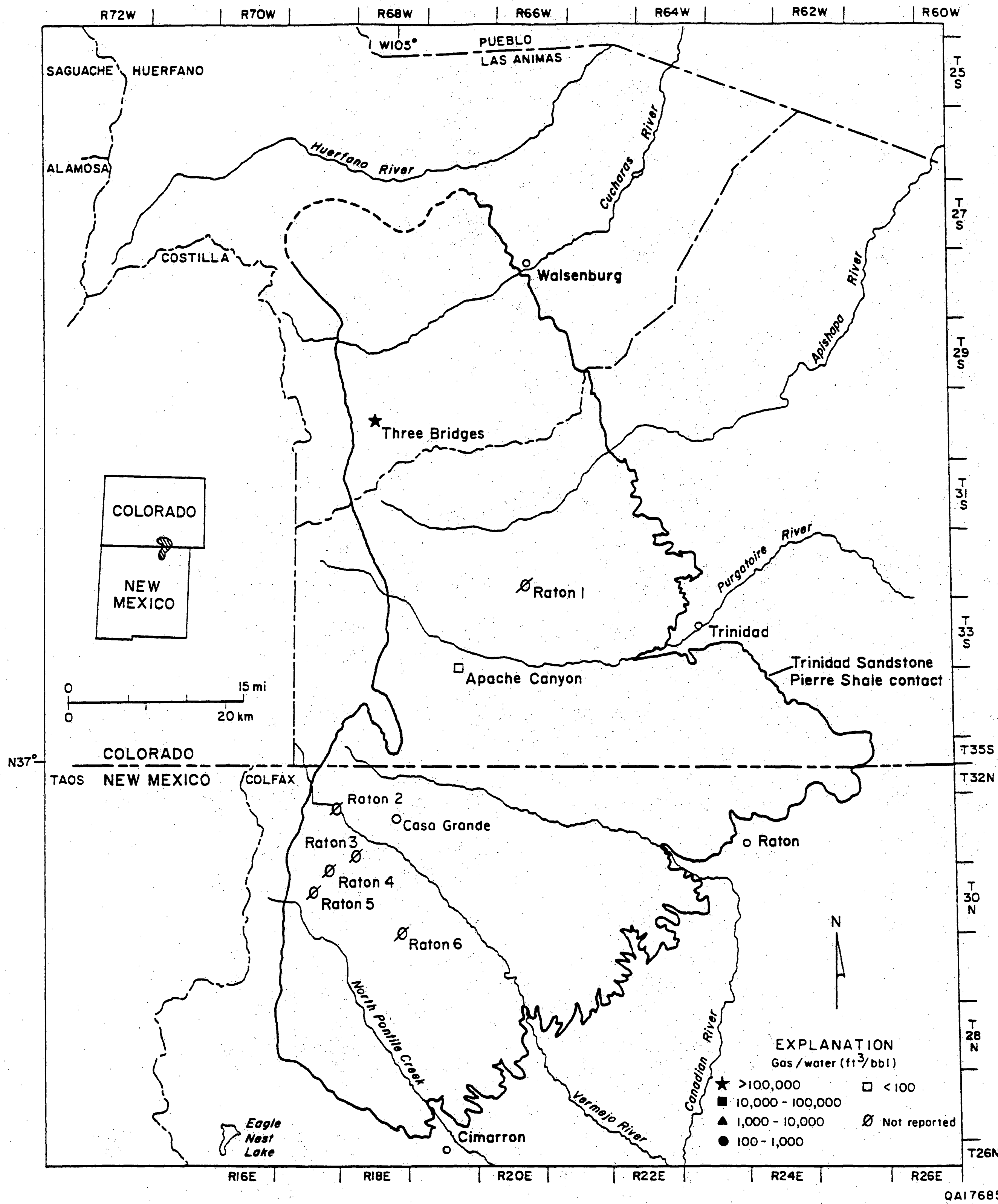


Figure 103. Cumulative gas/water ratio in coalbed methane fields in the Raton Basin. Data from Petroleum Information (1990a–k; 1991b–f).

Table 7. Liquid hydrocarbon, cumulative coalbed gas, and water production from fields in the Raton Basin and production from October 1989 to January 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Raton Basin fields	Oct 89–Jan 91 Liquid (bbl)	Oct 89–Jan 91 Gas (Mcf)	Oct 89–Jan 91 Water (bbl)	Cumulative to Jan 91 Liquid (bbl)	Cumulative to Jan 91 Gas (Mcf)	Cumulative to Jan 91 Water (bbl)
Apache Canyon	0	3,382	821,710	0	3,382	821,710
Three Bridges	0	0	0	0	8,313	0
Raton 1	*	*	*	*	*	*
Raton 2	*	*	*	*	*	*
Raton 3	*	*	*	*	*	*
Raton 4	*	*	*	*	*	*
Raton 5	*	*	*	*	*	*
Raton 6	*	*	*	*	*	*
Raton Basin Total	0	3,382	821,710	0	11,695	821,710

* = No production reported

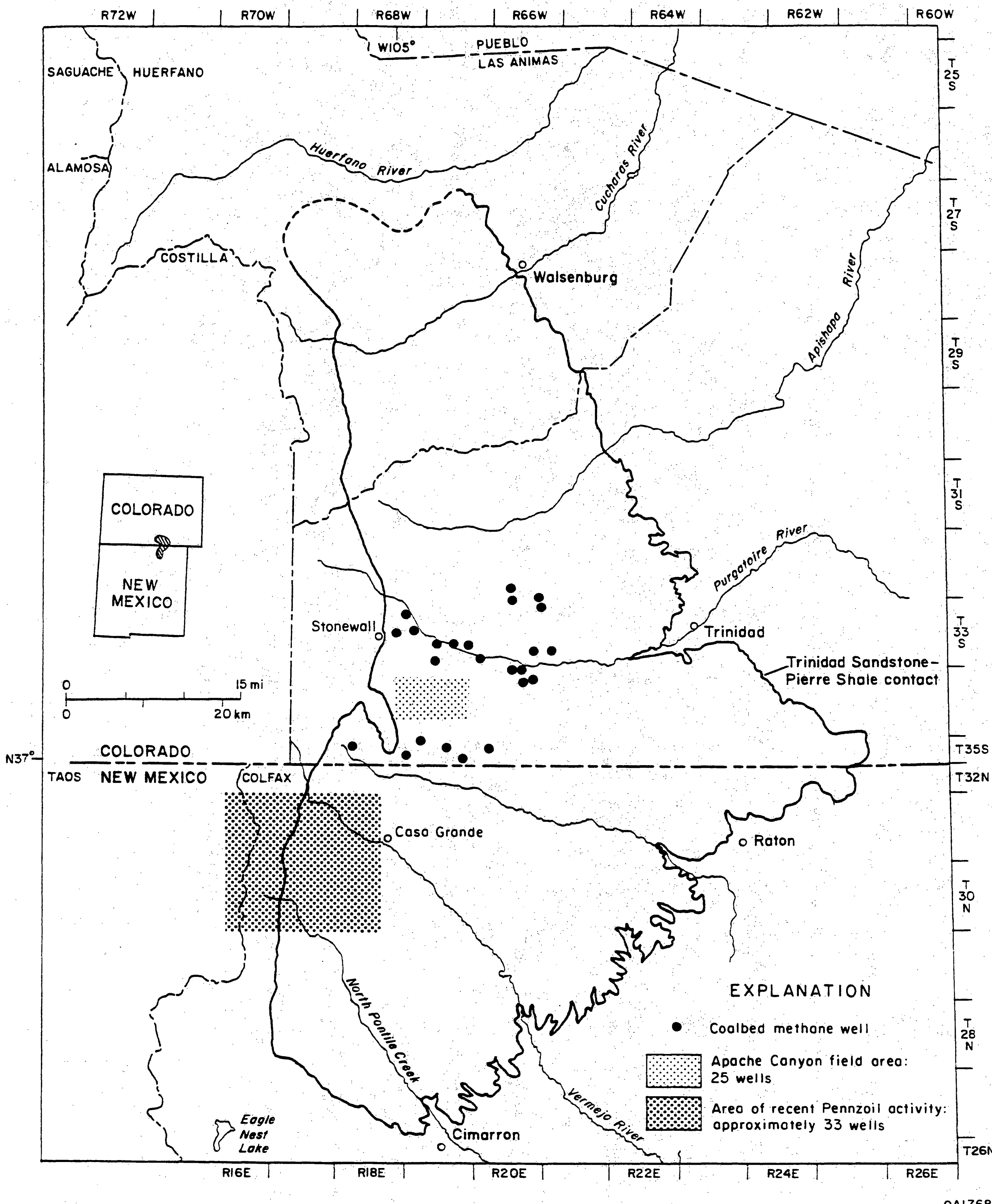


Figure 104. Recent (1990 and 1991) coalbed methane wells in the Raton Basin. Data from Petroleum Information (1990a–k; 1991b–f), and the Gas Research Institute (1990c).

completion data from February 1990 to May 1991, single completions in the Vermejo and Raton Formations were the most common (10 completions), although there were 7 commingled completions in both formations (fig. 105). Approximately 60 percent of these completions had been in wildcat wells. All of the single completions were in the Vermejo Formation at depths to top of perforations ranging from 894 to 2,246 ft (273 to 684 m) (fig. 106). Commingled completions were in both the Vermejo and Raton Formations at depths to top of perforations ranging from 788 to 1,828 ft (240 to 557 m). Total depths of gas wells in the basin ranged from 620 to 2,876 ft (189 to 877 m) and averaged 2,148 ft (655 m) (fig. 107). No drill-stem tests in coalbed methane wells in the Raton basin have been reported.

Pennzoil and Meridian were recently the most active of the 6 coalbed methane operators in the Raton Basin, with 22 wells each from February 1990 to May 1991 (fig. 108a). Western Oil has drilled 17 coalbed methane wells, whereas the remaining operators have drilled only 1 or 2 wells each. Most coalbed methane wells have been drilled in the Colorado part of the basin, except those drilled by Pennzoil, which had been drilling in New Mexico before shutting in its wells in 1991(fig. 108b).

Meridian Oil, Inc., has been active only in the Colorado part of the basin and has drilled 25 wells at Apache Canyon field to test the Vermejo Formation (see previous section: Gas and Water Production) and deeper targets, including the Niobrara Formation and Pierre Shale (Petroleum Information, 1990d). In 1989, Pennzoil Exploration and Production began a $7 million coalbed methane exploration program in the New Mexico part of the basin to evaluate methane-charged sandstones and coal beds in the Vermejo Formation at maximum depths of 2,000 to 2,300 ft (610 to 701 m) (Gas Research Institute, 1989c). Some of Pennzoil's early wells were drilled in T29–30N, R18–19E, south of, and on trend with, the Tercio and Vermejo Domes, which are structurally higher areas on the west flank of the La Veta Syncline (figs. 84 and 88). Two wells (Van Bremmer Canyon 311G and 322D) were perforated and completed with sand-water fracture stimulations in the Raton Formation at 1,340 to 1,600 ft (409 to 488 m) and the Vermejo Formation at 1,725 to 1,975 ft (526 to 602 m) and had initial potentials of 33 to 34 Mcf/d (934 to 962 m^3/d) of gas and 134 to 431 bbl/d (21.3 to 68.5 m^3/d) of water (Gas Research Institute, 1990c). Pennzoil also tested three new prospects in the Vermejo Ranch area in T30–31N, R17–18E, 25 to 29 mi (40 to 47 km) northwest of Cimarron, New Mexico. An early well, the No. 1 Leandro Creek (Sec. 18, T31N, R18E), was abandoned at 668 ft (204 m) in the Vermejo Formation. Pennzoil then recompleted the No. 3-1 Vermejo Park well (Sec. 1, T31N, R17E) in the Vermejo Formation at a depth of 620 ft (189 m) with an initial potential of 650 Mcf/d (18,395 m^3/d) of gas and 5 bbl/d (0.8 m^3/d) of water. The No. 30-33 Bremmer (Sec. 30, T30N, R19E) was recompleted in the Vermejo Formation at 2,037 ft (621 m) with a sand-gel fracture stimulation and tested at only 20 Mcf/d (566 m^3/d) of gas and 274 bbl/d (43.5 m^3/d) of water (Gas Research Institute, 1989c). By 1990, Pennzoil had drilled 33 wells in the Vermejo Ranch area. These wells are shut-in, pending connection to pipeline. Total gas flow from 15 of these wells was 963 Mcf/d (27,253 m^3/d) (64.2 Mcf/d per well [1,817 m^3/d per well]) and water production was 2,224 bbl/d (353 m^3/d) or 148 bbl/d per well (23.5 m^3/d per well) (Johnson, 1990).

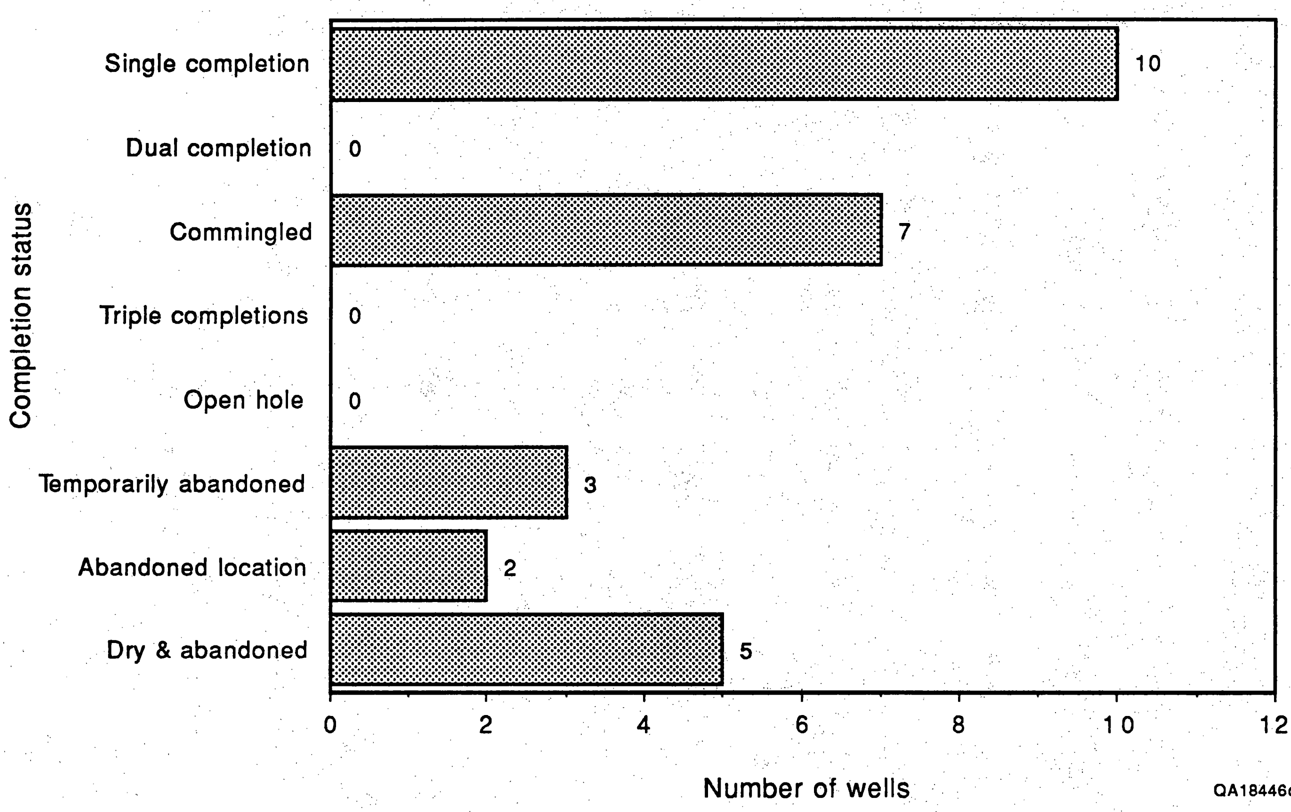
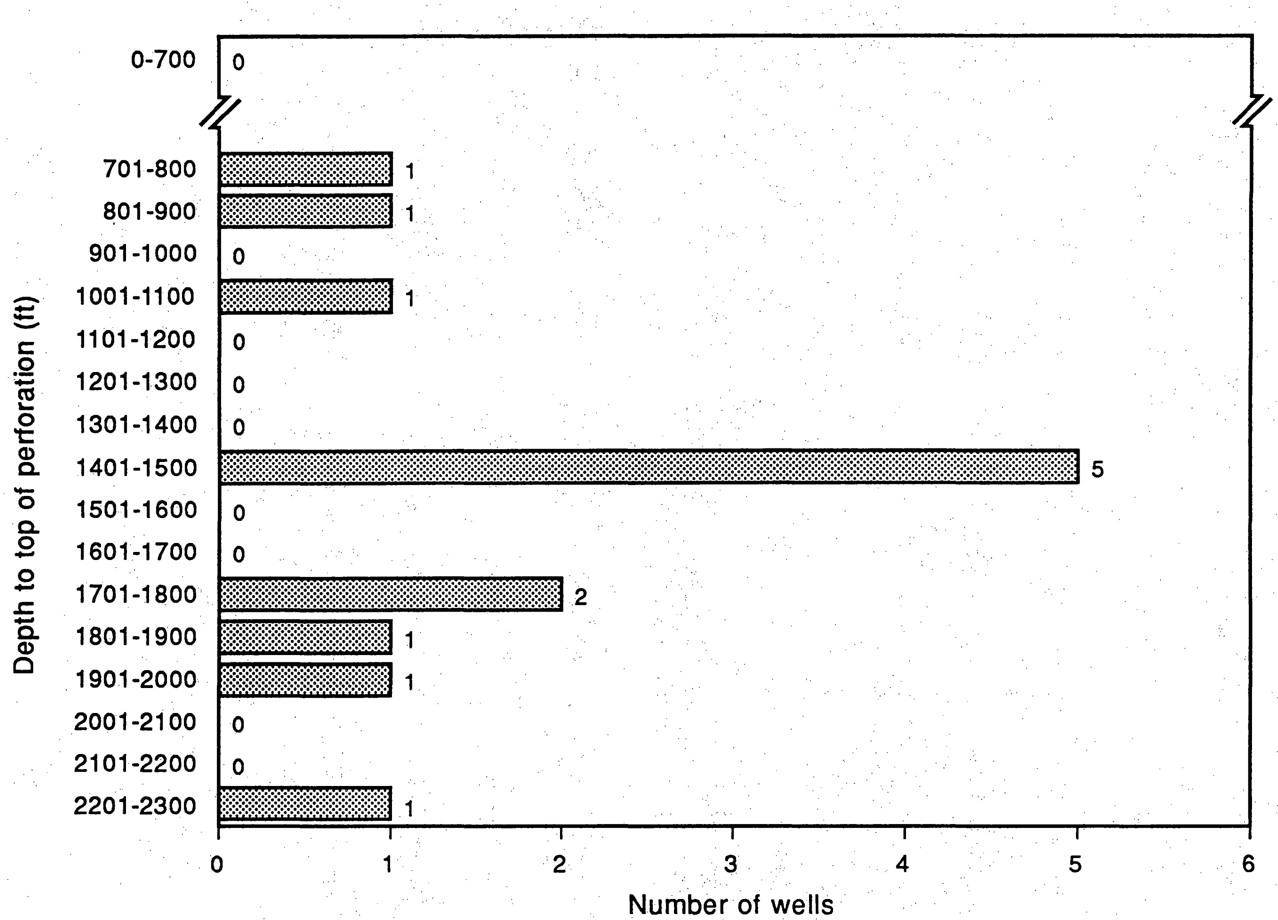


Figure 105. Completion status of coalbed methane wells in the Raton Basin from February 1990 to May 1991. Data from Petroleum Information (1990a–k; 1991b–f).



Single completions	Commingled completions	All gas completions
Number of well depths used = 6	Number of well depths used = 7	Number of well depths used = 13
Minimum depth = 894 ft	Minimum depth = 788 ft	Minimum depth = 788 ft
Maximum depth = 2,246 ft	Maximum depth = 1,825 ft	Maximum depth = 2,246 ft
Average depth = 1,641 ft	Average depth = 1,402 ft	Average depth = 1,512 ft

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Figure 106. Depths to top of perforation in coalbed methane wells in the Raton Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

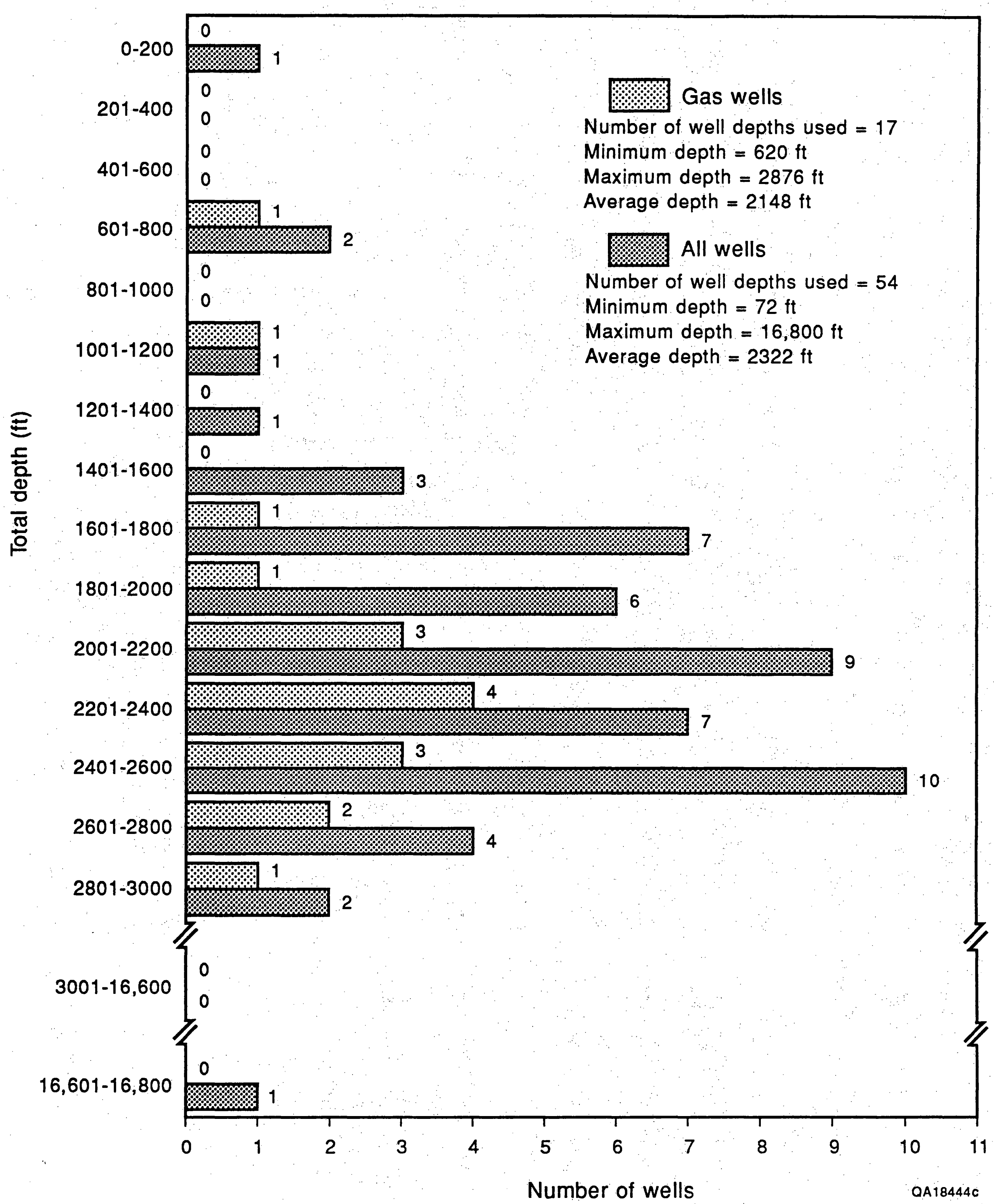

Figure 107. Total depths of coalbed methane wells in the Raton Basin from February 1990 through May 1991. Light bars represent completed gas wells. Dark bars represent all wells, completed or not. See figure 105 for types of completion. Data from Petroleum Information (1990a–k; 1991b–f).

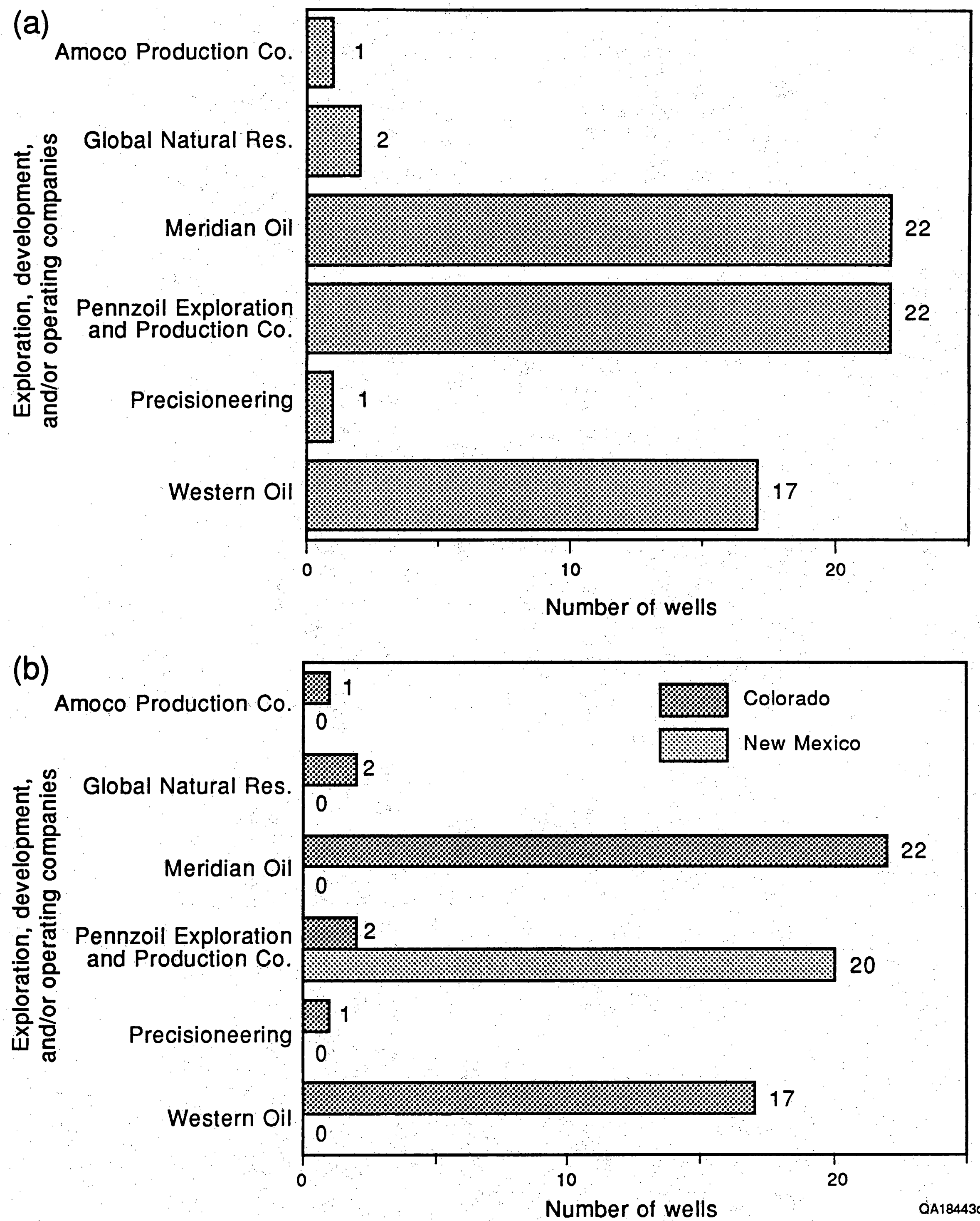

Figure 108. (a) Total number and (b) distribution by state (New Mexico or Colorado) of coalbed methane wells drilled by exploration, development, and/or operating companies in the Raton Basin from February 1990 through May 1991. Data from Petroleum Information (1990a–k; 1991b–f).

Pennzoil has shut in their coalbed methane wells because of lack of pipelines and the recent (1991) decline in the price of natural gas.

Other companies that have tested the coalbed methane potential of the Raton Basin include Amoco Production Company, Global Natural Resources Corporation, Precisioneering, Inc., RJF, Inc., Western Oil Corporation, and Industrial Gas Services, Inc. In 1988, Amoco was the only active coalbed methane operator in the basin, but has since discontinued drilling. Amoco's coalbed methane wells were west of Trinidad, Colorado, and targeted coal beds of the Raton Formation at depths ranging from 360 to 1,722 ft (110 to 525 m) and the Vermejo Formation, 878 to 2,160 ft (268 to 659 m) deep. In the first quarter of 1989, Amoco released data from the No. 1 AS State of Colorado well, which had an initial potential of 239 Mcf/d (6,764 m^3/d) of gas and no water. No test data were released from the other wells, but Amoco estimated that five other wells flared from 68 to 160 Mcf/d (1,924 to 4,528 m^3/d) per well before they were shut-in owing to lack of market (Gas Research Institute, 1989c).

Global has drilled three test wells 5 mi (8 km) southeast of Meridian's Apache Canyon lease. Gas shows were indicated at 2,520 ft (768 m) in the Vermejo Formation, but no initial-potential data were released (Petroleum Information, 1990c). Precisioneering and RJF have tested for coalbed methane in Vermejo and Raton coal beds to 2,000 ft (610 m) west of Trinidad, Colorado, but no initial-potential data are available (Petroleum Information, 1990c). Western Oil has drilled and tested 17 wells in the Apache Canyon field area. One well, completed in the Vermejo Formation at 1,465 to 1,556 ft (447 to 474 m), had an initial potential of 161 Mcf/d (4,556 m^3/d) of gas and 375 bbl/d (59.6 m^3/d) of water. This well (No. 28-16 Golden Eagle, Sec. 28, T33S, R67W) is still dewatering (Petroleum Information, 1991d).

Pipeline Availability

As of February 1977, one pipeline owned by Raton Natural Gas Company bordered the east edge of the Raton Basin (Federal Energy Regulatory Commission, 1977a; Federal Energy Regulatory Commission, 1977b). This pipeline begins at Las Vegas, New Mexico, which is south of the Raton Basin, continues through Raton, New Mexico, and ends at Trinidad, Colorado, where the pipeline connects to the Colorado Interstate Gas Company (CIG) spur, which connects to the major CIG pipeline through Colorado (fig. 34). One pipeline spur connects Three Bridges field to the town of Walsenberg, Colorado and the CIG spur.

Of the eight fields listed in the Raton Basin (fig. 103), none are near the present system. An additional pipeline has been proposed to connect Trinidad, Colorado, to the major CIG pipeline (Western Oil World, 1990). This project would cost $20 million and be 31 mi (50 km) long, conveying 40 MMcf/d (1.1 MMm^3/d). This project is still under negotiation but is not expected to connect to the existing coalbed methane fields of the southern Raton Basin, leaving coalbed methane wells without transmission lines to markets in other parts of the United States.

Coal and Coalbed Methane Resources and Potential

Total coal-resource estimates for the Raton Basin range from 1.5 billion tons (1.36 billion t) (Wanek, 1963) to 4.8 billion tons (4.35 billion t) (Read and others, 1950). Almost all of these coal resources are in the Vermejo and Raton Formations, in which net-coal thickness in the combined formations locally exceeds 100 ft (30 m) (ARI, Inc., 1991). These coal beds exist in a 2,100-mi^2 (5,440-km^2) area from outcrop to depths greater than 4,000 ft (1,220 m) (Jurich and Adams, 1984b).

As much as 18.4 Tcf (520.7 Bm^3) of coalbed gas resources are estimated for the Raton Basin, assuming that approximately 50 percent of the estimated 38.7 Tcf (1.1 T m^3) of original gas generated is still confined in coal beds (Dolly and Meissner, 1977). On the basis of projections of local estimates by Danilchik and others (1979a) and Tremain (1980a), approximately 8 and 12 Tcf (226.4 and 339.6 Bm^3), respectively, of coalbed gas is thought to be in the basin. These figures are projections of volumetric calculations of gas in single coal beds (7 to 10 ft [2.1 to 3 m] thick) that are thought to exist in local areas extending for 25 to 54 mi^2 (65 to 140 km^2) in the north part of the basin.

Thickness and continuity trends of many individual coalbed methane reservoirs (coal beds) in the Vermejo and Raton Formations are difficult to predict because these coal beds are discontinuous and thin, with average thickness of approximately 5 ft (1.5 m). Detailed stratigraphic studies, based on correlations of individual coal beds and sandstones between closely spaced wells, are needed to predict the extent of these reservoirs.

Major coalbed methane exploration targets can be delineated in the thick, basal Vermejo coal seam that directly overlies the Trinidad Sandstone. Although the basal Vermejo coal seam formed parallel to and landward of strike-elongate barrier-island and delta-front shorelines, locally it may exhibit dip-elongate net-coal thickness trends where peat (coal) formed between distributaries on the lower coastal plain. Detailed mapping of secondary, dip-elongate net-coal thickness trends should enable prediction of local variations in coalbed reservoir continuity and geometry.

Thinner alluvial coal beds (Raton and Upper Vermejo Formations) are more difficult to predict because they are discontinuous. Although many of these coal beds are dip-elongate (east-trending), they pinch out over a few hundreds to thousands of feet. However, coal beds of the combined Vermejo and Raton Formations occur in two depocenters, where combined net-coal thickness is locally more than 100 ft (30 m). The northern depocenter is approximately 15 mi (24 km) northwest of Trinidad, Colorado, whereas the southern depocenter is in the vicinity of Casa Grande, New Mexico. Both of these depocenters have been targeted for early coalbed methane exploration, partly on the basis of substantial net-coal thickness. Subsequent development of coalbed methane reservoirs in these depocenters should be based partly on coalbed-thickness trends of individual coal seams projected from detailed depositional models.

CONCLUSIONS

Resources

The Greater Green River and Powder River Basins have the largest coal resources (>302 billion short tons [>274 billion t] and 1,031 billion short tons [935 billion t], respectively) because of their large sizes and great net-coal thicknesses. Small coal resources (17 billion tons [15.4 billion t]) limit the Raton Basin's coalbed methane potential. All coal resources in the Powder River and Raton Basins occur at shallow depths (<6,000 ft [<1,830 m]), whereas considerable resources in the Greater Green River and Piceance Basins occur deeper. Gas resources are large in all four basins and each basin is attractive for coalbed methane exploration. Gas resources are large in the Piceance and Greater Green River Basins, 84 Tcf (2.38 Tm^3) and 29 Tcf (0.82 Tm^3), respectively. In the Greater Green River Basin, gas resources are potentially larger than reported because of the basin's large size and great net-coal thickness.

Tectonic and Stratigraphic Setting

The structural configuration of the Greater Green River, Piceance, Powder River, and Raton Basins is the result of similar tectonic histories. These basins lie in the Rocky Mountain Foreland, a major tectonic element between the Overthrust Belt and the North American Craton. During Cretaceous time this foreland was a rapidly subsiding, elongate, asymmetric trough occupied by the Western Interior Seaway. During the Laramide Orogeny, in Late Cretaceous and early Tertiary time, the foreland was broken into a number of smaller basins by basement-cored thrusting, which elevated highlands and caused sediments to be shed into the newly formed intermontane basins. These thick sequences of Late Cretaceous and early Tertiary sediments host the nation's thickest coal seams, and they are targets for coalbed methane exploration. The Laramide Orogeny was followed by an episode of erosion, a period of widespread magmatism and volcanism in the Oligocene, and finally an episode of renewed tectonic uplift about 10 mya. By the end of the Pliocene, the basins' present structural configuration, topography, surface drainage, and hydrodynamics were largely established.

Within the Rocky Mountain Foreland, the Greater Green River Basin, bounded by the Overthrust Belt on the west and by thrust-faulted uplifts on the remaining three sides, is structurally complex. The basin is broken into a number of subbasins (Green River, Great Divide, Washakie, and Sand Wash Basins) separated by the Rock Springs Uplift and Wamsutter and Cherokee Arches. Face-cleat strikes are typically oriented parallel to tectonic shortening directions and at right angles to orogenic thrust fronts. Maximum horizontal compressive stress orientations are northeast in the north and center of the basin and north-northwest in the southeast—a configuration that may be reflected in cleat patterns. The structurally complex Piceance Basin is bounded by basement-cored thrust faults adjacent to the Uinta Mountain

Uplift, Axial Arch, White River Uplift, and Elk Mountains; therefore, strata dip steeply on the north and east margins of the basin. Anticlines and domes within the basin are also believed to be underlain by reverse and thrust faults. Face and butt cleats trend east-northeast and north-northwest, respectively, and correspond in relative age, orientation, and joint style to the regional F_3 and F_4 fractures in sandstone. Maximum horizontal compressive stresses are west-northwest. The Powder River Basin, bounded by thrust-emplaced uplifts on the west, south, and east margins, adjacent to the Big Horn, Laramie, and Black Hills Uplifts, respectively, is locally structurally complex. However, coal-bearing strata are essentially flat-lying to gently dipping in the center of the basin. Cleat orientation is variable throughout much of the basin, and several cleat domains are recognized. The Raton Basin, bounded on its west margin by the thrust-emplaced Sangre De Cristo Mountains, is locally structurally complex. Tertiary intrusives also cause local structural complexity within the coal seams. Fracture data indicate that systematic joints and face cleats trend east to east-southeast, orthogonal to the Sangre de Cristo thrust front, whereas nonsystematic joints and butt cleats trend north to north-northwest. Maximum horizontal stress orientations are east to east-northeast. In effect, east-trending face cleats and horizontal stress orientations probably indicate the trend of permeability anisotropy in the basin.

The abundance of major structural elements associated with the intermontane basins, as a result of Laramide and post-Laramide tectonism, could be a measure of structural complexity. On a regional scale, structural discontinuities (hingelines) and regional changes in structural dip may represent sites of conventional trapping of gas and fracture-enhanced permeability and thus could potentially be areas for enhanced production. In the San Juan Basin, the most productive wells occur along the basin's structural hingeline. Consequently, the Greater Green River and Piceance Basins have a structural advantage over the Powder River and Raton Basins because of their numerous regional dip changes. Local tectonic or compaction-induced folds and faults, not identified on regional maps, are present in all basins and may be additional sites of fracture-enhanced permeability.

Depositional Setting

In the Greater Green River, Piceance, Powder River, and Raton Basins, Upper Cretaceous and/or lower Tertiary coal-bearing strata are the potential coalbed methane targets. Upper Cretaceous sediments were deposited along linear clastic shorelines by wave-dominated deltas and barrier/strandplains. The thickest coal seams were preserved landward and parallel to these ancient shorelines. Commonly thick coals directly overlie marine shoreline sandstones. In contrast, lower Tertiary coals are hosted by fluvial-lacustrine sediments where interchannel floodplains and foundered lacustrine deltas were sites of organic accumulation. The Greater Green River Basin contains several Upper Cretaceous and lower Tertiary coal-bearing units, collectively 4,000 to 9,000 ft (1,220 to 2,745 m) thick. The most continuous and thickest Cretaceous coal beds (individually as much as 35 ft [11 m] thick) top progradational sequences in the lower part of the Mesaverde Group (Williams Fork, Almond, and Rock Springs Formations) and the Lance Formation. Less continuous fluvial coals occur in the lower Tertiary Fort Union and Wasatch Formations. The Piceance Basin has a single major coalbed methane target, the Cameo coal group (Mesaverde Group), that ranges from 300 to 600 ft (91 to 183 m) thick and lies at an average depth of approximately 5,000 ft (1,524 m). The most continuous and thickest Cameo coal beds (individual seams from 20 to 35 ft [6 to 11 m] thick) formed in coastal-plain environments landward (northwestward) of delta-front and barrier-island deposits of the Rollins Sandstone. In the Powder River Basin, thick, laterally continuous coal seams are found in the Tongue River Member of the Paleocene Fort Union Formation. These coal seams, locally as much as 150 ft (46 m) thick, are of lacustrine-deltaic origin. The Raton Basin contains two main coal-bearing stratigraphic units: the Upper Cretaceous Vermejo and Upper Cretaceous–Paleocene Raton Formations. Vermejo coal beds, typically 5 to 10 ft (1.5 to 3 m) thick, formed on a coastal plain landward (westward) of wave-modified delta-front deposits of the Trinidad Sandstone. Less continuous, fluvial coal beds in the Raton Formation are typically less than 6 ft (<1.8 m) thick.

Hydrology

Hydrologic regimes are similar in the Greater Green River, Piceance, Powder River, and Raton Basins. They reflect the present-day structural configuration, aquifer permeability, topography, and climate. Recharge occurs over the wet, elevated margin of each basin. Ground-water flow is convergent on the basin's topographically lowest point, which may be the basin center, major river valley, or discharge outcrop belt. Regional permeability contrasts were inferred from hydraulic gradient, pressure regime, and hydrochemistry. Target coal seams in Upper Cretaceous and lower Tertiary strata are overpressured, underpressured, and normally pressured. Artesian overpressure reflects high permeability and because of higher pressure, correspondingly higher gas contents. Underpressured conditions usually indicate lower permeability and lower gas contents. Normal pressure probably indicates intermediate conditions and acceptable permeability. The presence of low-chloride formation water suggests active basinward recharge and flow along permeable pathways.

In the Greater Green River Basin, normally pressured or artesian coal seams yield low chloride formation waters, indicating good permeability. Areas of pressure transition and convergent, upward flow may be extensive and, by analogy with the San Juan Basin, very productive. In the Raton Basin, high water production in the western basin indicate good coal-seam permeability. Regional underpressure may reflect an eastward decrease in permeability. The Piceance Basin is dominated by underpressure and hydrocarbon-related overpressure, which indicates low permeability, which in turn may ultimately limit the basin's coalbed methane potential. Paradoxically, high permeability will limit development in the Powder River Basin, where coal seams are major aquifers and are difficult to dewater.

Thermal Maturity

In the Greater Green River Basin, coal rank ranges from subbituminous in Fort Union coals adjacent to the Rock Springs Uplift to semianthracite in Cretaceous coals in the Washakie Basin. Coal rank and vitrinite reflectance profiles indicate that the eastern Greater Green River Basin probably has higher coalbed methane potential than does the western. These profiles also indicate that Tertiary coals in the Greater Green River Basin have not reached the maturity required to generate significant quantities of thermogenic methane except in the Washakie Basin. Coal found at depths of 6,000 ft (1,829 m) probably has vitrinite reflectance values of less than 0.6 percent (high-volatile C bituminous). Therefore, Cretaceous coal beds adjacent to the Rock Springs Uplift probably have not reached the threshold of significant gas generation, although they have high gas contents. This anomaly suggests migration of thermally mature gases from deeper parts of the basin or biogenic gas. Coal beds that have reached the gas generating stage in deeper parts of the basin are potentially gas rich.

Coal rank in the Piceance basin ranges from high-volatile C bituminous along the basin margins to semianthracite in the synclinal axes. Coal rank changes laterally more abruptly in this basin than in the other three basins reviewed. Cameo coals found at depths of 6,000 ft (1,829 m) in the Piceance Basin range in rank from high-volatile C bituminous to medium volatile bituminous, indicating that this basin has has a good coalbed methane potential based on coal rank alone. Coal rank in the Coal Ridge and Black Diamond coal groups generally parallel Cameo coal-rank trends. Although coalbed methane in the Piceance Basin is thermogenic in origin and indigenous to the coal beds, some biogenic gases are present in the northwest part of the basin.

Coals in the Powder River Basin are low rank, having only reached the lignite to subbituminous level and locally to the high-volatile C bituminous level. Vitrinite reflectance profiles indicate that these coals have not reached the thermal maturity required to generate significant quantities of thermogenic methane. Therefore, the Powder River Basin probably has a relatively low coalbed methane potential. Coalbed gases are probably biogenic in origin, although minor amounts of early thermogenic gases may be present. Migration of gases within the shallow Tertiary coal beds is possible for consequent conventional trapping on local structural anomalies.

The Raton Basin has the highest coalbed methane potential of all the basins reviewed judging from coal rank, which ranges from high-volatile C bituminous in the north part of the basin to low-volatile bituminous along the Purgatoire River. The Raton Basin has relatively high-rank coals at shallow depths; at a depth of 1,100 ft (335 m), vitrinite reflectance values generally range from less than 1.0 to 1.5 percent. The distribution of high-rank coal along the Purgatoire River may be a function of basin hydrology and proximity of the coal beds to igneous intrusions and advective heat transfer resulting from vertical movement upward of hot fluids associated with a localized heat source.

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