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GEOLOGIC AND HYDROLOGIC ASSESSMENT OF NATURAL GAS FROM COAL SEAMS IN THE MESAVERDE GROUP AND FORT UNION FORMATION, GREATER GREEN RIVER BASIN, WYOMING AND COLORADO

TOPICAL REPORT
(January 1993–January 1994)

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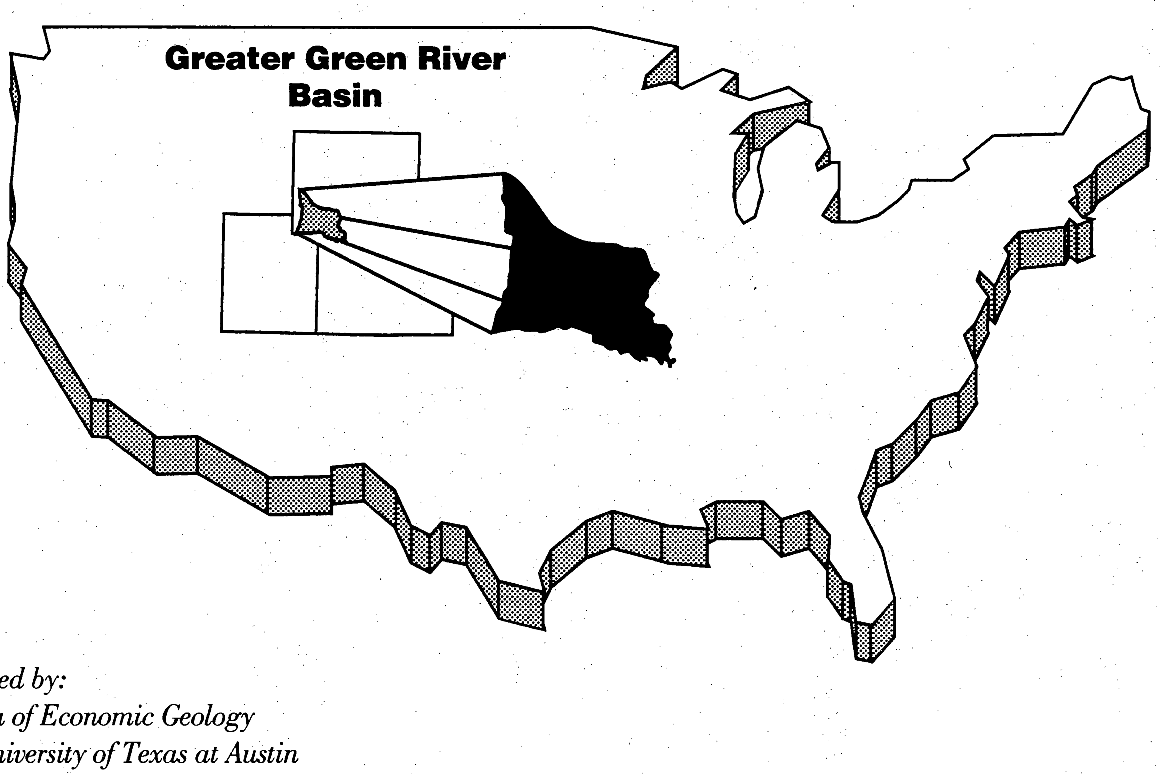

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16. Abstract (Limit: 200 words)

The Greater Green River Basin is a fault-bounded, structurally complex intermontane basin that is subdivided into four subbasins. Face cleats strike northeast in most of the greater basin but northwest in the Sand Wash Basin to impose permeability anisotropy on the coal beds. Major coal-bearing units are the Upper Cretaceous Mesaverde Group—primarily the Rock Springs and Williams Fork Formations—and the lower Tertiary Fort Union Formation's lower coal-bearing unit. The combined net coal thickness exceeds 300 ft (91 m); individual seams are as much as 40 ft (12.2 m) thick. Coal rank ranges from subbituminous to high-volatile A bituminous, except in deeper subbasins, where rank is medium-volatile bituminous and higher. Gas contents average less than 200 scf/ton (<6.24 m^3/t) at depths of less than 6,000 ft (<1,830 m). Areas of high gas content (350 to 500 scf/ton [10.92 to 15.60 m^3/t] reflect conventional trapping of migrated thermogenic and biogenic gases and correspond to areas of flow orthogonal to flow barriers, pressure transition, and convergent, upward flow of ground water. Regionally, ground water flows from the basin margins to discharge eventually basinward along the boundary between hydropressure and hydrocarbon overpressure and along major river valleys. Coal and coalbed methane resources are very large: 1,276 billion short tons (1,158 billion t) and 314 Tcf (8.89 Tm^3), respectively. Despite huge resources, coalbed wells drilled to date have yielded little or no gas and large volumes of water, for a basinwide cumulative gas–water ratio of approximately 20 scf/bbl (~3.6 m^3/m^3). Deeper drilling will be required to penetrate higher rank, higher gas content coals. For example, Mesaverde gas contents between 6,000 and 7,500 ft (1,830 and 2,286 m) are approximately 350 scf/ton (~10.92 m^3/t) and exceed 500 scf/ton (15.60 m^3/t) below 7,500 ft (2,286 m). Deeper drilling is justified at the northwest end of the Cedar Mountain fault system in the Sand Wash Basin, along the east margin of the Washakie Basin, and around the northeast flank of the Rock Springs Uplift. In the Fort Union Formation, the Sandy Bend Arch and the Big Piney are thought to be prospective, where structural and/or stratigraphic trapping may enhance gas contents in low-rank coals.

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Coalbed methane, Greater Green River Basin, Colorado and Wyoming, Upper Cretaceous, Mesaverde Group, Rock Springs and Williams Fork Formations, Lower Tertiary, Paleocene, Fort Union Formation, structural setting, cleat, genetic stratigraphy, depositional systems, coal occurrence, coal rank, thermal maturity, gas content, hydrology, coalbed methane production, coalbed methane resources and fairways

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Research Summary

Title

Geologic and Hydrologic Assessment of Natural Gas from Coal Seams in the Mesaverde Group and Fort Union Formation, Greater Green River Basin, Wyoming and Colorado

Contractor

Bureau of Economic Geology, The University of Texas at Austin, GRI Contract No. 5091-214-2261, entitled "Geological Evaluation of Critical Production Parameters for Coalbed Methane Resources."

Principal Investigator

W. R. Kaiser

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Objectives

To assess the coalbed methane potential in the Greater Green River Basin on the basis of geologic and hydrologic controls identified in the San Juan and Sand Wash Basins, to evaluate the coal and coalbed methane resources, and to identify fairways for future exploration and development.

Technical Perspective

Coalbed methane production is established in the Greater Green River Basin. Large coal and gas resources and high gas contents in some coal beds triggered initial development along the southeast basin margins and around the Rock Springs Uplift. Results to date have been disappointing, however. Coalbed wells have yielded little gas and large volumes of water. A thorough knowledge of the major geologic and hydrologic controls on occurrence and producibility of coalbed methane is critical to efficient evaluation, exploration, and exploitation of these resources in the Greater Green River Basin. Recent reports to GRI compared the geologic and hydrologic controls on coalbed methane producibility in the San Juan and Sand Wash Basins. On the basis of lessons learned in those basins, in this report we review coalbed methane potential of the Greater Green River Basin.

Results

The structurally complex Greater Green River Basin is bounded by the Wyoming–Idaho Overthrust Belt in the west and by basement-cored thrust faults on the remaining three sides. The basin has four subbasins (Green River, Great Divide, Washakie, and Sand Wash Basins) separated by the Rock Springs Uplift, and Wamsutter and Cherokee Arches. Maximum horizontal compressive stress orientations have rotated about a vertical axis with time, a configuration that is reflected in cleat orientations, which are currently northeast in the north and central parts of the basin and are north-northwest in the southeast. The Upper Cretaceous Mesaverde Group and lower Tertiary Fort Union Formation, containing coals that have a maximum combined net thickness of greater than 300 ft (>91.4 m), are the major coalbed methane targets. Coal rank ranges from subbituminous to high-volatile A bituminous, except in deeper subbasins, where coal rank is medium-volatile bituminous and higher. Most of the coalbed gases are thought to be secondary biogenic or migrated thermogenic. Gas contents are less than 200 scf/ton (<6.24 m^3/t) at depths drilled to date. Conventional trapping will be required to enhance gas content in low-rank coals. Permeable, normally pressured and artesian coal seams occur as deep as 8,000 ft (2,440 m), above regional hydrocarbon overpressure. Areas of pressure transition and convergent flow are extensive and are thought to have high production potential. To date, cumulative gas and water production, mostly from Mesaverde (Williams Fork) coals at Dixon field, is 134 MMscf (3.8 MMm^3) and 6.8 MMbbl (1.1 MMm^3) of water, respectively, for a basinwide gas–water ratio of approximately 20 scf/bbl (~3.6 m^3/m^3). Average completion depth is 2,671 ft (814 m). Coal and coalbed methane resources are very large: 1,276 billion short tons (1,158 billion t) and 314 Tcf (8.89 Tm^3).

Coal and gas resources in the Mesaverde Group and Fort Union Formation are 627 billion tons (569 billion t) and 264 Tcf (7.47 Tm^3) and 649 billion tons (589 billion t) and 50 Tcf (1.42 Tm^3), respectively. The deeper drilling required to penetrate higher rank, higher gas content coals is thought justified in the Mesaverde Group at the northwest end of the Cedar Mountain fault system in the Sand Wash Basin, along the east margin of the Washakie Basin, and around the northeast flank of the Rock Springs Uplift and in the Fort Union Formation on the Sandy Bend Arch and in the Big Piney area.

Technical Approach

The Greater Green River Basin is described in terms of its structures, genetic stratigraphy, coal occurrence and sedimentology, thermal maturity and gas content, composition, origin, and hydrology. Tectonic and stratigraphic setting, as well as basin margin and intrabasin uplifts associated with basement-cored thrust faults, is described in order to document fairways where coalbed methane production may be favored because of fracture-enhanced permeability and conventional trapping of gas. Coalbed cleats and stress orientations were recorded so that variations of permeability anisotropy within coalbed reservoirs could be determined.

Thickness data from more than 500 geophysical well logs were compiled from Mesaverde and Fort Union coal beds and interbedded sandstones, the major coal- and gas-bearing stratigraphic units. Coal-seam continuity was determined using density and gamma-ray log profiles. A grid of interlocking cross sections was made to identify and define genetic stratigraphy and to define major coal-bearing horizons. These data include (1) net and maximum coal thickness, (2) number, continuity, and depth of coal beds, (3) net and maximum sandstone thickness in coal-bearing intervals, and (4) coal–sandstone relations. Coal and sandstone characteristics and their regional trends were used to define coalbed methane exploration fairways and to calculate coal and gas resources.

Vitrinite-reflectance and proximate analyses from more than 50 wells were used to construct coal-rank maps and to evaluate thermal maturation history. The relation between volatile matter (dry, ash-free basis) and vitrinite-reflectance values (R_m) was used to convert volatile matter to calculated vitrinite-reflectance values in basins where sufficient data were available. Structure, heat flow, subsurface temperature, and vitrinite-reflectance depth maps were also used to determine and constrain thermal maturity trends. Vitrinite-reflectance profiles were used to evaluate the relationship between depth and coal rank and to predict at what depth the threshold of significant gas generation from coal beds could be expected. Compositional data on coalbed gases were also collected and were used to (1) determine coalbed gas origin, (2) explore the possibility of gas migration, and (3) evaluate the relation between coal rank and gas composition.

Stratigraphic, structural, topographic, and precipitation data were combined with hydraulic head and hydrochemical data to delineate ground-water circulation patterns. The direction of ground-water flow was inferred from the potentiometric surface, hydrochemistry, topographic gradient, and structural dip. Pressure regime was evaluated from shut-in pressures recorded in drill-stem tests. Regional permeability contrasts were inferred mainly from the pressure regime.

Gas and coal resources were calculated from digitized structure, topographic, and net-coal-thickness maps on a 3.5-mi^2 (9.1-km^2) grid, using plots of gas content versus depth, density, and coal volume. Production data from 57 coalbed methane wells were tabulated. Major coalbed methane fields were described and drilling activity summarized. Production was evaluated to establish typical rates and the range of gas and water production. Coalbed methane exploration fairways were identified using an evolving basin-scale coalbed methane producibility model.

Project Implications

This report assesses the coalbed methane potential of the Greater Green River Basin and identifies the most promising fairways for future coalbed methane research, development, and production. The report transfers technology from earlier studies of the San Juan and Sand Wash Basins to the Greater Green River Basin and advances our understanding of geologic and hydrologic controls on coalbed methane occurrence and producibility in the United States.

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Executive Summary and Introduction

Douglas S. Hamilton, Roger Tyler, William R. Kaiser, and Andrew R. Scott

Methane from coal beds, an important emerging source of natural gas in the Lower 48 States, is set to make a substantial contribution to the United States domestic gas resource base. Production of coalbed gases has increased nearly fivefold since 1990, accounting for 3 percent of U.S. gas production and 5 percent of proved reserves by the end of 1992 (Oil and Gas Journal, 1993). However, 96 percent of this gas was produced from just two basins, the San Juan and Black Warrior, and current development represents only a fraction of the estimated 675 Tcf (19.1 Tm^3) of coalbed methane resources in place in U.S. basins (ICF Resources, 1990; Scott and others, this volume; Kaiser and others, 1993a). The Gas Research Institute (GRI), on behalf of the U.S. natural gas industry, is actively fostering development in other U.S. basins. As part of this effort, the GRI has commissioned investigations of the western interior basins: San Juan, Greater Green River, Piceance, Powder River, and Raton, which, by virtue of their tremendous coal tonnages, contain 558 Tcf (16 Tm^3) of methane, or 83 percent of the nation's total coalbed methane resource.

This report focuses on the Greater Green River Basin and aims at assessing its coalbed methane potential through integrated hydrologic and geologic studies. The Greater Green River Basin report is the latest of the GRI-sponsored investigations of the western interior basins and complements the earlier reports of McFall and others (1986), Kelso and others (1988), and Stevens and others (1992); the detailed studies of the San Juan (Ayers and others, 1991) and Sand Wash (Kaiser and others, 1993a) Basins; and the four-basin overview report of Tyler and others (1991).

This report also embodies the current ideas of the Bureau of Economic Geology's continuing assessment of the geologic and hydrologic conditions necessary for producibility of coalbed methane. The comprehensive studies of the San Juan (containing 88 Tcf; Ayers and others, 1991) and Sand Wash Basins (containing 101 Tcf; Kaiser and others, 1993a) indicate that coalbed methane producibility is profoundly influenced by several key geologic and hydrologic controls, including tectonics, structure, deposition, hydrologic setting, coal rank, and gas content (Kaiser and others, in press). These controls and their influence on producibility are discussed in terms of the Upper Cretaceous Mesaverde Group and lower Tertiary Fort Union Formation in the Greater Green River Basin. Their relative importance is assessed in the context of lessons learned in the San Juan and Sand Wash Basins.

Tectonic and Structural Setting

The tectonic and structural setting of a basin is the most fundamental underlying control on coalbed methane resources because it (1) determines the subsidence regime that in turn determines sedimentation patterns and the locus of peat accumulation, (2) dictates whether coalification proceeds to ranks sufficient for thermogenic gas generation through burial and thermal history, (3) orients stress-induced fractures in the coal's cleat network and determines whether the fractures are open to enhance permeability, (4) defines drilling depth to target coalbed reservoirs, and (5) creates structures for conventional trapping of gas.

The Greater Green River Basin is located in the Rocky Mountain Foreland, a major tectonic element between the Wyoming–Idaho 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, a shallow continental seaway extending from the Gulf of Mexico to the Canadian Arctic. Periodic thrust faulting and uplift in the Overthrust Belt caused sediment to be shed eastward into the seaway, resulting in episodic advancement eastward of the Late Cretaceous shorelines. These wedges of clastic sediment include the thick Mesaverde Group coals currently being targeted for coalbed methane. During the Laramide Orogeny, in Late Cretaceous and early Tertiary time, the Rocky Mountain Foreland was broken into a number of smaller basins by thick-skinned thrusting. Basement-involved thrusts elevated highlands, which shed sediment into the newly formed intermontane basins. Thick sequences of lower Tertiary intermontane fluvial-lacustrine sediments host the Paleocene Fort Union Formation's thickest coal seams, which are also being targeted for coalbed methane exploration and development. Organic accumulation and peat preservation was favored by rapid subsidence and syntectonic sedimentation.

The present structural configuration of the Greater Green River Basin began to emerge during the late Laramide Orogeny. Then an initial episode of erosion occurred, followed by a period of widespread magmatism and volcanism in the Oligocene, and finally an episode of renewed tectonic uplift about 10 Ma. By the end of the Pliocene, the basin's present structural configuration, topography, surface drainage, and hydrodynamics were largely established.

Local tectonic and/or compaction-induced folds and faults that are present throughout the basin may be more important controls as sites of fracture-enhanced permeability and conventional trapping of gas. Structural complexity (folds and faults) may favor the presence of fracture-enhanced permeability and conventional trapping of gas, but it also causes steep dips and deep burial of target coal seams. Most of the coal seams are deeply buried except along the southeast margin of the basin (Sand Wash and Washakie Basins), at the Rock Springs Uplift, and on the north end of the Moxa Arch (La Barge Platform), where coals are less than 6,000 ft (<1,830 m) deep.

Stratigraphic and Depositional Setting

Depositional setting imposes a strong control on coalbed methane producibility because it determines the size, thickness orientation, and stratigraphy of the coalbed reservoirs. The processes of peat accumulation and its preservation as coal require a delicately balanced subsidence rate that maintains optimum water table levels but excludes disruptive clastic sediment influx. Depositional setting defines the substrate upon which peat growth begins and within which peat swamps proliferate. Size of the coal bed is thus controlled by the area of sediment bypass in the peat swamp, and coalbed thickness is determined by the length of time the swamp remains uninterrupted by sediment influx. Depositional architecture dictates the orientation of the coals. Coastal plain coals, for example, are strike aligned and parallel to the orientation of the shoreline systems. Fluvial coals, in contrast, are commonly dip oriented and closer in geometry to the fluvial-channel belts. Sandstone distribution and coal distribution are generally intimately associated, and an understanding of depositional architecture and sand-body geometry can enable prediction of coalbed distribution throughout a basin. Large net-coal thickness is critical to establishing a coalbed gas resource, and individual coalbed thickness indicates productivity.

In the Greater Green River Basin, the coal-bearing stratigraphic interval extends from the Upper Cretaceous Frontier Formation through to the base of the lower Tertiary Wasatch Formation, but the Upper Cretaceous Mesaverde Group and lower Tertiary Fort Union Formation are the main targets. Upper Cretaceous depositional systems were predominantly wave-dominated deltas and barrier/strandplains that formed linear clastic shorelines. The thickest coal seams were preserved on the coastal plain landward and parallel to these ancient shorelines. In the Mesaverde Group, the Rock Springs and Williams Fork Formations host thick, continuous, shore-parallel coal beds. The Rock Springs coals reach a maximum net-coal thickness of a little more than 100 ft (33 m) in as many as 12 coal beds along an 8.5-mi-wide (13.4-km) zone on the flanks of the Rock Springs Uplift that extends from the town of Rock Springs, Wyoming, northeast for approximately 60 mi (~197 km) and southwest for 40 mi (131 km). The coals thin rapidly to the southeast, where they are bounded by shoreline sandstones. By late Mesaverde Williams Fork time, southeastward progradation of the shorelines had established favorable coal-forming conditions in the southeastern Sand Wash Basin, in the Craig, Colorado, area. The northeast-oriented Williams Fork coals extend in the subsurface for at least 40 mi (131 km) before being exposed at outcrop along the south and northeast margins of the Sand Wash Basin. Maximum net-coal thickness in the Craig area is 220 ft (67 m) in as many as 40 coal beds. The dominant strike-elongate (northeast) orientation of the Rock Springs and Williams Fork coals and their overlap with sandstone-poor coastal plain areas behind the paleoshorelines indicate that the coastal plain systems provided optimal conditions of subsidence, water table level, and shelter from clastic influx for peat to accumulate and be preserved. The coals thin to the west and north–west in both units, suggesting that peat growth and preservation in that direction was inhibited by disruptive clastic influx and lowering of water table levels associated with the transition landward into slightly elevated fluvial environments.

The stratigraphy that provides the framework for analyzing the Mesaverde coals was defined by several regional unconformities and widespread marine flooding events. The Mesaverde Group is divided into upper and lower units by the Trout Creek marker, a widespread marine flooding event. The lower Mesaverde is further subdivided by the regionally extensive Moxa unconformity that separates the coal-bearing Rock Springs Formation from the younger, aggradational part of the Iles Formation to the east. The upper Mesaverde, consisting of the Williams Fork Formation and overlying Almond barrier/strandplain facies, is divided into five genetic depositional sequences that are each bounded by regionally extensive shale markers representing marine flooding surfaces basinward and nondepositional hiatal surfaces (or surfaces of sediment starvation) landward. The shale marker that bounds Williams Fork genetic units 2 and 3 is the most prominent of the markers and correlates with the Pine Ridge unconformity to the west. This unconformity is readily identified across the west half of the Greater Green River Basin.

In contrast to the coals of the Upper Cretaceous, the lower Tertiary coals, hosted by fluvial-lacustrine sediments, show strong evidence of syntectonic control. The lower Tertiary coal beds (lower coal-bearing unit; Fort Union Formation) are thick and widespread. The maximum net-coal thickness of 140 ft (42.7 m) occurs in the depositional center of the Green River Basin, but net coal thickness exceeds 80 ft (24.4 m) in all subbasins. Individually the coal beds can be as much as 40 ft (12.2) thick, extending laterally typically more than 10 mi (>16 km). Syntectonic control is indicated by marked thinning of the coals over the major structural features, the Rock Springs Uplift, Moxa Arch, and Pinedale Anticline, and subtle thinning across the Cherokee and Wamsutter Arches. The syntectonic control is further suggested by the relationship between trends in coal thickness and sandstone distribution of the Fort Union fluvial systems. Net coal is thickest along the depositional axes of the greater basin, and on the basis of detailed studies in the Sand Wash Basin (Tyler and McMurry, 1993), is thought to overlap the trend of high net sandstone. The coals thus occupy the same axial position as the fluvial systems. This suggests that tectonism provided optimal subsidence rates for peat accumulation, periodically shutting down the sediment supply to the intermontane fluvial systems. Channel-fill sandstones focused ground-water flow to initiate peat swamps, maintain water table levels, and preserve peat.

To correlate the major coal-bearing horizons in the Paleocene Fort Union Formation, lithostratigraphic zones and units in the Upper Cretaceous and lower Tertiary rocks were defined. These lithostratigraphic zones include the Fox Hills Sandstone, the Lance Formation, the massive Cretaceous and Tertiary (K–T) sandstone unit, the Fort Union Formation, and the Wasatch Formation. Nearshore-marine and marginal-marine deposits of the Fox Hills Sandstone intertongue with offshore marine deposits of the underlying Lewis Shale and fluvial deposits of the overlying Lance Formation. An intermontane fluvial sandstone sequence overlies and intertongues with the Lance Formation and is overlain and intertongues with the lower coal-bearing unit of the Fort Union Formation. This sequence of rock, referred to as the massive K–T sandstone unit, contains the regional Upper Cretaceous and Tertiary unconformity. Laramide uplift and erosion of parts of the Mesaverde Group Lewis Shale, Fox Hills Sandstone, and Lance Formation along the basin margins and Rock Springs Uplift resulted in the angular unconformity between the Fort Union Formation and the underlying sediments.

Characteristic syntectonic sedimentary facies of the coal-bearing Paleocene Fort Union Formation in the basin include a narrow conglomerate facies adjacent to basement-cored thrusts, a narrow sandstone–mudstone–coal facies just basinward, a basinal thrustward-thickening mudstone facies associated with basement-cored thrusts, and a wide distal sandstone–mudstone–coal facies (Tyler and McMurry, 1993). On the basis of this facies architecture, the Fort Union Formation may be operationally divided into the lower coal-bearing unit, the gray-green mudstone unit, the basin sandy unit, and the upper shaly unit. Depositionally the lower coal-bearing unit contains thick, laterally continuous coal beds that occur associated with bed- and mixed-load channel-fill sandstone sequences. The channel-fill sandstone sequences are considered to be part of a much larger intermontane fluvial trunk-stream system that flowed through the Greater Green River Basin and exited on the east edge of the Great Divide Basin. An increase in the suspended load carried by the fluvial system through tectonism and/or major upstream avulsion resulted in the formation of extensive floodplains and coal deposits. Coal beds are thicker and more numerous in floodplain areas above and on the flanks of the thickest sandstones.

Coal Rank, Gas Content, and Gas Composition

In comparison with other western interior basins such as the San Juan, Piceance or Raton Basins, the Greater Green River Basin is characterized by relatively low coal rank. Although reaching semianthracite rank in the deep Washakie Basin, coal ranks at exploitable drilling depths more typically range from high-volatile C to high-volatile A bituminous and have thus barely reached the threshold of thermogenic gas generation. In the Mesaverde Group, coal rank along the basin margins and around the Rock Springs Uplift is subbituminous to high-volatile C bituminous, increasing with depth to high-volatile A bituminous at around 7,500 ft (~2,286 m). Only below these depths have the coals reached ranks sufficient to generate large volumes of thermogenic gas. Fort Union coal rank is also low, ranging from subbituminous along the basin margins and the Rock Springs Uplift to low-volatile bituminous in the Washakie Basin.

Consistent with the coal rank trends, gas contents of the Greater Green River Basin coals are generally low; dry, ash-free gas content values are typically less than 200 scf/ton (<6.24 m^3/t) in the Mesaverde coals and less than 100 scf/ton (<3.12 m^3/t) in the Fort Union coals. However, despite generally low gas contents, areas of high gas content do exist. Areas having higher Mesaverde gas contents in the Sand Wash Basin are located (1) in an area of artesian overpressure along the Cherokee Arch and (2) along the northwestward-trending Cedar Mountain fault system where ground-water flow turns upward at the transition between hydropressure and hydrocarbon overpressure (Scott and Kaiser, 1993). Gas contents average 350 scf/ton (10.92 m^3/t) in Rock Springs coals north of the Rock Springs Uplift. The gas content profile in these coals is not fully understood, however, because gas content decreases with increasing depth. This atypical profile is not readily explained, but it may reflect a Pleistocene recharge event and generation of secondary biogenic gases. Gas contents of approximately 500 scf/ton (~15.6 m^3/t) were reported in Fort Union subbituminous coals in the Big Piney area and may reflect conventional trapping of gas.

Greater Green River Basin coalbed gases are early thermogenic, thermogenic, and secondary biogenic. The Mesaverde coalbed gases are early thermogenic and/or secondary biogenic in the hydropressured parts of the basin and predominantly thermogenic in deeper parts of the basin near the hydropressure–hydrocarbon overpressure boundary. Fort Union coals are lower rank and, therefore, the coalbed gases are predominantly early thermogenic and/or secondary biogenic, although thermogenic gas may be more important in the deeper parts of the basin, where the coals approach or exceed high-volatile A bituminous rank.

Thermal maturity is the biggest impediment to coalbed methane potential of the Greater Green River Basin. However, mechanisms that enhance gas contents of the generally low rank coals, such as updip gas migration from thermally mature coals at depth, generation of secondary biogenic gas in dynamic flow systems, and conventional trapping at the transition of hydropressure and hydrocarbon overpressure, have been demonstrated in a number of areas. More than likely these same mechanisms have operated in other parts of the basin where data are currently sparse. Exploration and development strategies should allow for these mechanisms.

Hydrology

Hydrology affects coalbed methane producibility in several ways. In a typical coalbed methane reservoir, for example, hydrodynamics promotes sorption of gas on the coal surface by maintaining reservoir pressure. Where the coalbed methane reservoir is dominated by (or has a component of) conventional trapping, vigorous ground-water flow provides the means (in solution or by entrainment) for long distance migration of the coalbed gases to the trap and introduces bacteria for generating secondary biogenic gases. Although hydrodynamics clearly helps enrich gas content for commercial production, it can also be detrimental, if production is attempted close to recharge areas and too much water is produced.

Hydrologic characterization can reveal much about reservoir conditions because hydraulic gradient, pressure regime, and hydrochemistry reflect an aquifer's ability to accept and transmit fluid and, thus, regional permeability contrasts. An example in the Fruitland Formation, San Juan Basin, shows enhanced permeability correlating with gentle hydraulic gradients, artesian overpressure, and low-chloride formation waters. We would argue that artesian overpressure requires enhanced permeability and recharge at an elevated outcrop and aquifer confinement in the subsurface. The presence of low-chloride water also indicates active flow and permeable pathways. Underpressure, in contrast, reflects hydrologic isolation, reduced permeability, and limited recharge in the absence of a high-permeability drain. Exceptionally high coal gas production occurs at the transition between pressure regimes.

In our basin-scale conceptual model (Kaiser and others, in press), producibility of coalbed methane is enhanced when hydrodynamics are favorable. We suggest that optimal conditions occur when ground water flows through coals of high rank and gas content orthogonally toward no-flow boundaries (regional hingelines, fault systems, facies changes, and/or discharge areas), enabling efficient sweeping of gas for eventual resorption and conventional trapping basinward. The extent to which these optimal conditions are met in the Greater Green River Basin is assessed in the Mesaverde and Fort Union coal-bearing stratigraphic units.

Recharge into the Mesaverde aquifer occurs primarily at outcrop along the east margin of the Greater Green River Basin, in the foothills of the Sierra Madre Uplift, Park Range, and Williams Fork Mountains. Ground water flows westward, from the wet elevated basin margin, down hydrologic gradient, to discharge eventually basinward along fault systems and facies changes that separate hydropressure from regional hydrocarbon overpressure in the central basin. In the Tertiary aquifer system, recharge occurs primarily along the foothills of the Sierra Madre Uplift and Park Range, Wind River, Wyoming, and Uinta Mountains. Dynamic flow throughout the greater basin is basinward toward topographically low areas such as the Green River and Little Snake River valleys for eventual discharge. Dynamic flow promotes generation of secondary biogenic gas, migration of it and thermogenic gas, and presumably delivery and concentration at traps when oriented at a high angle to them. Ground-water flow in the Mesaverde aquifer is dynamic in the eastern Sand Wash and Washakie Basins but is restricted off the flanks of the Rock Springs Uplift and in the Green River Basin by low precipitation, high evaporation rates, and faults. Hydrodynamics in the Green River Basin is difficult to assess because the Mesaverde is fault-severed from the wet basin margin and receives little direct recharge. Sluggish ground-water flow is postulated in the basin interior, but data are limited and identification of pressure transition zones that may favor coalbed methane accumulation was impossible.

In the deep central part of the eastern Greater Green River Basin, hydrocarbon overpressuring dominates the Mesaverde aquifer, being flanked by hydropressured strata above approximately 8,000 ft (~2,440 m). No pressure regime regionally dominates in the hydropressured section, but artesian overpressure occurs locally on the eastern Cherokee Arch and along the east margin of the Washakie Basin. A large fault system, the Savery fault system, separates hydrocarbon overpressured and hydropressured strata along the east margin of the Washakie Basin. The potential for conventional trapping, upward flow at the pressure boundary, and generation of biogenic gas may favor coalbed methane accumulation. The same can be said of the Cedar Mountain fault system in the Sand Wash Basin. The transition zone between hydropressure and hydrocarbon overpressure on the east side of the Rock Springs Uplift may also indicate potential for upward flow and hydrodynamic conditions favorable to coalbed methane accumulation at depth. The transition zone may signify a no-flow boundary caused by extensive diagenesis, where meteoric water moving basinward has mixed with late compactional fluids moving out of the basin. Mixing of chemically disparate waters would favor mineral precipitation and permeability reduction.

Resources and Production

In the Greater Green River Basin, coal and gas resources total 1,277 billion short tons (1,158 billion t) and 314 Tcf (8.89 Tm^3), respectively. The Mesaverde Group contains 627 billion tons (569 billion t) and 264 Tcf (7.47 Tm^3), accounting for 49 and 84 percent of the total resources, respectively. The Fort Union Formation contains 649 billion tons (589 billion t) and 50 Tcf (1.42 Tm^3), accounting for 51 and 16 percent of the total resources, respectively. At depths of less than 7,500 ft (<2,286 m) coal and gas resources are 688 billion tons (624 billion t) and 84 Tcf (2.38 Tm^3), respectively. At those depths, Mesaverde resources are 243 billion tons (220 billion t) and 56 Tcf (1.58 Tm^3), accounting for 35 and 67 percent, respectively, of the resources at less than 7,500 ft (<2,286 m). Fort Union resources are 445 billion tons (404 billion t) and 28 Tcf (0.79 Tm^3), accounting for 65 and 33 percent of the resources, respectively.

Coalbed methane production in the Greater Green River Basin has been established only in the Sand Wash Basin, where gas production from the Williams Fork Formation has been minimal and water production has been excessive. Cumulative gas and water production is 134 MMscf (3.8 MMm^3) and 6.8 MMbbl (1.1 MMm^3), respectively, for a cumulative basinwide gas–water ratio of approximately 20 scf/bbl (~3.6 m^3/m^3). Among the 11 wells in Dixon field, 3 structurally high wells currently produce gas at rates of less than 40 Mcf/d (<1.1 Mm^3/d). Initially, eight wells were flowing artesian and served as dewatering wells; they flowed at rates ranging from 600 to 1,000 bbl/d (95 to 159 m^3/d) for a per-well average of approximately 700 bbl/d (~111 m^3/d) in 1991. Upon production, rates have declined to approximately 500 bbl/d (~64 m^3/d). In Craig Dome field, 16 plugged and abandoned wells produced no gas and large volumes of water (~500 bbl/d [~80 m^3/d] per well) over a 12- to 18-mo test period. Nine Fort Union coalbed wells were completed, production tested, plugged, and abandoned. During test periods ranging from 9 d to 7 mo, the wells made zero to negligible volumes of gas and tens of thousands of barrels of water (thousands of cubic meters). Because of proximity to the recharge area and high permeability, economically dewatering (depressuring) coal beds near the basin margin may be impossible. Disposal costs of large volumes of produced water can adversely affect project economics to the extent that development may be deemed uneconomical.

Along the northeast flank of the Rock Springs Uplift, coals of the Fort Union, Almond, and Rock Springs Formations were tested. Only Rock Springs coals showed commercial promise. Production forecasts predicted recoveries of 1 to 3 Bcf/160 ac (28 to 84 MMm^3/65 ha) and peak rates of 240 to 1,200 Mcf/d (6.79 to 34.00 Mm^3/d). Despite these promising forecasts, test results were disappointing. During a 530-d production test, the most successful well (2 UPRC-1) averaged 78 Mcf/d (2.2 Mm^3/d) and 200 bwpd (32 m^3/d) from a 50-ft (15.3-m) interval (Stevens, 1993). Development was stopped in 1992 primarily by low gas prices and disappointing test results and secondarily by environmental concern over disposal of produced water. A pair of northern wells, completed in Fort Union and Almond coals, were tested for 4 mo and produced less than 100 Mcf/d (<2.8 Mm^3/d); low permeability and low gas content (~200 scf/ton [~6.24 m^3/t]) doomed these wells.

Exploration Fairways

The Greater Green River Basin is a largely untested, frontier coalbed methane basin, in which deeper drilling will be required to penetrate higher-rank, higher-gas-content Mesaverde and Fort Union coals. Gas contents of the Mesaverde Group, between 6,000 and 7,500 ft (1,830 and 2,286 m), are approximately 350 scf/ton (~10.92 m^3/t) and exceed 500 scf/ton (15.60 m^3/t) below 7,500 ft (2,286 m). Mesaverde and Fort Union coal distribution and steep structural dip limit deeper drilling to the Sand Wash Basin, eastern Washakie Basin, northeast flank of the Rock Springs Uplift, the Sandy Bend

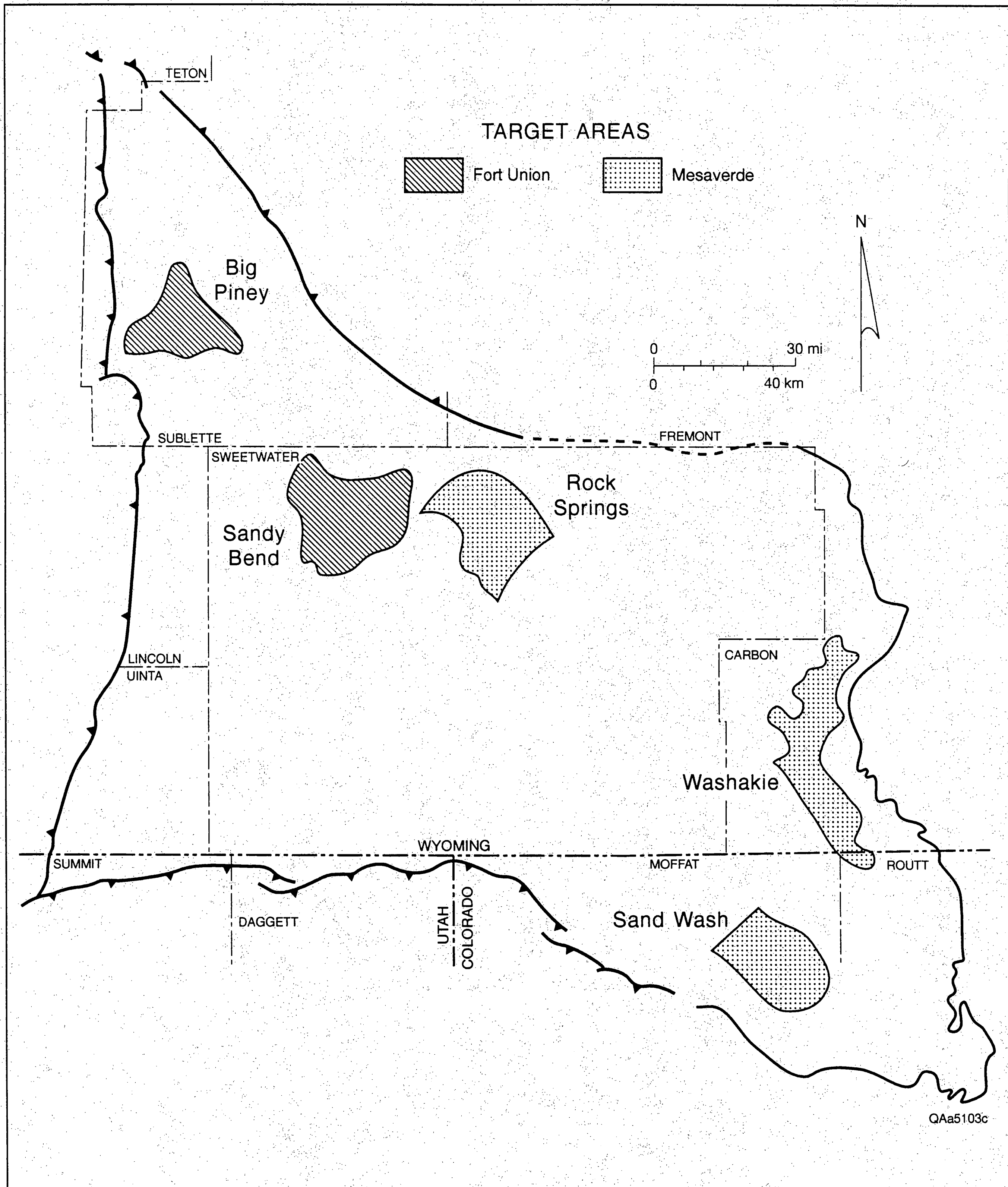


Figure ES-1. Exploration target areas, Greater Green River Basin.

Arch, and the La Barge Platform in the Big Piney area (fig. ES-1).

In the Sand Wash Basin (fig. ES-1) northwest of Craig, the Cedar Mountain fault system terminates in a zone of convergence along the boundary between hydropressure and regional overpressure. Higher-rank, high-gas-content Mesaverde coals are present in the area, suggesting high production potential. Along the east margin of the Washakie Basin (fig. ES-1), normally pressured and artesian overpressured coals have gas contents ranging from 250 to 350 scf/ton (7.80 to 10.92 m^3/t). However, although excessive water production has limited producibility, it is predicted to decrease northward coincident with decreasing recharge. On the northeastern Rock Springs Uplift (fig. ES-1), coals of the Rock Springs Formation have been targeted for development because thickness, resources, and gas content are favorable. Net-coal thickness in 5-ft (1.5-m) seams exceeds 40 ft (12 m) (Kaiser, 1992), gas resources at less than 7,500 ft (<2,286 m) are approximately 9 Tcf (~0.25 Tm^3), rank ranges from hvCb to hvAb, and gas content averages 350 scf/ton (10.92 m^3/t) over a 1,000-ft (305-m) interval. However, an atypical gas-content profile shows decreasing gas content with depth and implies a narrow exploration fairway, which may constrain future development. Thick Rock Springs coals on the southwest flank of the Rock Springs Uplift are probably too deep for economic drilling, thus eliminating these coals as near-term coalbed methane targets.

Although generally thin, Almond coals are not primary coalbed methane targets, they are possible secondary targets in the course of conventional Almond gas development in the deeper, overpressured parts of the Washakie Basin. Reservoir volumetrics clearly demonstrate that Almond gas production does not only originate from the targeted upper Almond sandstone (Iverson, 1993). Examples are numerous where cumulative gas production has exceeded, or will soon exceed, the total gas in place in the perforated upper sandstone. Iverson (1993) attributed the extra gas to laminated sandstones (below the upper sandstone) that were interconnected after hydraulic fracturing. Undoubtedly they contribute gas, but numerous thin coals are present in the upper Almond and may instead be the major contributors and thus should be considered for completion. Completion practices should be reevaluated to consider dual completion of tight sandstones and coals, as is done in the Piceance Basin, for higher-yield, longer-lived gas wells.

Fort Union Formation coals are present throughout much of the basin, but recorded gas contents are low (~100 scf/ton [~3.12 m^3/t] or less) and thus considered secondary coalbed methane targets. However, structural and/or stratigraphic trapping may enhance gas contents. In the Big Piney area (fig. ES-1), on the La Barge Platform, where considerable Fort Union conventional oil and gas production has been established, gas contents of approximately 500 scf/ton (~15.6 m^3/t) were reported in subbituminous coals. The coals' low rank and area's location, flanking the deep Pinedale Basin, are circumstantial evidence of updip migration and conventional trapping of thermogenic gases. In the northern Green River Basin, more than 100 net ft (>30 m) of coal is present, individual coals ranging to 40 ft (12.2 m) in thickness. These coals have never been tested and may be prospective on the Sandy Bend Arch (fig. ES-1). Again, migrated thermogenic gas and secondary biogenic gas are postulated sources of gas. Ground water flows orthogonally to the arch and may bring dissolved and/or entrained gas to the arch for resorption and trapping.

Exploration strategy in the Greater Green River Basin must be to maximize gas content and minimize water production through integrated geologic, hydrologic, and engineering studies. To do so, we must fine-tune three-dimensional modeling of regional system tracts within the regional tectonic, structural, and hydrologic framework. In addition, delineating reservoirs on a field scale and determining reservoir-scale physical properties should be achieved. Greater emphasis should be placed on identifying conventional traps (no-flow boundaries). Conventionally trapped gas and solution gas that can be produced with less associated water are overlooked sources of coalbed methane. Proximity to recharge areas should be avoided because water production has been excessive to date. High water production may be the primary technological challenge facing commercial development in the Greater Green River Basin.

Tectonic and Stratigraphic Setting and Coal Occurrence of the Upper Cretaceous Mesaverde Group and Lower Tertiary Fort Union Formation, Greater Green River Basin

Roger Tyler and Douglas S. Hamilton

Geologic Overview

The Greater Green River Basin, Wyoming's largest coal-bearing area, covers approximately 15,000 mi^2 (~38,870 km^2) of southwestern Wyoming and 5,600 mi^2 (14,511 mi^2) of northwestern Colorado (figs. 1 and 2). Tectonic fragmentation of the Rocky Mountain Foreland during latest Cretaceous to earliest Oligocene Laramide deformation resulted in the Greater Green River Basin being bounded by the Gros Ventre, Wind River, and Granite Mountain Uplifts to the north; the Lost Soldier and Wertz Anticlines, Rawlins Uplift, and Hatfield and Miller Hill Anticlines to the east; the Sierra Madre and Park Uplifts to the southeast; and the Axial Arch and White River and Uinta Uplifts to the south (figs. 1 and 2) (Berg, 1961, 1962, 1983; Armstrong and Oriel, 1965; Royse and others, 1975; Smithson and others, 1978; Gries, 1981, 1983; Garing and Tainter, 1985; Tyler and Tremain, 1993). 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 each basin reach a maximum thickness of 32,000 ft (9,750 m). Most (~23,000 ft; ~7,012 m) of these rocks are Late Cretaceous, Paleocene, and Eocene in age (fig. 3) (Dickinson, 1989). Depth to Cretaceous coal-bearing strata varies from outcrop to more than 16,000 ft (>4,877 m) below land surface in the east and from outcrop to more than 12,000 ft (>3,658 m) in the west (fig. 4). Lower Tertiary Fort Union coal-bearing strata range from outcrop to nearly 10,000 ft (3,048 m) in depth (fig. 5).

Tectonism has also affected depositional patterns, coal occurrence, hydrodynamics, and thermal maturity (gas generation) and has determined the distribution and orientation of faults, folds, and fractures within the basin. Emplacement of uplifts along basement-cored thrust sheets, verging perpendicular to maximum horizontal stresses, has implications for fracture and fault genesis in buried and less deformed parts of the Greater Green River Basin. Compression along salients in the thrust belt of the Tertiary uplifts has resulted in east-, northeast-, and northwest-oriented fractures and faults. The range of fracture and fault strikes implies that after deposition of the Mesaverde Group in the Late Cretaceous and Cenozoic, the maximum horizontal stresses rotated about a vertical axis. Such fractures and faults play a role in fluid-flow patterns by providing permeable pathways for both gas and water. Systematic fractures (face cleats) and faults generally parallel current maximum horizontal stress directions in the Greater Green River Basin.

Tectonic and Stratigraphic Setting

The Overthrust Belt (Wyoming–Idaho Overthrust Belt) (figs. 1 and 2), a region of north-trending folds and thin-skinned, generally west-dipping imbricate thrust faults, moved eastward during Late Cretaceous to early Tertiary times (fig. 6). The Greater Green River Basin, to the east of the Overthrust Belt, is a structurally complex intermontane basin. During the Cretaceous, the area of the present Greater Green River Basin was near the west margin of the Western Interior Seaway, a shallow sea that extended from north to south across much of the North American midcontinent (Kauffman, 1977). The Western Interior Seaway occupied a foreland basin bounded on the west by the Cordilleran thrust belt. Greatest subsidence and deposition occurred along the west margin of the seaway, adjacent to the overthrust belt. Initiation of deformation in the thrust belt during the Early to Late Cretaceous Sevier Orogeny coincided with a major

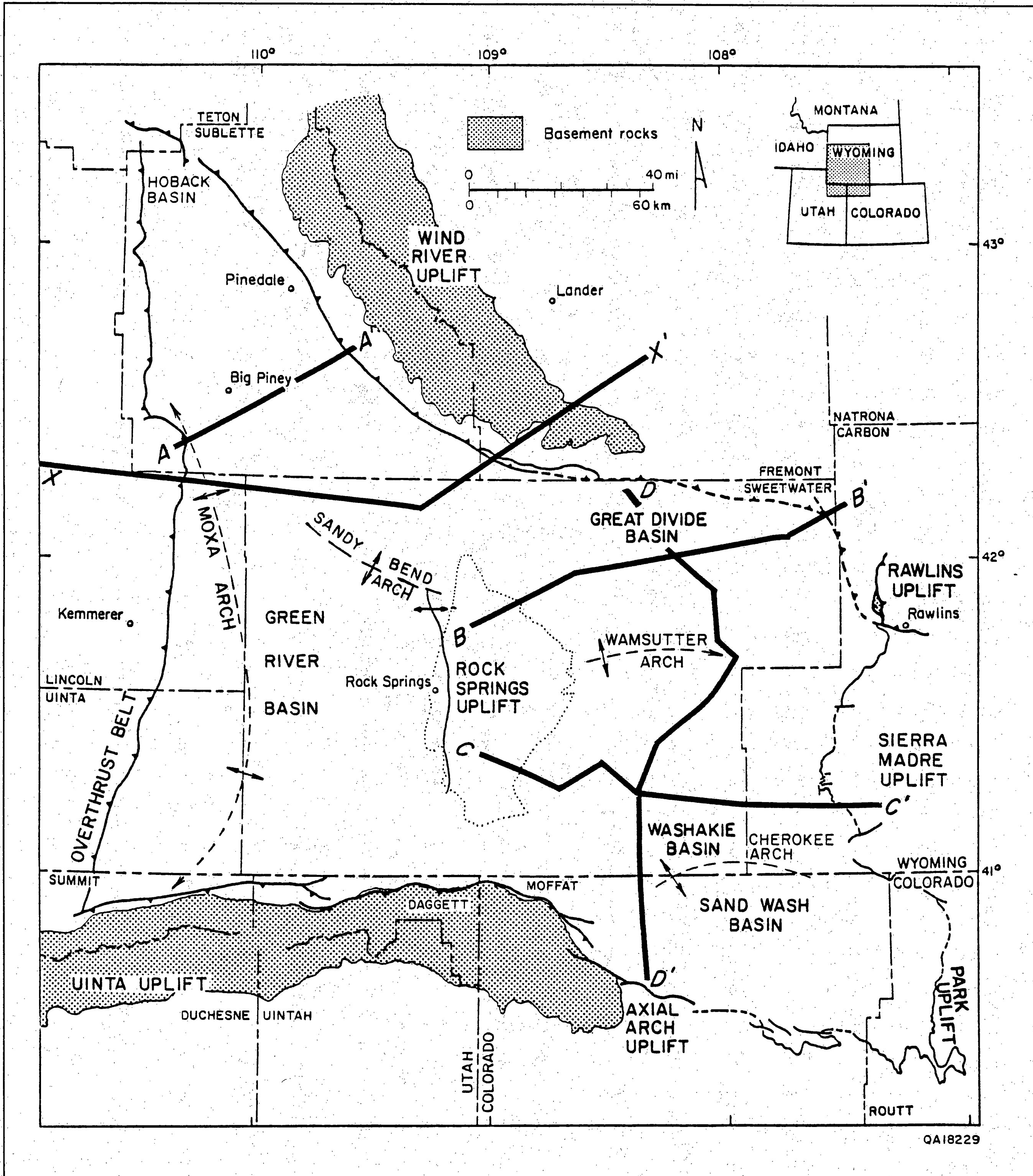


Figure 1. Location and physiography, Greater Green River Basin. Modified from Law and others (1989). Cross sections X–X′ and A–A′ through D–D′ shown in figures 4 through 8.

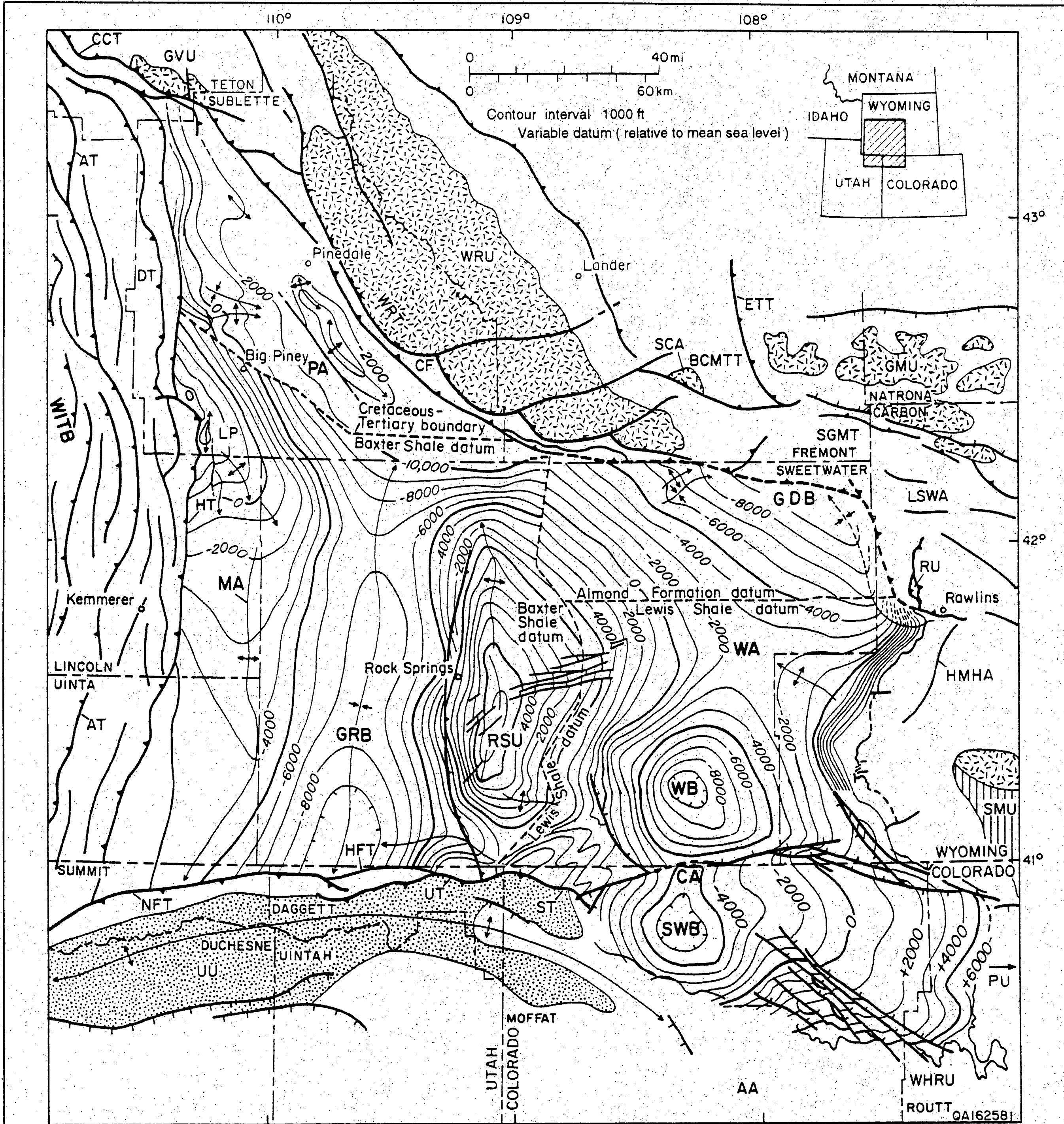


Figure 2. Tectonic map of southwestern Wyoming and adjacent states showing the major tectonic elements of the Greater Green River Basin. The map is taken from King (1969) with modifications from Reynolds (1968), Blackstone (1979), Love and Christiansen (1985), Lickus and Law (1988), and Tyler and Tremain (1993). Structure contours are drawn on marker horizons in the Upper Cretaceous Formations. Major tectonic features are 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, vertical-line, and stippled patterns.

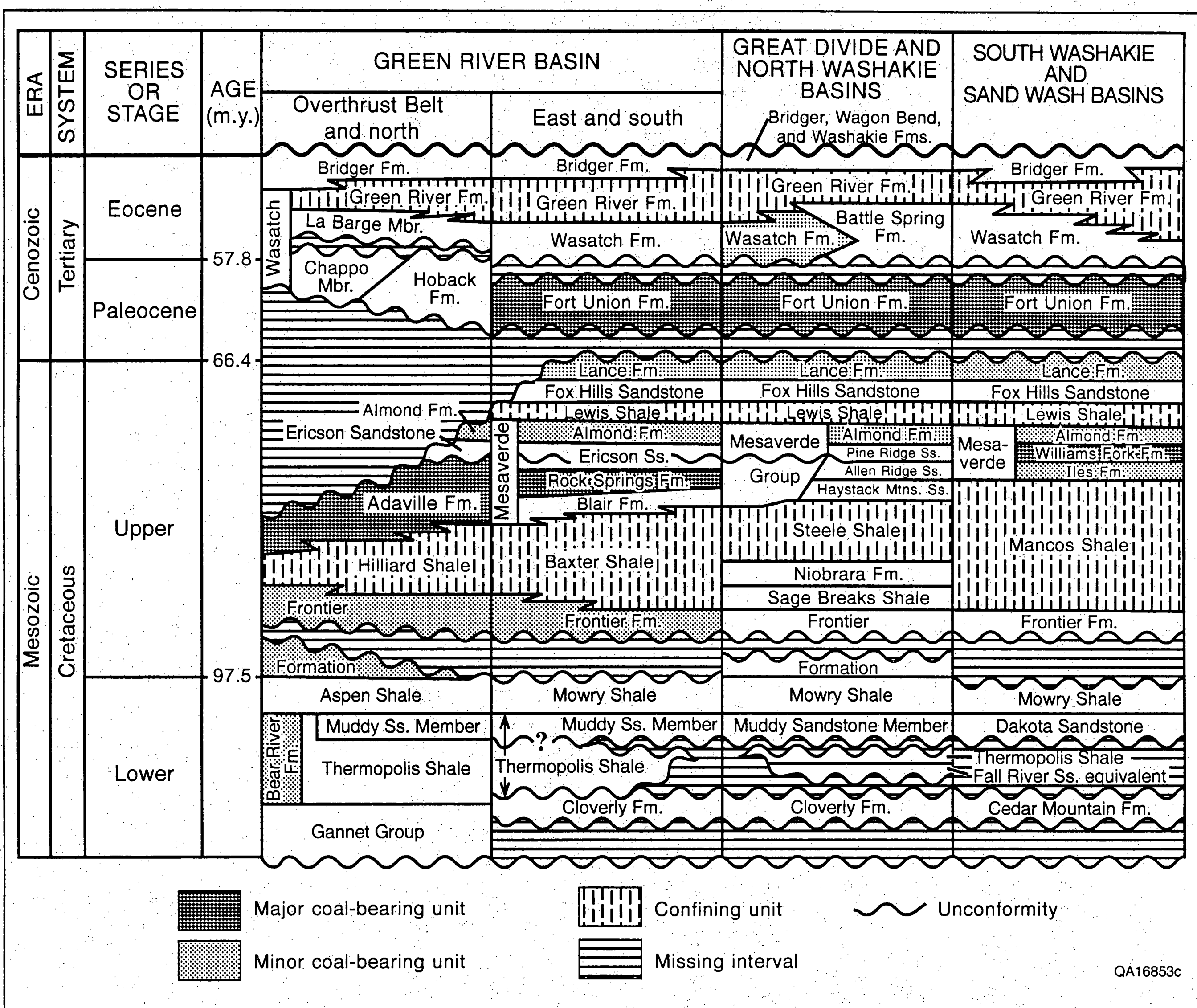


Figure 3. Coal-bearing stratigraphic and hydrologic confining units, Greater Green River Basin. Modified from Baars and others (1988).

episode of subsidence of the Western Interior Seaway (Heller and others, 1986), and sediments derived from the uplifts to the west gradually filled the basin, causing the northeast-trending shoreline to advance eastward.

Numerous transgressions and regressions of the shoreline recorded in the Cretaceous sediments reflect episodic thrust-belt deformation and eustatic change. The basin records three major progradational cycles in Late Cretaceous, pre-Laramide sequences (fig. 3). Each cycle extended deltaic and coastal-plain deposits farther basinward than had the preceding cycle, indicating an overall filling of the Western Interior Seaway. Progradation extended coal-bearing strata (Frontier Formation) as far east as the Rock Springs Uplift during the first cycle. 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, representing the final regressive Cretaceous shoreline facies of the Western Interior Seaway, and the Lance Formation, the succeeding aggradational facies (Irwin, 1986), record the end of Cretaceous sedimentation. The Fox Hills–Lance couplet is depositionally equivalent and homotaxial to the prolific gas-producing Pictured Cliffs–Fruitland couplet in the San Juan Basin.

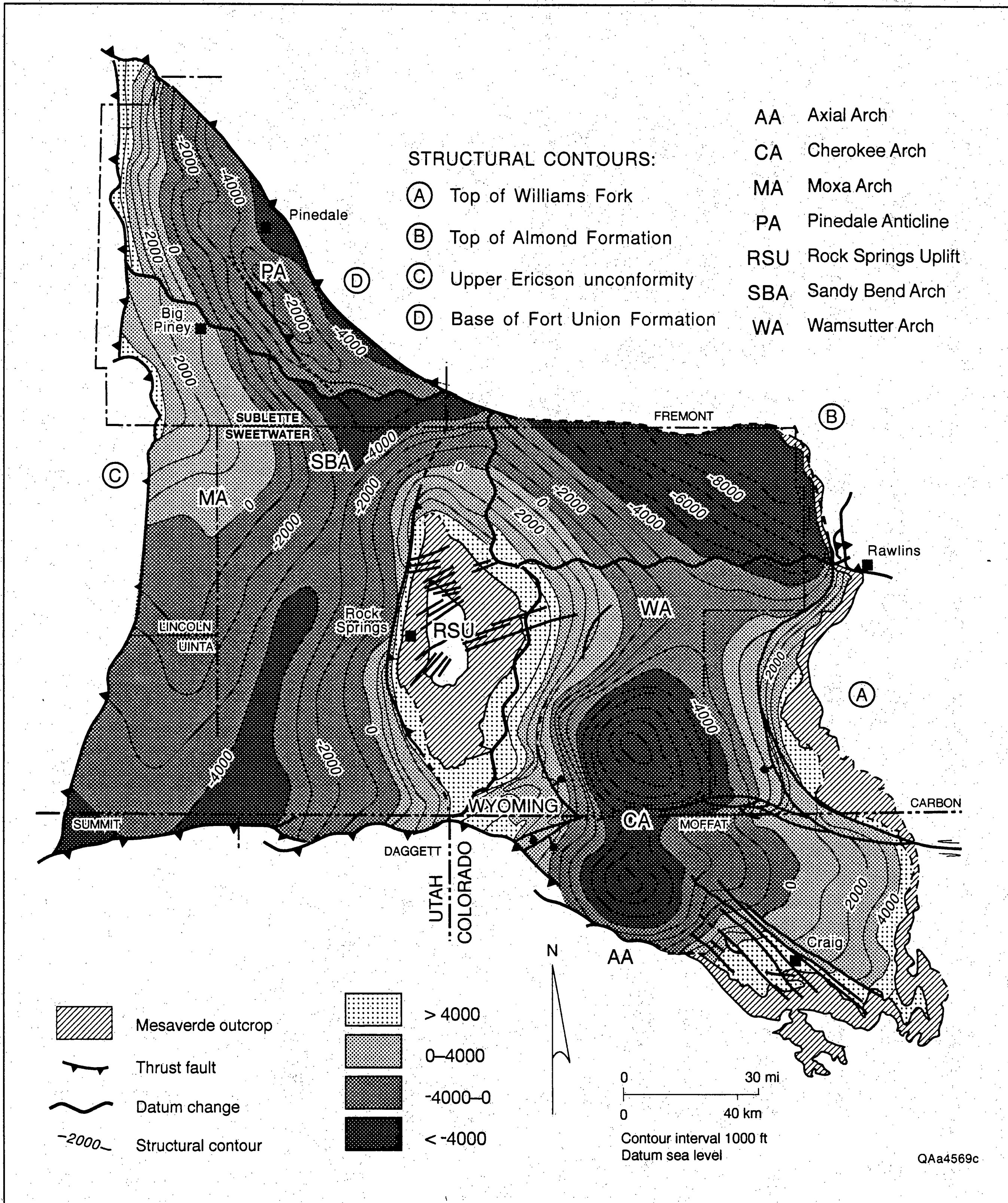


Figure 4. Structural map contoured on various marker beds within the Upper Cretaceous Mesaverde Group and lower Tertiary Fort Union Formation, Greater Green River Basin. Major tectonic features are AA = Axial Arch, CA = Cherokee Arch, MA = Moxa Arch, PA = Pinedale Anticline, RSU = Rock Springs Uplift, SBA = Sandy Bend Arch, and WA = Wamsutter Arch.

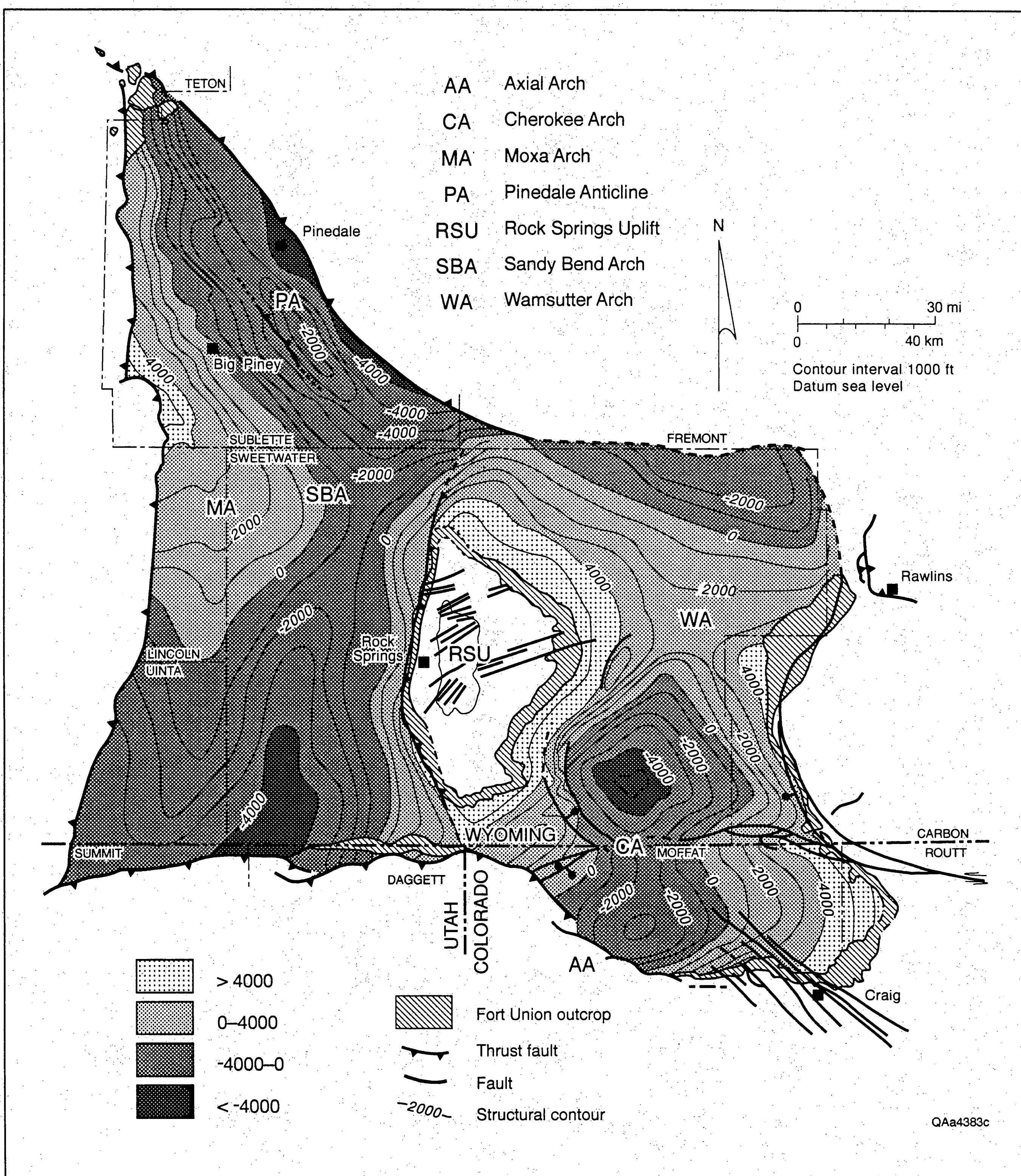


Figure 5. Structural map contoured on the base of the lower Tertiary Fort Union Formation, top of the Massive Cretaceous and Tertiary (K/T) sandstone unit, Greater Green River Basin. Major tectonic features are AA = Axial Arch, CA = Cherokee Arch, MA = Moxa Arch, PA = Pinedale Anticline, RSU = Rock Springs Uplift, SBA = Sandy Bend Arch, and WA = Wamsutter Arch.

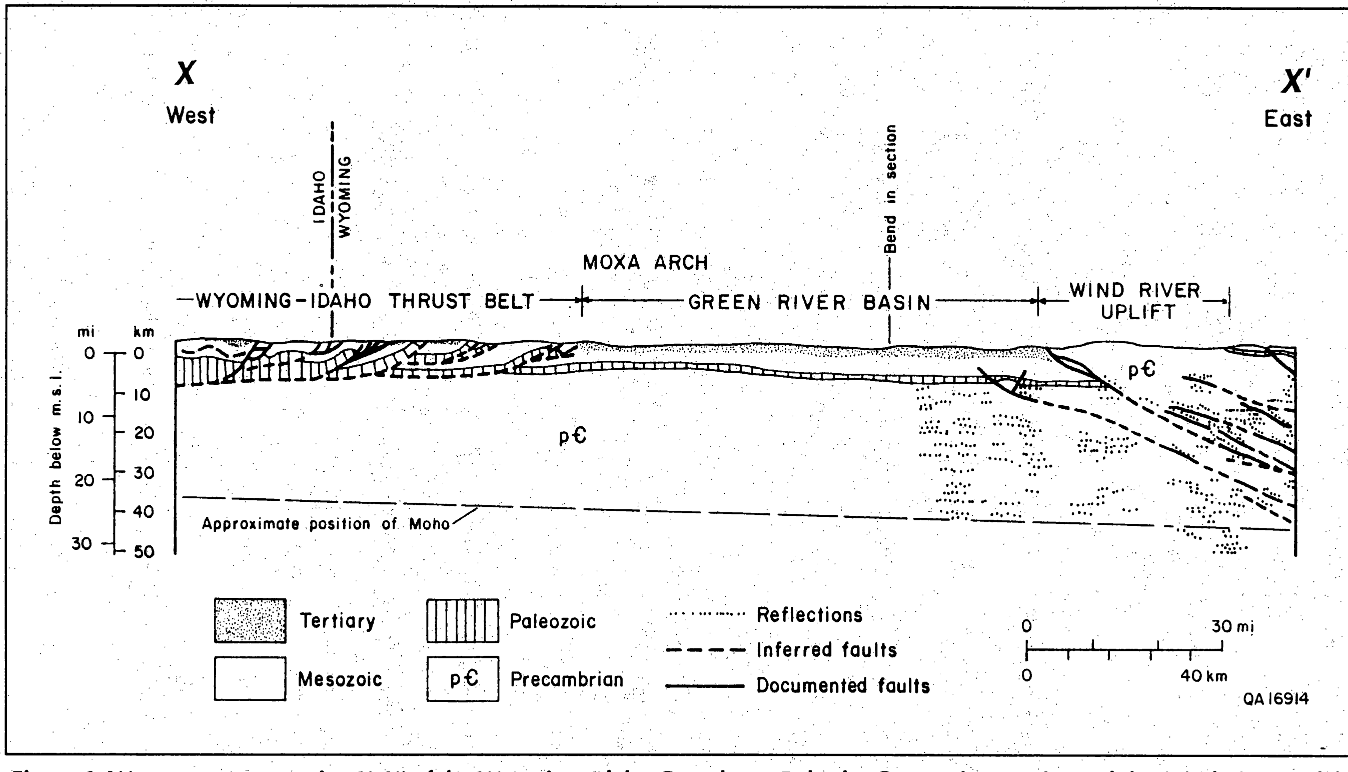


Figure 6. West-east cross section X–X′ of the Wyoming–Idaho Overthrust Belt, the Green River Basin, and the Wind River Uplift. Line of section shown in figure 1. The section is from Bally and Snelson (1980); modified from Baars and others (1988).

Basement uplifts subsequently broke the foreland of the Cordilleran thrust belt into smaller structural and depositional basins during Laramide deformation (mainly Tertiary in age, between 70 and 30 mya). This structural event subdivided the Greater Green River Basin into intermontane basins, such as the Green River, Great Divide, Washakie, and Sand Wash Basins (fig. 2). Activation of the late Campanian phase of thrust-emplaced uplifts and erosion along the margins of the present-day Greater Green River Basin produced the intermontane-fluvial deposits of the Paleocene Fort Union Formation (Beaumont, 1979; Osmond, 1986; Tyler and Tremain, 1993). Major lithologic components of the Fort Union Formation (fig. 3) are conglomeratic sandstone and sandstone, siltstone, shale, and coal that were deposited in fluvial, floodplain, and lacustrine settings (Tyler and McMurry, 1993).

Early Eocene time brought even greater 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 terrain (Ryder, 1988). In contrast, the Wasatch of the south and west Green River Basin was derived from a sedimentary terrain (Oriel, 1962; Hansen, 1965). Although precise timing of the uplifts remains controversial, preexisting structural grain may have controlled the orientation of some uplifts.

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 containing an extensive lacustrine system. Uplift occurred again during the Oligocene, and extensional deformation began in the early Miocene (Hansen, 1986). After 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). Extensional faulting continued at a diminished rate into the Quaternary (Hansen, 1986). Dikes, sills, and other intrusives were also emplaced during the late Tertiary (Tweto, 1979), and they locally coked or metamorphosed coals to anthracite (Bass and others, 1955). The dikes exhibit trends similar to those of fractures and faults (Tyler and Tremain, 1993).

Geometry and Age of Intrabasin Uplifts and Subbasins

Intrabasin Uplifts

The doubly plunging Rock Springs Uplift, having rocks as old as Santonian (Late Cretaceous) age exposed in its core, is the most conspicuous uplift within the Greater Green River Basin (fig. 2; Ryder, 1988). This 60-mi-long (97-km), 35-mi-wide (56-km), north-trending anticline extends from the southeast 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 were probably caused by east-west-oriented compression and by east-dipping thrust faults along the west margin of the uplift (Garing and Tainter, 1985). The thrust fault along the west flank of the uplift must have formed in latest Cretaceous time because its subcrop trace is buried beneath Paleocene rocks (Love and Christiansen, 1985). East-northeast-trending, high-angle normal faults as much as 20 mi (32.2 km) long are common in the area. 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-trending normal faults (Roehler, 1978; Ryder, 1988).

The Moxa Arch, to the west of the Rock Springs Uplift, a broad, gently folded basement uplift in the Green River Basin (Stockton and Hawkins, 1985) (fig. 2), 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 Big Piney–La Barge Platform, is a prominent structural feature that projects eastward approximately 6 mi (~9.7 km) into the basin (Krueger, 1968) and is associated with large accumulations of oil and gas in the Big Piney–La Barge area. Drill-hole data indicate that the arch plunges to the south and is convex eastward in plan view (Ryder, 1988). Angular unconformities, identified in subsurface stratigraphic studies, indicate that the arch experienced initial uplift and truncation in early to middle Turonian (Baxter–Hilliard Shale) time and then during a second period of major uplift and truncation in late Campanian time (Roehler, 1965b; Merewether and others, 1984). Stratigraphic studies indicate that the Moxa Arch was highly active in latest Cretaceous and early Tertiary time. Isopach maps of the lower Fort Union Formation show that the arch was a positive topographic feature during deposition of the coal-bearing sequences.

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, the larger of the two uplifts, separates the Great Divide Basin to the north from the Washakie Basin to the south. The Cherokee Arch separates the Washakie Basin to the north from the Sand Wash Basin to 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 during the early Late Cretaceous and into Paleocene and Eocene time. Weimer (1966) also 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, a broad synclinal basin covering approximately 10,000 mi^2 (~25,913 km^2), is overlain almost entirely by Eocene rocks. These 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). North and northeast of the axis, the basin is bounded by the Wind River Uplift forming a deep syncline (fig. 7). Within this zone, the Pinedale Anticline is an asymmetric, thrust-rooted detachment structure that probably formed in response 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 2° to 8° to the east.

The Great Divide Basin, also known as the Red Desert or Shoshone Basin, is a large topographic and structural basin having interior drainage (fig. 8). A simple synclinal basin modified by broad shallow folds and widespread small-scale faults (Mroz and others, 1983), it has a synclinal axis that trends north-south in the southeast and curves around to approximately 300° in the northeast. In the west and southwest, the strata dip from 2° to 3° toward the east and northeast. In the east, the strata dip as much as 20° west on the west flank of the Rawlins Uplift (McCord, 1984).

The Washakie Basin, a deep synclinal basin, covers an area of about 3,000 mi^2 (~7,774 km^2; fig. 9). Whereas along the basin margins the Eocene beds dip from 3° to

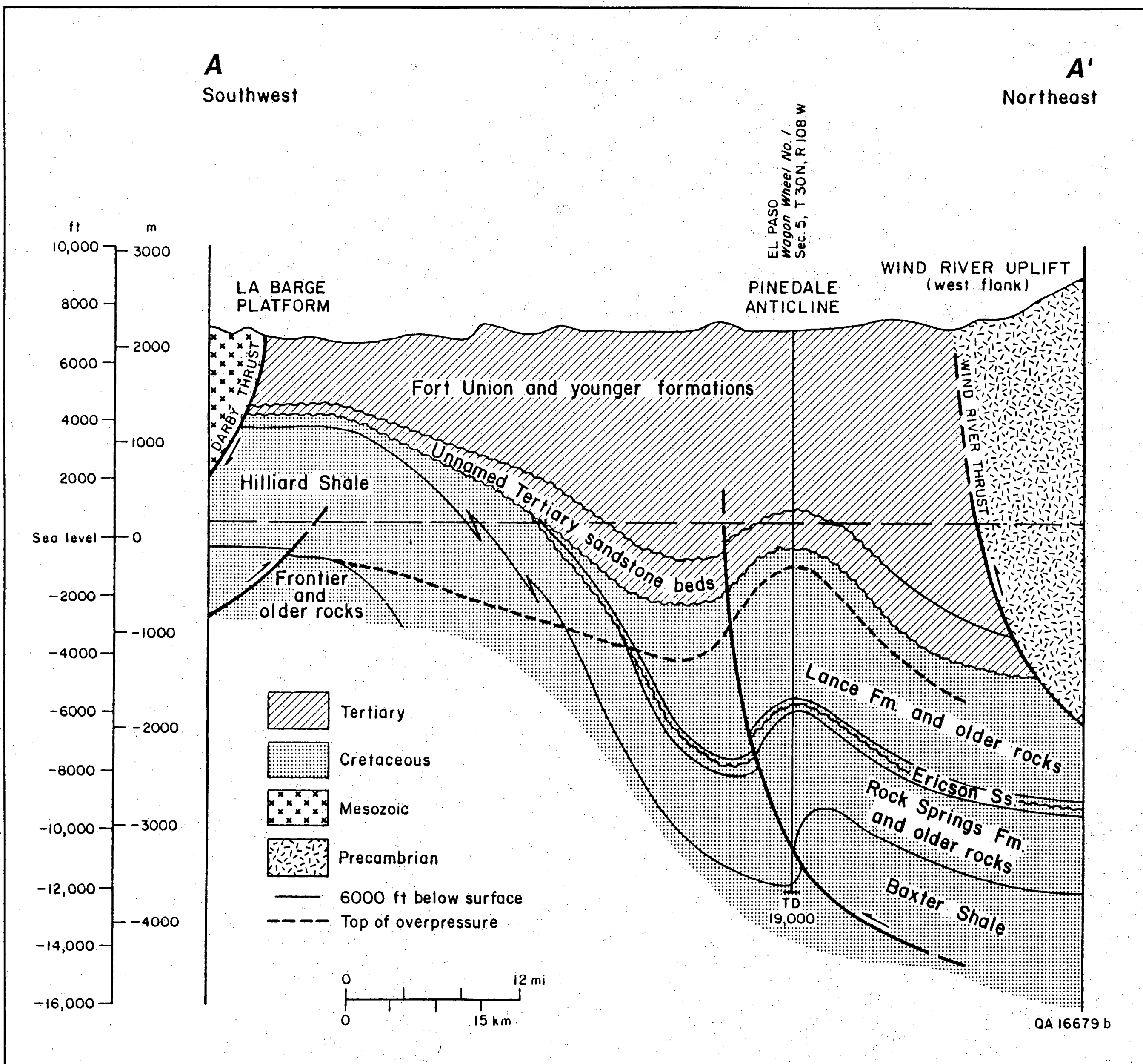


Figure 7. Southwest-northeast cross section A–A′ showing relationship between structure and top of regional overpressure. From Law and Dickinson (1985). Thrust faults may limit recharge to coal-bearing units. Line of section shown in figure 1.

5° toward the center of the basin, away from the edges of the basin, these strata are essentially horizontal (McCord, 1984), and Upper Cretaceous sediments dip steeply toward the center of the basin (fig. 2). This basin, the deepest part of the eastern Greater Green River Basin, has depths to the coal-bearing Mesaverde Group that can exceed 16,000 ft (4,877 m) (fig. 9).

The Sand Wash Basin, a southeast-trending synclinal prong of the Washakie Basin (figs. 2 and 10), in which basement rocks are as deep as 17,000 ft (5,182 m) below sea level (Tweto, 1975) and Cambrian- through Tertiary-age rocks may be as much as 30,000 ft (9,144 m) thick (Irwin, 1986). In the deepest part of the basin (T10N, R96W, and T10N, R98W), the top of the Mesaverde Group is 11,000 to 11,500 ft (3,353 to 3,505 m) below land surface (Tyler and Tremain, 1993). Basal Mesaverde sandstones probably attain maximum depths of 15,000 to 16,000 ft (4,570 to 4,800 m). Upper Cretaceous and lower Tertiary strata, comprising the Mesaverde Group, Lewis Shale, Fox Hills Sandstone, and Lance and Fort

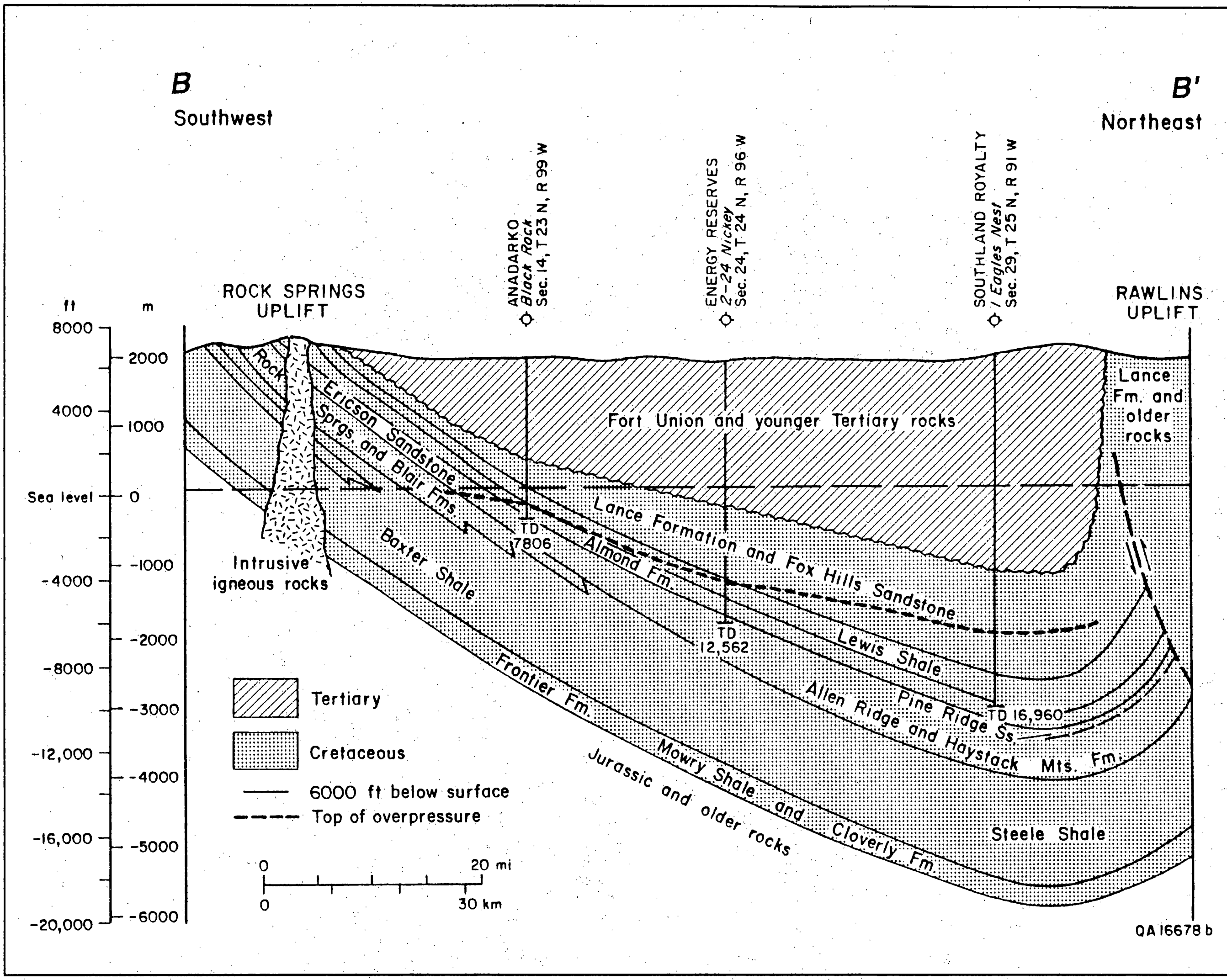


Figure 8. Southwest-northeast cross section B–B′, Great Divide Basin, showing relationships among structure, stratigraphy, and top of regional overpressure. Modified from Law and others (1989). Recharge occurs over Rock Springs Uplift. Line of section shown in figure 1.

Union Formations (fig. 2), crop out mainly on the east and southeast margins of the basin and along the Rock Springs Uplift. The strata dip moderately to steeply basinward, ranging in dip from about 5° to 20°.

Structural Setting—Faults and Folds

The subsurface and surface structures of the Greater Green River Basin have complex north-, northeast-, northwest-, and west-striking faults of diverse origins, strong north- and northwest-striking anticlinal and synclinal folding, and a complex history of fracture genesis. Six major fault systems occur within the basin, as mapped on the Williams Fork and Fort Union Formations (Tyler and Tremain, 1993). A north-south thrust-fault system lies to the west of the Rock Springs Uplift; a southwest-northeast-trending fault system coincides with the Wamsutter Arch and Rock Springs Uplift to the east of Rock Springs; a west-east-trending strike-slip and fault system coincides with the Cherokee Arch to the west of Baggs; a north- and northwest-trending fault system is located east of Baggs; and a northwest-trending thrust and strike-slip fault system occur northwest and southeast of Craig (Tyler and Tremain, 1993). The orientation of fold axes generally parallels the major faults, showing a gradual shift from north-south on the west margin of the basin to more northwest-southeast in the

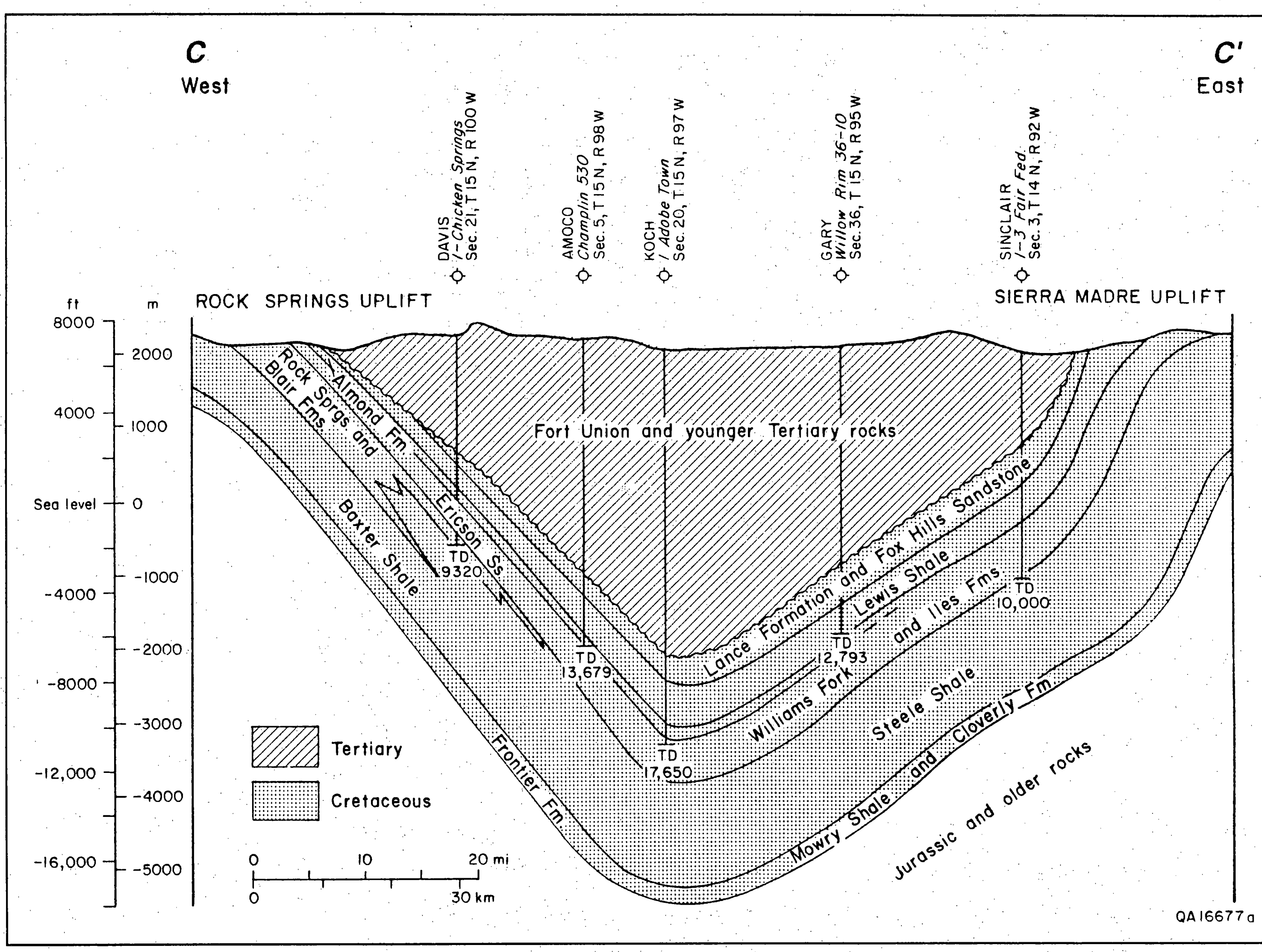


Figure 9. West-east cross section C–C′, Washakie Basin, showing relationships among structure, stratigraphy, top of regional geopressure, and ground-water flow. Modified from Law and others (1989). Recharge over the Sierra Madre–Park and Rock Springs Uplifts. Ground water flows basinward, turning upward upon aquifer pinch-out, convergence from the basin margins, or both. Top of regional overpressure is a no-flow boundary. Line of section shown in figure 1.

east parts of the Greater Green River Basin, suggesting rotation of the maximum horizontal compressive stresses. Natural fractures (cleats) similarly record a complex genetic history as a result of Laramide and post-Laramide structural deformation. These fault, fold, and fracture systems and the thrusts and faults that bound the uplifts surrounding the basin result in a highly complex structural grain both within and along the margins of the Greater Green River Basin (fig. 2).

Faults in the Greater Green River Basin may also contribute to coal permeability and conventional trapping of gas. Oil and gas fields occur on north-, northwest-, and northeast-trending faulted structures on the flanks of the Moxa, Wamsutter, Cherokee, and Axial Arches and in the center of the basin associated with the Rock Springs Uplift (figs. 4 and 5). The west-east-trending Cherokee Arch, located north of the Wyoming–Colorado state line, is a westward-plunging anticline cut by numerous faults. Structural contours drawn on top of the Mesaverde Group and the Fort Union Formation reveal a major west-east-trending fault that splays out toward the west and east, producing a complex normal and reverse fault system, having a left-lateral strike-slip component (Tyler and Tremain, 1993). To the east and northeast of the Cherokee Arch fault system, two major north- and northwest-trending faults extend for approximately 40 to 80 mi (~64 to 129 km) along the Mesaverde Group and Fort Union Formation outcrop. Maximum displacements across the fault system may be as much as 2,500 ft (762 m); downthrown blocks are on the west side of the faults.

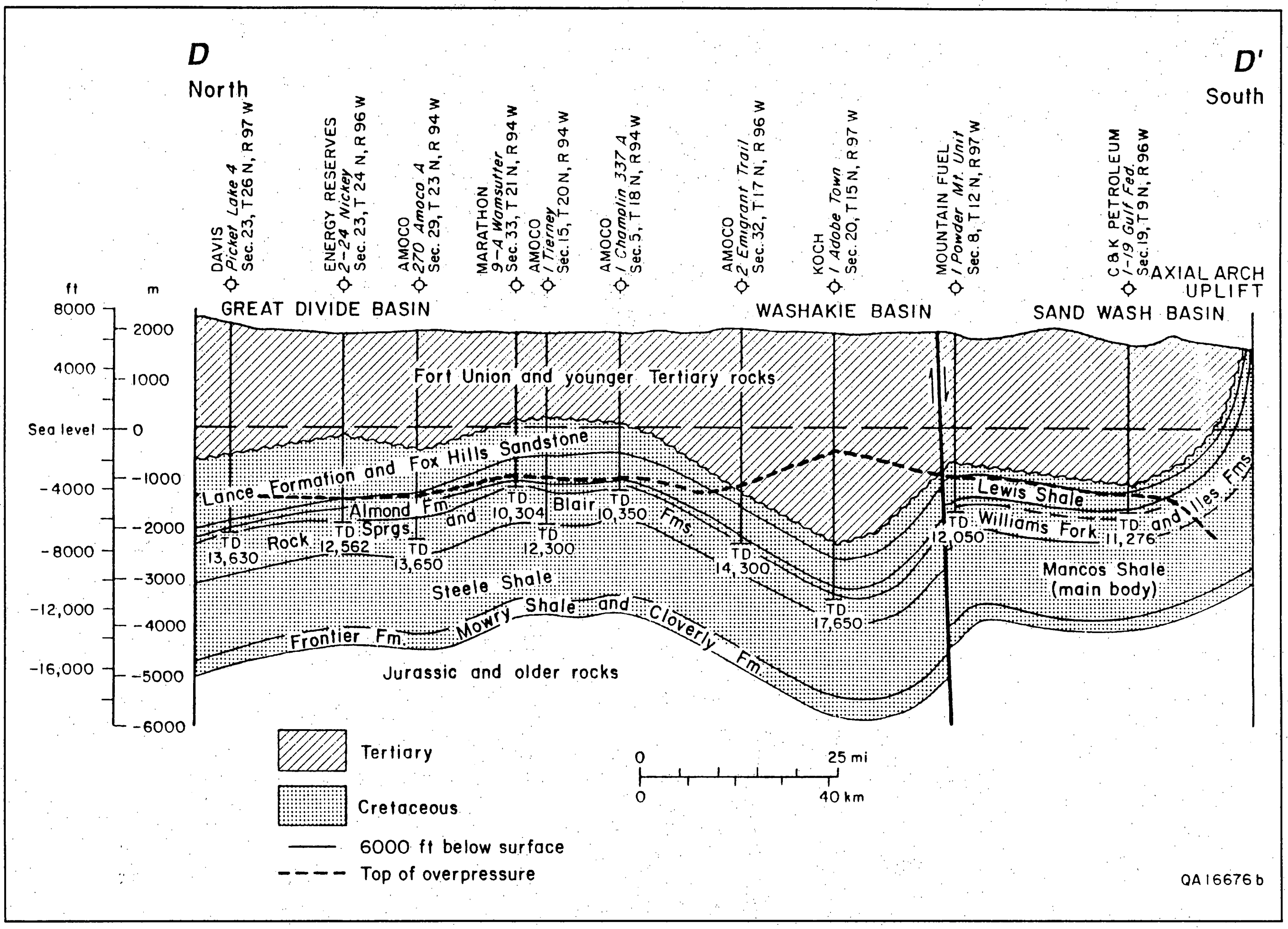


Figure 10. North-south cross section D–D′ of Great Divide, Washakie, and Sand Wash Basins, showing relationships among structure, stratigraphy, and top of regional overpressure. Modified from Law and others (1989). Depth to pressure transition unknown. Line of section shown in figure 1.

The east-trending Cherokee Arch fault system and the north-trending fault system, when traced to the southeast, coincide with a strike-slip fault system that crops out within the Sierra Madre Uplift (Petroleum Information Corporation, 1992).

The southeast part of the basin is bordered by thrust-, reverse-, and strike-slip-fault systems that parallel thrusts and faults on the north flank of the Uinta Mountains and Axial Arch and the basin margin (figs. 2, 4, and 5). Northwest of Craig a major system of faults has been identified in the subsurface from geophysical logs and seismic lines provided by Union Pacific Resources (Tyler and Tremain, 1993). The fault system is at least 10 mi (16 km) wide and extends approximately 30 mi (~48 km) northwest and 15 mi (24 km) southeast of Craig. Maximum displacements across the fault system may be as much as 5,000 ft (1,524 m); downthrown blocks are on the northeast side of the faults (Tyler and Tremain, 1993). Southeastward projection of the fault system boundaries corresponds to northwest-trending outcrop segments of the Mesaverde Group–Lewis Shale contact and also coincides with thrust and reverse faults mapped on seismic data (Livesey, 1985) and prominent northwest-trending lineaments. Large, predominantly northwest- and north-trending folds also occur along the southeast border of the basin (Tweto, 1976). These folds include the northwest-trending Williams Fork, Beaver Creek, Breeze, and Buck Peak Anticlines (Hancock, 1925) and the more north-trending Tow Creek, Oak Creek, Fish Creek, and Sage Creek Anticlines (Bass and others, 1955) on the east margins of the Sand Wash Basin. Northwest faults, 5 to 10 mi (8 to 16 km) long, are recorded on surface geologic maps (Hancock, 1925; Bass and others, 1955; Tweto, 1976) parallel to the fold axes. Smaller faults, oblique to the folds, have also been reported.

Natural Fracture Attributes in Coal

Permeability in coal largely results from fractures (cleats) and faults. Cleat and fault characteristics were recorded from field observations in the Mesaverde Group and Fort Union Formation coal beds (at approximately 36 stations, principally in the center and southeast corner of the Greater Green River Basin), from literature, and from core descriptions. A survey of outcrops and mine highwalls of interbedded lenticular, channel-fill sandstone and coal in several locations of the Greater Green River Basin also shows that subbituminous coal seams have vertical to subvertical, uniformly developed, 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 (Tyler and others, 1991; Tyler and Tremain, 1993).

Cleat Strike

In the west and central parts of the Greater Green River Basin, average face-cleat strikes are east to northeast (060° to 090°) (fig. 11), and butt-cleat strikes are north to northwest (N to 330°) in Cretaceous and Tertiary coals. In the southeastern Greater Green River Basin, face cleats generally strike northwesterly. Boreck and others (1977) and Khalsa and Ladwig (1981) measured north-northwest face cleats in seven mines in the southeast part of the basin. They reported face cleats striking at 003° in T4N, R86W, 353° in T4N, R85W, between 300° and 335° in T5N, R86W–R87W, and 315° in 6N, R87W. Face-cleat orientations measured at 26 stations in the Sand Wash Basin generally trend northwestward (fig. 11; Tyler and others, 1991, 1992a, b; Laubach and others, 1992a, b; Tyler and Tremain, 1993), parallel to the current maximum horizontal stress direction (Zoback and Zoback, 1989) and the major northwest-trending faults in the area. South of Craig, face cleats form two mutually crosscutting and abutting cleat sets that strike both northwestward and northeastward. We tentatively interpret these orientations to indicate the presence of at least two major, possibly contemporaneous, face-cleat sets that are related to maximum horizontal compressive stresses during late Late Cretaceous to early Tertiary times. These mutually abutting crosscutting fracture sets may also enhance permeability (Tremain and others, 1991a, b). Field mapping of Cretaceous and younger joints and analysis of linear features at multiple scales on the Rock Springs Uplift and within the Great Divide and Washakie Basins consistently demonstrate regional structural trends of N60°E to N80°E and N25°W to N60°W (Jaworowski, 1993). Locally, north-northeast- and north-northwest-trending photolineations are also apparent on the northern Rock Springs Uplift and in the northern Washakie Basin (Jaworowski, 1993), corresponding to the north-northeast-trending systematic joints and face cleats and north-northwest-trending nonsystematic joints and face cleats along the Rawlins Uplift of Laubach and others (1992a, b) and Grout and Verbeek (1992a, b). Generally, regional face-cleat strikes in the basin form parallel to tectonic shortening, and they are typically oriented at right angles to orogenic thrust fronts.

On the Rock Springs Uplift, local variations in cleat strike are associated with low-amplitude folds caused by differential compaction (Tyler and others, 1991; Laubach and others, 1993, 1994a, b). 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. No typical regional face cleats are evident; instead, closely spaced normal faults have replaced face cleats. These faults have striated slip surfaces that are mineralized and curviplanar, the latter being 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, shear-related, mode-II fault cleat sets that formed instead of opening-mode (mode-I) cleats during coalification (Tyler and others, 1991). These fault cleats, occurring along with localized zones of opening-mode face-cleat systems, could compartmentalize and channelize gas and water flow to create structural traps in which gas could accumulate. Any ability to predict varying cleat characteristics and reservoir compartmentalization would be extremely useful in methane exploration because areas of degasification could then be identified using structural and lithofacies maps.

Cleat Spacing

In many coals, cleat spacing varies with coal rank, coal lithotype, ash content, and bed thickness (Ammosov and Eremin, 1960) and with position relative to structural deformation. The spacing between cleats is currently used in reservoir modeling to indicate potential fracture permeability (Mavor and others, 1991a, b). Cleat spacing in the Greater Green River Basin ranges from 0.5 inch (1.3 cm) to more than 12 inches (>30.5 cm) in fractures of different sizes. Cleat spacing is less than 0.5 inch (<1.3 cm) in the smallest tertiary cleats, 0.5 to 2 inches (1.3 to 5 cm) in secondary cleats within coal layers or coal lithotypes, more than 2 inches (>5 cm) in primary cleats that extend the entire height of a coal lithotype, and more than 12 inches (>30 cm) in master cleats that

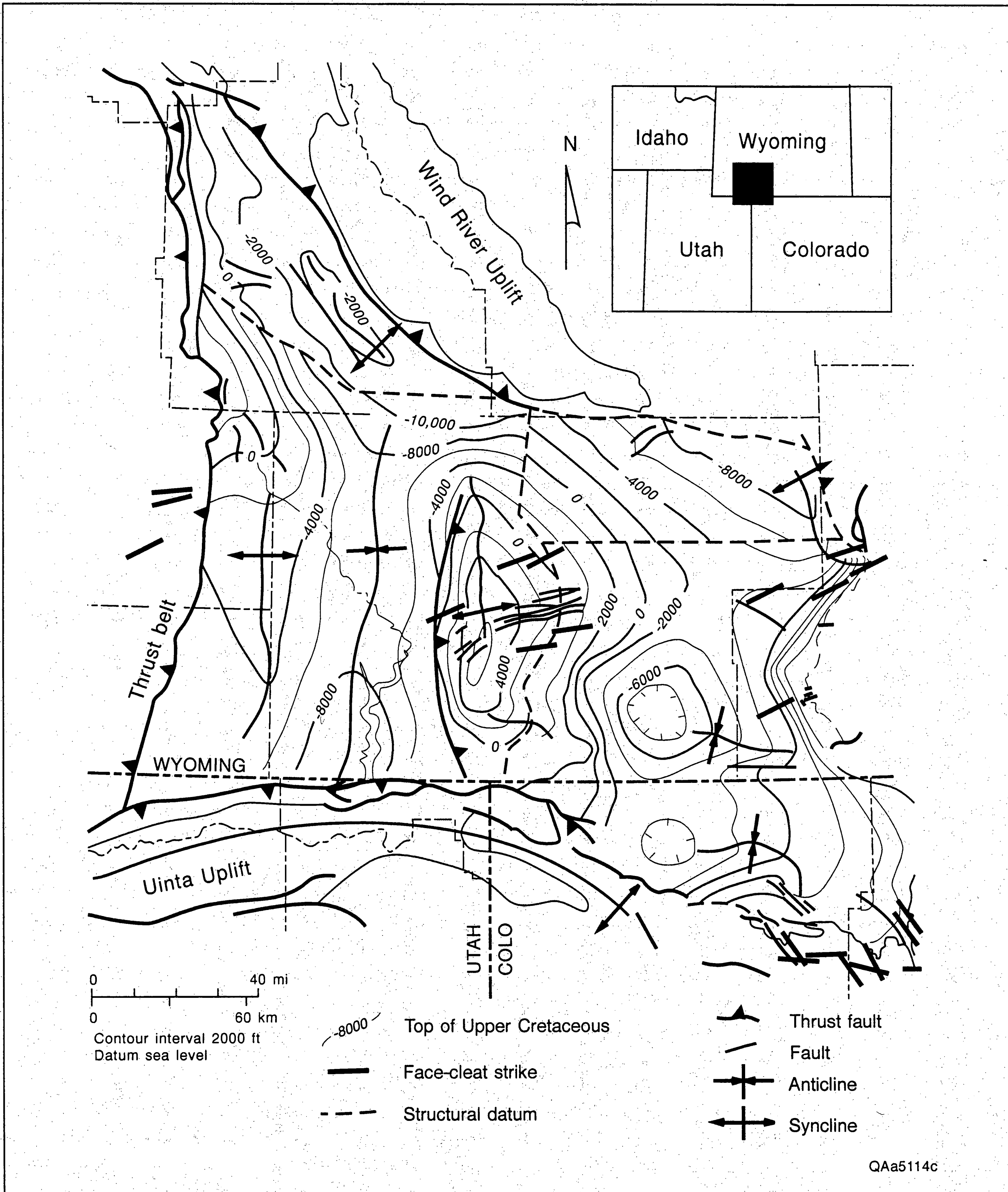


Figure 11. Structure map of the Greater Green River Basin contoured on Upper Cretaceous marker horizons. Face-cleat strikes occur in Upper Cretaceous and lower Tertiary coal seams.

cut through an entire coal seam, including thin, noncoal interbeds. Cleat frequency, the inverse of spacing, ranges from less than one cleat per inch (2.5 cm) to more than five cleats per inch. One- to 2-inch (2.54- to 5.1-cm) cleat spacing was recorded in a Mesaverde coal at 4,914 to 4,923 ft (1,498 to 1,500 m) in the Helmerich and Payne Colorado State No. 1-31 well (Sec. 31, T7N, R88W). Spacing between butt cleats in a Fort Union coal, from approximately 5,000 ft deep (~1,524 m) in the Chevron Federal Land Bank (F.L.B.) No. 15-4C, is 0.25 inch (0.6 cm). Thin vitrain bands in Fort Union coals, as in most coals, are closely cleated, on the order of <0.25 inch (<0.6 cm) in a Fort Union coal from 2,072 to 2,077 ft (631 to 633 m) in the F.L.B. No. 1-29 well (Sec. 29, T7N, R92W) (Tyler and Tremain, 1993).

Cleat Mineralization

Minerals deposited in cleats can obstruct the permeability of fracture systems in coal seams. Although cleats in many Greater Green River Basin coals have only insignificant cleat-filling minerals in outcrop, several instances of mineralization have been noted. Calcite fills some cleats in mine exposures near Savery, Wyoming. Along with pyrite, calcite lines cleats in a few coals cored in the USGS C-IC-H well (Sec 23. T4N, R93W). Calcite was also reported throughout cleats in an 8-ft (2.4-m) coal cored in the Helmerich & Payne Colorado State No. 1-31 well. Hancock (1925) reported several instances of selenite (gypsum) along joint planes in blocky coals at a few old mines and prospects. Minor amounts of pyrite are also frequently reported in coal mines and cores. The pyrite occurs as isolated rosettes on cleat surfaces in fresh coal samples. Reddish-brown staining in outcropping coals and associated sandstones may be weathered pyrite formerly present in the cleats and joints (Tyler and Tremain, 1993).

Stress Regime

The interpretation and timing of the orientation of the principal shortening direction in the Greater Green River Basin are controversial. The major compressive force during the Laramide Orogeny were east-west (Livesey, 1985), southwest-northeast (Gries, 1983), west-southwest–east-northeast (Stone, 1975) or typically oriented at right angles to orogenic thrust fronts and parallel to tectonic shortening (Laubach and others, 1992a, b; Tyler and Tremain, 1993). Dynamic analysis of subsurface and surface structures in northwestern Colorado (Stone, 1975; Tyler and Tremain, 1993) indicates that structural patterns of the Greater Green River Basin are consistent with regional tectonic patterns of the Rocky Mountain Foreland. Spatially the orientation of faults and fold axes shows a gradual change from almost north-south on the west margin of the basin, adjacent to the Overthrust Belt, to northeast in the center of the basin, to a more northwest-southeast orientation in the east parts of the basin, suggesting rotation of maximum horizontal stresses about a vertical axis.

Laramide and post-Laramide stresses associated with genesis of natural fractures (cleats) have similarly rotated about a vertical axis. Upper Cretaceous and lower Tertiary coal beds are cut by a complex network of extensional fractures and cleats. Fracture data reveal at least three principal face-cleat strikes, which correspond to stress variations in the Greater Green River Basin. Regionally the Mesaverde Group has dominant face-cleat strikes to the northeast along the Overthrust Belt, the Rock Springs Uplift, and the east margin of the Washakie Basin and to the northwest within the eastern Sand Wash Basin. But evidence of mutually abutting northwest and northeast face-cleat strikes exists in the southern Sand Wash Basin. A gradual change in face-cleat strike from the northeast along the west margin of the basin to the northwest on the southeast edge of the basin suggests a shifting of principal horizontal stresses from late Mesozoic through Cenozoic time. A record of Laramide and post-Laramide stress rotation has also been documented in joints in the Piceance and Washakie Basins (Verbeek and Grout, 1986; Grout and Verbeek, 1992a, b).

Currently the Greater Green River Basin lies within the Cordilleran Extension stress province, north of the Colorado stress province and west and southwest of the Mid-Plate stress province (fig. 12; 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 Overthrust Belt (figs. 2 and 12). Zoback and Zoback (1989) tentatively included southwestern Wyoming in this Cordilleran Extension stress province because their data indicate 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 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,

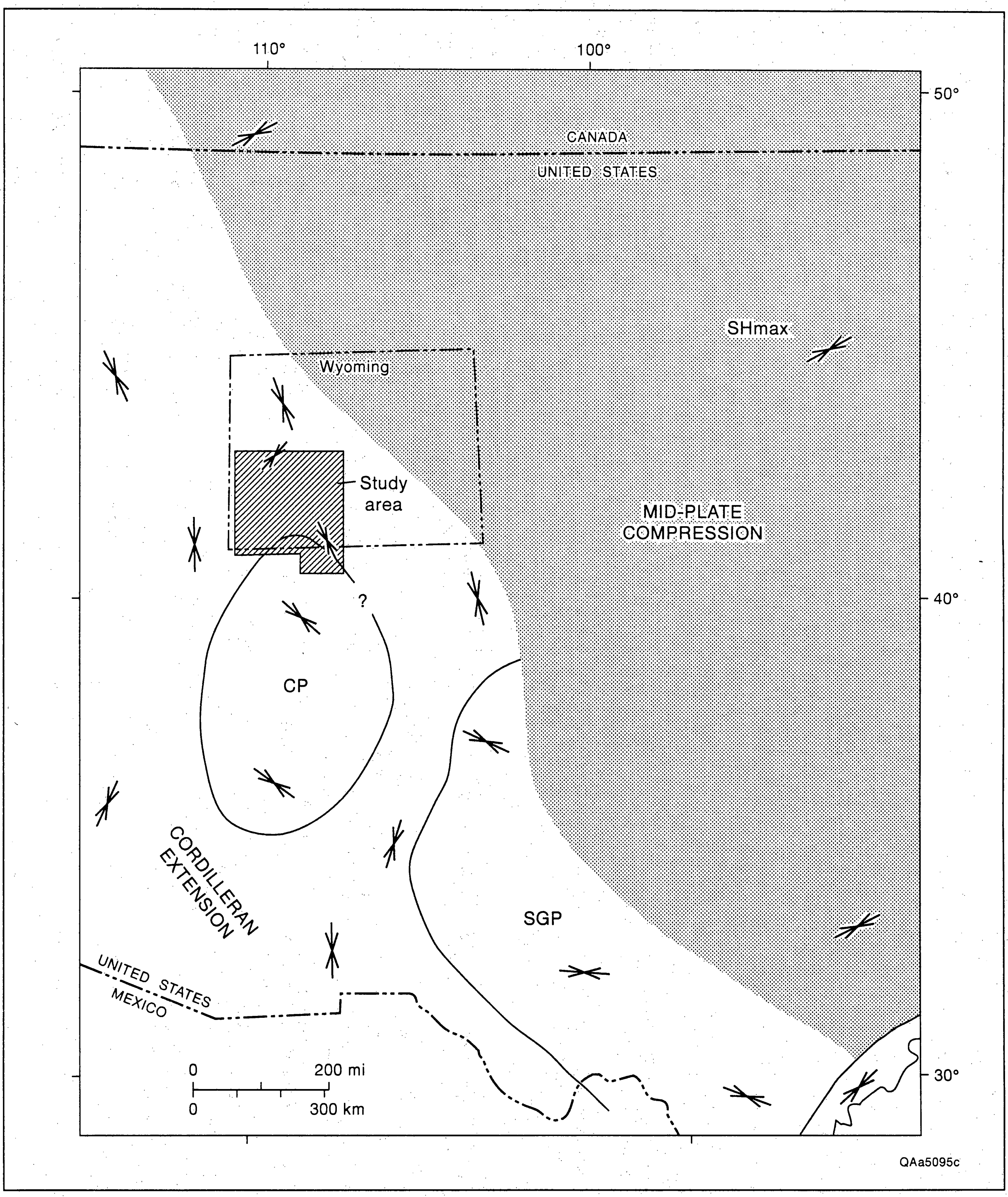


Figure 12. Maximum horizontal compressive stress orientations of the western United States. Stress provinces are delineated by thick, solid and dashed lines: CC = Cascade convergent province; PNW = Pacific Northwest; SA = San Andreas province; CP = Colorado Plateau interior; SGP = Southern Great Plains. 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).

1976). The induced 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 result from 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 coal- and coalbed-methane-bearing formations in the Greater Green River Basin occur in Upper Cretaceous and lower Tertiary strata (Tyler and others, 1991, 1992a, b; Tyler and Tremain, 1993) (fig. 3). The Upper Cretaceous contains several coal-bearing, nonmarine stratigraphic units (Frontier, Rock Springs, Iles, Williams Fork, Almond, and Lance Formations) deposited in coastal-plain, delta-plain, and back-barrier settings, landward of delta-front and barrier-island systems (Haun, 1961; Asquith, 1970; Roehler, 1990). Fluvial coals are also present in the Upper Cretaceous units (Hamilton, 1993). Lower Tertiary Fort Union and Wasatch Formation coal-bearing units in the Greater Green River Basin were deposited in fluvial-floodplain and lacustrine settings.

The complex tectonic, structural, and depositional history of the Greater Green River Basin is reflected in its stratigraphy. Regional correlation of stratigraphic units across the basin is made difficult because of (1) multiple unconformities, (2) missing or duplicate sections related to faulting, (3) scarcity of consistent marker beds over considerable thicknesses of nonmarine section, and (4) deposition in separate subbasins. In particular, the Rock Springs Uplift separates the Greater Green River Basin into east and west halves, and structural arches further subdivide the east basin into three subbasins. The east half of the basin contains the Great Divide, Washakie, and Sand Wash Basins; the west half contains the Green River Basin and Pinedale Anticline (fig. 2). Despite correlation difficulties, a regional stratigraphic framework was established in this study and correlation across the entire Greater Green River Basin was achieved (fig. 13). The stratigraphic framework focuses on the coal-bearing packages, the major stratigraphic units delineated being the Mesaverde Group and the Fort Union Formation.

Within the Mesaverde Group, regional unconformities and widespread marine flooding events were identified that allowed subdivision of a sequence. The group is divided into upper and lower units by the widespread Trout Creek marker, which is attributed to a marine flooding event basinward and its equivalent surface of nondeposition landward (figs. 14 through 16). The lower Mesaverde Group is further subdivided by the regionally extensive Moxa unconformity, which overlies the coal-bearing Rock Springs Formation near the Rock Springs Uplift but cuts more deeply to the west and erodes the Rock Springs Formation west of R108W to R109W (fig. 14). Basinward (southeast), the Moxa unconformity passes gradually into its correlative conformity surface near the lower, predominantly progradational part of the Iles Formation in the Sand Wash Basin and east parts of the Washakie Basin. The Moxa unconformity and its correlative conformity surface thus provide a good operational boundary that distinguishes the Rock Springs Formation from the aggradational part of the Iles Formation. This stratigraphic relationship is consistent with the relative ages determined from palynofloras by Miller (1977), who found that the Iles Formation is mostly younger than the Rock Springs Formation. Only the lower, progradational part of the Iles Formation is a time equivalent of the Rocks Springs Formation.

The upper Mesaverde is grouped into the Williams Fork Formation throughout the Greater Green River Basin and includes the lower part of the Almond Formation as formally defined at the Rock Springs Uplift (Sears, 1924). We restrict the use of the term Almond Formation to the barrier–strandplain facies that are traditionally classified as the "upper Almond" at the Rock Springs Uplift (Hale, 1950; Jacka, 1965; Weimer, 1965, 1966; Van Horn, 1979). The Williams Fork Formation can be divided into four genetic depositional sequences that are each bounded by regionally extensive shale markers. These markers are interpreted as marine flooding surfaces in basinward positions and nondepositional hiatal surfaces or surfaces of sediment starvation in landward positions (Hamilton, 1993; fig. 17). The shale marker that divides genetic units 2 and 3 is the most regionally extensive and extends westward until it is eroded by the Pine Ridge unconformity (fig. 16). This unconformity underlies the Canyon Creek Member (Smith, 1961) of the Ericson Sandstone. The shale marker that divides genetic units 1 and 2 extends across the Sand Wash and eastern Washakie Basins but is also eroded by the Pine Ridge unconformity to the west (figs. 15, 18). The bounding shale marker between units 3 and 4, the most extensive of the markers, extends throughout the Greater Green River Basin. The boundary between the Williams Fork and Almond Formation (as defined herein) is a further extensive shale marker (figs. 14 through 16).

Although definition of the Cretaceous stratigraphic units above the Almond Formation, such as the Lewis Shale, Fox Hills Sandstone, and Lance Formation, are consistent with formal usage, subsurface correlations of the Paleocene Fort Union Formation in the Greater Green River Basin are complicated by the scarcity of regional marker beds. Different sources of clastic material

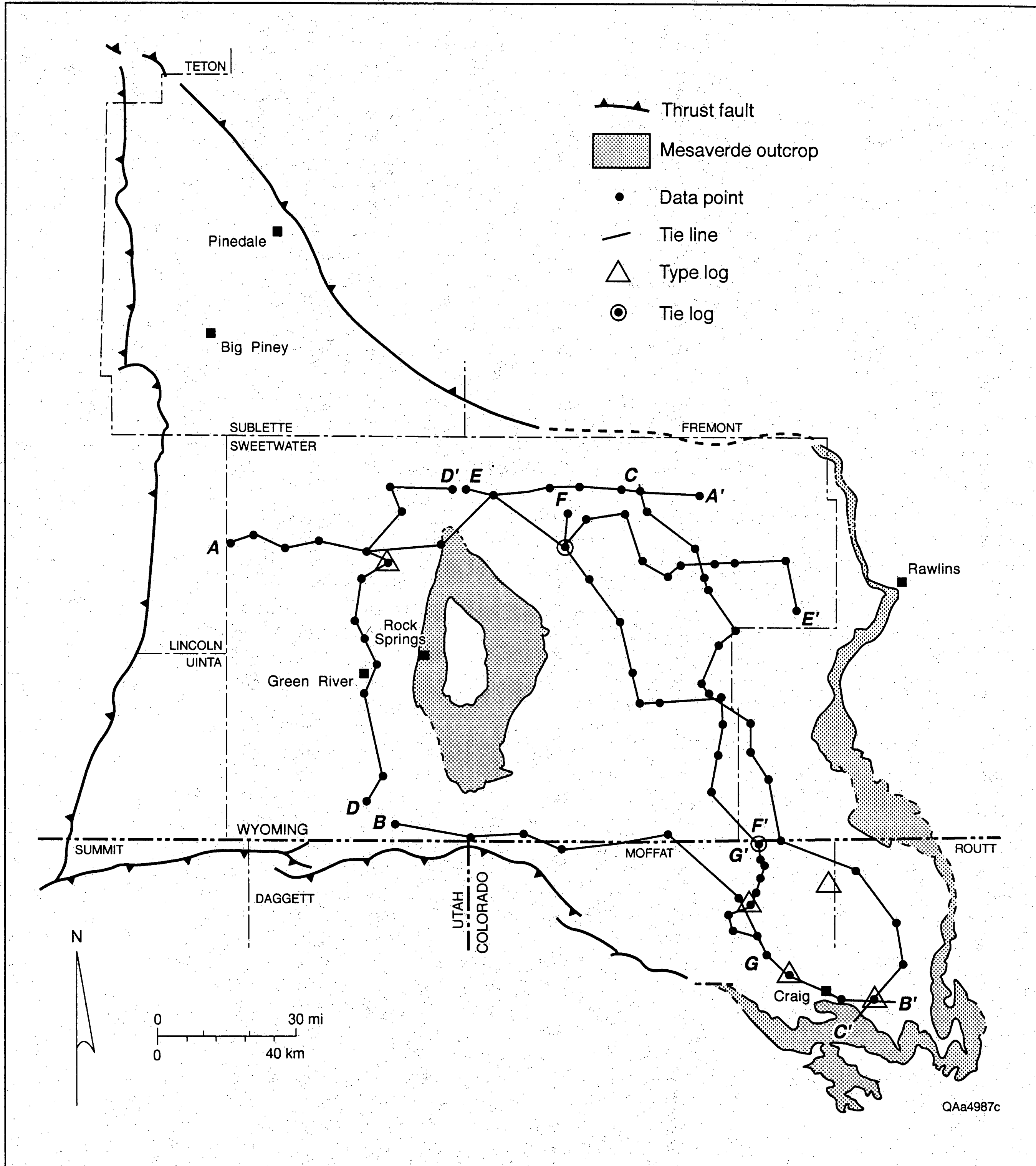


Figure 13. Location plan of Mesaverde and Fort Union stratigraphic cross sections A–A′ through G–G′ (figs. 14 through 16, 20 through 23) and type logs (figs. 17, 19, 30, 42, and 43), Greater Green River Basin.

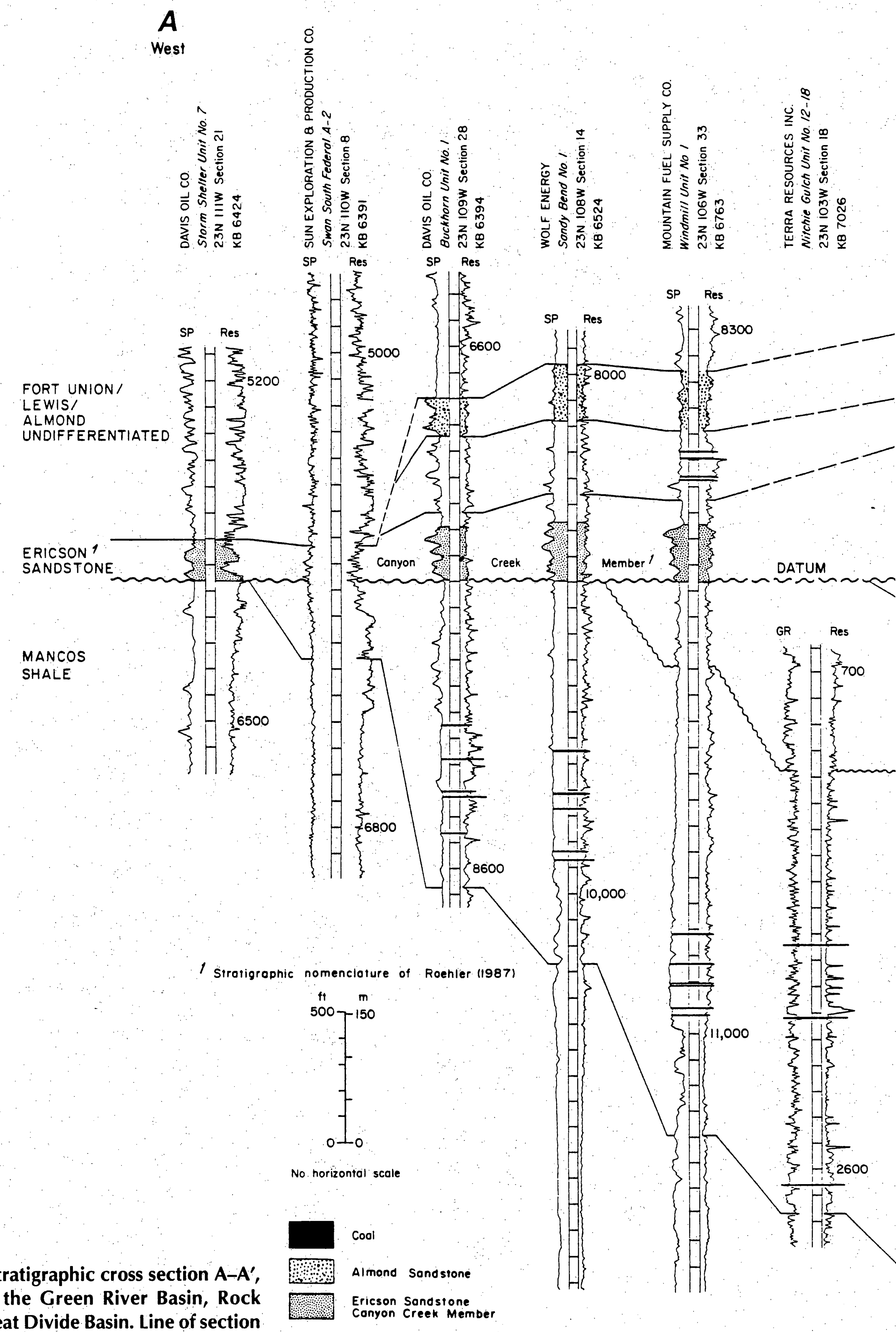
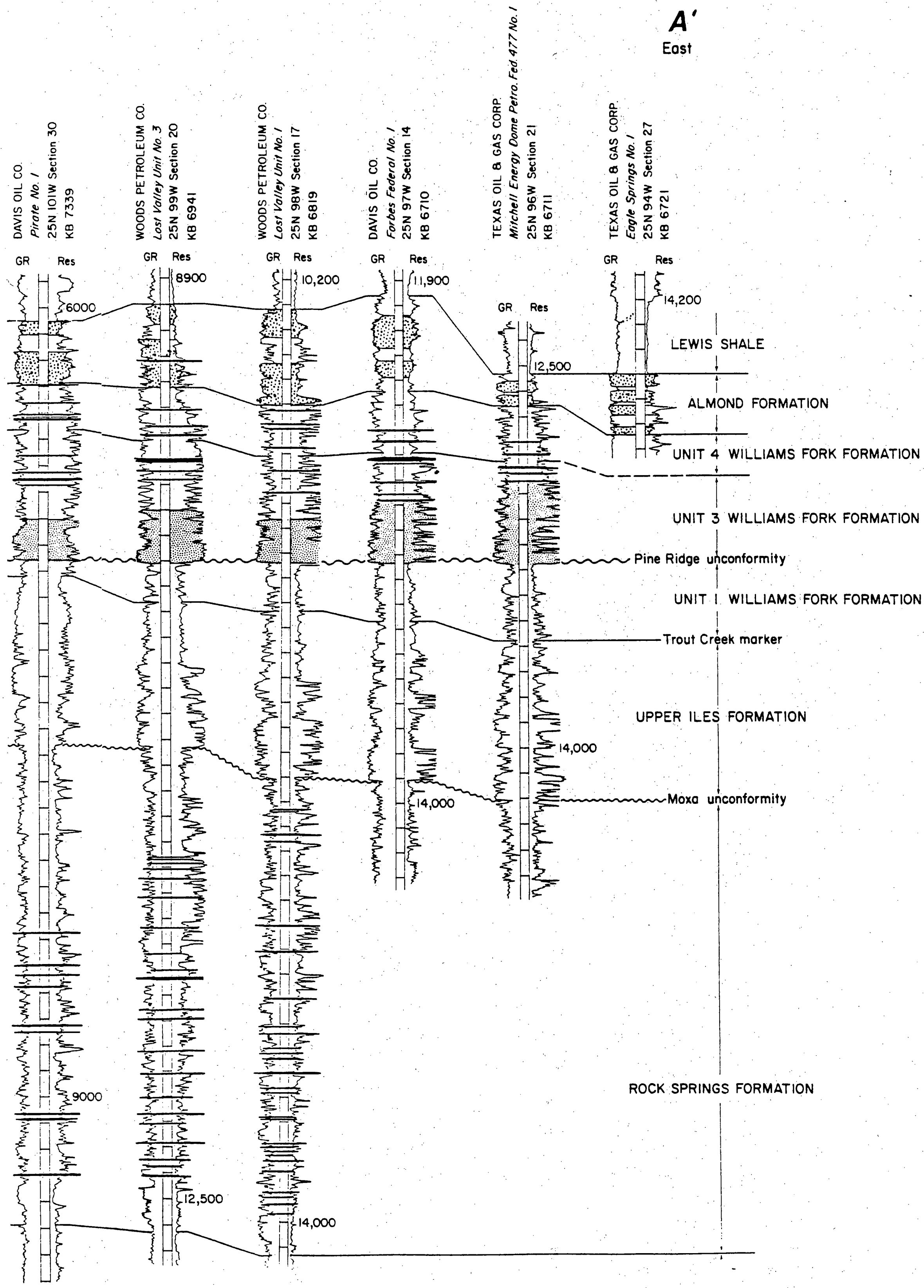


Figure 14. West-east stratigraphic cross section A–A′, Mesaverde Group of the Green River Basin, Rock Springs Uplift, and Great Divide Basin. Line of section shown in figure 13.


A'
East
DAVIS OIL CO.
Pirate No. 1
25N 101W Section 30
KB 7339
WOODS PETROLEUM CO.
Lost Valley Unit No. 3
25N 99W Section 20
KB 6941
WOODS PETROLEUM CO.
Lost Valley Unit No. 1
25N 98W Section 17
KB 6819
DAVIS OIL CO.
Forbes Federal No. 1
25N 97W Section 14
KB 6710
TEXAS OIL & GAS CORP.
Mitchell Energy Dome Petro. Fed 477 No. 1
25N 96W Section 21
KB 6711
TEXAS OIL & GAS CORP.
Eagle Springs No. 1
25N 94W Section 27
KB 6721
GR
Res
6000
8900
10,200
11,900
12,500
14,200
14,000
9000
12,500
14,000
LEWIS SHALE
ALMOND FORMATION
UNIT 4 WILLIAMS FORK FORMATION
UNIT 3 WILLIAMS FORK FORMATION
Pine Ridge unconformity
UNIT 1 WILLIAMS FORK FORMATION
Trout Creek marker
UPPER ILES FORMATION
Moxa unconformity
ROCK SPRINGS FORMATION

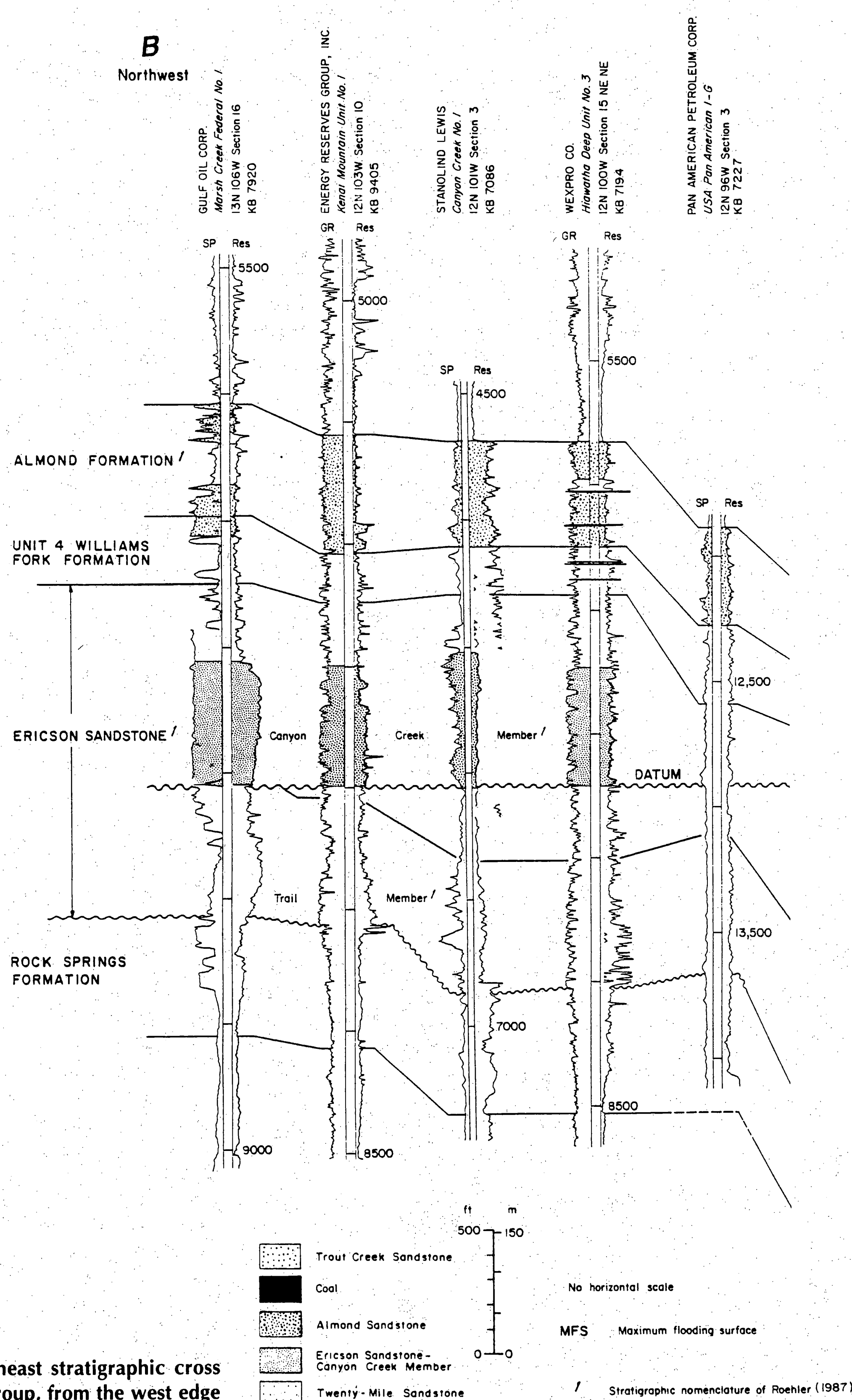
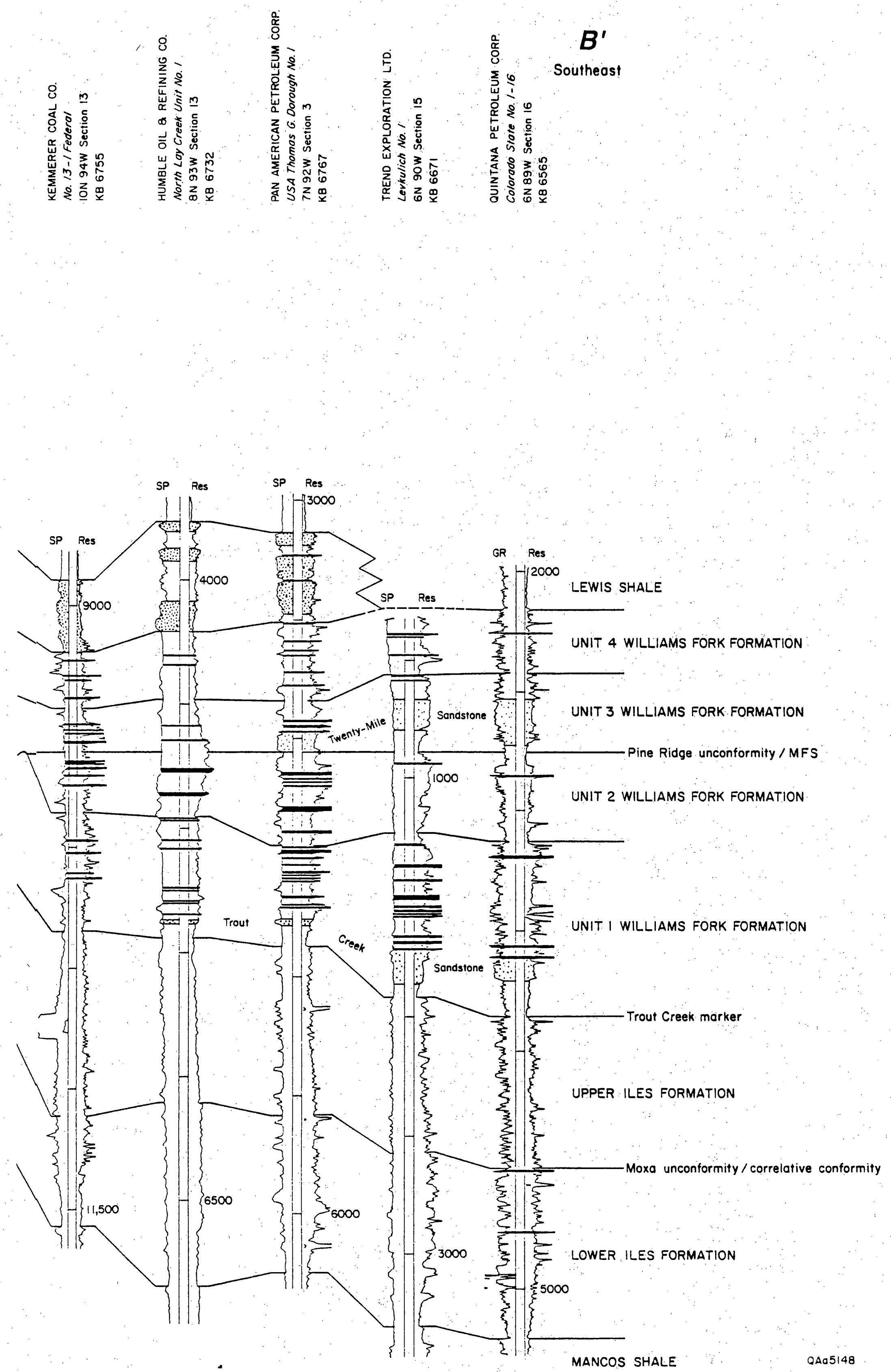


Figure 15. Northwest-southeast stratigraphic cross section B–B′, Mesaverde Group, from the west edge of the Rock Springs Uplift to the southeastern Sand Wash Basin. Line of section shown in figure 13.


B'
Southeast
KEMMERER COAL CO.
No. 13-1 Federal
10N 94W Section 13
KB 6755
HUMBLE OIL & REFINING CO.
North Lay Creek Unit No. 1
8N 93W Section 13
KB 6732
PAN AMERICAN PETROLEUM CORP.
USA Thomas G. Dorough No. 1
7N 92W Section 3
KB 6767
TREND EXPLORATION LTD.
Levkulich No. 1
6N 90W Section 15
KB 6671
QUINTANA PETROLEUM CORP.
Colorado State No. 1-16
6N 89W Section 16
KB 6565
SP
Res
GR
9000
4000
3000
2000
1000
11,500
6500
6000
3000
5000
Twenty-Mile
Sandstone
Trout
Creek
Sandstone
LEWIS SHALE
UNIT 4 WILLIAMS FORK FORMATION
UNIT 3 WILLIAMS FORK FORMATION
Pine Ridge unconformity / MFS
UNIT 2 WILLIAMS FORK FORMATION
UNIT 1 WILLIAMS FORK FORMATION
Trout Creek marker
UPPER ILES FORMATION
Moxa unconformity / correlative conformity
LOWER ILES FORMATION
MANCOS SHALE
QAa5148

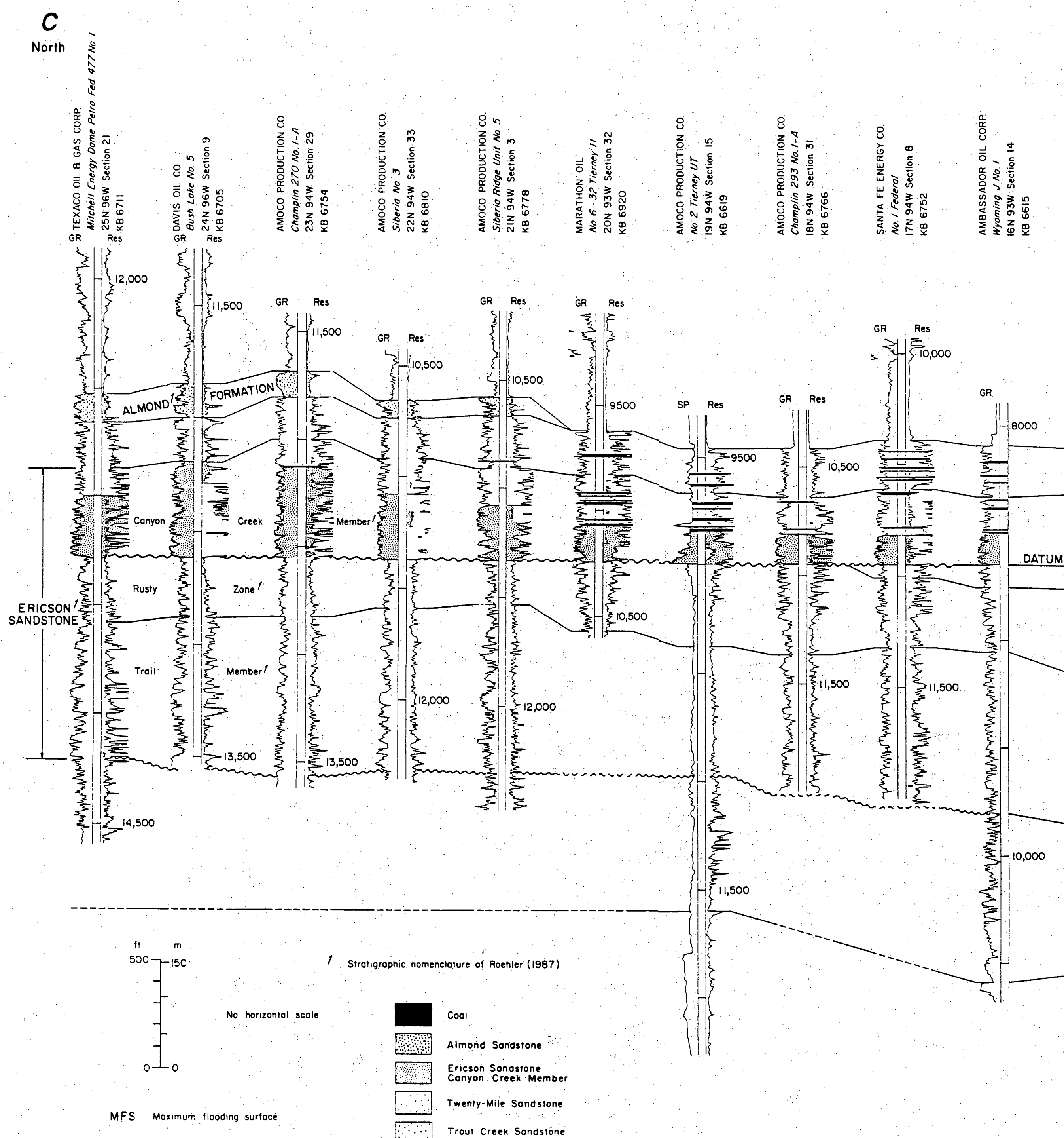
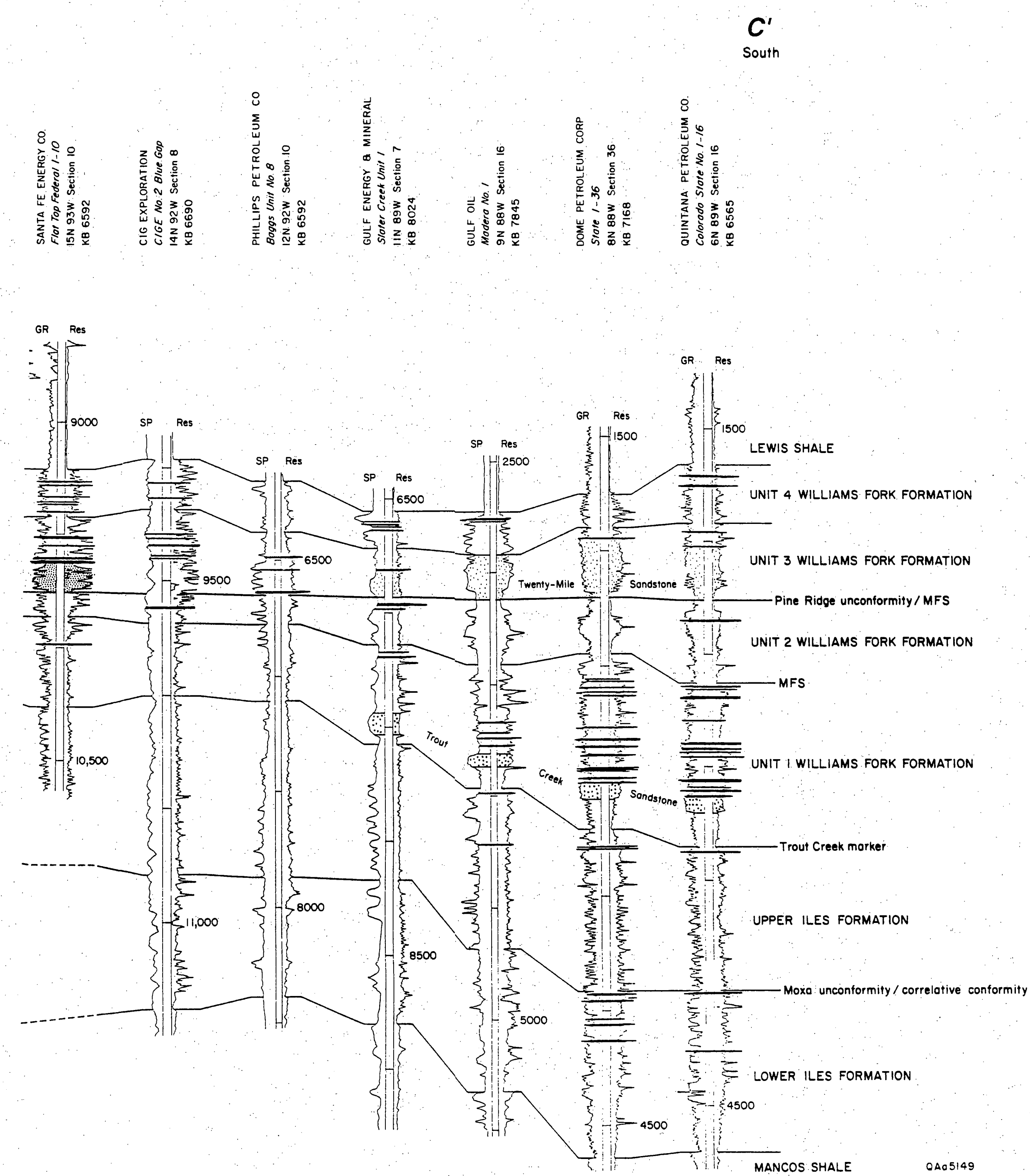


Figure 16. North-south stratigraphic cross section C–C′, Mesaverde Group, and the Great Divide, Washakie, and Sand Wash Basins. Line of section shown in figure 13.



C'
South
SANTA FE ENERGY CO.
Flat Top Federal 1-10
15N 93W Section 10
KB 6592
CIG EXPLORATION
CIGE No. 2 Blue Gap
14N 92W Section 8
KB 6690
PHILLIPS PETROLEUM CO
Baggs Unit No 8
12N 92W Section 10
KB 6592
GULF ENERGY & MINERAL
Slater Creek Unit 1
11N 89W Section 7
KB 8024
GULF OIL
Madera No. 1
9N 88W Section 16
KB 7845
DOME PETROLEUM CORP
State 1-36
8N 88W Section 36
KB 7168
QUINTANA PETROLEUM CO.
Colorado State No. 1-16
6N 89W Section 16
KB 6565
GR
Res
SP
9000
9500
10,500
11,000
6500
8000
8500
2500
5000
1500
4500
Twenty-Mile
Sandstone
Trout
Creek
Sandstone
LEWIS SHALE
UNIT 4 WILLIAMS FORK FORMATION
UNIT 3 WILLIAMS FORK FORMATION
Pine Ridge unconformity / MFS
UNIT 2 WILLIAMS FORK FORMATION
MFS
UNIT 1 WILLIAMS FORK FORMATION
Trout Creek marker
UPPER ILES FORMATION
Moxa unconformity / correlative conformity
LOWER ILES FORMATION
MANCOS SHALE
QAa5149

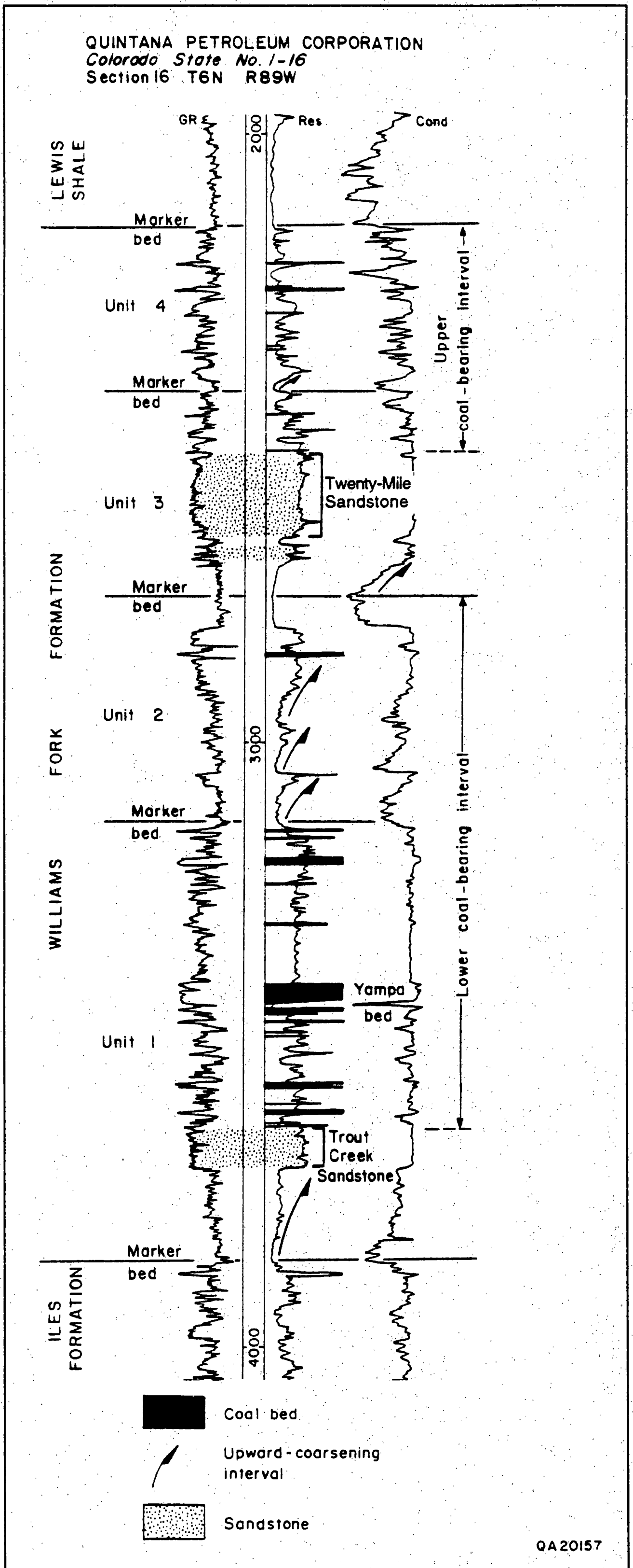


Figure 17. Genetic stratigraphy of the upper Mesaverde Group in the eastern Greater Green River Basin. Surface-bounding genetic units are defined by regionally extensive, low-resistivity shale marker beds. Modified from Hamilton (1993). Location of type log shown in figure 13.

involving similar or different rock types, mixed environments of deposition (for example, coarse clastics deposited into a floodplain or lacustrine environment), and unconformities further complicate the stratigraphy of the Fort Union Formation (Masters, 1961; Colson, 1969; Beaumont, 1979; Tyler and McMurry, 1993). To correlate the major coal-bearing horizons in the Fort Union Formation, we defined operational lithostratigraphic zones and units in the Upper Cretaceous and lower Tertiary rocks (fig. 19): the Fox Hills Sandstone, the Lance Formation, the Massive Cretaceous and Tertiary (K/T) Sandstone unit, the Fort Union Formation, and the Wasatch Formation. The Massive K/T Sandstone unit is host to a regional unconformity that separates Cretaceous from Tertiary rocks. The Massive K/T Sandstone unit intertongues with the underlying Lance Formation and the overlying fluvial Paleocene Fort Union Formation. Uplift and erosion of parts of the Mesaverde Group and Lewis Shale, Fox Hills Sandstone, and Lance Formation along the basin margins and Rock Springs Uplift resulted in an angular unconformity between the Fort Union Formation and the underlying sediments (figs. 14, 20 through 23).

Similar Upper Cretaceous and lower Tertiary lithostratigraphic zones were defined by Colson (1969), Beaumont (1979), Honey and Hettinger (1989), Honey and Roberts (1989), Hettinger and Kirschbaum (1991), and Hettinger and others (1991) in the eastern Greater Green River Basin (figs. 20 through 23). The Fox Hills Sandstone was deposited in nearshore-marine and marginal-marine environments during the final regressive phase of the Western Interior Seaway (Tyler and McMurry, 1993). Nearshore-marine and marginal-marine deposits of the Fox Hills Sandstone intertongue with offshore-marine deposits of the underlying Lewis Shale and continental deposits of the overlying Lance Formation (Gill and others, 1970). The upper contact of the Fox Hills Sandstone with the Lance Formation is placed on top of the highest regressive marine sandstone (fig. 22). Fluvial deposits of the Lance Formation conformably overlie and intertongue with the Fox Hills Sandstone (Tyler and McMurry, 1993). The formation is 800 to 1,000 ft (244 to 305 m) thick in the southeastern Greater Green River Basin (Tyler and McMurry, 1993) and 200 ft (61 m) or less along the flanks of the western Green River Basin (Moxa Arch) and the Rock Springs Uplift. In the west part of the basin and on the Rock Springs Uplift, the Lance Formation thins dramatically as a result of erosional truncation associated with the Cretaceous/Tertiary unconformity. Where present in the deeper part of the basin, the Lance Formation is characterized by multistoried channel-fill sandstone bodies and thin, interbedded shale and coal beds (Tyler and McMurry, 1993). The basal 150 to 200 ft (46 to 61 m) of the formation commonly contains from one to five lenticular

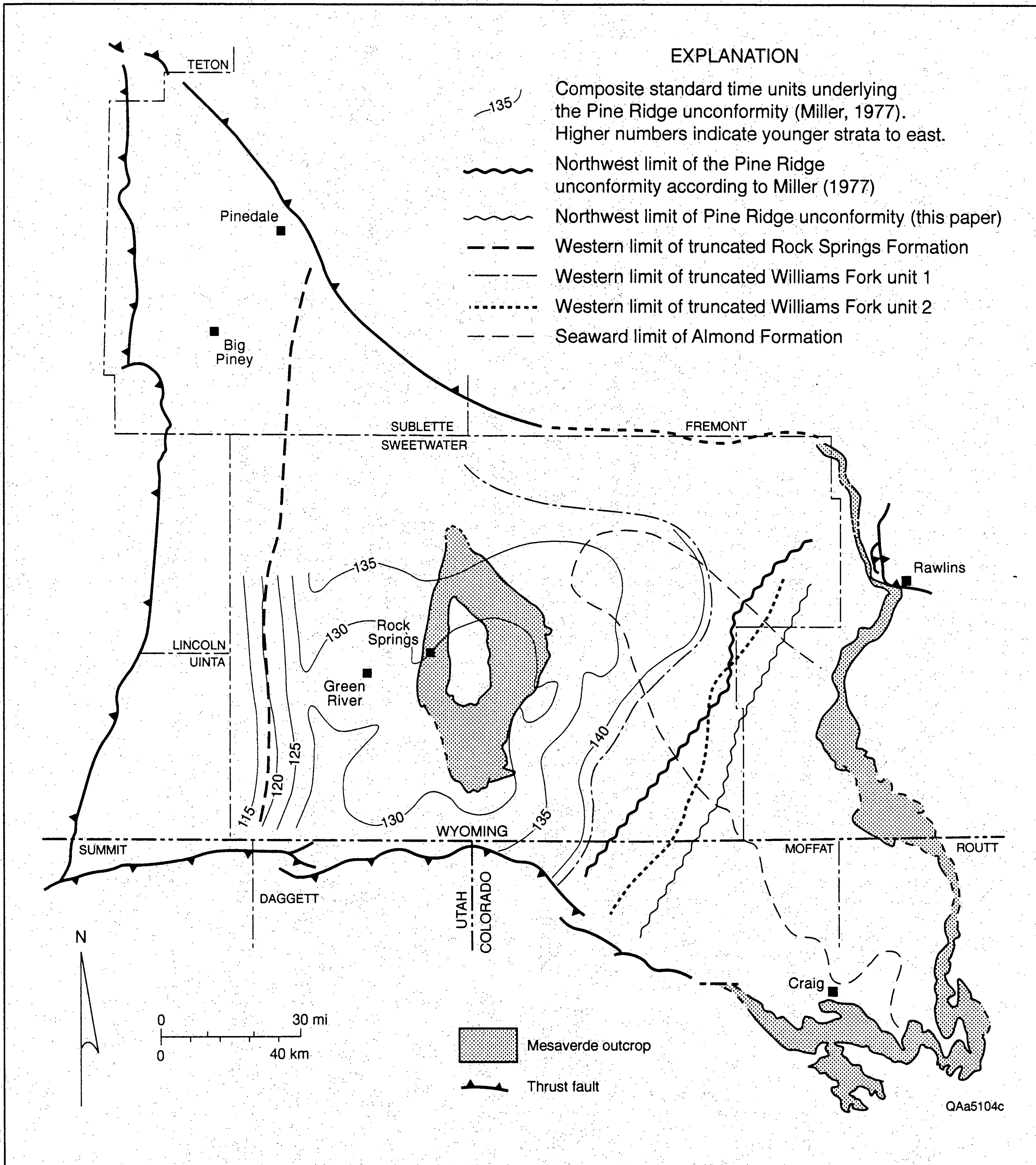


Figure 18. Plan view showing the updip (western) limits of Mesaverde shale markers and unconformities. The unbroken lines show the relative age of strata immediately underlying the Pine Ridge unconformity as defined by Miller (1977). These strata are younger (numbers increase) eastward.

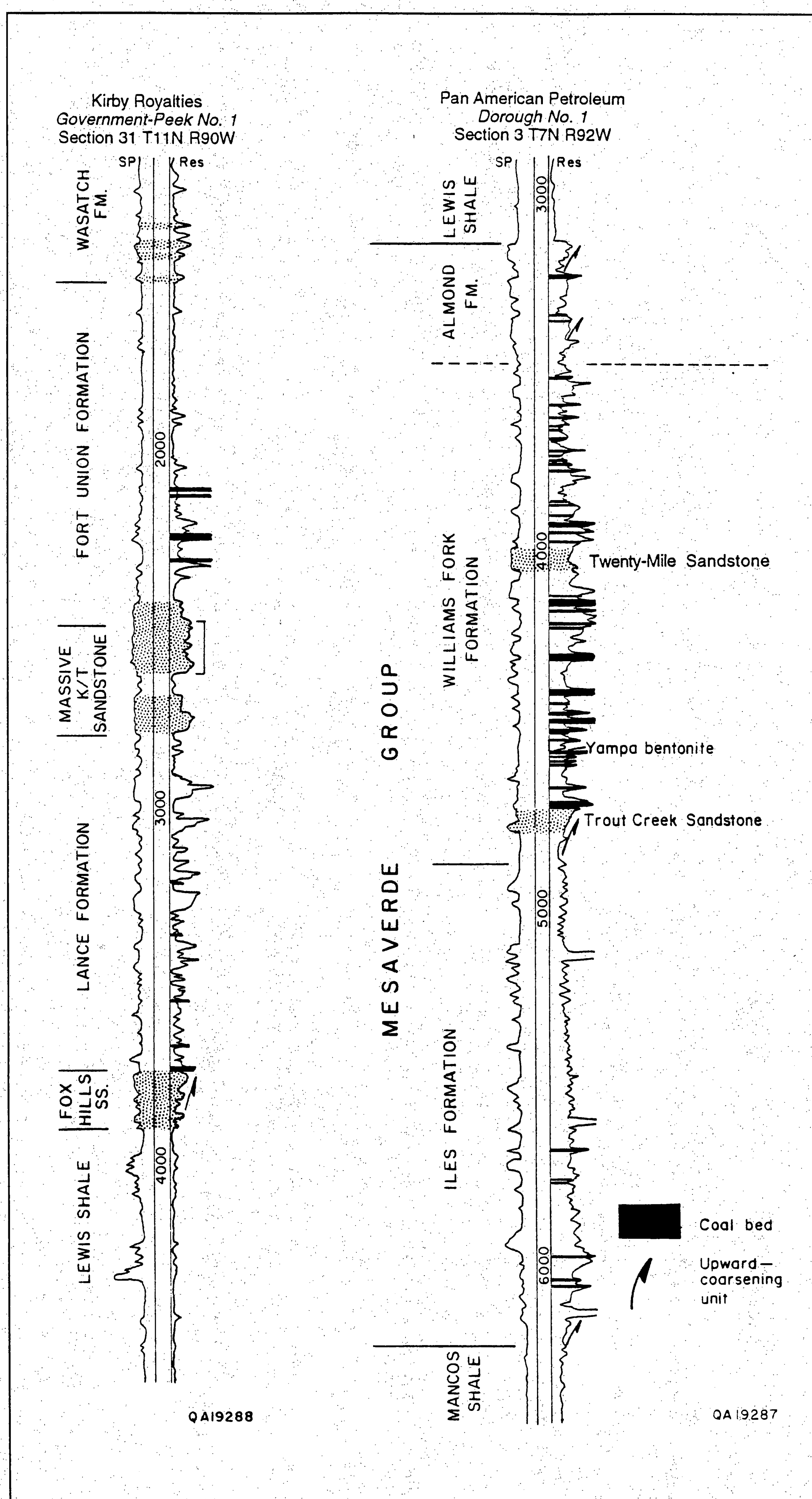


Figure 19. Type log showing location of coal and stratigraphic nomenclature of the Upper Cretaceous Mesaverde Group and Paleocene Fort Union Formation, southeastern Greater Green River Basin. Coal beds identified from density and sonic logs where available. Location of type log shown in figure 13.

coal beds 1 to 10 ft (0.3 to 3.1 m) thick (fig. 22). Locally these coal beds merge into single seams that are 15 to 20 ft (4.6 to 6.1 m) thick but laterally discontinuous. In the eastern Sand Wash Basin, a second and third coal package is locally present about 250 and 500 ft (~76 to 152 m) above the base of the formation. These packages, which contain one or two discontinuous coal beds, are minor coalbed methane targets.

An interval dominated by a thick sandstone sequence overlies and intertongues with the upper zone of the Lance Formation and is overlain by and intertongues with the lower coal-bearing unit of the Fort Union Formation (figs. 20 through 23). This sequence of rock, referred to as the Massive K/T Sandstone unit (unnamed Cretaceous and Tertiary sandstones of Hettinger and others [1991] and Ohio Creek Sandstone of Irwin [1986]), is identified on geophysical logs by its commonly great thickness (hundreds of feet) and stratigraphic position below the coal-bearing Fort Union Formation. The Massive K/T Sandstone contains a regional unconformity as manifested in an erosional surface and floral hiatus (palynomorphs) (Hettinger and others, 1991), and it may be further subdivided into lower and upper zones on the basis of the presence of this regional unconformity. The lower zone is partly laterally equivalent to some of the sandstone in the upper part of the Lance Formation (Hettinger and others, 1991). The lower zone, separated from the upper zone by the erosional surface, is commonly depicted in outcrop (eastern and southeastern Greater Green River Basin) by a distinct conglomerate horizon, representing the unconformity between Cretaceous and Tertiary rocks. Palynological evidence indicates that the lower zone is Late Cretaceous and the upper zone is Paleocene (Hettinger and others, 1991). The upper (Paleocene) sandstone overlying the basal conglomerate horizon is as much as 220 ft (67 m) thick in the eastern Greater Green River Basin and consists of multistoried sandstone sequences (figs. 21 through 23). Interbedded with the sandstone bodies are a few thin (<10-ft-thick [<3.1-m]) shales. To the west, the upper zone is thinner and contains sandstones that intertongue with shale and coal beds that are equivalent to the basal part of the lower coal-bearing unit of the Fort Union Formation.

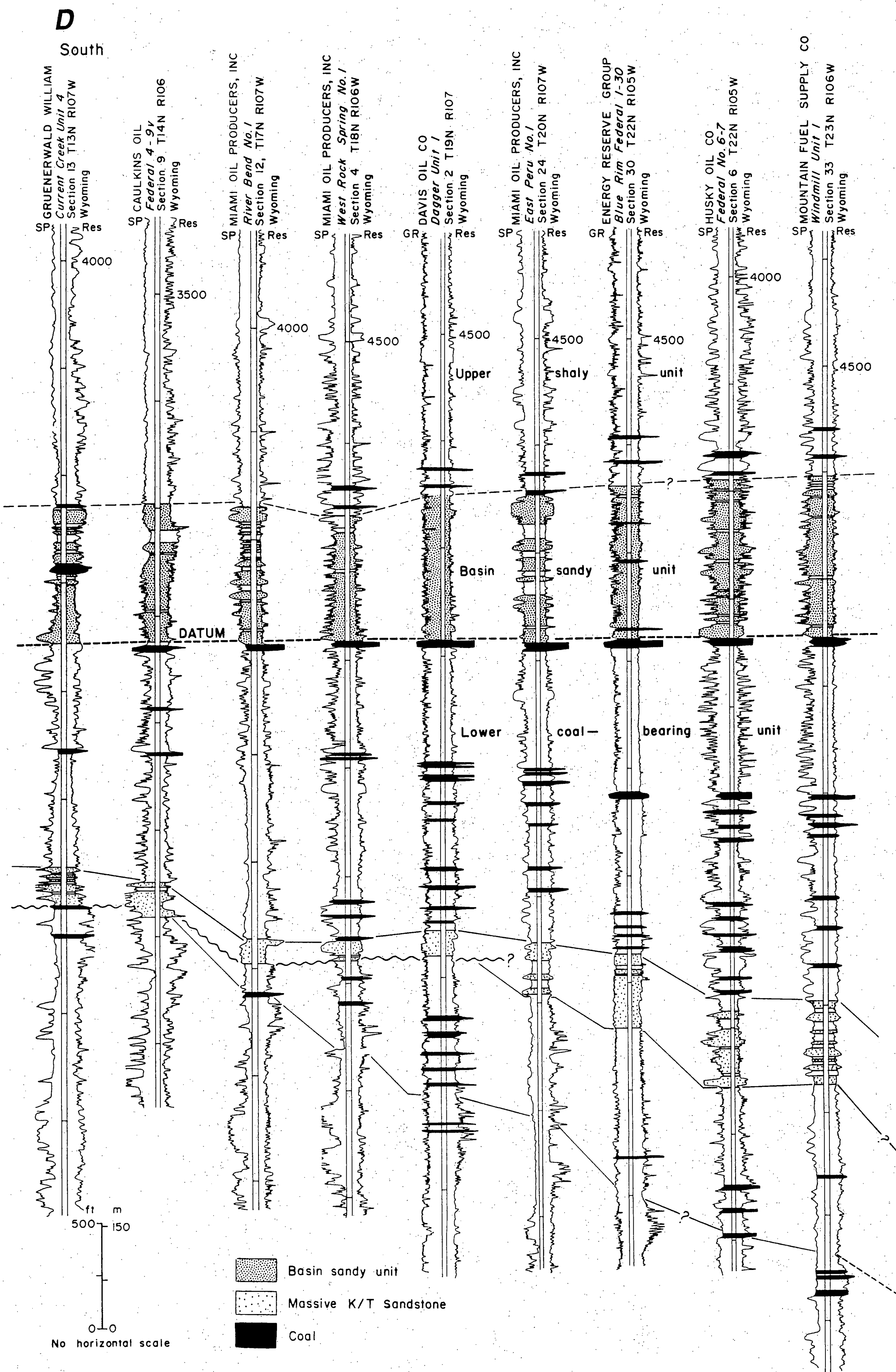
The operational base of the coal-bearing Paleocene Fort Union Formation is placed on top of the Massive K/T Sandstone unit. The Fort Union Formation may be operationally subdivided into lower coal-bearing, gray-green mudstone, basin-sandy, and upper shaly units (Tyler and McMurry, 1993) (figs. 20, 21, 22, and 23). Although in the southeastern Greater Green River Basin, the lower coal-bearing unit is overlain by the noncoal gray-green mudstone, basin-sandy, and upper shaly units (fig. 23), it is overlain only by the basin-sandy and upper shaly units in the western and northeastern Greater Green River Basin (figs. 21 and 23). Regionally the Fort Union Formation, as defined here, thickens to the north and west from 1,300 ft (396 m) in the Sand Wash Basin (T8N, R91W) to between 3,000 and 4,000 ft (914 and 1,219 m) in the Washakie and Great Divide Basins (T20N, R91W) and then thins farther west to between 2,000 and 2,400 ft (609.6 and 731.5 m) on the Rock Springs Uplift (T19N, R98W) and to between 3,000 and 3,400 ft (914 and 1,036 m) on the Moxa Arch in the western Green River Basin (T25N, R111W). Thickness variations of the Fort Union Formation reflects its depositional setting, periods of nondeposition, or both, and erosion along the Eocene–Paleocene (Wasatch Formation–Fort Union Formation) unconformity. The Paleocene Fort Union Formation is considered a major coal and coalbed methane target in the Greater Green River Basin. Because the Wasatch Formation and overlying strata are minor coal-bearing and coalbed methane targets, they are not discussed in great detail in this report.

Upper Cretaceous Coal-Bearing Units

The Rock Springs and Williams Fork Formations are the major coal-bearing units in the Upper Cretaceous Mesaverde Group, whereas the Frontier, Iles, Almond, and Lance Formations are minor coal-bearing units. The coal-bearing strata are less than 6,000 ft (<1,892 m) deep on the north edge of the Moxa Arch, on the north and east flanks of the Rock Springs Uplift, and along the east margin of the Sand Wash, Washakie, and Great Divide Basins (fig. 24). Structural dips are steep from the outcrop belt to the basin centers, and the coal-bearing strata are more than 18,000 ft (>5,486 m) deep in the Washakie and Great Divide Basins and 13,000 ft (3,962 m) in the Sand Wash Basin. In the west part of the Greater Green River Basin, depths of coal-bearing rocks vary greatly. The Mesaverde Group is less than 2,000 ft (<600 m) deep on the La Barge Platform near the edge of the 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 11,000 ft (>3,353 m) deep in the Green River Basin, 15 mi (24 km) southwest off the south flank of the Rock Springs Uplift (figs. 2 and 4).

Frontier Formation

The Frontier Formation, separated from the overlying Mesaverde Group by the marine Hilliard–Baxter 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



D
South
GRUENERWALD WILLIAM
Current Creek Unit 4
Section 13 T13N R107W
Wyoming
CAULKINS OIL
Federal 4-9v
Section 9 T14N R106
Wyoming
MIAMI OIL PRODUCERS, INC
River Bend No.1
Section 12, T17N R107W
Wyoming
MIAMI OIL PRODUCERS, INC
West Rock Spring No.1
Section 4 T18N R106W
Wyoming
DAVIS OIL CO
Dagger Unit 1
Section 2 T19N R107
Wyoming
MIAMI OIL PRODUCERS, INC
East Peru No.1
Section 24 T20N R107W
Wyoming
ENERGY RESERVE GROUP
Blue Rim Federal 1-30
Section 30 T22N R105W
Wyoming
HUSKY OIL CO
Federal No.6-7
Section 6 T22N R105W
Wyoming
MOUNTAIN FUEL SUPPLY CO
Windmill Unit 1
Section 33 T23N R106W
Wyoming
SP
Res
GR
4000
3500
4500
Upper shaly unit
Basin sandy unit
DATUM
Lower coal-bearing unit
?
ft m
500 150
0 0
No horizontal scale
Basin sandy unit
Massive K/T Sandstone
Coal

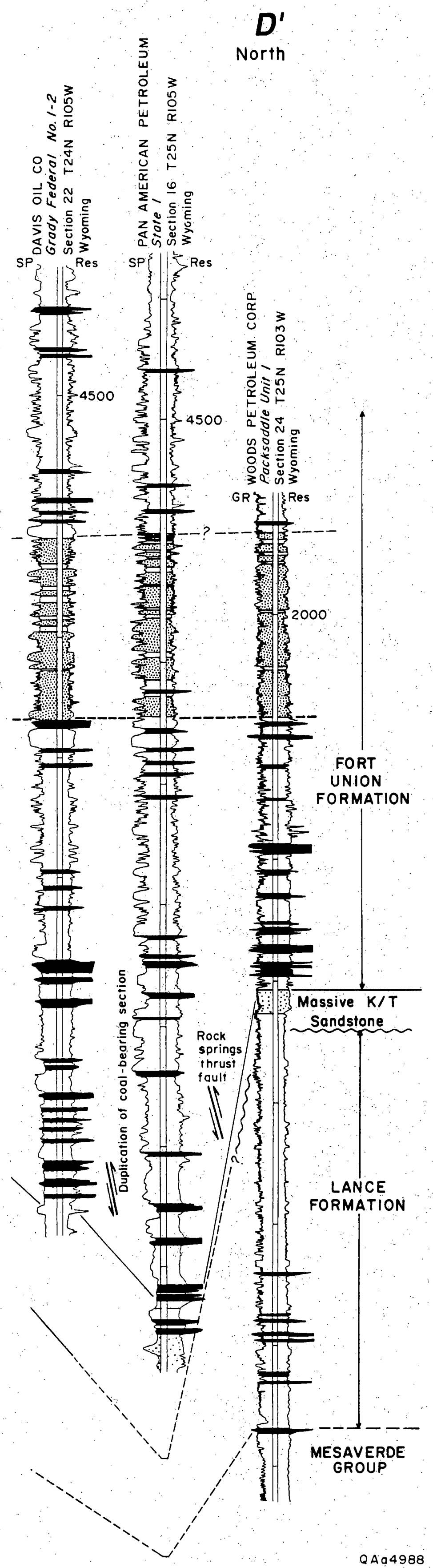
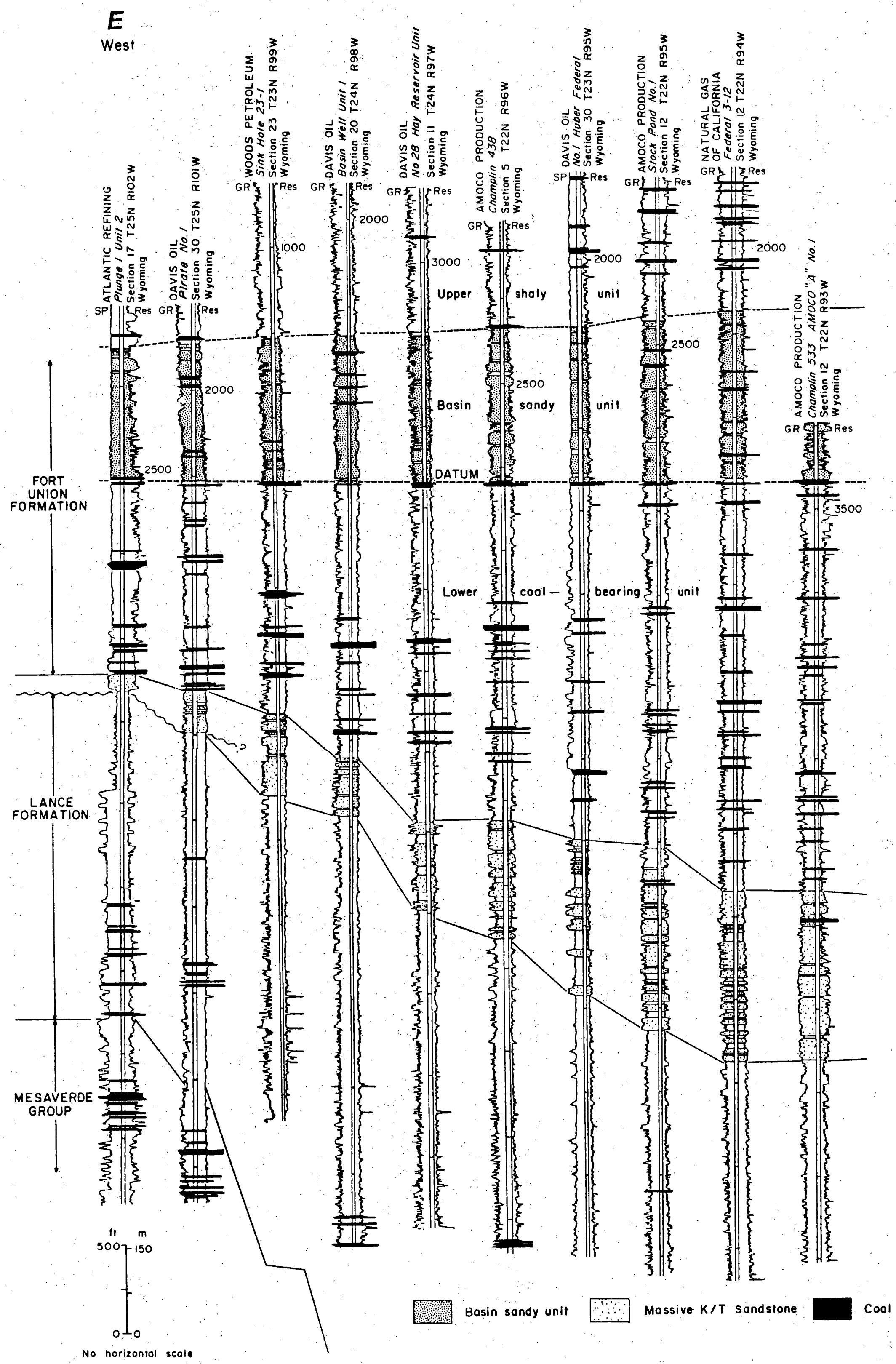


Figure 20. South-north stratigraphic cross section D–D′, Green River Basin, Greater Green River Basin, illustrating operationally defined stratigraphic units. Thickest and most continuous Paleocene Fort Union Formation coal beds lie in the deepest part of the basins above thickest Massive K/T Sandstone development. Line of section shown in figure 13.



E
West
ATLANTIC REFINING
Plunge I Unit 2
Section 17 T25N R102W
Wyoming
DAVIS OIL
Pirate No. I
Section 30 T25N R101W
Wyoming
WOODS PETROLEUM
Sink Hole 23-1
Section 23 T23N R99W
Wyoming
DAVIS OIL
Basin Well Unit I
Section 20 T24N R98W
Wyoming
DAVIS OIL
No 28 Hay Reservoir Unit
Section 11 T24N R97W
Wyoming
AMOCO PRODUCTION
Champlin 438
Section 5 T22N R96W
Wyoming
DAVIS OIL
No. I Huber Federal
Section 30 T23N R95W
Wyoming
AMOCO PRODUCTION
Stock Pond No. I
Section 12 T22N R95W
Wyoming
NATURAL GAS
OF CALIFORNIA
Federal 3-12
Section 12 T22N R94W
Wyoming
AMOCO PRODUCTION
Champlin 533 AMOCO "A" No. I
Section 12 T22N R93W
Wyoming
SP
GR
Res
1000
2000
2500
3000
3500
Upper shaly unit
Basin sandy unit
DATUM
Lower coal-bearing unit
FORT UNION FORMATION
LANCE FORMATION
MESAVERDE GROUP
ft m
500 150
0 0
No horizontal scale
Basin sandy unit
Massive K/T Sandstone
Coal

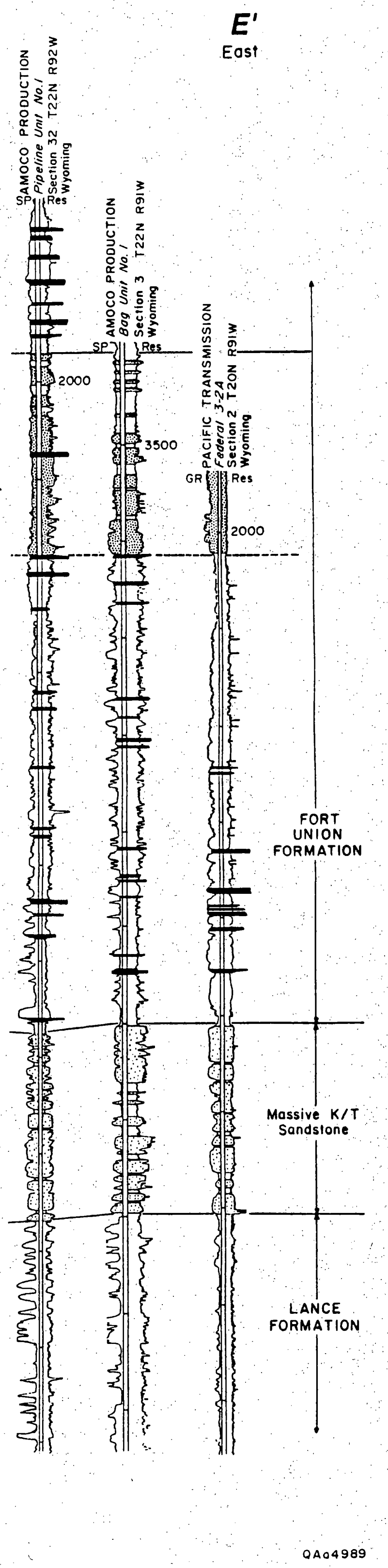
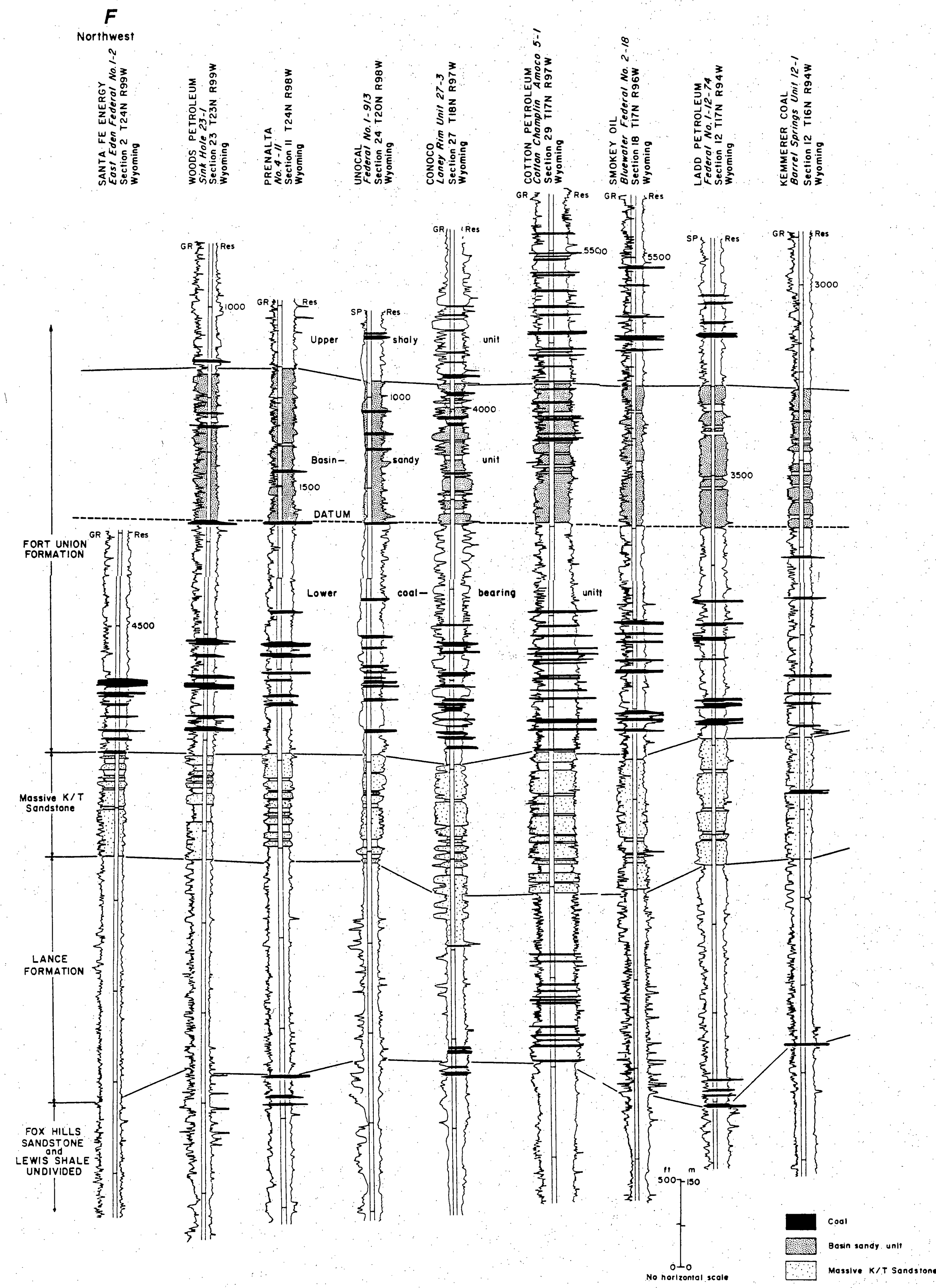


Figure 21. West-east stratigraphic cross section E–E′, Great Divide Basin, Greater Green River Basin, illustrating operationally defined stratigraphic units. Thickest and most continuous Paleocene Fort Union Formation coal beds lie in the eastern Sand Wash Basin above thickest Massive K/T Sandstone development. Line of section shown in figure 13.


F
Northwest
SANTA FE ENERGY
East Eden Federal No. 1-2
Section 2 T24N R99W
Wyoming
WOODS PETROLEUM
Sink Hole 23-1
Section 23 T23N R99W
Wyoming
PRENALTA
No. 4-11
Section 11 T24N R98W
Wyoming
UNOCAL
Federal No. 1-9/3
Section 24 T20N R98W
Wyoming
CONOCO
Laney Rim Unit 27-3
Section 27 T18N R97W
Wyoming
COTTON PETROLEUM
Cotton Champlin Amoco 5-1
Section 29 T17N R97W
Wyoming
SMOKEY OIL
Bluewater Federal No. 2-18
Section 18 T17N R96W
Wyoming
LADD PETROLEUM
Federal No. 1-12-74
Section 12 T17N R94W
Wyoming
KEMMERER COAL
Barrel Springs Unit 12-1
Section 12 T16N R94W
Wyoming
GR
Res
SP
1000
1500
4500
4000
5500
3000
3500
Upper shaly unit
Basin-sandy unit
DATUM
Lower coal-bearing unit
FORT UNION FORMATION
Massive K/T Sandstone
LANCE FORMATION
FOX HILLS SANDSTONE and LEWIS SHALE UNDIVIDED
ft
m
500
150
0
0
No horizontal scale
Coal
Basin sandy unit
Massive K/T Sandstone

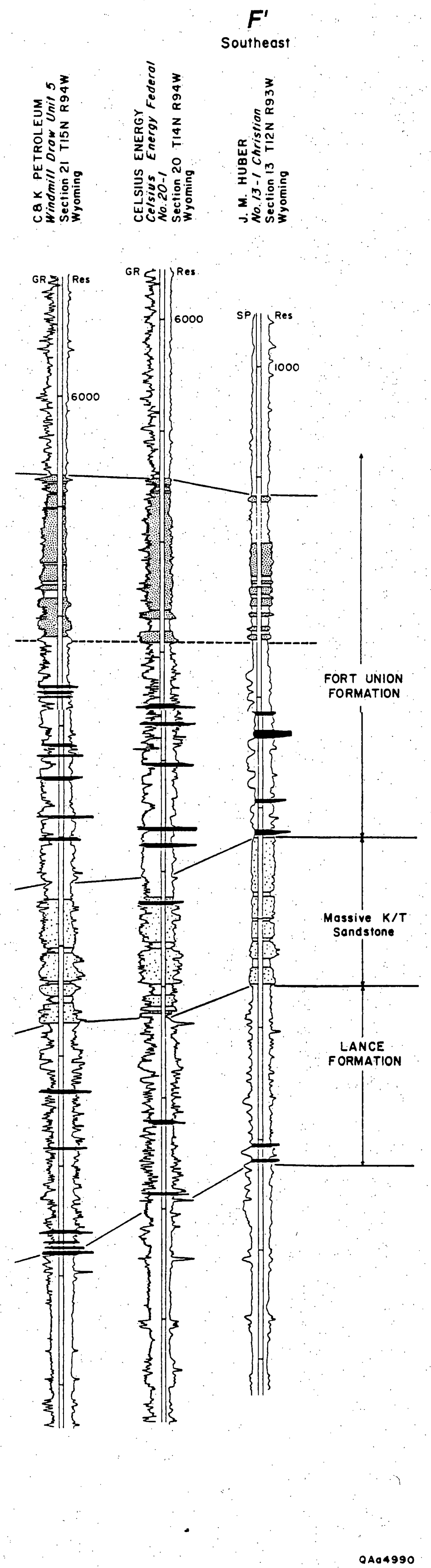


Figure 22. Northwest-southeast stratigraphic cross section F–F′, Great Divide and Washakie Basins, Greater Green River Basin, illustrating operationally defined stratigraphic units. Thickest and most continuous Paleocene Fort Union Formation coal beds lie in the deepest parts of the basins above thickest Massive K/T Sandstone development. Line of section shown in figure 13.

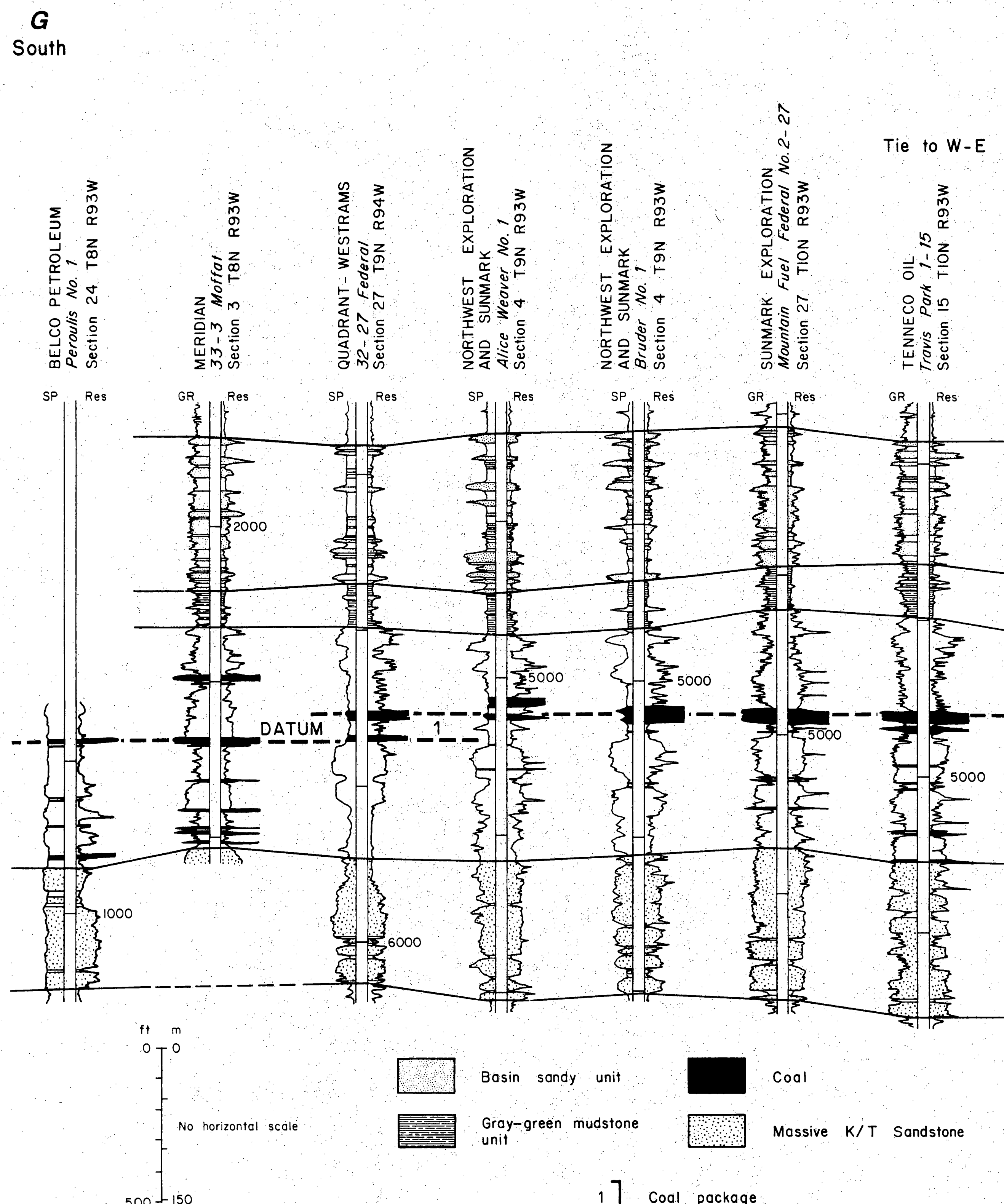
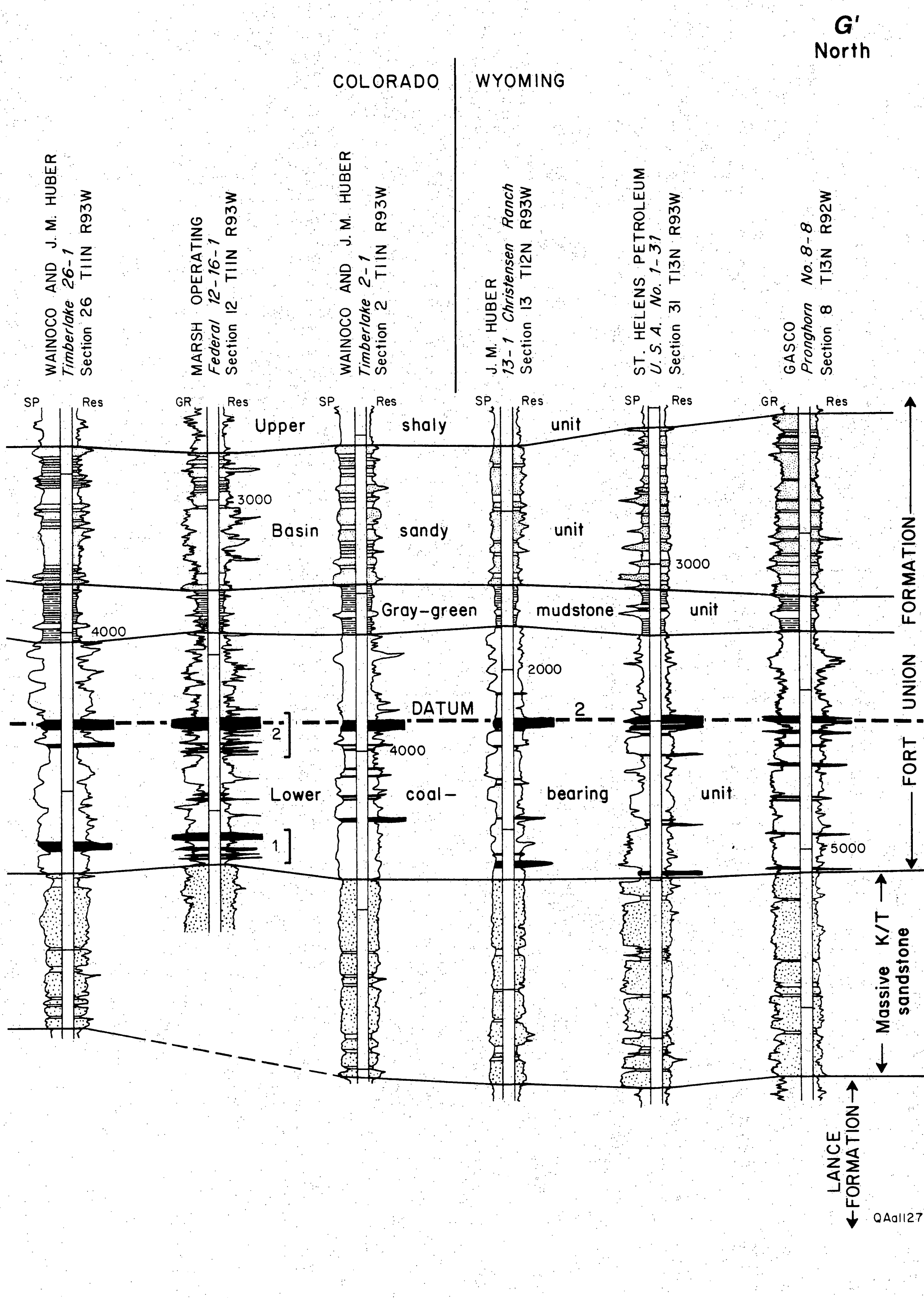


Figure 23. South-north stratigraphic cross section G–G′, Sand Wash Basin, Greater Green River Basin, illustrating operationally defined stratigraphic units. Paleocene Fort Union Formation coal beds lie in the eastern Sand Wash Basin in the lower coal-bearing unit. Coal packages 1 and 2 are best developed above thick fluvial sandstones. Line of section shown in figure 13.


G'
North
COLORADO
WYOMING
WAINOCO AND J. M. HUBER
Timberlake 26-1
Section 26 T11N R93W
MARSH OPERATING
Federal 12-16-1
Section 12 T11N R93W
WAINOCO AND J. M. HUBER
Timberlake 2-1
Section 2 T11N R93W
J. M. HUBER
13-1 Christensen Ranch
Section 13 T12N R93W
ST. HELENS PETROLEUM
U. S. A. No. 1-31
Section 31 T13N R93W
GASCO
Pronghorn No. 8-8
Section 8 T13N R92W
SP
Res
GR
Upper shaly unit
Basin sandy unit
Gray-green mudstone unit
DATUM 2
Lower coal-bearing unit
3000
4000
2000
5000
2
1
FORT UNION FORMATION
Massive K/T sandstone
LANCE FORMATION
QAa1127

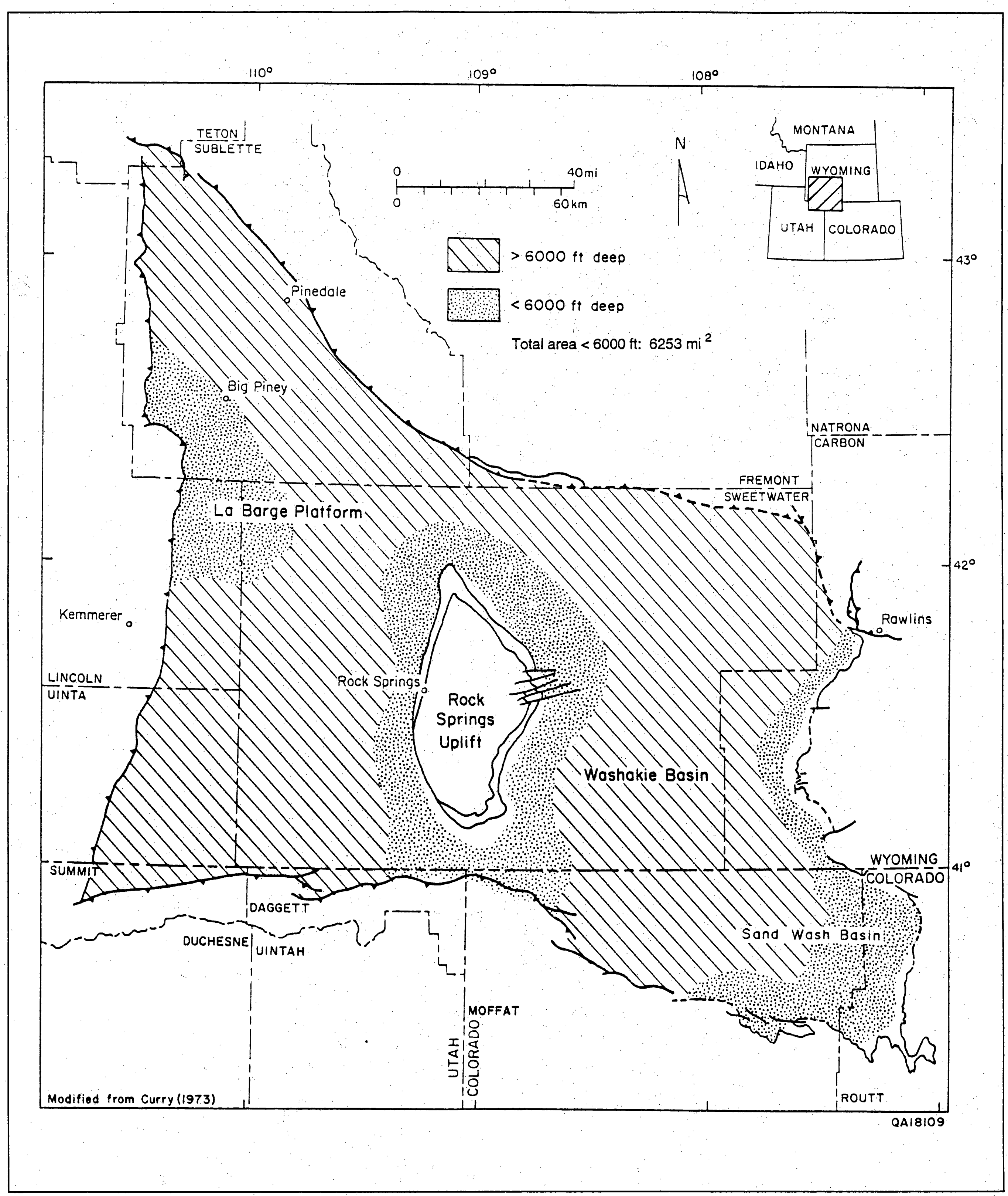


Figure 24. Depth to top of the Mesaverde Group, Greater Green River Basin. Modified from Curry (1973) and Lickus and Law (1988).

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) east of 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). Frontier Formation coal beds are considered minor coalbed methane targets in the western Greater Green River Basin.

Rock Springs Formation

The Rock Springs Formation is an important coal-bearing unit and potential coalbed methane target in the northwest part of the Great Divide Basin. Regional coal thickness trends indicate that net coal is at a maximum along an 8.5-mi-wide (13.4-km) zone that extends northeast from T22N, R102W, where it averages 100 ft (33 m) in thickness (fig. 25). Although absence of well control makes defining coal distribution trends to the northwest difficult, the coals thin gradually in that direction and tend to be oriented northwesterly. The coals are absent west of R108–109W because the Rock Springs Formation is eroded by the Moxa unconformity. To the southeast, the coals thin rapidly and are lost beyond a northeast-trending line from T21N, R101W, to T26N, R95W. Levey (1985) investigated the geologic controls on Rock Springs coal distribution along the outcrop and in mine sections around the west, north, and northeast flanks of the Rock Springs Uplift. He interpreted the Rock Springs Formation as a wave-dominated delta system and described extensive coal deposits that developed landward of, and on top of, cuspate to arcuate delta-front sheet sandstones. He also described less extensive upper delta-plain-fluvial coals in the nonmarine components of the Rock Springs Formation.

The subsurface distribution of the coals (fig. 25), similar to that in the outcrop belt, indicates a comparable depositional setting. The northeast-oriented trend of thick coals accumulated on the coastal plain landward of the shoreline sandstones, and the rapid southeast thinning of the coals coincides with the shoreline position. Northwesterly reorientation of the coals landward suggests that the peats there accumulated in dip-oriented trends between fluvial-delta distributaries.

Local, detailed studies of the Rock Springs Formation indicate that at least 12 coal beds, which average 6 ft (1.8 m) in thickness, are present (McCord, 1984). Levey (1985) grouped these coal beds into three types (A, B, and C) and related them to specific depositional environments (fig. 26). The thickest, type-A coal beds, can be as much as 22 ft (6.7 m) thick. Extending for 500 mi^2 (1,300 km^2) or more, they overlie delta-front sandstones. Levey (1985) attributed these coals to a lower delta-plain setting. Type-B coal beds, more variable in thickness and less continuous than type-A and having an area of 50 to 200 mi^2 (130 to 520 km^2), 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 areal extent of only 50 mi^2 (130 km^2).

Sandstone distribution in the Rock Springs Formation is highly variable. Delta-front (shoreline) sandstones, which extend northeastward in the basin, 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. 27). Rock Springs distributary-channel sandstones are flanked by thin (2- to 15-ft-thick [0.6- to 4.5-m]) crevasse splay sandstones, which were platforms where peat accumulated locally and which partly controlled coalbed continuity (Tyler and others, 1991). Recent exploration for coalbed methane in the Rock Springs Formation (Triton Oil and Gas Exploration) indicates geologic and reservoir conditions favorable for commercial development (Kelso and others, 1991).

Iles Formation

The Iles Formation is a minor coal-bearing unit in the Greater Green River Basin. Although the maximum net coal thickness of 32 ft (9.8 m) occurs in the easternmost part of the Great Divide Basin (fig. 28), net coal thickness elsewhere is typically less than 15 ft (<4.5 m). No apparent trends to net coal thickness exist regionally, although Boyles and Scott (1981) documented a northeastward trend to the thickest seams (individual seams as much as 10 ft [3 m] thick) in outcrops to the south of Craig, Colorado. These coals are oriented parallel to the paleoshoreline. Other, thinner (3- to 6-ft-thick [0.9- to 1.8-m]) Iles coal beds at these outcrops overlie thin (<5-ft-thick [<1.5-m]) crevasse splay sandstones that were platforms where peat accumulated locally in interchannel swamps (W. A. Ambrose, Bureau of Economic Geology, personal communication, 1993).

Boyles and Scott (1981) interpreted progradational shoreface sandstones at the base of the Iles Formation in the outcrops south of Craig, and similar progradational sandstone units are present in the subsurface. The main body of the Iles Formation, however, displays aggradational log facies on gamma-ray and SP logs that are interpreted as interbedded channel sandstones and floodplain deposits of a mixed-load fluvial system. The channel sandstones vary from 5 to 35 ft (1.5 to 10.6 m)

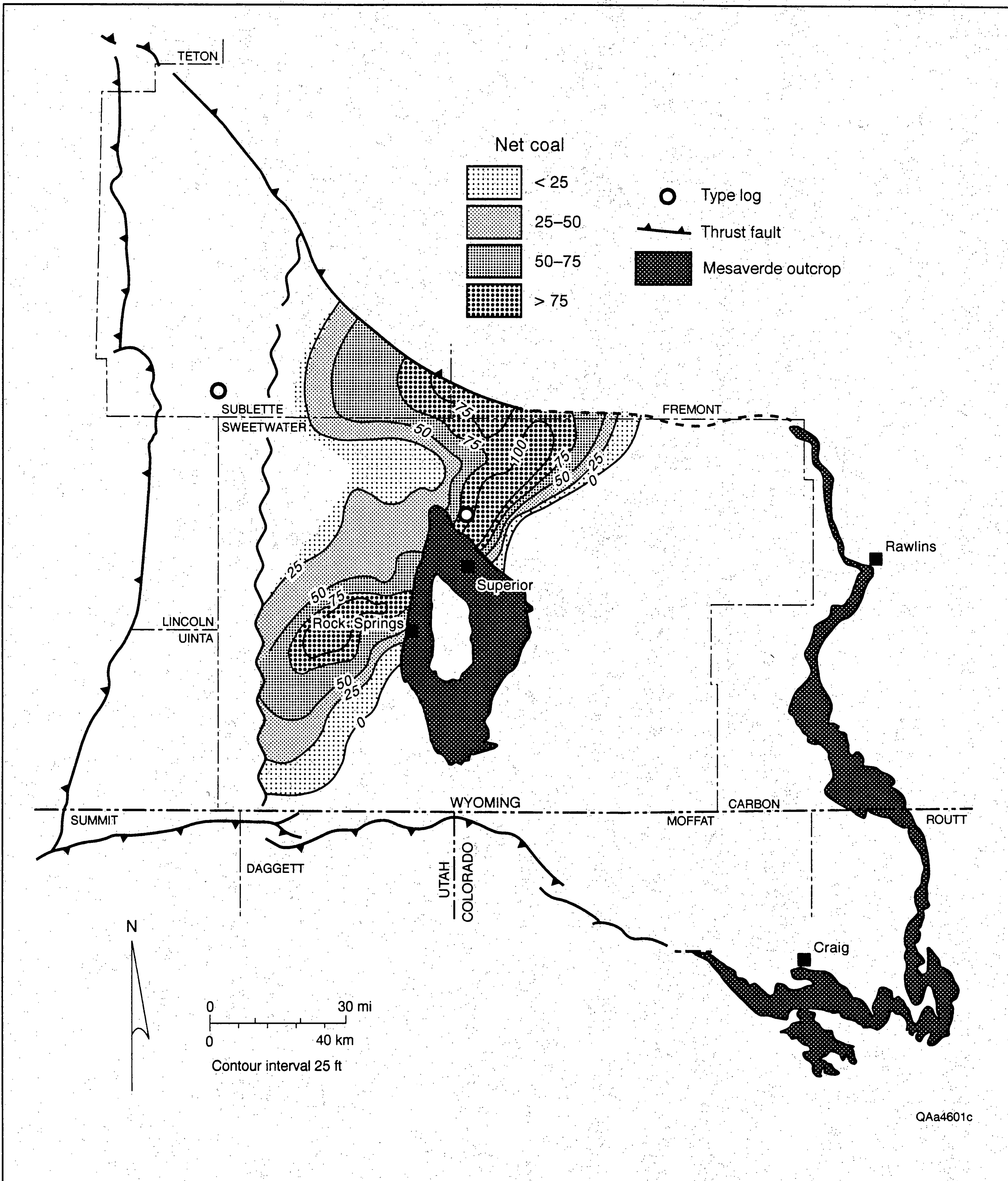
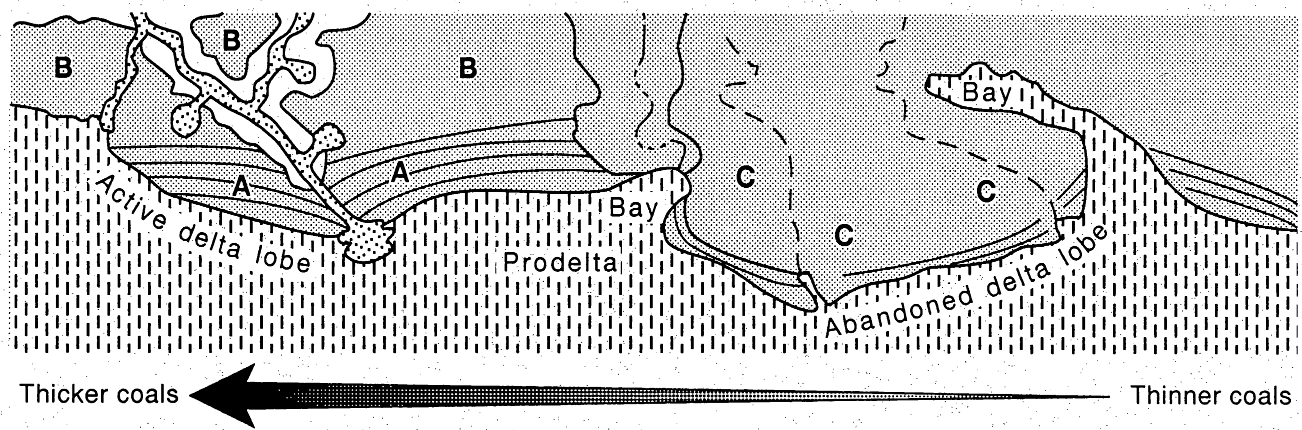


Figure 25. Net-coal-thickness map, Rock Springs Formation. Thickest net coal occurs in a strike-oriented (northeast) trend across the Rock Springs Uplift. The coals thin abruptly to the southeast, coincident with the paleoshoreline.



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 mi² (>1300 km²)	Variable areal extent 50 – 250 mi² (130 – 650 km²)	Medium areal extent 50 mi² (130 km²)
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.

QA16862c

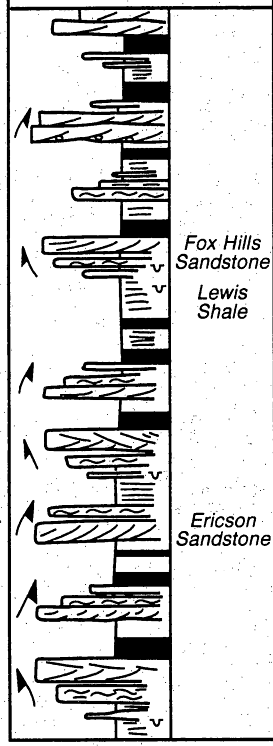
Figure 26. Depositional setting of three types of coal beds in the Rock Springs Formation, Rock Springs Uplift. Modified from Levey (1985).

in thickness and are characterized by blocky electric log patterns having upward-fining tops. Interbedded, fine-grained floodplain deposits, as much as 80 ft (24.4 m) thick, display slightly serrate log patterns. The Iles Formation is a minor coal-bearing and coalbed methane target.

Williams Fork Formation

The thickest and most extensive of the Upper Cretaceous Greater Green River Basin coals, which occur in the Williams Fork Formation in the east half of the Sand Wash Basin, are the Greater Green River Basin's prime coalbed methane targets. The maximum net coal thickness of 220 ft (67 m) is contained in as many as 40 coal beds, and individual coalbed thickness can range from 20 to 30 ft (6 to 9 m) (fig. 29). Net coal thickness in the eastern Sand Wash Basin is typically as much as 100 ft thick (30 m) (fig. 29). The coals, thinning gradually westward, are from 25 to 55 ft (7.6 to 16.7 m) thick in the west half of the Sand Wash Basin. The coals thin substantially north of the Colorado–Wyoming border, net coal thickness in the Washakie Basin averaging 30 ft (9.1 m) and 15 ft (4.5 m) in the Great Divide. In local areas in the latter two subbasins, net coal thickness exceeds 50 ft (15 m). In the southeast part of the Washakie Basin, net coal thickness averages 70 ft (21.3 m) over a six-township area centered on T14N, R92W (fig. 29). In the Great Divide Basin, net coal thickness exceeds 50 ft (15 m) in T25 26N, R103–99W, and in T20–21N, R92–90W. The Williams Fork coals, from 10 to 20 ft (3.1 to 6.2 m) thick west of the Rock Springs Uplift (fig. 29), are absent west of R109W because of postdepositional erosion associated with the Pine Ridge unconformity. The unconformity eroded most deeply along the Moxa Arch (R111–113W), where Ericson Sandstone facies lie directly on the Hilliard Shale (fig. 30).

Previous workers identified wave-dominated deltaic and fluvial deposits in the Williams Fork Formation (Boyles and Scott, 1981; Siepman, 1985) and thought that the wave-dominated deltaic sandstones provided platforms for peat to accumulate (Siepman, 1985). In this study, we identify a northwesterly gradation in the Williams Fork Formation from linear shoreline systems



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
FORT UNION FORMATION (Fluvial)	10 to 20	40	>80	5 to 10	Moderate: most continuous coal beds above and on flanks of channel sandstone	20 to 40	>60	Good: numerous intermontane channel-fill sandstone	Thickest, most continuous coal beds associated with channel-fill sandstone
LANCE FORMATION (Delta plain)	5	8 to 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
ALMOND FORMATION (Coastal plain, wave-dominated shoreline)	3	8 to 12	25 or less	6 or less	Good along strike (north-northeast); moderate along dip (northwest-southeast)	50 to 60	100	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.
ROCK SPRINGS FORMATION (Wave-modified delta)	10	14 to 22	110 or less	12 or less	Continuous, north-northeast-trending delta-front coal beds; delta-plain coal beds pinch out over thousands of feet	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

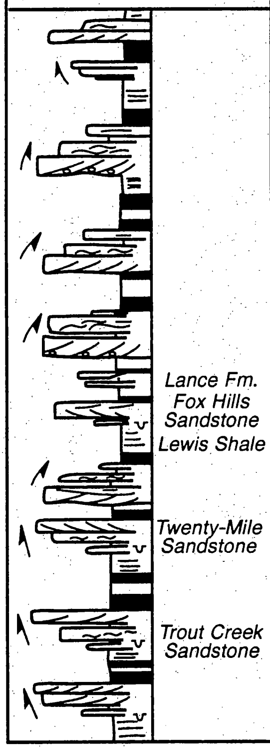
∘∘ Clasts — Upward coarsening — Planar bedding — Ripples
v Burrows — Upward fining — Crossbedding — Coal

QA16954c

Figure 27. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units at the Rock Springs Uplift, Greater Green River Basin.

(in the southeast Sand Wash Basin) to coastal-plain systems (in the central Sand Wash and southeast Washakie Basins) that in turn grade to an alluvial piedmont (over the west half of the Sand Wash and Washakie Basins and most of the Great Divide Basin; fig. 29). Several depositional cycles within this general framework cause the location of the shoreline, coastal-plain, and alluvial piedmont systems to fluctuate through time. In the Sand Wash Basin area, detailed mapping of sandstone distribution and coal occurrence of the four Williams Fork genetic units provides depositional architecture models for extrapolating to other parts of the Greater Green River Basin and allowing investigation of the geologic controls on peat accumulation and preservation as coal.

The first genetic depositional sequence, unit 1, is a clastic wedge that extended coal-bearing coastal-plain deposits beyond the present-day structural basin margin. Three depositional systems have been identified in the unit (Hamilton, 1993). A linear shoreline system dominated the easternmost part of the basin and was backed landward by a coastal-plain system, which in turn graded westward into an alluvial-plain system (fig. 31). Units 2 and 3 are clastic wedges displaying a similar arrangement of depositional systems (figs. 32, 33), but these units did not prograde as far basinward. Unit 4 deposition differs markedly from that of the underlying units; it was dominated by a low- to moderate-sinuosity mixed-load fluvial system oriented northwest-southeast (fig. 34).



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)	<5	5 to 10	—	—	Discontinuous: coal beds extend 2–5 miles between fluvial complexes	50?	—	Discontinuous, lenticular channel-fill sandstone	Similar to Fort Union Formation
FORT UNION FORMATION (Fluvial)	20	15 to 40	90 or less	12 or less	Coal beds continuous along dip (north); discontinuous along strike	35 to 70	—	Continuous; channel-fill sandstone 1,000–2,000 ft wide	Coal beds occur above and on flanks of intermontane channel-fill sandstones; upper Fort Union coal beds commonly eroded
WILLIAMS FORK FORMATION (Fluvial-dominated, wave-modified delta)	10	30	100	40 or less	Coal beds continuous along strike (northeast); discontinuous along dip (northwest)	50	1,000	Continuous shoreline sandstone; discontinuous distributary-channel sandstone	Thickest coal beds overlie shoreline sandstone; thinner, discontinuous coal beds split and interfinger with distrib.- channel sandstones
ILES FORMATION (Wave-dominated shoreline)	<5	5 to 10	32	—	Continuous along strike (northeast)	20 to 40	90 or less	Blanket shoreline sandstone; thin, discontinuous crevasse splay sandstone	Thin coal beds overlie shoreface and crevasse splay sandstones

SEDIMENTARY STRUCTURES AND ROCK TYPES

Clasts; Burrows; Upward coarsening; Upward fining; Planar bedding; Crossbedding; Ripples; Coal

QA16955c

Figure 28. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in the Sand Wash and Washakie Basins, Greater Green River Basin.

Units 1 and 2 contain the thickest, most laterally extensive coals (figs. 35, 36), and the northeast-southwest alignment of coal-seam thickness trends is pronounced. The coals are thickest near Craig, where net coal thickness averages 90 ft (27.4 m) and 40 ft (12.2 m) in units 1 and 2, respectively. Unit 3 coals are thickest northwest of Craig (average 30 ft [9.2 m]) and north of Baggs (average 40 ft [12.2 m]), and they display a similar northeast-southwest orientation, although a strong northwest-southeast component to the net coal thickness trends also exists (fig. 37). Thickest unit 4 coals (average 40 ft [12.2 m]) occur in a trend of isolated pods that extends northwesterly from the outcrop belt near Craig (fig. 38). Coal occurrence in all units concentrates in the east half of the basin, and, except in unit 4, no significant coal lies west of the Little Snake River.

Williams Fork coal distribution is strongly controlled by the depositional systems. Coals in units 1 through 3 are dominantly strike oriented (northeast) and overlap with sandstone-poor coastal-plain areas behind the paleoshorelines. The coastal plain is an area of sediment bypass, permitting uninterrupted peat accumulation. It is also the ideal location for peat preservation because the water table is maintained at optimum levels

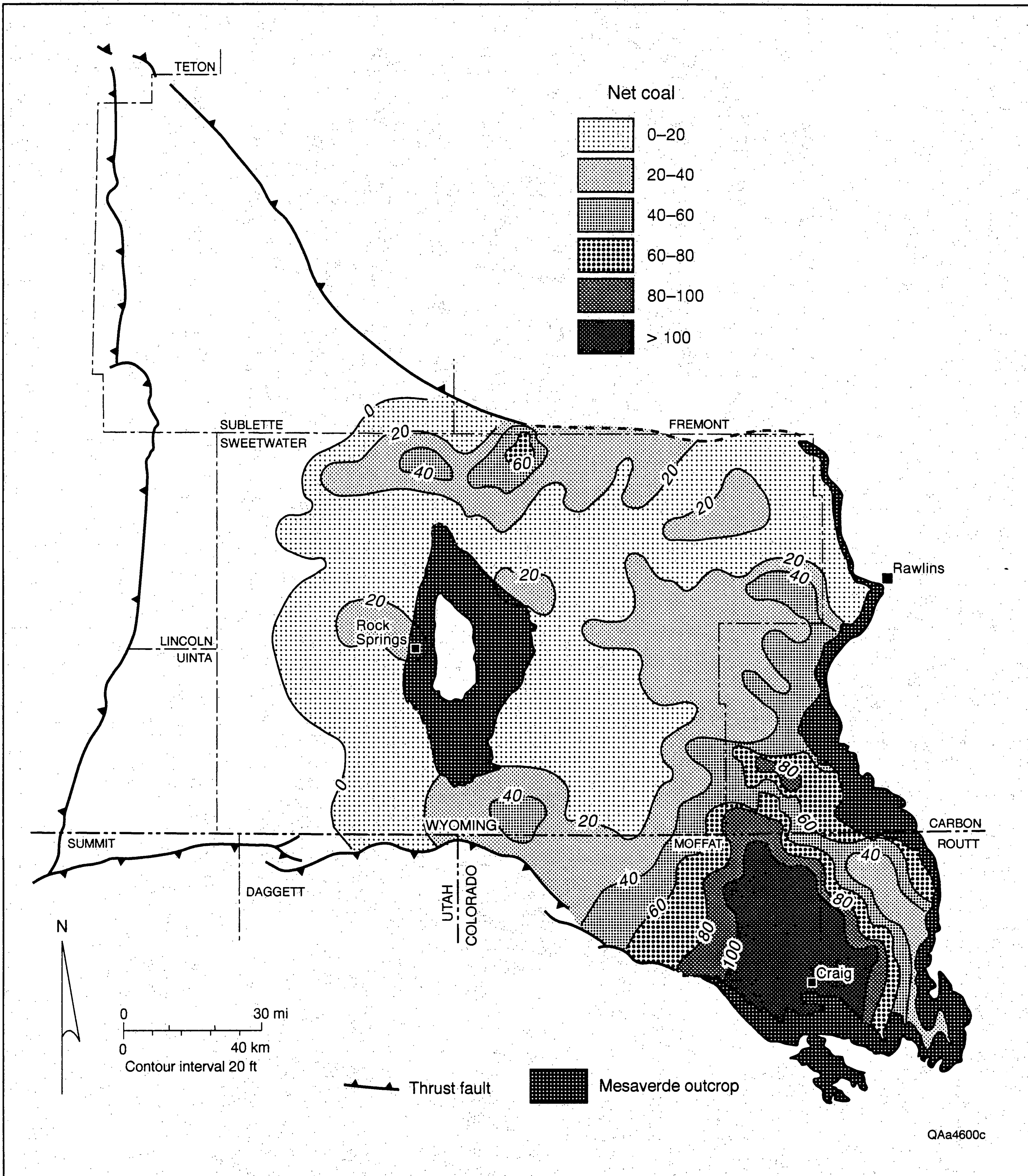


Figure 29. Net-coal-thickness map, Williams Fork Formation. Thickest coals in the Sand Wash Basin are associated with the shoreline and coastal-plain systems. The coals thin to the north and west on the alluvial piedmont.

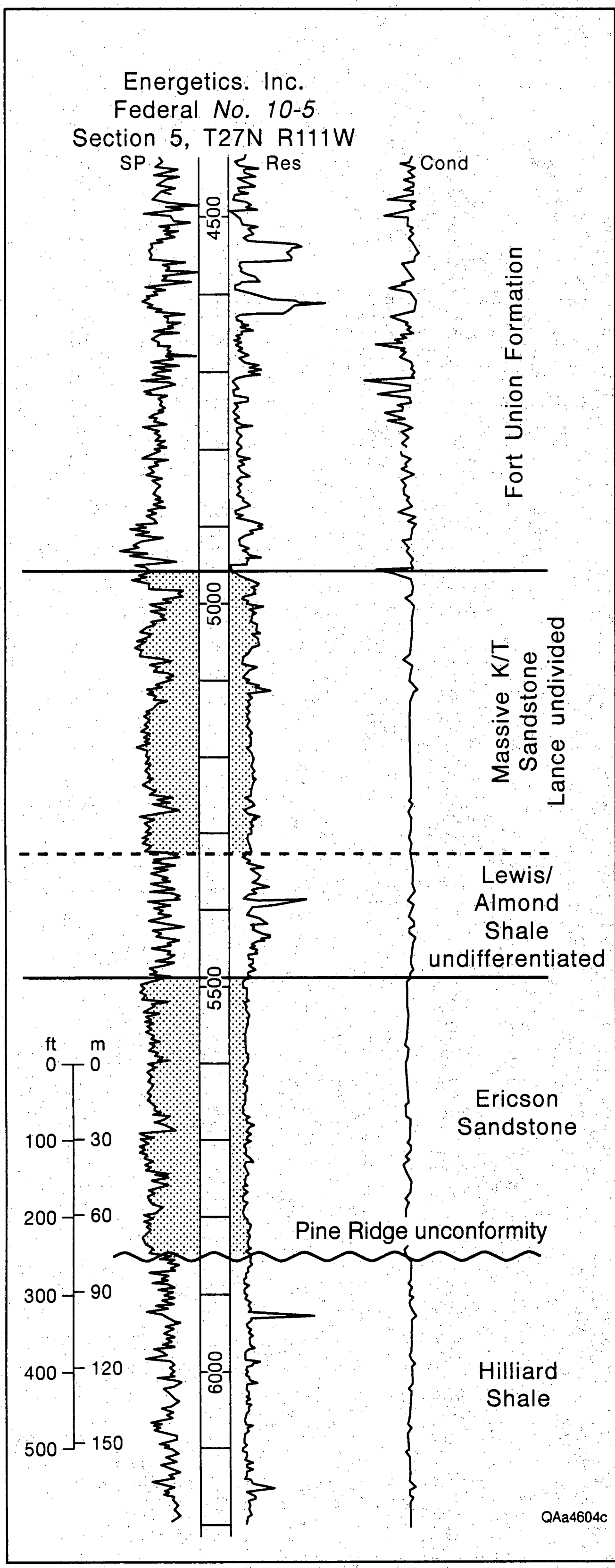


Figure 30. Type log on the Moxa Arch illustrating the occurrence of the Pine Ridge unconformity. Location of type log shown in figure 25.

immediately behind the shorelines systems. Thinning of the coals to the west and northwest suggests that peat growth and preservation were inhibited on the alluvial piedmont because clastic influx from laterally migrating fluvial channels caused a disruption and water-table levels associated with the rising gradient of the piedmont surface became lower. In unit 4, and in the most landward of the unit 3 coals, the dominant dip-elongate (southeast) orientation and association with sandstone-poor areas between major sandstone-rich belts indicate that optimum coal-forming conditions occurred in the interchannel positions between large fluvial-channel axes (Hamilton, 1993).

Almond Formation

The Almond Formation in the eastern and southeastern Greater Green River Basin was deposited in a wave-dominated delta system; at the Rock Springs Uplift, back-barrier facies of the formation grade seaward (eastward) into north-trending barrier-island sandstones (fig. 39) (Weimer, 1965; Roehler, 1988, 1990). Almond barrier-island complexes are more than 60 mi (>96 km) long and approximately 4 mi (~6.4 km) wide; net sandstone thickness in these complexes is as much as 100 ft (30 m) thick (McCubbin and Brady, 1969) (fig. 27). Coal beds east of the Rock Springs Uplift 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). Almond net-coal thickness east of the Rock Springs Uplift ranges from 6 to 12 ft (1.8 to 3.6 m) in three to four seams (fig. 27). Many 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).

In the Sand Wash Basin, net coal thickness ranges from 15 to 25 ft (4.5 to 7.6 m) in three areas: west of Craig, Colorado; southeast of the Rock Springs Uplift, where the coals trend northwest; and west of the Sweetwater–Carbon county line, where the coals trend northeastward (fig. 40). Comparison between net-coal-thickness and percent-sandstone maps (figs. 40, 41) suggests two relationships between coal distribution and depositional setting. The northwest-oriented coals correspond to low sandstone percentage and occupy a coastal-plain position behind the barrier core of the strandplain system. The northeast-trending coals lie in an area of low sandstone percentage adjacent to a major delta distributary (Hamilton, 1993). Peat growth probably initiated on the stable subdelta platform constructed by the distributary-channel complex and was maintained by freshwater discharge delivered by the distributary complex. Almond Formation coal beds are minor coalbed methane targets in the eastern Greater Green River Basin.

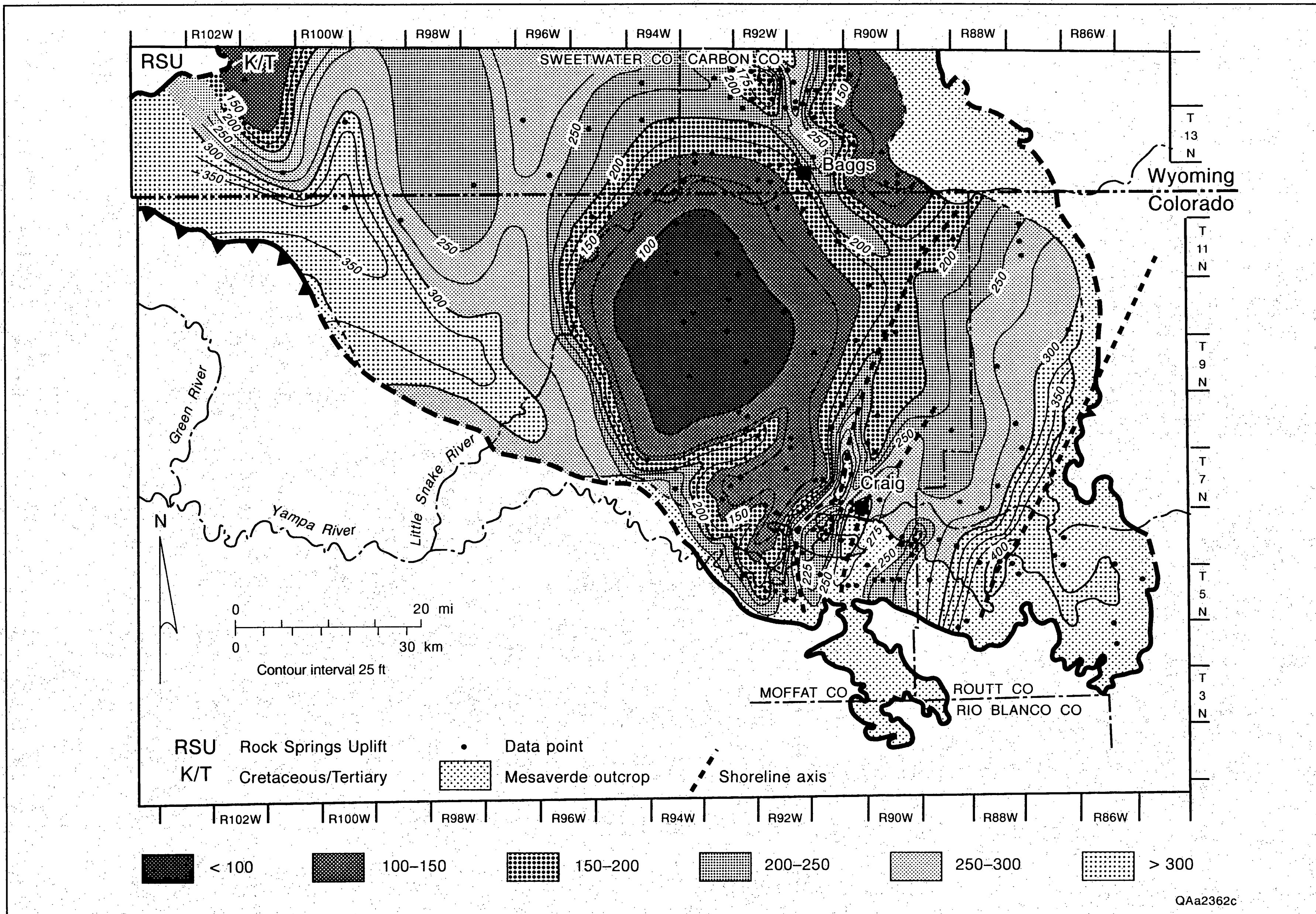


Figure 31. Net-sandstone map of unit 1, Williams Fork Formation. Several strike-oriented (northeast-southwest) linear clastic shorelines are evident, backed landward by a coastal-plain system (net sandstone less than 125 ft [<38 m]), which grades westward into a large fluvial system. A dip-oriented distributary-channel system extends southeastward from Baggs. From Hamilton (1993).

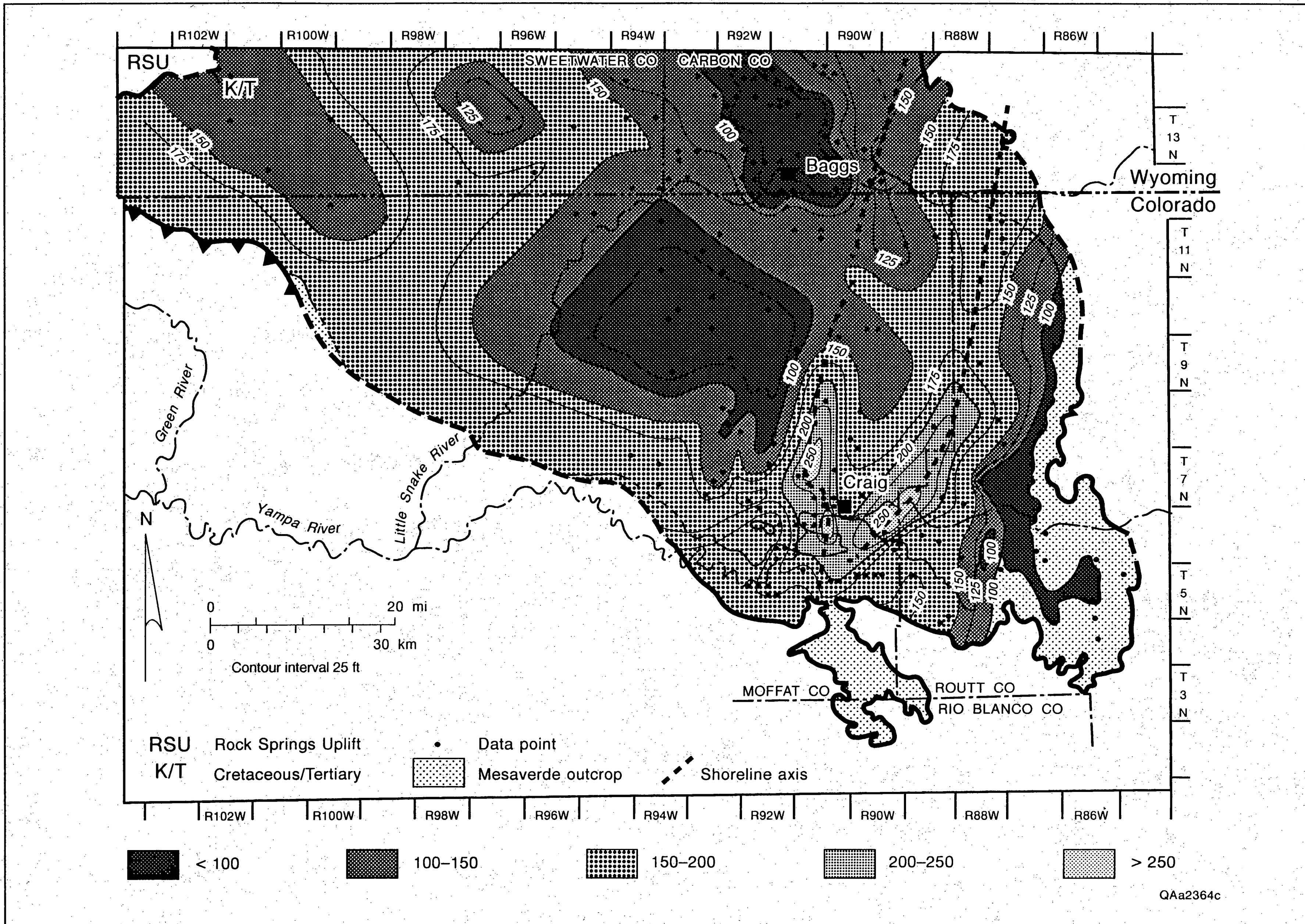


Figure 32. Net-sandstone map of unit 2, Williams Fork Formation. Two subparallel, sandstone-rich trends define the shoreline system that is backed landward by a coastal-plain system (net sandstone less than 150 ft [<46 m]), which grades westward into the alluvial plain. The sandstone-poor trend crosscutting the seawardmost shoreline is interpreted as a tidal-inlet complex. The sandstone-rich trend crosscutting the coastal plain represents a distributary-channel complex. From Hamilton (1993).

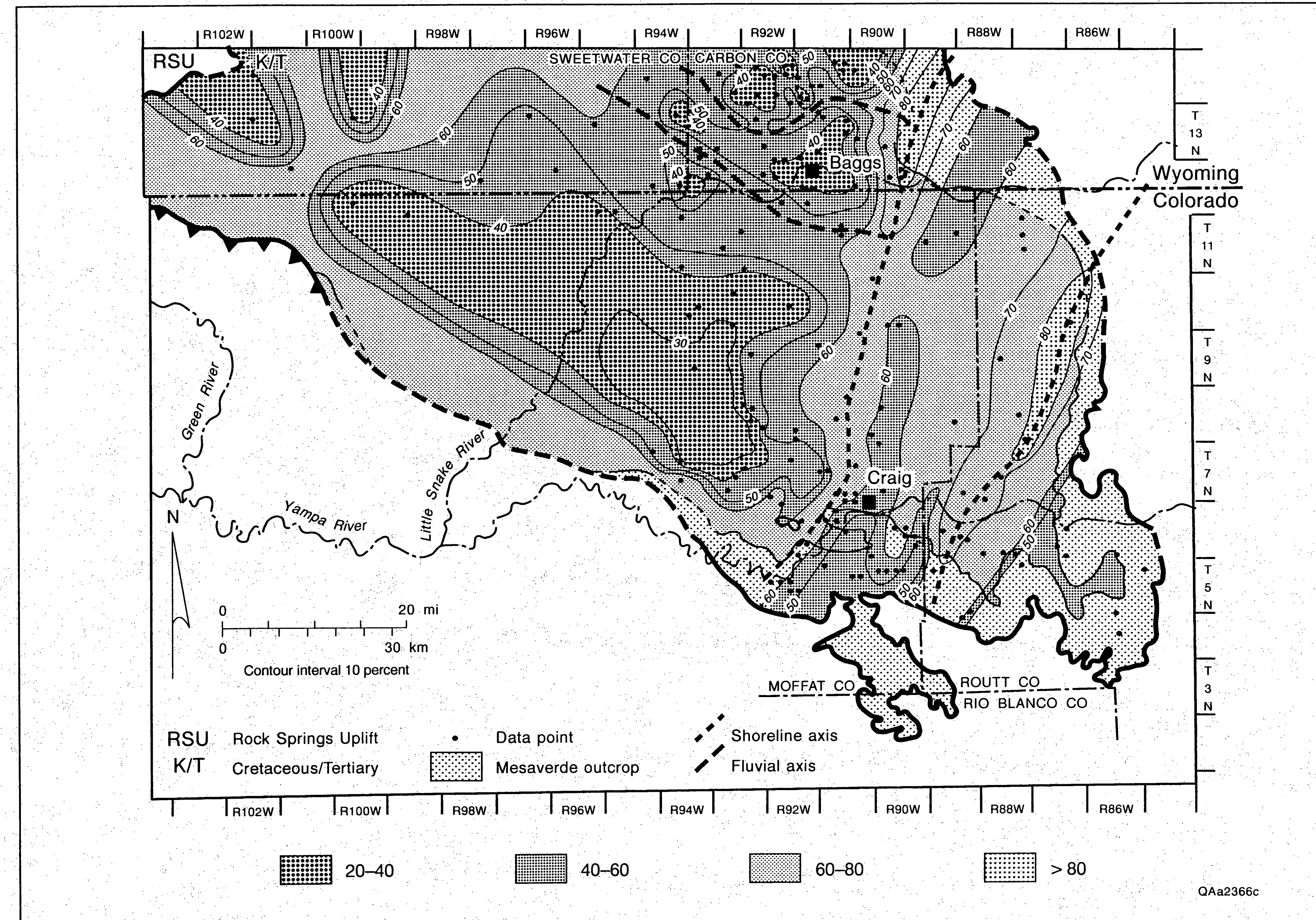


Figure 33. Percent-sandstone map of unit 3, Williams Fork Formation. Two parallel, strike-oriented sandstone-rich trends define the shoreline system that is backed landward by a coastal-plain system, which in turn grades westward into the alluvial plain. The coastal plain is cut by a number of broad, dip-oriented sandstone-rich belts representing moderately sinuous mixed-load channels. From Hamilton (1993).

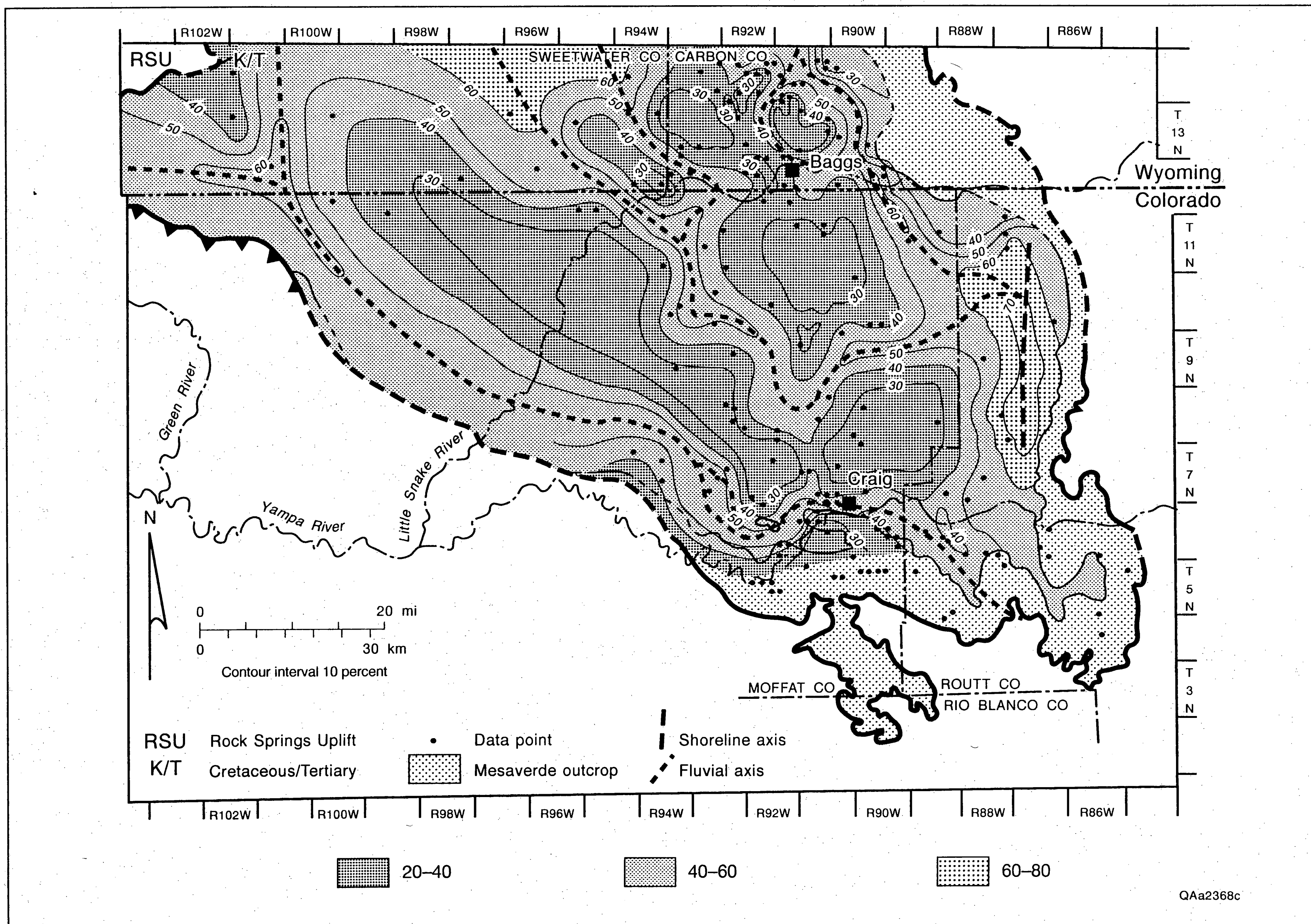


Figure 34. Percent-sandstone map of unit 4, Williams Fork Formation. The sandstone map defines several well-integrated sandstone-rich channel belts displaying moderate sinuosity. The channel belts are separated by sandstone-poor interchannel areas and merge in the southeast with a linear shoreline. From Hamilton (1993).

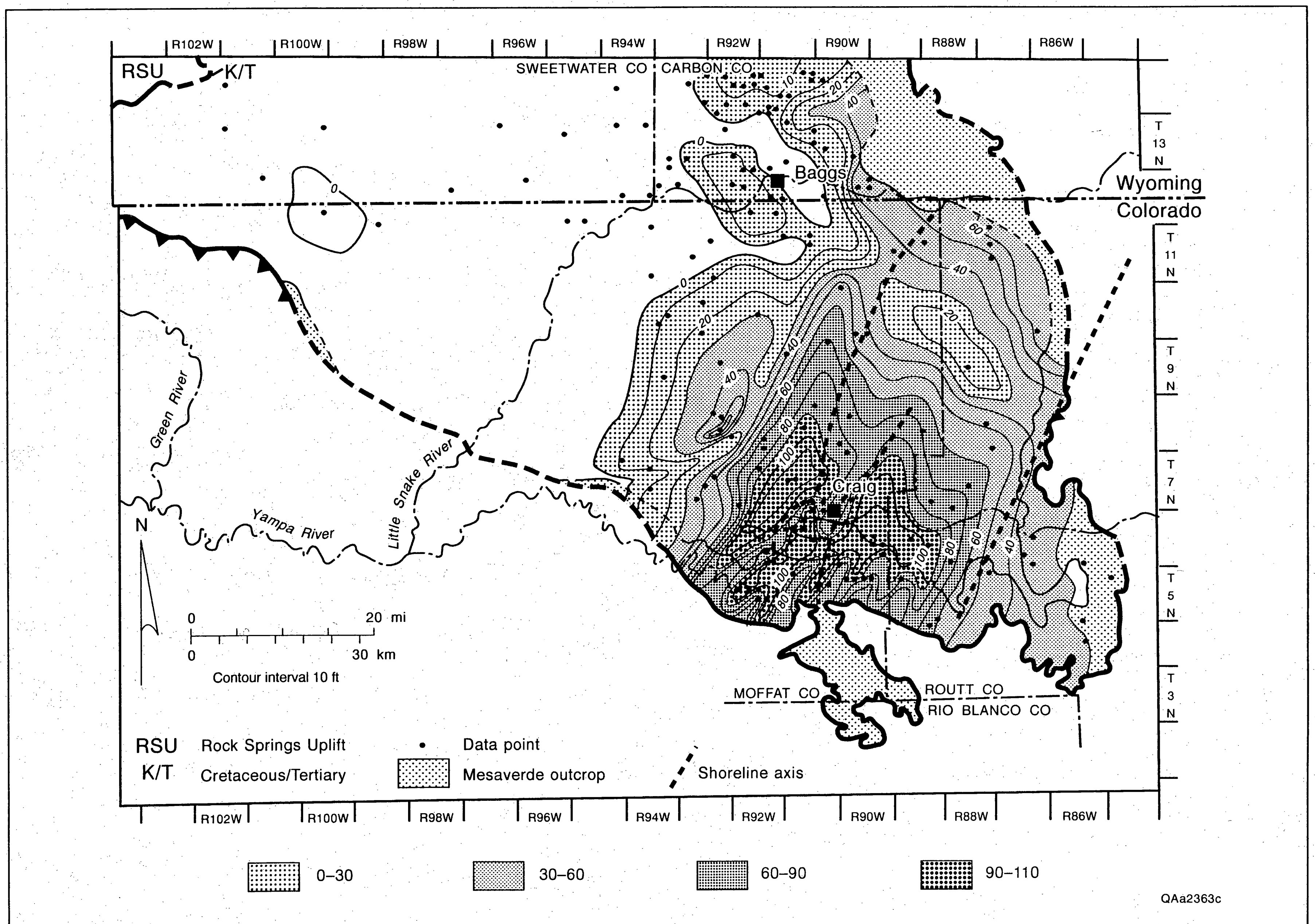


Figure 35. Net-coal-thickness map of unit 1, Williams Fork Formation. Modified from Hamilton (1993). Thickest net coal occurs in the Craig area, where peat accumulated on the coastal plain behind linear shoreline systems. Coals thin to the west at the coastal–alluvial-plain transition.

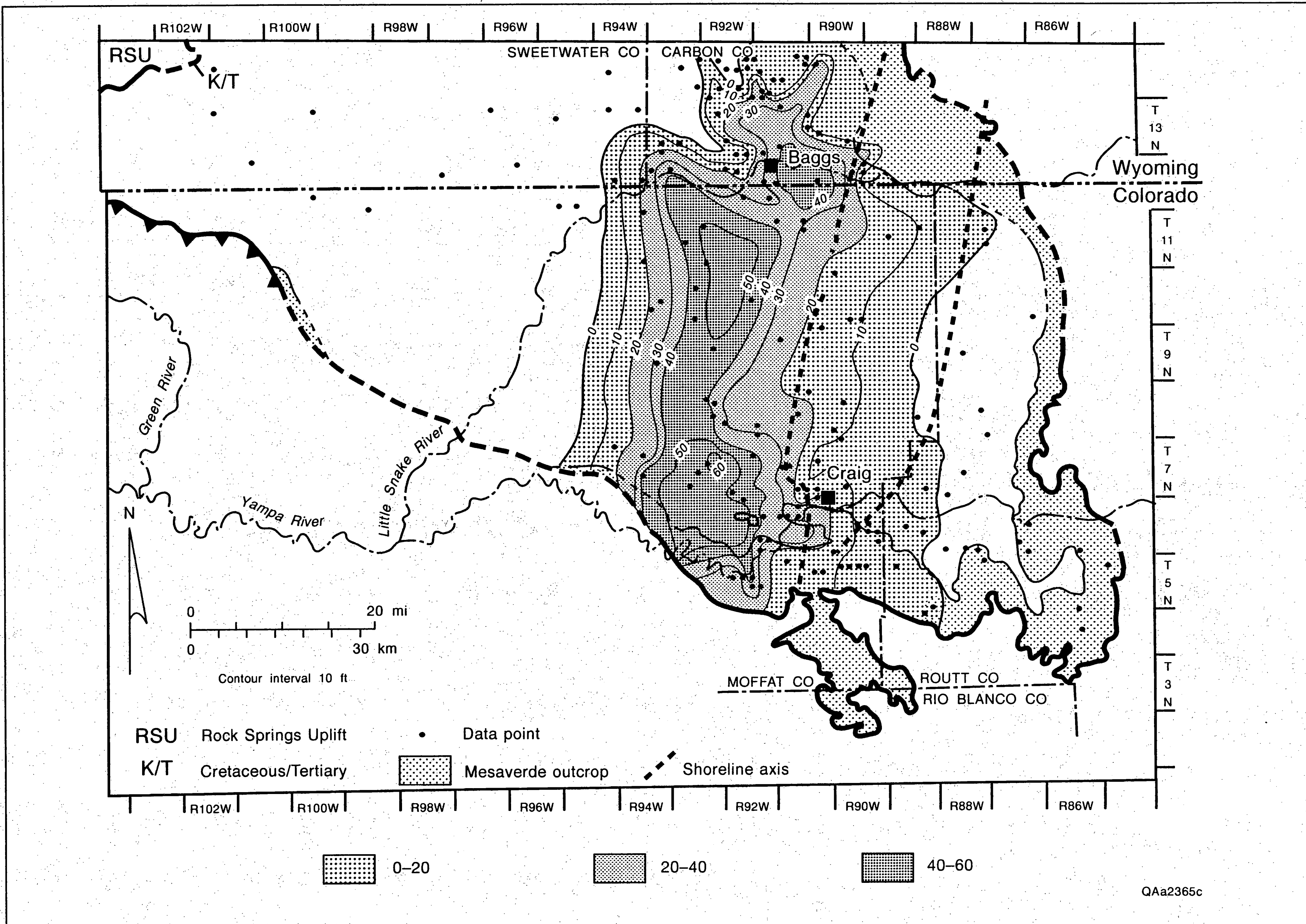


Figure 36. Net-coal-thickness map of unit 2, Williams Fork Formation. Modified from Hamilton (1993). Thickest net coal occurs west and northwest of Craig, where peat accumulated on the coastal plain behind linear shoreline systems. Coals thin to the west at the coastal–alluvial-plain transition.

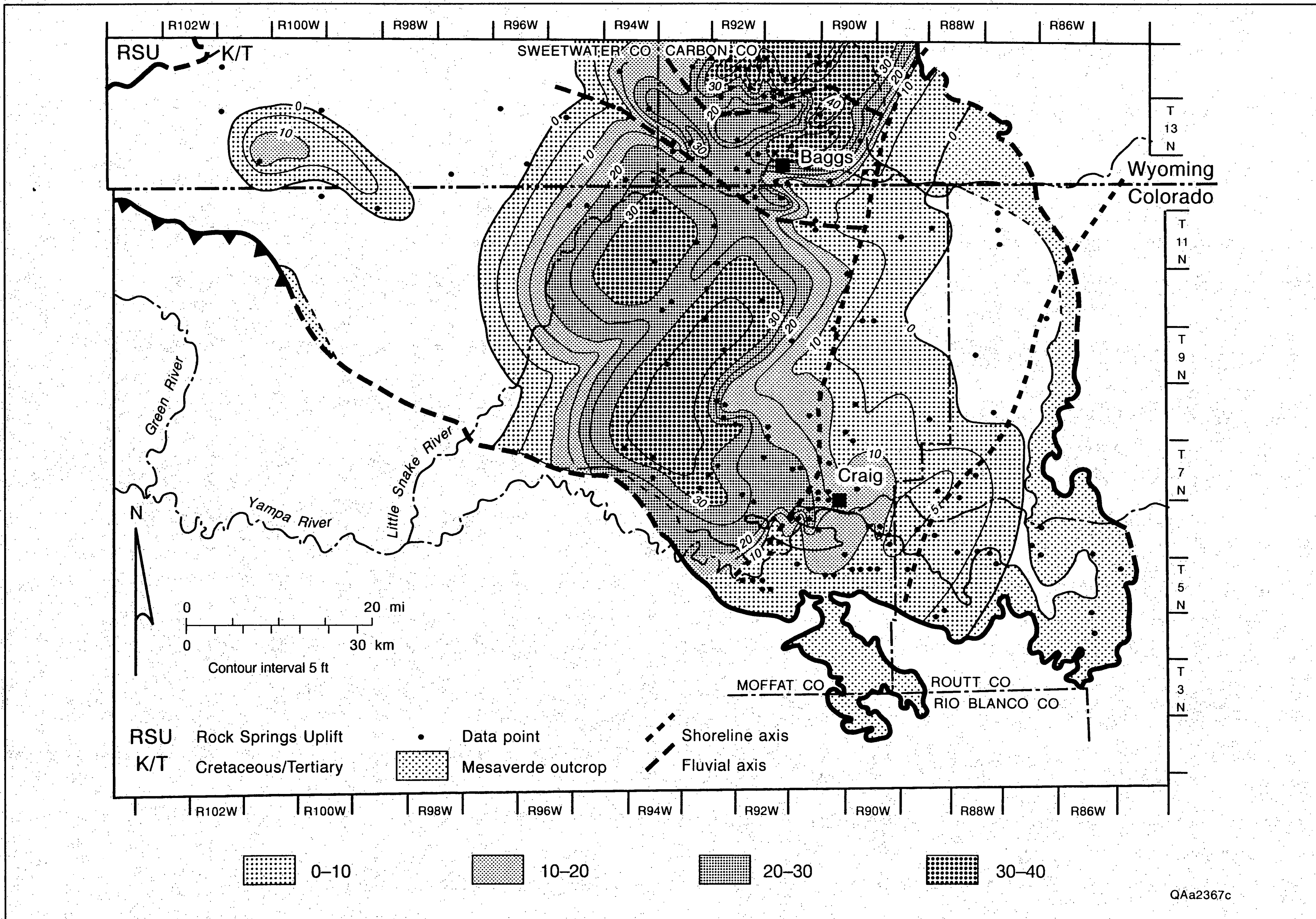


Figure 37. Net-coal-thickness map of unit 3, Williams Fork Formation. Modified from Hamilton (1993). Thickest net coal occurs west and northwest of Craig, where peat accumulated on the coastal plain behind the linear shoreline systems. Coals thin to the west at the coastal–alluvial-plain transition and also along broad, dip-oriented (northwest-southeast) trends that were cut by fluvial channels.

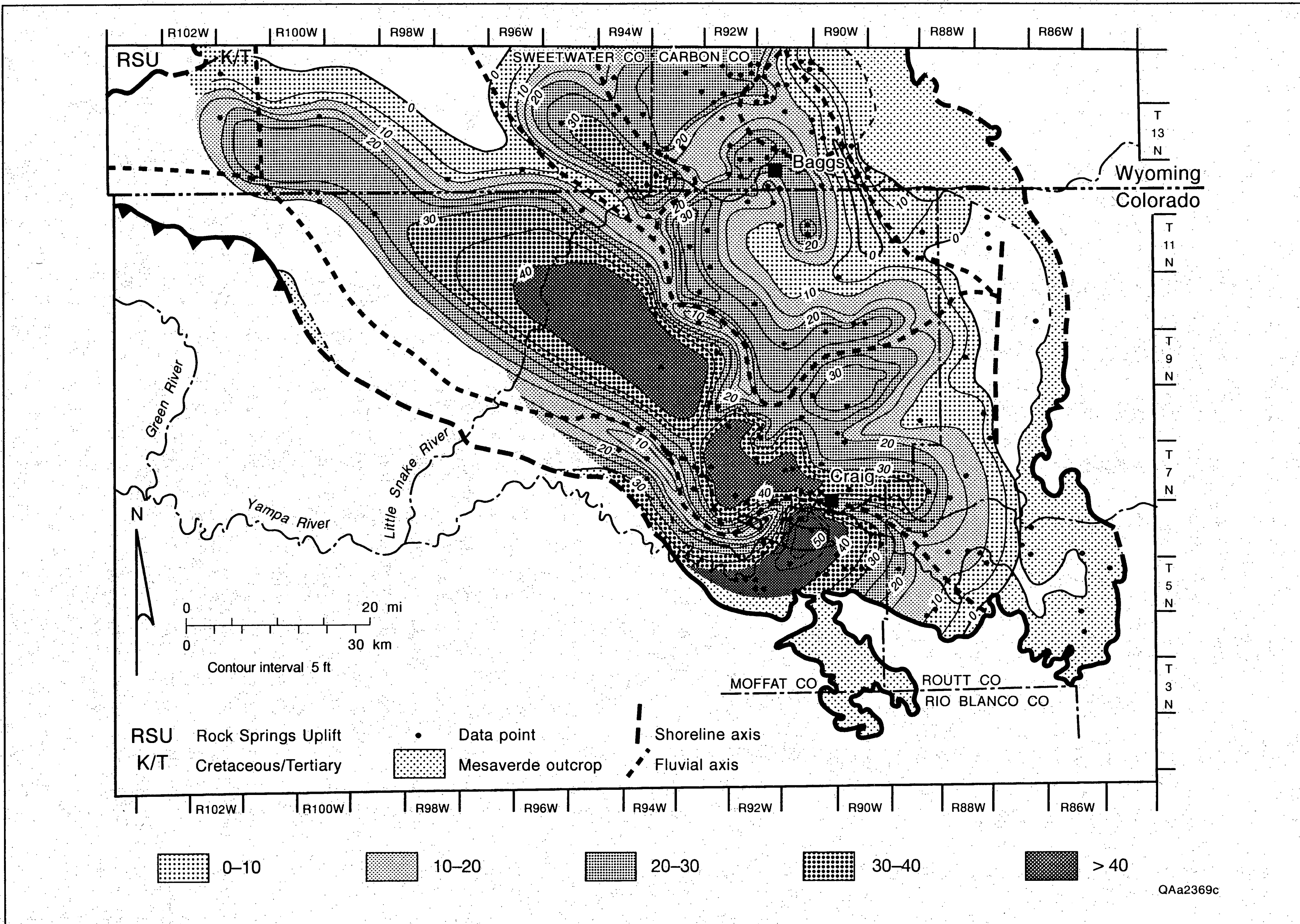


Figure 38. Net-coal-thickness map of unit 4, Williams Fork Formation. Modified from Hamilton (1993). The coals occupy the areas adjacent to major channel belts. Thickest net coal occurs along a dip-oriented trend of isolated pods extending northwestward from the Craig area.

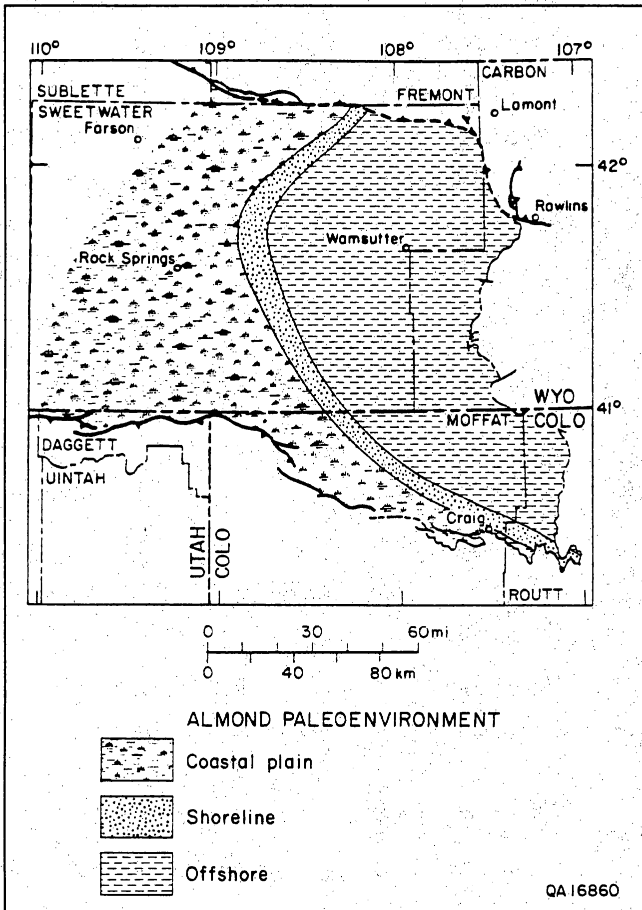


Figure 39. Paleogeography of the upper Almond Formation and lower Lewis Shale, east half of the Greater Green River Basin. Modified from Roehler (1990).

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. The formation consists of brackish and nonmarine shales, lenticular sandstones, and coal beds (Land, 1972). The Lance Formation, approximately 900 ft (~274 m) thick in the eastern Greater Green River Basin (Masters, 1961), is separated from the overlying Fort Union Formation by a regional unconformity.

Coal beds, thicker and more abundant in the lower part of the Lance Formation above the platform Fox Hills sandstone, range from a few inches to 8 ft (2.4 m) in thickness at the Rock Springs Uplift (fig. 27) (Tyler and McMurry, 1993). Locally these coal beds merge into single seams that can be 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 pinch out over a few hundred feet (fig. 27). Lance Formation coal beds are minor coalbed methane targets in the eastern Greater Green River Basin.

Lower Tertiary Coal-Bearing Units

Tertiary Fort Union coal-bearing units vary greatly in burial depth and reach a maximum of 12,000 ft (3,658 m) in the central parts of the Washakie and Great Divide Basins (Tyler and Tremain, 1993). To the west the Tertiary coals are more than 10,000 ft (>3,048 m) deep in the Pinedale basin area (Law and Spencer, 1989), less than 2,000 ft (<600 m) deep on the La Barge Platform, and more than 10,000 ft (>3,048 m) deep in the Green River Basin.

Fort Union Formation

Sedimentation within the Paleocene Fort Union Formation, defined as strata between the massive Upper Cretaceous and lower Tertiary (K/T) sandstone unit and the Eocene Wasatch Formation, results from syntectonic sedimentation and Laramide basement thrusting (Tyler, 1994). Characteristic syntectonic sedimentary facies in the basin include a narrow conglomerate facies adjacent to basement-cored thrusts, a narrow sandstone–mudstone–coal facies just basinward, a basinal thrustward-thickening mudstone facies associated with basement-cored thrusts, and a wide distal sandstone–mudstone–coal facies (Tyler and McMurry, 1993; Tyler, 1994). On the basis of this facies architecture, we can further operationally divide the Fort Union Formation in the southeastern and eastern Greater Green River Basin into the lower coal-bearing unit, the gray-green mudstone unit, the basin-sandy unit, and the upper shaly unit (fig. 42). In the western Greater Green River Basin, the upper shaly unit is absent, and the basin-sandy unit rests directly on the lower coal-bearing unit (fig. 43). Coal thickness and coal-seam continuity are greatest in the lower coal-bearing unit (figs. 20 through 23). Coals were deposited along predominantly north-, east-, and southeast-flowing intermontane fluvial trunk-stream systems and associated floodplain and lacustrine deposits (Ritzma, 1955; Masters, 1961; Colson, 1969; Tyler and McMurry, 1993), where thick sandstone sequences served as platforms for peat accumulation.

In the eastern Greater Green River Basin, lithofacies and coal-occurrence maps of the Sand Wash Basin (Tyler and McMurry, 1993) show that maximum coal development corresponds to floodplain deposits above,

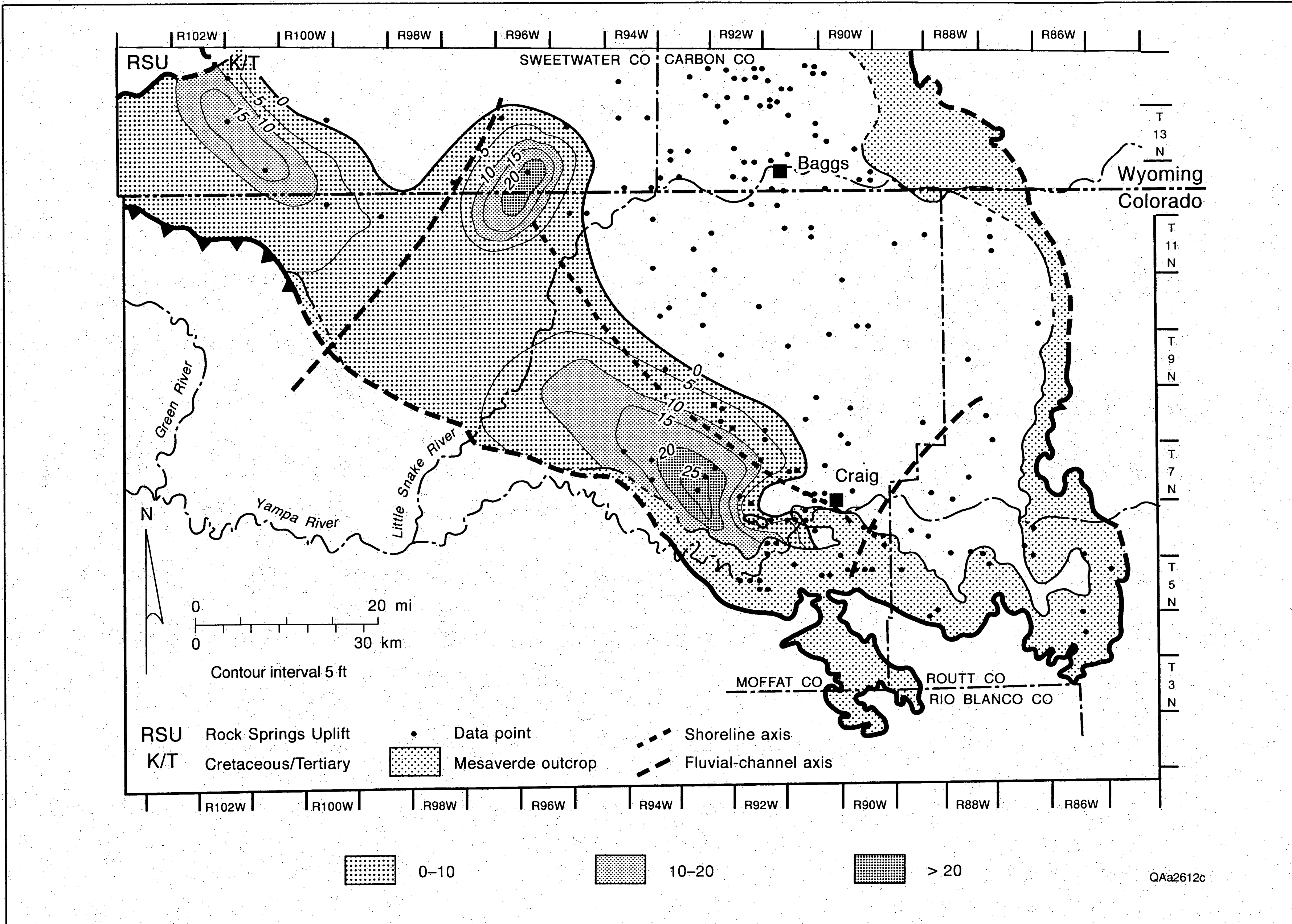


Figure 40. Net-coal-thickness map, Almond Formation. Coals are distributed (1) west of Craig, (2) southeast of the Rock Springs Uplift, and (3) west of the Sweetwater–Carbon county line. From Hamilton (1993).

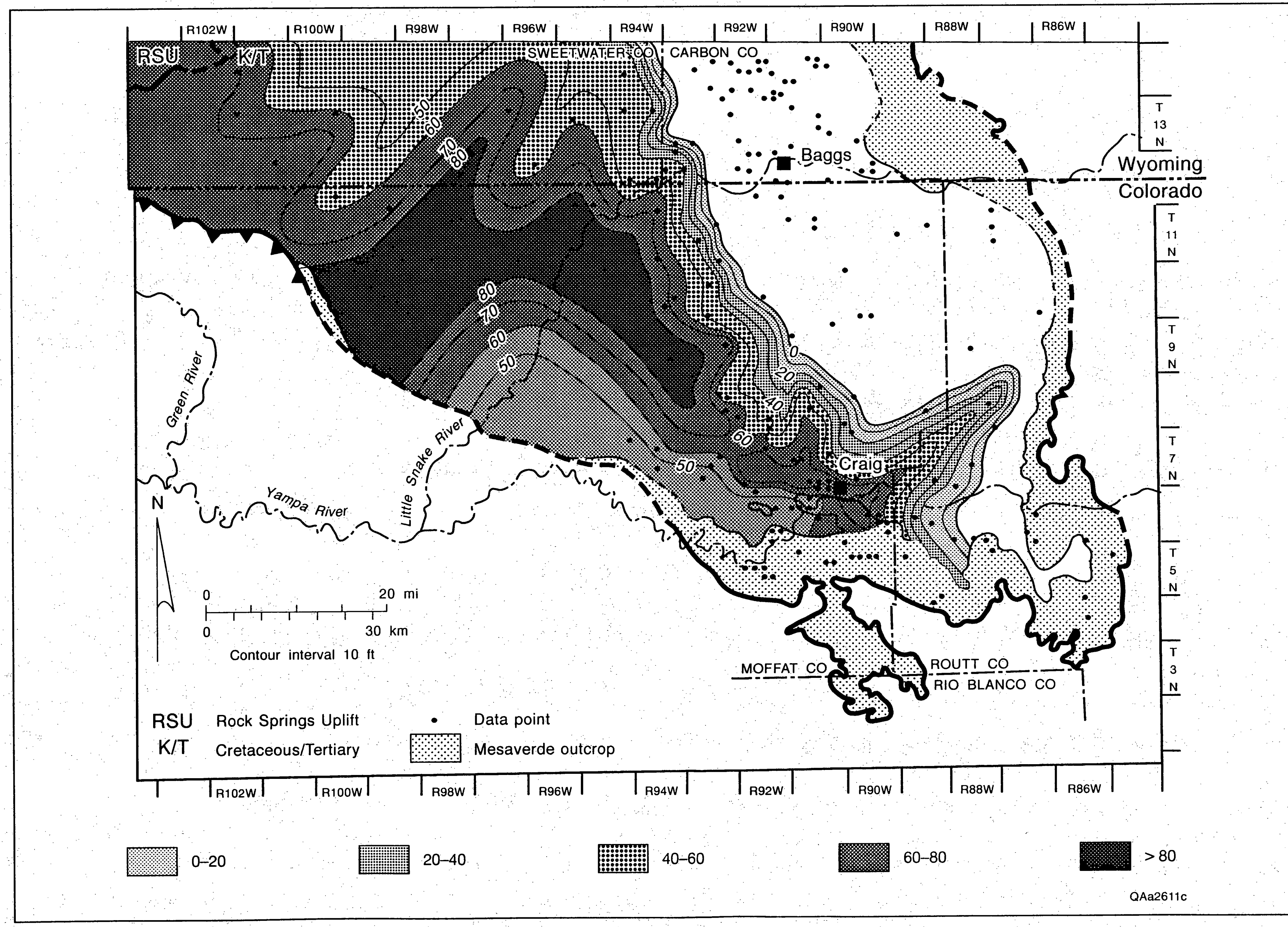


Figure 41. Percent-sandstone map, Almond Formation. The map defines a strike-oriented strandplain system that extends between deltaic distributaries.

and on the flanks of, south-north-oriented fluvial systems (fig. 44); individual coal seams have maximum thicknesses of 20 to 50 ft (6.1 to 15.2 m) and a combined maximum net coal thickness of approximately 80 ft (~12.2 m) (fig. 45). Thinner coal beds (3 to 10 ft [0.9 to 3.1 m] thick) also occur in the western Sand Wash Basin, in the lower coal-bearing unit away from the main trunk stream and in the upper shaly unit of the Fort Union Formation (Tyler and McMurry, 1993). By comparison, similar intermontane trunk-stream systems have been identified in the rest of the Greater Green River Basin.

The lower Fort Union coal-bearing unit in the Washakie and Great Divide Basins contains thick individual coal beds, less than 40 ft (<15.2 m) thick. Net coal thicknesses range from 0 to more than 100 ft (0 to >30.1 m; fig. 46) in as many as 10 seams at depths greater than 8,000 ft (>2,438 m) below surface. Net coal thickness and coal-seam continuity follow patterns similar to those of the Sand Wash Basin, trending northward and associating with north-flowing intermontane fluvial trunk-stream systems (fig. 46).

In the western Greater Green River Basin, the lower Fort Union coal-bearing unit, along the synclinal Green River Basin axis, consists of some of the most continuous and thickest individual coal beds, as much as 40 ft (15.2 m) thick, 15 mi (24 km) northwest of the north flank of the Rock Springs Uplift (fig. 46). Net coal thicknesses range from 10 to 140 ft (3.1 to 42.7 m) in as many as 12 seams, at depths as much as 8,000 ft (2,438 m) below surface. At least five Fort Union coal beds are thicker than 10 ft (3.1 m) along the south-north-trending belt, parallel to the Green River Basin synclinal axis. To the west, thin coal beds (<10 ft [<3 m] thick) occur at the north end of the Moxa Arch (fig. 46), 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. To the north, within the Pinedale basin area, coal seams thicken to a maximum net-coal thickness of approximately 140 ft (~42.7 m) in T30N, R111W. Lower Fort Union coal beds are absent east of the Pinedale Anticline thrust fault in the northwest part of the Greater Green River Basin (Curry, 1973; Law and Johnson, 1989). Coal beds did not form to the east of the thrust system because (1) floodplain environments were unstable or absent, (2) coarse alluvial-fan clastics sourced in the Wind River Uplift to the northeast were locally being deposited, and/or (3) the Pinedale Anticline was a positive topographic feature during the deposition of the lower coal-bearing unit and conditions were unfavorable for peat to accumulate.

Moreover, the net coal thickness and coal-seam continuity in the lower coal-bearing unit is greater than that in the upper shaly unit. In the northeast part of the Greater Green River Basin and within the Great Divide Basin, the upper shaly Fort Union Formation (Cherokee)

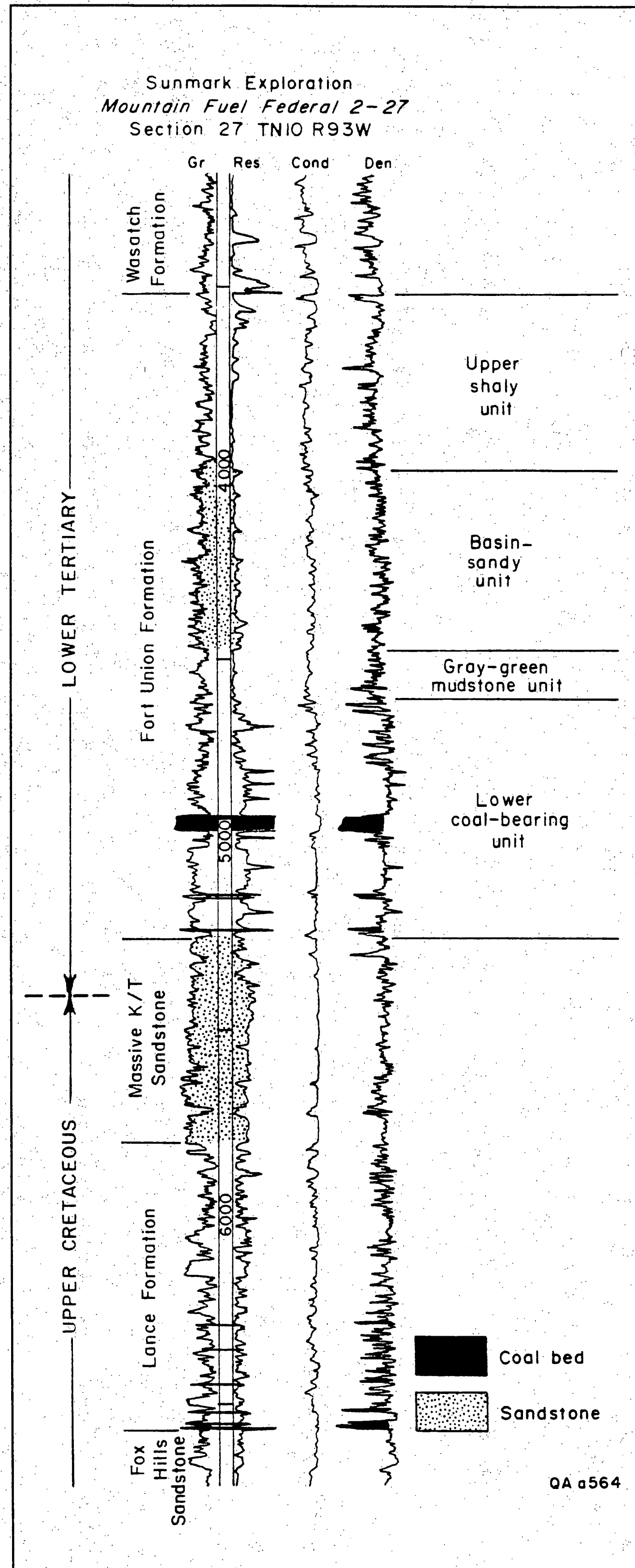


Figure 42. Type log showing location of coal and stratigraphic nomenclature of the Paleocene Fort Union Formation, southeastern Greater Green River Basin. Coal beds identified from density and sonic logs where available. Location of type log shown in figure 13.

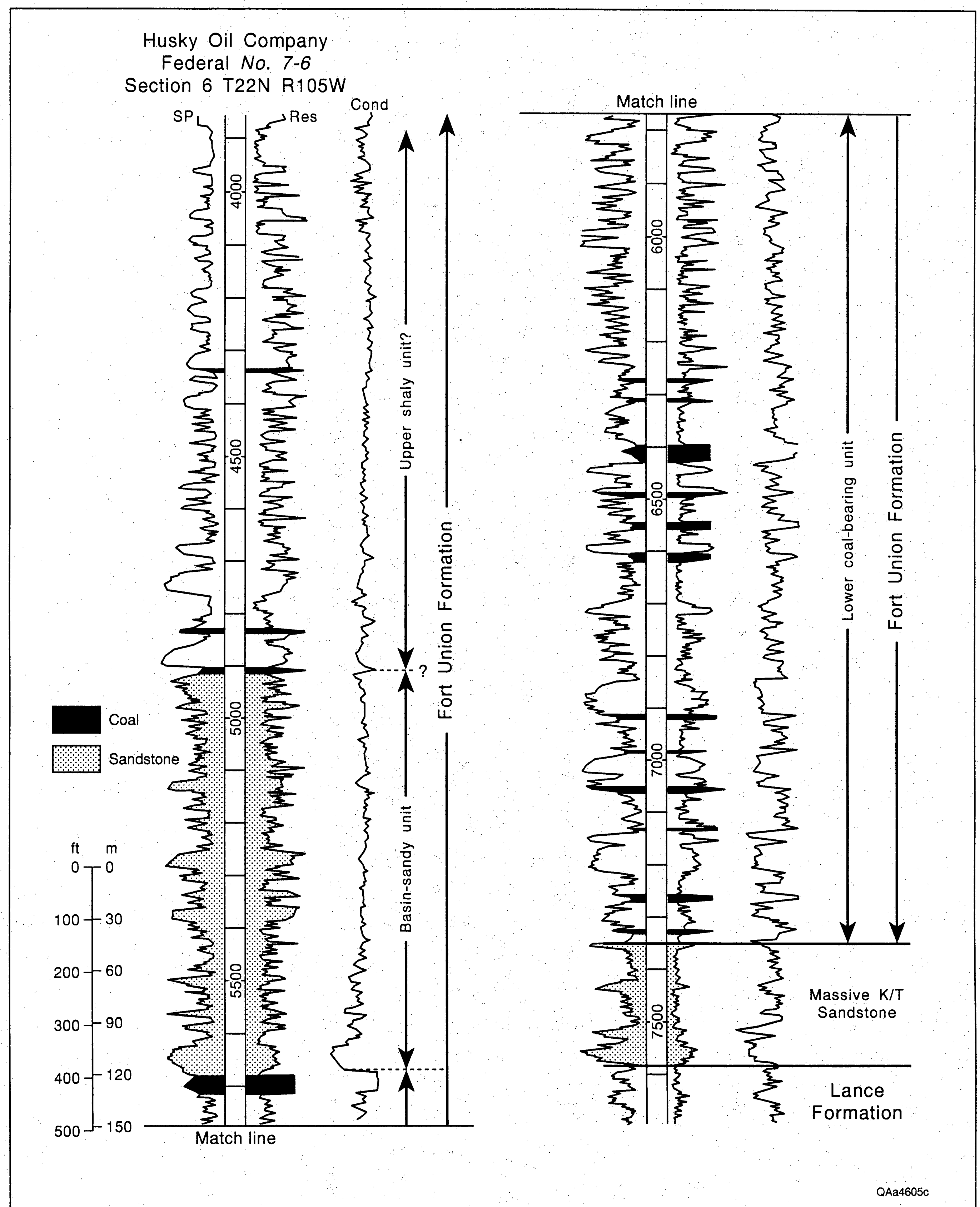


Figure 43. Type log showing location of coal and stratigraphic nomenclature of the Paleocene Fort Union Formation, northwestern Greater Green River Basin. Coal beds identified from density and sonic logs where available. Location of type log shown in figure 13.

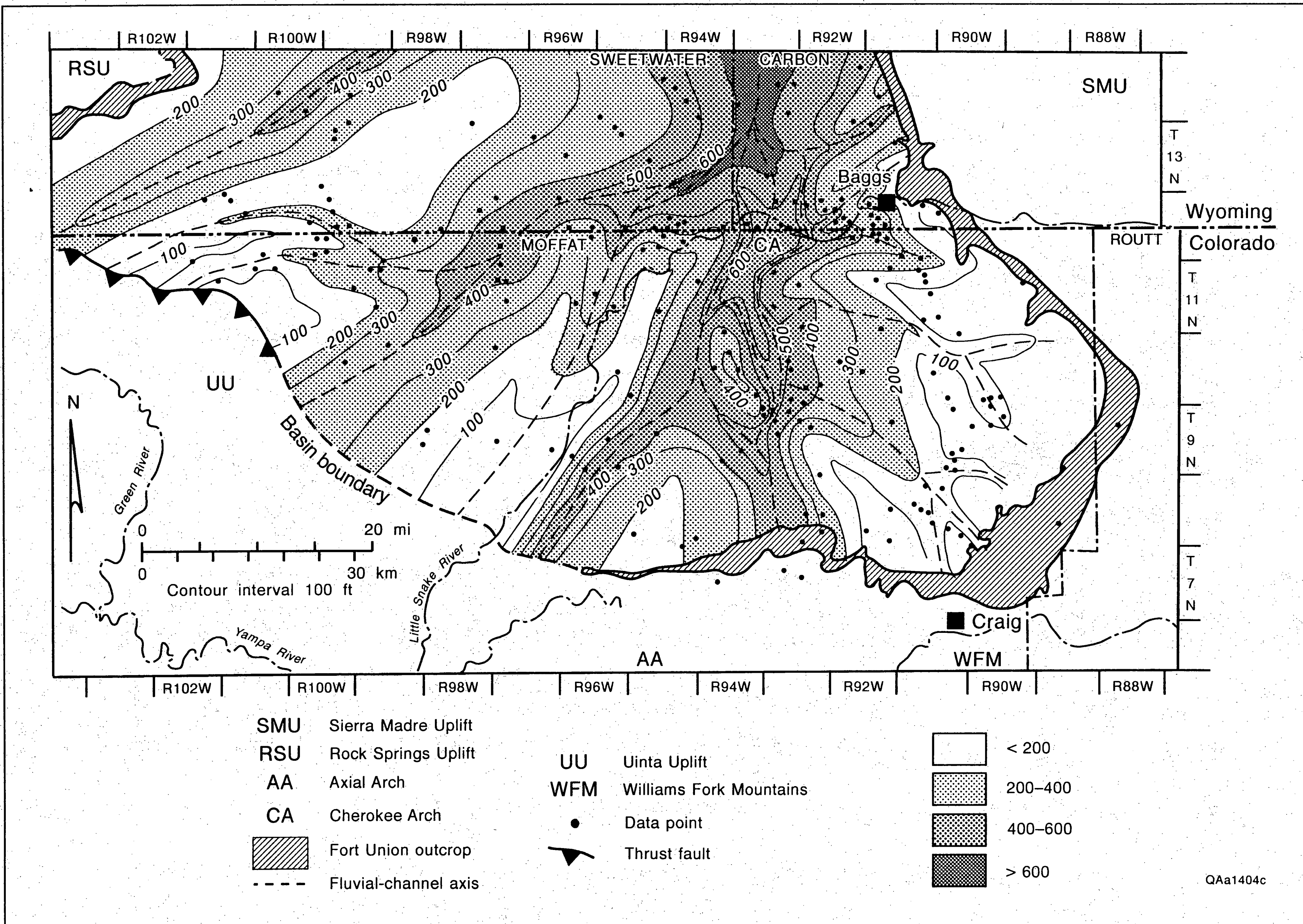


Figure 44. Net-sandstone-thickness map of the lower coal-bearing unit, Fort Union Formation, Sand Wash Basin. Modified from Tyler and McMurry (1993). Thickest net sandstone development (>600 ft [>182.8 m]) occurs along a south-north-oriented fluvial system between R92W and R94W. Smaller tributaries flowed both east and west toward the main trunk stream.

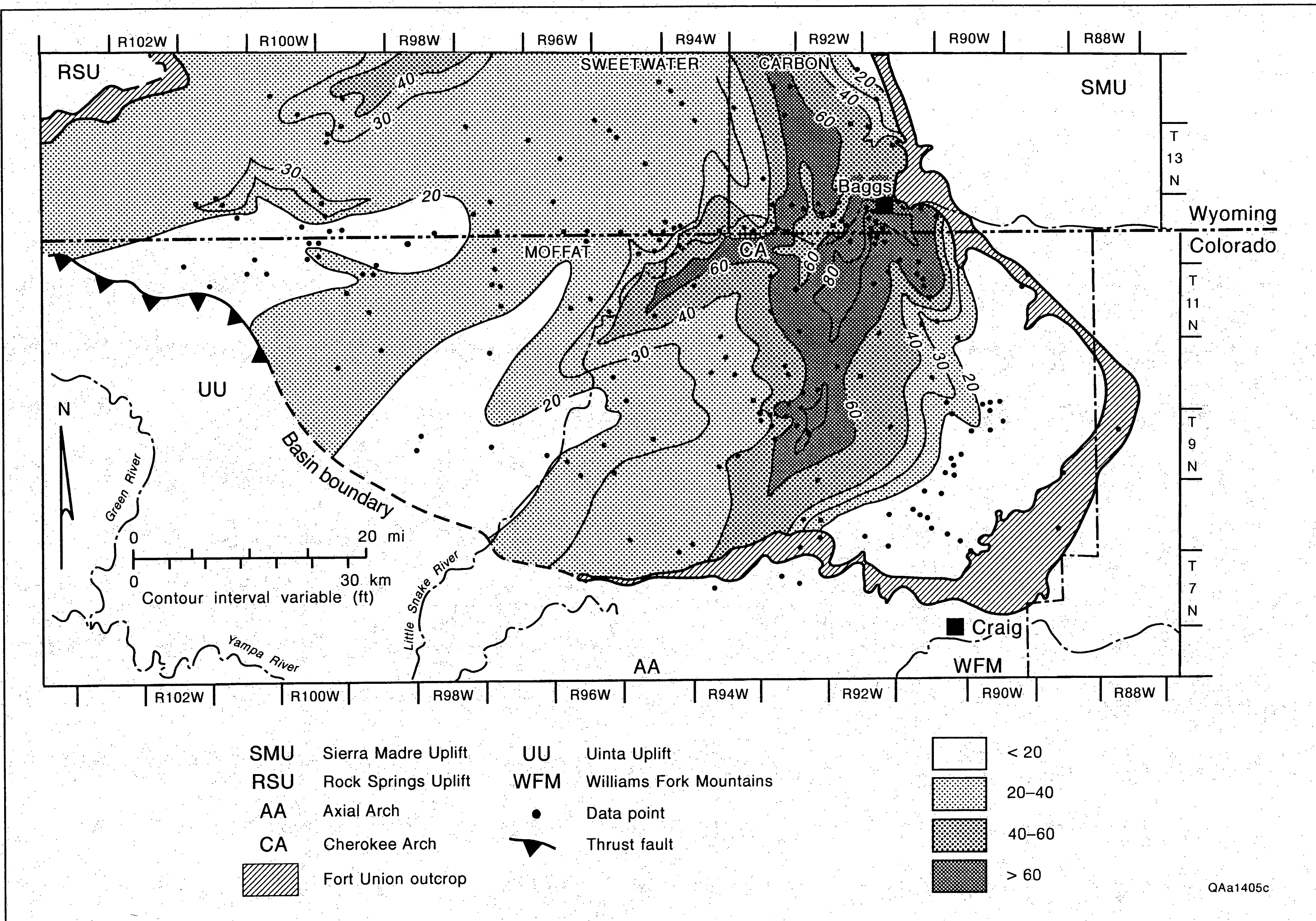


Figure 45. Net-coal-thickness map of the lower coal-bearing unit, Fort Union Formation, Sand Wash Basin. Modified from Tyler and McMurry (1993). Thickest net coal development (>60 ft [>18.3 m]) occurs above and alongside a south-north-oriented fluvial system between R92W and R94W.

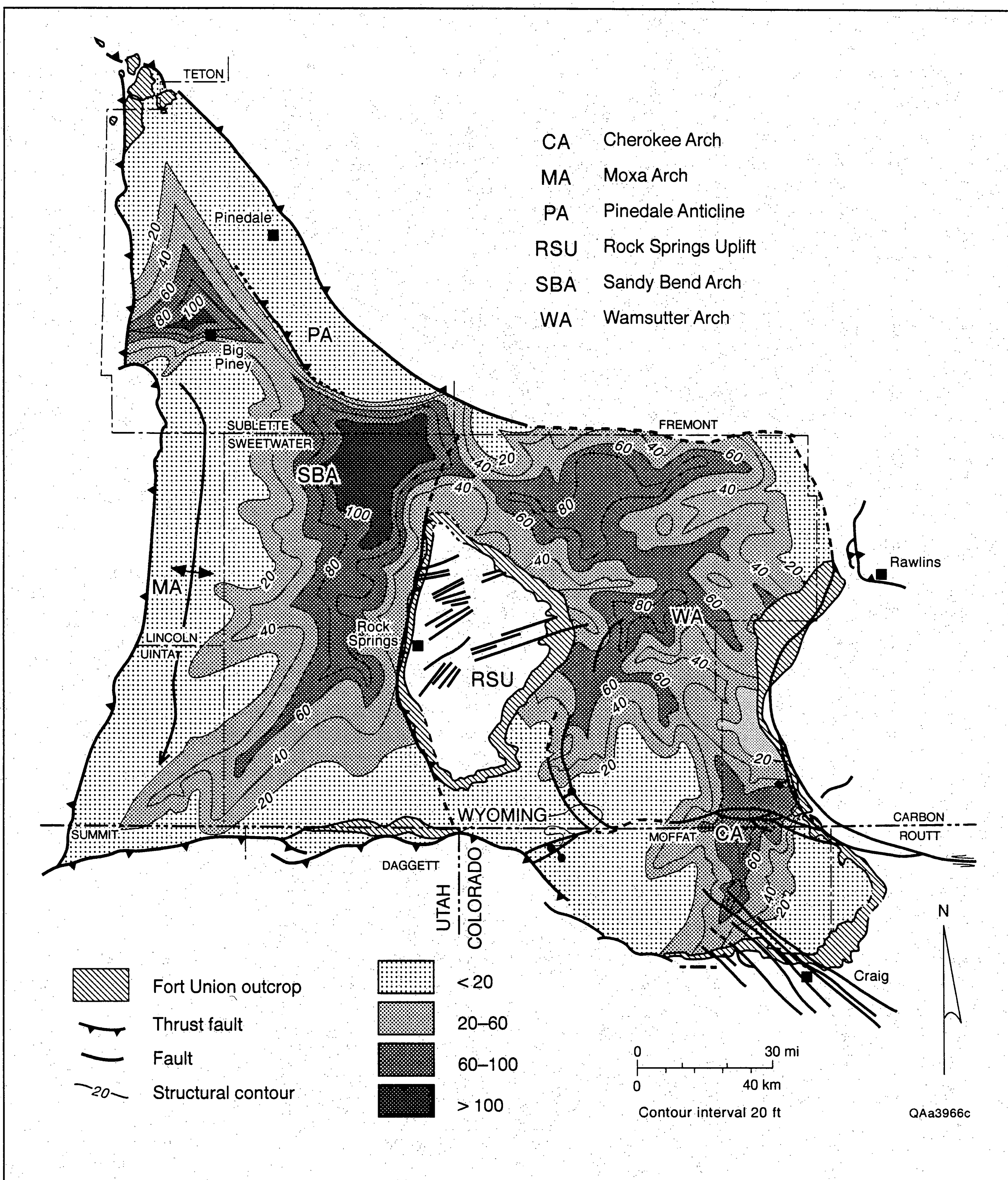


Figure 46. Net-coal-thickness map of the lower coal-bearing unit, Fort Union Formation, Greater Green River Basin. Thickest net coal development (>100 ft [>30.5 m]) occurs above and alongside a south-north-oriented fluvial system along the west and east flanks of the Rock Springs Uplift and along a northwest-southeast-oriented fluvial system along the west flank of the Pinedale Anticline. PA = Pinedale Anticline, MA = Moxa Arch, RSU = Rock Springs Uplift, CA = Cherokee Arch, and WA = Wamsutter Arch.

coal beds vary greatly in thickness, individual coalbed thicknesses ranging from less than 10 ft (<3 m) to more than 35 ft (>11 m), but they are laterally discontinuous (figs. 21 and 22). Two coal beds, however, do extend for 6 to 12 mi (9.6 to 19.3 km) in the basin and range in thickness from 10 to 32 ft (3 to 10 m) for a combined net coal thickness of 60 ft (18.3 m). The thickest coal beds formed on the stable platform provided by the basin-sandy unit.

Depositionally the Fort Union Formation contains some of the thickest intermontane fluvial sandstone and coalbed sequences in the Greater Green River Basin. The thick coal beds are laterally continuous over distances of approximately 40 mi (~64 km) and occur associated with bed- and mixed-load channel-fill sandstone sequences. The channel-fill sandstone sequences within the lower coal-bearing unit are thought to be part of a much larger intermontane fluvial trunk-stream system that flowed north through the Green River Basin from the Uinta Mountain area, along the synclinal Green River Basin axis, to the north edge of the Rock Springs Uplift, where the fluvial trunk-stream system was diverted to the east into the Great Divide Basin. This north-flowing fluvial trunk-stream system merges with the southeast-flowing trunk stream that originated on the northwest margins of the Pinedale Basin area and the north-flowing Sand Wash and Washakie Basins fluvial trunk-stream system, to exit the Greater Green River Basin on the east edge of the Great Divide Basin. An increase in the suspended load carried by the fluvial system through tectonism, major upstream avulsion, or both, resulted in the building of levees that stabilized the channel axes and allowed extensive floodplains and coal deposits to form. Coal beds are thicker and more numerous in floodplain areas above and on the flanks of the thickest sandstones. The considerable thickness and lateral continuity of the coal beds within the lower coal-bearing unit throughout the Greater Green River Basin make it a potential coal and coalbed methane target, whereas coals in the upper shaly unit in the northeastern Greater Green River Basin are shallowly buried and laterally discontinuous and are not considered coalbed methane targets.

Importantly, researchers demonstrated that the major control on Paleocene Fort Union Formation peat accumulation in the Greater Green River Basin is deposition within a syntectonic intermontane fluvial trunk-stream system and associated floodplain and lacustrine deposits. Further, coal and sandstone development coincide; the thickest coals occur above or on the flanks of the thickest fluvial sandstones, which act as platforms on which coal accumulates and conduits through which ground water flows. This is particularly true of the major north-, east-, and southeast-trending channel-sandstone belts, which facilitated ground-water flow basinward from recharge areas on the margins of the Greater Green River Basin. Recharge occurred in the highlands at the basin margins and ground water flowed basinward, down hydraulic gradient in response to the topographic gradient, eventually discharging at topographically low areas. At these postulated sites of regional ground-water discharge, peat swamps originated and ultimately spread across the floodplain as a result of reduced clastic influx. As a confined aquifer system, channel-fill sandstones focused discharge to begin organic accumulation and subsequently to maintain the water table at a level optimal for extensive peat accumulation. Bounding the fluvial trunk streams are paleotopographically high regions (such as the Moxa Arch and Pinedale Anticline in the western Greater Green River Basin, the Rock Springs Uplift, and the Wamsutter and Cherokee Arches in the eastern Greater Green River Basin) that were present during the early Paleocene. These paleotopographically high regions, having low subsidence rates, were areas unfavorable for peat to accumulate and thus had thin coal occurrence. Greatest potential for Paleocene coalbed methane exploration and development, therefore, exists where the coal beds are thickest and where they were buried to depths of more than 6,000 ft (>1,829 m), along an arch that extends from the Rock Springs Uplift to the north edge of the Moxa Arch, north of the La Barge Platform, along the northwest, north, and northeast flanks of the Rock Springs Uplift, and along the west limits of the Cherokee Arch.

Wasatch Formation

The Wasatch Formation exhibits net-sandstone trends and depositional systems similar to those of the underlying Fort Union Formation (McDonald, 1975). The main body of the Wasatch Formation in the Sand Wash Basin and near the Rock Springs Uplift consists of 1,500 to 2,500 ft (457 to 762 m) of conglomeratic, lacustrine fan-delta deposits that grade eastward into fluvial sandstones, floodplain and lacustrine shales, and minor coal-bearing floodplain deposits (Roehler, 1965a; Sklenar and Anderson, 1985). In the northeast part of the Greater Green River Basin, Wasatch coal beds are less than 10 ft (<3 m) thick. The thickest coal beds formed in stable swamps that were widespread in the Great Divide Basin. Most Wasatch coal beds are discontinuous and pinch out at sandy fluvial complexes over distances ranging from 2 to 10 mi (3.2 to 16 km) (Sklenar, 1982). Wasatch Formation coal beds are thin, discontinuous, and shallowly buried, and thus they are not considered to be coalbed methane targets.

Coal Rank, Gas Content and Composition, and Origin of Coalbed Gases

Andrew R. Scott

Coal Rank and Burial History

The amount of methane generated from coal beds is primarily a function of coal rank. Onset of significant methane generation from coal occurs at vitrinite-reflectance values (R_m) of approximately 0.8 to 1.0 percent (high-volatile A bituminous) (Meissner, 1984; Tang and others, 1991). Early thermogenic methane, however, can be derived from terrestrial organic matter at much lower levels of thermal maturity (R_m of approximately 0.40 percent; Galimov, 1988). Determining coal-rank trends and burial history of coal-bearing units in the Greater Green River Basin is complicated by insufficient vitrinite-reflectance and proximate data: most of the published vitrinite-reflectance data are from shales and sandstones rather than from coal beds. However, coal-rank data and thermal maturation studies by Glass (1975), Law and others (1980), Law (1984), Pawlewicz and others (1986), Merewether and others (1987), Dickinson (1989), Lickus and others (1989), MacGowen and others (1993), and Scott (1993a, b) provide a basis for determining vitrinite-reflectance and coal-rank trends in the Mesaverde Group and Fort Union Formation in the Greater Green River Basin.

We estimated vitrinite-reflectance and coal-rank trends in the Greater Green River Basin by combining data from many sources including (1) measured data from the formation being evaluated, (2) proximate and ultimate analyses, (3) measured vitrinite-reflectance data from formations immediately above or below the selected horizon, (4) vitrinite-reflectance profiles (R_m versus depth), and (5) thermal-maturity maps showing depths to specific vitrinite-reflectance values. The term "coal rank" defines a specific range of thermal maturity. Coal-rank trends are defined by vitrinite-reflectance data from shales and sandstones in addition to coal beds. Therefore, vitrinite-reflectance data from shales and sandstones allowed extrapolation of isoreflectance lines and coal-rank trends to areas of the basin where coal beds are thin or absent.

Measured vitrinite-reflectance values from the formation being evaluated are the most reliable data. However, coal-rank trends were constrained using measured vitrinite-reflectance data from formations immediately above or below the formation being evaluated. Vitrinite-reflectance values and other coal-rank data (proximate and ultimate) were obtained from Glass (1975), Boreck and others (1981), Tremain and Toomey (1983), Law (1984), Roehler (1988), Lickus and others (1989), MacGowan and others (1993), and Scott (1993a, b). Most of the vitrinite-reflectance data are from Law (1984) and Scott (1993a, b). More than 105 vitrinite-reflectance values from 41 wells in the Mesaverde Group and 55 vitrinite-reflectance values from 21 Fort Union wells were used to construct vitrinite-reflectance and coal-rank maps. Vitrinite-reflectance profiles and depths to the top of the Mesaverde or base of the Fort Union were used in areas where vitrinite-reflectance data were sparse or unavailable. Additionally, thermal-maturity maps (Pawlewicz and others, 1986; Merewether and 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 (Tyler and Hamilton, 1993, this volume, figs. 4 and 5) were used to supplement the vitrinite-reflectance data.

Vitrinite-reflectance data (Law, 1984; MacGowen and others, 1993; Scott, 1993a, b) from individual wells were grouped into five regional subdivisions (fig. 47). Area I covers the Pinedale Basin including the Pinedale Anticline; area II encompasses the northern Green River Basin and the Pacific Creek area; area III represents the Great Divide Basin; area IV contains the Washakie Basin; and area V is the Sand Wash Basin. We based the equation for area I on work from Lickus and others (1989), whereas we performed regression analyses on vitrinite-reflectance profiles for areas II though V (fig. 48). These equations, presented in table 1, work on the assumption that vitrinite reflectance increases logarithmically with depth, although vitrinite-reflectance profiles in some low-permeability rock sequences are segmented and have one or more kinks or bends (Law and Nuccio, 1986; Law and others, 1989).

A comparison of vitrinite-reflectance profiles in the eastern and western Greater Green River Basin (fig. 49) indicates that whereas vitrinite-reflectance values

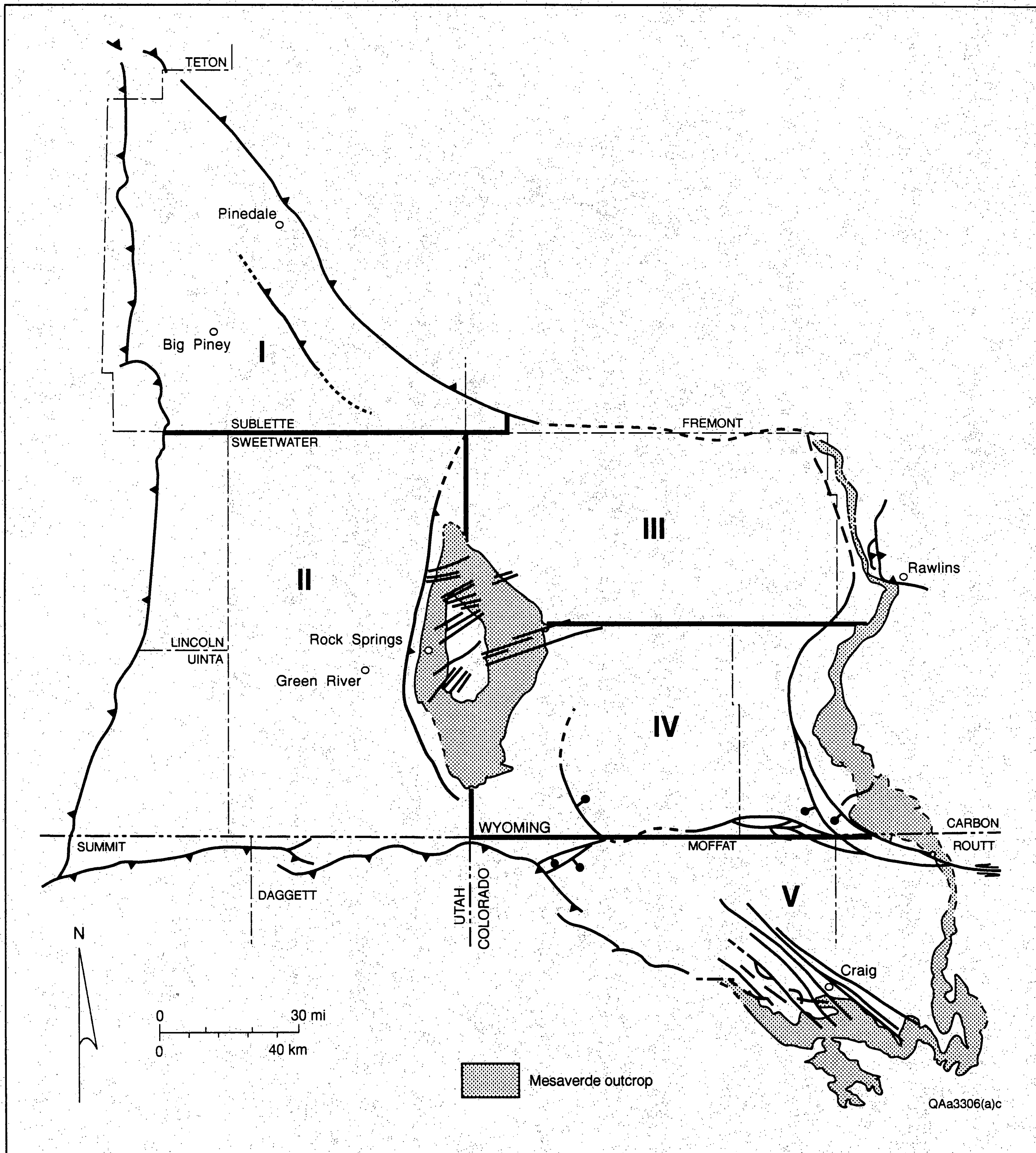


Figure 47. Map of Greater Green River Basin showing the five areas in which vitrinite-reflectance profiles were used to estimate coal-rank trends.

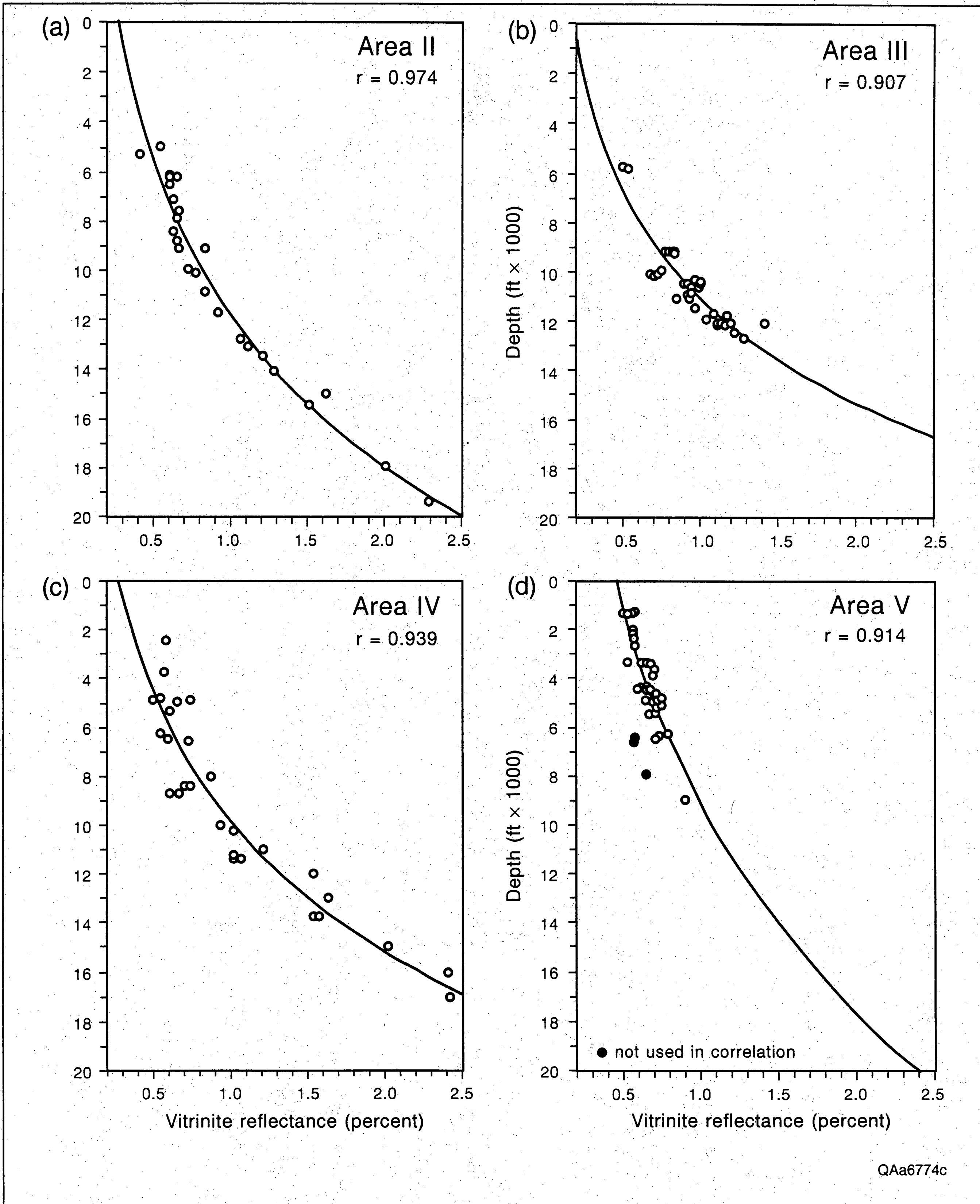


Figure 48. Vitrinite-reflectance profiles showing depth versus vitrinite-reflectance values of areas II through V. The vitrinite-reflectance profile of area I, based on the work by Lickus and others (1989), is not shown. Data from Tyler and others (1991) and Scott (1993a).

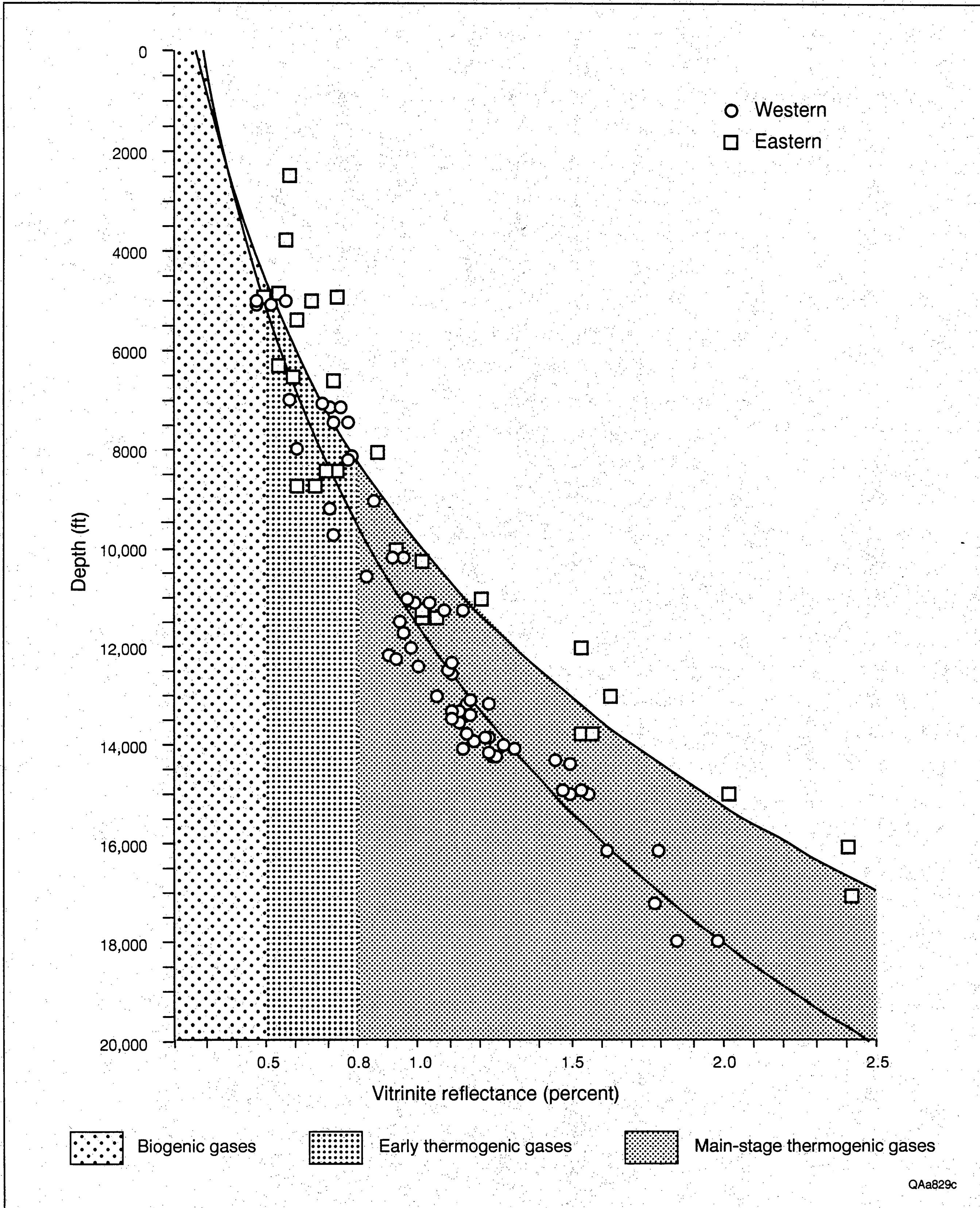


Figure 49. Vitrinite-reflectance profile of the eastern and western Greater Green River Basin (Scott and Ambrose, 1992). The threshold of thermogenic gas generation occurs at coal depths greater than approximately 8,000 ft (~2,625 m), suggesting that deeper drilling may be required to penetrate higher rank coals.

Table 1. Equations determined from vitrinite-reflectance profiles are from Lickus and others (1989), Tyler and others (1991), and Scott (1993a) R_m = vitrinite-reflectance value.

Area I	Pinedale Basin	LOG(R_m) = (Depth—11,247 ft)/19,740 ft LOG(R_m) = (Depth—3,690 m)/6,476 m
Area II	Green River Basin	LOG(R_m) = (Depth—11,829 ft)/20,495 ft LOG(R_m) = (Depth—3,881 m)/6,724 m
Area III	Great Divide Basin	LOG(R_m) = (Depth—11,095 ft)/14,101 ft LOG(R_m) = (Depth—3,640 m)/4,626m
Area IV	Washakie Basin	LOG(R_m) = (Depth—9,938 ft)/17,590 ft LOG(R_m) = (Depth—3,260 m)/5,771 m
Area V	Sand Wash Basin	LOG(R_m) = (Depth—9,210 ft)/27,985 ft LOG(R_m) = (Depth—3,022 m)/9,181 m

generally parallel one another at shallow depth, they increase more with depth in the east part of the basin than in the west. Temperature–depth plots constructed by Heasler and Surdam (1993) show that temperatures are higher in the eastern Greater Green River Basin than at equivalent depths in the western Greater Green River Basin. This bottom-hole temperature trend is evident in both the Mesaverde Group and the Fort Union Formation.

Vitrinite-Reflectance and Coal-Rank Trends

Thermal Maturity of Mesaverde Group

More than 106 Mesaverde Group vitrinite-reflectance data from 41 wells in the Greater Green River Basin were available for determining vitrinite-reflectance and coal-rank trends. Most of the vitrinite-reflectance data were from the Mesaverde Group (undifferentiated; 53); 35 vitrinite-reflectance values were from the Almond; the Ericson and Rock Springs Formations had 5 and 13 values, respectively.

Coal rank in the Greater Green River Basin ranges from subbituminous (R_m of 0.42 percent) to semianthracite (R_m of 2.41 percent) (Law, 1984), although coal rank over most of the basin is high-volatile C to high-volatile A bituminous (R_m of 0.5 to 1.1 percent). Vitrinite-reflectance isorank lines (fig. 50) show that coal rank along the basin margins ranges from subbituminous to high-volatile C bituminous. Subbituminous coals are found along the eastern Rock Springs Uplift and western Green River Basin, whereas high-volatile C bituminous coals occur along the east margin of the basin, including the Sand Wash Basin, and the west part of the Rock Springs Uplift (fig. 50). The slightly higher coal ranks along the east and southeast margins suggest that these parts of the Greater Green River Basin may have undergone more uplift and erosion. The presence of subbituminous and high-volatile C bituminous coals surrounding the Rock Springs Uplift indicates that this structural feature probably formed syntectonically with coalification. Significant vertical movement on the Rock Springs Uplift probably occurred at the end of the Cretaceous at the same time. Although the uplift is not evident from the distribution of Upper Cretaceous Rock Springs coals, it probably developed before or during the deposition of Fort Union coals during the early Paleocene (Tyler and Hamilton, this volume, figs. 25 and 46). Nondeposition, erosion, or both, of Cretaceous and Tertiary sediments along basin margins and the Rock Springs Uplift resulted in shallower maximum burial depths and lower coal ranks.

The increase in vitrinite-reflectance values and coal rank away from the Rock Springs Uplift and basin margins toward the deeper parts of the Greater Green River Basin reflects continued subsidence and greater maximum burial depths in the subbasins. The greatest burial depths and highest coal ranks are in the Washakie Basin, where coals have reached semianthracite rank. Coal ranks in the Sand Wash Basin range from high-volatile C bituminous along the south and east basin margins to medium-volatile bituminous in the west part of the subbasin. Low-volatile bituminous to semianthracite coal ranks may be present in the north part of the Great Divide Basin, although no vitrinite-reflectance data are available to confirm this supposition.

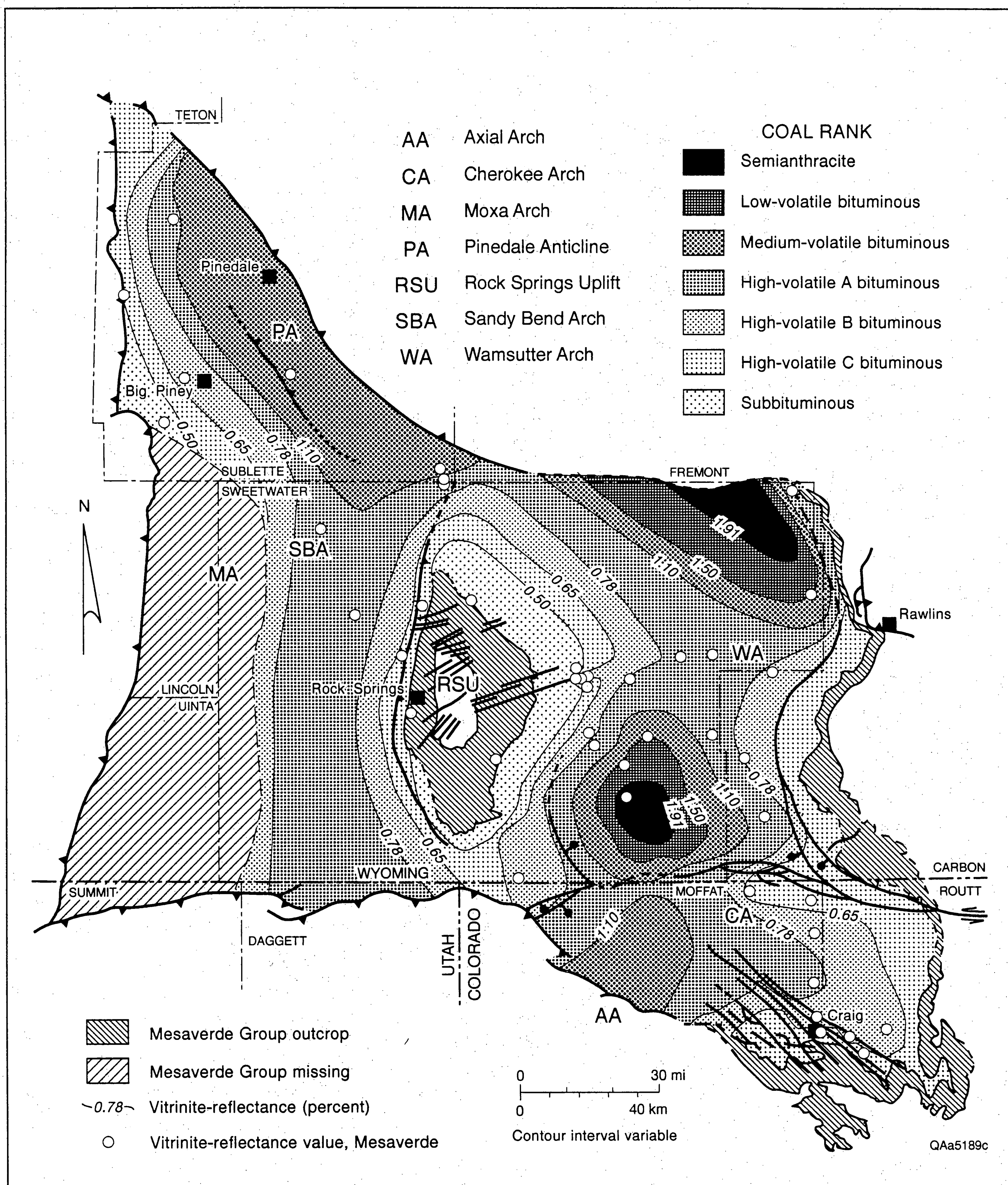


Figure 50. Coal-rank map, top of the Mesaverde Group. Vitrinite-reflectance and coal-rank trends were estimated by combining several types of data. Most of the vitrinite-reflectance data are from Law (1984) and Scott (1993a, b). Coal rank increases away from basin margins and the Rock Springs Uplift toward high-volatile A bituminous and higher rank coals in deeper subbasins. AA = Axial Arch, CA = Cherokee Arch, MA = Moxa Arch, PA = Pinedale Anticline, RSU = Rock Springs Uplift, and WA = Wamsutter Arch.

Paleofluid flow has contributed to unusually high vitrinite-reflectance values in Patrick Draw field, located off the east flank of the Rock Springs Uplift (Law and others, 1986; Pawlewicz and others, 1986; Law, 1992). Hot fluids migrating along fault planes or fracture systems, or both, have increased vitrinite-reflectance values from approximately 0.48 percent to 0.68 percent in this area (Law, 1992). This increased thermal-maturity level may be localized; however, vertical movement of hot fluids at depth could also have contributed to higher vitrinite-reflectance values in the Washakie Basin. According to McPeek (1981), the CIC Haystack well (Sec. 28, T14N, R96W) has 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 in the Pinedale Basin, northeast of the Rock Springs Uplift, and the 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 we need more evidence to confirm this hypothesis.

Coal rank in the Greater Green River Basin ranges from subbituminous to medium-volatile bituminous (measured R_m values of 0.47 to 1.22 percent, respectively). Lower coal ranks in the Green River Basin reflect a complex burial history. Sedimentation and burial in the east half of the basin, away from the basin margins and the Rock Springs Uplift, were relatively simple, whereas burial history in the west half of the basin along the Moxa Arch was more complex. Dutton and Hamlin (1992) and Dutton (1993) described the burial history of the Moxa Arch in detail. During the Late Cretaceous, uplift of the south end of the Moxa Arch resulted in erosion of Rock Springs and lower Mesaverde sediments (Dutton, 1993). After the Eocene, subsequent uplift of the north end of the arch produced the present southward plunge. The thickest Tertiary deposits lie at the south end of the arch because of subsidence of the southern arch during the Early Cretaceous and uplift of the north end after Eocene time (Curry, 1973; Sullivan, 1980). This oscillatory movement of the arch, northward plunge followed by uplift and southward plunge, resulted in relatively shallower burial depths and lower coal ranks along the Moxa Arch because the maximum burial depths were less than if continuous subsidence had occurred. Furthermore, influx of meteoric waters along the Moxa Arch during the unconformity would lower temperatures and inhibit thermal maturation. According to Law (1992), vitrinite-reflectance values from the Dakota sandstone at 15,000 ft (4,572 m) in Lucky Ditch field (T12N, R114W) are only 0.6 percent, vitrinite-reflectance profiles being almost vertical. This area of low geothermal gradients and coal rank may have resulted from temperatures being lowered by the descent of cool meteoric waters (Law, 1992).

Law and others (1980), Dickinson, (1989), Law and Johnson (1989), Lickus and others (1989), and Spencer (1989) discussed burial history, geothermal gradients, regional overpressure, and thermal maturity patterns in the northern Green River Basin (which includes the Pinedale Basin and Pacific Creek area; area I in fig. 47) in detail. The structural growth of the Wind River Mountains to the north controlled the burial history of the northern Green River Basin. The Wind River Mountains probably began to form during the Late Cretaceous or early Paleocene, and the Precambrian core of the mountains was probably exposed during the middle Paleocene (Law and Johnson, 1989, and references therein). Depression of the lithosphere by the Darby and Prospect thrust plates associated with the Wind River Uplift resulted in subsidence in the northern Green River basin (Schuster and Steidtmann, 1983). Structural growth of the Pinedale Anticline, which is probably associated with thrusting, began during the Late Cretaceous and continued through Eocene time (Law and Johnson, 1989). Although not shown in figure 50, isoreflectance lines parallel anticlinal structure and suggest that thermal maturation occurred before structural development, or hotter-than-present-day temperatures around the anticline resulted in higher vitrinite-reflectance values; these structures may have acted as the focus of vertical movement of hot fluids that locally affected maturation trends (Dickinson, 1989; Lickus and others, 1989). The higher vitrinite-reflectance values may result from greater maximum burial depths and/or higher paleogeothermal gradients in the northern Green River Basin relative to the Moxa Arch and southern Green River Basin.

Thermal Maturity of the Fort Union Formation

More than 55 Fort Union vitrinite-reflectance data from 26 wells in the Greater Green River Basin were available for determining vitrinite-reflectance and coal-rank trends (fig. 51). We supplemented these data using proximate and ultimate analyses from outcrops, and vitrinite-reflectance data from the Lance Formation constrained contouring in areas where Fort Union data were scarce. Vitrinite-reflectance and coal-rank data are from Glass (1975), Law (1984), Lickus and others (1989), and Scott (1993a, b).

Coal rank ranges from subbituminous along basin margins and around the Rock Spring Uplift to low-volatile bituminous in the deeper Washakie Basin, although coal rank throughout most of the basin is subbituminous to high-volatile C bituminous. Vitrinite-reflectance values range from 0.40 to 1.53 percent (Law, 1984).

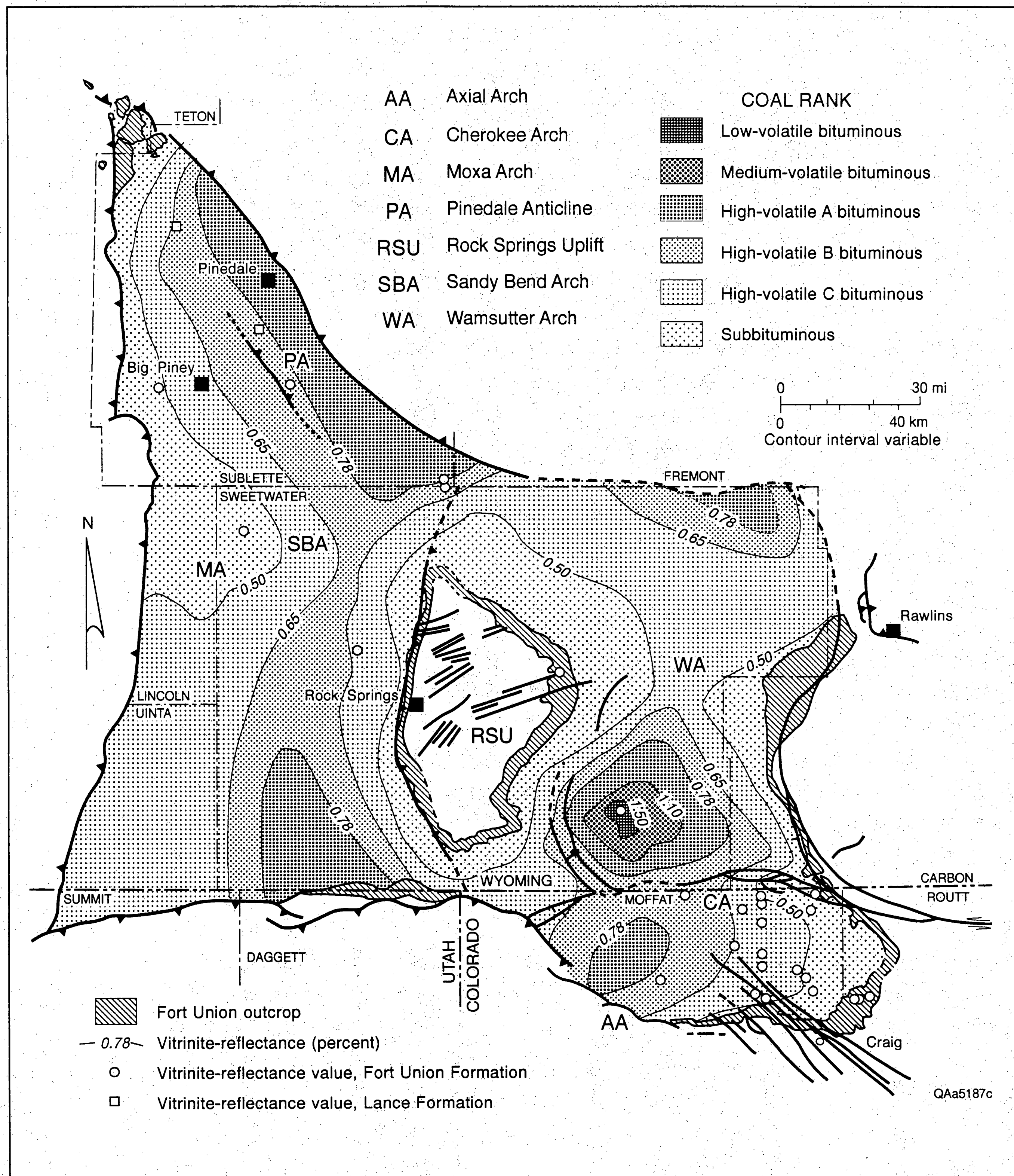


Figure 51. Coal-rank map, base of the Fort Union Formation. Subbituminous coals around basin margins and the Rock Springs Uplift indicate that these structures developed before, or syntectonically with, coalification. Net-coal and coalification trends suggest that although the Wamsutter and Cherokee Arches also formed syntectonically with coalification, they did not become as pronounced as the major uplifts. AA = Axial Arch, CA = Cherokee Arch, MA = Moxa Arch, PA = Pinedale Anticline, RSU = Rock Springs Uplift, and WA = Wamsutter Arch.

Subbituminous coals surrounding the Rock Springs Uplift and along the Moxa Arch indicate that these structural features were present before coalification or that they formed syntectonically with coalification. Because these structures have numerous unconformities associated with them (Tyler and Hamilton, this volume and references therein), a combination of nondeposition and erosion of Cretaceous and Tertiary sediments along basin margins and the Rock Springs Uplift must have resulted in maximum burial depths and coal ranks being shallower and lower, respectively. Coal distribution in the Fort Union (Tyler and Hamilton, this volume, fig. 46) supports this conclusion. The thinning of net-coal trends, absence of coal over these structures, or both, indicate that these structures had probably formed by Late Cretaceous to early Paleocene time before coal deposition.

Coalification patterns (figs. 50 and 51) suggest that the Cherokee and Wamsutter Arches were present before, or formed syntectonically with, coalification. Fort Union net-coal trends in the Sand Wash Basin are, however, orthogonal to the Cherokee Arch (Tyler and Hamilton, this volume, fig. 46), suggesting that the Cherokee Arch may have affected depositional trends only insignificantly. Although this structural feature may have been present, development and/or exposure was not as great as that of the Rock Springs Uplift and Moxa Arch. Thermal maturity decreases (figs. 50 and 51) and net-coal trends thin slightly over the Wamsutter Arch (Tyler and Hamilton, this volume) suggesting that development of this feature was syntectonic with coalification. However, relatively greater structural development, exposure of the Wamsutter Arch, or both, probably occurred during Fort Union deposition.

Coal rank in the western Greater Green River Basin is high-volatile A bituminous and lower ranks (fig. 51). Lower coal ranks along the Moxa Arch (subbituminous and high-volatile C bituminous) result from relatively shallow maximum burial depths, low geothermal gradients, or both. Vitrinite-reflectance trends in the northwestern Green River Basin (area I; fig. 47) generally follow Tertiary structures (Lickus and others, 1989), suggesting that structural deformation occurred after the main stage of coalification. Possible vertical migration of hot fluids, however, could make the relation between coalification and structural events difficult to interpret in this area (Lickus and others, 1989).

Gas Content of Cretaceous and Tertiary Coals

Gas-content measurements from 560 whole core, sidewall core, and cutting samples in 33 wells were available in the Greater Green River Basin (Boreck and others, 1981; Tremain and Toomey, 1983; Diamond and others, 1986; Kelso and others, 1991; Scott, 1993a, b). Most data are from the Sand Wash Basin, from which 387 gas-content analyses from 25 wells were available. Gas-content measurements from 166 coal samples from 9 wells around the north part of the Rock Springs Uplift and 7 coal samples from 1 well along the La Barge Platform were also compiled. We measured all gas contents using the U.S. Bureau of Mines method and corrected them to an ash-free basis when proximate data were available. In the absence of proximate data, all ash-content values from the same well were averaged to correct the gas contents to a calculated ash-free basis.

These factors affect gas-content measurements: coal rank, basin hydrodynamics, localized pressure variations, sample type, sampling procedures, coal properties, analytical methods, and sample quality. Gas content changes vertically between coal beds and laterally within individual coal beds between wells (Scott, 1993b, c). Variability in gas-content values could result when pressure between seams, sample type, coal characteristics, analytical methods and quality, migration of gases in coal beds, or all of these, vary.

Gas Content in Mesaverde Group

Gas-content values from the upper Mesaverde Group, which contain coals from the Almond, Williams Fork and the Ericson Formations, range from less than 1 to more than 540 scf/ton (<0.0312 to >16.8 m^3/t) but are generally less than 200 scf/ton (<6.24 m^3/t) (fig. 52a). Most gas-content data are from Almond and Williams Fork coals in the Sand Wash Basin, although we also used gas content data from Almond and Ericson Formation coals north of the Rock Springs Uplift. Gas content versus depth profiles of upper Mesaverde Group coals in the Sand Wash Basin show a gradual increase in gas content and wide scatter of gas-content data with increasing burial depth (fig. 53), much the way gas-content profiles do in other western basins (Scott and Ambrose, 1992). Coal rank does not increase significantly with depth in this area (Scott, 1993a), indicating that local pressure variations, variability of coal characteristics, and/or migration of thermogenic and/or biogenic coalbed gases and conventional trapping affect gas contents. Gas contents of samples shallower than 1,000 ft (<305 m) are less than 20 scf/ton (<0.6 m^3/t), indicating that coalbed gases may have migrated out of the system because confining pressures are low, seals are absent, or both.

Anomalously high Mesaverde gas contents adjacent to the major northwest-trending fault system and along the east part of the Cherokee Arch in the Sand Wash Basin may result from migration and conventional trapping of

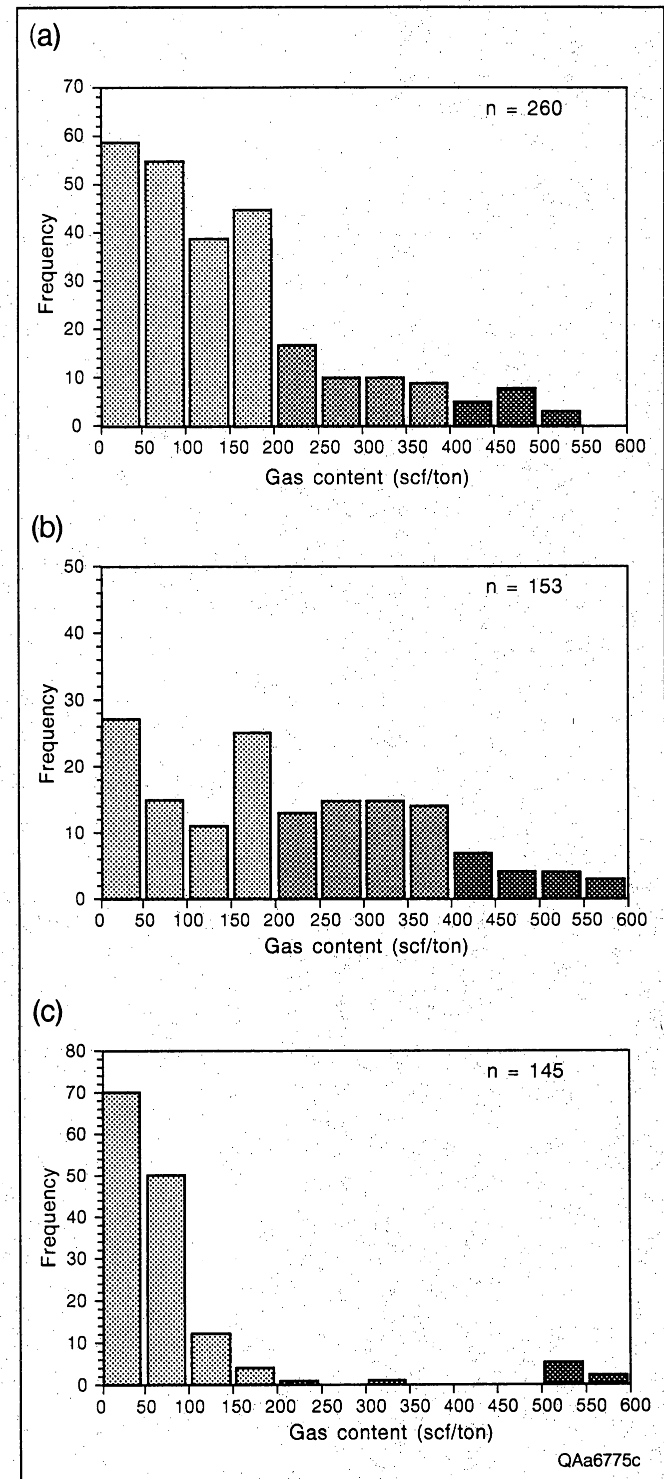


Figure 52. Histograms of gas content values: (a) upper Mesaverde Group, (b) lower Mesaverde Group, and (c) Fort Union Formation. Gas contents in the upper Mesaverde are generally less than 200 scf/ton (<6.24 m^3/t), whereas gas contents in the Fort Union are generally less than 100 scf/ton (<3.12 m^3/t). Lower Mesaverde gas content data are predominantly from the Rock Springs Formation north of the Rock Springs Uplift. Data from Boreck and others (1981); Tremain and Toomey (1983); Diamond and others (1986); Kelso and others (1991); and Scott (1993a, b).

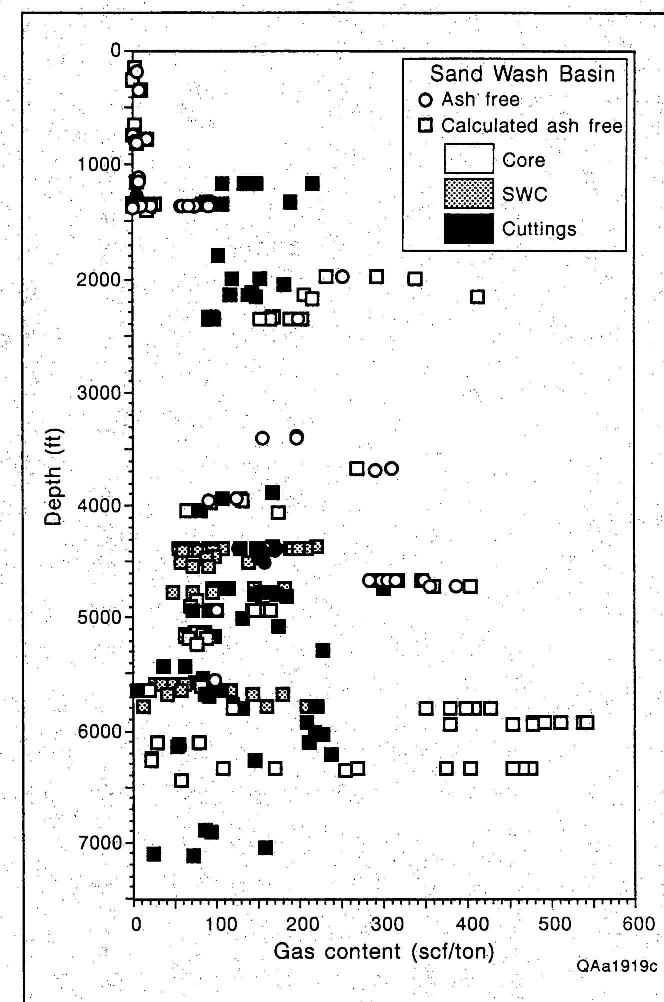


Figure 53. Gas-content profile of the upper Mesaverde Group, Sand Wash Basin. Gas content increases with depth as in other western U.S. basins. Gas content values vary widely at any particular depth. Sidewall cores and cuttings generally have lower gas contents than do whole cores. Ash-free values were calculated from average ash contents of adjacent coal beds. From Scott (1993a).

biogenic or thermogenic coalbed gases, or both, as well as overpressured conditions. Non-ash-free gas content of coals at 5,900 ft (1,798 m) in the Morgan Federal 12-12 well (Sec. 12, T8N, R93W) averages 414 scf/ton (13.0 m^3/t) (fig. 54), where coal beds pinch out behind a northeast-trending shoreline sandstone (Hamilton, 1993). Furthermore, this well is on the downthrown (northeast) side of a northwest-trending fault system (Tyler and Tremain, 1993), suggesting that the high gas contents may result from a combination of structural and stratigraphic trapping of migrating gases (Scott, 1993b). Conventional trapping of migrating gases during the main stage of coalification may have occurred, depending on the timing of fault development during migration of early thermogenic gases or during basinward migration of biogenic gases by ground water, or both.

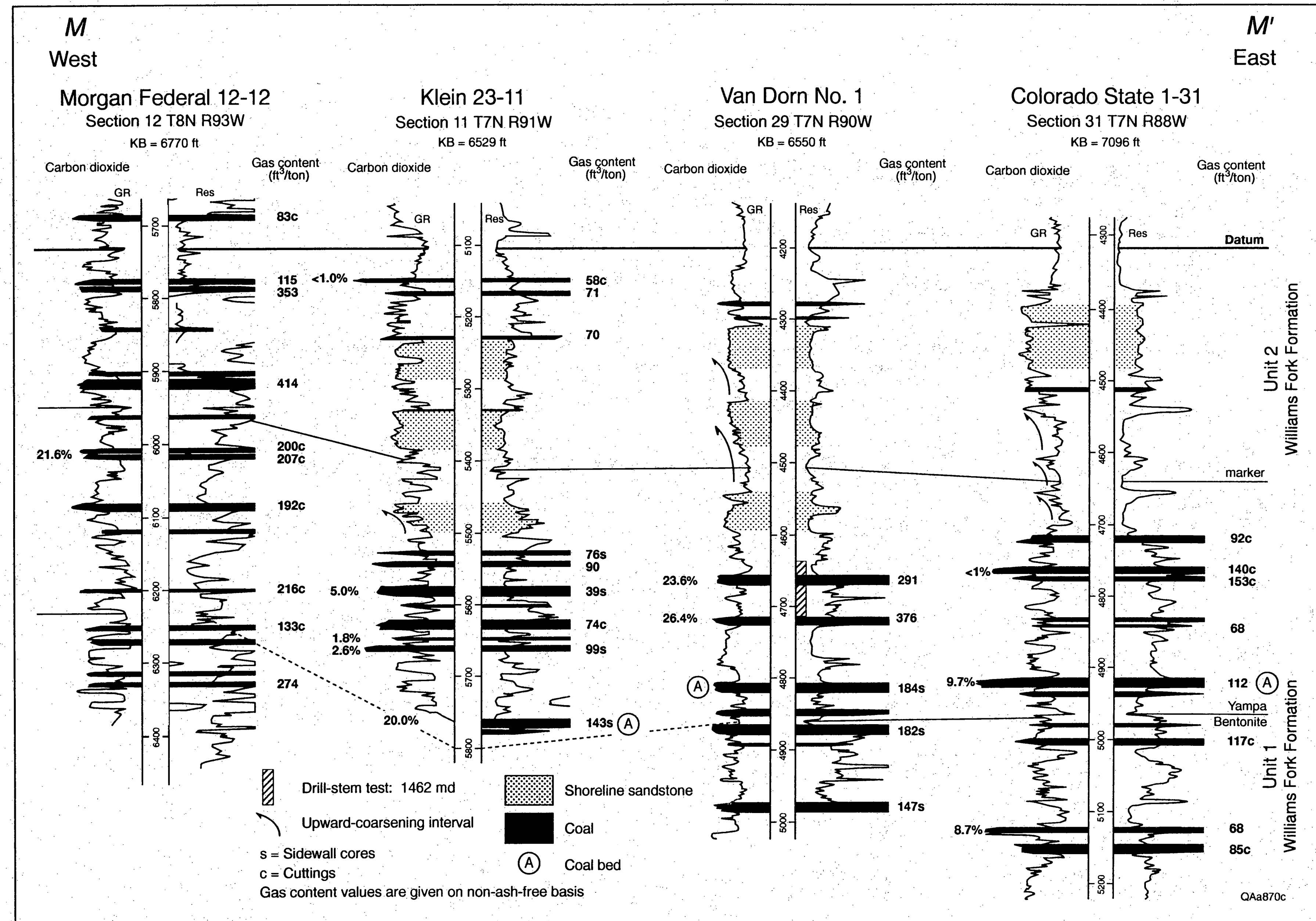


Figure 54. West-east cross section showing changes in gas content and gas composition between different Mesaverde coal beds. The high gas contents in coal beds at 5,900 ft (1,799 m) in the Morgan Federal 12-12 well may be caused by stratigraphic and structural trapping of migrating coalbed gases. From Scott (1993a).

Gas contents in the lower Mesaverde, which includes Rock Springs and Iles Formation coals, range from 0 to more than 650 scf/ton (0 to >20.3 m^3/t) (fig. 52b). Most of the gas-content data come from 7 wells near the north end of the Rock Springs Uplift although 11 Iles Formation coals from 1 well in the Sand Wash Basin are included in the gas-content ranges. On the basis of gas-content data from two coalbed methane wells in the northern Rock Springs Uplift area, Young and others (1991) and Kelso and others (1991) noted that gas-content profiles are unusual because gas content decreases with depth; gas-content data from five additional coalbed methane wells in the same area support these conclusions. Gas content in coals from the Fort Union, Almond, Ericson, and Rock Springs Formations at depths less than approximately 3,000 ft (<984 m) generally have gas contents less than 100 scf/ton (<3.12 m^3/t). Maximum gas content in Rock Springs coals, however, increases between depths of 3,000 ft and 3,700 ft (984 and 1,214 m) and then decreases at greater depths (fig. 55). Young and others (1991) and Kelso and others (1991) noted that sorption capacity (reflected by Langmuir volumes) generally decreases with depth, indicating that the gas-storage capacity, and therefore maximum gas-content values, should also decrease. Reasons for the changes in Langmuir volumes remain uncertain, although the distribution of 12Å micropores in the coal may control sorption capacity (Schwarzer, 1983). Coal beds within the same well can vary significantly in sorption capacity (Scott, 1993b), and more desorption data from Rock Springs coals in this area may be required to confirm that the decrease in Langmuir volume with increasing depth is a valid trend rather than coincidental. Because we had no gas-content data from Fort Union, Almond, or Ericson coals greater than 3,000 ft (>984 m), gas-content profiles in these formations may or may not be similar to Rock Springs Formation profiles.

Gas-storage capacity is generally assumed to increase with increasing coal rank (Kim, 1977). Research by Moffat and Weale (1955), Patching (1970), Thomas and Damberger (1976), and Schwarzer (1983), however, demonstrates that plugging of pores by bitumen reduces the methane sorption capacity with increasing rank until R_m values of approximately 0.9 percent are attained. The storage capacity subsequently increases with increasing thermal maturity as the bitumen is thermally cracked to produce additional micropores for sorption. The increase and subsequent decrease in gas content data in the northern Rock Springs area is independent of coal rank (fig. 56), however, suggesting that other factors may be influencing gas-content profiles. Basin hydrodynamics plays an important part in coalbed methane producibility (Kaiser and others, in press) and may contribute to the unusual gas-content profile in the northern Rock Springs Uplift. The interval in which gas contents increase with depth also corresponds to changes in water chemistry, where higher gas contents are generally associated with more saline waters. The presence of higher gas contents at the interface between fresh and saline formation waters therefore suggests that gas content is related to basin hydrogeology. The change in water chemistry may also reflect a decrease in permeability within coal beds that inhibits both the basinward movement of fresh water and the updip migration of methane from higher rank coals and shale deeper in the basin (fig. 56). Young and others (1991) noted that gas content in coal beds enclosed by shales is significantly higher than gas content in coals adjacent to sandstones, suggesting that conventional trapping of gases may explain the higher than expected gas contents in this area. Gas contents probably increase with increasing coal rank and burial depth, as suggested by Kelso and others (1991).

Gas Content in Fort Union Formation

Ash-free gas contents in the Fort Union Formation are generally less than 100 scf/ton (<3.12 m^3/t) (fig. 52c) but range from 9 to 561 scf/ton (0.3 to 17.5 m^3/t). Fort Union coals having the highest gas content values are from the Belco Petroleum Unit S-29-27 well (Sec. 28, T30N, R113W) (Diamond and others, 1986). These coals were reported to be from the Mesaverde Group but are operationally placed in the Fort Union Formation (Roger Tyler, personal communication, 1993). Although coal rank may be high-volatile A bituminous (Diamond and others, 1986), vitrinite-reflectance measurements ranging from 0.47 to 0.53 percent (Schwarzer, 1983) indicate that the coals may actually be subbituminous to high-volatile C bituminous. Suppression of vitrinite-reflectance values by bitumen (generated during the coalification) in Fort Union coals has been reported previously (Scott, 1993a), suggesting that the coals may be of higher rank than indicated by vitrinite reflectance. Vitrinite-reflectance values from other wells and formations along the northern Moxa Arch (figs. 50 and 51), however, are also low (R_m <0.50 percent; subbituminous), suggesting that the vitrinite-reflectance values may be valid. Regardless of whether the coals are subbituminous or high-volatile A bituminous in this area, artificial maturation experiments suggest that gas contents of 500 scf/ton (15.6 m^3/t) are not achieved until the medium-volatile bituminous rank (R_m ~1.1 percent) is attained (Tang and others, 1991). The unusually high gas-content values in this area therefore probably result from conventional trapping of gases that migrated from deeper, thermally mature parts

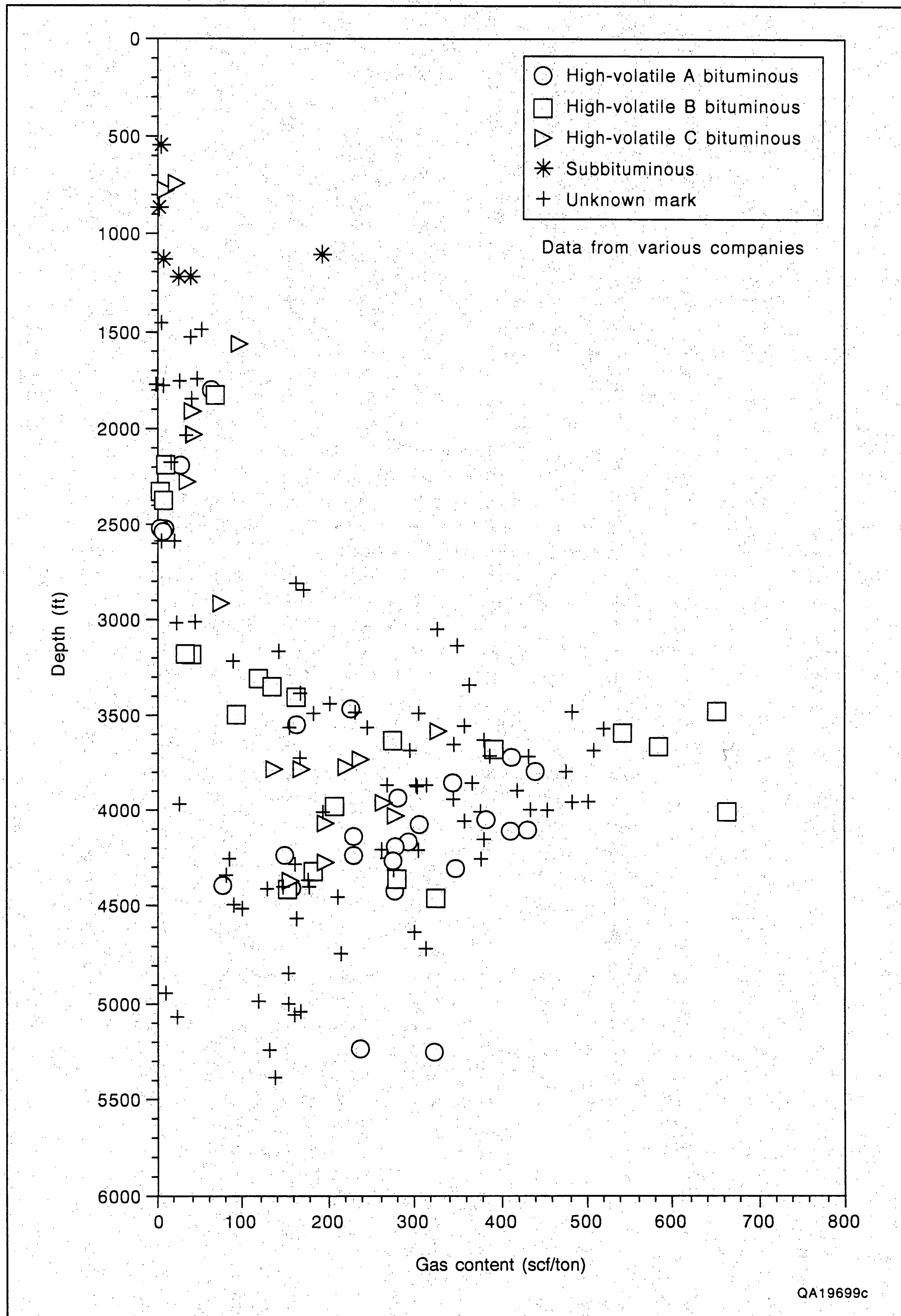


Figure 55. Gas-content profile, northern Rock Springs Uplift. Gas content increases abruptly at 3,000 ft (984 m), peaks at 3,700 ft (1,214 m), and atypically decreases with increasing depth. The same trend is evident irrespective of rank and clearly shows that gas content is not rank related. High gas content appears to be strata bound and may reflect a Pleistocene recharge event and consequent generation of secondary biogenic gas. From Scott and Ambrose (1992).

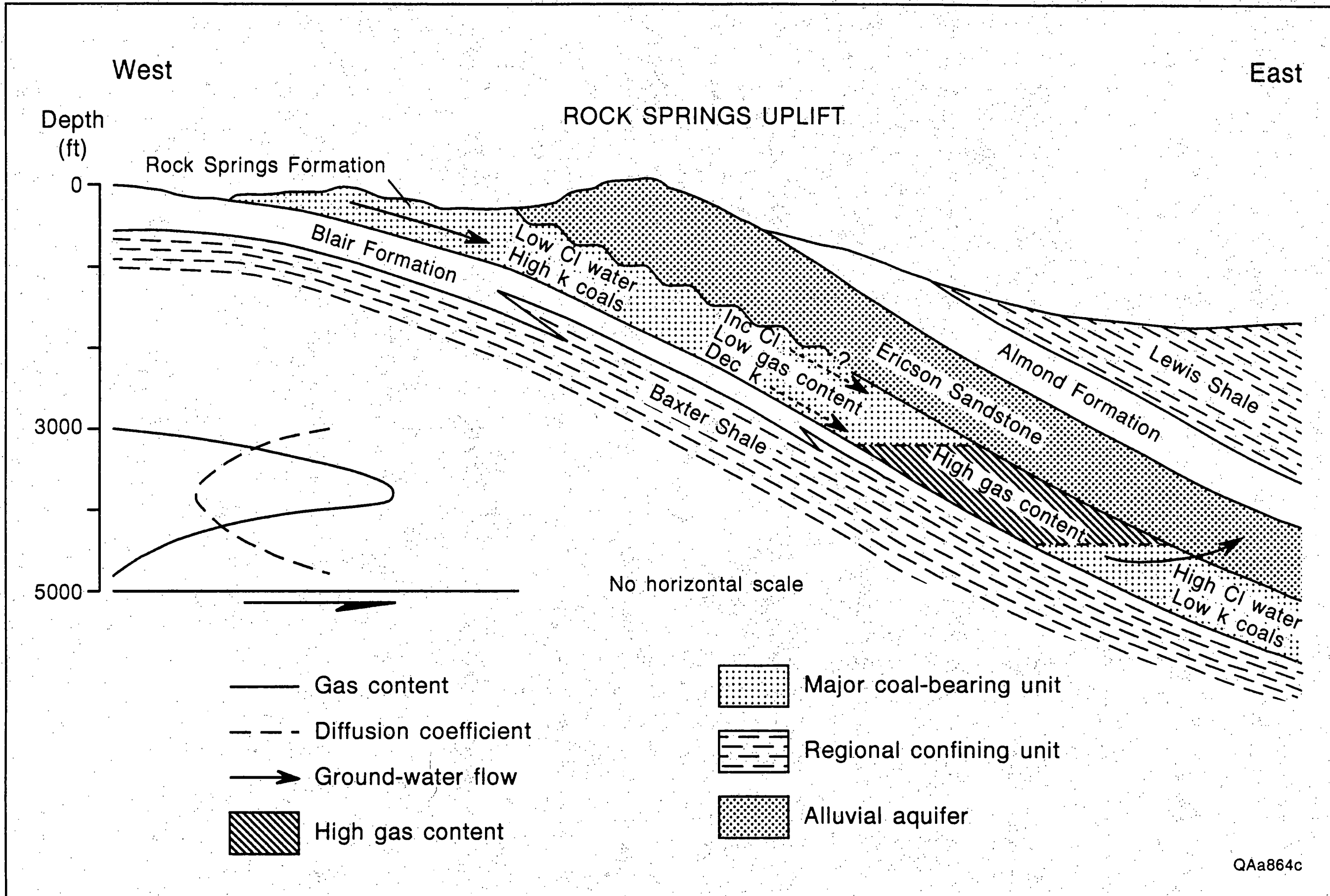


Figure 56. Schematic west-east cross-sectional ground-water flow, Rock Springs Formation, Rock Springs Uplift. Basinward flow of ground water, combined with better confinement, higher pressure, and lower permeability downdip (flow barriers), may serve to trap gas. Resistance to lateral flow, due to increasing coalbed permeability, causes flow to turn upward. Gas content is highest at this point and defines a narrow exploration target. From Kaiser (1992).

of the basin. Alternatively, incorrect sampling procedures can allow bacteria to generate methane and carbon dioxide from the coal after sample collection, resulting in erroneously high gas-content values.

Most of the Fort Union gas-content data are from the Sand Wash Basin. Gas-content profiles from other western basins generally show an increase in gas content with increasing coal rank, burial depth, and pressure (Scott and Ambrose, 1992). Gas-content profiles of Fort Union coal beds in the Sand Wash Basin are, however, unusual because gas content remains relatively constant with increasing burial depth (fig. 57). Gas content changes only insignificantly among sample types (whole core, sidewall core, cuttings), suggesting that factors other than sample quality are affecting this profile. Vitrinite-reflectance values also remain constant with increasing depth (Scott, 1993a), suggesting a relationship between low gas content and coal rank.

Composition of Cretaceous and Tertiary Coalbed Gases

Coal rank, basin hydrodynamics, and maceral composition affect coalbed gas composition (Scott and Kaiser, 1991). The gas dryness index (the ratio of methane to methane through pentane; C_1/C_{1-5}) reflects the amount of chemically wet gases generated during the thermal maturation of hydrogen-rich coals. Such coals in the oil-window or oil-generating stage (vitrinite reflectance of 0.5 to 1.2 percent) often produce large amounts of wet gases (ethane and propane, among others), whereas coals having vitrinite-reflectance values of less than 0.5 percent or greater than 1.2 percent will generate relatively few wet-gas components and have C_1/C_{1-5} values near unity

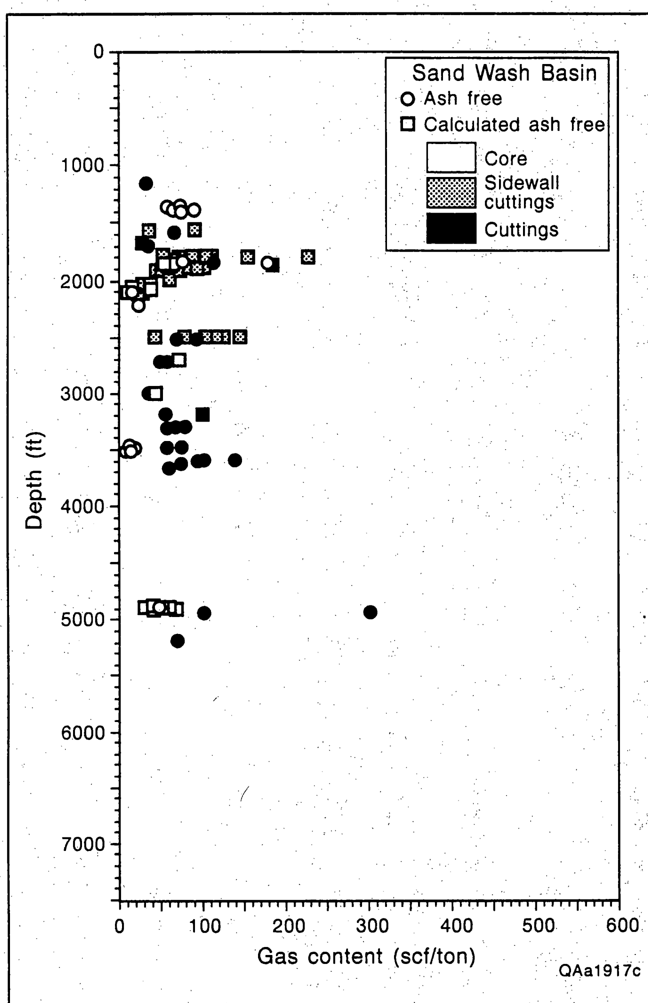


Figure 57. Gas-content profile, Fort Union coals, Sand Wash Basin. The slightly higher gas content values at 1,800 ft (549 m) are from wells in T12N, R91W, an area of artesian overpressure. Ash-free values were calculated from average ash contents of adjacent coal beds. From Scott (1993b).

(Scott and others, 1991b). Alteration of coalbed gases also affects coalbed gas composition. Bacterial alteration of chemically wet gases can remove nearly all of the wet-gas components, producing chemically dry gases resembling thermogenic methane (James and Burns, 1984). Furthermore, mixtures of biogenic and thermogenic coalbed gases are difficult to identify using only gas dryness indices and methane isotopic data. The isotopic composition of carbon dioxide from coal beds may prove to be more useful in determining the biogenic or thermogenic nature of coalbed gases than would methane isotopic data alone, particularly when mixtures of thermogenic and biogenic methane may be present.

Limited coalbed gas compositional data are available from the Greater Green River Basin (Tremain and Toomey, 1983; Scott, 1993a, b, c). Although no produced coalbed gases were available for analysis in the basin, the compositional ranges of desorbed coalbed gases were available for evaluation. These gases will generally contain more carbon dioxide, nitrogen, and wet-gas components than will produced gases (Scott, 1993c). Higher desorption temperatures produce more carbon dioxide and wet gases (Mavor and others 1991a).

Mesaverde Group Coalbed Gas Composition

The chemical compositions of desorbed gas samples from 36 coal samples in 6 Mesaverde wells were used to evaluate the chemical composition and origin of Williams Fork coalbed gases. Although no produced coalbed gases in the basin were available for analysis, we knew that the compositional ranges of a large number of desorbed coalbed gases could approximate the compositional ranges of produced gases (Scott, 1993c). Desorbed coalbed gases generally contain more carbon dioxide, nitrogen, and wet-gas components (Mavor and others, 1991a; Scott, 1993c), particularly if higher temperatures are used during desorption. The gas dryness index ranges from 0.79 to 1.00 and averages 0.95 (fig. 58), values similar to Fruitland coalbed gases in the San Juan Basin (C_1/C_{1-5} range of 0.77 to 1.00; average of 0.96; Scott and others, 1991a, b). Carbon dioxide content in Mesaverde coal beds ranges from less than 1 to more than 25 percent (fig. 59), a range similar to that in Fruitland coalbed gases, which range from less than 1 to more than 25 percent (Scott and others, 1991a, b; Scott, 1993b, c). The average carbon dioxide content of Mesaverde coals in the Sand Wash Basin (6.7 percent) is similar to the average carbon dioxide content of coals from the north part of the San Juan Basin (6.4 percent; Scott and others, 1991a, b) and slightly more than the overall average of Fruitland carbon dioxide content (4.5 percent). Nitrogen content in Mesaverde coalbed gases ranges from less than 1 to 20 percent and averages approximately 4 percent, an average significantly higher than the average Fruitland coalbed nitrogen values (<0.1 percent; Scott and others, 1991a, b). The higher average nitrogen values of Williams Fork coalbed gases may result from gas sampling; these gases were desorbed from coal samples, thus increasing the possibility of air contamination. Fruitland data are from produced coalbed gases.

Although gas composition changes vertically between coal beds within individual wells and laterally between wells (fig. 54), at least one coal bed, which can be traced laterally over several tens of miles using density log profiles, has consistently high carbon dioxide values

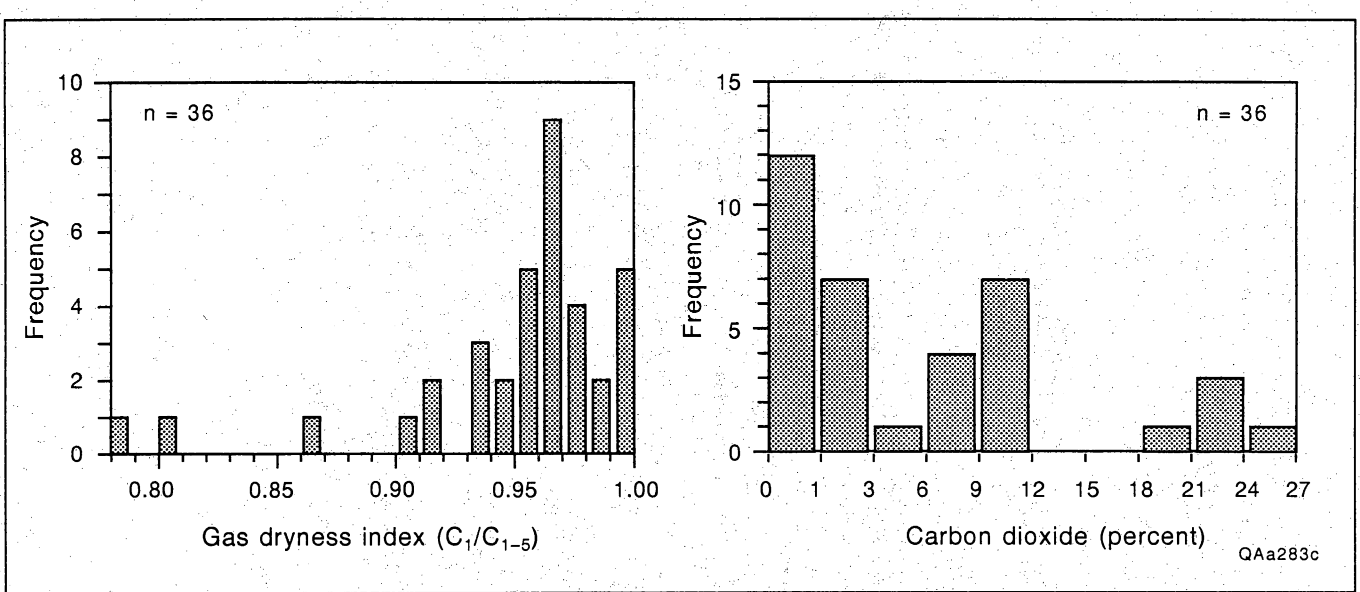


Figure 58. Composition of Mesaverde coalbed gases. Desorbed gases have a wide range of chemical compositions. Coal beds have entered the early gas-generation stage as indicated by the minor amounts of wet gases in the samples. High carbon dioxide content in some coal beds may reflect bacterial activity, gas migration, and/or variations in maceral composition. From Scott (1993a).

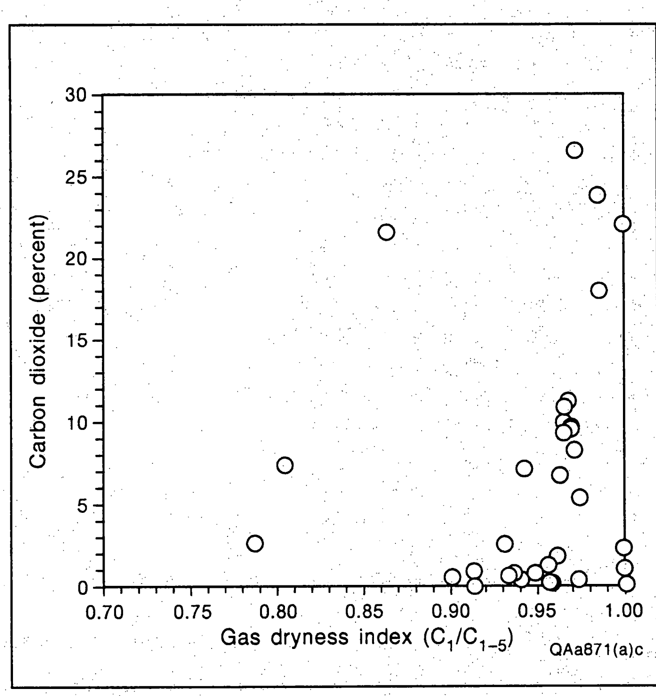


Figure 59. Variation of carbon dioxide content with the gas-dryness index (C_1/C_{1-5} values). Coals having high carbon dioxide contents generally have dry gases, although coals in the Morgan Federal 12-12 and Colorado State 1-31 wells have wet gases. From Scott (1993a).

near or above 10 percent (fig. 54). This situation suggests that factors controlling gas composition, such as basin hydrodynamics, gas migration, maceral composition, biogenic activity, or a combination of these factors, can operate consistently over laterally extensive areas in continuous seams. Coals having high carbon dioxide contents are generally characterized by high C_1/C_{1-5} values (fig. 59). Furthermore, coal beds in the lower part of the Williams Fork Formation (units 1 and 2) contain more carbon dioxide and fewer wet-gas components than do coals in units 3 and 4 of the upper Williams Fork Formation. Coal beds from the Morgan Federal 12-12 well (Sec. 12, T8N, R93W), however, tend to have chemically wet gases and relatively high carbon dioxide content (fig. 54), characteristics similar to those of coalbed gases in the northern Piceance Basin (Scott, 1993c).

Fort Union Formation Coalbed Gas Composition

Desorbed coalbed gas compositional data were available from 20 coal samples from 3 coalbed methane wells in the Sand Wash Basin; however, most of the data are from partial analyses that did not report the amount of carbon dioxide and nitrogen. Gas dryness indices of Fort Union coalbed gases range from 0.86 to 1.00 and average 0.95. These gas dryness indices resemble those of desorbed coalbed gases in the Piceance Basin, which range from 0.79 to 1.00 and average 0.95 (Scott, 1993c).

COALBED-GAS-GENERATING STAGE	VITRINITE REFLECTANCE (percent)
Primary biogenic methane	<0.30
Early thermogenic	0.50 to 0.80
Maximum wet-gas generation	0.60 to 0.80
Onset of intense thermogenic methane generation	0.80 to 1.00
Onset of secondary cracking of condensate to methane	1.00 to 1.35
Maximum thermogenic gas generation	1.20 to 2.00
Deadline for significant gas generation	1.80
Deadline for significant thermogenic methane generation	3.00
Secondary biogenic methane	0.30 to 1.50+

QAa4796c

Figure 60. Types of coalbed gases produced during gas-generating stages. Early thermogenic gases composed of nearly 100 percent methane at low ranks become progressively wetter (higher ethane, propane, butane content) during the wet-gas-generating stage. The wet gases and condensate generated during this stage are thermally cracked to produce additional methane with increasing burial depth and maturation; eventually the gases are composed nearly entirely of methane at higher coal ranks. From Scott (1993c).

Whereas carbon dioxide content in Fort Union coal beds ranges from 4.2 to 6.9 percent and averages 5.4 percent, more gas compositional data are required to evaluate carbon dioxide content of Fort Union coals fully. Nitrogen content data were available for only three samples, and two of these samples contained more than 20 percent nitrogen, indicating air contamination. Nitrogen content of gases produced from subbituminous coals probably varies, whereas nitrogen content in coalbed gases is generally highest in high-volatile C and B bituminous (R_m of 0.5 to 0.8 percent), subsequently decreasing with increasing coal rank (Scott, 1993c). Produced Fort Union coalbed gases could thus have nitrogen contents ranging from 0 to more than 10 percent, depending on rank and maceral composition.

Origin of Coalbed Gases

Determining the source of methane and carbon dioxide in coalbed gases is important for evaluating the origin and regional extent of unusually high gas contents in coal beds; anomalously high gas contents may reflect secondary biogenic gas generation or migration of thermogenic and/or biogenic gases. Coalbed gas composition is directly related to coal rank, basin hydrodynamics, and maceral composition (Scott and Kaiser, 1991; Scott 1993c). Therefore, combining coal distribution and basin hydrogeology with gas compositional and gas content data can help in evaluating gas migration pathways, the nature of the trapping mechanism, and the geographic area in which high gas contents occur.

Various types of coalbed gases are produced during several gas-generating stages (fig. 60). Early thermogenic, thermogenic, and secondary biogenic gases are found in coal beds (Scott, 1993c). Primary biogenic gases, generated during the early stages of coalification, are probably not preserved in coal beds (Scott, 1993c) because there is no mechanism for methane sorption. Early thermogenic gases are formed between vitrinite-reflectance values of 0.5 and 0.8 percent and initially have C_1/C_{1-5} near unity. If the coals are hydrogen-rich, then significant quantities of wet gases and condensate can be generated from the coal during the wet-gas generating stage between vitrinite-reflectance values of 0.6 and 0.8 percent (fig. 60) and C_1/C_{1-5} values may be less than 0.90; hydrogen-poor coals may not have a well-developed wet gas generating stage. Once a certain threshold of thermal maturity is reached during the high-volatile A bituminous rank, significant quantities of thermogenic gases are generated. With continued maturation, wet gases and condensate produced during the wet gas generating stage are thermally cracked. The thermal cracking of higher n-alkanes to methane combined with increased methane generation results in a progressive increase in C_1/C_{1-5} value toward unity.

The chemistry of coalbed gases can be significantly altered through biogenic activity. Bacterial alteration of chemically wet gases can remove nearly all of the wet gas components (James and Burns, 1984), producing chemically dry gases (C_1/C_{1-5} near 1.0) that resemble gases generated from higher-rank coals. Therefore, understanding basin hydrodynamics is important in evaluating coalbed gas origin. Mixtures of biogenic and thermogenic coalbed gases are difficult to recognize using only gas dryness indices and methane isotopic data. The isotopic composition of carbon dioxide from coal beds may prove to be more useful in determining the biogenic or thermogenic nature of coalbed gases than methane isotopic data alone, particularly in cases where mixtures of thermogenic and biogenic methane may be present.

Although coalbed gases produced in the Greater Green River Basin were unavailable for detailed isotopic analyses, coal rank, hydrogeology, and coalbed geometry can be used to evaluate gas origin. Vitrinite-reflectance profiles of Mesaverde coals indicate that coal beds along basin margins and the Rock Springs Uplift are thermally immature (subbituminous to high-volatile C bituminous) and have not reached the threshold of thermogenic methane generation, which indicate that coalbed gases in these areas are predominantly secondary biogenic. The distribution of C_1/C_{1-5} values around 0.96 (fig. 58) and the low coal rank suggest that early thermogenic gases are probably also present. Gases of high-volatile A bituminous and higher ranks are, however, probably thermogenic, although secondary biogenic gases in higher rank coals may also be present.

Carbon dioxide from Williams Fork coal beds in the Sand Wash Basin is thermogenic, biogenic, or a mixture of both gas types (Scott, 1993b). Large quantities of carbon dioxide are released from coals during coalification, suggesting that much of the carbon dioxide present in these coals could be thermogenic. Because the timing of carbon dioxide generation and retention in relation to the changes in coal adsorptive capacity during coalification remains uncertain or unknown, a biogenic source of some of the carbon dioxide cannot be ruled out. Furthermore, the increase in carbon dioxide with decreasing C_1/C_{1-5} values (fig. 58) suggests that some of the gases may be bacterially derived. Although the carbon dioxide content of individual seams ranges from less than 2 to more than 20 percent within the same well (fig. 54), carbon dioxide content remains consistently high (~10 percent) in some coal beds, which are correlated over tens of miles (Hamilton, 1993). The changes in carbon dioxide content vertically and laterally could result from variations in maceral composition, which could affect the types and quantities of gases generated from the coal, bacterial activity, migration of coalbed gases, or all of these. The presence of wet gases having high carbon dioxide values (fig. 54) in the Morgan Federal 12-12 and Colorado State 1-31 wells may indicate migration of coalbed gases. The carbon dioxide is probably indigenous to the coal beds, whereas the wet-gas components may have originated from shales and carbonaceous shale adjacent to the coal beds or from the coal beds themselves.

Hydrology of the Mesaverde Aquifer and Tertiary Aquifer System, Greater Green River Basin

William R. Kaiser

In the Greater Green River Basin, the major coal-bearing hydrostratigraphic units are the Mesaverde aquifer and the Tertiary aquifer system, in which the lower Tertiary Fort Union and Wasatch Formations are major aquifers. The Mesaverde aquifer is regionally confined below by the marine Mancos Shale and its equivalents to the west and above by the marine Lewis Shale (fig. 3). Coal beds are probably the most important Mesaverde aquifers because of their relatively high permeability (50 to 1,462 md) and lateral continuity (Scott and Kaiser, 1993). The Tertiary aquifer system comprises the Late Cretaceous Fox Hills Sandstone and Lance Formation and is regionally confined below by the Lewis Shale and above by the mud- and shale-rich Green River and Bridger Formations. The Tertiary aquifer system contains the most water-productive sandstones in the greater basin and is as much as 12,000 ft (3,660 m) thick. Permeabilities of Tertiary sandstones range from tens to thousands of millidarcys (Ahern and others, 1981; Collentine and others, 1981).

Mesaverde and Tertiary hydrology was evaluated in reconnaissance analysis of hydraulic head, pressure regime, and hydrochemistry. The Mesaverde is emphasized here because its coals are of highest rank and gas content and, thus, it constitutes the basin's major coalbed methane target. To map hydraulic head, equivalent fresh-water heads were calculated from shut-in pressures (SIP's) recorded in drill-stem tests (DST's) using a fresh-water hydrostatic gradient of 0.433 psi/ft (9.8 kPa/m). DST's having simple pressure gradients (pressure-depth quotients) of less than 0.30 psi/ft (<6.8 kPa/m) were eliminated from the data base because of their uncertain validity, which reflected insufficient shut-in time, bad test data, high gas saturation, pressure depletion, or a combination of these factors (Scott and Kaiser, 1993). The screened data set contained more than 200 Mesaverde DST's from approximately 100 wells and consisted mainly of DST's from the upper Mesaverde Almond Formation. An upper Mesaverde head map was prepared for the east part of the greater basin; Mesaverde coals are largely absent in the west (Tyler and Hamilton, this volume). The single highest head value in each township was contoured to better represent actual fluid-flow potential. Abnormal pressure is defined as that higher or lower than fresh-water hydrostatic pressure. Published total-dissolved-solids (TDS) maps were used to define patterns of ground-water circulation further. Because available water analyses are of questionable validity, TDS maps delineate only regional concentration gradients.

Hydrodynamics

The Mesaverde aquifer crops out along the southeast margin of the Sand Wash Basin and eastern Washakie Basin (Tweto, 1979; Love and Christiansen, 1985) and receives recharge primarily along these margins in the foothills of the Sierra Madre–Park Range and White River Uplifts. Average annual precipitation exceeds 16 inches (40 cm) over most of the outcrop and in places exceeds 20 inches (50 cm) (fig. 61). Although the Mesaverde crops out on the Rock Springs Uplift, recharge is limited by mean annual precipitation of less than 10 inches (<25 cm) and high evaporation rates of 10 times precipitation (Welder and McGreevy, 1966). Annual precipitation at Rock Springs, Wyoming, is about 7 inches (~18 cm). In the Green River Basin, Mesaverde recharge is severely limited by large stratigraphic displacement along major thrust faults, which hydraulically separate the wet basin margins from the basin interior (fig. 6). In other words, the Mesaverde is a fault-severed aquifer (Huntoon, 1985).

In the eastern Greater Green River Basin, the upper Mesaverde potentiometric surface slopes from the eastern recharge area basinward toward major fault systems and potentiometric depressions. A series of large potentiometric mounds occur along the deep central part of the basin (fig. 62), reflecting hydrocarbon overpressure. Equivalent fresh-water heads are greater than 10,000 ft (>3,050 m) and in excess of Mesaverde outcrop elevations. The potentiometric surface, except for one mound, is conspicuously flat off the east flank of the Rock Springs Uplift and slopes off the north and south ends of the uplift, reflecting higher precipitation there (fig. 61).

In the Mesaverde aquifer, hydropressured strata flank areas of regional hydrocarbon overpressure at the basin

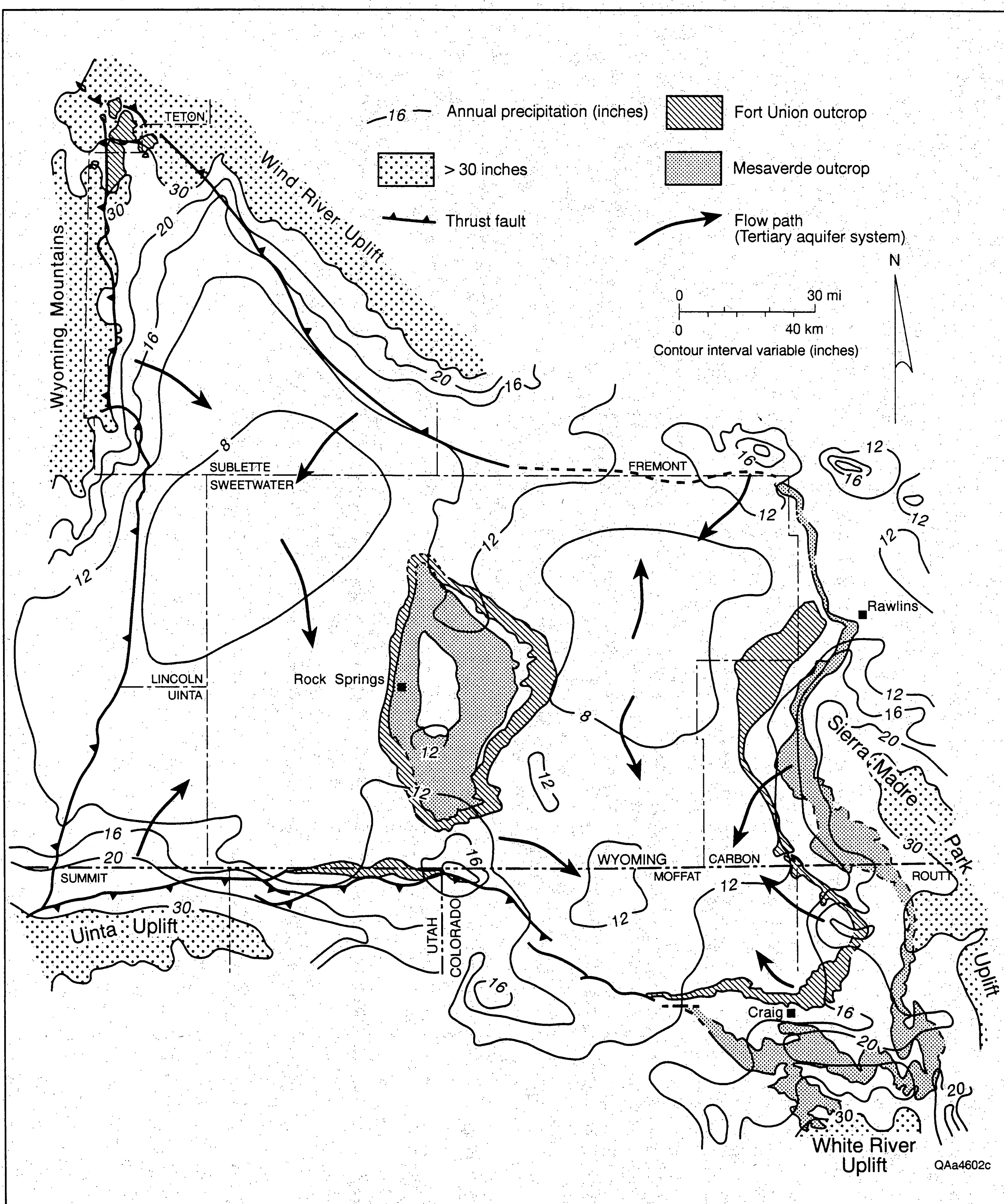


Figure 61. Mean annual precipitation, Greater Green River Basin. Precipitation is highest over highlands on the southeast, northwest, and southwest margins of the basin. Outcrop-related recharge occurs along the foothills of those highlands. In the Tertiary aquifer system, water flows from the wet, elevated basin margins to discharge into major river valleys and basin centers, and flow is dynamic throughout the basin.

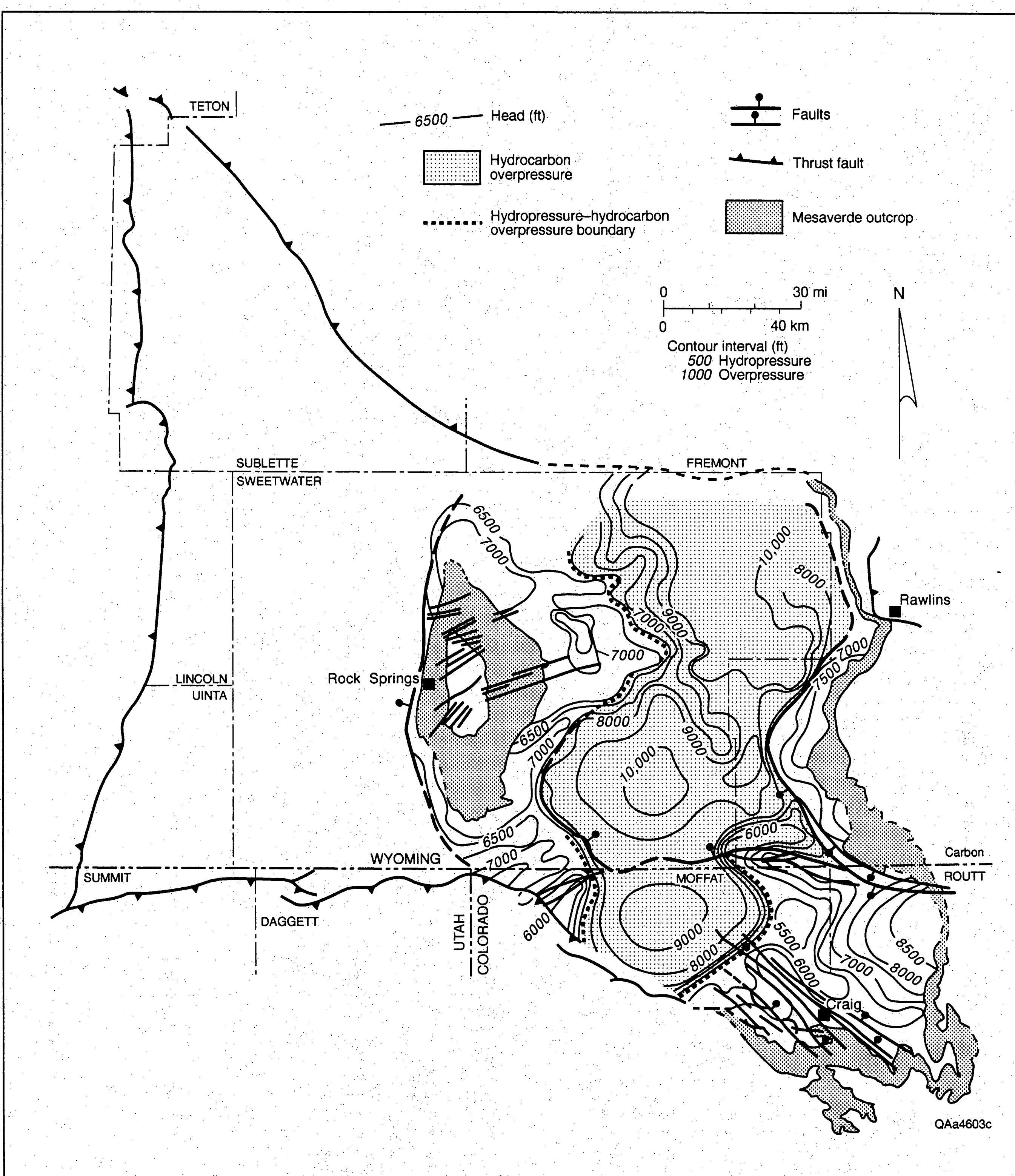


Figure 62. Upper Mesaverde potentiometric-surface map, eastern Greater Green River Basin. Recharge is mainly along the southeast margin of the basin. Ground water flows basinward eventually to discharge along the boundary between hydropressured and regional hydrocarbon overpressure. Flow to the east and west off the Rock Springs Uplift is restricted by low annual precipitation, high evaporation rates, and faults.

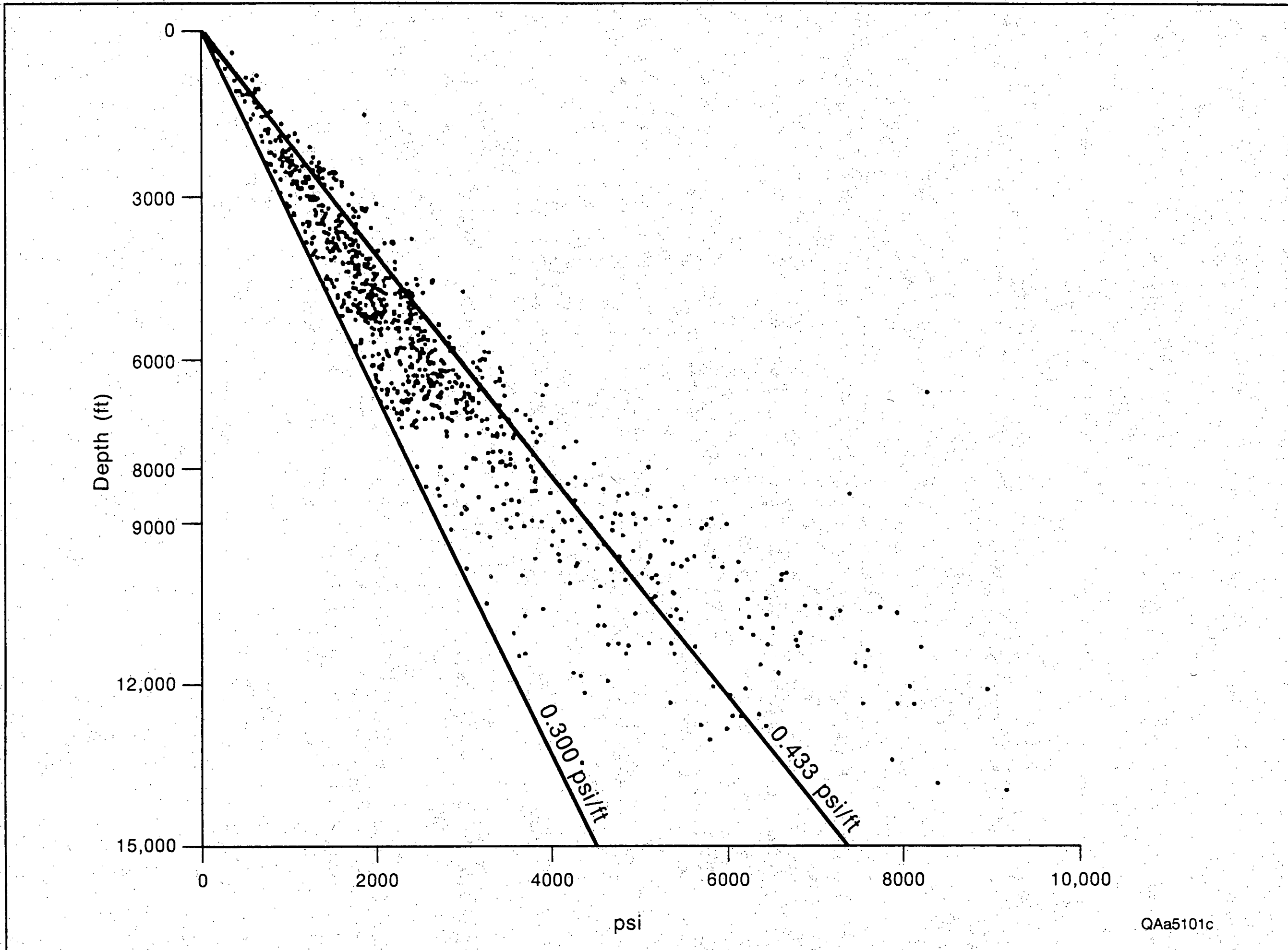


Figure 63. Mesaverde pressure–depth plot, Washakie and Great Divide Basins. Modified from Heasler and Surdam (1993). Hydropressured section is mostly slightly underpressured to normally pressured. Overpressure begins at about 8,000 ft (~2,440 m).

center (fig. 62). In the hydropressured section, no pressure regime regionally dominates. Most simple pressure gradients indicate slight underpressure to normal pressure (fig. 63). Artesian overpressure has been identified on the eastern Cherokee Arch (Scott and Kaiser, 1993), where simple gradients range from 0.44 to 0.54 psi/ft (9.95 to 12.22 kPa/m). Overpressure reflects proximity to the recharge area, basinward confinement, aquifer offset by faults along the Cherokee Arch, and high permeability; flowing artesian wells at Dixon field and southwest of Baggs, Wyoming, attest to artesian conditions in this area (Dana, 1962; Scott and Kaiser, 1993). Overpressure extends approximately 15 mi (~24 km) westward along the arch. Artesian wells southwest of Rawlins, Wyoming (Dana, 1962), indicate the presence of artesian conditions northward along the east margin of the Washakie Basin.

Regional overpressure is encountered at depths of 8,000 ft (2,440 m) or more in the central parts of the basin (figs. 62 and 63). Simple pressure gradients in the Washakie Basin range from 0.50 psi/ft to more than 0.85 psi/ft (11.3 to >19.2 kPa/m) (McPeek, 1981) and typically exceed 0.70 psi/ft (15.8 kPa/m). Hydrocarbon overpressuring is postulated from head data and bottom-hole temperatures (BHT's). Fresh-water equivalent heads are considerably higher than those of the Mesaverde outcrop on the east, indicating that these high heads are not due to artesian conditions. BHT's exceed 200° F (93° C) below depths of 9,000 ft (2,745 m) (Heasler and Surdam, 1993). Overpressuring in the deep basin is predicated on low permeability (<0.1 md) and active generation of gas (Law and Dickinson, 1985; Law and others, 1986) at temperatures above 200° F (>93° C) (Spencer, 1987). Gas rather than water is thus the pressuring fluid, and the potentiometric surface is not a true potentiometric surface because it is not the height to which the fluid column would freely rise. This pseudosurface consists of plateaus and valleys, in which the elevation difference between adjacent plateaus and valleys is as much as 5,000 ft (1,525 m) (Heasler and

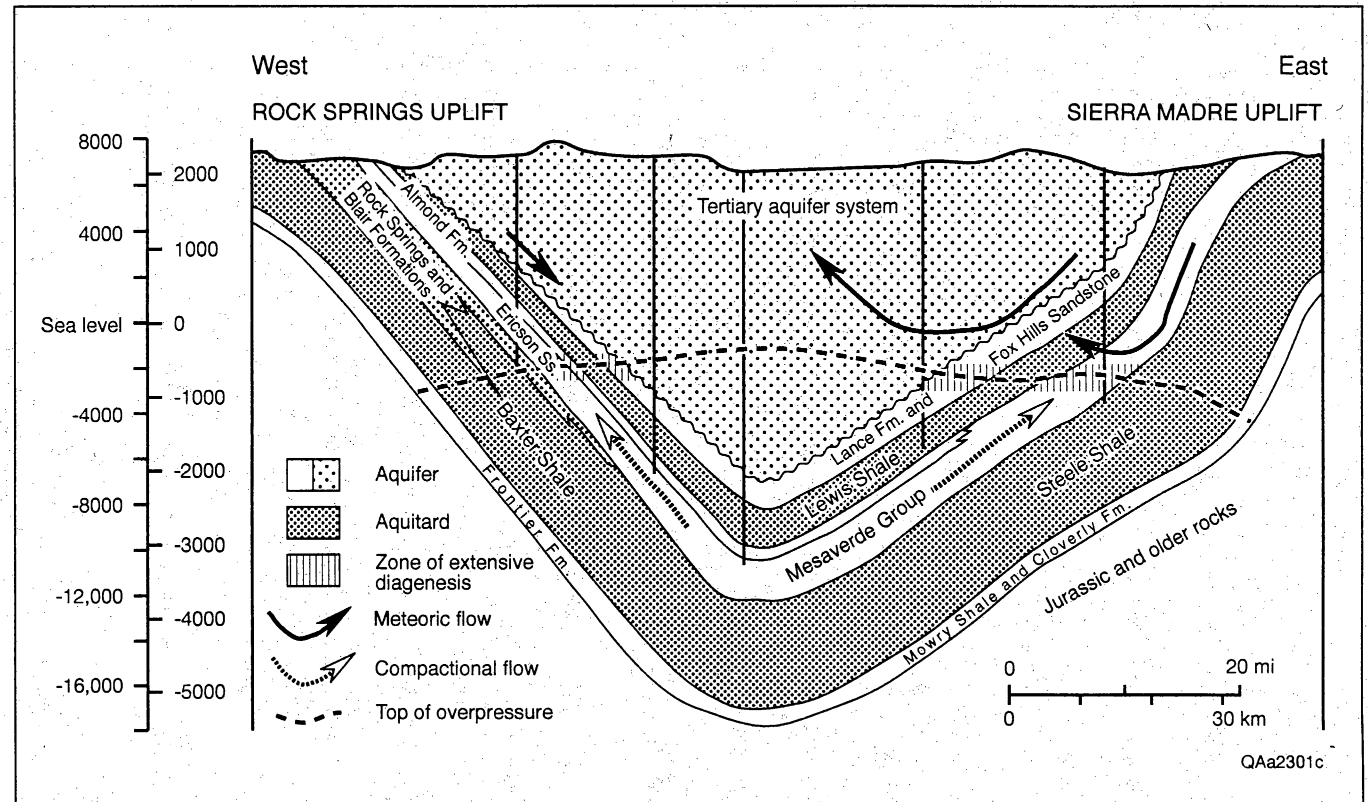


Figure 64. Schematic cross-sectional ground-water flow, Washakie Basin. From Scott and Kaiser (1993). Ground water flows basinward, turning upward upon convergence from the basin margins, aquifer pinch-out, encountering the top of regional overpressure, or a combination of these. Gravity and compactional flow converge at the top of overpressure.

Surdam, 1993). Heasler and Surdam (1992, 1993) postulated that anomalously high and low pressures reflect pressure compartmentalization.

Hydrocarbon overpressure is separated from hydropressure by major fault systems, zones of extensive diagenesis, and facies changes (Scott and Kaiser, 1993). The Savery fault system, which extends northward from Savery, Wyoming, and has as much as 5,000 ft (1,525 m) of throw, and the east-west-trending Cherokee Arch fault system separate shallow hydropressure on the east from hydrocarbon overpressure in the deep Washakie Basin on the west. On the upthrown side of the Savery system, artesian overpressure and normal pressure are present where ground water flows basinward from the east margin of the basin. Where not fault bounded, the boundary is thought to reflect diagenesis and facies changes and is placed at the basinward saddle in the potentiometric surface (fig. 62). On the east flank of the Rock Springs Uplift, the saddle corresponds to depth contours of 8,000 to 9,000 ft (2,440 to 2,745 m) on the top of the Mesaverde. Zones of diagenesis reflect the mixing of meteoric water moving basinward and compactional water moving up and out of the basin (fig. 64). Facies changes and associated loss of permeable elements may also serve to separate the two pressure regions.

Regional Flow

In the Mesaverde aquifer, ground water flows westward from an eastern recharge area, down hydraulic gradient, eventually to discharge basinward along fault systems and facies changes that separate hydropressure from regional hydrocarbon overpressure in the central basin (fig. 62). Fracture flow to the west and northwest along the Cherokee Arch and Cedar Mountain fault systems, respectively, is indicated by potentiometric ridges along the fault zones and hydrochemistry in which chlorinity increases downflow (Scott and Kaiser, 1993). Gravity-driven flow turns upward upon convergence from the basin margins, aquifer pinch-out, or both, and upon encountering the top of geopressure (fig. 64), which because of low permeability and high pressure is a no-flow boundary. Gravity-driven and compactional flow converge along this boundary.

Minor flow occurs off the north and south ends of the Rock Springs Uplift and is even more limited to the east and west off the uplift by low annual precipitation, high evaporation rates, and faults. Sluggish or restricted flow is indicated by the conspicuously flat potentiometric surface on the east and high chlorinity formation waters

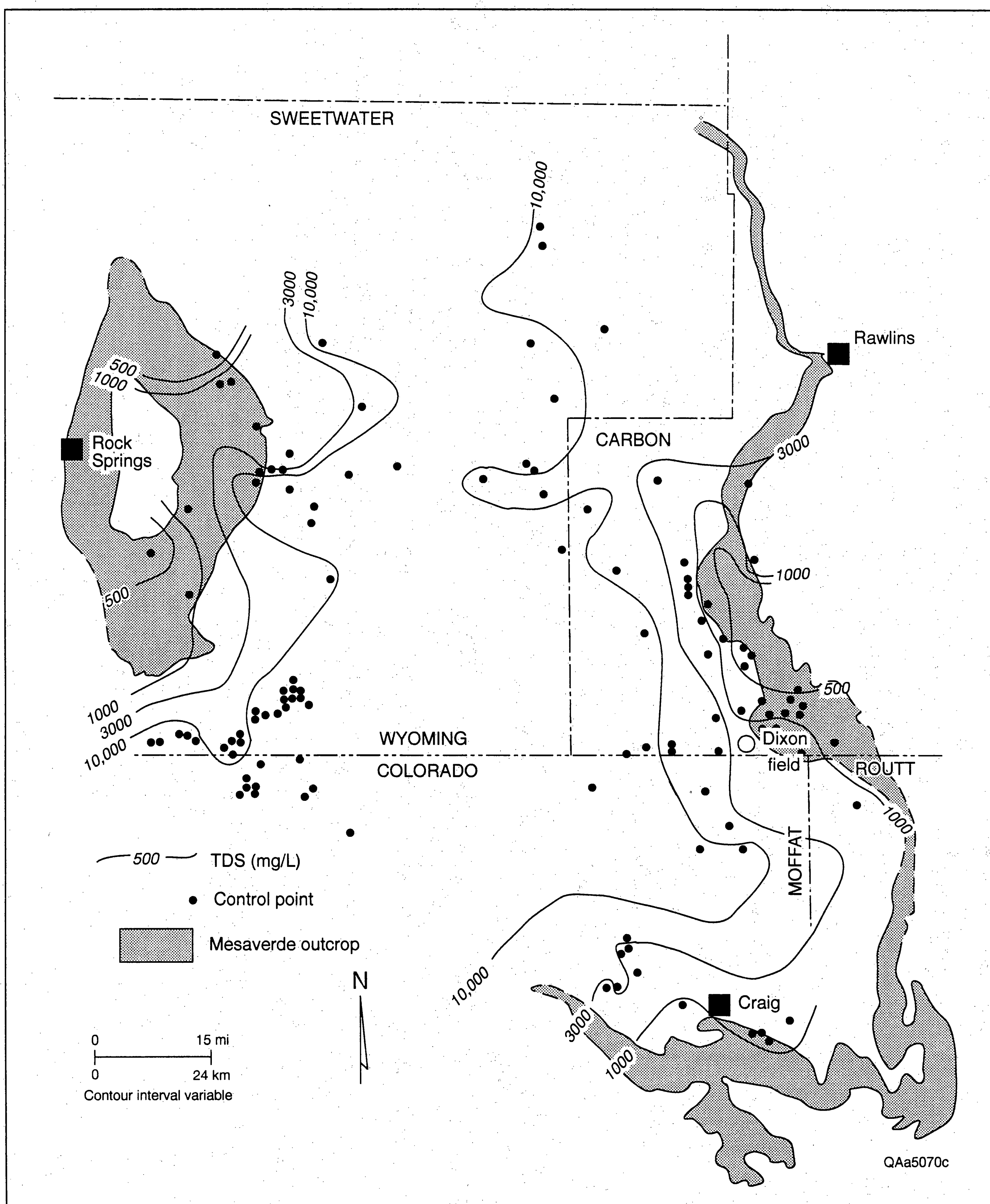


Figure 65. Map of total dissolved solids (TDS), Mesaverde Group, eastern Greater Green River Basin. Modified from Collentine and others (1981). High-TDS waters are close to outcrop on the east flank of the Rock Springs Uplift. Low-TDS waters project basinward, northwest of Craig, Colorado, along the Cedar Mountain fault system, and northwest off the Sierra Madre Uplift.

close to outcrop. TDS contents of less than 1,000 mg/L are limited to outcrop and shallow subsurface on the ends of the Rock Springs Uplift and east margins of the Sand Wash and Washakie Basins (fig. 65). The Mesaverde's most saline waters are found on the east flank of the uplift at a relatively short distance from outcrop (Collentine and others, 1981). Their presence may reflect reservoir heterogeneity, upward discharge along faults (numerous northeast-trending faults cross the uplift), waters of compaction discharging from the deep basin, or a combination of these influences. In the Green River Basin, the Mesaverde aquifer is fault severed and receives limited recharge from the wet margins of the basin. Consequently, we postulate that ground-water flow is sluggish in the basin interior. Available head data show sluggish flow southeast, from the La Barge Platform toward the south part of the basin. Restricted circulation is indicated by a flattened potentiometric surface and highly saline formation waters (Ahern and others, 1981).

In the Tertiary aquifer system, ground-water flow primarily results from outcrop-related recharge along the foothills of the Sierra Madre Uplift–Park, Wind River, and Uinta Uplifts and the Wyoming Mountains (fig. 61). Flow direction can be predicted because ground water flows down regional topographic gradient and structural dip, in response to the hydraulic gradient, from the wet, elevated margins of the basins toward topographically low areas eventually to discharge. Flow patterns conform to those delineated from head maps, which show high values near recharge areas and diminishing values basinward (Ahern and others, 1981; Collentine and others, 1981).

In the Sand Wash Basin and southeastern Washakie Basin, water flows basinward for ultimate discharge into the Little Snake River valley and its tributary valleys. The Great Divide Basin is a basin of internal drainage, and water flows toward the basin center to discharge into valleys and playas in the central basin. Recharge in most of the basin is small because annual precipitation is low and evaporation rates are high. The Washakie and Great Divide Basins, essentially independent hydrologic systems, are hydrologically separated by the Wamsutter Arch, which is a Tertiary ground-water divide (Collentine and others, 1981). In the Green River Basin, water flows toward the basin center and southward to discharge into the Green River valley south of the area where the Wilkins Peak Member of the Green River Formation is less extensive (Ahern and others, 1981). Head contours converge toward the Green River valley, and TDS content increases from outcrop, basinward and to the south. The best quality water is in the north third of the basin. In the southwest, water flows south to north from recharge areas along the north flank of the Uinta Mountains.

Coalbed Methane Resources, Production, and Exploration in the Greater Green River Basin

William R. Kaiser and Andrew R. Scott

Estimates of coal and gas resources rely on structure, topography, net coal thickness, gas and ash content (as reported earlier in this volume), and published coal-density data. These data were integrated to calculate coal and gas resources by geologic unit and drilling depth following the methodology of Kaiser and others (1993b), in which volume corrections and bulk and pure coal density were considered for the first time. Discussion of resources is followed by a review of production, which has been mainly water and little or no gas. In the Greater Green River Basin, structural configuration, coal distribution, gas content, and hydrodynamics are major controls on the occurrence and producibility of coalbed methane. A synergistic interplay among these geologic and hydrologic controls determines producibility. Exploration fairways were identified using an integrated geologic–hydrologic-centered approach or basin-scale producibility model, as outlined by Kaiser and others (1993b, 1994a, b). The model's essential elements are (1) ground-water flow basinward through coals of high rank and high gas content orthogonally toward no-flow boundaries (regional hingelines, fault systems, facies changes, and/or discharge areas) and (2) conventional trapping of gas along them. When flow direction and flow boundaries are orthogonal, the gas-gathering area is large and efficiently swept of gas, maximizing the opportunity for subsequent resorption and conventional trapping of gas. Free gas and solution gas provide additional sources of gas beyond that sorbed on the coal surface.

Resources

Coal and gas resources in the Greater Green River Basin were calculated using structure-contour, topographic, and net-coal-thickness maps, as well as gas content, coal density, and ash content and density. Net coal thickness and area were combined to estimate net coal volume, which was then used to calculate coal tonnage and gas in place, using bulk and ash-free coal density and gas content. Three resource estimates were made (1) using no depth restrictions, (2) at less than 6,000 ft (<1,830 m), and (3) at less than 7,500 ft (<2,287 m)). These basic equations were used to calculate coal tonnage and gas in place:

$$TON = (h \times A) \times \rho_b \times C, \qquad (1)$$

and

$$GIP = (h \times A) \times \rho_c \times GC \times C, \qquad (2)$$

where

- GIP = gas in place (scf),
- TON = coal tonnage (short tons),
- GC = ash-free gas content (scf/ton),
- h = coal thickness (ft),
- A = area (ft^2),
- ρ_c = density pure coal (g/cc),
- ρ_b = bulk density coal + ash (g/cc), and
- C = unit = correction factor to convert to English units.

On the basis of considerations of pure coal density and weight and volume percentages of coal and ash content, modified these equations for resource calculations (Kaiser and others, 1993b). Using generalized bulk coal-density data and failure to correct net coal volume for ash content can cause serious error in calculating in-place gas resources. Coal resources were calculated using the bulk coal density (which includes both coal and ash), whereas in-place gas calculations were made using pure coal density because gas is assumed to be sorbed by coal and not ash.

Pure coal density was related to a depth plot of pure coal density versus percent carbon in Levine (1993), which was first converted to equivalent vitrinite-reflectance values and then correlated with depth using a vitrinite-reflectance profile equation to attain a pure coal density versus depth equation (Kaiser and others, 1993b). Upon establishing that relation, we could calculate regional changes of bulk coal density with depth. Because the density of pure coal is less than that of ash, the volume fraction of ash in coal is commonly less than the weight percent of ash. Thus, coal volume cannot be multiplied simply by weight percent coal to determine net coal volume. Coal volume must be

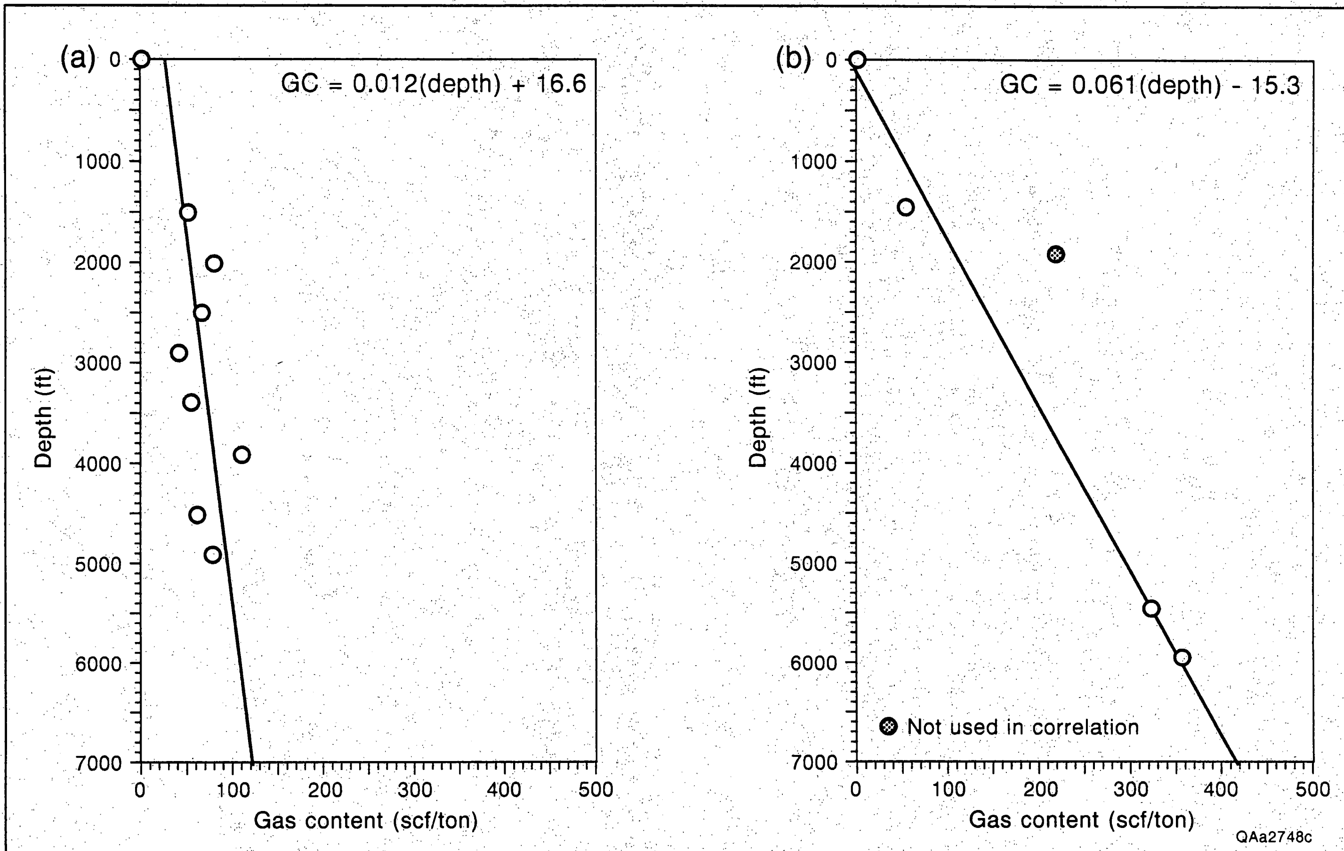


Figure 66. Gas-content profiles and equations used in coal and in-place gas resource calculations. A moving average of 1,000 ft (305 m) intervals with 500-ft (153-m) overlap was used to determine a general relation between gas content and depth in the (a) Fort Union and (b) Williams Fork Formations.

multiplied by a volume-correction factor, which is based on the weight percentages of ash provided by proximate analyses (Kaiser and others, 1993b). Therefore, equation 2 was modified to incorporate the volume-correction factor and to handle coal density appropriately in gas-in-place calculations:

$$GIP = (h \times A \times V_{cf}) \times \rho_c \times GC \times C, \quad (3)$$

where

V_{cf} = volume correction factor.

Coal thickness in GIP calculations were derived from net-coal maps, where net coal within each unit is assumed to occur as an aggregate thickness at the midpoint of the unit. Volume-correction factors of Mesaverde and Fort Union coals were made, assuming average ash contents of 9.2 and 10.2 weight percent, respectively. Equations relating gas content to depth in the Mesaverde Group and Fort Union Formation were determined by using a moving average over 1,000-ft (305-m) intervals with 500-ft (164-m) overlap (fig. 66). Resources were calculated using a grid size of 3.5 mi^2 (9.1 km^2).

In the Greater Green River Basin, coal and gas resources are huge, totaling 1,277 billion short tons (1,158 billion t) and 314 Tcf (8.89 Tm^3) (table 2). The Mesaverde Group contains 627 billion tons (569 billion t) and 264 Tcf (7.47 Tm^3), accounting for 49 and 84 percent of the total resources, respectively. The Rock Springs accounts for 16 and 31 percent of the Mesaverde coal and gas resources, respectively. The Fort Union Formation contains 649 billion tons (589 billion t) and 50 Tcf (1.42 Tm^3), accounting for 51 and 16 percent of the total resources, respectively. At depths of less than 7,500 ft (<2,286 m), coal and gas resources are 688 billion tons (624 billion t) and 84 Tcf (2.38 Tm^3). At those depths, Mesaverde resources are 243 billion tons (220 billion t) and 56 Tcf (1.58 Tm^3), accounting for 35 and 67 percent, respectively, of the resources at less than 7,500 ft (<2,286 m). Fort Union resources are 445 billion tons (404 billion t) and 28 Tcf (0.79 Tm^3), accounting for 65 and 33 percent of the resources, respectively.

Table 2. Coal and gas resources in the Greater Green River Basin. From Scott and others, (1994).

	Resources		Percent of total resource		Average gas content (scf/ton)
	Coal (billion short tons)	Gas (Tcf)	Coal	Gas	
Greater Green River Basin	1,277	314	100	100	
< 6,000 ft	482	47	38	15	96
6,000 to 7,500 ft	206	37	16	12	185
> 7,500 ft	588	230	46	73	390
upper Mesaverde Group	420	166	33	53	
< 6,000 ft	131	25	10	8	189
6,000 to 7,500 ft	65	22	5	7	348
> 7,500 ft	224	119	18	38	530
Rock Springs Formation	208	98	16	31	
< 6,000 ft	35	5	3	2	128
6,000 to 7,500 ft	12	4	1	1	348
> 7,500 ft	161	89	12	28	552
Fort Union Formation	649	50	51	16	
< 6,000 ft	316	17	25	5	54
6,000 to 7,500 ft	129	11	10	4	88
> 7,500 ft	204	22	16	7	110

Production

Coalbed methane drilling, having targeted coals of the Upper Cretaceous Mesaverde Group and Paleocene Fort Union Formation, is centered in the Sand Wash Basin, which has established production, and the northern Rock Springs Uplift, where commercial prospects have been evaluated.

Sand Wash Basin

We analyzed Williams Fork and Fort Union production on the basis of Petroleum Information reports (Petroleum Information, 1993a–h), Dwight's Oil and Gas drilling histories, Colorado Oil and Gas Conservation Commission well-completion updates, and operator records. Gas production from three Williams Fork fields has been minimal, whereas water production has been excessive (table 3). Cumulative gas and water production through June 1993 was 134 MMcf (3.8 MMm^3) and 6.8 MMbbl (1.1 MMm^3), for a cumulative gas–water ratio of approximately 20 scf/bbl (~3.6 m^3/m^3). This ratio has been increasing slowly with time. Only Dixon field has produced gas for a cumulative gas–water ratio of approximately 22 scf/bbl (~3.9 m^3/m^3). Eleven wells have been drilled in Dixon field (fig. 67) by Fuel Resources Development Company (Fuelco) (fig. 68); three structurally high wells currently produce gas at rates of less than 40 Mcf/d (<1.1 Mm^3/d). Initially, eight wells were flowing artesian and served as dewatering wells; they flowed at rates ranging from 600 to 1,000 bbl/d (95 to 159 m^3/d) for a per-well average of approximately 700 bbl/d (~111 m^3/d) in 1991. Rates have subsequently declined to approximately 400 bbl/d (~64 m^3/d).

Sixteen plugged and abandoned wells in Craig Dome field (fig. 67) were abandoned by Cockrell Oil because the Williams Fork coals had low gas contents and could not be economically depressured (dewatered). They produced for 12 to 18 mo with minor pressure drawdown and never produced gas (Stevens, 1993). In 1991, water production per well ranged from 200 to 1,000 bbl/d (32 to 159 m^3/d) and averaged about 500 bbl/d (~80 m^3/d);

Table 3. Cumulative gas and water production, Greater Green River Basin.

Operator	Well Name	S	TN		RG		TD (feet)	Spud Date	Completion Date	First Prod. Date	Gas Prod. (Mcf)	Water Prod. (bbl.)	Formation	Field
COCKRELL OIL	1 691-0311	3	6	N	91	W	2350	6/29/90	na	8/1/90	0	113,203	Williams Fork	Craig Dome
COCKRELL OIL	1 691-0513	5	6	N	91	W	2375	6/1/90	8/20/92	8/1/90	0	584	Williams Fork	Craig Dome
COCKRELL OIL	1 FARM CREDIT BANK	6	6	N	91	W	4150	1/24/90	8/31/92	3/1/90	0	215,869	Williams Fork	Craig Dome
COCKRELL OIL	1 691-0701	7	6	N	91	W	3528	5/15/90	8/22/92	8/1/90	0	6,811	Williams Fork	Craig Dome
COCKRELL OIL	1 691-0906	9	6	N	91	W	2100	6/15/90	8/26/91	8/1/90	0	1,518	Williams Fork	Craig Dome
COCKRELL OIL	1 EBERLE	9	6	N	91	W	2163	11/29/89	8/1/90	3/1/90	0	362,087	Williams Fork	Craig Dome
VETERAN EXPL	1 SCOTT	11	6	N	92	W	1646	11/28/90	10/3/91	abnd.	0	0	Williams Fork	Wildcat
HELMERICH & PAYNE	1-31 COLORADO-STATE	31	7	N	88	W	6833	11/12/89	7/30/90	na	0	0	Williams Fork/Fort Un.	Wildcat
COCKRELL OIL CORP.	VAN DORN #1	29	7	N	90	W	na	na	na	3/1/90	0	851	Williams Fork	Craig Dome
COCKRELL OIL	1 STELBAR-SCOTT	17	7	N	91	W	6447	12/11/89	8/16/92	3/1/90	0	248,124	Williams Fork	Craig Dome
COCKRELL OIL	1 791-2613	26	7	N	91	W	4100	6/26/90	7/10/92	9/1/90	0	151,722	Williams Fork	Craig Dome
COCKRELL OIL	1 791-2716	27	7	N	91	W	4020	9/4/90	7/10/92	9/1/90	0	114,468	Williams Fork	Craig Dome
COCKRELL OIL	1 791-2714	27	7	N	91	W	3875	8/5/90	8/18/92	10/1/90	0	185,818	Williams Fork	Craig Dome
COCKRELL OIL	1 791-2807	28	7	N	91	W	4200	9/30/90	8/17/92	5/1/91	0	130	Williams Fork	Craig Dome
COCKRELL OIL	1 791-3401	34	7	N	91	W	3930	6/4/90	7/10/92	9/1/90	0	237,943	Williams Fork	Craig Dome
COCKRELL OIL	1 791-3402	34	7	N	91	W	3770	7/16/90	7/10/92	9/1/90	0	189,112	Williams Fork	Craig Dome
COCKRELL OIL	1 791-3409	34	7	N	91	W	3279	5/8/90	7/10/92	10/1/90	0	172,039	Williams Fork	Craig Dome
COCKRELL OIL	1 791-3505	35	7	N	91	W	5020	5/14/90	8/20/92	9/1/90	0	108,178	Williams Fork	Craig Dome
GREAT EAST. ENERGY DEVL.	MCINTYRE 41-10	10	7	N	94	W	5657	na	na	na	na	na	Mesaverde	Wildcat
DOMINION ENERGY	1-36 STATE	36	8	N	88	W	11127	11/11/89	11/17/89	na	0	0	Mesaverde	Bull Mountain
MERIDIAN OIL INC	33-3 MOFFAT COUNTY	3	8	N	93	W	3100	11/19/89	4/19/90	na	0	0	Fort Union	Lay Creek
MERIDIAN OIL INC	12-12 MORGAN	12	8	N	93	W	6458	1/16/90	5/15/90	na	0	0	Williams Fork	Lay Creek
APEX ENERGY	7-1 N FORK	7	9	N	91	W	3700	3/29/90	8/1/91	na	0	0	Fort Union	Wildcat
MERIDIAN OIL INC	43-26 FEE	26	10	N	93	W	5317	11/1/89	1/23/90	na	0	0	Fort Union	West Side Canal
CHEVRON USA	15-4C FEDERAL LAND BANK	15	10	N	94	W	5793	10/13/89	12/14/89	na	0	0	Fort Union	Big Hole
MARSH OPERATING	12-16-1 FEDERAL	12	11	N	93	W	4400	12/12/89	10/1/90	na	0	0	Fort Union	Wildcat
FUEL RESOURCES DEV	M-1-12-90-N RUSSELL	1	12	N	90	W	1199	11/12/90	3/9/91	2/1/91	39,979	470,227	Williams Fork	Dixon[a]
FUEL RESOURCES	N-2-12-90-N RUSSELL	2	12	N	90	W	2530	6/16/90	8/27/90	8/1/90	9,336	492,983	Williams Fork	Dixon
FUEL RESOURCES DEV	C-2-12-90-N RUSSELL	2	12	N	90	W	1520	7/8/90	10/17/90	8/1/90	3,873	459,929	Williams Fork	Dixon
FUEL RESOURCES	E-2-12-90-N RUSSELL	2	12	N	90	W	2390	10/26/90	12/12/90	1/1/91	1,773	386,301	Williams Fork	Dixon
FUEL RESOURCES	G-2-12-90-N RUSSELL	2	12	N	90	W	1285	10/31/90	1/18/91	1/1/91	4,275	443,063	Williams Fork	Dixon
FUEL RESOURCES	O-2-12-90-N RUSSELL	2	12	N	90	W	2144	6/5/90	8/29/90	8/1/90	4,322	457,709	Williams Fork	Dixon
FUEL RESOURCES	C-11-12-90-N RUSSELL	11	12	N	90	W	2500	6/29/90	8/20/90	na	2,688	354,893	Williams Fork	Dixon
FUEL RESOURCES DEV	A-11-12-90 RUSSELL	11	12	N	90	W	2318	3/3/90	4/16/90	4/1/90	5,725	663,761	Williams Fork	Dixon

Table 3. Cumulative gas and water production, Greater Green River Basin, continued.

Operator	Well Name	S	TN		RG		TD (feet)	Spud Date	Completion Date	First Prod. Date	Gas Prod. (Mcf)	Water Prod. (bbl.)	Formation	Field
FUEL RESOURCES	D-12-12-90-N RUSSELL	12	12	N	90	W	1765	11/15/90	3/14/90	3/1/91	19,667	399,118	Williams Fork	Dixon
QUINTANA PETROLEUM	1-20 TIMBERLINE UNIT	20	12	N	91	W	2008	10/17/89	12/1/89	na	0	0	Fort Union	West Side Canal
QUINTANA PETROLEUM	3-20 TIMBERLAKE UNIT	20	12	N	91	W	2100	12/27/89	1/29/90	8/1/90	0	9,815	Fort Union	West Side Canal
MERIDIAN OIL INC	11-23 STATE	23	12	N	92	W	2150	10/10/89	1/15/90	na	0	0	Fort Union	West Side Canal
MERIDIAN OIL INC	14-33 FEDERAL	33	12	N	93	W	na	na	na	na	na	na	Fort Union	West Side Canal
MERIDIAN OIL INC	32-36 STATE	36	12	N	93	W	3760	9/24/89	10/19/89	na	0	0	Fort Union	Wildcat
GRYNBERG JACK J	1-21 GRYNBERG-FEDERAL	21	12	N	100	W	4706	8/15/88	12/1/89	na	0	0	Fort Union	Wildcat
MEADOWLARK OIL	36-1 WYOMING STATE	36	13	N	90	W	530	10/30/90	na	na	0	0	na	na
TEXACO INC	TABLE ROCK UNIT 69	17	19	N	97	W	6997	na	9/83, 5/90	na	na	na	Almond	Table Rock
TEXACO INC	TABLE ROCK UNIT 55	19	19	N	97	W	6953	na	11/-/1982	na	na	na	Almond	Table Rock
TEXACO INC	TABLE ROCK UNIT 96	36	19	N	98	W	6800	na	1/-/1991	na	na	na	Almond	Table Rock
BUTTONWOOD PET	9-5 UPRC	9	20	N	105	W	5718	4/23/90	7/20/91	na	0	0	Rock Springs	na
TRITON O&G	UPRC #2	1	22	N	102	W	4735	10/27/89	1/1/91	12/1/89	41,233	99,201	Rock Springs	Wildcat
TRITON O&G	UPRC #1	9	22	N	102	W	3355	9/22/89	8/1/90	na	0	0	Rock Springs	Wildcat
BUTTONWOOD PET	19-4 UPRC	19	22	N	104	W	5650	8/20/90	10/20/91	abnd.	0	0	Rock Springs/Blair	Wildcat
DEKALB ENERGY	22-36 ADAVILLE-STATE	36	22	N	117	W	0	na	2/20/91	na	0	0	na	na
TRITON O&G	2-32-23-102 FEDERAL	32	23	N	102	W	4680	11/17/90	12/2/91	abnd.	0	0	na	na
TRITON O&G	2-33 23-102 UPRC	33	23	N	102	W	4759	11/17/90	12/2/91	abnd.	0	0	Almond/Rock Springs	na
TRITON O&G	UPRC #3	33	23	N	102	W	4600	2/16/90	1/1/91	abnd.	933	194,124	Rock Springs	na
SAXON EXPL	7-11 FEDERAL	7	25	N	102	W	6954	9/19/90	7/25/91	na	0	0	Mesaverde	Wildcat
SAXON EXPL	23-15 SAXON-FEDERAL	23	25	N	103	W	7000	10/11/90	7/24/91	abnd.	0	0	Mesaverde	Wildcat
TRW ENERGY SYSTEM	BELCO PETROLEUM S-29-27	27	30	N	113	W	3539	na	na	na	436-539 Scf/t	na	Fort Union	Wildcat
PRIMA O&G	22-41 SPRINGMAN CREEK UNIT	22	30	N	114	W	4150	9/13/89	11/4/89	abnd.	0	0	Mesaverde	Wildcat
										Total	133,804	6,539,581		

[a]Producing formation carried by operator as Almond but is Williams Fork Unit 1 and 2.

SOURCE:
1. Gas Research Institute, Quarterly Review of Methane from Coal Seams Technology, v. 11, no. 1, August 1993.
2. Petroleum Information Corp., Rocky Mountain Coalbed Methane Report, various issues, 1993.

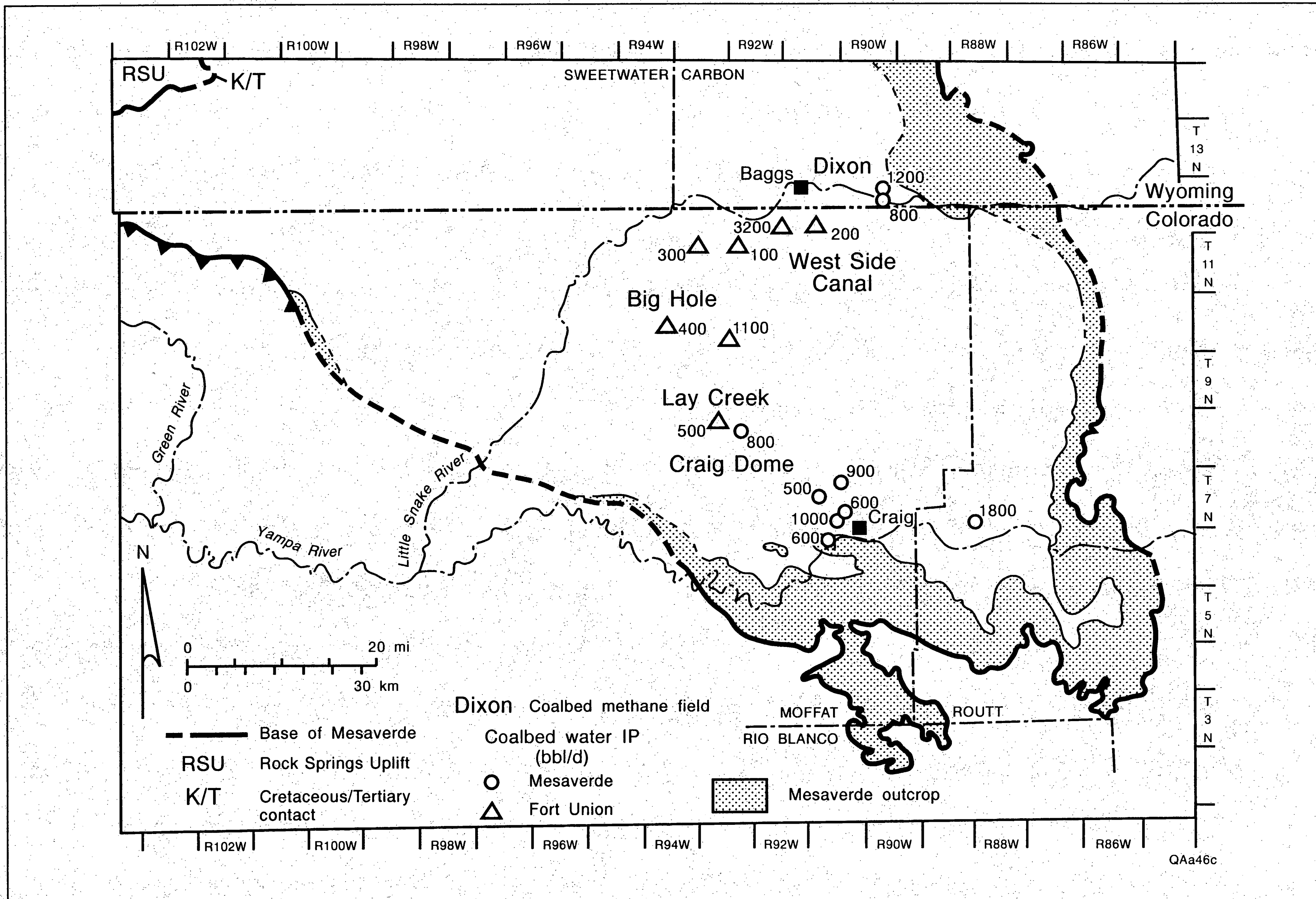


Figure 67. Initial water potentials (IP's), Williams Fork and Fort Union coals. Williams Fork IP's are high at the basin margin and reflect proximity to the recharge area and high coalbed permeability. Fort Union IP's are highest along the south-north trend of thick net coal.

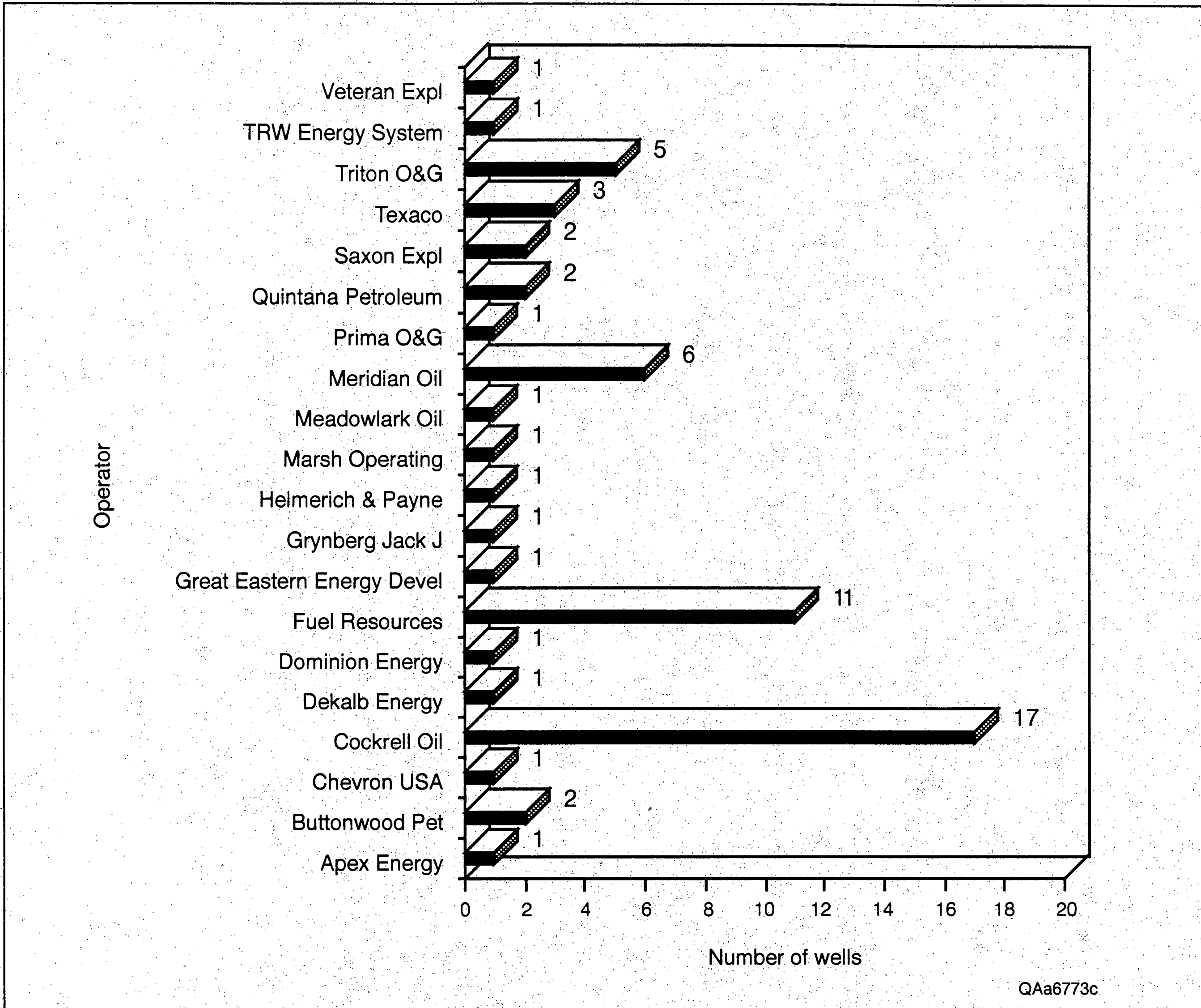


Figure 68. Coalbed methane tests by operator, Greater Green River Basin. Cockrell, Fuel Resources Development Company (Fuelco), and Meridian were active in the Sand Wash Basin.

two were flowing artesian wells. The one Williams Fork well in Lay Creek field tested initially at 74 Mcf/d (2.1 Mm^3/d) and 800 bwpd (127 m^3/d). During production testing it produced 80 to 100 Mcf/d (2.3 to 2.8 Mm^3/d) and hundreds of barrels of water per day (tens of m^3/d). The Van Dorn well (Sec. 29, T7N, R90W) produced 100 Mcf/d (2.8 Mm^3/d) upon swabbing after an unsuccessful attempt at fracturing, and then ceased production.

In 1989 and 1990, nine Fort Union coalbed wells were completed, production tested, plugged, and abandoned. During test periods ranging from 9 d to 7 mo, the wells produced zero to negligible volumes of gas and tens of thousands of barrels of water (thousands of cubic meters); one well averaged 2 Mcf/d (57 m^3/d). Most of the activity was in West Side Canal field (fig. 67).

Initial water production (IP) increases with permeability (Oldaker, 1991) and high water IP's (hundreds of barrels per day [tens of cubic meters per day]) indicate high permeability. Williams Fork coal IP's were highest in the Yampa River valley (1,800 bbl/d [286 m^3/d]) and at the northeast margin of the basin in Dixon field, east of Baggs, Wyoming, where 1,200 bbl/d (191 m^3/d) is representative (fig. 67). The field's first well initially produced 2,200 bbl/d (350 m^3/d). In Craig Dome field, IP's ranged from 500 to 1,000 bbl/d (80 to 159 m^3/d). At West Side Canal field, IP's from Fort Union coals ranged from 100 to 3,200 bbl/d (16 to 509 m^3/d), which is a range much wider than that exhibited by Williams Fork coals at nearby Dixon field (800 to 2,200 bbl/d [127 to 350 m^3/d]). The wide Fort Union range probably reflects reservoir heterogeneity possibly caused by variability in vertical flow (interconnectedness), coalbed orientation perpendicular to the lateral flow direction, offset by faults and diagenesis along the Cherokee Arch fault system, or all three. High water potentials reflect proximity to the outcrop recharge area, basinward flow in an interconnected aquifer system, artesian conditions, and laterally extensive coal beds of high permeability. Coalbed permeability at Dixon field averages about 170 md. Because of proximity to the recharge area and high permeability, dewatering (depressuring) coal beds near the basin margin may be uneconomical. 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]). Nevertheless, disposal costs of these volumes of water can adversely affect project economics to the extent that development may be deemed uneconomical.

Rock Springs Uplift

Commercial prospects have been evaluated on the north flank of the Rock Springs Uplift, where coals of the Fort Union, Almond, and Rock Springs Formations were tested. Only Rock Springs coals showed commercial promise. Production forecasts predicted recoveries of 1 to 3 Bcf/160 ac (28 to 84 MMm^3/65 ha) and peak rates of 240 to 1,200 Mcf/d (6.79 to 34.00 Mm^3/d) (Kelso and others, 1991; Kaiser, 1992). Despite these promising forecasts, test results were disappointing. During a 530-d production test, the most successful well, Union Pacific Resources Company Well No. 2-1 (2 UPRC-1, fig. 69), averaged 78 Mcf/d and 200 bwpd from a 50-ft interval (Stevens, 1993). Development was stopped in 1992 primarily by low gas prices and disappointing test results and secondarily by environmental concern over disposal of produced water.

A pair of northern wells (fig. 69) completed in Fort Union and Almond coals were tested for 4 mo and produced less than 100 Mcf/d (<2.8 Mm^3/d); low permeability and low gas content (~200 scf/ton [~6.24 m^3/t]) doomed these wells. Three wells at Table Rock field tested Almond coals of low permeability and were subsequently completed in Almond sandstones by Texaco (table 3) (Roger Dickenson, Texaco Inc., personal communication, 1993).

Exploration Fairways

The Greater Green River Basin, a largely untested, frontier coalbed methane basin, will require deeper drilling to penetrate higher rank, higher gas content coals. Mesaverde gas contents between 6,000 and 7,500 ft (1,830 and 2,286 m) and approximately 350 scf/ton (~10.92 m^3/t), exceed 500 scf/ton (15.60 m^3/t) below 7,500 ft (<2,286 m) (table 2). Fort Union gas contents are approximately 100 scf/ton (~3.12 m^3/t) or less regardless of depth. High overall basin permeability may lower the permeability floor for coalbed methane exploration below that expected in other western coal basins. Deeper drilling may thus be economical in the greater basin, Mesaverde and Fort Union coals being primary and secondary targets, respectively. Because exploration strategy is to maximize gas content and minimize water production, additional emphasis must be placed on the identification of conventional traps (no-flow boundaries). Conventionally trapped gas and solution gas can be produced with less associated water, and yet they are overlooked sources of coalbed methane. Recharge areas should be avoided because of possible high water production.

Mesaverde Group

Coal distribution and steep structural dip limit deeper Mesaverde drilling to the eastern Sand Wash and Washakie Basins and flanks of the Rock Springs Uplift (fig. 24), where Mesaverde coals are prospective in (1) the Cedar Mountain fault system northwest of Craig, Colorado, (2) the east margin of the Washakie Basin south of Rawlins, Wyoming, and (3) the north flank of the Rock Springs Uplift (fig. 70).

Northwest of Craig, the Cedar Mountain fault system terminates in a zone of convergence along the boundary between hydropressure and regional overpressure (fig. 70). Higher rank, high gas content coals are present in the area, suggesting high production potential (Kaiser and others, 1993b)—the updip limit of hvAb rank overlaps the area of interest. Moreover, at the basin margin in the Craig Dome area, because wells have yielded little or no gas and large volumes of water, moving basinward should facilitate dewatering. In cross section, gravity-driven meteoric water moving basinward and compactional fluids moving up and out of the basin converge and turn upward along the boundary between hydropressure and hydrocarbon overpressure, which is a no-flow boundary (fig. 64). Presumably hydrocarbons and other organic compounds are delivered from updip and downdip to become concentrated and trapped along the boundary. Prolific Mesaverde oil-and-gas-producing fields, such as Patrick Draw, Desert Springs, Echo Springs, and Standard Draw, lie along the boundary between hydropressure and overpressure, indicating that the boundary between pressure regimes is hydrocarbon productive (fig. 71). Sandstones at Patrick Draw and Desert Springs on the hydropressured side of the boundary have conventional permeabilities, whereas those at Echo Springs and Standard Draw on the overpressured side qualify as FERC

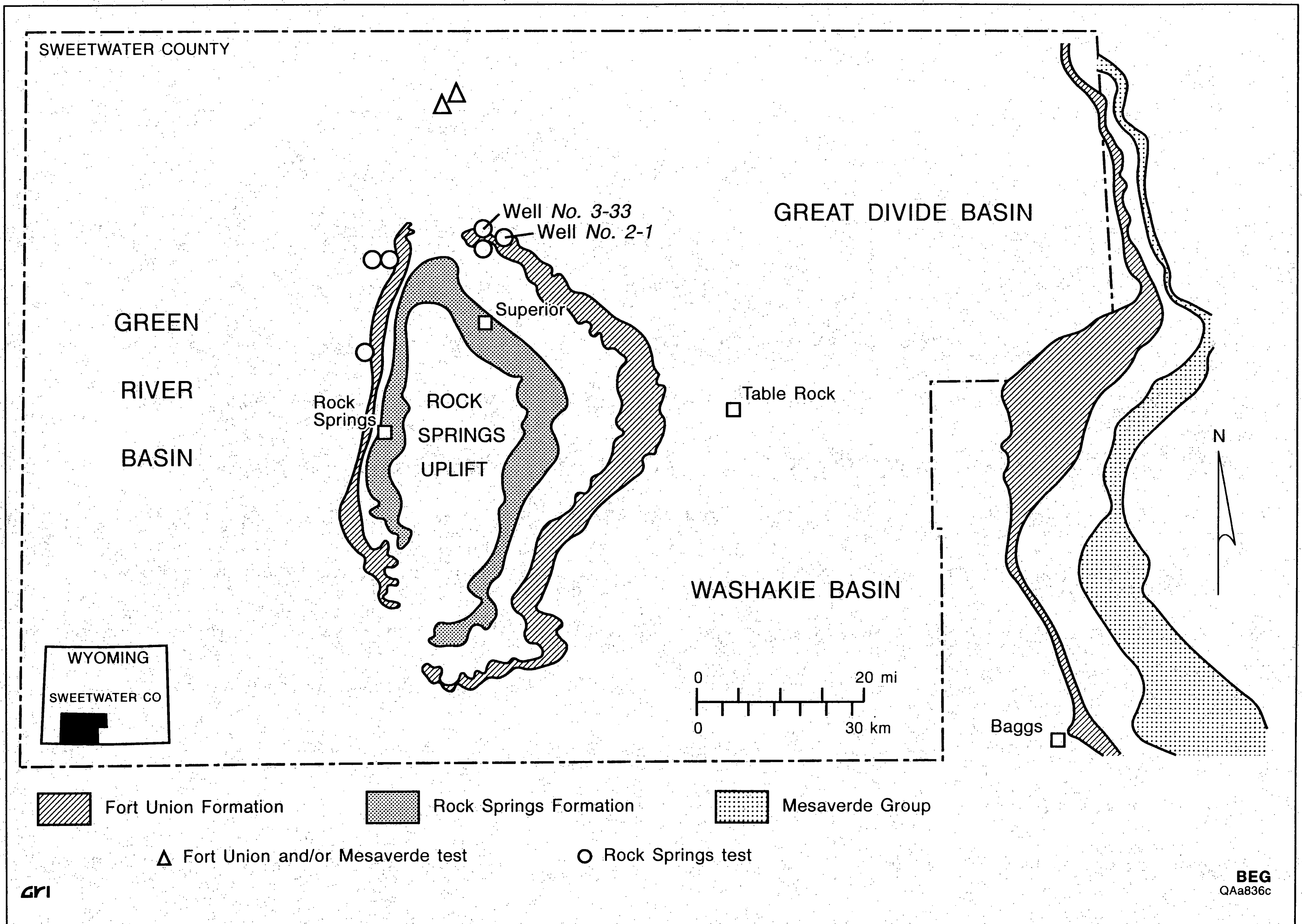


Figure 69. Coalbed methane activity on the Rock Springs Uplift, Greater Green River Basin (from Kaiser, 1992). Coals of the Rock Springs Formation were targeted. Outcrop from Love and Christiansen (1985).

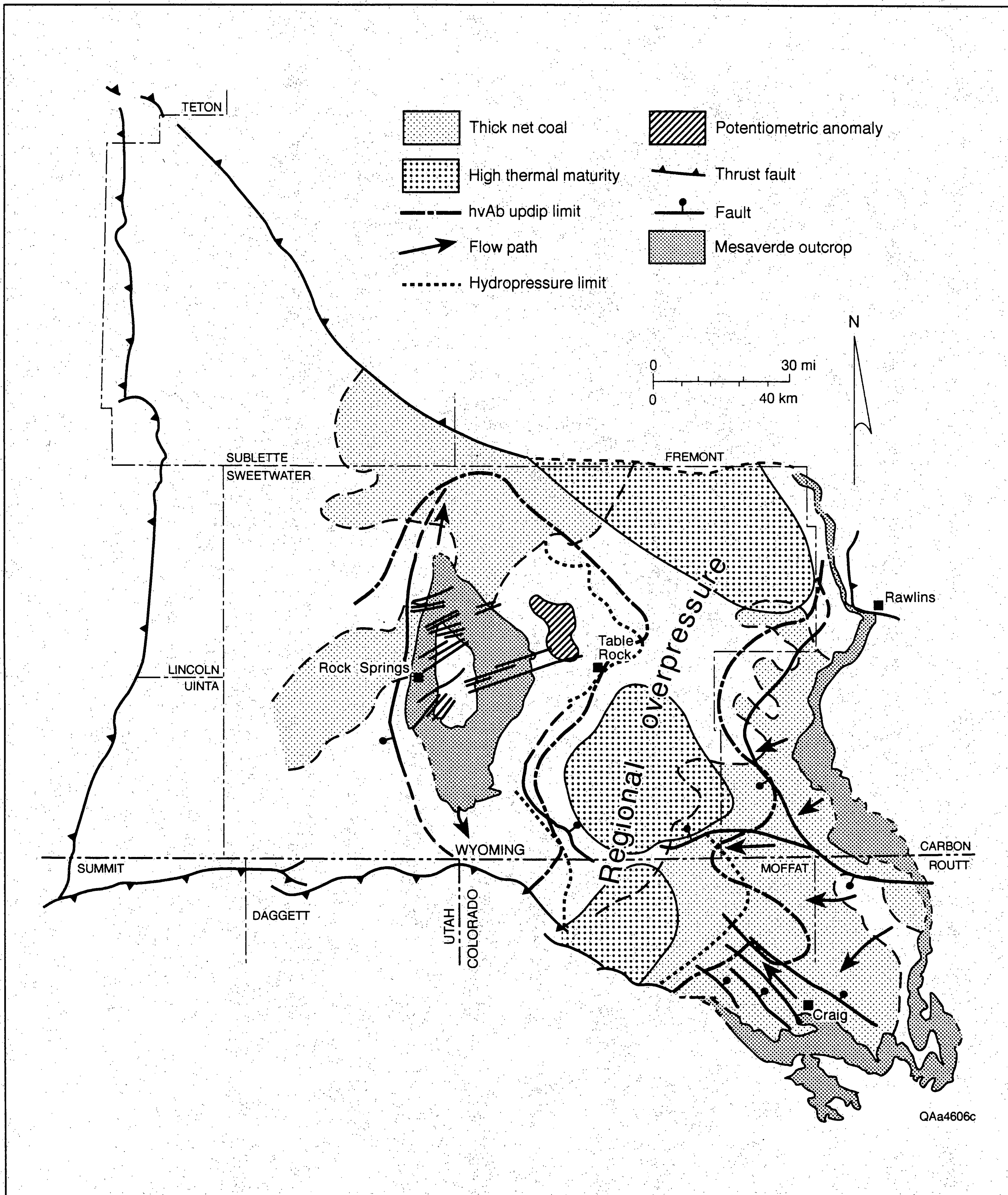


Figure 70. Geologic and hydrologic characterization of the Mesaverde Group, Greater Green River Basin. Because of high overall permeability, the permeability floor for coalbed methane exploration may be lower than normally expected in western coal basins. Deeper drilling to test higher rank, higher gas content coals may be in order at the (1) termination of the Cedar Mountain fault system northwest of Craig, (2) east margin of Washakie Basin, and (3) northeast flank of the Rock Springs Uplift. Prime targets are the northeast Rock Springs Uplift, eastern Washakie Basin, and southeastern Sand Wash Basin.

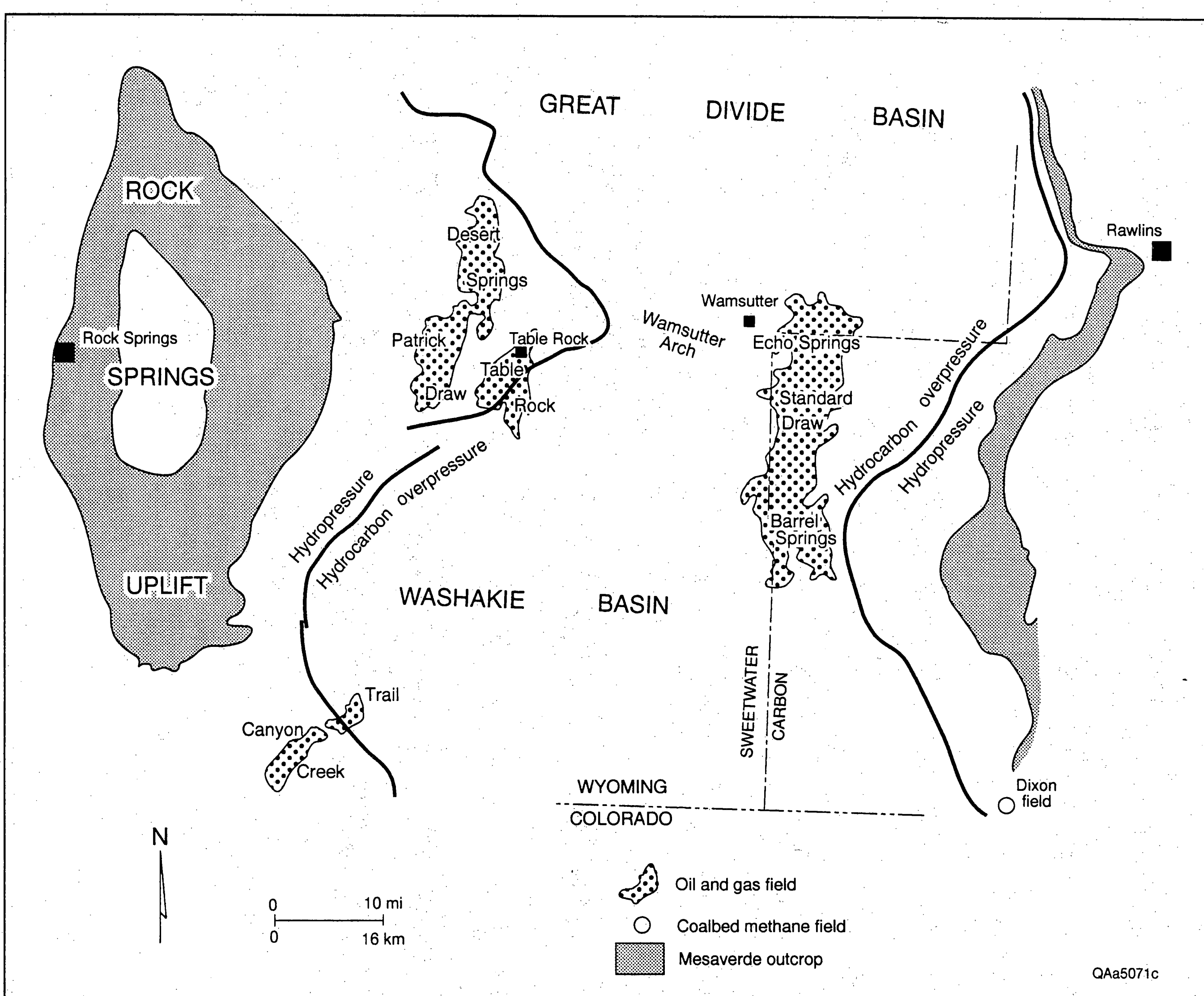


Figure 71. Major Mesaverde oil and gas fields, eastern Greater Green River Basin. Fields lie on either side of the hydropressure–hydrocarbon overpressure boundary. Fields from Gregory and DeBruin (1991).

tight gas sandstones (Iverson, 1993). Hydropressured coals are the prime coalbed methane target, whereas hydrocarbon overpressured coals are of low permeability and too deep to be primary targets.

Along the east margin of the Washakie Basin, upthrown to a major fault system, normally pressured and artesian overpressured coals have good gas contents (250 to 350 scf/ton [7.80 to 10.92 m^3/t]). To date, however, excessive water production has limited producibility. At Dixon field, the coals could not be dewatered (depressured) for consequent high gas production rates, but because precipitation (recharge) decreases northward (fig. 61), chances of dewatering should improve to the north toward Rawlins, Wyoming.

On the northern Rock Springs Uplift, coals of the Rock Springs Formation have been targeted for development because thickness, resources, and gas content are favorable. Net coal thickness in 5-ft (1.5-m) seams exceeds 40 ft (12 m) (Kaiser, 1992), gas resources at less than 7,500 ft (<2,286 m) are approximately 9 Tcf (~0.25 Tm^3) (table 2), rank ranges from hvCb to hvAb, and gas content averages 350 scf/ton (10.92 m^3/t) over a 1,000-ft (305-m) interval. Although the gas-content profile of Rock Springs coals is atypical, it cannot be ignored in this evaluation. Whereas normally gas content steadily increases with depth, here gas content increases abruptly, peaks, and then decreases with depth (fig. 55). If the profile is not an analytical artifact, then quite possibly the exploration fairway is narrow, which would constrain future development. Because of limited recharge, limited flow off the uplift should favor ultimate dewatering of Rock Springs coals, and coals hosted by muddy sediments should be targeted to minimize water production. Coals on the southwest, downthrown side of a 5,000-ft (1,525-m) fault (throw decreases to 2,000 ft [610 m] north and south), west of Rock Springs, are probably too deep for drilling economically, thus eliminating them as potential coalbed methane targets (fig. 70).

Although upper Mesaverde Almond coals are generally thin and not primary coalbed methane targets, they are possible secondary targets in the course of conventional Almond gas development in the deeper, overpressured parts of the Washakie Basin. Reservoir volumetrics clearly demonstrate that Almond gas production does not originate solely from the targeted upper Almond sandstone (Iverson, 1993). Examples abound where cumulative gas production has exceeded, or will soon exceed, total gas in place in the perforated upper sandstone. Iverson (1993) attributed the extra gas to laminated sandstones below the upper sandstone that interconnected after hydraulic fracturing. Whereas they undoubtedly contribute gas, the numerous thin coals present in the upper Almond may instead be the major contributors and should thus be considered for completion. Perhaps completion practices should be reevaluated, as is done in the Piceance Basin, to consider joint completion of tight sandstones and coals for higher yield, longer lived gas wells.

Fort Union Formation

Fort Union coals are present throughout much of the basin (fig. 46) but gas contents are low (~100 scf/ton [~3.12 m^3/t] or less) (table 2), and thus are secondary coalbed methane targets. The possibility of structurally or stratigraphically trapped gas always remains, however. Fort Union coals at 3,500 ft (1,067 m) in a well in the Big Piney area (fig. 72) are reported to have gas contents of approximately 500 scf/ton (~15.60 m^3/t) (table 3) that may reflect conventional trapping of gas. Fort Union sandstones produce oil and gas from structural, stratigraphic, and combination traps on the La Barge Platform (Dunnewald, 1969). Hydrocarbons apparently migrated from the nearby deep Pinedale Basin, where coals and shales were thermally mature for hydrocarbon generation (Curry, 1973). Ranks of hvAb or higher occur in the basin and flank the Big Piney area (fig. 72). Secondary biogenic gas can also be added as a source of gas, wherever its generation is favored by active meteoric circulation (Scott, 1993c) in the dynamic Tertiary aquifer system (Kaiser, this volume). Ground water flows southeastward across the La Barge Platform.

In the northern Green River Basin, more than 100 net ft (>30 m) of coal is present in individual coals as much as 50 ft (15 m) thick. These coals have never been tested and may be prospective on the Sandy Bend Arch, which lies between the La Barge Platform and the northern Rock Springs Uplift (fig. 72). Again, the Pinedale Basin is a potential source of migrated thermogenic gas, and secondary biogenic gas may also be present to increase gas contents. Ground water flows southward, orthogonal to the arch and down the coal-rank gradient, to maximize possible contribution from thermogenic and/or secondary biogenic gas dissolved, entrained, or both, in south-flowing meteoric water. Potential conventional traps may also occur on the downthrown side of the Rock Springs thrust fault.

From an engineering standpoint, even with good gas content, the hydrologic occurrence of Fort Union coals will probably constrain their exploitation. The Fort Union is a major aquifer within the Tertiary aquifer system. Hydraulic stimulation or cavitation of coals could interconnect them with water-bearing sandstones and thus induce high water production and limit coalbed methane producibility. However, if permeability is inherently high, stimulation may be unnecessary.

Finally, along the Cherokee Arch, considerable Fort Union conventional gas and oil production has been established that probably reflects convergent, upward flow as well as structural and stratigraphic trapping. Upward leakage and/or migration updip of water and hydrocarbons from deeper parts of the basin along the Cherokee Arch fault system and flanks of the arch has been postulated (Kaiser and others, 1993b). Although Fort Union coals are thinner or less numerous and still of low rank westward along the Cherokee Arch, they may be highly charged with gas and thus be possible candidates for completion in the course of conventional gas development, as suggested of Almond coals. Such completions have been proposed for the Powder Wash area (fig. 72).

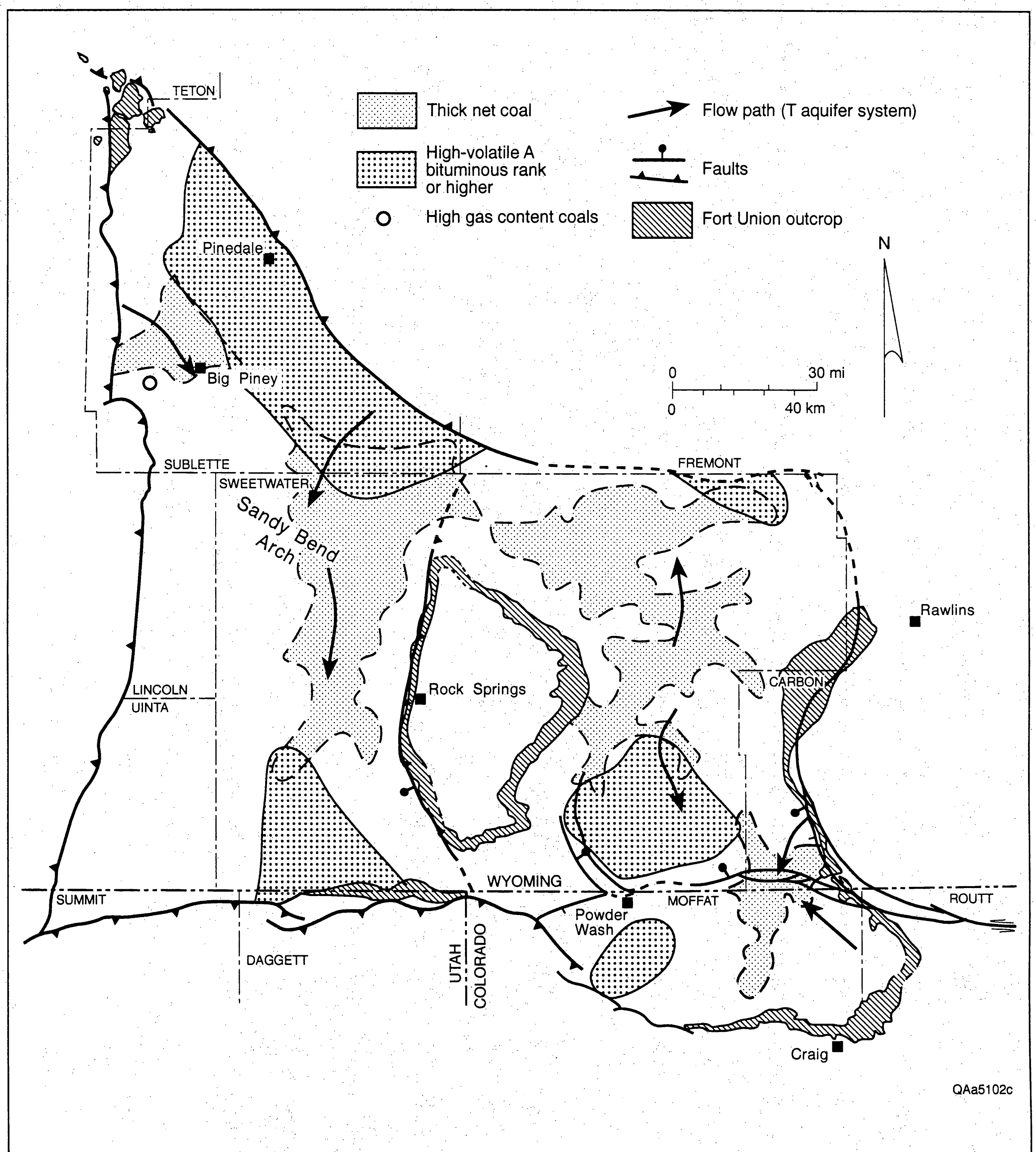


Figure 72. Geologic and hydrologic characterization of the Fort Union Formation, Greater Green River Basin. Prime targets are in the Big Piney area and on the Sandy Bend Arch.

Conclusions

Roger Tyler, Douglas S. Hamilton, William R. Kaiser, and Andrew R. Scott

1. The Gas Research Institute (GRI), on behalf of the natural gas industry, is actively fostering coalbed methane exploration and development in United States coal basins. As part of these efforts, the GRI has commissioned investigations of the San Juan, Greater Green River, Piceance, Powder River, and Raton Basins.

2. This report has focused on the Greater Green River Basin and has aimed at assessing its coalbed methane potential through integrated hydrologic and geologic studies. The report embodies the current ideas of BEG's continuing assessment of the geologic and hydrologic conditions necessary for producibility of coalbed methane.

3. The comprehensive San Juan (88 Tcf) and Sand Wash Basins (101 Tcf) studies indicate that coalbed methane producibility is profoundly influenced by several key geologic and hydrologic controls (structural, depositional, and hydrologic setting; coal rank; and gas content), which are discussed in terms of the Upper Cretaceous Mesaverde Group and lower Tertiary Fort Union Formation in the Greater Green River Basin.

Tectonic and Stratigraphic Setting

1. Within the Rocky Mountain Foreland, the Greater Green River Basin is structurally complex, being bounded by the Overthrust Belt on the west and by thrust-faulted uplifts on the remaining three sides. 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. Maximum horizontal compressive stress orientations have rotated about a vertical axis with time, a configuration that is reflected in cleat patterns, which are currently oriented northeast in the north and center of the basin, and north-northwest and east-northeast in the Sand Wash Basin (table 4).

2. Upper Cretaceous Mesaverde Group and/or lower Tertiary Fort Union Formation coal-bearing strata are the major coalbed methane targets. In the Mesaverde, the Rock Springs and Williams Fork Formations contain coals having the best coalbed methane potential. In the Rock Springs Formation, net coal thickness averages 100 ft (33 m) along an 8.5-mi-wide (13.4-km) zone trending northeasterly across the Rock Springs Uplift. Williams Fork coals also trend northeasterly and are preserved in the southeast part of the Sand Wash and Washakie Basins, where net coal thickness typically ranges from 100 to 200 ft (30 to 60 m) (table 4). Thickest individual coal beds in the Rock Springs Formation can be as much as 22 ft (6.7 m), whereas in the Williams Fork, beds are as much as 35 ft (11 m) thick.

3. The Rock Springs and Williams Fork coals, predominantly strike aligned (northeast), lie immediately behind sandstone-rich trends that are interpreted as linear clastic shorelines. The relationship between coal distribution and sandstone geometry suggests that the site optimal for peat accumulation and preservation was on the coastal plain, landward of the shoreline systems. Subsidence rate, water-table level, and shelter from clastic influx in this setting provided ideal conditions for thick coal to accumulate.

4. The intermontane fluvial Paleocene Fort Union coal-bearing units consist of some of the thickest individual coal beds, as much as 40 ft (15.2 m), and most continuous (>40 mi [>64 km]) coal beds. Net coal thicknesses range from 10 to 140 ft (3.1 to 42.7 m) in as many as 12 seams, above and on the flanks of thick fluvial trunk-stream systems. Lower Fort Union coal beds are thin (net coal <40 ft [<12.4 m]) or absent east of the Pinedale Anticline thrust fault, on the Moxa Arch, on the Rock Springs Uplift, and on the south basin margins, adjacent to the Uinta Uplift.

5. Depositionally the Fort Union Formation contains some of the thickest intermontane fluvial sandstone and coalbed sequences in the Greater Green River Basin. The thick coal beds occur in association with bed- and mixed-load channel-fill sandstone sequences. The channel-fill sandstone sequences, showing strong evidence of syntectonic control, are thought to be part of a much larger intermontane fluvial trunk-stream system that flowed north and east through the basin. Syntectonic control is indicated by thinning of coals over major structural features, the Rock Springs Uplift, Moxa Arch, and Pinedale Anticline, and subtle thinning across Cherokee and Wamsutter Arches. Syntectonic control is further suggested by the relationship between trends in coal thickness and sandstone distribution of the Fort Union fluvial systems. Net coal is thickest along the

Table 4. Coalbed methane characteristics of the Greater Green River Basin.

RESOURCES

Total drillable area (mi^2)	18,000
Drillable area (mi^2) to depths < 6000 ft	3,400
Coal resource (billion tons)	1,277
Published max. gas-in-place (Tcf)	314
Average gas content (Scf/ton)	246

STRUCTURE

Structural relations	Complex
Thrusted/elevated margins (sides)	Steep (4)
Intrabasin uplifts	Numerous
Face-cleat orientation	NE; ENE; WNW
Overlapping face-cleat domains	Yes
Structural dip changes	Numerous

DEPOSITIONAL SETTING WILLIAMS FORK FORMATION

Typical thickness of Williams Fork Formation (ft)	1,500 - 2,000
Maximum-coal thickness (ft)	25 – 35
Typical net-coal thickness (ft)	100 – 200
Coal seam continuity	Good
Coal seam orientation	NE

DEPOSITIONAL SETTING FORT UNION FORMATION

Typical thickness of lower coal-bearing unit (ft)	<1,000-2,500
Maximum-coal thickness (ft)	30 – 40
Typical net-coal thickness (ft)	80 –140
Coal seam continuity	Good
Coal seam orientation	N-NE

THERMAL MATURITY

Coal rank, avg R_o (%) at 6000 ft	0.55 – 0.60
Typical gas content (Scf/ton)	50 – 350
Gas composition (C_1/C_{1-5})	0.78 - 1.00
CO_2 content (mole %)	<0.1 - 26
Dominant gas origin	Secondary biogenic; migrated thermogenic
Geothermal gradient (^oF/100 ft)	2.2

HYDROLOGY

Artesian overpressure (0.45 - 0.55 psi/ft)	Present
Hydrocarbon overpressure (0.70 psi/ft)	Extensive
Normal to slight underpressure (0.42 psi/ft)	Extensive
Chlorinity (mg/L)	100's – 1,000's
Permeability (md)	10's – 100's
Pressure transition boundary	Extensive
Area of convergent flow	Extensive

DATA BASE

Geophysical logs	19,294
DST's (coal intervals)	1,803
DST's (coalbed)	11

PRODUCTION (June 1993)

Cumulative gas (MMcf)	134
Cumulative water (MMbbl)	6.8
Cumulative gas/water ratio (ft^3/bbl)	20
IP gas (Mcf/d)	50 – >200
IP water (bbl/d)	<200 – >1,000
Avg. depth of CBM completion (ft)	2,671

INDUSTRY ACTIVITY

Companies active	~5
Coalbed completions	~28
Producing wells (6/93)	3 (<40 Mcf/d, 400 bwpd)

EXPLORATION FAIRWAYS

Williams Fork Formation	S Sand Wash; E Washakie; NE RockSprings
Fort Union Formation	Big Piney; Sandy Bend

depositional axes of the greater basin and overlaps with the trend of high net sandstone. The coals thus occupy the same axial position as do the fluvial systems, suggesting that tectonism provided subsidence rates optimal for peat accumulation, periodically shutting down the sediment supply to the intermontane fluvial systems. Channel-fill sandstones focused ground-water flow in order to initiate peat swamps, maintain water table levels, and preserve peat. The thickness and lateral continuity of the coal beds within the lower coal-bearing unit throughout the basin make it a potential coalbed methane target.

Coal Rank, Gas Content and Composition, and Origin of Coalbed Gases

1. Mesaverde coal rank ranges from subbituminous and high-volatile C bituminous along basin margins and the Rock Springs Uplift to semianthracite in the deep Washakie Basin. Coal ranks at depths of less than 7,500 ft (<2,286 m) are generally high-volatile C to high-volatile A bituminous, indicating that deeper coals, at exploitable drilling depths, have barely reached the threshold of thermogenic gas generation. Only deeper, higher-rank coals will therefore have economic gas content levels unless migration and conventional trapping of gases have occurred at shallower depths.

2. Fort Union coal rank is low, ranging from subbituminous along basin margins and the Rock Springs Uplift to low-volatile bituminous in the Washakie Basin. Low coal rank in the Fort Union Formation indicates that gas contents will be generally low and conventional trapping of migrating thermogenic and/or secondary biogenic gases may be required to reach gas content levels high enough to explore and develop the Fort Union (table 4).

3. Dry, ash-free gas contents from Mesaverde coals, generally less than 200 scf/ton (<6.24 m^3/t), range from less than 1 to more than 650 scf/ton (>20.28 m^3/t). Areas of high gas content lie in the Sand Wash Basin and north of the Rock Springs Uplift.

4. Dry, ash-free gas contents in Fort Union coals, generally less than 100 scf/ton (<3.12 m^3/t), range from 9 to 561 scf/ton (0.28 to 17.5 m^3/t). These generally low gas contents reflect shallow burial depth and low coal rank. Anomalously high gas contents in subbituminous Fort Union coals in the Big Piney area probably result from conventional trapping of thermogenic gases migrating updip from the deep Pinedale Basin, as well as possible secondary biogenic gases.

5. Mesaverde and Fort Union coalbed gases are early thermogenic, thermogenic, and secondary biogenic. Coalbed gases in the Mesaverde Group are early thermogenic and/or secondary biogenic in the hydropressured parts of the basin and predominantly thermogenic in deeper parts of the basin near the hydropressure—hydrocarbon overpressure boundary. Because Fort Union coals are lower rank, the coalbed gases are predominantly early thermogenic and/or secondary biogenic. However, thermogenic gases are probably more important in deeper parts of the basin as the coals approach or exceed high-volatile A bituminous rank.

Hydrology

1. In the Greater Green River Basin, the major coal-bearing hydrostratigraphic units are the Mesaverde aquifer and Tertiary aquifer system. The Mesaverde aquifer is regionally confined below by the marine Mancos Shale and its equivalents to the west and above by the marine Lewis Shale. The Tertiary aquifer system is confined by the Lewis Shale below and Green River Formation above.

2. The Mesaverde aquifer crops out along the east margin of the greater basin, recharges primarily along that margin in the foothills of the Sierra Madre Uplift, Park Range, and Williams Fork Mountains, and flows dynamically to favor generation of secondary biogenic gases. Although the Mesaverde crops out on the Rock Springs Uplift, recharge is limited by low annual precipitation, high evaporation rates, and faults; flow is consequently restricted. In the Green River Basin, Mesaverde recharge is severely limited by large stratigraphic displacement along major thrust faults, which hydraulically separates the wet basin margins from the basin interior and results in sluggish flow in the basin interior.

3. In the eastern Greater Green River Basin, the upper Mesaverde potentiometric surface slopes from the east recharge area basinward toward major fault systems and potentiometric depressions. A series of large potentiometric mounds along the deep central part of the basin reflect hydrocarbon overpressure. Equivalent fresh-water heads are greater than 10,000 ft (>3,050 m), exceeding Mesaverde outcrop elevations. The potentiometric surface is conspicuously flat off the east flank of the Rock Springs Uplift.

4. Mesaverde hydropressured strata flank regional hydrocarbon overpressure at the basin center. In the hydropressured section, no pressure regime regionally dominates. Most simple pressure gradients (pressure-depth quotients) indicate slight underpressure to normal pressure. Artesian overpressure has been identified on the eastern Cherokee Arch and northward along the east margin of the Washakie Basin, where simple gradients range from 0.44 to 0.54 psi/ft (9.95 to 12.22 kPa/m) (table 4). Regional hydrocarbon

overpressure is encountered at depths of 8,000 ft (2,440 m) or more in the central parts of the basin, where simple pressure gradients typically exceed 0.70 psi/ft (15.8 kPa/m).

5. In the Mesaverde aquifer, ground water flows mainly westward from an eastern recharge area, down hydraulic gradient, to discharge eventually basinward along regional fault systems, zones of extensive diagenesis, and facies changes that separate hydropressure from regional hydrocarbon overpressure in the central basin. Flow is sluggish or restricted off the Rock Springs Uplift and in the Green River Basin. Gravity-driven flow turns upward upon converging from the basin margins, aquifer pinch-out, or both, and upon encountering the top of geopressure, which because of low permeability and high pressure, is a no-flow boundary.

6. In the Tertiary aquifer system, ground-water flow primarily results from outcrop-related recharge along the foothills of the Sierra Madre Uplift and Park Range, Wind River Uplift, Wyoming Mountains, and Uinta Uplift. It flows basinward down regional topographic gradient and structural dip, in response to the hydraulic gradient from the wet, elevated margins of the basins, toward topographically low areas, to eventually discharge along major river valleys and central parts of the basin. Flow is dynamic throughout the greater basin.

Coal and Gas Resources

1. In the Greater Green River Basin, coal and gas resources total 1,276 billion short tons (1,158 billion t) and 314 Tcf (8.89 Tm^3), respectively. At depths of less than 7,500 ft (<2,286 m), resources are 688 billion short tons (624 billion t) and 84 Tcf (2.38 Tm^3).

2. The Mesaverde Group coal and gas resources are 627 billion tons (569 billion t) and 264 Tcf (7.47 Tm^3), respectively, accounting for 49 and 84 percent of the total resources, respectively. At depths of less than 7,500 ft (<2,286 m), resources are 243 billion short tons (220 billion t) and 56 Tcf (1.58 Tm^3).

3. The Fort Union Formation contains 649 billion tons (589 billion t) and 50 Tcf (1.42 Tm^3), accounting for 51 and 16 percent of the total resources, respectively. At depths of less than 7,500 ft (<2,286 m), resources are 445 billion short tons (404 billion t) and 28 Tcf (0.79 Tm^3).

Production

1. In the Sand Wash Basin, gas production from three Williams Fork fields has been minimal, whereas water production has been excessive. Cumulative gas production and water production through June 1993 were 134 MM scf (3.8 MM m^3) and 6.8 million barrels (1.1 million m^3), respectively, for a basinwide cumulative gas–water ratio of approximately 20 scf/bbl (~3.6 m^3/m^3) (table 4). Among the 11 wells in Dixon field, 3 currently produce gas at rates of less than 40 Mcf/d (<1.1 Mm^3/d). The 16 plugged and abandoned wells in Craig Dome field were abandoned because the Williams Fork coals had low gas contents and could not be economically depressured (dewatered).

2. Nine Fort Union coalbed wells were completed, production tested, plugged, and abandoned in the Sand Wash Basin. During test periods ranging from 9 d to 7 mo, the wells made zero to negligible volumes of gas and tens of thousands of barrels of water (thousands of cubic meters).

3. On the northern Rock Springs Uplift, Rock Springs coals showed commercial promise. Production forecasts predicted recoveries of 1 to 3 Bcf/160 ac (28 to 84 MMm^3/65 ha) and peak rates of 240 to 1,200 Mcf/d (6.79 to 34.00 Mm^3/d). Despite these promising forecasts, test results were disappointing. During a 530-d production test, the most successful well (2 UPRC-1) averaged 78 Mcf/d (2.21 Mm^3/d) and 200 bwpd (32 m^3/d) from a 50-ft (15-m) interval.

Exploration Fairways

1. The Greater Green River Basin is a largely untested, frontier coalbed methane basin, where deeper drilling will be required to penetrate higher rank, higher gas content coals. Mesaverde gas contents between 6,000 and 7,500 ft (1,830 and 2,286 m) are approximately 350 scf/ton (~10.92 m^3/t) and exceed 500 scf/ton (~15.60 m^3/t) at depths below 7,500 ft (2,286 m).

2. Coal distribution and steep structural dip limit deeper drilling to the eastern Sand Wash and Washakie Basins and flanks of the Rock Springs Uplift, where Mesaverde coals are prospective along the Cedar Mountain fault system, the east margin of Washakie Basin, and the north flank of the Rock Springs Uplift (fig. 70 and table 4).

(a) The Cedar Mountain fault system in the Sand Wash Basin terminates in a zone of convergence and upward flow along the boundary between hydropressure and regional overpressure. Higher rank, high gas content coals are present in the area, suggesting high production potential. Moving basinward away from the recharge area should facilitate dewatering.

(b) Along the east margin of the Washakie Basin, upthrown to a major fault system, normally pressured and artesian overpressured coals have gas contents ranging from 250 to 350 scf/ton (7.80 to 10.92 m^3/t). To date, excessive water production has limited producibility, however. At Dixon field the coals could not be dewatered (depressured) to promote high gas production rates. Because precipitation (recharge) decreases northward, chances for dewatering should improve to the north.

(c) On the northern Rock Springs Uplift, coals of the Rock Springs Formation have been targeted for development because thickness, resources, and gas content are favorable. Net coal thickness in 5-ft (1.5-m) seams exceeds 40 ft (12 m), gas resources at less than 7,500 ft (<2,286 m) measure approximately 9 Tcf (~0.25 Tm^3), rank ranges from hvCb to hvAb, and gas content averages 350 scf/ton (10.92 m^3/t) over a 1000-ft (305-m) interval. Development was stopped primarily by low gas prices and disappointing test results and secondarily by environmental concern over disposal of produced water.

3. Because Fort Union gas contents are low (~100 scf/ton [~3.12 m^3/t] or less), Fort Union coals are secondary coalbed methane targets. However, two areas, the Big Piney area and Sandy Bend Arch (fig. 72), are thought prospective, where structural and/or stratigraphic trapping may enhance gas contents. In the Big Piney area, adjacent to the deep Pinedale Basin, shallow subbituminous coals are reported to have gas contents of approximately 500 scf/ton (~15.6 m^3/t), suggesting updip migration and conventional trapping of thermogenic gases. In the northern Green River Basin, more than 100 net ft (>30 m) of coal is present, and individual coals range to as much as 40 ft (12.2 m) in thickness. On the Sandy Bend Arch thick coals have never been tested. These coals may conventionally trap considerable migrated thermogenic and secondary biogenic gas. Ground water flows orthogonally to the arch to maximize delivery of gas to the arch.

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Conversion Chart

NONMETRIC UNIT		CONVERSION FACTOR		METRIC UNIT
feet (ft)	×	0.3048	=	meters (m)
inches (inch)	×	2.540	=	centimeters (cm)
miles (mi)	×	1.609	=	kilometers (km)
feet/mile (ft/mi)	×	0.1894	=	meters/kilometer (m/km)
square miles (mi^2)	×	2.589	=	square kilometers (km^2)
cubic feet (cf)	×	0.02832	=	cubic meters (m^3)
short tons	×	0.9072	=	metric tons (t)
pounds per square inch (psi)	×	6.895	=	kilopascals (kPa)
psi/ft	×	22.62	=	(kPa/m)

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