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GEOLOGIC AND HYDROLOGIC CONTROLS ON COALBED METHANE: SAND WASH BASIN, COLORADO AND WYOMING

ANNUAL REPORT

(August 1, 1991 – July 31, 1992)

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for
GAS RESEARCH INSTITUTE
Contract No. 5091-214-2261
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September 1992

DISCLAIMER

RESEARCH SUMMARY

Title	Geologic and Hydrologic Controls on Coalbed Methane Production: Sand Wash Basin, Colorado and Wyoming
Contractor	Bureau of Economic Geology, The University of Texas at Austin, GRI Contract no. 5091-214-2261
Principal Investigator	W. R. Kaiser
Report Period	August 1, 1991–July 31, 1992
Objective	To identify geologic and hydrologic controls on the occurrence and producibility of coalbed methane in the Sand Wash Basin, northwest Colorado and southwest Wyoming.
Technical Perspective	Coalbed methane production has been established in the Sand Wash Basin. Large coal resources, gas shows during drilling of coal beds, and high gas contents in some coals triggered initial development along the basin margins. Results to date have been disappointing. Coalbed wells have yielded little gas and large volumes of water. In the absence of a regional analysis, neither production data nor the basin's ultimate coalbed methane potential could be fully evaluated. Thus, an integrated geologic and hydrologic study of the basin was needed to provide the framework for evaluating development properties and the rationale for future exploration.
Results	Geologic and hydrologic analysis of the Upper Cretaceous Mesaverde Group shows that the major controls on the production of coalbed methane are: structural configuration, coal occurrence, gas content, hydrodynamics, and water production. Steep structural dip (500 ft/mi) and coal occurrence limit economic exploration to the eastern and southeastern margins of the basin. Coal resources occur mainly in the lower Williams Fork Formation (upper Mesaverde) in the eastern part of the basin. Most coal beds are high-volatile C to B bituminous rank and have gas contents of less than 200 scf/ton. Moreover, Williams Fork coals do not extend westward to the area of highest thermal maturity. Thus, they could not serve as conduits for long-distance migration of gas. Regionally, ground water flows westward from an eastern recharge area across an area of low thermal maturity up the coal-rank gradient. Consequently, only a relatively small volume of gas may be available to be swept basinward for conventional trapping. The most prospective areas lie basinward, northwest of Craig, Colorado, on the upflow, downward side of a major fault zone. Gas contents in some coal beds on the downthrown side of the fault exceed 400 scf/ton. The Mesaverde is a thick, regionally interconnected aquifer system of high transmissivity, yielding large volumes of water. Paradoxically, coalbed permeabilities of 10's to 1,000's of md may be too high for economic gas production. To date, high water production and low gas content at the basin margins have limited coalbed activity in the Sand Wash Basin. Major Tertiary coal resources occur in the lower part of the Paleocene Fort Union Formation.
Technical Approach	In geologic studies, approximately 75 geophysical logs were used to evaluate Mesaverde structure, genetic stratigraphy, sedimentology, and coal

occurrence. More than 100 logs were used in a preliminary stratigraphic analysis of the Fort Union Formation. A grid of interlocking cross sections was made to identify and define the major coal-bearing stratigraphic unit in the Mesaverde, which is the Williams Fork Formation. Structure-contour maps were made on the top and bottom of the Williams Fork. Major structural elements and unconformities were further defined from 115 mi of seismic data.

The Williams Fork Formation was divided into four genetic stratigraphic units and lithofacies and coal-occurrence maps were made for each unit. Genetic units provided the foundation for subsurface correlation and mapping and more importantly the basis for predicting the geometry and distribution of framework sandstones and coal deposits in areas of meager control. In the absence of porosity logs, coals were operationally identified by very high resistivity, low natural gamma response, and shale-like SP response. Individual coal beds were correlated on the basis of their gamma-ray and density profiles, seam signatures sensitive to minor fluctuations in the coal lithotypes.

A coal-rank map was prepared from 50 measured vitrinite reflectance values from 10 Mesaverde wells, 39 values calculated from proximate and ultimate analyses, and 55 values calculated from a vitrinite reflectance profile. Coal heating value (Btu/lb) was converted to equivalent vitrinite reflectance values. In the absence of measured values and analyses, vitrinite-reflectance values were calculated from equations established by regression analysis of Mesaverde coal and shale data taken from profiles in the Sand Wash and Washakie Basins. Gas content data (about 250 values) were obtained from the literature and five operators.

Mesaverde hydrology was evaluated in an analysis of hydraulic head, pressure regime, and hydrochemistry. Hydraulic heads were calculated from SIP's recorded in DST's and BHP's calculated from WHSIP's. Approximately 90 head values were used to prepare a potentiometric-surface map. Pressure regime and vertical flow direction were evaluated from simple and vertical pressure gradients, respectively, calculated on data screened from several hundred DST's. Chlorinity and TDS maps, made from 155 water analyses from 66 Mesaverde wells, were used to further evaluate ground-water flow.

Production data was obtained from commercial companies, public agencies, the literature, and operators and related to the geology and hydrology to identify controls on production.

Implications

Geologic and hydrologic models developed here provide a basis for more informed decisions about future development and exploration in the Sand Wash Basin. The models provide a rationale for development and exploration strategies. Prospective areas lie basinward and are controlled by basin structure, coal occurrence, gas content, and hydrodynamics as described in this report.

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Tectonic and Stratigraphic Setting and Coal Fracture Patterns of the Sand Wash Basin

C. M. Tremain, Roger Tyler, and S. E. Laubach

ABSTRACT

Tectonism has affected depositional patterns, coal occurrence, hydrology and thermal maturity (gas generation) in the Sand Wash Basin of northwest Colorado and southwest Wyoming. Tectonism has also determined the distribution and orientation of folds, fractures and faults within the basin. Permeability in coals and adjacent rocks is largely due to the occurrence of fractures (cleats) and faults. Northwest trending systematic fractures (face cleats) and faults, on the southeast margin of the Sand Wash Basin, are parallel to current maximum horizontal stress directions and may provide permeable pathways for both gas and water; fracture and fault swarms may further enhance coal permeability. This section provides the tectonic and stratigraphic setting for studies of depositional, coal occurrence, hydrology, and thermal maturity patterns in Cretaceous and Tertiary coals of the Sand Wash Basin, and includes a brief summary of preliminary observations of fracture patterns. An understanding of the tectonic setting of the basin, combined with the studies in the following chapters, provides a basis for predicting coalbed methane occurrence and producibility.

TECTONIC AND STRATIGRAPHIC SETTING

The Sand Wash Basin of northwest Colorado and southwest Wyoming, is a subbasin of the Greater Green River Basin, east of the Wyoming-Idaho segment of the Cordilleran thrust belt (fig. 1). The Sand Wash Basin is a southerly continuation of Wyoming's Washakie Basin, and its synclinal axis trends north-south (fig. 1). The east-west-trending Cherokee Arch (ridge), a complexly faulted, westward plunging anticline (Masters, 1961), separates the Sand Wash Basin from the Washakie Basin. To the east, the Sand Wash Basin is bounded by the Sierra Madre and Park Uplifts, to the south by the White River Uplift, to the southwest by the Uinta Uplift, and its southeast extension, the Axial Arch, and to the northwest by the Rock Springs Uplift (fig. 1). The Vermillion Basin area (between T12N; R100W and T13N; R102W), a topographic basin formed by drainage of the Vermillion Creek and its tributaries, differs from the rest of the Sand Wash Basin in that there are many structures, facies changes, and stratigraphic thickness variations within this area (Colson, 1969) (fig. 1).

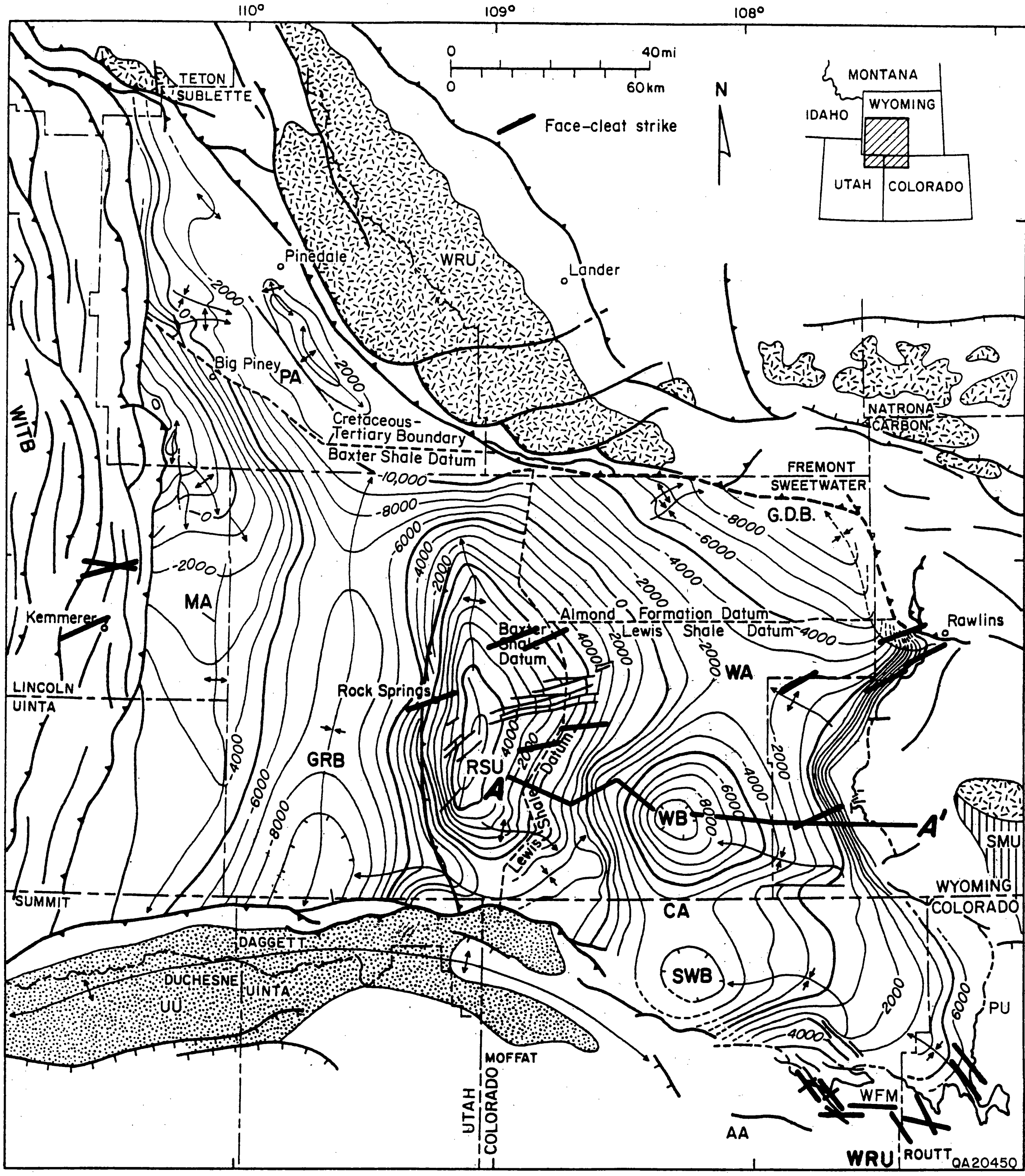

Figure 1. Tectonic map of southwestern Wyoming and adjacent states showing the major tectonic elements of the Greater Green River Basin. The map is taken from Lickus and Law (1988). Structure contours, in feet relative to mean sea level, are drawn on Upper Cretaceous marker horizons. Major tectonic features are identified as follows: AA, Axial Arch; CA, Cherokee Arch; GDB, Great Divide Basin; GRB, Green River Basin; PA, Pinedale Anticline; PU, Park Uplift; RSU, Rock Springs Uplift; SMU, Sierra Madre Uplift; SWB, Sand Wash Basin; UT, Uinta thrust fault; UU, Uinta Uplift; WA, Wamsutter Arch; WB, Washakie Basin; WFM, Williams Fork Mountains; WRU, White River Uplift, WITB, Wyoming-Idaho thrust belt; and WRU, Wind River Uplift. Basement rocks are identified as random-dash, vertical-line, and stippled patterns.

In the Sand Wash Basin, Cambrian through Tertiary age rocks are up to 30,000 ft thick (Irwin, 1986). During the Upper Cretaceous up to 11,000 ft of clastic sediments were deposited (Haun and Weimer, 1960). In the Sand Wash Basin, the major coal bearing intervals and coalbed methane targets occur in Upper Cretaceous-Mesaverde Group rocks (Williams Fork Formation) and in Paleocene Fort Union Formation rocks (lower coal-bearing unit) (Tyler and others, 1991, 1992a and b) (fig. 2). In the deepest part of the basin (between T9N, R96W and T10N, R99W), the top of the Mesaverde Group is about 11,500 to 12,000 ft below surface, with the base of the major coal-bearing Williams Fork Formation about 5,000 to 6,000 ft below sea level (fig. 3). Basal Mesaverde Group sandstones probably attain maximum depths of about 15,000 to 16,000 ft. The top of the Fort Union Formation is approximately 8,500 ft below the surface, with the base of the lower coal-bearing unit about 3,000 ft below sea level (fig. 4). The basin covers an area of approximately 5,600 mi^2 (Tyler and others, 1991) as defined by the outcrop trace of the base of the Mesaverde Group (fig. 3).

Evolution

During the Cretaceous, the area of the present Sand Wash Basin was near the western margin of the Western Interior Seaway, a shallow sea that extended from north to south across much of the North American midcontinent (Kauffman, 1977) (fig. 5). The Western Interior Seaway occupied a foreland basin bounded on the west by the Cordilleran thrust belt. Greatest subsidence and deposition was along the western margin of the seaway, adjacent to the Cordilleran thrust belt. The initiation of deformation in the thrust belt during the Early to Late Cretaceous Sevier Orogeny coincided with a major episode of subsidence of the Western Interior Seaway (Heller and others, 1986). Sediments derived from the uplifts to the west gradually filled the basin causing the northeast trending shoreline to retreat eastward. Numerous transgressions and regressions of the shoreline are recorded in the Cretaceous sediments and reflect episodic thrust belt deformation and eustatic sea level change. The Fox Hills Sandstone (fig. 2) represents the final regressive shoreline facies of the Western Interior Seaway and the Lance Formation the succeeding aggradational facies (Irwin, 1986), terminating Cretaceous sedimentation. The Fox Hills/Lance couplet is depositionally equivalent to the Pictured Cliffs/Fruitland couplet, a prolific methane producer in the San Juan Basin.

In late Cretaceous to early Tertiary time, the Laramide Orogeny caused large uplifts, folds, and faults to appear in the foreland of the Cordilleran thrust belt. This structural event subdivided the foreland area into smaller basins, such as the Greater Green River Basin (fig.1), and formed the faults and folds that bound the Sand Wash Basin (fig. 6). Reverse and/or thrust faults occur on one or more sides of these uplifts. Precise timing of the uplifts remains controversial, but preexisting structure grain may have

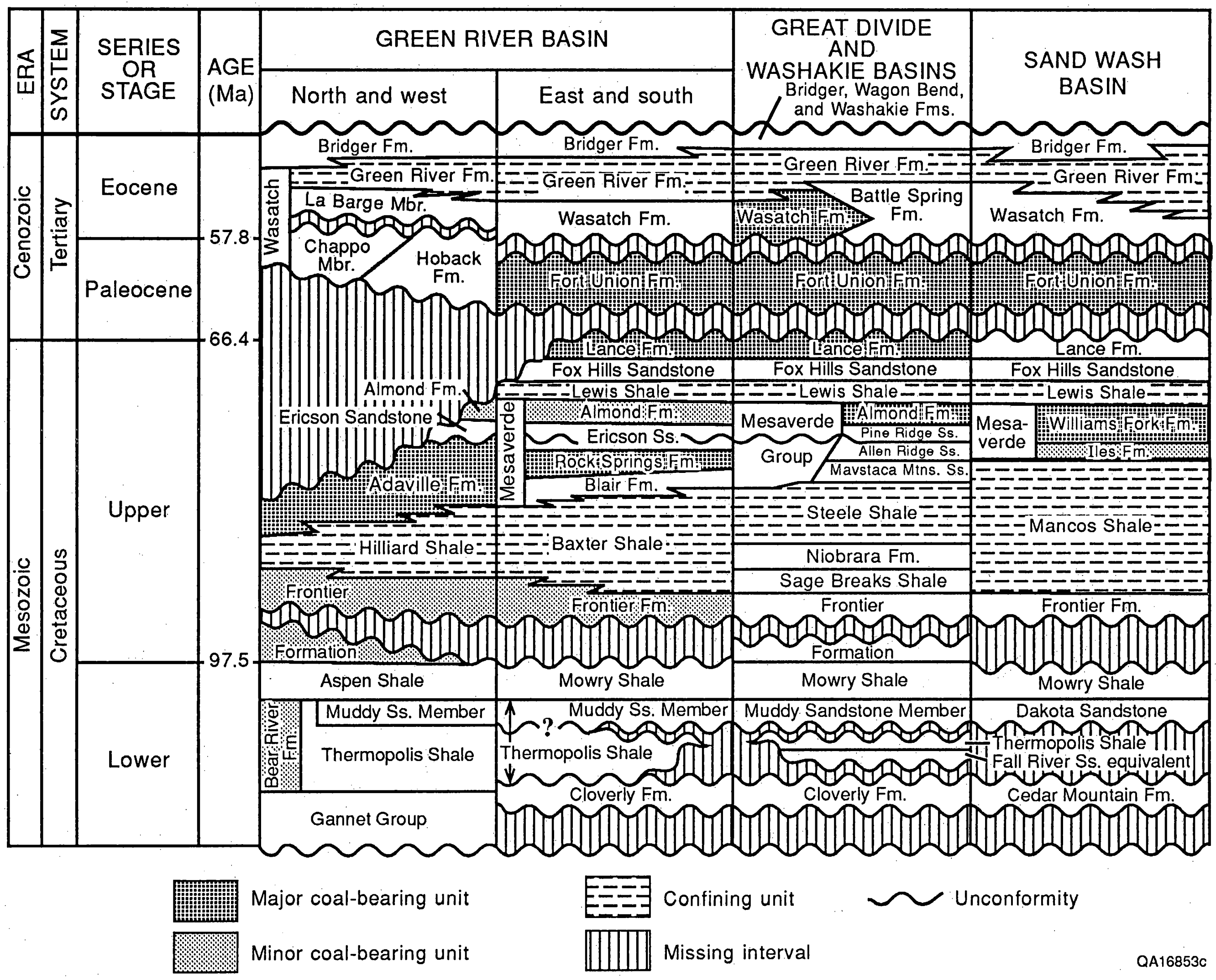

Figure 2. Coal-bearing stratigraphic and confining units in the Sand Wash Basin, and surrounding basins. Modified from Baars and others (1988).

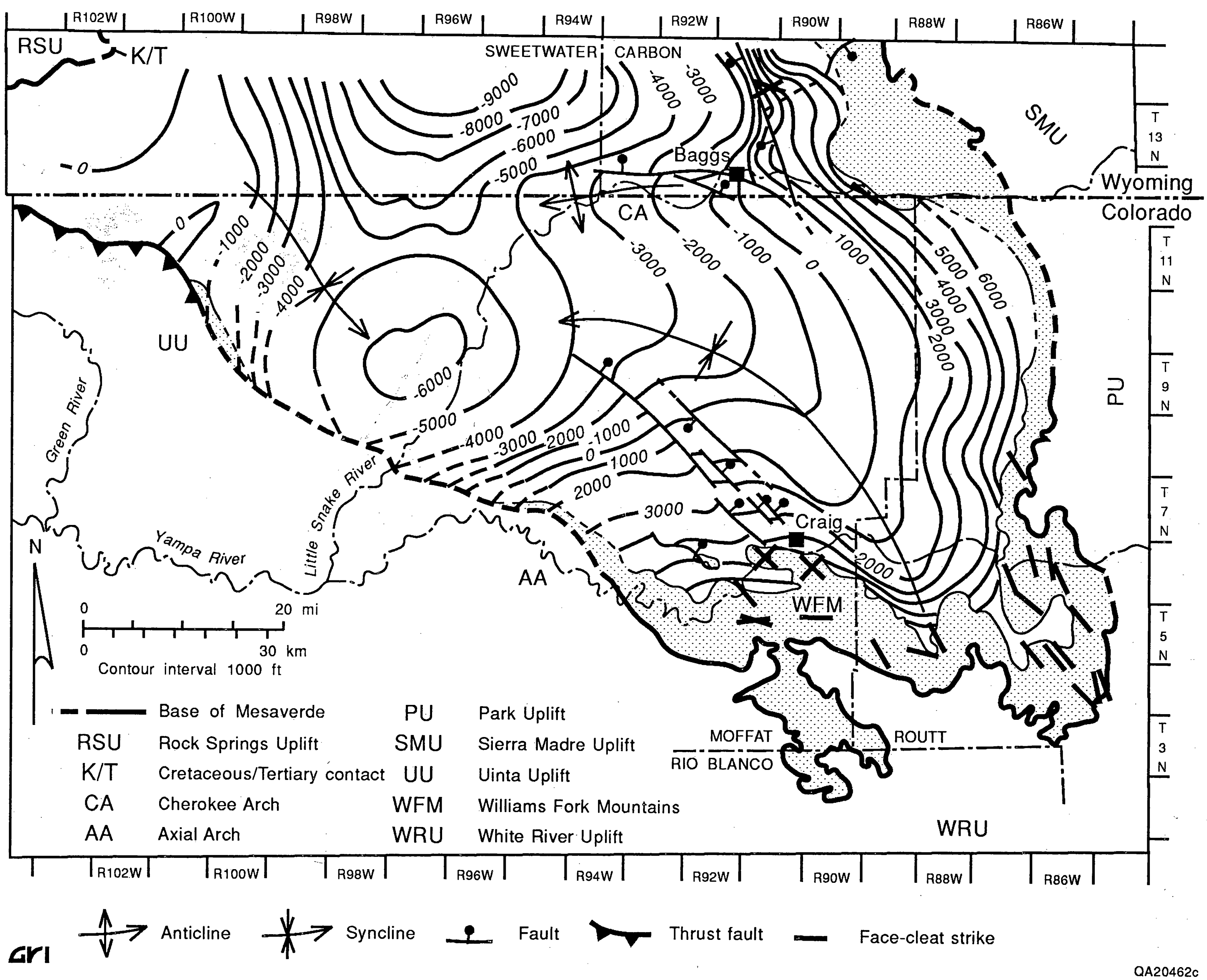

Figure 3. Structure map contoured on the base of the Williams Fork Formation, Sand Wash Basin, showing face-cleat trends. Cleat observations are listed in Table 2 or taken from Tyler and others 1991, 1992a, Khalsa and Ladwig, 1981, and Boreck and others, 1977.

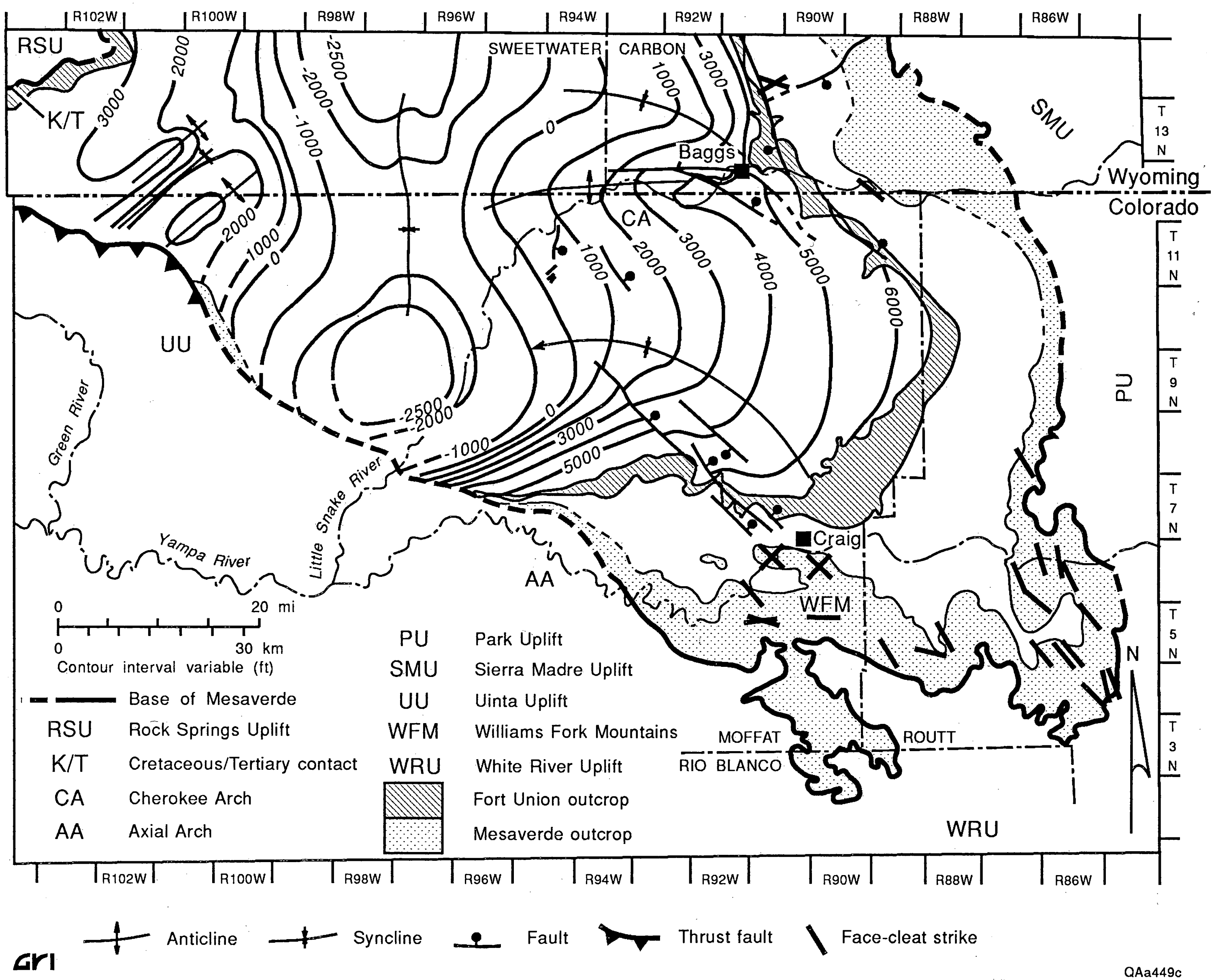

Figure 4. Structure map contoured on the base of the Fort Union Formation, Sand Wash Basin, showing cleat trends.

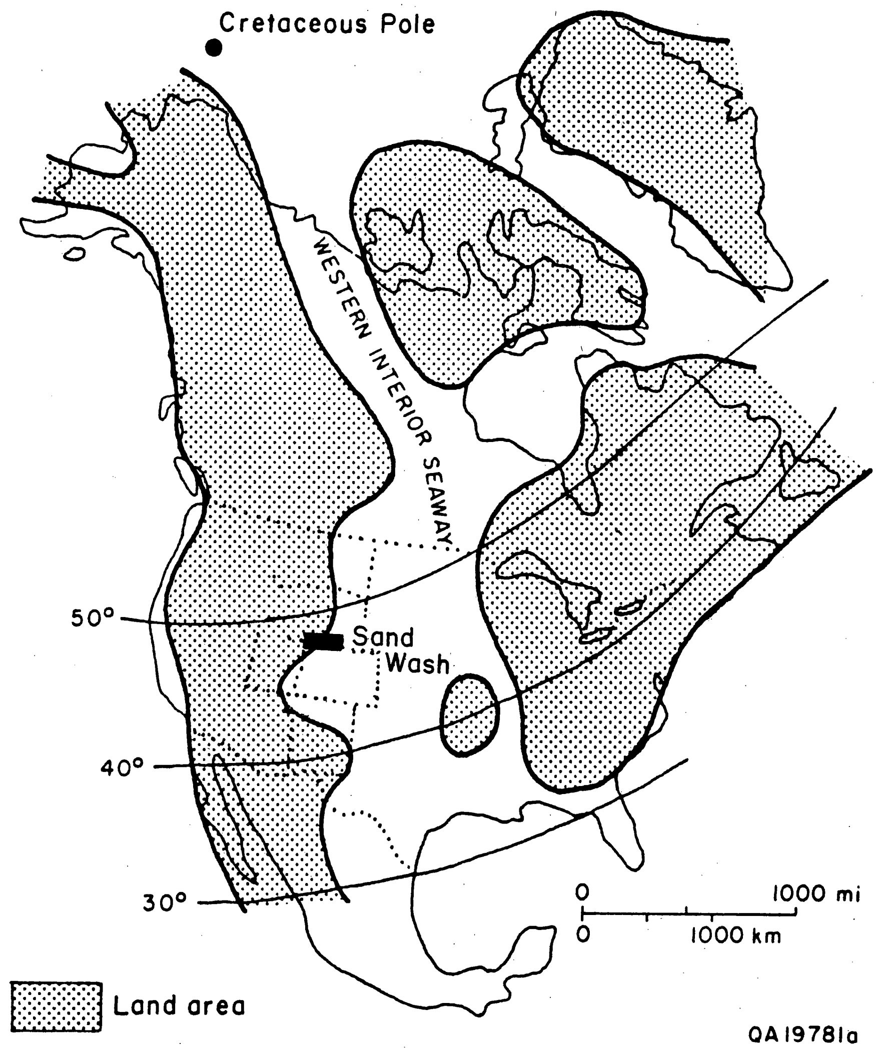

Figure 5. Location of the Sand Wash Basin relative to the Western Interior Seaway. Modified from Palmer and Scott (1984) after Irving (1979).

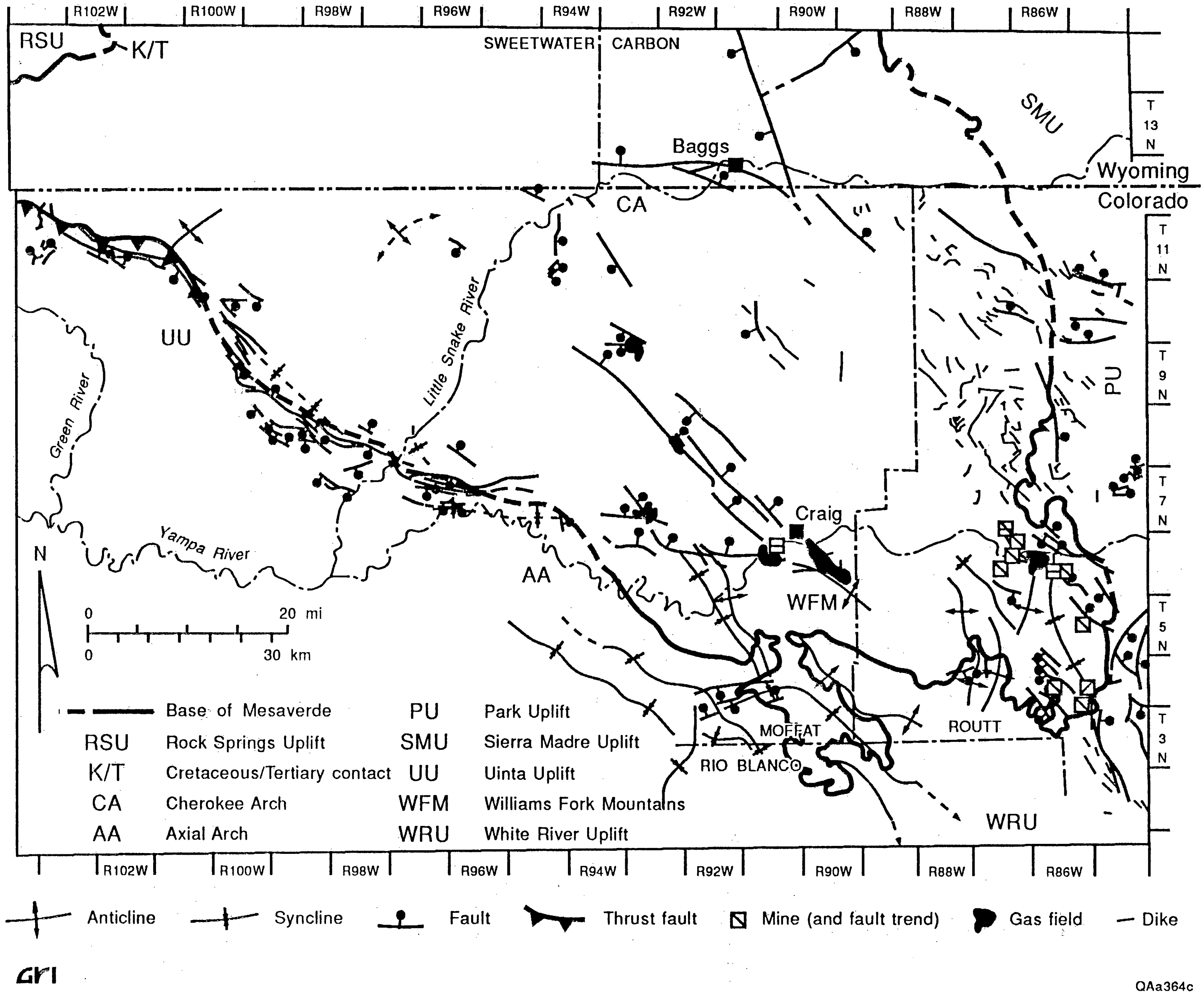

Figure 6. Map of tectonic elements in the Sand Wash Basin (modified from Tweto, 1976; Tweto, 1979; Hancock, 1925; and Rowley and others 1985). The location of faults associated with coal mines and gas fields are shown. Note predominantly northwest trend of faults, folds and dikes.

controlled the orientation of some uplifts. For example, in the Uinta Uplift, structural fabric having east-west trends in 2.7 b.y. old gneisses and quartzites plus seismic data indicate that the Uinta Mountains and their southeast extension, the Axial Arch may have been influenced by faulting dating back to the Proterozoic (Hansen, 1986). In addition, the east-west trend of the Cherokee Arch on the northern boundary of the Sand Wash Basin may also have been inherited from major Precambrian structures (Osmond, 1986).

During the Laramide Orogeny, the Sand Wash Basin was filled with continental-fluvial sediments of the Fort Union and Wasatch formations (fig. 2). The Fort Union and Wasatch formations contain sediment shed from the surrounding Sierra Madre-Park and Uinta Uplifts (Osmond, 1987), and the Sawatch Range (Beaumont, 1979). Uplift occurred again during the Oligocene, and extensional deformation began in the early Miocene (Hansen, 1986). Extensional faulting continued at a diminished rate into the Quaternary (Hansen, 1986). Dikes, sills, and other intrusives were also emplaced in the upper Tertiary (Tweto, 1979) in the eastern part of the basin and locally coked or metamorphosed coals to anthracite (Bass and others, 1955). The dikes exhibit northwesterly trends similar to fractures and faults in the area (fig. 6).

Faults, Folds, and Stress Regime

Faults in the Sand Wash Basin could contribute to coal permeability and conventional trapping of gas. Oil and gas fields occur on north-, northwest-, and west-trending faulted structures on the flanks of the Axial and Cherokee Arches, and in the center of the basin (fig. 6). The southwestern part of the basin is bordered by thrust and reverse faults, some with displacements up to 2,000 ft (Livesey, 1985). The thrust and reverse faults extend for approximately 80 miles along the edge of the basin and are parallel to faults on the northeast flank of the Uinta Mountains and Axial Arch (fig. 6). Except for a small area in T100-101W, R10N, the thrust faults bury the Mesaverde Group (fig. 6). Normal faults have also been recognized on seismic lines (Livesey, 1985).

Large predominantly northwest- and north-trending folds 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 in the west (Hancock, 1925) and the more northerly trending Tow Creek, Oak Creek, Fish Creek, Sage Creek anticlines in the east (Bass and others, 1955). Major northwest faults, 5 to 10 mi long, are recorded on surface geologic maps (Bass and others, 1955; Hancock, 1925; and Tweto, 1976) parallel to these anticlines. Smaller faults, oblique to the folds, have also been reported (for instance near the Edna Mine). Faults, with displacements of 2 to 215 ft. have been mapped in the subcrop in 11 abandoned and six operating mines (table 1). The majority of these in-mine faults trend northwest although several east, west, and northeast faults (and a few northwest-trending dikes) have also been

Table 1. Coal mine faults in the Sand Wash Basin.

MINE NAME	SECTION	TWP	RGE	MINE TYPE	MINE STATUS	FAULTS MAPPED	FAULTS TRENDS	FAULT THROWS	NOTES
Apex	21,22	4N	86W	U	abd.	2	NW,NW	25 and 100'	
Bear River	11,2	6N	87W	U	abd.	4	EW,NW,NW,NW	One at 8'	
Blair	SW,NW 10	6N	91W	U	abd.	1	ENE		
Curtis	NE,SW 22	6N	86W	U	abd.	1	NW	70'	
Denton Strip	20,21	6N	86W	S	abd.	3	NNE,WNW,WNW		
Hammond	SE,NW 34	7N	87W	U	abd.	2	NNE,NW		
Harris	16,21,28, 15,22,27	6N	87W	U	abd.	15	NW	2-215'	
Keystone	19	4N	85W	U	abd.	3	SW,WNW,NW		
	24	4N	86W						
Lenox	SW 22	6N	86W	U	abd.	1	N7 W	6'	
Pinnacle	35,36	4N	86W	U	abd.	4	WNW,NNW,NNW,NW	3-20'	NW trending dike
	1,2	3N	86W						
Wadge	9,10,15	6N	87W	U	abd.	10	NW & 9 at NNW	4-7'	9' wide NNW dike, coked coals between 18'-22' on each side
Seneca Strip	2,3,10,11	6N	87W	S	act.	4	EW,NNW	E-W is 40-60' NNW are 4'	
Energy #1	13	5N	86W	S	act.	1 major	NW-SE	60-100'	
Edna	19,30,31	5N	85W	S	act.	many	major faults NW smaller faults NE		pyrite in Wolf Creek and Wadge seams
	36	5N	86W						
	7,18,19	4N	85W						
Trapper	5 & 6,	5N	90 W	S	act.	1	E-W		
	1,2,3,4,5	5N	91W						
	30-32	6N	90 W						
Eagle Mine	31,32	6N	91W	U	act.	7	WNW	10-40'	
	5,6	5N	91W						
Foidel Creek	32	5N	86W	U	act	1	NW	6'	

S surface mine
U underground mine
act. active mine
abd. abandoned mine

mapped. In addition to offsetting the stratigraphy, faulting has created an extensively fractured zone of rock (fracture swarm) within or between several fault planes that parallel the fault traces. Some of the fault offsets may be the result of strike-slip movement on the dip slope as indicated by slickensides observed in coal mines in the area (Robson and Stewart, 1990). Northwest-trending faults also appear on subsurface maps of gas fields such as Buck Peak, Craig Dome, Great Divide, Tow Creek and Big Gulch.

Northwest of Craig, between T7N; R91W and T9N; R94W (fig. 6), a major system of faults, that cuts the Miocene Browns Park Formation, has been recognized in the subsurface on seismic lines provided by Union Pacific Resources. The largest of these faults has a throw of 1,650 ft in T8N;R92W, based on structural contours of the top of the Williams Fork Formation, Mesaverde Group (fig. 3). The downthrown block is on the northeast side of the fault. Faults parallel to this large fault have up- and down-throws ranging from about 100 ft to 500 ft. This fault system may have occurred as a result of the Laramide Orogeny, continued intermittently into late Eocene time (Tweto, 1980), and may have been reactivated during regional uplift in late Miocene.

The interpretation of the orientation of the principal shortening direction is controversial in the Sand Wash Basin. The consensus is that the major compressive force during the Laramide Orogeny was east-west (Livesey, 1985) then shifted to southwest-northeast (Gries, 1983). The present stress regime of the Sand Wash Basin is extensional and lies within the Cordilleran stress province of Zoback and Zoback (1989) between the Colorado Plateau interior and the southern Great Plains stress province (fig. 7). Using sparse stress measurements, Zoback and Zoback (1989) suggest that the maximum horizontal compressive stress orientation is north-northwest in the Sand Wash Basin.

Fracture Patterns

Permeability in coal is largely due to the occurrence of fractures (cleats) and faults. Cleat and fault characteristics were recorded in Sand Wash Basin, from field observations in the Mesaverde Group and Fort Union Formation coalbeds (at approximately 18 stations, principally in the southeast corner of the basin), literature, and core descriptions (Colorado Oil & Gas Commission's well files). Additional information on faults was obtained from geologic maps (including 100 maps of abandoned mines), and mine permits (fig. 6).

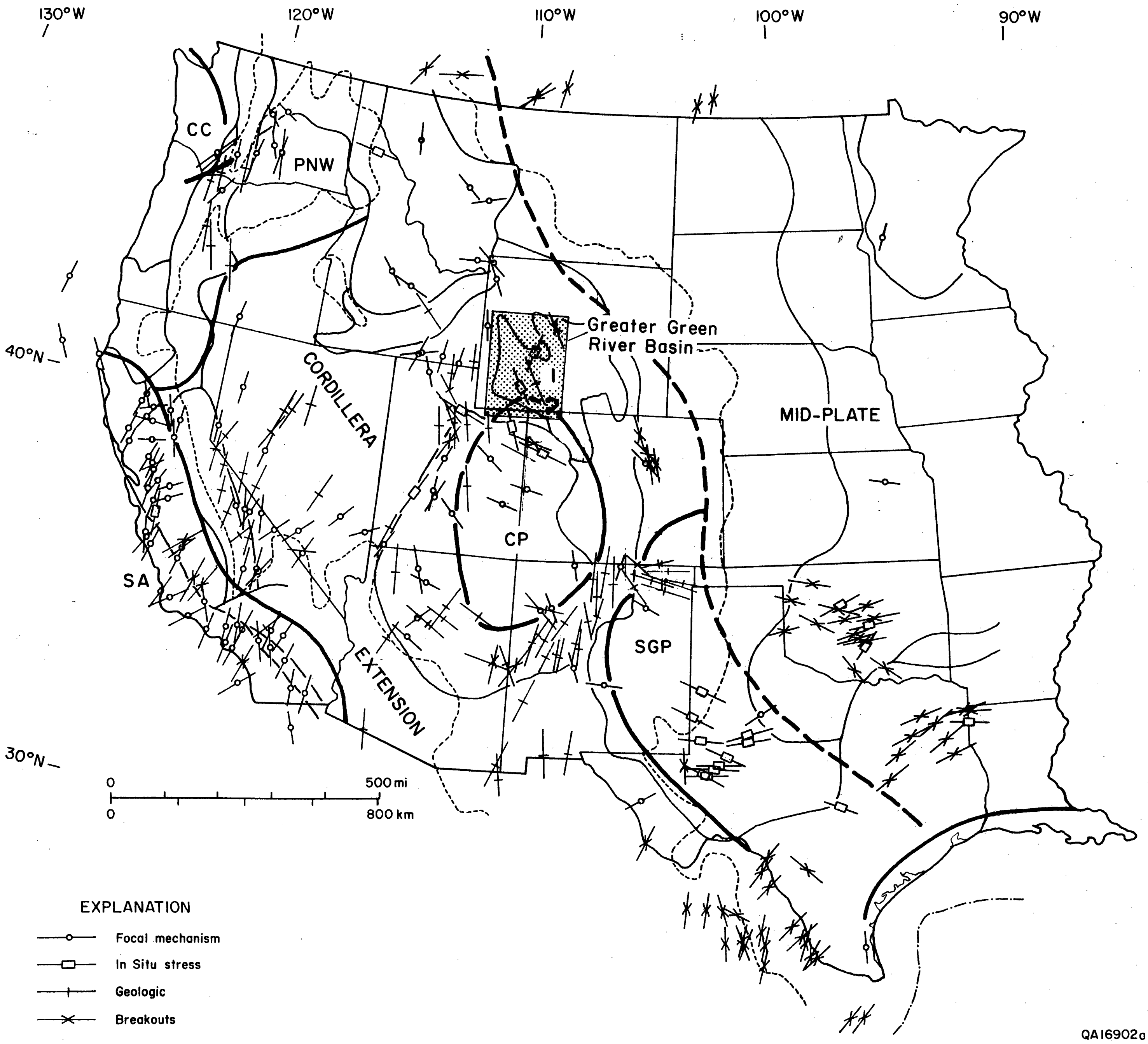

Figure 7. Maximum horizontal compressive stress orientation of the Western United States. Stress provinces are delineated by thick solid and dashed lines: CC = Cascade convergent province; PNW = Pacific Northwest; SA = San Andreas province; CP = Colorado Plateau interior; SGP = Southern Great Plains. Thin dashed lines mark the 3,609 ft (1,100-m) elevation contour based on 1 degree average elevations. (Modified from Zoback and Zoback, 1989).

Cleat Types

According to the definition of Tremain and others (1991), the first formed and commonly better developed fracture set in coal is the *face cleat*, which generally is the more prominent because their fracture traces are long and have smooth, planer surfaces. The less well developed, more irregularly shaped set is the *butt cleat*, which abuts the face cleat. Observations in the Sand Wash Basin commonly show well developed face cleats; butt cleats are less pronounced. The face and butt cleats are usually mutually perpendicular. They are also generally perpendicular to the coal bedding planes, although some cleat inclinations may vary between 60° to 90°. In addition to the face and butt cleats, occasionally crosscutting third- and fourth-order cleats were observed. Also, striated and sheared coals were seen at several locations, as were curved cleats and conchoidal fractures (table 2). Previous workers have not specified the abutting relations used to identify and define face cleats. All face cleats are not necessarily of the same age.

Face-Cleat Orientation

Boreck and others (1977) measured north to northwest face cleat directions in seven mines in the southeast part of the basin. They reported face cleat striking at 003° at the Apex Mine (T4N, R86W), 353° at the Edna Strip (T4N, R85W), between 300° and 335° at four Energy Strip pits (T5N, R86-87W), and 315° at the Seneca Strip (T6N, R87W). Khalsa and Ladwig (1981) also measured northwest face cleat strikes of 300°-312° at the Denton Strip (T6N, R86W) and 314°-320° at the Eagle #5 underground mine (T6N, R89W) (fig. 3). Face-cleat orientations measured at 18 stations in the Sand Wash Basin (table 2 and fig. 6) generally trend northwest (Laubach and others, 1992), parallel to the current maximum horizontal stress direction (Zoback and Zoback, 1989), and the major northwest trending faults in the area (fig 6). However, the northwest strike of the face cleats is less consistent south of Craig. On the Yampa River, on Highway 789, and at the abandoned Walker Mine, mutually crosscutting and abutting face cleat strike northwest and northeast. In this area , face cleat, as defined by Tremain and others (1991), is undefined. We tentatively interpret this to indicate the presence of at least two major, possibly contemporaneous "face" cleat sets (Laubach and others, 1992). Hancock (1925) mapped an east-striking fault, north of these two cleat stations. Mutually abutting crisscrossing fracture sets may also enhance cleat permeability (Tremain and others, 1991). Farther south in T5N, R90-91W, on Highway 13 and in Jeffway Gulch, face-cleat strike is nearly east-west (fig. 6); major faults south of Craig, in T4N, R91-92W, also strike east-west.

Table 2. Cleat and fracture observations in the Sand Wash Basin.

AREA		LOCATION	LITHOLOGY	CLEAT/ FRACTURE	FM.	FACE CLEAT ORIENTATION	COMMENTS
Haybro roadcut	SW	Sec. 17, T4N, R85W	coal	face cleat	Ki	350	3rd,curved,fracture swarm in butt direction
abandoned mine		Sec. 18, T4N, R85W	sandstone	joint	Ki	85	
Edna mine	SW	Sec. 24, T4N, R86W	coal	face cleat	Kwf	320	
Foidel Creek roadcut	NW	Sec. 28, T5N, R86W	coal	face cleat	Kwf	87	
Foidel Creek	NE	Sec. 29, T5N, R86W	sandstone	joint	Kwf	310	
Hayden Gulch	SE	Sec. 17, T5N, R88W	coal	face cleat	Kwf	330	bright, friable coal
Hayden Gulch	NE	Sec. 30, T5N, R88W	coal	face cleat	Kwf	290	
Berry Gulch	NW	Sec. 28, T5N, R89W	coal	face cleat	Kwf	335	
Jeffway Gulch	SE	Sec. 9, T5N, R90W	coal	face cleat	Ki	89	dull coal
Jeffway Gulch	NE	Sec. 9, T5N, R90W	coal	face cleat	Kwf	95	moderately dull coal
Jeffway Gulch	NE	Sec. 9, T5N, R90W	coal	face cleat	Kwf	90	boney coal
roadcut Highway 13	NE	Sec. 17, T5N, R91W	coal	face cleat	Ki	90	
roadcut past McGregor	SW	Sec. 9, T6N, R86W	coal	face cleat	Kwf	350	3rd, 4th, and sheared & conchoidal
roadcut past McGregor	SW	Sec. 9, T6N, R86W	coal	butt cleat	Kwf	82	
Meadow #1 mine roadcut	SW	Sec. 12, T6N, R87W	coal	face cleat	Ki	338	
Mt.Harris roadcut	SE	Sec. 15, T6N, R87W	coal	butt cleat	Kwf	50	3rd & 4th cleats
Mt.Harris roadcut	SE	Sec. 15, T6N, R87W	coal	face cleat	Kwf	330	
Walker mine	SE	Sec. 17, T6N, R90W	coal	longer cleat	Kwf	44	2 mutually abutting & crosscutting cleats
Walker mine	SE	Sec. 17, T6N, R90W	coal	more frequent cleat	Kwf	316	
Yampa River	NE	Sec. 16, T6N, R91W	coal	more frequent cleat	Kwf	320	2 mutually abutting & crosscutting cleats
Yampa River	NE	Sec. 16, T6N, R91W	coal	longer cleat	Kwf	45	
roadcut Eagle mine	NE	Sec. 31, T6N, R91W	coal	face cleat	Kwf	325	
roadcut Eagle mine	NE	Sec. 31, T6N, R91W	coal	butt cleat	Kwf	50	
Routt Cty. 52 roadcut	NE	Sec. 27, T7N, R87W	coal	face cleat	Ki	320	dull coal, some curved cleats, ss dikes
Franz mine	W 1/2	Sec. 36, T8N, R87W	sandstone	joint	Ki	326	
Thomas mine, Savery WY	SE	Sec. 5, T12N,R89W	coal	butt cleat	Kmv	63	bright coal, slickensides, calcite & pyrite
Thomas mine, Savery WY	SE	Sec. 5, T12N,R89W	coal	face cleat	Kmv	312	good cleat, some curved, fault zones in butt direction

Kfu Fort Union Formation
Kwf Williams Fork Formation
Ki Iles Formation
Kmv Mesaverde Group

Cleat Spacing and Fracture Swarms

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 as an indicator of potential fracture permeability (Mavor and others, 1991), although fracture interconnectedness is undoubtedly a more important control. Interconnectedness, however, cannot be measured in core, so we report spacing. However, the measurement of cleat spacing is a subjective procedure, since fractures are present in a spectrum of sizes; in many cases small but visible fractures are neglected in spacing measurements.

To standardize cleat spacing description, Tremain and others (1991) divided cleats into four groups based on their relationship to coal lithotypes or bedding surfaces. Master cleats cut through an entire coal seam including thin, non-coal interbeds. Primary cleats are contained within, but extend the entire height of a coal lithotype. Secondary cleats are more frequent than primary cleats, but they do not cut an entire lithotype. Tertiary cleats are very closely-spaced fractures that occur between secondary cleats, with heights generally <0.5 inches. Because they are large, primary cleats may be significant for fluid migration, but they are only rarely seen in core because of their wide spacing.

Primary cleat spacing in high volatile C Mesaverde coals studied in mine and outcrop is highly variable. Primary spacing between face cleats in Mesaverde coals at the Edna and Energy surface mines, is 2.4 to 6 inches (Boreck and others, 1977). Primary spacing between face cleats at the Haybro roadcut is 0.5 - 1 inches, at Hayden Gulch 1 inch, and at the Thomas Mine 12 inches (for locations see table 2). Spacing between secondary cleats in high volatile C Mesaverde coal outcrops is generally between 0.25 and 0.50 inches. One to 2 inch cleat spacing was recorded in a Mesaverde coal at 4914-4922.5 ft in the Helmerich and Payne Colorado State #1-31 well (Sec. 31, T7N, R88W). Spacing between butt cleats from approximately 5000 ft in a Fort Union coal in the Chevron Federal Land Bank (F.L.B.) #15-4C is 0.25 inches. Thin vitrain bands in Fort Union coals, as in most coals, are closely cleated, on the order of < 0.25 inches in a Fort Union coal from 2072-2077 ft in the F.L.B #1-29 hole (Sec. 29, T7N, R92W).

An intensification of cleat spacing and interconnectedness was observed in fracture swarms associated with fault zones at the Thompson Mine and Haybro roadcut. If fracture swarms are a widespread phenomenon, they could contribute to conventional trapping of the methane. Some mine operators report an influx of methane near fracture swarms, and anomalously high gas contents have been measured associated with faults along the southern edge of the basin (Kaiser, this volume). Because fracture swarms in coal mines have not been studied in detail and limited exposure, it is currently not possible to evaluate how widespread the fracture swarms are.

In general, the northwest-striking face cleats are parallel to current maximum horizontal stress directions and may provide permeable pathways for gas and water migration. Fracture swarms, faults, and folds, trending in similar directions to face cleats, may further enhance coalbed permeability and/or create conventional traps for gas.

Cleat Mineralization

Minerals deposited in cleats can obstruct the permeability of fracture systems in coal seams. Although cleats in many Sand Wash Basin coals lack cleat-filling minerals in outcrop, several instances of mineralization have been noted (table 3). Minor amounts of pyrite are 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. Calcite and gypsum also occur in cleats. Calcite fills some cleats at the Thomas Mine (table 3) near Savery, Wyoming. Accompanied by pyrite, calcite lines cleats in a few coals cored in the USGS C-IC-H well. Calcite was also reported "throughout cleats" in an eight foot coal cored in the Helmerich & Payne Colorado State #1-31 well (table 3). Hancock (1925) reported several instances of selenite (gypsum) along joint planes in blocky coals at a few old mines and prospects (table 3).

Table 3. Cleat mineralization in the Sand Wash Basin.

AREA	LOCATION	FM.	COAL DEPTH INTERVAL	MINERALS	REFERENCE
USGS C-IC-H coal core hole	Sec. 23, T4N, R91W	Kwf	176-800 ft	P,C,R	Tremain and Toomey, 1983
Prospect, Locn. #251	Sec. 29, T4N, R92W	Kwf	surface	G	Hancock, 1925
Battle Era Mine, Locn. #47	Sec. 14, T4N, R94W	Kwf	surface	G,P	Hancock, 1925
Prospect, Locn. #405	Sec. 6, T5N, R92W	Kwf	surface	G	Hancock, 1925
Helmerich & Payne State 1-31	Sec. 31, T7N, R88W	Kwf	4,914-4,923 ft	C	COGCC Files
Energy Reserves Van Doren #1	Sec. 29, T7N, R90W	Kwf	4,649-4,706 ft	P,R	Tremain and Toomey, 1983
Thomas Mine	Sec. 5, T12N, R89W	Kmv	surface	C,P	Personal Observation
Meridian #11-23 State	Sec. 23, T12N, R92W	Kfu	1,530-1,790 ft	P	COGCC Files
Mountain Fuel #B-6 Allen	Sec. 33, T12N, R97W	Kfu	5,420-5,890 ft	P	COGCC Files
Edna Mine	Sec. 36, T5N, R86W	Kwf	surface	P	COMLRD Files
Energy Strip #1A	Sec. 32, T5N, R86W	Kwf	surface	P	Boreck and others, 1977

COGCC	Colorado Oil and Gas Conservation Commission
COMLRD	Colorado Mined Land Reclamation Division
G	gypsum
P	pyrite
R	resin
C	calcite

CONCLUSIONS

1. High water production (Kaiser, this volume) from coalbed methane wells in the Sand Wash Basin indicates high permeability. This permeability may in part reflect open northwest-trending face cleats in the southeast part of the basin, where face-cleats are parallel to current maximum horizontal stress directions.

2. Local areas of crosscutting and mutually abutting face cleats and fracture swarms, may be areas of increased cleat connectedness and permeability. Such areas could be favorable targets for the cavity completions that have proved successful in the northern San Juan Basin. Fracture swarms and faults could also create conventional methane traps.

3. Additional cleat characterization in Mesaverde and Fort Union coals, from outcrop and oriented core, are needed to further delineate cleat patterns in the Sand Wash Basin. Documentation could result in the prediction of cleat characteristics within the interior of the basin.

4. Additional measurements of cleat strike would compare the relation of the predominantly northwest and east cleat strikes of the Sand Wash Basin to the predominantly east-northeast and east cleat patterns in the rest of the Greater Green River Basin and the northeast cleat patterns of the Piceance Basin (Tyler and others, 1992c).

ACKNOWLEDGMENTS

We thank N. Zhou, R. G. McMurry, L. M. Scott and L. T. Ortiz for compiling structural, cleat, fault, and fold data.

GENETIC STRATIGRAPHY AND COAL OCCURRENCE OF THE WILLIAMS FORK FORMATION, SAND WASH BASIN

Douglas S. Hamilton

ABSTRACT

The Williams Fork Formation is the most important coal-bearing unit in the Sand Wash Basin, and is divided into four genetic depositional sequences that are each bounded by regionally extensive, low resistivity shale markers. Although coal is present throughout the Williams Fork sequence, the two lowermost genetic units, Units 1 and 2, contain the thickest, most laterally extensive coals. These coals are concentrated in the eastern half of the basin, and are thickest in the vicinity of Craig where net-coal thickness of Unit 1 averages 90 ft and Unit 2 averages 35 ft.

Coal seam continuity is variable. Whereas some seams could be traced by their characteristic density and gamma-ray log profiles over most of the eastern half of the basin, others could only be correlated when grouped as broad coal packages. Unit 1 and 2 coals are continuous to the outcrop belts in the south and northeast and are thus exposed for ground-water recharge.

The thickest, most extensive Unit 1 and 2 coals were preserved on an aggradational coastal plain immediately landward of equivalent shoreline sandstones. Bypass of coarse clastic sediment, maintenance of high-water table levels, and subsidence in this setting provided optimum conditions for peat accumulation and preservation. Gradual westward thinning of coals toward the coastal-plain/alluvial-plain transition is explained by a lowering water table associated with the rise in surface gradient of the alluvial piedmont. Coals also thin to the east as they override the shoreline sandstones. Marine conditions ultimately limit coal distribution to the east.

INTRODUCTION

A general assessment of all coal-bearing intervals of the Sand Wash Basin was undertaken to target those units with greatest potential for coal-bed methane production. The Williams Fork Formation was quickly identified as containing the thickest, most extensive, and greatest number of coal seams, and was selected as the principal focus for the first year's study.

The Williams Fork Formation forms the upper part of the Mesaverde Group which is a major pre-Laramide, Upper Cretaceous coal-bearing sequence (fig. 8). During the Upper Cretaceous, the area of the Sand Wash Basin was occupied by the Western Interior Seaway which received clastic sediment in

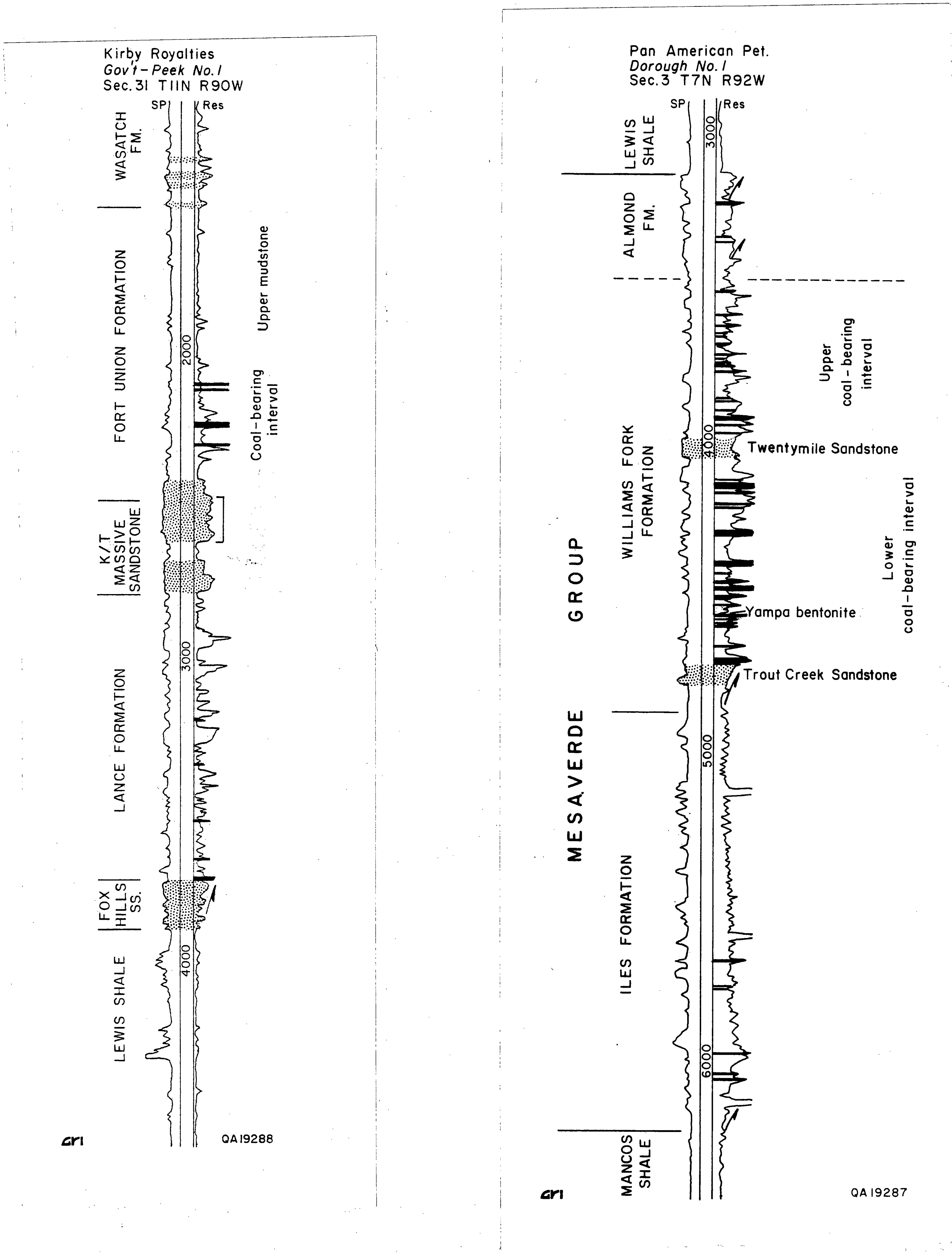

Figure 8. Stratigraphy of the Sand Wash Basin. The most important coal-bearing interval is the lower Williams Fork Formation. Fort Union coals are also important.

cycles initiated by tectonic uplift and loading of the Overthrust Belt to the west. Sedimentation patterns are also thought to be influenced by eustatic sea-level fluctuations (Kauffman, 1977).

The first step taken in this study was to establish a stratigraphic framework in which detailed and meaningful analysis of the coals, and their enclosing sediments, could be carried out. A genetic approach to stratigraphic analysis was applied to the Williams Fork Formation. The genetic stratigraphic framework then provided the basis for delineation of the major depositional systems and mapping the distribution and thickness of the coals. This stratigraphic framework further provided a basis for investigating the depositional controls on coal occurrence.

GENETIC APPROACH TO STRATIGRAPHIC ANALYSIS

The best possible way to achieve meaningful understanding of a sedimentary sequence is to identify and investigate those strata that are genetically linked. Ideally, genetic units to be mapped should have widespread correlatability and be deposited during discrete episodes of general tectonic, climatic and/or base level stability (Galloway, 1989). Such units are the fundamental time stratigraphic increments of the basin-fill, and provide the foundation for establishing a correlation framework and construction of basic lithofacies maps necessary for further interpretation. More detailed analysis allows the delineation of the component depositional systems, which are characterized by specific geometries and bedding architecture (Galloway and Hobday, 1983) that are readily determined from subsurface data.

Depositional systems are also characterized by specific processes of sediment dispersal that can be observed directly in modern-day analogs. Herein lies the real strength of the genetic approach. Recognition of the depositional system in conjunction with an understanding of its sediment dispersal processes, provides a powerful guide for predicting lateral changes in geometry and distribution of the framework sandstone facies and associated coal-bearing mud rocks. Detailed understanding at the facies level is the ultimate objective in coalbed methane research because it is at this scale that (1) the lateral continuity and thickness of the coalbed reservoirs are determined and (2) the basin's fluid migration pathways, including the target coalbed gases and the produced waters are established.

Interrelated with the task of delineating the major genetic units is recognizing the hiatal surfaces that bound these units. The hiatal surfaces record major interruptions in basin depositional history and represent significant periods of non-deposition or very slow clastic accumulation. The bounding surfaces are generally easily recognized in marginal marine basin settings where widespread marine shales separate successive progradational clastic wedges (Frazier, 1974; Galloway, 1989). However, recognition of the bounding surfaces in non-marine basin-fills is more problematic, and possibly only the erosional unconformities provide obvious sequence boundaries. More subtle, conformable bounding surfaces are important but require considerably more intensive investigation for recognition.

Recognition of the principal bounding surfaces of the Williams Fork genetic sequences was relatively straightforward in the eastern half of the basin. The basin occupied a marginal marine setting along the western edge of the Western Interior Seaway during Williams Fork deposition, and the successive clastic wedges are bracketed by transgressive marine flooding surfaces. Defining bounding surfaces in the continental facies to the west was more difficult but still possible.

GENETIC STRATIGRAPHY OF THE WILLIAMS FORK FORMATION

A genetic stratigraphic framework was established for the Williams Fork Formation. The formation is divided into four genetic units, Unit 1, 2, 3, and 4 (fig. 9), each representing a discrete depositional episode within the basin's history. The genetic units are bounded by regionally extensive, low-resistivity shale markers that have been mapped from the southeastern margin of the basin to at least as far west as T13N, R102W on the southern flank of the Rock Springs Uplift, and to the north beyond the limits of the study area (figs. 10 and 11). The shale markers are attributed to marine flooding surfaces in the basinward direction (east and southeast), where they are easily recognized separating aggradational coal-bearing coastal plain facies of one depositional episode from overlying upward-coarsening progradational sequences of the next. In the landward direction, genesis of the shale markers is less clear. Either the marine flooding events that punctuated the Williams Fork extended further west than is generally recognized, or the controls on the flooding events, such as shutting-off sediment supply, similarly affected the non-marine environment and are also recorded by low resistivity shale markers indicative of sediment starvation. Units 1-4 are thus true genetic depositional sequences as defined by Galloway (1989) because they are depositional units bounded by flooding-surfaces (and their non-marine correlative surfaces).

Comparison with Traditional Stratigraphy

The Williams Fork Formation as defined here varies from the traditional stratigraphy in three main ways.

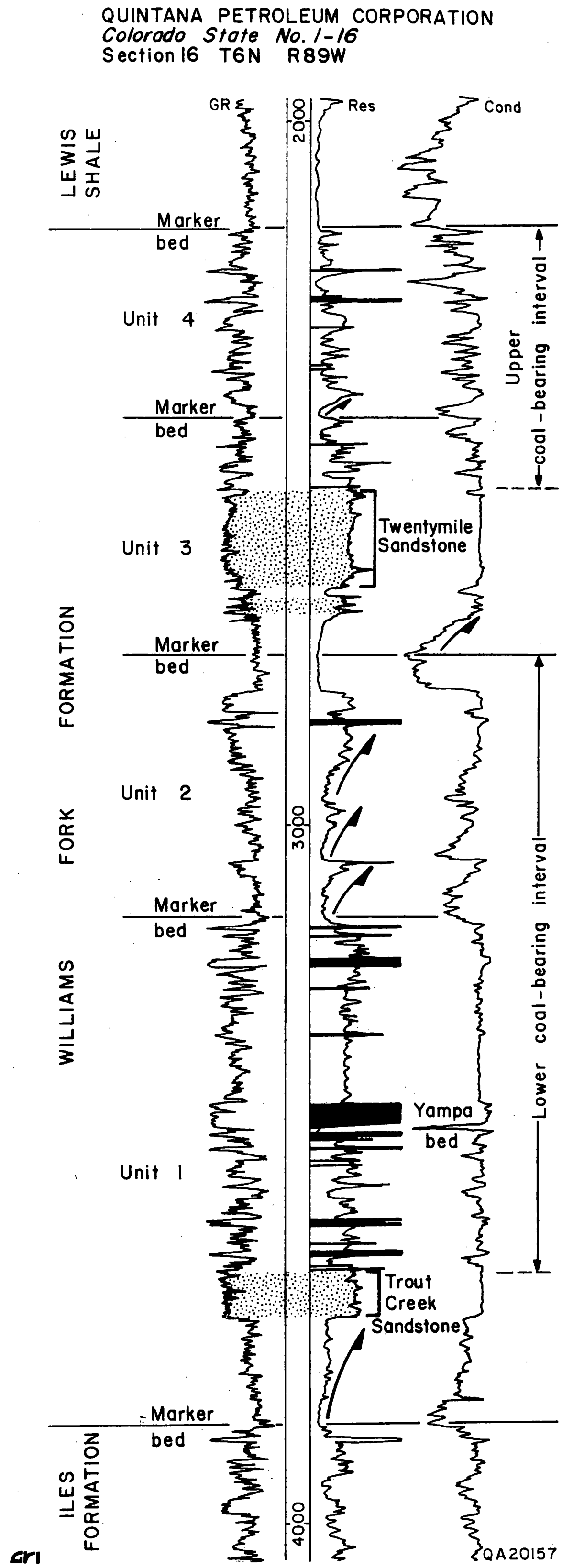

Figure 9. Genetic stratigraphy of the upper Mesaverde Group in the eastern Sand Wash Basin. Coal Beds identified on an accompanying density log. Surfaces bounding genetic units are defined by regionally extensive, low resistivity shale marker beds.

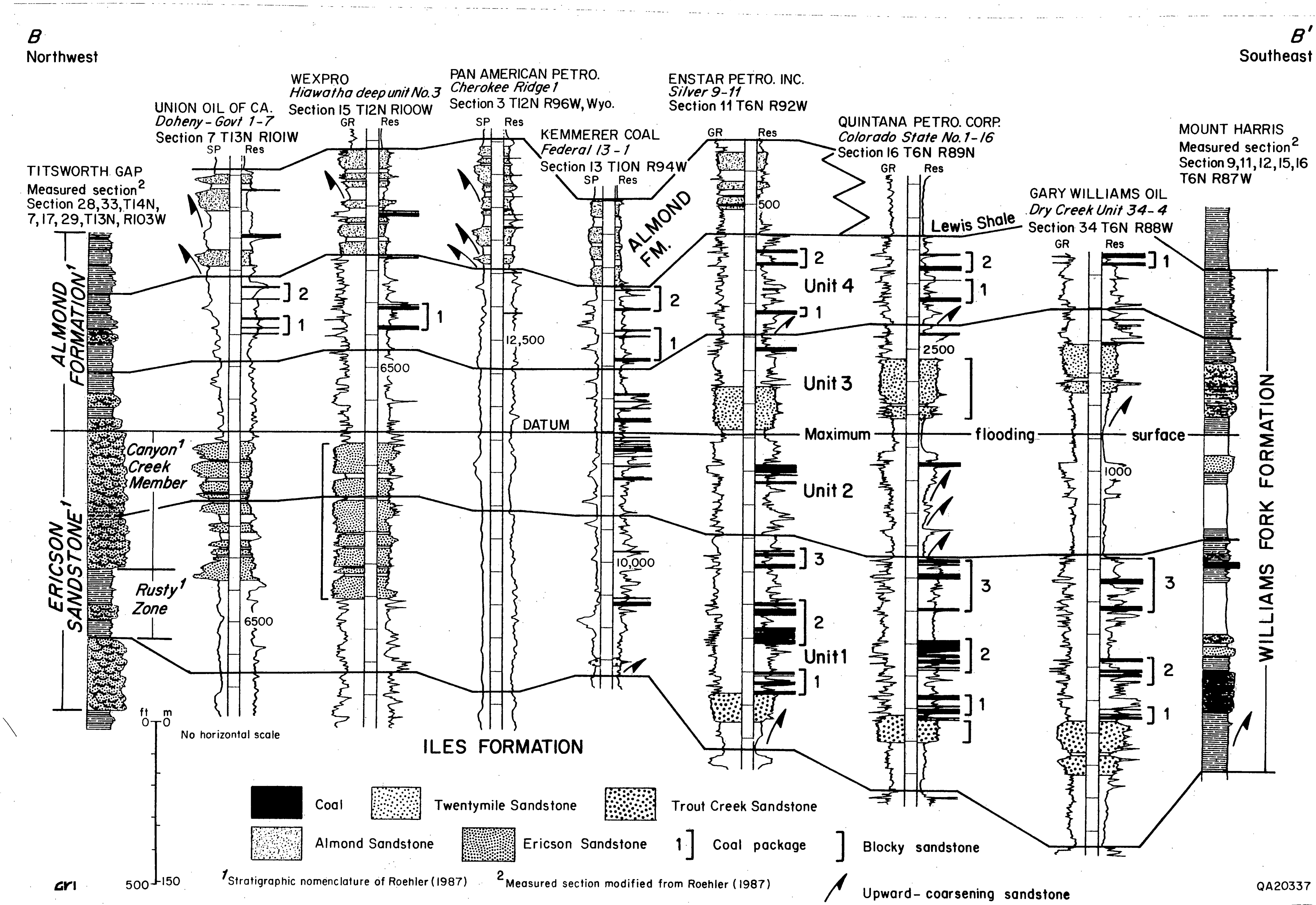

Figure 10. Northwest-southeast cross-section of the upper Mesaverde Group, Sand Wash Basin illustrating genetic stratigraphy of the Williams Fork Formation and coal occurrence. Coals of Units 1 and 2 are lost westward of the transition to alluvial Ericson Sandstone at the basin's structural center.

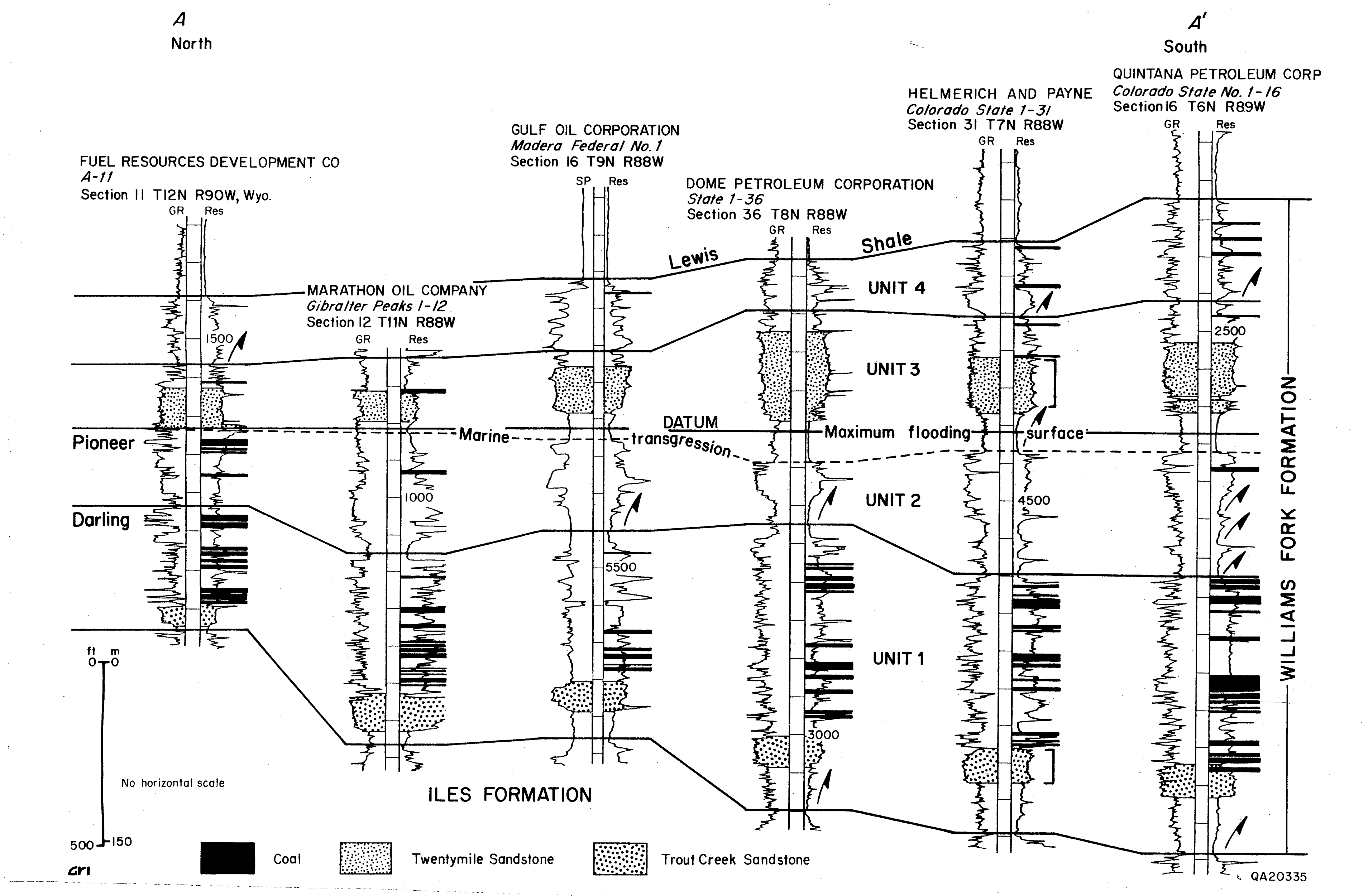

Figure 11. North-south cross-section of the upper Mesaverde Group, eastern Sand Wash Basin. The Williams Fork Formation extends northward into Wyoming, and the Darling and Pioneer coals (Dixon field) top genetic units 1 and 2 respectively.

1. The Trout Creek Shale and overlying Sandstone Member, which are traditionally assigned to the uppermost part of the underlying Iles Formation (Siepman, 1986) are in this study included with the Williams Fork Formation. Depositionally, the Trout Creek Shale/Sandstone couplet records an episode of marine transgression and subsequent progradation. Thus, the progradational Trout Creek sequence belongs genetically with the Williams Fork Formation (figs. 8 and 9).

2. The Williams Fork Formation is distinct or separated from the Almond Formation. In his published cross-section, Roehler (1987) showed the Almond Formation as partially equivalent to the upper part of the Williams Fork Formation. The Almond Formation, as traditionally defined, includes two dissimilar sedimentary sequences, that is, a prominent aggradational sequence of interbedded sandstones, siltstones and coals, and an overlying, strongly progradational sequence of upward-coarsening and blocky sandstones with coal-beds. Here we restrict the term Almond Formation to the upper, strongly progradational sequence and the Williams Fork to the underlying aggradational coal-bearing sequence (fig. 10). A regionally extensive, low resistivity shale marker separates these two sequences, and the change in their character is evident on gamma-ray, spontaneous potential (SP), and resistivity logs. Genetically, the Almond Formation represents a barrier-bar/strandplain complex that lies above the main Williams Fork coal-bearing interval.

3. The genetic depositional sequences of the Williams Fork Formation (Units 1, 2, 3 and 4) cut across many of the traditionally defined lithological members. For example, the top of Unit 1 cuts through the middle of the Canyon Creek Member (fig. 10), and the top of Unit 2 cuts through the middle of the Pine Ridge Sandstone Member (as illustrated in Roehler and Hansen, 1989).

COAL OCCURRENCE OF THE WILLIAMS FORK FORMATION

Coal Identification

Coals were identified in this study from geophysical well logs by low bulk density, low natural gamma response, very high resistivity, high neutron and density porosities, low sonic velocity, and/or low neutron count. Some combination of these criteria were used because no uniform well log suite was available. Bulk density or sonic logs were run in most wells, and these are the most reliable logs for coal identification. However, natural gamma response was consistently low for all coalbeds, and was used in conjunction with very high resistivity, and shale-like SP response to operationally define coal in some wells.

Coal Seam Continuity

Continuity of the Williams Fork coals is variable. Some individual seams were correlatable in the subsurface throughout the eastern half of the Sand Wash Basin, and extend to the southern and northeastern outcrop belts. Other seams could only be correlated extensively when grouped as broad coal packages. Understanding coal seam continuity is critical to coal gas production and water production because (1) coal seams with considerable continuity provide pathways for diffusion and long-distance migration of coal gases and (2) continuous coals act as major aquifers.

Coal seams are correlatable because of their unique seam signature. They are biochemical sediments that are composed of discrete bands (or lithotypes) which are a function of the original peat-forming plants, and the physical and chemical conditions that prevailed in the peatswamp. Coal seam correlation is achieved by recognizing the unique seam signature in adjacent well bores.

Seam signatures for some typical, laterally continuous, Williams Fork coals are illustrated in figure 12. The seam signatures are defined by the gamma-ray and density logs, which are sensitive to minor fluctuations in the coal-seam lithotypes. Seam 1 gamma-ray and density log profile has a serrate key-like shape. Seam 2 is characterized by several splits which display an upwards decrease in density. Seam 3 is recognized by its three parts, or plies, and the middle ply is consistently the most prominent. The top coal, seam 4, is characterized by its blocky signature. A number of discontinuous coals are also illustrated in figure 12. These show a featureless spike on both the gamma-ray and density logs.

Detailed discussion of individual Williams Fork coals will be dealt with in the context of their encompassing depositional system, which controls the coal distribution and thickness.

WILLIAMS FORK GENETIC DEPOSITIONAL SEQUENCES

Unit 1

The lowermost genetic depositional sequence of the Williams Fork Formation, Unit 1, is a clastic wedge that extended coal-bearing coastal-plain deposits to beyond the present day basin margin. The unit is bounded by regionally extensive, low resistivity shale markers. The lower bounding surface occurs near the base of the Trout Creek Shale Member in the eastern and southeastern parts of the basin, where the sequence is characterized by the upward-coarsening, progradational Trout Creek Sandstone Member and overlying aggradational coal-bearing rocks. There is a prominent facies change to the west as the coal-bearing strata are replaced by aggradational log motifs of thick, stacked sandstone units and interbedded mudstones of the Ericson Sandstone (fig. 10). Stratigraphically, Unit 1 is equivalent to the

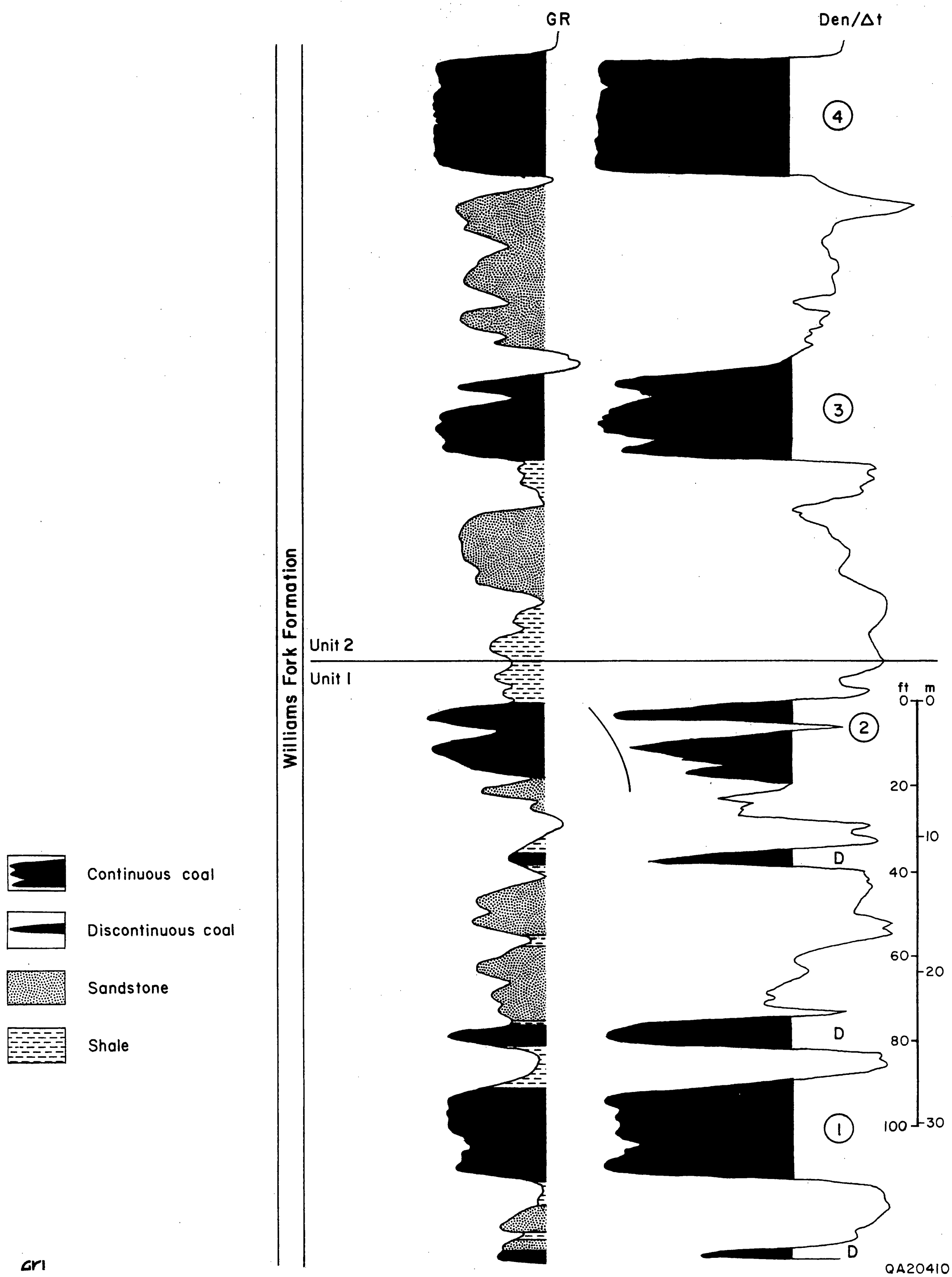

Figure 12. Density profile of typical Williams Fork coals. Coal seams can have a unique profile, or signature, owing to variations in their lithotypes. The lithotypes are a function of the original peat-forming plants and the physical and chemical conditions of the peat swamp. Gamma-ray and density logs are sensitive to minor fluctuations in coal seam lithotypes, and thus provide a tool for correlation.

Trout Creek Shale and Sandstone Members and lower one-third of the Williams Fork Formation in the eastern part of the basin, and the middle part of the Ericson Sandstone in the west. To the north, this unit is equivalent to the upper part of the Allen Ridge Formation (Roehler, 1987). Unit 1 thickness ranges from 900 ft in the southeast, where basin subsidence was at a maximum, to 400 ft in the northeast. Basin subsidence trends have a pronounced northeast-southwest alignment.

Depositional Systems

Three major depositional systems are recognized in Unit 1 from the geometry of framework sandstones and log facies mapping. A linear shoreline system dominates the easternmost part of the basin and is backed landward by a coastal plain system which grades westward into a mixed-load to bed-load fluvial system (fig. 13).

Two parallel strike-oriented (northeast-southwest) sandstone-rich trends are apparent in the easterly shoreline system (fig. 13). This, coupled with the strong upward-coarsening log motifs, provides evidence of shoreline progradation. The shoreline system is backed by a sand-poor area (net sandstone <100 ft) which defines the coastal plain system. The coastal plain was largely an area of sediment bypass, and the aggradational log patterns which characterize this system reflect thick coals and interbedded mudrocks. A dip-oriented sandstone-rich trend extending southeasterly from Baggs cuts across the coastal plain (fig. 13), and is interpreted as a distributary channel complex that fed sediment to the shoreline system. Log patterns of this zone are blocky and upward-fining, consistent with such an interpretation. The coastal plain passes landward (westerly) into the alluvial plain where contributary patterns in sandstone distribution define a major fluvial system (Ericson Sandstone). Log patterns are aggradational and associated with thick, stacked channel sandstones with interbedded floodplain muds.

Coal Stratigraphy

Unit 1 coals are the thickest and most extensive in the Sand Wash Basin. Three discrete coal packages are recognized, and each extends over the entire eastern part of the basin (fig. 10). The first (or lowermost) package immediately overlies, and is genetically-related to the Trout Creek Sandstone. Three coal seams from 3-10 ft thick are typically present in this package, but up to 5 much thinner (2-5 ft thick) seams may be present locally, where seam splitting occurs.

The second coal package overlies the first, and consists of two coal seams that can be correlated individually over most of the eastern part of the basin. Correlation is achieved by matching their characteristic profiles as displayed on the gamma and density logs. Correlatability is further enhanced by

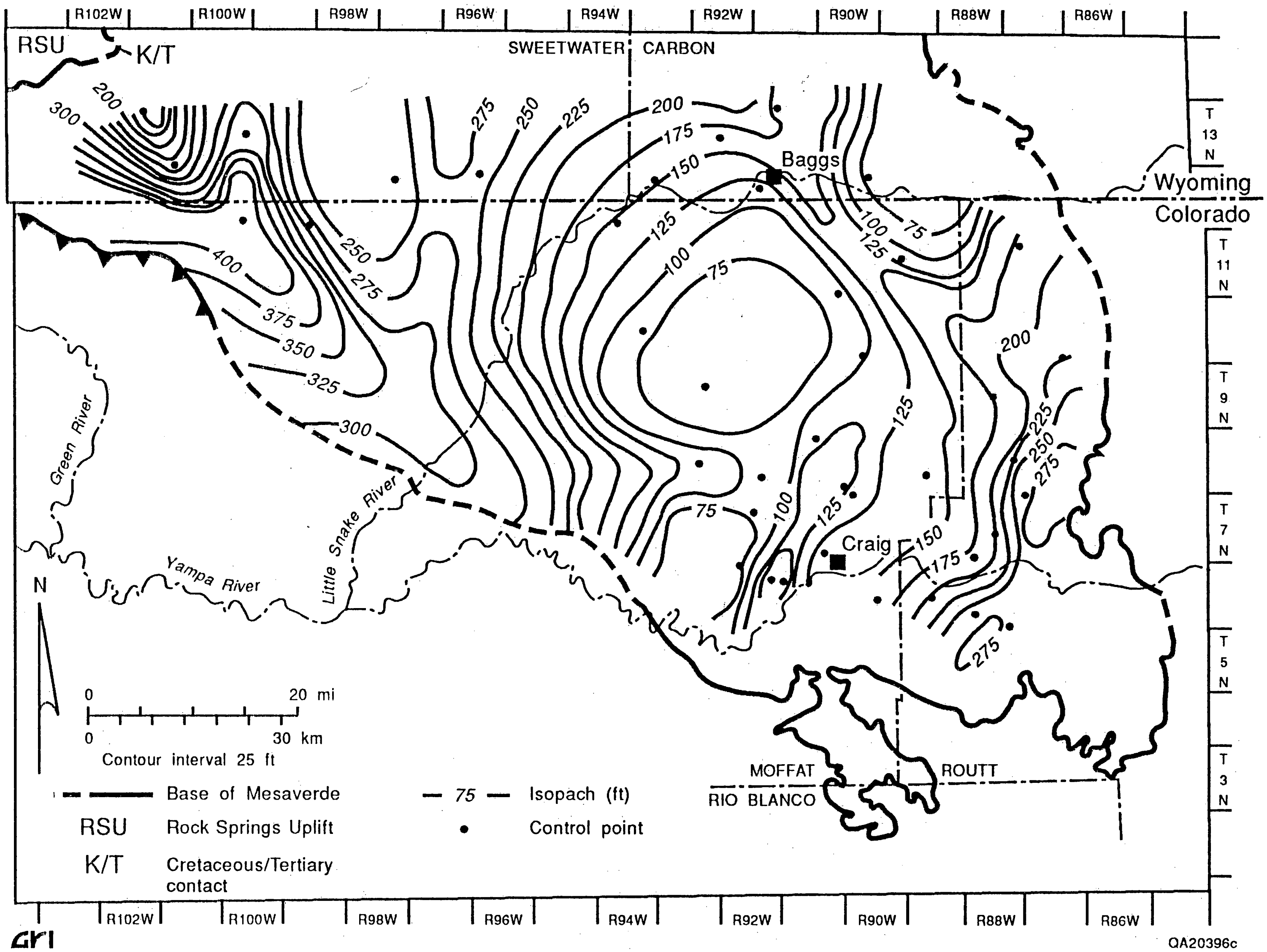

Figure 13. Net sandstone map of Unit 1, Williams Fork Formation. Two strike-oriented (northeast-southwest) linear clastic shorelines are evident, backed landward by a coastal plain system (net sandstone <100 ft), which grades westward into a large fluvial system (Ericson Sandstone). A dip-oriented distributary channel system extends southeasterly from Baggs.

the presence of the distinctive Yampa bentonite bed (fig. 9), which occurs within the lower of the two seams. The upper seam correlates with the Darling seam in the Dixon field, Wyoming. The seams merge in T6N, R89W where the combined coal thickness is 43 ft, but elsewhere seam splitting is common. Individual seam splits range from 5-25 ft thick.

The third (or uppermost) coal package consists of up to 5 seams ranging in thickness from 2-20 ft (fig. 10). Correlation of individual seams in this coal package was only possible over an area of approximately 80 mi^2 (T7-8N; R92W) where one 15-20 ft seam had a characteristic gamma and density log profile.

Coal Distribution

Net coal thickness is at a maximum in the Craig area where it is up to 117 ft thick, and averages 90 ft thick (fig. 14). Net thickness decreases westward to less than 10 ft along a line from T9N R97W to Baggs, Wyoming, approximating the course of the Little Snake River. There is no significant Unit 1 coal west of the Little Snake River in the structurally deepest and most thermally-mature part of the basin. Thinning also occurs in the southeasternmost part of the basin where net coal thickness is 30-40 ft. The pronounced northeast-southwest alignment of coal-seam thickness trends parallels the basin subsidence trends. Unit 1 isopachs indicate a northeast-southwest depositional strike and gradual thickening of the section to the southeast. Coals are also thin along a narrow, dip-oriented zone extending in a southeasterly direction from Baggs, where they are partially replaced by stacked sandstone units. Although some of the coals are replaced, the net-coal-thickness map indicates that the coal packages are continuous from the subsurface to the eastern, northeastern, and southern outcrop belts. They are thus exposed to meteoric recharge and are potential conduits for basinward flow of ground water.

Geological Controls on Coal-Seam Occurrence

Peat accumulation and preservation as coal is dependent on three critical factors (1) substantial growth of vegetation, (2) maintenance of the water table at, or above the sediment surface, and (3) nondeposition of clastic sediment during peat accumulation. Substantial vegetation growth is mostly determined by climate, and the second two critical factors are controlled by the depositional systems, basin subsidence, and hydrology. The depositional systems provide the framework within which the peatswamps are established, and, combined with subsidence and hydrologic regime, are important in maintaining optimum water table levels for peat preservation.

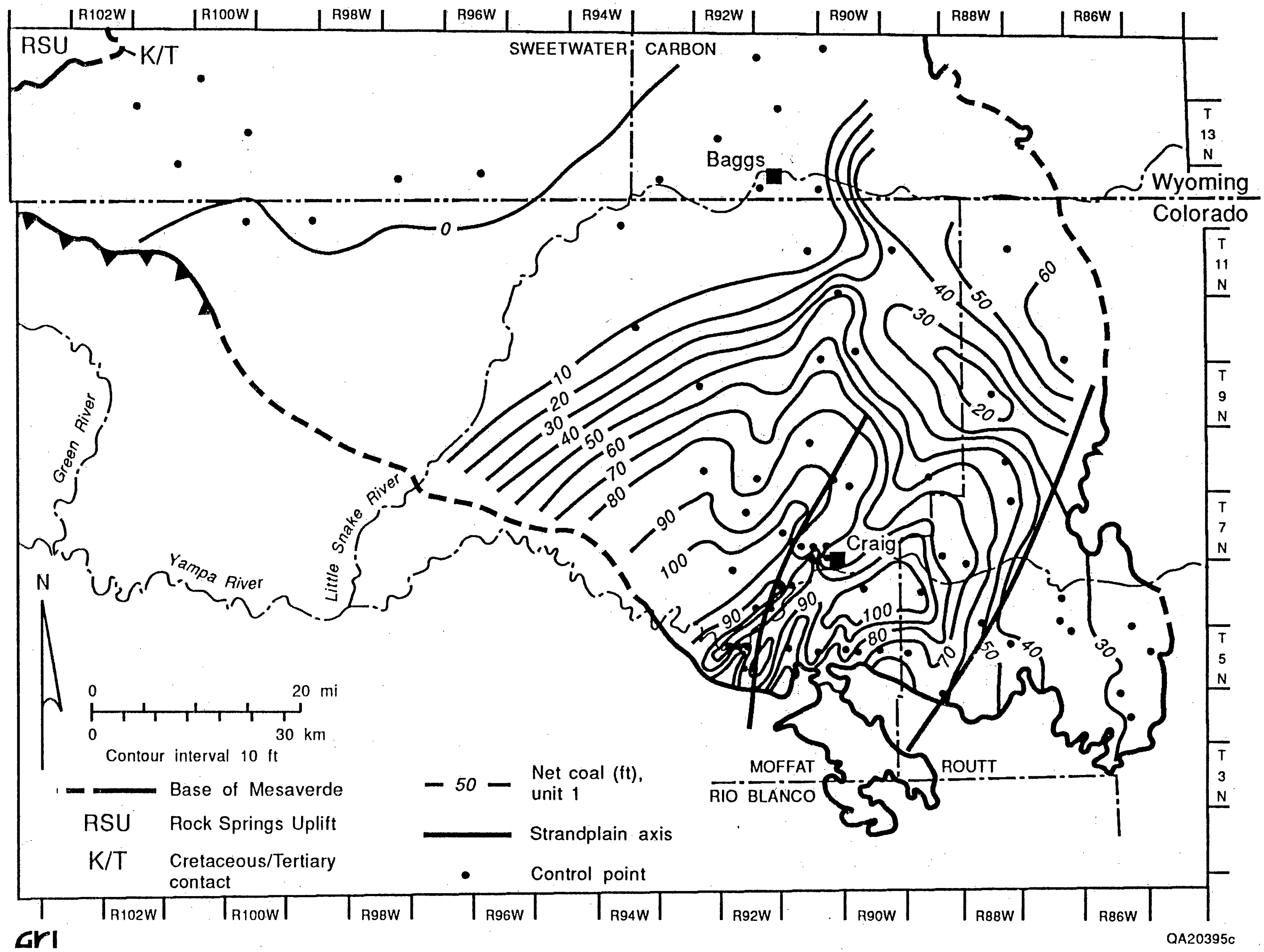

Figure 14. Net-coal-thickness map of Unit 1, Williams Fork Formation. Thickest net coal occurs in the Craig area where peat accumulated on the coastal plain behind the linear shoreline systems. Coals thin to the west at the coastal-alluvial plain transition. Coal is also thin along a dip-oriented (northwest-southeast) distributary channel complex extending southeasterly from Baggs.

Distribution of the Unit 1 coals is intimately related to the depositional systems and basin subsidence trends. Two salients (net coal > 100 ft) are apparent on the net coal thickness map (fig. 14), and each lie immediately landward of successive strandplain axes of the linear shoreline system (compare figs. 13 and 14). The coastal plain is an area of sediment bypass and provides opportunity for uninterrupted peat accumulation. The ideal location for preservation of the peat is immediately behind the shoreline system where water tables are maintained at optimum levels. Basin subsidence is also an important underlying control on coal occurrence. It determines the location of clastic sedimentation, and accommodation space for peat accumulation. The Unit 1 coals are oriented northeast-southwest which parallels the basin subsidence trend. The coals thin to the southeast and are ultimately limited by the final position of the shoreline, beyond which marine conditions existed.

Net coal thickness gradually thins westward to less than 10 ft at the transition between the coastal and alluvial plain systems. The alluvial plain probably resembled a piedmont surface that graded slowly down to the low-lying coastal plain. This surface gradient would have strongly influenced ground-water levels such that the water table was highest immediately behind the shoreline and progressively lower in the landward direction. Lowering of the water table is postulated to account for the gradual westward thinning of the coastal-plain coals. Thick coals were not preserved toward the landward side of the coastal plain despite there being a uniformly broad area bypassed by coarse clastic sediments (as defined by the 75 ft contour; fig. 13).

Unit 1 coals are also thin along a narrow, dip-oriented zone that extends southeasterly from Baggs (fig. 14). The coals are partially replaced by stacked sandstone units that are interpreted as distributary channels. These distributaries cut across the coastal plain and were the dispersal pathways for coarse clastic sediment delivered to the prograding shoreline system.

Unit 2

The second genetic depositional sequence of the Williams Fork Formation, Unit 2, is a clastic wedge similar to that of Unit 1, except that it did not prograde as far basinward. Unit 2 is bounded by regionally extensive, low resistivity shale markers. The lower boundary is a flooding surface that terminates the coal-forming conditions of Unit 1 (fig. 9). The upper bounding surface is another maximum flooding surface that underlies the progradational Twentymile Sandstone. Unit 2 is characterized by upward-coarsening, progradational log patterns of the Sub-Twentymile Sandstone in the eastern and southeastern parts of the basin (Siepman, 1986). Log facies change to the west into aggradational, blocky channel-fills and interbedded mudstones of the upper Ericson Sandstone (Canyon Creek Member; fig. 10). Unit 2 is therefore stratigraphically equivalent to the Sub-Twentymile Sandstone sequence in the eastern part of the basin, and the Canyon Creek Member of the Ericson Sandstone on the southern flank of the Rocks Springs Uplift. Unit 2 ranges from 200-350 ft thick and basin subsidence is greatest in the southeast.

Depositional Systems

Depositional setting of Unit 2 is comparable to that of Unit 1, and three major depositional systems are recognized from the geometry of the framework sandstones and log facies mapping. The eastern part of the basin was characterized by a linear shoreline system that was backed landward by the coastal plain and farther landward by the alluvial plain.

The shoreline system is defined by two parallel strike-oriented (northeast-southwest) sandstone-rich trends in the Craig area (fig. 15). The progradational character of this system is indicated by the prominent upward-coarsening log profiles of the sandstones (figs. 10 and 11). The sandstone-rich trend to the east of Baggs is a continuation of the shoreline system, but there is a sand-poor trend cross-cutting the strandplains. This is interpreted as a tidal-inlet complex. The Unit 2 shoreline system is similar to that of Unit 1 except that progradation did not extend as far basinward. The coastal plain lies landward of the shoreline system and is defined by net sandstone from approximately 50-150 ft. There is a gradual transition from the tidal-inlet complex to the coastal plain. As in Unit 1, the Unit 2 coastal plain was largely an area of coarse clastic sediment bypass, and log patterns are aggradational reflecting thick coals and interbedded mudrocks. The coastal plain grades landward into the alluvial plain to the west. Sandstone trends are ill-defined on the alluvial plain but the aggradational log patterns are the result of stacked channel-fills and interbedded muds. The alluvial plain was probably an elevated piedmont broadly traversed by a sandy bed-load fluvial complex.

Coal Stratigraphy

Unit 2 contains two coal seams that can be individually correlated over broad areas by their distinctive density and gamma-ray profile (fig. 12). The seams do not extend to the east as far as those of Unit 1 because they were limited by the extent of the Unit 2 progradational platform. Unit 2 was a minor progradational episode. The lower of the two coals (seam no. 3; fig. 12) is correlated throughout T6-8N; R92W and varies in thickness from 15-20 ft. The upper coal (seam no. 4; fig. 12) is correlated from the southern outcrop belt (T5N; R91-92W) to the northeastern outcrop (T13N; R90W) where it is equivalent

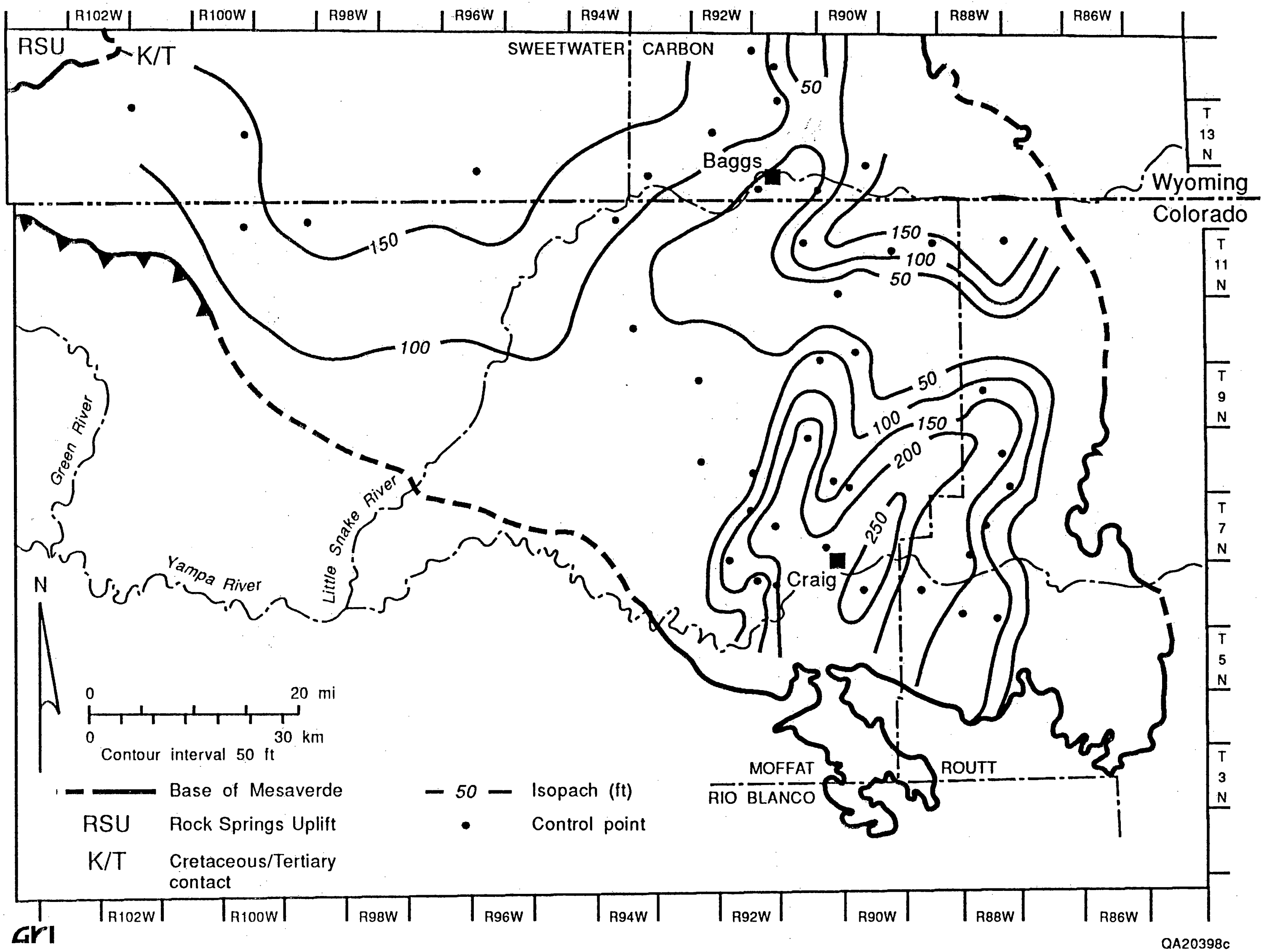

Figure 15. Net sandstone map of Unit 2, Williams Fork Formation. Two parallel, strike-oriented sandstone-rich trends define the shoreline system which is backed landward by a coastal plain system (net sandstone <100 ft), which grades westward into the alluvial plain. The sand-poor trend cross-cutting the shoreline represents the tidal-inlet complex.

to the Pioneer Coal in the Dixon field (fig. 11). This coal is up to 25 ft thick but splits locally into three seams 5-15 ft thick (fig. 16). The upper coal appears to be continuous as far east as T6N; R89W where a 6 ft seam is present. However, the seam character is not definitive where the coal is thin.

Coal Distribution

Net coal thickness within Unit 2 is at a maximum to the west and northwest of Craig where it averages 35 ft thick (fig. 17). There is a pronounced north-south alignment to coal-thickness trends. Net thickness decreases westward to less than 10 ft along a north-south line defined by R95W. Thinning also occurs in the easternmost part of the basin where coal is absent beyond R87W, and along a narrow, west-northwest/east-southeast trending zone from T11N R93W to T10N R88W (fig. 17). Although the coals are thinned along this trend, the net-coal-thickness map indicates that the coal-bearing packages are continuous from the subsurface to the northeastern and southern outcrop belts. Similar to Unit 1 coals, these coals are exposed to meteoric recharge and are potential conduits for basinward flow of ground water.

Geological Controls on Coal-Seam Occurrence

Geological controls on Unit 2 coal distribution are comparable to those of Unit 1. The coals are thickest and most continuous on the coastal plain immediately landward of the shoreline system (compare figs. 15 and 17). Isolation from sedimentation and maintenance of high water table levels provided by the coastal plain make it the optimum site for peat accumulation and preservation. The Unit 2 coals trend northerly which is slightly divergent from the northeasterly shoreline trend. This occurrence is not well understood, but one might speculate that it is caused by a local subsidence effect. Net coal thickness gradually thins to the southeast (fig. 17), reflecting increasingly marine-dominated deposition, and is limited ultimately by the seaward extent of the shoreline system. A cross-section illustrating the relationship between the thick Unit 2 coals and the prograding shoreline system is shown in figure 18. Peat accumulation is greatest on the aggradational coastal plain. The peats can override the shoreline sandstones to achieve greater lateral extent, but are thinner.

As was the case in Unit 1, the Unit 2 coals also thin gradually westward, and are lost just beyond the transition between the coastal and alluvial plain systems. Gradual westward thinning of the coastal-plain coals is again thought to be the result of a lowering water table with increased gradient on the piedmont surface of the alluvial plain system.

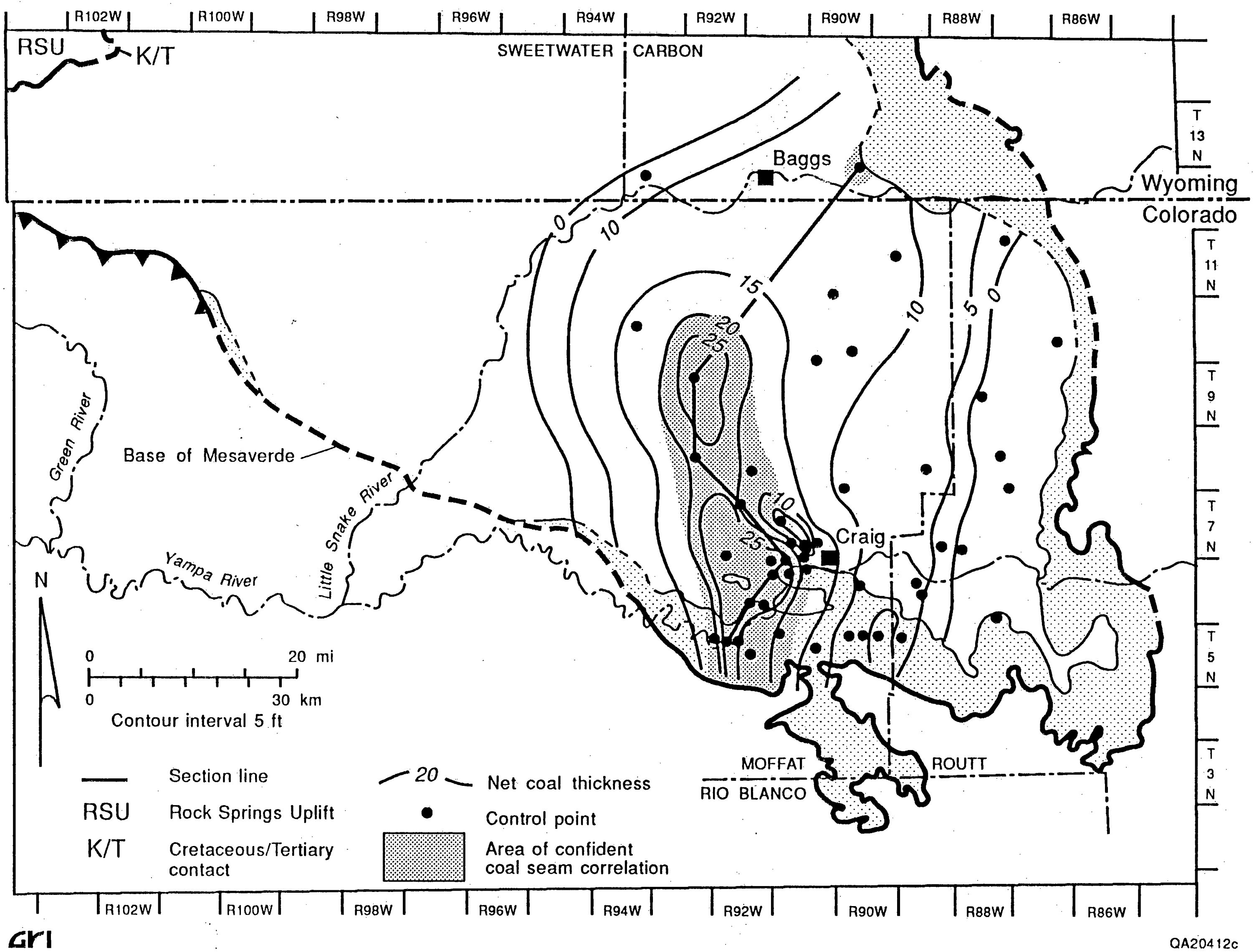

Figure 16. Isopach of the Unit 2 coal seam. The seam trends north-south, and is continuous to the northern and southern outcrop belts, where it is exposed for recharge. Peat accumulated on the coastal plain behind a linear shoreline system.

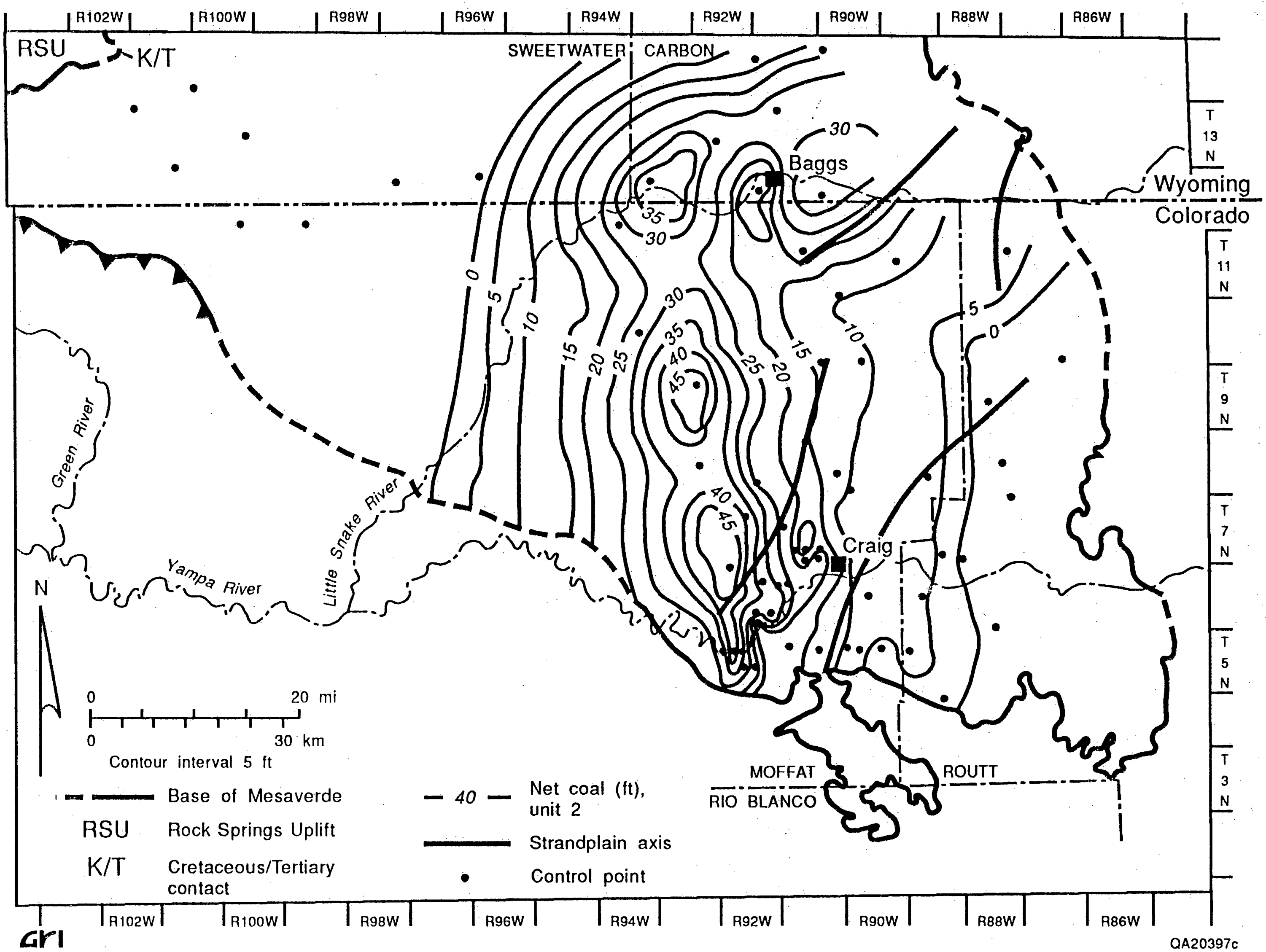

Figure 17. Net-coal-thickness map of Unit 2, Williams Fork Formation. Thickest net coal occurs to the west and northwest of Craig where peat accumulated on the coastal plain behind the linear shoreline systems. Coals thin to the west at the coastal-alluvial plain transition. Coal is also thin along a dip-oriented (northwest-southeast) trend that overlaps the tidal-inlet complex.

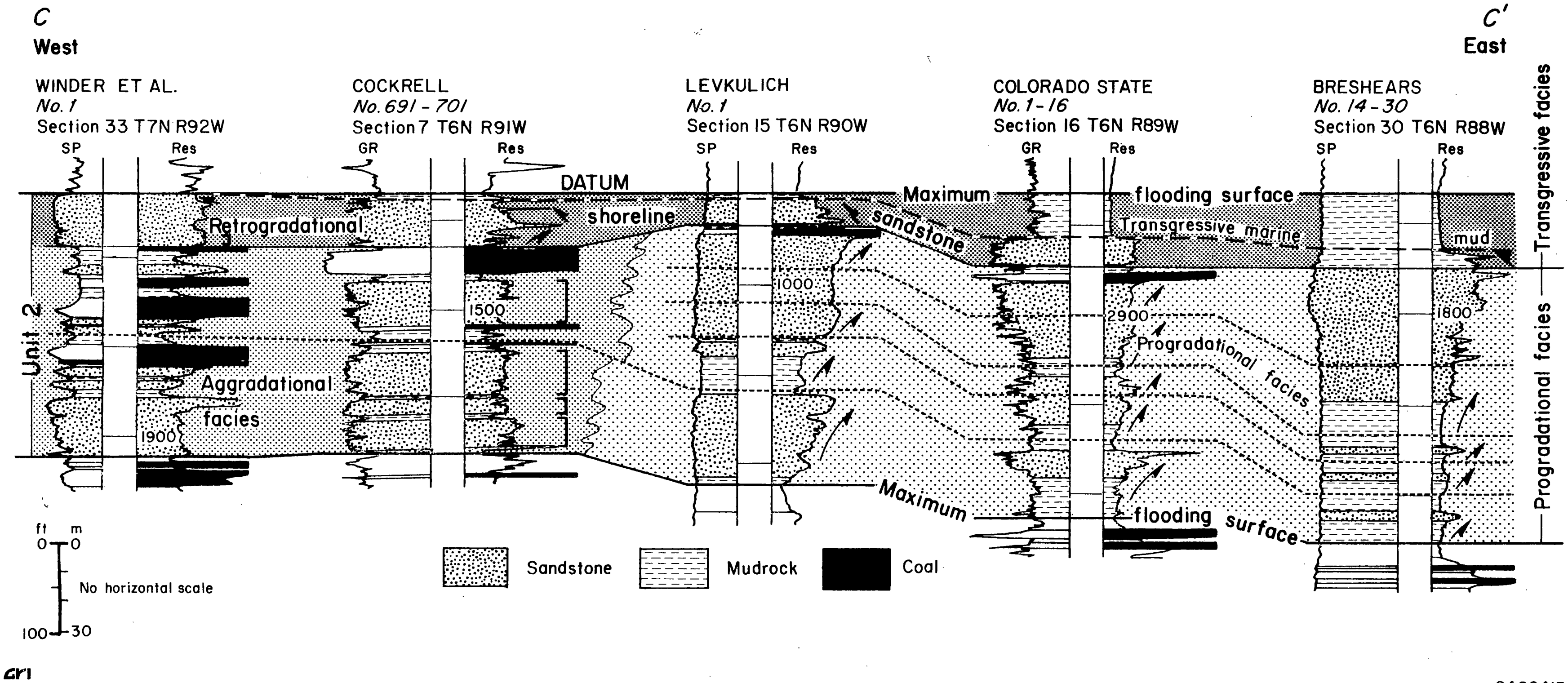

Figure 18. Cross-section of the Unit 2 coals. Peat accumulated on an aggrading coastal plain behind the progradational shoreline facies. Coals override the shoreline sandstones to achieve great lateral extent.

Thinning of the Unit 2 coals along the narrow, west-northwest/east-southeast trending zone from T11N R93W to T10N R88W overlaps the tidal-inlet complex illustrated on the net sandstone map (fig. 15). Peat accumulation was probably inhibited along this zone because of marine influence.

Unit 3

The third genetic depositional sequence of the Williams Fork Formation, Unit 3, is a clastic wedge that extended shoreline and coastal plain deposits farther basinward than Unit 2, but not as far as Unit 1. Unit 3 is also bounded by regionally extensive, low resistivity shale markers. The lower boundary is the maximum flooding surface that precedes the Twentymile Sandstone progradation (figs. 9, 10, and 11). The upper boundary represents a minor transgressive event, and the facies offset above this marker is subtle (fig. 10). Unit 3 is dominated by the upward-coarsening and blocky log profiles of the Twentymile Sandstone over the eastern half of the basin. To the west, the log facies change to mud-rich aggradational patterns (fig. 10). Stratigraphically, Unit 3 includes the Twentymile Sandstone and overlying coals in the east, and the lower part of the Almond Formation (as defined at the Rock Springs Uplift by Roehler, 1987) in the west. Unit 3 is also equivalent in part to the Pine Ridge Sandstone to the north. Thickness of the unit varies from 200 ft in the northeast to 450 ft in the southeast. Basin subsidence trends continue to show northeast-southwest alignment.

Depositional Systems

Unit 3 includes the Twentymile Sandstone in the eastern half of the basin, and Siepman (1986) regarded this sandstone as a progradational shoreface unit of either a wave-dominated delta, strandplain or barrier island system. The sandstone has blocky/upward-coarsening log motifs suggestive of a progradational shoreline system comparable to those of Units 1 and 2. The sandstone is overlain by mud-rich, coal-bearing aggradational log packages that probably represent coastal plain deposits. To the west, similar mud-rich aggradational packages may represent floodplain deposits of a mixed-load fluvial system. Blocky and upward-fining log patterns, inferred to represent mixed-load channel fills, are interspersed with the floodplain muds (fig. 10).

Coal Stratigraphy

Coals associated with Unit 3 can be mapped only in broad packages and are thin except in the vicinity of T7-8N; R92W where up to three seams ranging from 2-8 ft thick are present. Downdip, the coal package consists of three to six seams, and although only 2-3 ft thick, the coals extend to the limit of well data (T6N; 88W) and probably continue to outcrop.

Coal Distribution

Net coal thickness of Unit 3 is at a maximum in the Baggs area where the coals are up to 45 ft thick. The coals trend southwesterly from Baggs, and then swing southeasterly in an arcuate pattern to the southern outcrop belt near Craig (fig. 19). Average coal thickness of this trend is approximately 25 ft. Net coal thickness decreases to the east, but the arcuate trend is maintained and the coals, although absent beyond R88W around T8-11N, are still present farther south (T5-6N) in R86W (fig. 19). Net coal thickness also thins to the west where the coals are generally thinner than 10 ft west of the Little Snake River. Locally, however coals can be up to 25 ft thick. The coals are exposed in the southern and northeastern outcrop belts.

Unit 4

The uppermost genetic depositional sequence of the Williams Fork Formation is Unit 4. It is characterized throughout by aggradational, mudstone-rich coal-bearing deposits overlying a very thin progradational base (figs. 9, 10, and 11). Thus, the facies offset from underlying mudstone-rich coal-bearing rocks of Unit 3 is subtle. The flooding event that defines the base of Unit 4 was minor when compared to the other flooding surfaces that punctuate the Williams Fork sequence. The upper bounding surface separates the Williams Fork Formation from the overlying Lewis Shale in the northeastern half of the basin, and upward-coarsening barrier/strandplain facies of the genetically-defined Almond Formation in the west and southwest (fig. 10).

Depositional Systems

Unit 4 does not contain any major progradational units. There is evidence of minor progradation overlying the basal bounding surface, but large shoreface sandstone facies are absent. The general character of the unit is one of extensive aggradational, mudstone-rich coal-bearing deposits. The

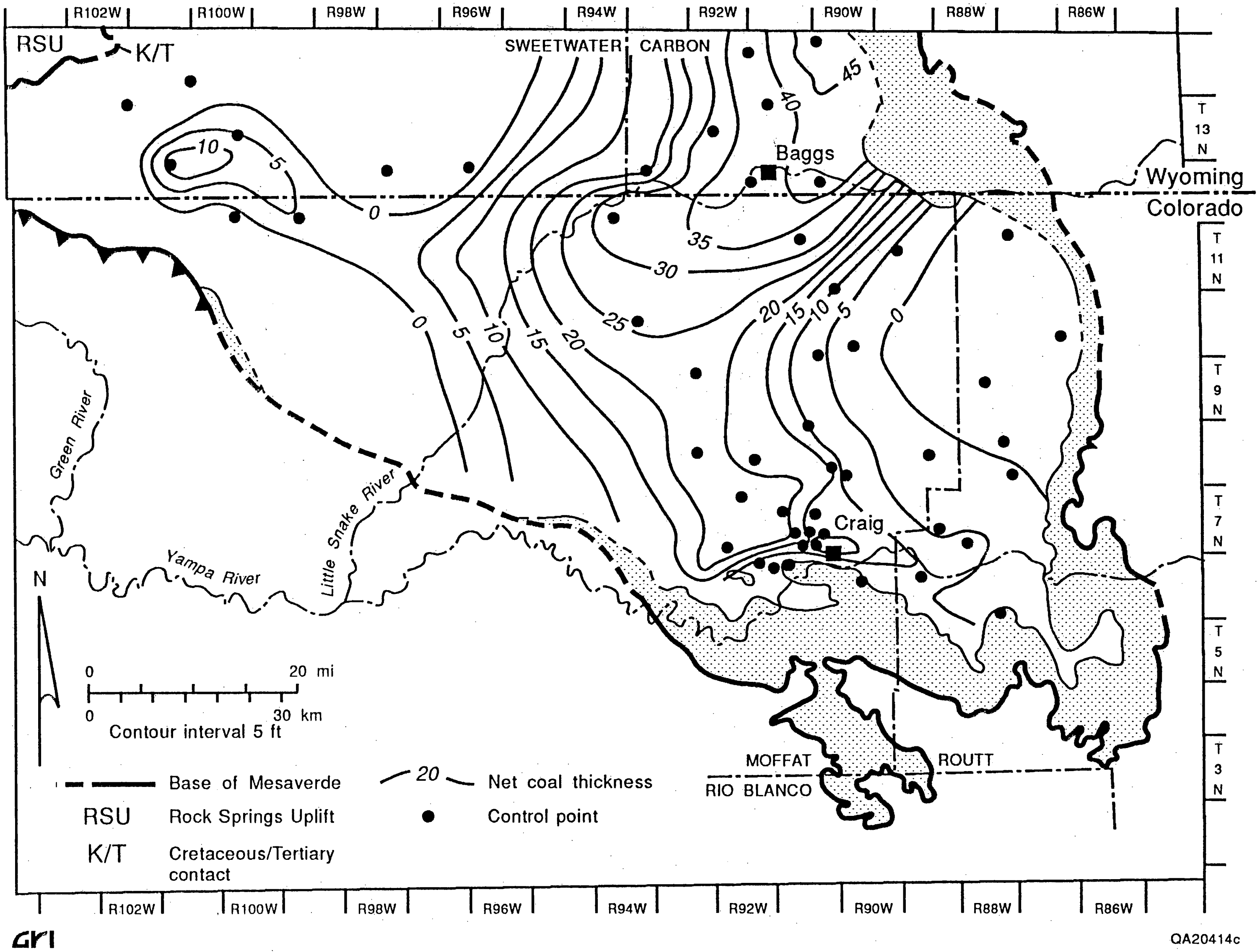

Figure 19. Net-coal-thickness map of Unit 3, Williams Fork Formation. Thickest net coal occurs in the Baggs area, and extends in an arcuate pattern to Craig.

inference is that this unit is an alluvial plain sequence with possible lacustrine influence. The very thin progradational sequence at its base for example, may represent lacustrine infilling. The sandstone facies of Unit 4 are generally thinner and much less abundant than their counterparts in Units 1, 2, and 3. Log character of the sandstones is fining-upward to blocky/upward-fining and may represent channel-fills of mixed-load or suspended load fluvial systems.

Coal Stratigraphy

Coals of Unit 4 can be correlated throughout the eastern part of the Sand Wash Basin as two broad groups (fig. 10), although individual seams can be correlated locally. The lower group consists of one to five seams 1-15 ft thick whereas the upper group consists of two to four coals 1-8 ft thick. Coals tend to be thicker west of R91W. The coals are present to the eastern limit of well information and appear to project to the eastern outcrop belt, despite the fact that they thin to the east.

Coal Distribution

Two trends are apparent in the net coal thickness map of Unit 4 (fig. 20). The thickest net coal trend extends from the southern outcrop belt near Craig in a northerly direction towards Baggs. The net coal thickness averages 30 ft, but is up to 40 ft thick near Craig. A second trend evident on the net coal map is oriented in a southeasterly direction (dip-oriented) and extends from the southern edge of the Rocks Springs uplift to the Little Snake River. Net coal thickness of this trend averages 25 ft. These coals represent the first significant Williams Fork coal occurrence west of the Little Snake River. The coals are exposed along the southern outcrop belt, the southern edge of the Rocks Springs Uplift, and the northeastern outcrop near Baggs, although they are substantially thinned in the latter two outcrops.

CONCLUSIONS

1. The Williams Fork Formation, the most important coal-bearing unit in the Sand Wash Basin, can be divided into 4 genetic depositional sequences. These sequences were deposited during discrete episodes of basin history, and are bounded by regionally extensive, low resistivity shale markers that represent marine flooding surfaces in the basinward direction and hiatal, non-depositional surfaces (surfaces of sediment starvation) in terrestrial facies.

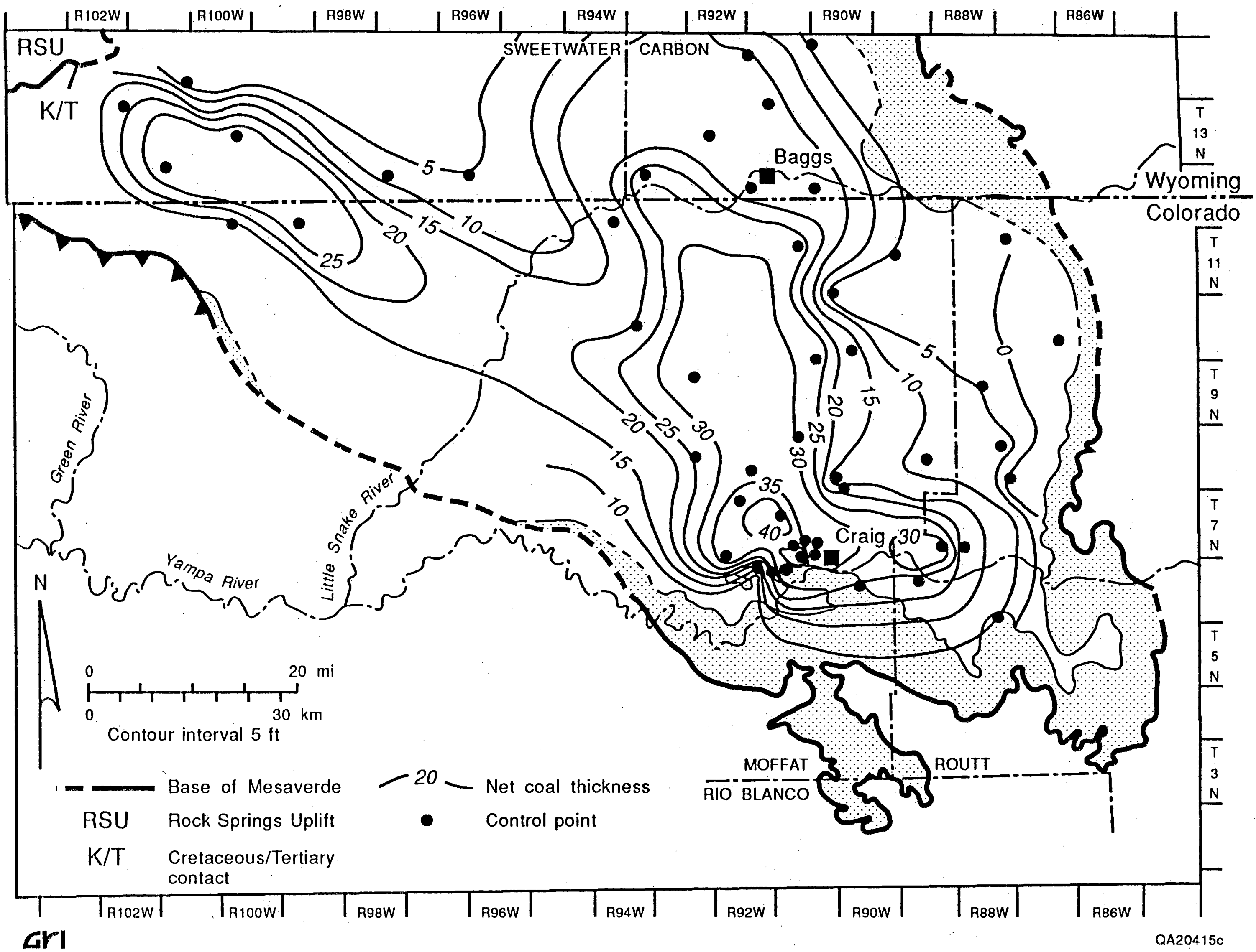

Figure 20. Net-coal-thickness map of Unit 4, Williams Fork Formation. Thickest net coal occurs in the Craig area. The main coal trend is oriented north-south from Craig to Baggs, but a second southeasterly oriented thick coal trends extends from the southern edge of the Rocks Springs Uplift.

2. The first genetic depositional sequence, Unit 1, is a clastic wedge that extended coal-bearing coastal-plain deposits beyond the present day basin margin. Three depositional systems are recognized in the unit. A linear shoreline system dominated the easternmost part of the basin, and was backed landward by a coastal plain system, that in turn graded westward into an alluvial plain system. Unit 2 is clastic wedge displaying a similar arrangement of depositional systems, but this unit did not prograde as far basinward.

3. Units 1 and 2 contain the thickest, most laterally extensive coals. Coal occurrence in all units is concentrated in the eastern half of the basin, and, with the exception of Unit 4, there is no significant coal to the west of the Little Snake River. Coals are thickest in the vicinity of Craig where net coal thickness of Unit 1 averages 90 ft and Unit 2 averages 35 ft. Continuity of the Williams Fork coals is variable. Some individual seams, particularly in Units 1 and 2, were correlatable throughout the eastern half of the basin by their characteristic profile on density and gamma-ray logs. Other seams could only be correlated when grouped as broad coal packages. The coals of Units 1 and 2 are continuous in the subsurface to the southern and northeastern outcrop belts and are exposed for meteoric recharge.

4. Coal occurrence of Units 1 and 2 is intimately related to the depositional systems. The coastal plain immediately landward of the shoreline system was the ideal site for peat accumulation and preservation. This was an area of sediment bypass, and maintenance of optimum water table levels. Lowering of the water table is thought to account for the gradual westward thinning of the coals at the coastal- plain/alluvial plain transition. The coals override the shoreline sandstone to the east, but also thin in this direction. Their ultimate lateral extent was limited by the final shoreline position, beyond which marine conditions prevailed.

5. Future research planned for the Williams Fork Formation includes the following:

- An analysis of the depositional systems of Units 3 and 4 by mapping framework sandstones and log facies, and their controls on coal occurrence.
- Further assessment of coal seam continuity. Correlation of individual seams within Unit 1 is not yet complete, nor is correlation of the Unit 3 and 4 coals.
- Coal resources for each unit remains to be calculated.
- A geologic characterization of the major fault zone northwest of Craig, Colorado.

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

Andrew R. Scott

ABSTRACT

Mesaverde coal rank ranges from high-volatile C bituminous along the basin margins to medium-volatile bituminous in the deeper parts of the basin. Coal rank in the eastern half of the basin, where the thickest coal beds occur, is generally high volatile C to B bituminous. Mesaverde gas contents range from less than one to more than 540 scf/ton but are generally less than 200 scf/ton. Gas contents change vertically within a well and laterally between wells. Factors controlling the distribution of high gas contents in the basin include coal rank, coal characteristics, localized pressure variations, basin hydrodynamics, and conventional trapping of migrating thermogenic and biogenic gases. Coalbed gases range from very wet to very dry (average C_1/C_{1-5} value of 0.96) but generally fall between C_1/C_{1-5} values of 0.94 to 0.99. Carbon dioxide content is variable ranging from less than one to more than 25 percent. Coalbed gases are most likely early thermogenic and biogenic in origin.

THERMAL MATURITY

The thermal maturity of coal-bearing basins is one of several factors that are important in determining the types and quantities of gases generated from coal beds. Coal is unusual because it acts as both the source of gas and the reservoir in which the generated gas is stored. Significant quantities of methane will be generated from coal once the threshold of thermogenic gas generation has been reached at approximately 0.73 percent vitrinite reflectance (Meissner, 1984). Gas contents for higher-rank coal beds may exceed 400 to 500 scf/ton (Scott and Ambrose, 1992). At thermal maturity levels below the main stage of thermogenic gas generation, the dominant gas types will be early thermogenic and biogenic, and gas contents are often less than 100 scf/ton (Scott and Ambrose, 1992). However, migration and conventional trapping of thermogenic gases derived from higher rank coals and/or biogenic gases generated in the coal can result in unusually high gas contents.

Over 50 vitrinite reflectance (VR) values from 10 Mesaverde wells in the study area were obtained from coalbed methane operators, Law (1984), and MacGowan and Britton (1992) and used in constructing a Mesaverde coal rank map. Unfortunately, with the exception of one sample from Law (1984), all of the measured VR data is restricted to the eastern half of the basin. Proximate and ultimate data from 39 samples along the eastern margin of the basin were used to supplement the measured vitrinite reflectance data. The heating value of the coal (BTU/lb) was calculated on a mineral matter moisture free (mmmf) basis and then converted to equivalent vitrinite reflectance values using the polynomial equation:

$$VR = 0.87302 - (1.35 \times 10^{-4})(BTU) + (9.14 \times 10^{-9})(BTU)^2 \qquad (1)$$

This equation (fig. 21a), determined by regression line using coal rank data from Murray and others (1977), Stach and others, (1982) and American Society for Testing Materials (1983), can be used to estimate vitrinite reflectance values for high-volatile A bituminous and lower rank coals. A comparison of measured vitrinite reflectance values with vitrinite reflectance data calculated from equation 1, using coal rank data provided by the operators and from Tremain and Toomey (1983), shows that calculated vitrinite reflectance values less than 0.78 percent (high-volatile B bituminous and lower rank) generally fall within 0.1 percent VR of the measured values (fig. 21b). However, the calculated vitrinite reflectance values tend to be slightly overestimated in the high-volatile A bituminous range. In the absence of measured vitrinite reflectance data and proximate and ultimate analyses, vitrinite reflectance profiles of Mesaverde coals and shales were used. Vitrinite reflectance profiles were constructed from data obtained from coalbed methane operators, Tremain and Toomey (1983), Law (1984), and MacGowan and Britton (1992). Regression analyses were performed on the vitrinite reflectance data from profiles in the Sand Wash and Washakie Basins (fig 22). The equations calculated by regression analyses (fig. 22) were subsequently used to estimate vitrinite reflectance values for the top of the Mesaverde at approximately 55 locations in the Washakie and Sand Wash Basins (fig. 22). Vitrinite reflectance versus depth profiles for Mesaverde coals in the Sand Wash Basin were also generated to estimate the amount of overburden removed but were not used in calculating coal rank (fig. 23). The logarithmic increase in vitrinite reflectance values with increasing burial depth (figs. 22 and 23a) is common in many western basins (Tyler and others, 1991). Although vitrinite reflectance profiles are useful for estimating coal rank and gas generating stages in a basin, estimated vitrinite reflectance values alone cannot be used to interpret burial history and the timing of structural element formation. Calculated vitrinite reflectance values will be underestimated if uplift and subsequent removal of section from areas of higher-rank coals has occurred. Furthermore, calculated values can overestimate or underestimate coal rank if different parts of the basin have had significantly different paleogeothermal gradients and/or coalification histories. However, a generalized interpretation of the burial history is possible using additional information from other sources.

a)

b)

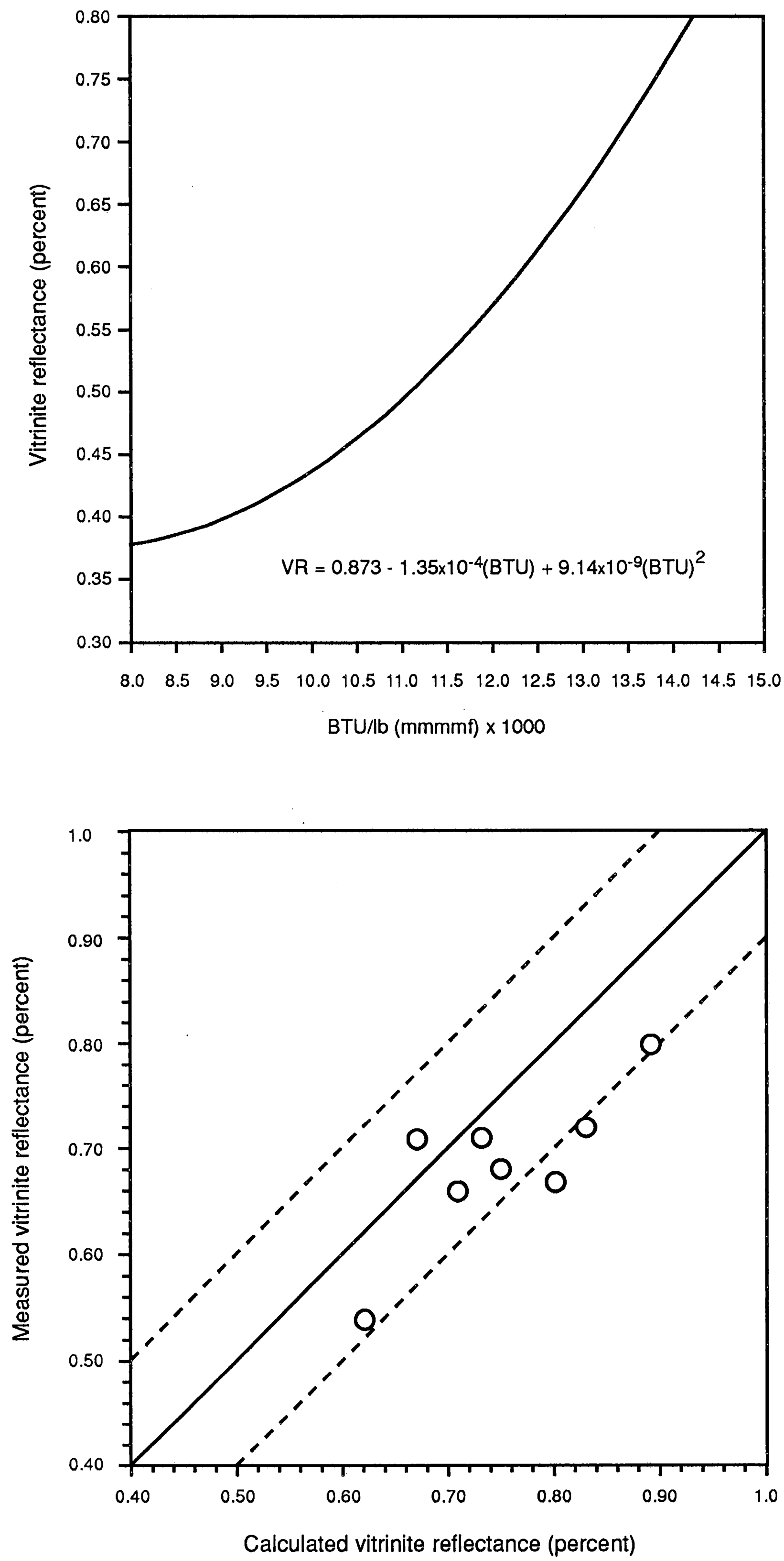

Figure 21. Correlation between vitrinite reflectance and coal BTU (mmmf). a) Equation and graph used to convert BTU data into equivalent vitrinite reflectance values. b) Comparison between calculated and measured vitrinite reflectance values. Vitrinite reflectance, proximate, and ultimate data were provided by operators and Tremain and Toomey (1983).

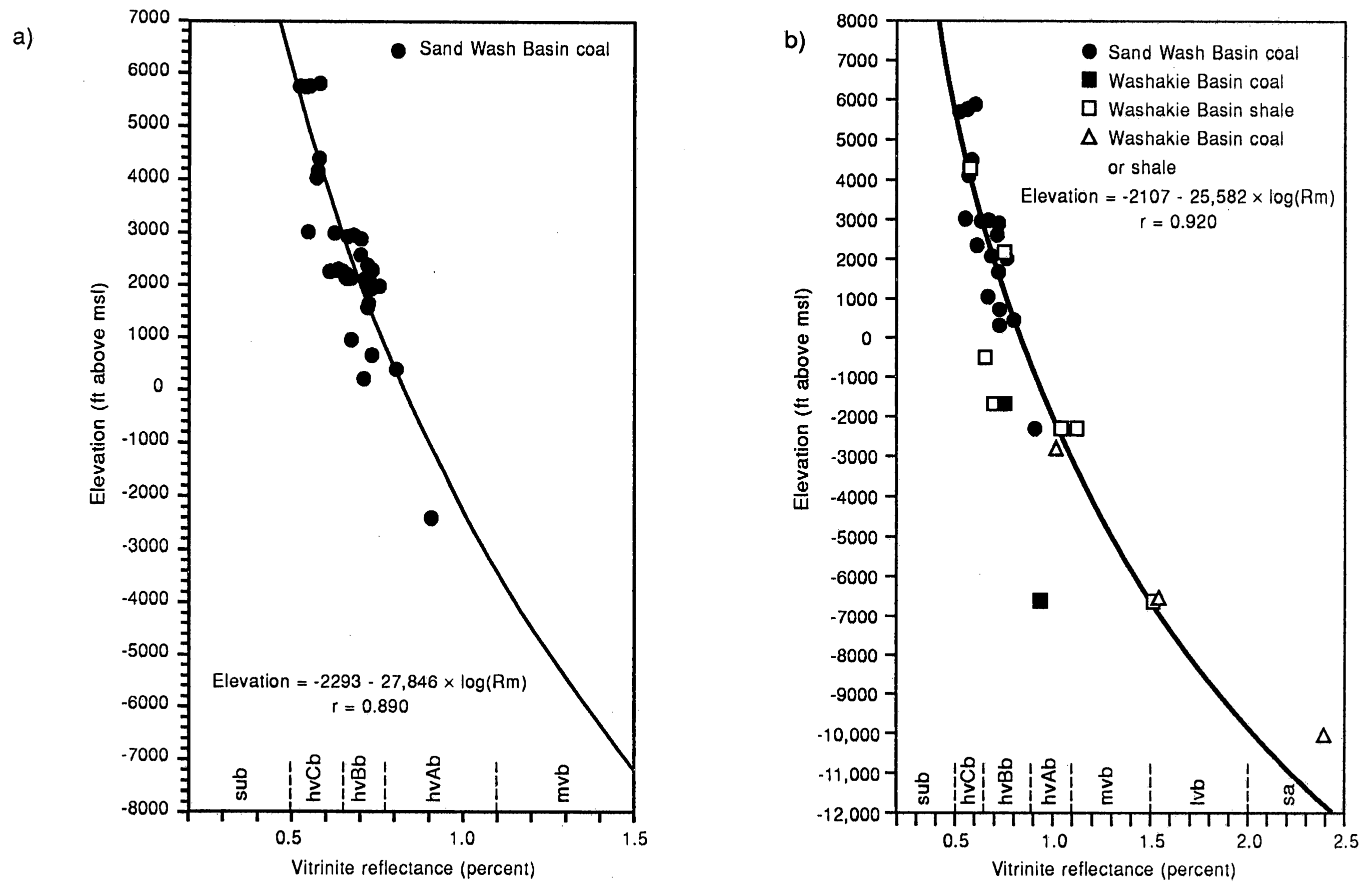

Figure 22. Vitrinite reflectance profiles for the Sand Wash Basin. a) Elevation versus vitrinite reflectance values for Mesaverde coals in the Sand Wash Basin. b) elevation versus vitrinite reflectance values for Mesaverde coals and shales from the Sand Wash and Washakie Basins. The equations in (a) and (b) were used to estimate vitrinite reflectance values based on depth in the two basins.

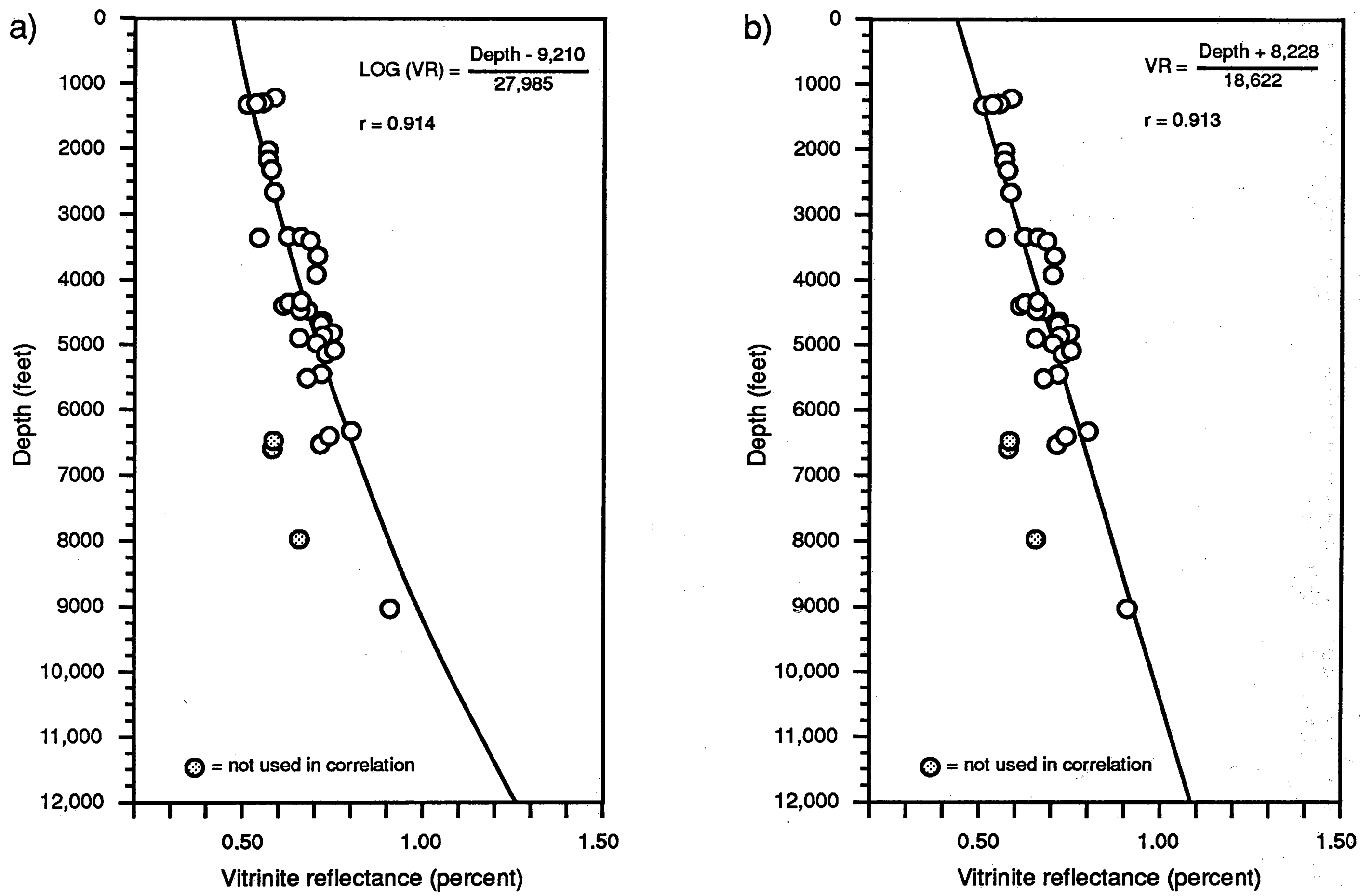

Figure 23. Vitrinite reflectance profiles using depth versus vitrinite reflectance for Mesaverde coals in the Sand Wash Basin. a) logarithmic regression analyses and b) linear regression analyses. These equations were used to estimate the amount of overburden removal from the basin.

Coal rank ranges from high-volatile C bituminous along the eastern and southern margins of the basin to medium-volatile bituminous in the Sand Wash Basin's structural center along the Little Snake River and up to the semianthracite rank in the Washakie Basin (fig. 24). Coal rank in the eastern part of the basin where the thickest coals are located is generally high-volatile C to B bituminous rank although some basinward coal beds may approach high-volatile A bituminous rank. The lower coal-rank along the basin margins, White River Uplift, and the eastern part of the Cherokee Arch suggest that these structures probably started to form during the Paleocene and Eocene (Tremain and others, this vol., Johnson and Nuccio, 1986) before the main-stage of coalification. Previous studies on the timing of coalification in the Piceance and Sand Juan Basin suggest that maximum temperatures and burial depths were attained during the Late Eocene and Oligocene (Johnson and Nuccio, 1986; Law, 1992). Tertiary intrusives in the Elkhead Mountains were emplaced during the Oligocene to Miocene and upper Tertiary dikes were formed during the middle to late Miocene (Tweto, 1979; Tremain and others, this vol., fig. 6). Therefore, maximum burial depth and coalification in the San Wash Basin may also have occurred during this time, although the exact timing of maximum burial and coalification remains uncertain.

Assuming that vitrinite reflectance values are approximately 0.2 to 0.3 percent at the surface (Teichmüller and Teichmüller, 1981), the relatively high vitrinite reflectance values of 0.4 to 0.5 percent along the basin margins suggest that the basin has probably undergone significant uplift and erosion following the main-stage of coalification. The amount of overburden removal can be approximated using the equations determined from vitrinite reflectance profiles in figure 23. Both equations in figure 23 have essentially the same correlation coefficient, but the amount of overburden removal estimated from each equation differs significantly depending on which equation and the surface vitrinite reflectance value used. Overburden removal estimates range from 2,600 ft (fig. 23b; surface VR = 0.3 percent) to 10,300 ft (fig. 23a; surface VR = 0.2 percent). However, assuming a surface vitrinite reflectance value of 0.25 percent, the amount of overburden removed from the basin ranges between 3,500 to 7,600 ft. This range of overburden removal is probably a more reasonable estimate and is similar to the amount of overburden removed in the Piceance Basin (Johnson and Nuccio,1986).

A major northwest trending fault system extending northwest from Craig cuts the Miocene Browns Park Formation (Tweto, 1979), suggesting that the main stage of coalification, during which maximum gas generation was attained (Late Paleocene and Oligocene), may have occurred before the fault system formed. However, this fault system could also have developed simultaneously with the main-stage of thermogenic gas generation and been reactivated during regional uplift in the late Miocene, thus cutting the Brown's Park Formation. Therefore, it is not know at this time whether or not this fault system was in place to conventionally trap migrating thermogenic gases. However, conventional trapping of thermogenic and/or biogenic gases after the present-day hydrologic regime developed probably has

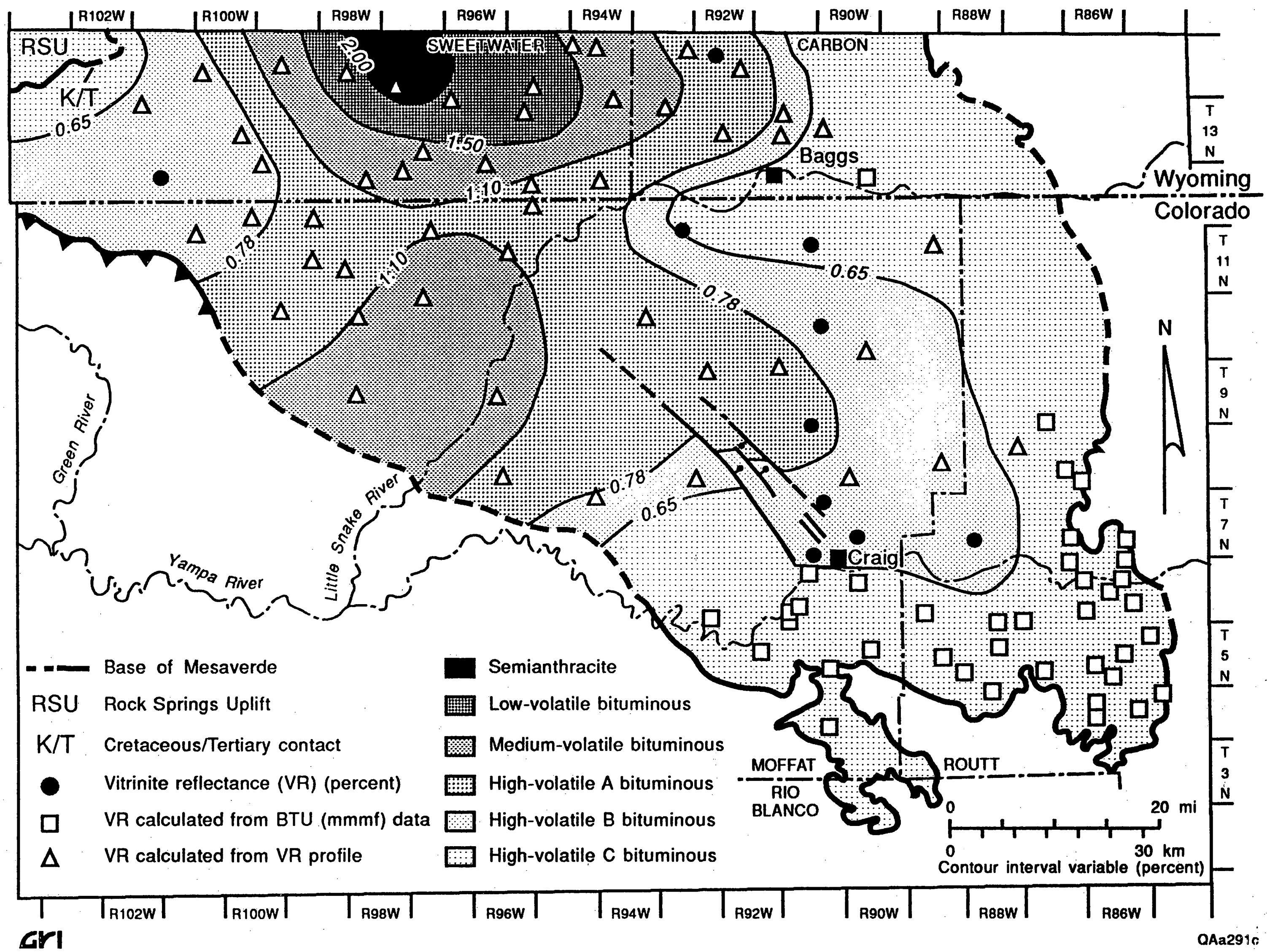

Figure 24. Mesaverde coal rank map. Coal rank is mainly high-volatile C to B bituminous in the eastern part of the basin and reaches medium volatile bituminous in the basin's structural center. Measured vitrinite reflectance values are from operators, Tremain and Toomey (1983), Law, (1984), and MacGowan and Britton (1992).

occurred. Active hydrocarbon overpressure in the deeper parts of the Sand Wash Basin is probably not occurring today. However, coals in the Washakie Basin are buried much deeper and have reached the semianthracite rank suggesting that active hydrocarbon overpressure may be occurring (McPeek, 1981).

Gas Content

Gas content from 261 Mesaverde and 126 Fort Union coal samples from 19 wells were used to evaluate the distribution of gas contents in the Sand Wash Basin. Gas content data were obtained from operators, Boreck and others (1983), and Tremain and Toomey (1983). All gas content readings were measured by the U.S. Bureau of Mines method and were corrected to an ash-free basis when proximate data were available; ash content ranged from three to 21 percent and averages 9.5 percent. In the absence of proximate data, all ash content values from the same well were averaged in order to correct the gas contents to a calculated ash-free basis. Mesaverde gas contents (ash-free) range from less than one to more than 540 scf/ton but are generally less than 200 scf/ton (average 147 scf/ton) (fig. 25).

Gas content versus depth profiles show a gradual increase in gas content and wide scatter of gas content data with increasing burial depth (fig. 26) similar to gas content profiles in other western basins (Scott and Ambrose, 1992). Coal rank does not increase significantly with depth (fig. 23) indicating that gas content is related to local pressure variations, variability of coal characteristics, and/or migration of thermogenic and/or biogenic coalbed gases and conventional trapping. Gas contents are less than 20 scf/ton for samples shallower than 1,000 feet indicating that coalbed gases may have migrated out of the system due to low confining pressures and/or lack of seals. Scatter of gas content data probably reflects experimental and handling procedures and/or the type of sample. Gas content measurements for core samples are significantly greater than gas content values for cuttings and sidewall core samples. Comparison of gas content values of whole core samples with sidewall core and cutting samples over approximately the same depth interval indicates that whole core gas content measurements are 1.6 and 1.4 times greater than sidewall core and cutting samples, respectively. However, gas contents from whole core samples within several feet of each other can show a large difference in gas content values (fig. 26) indicating that factors other than sample type affect gas content values. Factors controlling gas content measurements include sample type, sampling procedures, coal properties, and analytical methods and quality. Most gas content measurements are performed at room temperature rather than reservoir temperature. Since more gas is desorbed from coal surfaces at higher temperatures, gas contents measured at reservoir temperatures are usually higher than gas content measurements taken at room temperature (fig. 27). Gas contents determined at reservoir temperatures (98° or 130°F) are generally 1.2 times higher than gas contents determined at room temperature. However, some gas content

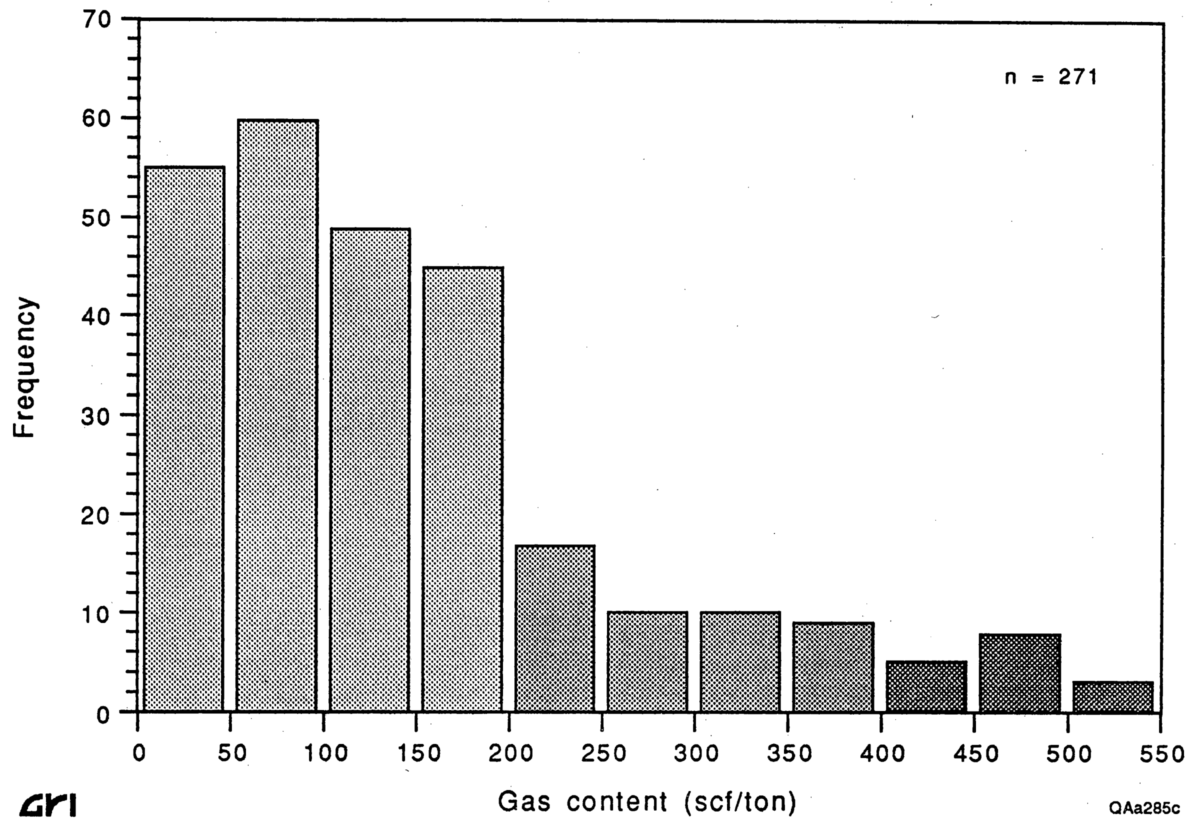

Figure 25. Histogram of ash-free Mesaverde gas contents. Most gas content are less than 200 scf/ton but locally exceed 400 scf/ton in some coal beds.

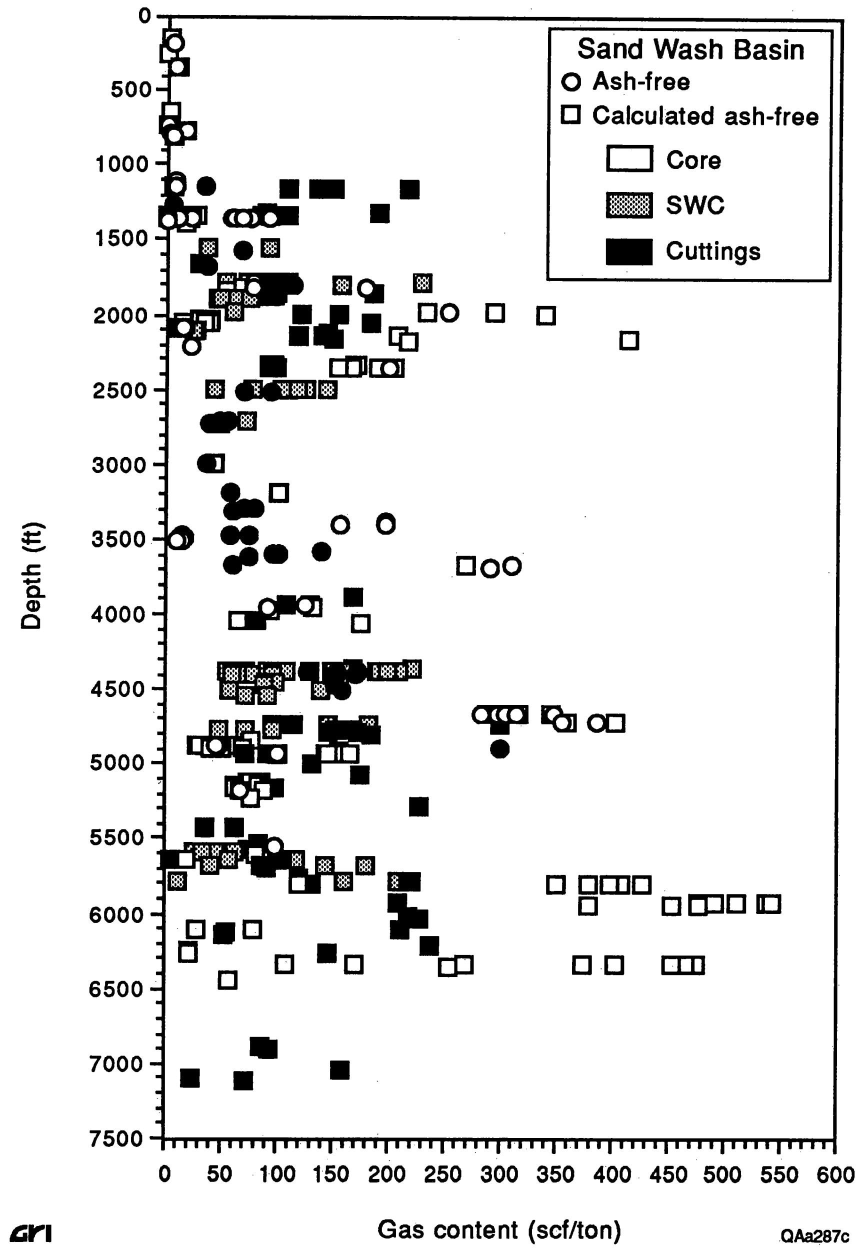

Figure 26. Gas content profile for the Sand Wash Basin Mesaverde and Fort Union coals. Gas content increases with depth, as in other western coal basins. At any particular depth, there is a wide range of gas content values. Sidewall cores and cuttings generally have lower gas contents than whole cores, indicating that sampling and handling procedures influence gas content measurements. Data are ash-free and ash-free values calculated from average ash contents of adjacent seams.

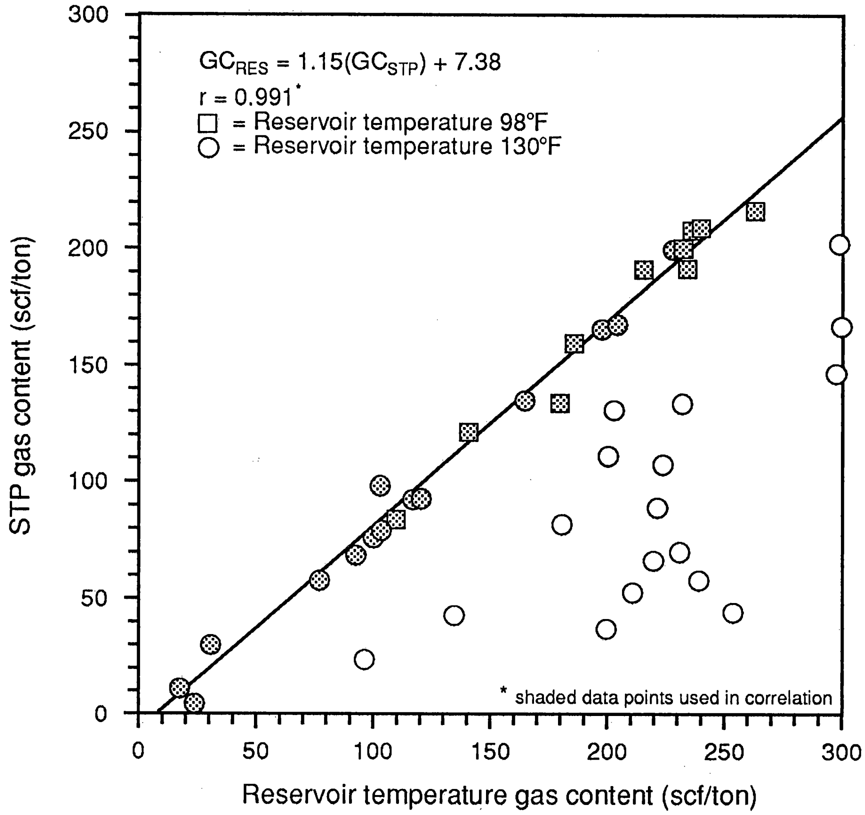

Figure 27. Relation between gas contents determined at room (STP conditions) and reservoir temperatures.

measurements made at 130°F are significantly higher than gas contents made at room temperatures (fig. 7). The factors behind the variability in gas content values at higher reservoir temperatures are uncertain at this time.

Factors controlling the distribution of gas contents in coal beds include coal rank, the presence or absence of seals, stratigraphic or structural traps, coal characteristics, local pressure variations, and basin hydrodynamics. Gas content measurements of coal beds in the Sand Wash Basin show a gradational increase in gas content with increasing burial depth and pressure. However, the gas contents of several wells are higher than gas contents in other wells over equivalent depth intervals. The Morgan Federal 12-12 (T8N, R93W, Sec. 12) and Van Dorn No. 1 (T7N, R90W, Sec. 29) are on the downthrown side of a major northwest trending fault system extending from near Craig (T6N, R90W) 30 miles northwestward to T10N, R94W (Tremain and others, this vol., fig. 6). Maximum gas contents in these wells range from more than 300 to 500 scf/ton between 4,500 to 6,500 ft. Other Mesaverde coals with anomalously high gas contents are located east of Baggs (T12N, R90W) in an area of artesian overpressuring (Scott and Kaiser, this vol., figs. 32 and 34) along the eastern part of the Cherokee Arch. Maximum gas contents for these wells ranges from more than 170 to 300 scf/ton over a depth interval of 1,000 to 2,400 ft.

Gas contents change vertically between coal beds and laterally within individual coal beds between wells (fig. 28). The variability in gas content values could be due to variations in pressure between seams, sample type, coal characteristics, analytical methods and quality, and/or migration of gases in coal beds. Anomalously high Mesaverde gas contents adjacent to the major northwest trending fault system and along the eastern portion of the Cherokee Arch may be due to migration and conventional trapping of biogenic and/or thermogenic coalbed gases as well as overpressured conditions. Non-ash free gas content for coals at 5,900 ft in the Morgan Federal 12-12 (T8N, R93W, Sec. 12) average 414 scf/ton (fig. 28). These coals pinch out behind a northeast-trending shoreline sandstone (fig. 28; Hamilton, this vol., figs. 15, 16, and 18). Furthermore, this well is also located on the downthrown (northeast) side of a northwest trending fault system (Tremain and others, this vol., fig. 6) suggesting that the high gas contents may be due to a combination structural and stratigraphic trapping of migrating gases. Migrating gases could have been trapped during the main stage of coalification, depending on the timing of fault development, and/or during migration of early thermogenic and/or biogenic gases transported basinward by ground water.

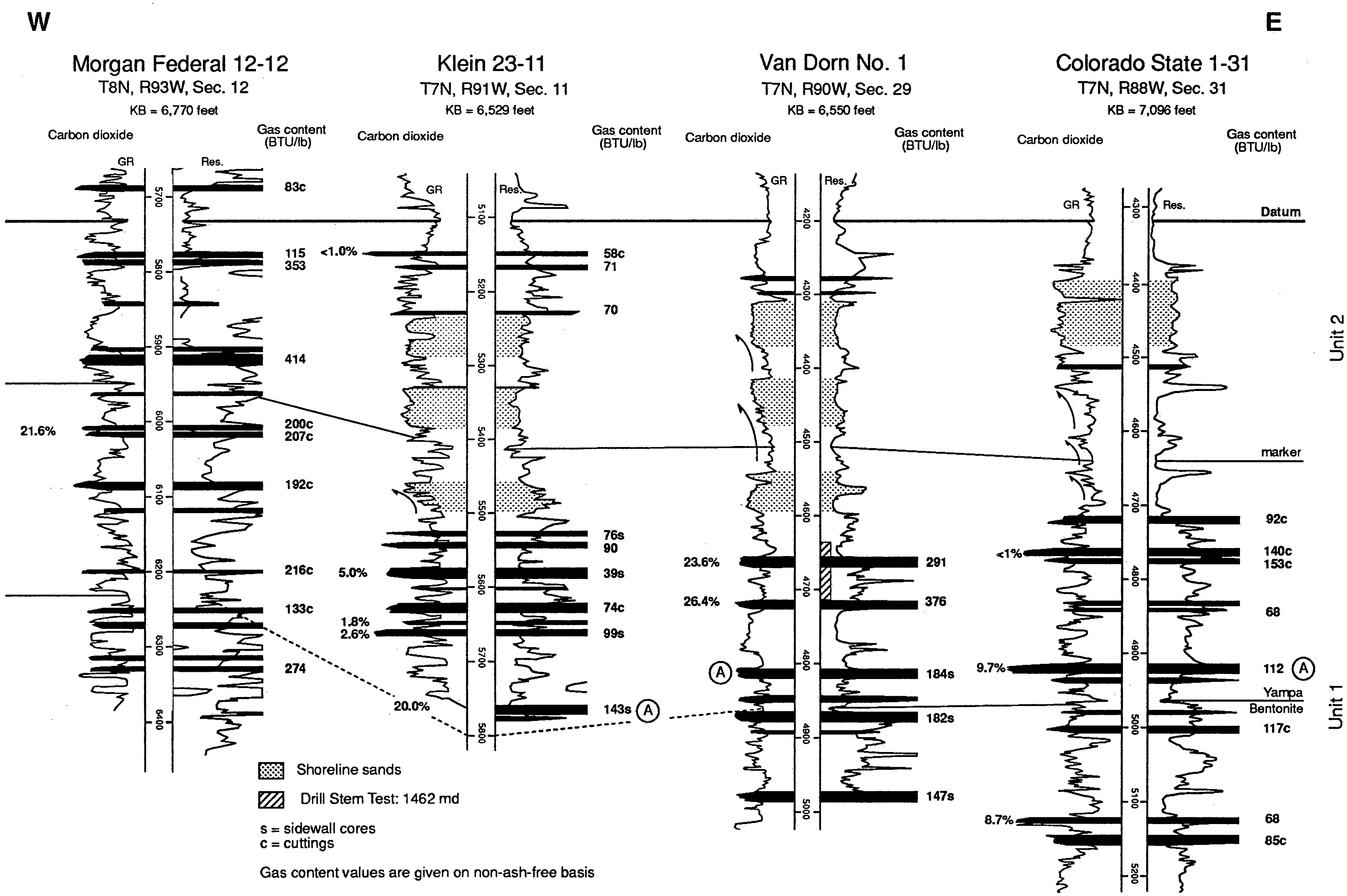

Figure 28. West to east cross section showing the changes in gas content and gas composition between different Mesaverde coal beds. The high gas contents in coal beds at 5,900 ft in the Morgan Federal 12-12 well may be due to stratigraphic and structural trapping of migrating coalbed gases.

GAS COMPOSITION

The composition of coalbed gases is directly related to coal rank, basin hydrodynamics, and maceral 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. In general, hydrogen-rich coals in the oil-window or oil-generating stage (vitrinite reflectance of 0.5 to 1.2 percent) produce significant amounts of wet gases (ethane, propane, etc.), whereas coals having vitrinite reflectance values 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 (Scott and others; 1991a). 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, producing chemically dry gases resembling thermogenic methane (James and Burns, 1984). Furthermore, 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 coal bed gases than methane isotopic data alone, particularly when mixtures of thermogenic and biogenic methane may be present.

The chemical composition of desorbed gas samples from 36 coal samples in six Mesaverde wells were used to evaluate the chemical composition and origin of Williams Fork coalbed gases. No produced coalbed gases were available for analysis in the basin. The gas dryness index ranges from 0.79 to 1.00 and averages 0.95 (fig. 29). These values are 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 for Mesaverde coal beds ranges from less than one percent to more than 25 percent (fig. 29). The range of carbon dioxide content for Mesaverde coalbed gases is also similar to Fruitland coalbed gases, which range from less than one to more than 25 percent (Scott and others, 1991a, b; A. R. Scott, unpublished data). 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 northern 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 one percent to 20 percent and averaged approximately four percent. This average nitrogen content is 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 be due to gas sampling; these gases were desorbed from coal samples which increases the possibility of air contamination whereas Fruitland data is from produced coalbed gases.

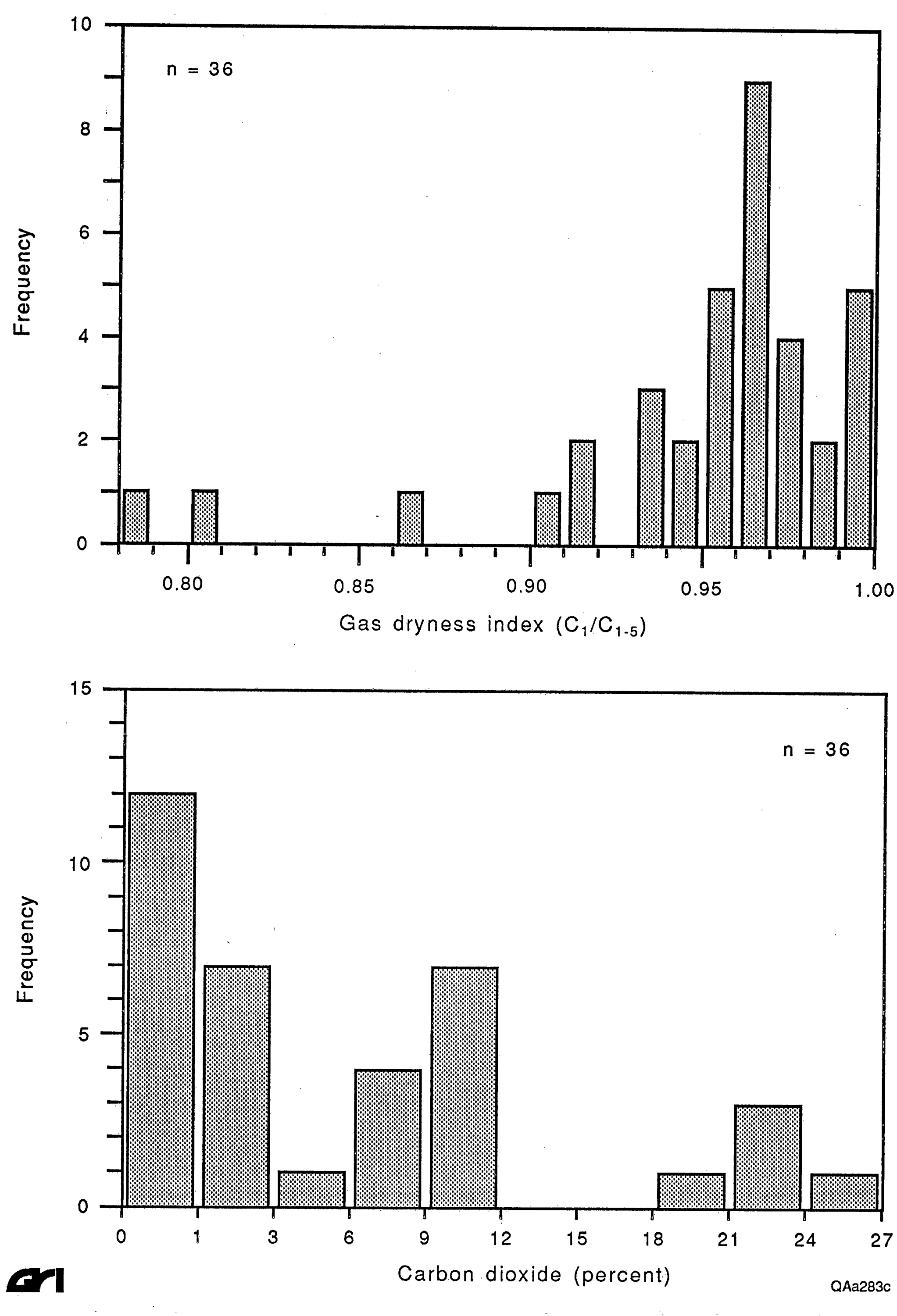

Figure 29. Composition of Mesaverde coalbed gases. Desorbed gases have a wide range of chemical compositions. Coal beds have entered the early gas generation stage as indicated by the minor amounts of wet gases in the samples. High carbon dioxide contents in some coal beds may reflect bacterial activity, gas migration, and/or variations in maceral composition.

Gas composition changes vertically between coal beds within individual wells and laterally between wells (fig. 28). However, at least one coal bed, (coal bed A, fig. 28) which can be traced laterally over several tens of miles using density log profiles, has consistently high carbon dioxide values (fig. 28) near or above ten percent. This 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 with high carbon dioxide contents are generally characterized by high C_1/C_{1-5} values (fig. 30). 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 coals in Units 3 and 4 of the upper Williams Fork Formation. However, coal beds from the Morgan Federal 12-12 (T8N,R93W, Sec. 12) tend to have chemically wet gases and relatively high carbon dioxide content (fig. 28).

ORIGIN OF COALBED GASES

Determining the source of methane and carbon dioxide in coalbed gases is important for evaluating origin of coalbed gases and the migration of coalbed gases within the basin. Significant amounts of carbon dioxide are released from coals during maturation. Based on the equations and data presented by Levine (1987), up to 4,186 scf/ton (STP; 25°C, 1 atm) carbon dioxide and 6,040 scf/ton methane can be released from vitrinitic material over the bituminous to semi-anthracite coal rank (VR values of 0.5 to 2.0 percent) during coalification. Assuming that water is released in liquid form, carbon dioxide and methane represent approximately 40 and 60 percent (by volume), respectively, of the total volatiles released from the coal. However, assuming no heavier hydrocarbons are generated, significantly more methane (over 16,200 scf/ton) is released from hydrogen-rich organic material (Levine, 1987) relative to vitrinitic material. Therefore, even minor amounts of hydrogen-rich organic matter can dramatically increase the amount of methane generated from coal beds.

Significant amounts of carbon dioxide are generated during the early stages of coalification before the main stage of thermogenic gas generation; the amount of carbon dioxide decreases with increasing maturation (Juntgen and Karweil, 1966; Hunt, 1979; Creedy, 1988). Thermogenic carbon dioxide generated during coalification can remain sorbed to the coal surface or be dissolved in formation waters and subsequently transported out of the system. An additional source of carbon dioxide is from bacterial activity. Bacteria transported in ground water through coal beds can metabolize the chemically wet coalbed gases to produce biogenic carbon dioxide and methane (Scott and Kaiser, 1991). The origin of carbon dioxide in coalbed gases can be determined from the isotopic composition of the carbon dioxide. Carbon dioxide released during coalification will be depleted in $\delta^{13}C$ having $\delta^{13}C$ values of -25 to -15 ‰.

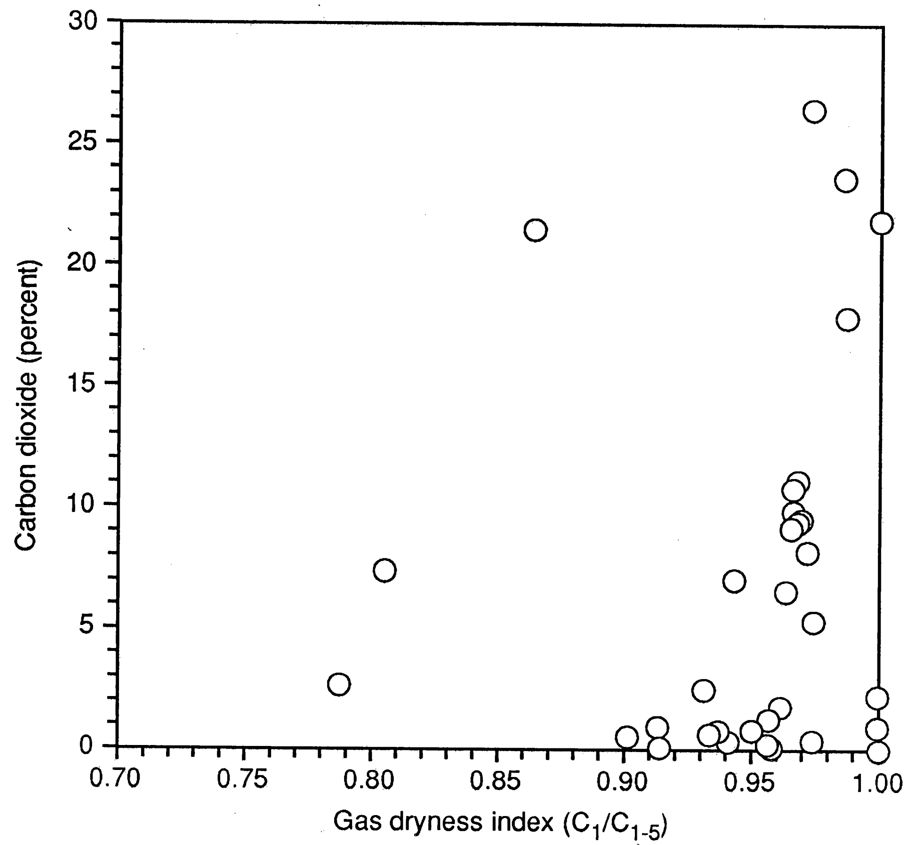

Figure 30. Variation of carbon dioxide content with the gas dryness index (C_1/C_{1-5} values). Coals with the higher carbon dioxide content generally have very dry gases although coals in the Morgan Federal 12-12 and Colorado State 1-31 wells have wet gases.

Biogenic carbon dioxide is enriched in $\delta^{13}C$ with $\delta^{13}C$ values ranging from -20 to +30 o/oo (Jenden, 1985) depending on the intensity and duration of bacterial activity. Therefore, carbon dioxide with positive $\delta^{13}C$ values is predominantly biogenic whereas $\delta^{13}C$ values less than -15 o/oo are generally thermogenic; mixtures of biogenic and thermogenic gases falling somewhere between. However, carbon dioxide derived from magmatic sources ($\delta^{13}C$ values of -7 to -9 o/oo ; Jenden, 1985) should also be considered when evaluating gas origin.

Williams Fork coalbed gases were not available for detailed isotopic analyses. Even with isotopic analyses, gas origin may be difficult to determine but the maturation level coalbed gas generation can be evaluated based on coal rank data. Vitrinite reflectance profiles, using Mesaverde coals, indicate that coal beds in the eastern part of the Sand Wash Basin at depths of 6,000 feet are just entering the main stage of thermogenic gas generation (fig. 23). The relatively low rank of these coals suggest that Williams Fork coalbed gases are predominantly early thermogenic and biogenic although migration of thermogenic gases from coals or shales deeper in the basin may have occurred. However, the migration of main stage thermogenic gases from areas of high coal rank is limited because there are few coal beds located in the thermally most mature part of the basin (fig. 24; Hamilton, this vol., figs. 14, 17, 19, and 20). The distribution of C_1/C_{1-5} values around 0.96 suggests that some of the coalbed gases are predominantly early thermogenic (fig. 29). Early thermogenic gases, which are generated between vitrinite reflectance values of approximately 0.50 and 0.73 percent, will contain minor amounts of wet gas components. The wettest gases (C_1/C_{1-5} values less than 0.90) are associated with coals in the main-stage of thermogenic gas generation between VR values of 0.73 to 1.3 percent. Biogenic gases and coalbed gases from higher-rank coals (vitrinite reflectance values greater than approximately 1.3 percent) are composed primarily of methane having C_1/C_{1-5} values near unity.

Carbon dioxide from Williams Fork coal beds is thermogenic, biogenic, or a mixture of both gas types. Calculations of carbon dioxide generation from coal beds using data from Levine (1987) indicate that over 50 percent of the total amount of carbon dioxide generated from vitrinite (type III organic matter) is produced before coals reach the high-volatile A bituminous rank and approximately 17 percent of the total is generated during the high-volatile A stage. Therefore, a significant portion of the carbon dioxide reported in some Williams Fork coals may have been generated during the earlier stages (high-volatile C and B bituminous) of coalification. However, the timing of carbon dioxide generation and retention in relation to the changes in adsorptive capacity of the coal during coalification remain uncertain or unknown and, therefore, a biogenic source for some of the carbon dioxide cannot be ruled out. Furthermore, the increase in carbon dioxide content with decreasing C_1/C_{1-5} values (fig. 30) suggest that some of the gases may be bacterially derived. The carbon dioxide content of individual seams ranges from less than two percent to more than 20 percent within the same well (fig. 28). However, carbon dioxide content remains consistently high (approximately ten percent) in some coal beds, which are correlated over tens of miles (fig. 28; coal bed A; Hamilton, this vol. fig. 12). The changes in carbon dioxide content vertically and laterally could be due to variations in maceral composition, which could affect the types and quantities of gases generated from the coal, bacterial activity, and/or migration of coalbed gases. The presence of wet gases with high carbon dioxide values (fig. 30) 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.

CONCLUSIONS

1. Mesaverde coal rank ranges from high-volatile C along the basin margins to medium-volatile bituminous in Sand Wash Basin and semianthracite in the Washakie Basin. Coals in the eastern half of the basin are generally high-volatile C and B bituminous and are in the early stages of thermogenic gas generation.

2. Ash-free Mesaverde gas contents range from less than one to more than 540 scf/ton but are generally less than 200 scf/ton. Gas contents change vertically and laterally between wells for continuous coal beds in the basin. Gas contents from conventional cores are approximately 1.5 times higher than gas contents than sidewall and cuttings samples over approximately the same depth interval.

3. Factors controlling gas content distribution include coal rank, coal characteristics, localized pressure variations, basin hydrodynamics, and conventional trapping of migrating early thermogenic and biogenic gases.

4. C_1/C_{1-5} values ranging from 0.79 to 1.00 and average 0.96. Carbon dioxide ranges from less than one percent to more than 25 percent. Mesaverde coalbed gases are probably early thermogenic and biogenic in origin.

5. Future research will focus on more detailed evaluation of the major factors, such as coal rank, conventional trapping, coal characteristics, and basin hydrodynamics, which control the distribution of Mesaverde gas contents in the Sand Wash Basin.

HYDROLOGIC SETTING OF THE UPPER MESAVERDE GROUP

Andrew R. Scott and W. R. Kaiser

ABSTRACT

The Mesaverde Group is a regional aquifer system of high transmissivity. Coal beds may be the most permeable aquifers. Recharge is received at outcrop over the basin's west, elevated eastern and southeastern margins. Ground water flows westward for eventual discharge basinward and toward the Yampa River valley on the east. No pressure regime is regionally dominant although artesian overpressure is present on the eastern part of the Cherokee Arch.

INTRODUCTION

In the Sand Wash Basin, the Mesaverde Group is a regional aquifer system, confined below and above, respectively, by the marine Mancos and Lewis Shales, regional confining units thousands of feet thick (Hamilton and others, this vol., fig. 8). Mesaverde hydrology was evaluated in an analysis of hydraulic head, pressure regime, and hydrochemistry in the context of Mesaverde stratigraphy, structure, and depositional setting. To map hydraulic head, equivalent fresh-water heads were calculated from shut-in pressures (SIP) recorded in drill-stem tests (DST) and bottom-hole pressures (BHP) calculated from well head shut-in pressures (WHSIP). Static water levels at the basin's south and east margins were also used to map hydraulic head (Robson and Stewart, 1990). The pressure regime was evaluated on the basis of simple and vertical pressure gradients calculated from screened DST data. Chlorinity and total-dissolved-solids maps further defined ground water circulation patterns. Mesaverde hydrostratigraphy is reviewed as a prelude to a discussion of Mesaverde hydrodynamics (hydraulic head, pressure region, and hydrochemistry). In the context of depositional and structural settings, hydrodynamics serves as the basis for interpretation of regional flow.

HYDROSTRATIGRAPHY

The Williams Fork and Almond Formations are major coal-bearing hydrostratigraphic units in the Mesaverde Group. These units are confined above by the Lewis shale (Hamilton and others, this vol., fig. 8) and only partially confined or unconfined below by the Iles Formation which overlies the marine

Mancos Shale. In the eastern part of the basin, regionally, extensive marine shales at the base of the Trout Creek and Twentymile Sandstones serve to stratigraphically divide the Williams Fork and Almond into a lower Williams Fork unit and an upper Williams Fork/Almond unit (Hamilton and others, this vol., fig. 9). However, these shales may not divide them hydrologically. Hydraulic communication is inferred from similar heads within the Mesaverde in various parts of the basin. For example, heads from the Iles, Williams Fork Units 1 and 4, and Almond in the southern part of the basin differ by 100 ft or less. Therefore, the Mesaverde Group is regionally a hydraulically interconnected aquifer system, or single hydrologic unit.

The Mesaverde is composed of interbedded, permeable coal beds and sandstone of regional and local extent. At the southeast outcrop, coal beds are 10 to 20 times more permeable (50 to 100 md) than the regionally extensive Trout Creek and Twentymile Sandstones (~ 5 md) (Robson and Stewart, 1990). From Drill-stem tests (DST's) in lower unit coals in the Van Dorn well (T7N, R90W) indicate high permeability (1,462 md; Scott this vol., fig. 28) whereas relatively lower permeabilities (10's of md) were calculated for upper unit coals. Permeability of coal beds in the Baggs area ranges between 100 to 200 md and averages approximately 170 md. There are no public permeability data for Mesaverde coal beds basinward in the subsurface although sandstones are reported to have permeabilities of 5 to 100 md (Collentine and others, 1981; Mountain Fuel Supply Company, 1961)

HYDRODYNAMICS

The hydrodynamics of the Mesaverde Group was established from its potentiometric surface (hydraulic head), formation fluid pressure, and hydrochemistry. Nearly 450 Mesaverde DST data from 176 wells were taken from the Petroleum Information data base and the actual stratigraphic interval of screened DST data was verified from geophysical logs. The quality of DST data was characterized as good if the final shut-in time was greater than 60 minutes; moderate, if the final shut-in time was 30-60 minutes; and, unknown if the initial and/or final shut-in times were not reported. Approximately 49 and 34 percent of the data was considered as good and moderate, respectively, whereas 17 percent were of unknown quality. Using the highest pressure recorded, whether initial or final SIP, a pressure gradient (pressure-depth quotient) was calculated for all available DST's. DST's with pressure gradients of less than 0.30 psi/ft were eliminated from the data base because of their uncertain validity, reflecting insufficient shut-in time, bad test data, presence of gas, pressure depletion, or a combination of these factors. Furthermore, a plot of elevation versus psi/ft showed a break in the data at approximately 0.30 psi/ft (fig. 31). Hydraulic heads and vertical pressure gradients were calculated from shut-in pressures (SIP's) on a screened data set of 181 Mesaverde DST's from 80 wells.

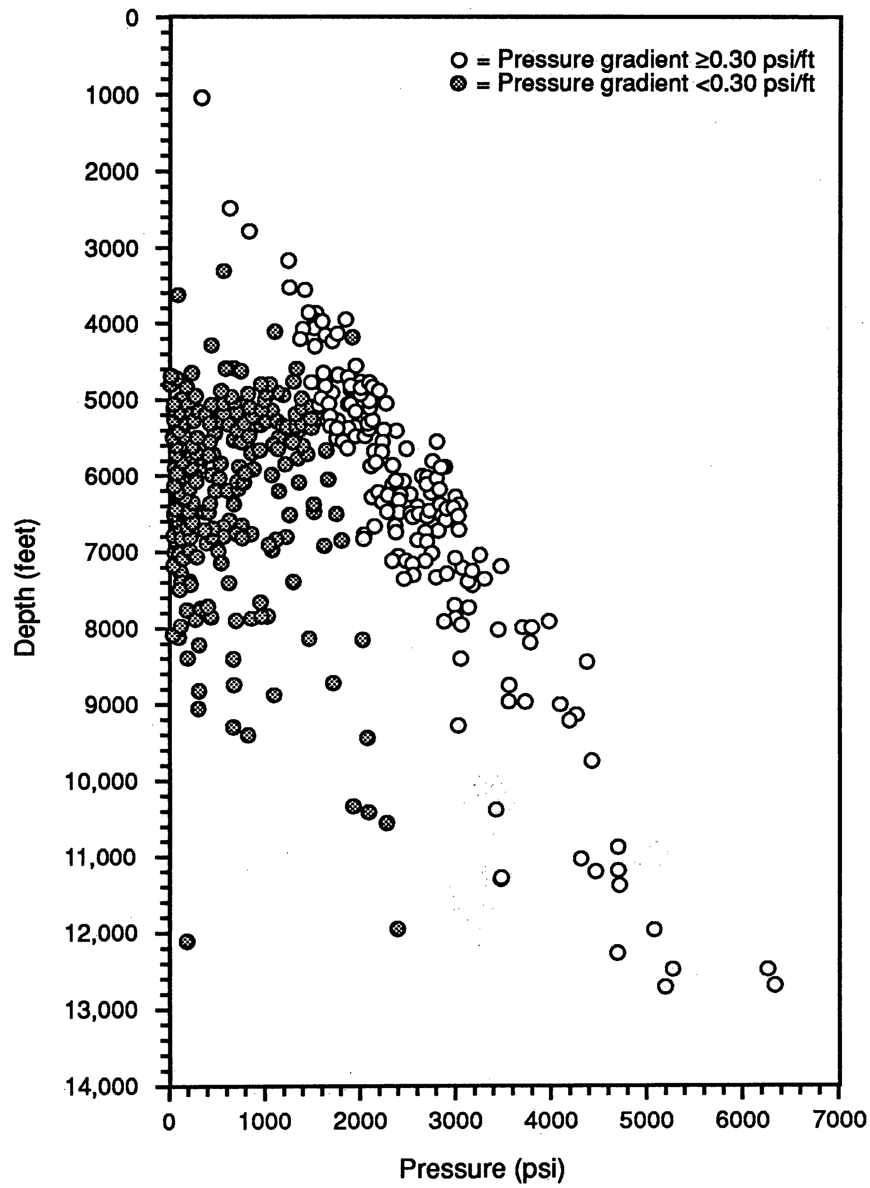

Figure 31. Depth versus pressure plot for Mesaverde DST data from the Sand Wash Basin. DST data with simple pressure gradients less than 0.30 psi/ft were eliminated from the data base because of their uncertain validity.

Bottom-hole pressures were converted to pressure heads (BHP/hydrostatic gradient) using a fresh-water hydrostatic gradient of 0.433 psi/ft and combined with elevation heads (kelly bushing–midpoint of test) to obtain equivalent fresh-water heads. Over 155 water analyses from 66 Mesaverde wells were available to evaluate basin hydrodynamics. Chemical analysis used for hydrochemical maps were dominantly of fluids recovered in DST's and secondarily of produced water. The analyses were screened for analytical accuracy, using an ionic balance formula (Edmunds, 1981). In most cases, they balanced exactly indicating that potassium and/or sodium were determined by analytical difference. Consequently, because of the nature of the fluids analyzed and the exact ionic balance, the water analyses are of questionable validity and were only used to delineate general concentration gradients rather than for detailed contouring of concentrations.

Potentiometric Surface

The potentiometric surface map of the Upper Mesaverde Group (Upper Williams Fork/Almond unit) shows potentiometric highs along the topographically higher eastern margin of the basin, and along the southern flank of the Rock Springs Uplift (fig. 32), where the higher heads reflect a structural platform (Tremain and others, this vol., fig. 3). Relatively higher heads also extend north from the southern margin of the basin northwestward from Craig. A potentiometric mound of uncertain origin lies basinward, north of Lay Creek field (T10N, R94W). Regionally, the surface slopes basinward toward the basin's structural center located west of the Little Snake River. The potentiometric low north of Craig may also be structurally controlled; it lies along a syncline and on the downthrown side of a major fault zone (Tremain and others, this vol., fig. 3). Recharge occurs along the wet elevated eastern and southern margins of the basin, where annual precipitation exceeds 20 inches/yr (50 cm/yr) (fig. 33), whereas recharge over the Rock Springs Uplift is limited by lower precipitation (10 to 12 inches/yr [25 to 30 cm/yr]). Burial of the Mesaverde by thrust faults on the southwest margin of the basin (Tremain and others, this vol., fig 3.) also limits recharge from that margin of the basin.

Pressure Regime

Over 300 DST's from six study areas (fig. 33) were used to evaluate local variations in pressure regime and to determine potential for vertical flow. These detailed study areas were selected based on DST availability and the geographic distribution of the areas. Only three of these areas contained a sufficient number of Mesaverde DST data to fully evaluated simple and vertical pressure gradients within the Mesaverde (fig. 32).

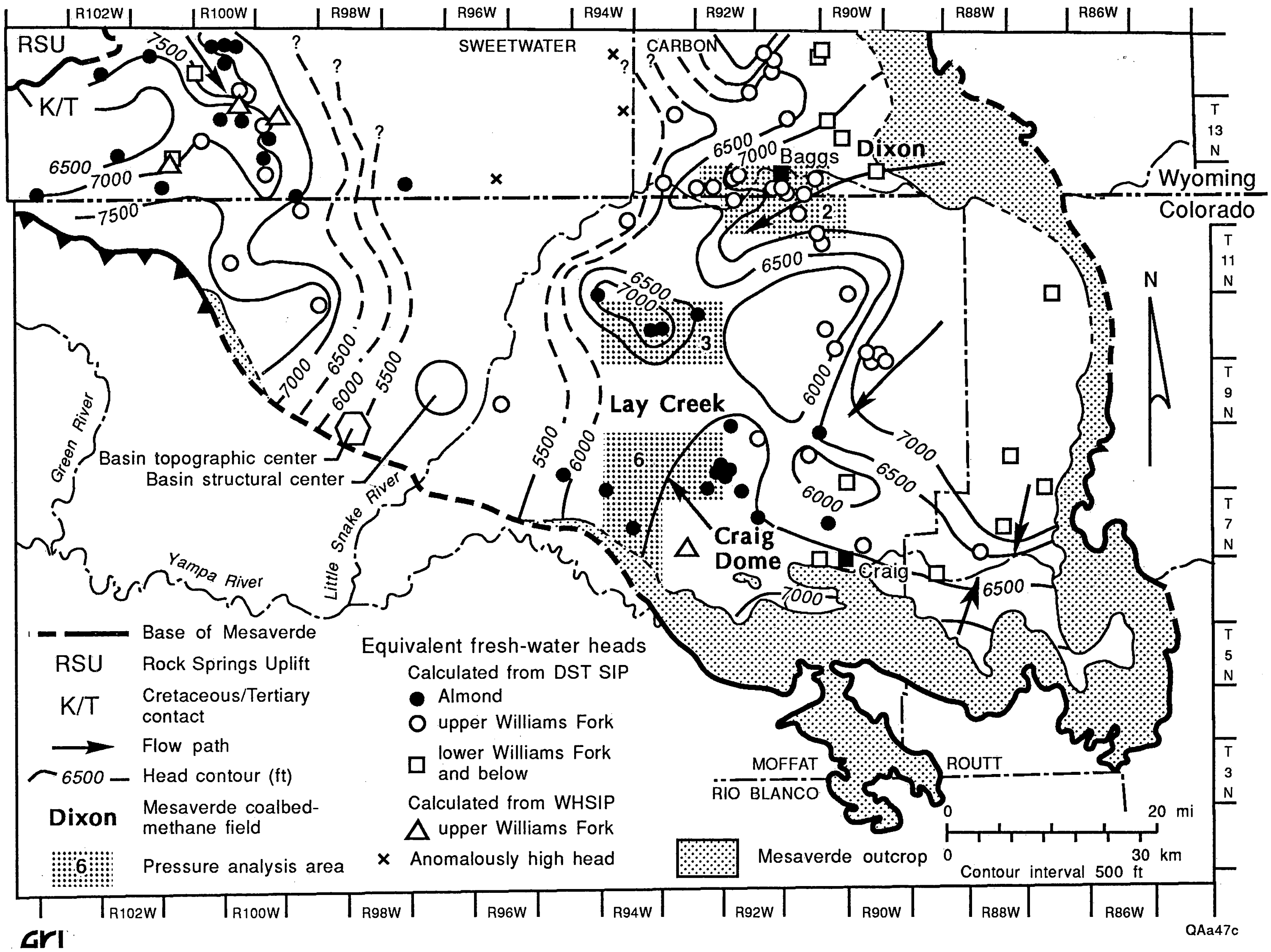

Figure 32. Upper Mesaverde potentiometric-surface map. Ground water flows westward from an eastern and southern recharge area for eventual discharge to the basin center and Yampa River valley. Flow is minor off the southern flank of the Rock Springs Uplift. Simple pressure gradients in pressure-analysis Areas 2, 3, and 6 are 0.48, 0.44, and 0.36 psi/ft, respectively.

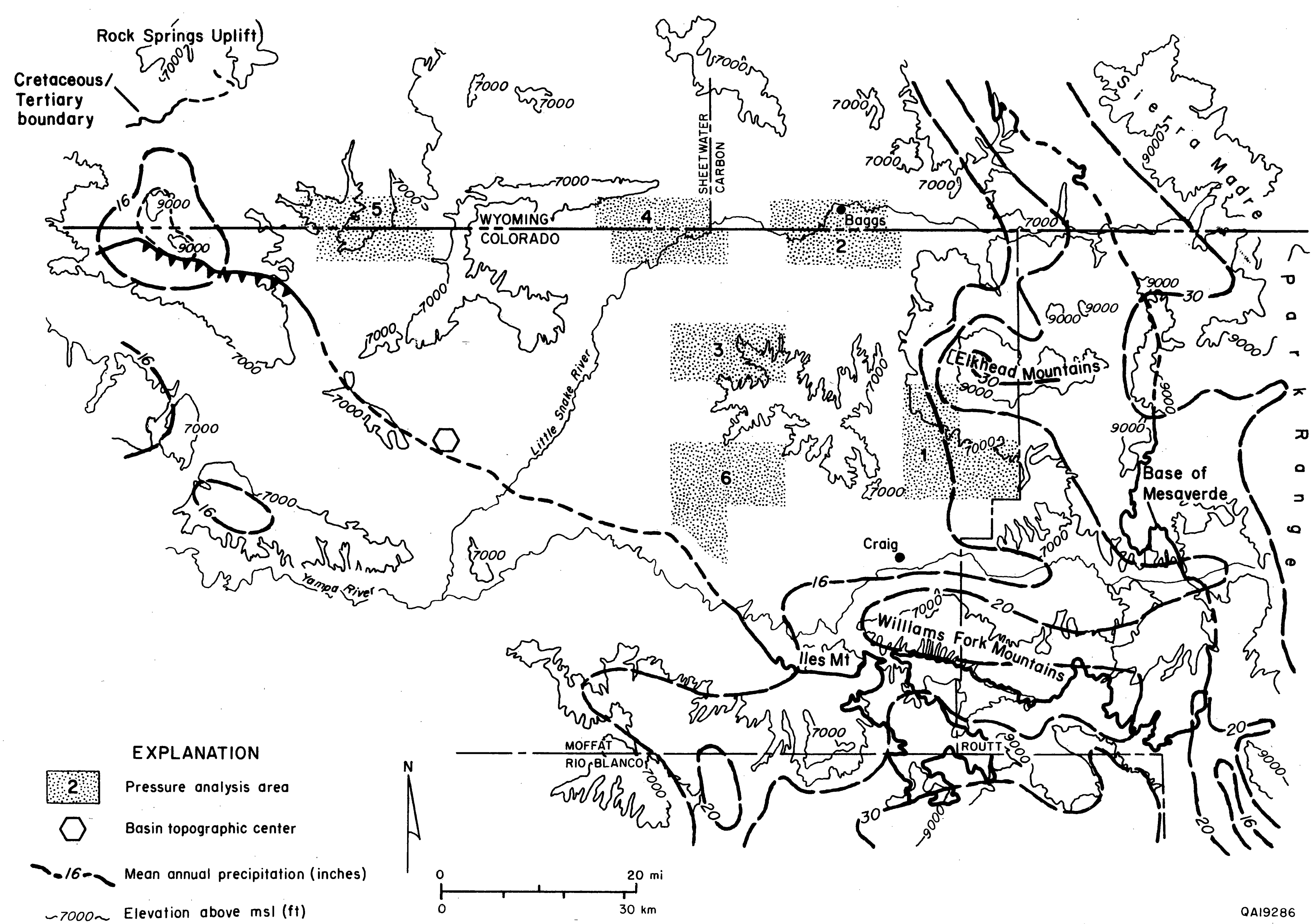

Figure 33. Mean annual precipitation, topography, and major drainage in the Sand Wash Basin. Ground water is recharged over the wet, elevated eastern and southern margins of the basin. Precipitation data from Soil Conservation Service (1983) and Colorado Climate Center (1984).

Simple pressure gradients (pressure-depth quotients) from three areas in the Sand Wash Basin indicate that no pressure regime is regionally dominant. However, most gradients indicate slight underpressure to normal pressure. Simple pressure gradients in pressure analysis Areas 2, 3, and 6 are 0.48, 0.44, and 0.36 psi/ft, respectively (fig. 32). Overpressure in Area 2 is artesian in origin and 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 atest to artesian conditions in this area. Overpressure extends approximately 15 miles west of the outcrop to the middle of T12N, R 92W. Underpressure in Area 6 may reflect poor connection with the outcrop recharge area or higher permeability downflow such that discharge exceeds recharge, keeping the area underpressured. Head contours in Area 6 are perpendicular to the outcrop, indicating limited recharge from the margin (fig. 32). Moreover, discharge to the Yampa River valley may limit under flow available for recharge basinward to the confined aquifer.

The vertical pressure gradient, which is the slope of the pressure-elevation plot, is used to indicate vertical flow direction. Vertical flow in the Mesaverde is potentially upward in the northern part of the basin and downward in the southern part. The vertical pressure gradient in Area 2 is 0.88 psi/ft (fig. 34), well in excess of the hydrostatic pressure gradient (0.43 psi/ft), indicating very strong potential for upward flow and poor vertical connectivity (good confinement), which is consistent with overpressured conditions. Vertical gradients in Areas 3 and 6 (0.47 and 0.39 psi/ft, respectively) indicate weak upward and moderate downward potential for vertical flow, respectively. The relatively low vertical pressure gradient in Area 6 probably reflects flow down steep structural dip (Tremain and others, this vol., fig. 3).

Geopressure is reflected in anomalously high fresh-water equivalent heads in southeastern Sweetwater County (Washakie Basin). Heads in R94W range from 8,400 to 8,800 ft, and are significantly higher than the highest elevation of Mesaverde outcrops to the east indicating that these anomalously high heads are probably not due to artesian conditions. Simple pressure gradients for the Washakie basin range from 0.50 psi/ft to more than 0.85 psi/ft (McPeek, 1981). Overpressure in the deep Washakie basin is probably hydrocarbon related, where gas is the pressuring fluid rather than water. Overpressure is predicted on low permeability (<0.1 md) and active generation of gas (Law and Dickinson, 1985; Law and others, 1986) and is characterized by pressure gradients greater than 0.70 psi/ft. Thus, geopressure and hydropressure are present in the same basin. Based on limited data, the transition between hydrocarbon related geopressure and artesian hydropressure appears to be abrupt. Water moving up and out of the basin center and water moving basinward from the margins can mix and/or turn upward at this transition zone (fig. 35). Therefore, this zone might be characterized by intense diagenesis at the interface between thermobaric and meteoric waters. Reduction of permeability through cementation would also

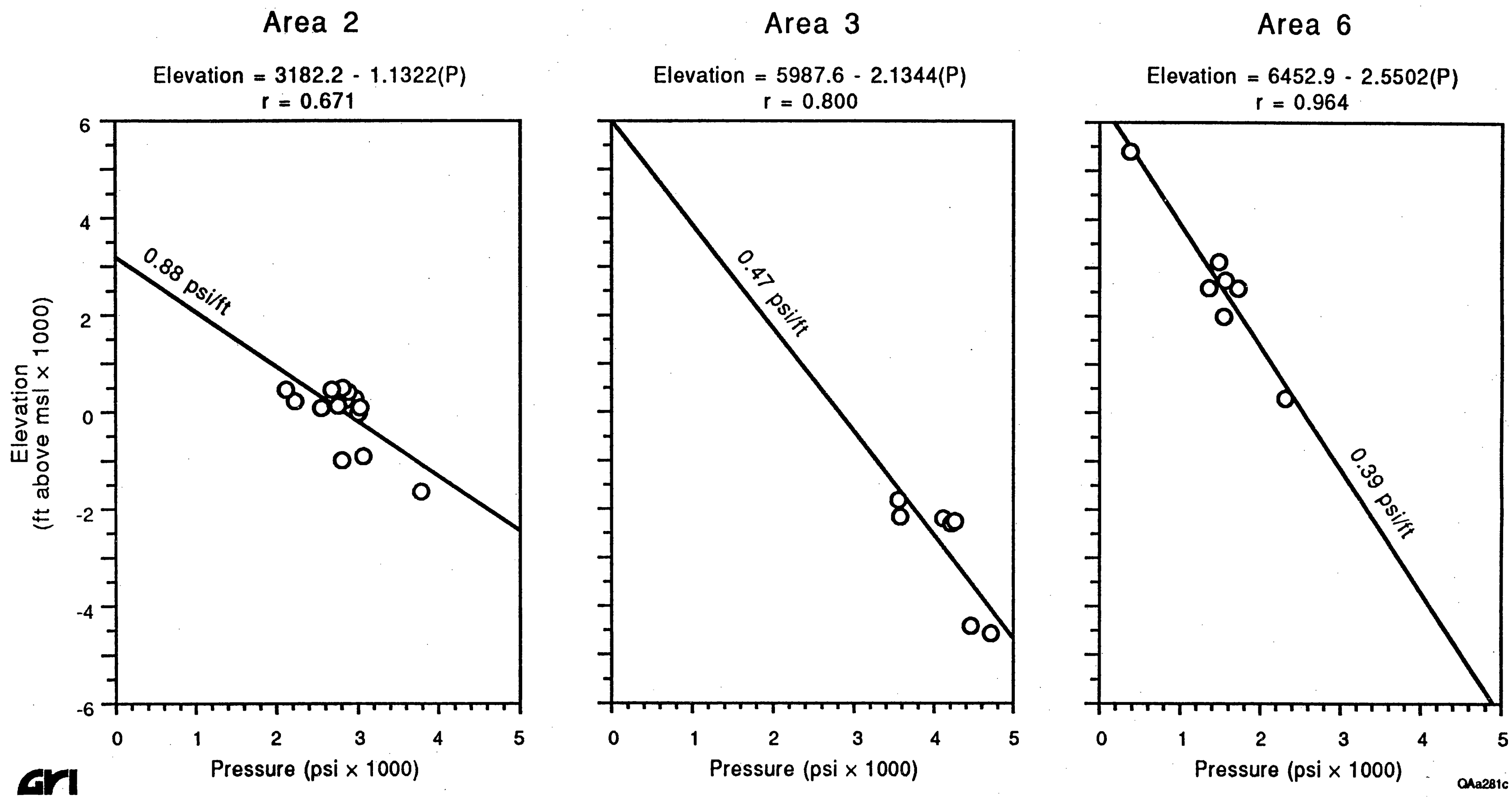

Figure 34. Mesaverde pressure-elevation plots for three pressure-analysis areas. The large vertical-pressure gradient in Area 2 (~0.88 psi/ft) indicates a strong potential for upward flow and poor vertical connectivity (good confinement), whereas Areas 3 and 6 indicate weak upward and moderate downward flow potentials, respectively. Downward flow in Area 6 may reflect flow down steep structural dip.

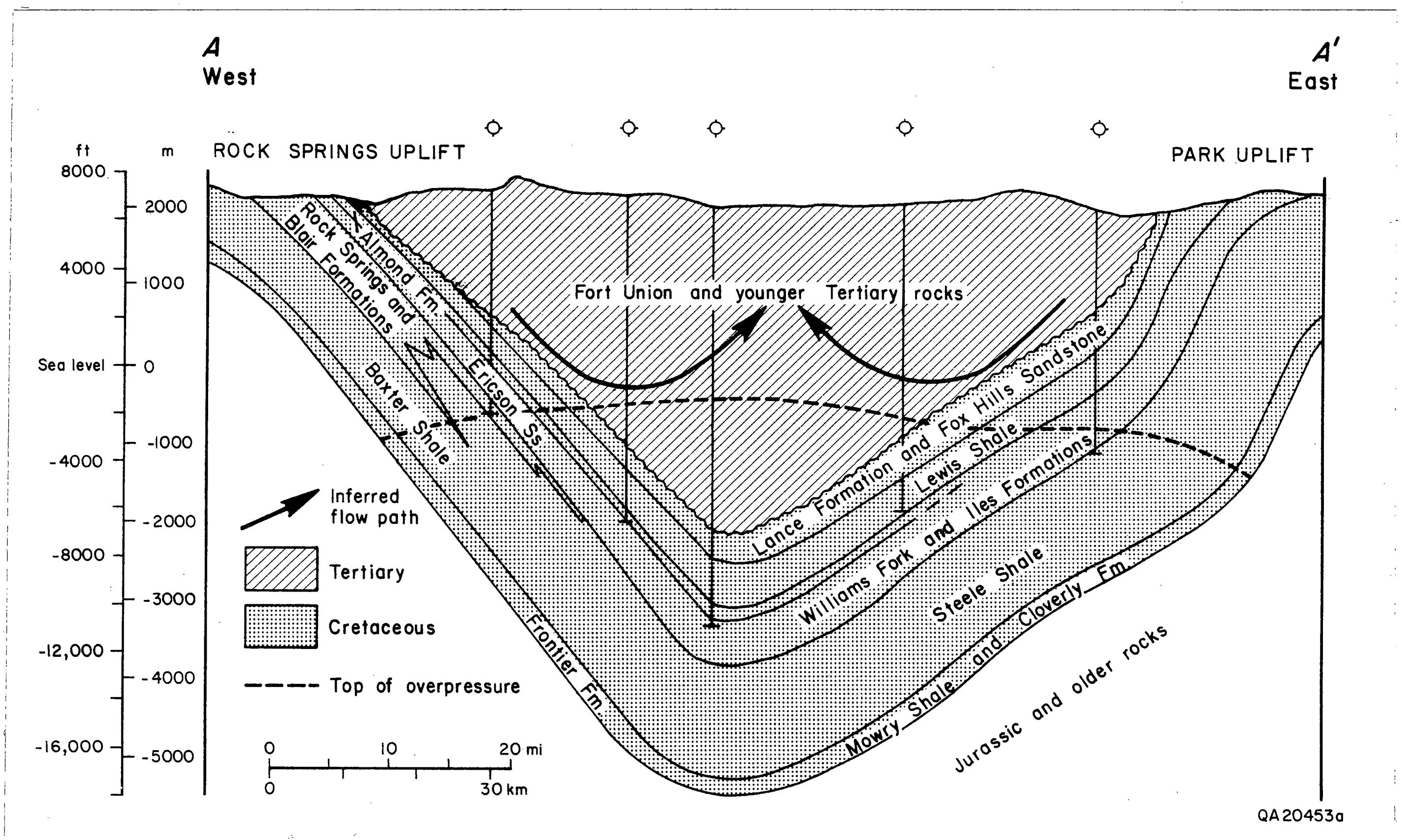

Figure 35. West-east cross section through Washakie Basin (modified from Law and others, 1989). Recharge is over Sierra Madre and Rock Springs uplifts. Ground water flows basinward, turning upward upon convergence from the basin margins, aquifer pinch-out, encountering the top of geopressure, or a combination of all the above. The top of regional overpressure is a no-flow boundary. Line of section is shown in figure 1 of Tremain and others, this volume.

direct fluid movement vertically and result in a relatively abrupt transition between pressure regimes. The presence of unusual calcium-chloride waters in the Fort Union Formation in T12N, R93-94W may be evidence for the vertical movement of fluids along this interface and/or faults in the basin.

Hydrochemistry

Chlorinity and total dissolved solids (TDS) content are lowest along the eastern and southern Mesaverde outcrop belt and increase westward along the Cherokee Arch and northwestward from the Craig area (fig. 36 and 37). With few exceptions, chlorinity and TDS contents for the eastern half of the Sand Wash Basin are less than 8,000 mg/L and 15,000 mg/L, respectively. The highest chlorinities and TDS contents are found between the south end of the Rock Springs Uplift and the Uinta thrust belt farther south. Chlorinity and TDS content southeast of the Rock Springs Uplift are generally less than 10,000 mg/L and 15,000 mg/L, respectively.

Chlorinities ranged from less than 50 mg/L to more than 61,000 mg/L along the Unita thrust belt. At the Dixon field (T12N, R90W), chlorinities are less than 250 mg/L, but increase west of Baggs, along the Cherokee Arch, to greater than 7,000 mg/L. Chlorinities are low northwest of Craig (<500 mg/L), and highest south of the Rock Springs Uplift (fig. 36). TDS ranged from less than 1,000 mg/L in the eastern outcrop to more than 104,000 mg/L along the Uinta thrust belt (fig. 37). Westward along the Cherokee Arch, TDS increased from less than 5,000 mg/L in T12N, R91W to over 13,000 mg/L in T12N, R92W. TDS is less than 2,000 mg/L along the southern outcrop, generally less than 4,000 mg/L northwest of Craig (T7-8N, R93W), and highest south of the Rock Springs Uplift, where TDS is typically greater than 25,000 mg/L. At Craig Dome field TDS ranges from 700 to 1,100 mg/L and waters are Na-HCO_3 type.

REGIONAL FLOW

Regional ground-water circulation reflects present-day structural configuration (attitude of aquifers and aquitards), topography, climate (precipitation and infiltration), and permeability. In the Sand Wash Basin, ground water flows westward down hydraulic gradient, perpendicular to the head contours, in response to structural and topographic gradients (fig. 33; Tremain and others, this vol., fig. 3) from an eastern and southern recharge area for eventual discharge basinward and to the Yampa River valley east of Craig (fig. 32). The chlorinity gradient shows that ground water flows westward and northwestward from the eastern and southern margins of the basin, respectively (fig. 35). Flow to the southwest parallels depositional strike (Hamilton, this vol.) and is promoted by southwest-northeast trending shoreline

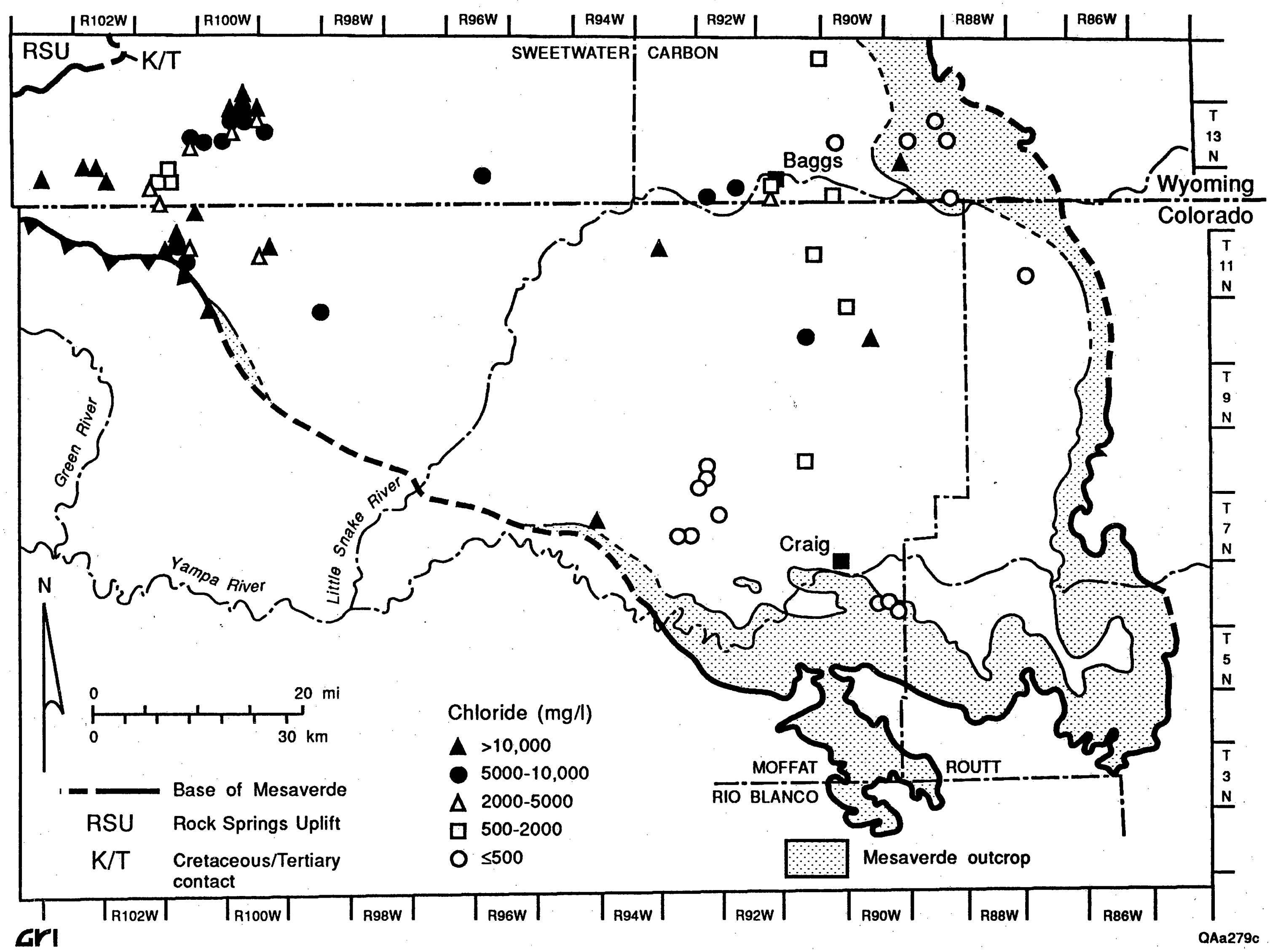

Figure 36. Mesaverde chlorinity map. Chlorinity of formation waters ranges from less than 100 mg/L east of Baggs to generally more than 10,000 mg/L in the western part of the basin. The chlorinity gradient shows that ground water flows westward and northwestward from the eastern and southern margins of the basin, respectively. Chlorinities from Dwight's Energydata, Inc.

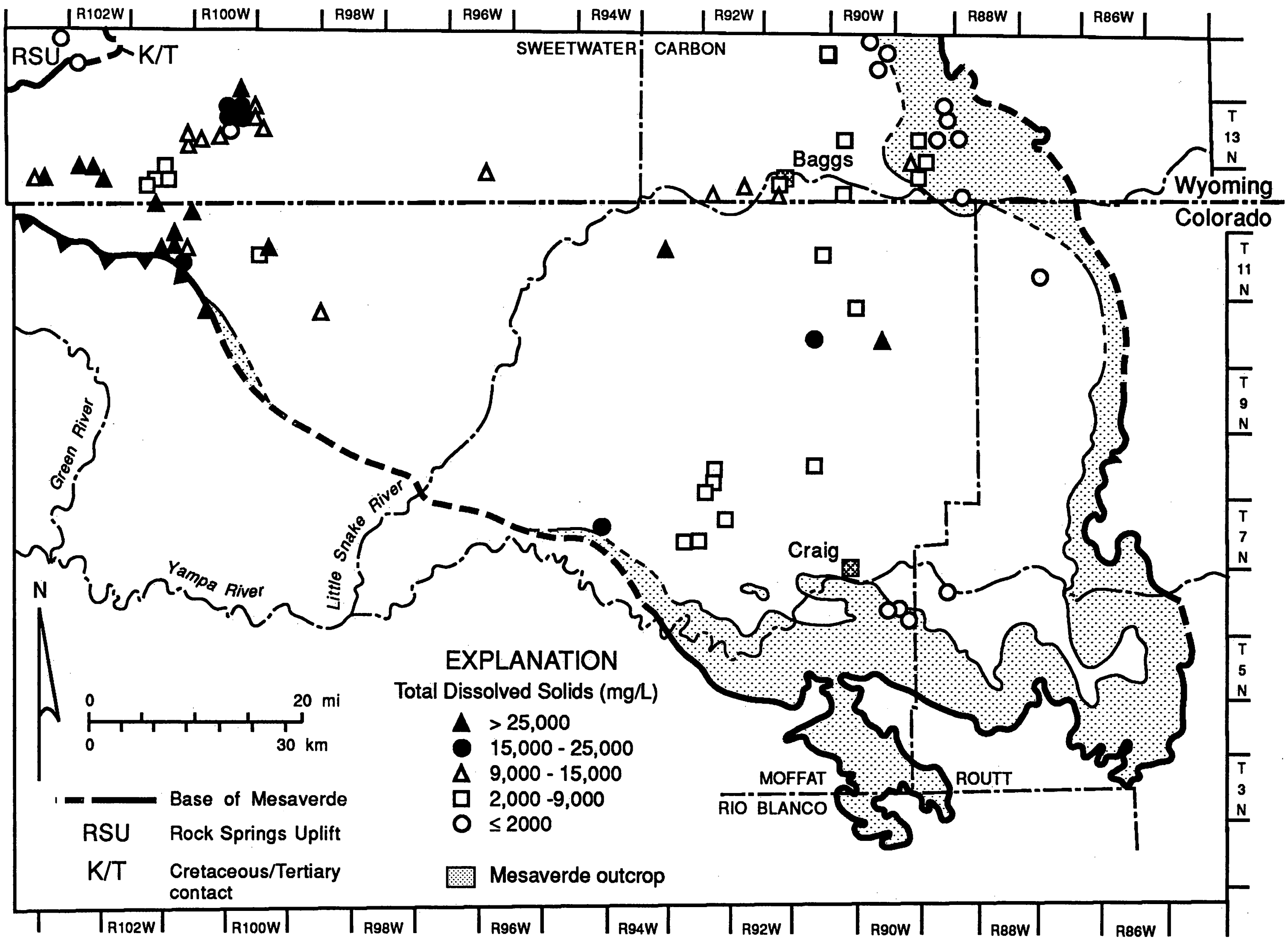

Figure 37. Mesaverde total dissolved solid map. Total dissolved solids are generally less than 2,000 mg/L along the eastern and southern outcrops and increase to over 104,000 mg/L near adjacent to the thrust front south of the Rock Springs uplift. TDS increase from approximately 5,000 mg/L in the Baggs area to over 11,000 mg/L in T12N, R92W. The TDS gradient indicates that ground waters flow basinward from Mesaverde outcrops. TDS values from Dwight's Energydata, Inc. and Collentine and others (1981).

sandstones and coal beds (Hamilton, this vol., figs. 13 and 14) that extend basinward from the recharge outcrop. Regionally, extensive coal beds may be the most important aquifers in the Mesaverde Group because of their high permeability and lateral continuity.

Fracture flow may be promoted westward along the complexly faulted Cherokee Arch (Tremain and others, this vol., fig. 3). However, faulting may also serve to compartmentalize the aquifer and actually impede westward flow. A decrease in the potentiometric surface north of Baggs (T13-14N, R91W) probably reflects a "shadow effect" caused by a north-trending fault with over 5,000 ft throw (fig. 32; Tremain and others, this vol. fig. 3). As throw decreases southward along the fault, communication with the recharge area is reestablished and heads rise to over 7,000 ft. Northwestward flow from the southern outcrop may also be influenced by fractures. Faults, fold axes, and dikes show a strong northwest structural grain (Tremain and others, this vol., fig. 6). Directional uniformity of face-cleat strikes may promote basinward flow from the southeastern corner of the basin, whereas non-uniformity to the west may impede flow (Tremain and others, this vol., fig. 3), contributing to underpressure in pressure-analysis Area 6 (fig. 32). Fracture flow along the major fault zone, extending northwest from Craig (Tremain and others, this vol., fig. 3) may help explain the potentiometric mound north of Lay Creek (T10N, R94W). It is probably not a recharge mound (downward flow) because there is no apparent local source for the recharge. Downward flow from the overlying Lance-Fort Union interval would require extensive leakage across the thick (~1,000 ft) Lewis confining unit. Pressure heads of the overlying Lewis and Fort Union Formations are lower than in the Mesaverde in this area and, therefore, do not indicate downward flow. The mound lies at the mapped termination of the fault zone in an area of slight potential for upward flow (fig. 32, Area 3; fig. 34). Elevations of Mesaverde outcrops in the Williams Fork Mountains south of Craig (>7,700 ft) are higher than the fresh-water equivalent heads in the Lay Creek field, indicating that meteoric water could have been derived from the southern margin of the basin. Resistance to lateral flow would raise pressure (thus increasing pressure head), causing flow to turn upward. The subsequent increase in pressure head causes total heads to exceed those of the surrounding area resulting in a potentiometric mound. Therefore, the mound is thought to be a discharge mound, an area of local upward flow. The potentiometric low north of Craig is also considered a site of local discharge. Flow moving laterally into this area must turn upward, possibly along the major fault zone to the southwest (Tremain and others, this vol., fig. 3), to exit. This is particularly true if the major fault zone to the southwest is a no-flow boundary.

Basinward, flow turns upward upon convergence from the basin margins, aquifer pinch-out, or both, and upon encountering the top of geopressure (fig. 35). Ground water flows mainly from the east, whereas flow from the west is restricted due to a more arid climate. Limited recharge over the Rock Spring Uplift is indicated by high chlorinity formation waters (fig. 36). The pinch-out of aquifer coals at the approximate position of the Little Snake River (Hamilton, this vol.) may be reflected in the steepening of the potentiometric surface just east of the river (fig. 32). Because of low permeability and high pressure, the top of geopressure acts as a no-flow boundary. Hydropressured waters turn upward, or discharge, along the postulated boundary between geopressure and hydropressure in eastern Sweetwater County (fig. 32; Tremain and others, this vol., fig. 6).

CONCLUSIONS

1. The Mesaverde Group is a thick, regionally interconnected aquifer system of high transmissivity confined by the marine Lewis and Mancos Shales. Coal beds may be the most permeable aquifers with permeabilities of 10's to 1,000's of md.

2. Recharge is at outcrop along the wet, elevated eastern and southeastern margins of the basin in the foothills of the Sierra Madre and Park Uplifts and the Williams Fork Mountains, where annual precipitation exceeds 20 inches/yr (50 cm/yr). Lesser amounts of recharge are received over the south end of the Rock Springs Uplift.

3. Ground water flows westward and northwestward, respectively, from an eastern and southern recharge area for eventual discharge to the basin center and toward the Yampa River valley east of Craig, Colorado. Flow direction is influenced by northeast-trending depositional fabric and northeast-trending structural grain. The chlorinity and TDS gradients reflect the regional flow direction.

4. A hydropressured and geopressured system are recognized in the shallow and deep basin, respectively. The hydropressured section is underpressured, normally pressured, and overpressured. No pressure regime is regionally dominant. Artesian overpressure is present along the eastern part of the Cherokee Arch.

5. Future work includes a hydrologic characterization of the major fault zone northwest of Craig and a more extensive investigation of aquifer interconnectedness.

OCCURRENCE AND PRODUCIBILITY OF COALBED METHANE

W. R. Kaiser

ABSTRACT

Geologic and hydrologic data were compared with available production data to identify controls on coalbed methane production. In the Sand Wash Basin, low gas content (<200 ft^3/ton) and high water production (100's of bbl/d) at the basin margins are the major controls on the production of coalbed methane. Low gas content reflects low coal rank, non-deposition of coals in the basin's most thermally mature area, and regional hydrodynamics. The Mesaverde Group is a thick aquifer system of high transmissivity; it yields large volumes of water, which is evident in a basinwide cumulative gas/water ratio of 13 ft^3/bbl. The most prospective areas lie basinward, northwest of Craig, Colorado, on the upflow, downward side of a major fault zone, extending northwest of Craig, Colorado. On the downthrown side gas contents exceed 400 scf/ton. Fundamental hydrogeologic differences between the Sand Wash and San Juan Basins may help explain marginal and prolific production of coalbed methane, respectively, to date in the two basins.

INTRODUCTION

Reservoir characteristics of Williams Fork coal beds reflect their geologic and hydrologic settings. Geologic and hydrologic controls on the production of coalbed methane include coalbed permeability, structural configuration, coal rank, gas content, coal occurrence, and ground-water circulation. Permeability that is too high results in high water production and is as detrimental to the production of coalbed methane as very low permeability. Structural dip defines the drilling-depth fairway, faults and fold axes may be sites of enhanced permeability and conventional trapping, and cleat orientation imposes permeability anisotropy. Coal ranks of maximum gas generation are medium-volatile bituminous and greater. Higher rank coals have higher gas contents. Values of more than 300 scf/ton are thought necessary for commercial production. Coal thickness determines gas resources and production by influencing the size of the dewatered area (volume of gas freed). Laterally extensive seams can serve as conduits for long-distance migration of gas. Hydrologic areas of recharge and discharge are commonly sites of high water and gas production, respectively. The pressure regime can commonly be explained hydrodynamically. Moreover, no-flow boundaries are potential sites for conventional trapping of gas.

Conventional structure and stratigraphic trapping is more important than previously recognized; it provides an explanation for water-free gas production.

By comparing geologic and hydrologic maps with available production data, controls on the occurrence and production of coalbed methane were identified. A review of coalbed production is followed by a discussion of key controls on production. Further insight about the producibility of coalbed methane is gained in a hydrogeologic comparison of the Sand Wash and San Juan Basins.

PRODUCTION

Analysis of Williams Fork production is based on Petroleum Information reports (Petroleum Information, 1992), Dwight's Oil and Gas drilling histories, and Colorado Oil and Gas Conservation Commission well completion updates. Gas production from three Mesaverde coalbed fields (fig. 38) has been minimal, whereas water production has been excessive (table 4). Cumulative gas production for the Sand Wash Basin, as of February 1992, was 62 MM ft^3, and cumulative water production was 4.9 million barrels for a cumulative gas/water ratio of approximately 13 ft^3/bbl. Only Dixon field has produced gas. There are 11 wells in Dixon field, 3 produce gas at rates of 50 to 100 Mcf/d, and 8 are flowing artesian wells. The gas wells are the structurally highest wells. The artesian wells serve as dewatering wells and in 1991 individually flowed at rates ranging from 600 to 1,000 bbl/d for a per well average of approximately 700 bbl/d. There are 16 wells, now shut in, in the Craig Dome field. They were produced about 18 months and never produced gas. Evidently, gas contents were low and coals undersaturated with gas. In 1991, water production per well ranged from 200 to 1,000 bbl/d, and averaged about 500 bbl/d. The one well in Lay Creek field tested initially for 74 Mcf/d and 800 bwpd. On production test, it produced 80 to 100 Mcf/d and 100's of bwpd. The Van Dorn well (T7N, R90W, sec. 29) made a 100 Mcf/d upon swabbing after an unsuccessful frac job and then died.

Initial water production (IP) increases with permeability (Oldaker, 1991) and high water IP's (100's of bbl/d) are indicative of high permeability. By water-well standards, coalbed methane wells are low-yield water wells; that is, they produce less than 100 gal/min (<3,430 bbl/d). Nevertheless, disposal costs for these volumes of water can adversely affect project economics to the extent that development is deemed uneconomic. It may be impossible to economically depressure (dewater) some coal beds.

Initial water production from coalbeds is highest in the Yampa River valley (1,800 bbl/d) and at the northeast margin of the basin, east of Baggs, in the Dixon field, where 1,200 bbl/d is representative (fig. 38). The field's first well potential for 2,200 bbl/d. In Craig Dome field, potentials range from 500 to 1,000 bbl/d. High water potentials reflect proximity to the recharge area (Mesaverde outcrop), basinward flow in an interconnected aquifer system, artesian conditions, and laterally extensive coal beds of high

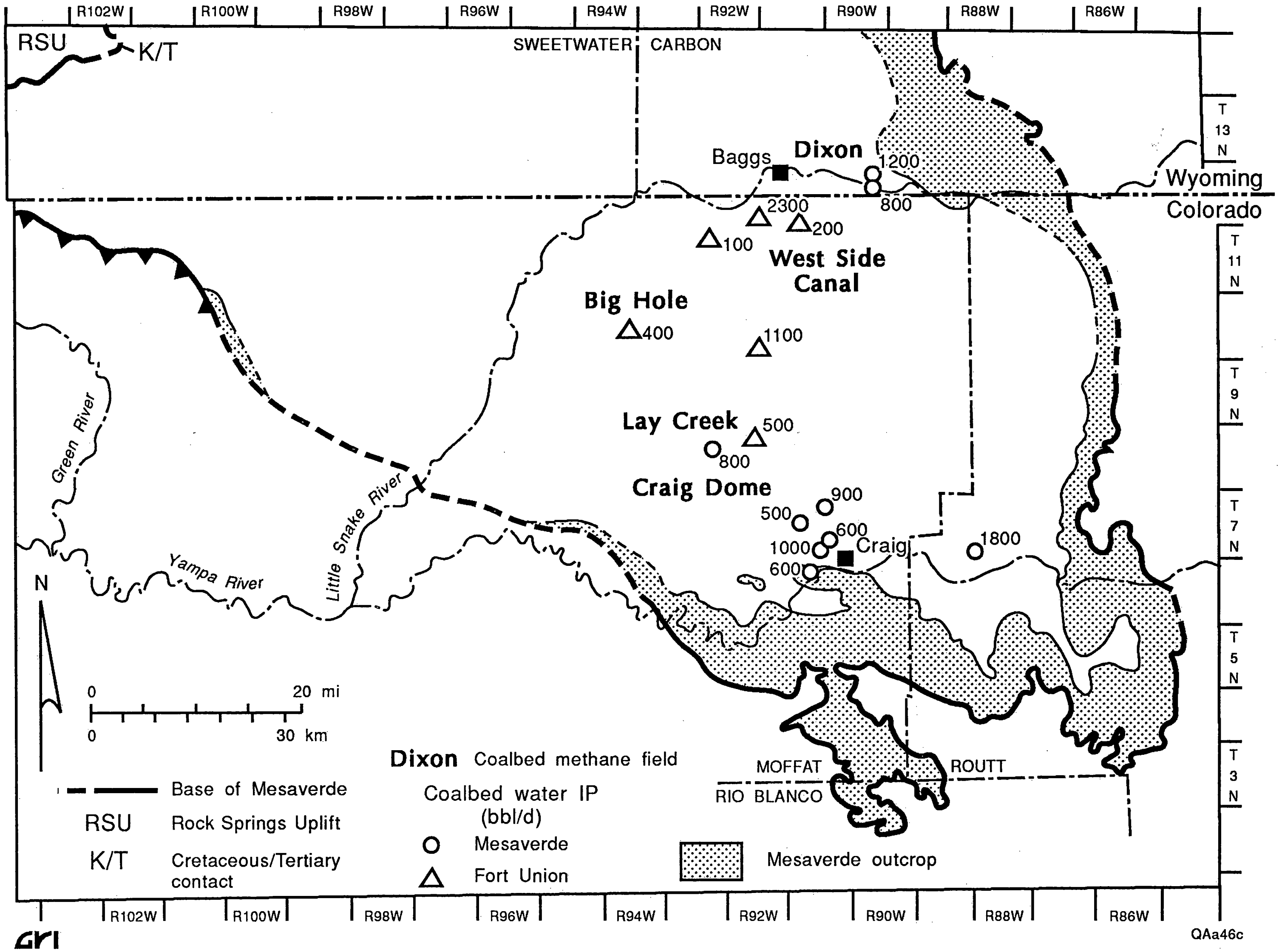

Figure 38. Initial water potentials, Mesaverde and Fort Union coal beds. Mesaverde IP's are high at the basin margins and in the Yampa River valley. Reflected are proximity to the recharge area, basinward flow, and high coalbed permeability.

Table 4. Cumulative gas and water production by field, Greater Green River Basin[a]

Field	No. of Wells	Geologic Unit	Gas (Mcf)	Water (bbl)
Big Hole	1	Fort Union	-	-
Craig Dome	16	Lower Williams Fork	0	2,095,735
Dixon	11	Lower Williams Fork	62,125	2,818,074
Lay Creek	1	Lower Williams Fork	-	-
Table Rock [b]	3	Almond	192,235	5,933
West Side Canal	1	Fort Union	0	9,815

[a] Cumulative to February 1992, data from Petroleum Information (1992)

[b] Washakie Basin, all other fields in Sand Wash Basin

permeability. Coalbed permeability at Dixon field averages about 170 md. Because of proximity to the recharge area and high permeability, it may not be possible to dewater (depressure) coal beds near the basin margin.

CONTROLS ON PRODUCTION

In the Sand Wash Basin, structural configuration, coal occurrence, thermal maturity (gas content), and hydrodynamics are major controls on the occurrence and production of coalbed methane. Faults and fold axes may be zones of enhanced permeability or conventional traps for gas. Steep structural dip (500 ft/mi)(Tremain and others, this vol. fig. 3) and coal occurrence have to date limited the exploration fairway to the eastern and southeastern margins of the basin. Coal resources occur mainly in the eastern part of the basin, east of the Little Snake River (Hamilton, this vol.). The thickest, most laterally continuous coal beds occur in the lower Williams Fork Formation. Individual coal beds are 10 to 20 ft thick; up to 20 beds are present for an aggregate thickness of more than 100 ft.

Assuming an economic drilling depth of 6,000 ft, a drilling-depth fairway is defined by the 1,000-ft structure contour on the base of the Williams Fork Formation (fig. 39). At surface elevations of 7,000 ft or less, all Williams Fork coals are testable at drilling depths of 6,000 ft or less. Topography and inaccessibility will further limit development on the east to the Yampa and Little Snake River valleys. The area between the rivers has surface elevations of 7,000 ft or more and includes the Elkhead Mountains, where elevations exceed 9,000 ft (Scott and Kaiser, this vol., fig. 33).

The Sand Wash Basin has no extensive area of medium-volatile bituminous and greater rank coal (Scott, this vol., fig. 24), the ranks of maximum gas generation. Thus, large volumes of thermogenic gas may never have been generated from coal beds. Most coal beds are high-volatile C to B bituminous rank and have gas contents of less than 200 scf/ton (Scott, this vol.). Furthermore, the production of n-alkanes is maximized at a rank of high-volatile A bituminous, which could mean a smaller contribution from biogenic gas. Bacterial metabolization of n-alkanes yields methane as a by product. Moreover, Williams Fork coals do not extend westward to the area of highest thermal maturity in the basin's structural center (Hamilton, this vol., figs. 10, 14, 17, 19 and 20). Thus, they could not serve as conduits for updip, eastward, long-distance migration of gas for eventual resorption as well as possible conventional trapping.

Ground water flows westward, parallel to net-coal trends, toward the basin's structural center and a potentiometric low north of Craig (fig. 39). Flow is across an area of low thermal maturity, up the coal rank gradient. Consequently, only a relatively small volume of gas may be available to be swept basinward for conventional trapping. Chances are best for this on the down thrown side of a major fault zone extending northwest of Craig (Tremain and others, this vol.), particularly, if the fault zone is a no-flow boundary along which convergent upward flow occurs. Gas contents in some coal beds on the down thrown side of the

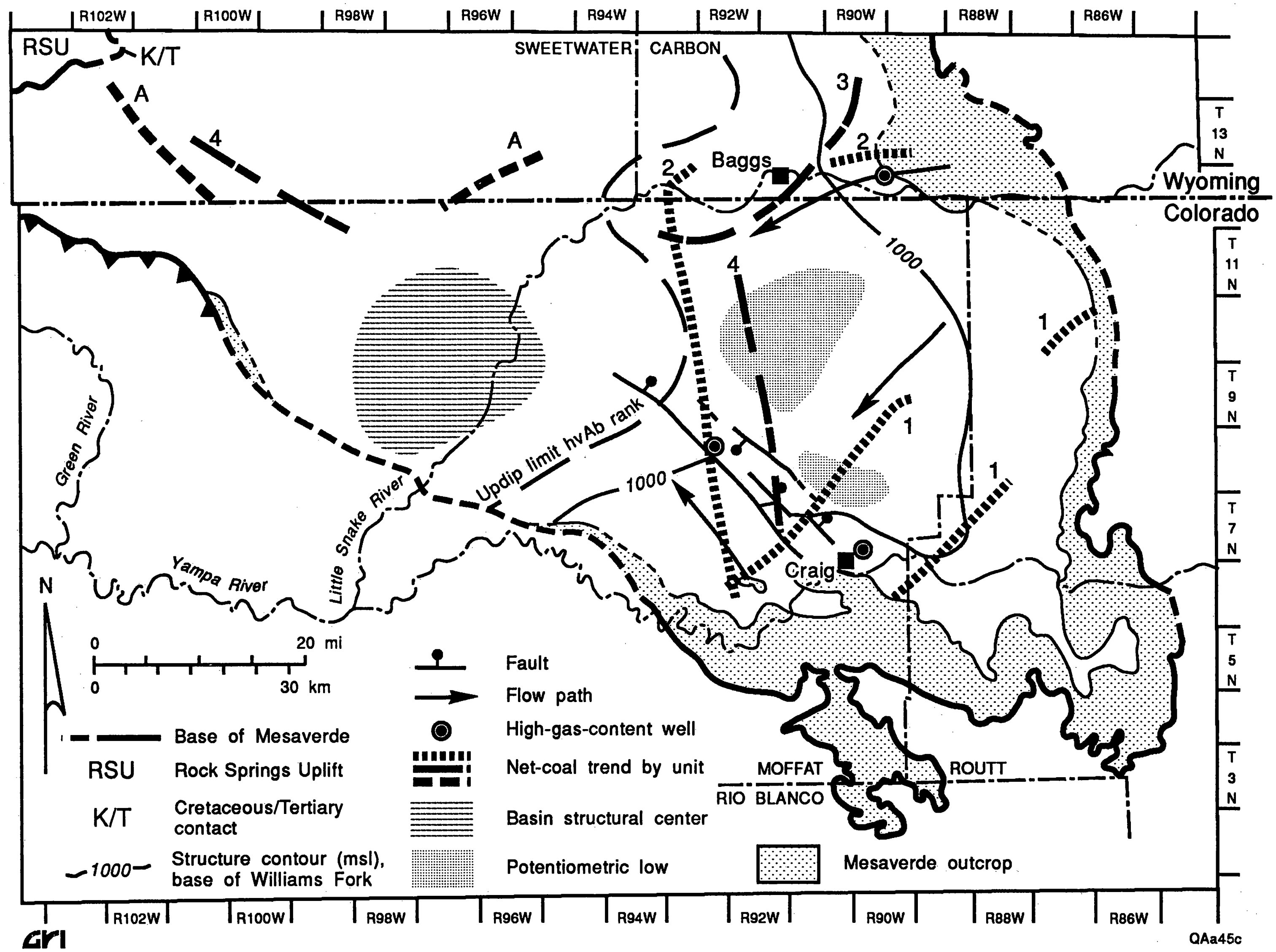

Figure 39. Hydrogeologic characterization of the Sand Wash Basin. A drilling-depth fairway is defined by the 1000-ft structure contour on base of Williams Fork. At surface elevations of 7,000 ft or less, all Williams Fork coals are testable at drilling depths of 6,000 ft or less. Coal resources occur mainly east of Little Snake River. Ground water flows westward, parallel to net-coal trends, up the coal-rank gradient, toward the basin center and a potentiometric low north of Craig. Gas contents on downthrown side of a major fault zone northwest of Craig exceed 400 ft^3/ton. Underpressure on the upthrown side may indicate improved chances for dewatering.

fault zone exceed 400 scf/ton in two wells (fig. 39; Scott, this vol., fig. 28). Underpressure on the upthrown side may indicate poor connection to the recharge outcrop and hence improved chances for depressuring (dewatering) the coal beds there. The upthrown block offers a large area with favorable drilling depths. Finally, aquifer interconnectedness may also influence gas content. The Mesaverde is a regionally interconnected aquifer system with good vertical connectivity, reflecting a lack of seals and few permeability contrasts, which decrease the chances for conventional trapping and increase the chances for gas leakoff.

BASIN COMPARISON

There are fundamental differences in the hydrogeologic settings of the Sand Wash and San Juan Basins. In the Sand Wash Basin, areas of thick coal and high thermal maturity do not coincide, whereas in the San Juan Basin these areas coincide to maximize the potential for long-distance migration of gas and its subsequent accumulation (fig. 40). In the Sand Wash Basin, ground water flows across an area of low thermal maturity toward a major fault zone, whereas in the San Juan Basin flow is across an area of high thermal maturity toward a structural hingeline. In the latter case, a relatively large volume of gas is available to be swept basinward for conventional trapping along the hingeline. Flow turns steeply upward at this point upon pinch-out of thick aquifer coal beds and/or their offset by faults along the hingeline (fig. 41). Northeast of this no-flow boundary (permeability barrier), appreciable conventional free and solution gas, in addition to that sorbed on the coal surface, is thought to be present (Kaiser and others, 1991a; Kaiser and Ayers, 1991). Contribution from gas conventionally trapped and concentrated at the no-flow boundary and high coalbed permeability explain exceptionally high production at this point in the San Juan Basin (fig. 40). A giant conventional-hydrodynamic trap is postulated along the hingeline. The most prospective area in the Sand Wash Basin is likewise associated with a structural discontinuity (major fault zone) along its upflow side (fig. 40). The presence of permeability contrasts in the San Juan Basin is implicit in regional overpressure and underpressure (fig. 40) (Kaiser and others, 1991b). Their apparent absence in the Sand Wash Basin and good aquifer interconnectedness suggest less potential for conventional traps and trapping.

In the Sand Wash Basin, exploration strategy is obviously to minimize water production and maximize gas content. This can be achieved by moving basinward at the economic cost of deeper drilling. Development to date has been at the basin margins where water production is high (100's bbl/d) and gas content low (<200 scf/ton). Moving basinward from the recharge area will facilitate dewatering (depressuring). Moreover, water production should be less in association with conventional traps. Conventionally trapped gas and solution gas are overlooked sources of coalbed methane. Thus, greater emphasis should be placed on the identification of conventional traps (no-flow boundaries). Furthermore,

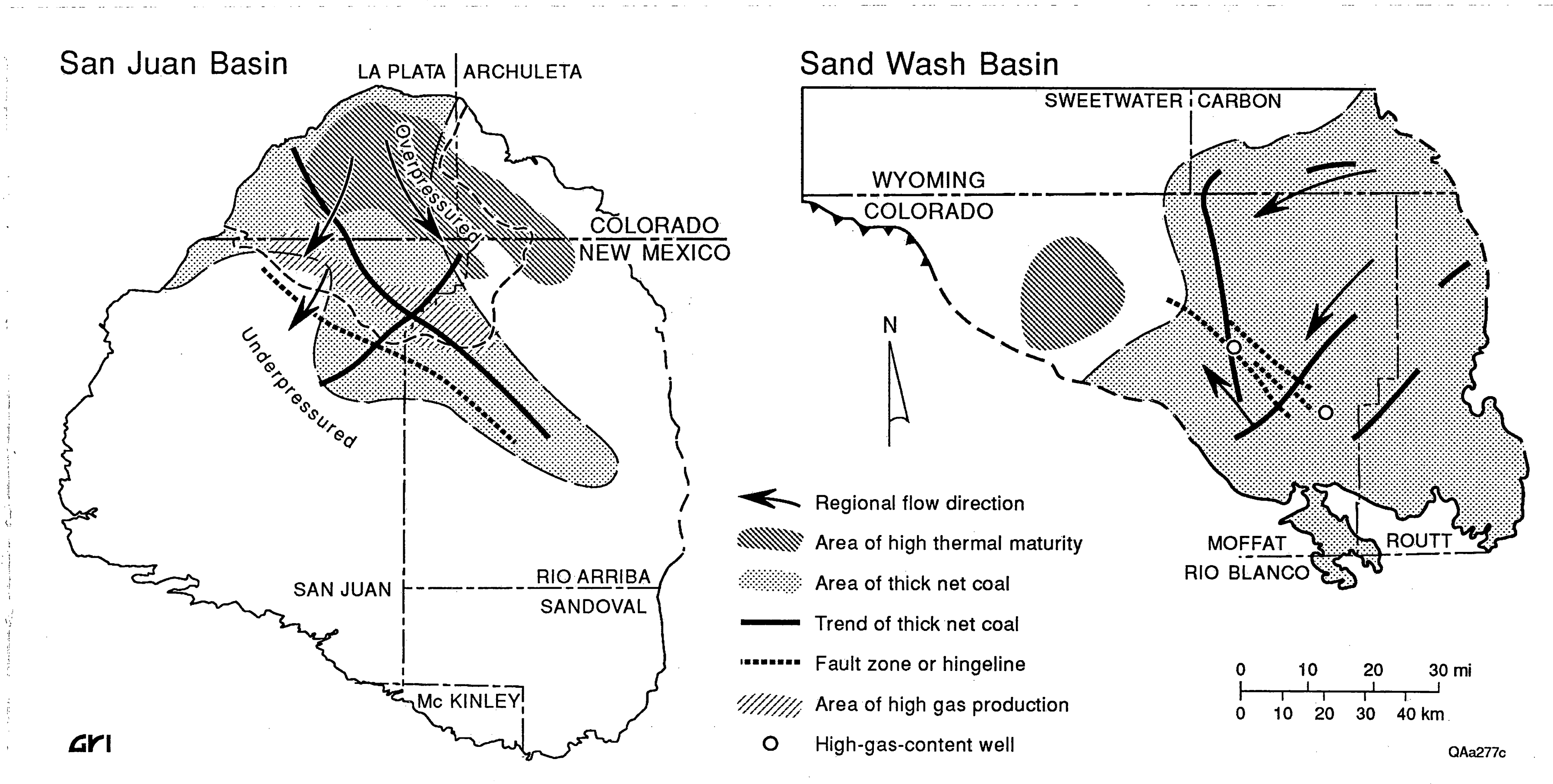

Figure 40. Hydrogeologic comparison of the San Juan and Sand Wash Basins. In the San Juan Basin, ground water flows from coincident areas of thick coal and high thermal maturity toward a structural hingeline (no-flow boundary) along which prolific production occurs. In the Sand Wash Basin, those areas do not coincide and flow is toward the area of high thermal maturity. The most prospective area in the Sand Wash Basin is associated with a major fault zone.

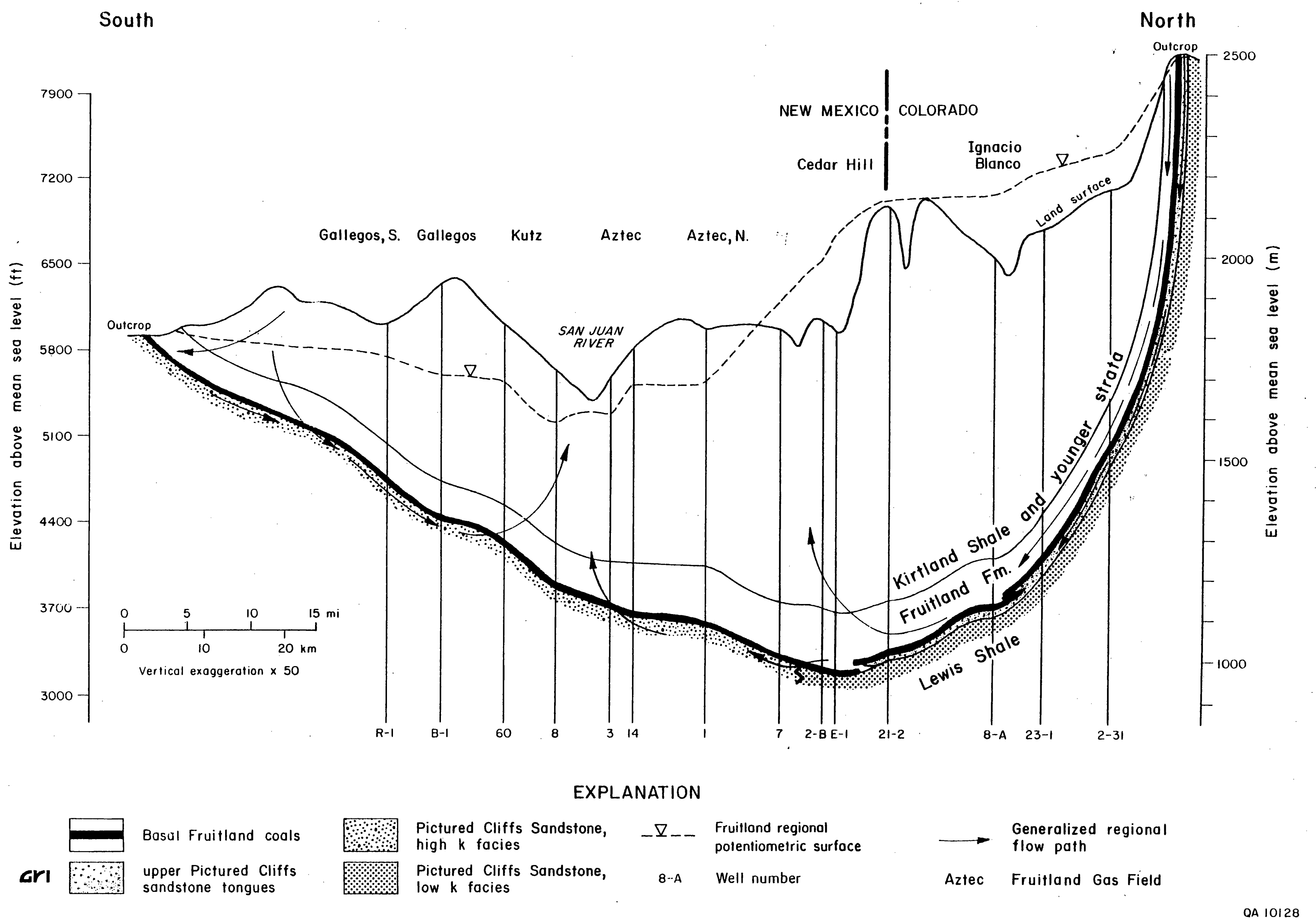

Figure 41. Schematic cross-sectional ground-water flow, San Juan Basin (modified from Kaiser and others, 1991a). Flow is down the steep northern limb from high to lower rank coal. Upon confinement basinward overpressure develops and head rises above land surface. Flow turns steeply upward in the vicinity of Cedar Hill field, upon pinch-out of thick aquifer coal beds and/or their offset by faults along a structural hingeline. Contribution from free and solution gas, conventionally trapped and concentrated at a no-flow boundary, and high coalbed permeability explain exceptionally high production at this point in the basin.

their orientation relative to ground-water flow direction should not be ignored. Their location upflow and orientation perpendicular to the flow direction will maximize the area available for entrapment. Finally, because of better confinement and higher coal rank, deeper drilling should mean higher gas content. The basin's gassiest coals are downthrown to a major fault zone.

CONCLUSIONS

1. Steep structural dip and coal occurrence currently direct economic development to the eastern and southeastern margins of the Sand Wash Basin.

2. The Mesaverde Group is a thick, regional aquifer system of high transmissivity, yielding large volumes of water.

3. Low gas contents in areas drilled to date reflect (a) non-deposition of coals in the basin's most thermally mature area, which reduces the potential for long-distance migration of gas, (b) low coal rank (below that for maximum gas generation) at drilled total depths, (c) hydrodynamics such that flow up the coal-rank gradient and good interconnectedness reduce the chances for conventional trapping of gas, and (d) apparent lack of conventional traps.

4. High water production (100's bbl/d) and low gas content (<200 scf/ton) at the basin margins have limited coalbed methane activity in the Sand Wash Basin.

5. The most prospective and mainly untested areas lie basinward, northwest of Craig, Colorado, in association with a major fault zone. On the downthrown side, gas content in some coal beds exceeds 400 scf/ton. Drilling in association with conventional traps could minimize and maximize water and gas production, respectively.

6. In the Sand Wash Basin, areas of thick coal and high thermal maturity do not coincide and ground water flows up the coal-rank gradient, whereas in the San Juan Basin, these areas coincide and flow is down the rank gradient toward a no-flow boundary. These fundamental differences may help explain marginal and prolific production of coalbed methane, respectively, to date in the two basins.

PRELIMINARY STRATIGRAPHIC ANALYSIS OF THE FORT UNION FORMATION

Roger Tyler and R. G. McMurry

ABSTRACT

The Fort Union Formation is the major coal-bearing unit and coalbed methane target in Tertiary-age rocks of the Sand Wash Basin. Subsurface studies of the Paleocene, Fort Union Formation indicate that continental-fluvial sandstone bodies generally dominate along a north-trending central and southeastern belt. The upper part of the Fort Union is shaly and the lower part is sandy. The Fort Union Formation is operationally divided into lower coal-bearing, gray-green mudstone, basin sandy, and upper shaly units. The thickest, most continuous coals occur in the lower coal-bearing unit in the central and eastern Sand Wash Basin. Individual seams have maximum thicknesses of 20 to 50 ft and combine for a maximum net-coal thickness of approximately 80 ft. Thinner coal beds (3 to 10 ft) occur in the west, in the lower coal-bearing unit and upper shaly unit (Cherokee coals).

INTRODUCTION

One of the problems in regional correlations of the Fort Union Formation in the Sand Wash Basin is the uncertainty of lithostratigraphic boundaries. This problem was recognized and discussed by Masters (1961), Colson (1969), and Beaumont (1979). Different sources of clastic material involving similar or different rock types, mixed environments of deposition (for example, coarse clastics deposited into a paludal or lacustrine environment) and unconformities all added to complicating the stratigraphy of the Fort Union Formation.

To correlate the major coal-bearing horizons in the Fort Union Formation of the Sand Wash Basin, operational lithostratigraphic zones and units in the Upper Cretaceous and lower Tertiary rocks were defined. The lithostratigraphic zones and units include the Fox Hills Sandstone, Lance Formation, massive Cretaceous and Tertiary (K/T) sandstone unit, Fort Union Formation and Wasatch Formation (fig. 42). Similar Upper Cretaceous and Lower Tertiary lithostratigraphic zones and units have been identified by Colson (1969), Beaumont (1979), Honey and Hettinger (1989), Hettinger and others (1991) and Hettinger and Kirschbaum (1991). The Fox Hills Sandstone and Lance Formation couplet is depositionally equivalent to the Pictured Cliffs Sandstone and Fruitland Formation couplet in the San Juan Basin. The Fort Union Formation was further operationally divided into the lower coal-bearing, gray-green mudstone, basin sandy, and upper shaly units (fig. 42). In the western Sand Wash Basin, the main

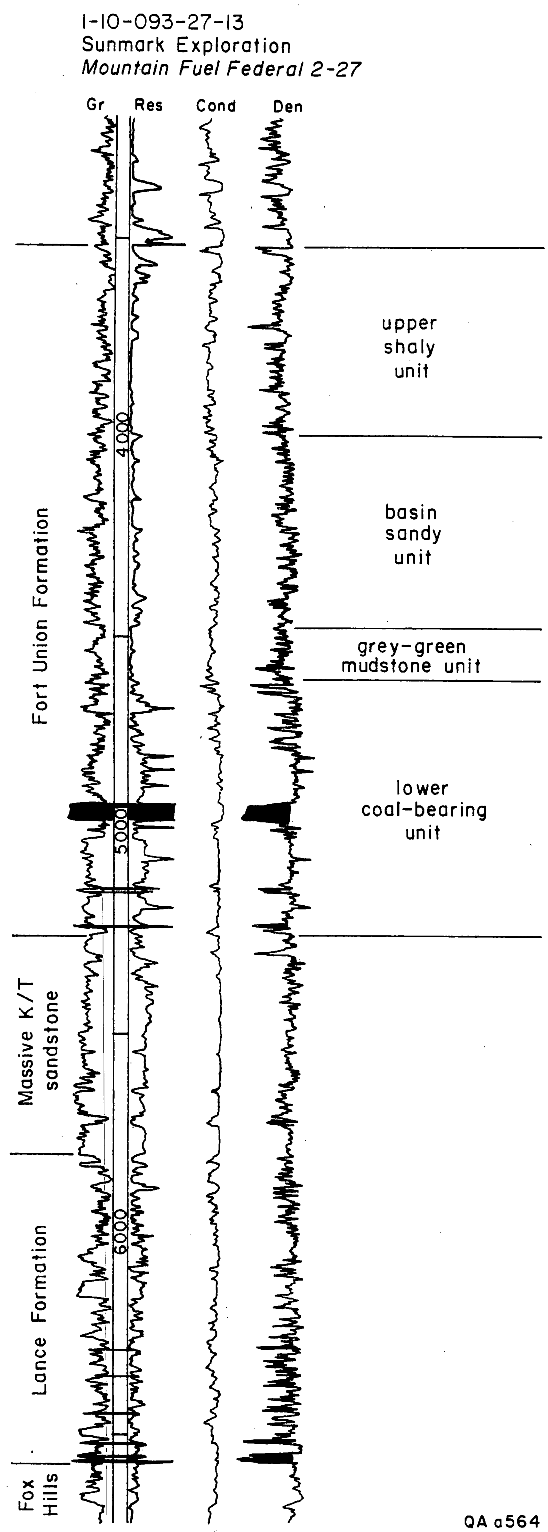

Figure 42. Type log showing late Upper Cretaceous and Early Tertiary lithostratigraphic zones and units in the Sand Wash Basin.

body of the Wasatch Formation overlies the upper shaly unit of the Fort Union Formation. However, subsurface studies in the central and eastern Sand Wash Basin show that the contact between the Fort Union and the Wasatch Formation is disconformable and difficult to recognize.

Fox Hills Sandstone

The Fox Hills Sandstone was deposited in nearshore marine and marginal marine environments during the final regressive phase of the Western Interior Seaway. 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 contact with the Lance Formation is placed on top of the highest regressive marine sandstone. In the eastern Sand Wash Basin, the progradational Fox Hills Sandstone is about 200 ft thick and consists of superimposed coarsening upwards sequences that begin with shale and coarsen upwards into thick sandstone bodies, recognized on geophysical logs by their blocky-log signatures. When traced west these sequences are facies of interbedded marine and non-marine units, that previously were included in the Lewis Shale, and the Lance Formation. Thin beds of coal from 1 to 2 ft thick are commonly present in facies within the aggradational Fox Hills in the west, near the upper contact with the Lance Formation.

Lance Formation

Continental-fluvial deposits of the Lance Formation conformably overlie and intertongue with the Fox Hills Sandstone. The Lance Formation is divided into lower and upper zones with a combined thickness of about 800 to 1,000 ft in the southeast and about 200 ft in the northwest. The upper zone is distinguished from the lower zone by an increase in abundance and thickness of sandstones in the upper zone, recognized on geophysical logs by their blocky-log signatures. The lower zone of the Lance Formation thins from about 500 ft in the east to less than 100 ft in the west. The basal 150 ft to 200 ft of the lower zone usually contains from one to five lenticular coal beds 1 to 10 ft thick. Locally, these coal beds merge into single seams that are 15 to 20 ft thick, but laterally discontinuous. In the east, a second and third coal zone are sometimes present about 250 ft and 500 ft above the base of the formation and contain one or two discontinuous coal beds 1 to 3 ft thick. The upper zone of the Lance Formation thins from about 600 ft in the east to less than 100 ft in the west. Hettinger and Kirschbaum (1991) interpret the thinning of the Lance Formation to be the result of truncation of strata by erosion at the overlying Cretaceous-Tertiary unconformity. The upper zone consists of laterally discontinuous sandstone sequences that range from 20 ft to 100 ft thick separated by shale and mudstone layers 10 to 20 ft thick. Each zone is composed of multistoried sandstone bodies interpreted to be fluvial channel-fills (Hettinger and others, 1991).

Massive Cretaceous and Tertiary (K/T) Sandstone Unit

An interval dominated by thick sandstone sequences overlies and intertongues with the upper zone of the Lance Formation. 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 of Irwin, 1986), has been inconsistently assigned to both the Lance and the Fort Union Formations. On geophysical logs the massive K/T sandstone unit is recognized by its blocky-log signature, thicknesses of hundreds of feet, and stratigraphic position below the coal-bearing Fort Union Formation. The blocky signatures are correlatable throughout the basin and north into the Washakie Basin (Hettinger and others, 1991). The massive sandstone unit thickens from about 500 ft in the east (T12N; R91W) to 600 ft in the basin center (T12N; R93W) and then dramatically thins to about 50 ft in the west (T12N; R101W). Hettinger and Kirschbaum (1991) interpret the westward thinning to be the result of erosion at the Cretaceous/Tertiary unconformity, as well as lateral facies change into the Fort Union Formation. This unit is composed of laterally extensive, superimposed sandstone sequences as much as 200 ft thick, each sequence consisting of multistoried sandstone bodies with individual sandstone bodies up to 50 ft thick. The thick sandstone sequences are separated by lenses of mudstone usually 1 to 50 ft thick.

The massive sandstone unit may be subdivided into lower, middle, and upper zones on the basis of grain size, the presence of a regional unconformity and palynology (Hettinger and others, 1991) . The lower zone is, in part, laterally equivalent to some of the sandstone in the upper part of the Lance Formation (Hettinger and others, 1991), and is often separated from the middle zone by a 10 to 50 ft thick mudstone. The middle zone is separated from the upper zone by a distinct conglomerate horizon which represents the unconformity between Cretaceous and Tertiary age rocks. On geophysical logs, the unconformity was picked where the resistivity log deflects strongly to the right in response to the basal Tertiary conglomerate (Hettinger and others, 1991). Palynology indicates that the lower and middle zones are 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 thick in the east and consists of multistoried blocky sandstone bodies. Interbedded with the sandstone bodies are a few thin shales. To the west the upper zone contains thinner sandstones that intertongue with shale and coalbeds equivalent to the basal part of the lower coal-bearing unit of the Fort Union Formation. The massive K/T sandstone bodies are all interpreted to be fluvial channel-fill sediments with depositional axes oriented south-north.

Fort Union Formation

The operational base of the Paleocene Fort Union Formation is placed on top of the massive K/T sandstone unit. The Fort Union Formation is operationally subdivided into the lower coal-bearing unit, the gray-green mudstone unit, the basin sandy unit, and the upper shaly unit. In the east and west parts of the Sand Wash Basin, the lower coal-bearing unit is overlain by both the non-coal gray-green mudstone unit and the basin sandy unit, but only by the basin sandy unit in the center (between R98W and R101W). The Fort Union Formation, as defined here, thickens to the west from 1,300 ft (T8N; R91W) to between 2,600 and 3,000 ft (T12N; R96W) and then thins to between 1,600 and 2,000 ft (T12N; R101W). The thickness of the Fort Union Formation reflects its depositional setting and/or periods of non-deposition and erosion along the Eocene-Paleocene (Wasatch-Fort Union) unconformity. The characteristics of the lithostratigraphic units of the Fort Union Formation are discussed in a later section.

Wasatch Formation

The main body of the Wasatch Formation overlies the upper shaly unit of the Fort Union Formation and is overlain by the Tipton Tongue of the Green River Formation. The main body of the Wasatch Formation can exceed 2000 ft in thickness (Hettinger and others, 1991). The contact between the Wasatch and the underlying upper shaly unit of the Fort Union Formation is marked by an erosional surface and is interpreted to be disconformable (Hettinger and others, 1991). Seismic lines provided by Union Pacific Resources helped identify the Fort Union/Wasatch disconformity. On geophysical well logs, in the west of the Sand Wash Basin, the base of the Wasatch Formation is characterized by sharp spontaneous potential, gamma ray, and resistivity responses associated with influx of fresh water along channel-fill sandstones. Hettinger and others (1991) placed the base of the Wasatch at a basal conglomerate zone. Where absent, the base is placed by utilizing descriptions of drill-hole readings from the American Stratigraphic Company and on the first occurrence of varicolored mudstone (Hettinger and others, 1991). These descriptions are generally consistent with field observations by Hettinger and others (1991) regarding thicknesses, grain sizes, and lithologies of the Wasatch Formation. In outcrop, near Baggs, the contact between these formations is placed at the first occurrence of coarse-grained or conglomeratic sandstone overlain by variegated mudstone (Hettinger and others, 1991). West of Baggs in R91W, it is placed where a coarse-grained sandstone overlies coal beds of the Cherokee coal zone. Depositionally, the Wasatch Formation is similar to the underlying Fort Union Formation. The main body of the Wasatch Formation consists of conglomeratic fan-delta deposits that grade laterally into fluvial sandstones, floodplain and lacustrine shales, and minor coal-bearing paludal deposits (Roehler, 1965; Sklenar and Anderson, 1985). However, if the operational lithostratigraphic units defined herein are sound, then the Wasatch Formation in the Sand Wash Basin may contain no significant coals.

LITHOSTRATIGRAPHIC UNITS OF THE FORT UNION FORMATION

Lower Coal-Bearing Unit

The lower coal-bearing unit thickens to the west from 500 ft (T8N; R90W) to 900 ft (T12N;R97W) and then thins to about 500 ft (T12N; R101W). The sandstones within the unit consist of repetitive, fining upward sandstone sequences averaging about 140 ft thick, which are laterally discontinuous, and are interpreted to be fluvial channel deposits (Hettinger and others, 1991). Coal beds range in thickness from a few feet to 50 feet, with a maximum net-coal thickness of 80 ft in 9 coal seams (in the vicinity of T10N; R93W). Two to 12 coal beds may be present in the Fort Union Formation in various parts of the basin, the greater number being located close to the Cherokee Arch. Two major north-south trending coal seams occur in the central and eastern Sand Wash Basin. The lower coal seam may be as much as 35 ft thick and is centered along R91W. The upper coal seam is up to 50 ft thick and is centered along R93W. In the northeastern part of the Sand Wash Basin (T12N; R91W), the approximate depth to the base of the Fort Union coal seams is less than 2,000 ft. These coal seams are up to 22 ft thick and combine for a typical net-coal thickness of 76 ft (in as many as 6 coal seams). Coal beds are laterally continuous and correlatable in the eastern portion of the basin for up to roughly 18 mi between R95W and R90W. Westward the Fort Union coal seams are up to 12 ft thick and commonly combine for net-coal thicknesses of less than 34 ft (in as many as 10 coal seams). Approximate depth to the base of the Fort Union Formation is 6,000 ft. Further west, the Fort Union coal beds are thinner (up to 6 ft), deeper (> 8,500 ft), less continuous, and fewer in number. The coal beds in the Sand Wash Basin are partly continuous into the southern Washakie Basin. The lower coal-bearing unit probably represents coarse clastic deposition from several tectonically active source areas into a floodplain, paludal, and/or lacustrine environment.

Gray-Green Mudstone Unit

The non-coal bearing, gray-green mudstone unit (stagnant lake of Colson, 1969) is present throughout the Vermilion Basin area and the eastern Sand Wash Basin. It is about 570 ft thick near Baggs (T12N; R91W) and it thins to 0 feet between T11N; R94W and T12N; R97W. On the west margin of the basin the unit averages 100 to 200 ft thick (between T12N; R98W and T12N; R101W). The gray-green mudstone is recognized on geophysical logs by its distinctive low-resistivity, and corresponds to the lower part of Beaumont's (1979) "upper shaly zone" of the Fort Union Formation, but was included within the Eocene Wasatch Formation by McDonald (1975). The gray-green mudstone is probably lacustrine or paludal in origin, reflecting tectonic quiescence and cessation of coarse clastic sedimentation.

Basin Sandy Unit

The non-coal-bearing, basin sandy unit (Basin Sandy Interval of Colson, 1969, or portion of the unnamed upper Paleocene unit of Hettinger and others, 1991) overlies the gray-green mudstone unit in the Sand Wash Basin, but directly overlies the lower coal-bearing unit of the Fort Union Formation between T11N; R94W and T12N; R97W. In the basin center the basin sandy unit has thick (140 ft), laterally extensive sandstone bodies overlain by thin mudstones. The basin sandy interval thickens from 100 ft near Baggs to about 600 ft (T12N; R97W), and is interpreted as multistoried fluvial channels (Hettinger and others, 1991). The basin sandy unit appears to be restricted to the central parts of the Sand Wash Basin, with its fluvial depositional axis oriented north-south. It is not known at this stage if these fluvial deposits were deposited contemporaneously with the gray-green mudstone unit or if the lacustrine/paludal deposits were eroded upon deposition of the basin sandy unit.

Upper Shaly Unit

The coal-bearing, upper shaly Fort Union unit is found above the basin sandy unit and includes the Cherokee coal zone. The upper unit thickens to the west from 300 ft near Baggs to over 1300 ft (T12N; R96W) and then thins to about 200 to 300 ft in T12N; R101W. The thinning could be due to lateral facies changes in the basin sandy unit or to Wasatch downcutting (erosion) associated with a major unconformity. The Cherokee coal zone, constituting the upper 250-450 ft of the upper shaly zone occurs only in the west part of the Sand Wash Basin (west of R96W). This zone has previously been included in the Wasatch Formation (Smith and others, 1972). The Cherokee coal beds are each about 3 to 10 ft thick but are removed by the Wasatch downcutting (erosion) to the east of T12N; R95W.

FORT UNION GEOLOGIC HISTORY

Upper Cretaceous to lower Tertiary rocks in the Sand Wash Basin represents a transition from marine to continental environments (Beaumont, 1979). Deposition of the marine Lewis Shale was followed by deposition of the nearshore marine and marginal marine Fox Hills Formation and the continental-fluvial Lance and Fort Union Formations. During the accumulation of sediments in the Lance Formation, streams flowed eastward through the basin (Masters, 1961). Uplift of the Sierra Madre-Park Range resulted in north-south oriented division of drainage and one large river system was established; the river system forming the massive K/T sandstone unit flowed north from the Sawatch Range (Tweto, 1975; Beaumont, 1979). Smaller rivers flowed east and west contributing additional sediments to the massive K/T fluvial system (Colson, 1969). The Uinta Uplift to the west probably shed some sediments eastward into the Vermilion Basin area and the southwestern Sand Wash Basin. An eastern source was the Sierra Madre-Park Uplift where tectonic activity may have been greater than in the Uinta Uplift. Erosion had reached the core of the Sierra Madre-Park Uplift by early Fort Union time and coarse arkosic clastic material was deposited basinward (Colson, 1969). A high concentration of sand in the south and southeastern corner of the basin and northerly paleocurrent directions (Beaumont, 1979) confirm that the K/T river system entered from the south and flowed north. The broad distribution of the fluvial sandstone bodies indicates that these early streams ranged widely across the basin but tended to return to their original fluvial axis. This massive K/T fluvial sandstone provided the stable platform upon which peat of the lower coal-bearing unit, could accumulate.

An increase in sinuosity of the predominantly north-flowing streams brought about initial stabilization of stream meander belts (Beaumont, 1979). Stabilization, in turn, caused the formation of extensive flood-plains in which coal and thick deposits of mudstone could develop, further inhibiting lateral migration of streams. The thick flood plain deposits underwent differential compaction, and where the rate of compaction exceeded the rate of deposition, subsidence took place and shallow ephemeral lakes and ponds formed (Beaumont, 1979). Where subsidence kept pace with organic accumulation and reducing conditions prevailed, peat accumulated in the *lower-coal bearing unit.* Abrupt changes in coal thickness are due to differential compaction in the flood-basin, erosion by subsequent fluvial channels, and expansion of lakes. The thickest coal accumulations occur in the central and eastern portion of the Sand Wash Basin above the thickest, massive K/T sandstone development, suggesting a direct relation between the position of the massive sandstone, which formed a stable platform, and the location of thick coal beds.

The *gray-green mudstone unit* in the west and east Sand Wash Basin represents a cessation of coarse clastic sedimentation around the edge of the Vermilion Basin area and the eastern Sand Wash Basin. Subsequently, streams flowing north, as suggested by the sandstone geometry, changed from high sinuosity to low sinuosity during the deposition of the *basin sandy unit*. This process was probably caused by a change in base level or by renewed tectonic activity, which uplifted the margins of the Sand Wash Basin, rejuvenating the streams. Streams depositing the basin sandy unit flowed predominantly in the center of the basin (R94W), in a north-trending belt similar to the massive K/T sandstone unit, creating a stable platform upon which additional peat could accumulate. The basin sandy unit appears to be restricted to the central parts of the Sand Wash Basin although it is not known whether these fluvial beds were deposited contemporaneously with the gray-green mudstone unit or if the mudstone was eroded before deposition of the basin sandy unit.

An increase in the sinuosity of streams brought about a further stabilization of the stream meander belts and again caused the formation of extensive flood plains and the *upper shaly unit* The fluvial sediment source for the upper shaly unit was to the west of the Vermilion and Sand Wash Basin. Minor coal accumulations (Cherokee Coals) occur in this area above the thickest development of the basin sandy unit. This, again, suggests a direct relation between the position and thickness of coarse clastics and the location of coal swamps. The thick fluvial sandstone sequences result in favorable hydrology and a stable platform upon which thick peat could accumulate. Within the Vermilion Basin the upper shaly unit is a paludal sequence with many fluvial channels. Eastward, the paludal environment gives way to a more lowland fluvial environment which contains some sediments of a recurrent lacustrine environment (Roehler, 1965). It is possible that a similar lithologic sequence was present in the eastern part of the Sand Wash Basin, however post-Paleocene uplift and erosion has removed much of this unit (Colson, 1969). Deposition of the Fort Union Formation ended in the early Eocene when renewed tectonic activity caused the erosion of the margins of the Sand Wash Basin and the coarse sediments of the Wasatch Formation were deposited.

CONCLUSIONS

1. The major Tertiary age coalbed methane target in the Sand Wash Basin, is the lower coal-bearing unit of the Paleocene Fort Union Formation.

2. Coal beds are also found in the Upper Cretaceous Lance Formation and upper shaly units of the Paleocene Fort Union Formation.

3. The Lance Formation, the youngest Cretaceous stratigraphic unit in the Sand Wash Basin, overlies and intertongues with nearshore-marine deposits of the Fox Hills Sandstone and consists of nonmarine shales, lenticular sandstones, and coal beds.

4. Coal beds are thicker and more abundant in the lower part of the Lance Formation above the Fox Hills sandstone platform and range from a few inches to 10 ft. Locally, these coal beds have a limited lateral extent, can be traced for only a few hundred feet in the subsurface, and may merge into single seams that are 15 to 20 ft thick.

5. The massive K/T sandstone, lower coal-bearing unit and basin sandy unit are present throughout the Sand Wash Basin and consist of continental-fluvial, lacustrine, and paludal deposits.

6. The Fort Union Formation is sand-rich in the central and eastern portions of the basin.

7. The lower coal-bearing unit contains northerly-trending fluvial sandstones and floodplain coal beds, which are laterally continuous. Coal beds are thicker and more numerous in floodplain areas above the thickest massive K/T sandstone. The lower coal-bearing unit contains some of the thickest (individual coal beds as much as 50 ft thick) in the Sand Wash Basin. Net-coal thickness range from 0 to 80 ft in as many as 12 seams at depths as much as 8,000 ft. Net-coal thickness and coal-seam continuity in the lower coal-bearing unit are greater than that in the upper shaly unit.

8. The Cherokee coal zone, constituting the upper 250-450 ft of the upper shaly zone occurs only in the west part of the Sand Wash Basin. The coal beds, about 3 to 10 ft thick, are not potential coalbed methane targets due to their thin and discontinuous nature and shallow burial depths. The Cherokee coal zone is removed by the Wasatch unconformity to the east.

9. Operationally defined lithostratigraphic correlations indicate that the Wasatch Formation contains no significant coals.

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