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Genetic Stratigraphy, Coal Occurrence, and Regional Cross Section of the Williams Fork Formation, Mesaverde Group, Piceance Basin, Northwestern Colorado

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GENETIC STRATIGRAPHY, COAL OCCURRENCE, AND REGIONAL CROSS SECTION OF THE WILLIAMS FORK FORMATION, MESAVERDE GROUP, PICEANCE BASIN, NORTHWESTERN COLORADO

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CONTENTS

Figures

Plate (in pocket)

ABSTRACT

The principal Upper Cretaceous coal-bearing horizons and coalbed gas exploration and production targets in the Piceance Basin occur in the Williams Fork Formation, Mesaverde Group, and are associated with the progradational Rollins-Trout Creek shale and sandstone shoreline sequence. We have genetically defined the bottom of the Williams Fork Formation as the base of the Rollins-Trout Creek Shale (Mancos Tongue, maximum flooding surface), above which a series of at least seven seaward-stepping, progradational sequences extend the Rollins-Trout Creek shoreline sandstone from R97W to R89W. Coal-bearing strata extend upsection above the progradational Rollins-Trout Creek Sandstone for approximately 1,500 to 2,000 ft (460 to 600 m) and are divided into three coal zones (Cameo-Wheeler-Fairfield, South Canyon, and Coal Ridge) by Mancos tongues (flooding surfaces); net coal thickness averages 80 to 120 ft. In the absence of the Lewis Shale, the top of the Williams Fork is defined above coal zone 3 coals and below a thick sequence of fluvial, undifferentiated Upper Cretaceous strata. The undifferentiated Upper Cretaceous strata above the Williams Fork coals are 1,500 ft (460 m) thick and locally contain thin, discontinuous coals. The undifferentiated Upper Cretaceous strata have been assigned Lance Formation status.

The Williams Fork Formation can be further subdivided into several genetic depositional sequences bounded by regionally extensive, low-resistivity shale markers that represent marine flooding surfaces. The first regionally correlatable genetic depositional sequence, genetic 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 genetic unit 1: (1) a linear shoreline (strandplain/delta plain) system, backed landward by (2) a coastal plain system, traversed by fluvial systems feeding the advancing shoreline, which in turn grade into (3) an alluvial plain system. Genetic unit 1 contains the thickest, most laterally extensive coals (Cameo-Wheeler-Fairfield coal zone, Bowie Shale Member). Maximum thickness of individual Cameo-Wheeler-

Fairfield coal beds is 20 to 35 ft (6 to 11 m), and net coal thickness ranges from less than 20 ft (<6 m) to more than 80 ft (>24 m). The most continuous Cameo-Wheeler-Fairfield coal beds formed landward (westward) of the Rollins-Trout Creek progradational shoreline sandstones and have extended northward, along depositional strike, for more than 10 mi (16 km) in the southeastern Piceance Basin. Less continuous, fluvial Williams Fork coal beds occur up the paleoslope to the west. The western limit of coal occurrence is controlled by the transition from coastal plain to alluvial plain deposition. To the east, coal beds pinch out against and/or override the progradational Rollins-Trout Creek shoreline sequences; their ultimate lateral extent is limited by the final shoreline position beyond which marine conditions prevailed. Genetic units 2 and 3 are clastic wedges displaying a similar arrangement of depositional systems to unit 1. Although genetic unit 2 did not prograde as far basinward as unit 1, unit 3 prograded farther basinward than both units 1 and 2.

Introduction

A regional assessment of coal-bearing stratigraphic units of the Piceance Basin was undertaken to target those horizons with greatest potential for coalbed gas exploration and production (Tyler and others, 1994). The Cameo-Wheeler-Fairfield coal zone, Williams Fork Formation, Mesaverde Group (fig. 1), was identified as containing the thickest, most extensive, and greatest number of coal seams and was thus selected as the principal focus of this study.

Our approach was to review the existing literature of the Mesaverde Group in the Piceance Basin and to establish a genetic stratigraphic framework in which detailed analysis of the coals, and their host sediments, could be carried out. The genetic stratigraphic framework then provided the basis for delineation of the major depositional systems and mapping of the distribution and thickness of the coals. This stratigraphic framework further provided a basis for investigating the depositional controls on coal occurrence and provided a rationale for arriving at coal and coalbed gas exploration targets and resource estimates. The genetic approach and concepts applied in the stratigraphic analysis of the Piceance Basin were similar to that used by

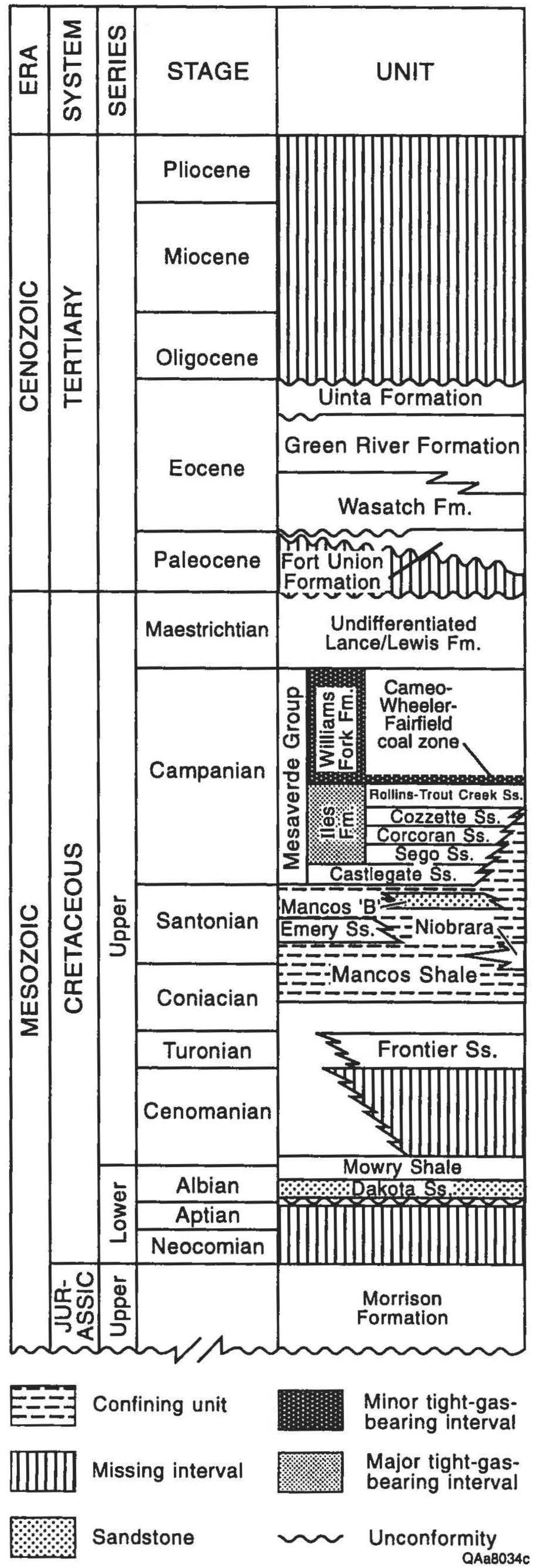


Figure 1. Coal-bearing stratigraphic and confining units in the Piceance Basin. Modified from Rocky Mountain Association of Geologists (1977) and Finley (1984).

Hamilton (1993, 1994) for the Williams Fork Formation, Mesaverde Group, in the Sand Wash Basin. The genetic stratigraphy, depositional controls, and lessons learned in the Sand Wash Basin study have been transferred to the Piceance Basin.

STRATIGRAPHIC SETTING OF THE MESAVERDE GROUP, PICEANCE BASIN, COLORADO: A REVIEW

The following review of the stratigraphic setting of the Mesaverde Group, Piceance Basin, Colorado, relies heavily on published regional and field studies and cross sections (fig. 2), although they were interpreted with insight gained in this study. The Mesaverde Group was first named by Holmes (1877) for Upper Cretaceous outcrop exposures of interbedded sandstone, shale, and coal in the San Juan Basin of the Four Corners area. Mesaverde strata exposed in the Piceance Basin, northwest Colorado, are lithologically similar to but younger than the Mesaverde at its type section (Weimer, 1960; Collins, 1976). The Mesaverde in northwest Colorado was deposited in the Eagle Basin of Utah and Colorado. The Eagle Basin was destroyed by the Late Cretaceous–early Tertiary Laramide Orogeny that formed the Uinta, White River, Sawatch, and Uncompahgre Uplifts, and the Douglas Creek Arch, which define the margins of the Piceance Basin (Quigley, 1965; Kauffman, 1977; Johnson and Keighin, 1981).

During the Cretaceous Period, the region now occupied by the Piceance Basin was covered by the Cretaceous Interior Seaway (Quigley, 1965; Kauffman, 1977). More than 5,000 ft (>1,525 m) of intertonguing marine (shoreface and shelf) and nonmarine (deltaic and fluvial) sediments was deposited in the Piceance Basin during the Late Cretaceous. Intertonguing of these deposits resulted from southeastward progradation of the shoreline, which was interrupted by northwestward shoreline retreat during periods of relative sea-level rise (Spieker, 1949; Young, 1955; Weimer, 1960; Gunter, 1962; Warner, 1964), resulting in the fluvial, paludal, strandplain/deltaic, and paralic depositional systems (Young, 1955; Warner, 1964; Quigley, 1965; Collins, 1976; Lorenz and Rutledge, 1985; Johnson, 1987, 1989). The coal-bearing

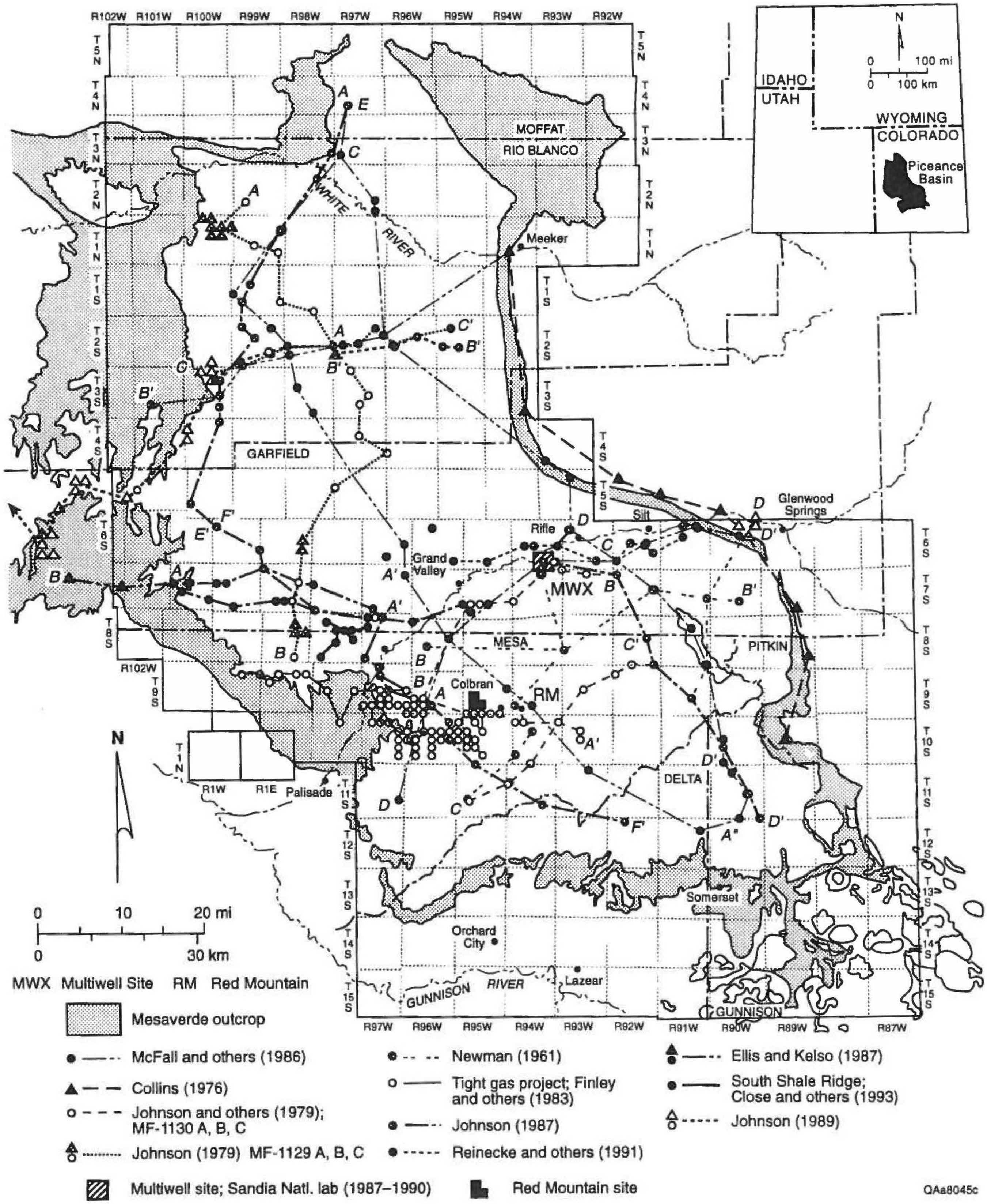


Figure 2. Location of study areas of published studies and cross sections used in this report.

sequences have been interpreted as wave-dominated linear clastic shoreline (Young, 1966) or as deltaic deposits (Collins, 1970, 1976).

Collins (1976), Johnson (1987, 1989), Lorenz (1989), and Sandia National Laboratories and CER Corporation (1987–1990) divide the Mesaverde Group into the two formations first proposed by Hancock (1925): the basal Iles Formation and the overlying Williams Fork Formation (fig. 1). Collins (1976) and Johnson (1987, 1989) demonstrated the regressive and transgressive interfingering relationships between the Mancos Shale and the Morapos, Castlegate, Lloyd, Sego, Corcoran, Cozzette, and Rollins-Trout Creek sandstones (figs. 3 and 4). In the southern Piceance Basin, Johnson (1987), Lorenz (1989), Nowak (1990, 1991), Reinecke and others (1991), and other authors have further subdivided the Williams Fork Formation into the Bowie Shale Member (Cameo-Wheeler-Fairfield and South Canyon coal zones), the Paonia Shale Member (Coal Ridge coal zone), and the "undifferentiated" Williams Fork Formation (Lorenz, 1983b; Johnson, 1989) or fluvial Mesaverde (Reinecke and others, 1991) (figs. 5 through 7). The traditionally defined Williams Fork Formation ranges from 4,600 to 6,400 ft (1,400 to 2,000 m) thick and is overlain by conglomerates of the Ohio Creek Conglomerate and sandstone member (Collins, 1976; Dunn and Irwin, 1977; Lorenz, 1989; Johnson, 1987, 1989, and references therein). This traditional thickness of the Williams Fork Formation is most certainly too thick. Palynological data and correlation at outcrop between the Sand Wash Basin and the northern Piceance Basin confirm the presence of equivalent Lewis and Lance sediments (Newman, 1964; Tyler and others, 1994).

The principal coal-bearing zones in the Mesaverde Group are associated with regressive shoreline sequences (figs. 3 and 7) (Johnson, 1987, 1989, and references therein; Reinecke and others, 1991). Thin coal beds in the Iles Formation (Black Diamond coal zone) overlie the regressive Sego, Corcoran, and Cozzette sandstones. However, the thickest coal beds in the basin occur in the Williams Fork Formation (Bowie Shale Member, Cameo-Wheeler-Fairfield coal zone; Reinecke and others, 1991), which overlies the Rollins-Trout Creek progradational shale and sandstone sequence. We have operationally defined the base of the Williams Fork

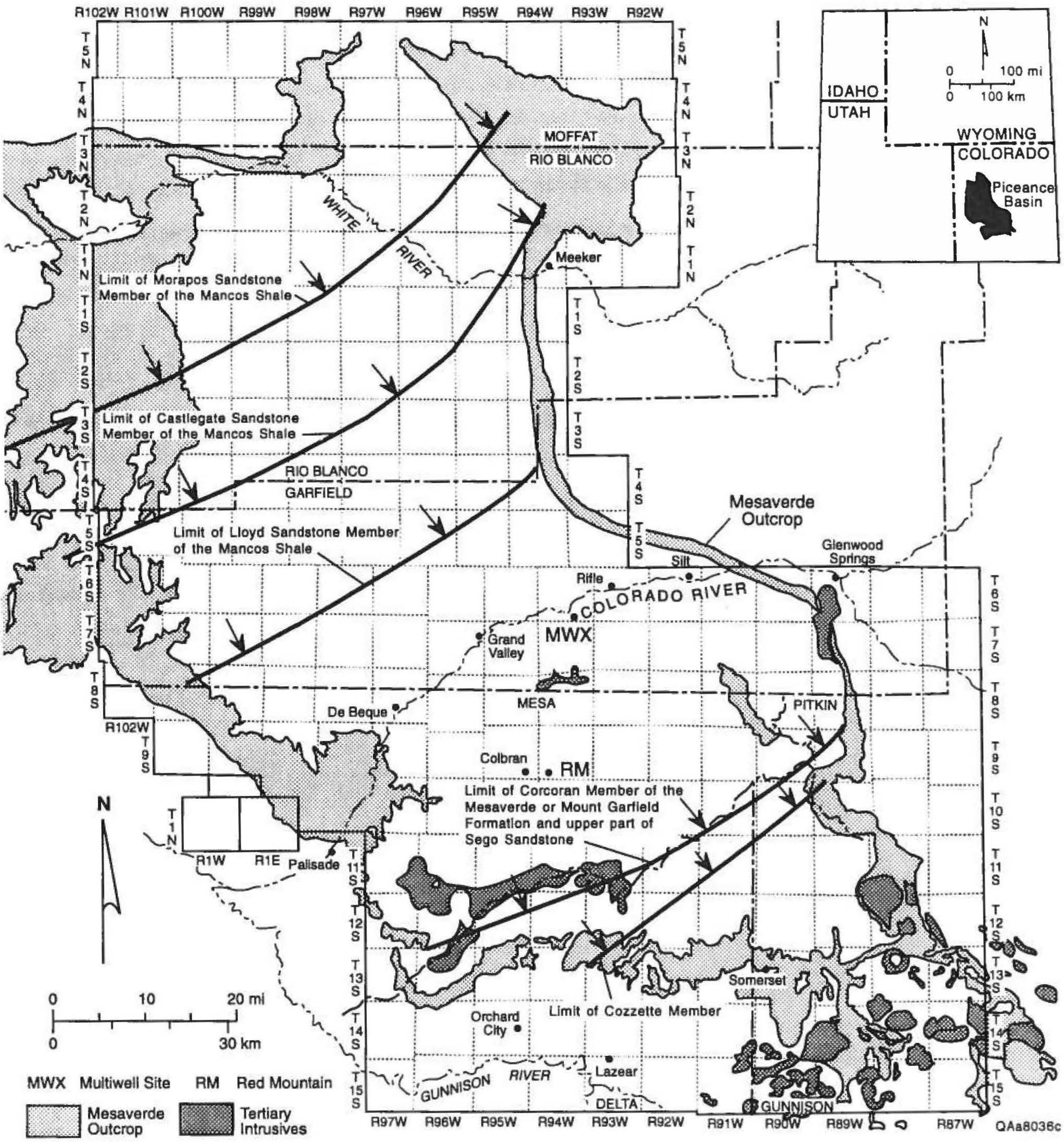


Figure 3. Regressive limits of the sandstone members of the Mancos Tongue and Iles Formation, Mesaverde Group. Limits of the Sego sandstone cannot be determined with certainty. Seaward limit of the Rollins-Trout Creek progradational sequence is beyond the southeastern corner of the Piceance Basin and the mapped area. Arrows indicate direction of regression. Modified from Zapp and Cobban (1960), Warner (1964), Gill and Cobban (1969), Gill and Hail (1975), and Johnson (1989).

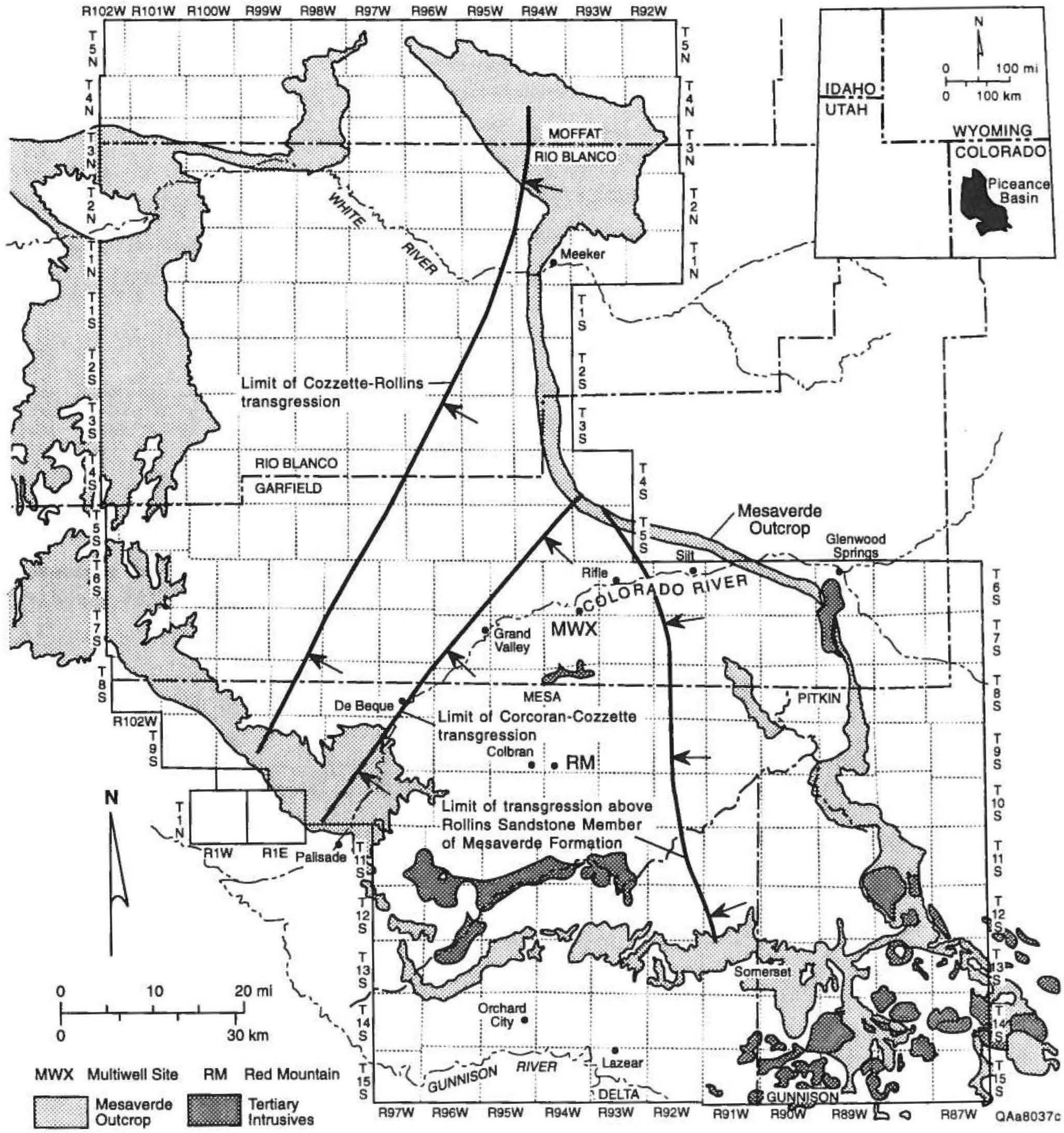


Figure 4. Transgressive limits of the Mancos shale tongues (flooding surfaces), Iles and Williams Fork Formations, Mesaverde Group. Arrows indicate direction of transgression. Modified from Zapp and Cobban (1960), Warner (1964), Gill and Cobban (1969), Gill and Hail (1975), and Johnson (1989). Note the north-south orientation in post-Rollins and Trout Creek strata.

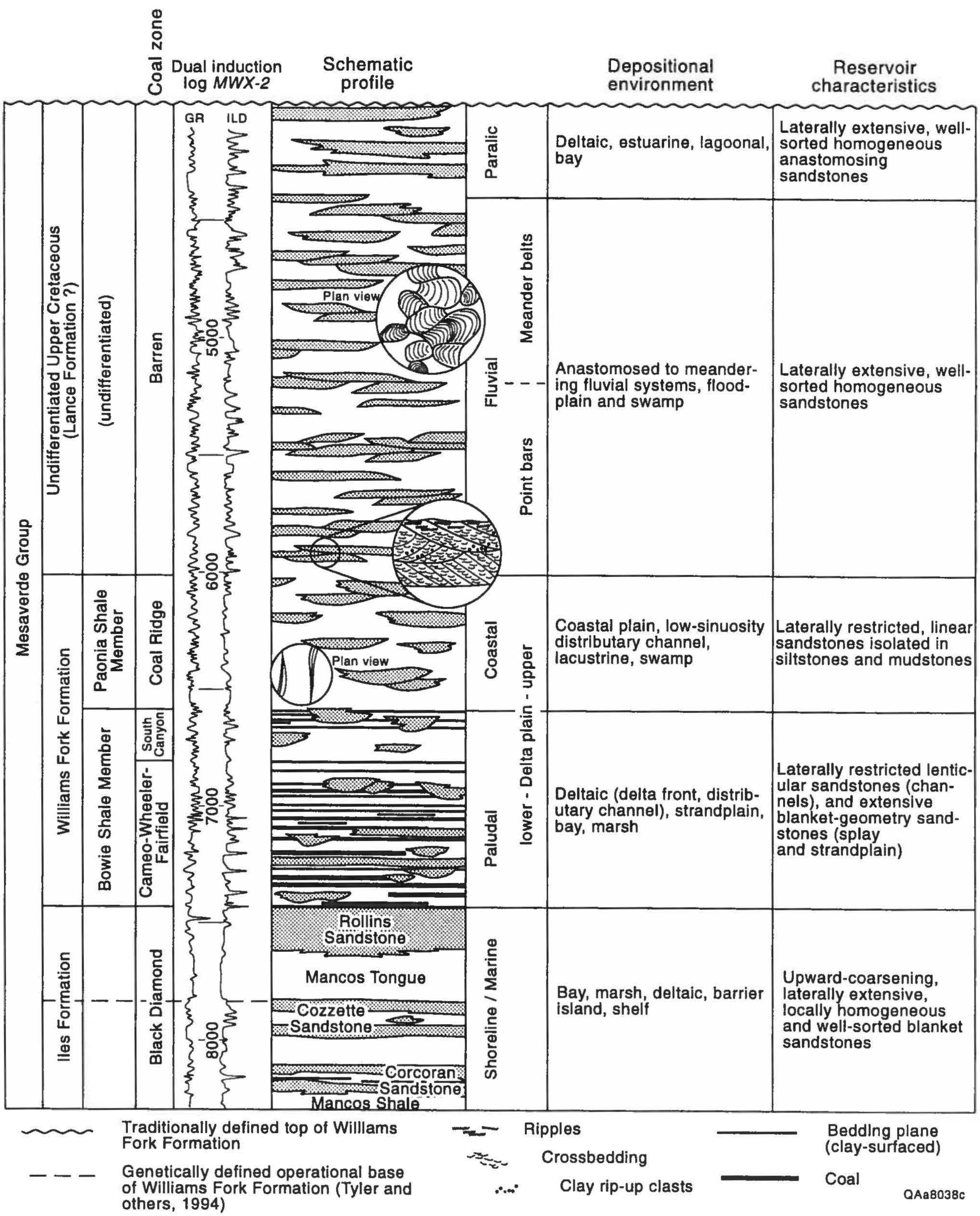
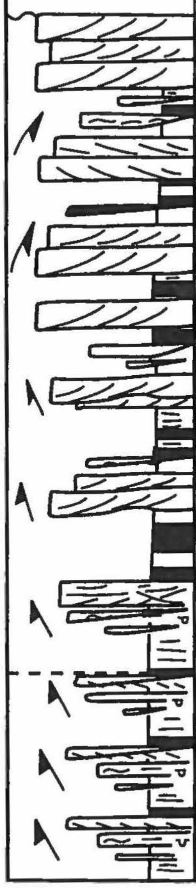


Figure 5. Traditionally defined stratigraphic column of principal coal-bearing zones, depositional environments, and sandstone reservoir characteristics in the Piceance Basin, showing inferred depositional environments and reservoir characteristics in the Rulison field. Modified from Lorenz (1983b).



SAND-STONE MBR.	COAL ZONE	FORMATION (Depositional system)	COAL BEDS Thickness (ft) Average	Maximum	Net	Number	Continuity	SANDSTONES Thickness (ft) Maximum	Net	Continuity	COAL–SANDSTONE RELATIONS
Ohio		OHIO CREEK (Fluvial)						>70	—	Continuous	No Coal
		UNDIFFEREN-TIATED UPPER CRETACEOUS (Fluvial)	<5	3	<20 ?	2–5	Very discon-tinuous	50–70	—	Discontinuous, lenticular sandstones	Most coal beds eroded by channels; coalbed pinch-outs common
Upper Sandstone	Coal Ridge	UPPER WILLIAMS FORK FORMATION (Coastal plain)	<10	5–10	20–40	10 or less	Moderate	20–30	—	Isolated lenticular sandstones	Poorly documented: coal beds probably dip elongate and split or pinch out against channel sandstone
Middle Sandstone; Rollins-Trout Creek Sandstone	S. Canyon; Cameo-Wheeler-Fairfield	LOWER WILLIAMS FORK FORMATION (Delta/strand-plain)	10	20–35	30–60	12 or less	Most continuous in basin	35	70–110 at Rifle Gap	Good, parallel to depositional dip	Continuous coal beds directly overlie marine Rollins Ss.; some coal beds split and override lenticular, distributary-channel sandstone
Cozzette Sandstone; Corcoran Sandstone; Sego Sandstone	Black Diamond	ILES FORMATION (Wave-dominated shoreline)	5–10	10–20	15–30	2–4	Continuous, parallel to depositional strike	>50	100–150	Excellent, parallel to depositional strike	Major coal beds directly overlie marine, blanket sandstones; minor coal beds overlie crevasse splay sandstones

Traditionally defined top of Williams Fork Formation

x-x-x-x-x-x Traditionally defined top of Iles Formation

- - - - Genetically defined base of Williams Fork Formation

Burrows

Upward coarsening

Upward fining

SEDIMENTARY STRUCTURES AND ROCK TYPES

Planar bedding

Ripples

Crossbedding

Coal

QAa8039c

Figure 6. Schematic section and characteristics of coal beds and sandstones in major coal-bearing units in the Piceance Basin. Modified from Tyler and others (1991, 1994).

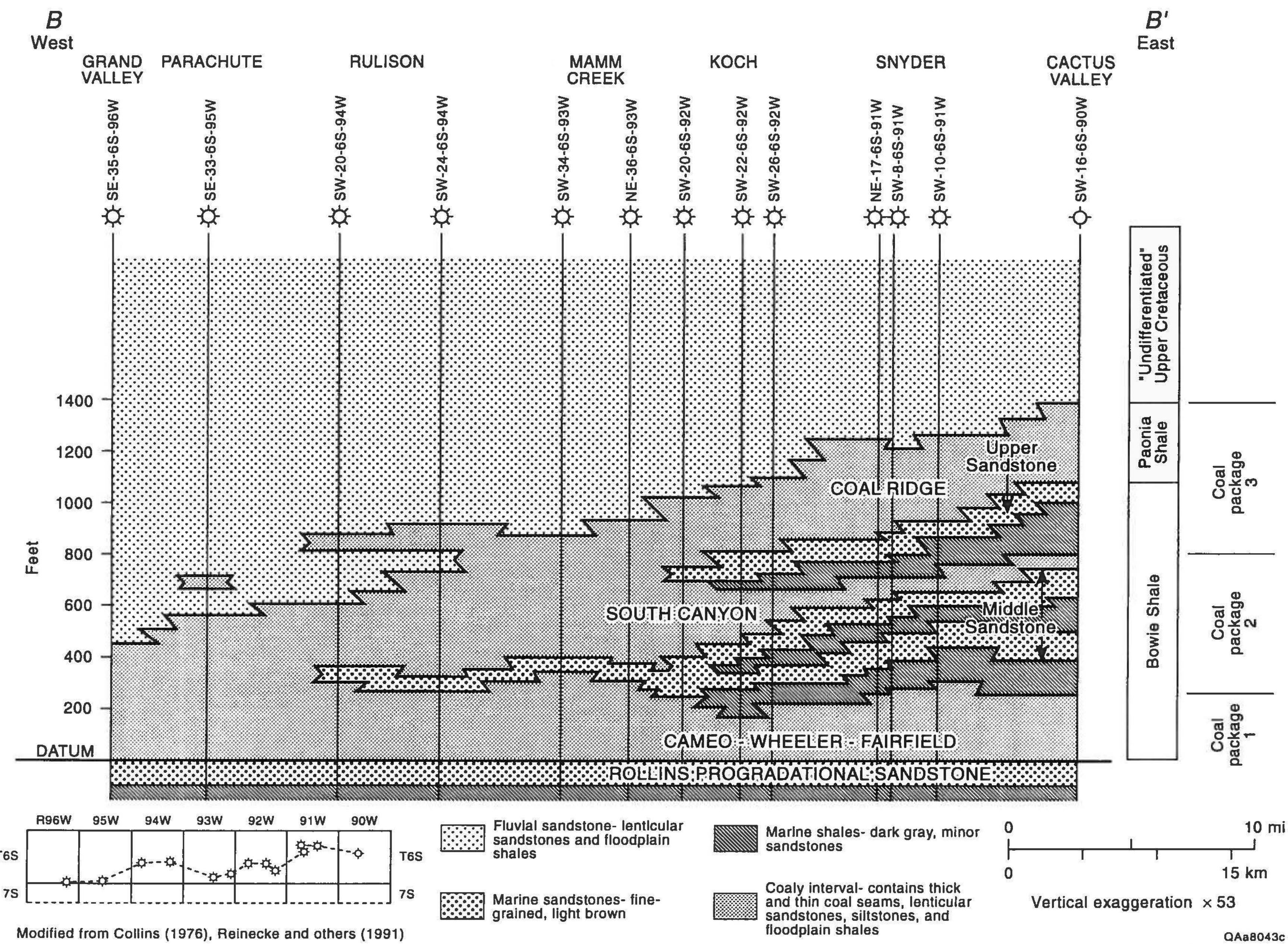


Figure 7. Cross section of east end of Grand Valley field to southeast of New Castle, showing stratigraphic relationships and changes in the coal zones. Modified from Reinecke and others (1991).

Formation as the base of the progradational Rollins-Trout Creek shale (maximum flooding surface of the Mancos Tongue), to be consistent with the sequence stratigraphy defined in the Sand Wash Basin study (Kaiser and others, 1994). Other coal beds are found in the South Canyon coal zone (Bowie Shale Member, Williams Fork Formation; Reinecke and others, 1991), the Coal Ridge coal zone (Paonia Shale Member, Williams Fork Formation; Reinecke and others, 1991) and in the upper, undifferentiated Upper Cretaceous strata (Williams Fork Formation; McFall and others, 1986; Lorenz, 1989). This overall regressive package overlies and intertongues with the Mancos Shale and is probably overlain by the Lance Formation, the Ohio Creek Conglomerate, and/or the Lewis Shale in various parts of the basin (Collins, 1976; Lorenz, 1989). Detailed descriptions of the coal-bearing formations and their component members follow.

Iles Formation (Black Diamond Coal Zone)

Interbedded sandstones, siltstones, coals, and shales, having a combined thickness ranging from 890 to 1,600 ft (270 to 490 m), compose the Iles Formation (Collins, 1976) (figs. 5 and 6). Sandstones and coalbeds of the Iles Formation were deposited in a regressive, wave-dominated coastal setting (Young, 1966; Collins, 1976; Finley and Ladwig, 1985; Madden, 1985; Johnson, 1987, 1989; Lorenz, 1989). Marine deposits (shelf, shoreface, barrier-island, strandplain, delta-front, bay-lagoon, and tidal-inlet) in the Iles Formation grade northwestward (up paleoslope) into nonmarine deposits (coastal plain marsh and swamp, fluvial, and floodplain). The thickest coal beds occur landward (northwestward) of thick, northeast-trending barrier-strandplain sequences (fig. 8) (Finley and others, 1983). These coal beds override the barrier-strandplain sandstones and pinch out seaward (southeastward) into transgressive mudstones (Finley, 1985).

Black Diamond coal zone. Coal beds in the Black Diamond coal zone overlie progradational sandstones in the Iles Formation (fig. 6). These sandstones (Sego, Corcoran, and Cozzette Members) are each 0 to 220 ft (0 to 67 m) thick and contain individual sandstone units that range from 0 to 100 ft (0 to 30 m) thick (fig. 6). Iles sandstones exhibit excellent continuity (50

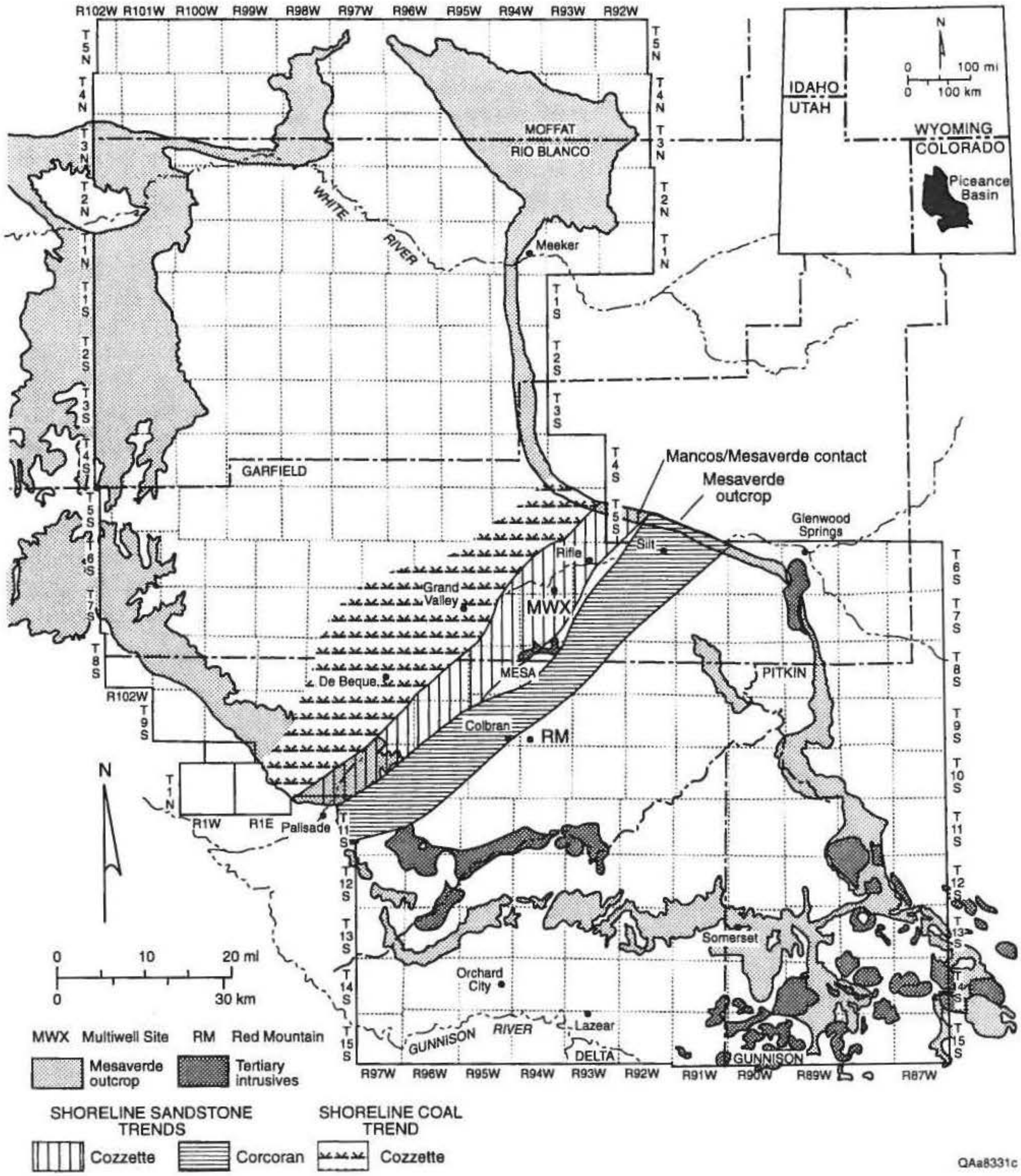


Figure 8. Shoreline trends of the Corcoran and Cozzette sandstones in the southeast part of the Piceance Basin. Thick northeast-trending coal beds formed landward (northwest) of these shoreline trends. Modified from Finley and others (1983).

by 75 mi [80 by 120 km]) and are described as blanket sandstones (Lorenz, 1983a). They trend northeastward and intertongue to the southeast with marine Mancos Shale wedges and to the northwest with the terrestrial coal-bearing deposits (Young, 1955; Warner, 1964; Finley, 1985) (figs. 3, 4, and 8). Iles paleoshorelines advanced to the southeast; the greatest advance of the shoreline was approximately 15 mi (24 km) northwest of the present southeast margin of the basin (fig. 3). Black Diamond coal beds are interbedded with carbonaceous mudstones or thin sandstones (Madden, 1985). Two to four Black Diamond coal beds typically occur in the 300-ft (90-m) thick interval (McFall and others, 1986). Individual coal beds are commonly less than 3 ft (<1 m) thick, although some are as thick as 10 ft (3 m) (fig. 6) (Madden, 1985). Net coal thickness is also commonly less than 10 ft (<3 m), but in the northeast part of the basin it is more than 30 ft (>9 m). Black Diamond coal beds are thin or absent in the far west and southeast parts of the basin (McFall and others, 1986; Johnson, 1989). Black Diamond net coal thickness trends contain both strike- and dip-parallel elements (McFall and others, 1986). The Black Diamond coal zone contains the most deeply buried Mesaverde coal beds in the Piceance Basin; in Rio Blanco and Garfield Counties, these coal beds are more than 12,000 ft (>3,660 m) deep.

Williams Fork Formation (Cameo-Wheeler-Fairfield, South Canyon, and Coal Ridge Coal Zones)

The Williams Fork Formation overlies the Iles Formation and consists of a series of marine and nonmarine conglomerates, sandstones, siltstones, mudstones, claystones, coals, and rare fresh water algal limestones (Collins, 1976). The Williams Fork Formation, as defined here, varies from the traditional stratigraphy of Collins (1976), Johnson (1987, 1989), Lorenz (1989), and Reinecke and others (1991) (figs. 5 through 7). In this study, the Rollins-Trout Creek shale and overlying sandstone member, which are traditionally assigned to the uppermost part of the underlying Iles Formation, are included with the Williams Fork Formation. Depositionally, the Rollins-Trout Creek shale/sandstone couplet records an episode of marine transgression and subsequent progradation. Thus, the progradational Rollins-Trout Creek sequence is genetically coupled with the Williams Fork to define progradational/aggradational couplets. Above the Rollins-Trout Creek, in the southeastern Piceance Basin, the Williams Fork has been divided into major coal-bearing packages: coal package 1, the Cameo-Wheeler-Fairfield coal zone (Bowie Shale Member); coal package 2, the South Canyon coal zone (Bowie Shale Member); coal package 3, the Coal Ridge coal zone (Paonia Shale Member), and finally an upper (very minor) coal package of undifferentiated fluvial sediments (fig. 7). The Cameo-Wheeler-Fairfield and Coal Ridge coal zone intervals are separated by marine tongues of the Mancos Shale and progradational shoreline sandstones of the Middle and Upper Sandstone Members (Reinecke and others, 1991) (fig. 7). Each sequence consists of a basal marine shale and sandstone that is overlain by nonmarine coal-bearing rocks.

Rollins-Trout Creek Shale and Sandstone Progradational Sequence

The Rollins-Trout Creek shale and sandstone consists of a major transgressive tongue of the Mancos Shale (Young, 1955) and a thick progradational shoreline sandstone sequence, which Collins (1976) interpreted as a prograding bar–beach–delta-front sand complex. This sequence is less than 100 ft (<30 m) thick in northwestern Mesa County (Dunn and Irwin, 1977), and the sandstone (Rollins-Trout Creek) can reach 125 ft (38 m) in thickness (Warner, 1964). In the southeastern Piceance Basin (T10S; R89W), the Rollins-Trout Creek shale and sandstone progradational sequence is greater than 900 ft (>275 m) thick.

Cameo-Wheeler-Fairfield Coal Zone (Bowie Shale Member)

The Cameo-Wheeler-Fairfield coal zone is the major coal-bearing horizon in the Mesaverde Group and composes the lowermost 680 ft (207 m) of the Williams Fork Formation above the Rollins-Trout Creek sandstone member (figs. 5 and 6). It generally consists mostly of shale, interbedded with sandstone and coal beds. Fresh-water swamps in the coal zone formed landward of wave-dominated shoreline deposits of the Rollins-Trout Creek sandstone (Lorenz, 1983b, 1989). These swamp deposits overrode the Rollins-Trout Creek sandstone and, with continued progradation of the shoreline, resulted in thick, somewhat continuous coal beds (Collins, 1976). Peat formation was periodically interrupted by transgressions; some lower coal beds are overlain by nearshore-marine and distributary-mouth-bar sandstones that formed the platform for subsequent peat swamps (Bell and Wiman, 1985). These sandstones in the Cameo-Wheeler-Fairfield coal zone are thin, averaging less than 20 ft (<6 m), and occur in strike-elongate sheets crosscut by lenticular sandstone pods, 370 to 520 ft (113 to 159 m) wide (fig. 6) (Lorenz, 1989). Maximum sandstone thickness is 35 ft (11 m), and net sandstone thickness is 70 to 110 ft (21 to 34 m) in the eastern part of the Piceance Basin (Madden, 1985; Lorenz, 1989). Coal beds compose 10 to 15 percent of the Cameo-Wheeler-Fairfield coal zone (Lorenz, 1989). Thickness of individual seams is as great as 35 ft (11 m) on the eastern margin of the basin (Collins, 1976). Net coal thickness ranges from less than 20 ft (<6 m) in the southeast part of the basin to more than 60 ft (>18 m) in the east-central part of the basin (Johnson 1987, 1989). At the Red Mountain site in northeastern Mesa County, at least five coal beds have a net thickness of more than 50 ft (>15 m). The thickest coal bed (D coal seam, 16 to 20 ft [4.9 to 6.1 m] thick) at the Red Mountain site is in the lower part of the group, 50 to 150 ft (15 to 46 m) above the A coal seam (12 ft [3.7 m] thick) that directly overlies the Rollins Sandstone (Bell and Wiman, 1985). Lower coal beds at the Red Mountain site extend for more than 4 mi (>6.4 km) parallel to depositional strike (Bell and Wiman, 1985). However, these coal beds are locally truncated by crosscutting channel-sandstone deposits (Lorenz, 1983b). Coal-seam splits also occur along margins of channel sandstones. Collins (1976), for example, reported a 35-ft-thick (11-m) coal seam in the east part of the basin splitting into four thinner coal seams over a distance of less than 3,000 ft (<1,200 m). Cameo-Wheeler-Fairfield net coal thickness decreases to less than 20 ft (<6 m) in the southeast part of the Piceance Basin because of seaward pinch-out of the underlying Rollins sandstone platform into the marine Mancos Shale (Murray and others, 1977).

Although coal beds in the Cameo-Wheeler-Fairfield coal zone are thickest and most continuous in the Piceance Basin, they are more than 6,000 ft (>1,800 m) deep throughout much of the basin, and as much as 10,000 ft (3,050 m) deep in the northeast part of the basin. However, Cameo-Wheeler-Fairfield net coal thickness of more than 40 ft (>12 m) is present in the center and southeast part of the basin, where these coal beds are less than 6,000 ft (<1,800 m) deep (McFall and others, 1986).

South Canyon Coal Zone (Bowie Shale Member)

The South Canyon coal zone occurs directly above the first persistent sandstone outcrop within the Bowie Shale Member (Collins, 1976), locally known as the middle sandstone. Collins (1976) separated the South Canyon coal zone from the Cameo-Wheeler-Fairfield coal zone because of the thick development of coals in that area. Two major coal seams occur in the basal 100 ft (31 m) of the South Canyon coal zone. However, coals in the South Canyon are much less persistent than those in the Cameo-Wheeler-Fairfield, varying widely in thickness from 3 to more than 20 ft (>1 to 6 m) (Collins, 1976).

Coal Ridge Coal Zone (Paonia Shale Member)

The Coal Ridge Group consists of basal marine shale and sandstone that grades upward into nonmarine sandstone, siltstone, shale, and coal (fig. 6) (Lorenz, 1983a). This group has a gradational upper contact with the overlying, undifferentiated sediments and averages 560 ft (170 m) in thickness in the east part of the basin (Collins, 1976). Sandstone bedding is variable; the thickest sandstones (12 to 60 ft [3.7 to 18 m] thick, 400 to 600 ft [120 to 180 m] wide) are lenticular in cross section, linear in plan view (Lorenz, 1989) (fig. 6), and are associated laterally with thin-bedded sandstone and siltstone. Coal beds in the Coal Ridge Group vary greatly in thickness over relatively small distances (Collins, 1976). Individual coal beds are commonly less than 5 ft (<1.5 m) thick (Lorenz, 1983b) and occur only in the southeast part of the basin, where as many as 10 coal seams have a net thickness of as much as 40 ft (12 m) (McFall and others, 1986). The coal beds are also discontinuous as a result of having formed in restricted swamps between low-sinuosity distributaries on a low-gradient coastal plain (Lorenz, 1989). These coal beds commonly contain siltstone partings of overbank (levee and splay) origin.

Undifferentiated Upper Cretaceous Strata (Undifferentiated Mesaverde Formation [Collins, 1976]; Upper Williams Fork Formation [McFall and others, 1986; Lorenz, 1989]; Lance Formation [Tyler and others, 1994])

Upper Cretaceous strata consist of lithologically variable sediments (conglomerate, sandstone, siltstone, shale, coal) that range from 2,000 to 4,000 ft (610 to 1,220 m) in thickness. Lenticular sandstones and thin-bedded coals are common. Regionally, we have correlated the undifferentiated Upper Cretaceous strata in the Piceance Basin with the Lance Formation in the Sand Wash Basin.

Thin, minor coal beds are present in the upper strata, but they are commonly discontinuous and grade into carbonaceous shales interbedded with mudstones and lenticular sandstones (fig. 6). Thickest coal beds (as much as 3 ft [1 m] thick) occur in the east part of the basin (Horn and Gere, 1959). Upper Cretaceous coal beds were deposited in stable floodplains between laterally restricted, anastomosing rivers (Payne and Scott, 1982) or in unstable, restricted floodplains between meandering streams (Lorenz, 1983a).

REGIONAL GENETIC STRATIGRAPHY, COAL OCCURRENCE, AND CROSS SECTION OF THE UPPER CRETACEOUS MESAVERDE GROUP, WILLIAMS FORK FORMATION

Tyler and others (1994) and Kaiser and others (1994) proposed a regional genetic stratigraphic framework for the Piceance and Sand Wash Basins. The Mesaverde Group, as defined in the Sand Wash Basin (Hamilton, 1993, 1994), was traced southward in the subsurface into the Piceance Basin. Tyler and others (1994) divided the Mesaverde Group in the Piceance Basin into the Iles and Williams Fork Formations and the undifferentiated Upper Cretaceous strata (fig. 9). The Williams Fork Formation is the most important coal-bearing formation and can be divided into several genetic depositional sequences, each bounded by marine shales that define flooding surfaces (fig. 9). The base of the Williams Fork Formation is readily identified by a characteristic high-conductivity kick on geophysical logs at the base of the Mancos Tongue (Rollins-Trout Creek shale and sandstone progradational sequence) (fig. 9). This marker represents a marine maximum flooding surface and is a regional genetic sequence boundary. Coal-bearing strata extend upsection above the Rollins-Trout Creek sandstone for approximately 1,500 to 2,000 ft (450 to 600 m) and can be divided into at least three genetic sequences (coal zones or packages) (Cameo-Wheeler-Fairfield, South Canyon, and Coal Ridge coal zones) by Mancos tongues/marine flooding surfaces and progradational shoreline sequences. These genetic sequences correspond regionally to progradational shoreline sequences of genetic units 1, 2, and 3/4, Sand Wash Basin (Hamilton, 1993, 1994) (figs. 9 and 10). In the absence of the Lewis Shale, the top of the Williams Fork Formation is placed above genetic sequence 3 (coal package 3) and is associated with a high-conductivity interval, below a sequence of thick fluvial sandstones (undifferentiated Upper Cretaceous strata) (fig. 9). This operationally defined boundary separates sand-poor rocks below from sand-rich rocks above and has been assigned Lewis/Lance Formation status in the Piceance Basin (fig. 1; Tyler and others, 1994). The undifferentiated Upper Cretaceous strata above the Williams Fork Formation are approximately 1,500 ft (460 m) thick and are characterized by aggradational, sandstone- and mudstone-rich bed-load to mixed-load fluvial systems. In the southeastern Piceance Basin, the undifferentiated Cretaceous strata form a clastic wedge that extended shoreline and coastal plain deposits much farther basinward than genetic units 1, 2, and 3.

Regional Correlation of the Williams Fork Genetic Depositional Sequences in the Piceance and Sand Wash Basins

Using the genetic stratigraphic framework established in previous studies of the Sand Wash Basin (Hamilton, 1993, 1994), we readily correlated the Williams Fork Formation and its coal-

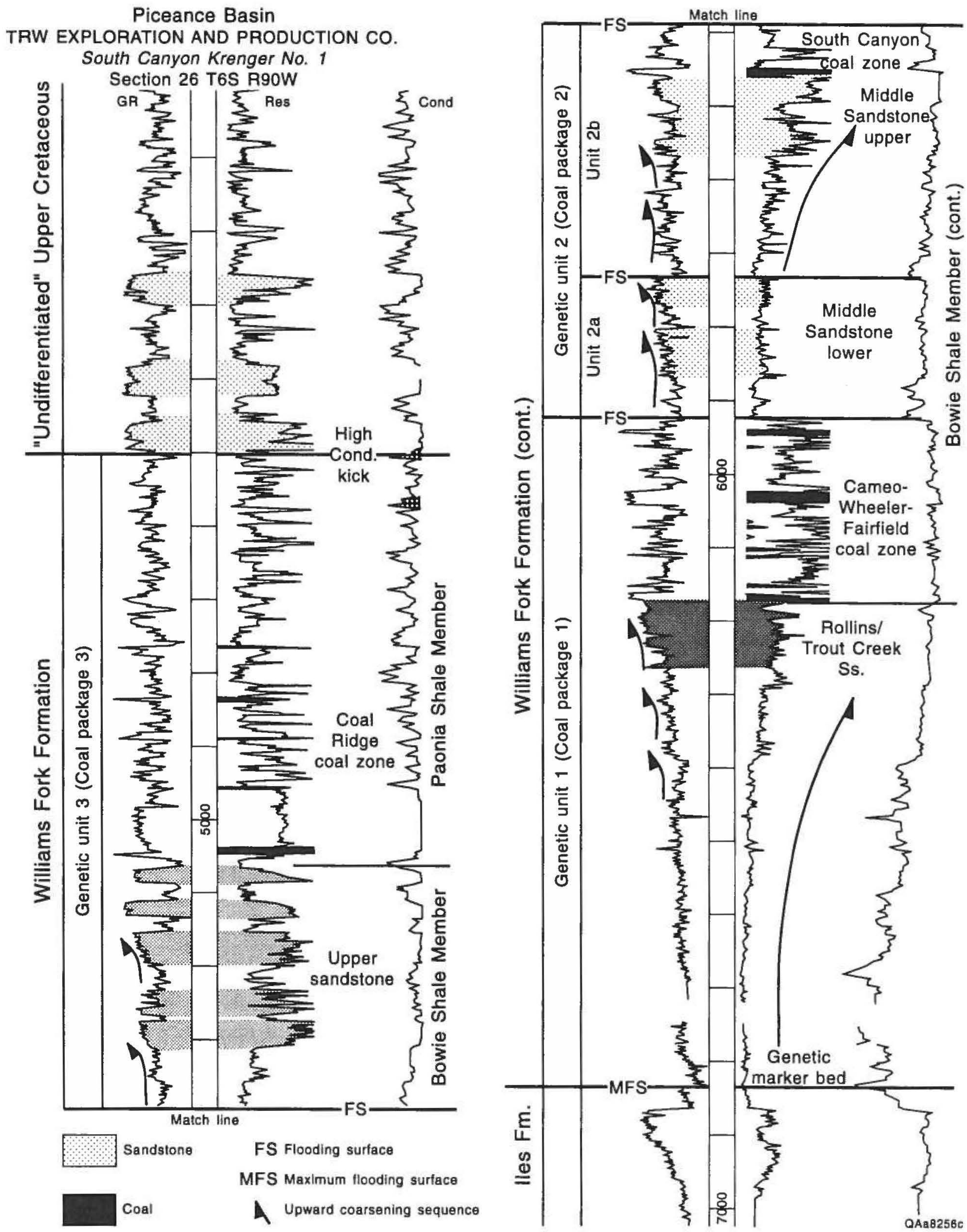


Figure 9. Genetic stratigraphy and type log of the upper Mesaverde Group in the southeastern Piceance Basin. Coal beds are identified on accompanying density logs. Surfaces bounding genetic units are defined by regionally extensive, low-resolution shale marker beds, which define flooding surfaces.

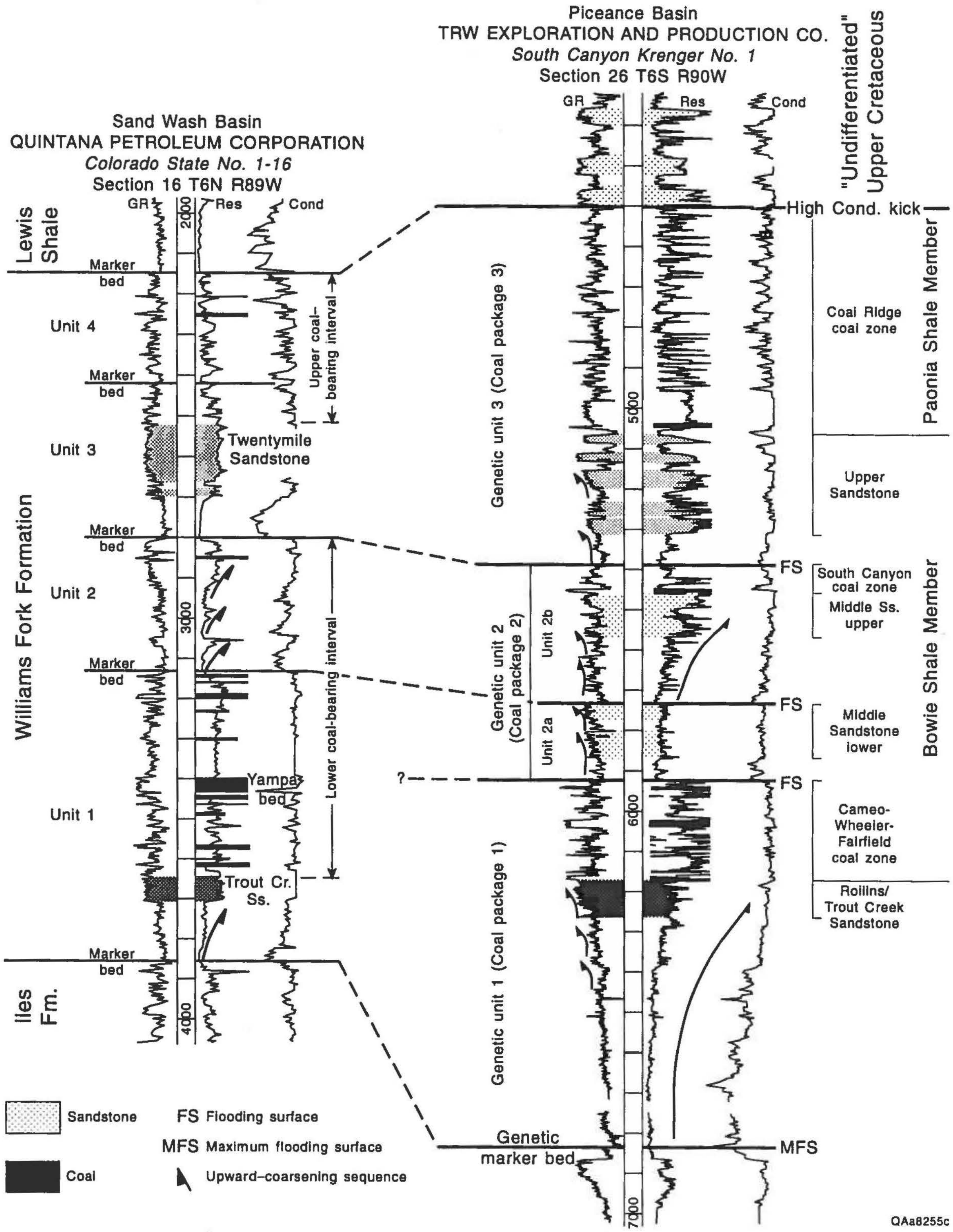


Figure 10. Comparison between the genetic stratigraphy and a type log of the Williams Fork Formation in the southeastern Piceance Basin and southeastern Sand Wash Basin. Coal beds are identified on accompanying density logs. Surfaces bounding genetic units are defined by regionally extensive low-resistivity shale marker beds, which define flooding surfaces.

bearing units southward into the Piceance Basin. Identifying the principal bounding surfaces of the Iles and Williams Fork genetic sequences on the basis of log character, including the occurrence of Mancos Shale flooding surfaces, bentonite beds (Yampa), and Foraminifera, is relatively straightforward in the Sand Wash and Piceance Basins (figs. 9 and 10). The Sand Wash and Piceance Basins occupied a marginal marine setting along the western edge of the Western Interior Seaway during Mesaverde deposition; the successive clastic wedges are bracketed by transgressive marine flooding surfaces. Defining genetic bounding surfaces in the continental/alluvial plain facies to the west of the coastal plains in these basins was more problematic but still regionally possible (Tyler and others, 1994).

In the Piceance and Sand Wash Basins, the Williams Fork Formation is divided into at least three to four genetic depositional sequences (coal zones or packages), each bounded by regionally extensive low-resistivity shale markers (Mancos tongues/marine flooding surfaces). Each genetic unit is a progradational-aggradational couplet characterized by fluvial-deltaic sedimentation where a progradational strandplain/delta plain system is flanked landward by a coastal plain system, which is traversed by a fluvial system feeding the advancing shoreline. In the southeastern Piceance Basin, the shale markers are easily recognizable, separating aggradational coal-bearing coastal plain facies of one depositional episode from the overlying upward-coarsening progradational sequence of the next. In a landward direction (westward), identification of the shale markers is less precise.

Comparison with Traditional Stratigraphy

In the Piceance Basin the Williams Fork Formation, as operationally defined herein, varies from the traditional stratigraphy in three main ways:

1. The Rollins-Trout Creek shale and overlying sandstone member, which are traditionally assigned to the uppermost part of the underlying Iles Formation (Johnson, 1987, 1989, and references therein; Siepman, 1985), are in this study included with the Williams Fork Formation. Depositionally, the Rollins-Trout Creek shale/sandstone couplet records an episode

of marine transgression and subsequent progradation and served as a platform for peat accumulation. Thus, the progradational Rollins-Trout Creek sequence belongs genetically with the overlying aggradational Williams Fork Formation (figs. 9 and 10).

2. The operationally defined Williams Fork Formation is made distinct or is separated from the undifferentiated Upper Cretaceous strata by mapping variations in sandstone and coal stacking patterns. In his published cross sections, Johnson (1989) showed the upper part of the Williams Fork Formation as partly equivalent to the Mesaverde Formation. The upper Williams Fork Formation, as traditionally defined by Johnson (1989) and others, is herein separated into a distinct genetic sequence; that is, it is a prominent aggradational sequence of interbedded bed-load and mixed-load fluvial sandstones, together with minor siltstones and coals (figs. 9 and 10). We also correlate the undifferentiated Upper Cretaceous strata as equivalent to the Lance/Lewis depositional sequence. In the Meeker area the associated rocks contain arenaceous Foraminifera (Newman, 1965). The presence of Foraminifera indicates that nearshore marine deposits of the undifferentiated Upper Cretaceous strata are part of the Lewis transgression and regression (Lewis Shale of the Craig area; Newman, 1964, 1965). Hence, the traditionally defined thick Williams Fork Formation at Meeker can be split into units that are time equivalents of the Williams Fork, Lewis, and Lance Formations of the Craig area (Newman, 1964). Moreover, the coaly sequence above the Lion Canyon Sandstone (the Lion Canyon Sandstone Member is stratigraphically equivalent to the Fox Hills Sandstone; Gill and Cobban, 1966) and below the Fort Union Formation contain the gastropod *Tulotomopos Thompsoni*, which is restricted to the Lance and equivalent formations (Pipiringos and Rosenlund, 1977).

3. The genetic depositional sequences of the Williams Fork Formation (genetic units 1, 2, and 3) cut across many of the traditionally defined lithological boundaries. For example, the Cameo coal group in the southwestern part of the basin is not genetically related or stratigraphically equivalent to the South Canyon and Coal Ridge coal groups (fig. 7), as illustrated in Reinecke and others (1991), but is a coal zone that is found directly above Rollins-

Trout Creek progradational shoreline sequences. The Cameo-Wheeler-Fairfield, South Canyon, and Coal Ridge coal zones are genetically separated by progradational/aggradational couplets, bounded by regional flooding surfaces (retrogradational sequences).

Regionally Correlatable Williams Fork Genetic Sequences

Genetic Unit 1 (Coal Package 1)

The regionally correlatable, lowermost depositional sequence of the Williams Fork Formation, genetic unit 1, is a clastic wedge bounded by regionally extensive, low-resistivity shale markers. The lower bounding surface occurs near the base of the Rollins shale member (Mancos Tongue), where the sequence is characterized by the upward-coarsening, progradational Rollins sandstone member and overlying aggradational coal-bearing rocks (fig. 9). The Rollins shale and sandstone member is depositionally equivalent and homotaxial to the Trout Creek shale and sandstone member in the Sand Wash Basin. The Rollins-Trout Creek shale and sandstone genetic unit is characterized by seaward-stepping progradational sequences, extending, in a depositional-dip direction, for over 60 mi (>100 km) into the basin and containing the thickest and widest linear shoreline (strandplain/delta plain) system in the entire Mesaverde Group. This stacking pattern is best displayed in a regional cross section through T9S and T10S, R97W to R89W in the southern Piceance Basin (plate 1), where at least seven correlatable progradational Rollins-Trout Creek shoreline sequences are recognized (PS-1 to PS-7). Each sequence is bounded by low-resistivity Mancos shale tongues that represent marine flooding surfaces and consist of upward-coarsening, progradational shoreline sandstones (plate 1). The youngest regionally correlatable sequences, PS-7 and PS-8, are progradational shoreline sandstones that extended coal-bearing coastal plain deposits beyond the present-day basin margin.

Above each progradational sequence, log facies change into aggradational blocky channel-fill sandstones, interbedded with mudstones and relatively continuous coal beds (Cameo-

Wheeler-Fairfield coal zone). The basin's thickest and areally most extensive coals occur in this zone (fig. 11). Maximum thickness of individual Cameo-Wheeler-Fairfield coal beds is 20 to 35 ft (6 to 11 m), and net coal thickness ranges from less than 20 ft (<6 m) to more than 80 ft (>24 m). The most continuous coal beds form just landward (westward) of each Rollins-Trout Creek progradational shoreline sequence. Less continuous, fluvial Williams Fork coal beds occur up the paleoslope to the west, the western limit of coal occurrence being controlled by the transition from coastal plain to alluvial plain deposition. To the east, coal beds pinch out against and/or override the progradational Rollin-Trout Creek shoreline sequences; their ultimate lateral extent is limited by the final shoreline position beyond which marine conditions prevail.

Genetic Unit 2 (Coal Package 2)

The second regionally correlatable, genetic depositional sequence, unit 2, is a clastic wedge similar to that of unit 1, except that it did not prograde as far basinward as unit 1. In the southeastern Piceance Basin, unit 2 is subdivided into two genetic units, units 2a and 2b (fig. 9). Unit 2a 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 a minor transgressive event (flooding surface), and the log-pattern change above this marker is subtle. Unit 2a is characterized by the upward-coarsening, progradational log patterns of the lower member of the Middle Sandstone (Collins, 1976; Reinecke and others, 1991) in the southeastern parts of the basin and by overlying minor aggradational coal-bearing rocks. Log facies change to the northwest into aggradational blocky channel-fill sandstones, interbedded with mudstones and discontinuous coal beds.

The third regionally correlatable genetic depositional sequence of the Williams Fork Formation, unit 2b, is a clastic wedge that possibly extended shoreline and coastal plain deposits farther basinward than unit 2a, but not as far as unit 1. Unit 2b is also bounded by regionally extensive, low-resistivity shale markers (fig. 9). The flooding event that defines the base of unit 2b is minor when compared to other flooding surfaces that punctuate the Williams

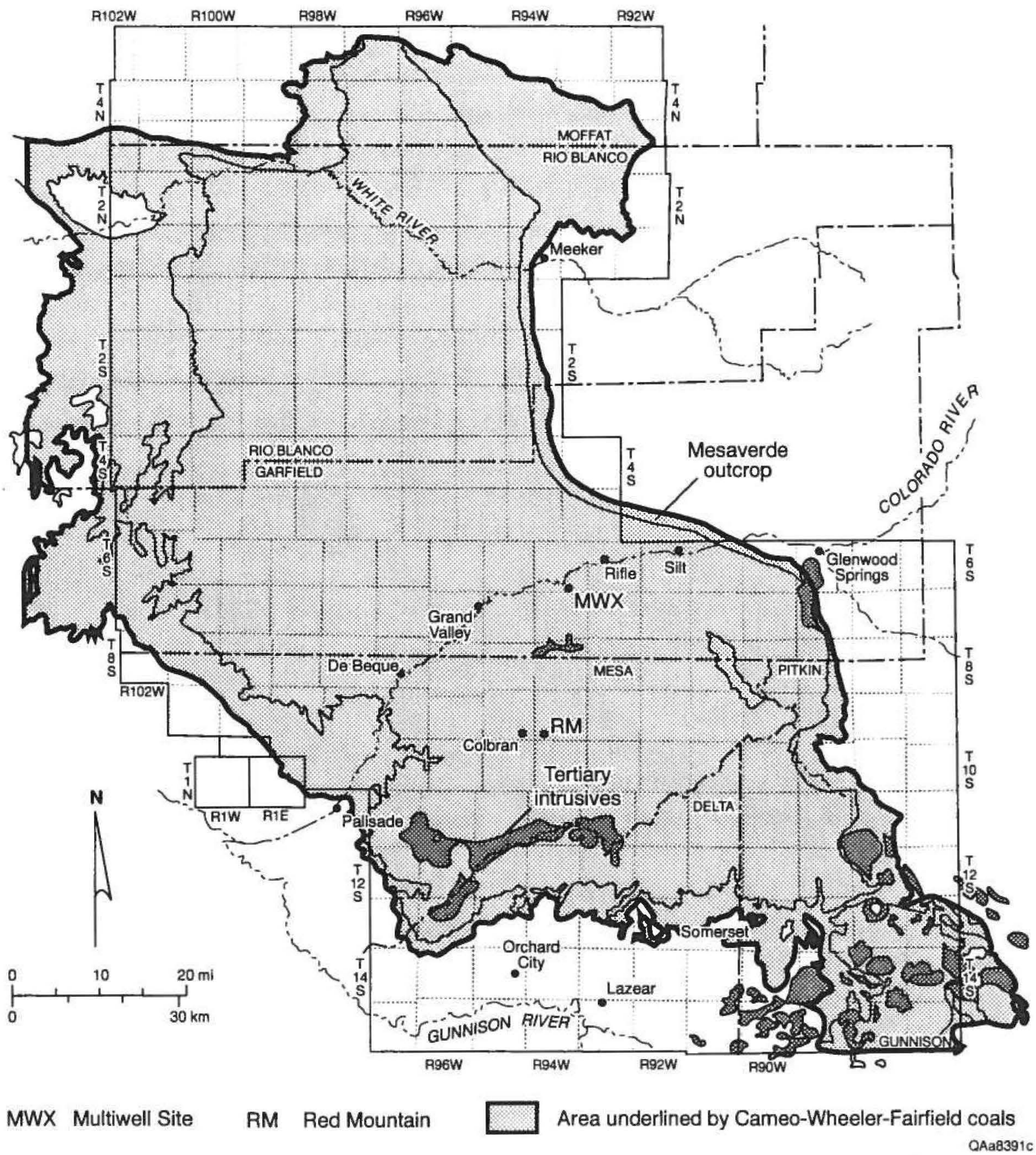


Figure 11. Areal extent of genetic unit 1 coals. Coal-bearing coastal plain deposits extended beyond the present-day margin of the Piceance Basin.

Fork Formation. Thus, the facies offset from underlying mudstone-rich coal-bearing rocks of unit 2a is subtle. The lower boundary is the maximum flooding surface that precedes the upper member of the Middle Sandstone progradation and the overlying aggradational coal-bearing rocks (South Canyon coal zone). Log facies change to the northwest into aggradational blocky channel-fill sandstones, interbedded with mudstones and discontinuous coal beds. The upper boundary represents another transgressive event, a flooding surface at the base of unit 3.

Recognition of genetic units 2a and 2b is limited to the central and eastern parts of the Piceance Basin (fig. 12), east of R97W. Confident correlation of the maximum flooding surface is possible east of R95W. To the west of R95W, genetic sequence correlation becomes difficult but is still possible.

Genetic Unit 3 (Coal Package 3)

The uppermost regionally correlatable genetic depositional sequence of the Williams Fork Formation is genetic unit 3. It is characterized by progradational and aggradational sandstone- and mudstone-rich deposits with minor coal-bearing (Coal Ridge coal zone) horizons. In the southeastern Piceance Basin, unit 3 is dominated by the upward-coarsening and blocky log profiles of the Upper Sandstone progradation (fig. 9), which extended shoreline and coastal plain deposits farther basinward than unit 1. To the northwest, the log facies change to mud-rich aggradational patterns. The upper bounding surface that operationally separates the Williams Fork Formation from the overlying undifferentiated Upper Cretaceous strata is defined on geophysical logs as a change in stacking pattern to blocky, thick fluvial sandstones and accompanying high-conductivity kicks. Coal-bearing strata of genetic unit 3 are limited to the eastern part of the Piceance Basin, east of R95W (fig. 13).

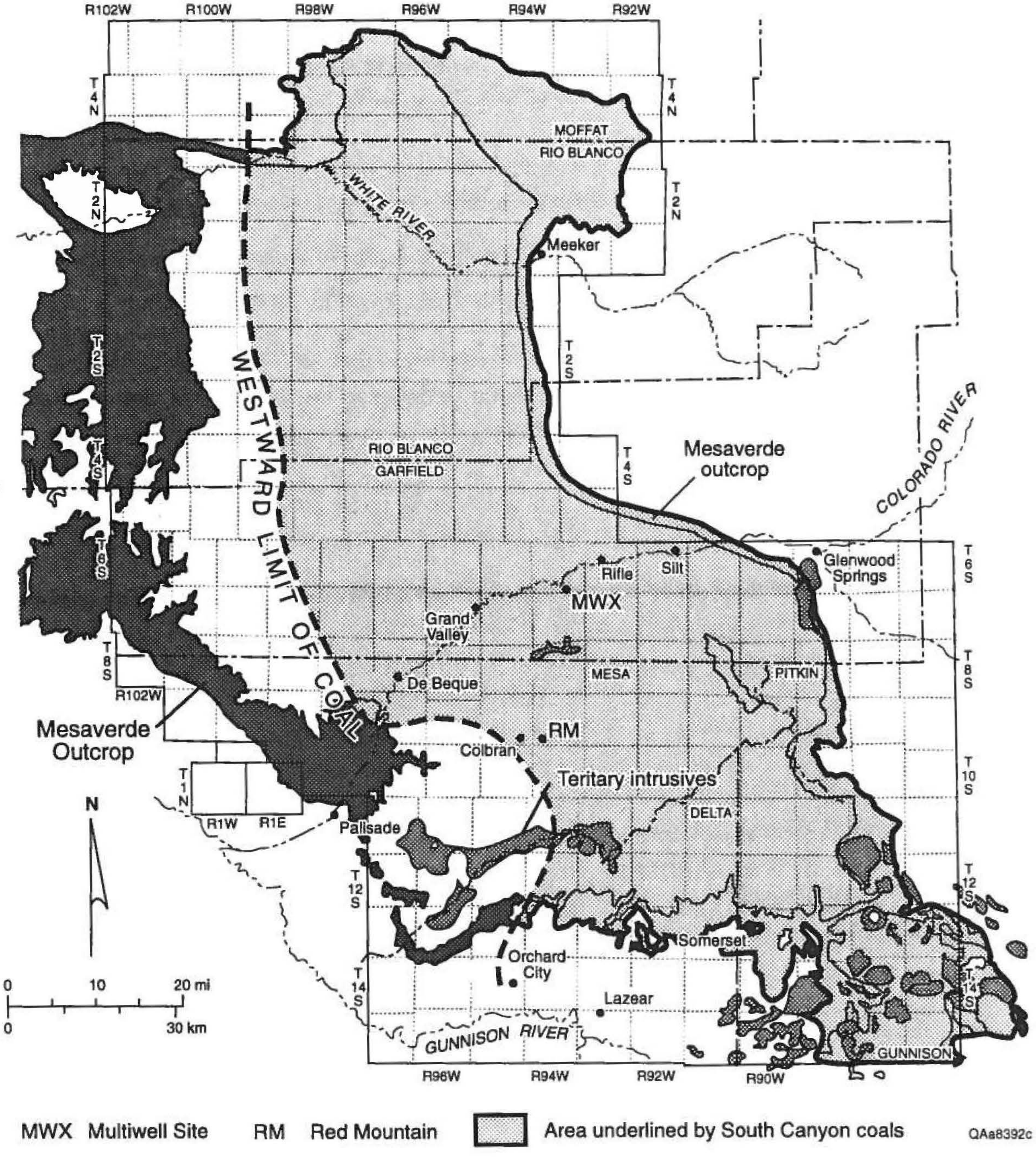


Figure 12. Westward limit of genetic unit 2 coals, indicating a north to northwest orientation to coal thickness trends. Distribution of the coals is intimately related to the depositional systems and basin subsidence trends, indicating an apparent north-south linear shoreline relationship.

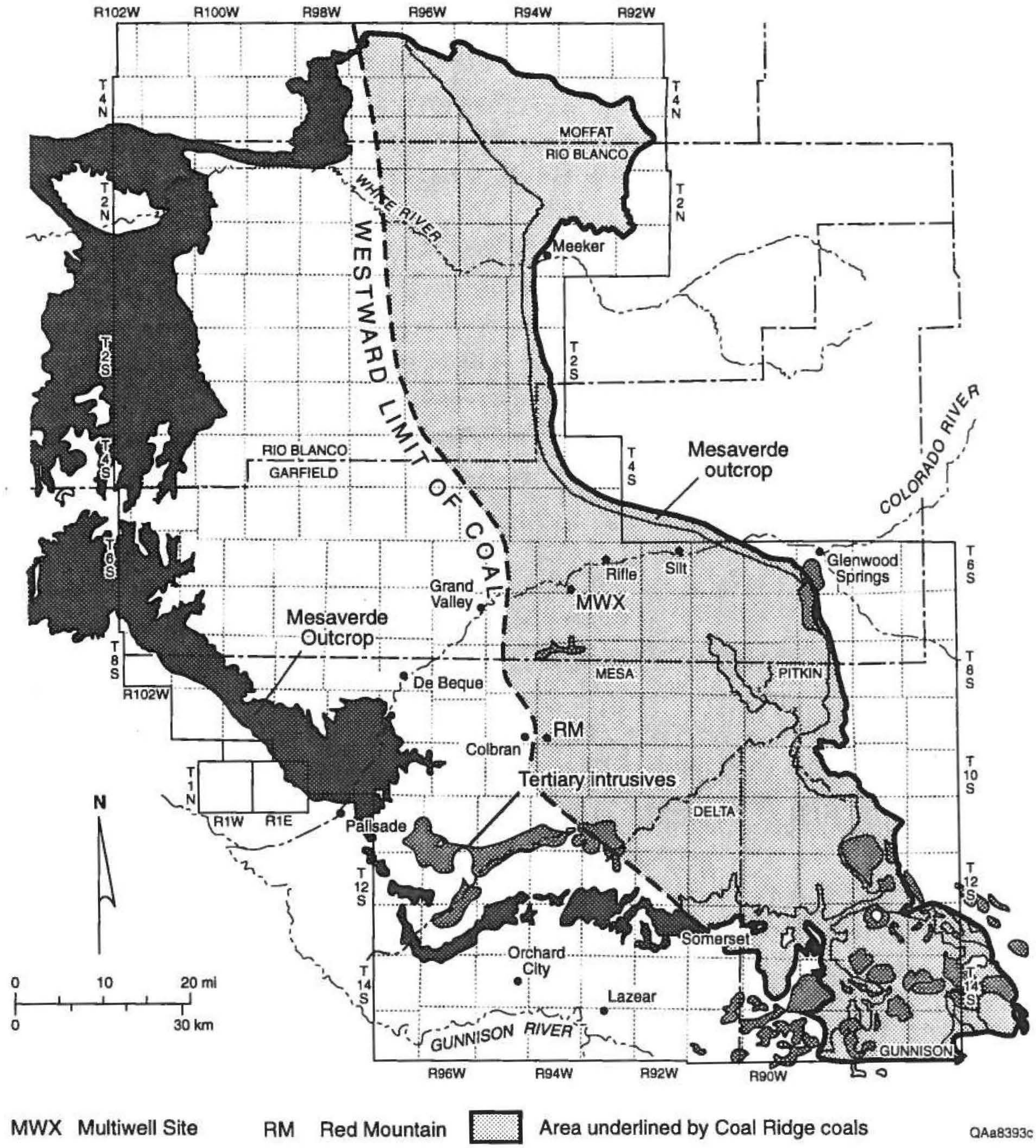


Figure 13. Westward limit of genetic unit 3 coals, indicating a north to northwest orientation to coal thickness trends. Distribution of the coals is intimately related to the depositional systems and basin subsidence trends, indicating an apparent north-south linear shoreline relationship.

Coal Occurrence of the Williams Fork Formation

Coal Identification and Mapping

Coals are identified on geophysical 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. Combinations 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 coal beds and was used in conjunction with very high resistivity and shalelike SP response to operationally define coal in some wells.

Regional net coal mapping was undertaken throughout the Piceance Basin. In some areas net coal thickness is inferred because of the lack of data or because of the assimilation of coals by Tertiary intrusive sills. Caution in net coal mapping is advised where thrusting has resulted in the duplication of the coal-bearing section, especially along the Grand Hogback, Divide Creek Anticline, and the Danforth Hills/Wilson Creek area. Unusually thick net coal, in excess of 120 ft (>36 m), may indicate duplication of the coal section. Confirmation of the thrust duplication of the coal-bearing section will be addressed once regional seismic data have been obtained and interpreted. Furthermore, the following discussion of coal depositional systems inferred from coal orientation is undertaken using a net coal map that is an aggregate or average of several genetic sequences and as such is appropriate for regional interpretation.

Net Coal Occurrence

In the Piceance and Sand Wash Basins, conditions for peat accumulation and preservation occur on the coastal plain immediately landward of shoreline (strandplain/delta plain) sandstones (Hamilton, 1993, 1994; Tyler and others, 1994). Bypassing of coarse clastic sediment, maintenance of high water tables, and optimum subsidence combine in this setting to favor peat accumulation. 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 plain (Hamilton, 1993, 1994; Tyler and others, 1994). Coals also thin to the east as they pinch out against and override the shoreline sandstones. Marine conditions ultimately limit coal distribution to the east.

In the Piceance Basin coals are thickest in a north-trending belt (fig. 14). Net coal thickness of the Williams Fork Formation is at a maximum thickness in the eastern Piceance Basin, where it is as much as 150 ft (45 m), averaging between 80 to 120 ft (24 to 36 m) (fig. 14). In the southeastern Piceance Basin, coals are thickest in the vicinity of the Divide Creek Anticline. Data are scarce on Williams Fork Formation coal distribution between T5S-T1N, R92W-R97W, north of the Colorado River and approximately 24 mi (38 km) west of the Grand Hogback. North of the White River and east of R98W, net coals of the Williams Fork are oriented northeastward and exceed 150 ft (>45 m) in thickness. Generally the net coal thicknesses average between 80 and 150 ft (24 and 45 m). The thick net coal values may reflect structural duplication of section. Net coal thickness decreases westward to less than 50 ft (<15 m) west of R97W. Thinning also occurs in the southeasternmost part of the basin, where net coal thickness is less than 30 to 40 ft (<9 to 12 m). The thickest and most laterally extensive coals occur in Williams Fork genetic unit 1, the lowermost genetic unit. These coals are generally concentrated in the eastern half of the basin, southeast of the Colorado River and northeast of the White River.

Coal Seam Continuity

Continuity of the Williams Fork coals is highly variable. Some individual coal beds were correlatable in the subsurface throughout the eastern half of the Piceance Basin for up to 30 mi (48 km); however, some coal beds only partially extended to the southern and northeastern outcrop belts. 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-

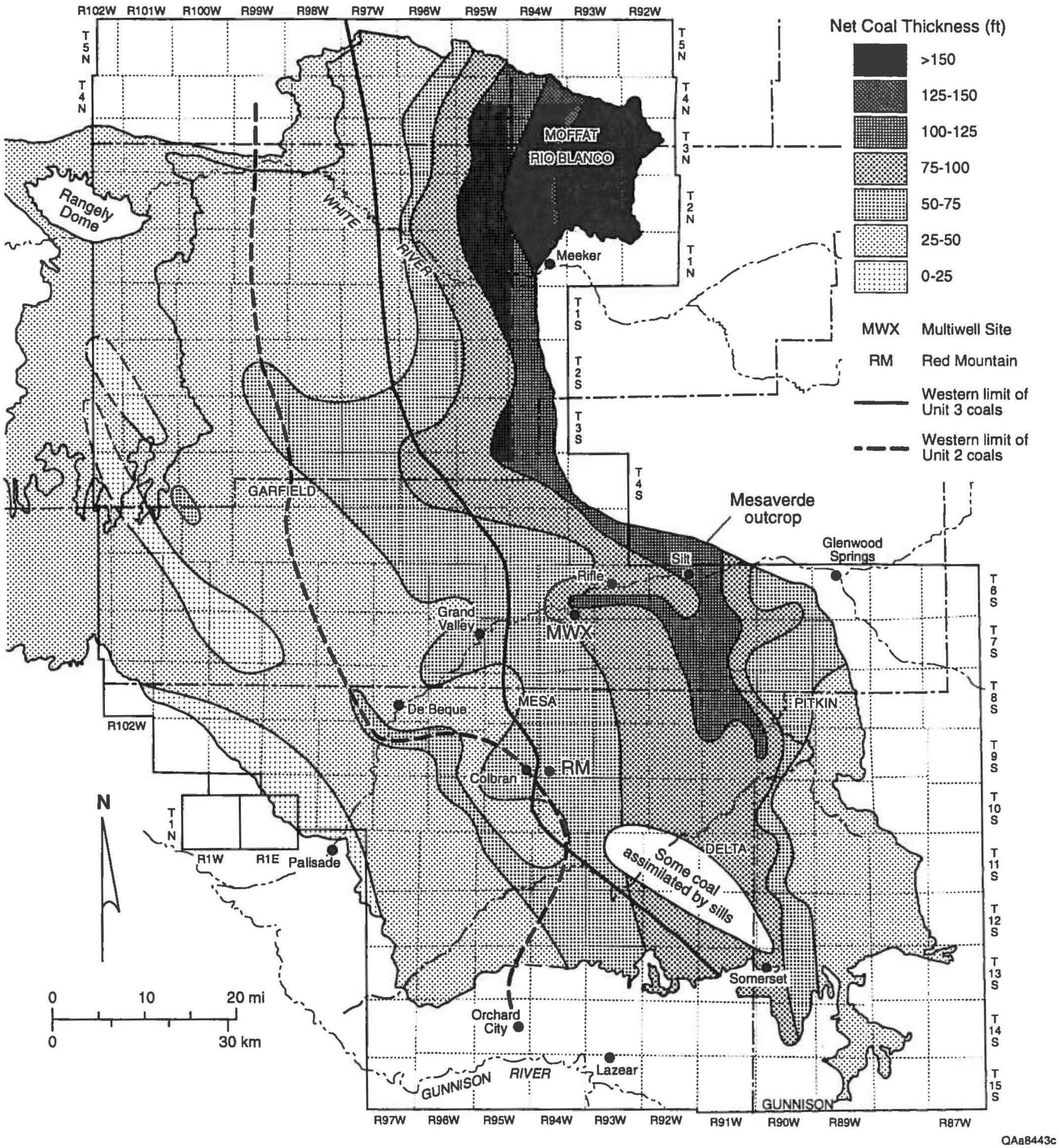


Figure 14. Net coal thickness map of genetic units 1 through 3, Williams Fork Formation. Northerly oriented net coal thickness trends in the eastern Piceance Basin occur above thick, north-south-oriented progradational shoreline (strandplain/delta plain) systems.

distance migration of coal gases and (2) continuous coals act as major aquifers. Any lack of communication between outcrop and subsurface will influence the hydrodynamics and producibility of coal gases within the basin.

Variability in coal continuity is demonstrated in detailed regional and local genetic stratigraphic cross sections (plate 1). Although some coal seams could be traced by their characteristic density and gamma-ray log profiles over most of the southeastern half of the basin, others could be correlated only when grouped within coal packages. Genetic unit 1 coals are somewhat continuous from the subsurface to the outcrop belts in the south and southeast and are thus potential conduits for basinward flow of ground water (plate 1). However, where genetic unit 1 coals reach outcrop, they are reduced in number and total thickness relative to the area immediately basinward in R90W-R93W (plate 1). Thus, not all coal beds are positioned to receive recharge and their ability to transmit water basinward is reduced.

In the southern Piceance Basin, genetic unit 2 coals are less continuous in the subsurface than genetic unit 1 coals and most do not extend to outcrop because their platform of accumulation does not prograde far enough to the east. Genetic unit 2 coals are unlikely to provide potential for interconnected aquifer systems. Genetic unit 3 coals increase in abundance and thickness toward outcrop but have limited westward extent into the basin.

Depositional Systems

Three major depositional systems are identified in the coal-bearing Williams Fork Formation from the geometry of framework sandstones and coals and from log facies. A linear shoreline (strandplain/delta plain) system dominates the southeastern part of the basin and is backed landward by a coastal plain system that grades westward into a predominantly fluvial system. Numerous strike-oriented (north to north-northwest) sandstone trends are apparent in the shoreline system. This, coupled with the strong upward-coarsening log motifs, provides evidence of shoreline progradation. The coastal plain was largely an area of sediment bypass, and the aggradational log patterns that characterize this system reflect thick coals and interbedded mudrocks. The coastal plain passes landward (westward) into alluvial plain and fluvial systems. Log patterns are aggradational and associated with thick, stacked channel sandstones with interbedded floodplain muds.

Geologic Controls on Coal Seam Occurrence

Peat accumulation, metamorphism, and preservation as coal depend on three critical factors: (1) substantial growth of vegetation, (2) maintenance of the water table near the sediment surface, and (3) nondeposition of clastic sediment during peat accumulation. Substantial vegetation growth is determined mostly by climate, and the second two critical factors are controlled by the depositional systems, basin subsidence, and hydrology (Hamilton, 1993, 1994; Tyler and others, 1994). The depositional systems provide the framework within which the peat swamps are established and, combined with subsidence and hydrologic regime, are important in maintaining optimum water table levels for peat preservation.

The ideal location for preservation of the peat is immediately behind the shoreline system, a regional discharge area 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 and preservation. The Williams Fork coals are oriented north to northeast, which parallels the basin subsidence trend. The coals thin to the east and southeast and are ultimately limited by the final position of the shoreline, beyond which marine conditions existed. The western limit of Williams Fork coal-bearing horizons is controlled by the transition from coastal plain to alluvial plain deposition.

CONCLUSIONS

1. The Williams Fork Formation is defined on the basis of correlation with the Williams Fork of the Sand Wash Basin. The Williams Fork Formation has a single major coal-bearing

horizon, the Cameo-Wheeler-Fairfield coal zone, that ranges from 300 to 600 ft (91 to 183 m) thick and lies at an average depth of approximately 6,000 ft (~1,800 m). The most continuous and thickest coal beds (individual seams from 20 to 35 ft [6 to 11 m] thick) formed in coastal plain environments landward (westward) of the progradational strandplain/delta plain deposits of the Rollins-Trout Creek sandstone.

2. The Williams Fork Formation can be divided into several genetic depositional sequences. These sequences were deposited during discrete episodes of shoreline advance and retreat and are bounded by regionally extensive, low-resistivity shale markers that represent marine flooding surfaces in the basinward direction and hiatal, nondepositional surfaces in terrestrial facies.

3. The stratigraphically lowest regionally correlatable 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 genetic unit. A north- to northeast-oriented linear shoreline system dominated the easternmost part of the basin and was backed landward by a coastal plain system, which in turn graded westward into an alluvial plain system. Genetic units 2 and 3 are clastic wedges displaying a similar arrangement of depositional systems to unit 1, but genetic unit 2 did not prograde as far basinward as unit 1, whereas unit 3 prograded farther basinward than both units 1 and 2.

4. Genetic unit 1 contains the thickest, most laterally extensive coals. Coal occurrence in all units is concentrated in the southeastern and northeastern parts of the basin, landward of linear shoreline systems. Genetic units 1, 2, and 3 coals are concentrated in the eastern half of the basin and are thickest in a north-south-trending belt west of the Divide Creek Anticline. In the southern Piceance Basin, net coal thickness of the Williams Fork Formation averages 80 to 120 ft (24 to 36 m). Data are scarce on Williams Fork Formation coal distribution between T5S-T1N and R97W-R92W, north of the Colorado River, and for approximately 24 mi (39 km) west of the Grand Hogback. North of the White River and east of R98W, net coals of the Williams

Fork exceed 150 ft (>45 m) thick but generally average between 80 and 150 ft (24 and 45 m) thick.

5. Coal occurrence in all units is intimately related to the depositional systems. The coastal plain immediately landward of the shoreline (strandplain/delta plain) system was the optimum site for peat accumulation and preservation in Williams Fork genetic units 1 through 3. Coal beds pinch out against and/or override the shoreline sandstone to the east, and their ultimate lateral extent is limited by the final shoreline position beyond which marine conditions prevailed. In a landward direction, they are limited by rising surface gradient and falling water table, controlled by the transition from coastal plain to alluvial plain.

6. Continuity of the Williams Fork coals is variable. Some individual seams, particularly in genetic unit 1, are correlatable for up to 30 mi (48 km) in the southeastern half of the basin on the basis of their density and gamma-ray profiles. Other seams could be correlated only when grouped within coal packages. The coals of unit 1 are only moderately continuous from the subsurface to the southern, southeastern, and northeastern outcrop belts.

7. Limited recharge may have implications for the producibility of coal gas. In the absence of dynamic ground-water flow, less gas is dissolved and swept basinward for eventual resorption and conventional trapping along potential no-flow boundaries. At the same time, the generation of secondary biogenic gases is minimized. Thus, without additional sources of gas beyond that sorbed on the coal surface, high coal-gas productivity may be precluded. Perhaps the parts of the basin with the best potential for coal-gas production lie in conventional traps basinward of areas where outcrop and subsurface are in good hydraulic communication.

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Genetic Stratigraphy of the Coal-Bearing Williams Fork Formation Piceance Basin, Colorado

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Plate 1
Colorado Geological Survey
Open-File Report 95-2
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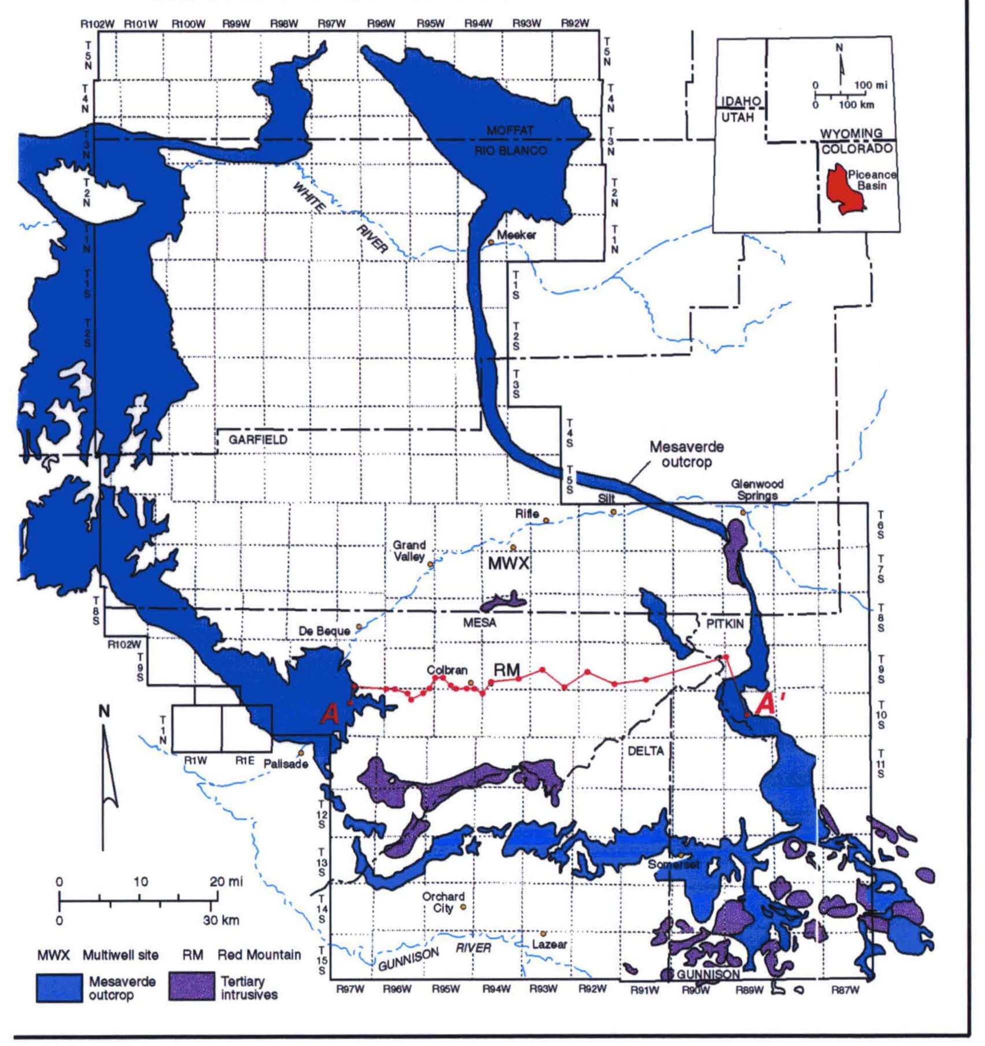
Location of Cross Section *A-A′*



Nonmarine sandstone

Marine and marginal-marine sandstone

Shale

Coal

Flooding surface

PS1 Progradational sequence 1

COAL ZONE

3 Coal Ridge

2 South Canyon

1 Cameo-Wheeler-Fairfield

* Measured section from Collins (1976)

** Terminology from Johnson (1989)

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