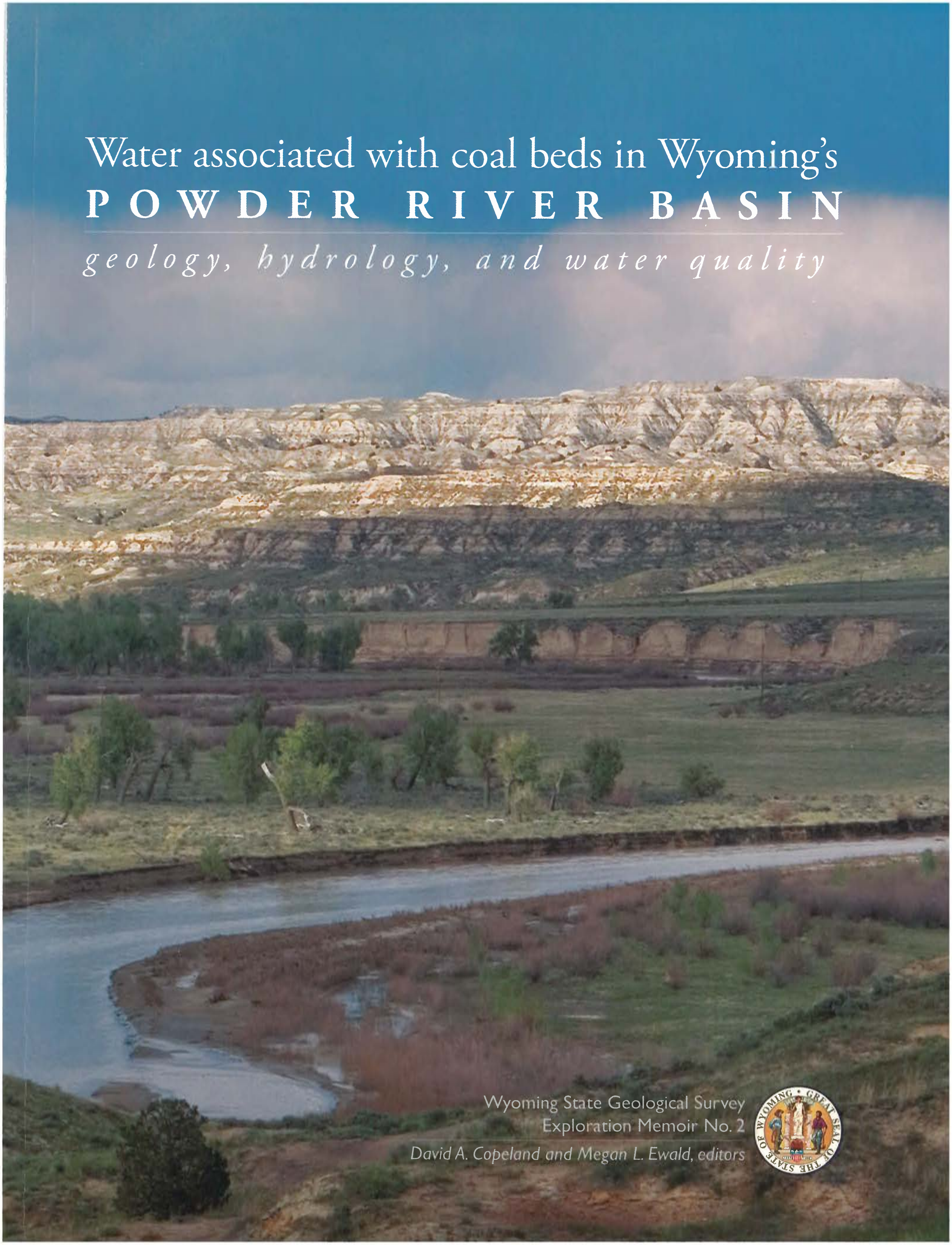
Water associated with coal beds in Wyoming's POWDER RIVER BASIN

geology, hydrology, and water quality



Wyoming State Geological Survey
Exploration Memoir No. 2

David A. Copeland and Megan L. Ewald, editors

Wyoming State Geological Survey
Ronald C. Surdam, State Geologist

Storm over outcrops of the Wasatch Formation along the Powder River.

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Cover: Outcrops of the Wasatch Formation tower over the Powder River in Wyoming's Powder River Basin. *Photo by Meg Ewald.*

CORRECTIONS & ADDITIONS

Exploration Memoir No. 2

Water associated with coal beds in
Wyoming's Powder River Basin

This memoir represents one of the first efforts by the WSGS to create a cross-disciplinary study using advanced computer technology to normalize, integrate, and visualize great quantities of data. A truncated final preparation stage led to inadequate editorial review, so there are many errors in the publication. Below, we offer several clarifications and address those errors that we believe warrant attention. The reader is seriously invited to point out what we have missed.

David Copeland
Megan Ewald
October 2008

Apologia

Figure 1-10 (page 28), an isopach map, shows an area of negative thickness. **Figure 4-123** (page 269) shows an area of negative sulfide concentration. Both impossibilities are plotted where steeply converging top and bottom surfaces are extrapolated to, and past, intersection. The model does not consider zero thickness or concentration below a detection limit. Thus may negative property values result from the smoothing of sparse data. And, make no mistake: spread over the 12,500 square miles of the Wyoming PRB, even the great amount of data with which we now work is sparse data.

Chapter 2 describes the subsurface distribution and thickness of 26 coal beds; Chapter 4 displays basin-wide structural and compositional characteristics of the coal beds described in Chapter 2. There are marked differences between the coal bed maps in Chapter 2 (**Figures 2-7** to **2-32**) and the corresponding maps in Chapter 4 (**Figures 4-5** to **4-82**), and between corresponding coal-bed volume estimates (and in different units – **Tables 2-9** and **4-2**). The reason: different scales of resolution were employed to fulfill the different purposes of the two chapters. Chapter 2 focuses on the thickness of a coal bed at any given location; the coal bed descriptions were developed from bore hole data as generated using ArcGIS™ Spatial Analyst™ at fine resolution, on a grid 30 meters square. Chapter 4 focuses on the structural elevation of the coal beds as stratigraphic units and the distribution of water quality parameters, basin-wide; the coal bed displays were developed from the bore hole data and correlations from Chapter 2, but were represented in Earth Vision© at coarse resolution, on a grid approximately one-half mile square.

Therefore, to evaluate the coal beneath a given ground location, the Chapter 2 presentation is more precise and more useful. To visualize the structural configuration of the coal bed sequence over the whole basin, the Chapter 4 presentation is more useful. And as for the coal bed volumes, the Chapter 4 authors' decision to use the more accurate Chapter 2 volume estimates was not carried into the final preparation stage. The values in **Table 2-9** are to be used.

On a lighter note: A computer, having no conscience, is not at all embarrassed to present numerical conclusions at far more significant figures than are justified by the precision of the data from which they are derived. Thus, for example, can the volume of the Canyon Rider coal bed shamelessly presented (**Figure 4-49**) as 3,147,517,616.0 m^3 reasonably be read as 3.15 billion cubic meters.

Corrigenda

Section	Location	As written	As corrected
Introduction	p. 11, RH column, acronyms	DEQ	WDEQ
Chapter 1	p. 19, RH column, ¶ 1, line 6–7	inidcates tectonic activity	indicates little tectonic activity
	p. 21, LH column, ¶ 1, line 4	Steele	Steele (Cody equivalent)
	p. 22, LH column, ¶ 2, line 4 from end	Oligocene	Oligocene rocks
	p. 38, line 1	Plate 1-1	Plate 1
Chapter 2	p. 54, LH column, line 2 from bottom	(DEQ)	(WDEQ)
	p. 54, LH column, ¶ 4, line 2	DEQ	WDEQ
	p. 57, LH column, ¶ 3, last sentence	Figure 2-6 shows the distribution of well data for both the 2003 northern correlation model and the 2007 basin-wide correlation model.	Figure 2-6 shows the distribution of well data used in the 2007 basin-wide correlation models.

Corrigenda

Section	Location	As written	As corrected
Chapter 2	p. 60, LH column, ¶ 4, line 1	$\sum\limits_{i} i$	$\sum i$
	p. 60, LH column, ¶ 5, line 1	$\sum\limits_{j} j$	$\sum j$
	p. 60, RH column, ¶ 2, line 11	Figure 2-7 shows the area	Figure 2-6a shows the area
	p. 60, RH column, ¶ 2, line 2 from end	T. 50 N.,	T. 49 N.,
	p. 61, table, Wall coal	Cocal	73, 112
	p. 70, LH column, ¶ 2, last line	p. 36	page 34 and last paragraph, page 37
	p. 70, LH column, ¶ 3, line 16	Tps. 51 and 53 N.	Tps. 52 and 53 N.
	p. 74, LH column, ¶ 1, line 2 from end	Rs. 72-77 W.	Rs. 73-77 W.
	p. 80, LH column, ¶ 2, last line	p. 68	p. 70
	p. 92, LH column, ¶ 2, line 6	1,097,580 acres	1,250,938 acres
	p. 94, figure caption	Figure 2-3	Figure 2-33
Appendix 2A	p. 97, RH column ¶ 2, line 2 from end	Figure 2A-2	Figure 2A-1
	p. 98, LH column, ¶ 1, line 2	Figure 2A-1	Figure 2A-2
Chapter 3	p. 128, RH column, ¶ 3, last line	minor aquifer	major aquifer
	p. 153, LH column, last ¶, line 5	basing	basins
	p. 155, LH column, ¶ 1, line 8	Appendix 4A	Appendix 4A2
	p. 157, RH column, ¶ 4, line 9	Receive	receives
Chapter 4	p. 163, LH column, last line	Appendix 4A	Appendix 4A1
	p. 165, LH column, ¶ 3, lines 1–2 from end	these maps	some of these maps
	p. 165, LH column, ¶ 6, lines 5–11	The five N-S cross sections are equally spaced (about 19 miles apart); they begin in the south, and each subsequent section is farther north (the viewer is looking north). The five E-W cross sections are also equally spaced (about 20 miles apart); they begin in the east, and each subsequent section is farther west (the viewer is looking west).	The five N-S cross sections are spaced about 19 miles apart; they begin in the west (4-3a), and each subsequent section is farther east (the viewer is looking west). The five E-W cross sections are spaced about 20 miles apart; they begin in the south (4-4a), and each subsequent section is farther north (the viewer is looking north).

Corrigenda

Section	Location	As written	As corrected
	p. 166, RH column, ¶ 2, line 2 from end	Figure 4-83 through Figure 4-91	Figure 4-83 and Figure 4-91
	p. 167, RH column, line 4	4-113	4-112
	p. 275, color-bar heading	ug	µg
	p. 276, color-bar heading	ug	µg
	p. 278, color-bar heading	ug	µg
	p. 283, color-bar heading	us/cm	µs/cm
Chapter 5	p. 304, table, North Platte River line	13%	12%
	p. 304, LH column, ¶ 2, line 2	(Plate 2)	(Plate 2, on DVD in pocket)
	p. 305, LH column, ¶ 1, line 3	or 234 ft^3/minute)	, 234 ft^3/minute, or 3.9 ft^3/second)
	p. 305, LH column, ¶ 1, line 7	1,750 gpm	1,750 gpm, 2.5 gpd
Chapter 6	p. 314, LH column, ¶ 3, line 12	linears	lineaments
	p. 321–323, Tables 6-3b to 6-3g, box heads	[All box head dates are 2007 and 2008]	[Box head dates correspond to table titles]
	p. 324, Table 6-3i, caption	(MCF/day)	(bbls/day)
	p. 325–328, Tables 6-4b to 6-4g, box heads	[All box head dates are 2007 and 2008]	[Box head dates correspond to table titles]
	p. 328, Table 6-4i, caption	(MCF/day.well)	(bbls/day)
	p. 342, caption, line 2	absorption	adsorption
	p. 343, RH column, ¶ 3, line 1	linears	lineaments

Addenda

Location	Add
p. 5, below "Figure 2-6..."	Figure 2-6a. Index map for 26 major coal bed maps...62a
p. 11, RH column, acronyms	IMS: Interactive Mapping Service, WSGS WQD: Water Quality Division, WDEQ
p. 62a: between pages 62 and 63	Figure 2-6a. Index map for maps of the 26 major coal bed maps...
p. 329, RH column, ¶ 2, end of ¶	(Figure 6-9)

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[*] Chapter 5 was first published in 2006 as Wyoming State Geological Survey Challenges in Geologic Resource Development 1, *Powder River Basin desalination project feasibility*.

[**] Chapter 6 was first published in 2007 as Wyoming State Geological Survey Challenges in Geologic Resource Development 3, *An evaluation of coalbed methane production trends in Wyoming's Powder River Basin: A tool for resource management*.

INTRODUCTION

David Copeland

This project was initiated to extend earlier coverage of the northern PRB to include the area of the basin south of the 12th Standard Parallel North. Partway into the project, concern about the quality and usefulness of our methods and results led us, rather, to incorporate the raw data from the northern PRB project into our database and to generate integrated models for the whole basin. This allowed us to model at a consistent level of quality, to present a seamless interpretation across the 12^{th} Standard Parallel, and to create an interactive website with uniform coverage over the basin. We count our three-dimensional modeling and visualization product as a major advance in our ability to understand and assess the coal, coal bed natural gas, and water resources of the PRB.

This report describes the subsurface of the Wyoming Powder River Basin north of the 10th Standard Parallel North and the surface of the entire basin. Insufficient reliable subsurface data exist at this time for the area of the basin south of the 10th Standard Parallel. In light of this and other data deficiencies, we designed our model to be upgraded (regenerated) annually from an annually expanded database. We count this capacity for continually improving our product as a major contribution of this project.

The project goal was to create a means of predicting the quality of the water that would be produced from any given coal bed anywhere in the basin. The objectives we identified to accomplish this goal were:

- Collect and rationalize databases of coal bed top and base elevations and of water analyses
- With data processing, create three-dimensional models of coal beds and water quality parameters
- Integrate these models, associating water quality with coal beds
- Display the coal, water, and integrated models geospatially as maps, contour maps, inclined views of volumes, and cross sections
- Create a framework for continually upgrading the water quality and integrated models

Pursuit of these objectives yielded several useful by-products:

- A new interpretation of basin-wide Tertiary coal distribution in the Wyoming PRB, the most accurate and useful to date
- A more precise estimate of coal volumes than previously attainable
- A comprehensive description of the water resources of the basin, as complete as available data allowed, with a look at subsurface water movement
- An interactive website where many other sorts of information can be superimposed on our maps and subsurface views – some examples are wildlife distribution, crops, pipelines, geologic hazards, soils, and microclimates

◆

Chapter 1 presents the geologic history of the PRB area within the geologic history of Wyoming. Various sedimentary sources and environments of deposition prefigured the aquifers, aquitards, and coal beds of today. Structure contour and isopach maps illustrate the present form of the Upper Cretaceous and Tertiary formations of interest.

Chapter 2 begins with a history of how coal deposits in the basin were perceived and classified during the 20th century. A new interpretation of the basin-wide distribution of Tertiary coals in coal beds and coal zones in the PRB is based on the computer analysis and configuring of the largest database assembled to date for these coals. We illustrate our three-dimensional modeling by distribution maps of thin and thick coal in each of the 26 major coal beds. An algorithm that sums coal volumes in consecutive thickness intervals gives a new coal volume estimate for each coal bed. An appendix describes how we identified coal beds and other lithologies on geophysical well logs.

Chapter 3 describes in detail the aquifers and aquitards in the basin, Precambrian to Recent, as well as surface water and drainage. As the availability of reliable data allows, water quality parameters and chemistry are tied to each aquifer in various parts of the basin and at various depths.

Chapter 4 describes our use of proprietary and WSGS in-house computer programs to associate water quality parameters and water chemistry with individual coal beds in integrated three-dimensional models. A water quality parameter – TDS, for example – from the analysis of a sample is tied to the geographical coordinates of the well from which the sample was taken and the depth of penetration of the well. The spatial information is matched with the particular coal bed (or aquifer) that occurs at that depth at those coordinates. A number of such matches across the basin in that coal bed allows the contouring of the coal bed with respect to TDS; the product is a TDS distribution map of the coal bed. This chapter contains many visualizations of the distribution of water quality parameters and ion concentrations on contour maps and cross sections. These visualizations show the flexibility and specificity that this product offers in water quality prediction. An appendix describes the interactive hydrological and geological database and how to use it.

This report is timely in that the state of Wyoming and the oil, gas, and coal industries, particularly the CBNG industry, must proactively address the twin problems of the quality and quantity of co-produced water in the PRB, or will have to do so reactively, and at greater cost, as the problems worsen. Chapters 5 and 6 suggest approaches to these problems.

Chapter 5 explores desalination as an option for CBNG produced water treatment that meets the first of the two greatest challenges facing CBNG development in the PRB, the quality and quantity of co-produced water. Treating all water produced during CBNG activities to drinking water quality standards would optimize beneficial use of the water and minimize waste; and plant to do it would be paid for promptly.

Chapter 6 addresses the quantity problem, identifying these factors that indicate increased water production all out of proportion to increased gas production. The WSGS supports regulation of CBNG wells, after a reasonable dewatering period, based on water/gas ratio, as well as a moratorium on development in areas where no promise of achieving minimum water/gas ratios can be shown. Implementation of these measures would be a first step in developing a strategy to minimize both produced water and animosity toward future CBNG development, and would set regulation of CBNG activity in the basin on a sound, scientifically-supported path.

* * *

The basin is defined a little differently for the purposes of each of chapter. The basin is most broadly defined as the Powder River Basin Drainage Area (PRBDA), that part of northeast Wyoming drained by the rivers originating in the PRB, and bounded by watershed divides and the state line. Within the PRBDA is the Powder River Basin (PRB), the geologic basin surrounded by uplifts, and, for purposes of coalbed description and interactive modeling, that area of the basin underlying the Fort Union formation. The Powder River basin is the drainage basin of the Powder River, one of the six rivers draining the PRBDA.

The authors of these chapters would like to acknowledge and thank several members of the WSGS staff, the Wyoming Oil and Gas Conservation Commission, and the Wyoming Water Development Commission. Throughout the course of this of project, every member of the WSGS staff made at least a small contribution and should be recognized; however, the authors would like to acknowledge a few that put a lot of time and effort into the completion of this report. Dave Copeland and Meg Ewald, thank you for a very thorough and swift editing and review process. The authors also thank Jim Rodgers, David Lucke, Allory Deiss, and Robin Lyons for creating the many graphics and figures in this report. Most of the data gathered to build these models came from the Wyoming Oil and Gas Conservation Commission, and the authors thank them for providing an up-to-date public information hub. Finally, the WSGS staff would like to thank the Wyoming Water Development Commission for funding this project. Their support brought about a comprehensive and in-depth study of the Wyoming Powder River Basin.

* * *

Acronyms: we don't like them much either, but they do save trees and diminish eye strain.

CBNG	coal bed natural gas
DEQ	Wyoming Department of Environmental Quality
NPDES	National Pollutant Discharge Elimination System (U.S. Environmental Protection Agency)
PRB	Powder River Basin – the structural and depositional basin
PRBDA	Powder River Basin Drainage Area – the area of northeast Wyoming drained by rivers originating in the PRB
TDS	total dissolved solids – in groundwater or surface water
USGS	United States Geological Survey
WOGCC	Wyoming Oil and Gas Conservation Commission
WSGS	Wyoming State Geological Survey
WWDC	Wyoming Water Development Commission
WYPDES	Wyoming Pollutant Discharge Elimination System

CHAPTER 1

geography and geology

Alan J. Ver Ploeg, Rodney H. DeBruin, and Richard W. Jones

The Powder River Basin (PRB) of northeastern Wyoming and southeastern Montana (**Figure 1-1**) occupies the western part of the Northern Great Plains physiographic region. This report deals only with the Wyoming PRB, which encompasses approximately 12,500 square miles in 350 townships in an area extending from T. 32 N. to T. 58 N., and from R. 66 W. to R. 86 W.

The geologic map of the Wyoming PRB (**Plate 1**, on DVD in pocket) prepared for this study is based on 16 Wyoming State Geological Survey (WSGS) bedrock geologic maps of 1:100,000-scale metric quadrangles (**Appendix 1A**) that make up the northeast quadrant of Wyoming. **Plate 1** shows the surface geology both in the basin and on the flanks of the surrounding uplifts.

In this chapter, we use the terms *Powder River Basin* or *PRB* to designate the present structural and depositional basin, and the term *PRB area* to describe that earlier, pre-Laramide area that became a basin in the Late Cretaceous.

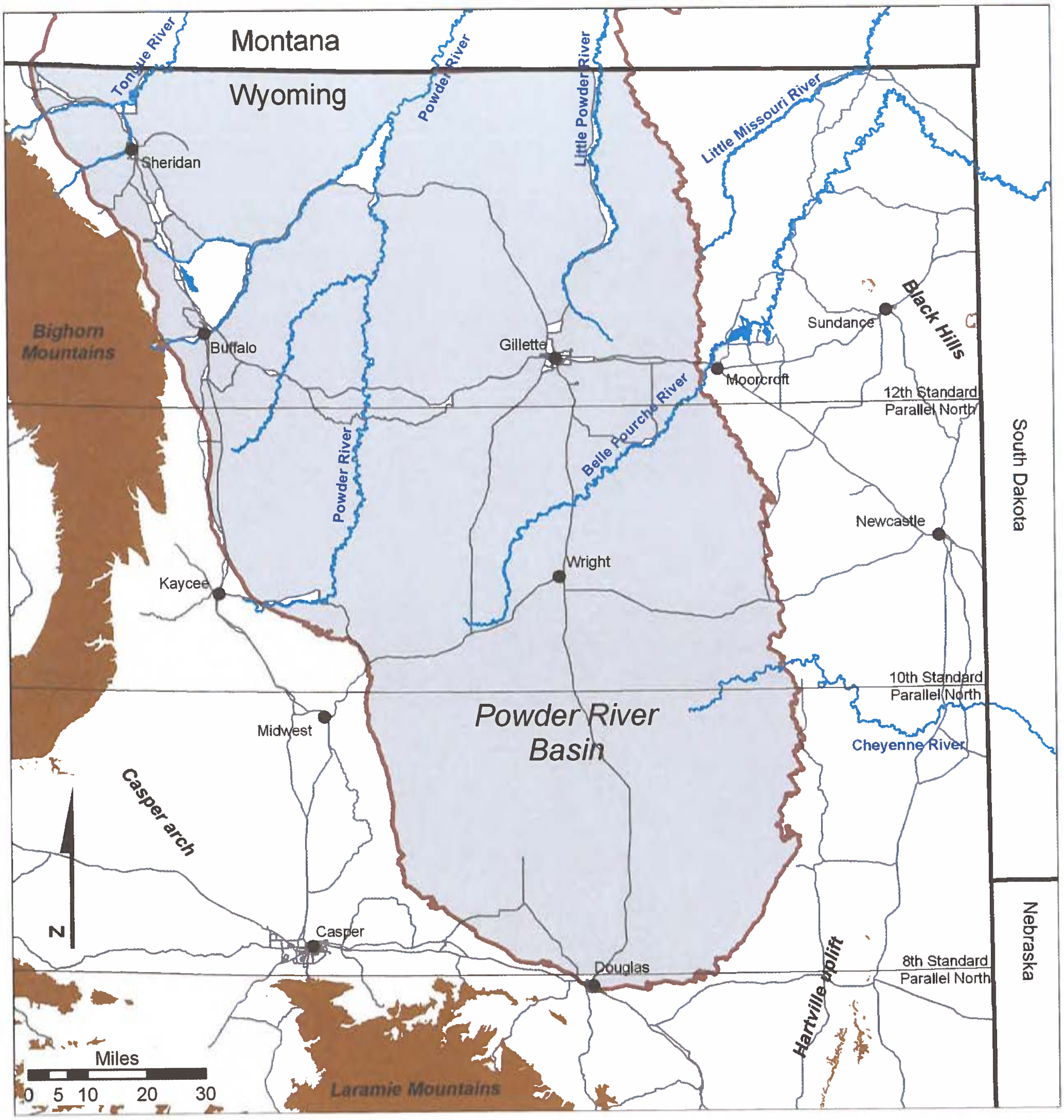


Figure 1-1. Location map of the Wyoming Powder River Basin showing major geographic features. The reddish brown line outlines the extent of the Fort Union Formation (gray), the area underlain by the coal beds of the basin. Brown areas are outcrops of Precambrian rocks.

Geography

The Wyoming PRB is a large intermontane basin surrounded by mountainous terrain on the south, east, and west. Elevations in the PRB range from approximately 3,200 to 7,480 feet above sea level (Knight, 1994); higher elevations occur on the basin margin along the flanks of the Bighorn and Laramie mountains and the Black Hills. Major drainages in the area include the Powder, Tongue, Belle Fourche, and Cheyenne rivers and their tributaries (**Figure 1-1**). Surface waters in the PRB flow north or east into the Missouri river system. Annual precipitation ranges from 12–16 inches in the basin (Knight, 1994) to more than 30 inches in the mountains.

Major industries in the PRB include oil, gas, and coal extraction and related activities; agriculture (ranching and irrigated farming); and recreation/tourism. Most of the area is sparsely populated and rural. Casper, Gillette, and Sheridan are the major population centers in the basin. Several railroads, mainly used by unit trains transporting large amounts of coal to out-of-state power plants, serve the PRB. Interstate Highway 90 crosses the basin from east to west, and I-25 crosses the western PRB from south to north, meeting I-90 near Buffalo. U.S. and state highways connect towns and smaller settlements in the area.

Geologic overview

The Powder River structural basin of northeastern Wyoming and southeastern Montana is a deep, asymmetric, mildly deformed trough approximately 250 miles long north to south and 100 miles wide east to west. This Laramide (approximately Late Cretaceous – Eocene) foreland basin is bordered on the south by the Hartville uplift, the Laramie Mountains, and the Casper Arch; on the west by the Bighorn Mountains; on the north by the Miles City Arch in Montana; and on the east by the Black Hills (**Figure 1-2**). The basin axis trends north-northwest in the Wyoming PRB, as expressed by structure contour maps of stratigraphic units (presented below). The axis runs parallel to and several miles east of the steeply dipping west margin of the basin. In Montana, the basin axis trends north-south.

Structural relief in the PRB (at the Precambrian-Cambrian contact) is more than 25,000 feet (Blackstone, 1981). The Paleozoic, Mesozoic, and Cenozoic rocks in the basin are more than 18,000 feet thick along the basin axis. Early Tertiary rocks crop out extensively in the central part of the basin (**Plate 1-1**) and dominate the surface geology. Surficial deposits and related landforms occur primarily along major drainages and the basin margins. Rocks at the surface dip gently 1 to 3 degrees west in the eastern basin (east of the basin axis and west of the Black Hills Monocline), and are steeply dipping to overturned on the west and southwest margins. Major faults and folds are mostly restricted to the mountain flanks surrounding the basin. Displacement on the major reverse and thrust faults is as great as 4,100 feet (Blackstone, 1981), and some faults may have strike-slip components. Normal faults with small displacement and shallow folds also exist within the basin.

Geologic history

Rocks exposed in the PRB area record a long and complex geologic history, and represent nearly all geologic time periods. However, unconformities (in the older rocks especially) reveal the incomplete nature of the geologic record actually preserved, and indicate periods of either non-deposition or deposition and later removal by erosion. Late Mesozoic and early Cenozoic rocks preserve the most complete geologic record of the PRB. Precambrian crystalline rocks form the basement in the PRB, and are exposed in most of the mountains and uplifts surrounding the basin. These oldest rocks are mostly Archean in age, having formed more than 2.5 billion years ago (2.5 giga-annum or Ga); this chapter does not address them further. Following a long period of erosion at the end of the Precambrian that resulted in a regional unconformity (nonconformity), deposition of the Phanerozoic sedimentary sequence in northeastern Wyoming and the area that would become the PRB began approximately 570 million years ago (570 mega-annum or Ma).

The PRB (and most of the surrounding uplifts) did not exist as a structural and depositional entity until its present structural configuration began to form at the beginning of the Laramide Orogeny during the latest Cretaceous (approximately 70 Ma) and early Tertiary (approximately 60 Ma). Earlier in the Cretaceous Period (approximately 120–80 Ma), the onset of the Cordilleran Orogeny (i.e., the Sevier

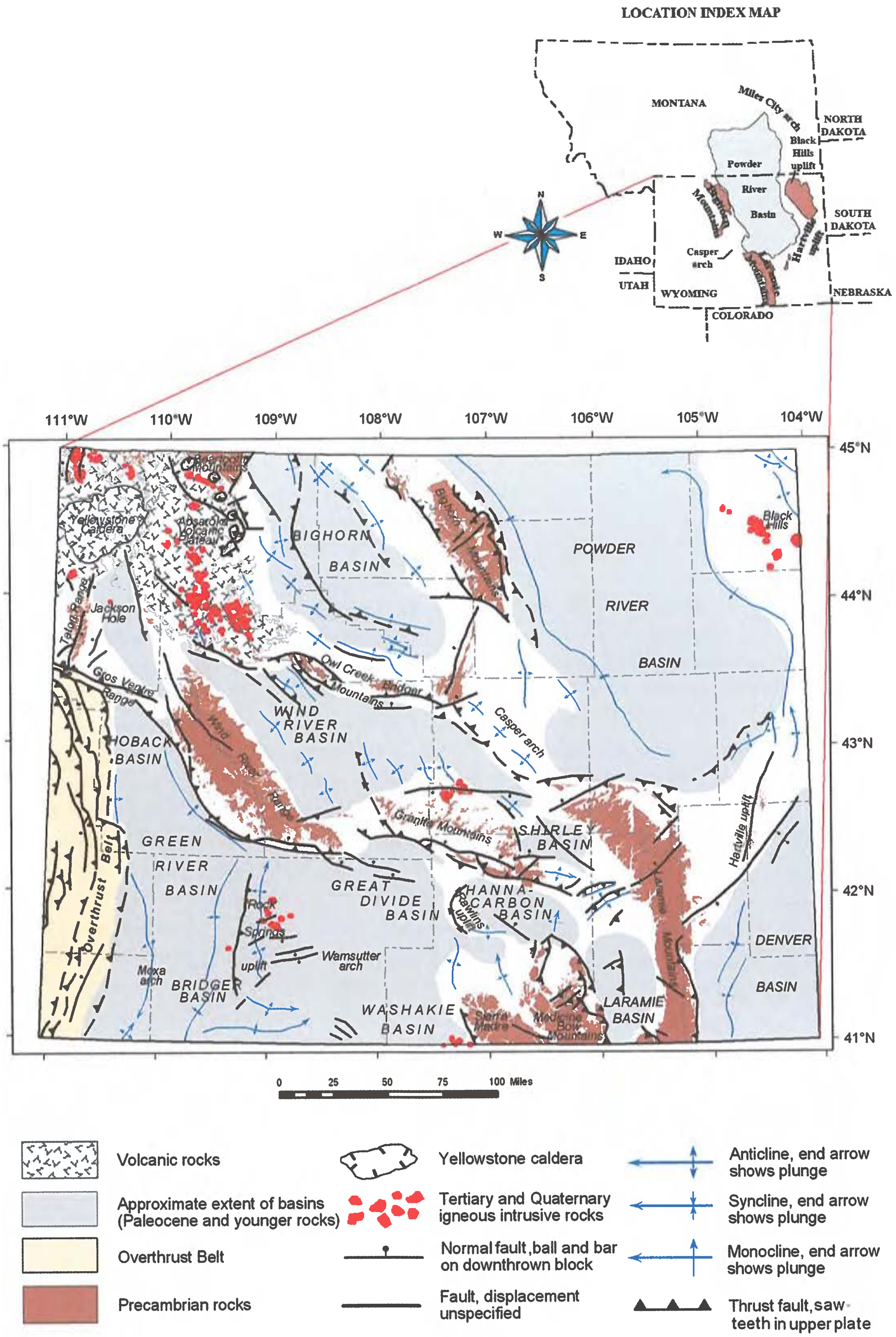


Figure 1-2. Index map of major structural and tectonic features in Wyoming and the Powder River Basin. Location index map modified from J.L. Brown (1993); Structural index map from De Bruin (2007).

Orogeny) some distance west of the PRB caused a large foreland basin to form east of that orogenic belt. A thick sequence of primarily marine, marginal marine, and deltaic sediments accumulated in this basin on the western edge of the Cretaceous Interior Seaway; a great thickness of Upper Cretaceous and early Paleocene strata is now preserved in much of Wyoming and the PRB. In the late Paleocene and early Eocene (the Laramide Orogeny in the PRB), orogenic pulses progressed eastward and segmented the area into the basins and uplifts that constitute northeastern Wyoming today. Prior to this orogenic activity, Paleozoic and lower Mesozoic rocks had been deposited in paleogeographic and paleotectonic settings very different from these later (Laramide) settings (Macke, 1993).

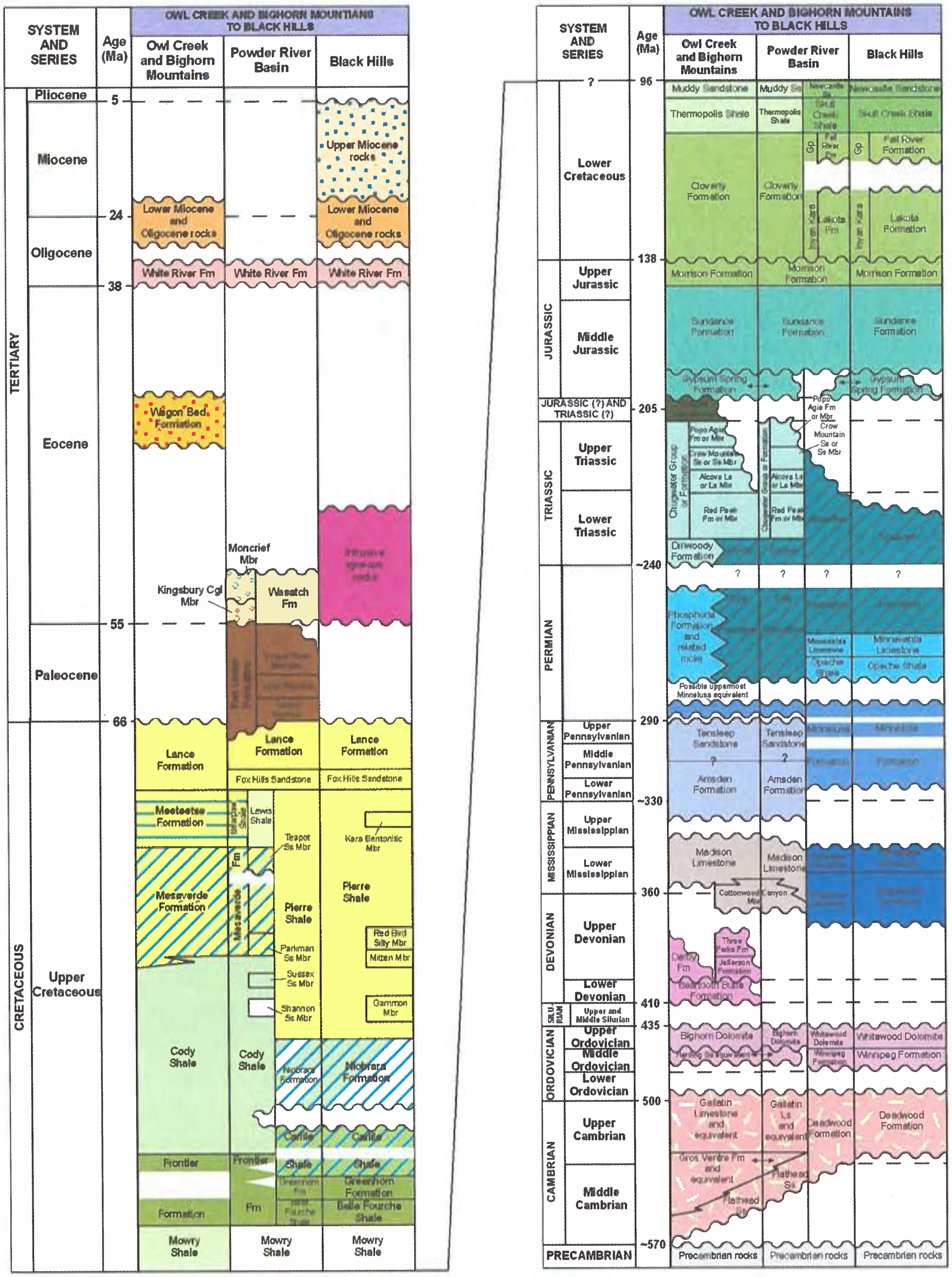
Paleozoic Era

The Paleozoic geologic history of the PRB area and that of the rest of Wyoming are essentially the same. Boyd (1993) provides a general and very informative synopsis for each period in the era. We abstracted much of the discussion below from that article. The stratigraphic chart of northeastern Wyoming (**Figure 1-3**), including the Bighorn and Black Hills uplifts and the PRB, records deposition of Cambrian, Ordovician, Devonian, Mississippian, Pennsylvanian, and Permian carbonate and clastic rocks, dominantly marine or marginal marine. In northeastern Wyoming, unconformities separate the formations in most of the Paleozoic geologic periods, indicating hiatuses in the record where sediments either were not deposited or are now absent due to uplift and erosion. For example, rocks from the Silurian Period are not present in the PRB. However, evidence from kimberlitic diatremes near the Colorado/Wyoming border indicates that marine rocks were probably deposited over much of Wyoming during Silurian time but have since eroded completely (Boyd, 1993).

Throughout much of the Paleozoic, most of Wyoming lay on the western edge of the North American craton: eastern and central Wyoming existed as a relatively wide, shallow shelf, while western Wyoming existed as a deeper trough area. Sedimentation was substantially less on the shelf than in the trough, and erosion and non-deposition were more likely, so the preserved thickness of Paleozoic rocks is much greater in western Wyoming than in eastern Wyoming. The total thickness of Paleozoic rocks in the PRB area is approximately 3,300 feet, compared to approximately 19,500 feet in the trough located in western Wyoming and Idaho.

The oldest Paleozoic rocks in the PRB are Middle and Upper Cambrian siliciclastic deposits (Flathead Sandstone and Deadwood Formation) and limestone (Gallatin Limestone) deposited by a sea that advanced (transgressed) from west to east across the state over an ancient topography developed on much older Precambrian rocks. After a long hiatus, Late Ordovician and Silurian marine carbonate rocks were deposited over the Cambrian sequence; a period of erosion then removed all of the Silurian rocks and some of the Ordovician rocks (leaving the Bighorn and Whitewood dolomites and the Winnipeg Formation). Devonian seas transgressed into parts of northern and western Wyoming, but regressed before reaching the PRB.

A major transgression of a seaway from the west and north occurred in the Early Mississippian and deposited a thick carbonate sequence (Madison Limestone; Pahasapa and Englewood limestones in the Black Hills). Regression of the sea exposed the Madison to subaerial processes, and prominent karst topography developed on its upper surface. Another transgressive cycle deposited the shales and carbonates of the Amsden Formation. Complexly alternating marine and nonmarine conditions prevailed in the Late Mississippian and Early Pennsylvanian. Windblown deposits (Tensleep Sandstone) from the north and west dominate Middle and Upper Pennsylvanian strata. Many of the windblown deposits contain carbonate beds from occasional incursions of shallow water. In eastern Wyoming, marine conditions were more continuous, and hundreds of feet of both limestone and sandstone (Minnelusa Formation) were deposited. These conditions persisted into the Early Permian, and were followed by a period of widespread subaerial erosion and increasing aridity throughout much of Wyoming. Redbed deposition in eastern Wyoming complexly interfingered with carbonate deposition in central Wyoming (Goose Egg Formation). Phosphate and chert deposition in a western Wyoming seaway formed the Phosphoria Formation. Some of these environments persisted into the Mesozoic Era.



Digital Figure by Robin W. Lyons

Figure 1-3. Stratigraphic columns of Phanerozoic rocks in the Owl Creek and Bighorn Mountains, Powder River Basin, and Black Hills uplift, Wyoming. Modified from Love, Christiansen, and Ver Ploeg, 1992.

Mesozoic Era

Like the Paleozoic geologic history of the PRB area, much of the Mesozoic history of the area is best described within the history of the whole state. Articles by Picard (1993) and Steidtmann (1993) summarize the Mesozoic history of Wyoming, and much of the discussion below has been abstracted from those articles. The stratigraphic chart of northeastern Wyoming (**Figure 1-3**) for the Bighorn and Black Hills uplifts and the PRB shows the thick sequence of rocks (**Figure 1-4**) deposited from approximately 240 to 66 Ma during the Triassic, Jurassic, and Cretaceous periods. Many of the same stratigraphic units occur throughout Wyoming basins and on the flanks of uplifts (Love, Christiansen, and Ver Ploeg, 1993), demonstrating that the Laramide structures that would later divide Wyoming into separate structural basins had not developed enough to generally influence deposition. During the Mesozoic, the broad Wyoming shelf that persisted throughout much of the Paleozoic began to narrow somewhat, and parts of Wyoming became emergent at times. Sediment sources became more localized in response to developing Cordilleran tectonics, and marine incursions from directions other than west influenced deposition.

The Mesozoic began with a transgression of marine waters onto the shelf in western Wyoming, while in the PRB area, deposition of terrestrial redbeds, evaporates, and carbonates (from marine waters that occasionally spread eastward) continued from the Permian. Deposition of rocks that would later be diagenetically altered to the ubiquitous redbeds of the Chugwater and Spearfish formations continued through the Triassic and into the Early Jurassic, as the Wyoming shelf was emergent and the region became a terrestrial plain covered by lakes, streams, and sand seas. A widespread unconformity at the base of Middle Jurassic rocks shows that some of the earlier Triassic and Early Jurassic rocks in northeastern Wyoming began to erode, and that the now "stable Wyoming shelf became a regional, low-lying erosion surface" (Picard, 1993). The Gypsum Spring Formation, a widespread evaporite unit of mostly anhydrite and gypsum, was deposited on this surface. The Middle Jurassic saw the return of marine conditions to the Wyoming shelf, as Sundance seas transgressed and regressed periodically across Wyoming from the west and north, depositing a number of rock types (Sundance Formation) in a variety of deep-water, offshore, barrier-island, lagoon, nearshore, beach, and coastal-plain environments. At times the area was emergent, and windblown sand reworked from the marine sediments was deposited. The fine-grained nature of the Middle Jurassic deposits indicates tectonic activity in most of Wyoming, and thus scant sources of coarser-grained materials (Johnson, 1992). Wyoming was again emergent in the Late Jurassic, and varicolored claystones, mudstones, and siltstones of the Morrison Formation were deposited in terrestrial environments: alluvial fans; braided and meandering stream systems; and small ephemeral lakes.

Sedimentary rocks in the PRB from the final period of the Mesozoic, the Cretaceous, represent deposition in a foreland basin adjacent to the fold-and-thrust belt to the west. A very thick sequence of sediments was deposited in this basin, mostly in the Western Interior Seaway – a great epicontinental seaway that developed in the interior of North America (**Figure 1-5**). Much of Wyoming remained at or near the western edge of the seaway throughout the Cretaceous. Some tectonic activity controlled the depositional patterns within the foreland, but not until late in the Cretaceous did Laramide deformation of the basement segment the foreland into the basins and uplifts of today.

The earliest Cretaceous rocks (dated at 125 to 112 Ma) deposited in the PRB unconformably overlie Jurassic rocks and consist of nonmarine gravels and sandstones (Cloverly Formation and the Inyan Kara Group, west to east) derived from the start of tectonic activity to the west. The unconformity at the base of the Cretaceous represents a part of the Early Cretaceous sedimentary record not preserved in northeastern Wyoming, and may partially explain why the Lower Cretaceous rocks are much thinner (between 500 and 1,000 feet thick) here than in western Wyoming (5,500 feet or more). The first Cretaceous marine transgression into the PRB area followed another, shorter hiatus and initiated deposition of a thick marine shale sequence (Thermopolis and Skull Creek shales, west to east). Volcanic activity to the west supplied windblown volcanic ash to the seaway: beds of this ash exist as extensive bentonite marker beds within the marine shales of Early and Late Cretaceous time.

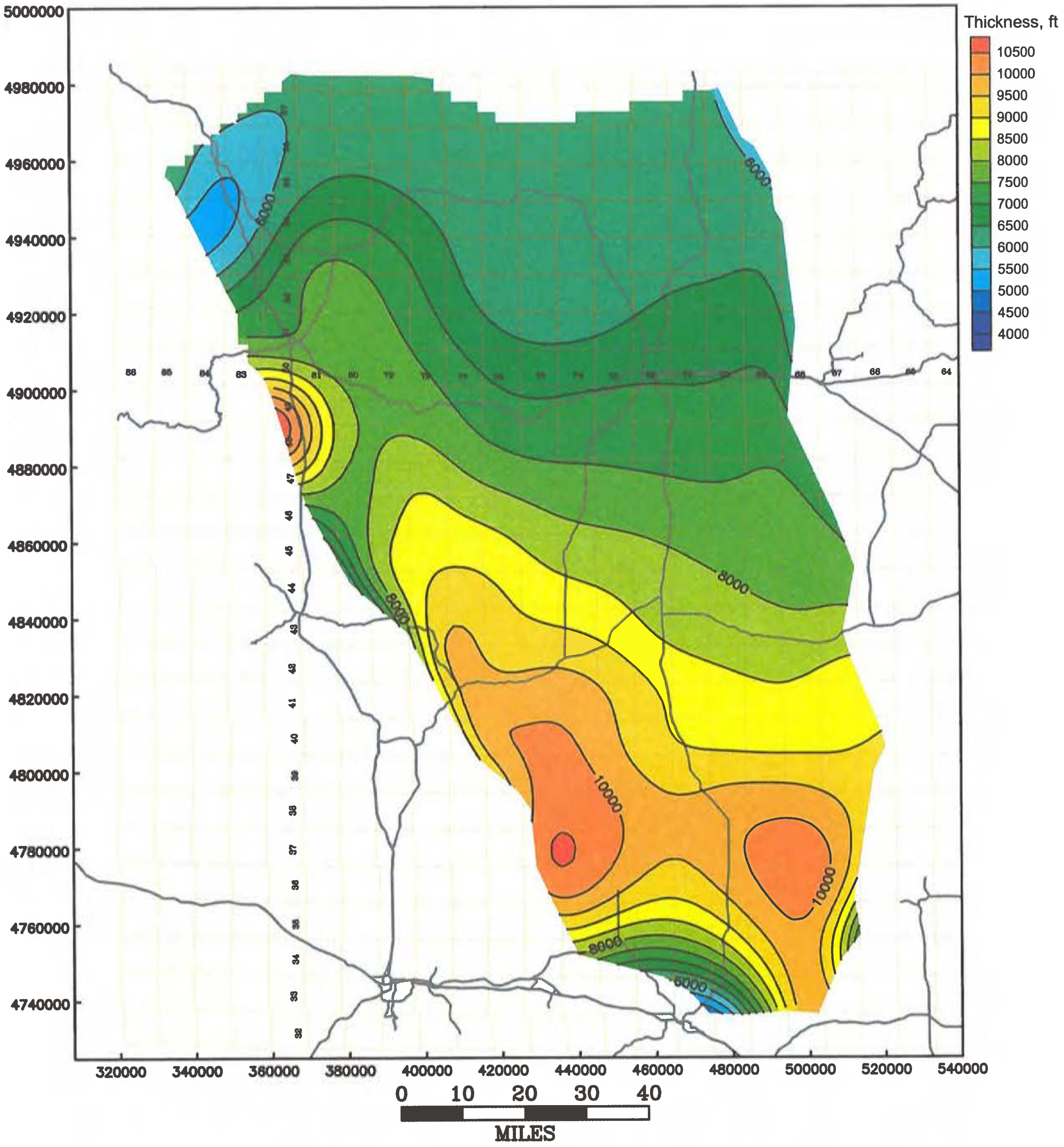


Figure 1-4. Isopach map of Mesozoic rocks in the Powder River Basin, Wyoming. The contour interval is 500 feet. The map represents the total thickness of Triassic, Jurassic, and Cretaceous rocks now present in the area, not the original thicknesses of the formations as deposited.

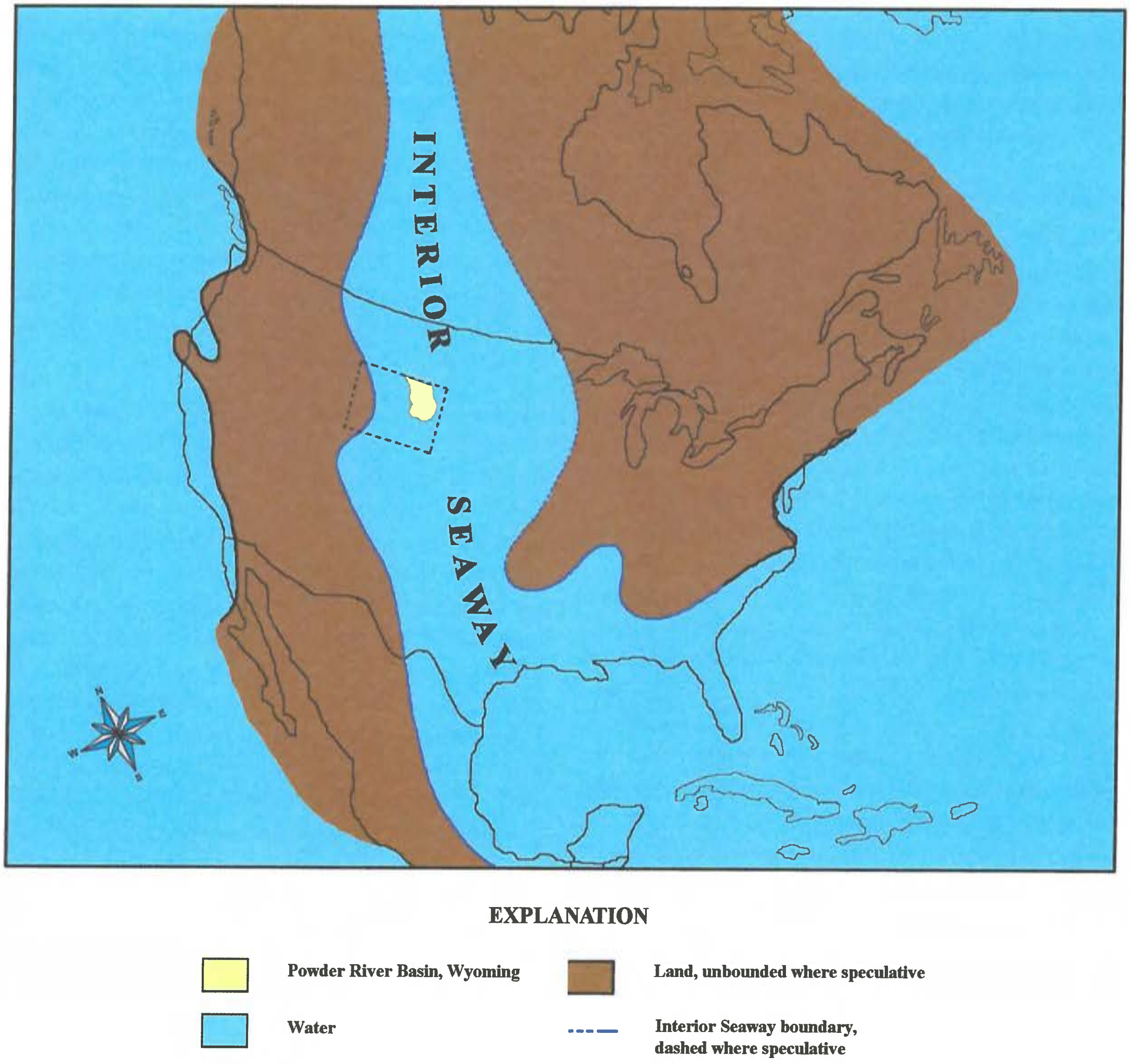

INTERIOR
SEAWAY
N
E
S
W
EXPLANATION
Powder River Basin, Wyoming
Land, unbounded where speculative
Water
Interior Seaway boundary, dashed where speculative

Figure 1-5. Wyoming and the Wyoming Powder River Basin in relation to the generalized paleogeography of the Late Cretaceous (Campanian) Western Interior Seaway. Modified from Flores and Cross (1991, Figure 6).

For the next 30 million years, through most of the Late Cretaceous, east-west transgressions and regressions of the Interior Seaway deposited mostly marine shales (Mowry, Cody, Steele, Pierre, Lewis, and Bearpaw shales) and thin limestones or chalks (Niobrara Formation) in the PRB area. The migrating shoreline also deposited a number of sand bodies (Frontier and Mesaverde formations) that interrupt this dominantly marine shale sequence, sands derived from the now tectonically active fold-and-thrust belt to the west. In places, deltaic, lagoonal, alluvial plain, and terrestrial environments followed the migrating shorelines. As in the Lower Cretaceous, the thickness of Upper Cretaceous rocks probably resulted from the rate of subsidence, sediment supply, and sea-level change in northeastern Wyoming. Upper Cretaceous rocks measure from 5,000 to more than 8,000 feet thick in the PRB, compared to 18,000 feet thick in southwestern Wyoming. Near the end of the Late Cretaceous (approximately 73 Ma), the last regression of the Interior Seaway to the east and north ended marine deposition (Lewis/Bearpaw/Pierre shales) in the PRB area, left a regressive shoreline deposit (Fox Hills Sandstone), and initiated a progressive change to terrestrial deposition (Lance Formation) as coastal-plain and alluvial-plain environments gave way to fluvial environments, and the Mesozoic Era ended.

Cenozoic Era

In the PRB and northeastern Wyoming, rocks from the Paleocene, early Eocene, and Oligocene epochs (**Figure 1-6**) were deposited in the sedimentary basin formed by the Laramide Orogeny. Deformation of the foreland basin during the Laramide Orogeny may have begun as early as 80 Ma (Late Cretaceous) in southwestern Wyoming. The tectonic front moved eastward over time (W.G. Brown, 1993) and segmented the foreland into discrete mountain uplifts and subsiding basins. Deformation and uplift of the Bighorn Mountains (and contemporaneous basin subsidence) may have started in the early Paleocene in some areas (J.L. Brown, 1993) or in the late Paleocene (~60 Ma) elsewhere, reached its maximum in the early Eocene (~51 Ma), and ended with some deformation in the middle Eocene (W.G. Brown, 1993). A similar chronology applies to the other uplifts surrounding the basin. Deposition across the Cretaceous/Tertiary boundary and into the early Eocene was continuous in most of the central basin, but several unconformities exist on both the east and west edges of the basin. The Paleocene rocks of the Fort Union Formation measure more than 5,000 feet thick in the deepest part of the basin and are overlain by Eocene rocks of the Wasatch Formation nearly 2,000 feet thick. Weathering of the ranges and intense distal volcanism produced the Oligocene rocks (White River Formation), which appear to have been deposited throughout the basin from the Bighorn Mountains to the Black Hills. Epeirogenic uplift late in the Tertiary and subsequent erosion removed most of the Oligocene, but left remnants in the Black Hills, high on the flank of the Bighorn Mountains, and as high mesas (Pumpkin Buttes; **Figure 1-7**) in the central PRB.

Lower Paleocene rocks (Tullock Member of the Fort Union Formation) were deposited in a fluvial system that developed on a lowland alluvial plain near sea level, with a river system flowing east and northeast toward the remnants of the Cretaceous Interior Seaway that existed as the Paleocene Cannonball Sea in the western Dakotas. Curry (1971) presented evidence that subsidence of the PRB (and of the Wind River Basin to the southwest) influenced deposition of latest Cretaceous rocks and continued into the Paleocene. J.L. Brown (1993) presented lithologic and sedimentologic evidence in the Tullock Member that doming and uplift of the Bighorn Mountains occurred in the early Paleocene, with deposition in the subsiding PRB, and that swampy (coal-forming) conditions that existed in the southeastern PRB during Lance deposition in the Late Cretaceous continued into the early Paleocene.

Middle Paleocene rocks (Lebo Shale Member of the Fort Union) are dominantly very-fine-grained siltstones, mudstones, and shales, all deposited in a lacustrine system with widespread mudflats and shallow lakes drained by a sluggish river system. Many authors have suggested that ponding occurred along the subsiding basin axis, and that many of the sediments were eroded from the older Cretaceous marine shales exposed on the Owl Creek and Bighorn uplifts. The sparsity of coarse-grained material in the Lebo, along with its thickness trends, suggests that most of the tectonic activity was basin subsidence, predominantly in the southwestern PRB. However, local relief along the western margin of the PRB during the middle Paleocene may have caused deposition of the pebbly sandstone channel fills cut into the fine-grained mudstones (Whipkey et al., 1991).

In the late Paleocene (deposition of the Tongue River Member of the Fort Union), tectonic activity intensified, especially in the Bighorn Mountains. This activity exposed Mesozoic and upper Paleozoic rocks, and deposited coarse-grained sandstones and conglomerates on the west margin of the basin and finer-grained sediments in the subsiding trough. The humid, semi-tropical climate allowed prolific plant growth, and extensive peat swamps formed throughout the basin. Basin tectonics and a fluctuating water table provided the accommodation space required to produce and preserve the great amounts of organic material (Seeland, 1993) that became the laterally extensive coal beds mined today.

Uplift and deformation of the Bighorn Mountains was most active in the latest Paleocene and early Eocene, with erosion exposing the Precambrian core along a thrust fault that surfaced along the eastern

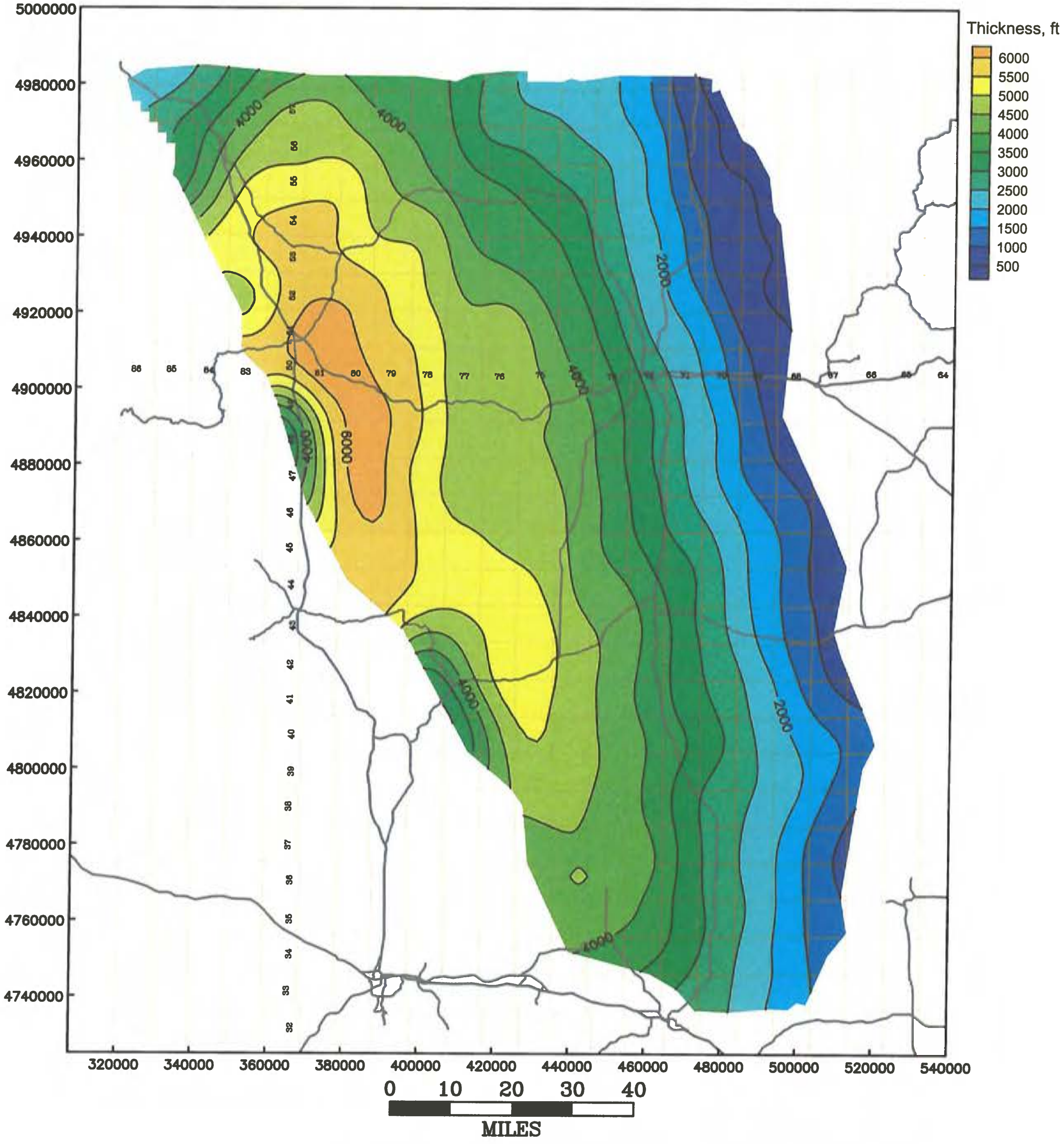


Figure 1-6. Isopach map of Cenozoic rocks in the Powder River Basin, Wyoming. The contour interval is 500 feet. The map represents the total thickness of Paleocene, Eocene, and Oligocene rocks now present in the area and not the original thicknesses of the formations as deposited.

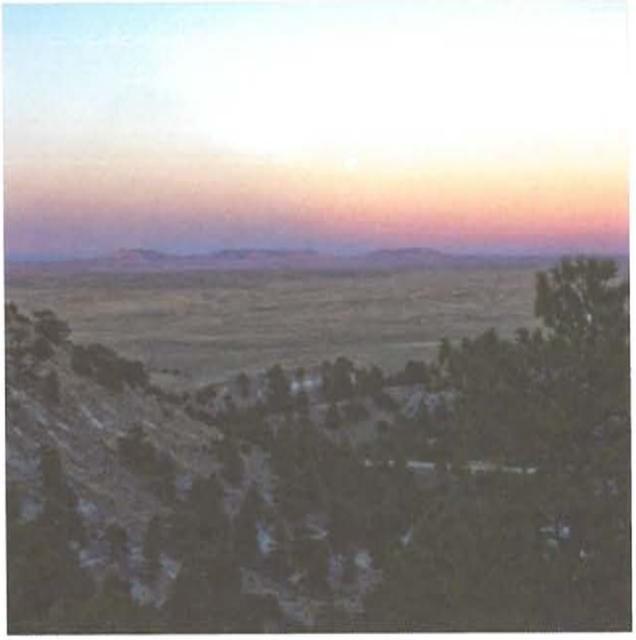


Figure 1-7. Pumpkin Buttes, lone remnants of the Oligocene White River Formation that once covered the Powder River Basin. View eastward into the south-central PRB. Photo by Meg Ewald.

mountain front. Several thick conglomerate sequences (Kingsbury Conglomerate Member and overlying Moncrief Member of the Wasatch Formation) were deposited as alluvial fans on the west edge of the PRB, and finer debris (main part of the Wasatch Formation) accumulated along with peat in the swamps of the subsiding basin to the east. Additional sediment entered the PRB from other surrounding uplifts, but in smaller amounts because the uplifts were smaller and the deformation less intense.

Seeland (1992), interpreting paleodrainages in the PRB, envisioned a large extrabasinal trunk stream that flowed south along the axis of the Wind River Basin, crossed the Casper Arch, and flowed north in the western PRB along the basin axis. A major tributary drained the southern and southeastern PRB, flowing northwest to join the major trunk stream near Buffalo. Seeland believed that three major alluvial depositional systems deposited the Wasatch in the PRB: a distal mud-rich source to the east in the Black Hills; a proximal sand-rich alluvial plain alluvial fan source to the south in the Laramie Mountains; and a stream-dominated alluvial fan source to the west in the Bighorn Mountains.

An erosional unconformity between early Eocene and Oligocene rocks in the PRB reflects removal of any evidence for deposition of middle and upper Eocene rocks in the PRB. However, the Absaroka volcanic field in northwestern Wyoming produced extensive volcaniclastic and ash-fall deposits in other basins in Wyoming during that time. We infer that the PRB was also filled with volcanic debris from the Absarokas during the middle Eocene. Deposition of the lower Oligocene White River Formation (now preserved on Pumpkin Buttes: see **Figure 1-7**) may have filled the PRB nearly to the level of the surrounding uplifts. The amount of basin fill is difficult to determine because Oligocene to Pliocene rocks are scarce in the basin. The Oligocene deposits consist of materials that, for the most part, were derived from remote sources. These deposits are volcanic ash with minor amounts of debris from the Precambrian mountain core. In the Black Hills, isolated outcrops of the upper Miocene-Pliocene Ogallala Formation unconformably overlie the White River Formation. These late Tertiary rocks were probably also deposited in the PRB, filling and overtopping the mountain uplifts (as they were in other Wyoming basins and in much of eastern Wyoming), but all evidence has been removed. Regional uplift in the latter part of the Tertiary brought about a new cycle of erosion, which continues to excavate the basin and expose the mountains today.

Stratigraphy

This section addresses the five major rock units that crop out and are nearest the surface in the Powder River Basin: the three uppermost Cretaceous formations (the Bearpaw/Pierre/Lewis shale, Fox Hills Sandstone, and Lance Formation); the Paleocene Fort Union Formation; and the Eocene Wasatch Formation. We modified previous descriptions of these units by WSGS authors (Lyman et al., 2003; De Bruin et al., 2003; Ver Ploeg et al., 2003; Jones et al., 2003) to reflect additional data from the southern PRB. The stratigraphic section below and above these five units is shown on the stratigraphic chart (**Figure 1-3**), and is described in Chapter 3 of this report and in the detailed explanations of stratigraphic units shown on the geologic map (**Plate 1**).

Pierre/Bearpaw/Lewis Shale

The name *Pierre Shale* applies to an Upper Cretaceous unit that crops out in Crook, Weston, and Niobrara counties. In the PRB, the Pierre Shale consists of gray shale and lesser amounts of siltstone, sandstone, and bentonite, all deposited in offshore marine environments. The Pierre Shale is conformably overlain by the Fox Hills Sandstone and conformably overlies the Niobrara Formation (Merewether, 1996). The Bearpaw Shale in the northwestern PRB correlates with the upper Pierre Shale in the eastern PRB. Outcrops of the Bearpaw consist of dark gray shale containing brownish gray, calcareous concretions (Merewether, 1996). In the southwestern PRB, the Bearpaw/upper Pierre (or Cody) Shale is mapped as the Lewis Shale. The Mesaverde Formation lies below the Bearpaw and Lewis shales in the western and southwestern PRB, and is equivalent to the middle Pierre Shale to the east. Sandstones that compose (and define) the Mesaverde thin out and interfinger with the Pierre Shale from west to east across the PRB. The contact between the Pierre/Bearpaw/Lewis Shale and the overlying Fox Hills Sandstone typically separates a major underlying shaly sequence from a major sandstone unit (see Type Log, **Figure 1-8**). This contact is placed at the base of the lowest sandstone unit associated with the Fox Hills sandstone sequence. In boreholes where the Fox Hills consists of a coarsening-upward shoreline sandstone sequence above a transition zone to shale, the contact is placed at the base of the transition zone (Seeland et al., 1993).

We constructed the Pierre/Bearpaw/Lewis structure contour map (**Figure 1-9**) by picking the top of the formation on geophysical logs and converting the formation depth to elevation above sea level. We used geophysical logs from the southernmost townships in Montana and from the townships just south of the mapped area to discern trends at the north and south edges of the map. The Pierre/Bearpaw/Lewis crops out on all basin margins except the extreme southern tip of the PRB. The structure contour map shows that the Pierre/Bearpaw/Lewis is relatively shallow at the east edge of the basin, becomes much deeper near the basin axis on the west side, and rises sharply west of the basin axis on the flank of the Bighorn Mountains. The Pierre/Bearpaw/Lewis generally measures between 2,000 and 6,500 feet thick in the PRB (**Figure 1-10**). The thickest section is located just south of Buffalo, and the thinnest areas occur in the northern and extreme southern PRB.

Fox Hills Sandstone

The Fox Hills Sandstone is an Upper Cretaceous, massive, regressive marine sandstone that generally coarsens upward. There may be more than one upward-coarsening sandstone unit separated by thin marine shales in the Fox Hills Sandstone. These thin shale units represent minor transgressions of the Pierre seaway. The Fox Hills Sandstone overlies the Upper Cretaceous Pierre/Bearpaw/Lewis Shale and underlies the Upper Cretaceous, nonmarine Lance Formation. The contact between the Fox Hills and the Pierre/Bearpaw/Lewis typically separates a major sandstone unit from a major underlying shaly sequence (see Type Log, **Figure 1-8**). The contact is placed at the base of the lowest sandstone unit associated with the Fox Hills sandstone sequence. In boreholes where the Fox Hills consists of a coarsening-upward shoreline sandstone sequence above a transition zone to shale, the contact is placed at the base of the transition zone (Seeland et al., 1993). The Lance-Fox Hills contact is placed at an abrupt change between massive sandstone in the Fox Hills and

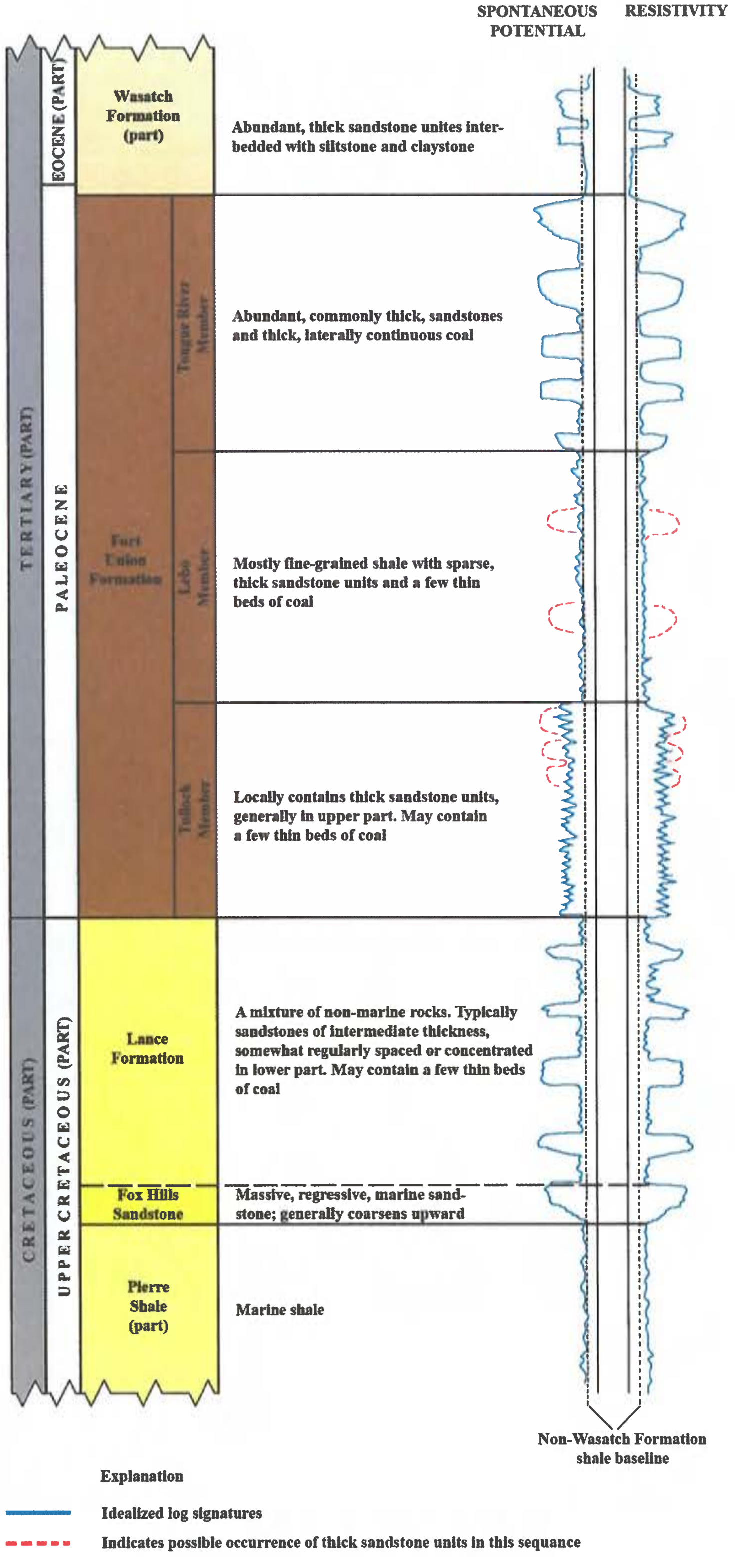

SPONTANEOUS POTENTIAL
RESISTIVITY
TERTIARY (PART)
CRETACEOUS (PART)
EOCENE (PART)
PALEOCENE
UPPER CRETACEOUS (PART)
Wasatch Formation (part)
Fort Union Formation
Tongue River Member
Lebo Member
Tullock Member
Lance Formation
Fox Hills Sandstone
Pierre Shale (part)
Abundant, thick sandstone unites interbedded with siltstone and claystone
Abundant, commonly thick, sandstones and thick, laterally continuous coal
Mostly fine-grained shale with sparse, thick sandstone units and a few thin beds of coal
Locally contains thick sandstone units, generally in upper part. May contain a few thin beds of coal
A mixture of non-marine rocks. Typically sandstones of intermediate thickness, somewhat regularly spaced or concentrated in lower part. May contain a few thin beds of coal
Massive, regressive, marine sandstone; generally coarsens upward
Marine shale
Non-Wasatch Formation shale baseline
Explanation
Idealized log signatures
Indicates possible occurrence of thick sandstone units in this sequence

Figure 1-8. Type geophysical logs of the Pierre/Bearpaw/Lewis shale, Fox Hills Sandstone, Lance Formation, Fort Union Formation, and Wasatch Formation (part), Powder River Basin, Wyoming. Not to scale. Modified from Seeland et al. (1993).

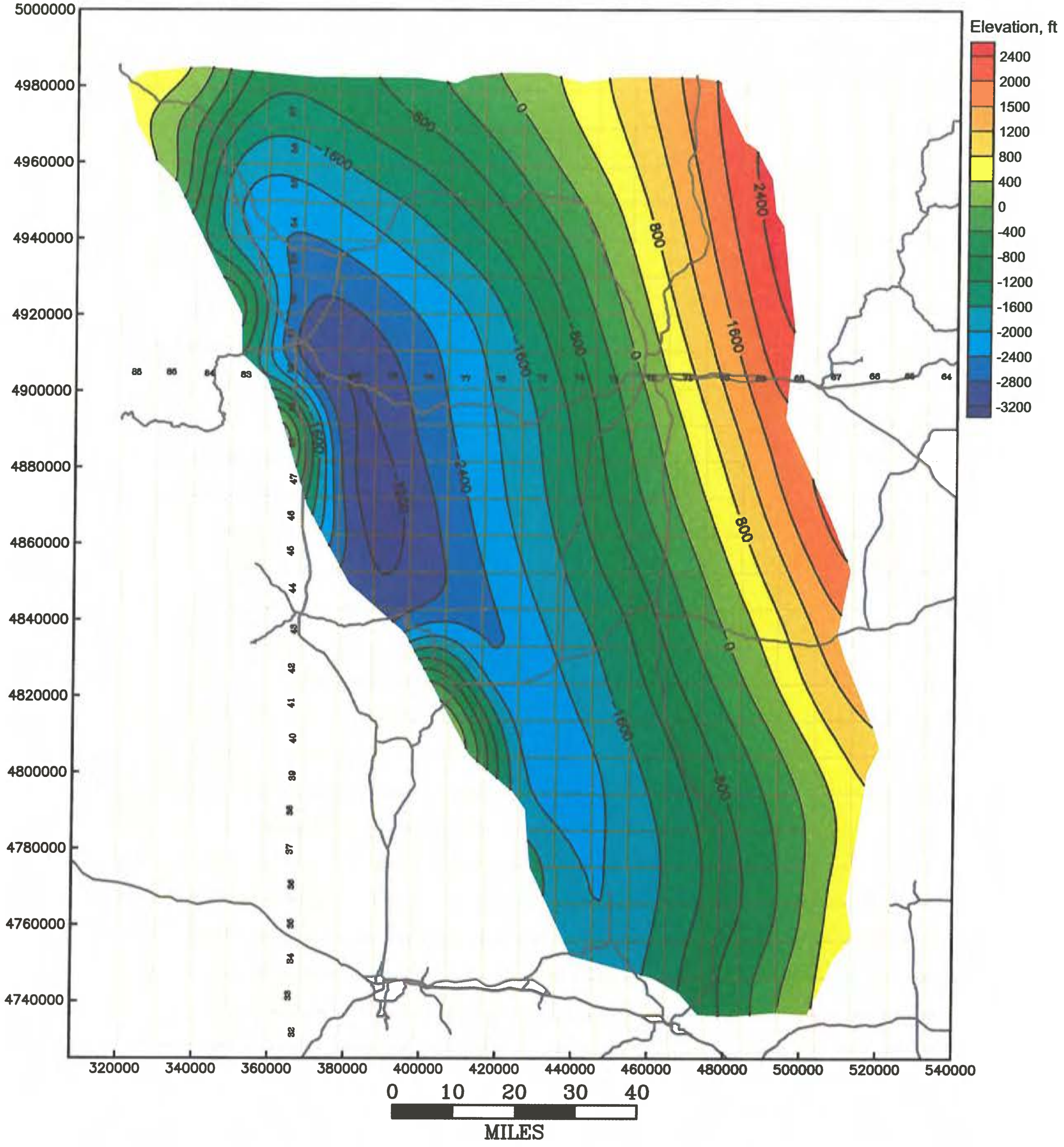


Figure 1-9. Structure contour map of the Pierre/Bearpaw/Lewis Shale, Powder River Basin study area, Wyoming. Elevations are shown in feet with respect to mean sea level. The contour interval is 400 feet.

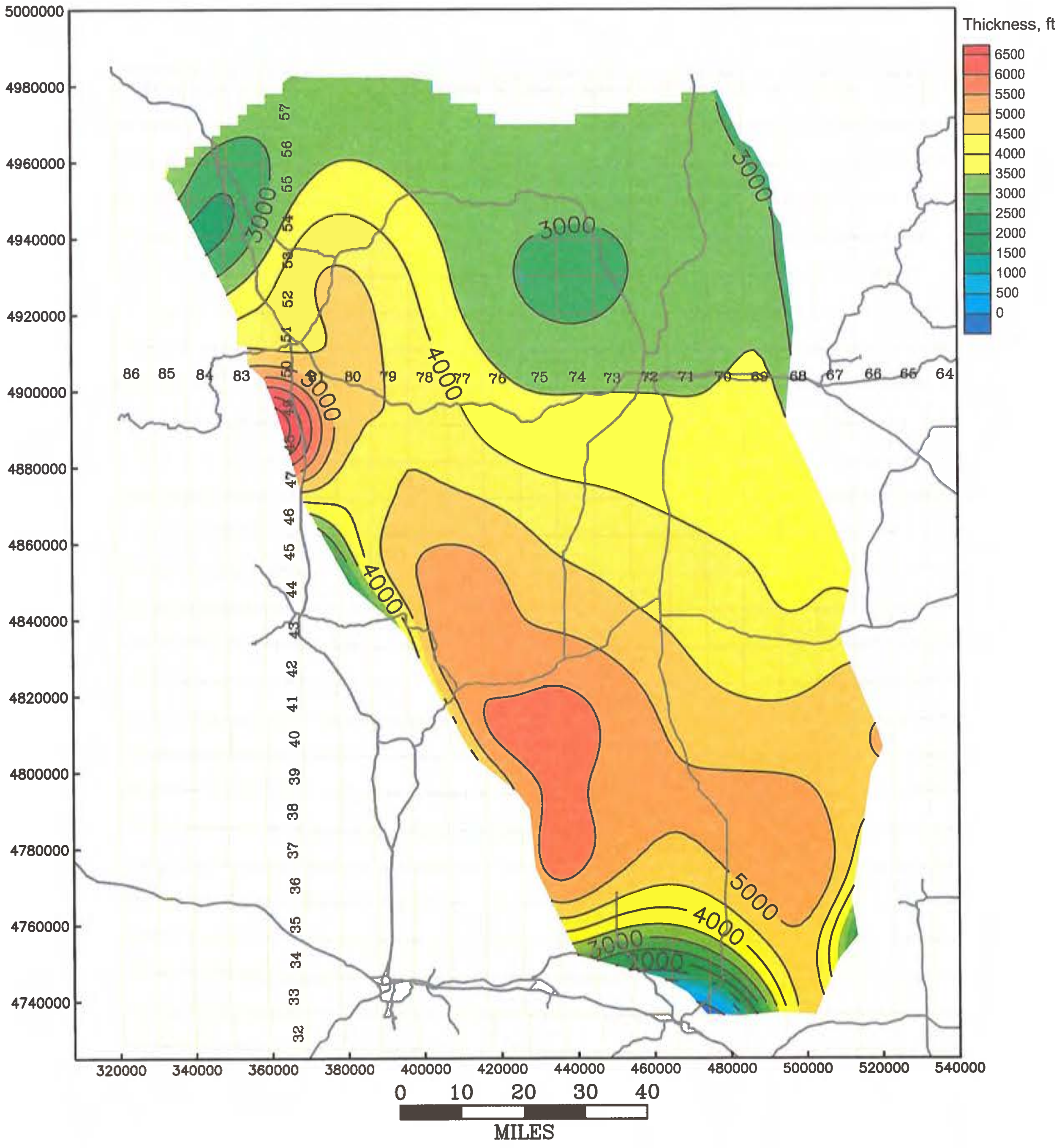


Figure 1-10. Isopach map of the Pierre/Bearpaw/Lewis Shale, Powder River Basin study area, Wyoming. The contour interval is 500 feet.

overlying mudstone in the Lance Formation (Seeland et al., 1993).

We constructed the Fox Hills structure contour map by picking the top of the formation on geophysical logs and converting the formation depth to elevation above sea level. We also used geophysical logs from the township south of the study area and from the southernmost township in Montana to discern trends at the south and north edges of the maps. The structure contour map (**Figure 1-11**) shows that the Fox Hills lies at fairly shallow depth on the east edge of the basin, is much deeper near the basin axis, and turns sharply upward farther west on the flank of the Bighorn Mountains. We constructed an isopach map of the Fox Hills Sandstone (**Figure 1-12**) by picking the top of the Fox Hills and the top of the Pierre/Bearpaw/Lewis Shale in 826 geophysical logs and calculating the thickness of the Fox Hills as the difference in their depths. The isopach map shows that the Fox Hills varies from less than 60 feet thick to 300 feet thick. Many of the thicker areas of the Fox Hills (**Figure 1-12**, Tps. 43 and 44 N., Rs. 74 and 75 W. and the area around T. 49 N., Rs. 69 to 71 W. and Tps. 50 and 51 N., R. 69 W. east of Gillette) contain more than one coarsening-upward sandstone sequence, a fairly thick transition zone above the Pierre/Bearpaw/Lewis Shale, or both.

Lance Formation

The Lance Formation consists of uppermost Cretaceous sequences of sandy, fluvial channel deposits and finer-grained interfluve deposits, all overlying and intertonguing with the marginal marine Upper Cretaceous Fox Hills Sandstone. The Paleocene Fort Union Formation overlies the Lance Formation. The Lance/Fox Hills contact is placed at an abrupt change between massive sandstone in the Fox Hills, generally showing as coarsening upward on geophysical logs (see Type Log, **Figure 1-8**), and overlying mudstone in the Lance Formation (Seeland et al., 1993). The Lance Formation generally contains sandstone beds of intermediate thickness that are locally either somewhat regularly spaced or concentrated in the lower part of the formation. The Lance may also contain a few thin coal beds. The Fort Union/Lance boundary is placed at the change from alternating thin sands and shales in the lower member of the Fort Union to alternating medium to thick sandstones and shales in the Lance (Connor, 1992). The pattern of the resistivity log for the Lance is finely serrate: it never reaches the shale baseline of the units above it in members of the Fort Union, or below it in the Pierre/Bearpaw/Lewis Shale. The Lance has a "normal" fluvial log pattern for alternating sandstones and shales, with the fluvial sandstones fining upward.

We constructed the Lance structure contour map (**Figure 1-13**) by picking the top of the formation on geophysical logs and converting the formation depth to elevation above sea level. We used geophysical logs from the southernmost townships in Montana and from the townships just south of the study area to discern trends at the north and south edges of the map. The structure contour map shows that the Lance, like the Fox Hills, lies at relatively shallow depth on the east edge of the basin, is much deeper near the basin axis, and turns sharply upward farther west on the flank of the Bighorn Mountains. We constructed an isopach map of the Lance Formation (**Figure 1-14**) by picking the tops of the Lance Formation and the Fox Hills Sandstone on 826 geophysical logs, and then calculating the thickness of the Lance Formation as the difference in their depths. The isopach map shows that the Lance varies from about 700 feet thick in the north to more than 3,200 feet thick in the extreme southwestern PRB: the formation thickens from north to south, but generally shows little change in thickness from east to west. This thickening to the south suggests that the southern PRB subsided more rapidly than the northern part of the basin, or possibly that subsidence in the south lasted longer. Connor (1992) suggested that streams transported sediments that became the Lance Formation eastward from an uplifted area near the Beartooth Mountains, and across the present Powder River Basin toward the Late Cretaceous Cannonball Sea (**Figure 1-15**).

Fort Union Formation

The early Tertiary (Paleocene) Fort Union Formation consists of three members: from bottom to top the Tullock Member, the Lebo Shale Member, and the Tongue River Member. The Eocene Wasatch Formation overlies the Fort Union: the contact is a minor unconformity along most of the lateral margins of the basin, and is generally considered conformable in the central basin. The Fort Union overlies the Upper Cre-

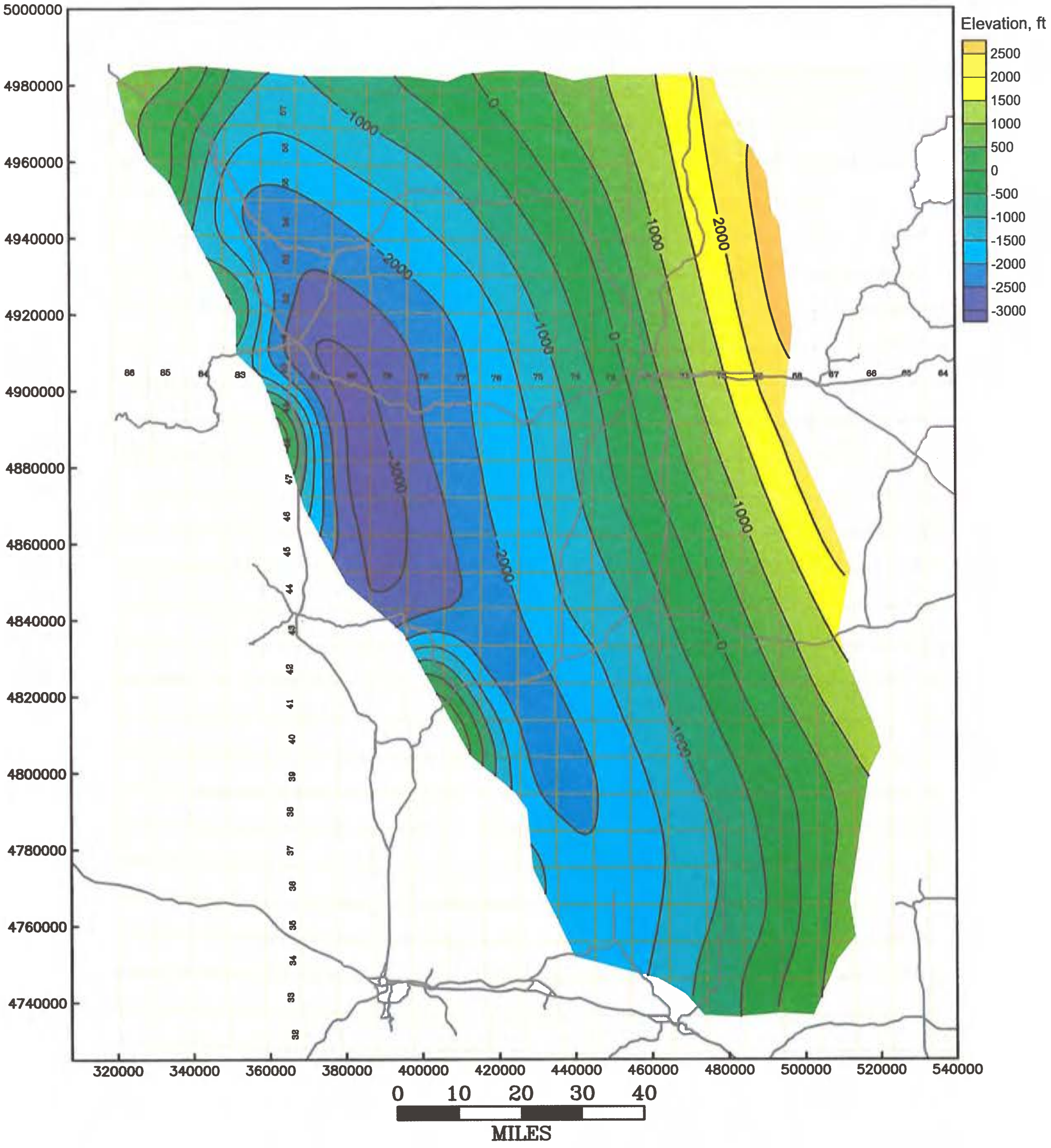


Figure 1-11. Structure contour map of the Fox Hills Sandstone, Powder River Basin, Wyoming. Elevations are shown in feet with respect to mean sea level. The contour interval is 500 feet.

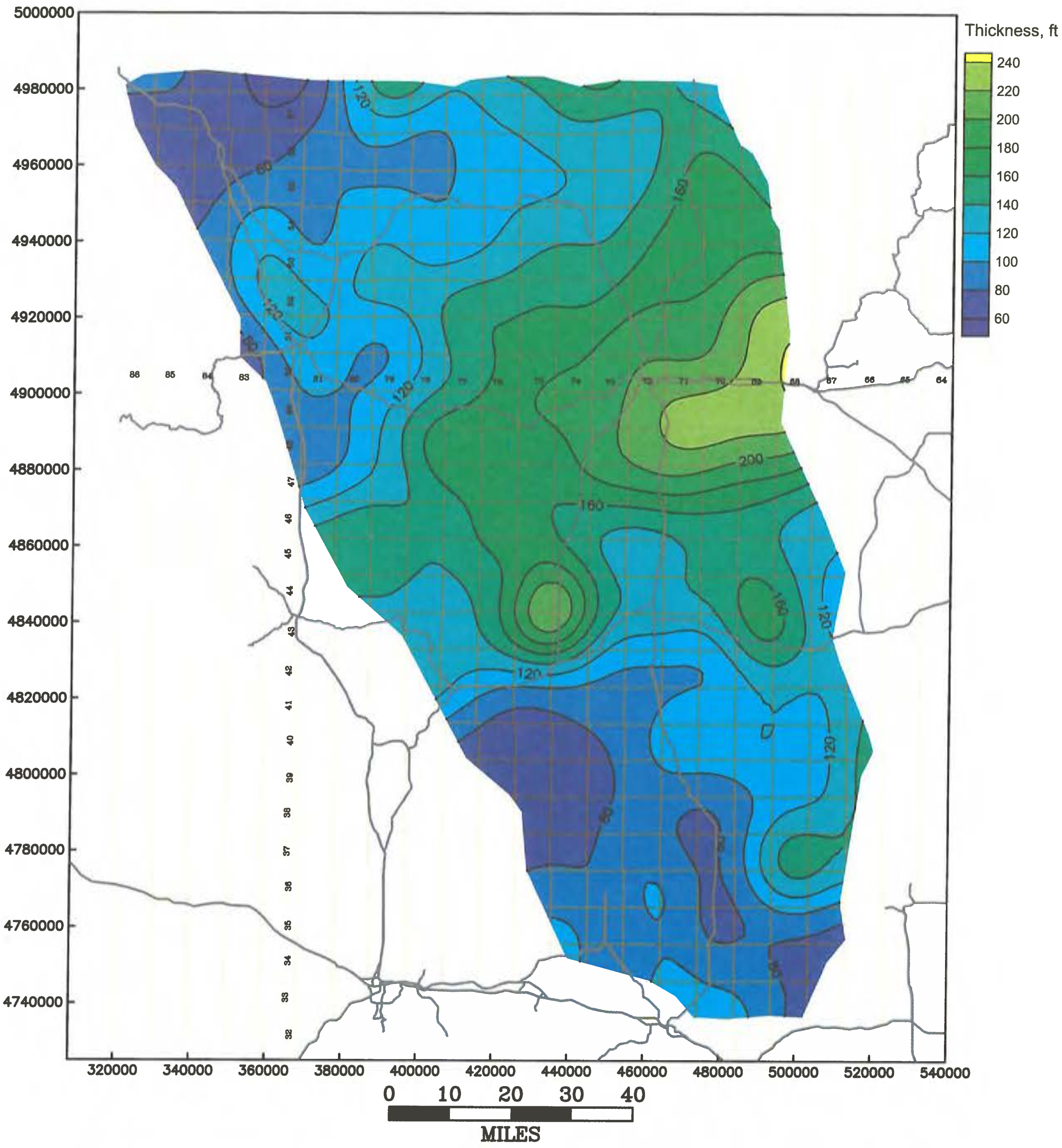


Figure 1-12. Isopach map of the Fox Hills Sandstone, Powder River Basin, Wyoming. The contour interval is 20 feet.

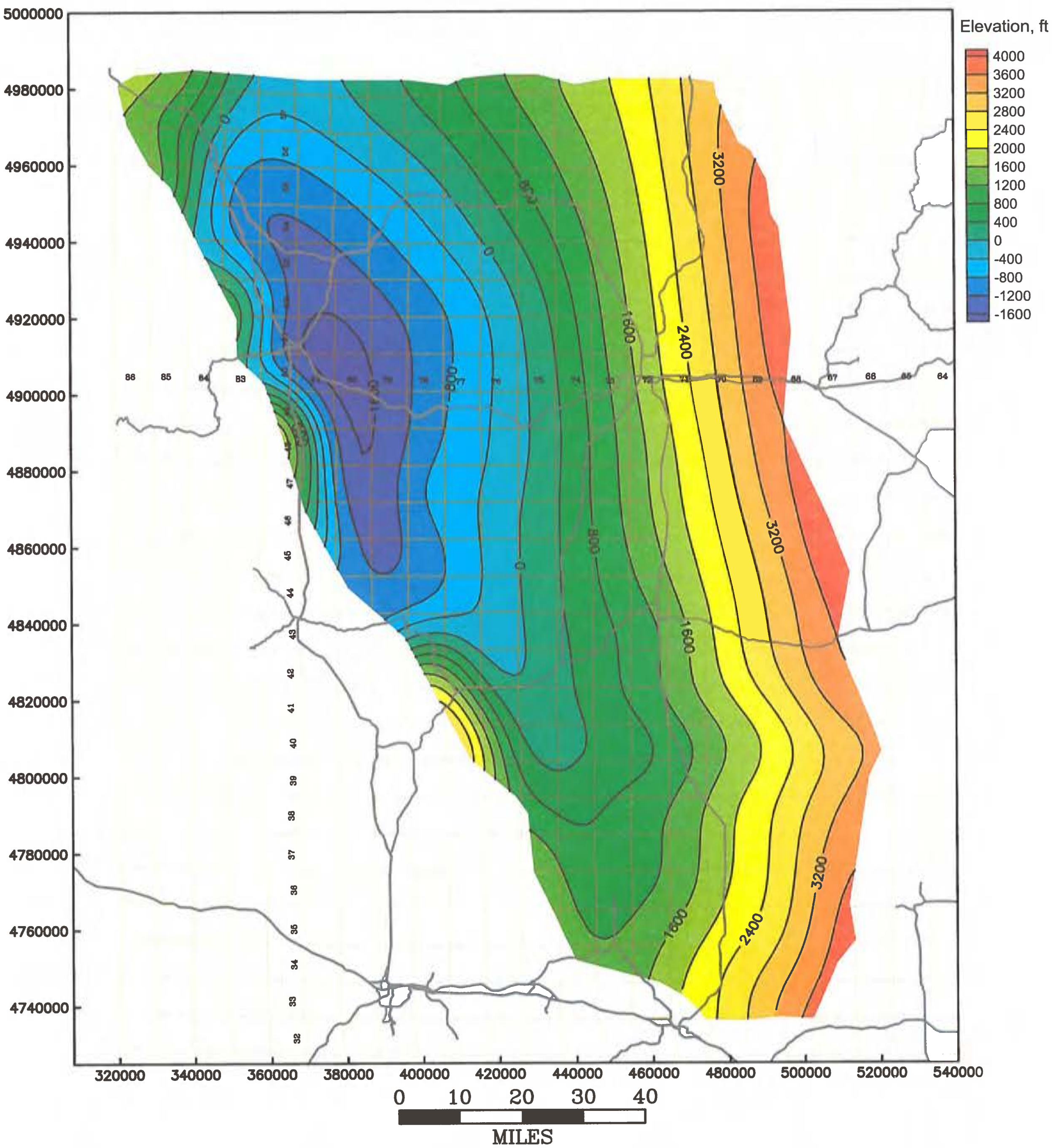


Figure 1-13. Structure contour map of the Lance Formation, Powder River Basin, Wyoming. Elevations are shown in feet with respect to mean sea level. The contour interval is 400 feet.

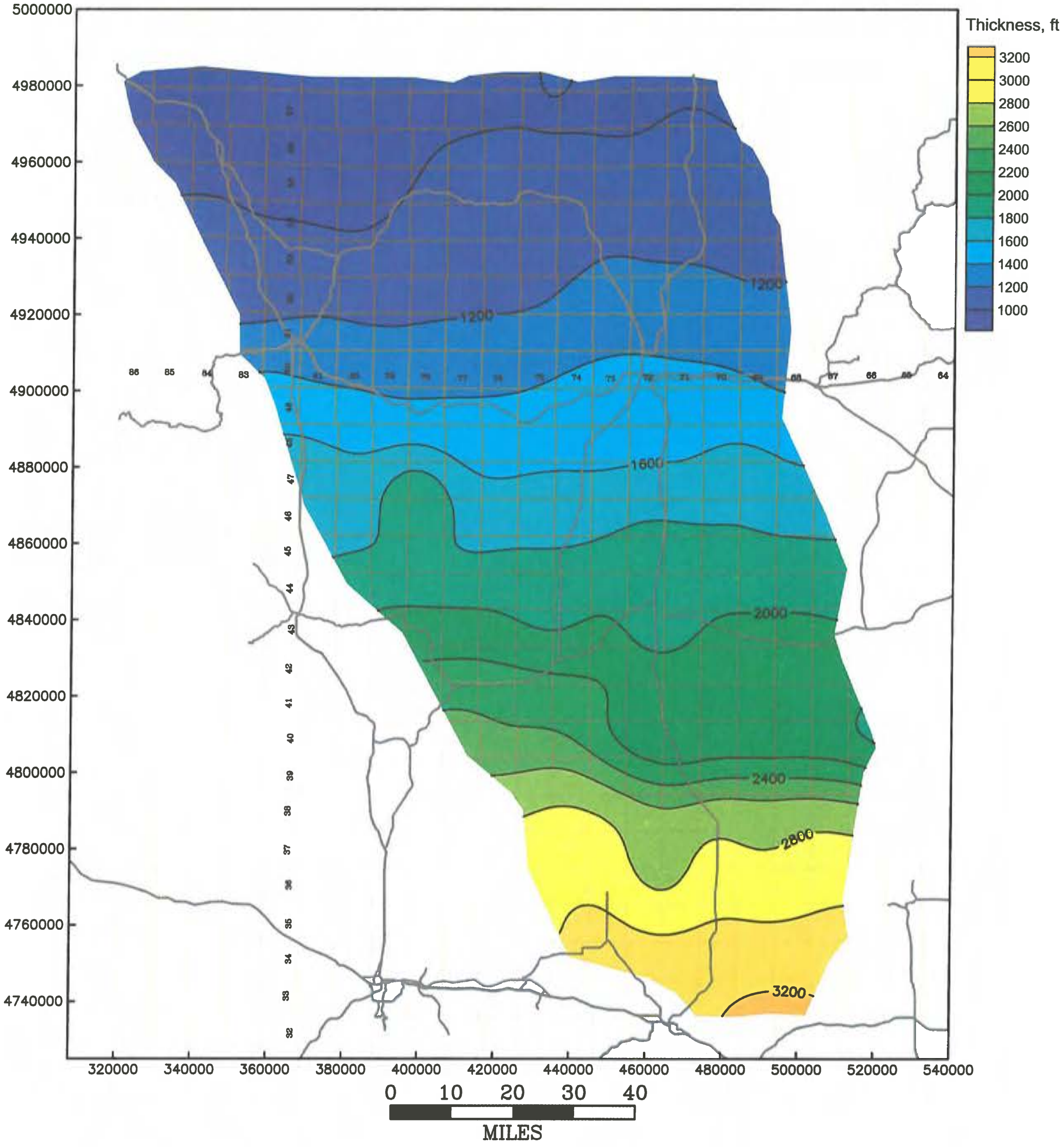


Figure 1-14. Isopach map of the Lance Formation, Powder River Basin, Wyoming. The contour interval is 400 feet.

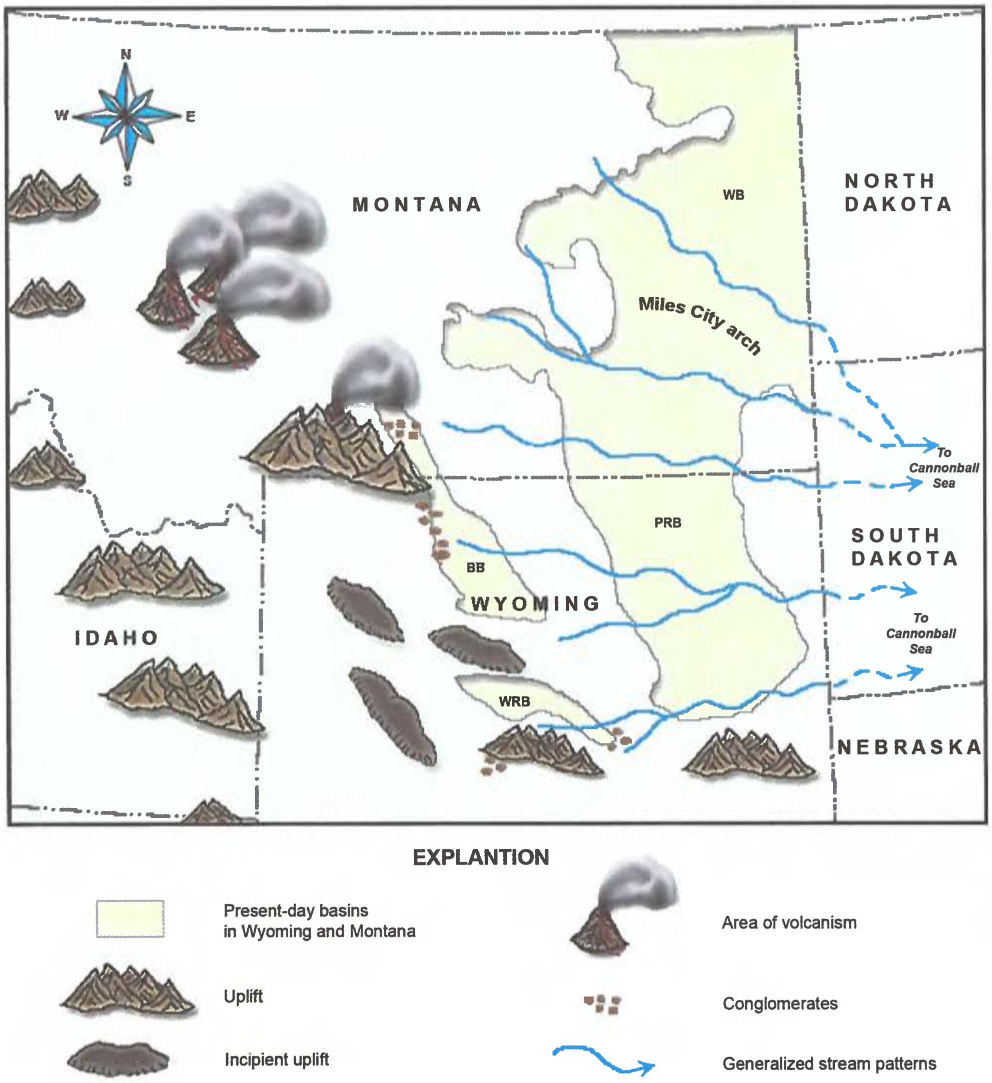


Figure 1-15. Paleogeographic map of the region surrounding the present-day Powder River Basin during Lance time. Modified from Connor (1992, Figure 11). BB, Bighorn Basin; PRB, Powder River Basin; WB, Williston Basin; WRB, Wind River Basin.

taceous, nonmarine Lance Formation conformably in the east and unconformably in the west. The Lance/Fort Union contact is the boundary (designated K-T) between the Cretaceous Period and the Tertiary. The contact is marked by high concentrations of iridium in a very thin layer of ash and shocked quartz deposited as fallout from the impact of a meteorite that struck the Earth near Mexico's Yucatan Penninsula.

The Fort Union structure contour map (**Figure 1-16**) is based on relationships between coals in the upper Fort Union and lower Wasatch formations (e.g., the Felix coal bed lies approximately 275 feet above the base of the Wasatch), because the Fort Union/Wasatch contact cannot be reliably picked from geophysical logs. The structure contours depict only those areas where the Fort Union is overlain by the Wasatch Formation; elsewhere, erosion has removed the top of the Fort Union along with all of the Wasatch. Similarly, the isopach map of the Fort Union (**Figure 1-17**) outside the areas where it is overlain by the Wasatch represents the present, or remaining, thickness after erosion. The Fort Union is thickest (probably more than 5000 feet thick) in the deepest part of the PRB, directly east of the highest

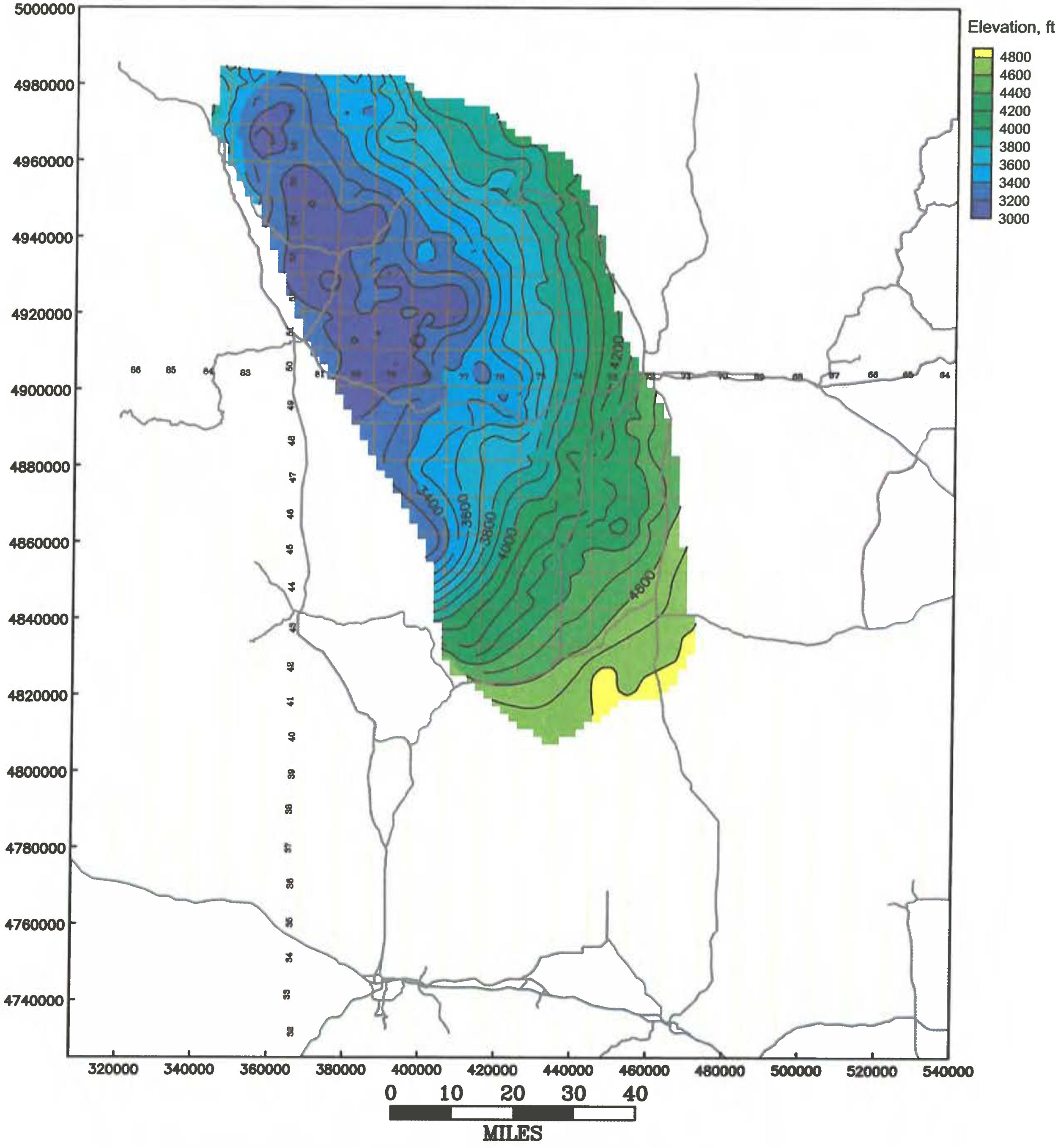


Figure 1-16. Structure contour map of the Fort Union Formation, Powder River Basin, Wyoming. Elevations are shown in feet with respect to mean sea level. The contour interval is 200 feet.

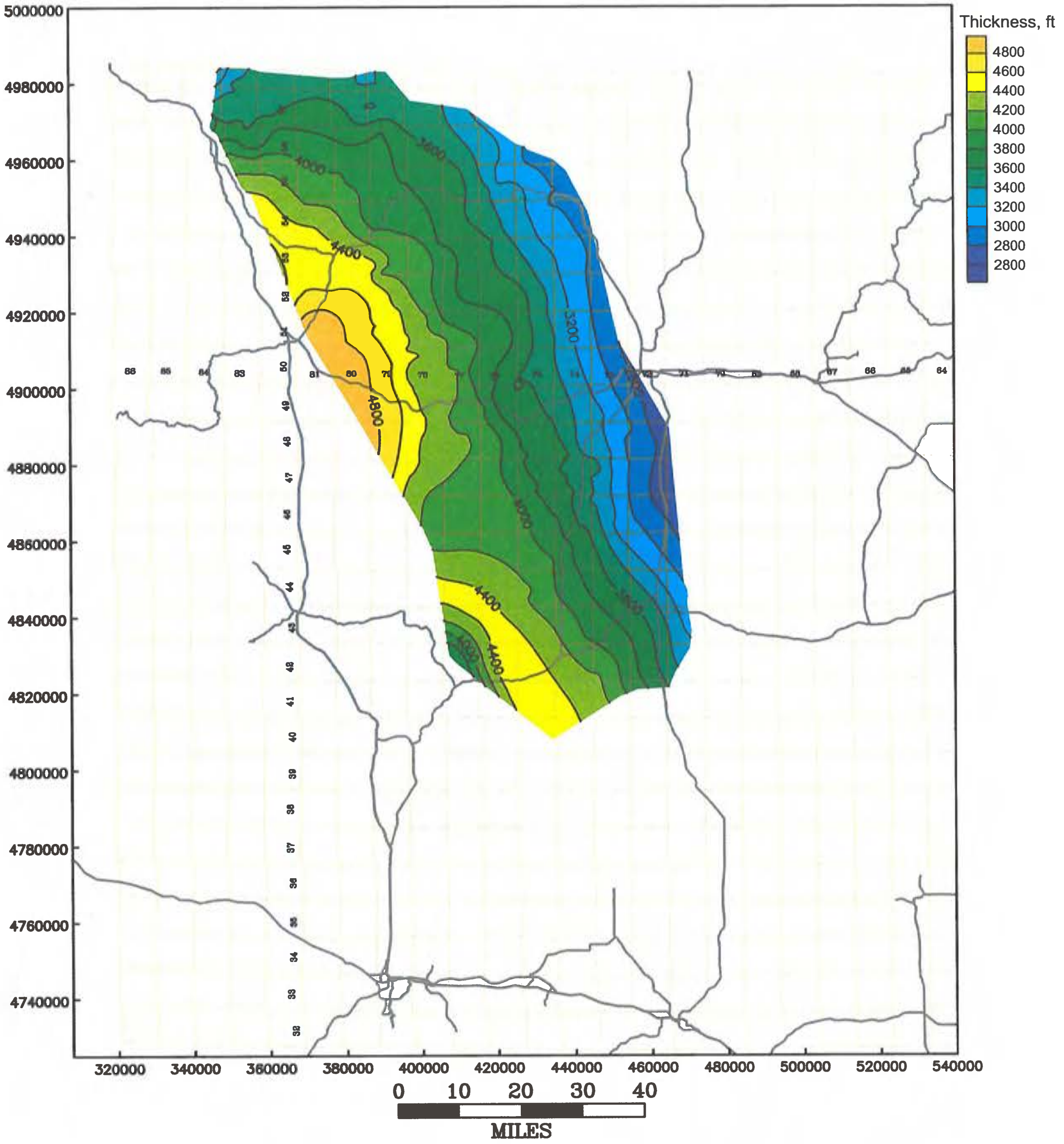


Figure 1-17. Isopach map of the Fort Union Formation, Powder River Basin, Wyoming. The contour interval is 200 feet.

area in the Bighorn uplift, and the formation thins gradually to the east.

The lowest member of the Fort Union, the Tullock Member, consists of brown, iron-stained sandstone ledges interbedded with siltstones and shales. Its thickness ranges from 500 feet in the northeastern PRB of Wyoming to 1,440 feet in the southeastern PRB (J.L. Brown, 1993). The middle Lebo Shale Member, which ranges in thickness from 500 feet in the northwestern PRB of Montana and Wyoming to 1,700 feet in the southwestern PRB (Law, 1975), consists of gray shales interbedded with fine-grained gray siltstones and claystones. Carbonaceous shales, sandstones, and coals compose the upper Tongue River Member.

Some coal beds in the Tongue River Member measure more than 200 feet thick. Most of the coal is subbituminous C in rank (as-received heat values between 8,300 and 9,500 Btu per pound on a moisture- and ash-free (MAF) basis). Some lignite is present on the periphery of the basin. Drill-hole data (geophysical logs) are the basis for delineating a number of coal zones, especially in the Tongue River Member, that contain thick, laterally extensive coal beds. Chapter 2 of this report describes these coal zones and the coal beds within them. Because of the complex nature of fluvial-dominated deposition in the basin, as well as the microtectonic regime that controlled local subsidence and uplift, the Tongue River coal beds vary unpredictably in thickness and configuration: they thicken and thin, split and merge, terminate abruptly or wedge out gradually.

The Wyodak coal zone in the Tongue River Member is the most economically important coal deposit in the United States for its exploitable resources – coal from this deposit fuels approximately 35% of the nation's coal-fired electrical generation. The Tongue River Member also contains most of the recoverable coalbed natural gas resources in the Wyoming PRB, currently estimated at 25.2 trillion cubic feet (De Bruin et al., 2001).

Wasatch Formation

The Eocene Wasatch Formation is divided into two members along the far western edge of the basin. The Kingsbury Conglomerate and the overlying Moncrief Member are alluvial fan deposits that originated in the emerging Bighorn Mountians. The Kingsbury contains Paleozoic clasts interbedded with drab sandstone and variegated claystone. The Moncrief contains Precambrian clasts interbedded with drab sandstone and claystone. East of the Kingsbury and Moncrief, the Wasatch is undivided and consists of tan to light gray, fine-grained sandstones; shales; and lenses of conglomeratic sandstone. In some places, a marker bed of coquina limestone or of conglomeratic sandstone marks the contact between the Wasatch and the Fort Union (Hose, 1955). The Wasatch hosts numerous coal beds, including the thickest coal bed in the United States: the 250-foot-thick Lake DeSmet coal bed near Buffalo (Glass and Jones, 1992). The Wasatch crops out at the surface throughout most of the PRB. Therefore, reported thicknesses are not original depositional thicknesses, as the formation has eroded. The Wasatch currently measures more than 2,000 feet thick in the central PRB and 1,500 feet thick in the northern PRB (Lillegraven, 1993).

Tschudy (1976) and Pocknall (1987) presented the Fort Union/Wasatch contact as problematic. Not only can the contact not be picked reliably on geophysical logs, it has to be conventionally placed in field studies: the rocks are generally not distinguishable in the field, and the contact is mapped as transitional. They cite palynological evidence they believe indicates a latest Paleocene age for all or part of the lowermost Wasatch Formation in places.

APPENDIX 1A

Compilation of the geologic map of the Wyoming Powder River Basin, Plate 1

To compile **Plate 1-1**, we combined and reduced the following 16 WSGS 1:100,000-scale 30' × 60' geologic quadrangles (**Figure A1-1**): Devils Tower (Sutherland, 2007b), Sundance (Sutherland, 2007a), Newcastle (McLaughlin and Ver Ploeg, 2006), Lance Creek (Micale, Gregory, and Johnson, in preparation), Lusk (Stafford and McLaughlin, in preparation), Recluse (Hallberg et al., 2002), Gillette (Boyd and Ver Ploeg, 1999), Reno Junction (Ver Ploeg and Boyd, 2004b), Bill (Gregory and Micale, 2007), Douglas (McLaughlin and Ver Ploeg, 2007), Sheridan (Ver Ploeg and Boyd, 2005), Buffalo (Ver Ploeg and Boyd, 2004a), Kaycee (Ver Ploeg and Boyd, 2004c), Midwest (Wittke, 2007), Casper (Hunter, Ver Ploeg, and Boyd, 2005), and Burgess Junction quadrangles (Ver Ploeg and Boyd, 2003).

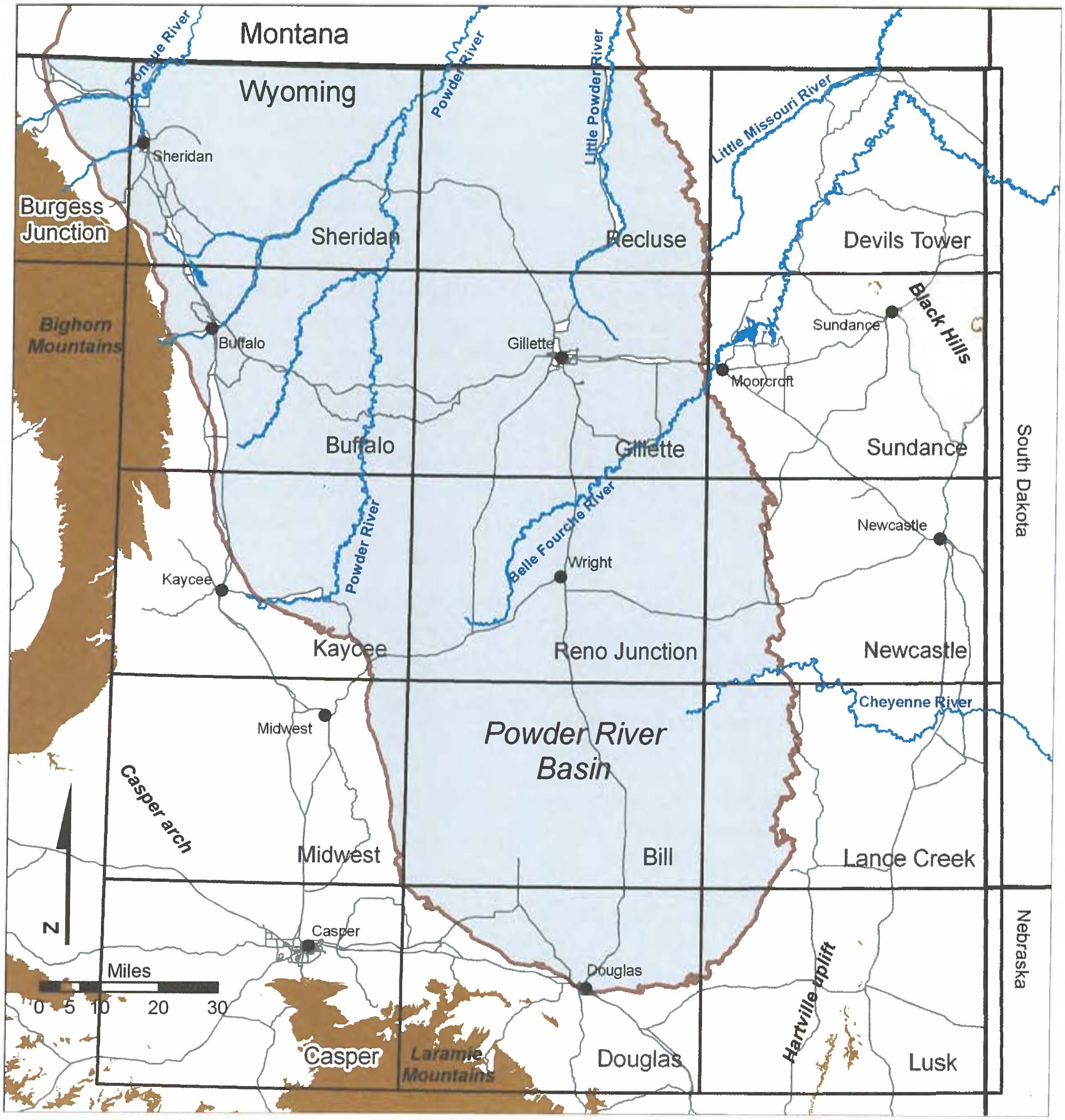


Figure A1-1. Index of WSGS geologic quadrangles used to compile the *Geologic map of the Powder River Basin and surrounding area, Wyoming,* Plate 1.

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CHAPTER 2

coal bed nomenclature and distribution

Nick R. Jones

History of PRB coal bed depiction

In 1907, the United States Geological Survey (USGS) began examining the coal fields in the western states for the purpose of classifying public lands. The Powder River Basin (PRB) lies in the Northern Great Plains Coal Province (**Figure 2-1**).

Early geological field work in the PRB was conducted to determine the acreage of land underlain by minable coal. The USGS did preliminary field mapping and developed preliminary coal bed nomenclature in the Powder River Basin between 1907 and 1912. Later surveys in 1915, 1924, and 1948-49, and publications in 1927, 1928, and 1957 completed the preliminary USGS assessment of coal resources in the basin.

The first surveys began in 1907 – one in the Sheridan area, led by J.A. Taff (1909), another at the southern end of the basin between Douglas and Casper, led by E.W. Shaw (1909) and C.T. Lupton. In 1908, a third survey led by H.S. Gale and C.H. Wegemann (1910) examined coal beds near Buffalo and Trabing. A fourth, by R.W. Stone and C.T. Lupton (1910) under Taff's supervision, surveyed the area that would be named the Powder River coal field (Figure 2-1). During 1910, A.R. Schultz directed V.H. Barnett's initial field mapping of the Gillette coal field; later in 1911, E.G. Woodruff directed the conclusion of Barnett's survey (Dobbin and Barnett, 1927). During 1909 and 1910, Wegemann (1912, 1913) did field work in the Sussex and Barber coal fields. In 1910, J.A. Davis (1912) surveyed the Little Powder River coal field, and D.E. Winchester (1912), under Schultz's supervision, surveyed the Lost Spring field. The culmination of this early work defined the geology, stratigraphy, and lithology of the Tertiary coal-bearing rock sequences in the PRB. In 1924, C.E. Dobbin and

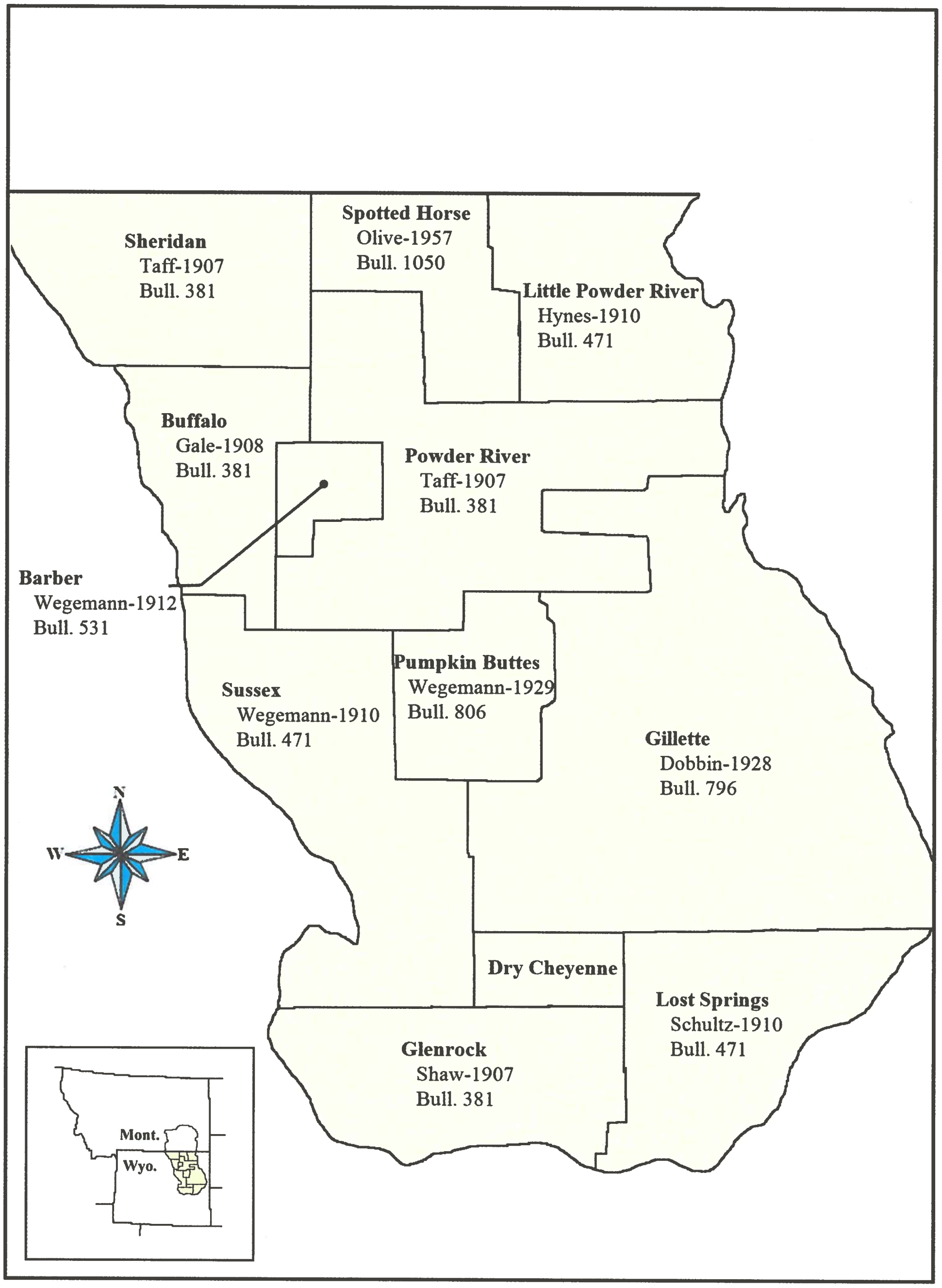


Figure 2-1. Index map, Wyoming Powder River Basin, and the eleven coal fields first delineated by USGS geologists, with field boundaries "revised so that the entire basinal area is included in one or another fields" (Glass, 1976, p. 209). The Dry Cheyenne was originally part of the Pumpkin Buttes coal field (Wegemann, Howel, and Dobbin, 1928). Coal field name, principal investigators, dates of field work, and USGS Bulletin number describe each field.

V.H. Barnett (1927) did additional field work in the Gillette coal field. Wegemann in 1915 and Dobbin again in 1924 examined the Pumpkin Buttes field (Wegemann, Howell, and Dobbin, 1928) – divided later into the Pumpkin Buttes and Dry Cheyenne coal fields (Berryhill et al., 1950, p. 14). W.W. Olive's (1957) report on the Spotted Horse coal field, based on his field work in 1948-49, rounded out the USGS preliminary assessment of the coal resources in the Powder River Basin.

USGS field work from 1907 to 1911 placed this Tertiary sequence of coal-bearing rocks in the Eocene Fort Union Formation. During the earliest geologic surveys, Taff divided the Fort Union into a lower Lebo Shale member and an upper Tongue River member on the basis of lithologic characteristics. His discernment of coal-bearing intervals influenced our use of coal zones in this report. Taff (1909) described the Lebo Shale member of the Fort Union as a thick sequence of dull-drab, blue-grey to brown shales and the Tongue River member as a blue-grey to brown sequence of shales, coals, and sands. He divided the Tongue River member into three coal-bearing intervals, from bottom to top the Tongue River coal group, the Intermediate coal group, and the Ulm coal group (**Table 2-1**).

C.E. Dobbin conducted the first comprehensive review and revision of the earlier field work in the basin in 1924. In 1927, Dobbin and V.H. Barnett published a detailed report on the Gillette coal field, based on the 1910 and 1911 field work by Barnett (Dobbin and Barnett, 1928). Under Dobbin's revisions of basin stratigraphy, the uppermost part of the Fort Union Formation was renamed the Wasatch Formation. The use of Wasatch was initially controversial, but work by Wegemann (1917) based on fossil evidence validated that assignment (**Table 2-2**).

Coal stratigraphy in the Gillette coal field according to Dobbin and Barnett defined principal coal beds in the Wasatch Formation, minor coal beds in both the Tongue River Member and Lebo Shale Member of the Fort Union Formation, and thin lenticular coal beds in the lower part of the Tullock Member and

Table 2-1. Coal groups and associated coal bed nomenclature, Tongue River member, Fort Union Formation, western Powder River Basin (circa 1910).

- Tongue River member
    - *Ulm coal group*
        - Walters coal bed
        - Healy/Lower Ulm coal bed
        - Dry Creek coal bed
    - *Intermediate coal group*
        - Felix coal bed
        - Arvada coal bed
        - Fossil shell bed
        - Roland coal bed
    - *Tongue River coal group*
        - Smith coal bed
        - Dietz No. 1 coal bed
        - Dietz No. 2 coal bed
        - Dietz No. 3 coal bed
        - Blue shale
        - Monarch coal bed
        - Carney coal bed

Table 2-2. Eastern Powder River Basin stratigraphy (circa 1927).

- **Eocene**
    - *Wasatch Formation*
    - *Fort Union Formation*
        - Tongue River Member
        - Lebo Shale Member
    - *Lance Formation*
        - Tullock Member
        - Hell Creek Member

upper part of the basal Hell Creek Member of the Lance Formation (Eocene). Under these revisions to basin stratigraphy, the upper two coal intervals – (1) Taff's (1909) Intermediate coal group with the exception of the Roland coal and (2) the Ulm coal group – were placed in the Wasatch Formation. Within the Fort Union Formation, Taff's Tongue River coal group and the Lebo Shale were raised to the stratigraphic rank of Member (**Table 2-3**).

J.D. Love and others did field work along the eastern flank of the Bighorn Mountains from 1950 to 1952 that resulted in two revisions to the stratigraphy of the Wasatch Formation. First: the Wasatch Formation was divided into two members, a lower Kingsbury Conglomerate Member and an upper Moncrief Member, along the western margin of the basin; east of the western margin the Wasatch Formation remained undivided. Second: on the basis of both fossil evidence and extensive field mapping, the Wasatch Formation was placed in the Eocene Epoch and the Fort Union Formation in the Paleocene Epoch of the Tertiary Period. The Lance was subsequently placed in the uppermost Cretaceous Period.

Table 2-3. Coal groups and associated coal bed nomenclature, eastern Powder River Basin (circa 1927).

Wasatch Formation		
		A
		B (Felix coal bed)
		C
Fort Union Formation		
	Tongue River Member	
		D (Roland coal bed)
		E
		F
	Lebo Shale Member	
		G
		H
		I
		J
		K
		L
		L'
		M
		N'
		N
Lance Formation		
	Tullock Member	
		O
		P
		P'
		Q
	Hell Creek Member	
		R
		S

During 1949 and 1950, W.J. Mapel conducted field work in the Lake De Smet area (Mapel et al., 1953; Mapel, 1954). Mapel's 1954 report outlined the coal stratigraphy within the upper part of the Wasatch Formation, and described conglomeritic units within the upper member of the Fort Union Formation and the two overlying members of the Wasatch Formation. To outline the coal stratigraphy in the Wasatch Formation, Mapel used Wegemann's (1912) nomenclature from the adjacent Sussex coal field, along with local names of nearby domestic mines and geographic features, for newly mapped coal beds (**Table 2-4**).

The final report by W.W. Olive (1957) on the Spotted Horse coal field concluded all preliminary work by the USGS on coal fields in the Powder River Basin. Olive's report contains the earliest published basin-scale fence diagram – a depiction of the subsur-

Table 2-4. Coal bed nomenclature, Lake De Smet area, western Powder River Basin (circa 1954).

Wasatch Formation	
	Local coal bed
	Walters coal bed
	Healy coal bed
	Local coal bed
	Upper Cameron coal bed
	Lower Cameron coal bed
	Murray coal bed
	Local coal bed
	Local coal bed
	Upper Ucross coal bed
	Middle Ucross coal bed
	Lower Ucross coal bed

face extent of principal coal beds (**Figure 2-2**) – and a coal nomenclature and correlation diagram (**Figure 2-3**).

In summary, between 1907 and 1957, USGS geologists published more than twelve reports discussing the coal geology of the Powder River Basin. The first few of these reports outlined the initial distribution, lithological characteristics, quality, and quantity of Tertiary coal beds within the basin. Later reports contained revisions to both the overall stratigraphy and correlation of coal beds: distinction of new members within formations; incorporation of new formations; reassignment of geologic age; and recognition, re-correlation, and mapping of additional coal beds. These changes resulted from geologic data gathered over the years during additional field work, the drilling of water wells, and ongoing exploration for coal and oil resources.

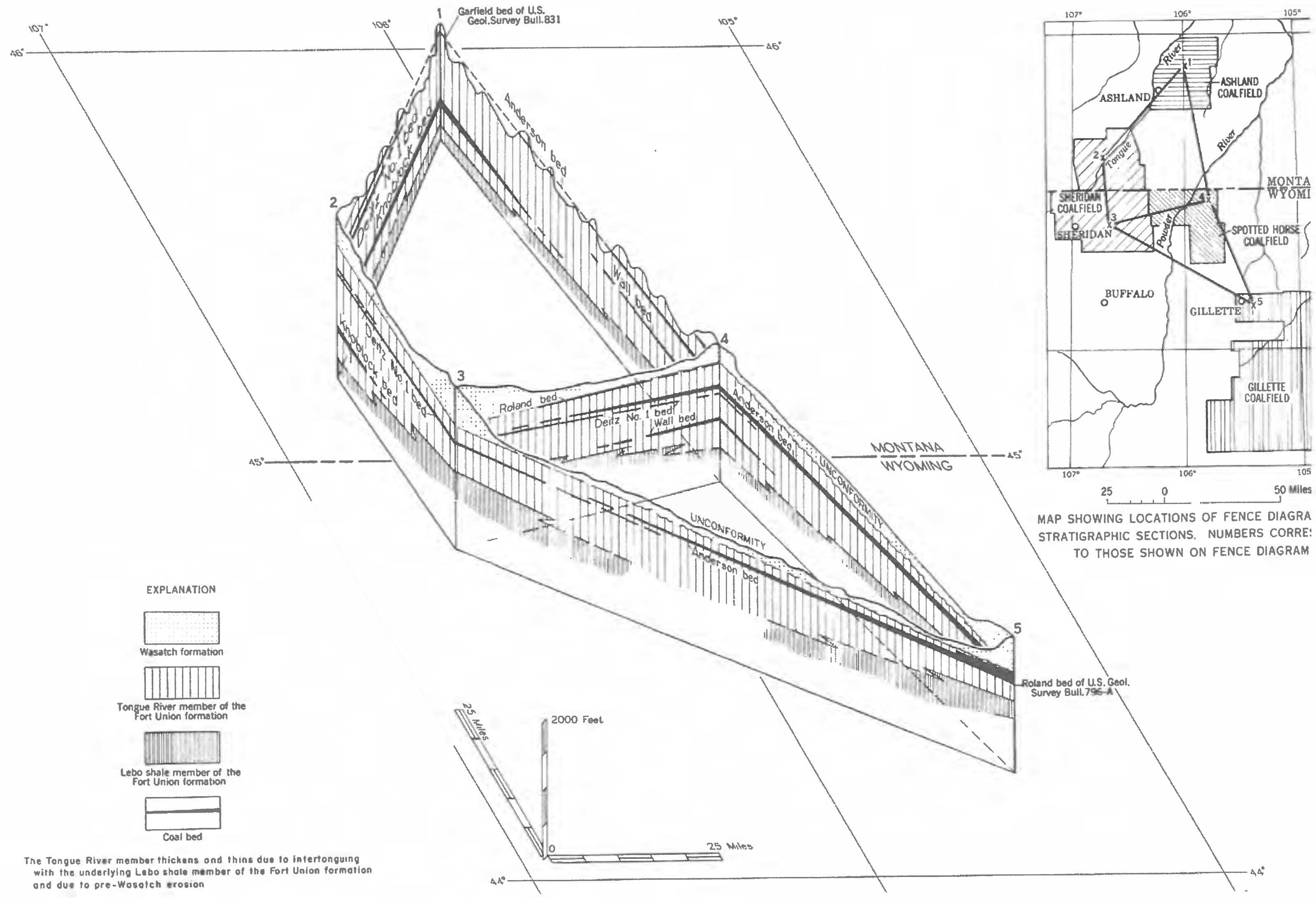
During the 1970s, a new generation of geologists began evaluating and correlating coal beds in the Powder River Basin. In 1973, N.M. Denson, W.R. Keefer, and G.H. Horn published a fence diagram showing subsurface coal correlations in the Gillette area. In 1977, S.L. Grazis published a report covering four contiguous quadrangles in Campbell County in the area around Caballo Creek, south of Gillette. This report was part of a USGS project to classify and evaluate coal resources on federal lands. Grazis designated four coal zones and three subzones in the eastern Powder River Basin. The three subzones are in the Wyodak coal zone and are defined W1, W2, and W3. Within these zones, Grazis incorporated the nomenclature and coal bed designations of Dobbin (1928), and compared them with those of Denson, Keefer, and Horn (1973) in a generalized columnar section (**Table 2-5**).

The coal known as the Wyodak received its name from the Wyodak coal mine, which opened in 1925. This uppermost coal in the Fort Union has been variously named: **Table 2-5** shows Grazis' designation of Wyodak, and Denson's designation of Canyon. This set of coal beds equates with Taff's Roland coal bed (reassigned to the Fort Union by Dobbin) and with the D coal bed designated by Dobbin and Barnett in 1927 (**Table 2-3**). This difference in nomenclature for a coal bed used to indicate the contact between upper Eocene and lower Paleocene strata is problematic. A quote from Grazis (1977), "...correlation of the Wyodak coal bed with beds outside the Gillette area is problematical," illustrates a growing awareness of the correlative complexity of Tertiary coal beds in the Powder River Basin. Although workers in the 1970s had access to more bore-hole data, they could not resolve the vertical and lateral distribution of coal beds due to insufficient data distribution and density. Because of the similarity between lower Wasatch and upper Fort Union strata, discrimination between them remained uncertain.

The development of Wyoming's coal industry in the Powder River Basin accelerated during the mid-1970s. Because most of the coal in the basin is federally owned, the USGS contracted with Intrasearch, Inc., a private consulting group, to conduct an extensive coal resource assessment in the Powder River Basin, and assessments in the Hanna, Carbon, Rawlins/Atlantic Rim, Green River, and Hams Fork coal fields. The purpose of the assessments was to determine the location, acreage, and tonnage of minable unleased federal coal resources in known recoverable coal resource areas in the western United States.

The USGS published 233 *Coal resource, occurrence and coal development potential* open-file reports between 1977 and 1980 for coal-bearing regions of Wyoming. Of these reports, 136 pertain to coal lands within the Powder River Basin (Martin, 1977; Intrasearch Inc., 1978a-c, 1979a-n). Each report consists of an inventory of plates (1:24,000 quadrangle maps, charts, correlations, and columnar sections), a brief discussion of the geologic history of the basin, discussion of geographic and social aspects of the particular quadrangle, and accompanying structure, isopach, delineated minable acreages, and surficial maps showing coal outcrops, clinker beds, and referenced bore-holes.

This coal correlation work by the USGS and Intrasearch Inc. in the Powder River Basin was based mainly on the previous work of Taff (1909), Stone and Lupton (1910), Dobbin and Barnett (1928), Baker (1929), Bass (1932), Olive (1957), and Denson et al. (1973). Intrasearch Inc. identified and informally named three coal beds within the lower part of the Tongue River Member of the Fort Union Formation – the Wildcat, Moyer, and Oedekoven beds. Due to the depths at which these coal beds occur, Intrasearch



The Tongue River member thickens and thins due to intertonguing with the underlying Lebo shale member of the Fort Union formation and due to pre-Wasatch erosion

MAP SHOWING LOCATIONS OF FENCE DIAGRA STRATIGRAPHIC SECTIONS. NUMBERS CORRE TO THOSE SHOWN ON FENCE DIAGRAM

Figure 2-2. Fence diagram of the Tongue River Member of the Fort Union Formation in part of the Powder River Basin, northeastern Wyoming and southeastern Montana.

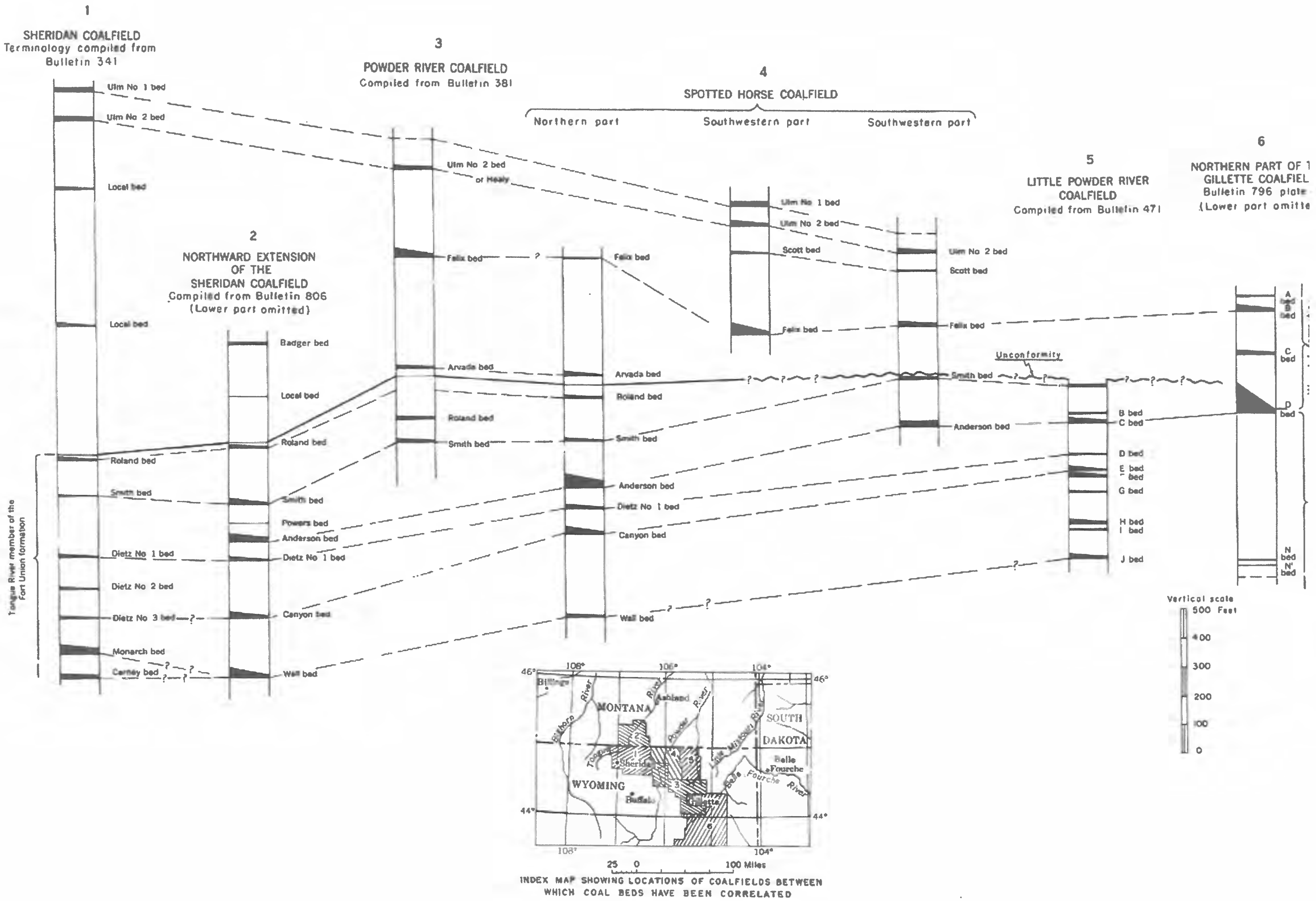


Figure 2-3. Correlation chart of principal coal beds in the Spotted Horse coalfield and suggested correlation with coal beds in nearby coalfields, Wyoming and Montana (Olive, 1957, Plate 5).

Table 2-5. Comparative coal stratigraphy of Grazis (1977) and Denson et al. (1973).

Grazis, 1977 (from Dobbin)	Denson et al., 1973 (from Dobbin)
Wasatch Formation	
I. Upper Wasatch coal zone	
A coal bed	—
Lower Ulm coal bed	—
Scott coal bed	—
II. Middle Wasatch coal zone	
F(1) coal bed	—
Felix coal bed	Felix
F(2) coal bed	—
III. Lower Wasatch coal zone	
C'' coal bed	Local
C' coal bed	Smith
C coal bed	Anderson
Fort Union Formation	
IV. Wyodak coal zone	
Wyodak coal bed (W1, W2, W3)	Canyon
Lower Tongue River coals	
M coal bed	Upper Cook
N coal bed	Lower Cook
P coal bed	Local
Q coal bed	Wall
R coal bed	—
S coal bed	Upper Pawnee
T coal bed	
U coal bed	Lower Pawnee
V coal bed	—
X coal bed	Cache

Inc. placed the three coal beds in an informal "lower coal zone".

Many discrepancies in the correlation of coal beds and their placement within formations exist among the 136 open-file reports pertaining to the Powder River Basin. Significant discrepancies exist even between adjacent report areas, such as inconsistent placement of coal beds in geologic formations and inconsistent naming of coal beds. To illustrate this problem, we compare Intrasearch Inc.'s lithostratigraphic columns representative of selected quadrangles. **Figure 2-4** compares the coal stratigraphy from eighteen of the reports along a north-to-south cross section.

Figure 2-4 shows a major discrepancy that begins in the southern part of the basin where the Smith is placed in the lower part of the Wasatch Formation and the Anderson is placed at the top of the Fort Union Formation (**Figure 2-4**, logs 17 and 16); a little farther north, the Anderson and Smith coal beds are both positioned in the upper part of the Wasatch Formation (log 15). Even farther north, the Smith

coal bed is placed within the uppermost Fort Union Formation (log 8). Other discrepancies, perhaps issues of local nomenclature, occur where coal beds at similar stratigraphic intervals in adjacent reports are given different names. For example, on log 6, the uppermost Eocene coal is called the Felix, but on log 5 the coal at that interval is named the Arvada.

Correlative work in the PRB continued throughout the 1970s and 1980s. Major contributions to the advancement of consistent coal bed nomenclature and correlation include the publications of D.R. Haddock (1976), G.B. Glass (1976), S.L. Grazis (1977), B.H. Kent (1977;1986), B.E. Law (1978), N.M. Denson et al. (1978a,b), R.M. Flores (1981), G.H. Wood (1983), and W.B. Ayers (1986) and their co-authors. For the late 1980s and early 1990s, the consensus on the geographic and stratigraphic distribution and conventional coal bed nomenclature in the basin is represented in the fence diagram of Glass and Jones (1992) (**Figure 2-5**).

First published in 1976, Glass' correlative fence diagram was compiled and modified by the WSGS from published USGS reports and open-file reports. It was later modified to include the Lake De Smet coal (Figure 2-10, F–B), (Glass, 1982) and the Big George coal (H–B, F–B), (Glass and Jones, 1992).

Revised PRB coal depiction

Identification during the late 1970s of a potentially rich unconventional gas resource in coal seams evolved into a prominent national energy industry. The discovery of coalbed natural gas (CBNG – also called coalbed methane, CBM) in the PRB resulted in increased energy development and drilling, beginning in 1987. Ten years later, 440 CBNG wells had been drilled. By the end of 2007, the basin had more than 25,000 CBNG wells.

Northern Powder River Basin Project

In 2003, the Wyoming State Geological Survey (WSGS) – in conjunction with the Wyoming Water Resource Data System (WRDS), Wyoming Oil and Gas Conservation Commission (WOGCC), Wyoming State Engineer's Office (WSEO), Wyoming Geographic Information Science Center, Wyoming Department of Environmental Quality (DEQ), and USGS Water Resources Division – completed a project titled *Interactive geologic, hydrologic, and water quality database and model for the northern Powder River Basin (PRB)*. The Wyoming Water Development Commission funded the two-year project. The project related water quality analyses from water, oil, gas, and CBNG wells to specific coal beds or geologic formations so that developers, water users, and regulators could better estimate the quality of water before it is produced.

The model used purchased geophysical well data from more than 6,000 oil, gas, and CBNG wells. Coal correlations by Goolsby, Finley & Associates of Casper, as modified by the WSGS, were used to generate the subsurface coal model.

We modeled coal beds 10 feet thick or thicker in the northern part of the basin, north of the 12th Standard Parallel North. We based coal bed names on current USGS coal stratigraphic nomenclature. Correlation of coal beds was based on Goolsby, Finley & Associates' interpretation (**Table 2-6**).

Southern Powder River Basin Project

In 2005, the WSGS – in conjunction with the WOGCC, WSEO, DEQ, and USGS Water Resources Division – began work on a similar model for the southern Powder River Basin. The project took three years and was also funded by the Wyoming Water Development Commission.

In the fall of 2004, we began collecting coal-occurrence data from geophysical well logs for two purposes: to create a coal-occurrence database for a cooperative National Coal Resource Data System (NCRDS) program funded by the USGS; and to develop a database for a coal correlation and water-quality model in the southern Powder River Basin funded by the Wyoming Water Development Commission.

To clarify uncertainties about the subsurface distribution of coal beds in the southern PRB, we used no thickness criteria during data collection: all detectable coal-type lithologies from geophysical well logs were collected.

During preliminary correlations of coal beds, we noted discrepancies in coal bed correlation across the boundary between the northern project area and the southern project area, the 12th Standard Parallel

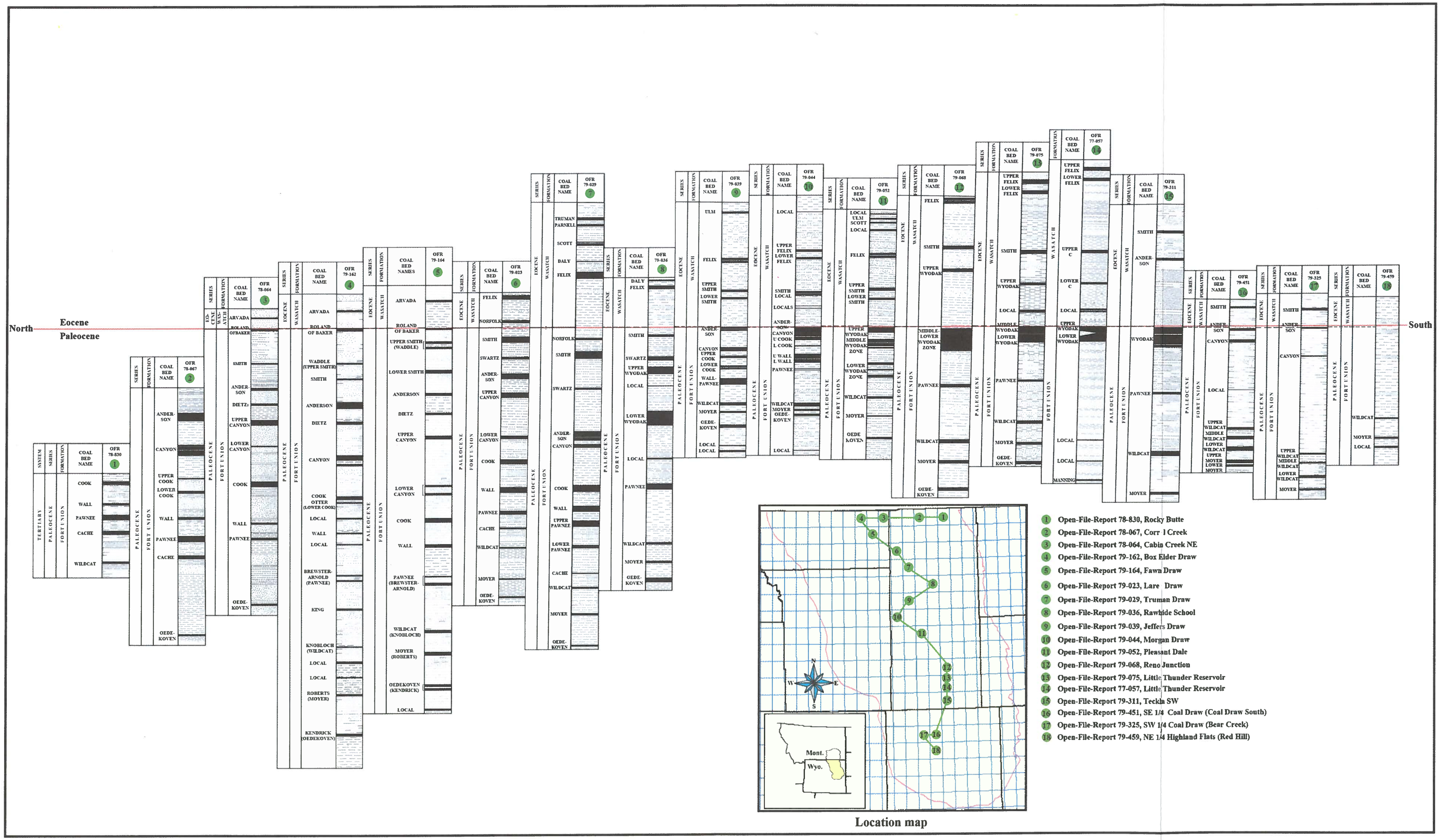

North
Eocene
Paleocene
South
Location map
Mont.
Wyo.
① Open-File-Report 78-830, Rocky Butte
② Open-File-Report 78-067, Corr l Creek
③ Open-File-Report 78-064, Cabin Creek NE
④ Open-File-Report 79-162, Box Elder Draw
⑤ Open-File-Report 79-164, Fawn Draw
⑥ Open-File-Report 79-023, Lare Draw
⑦ Open-File-Report 79-029, Truman Draw
⑧ Open-File-Report 79-036, Rawhide School
⑨ Open-File-Report 79-039, Jeffers Draw
⑩ Open-File-Report 79-044, Morgan Draw
⑪ Open-File-Report 79-052, Pleasant Dale
⑫ Open-File-Report 79-068, Reno Junction
⑬ Open-File-Report 79-075, Little Thunder Reservoir
⑭ Open-File-Report 77-057, Little Thunder Reservoir
⑮ Open-File-Report 79-311, Teckla SW
⑯ Open-File-Report 79-451, SE 1/4 Coal Draw (Coal Draw South)
⑰ Open-File-Report 79-325, SW 1/4 Coal Draw (Bear Creek)
⑱ Open-File-Report 79-459, NE 1/4 Highland Flats (Red Hill)

Figure 2-4. Comparative north-to-south cross section of the Powder River Basin (Martin, 1977; Intrasearch, Inc., 1978a–c, 1979a–n).

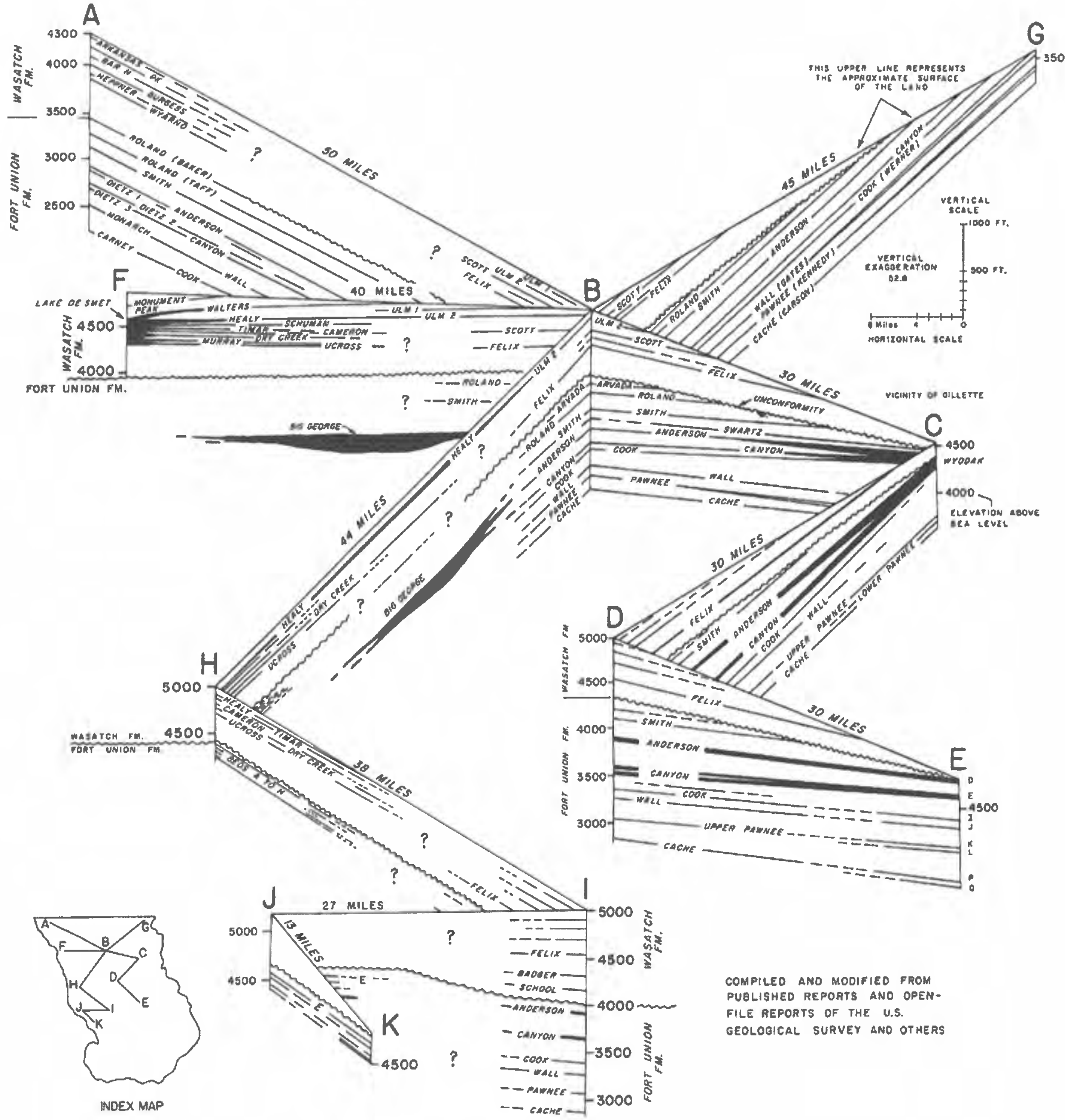


Figure 2-5. Fence diagram showing revised coal bed correlations throughout the Powder River Basin (Glass and Jones, 1992).

Table 2-6. Powder River Basin coal stratigraphy (2003).

Wasatch Formation		
		Lower Ulm
	Lake De Smet Coal Zone (western PRB)	
		Buffalo Cameron
		Murray
		Ucross
	Felix Coal Zone	
		Bull Creek
		Felix
		Dot
Fort Union Formation		
	Wyodak Rider Coal Zone	
		Roland of Baker
		Roland of Taff
		Smith
	Upper Wyodak Coal Zone	
		Anderson
		Dietz 2 (northwestern PRB)
		Lower Anderson
		Canyon
		Dietz 3 (northwestern PRB)
	Lower Wyodak Coal Zone	
		Monarch (northwestern PRB)
		Cook
		Gates
		Wall B
		Wall C
		Wall
		Wall D
		Carney (northwestern PRB)
		Pawnee
		Lower Pawnee
	Knobloch Coal Zone	
		Moyer
		Lower Moyer
	Sawyer Coal Zone	
		Zed
		Dannar
	Basal Tongue River Coal Zone	
		Terret
		Burley
		Broadus

North. This required a review of the northern project area correlations. Unfortunately, the thickness criteria used for data collected in the northern area made it impossible to correlate all detectable coal beds in the south with the selected coal beds in the north. Consequently, we reviewed and reinterpreted 2,743 available well logs in the north to incorporate all detectable coal beds, regardless of thickness.

We gathered coal occurrence data for the entire basin from well logs at the WSGS. This work produced a coal occurrence database of 49,859 coal tops and bases from 8,659 well logs, including 3,536 coal tops and bases from the 2,743 reinterpreted northern PRB well logs. The whole data set used for the 2003 coal correlation model in the northern Powder River Basin contained 6,535 wells with 21,831 coal tops and bases.

From this database, we selected a subset of 4,158 well logs containing 25,409 coal tops and bases for correlating the coal beds in the Powder River Basin. Using a subset of the data allowed us to incorporate wells with associated water-quality data and to develop evenly distributed representative well data over the basin. **Figure 2-6** shows the distribution of well data for both the 2003 northern correlation model and the 2007 basin-wide correlation model.

We used Rockworks™ software to correlate the coal beds. The correlation was completed in December 2007. We used the software to generate columnar representations of coal-type lithology in selected wells for display in cross section. Due to the large number of detectable coal beds of varying thickness, we developed an arbitrary numerical nomenclature for purposes of correlation; use of the numerical scheme allowed definition of individual coal beds where conventional coal bed nomenclature did not apply. **Table 2-7** shows the USGS coal bed names associated with our revised numerical designations. We adjusted coal zone boundaries to isolate vertically related coal beds in clearly defined stratigraphic intervals.

Coal zones

We offer a new interpretation of coal bed correlation that redefines the subsurface distribution of coal beds in the Powder River Basin. Changes to subsurface distribution and coal bed correlation were based on abundant and accessible bore-hole data. These changes include a new delineation of coal zones, re-correlation and remapping of the subsurface distribution of coal beds, and revised hypothetical resource assessments.

What is a coal zone?

The concept of coal zones originated with Taff's (1907) division of his Tongue River member of the Fort Union Formation into three coal-bearing stratigraphic intervals he called coal groups (see **Table 2-1**, page 47). As revised recently, USGS Circular 891, *Coal resource classification system of the U.S. Geological Survey*, defines coal zone as a "series of laterally extensive and (or) lenticular coal beds and associated strata that arbitrarily can be viewed as a unit" (Wood et al., 1983, p.8). (USGS Bulletin 1450, the 1975 predecessor of Circular 891, does not mention coal zones.) Between 1975 and 1983, Grazis (1977) and Denson et al. (1978a,b) used the concept of coal subzones and coal zones to locally describe two major coal beds – the Anderson and Canyon – that coalesce to form the Wyodak coal in the eastern PRB.

We define a coal zone as a litho-stratigraphic section that contains a recognizable sequence of coal beds across a series of well logs. We use the coal zones to clearly group individual coal beds within a particular stratigraphic sequence. A coal zone is not an identifiable horizon on well logs; rather, it represents a stratigraphic interval containing a suite of coal beds that vary in thickness, are interrelated by stratigraphic proximity, and may merge into or split apart from a single coal bed. Thick coal beds are known to split out into several thinner beds, abruptly terminate, and contain lenses of clastic sediments. These characteristics make it difficult to trace out and accurately define an individual subsurface coal horizon over a large area. The use of coal zones solves this problem, simplifying the spatial analysis by grouping each sequence of related beds into an appropriate stratigraphic interval. By convention, coal beds may split and coalesce within a coal zone, but not between coal zones.

Coal zones in the PRB and their resources

For this report, in order to distinguish and evaluate sequences of coal beds for the entire basin, we

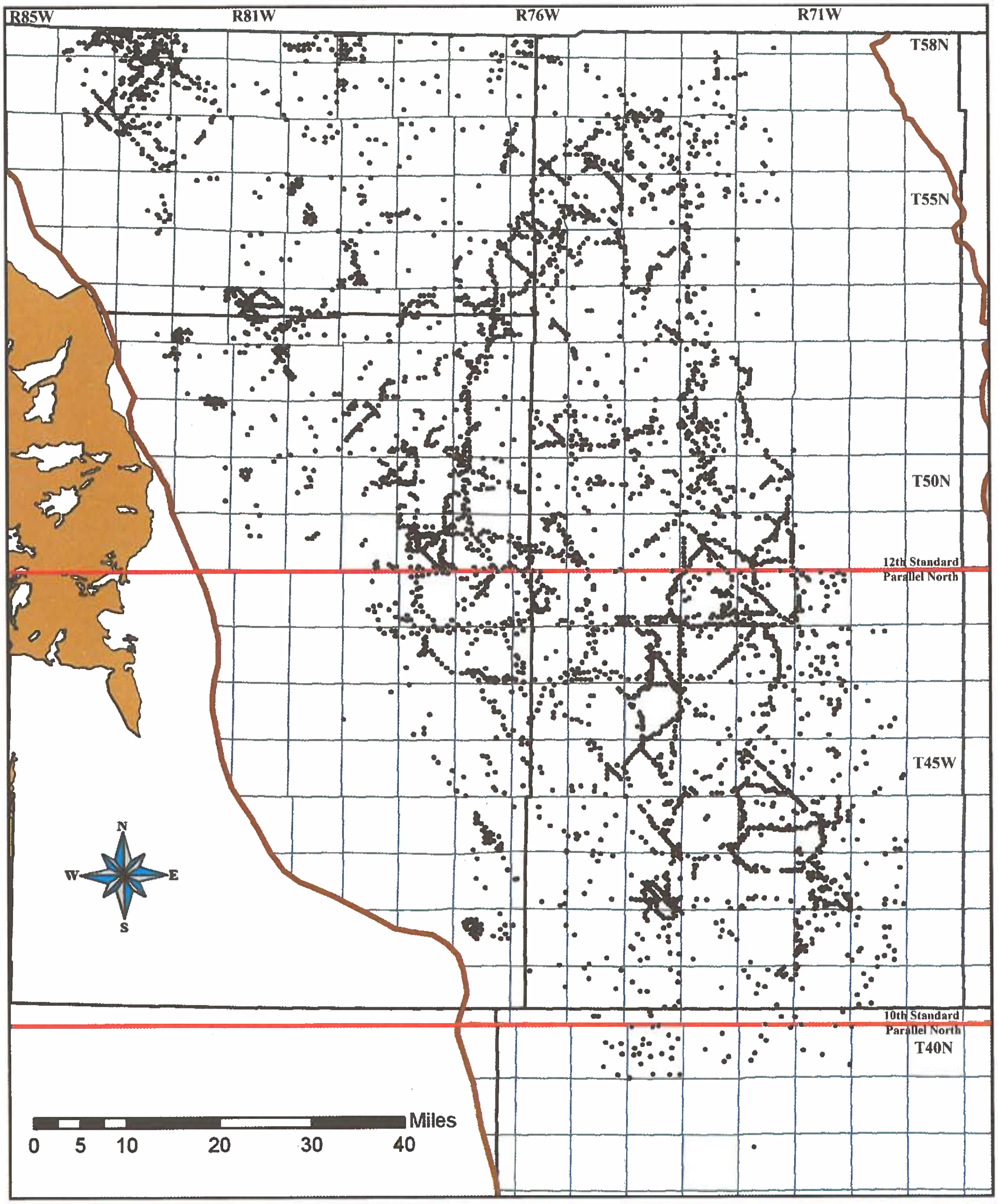


Figure 2-6. Distribution of wells in the Powder River Basin selected for the 2007 correlation models.

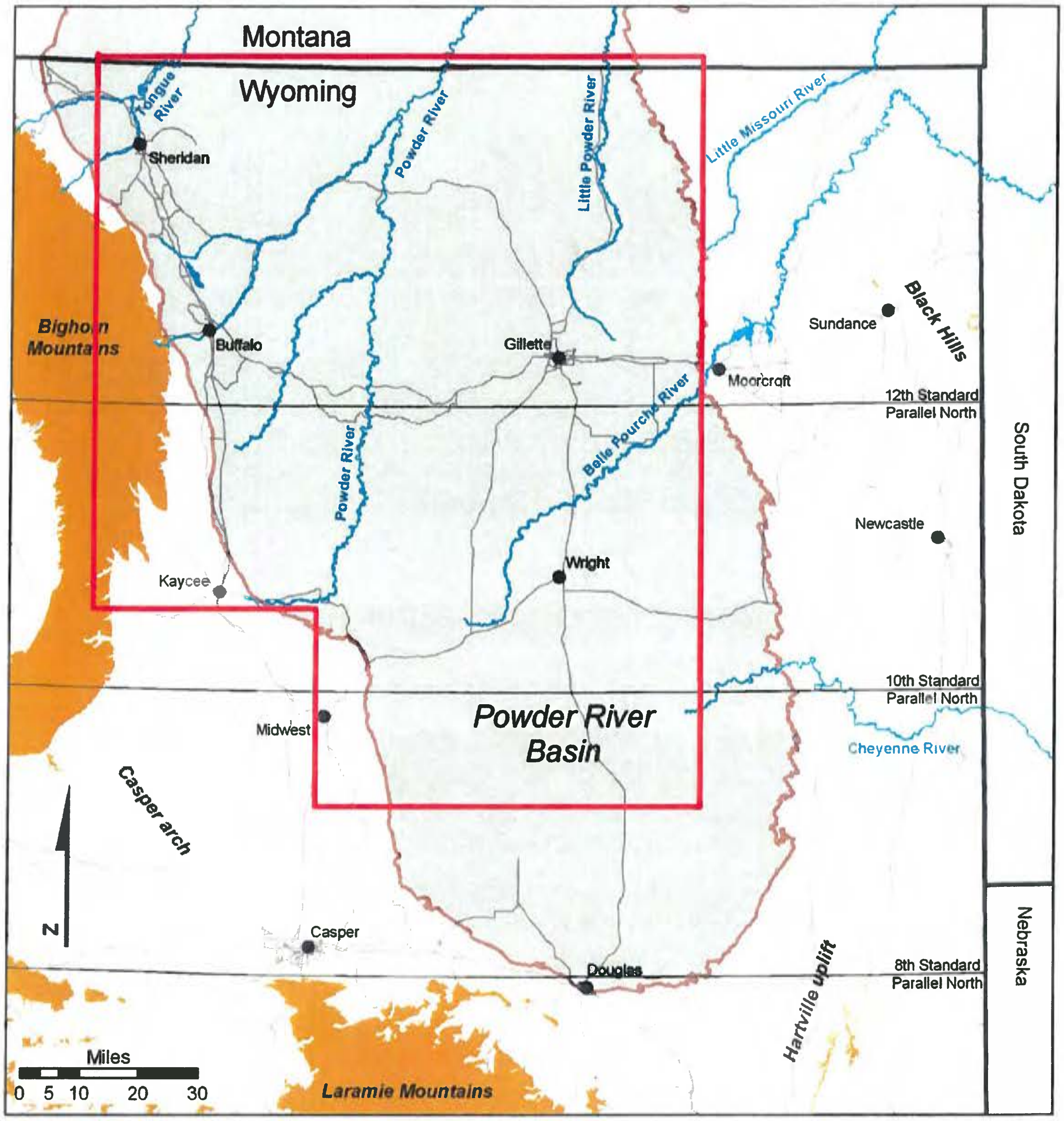


Figure 2-6a. Index map for 26 major coal bed maps, Powder River Basin, Wyoming. Area of Figures 2-7 through 2-32 outlined in red. Area of PRB underlying the Fort Union Formation outlined in brown, and shaded grey.

Table 2-7. Arbitrary coal designations as related to conventional coal nomenclature.

Formation	Order	Code	Coal bed name	Coal Zone
Wasatch	1	t3	Ulm	*Upper Wasatch*
	2	t4	Buffalo Cameron } Lake De Smet	
	3	t5	Murray	
	4	t5a	Ucross	
	5	t6a	Felix Rider	*Felix*
	6	t6	Upper Felix	
	7	t7	Felix	
	8	t7b	Arvada	*Lower Wasatch*
	9	t8a	unnamed	
Fort Union	10	t8	Upper Roland	*Roland*
	11	t9	Roland of Baker	
	12	t10	Roland of Taff	
	13	t11a	Smith Rider	*Wyodak Rider*
	14	t11	Smith/Big George	
	15	t12	Lower Smith	
	16	t14	Anderson Rider	*Upper Wyodak*
	17	t15	Anderson	
	18	t15a	Lower Anderson	
	19	t16r	Canyon Rider	*Lower Wyodak*
	20	t16	Canyon	
	21	t17	Cook	*Knoblock*
	22	t18	Lower Cook	
	23	t19	Wall	*Sawyer*
	24	t20	Lower Wall	
	25	t21	Pawnee	
	26	t22	Moyer	*Basal Tongue River*

define ten contiguous coal zones, from top to bottom the Upper Wasatch, Felix, Lower Wasatch, Roland, Wyodak Rider, Upper Wyodak, Lower Wyodak, Knobloch, Sawyer, and Basal Tongue River coal zones (**Table 2-8**).

To assess coal resources in the basin, we used ArcGIS™ geospatial software to plot tabular information (well-log data) representative of coal extent and thickness on digital maps. To assess each coalbed, we determined the volume of coal more than 3 feet thick in areas defined by outermost outcrop and arbitrary subsurface boundaries approximately 6 miles beyond the outermost well-log data points for that coalbed.

We used ArcGIS™ to calculate the thickness distribution over these areas on a 30- × 30-meter grid: the coal thickness in each grid cell was computed from the nearest 20 wells using the spline function option in the Spatial Analyst extension of ArcGIS™ (basic minimum curvature technique or thin plate interpolation). This spline function is a third-order polynomial that interpolates values within a defined region from multi-dimensional point data (x,y,z). Each cell fell within a 10-foot thickness interval, but the first interval truncated at 3 feet: 3–10 feet; 10–20 feet; 20–30 feet; etc. Because well spacing (one well per approximately 80 acres) is much greater than the grid dimension (30 meters) – the nominal ratio is about 19:1 – the computed coal thickness changes

Table 2-8. Revised coal zones in the Powder River Basin (2007).

Wasatch Formation
- Upper Wasatch Coal Zone
- Felix Coal Zone
- Lower Wasatch Coal Zone

Fort Union Formation
- Roland Coal Zone
- Wyodak Rider Coal Zone
- Upper Wyodak Coal Zone
- Lower Wyodak Coal Zone
- Knobloch Coal Zone
- Sawyer Coal Zone
- Basal Tongue River Coal Zone

very little from cell to cell; this characteristic of the interpolation, together with the map scale, causes the stepped boundaries between thickness intervals to plot as smooth isopachs (contour lines representing equal thickness). To calculate the coal volume in a coal bed, we used ArcGIS to compute the volume of coal in each thickness interval, then summed these volumes to give the volume of coal in the coal bed, as follows.

For each 10-foot thickness interval *i* in a coalbed *j*, we calculated the area A_i in acres (i.e. summed the grid cells in that thickness interval), the mean coal thickness MT_i in feet (i.e., averaged the thicknesses of coal in those grid cells), and the product of these components, the coal volume CV_i in acre-feet:

$$CV_i = A_i \cdot MT_i$$

Multiplying the coal volume CV_i (acre-feet) by a conversion factor (1,770 tons per acre-foot) gave tons of coal TC_i in thickness interval *i*:

$$TC_i = CV_i \cdot 1{,}770,$$

and the sum $\sum_i i$ of tonnages TC_i of all thickness intervals *i* gave the hypothetical coal resources CR_j in coalbed *j*, in tons of coal:

$$CR_j = \sum_i TC_i$$

The sum $\sum_j j$ of all coalbed resource CR_j gave the hypothetical coal resource of the basin:

$$\text{PRB hypothetical coal resource} = \sum_j CR_j$$

Individual coal zones and coal beds

This report defines three coal zones within the Wasatch Formation in the PRB, from top to bottom the Upper Wasatch, Felix, and Lower Wasatch coal zones. Within the Fort Union Formation, we define seven coal zones, from top to bottom the Roland, Wyodak Rider, Upper Wyodak, Lower Wyodak, Knoblock, Sawyer, and Basal Tongue River coal zones. These ten coal zones order the 26 major coal beds defined in this report. **Table 2-9** contains summary information for each coal zone and coal bed. **Figure 2-7** shows the area in the PRB covered by the 26 coal bed distribution maps, **Figure 2-7** through **Figure 2-32**. On the coal bed distribution maps, linear cutoffs of coal bed areas represent boundaries of reliable data rather than coal bed boundaries. To verify areas of no data, compare the coalbed distribution maps with **Figure 2-6**, which shows the distribution of wells. For example, see **Figure 2-9**, T. 50 N., R. 81 W. and T. 56 N., Rs. 80 and 81 W.

Wasatch Formation

Upper Wasatch Coal Zone

The Upper Wasatch Coal Zone contains many minor coals, ranging in thickness from inches to several hundred feet. We correlated and mapped four major coal beds in the Wasatch for this report. The lower three coals compose the Lake De Smet coal deposit.

The stratigraphically highest mappable coal in the Upper Wasatch Coal Zone is the Ulm coal bed (**Figure 2-7**). This coal lies at an average depth of 147 feet, and at a maximum depth of 548 feet in the southern third of T. 54 N., R. 82 W. The Ulm was measured in 41 wells, has an average thickness of 22 feet and a maximum thickness of 40 feet, underlies 87,684 acres, and contains approximately 4.1 billion tons of coal. Most of the Ulm coal bed is located in Sheridan County, and a very small part in north-central Johnson County. The thickest mapped Ulm coal is exposed in outcrop, and lies in south-central Sheridan County. Outcrops of the coal occur 6 miles east of Sheridan and along the western, eastern, northern, and southern margins of the deposit. The coal bed thins out in the subsurface in the eastern third of its mapped extent near Tps. 54 and 55 N., Rs. 80 and 81 W., 6 miles west of U.S. Highway 16-14. In the

Table 2-9. Summary information for coal zones and coal beds.

Formation	Order	Maximum thickness	Average thickness	No. of wells	Code	Coal bed	Coal zone	Acres	Million tons
Wasatch	1	40	22	41	t3	Ulm	*Upper Wasatch*	87,684	4,125
	2	54	11	164	t4	Buffalo Cameron } Lake De Smet		468,400	12,416
	3	147	11	251	t5	Murray		766,503	13,123
	4	212	18	377	t5a	UCross		814,184	19,736
	5	25	4	431	t6a	Felix Rider	*Felix*	1,412,514	13,269
	6	47	7	631	t6	Upper Felix		1,531,376	18,992
	7	77	13	1,517	t7	Felix		2,103,350	40,391
	8	75	14	431	t7b	Arvada	*Lower Wasatch*	904,397	21,899
	9	45	7	485	t8a	unnamed		162,702	4,352
Fort Union	10	39	6	1,185	t8	Upper Roland	*Roland*	402,998	11,121
	11	93	10	2,849	t9	Roland of Baker		1,208,048	37,110
	12	58	13	1,615	t10	Roland of Taff		1,127,022	37,087
	13	107	17	525	t11a	Smith Rider	*Wyodak Rider*	668,384	26,400
	14	216	38	2,311	t11	Smith/Big George		1,791,288	147,573
	15	100	18	603	t12	Lower Smith		1,703,440	37,848
	16	52	13	382	t14	Anderson Rider	*Upper Wyodak*	1,032,257	29,952
	17	208	47	2,856	t15	Anderson		3,789,227	225,800
	18	167	21	1,015	t15a	Lower Anderson		2,998,382	97,312
	19	38	10	270	t16r	Canyon Rider	*Lower Wyodak*	335,146	9,114
	20	205	25	1,131	t16	Canyon		1,689,675	79,848
	21	145	22	903	t17	Cook	*Knoblock*	1,788,301	76,430
	22	38	9	172	t18	Lower Cook		638,128	16,420
	23	139	19	996	t19	Wall	*Sawyer*	1,862,080	Cocal
	24	58	11	494	t20	Lower Wall		3,177,455	54,701
	25	50	11	586	t21	Pawnee		1,097,580	30,996
	26	45	13	374	t22	Moyer	*Basal Tongue River*	1,250,938	39,498

southern part of the deposit, the bed crops out along both sides of U.S. Highway 14 and extends south into T. 53 N., R. 81 W. in Johnson County.

The other three coal beds in the Upper Wasatch Coal Zone – the Buffalo Cameron, Murray, and Ucross coal beds – compose the Lake De Smet coal deposit, which lies along the western edge of the basin. Well data indicate that the beds within the Lake De Smet deposit constitute a single bed, with numerous thin partings along the western margin, that splits into several individual coal beds to the east. East of the main body of the De Smet coal deposit, individual beds either pinch out or have burned, creating red clinker deposits of baked and fused rock. These clinker beds crop out extensively over an area surrounding and east of Lake De Smet, east of Interstate 90 between Buffalo and Sheridan.

The uppermost coal of the Lake De Smet deposit is the Buffalo Cameron coal bed (**Figure 2-8**). This coal lies at an average depth of 159 feet, and at a maximum depth of 739 feet in Tps. 49 and 50 N., Rs. 81 and 82 W. The Buffalo Cameron was measured in 164 wells, has an average thickness of 11 feet and a maximum thickness of 54 feet, underlies 468,400 acres, and contains approximately 12.4 billion tons of coal. This coal bed comprises two regions, one in west-central Campbell County, the other in southwestern Sheridan and northwestern and central Johnson counties. The thickest mapped Buffalo Cameron coal is located in Tps. 47–49 N., Rs. 78–80 W. and in Tps. 50–54 N., Rs. 81 and 82 W.

The middle coal in the Lake De Smet deposit is the Murray coal bed (**Figure 2-9**). This coal lies at an average depth of 204 feet, and at a maximum depth of 879 feet in Tps. 49 and 50 N., Rs 81 and 82 W. The Murray was measured in 251 wells, has an average thickness of 11 feet and a maximum thickness of 147 feet, underlies 766,503 acres, and contains approximately 13.1 billion tons of coal. The Murray coal bed lies in the northern third of the basin in Campbell, Sheridan, and Johnson counties. The thickest Murray coal lies in Johnson County near Buffalo in Tps. 49–53 N., Rs. 81 and 82 W.

The lowermost coal in the Upper Wasatch Coal Zone and in the Lake De Smet coal deposit is the Ucross coal bed (**Figure 2-10**). This coal lies at an average depth of 264 feet, and at a maximum depth of 923 feet in Tps. 49 and 50 N., Rs. 81 and 82 W. and in the southeastern corner of T. 52 N., R. 83 W. The Ucross was measured in 377 wells, has an average thickness of 18 feet and a maximum thickness of 212 feet, underlies 814,184 acres, and contains approximately 19.7 billion tons of coal. The Ucross coal deposit occupies west-central Campbell, southern Sheridan, and northern Johnson counties. The thickest Ucross coal lies in northwestern Johnson County and southern Sheridan County in Tps. 49–54 N., Rs. 80–83 W.

Felix Coal Zone

The Felix Coal Zone contains as many as six individual coal beds, ranging in thickness from inches to several feet. We correlated and mapped three major coal beds in the Felix for this report.

The uppermost coal in the Felix Coal Zone is the Felix Rider coal bed (**Figure 2-11**). This coal lies at an average depth of 305 feet and a maximum depth of 1,038 feet. The Felix Rider was measured in 431 wells, has an average thickness of 4 feet and a maximum thickness of 25 feet, underlies 1,412,514 acres, and contains approximately 13.3 billion tons of coal. The Felix Rider is thickest in southwestern Sheridan and northwestern Johnson counties; thinner areas of this coal occur in western Campbell, northern Johnson, and southeastern Sheridan counties.

The middle coal in the Felix Coal Zone is the Upper Felix coal bed (**Figure 2-12**). This coal lies at an average depth of 346 feet, and at a maximum depth of 1,092 feet in Tps. 48–50 N., Rs. 78 and 79 W. The Upper Felix was measured in 631 wells, has an average thickness of 7 feet and a maximum thickness of 47 feet, underlies 1,531,376 acres, and contains approximately 19.0 billion tons of coal. The main body of the Upper Felix coal bed lies in west-central Campbell and northeastern Johnson counties; thinner areas of this coal were also mapped in central Sheridan County. The thickest Upper Felix coal lies in Campbell County east of Gillette in Tps. 47–52 N., Rs. 73–76 W., and just west and south of Wright in Tps. 43 and 44 N., Rs. 72 and 73 W.

The lowermost and main coal in the Felix Coal Zone is the Felix coal bed (**Figure 2-13**). This coal lies at an average depth of 380 feet, and at a maximum depth

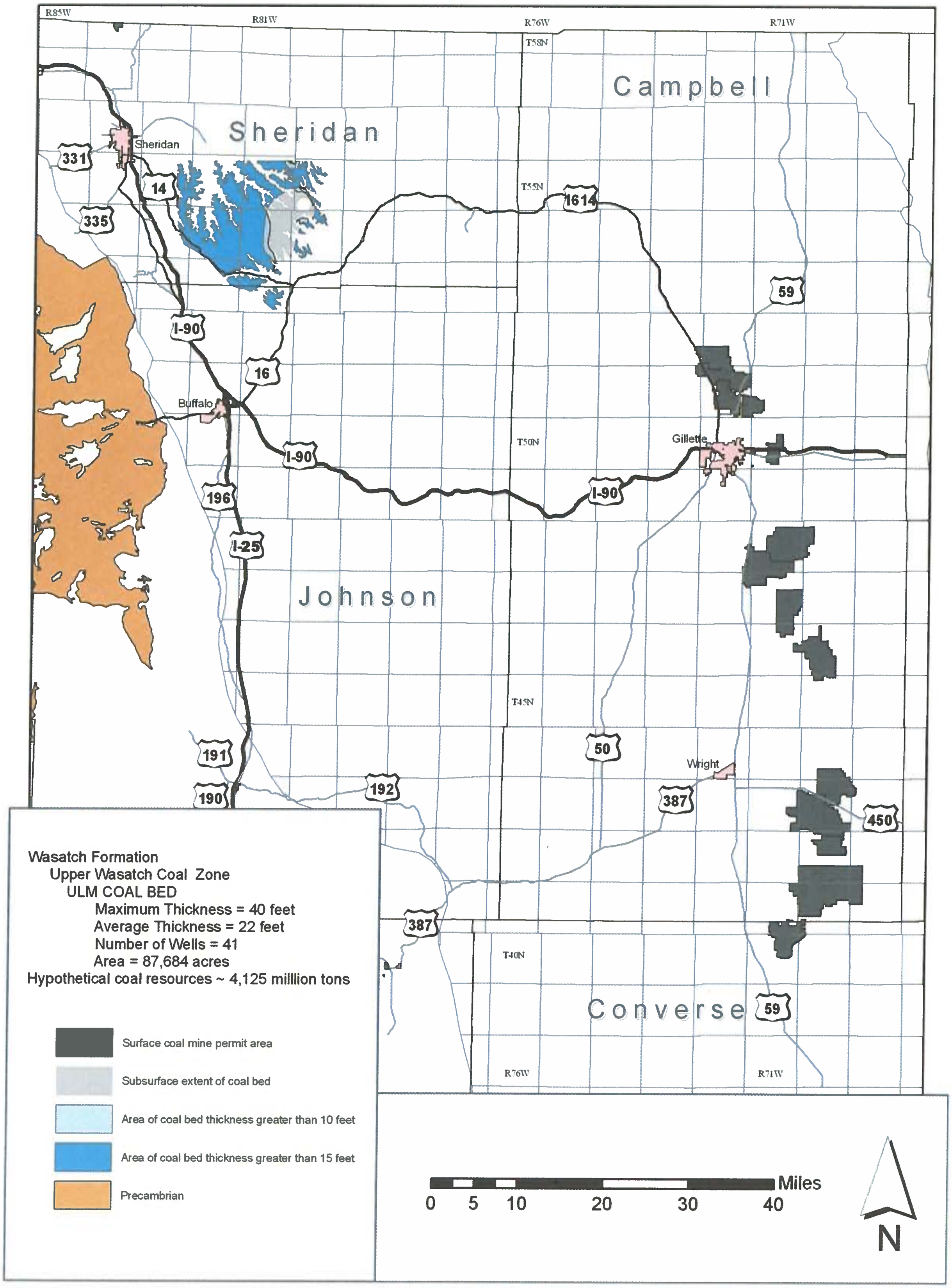


Figure 2-7. Map of Ulm coal bed, Powder River Basin, Wyoming.

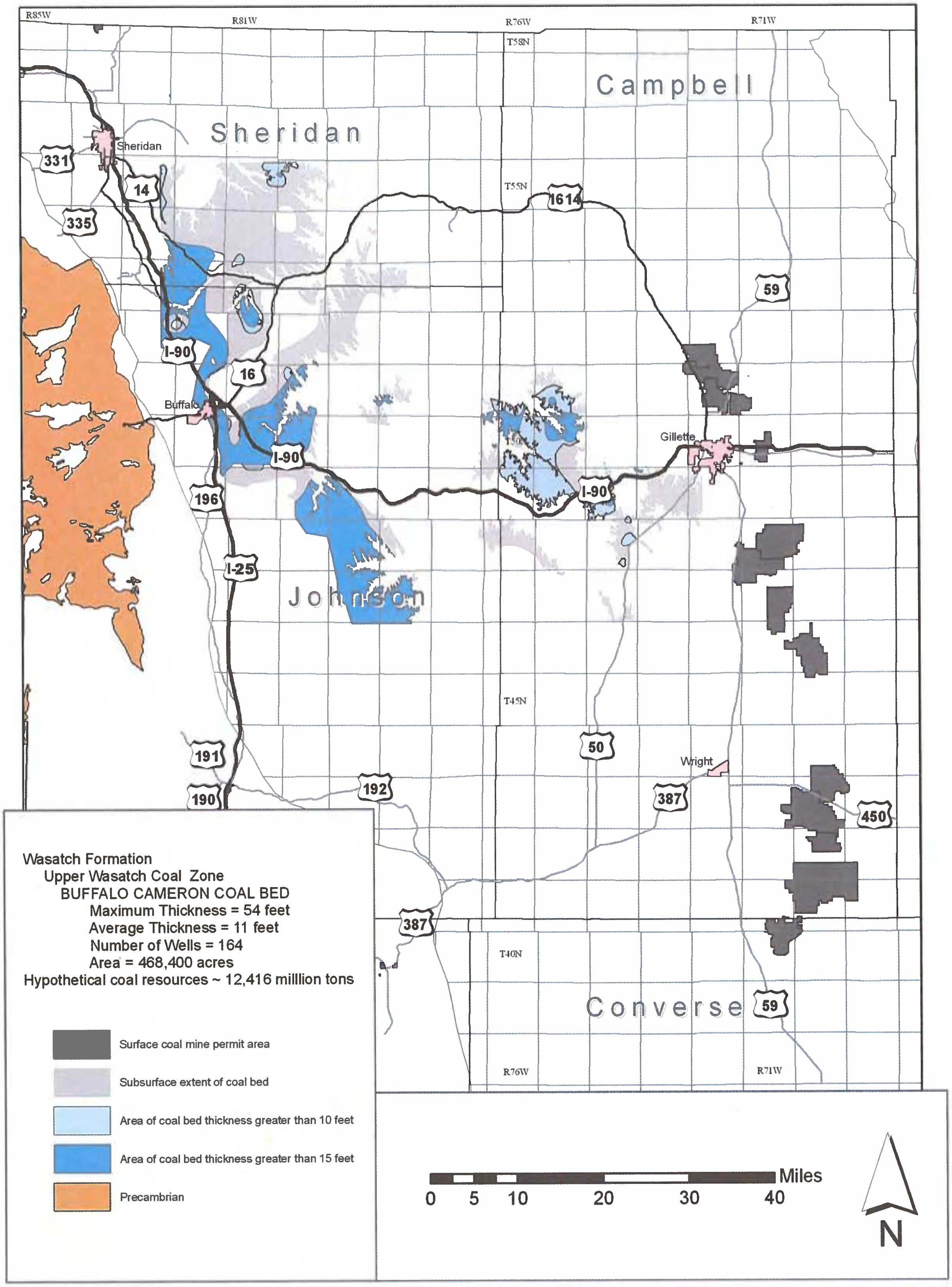


Figure 2-8. Map of Buffalo Cameron coal bed, Powder River Basin, Wyoming.

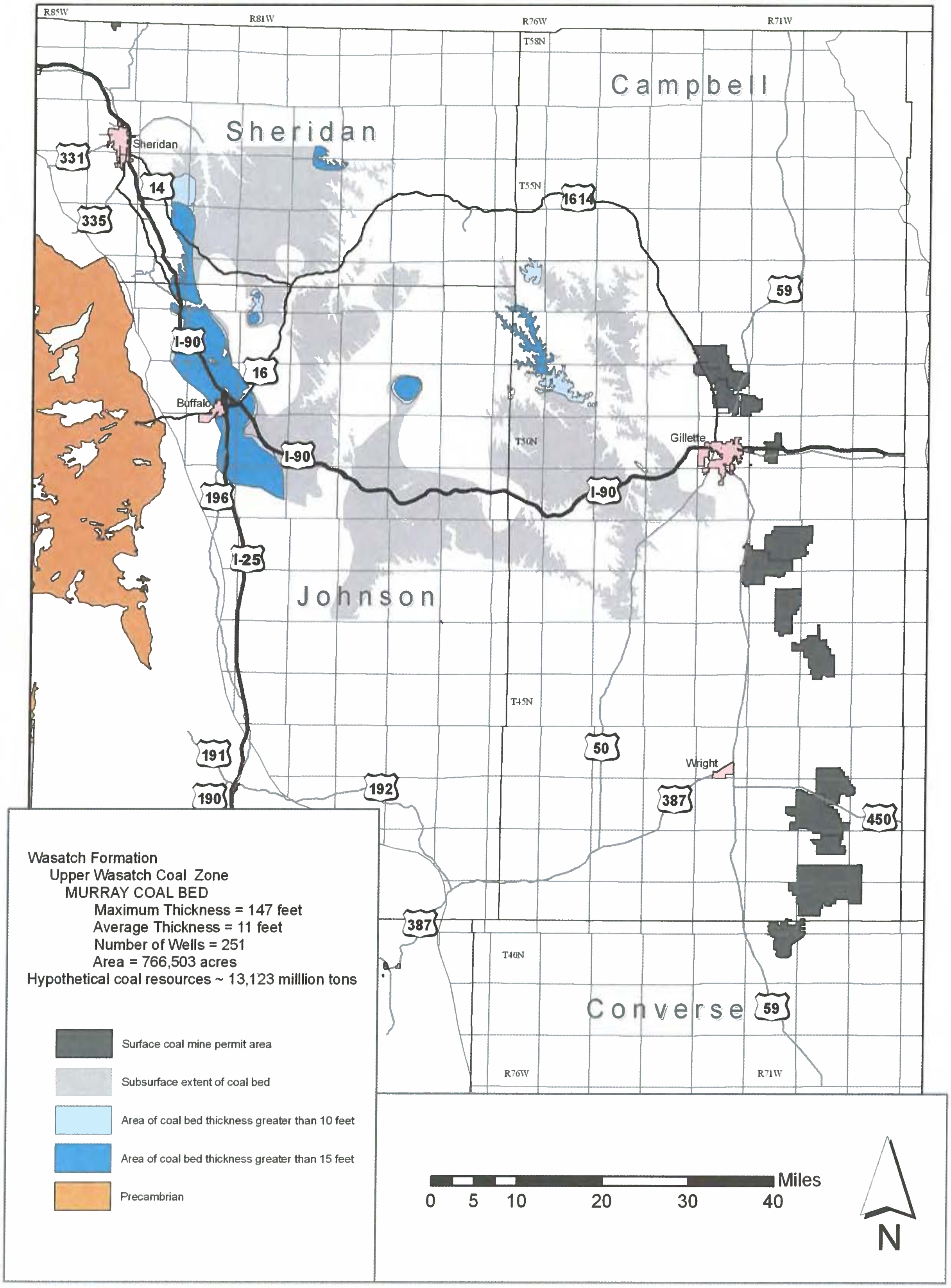


Figure 2-9. Map of Murray coal bed, Powder River Basin, Wyoming.

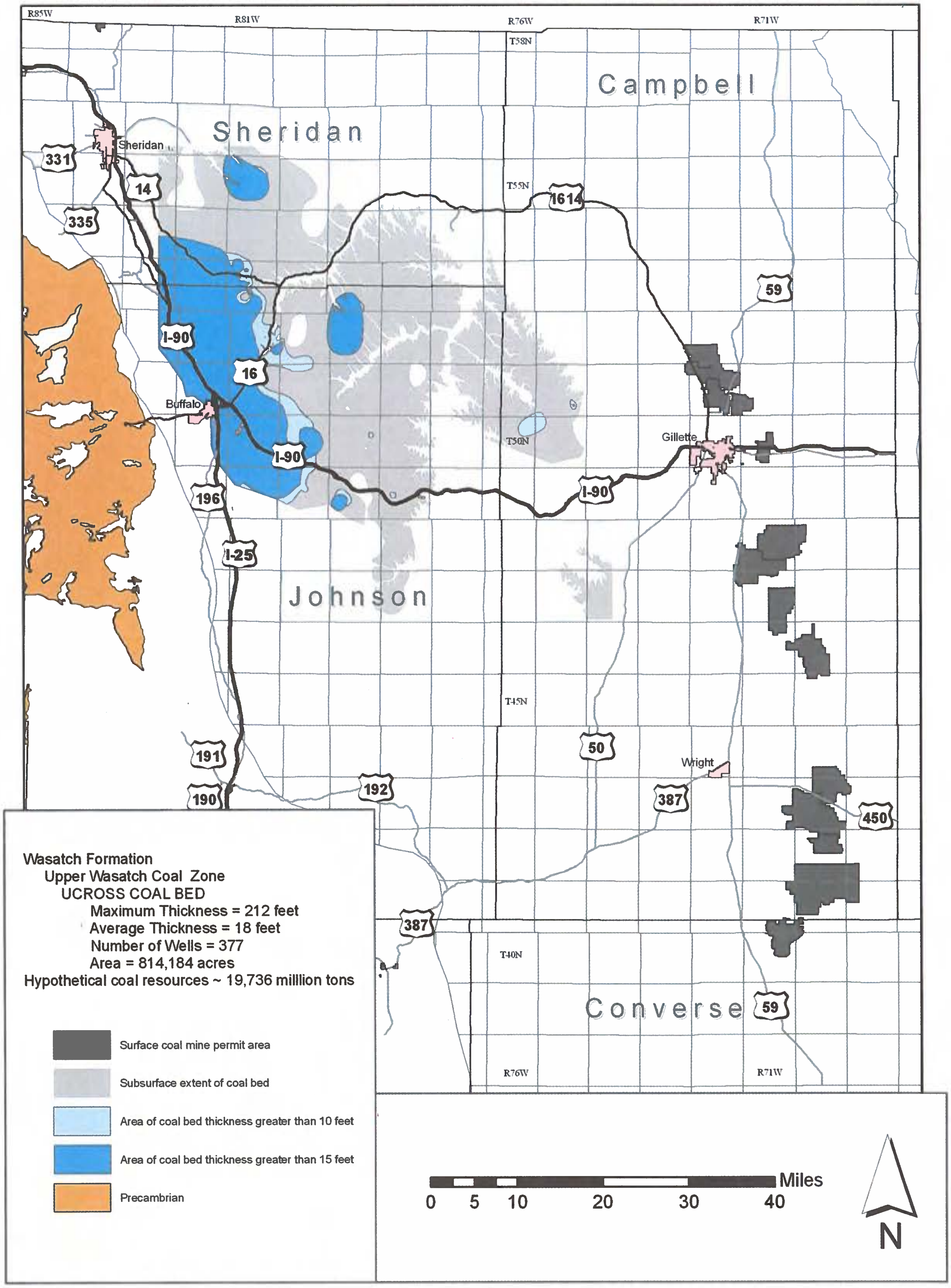


Figure 2-10. Map of Ucross coal bed, Powder River Basin, Wyoming.

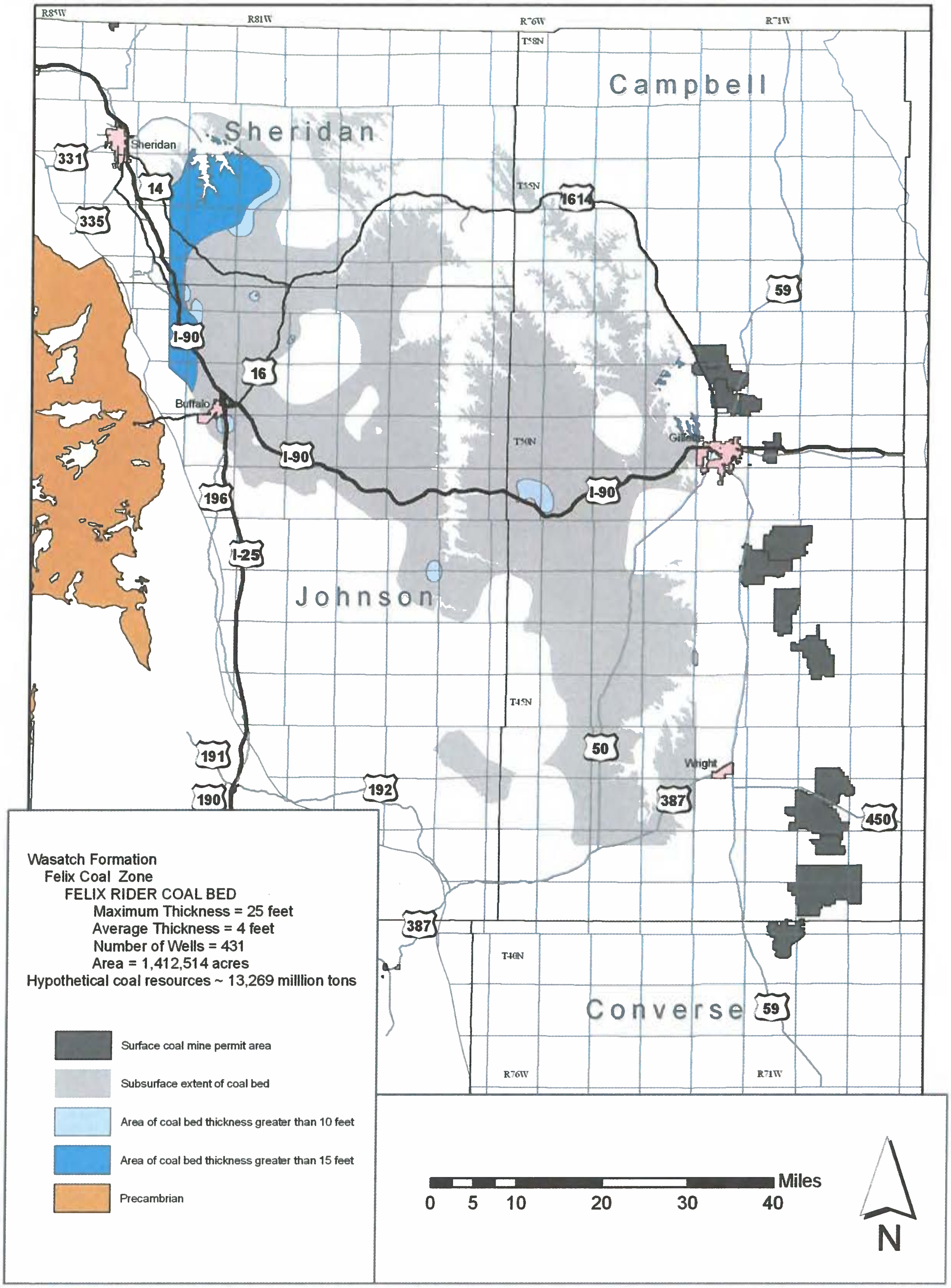


Figure 2-11. Map of Felix Rider coal bed, Powder River Basin, Wyoming.

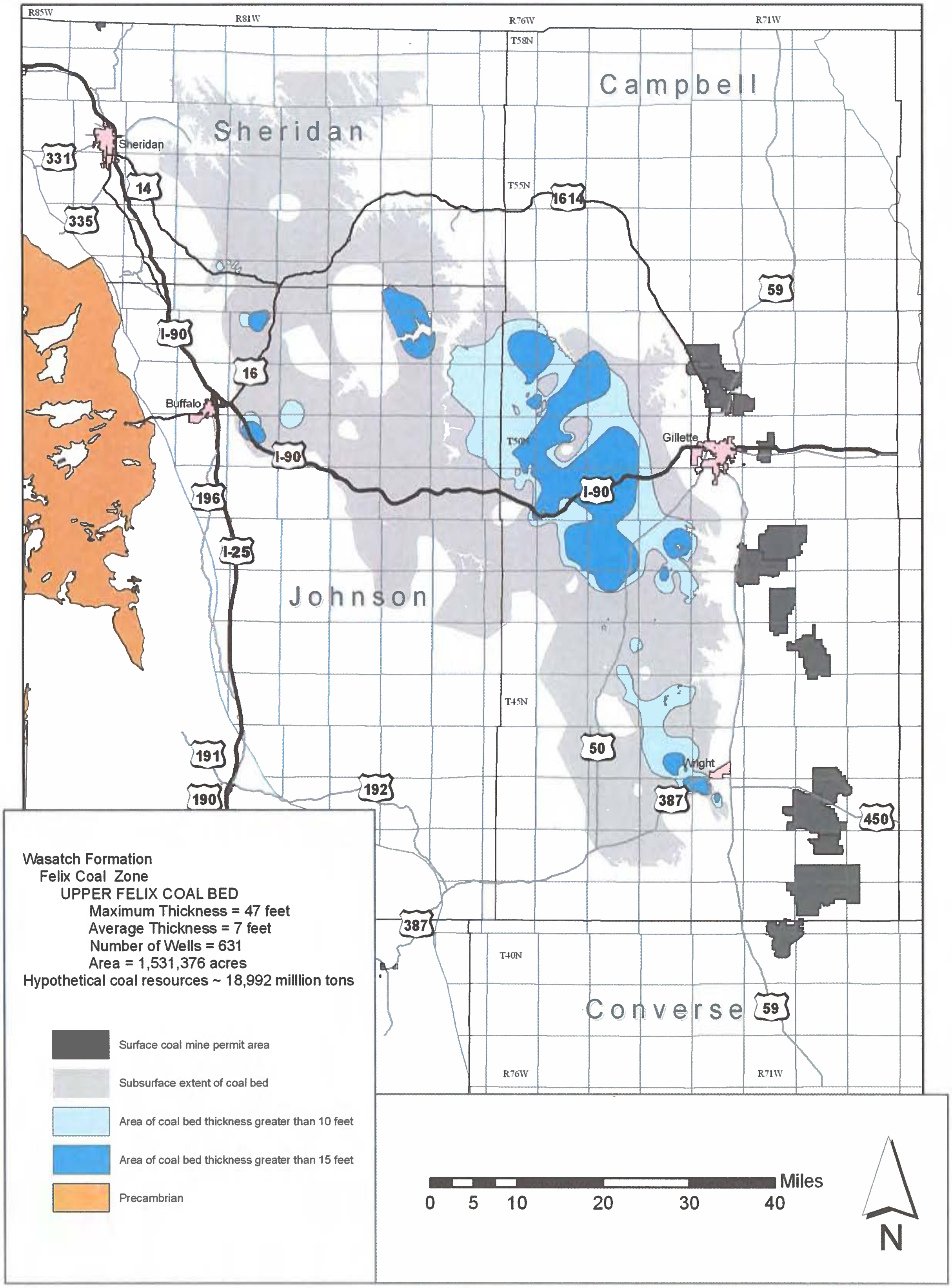


Figure 2-12. Map of Upper Felix coal bed, Powder River Basin, Wyoming.

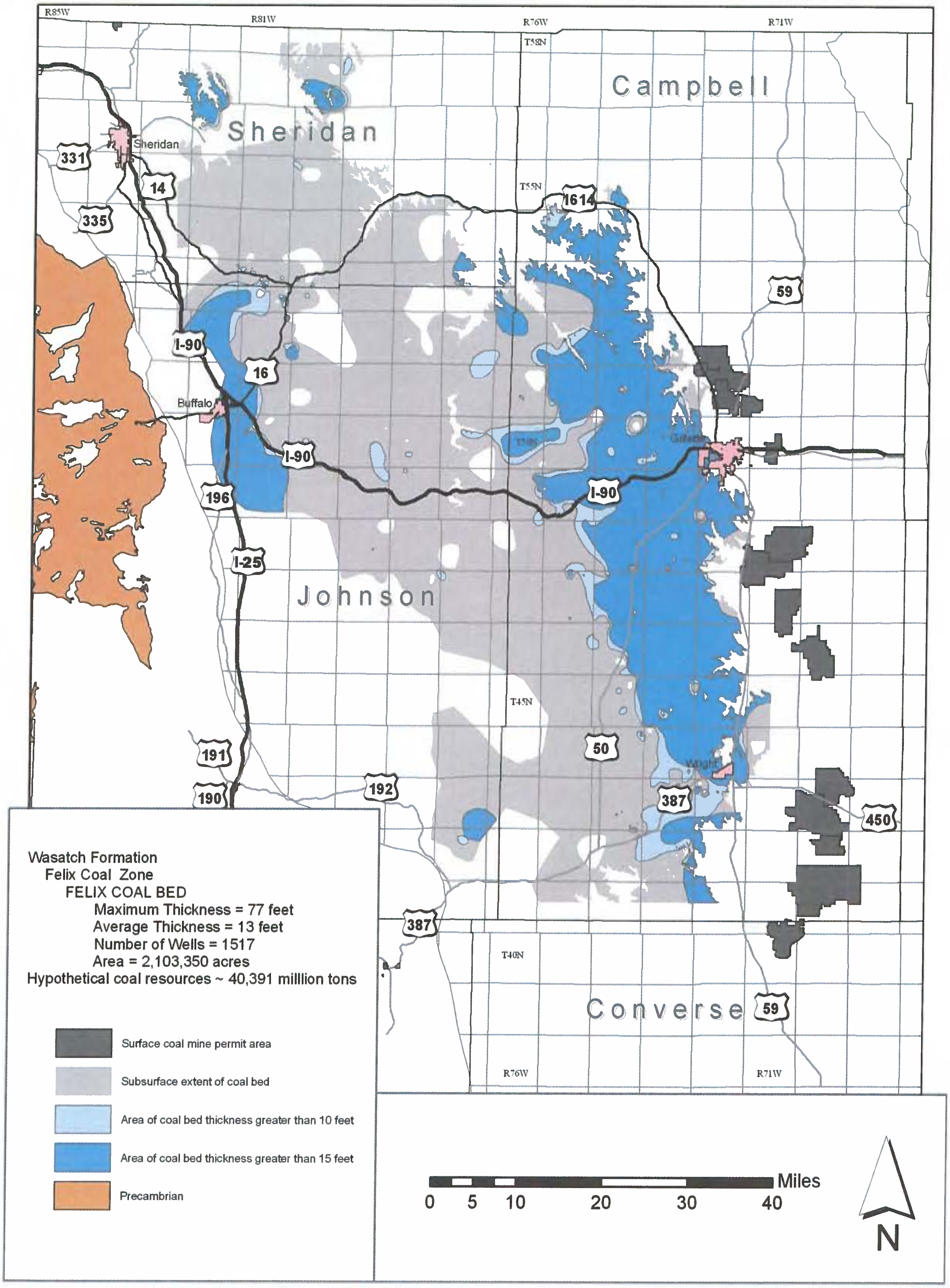


Figure 2-13. Map of Felix coal bed, Powder River Basin, Wyoming.

of approximately 1,350 feet in T. 51 N., R. 81 W. and in T. 43 N., R. 75 W. The Felix was measured in 1,517 wells, has an average thickness of 13 feet and a maximum thickness of 77 feet, underlies 2,103,350 acres, and contains approximately 40.4 billion tons of coal. The main body and thickest part of the Felix lies in central Campbell County in Tps. 44–54 N., Rs. 72–75 W. and in northwestern Johnson County in Tps. 49–53 N., Rs. 81 and 82 W.; thinner areas of this coal occur between the two main bodies in Johnson County and extend north into central Sheridan County.

Lower Wasatch Coal Zone

There are two mappable coal beds in the Lower Wasatch Coal Zone, the Arvada and the unnamed coal beds. These coals occur only in Sheridan and northern Johnson counties. At the base of this coal zone is a distinct coquina bed (Olive 1957): the base of the coquina bed is accepted as the contact between late Paleocene and early Eocene rocks in the Powder River Basin. This boundary is problematic; see discussion in Chapter 1, p. 36.

The upper coal in the Lower Wasatch Coal Zone is the Arvada coal bed (**Figure 2-14**). This coal lies at an average depth of 588 feet and a maximum depth of 1,474 feet. The Arvada was measured in 431 wells, has an average thickness of 14 feet and a maximum thickness of 75 feet, underlies 904,397 acres, and contains approximately 21.9 billion tons of coal. The Arvada is thickest in southwestern Sheridan and northwestern Johnson counties in Tps. 49–55 N., Rs. 80–82 W.; thinner areas of this coal occur in northern and eastern Sheridan County and northeastern Johnson County.

The lower and earlier coal in the Lower Wasatch Coal Zone is an unnamed bed (**Figure 2-15**) at the base of the Wasatch Formation. This coal lies at an average depth of 603 feet and a maximum depth of 1,496 feet. This unnamed coal was measured in 485 wells, has an average thickness of 7 feet and a maximum thickness of 45 feet, underlies 162,702 acres, and contains approximately 4.4 billion tons of coal. This coal bed is thickest in two areas: Tps. 57 and 58 N., Rs. 79 and 80 W., and a narrow elongated area in Tps. 51–54 N., R. 82 W. North and east of Sheridan, the unnamed coal bed averages 10 feet thick and occupies approximately three townships. Thinner areas of this coal occur in eastern Sheridan County and the extreme northeastern corner of Johnson County.

Fort Union Formation

Roland Coal Zone

We correlated three coal beds in the Roland Coal Zone: the Upper Roland, the Roland of Baker, and the Roland of Taff. In the northern part of the basin, each of these coal beds is locally split into several minor coal beds. Dobbin and Barnett (1928) used this series of coal beds to define the top of the Tongue River Member of the Fort Union Formation: the coal beds are still considered to represent the uppermost and last late Paleocene peat swamps.

The uppermost coal in the Roland Coal Zone, the Upper Roland coal bed (**Figure 2-16**) is sparsely distributed in the basin in localized pockets. All but a few of these pockets lie in a 40-mile-wide band that crosses the basin northwest-southeast, passing through Wright, Gillette, and Sheridan. This coal lies at an average depth of 715 feet and a maximum depth of 1,722 feet. The Upper Roland was measured in 1,185 wells, has an average thickness of 6 feet and a maximum thickness of 39 feet, underlies 402,998 acres, and contains approximately 11.1 billion tons of coal. The Upper Roland is relatively thick at several locations in the basin. The largest three areas where the Upper Roland measures more than 15 feet thick are located in Tps. 45 and 46 N., Rs. 71 and 72 W.; Tps. 51 and 53 N., Rs. 76–78 W.; and Tps. 52 and 53 N., R. 81 W. Along the extreme northwestern edge of the basin and east of Interstate 90, the Upper Roland coal averages 10 feet in thickness in an area beginning in northern Johnson County and extending past Sheridan to T. 58 N., Rs. 82 and 83 W. The Upper Roland crops out in the northeast in Tps. 53–56 N., Rs. 73–75 W. and in the extreme northwest in Tps. 57 and 58 N., Rs. 83 and 84 W. The Upper Roland is essentially a bed that splits off from and coalesces with the underlying Roland of Baker. Unlike the coal beds that compose the Eocene Lake De Smet coal deposit, which split out and apart fairly predictably towards the east, the Roland of Baker and the Upper Roland split locally and somewhat randomly, resulting in numerous disconnected pockets of the Upper Roland, as seen in **Figure 2-16**.

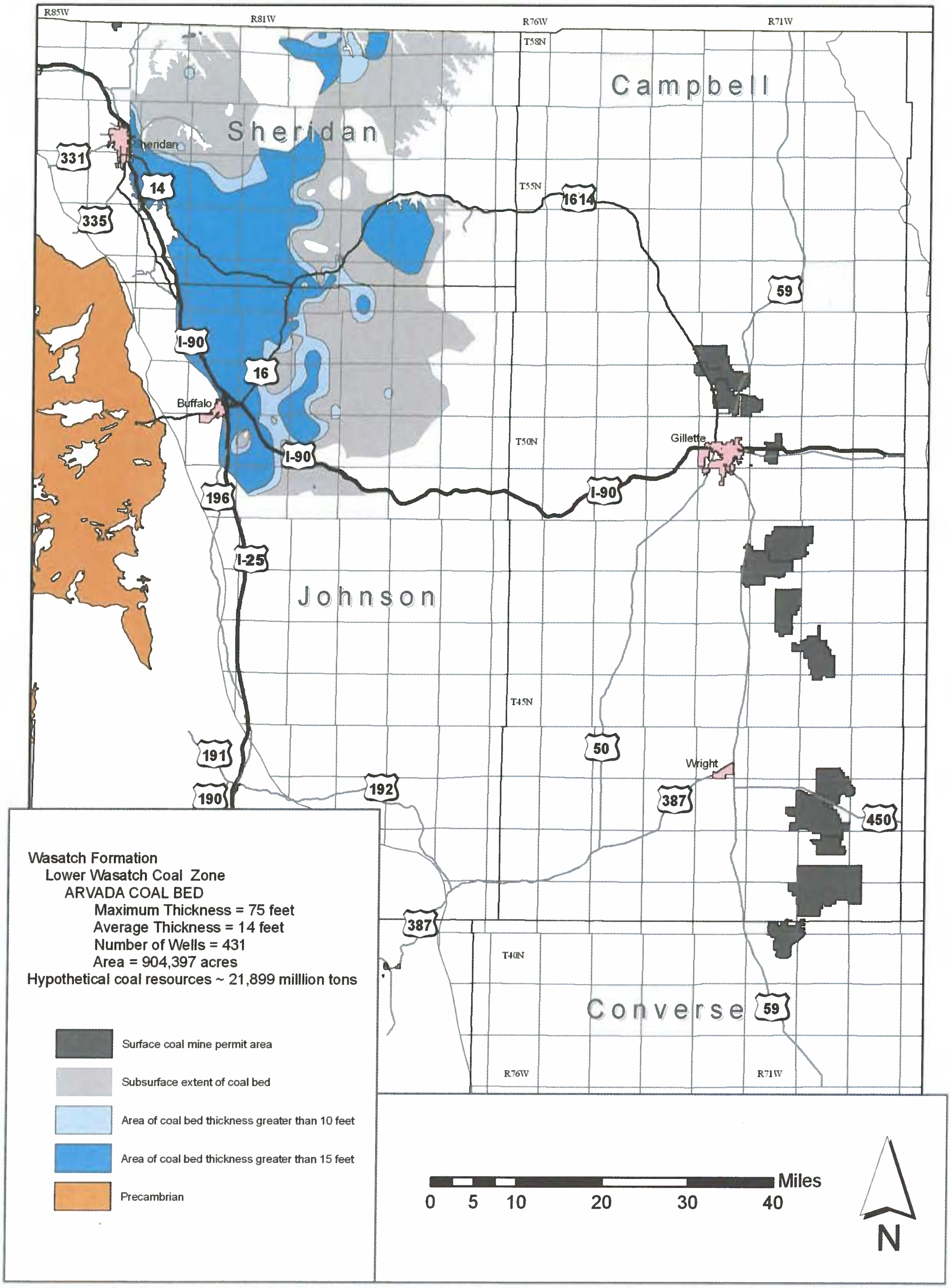


Figure 2-14. Map of Arvada coal bed, Powder River Basin, Wyoming.

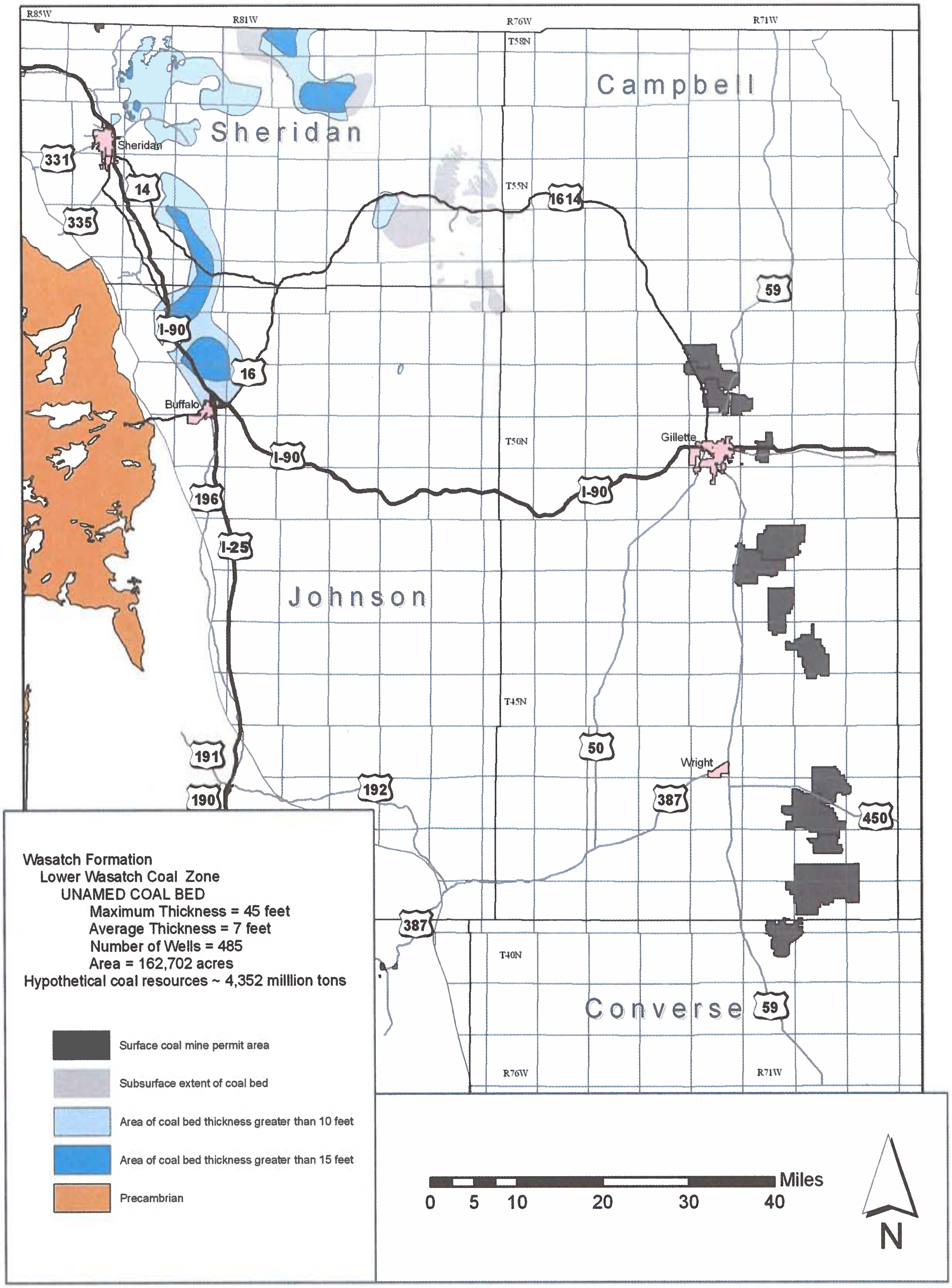


Figure 2-15. Map of unnamed coal bed, Powder River Basin, Wyoming.

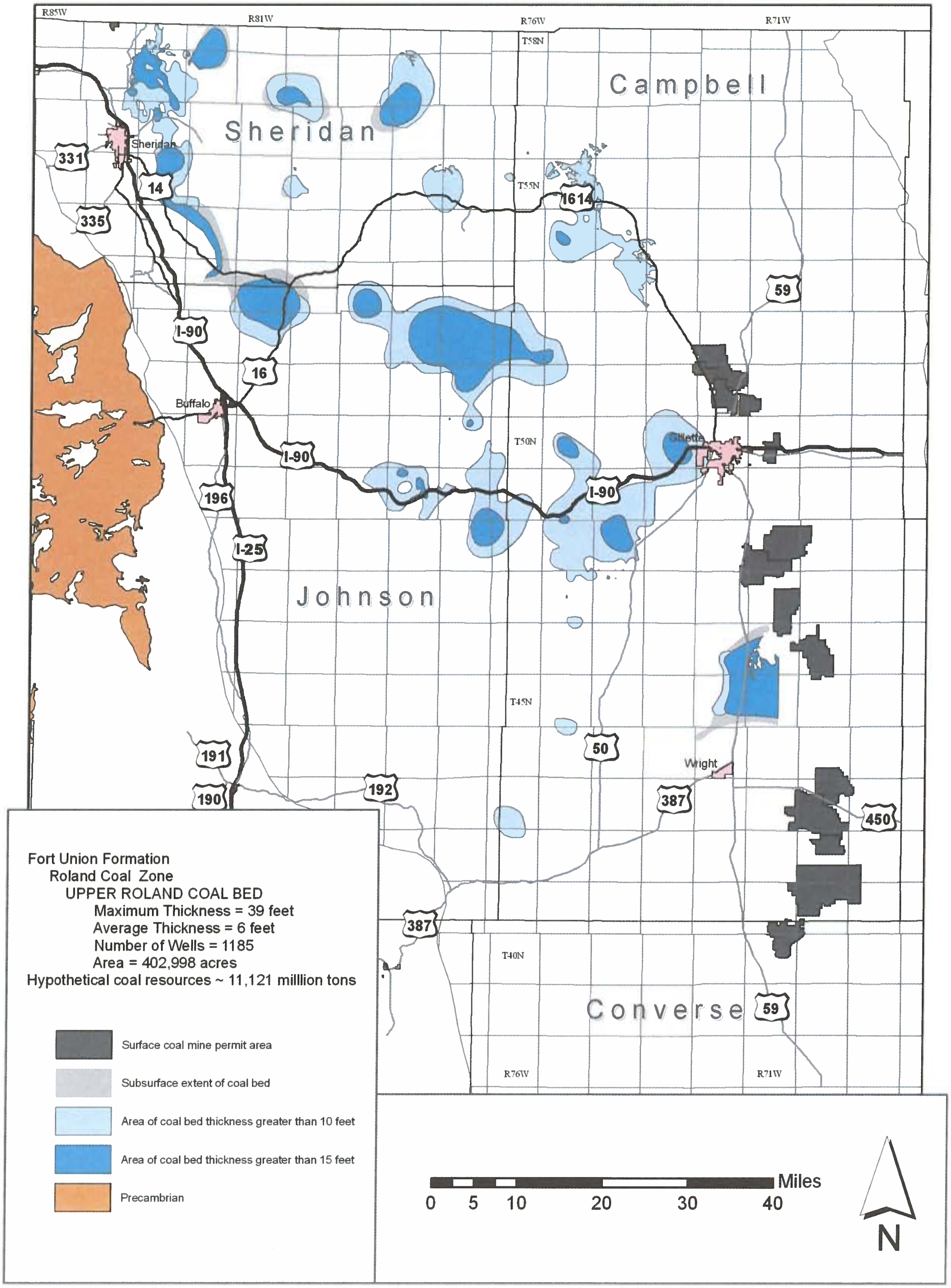


Figure 2-16. Map of Upper Roland coal bed, Powder River Basin, Wyoming.

The middle coal in the Roland Coal Zone is the Roland of Baker coal bed (**Figure 2-17**). This coal lies at an average depth of 802 feet and a maximum depth of 1,956 feet. The Roland of Baker was measured in 2,849 wells, has an average thickness of 10 feet and a maximum thickness of 93 feet, underlies 1,208,048 acres, and contains approximately 37.1 billion tons of coal. The shape of this coal bed is semi-arcuate, beginning in northern Converse County and extending into Campbell and northern Johnson counties and into the eastern two-thirds of Sheridan County. The thickest area of the Roland of Baker occurs in northern Johnson and central Sheridan counties. This coal crops out in the northeast in Tps. 53–57 N., Rs. 72–77 W., and in the extreme northwest in Tps. 56–58 N., Rs. 83 and 84 W.

The lowermost coal in the Roland Coal Zone is the Roland of Taff coal bed (**Figure 2-18**). This coal lies at an average depth of 923 feet and a maximum depth of 2,305 feet. The Roland of Taff was measured in 1,615 wells, has an average thickness of 13 feet and a maximum thickness of 58 feet, underlies 1,127,022 acres, and contains approximately 37.1 billion tons of coal.

Wyodak Rider Coal Zone

The Wyodak Rider Coal Zone contains as many as seven coal beds of varying thickness and subsurface extent. Two areas of thick coal are located in the central part and extreme northwestern corner of the basin. We correlated and mapped three related coal beds in the Wyodak Rider – the Smith Rider, the Smith/Big George (main body), and the Lower Smith – for this report. In the extreme northwestern corner of the basin, these three coals in the Wyodak Rider Coal Zone occur as individual, distinct coal beds stratigraphically separated by uniform deposits of clastic sediments such as fine sands, mudstones, and shales. These coal beds crop out north and west of Sheridan in T. 58 N., R. 84 W. Well data indicate that these coals constitute a single bed with numerous thin partings in the central part of the basin, and split into several individual coal beds to the west, southwest, and northwest. West of the main body of the Smith/Big George coal deposit, three individual beds – the Smith Rider, Smith/Big George, and Lower Smith – thin, grade into shale, and pinch out in the subsurface. East of the main body, the coal is a single bed that thins, grades into shale, and pinches out in the subsurface. There are sparse outcrops of this bed at the northeastern edge of the deposit in T. 53 N., R. 73 W.

The uppermost coal in the Wyodak Rider Coal Zone is the Smith Rider coal bed (**Figure 2-19**). This coal lies at an average depth of 1,107 feet and a maximum depth of 2428 feet. The Smith Rider was measured in 525 wells, has an average thickness of 17 feet and a maximum thickness of 107 feet, underlies 668,384 acres, and contains approximately 26.4 billion tons of coal. This coal coalesces with the underlying Smith/Big George in an arcuate area that begins in T. 43 N., R. 75 W., extends north along Rs. 75 and 76 W. and then around to the east, and ends in Tps. 52–54 N., Rs. 73 and 74 W.

The middle and main coal in the Wyodak Rider Coal Zone is the Smith/Big George coal bed (**Figure 2-20**). This coal bed lies at an average depth of 1,092 feet and a maximum depth of 2,558 feet. The Smith / Big George was measured in 2,311 wells, has an average thickness of 38 feet and a maximum thickness of 216 feet, underlies 1,791,288 acres, and contains approximately 147.6 billion tons of coal.

The lowermost coal in the Wyodak Rider Coal Zone is the Lower Smith coal bed (**Figure 2-21**). This coal lies at an average depth of 1,272 feet and a maximum depth of 2,751 feet. The Lower Smith was measured in 603 wells, has an average thickness of 18 feet and a maximum thickness of 100 feet, underlies 1,703,440 acres, and contains approximately 37.8 billion tons of coal.

Upper Wyodak Coal Zone

The Upper Wyodak Coal Zone is one of the richest minable, CBNG-producing, coal-bearing stratigraphic intervals in the world. The Upper Wyodak contains as many as five coal beds of varying thicknesses and subsurface extents. We correlated and mapped three main coal beds in the Upper Wyodak – the Anderson Rider, Anderson, and Lower Anderson coal beds – for this report. Of these, the Anderson, commonly called the Wyodak, is the most important: it is the largest actively mined coal deposit in the United States. These three coals and the underlying Canyon coal of the Lower Wyodak Coal Zone make up the most productive set of coal seams in the country, currently

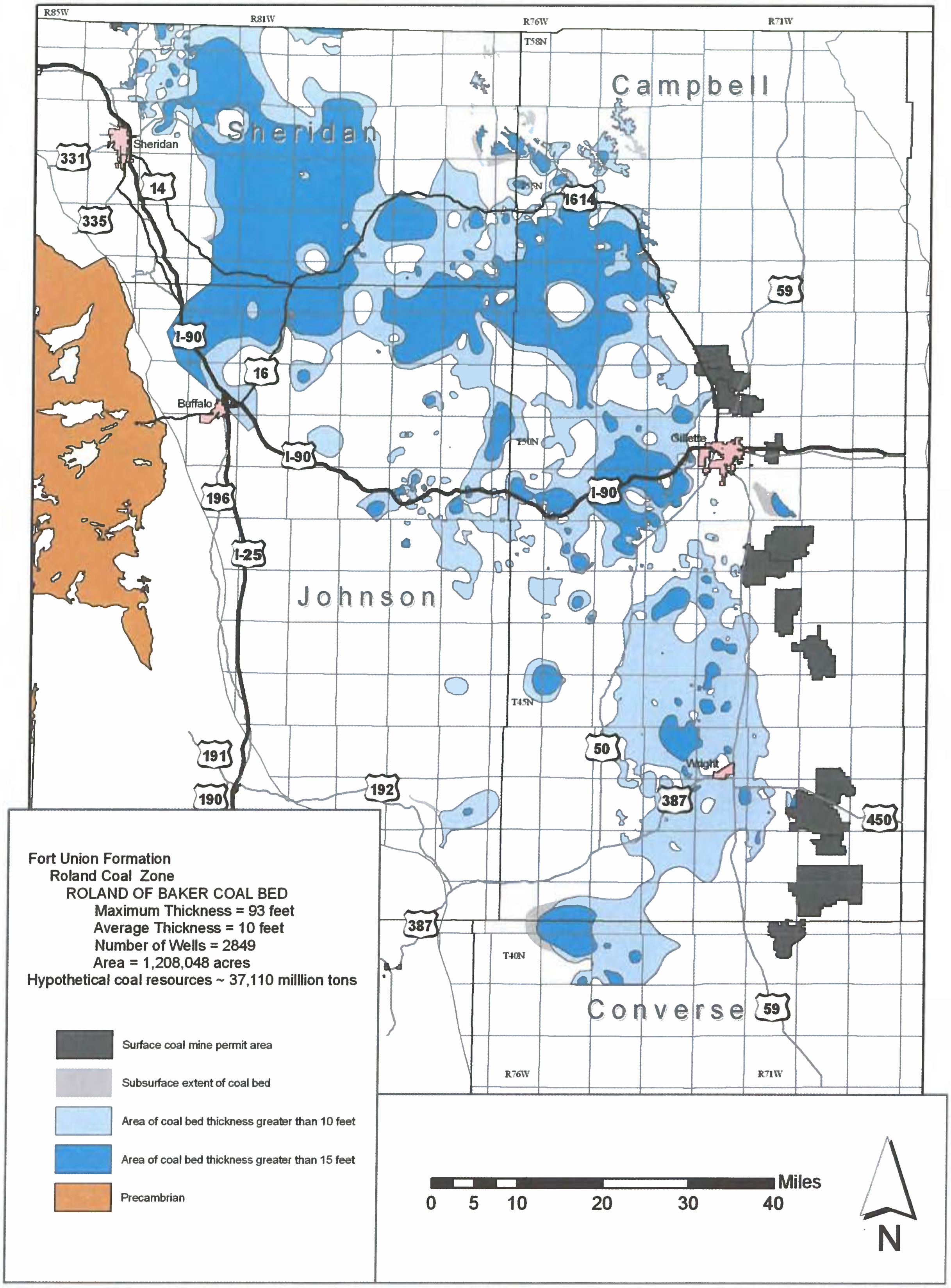


Figure 2-17. Map of Roland of Baker coal bed, Powder River Basin, Wyoming.

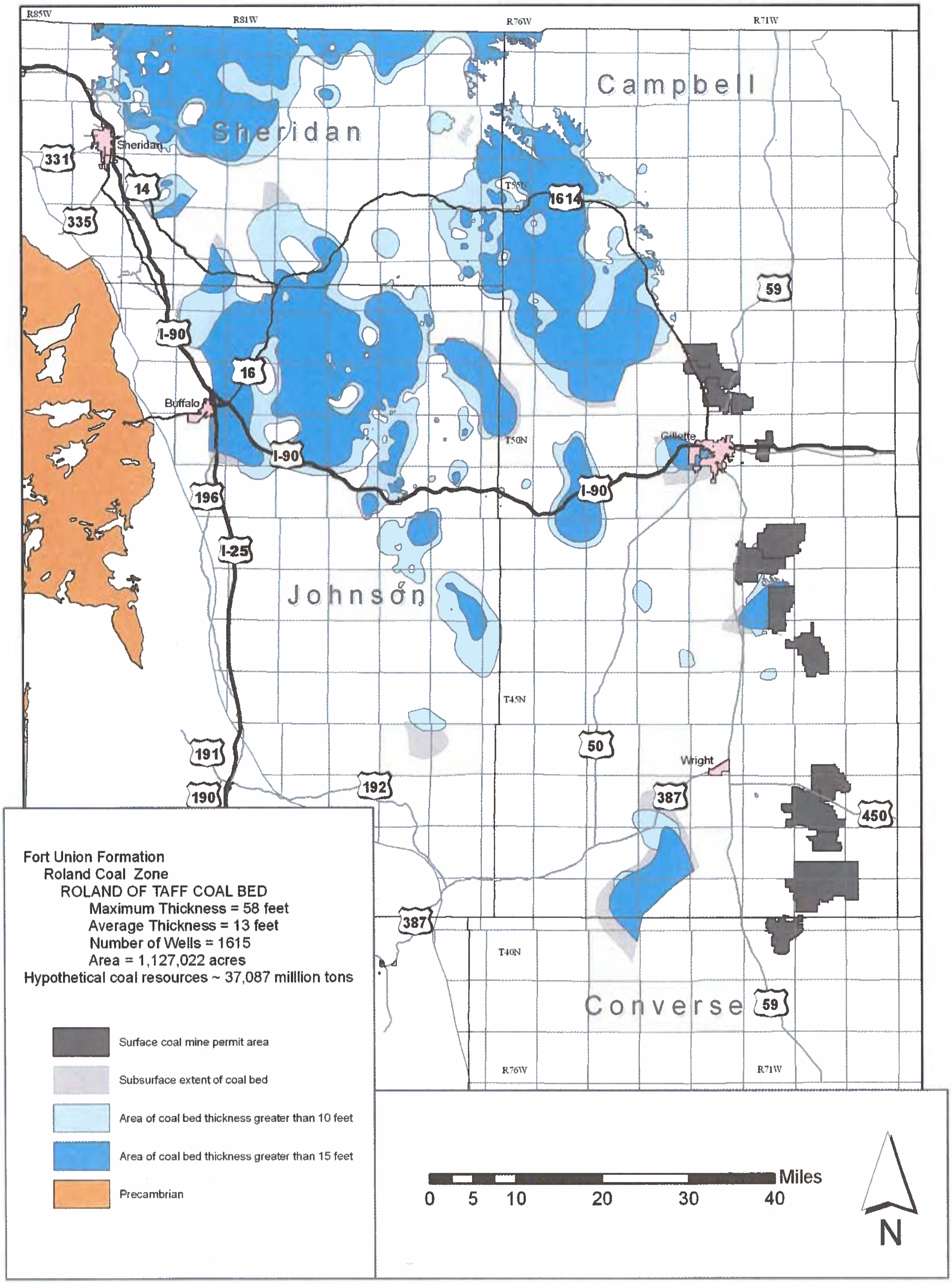


Figure 2-18. Map of Roland of Taff coal bed, Powder River Basin, Wyoming.

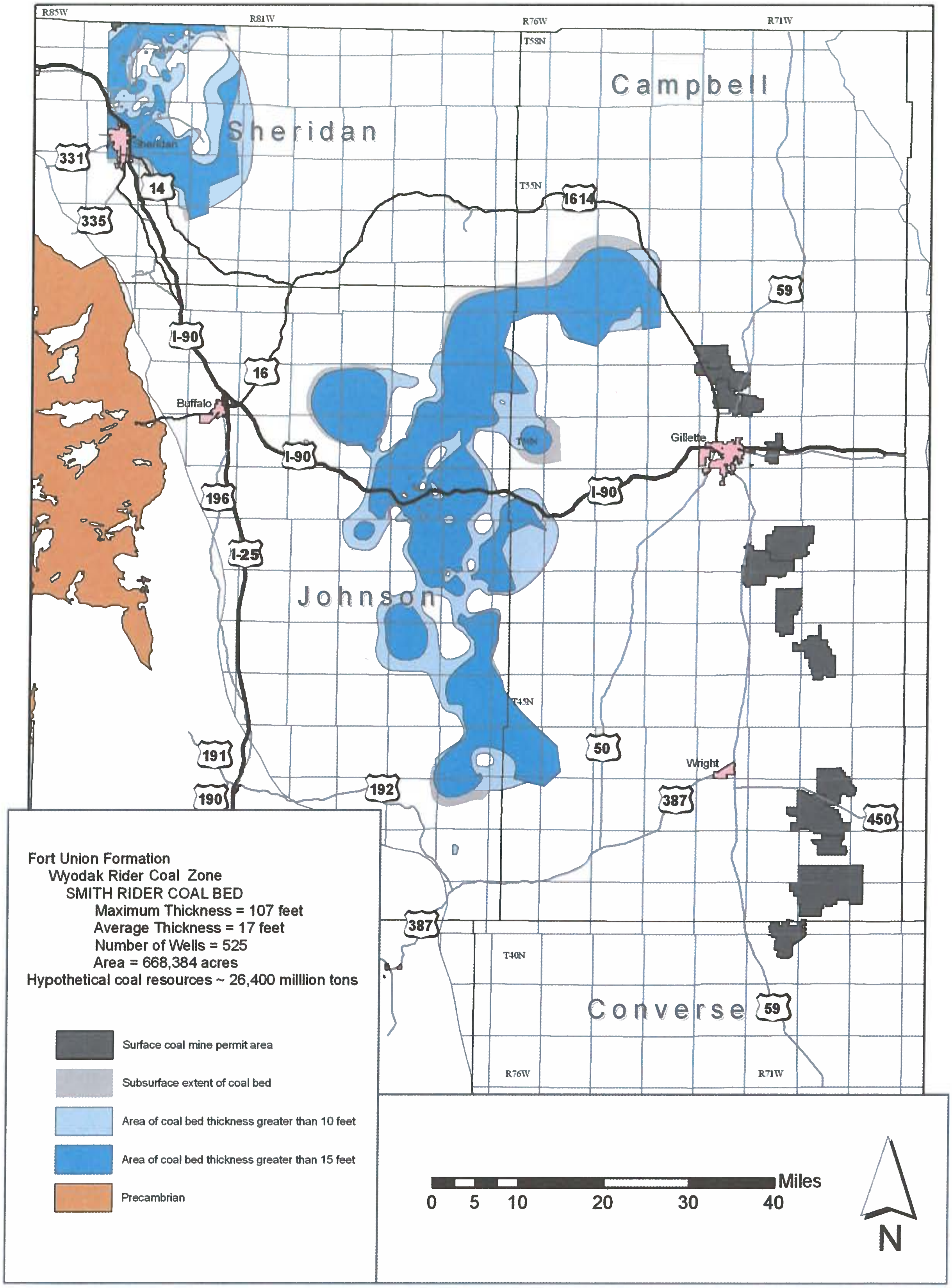


Figure 2-19. Map of Smith Rider coal bed, Powder River Basin, Wyoming.

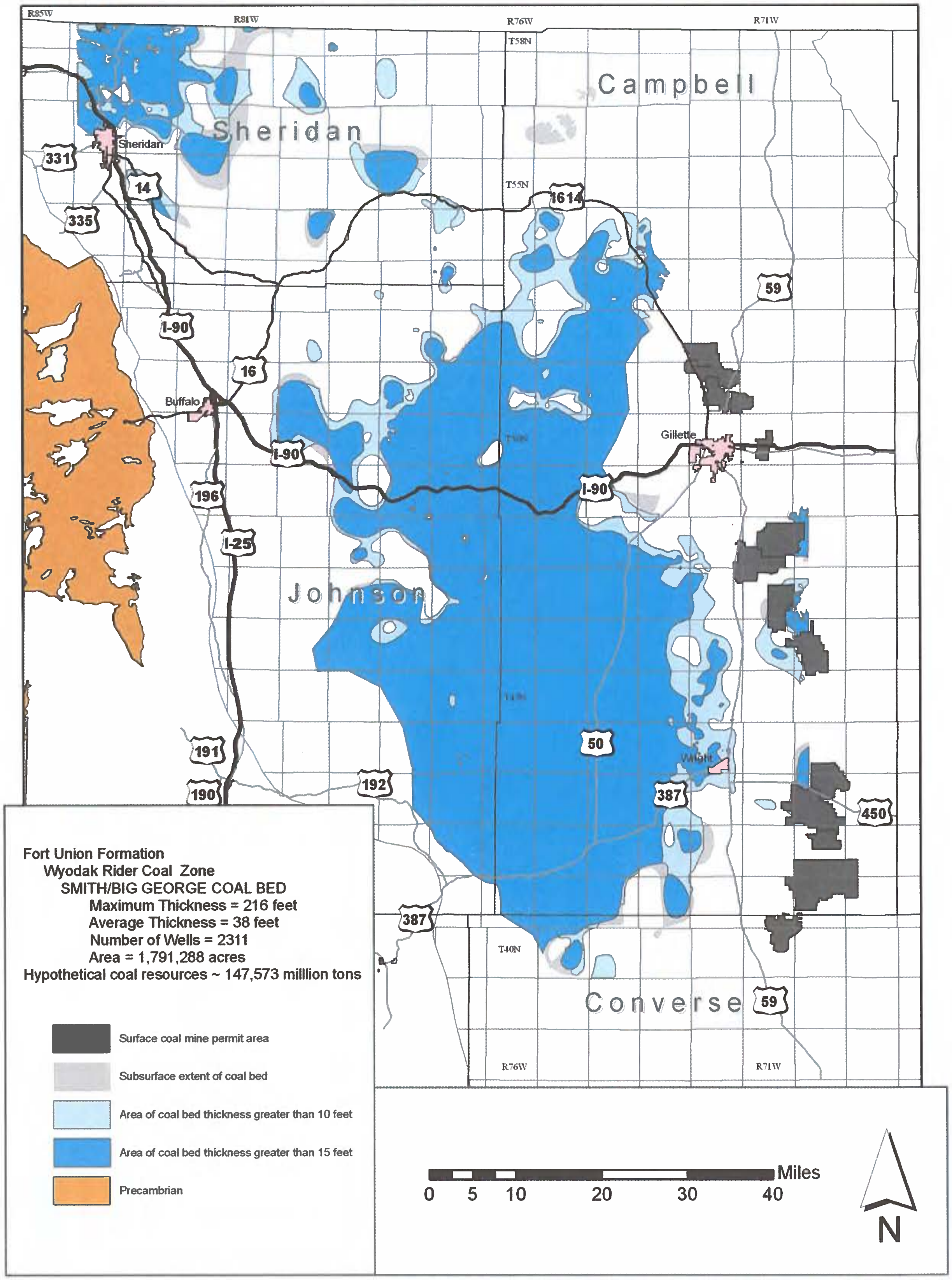

R85W
R81W
R76W
R71W
T58N
T55N
T40N
Campbell
Sheridan
Johnson
Converse
Sheridan
Buffalo
Gillette
Wright
331
335
14
1614
59
I-90
16
196
I-25
191
190
192
50
387
450
Fort Union Formation
Wyodak Rider Coal Zone
SMITH/BIG GEORGE COAL BED
Maximum Thickness = 216 feet
Average Thickness = 38 feet
Number of Wells = 2311
Area = 1,791,288 acres
Hypothetical coal resources ~ 147,573 milllion tons
Surface coal mine permit area
Subsurface extent of coal bed
Area of coal bed thickness greater than 10 feet
Area of coal bed thickness greater than 15 feet
Precambrian
Miles
0
5
10
20
30
40
N

Figure 2-20. Map of Smith/Big George coal bed, Powder River Basin, Wyoming.

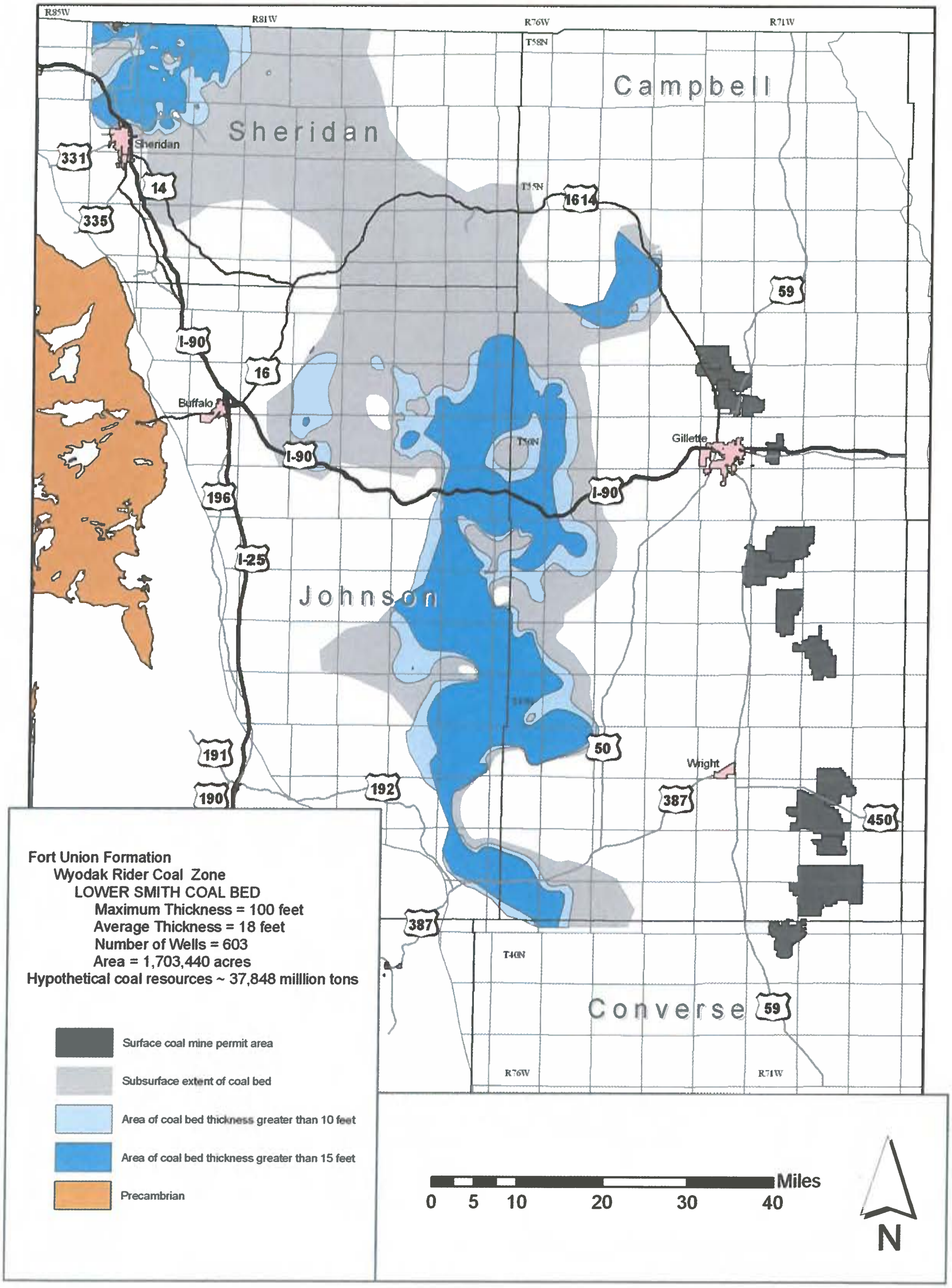


Figure 2-21. Map of Lower Smith coal bed, Powder River Basin, Wyoming.

fueling approximately 33 percent of U.S. coal-fired electric power generation.

The Anderson Rider, Anderson, and Lower Anderson coals split apart and coalesce in various regions throughout the coal zone. Unlike the Lake De Smet coals in the Upper Wasatch Coal Zone and the Smith/Big George and related coals in the Wyodak Rider Coal Zone, which also have three main coal beds splitting and coalescing, the Anderson's upper and lower related beds do not split off from the main body in a consistent direction within the coal zone. Rather, the Anderson Rider splits off from the main body to the north in Tps. 49 and 50 N., Rs. 70–80 W. and to the south and southeast in Tps. 45 and 46 N., Rs. 72–77 W.; and the Lower Anderson splits off randomly, similarly to how the Upper Roland splits from the Roland of Baker in the Roland Coal Zone (described above, p. 68).

The distribution of coal in the Upper Wyodak Coal Zone is similar to that in the overlying Wyodak Rider Coal Zone: there is a main body in the eastern and central basin, and a smaller area in the extreme northwestern corner of the basin where the coals that compose the main body occur as individual coal beds. Outcrops of the Anderson are mapped along the entire length of the eastern margin of the exposed Tongue River Member of the Fort Union Formation.

The uppermost coal in the Upper Wyodak Coal Zone is the Anderson Rider coal bed (**Figure 2-22**). This coal lies at an average depth of 1,011 feet and a maximum depth of 2,722 feet. The Anderson Rider coal was measured in 382 wells, has an average thickness of 13 feet and a maximum thickness of 52 feet, underlies 1,032,257 acres, and contains approximately 30.0 billion tons of coal. The Anderson Rider coal is deepest east of the basin axis. This coal crops out in the northeast in Tps. 49–56 N., Rs. 70–74 W. The thickest areas of this coal occur in T. 55 N., R. 82 W., Tps. 50 and 51 N., Rs. 78–80 W., T. 51 N., R. 76 W., and T. 54 N., R. 74 W. The coal bed consists of four discontinuous but correlative areas located in Sheridan, Johnson, and Campbell counties. In three of these areas, the Anderson Rider merges with the underlying Anderson coal bed; the exception is the area in Sheridan County, where the Anderson Rider remains an independent coal bed.

The middle coal in the Upper Wyodak Coal Zone is the Anderson coal bed (**Figure 2-23**). This coal lies at an average depth of 1,083 feet and a maximum depth of 2,856 feet. The Anderson was measured in 2,856 wells, has an average thickness of 47 feet and a maximum thickness of 208 feet, underlies 3,789,227 acres, and contains approximately 225.8 billion tons of coal. The Anderson is the most extensive and also one of the thickest coal beds in the Powder River Basin. This coal underlies the northern part of Converse County, the western three-quarters of Campbell County, the northeastern third of Johnson County, and the eastern three-quarters of Sheridan County. The Anderson is deepest along its westernmost extent in Tps. 49 and 50 N., Rs. 80 and 81 W. and T. 52 N., R. 82 W. The Anderson is thickest in two areas, one in northeastern Johnson County in Tps. 47–51 N., Rs. 77–79 W., the other in the southern two-thirds of east-central Campbell County in Tps. 41–51 N., Rs. 70–74 W. The combined areas of thick Anderson coal (coals more than 30 feet thick) occur in the shape of a wedge, wide in the northwest and tapering to the southeast. The Anderson crops out and has produced clinker along its northeastern and eastern margins.

The lowermost coal in the Upper Wyodak Coal Zone is the Lower Anderson coal bed (**Figure 2-24**). This coal lies at an average depth of 1,120 feet and a maximum depth of 2,606 feet. The Lower Anderson was measured in 1,015 wells, has an average thickness of 21 feet and a maximum thickness of 167 feet, underlies 2,998,382 acres, and contains approximately 97.3 billion tons of coal. It is deepest along its western margin in northern Johnson County and the lower two-thirds of Sheridan County. The Lower Anderson is more than 30 feet thick in several small areas: in northern Sheridan County in T. 56 N., R. 84 W. and Tps. 57 and 58 N., Rs. 83 and 84 W.; in east-central Johnson County in Tps. 46–50 N., Rs. 77 and 78 W., Tps. 52 and 53 N., R. 77 W., and T. 51 N., R. 80 W.; in northern Campbell County in Tps. 55 and 56 N., Rs. 72–76 W.; and in southern Campbell County in Tps. 41 and 42 N., Rs. 70–72 W. and Tps. 43–47 N., Rs. 71-73 W. The Lower Anderson crops out in northeastern Campbell and western Sheridan counties.

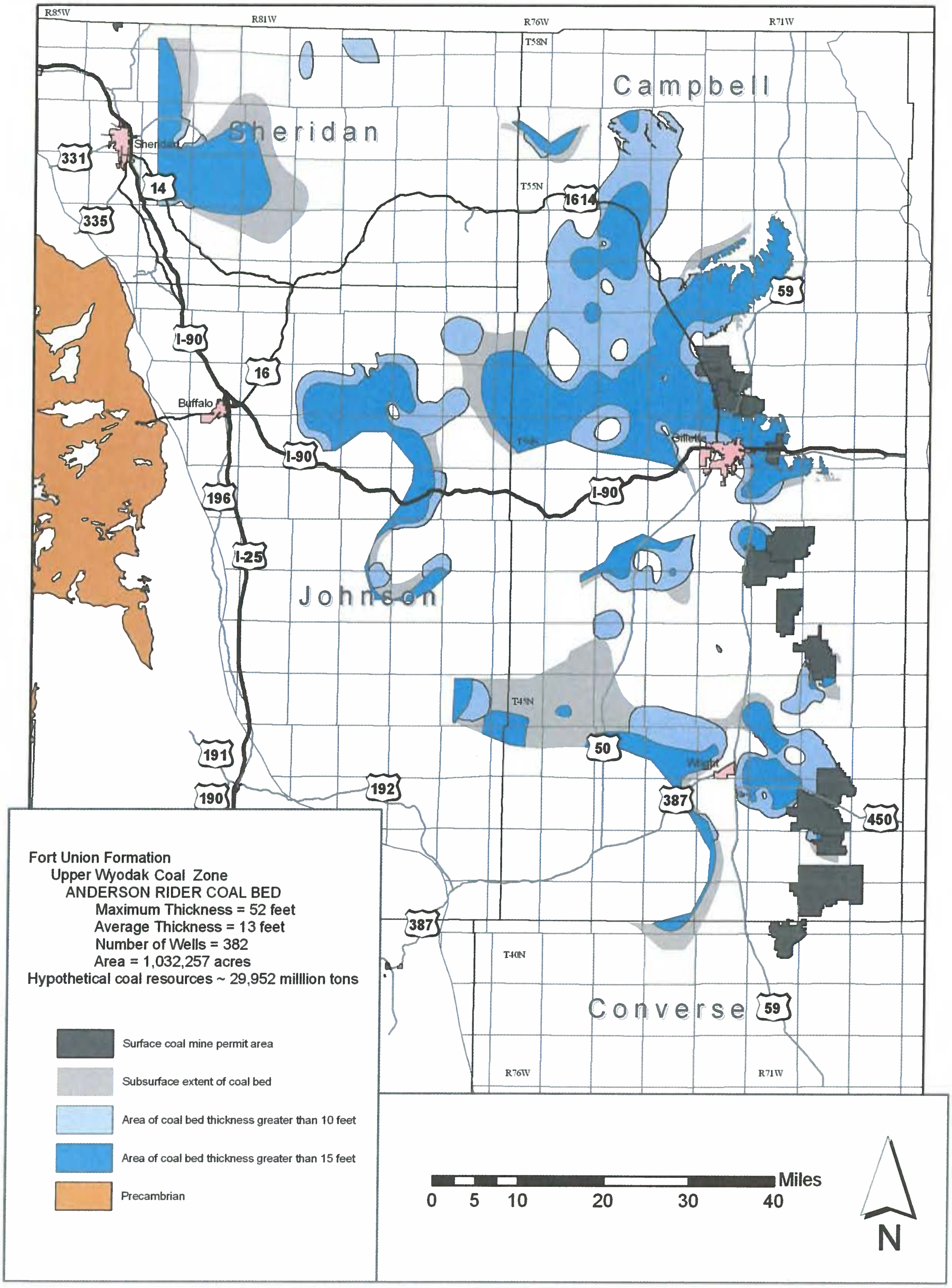


Figure 2-22. Map of Anderson Rider coal bed, Powder River Basin, Wyoming.

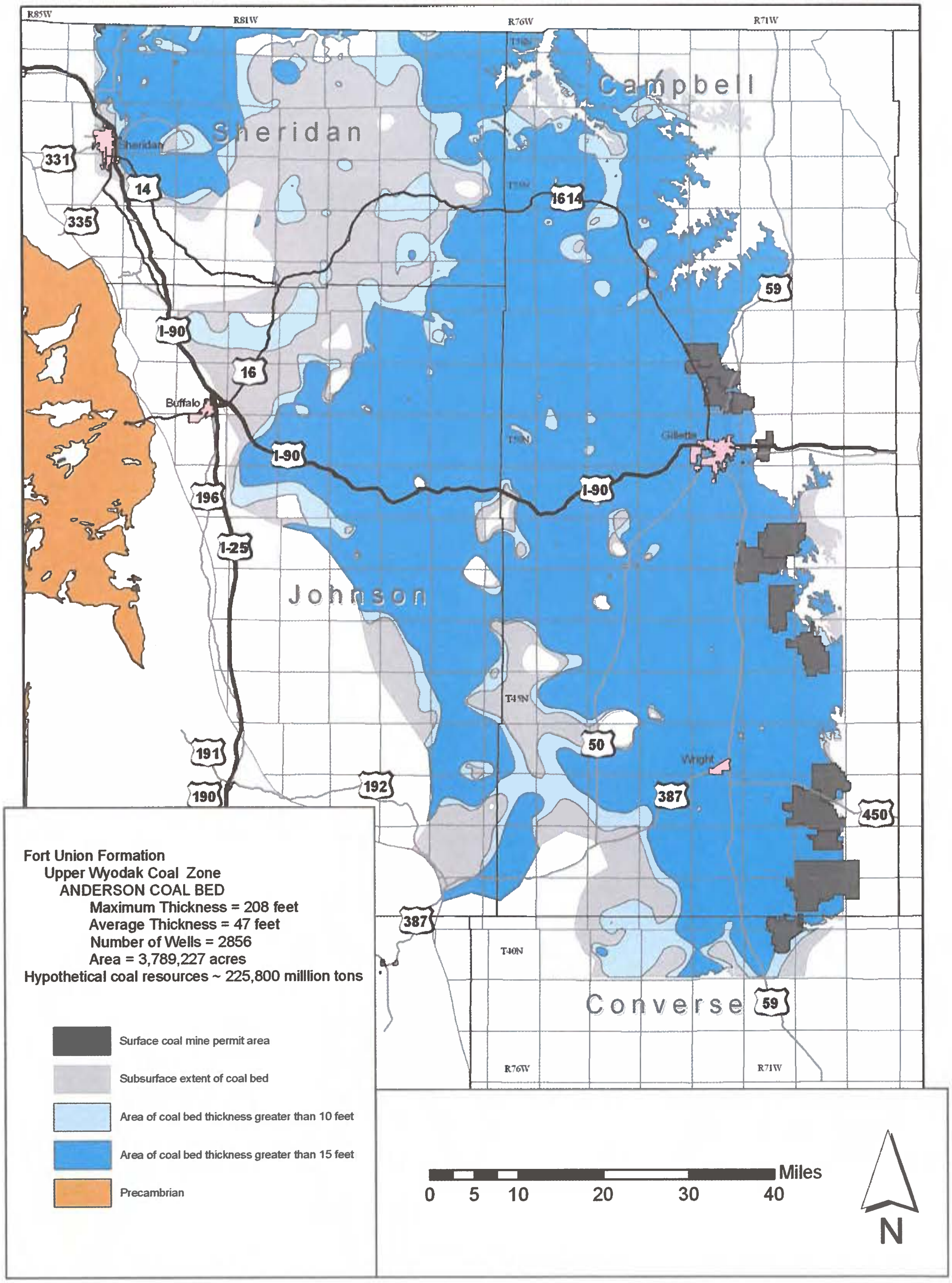


Figure 2-23. Map of Anderson coal bed, Powder River Basin, Wyoming.

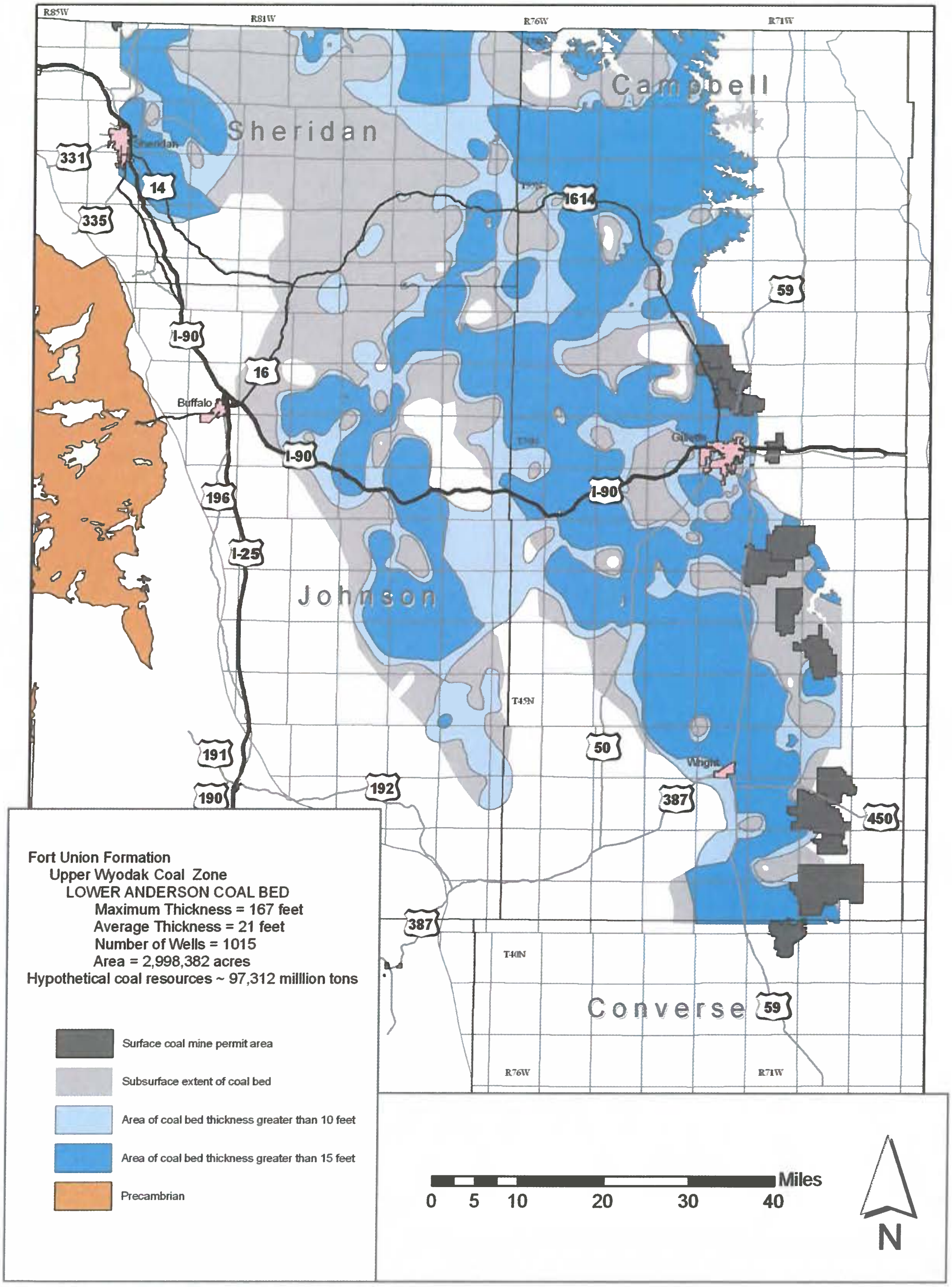


Figure 2-24. Map of Lower Anderson coal bed, Powder River Basin, Wyoming.

Lower Wyodak Coal Zone

The upper coal in the Lower Wyodak Coal Zone is the Canyon Rider coal bed (**Figure 2-25**). This coal lies at an average depth of 731 feet and a maximum depth of 2,415 feet. The Canyon Rider was measured in 270 wells, has an average thickness of 10 feet and a maximum thickness of 38 feet, underlies 335,146 acres, and contains approximately 9.1 billion tons of coal. The Canyon Rider occurs primarily in the northeastern part of the basin. The area of thickest coal occurs in Tps. 55 and 56 N., Rs. 72-75 W. This coal splits off from the underlying Canyon coal to the southwest along a line beginning in T. 53 N., R. 74 W. and ending in T. 58 N., R. 79 W.

The lower and main coal in the Lower Wyodak Coal Zone is the Canyon coal bed (**Figure 2-26**). This coal lies at an average depth of 1,059 feet and a maximum depth of 3,003 feet. The Canyon was measured in 1131 wells, has an average thickness of 25 feet and a maximum thickness of 205 feet, underlies 1,689,675 acres, and contains approximately 79.8 billion tons of coal. This coal occurs in the eastern half of the basin and occupies two areas: the northern and main area of the Canyon begins six miles south of I-90 in northern T. 47 N. and reaches north into Montana; the smaller, southern area begins in southern T. 47 N. and ends in northern Converse County. The western edge of these combined areas of the Canyon where the coal is 10 feet thick or thicker follows a linear trend northwest from T. 40 N., R. 72 W. to T. 51 N., R. 78 W., and then an arcuate trend north from T. 51 N. to T. 58 N., R. 78 W.

Knoblock Coal Zone

The upper coal in the Knoblock Coal Zone is the Cook coal bed (**Figure 2-27**). This coal lies at an average depth of 1,436 feet and a maximum depth of 3,223 feet. The Cook was measured in 903 wells, has an average thickness of 22 feet and a maximum thickness of 145 feet, underlies 1,788,301 acres, and contains approximately 76.4 billion tons of coal. This coal occurs in the northern two thirds of the basin. The main area of the Cook is located in eastern Sheridan and Johnson counties and in Campbell County. The Cook is also present in the northern third and western part of the basin, underlying an area that extends north from Buffalo past Sheridan.

The lower coal in the Knoblock Coal Zone is the Lower Cook coal bed (**Figure 2-28**). This coal lies at an average depth of 1,765 feet and a maximum depth of 3,038 feet. The Lower Cook was measured in 172 wells, has an average thickness of 9 feet and a maximum thickness of 38 feet, underlies 638,128 acres, and contains approximately 16.4 billion tons of coal. Areas where this coal is 10 feet thick or thicker occur as pockets distributed within a band oriented southeast-northwest in the northern two-thirds of the basin.

Sawyer Coal Zone

The uppermost and main coal in the Sawyer Coal Zone is the Wall coal bed (**Figure 2-29**). This coal lies at an average depth of 1,700 feet and a maximum depth of 3,455 feet. The Wall was measured in 996 wells, has an average thickness of 19 feet and a maximum thickness of 58 feet, underlies 1,862,080 acres, and contains approximately 73.1 billion tons of coal. This coal occurs throughout the northern third and eastern half of the basin. The main body of the Wall is located in eastern Sheridan County, the northern third of Johnson County, and the northern two-thirds of Campbell County. A second, minor area of Wall coal occurs in southern Campbell and northern Converse counties in two regions in Tps. 40-42 N., Rs. 71-74 W. and Tps. 43-45 N., Rs. 74-76 W.

The middle coal in the Sawyer Coal Zone is the Lower Wall coal bed (**Figure 2-30**). This coal lies at an average depth of 1,799 feet and a maximum depth of 3,495 feet. The Lower Wall was measured in 494 wells, has an average thickness of 11 feet and a maximum thickness of 58 feet, underlies 3,177,455 acres, and contains approximately 54.7 billion tons of coal. This coal occurs as several pockets of various sizes in the basin. The Lower Wall is most continuous and prevalent in eastern Campbell County; smaller, discontinuous areas occur in northernmost Johnson County and in eastern Sheridan County.

The lowermost coal in the Sawyer Coal Zone is the Pawnee coal bed (**Figure 2-31**). This coal lies at an average depth of 1,865 feet and a maximum depth of 3,582 feet. The Pawnee was measured in 586 wells, has an average thickness of 11 feet and a maximum thickness of 50 feet, underlies 1,097,580 acres, and contains approximately 31.0 billion tons of coal.

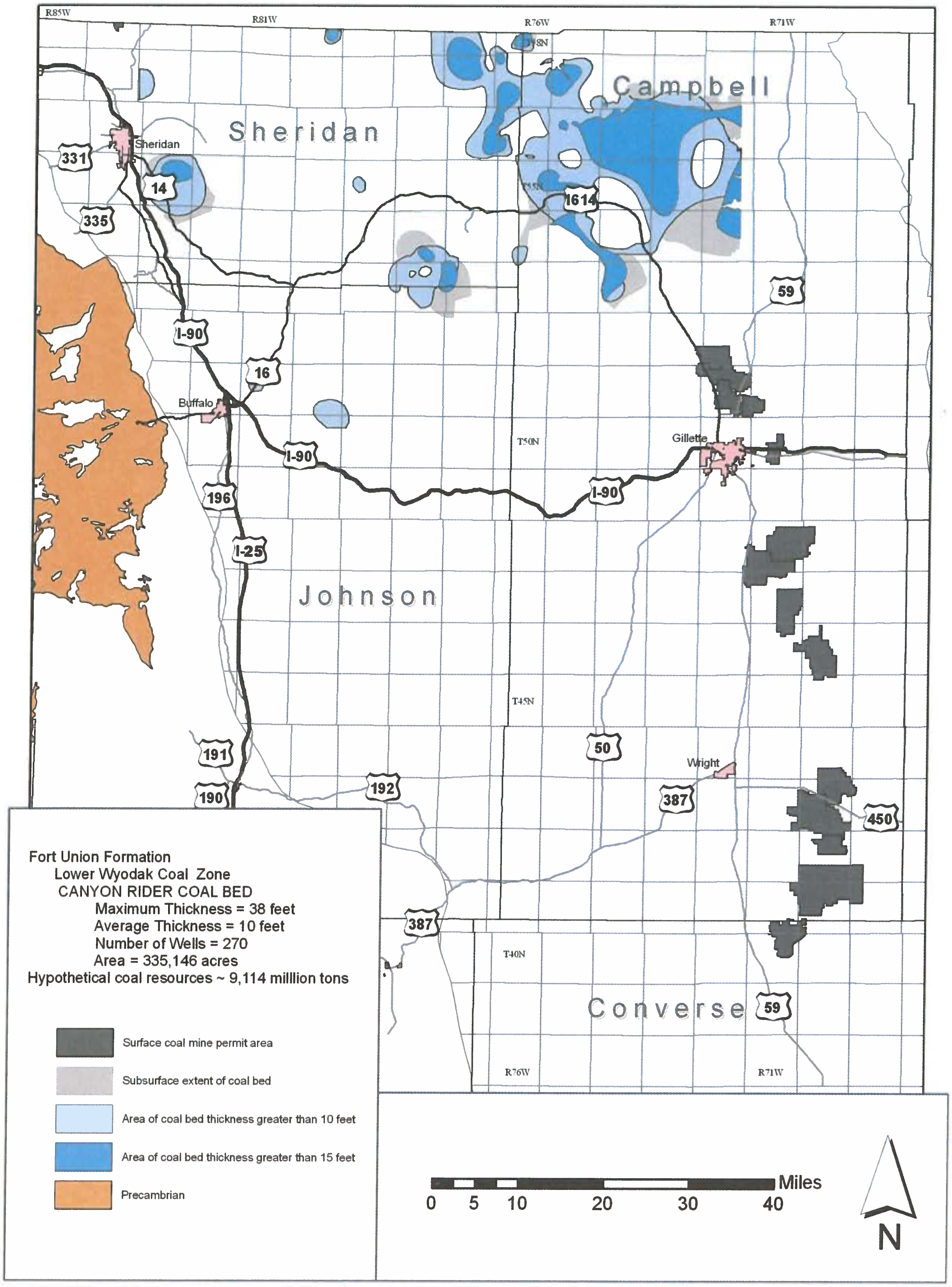


Figure 2-25. Map of Canyon Rider coal bed, Powder River Basin, Wyoming.

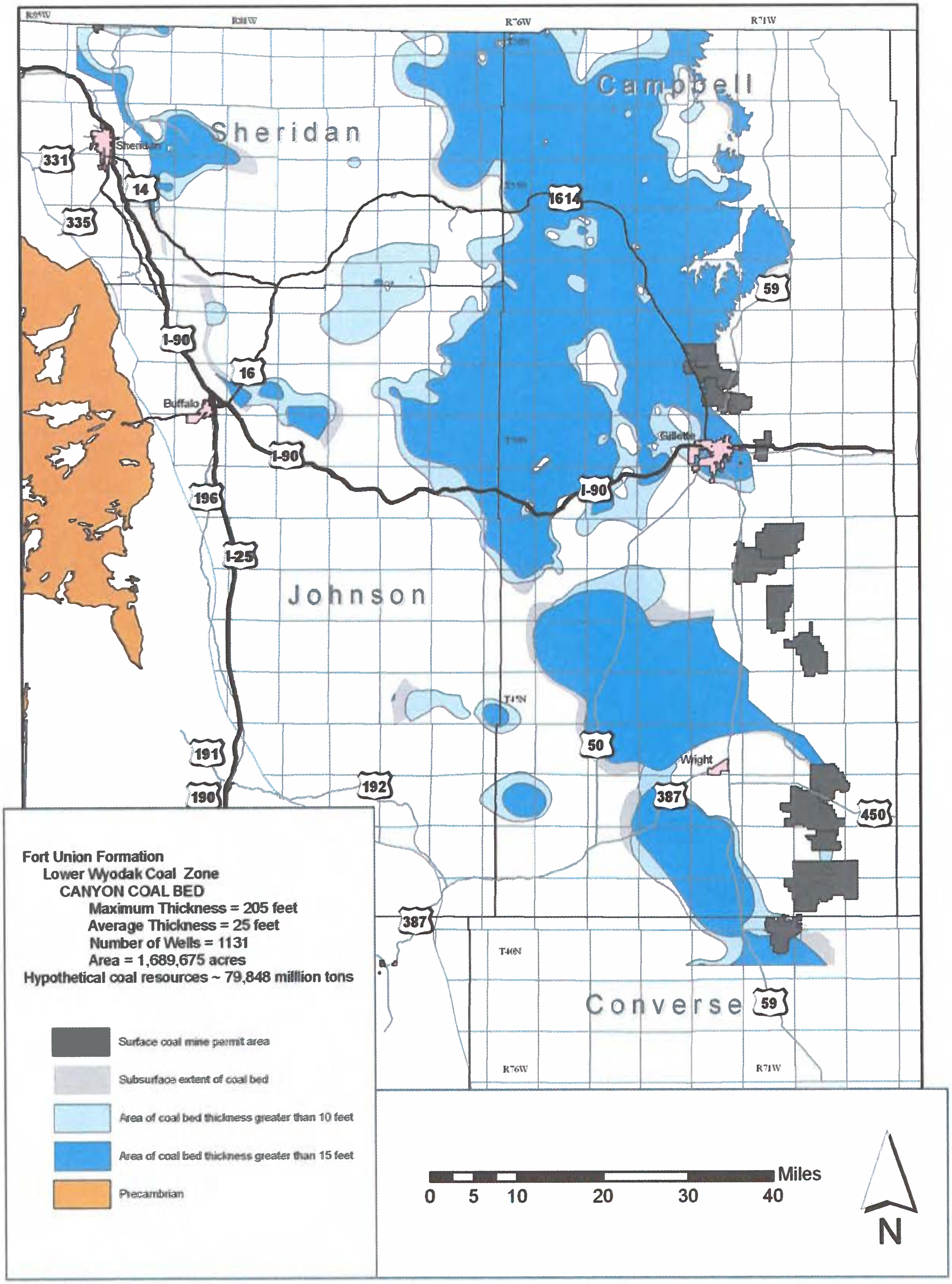


Figure 2-26. Map of Canyon coal bed, Powder River Basin, Wyoming.

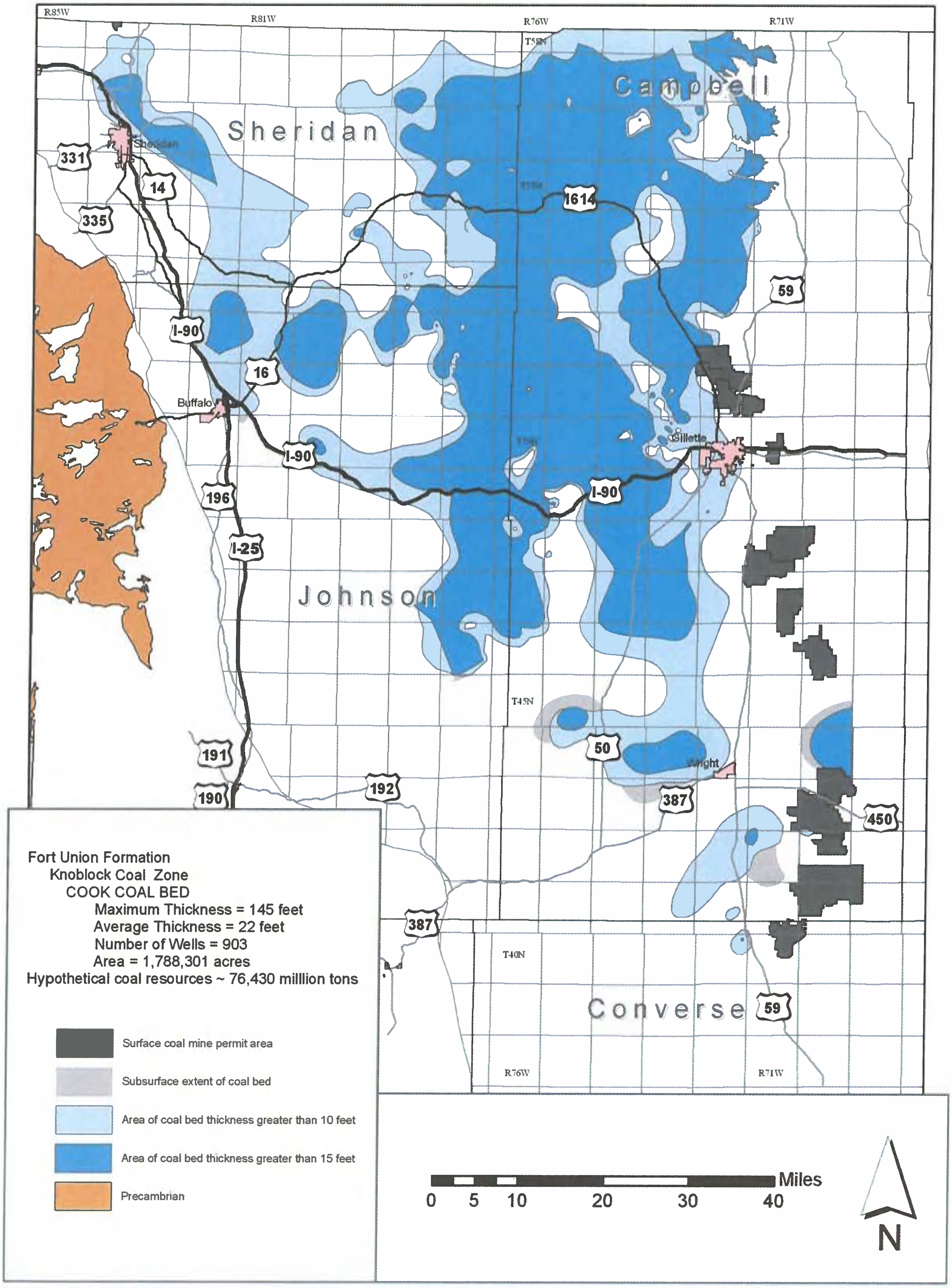


Figure 2-27. Map of Cook coal bed, Powder River Basin, Wyoming.

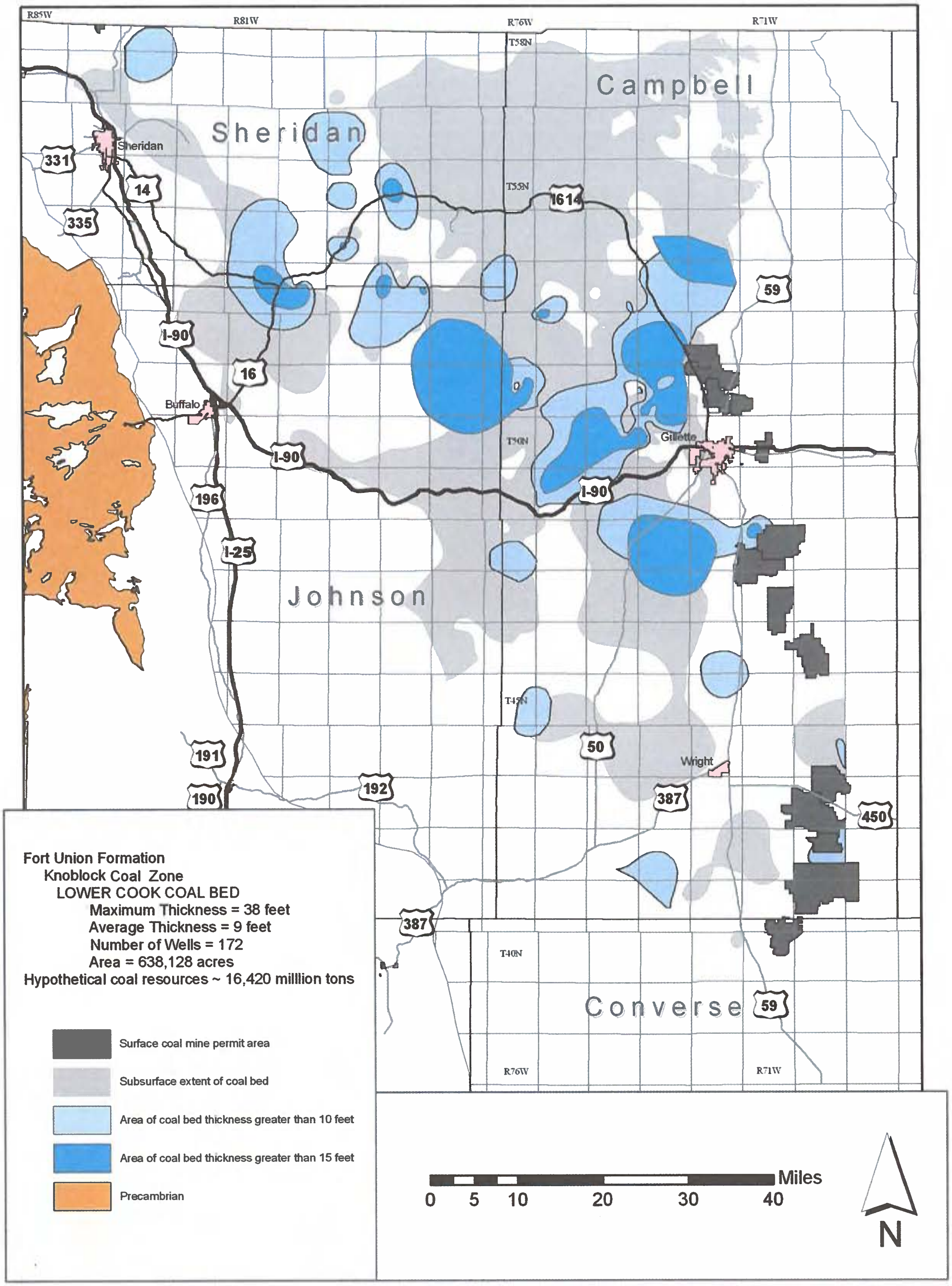


Figure 2-28. Map of Lower Cook coal bed, Powder River Basin, Wyoming.

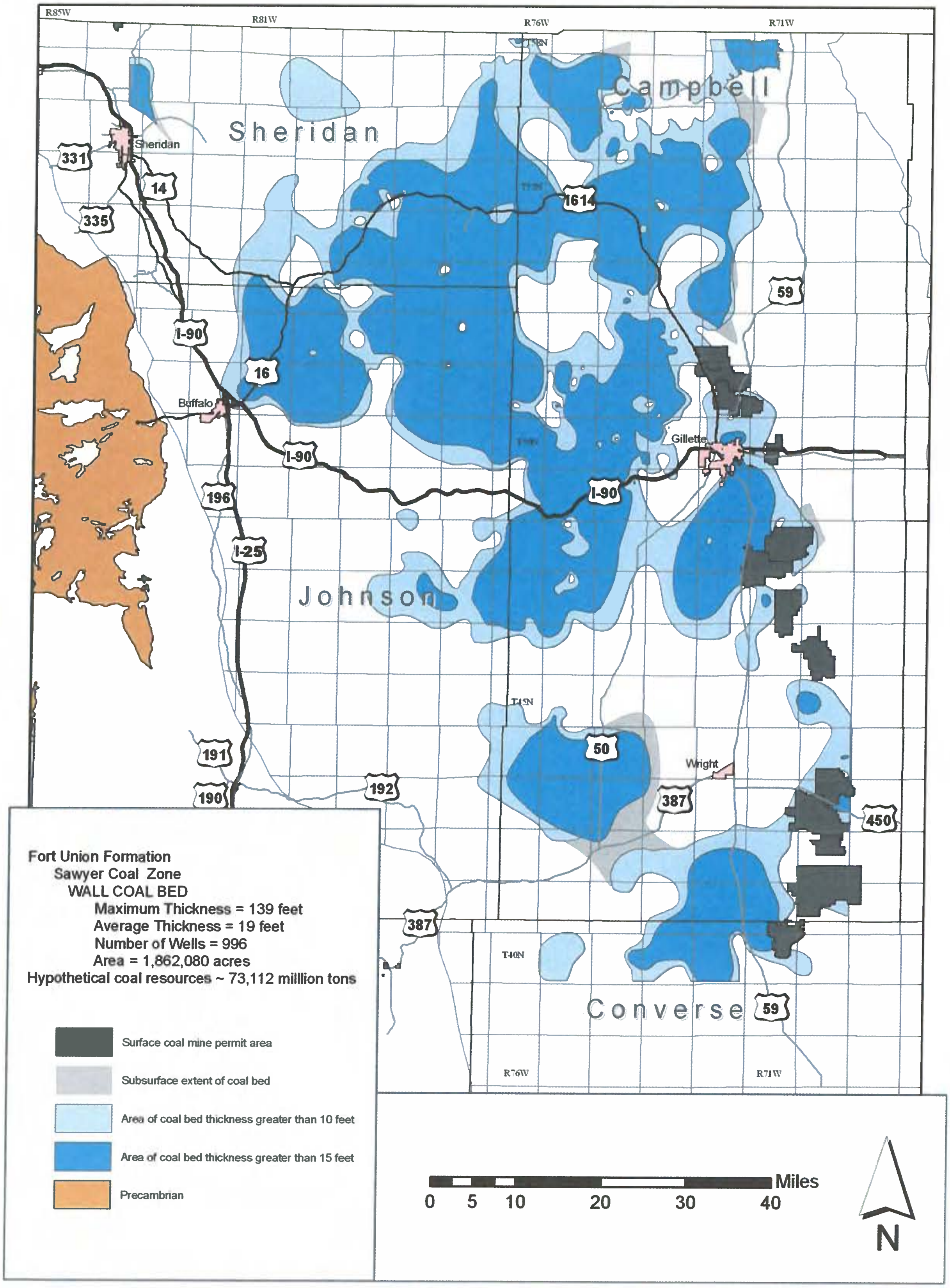


Figure 2-29. Map of Wall coal bed, Powder River Basin, Wyoming.

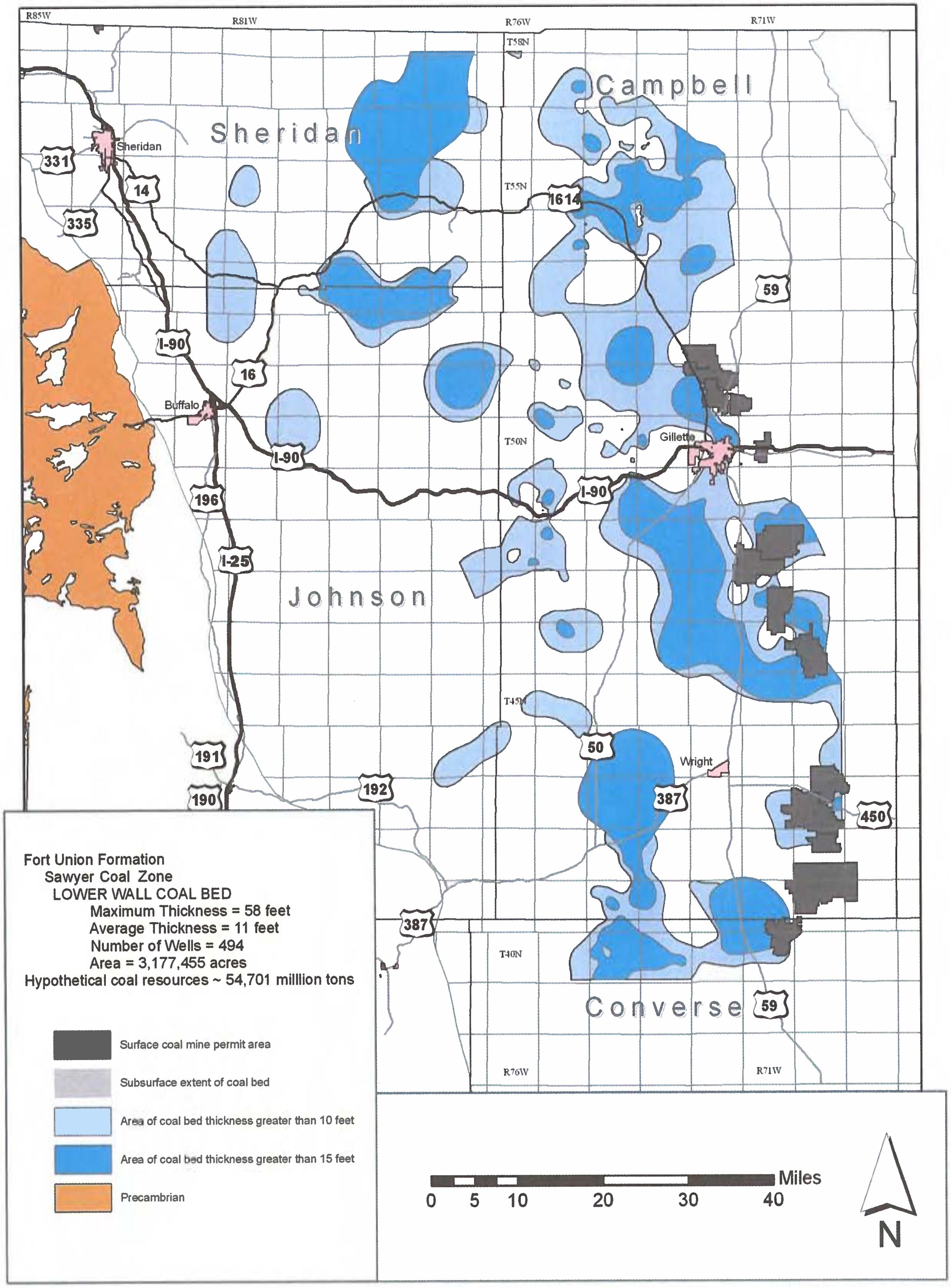


Figure 2-30. Map of Lower Wall coal bed, Powder River Basin, Wyoming.

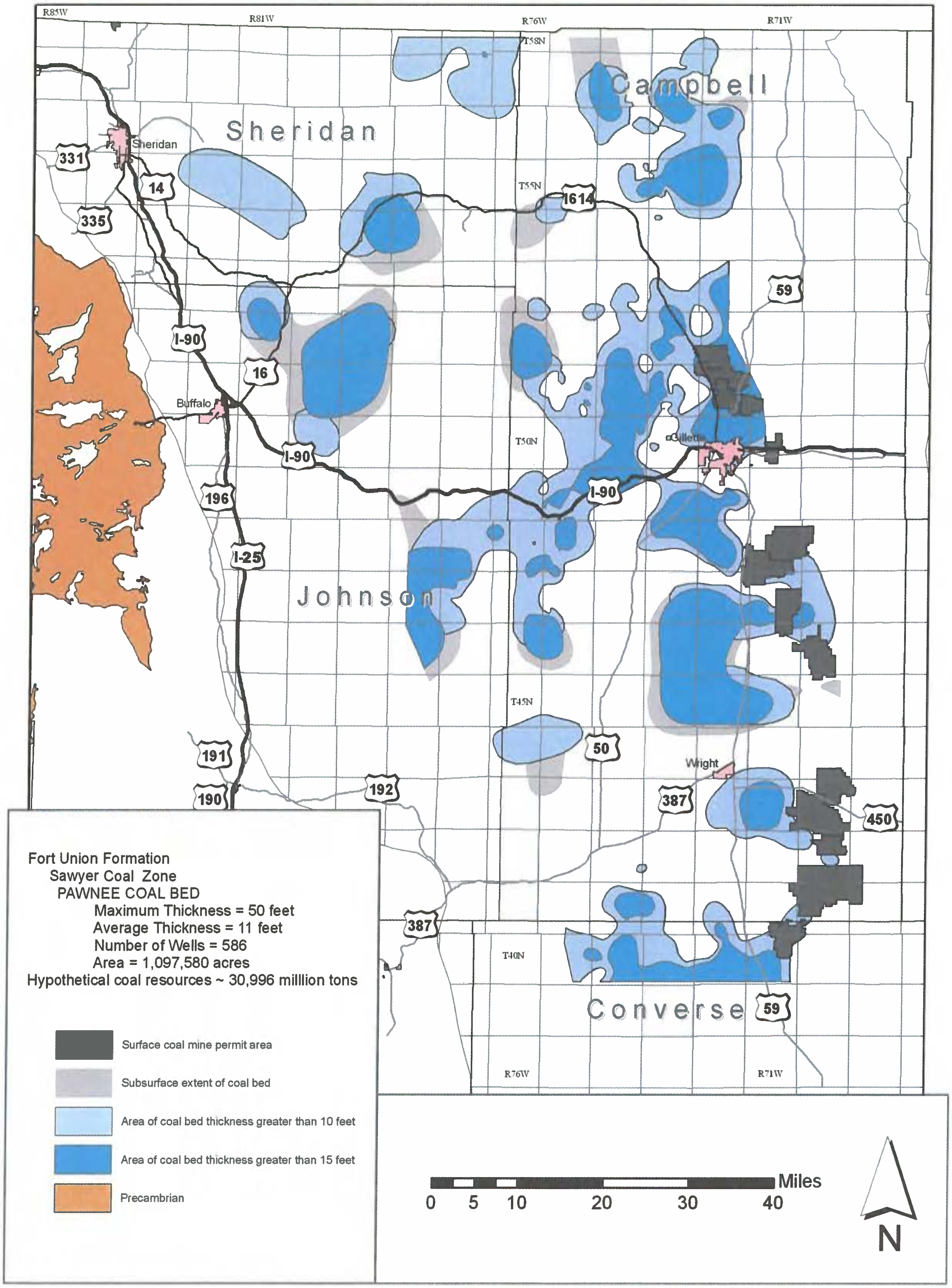


Figure 2-31. Map of Pawnee coal bed, Powder River Basin, Wyoming.

This coal occurs throughout the basin as discontinuous pockets, most of which are located in the eastern part of the basin in Campbell County. The largest and most contiguous part of the Pawnee begins in easternmost and central Johnson County and extends northeast across Campbell County through the area surrounding Gillette.

Basal Tongue River Coal Zone

The primary coal in the Basal Tongue River Coal Zone is the Moyer coal bed (**Figure 2-32**). This coal lies at an average depth of 2,003 feet and a maximum depth of 3,776 feet. The Moyer was measured in 374 wells, has an average thickness of 13 feet and a maximum thickness of 45 feet, underlies 1,097,580 acres, and contains approximately 39.5 billion tons of coal. This coal occurs in the basin as five discontinuous pockets distributed in a band beginning in southeast Campbell County and extending north-northwest into central Sheridan County. The largest and most continuous part of the Moyer is in Sheridan County.

Cartoon sections showing coal distribution

Four generalized cartoon cross sections, A–A' through D–D' (**Figure 2-33**), showing subsurface coal distribution in the PRB illustrate coal zones and correlations developed for this model. The cross sections are oriented northwest–southeast, semi-parallel to the major structural axis of the basin. These cartoon cross sections illustrate asymmetric basin structure, this author's interpretation of coal correlation, and the stratigraphic distribution and placement of certain coal beds within their respective coal zones. This interpretation of coal correlations, represented by these cross sections, shows the generalized locations of splits, pinch-outs, abrupt terminations, and gaps between occurrences of contemporaneous, correlative coals.

Acknowledgements

The author recognizes R.M. Lyman, S.A. Quillinan, J.F. Johnson, J.R. Rodgers, T.H. Heiple, and R.W. Hays for their help in collecting coal occurrence data for the entire basin. Jim Rodgers did a superb job drafting the figures and graphics for this chapter.

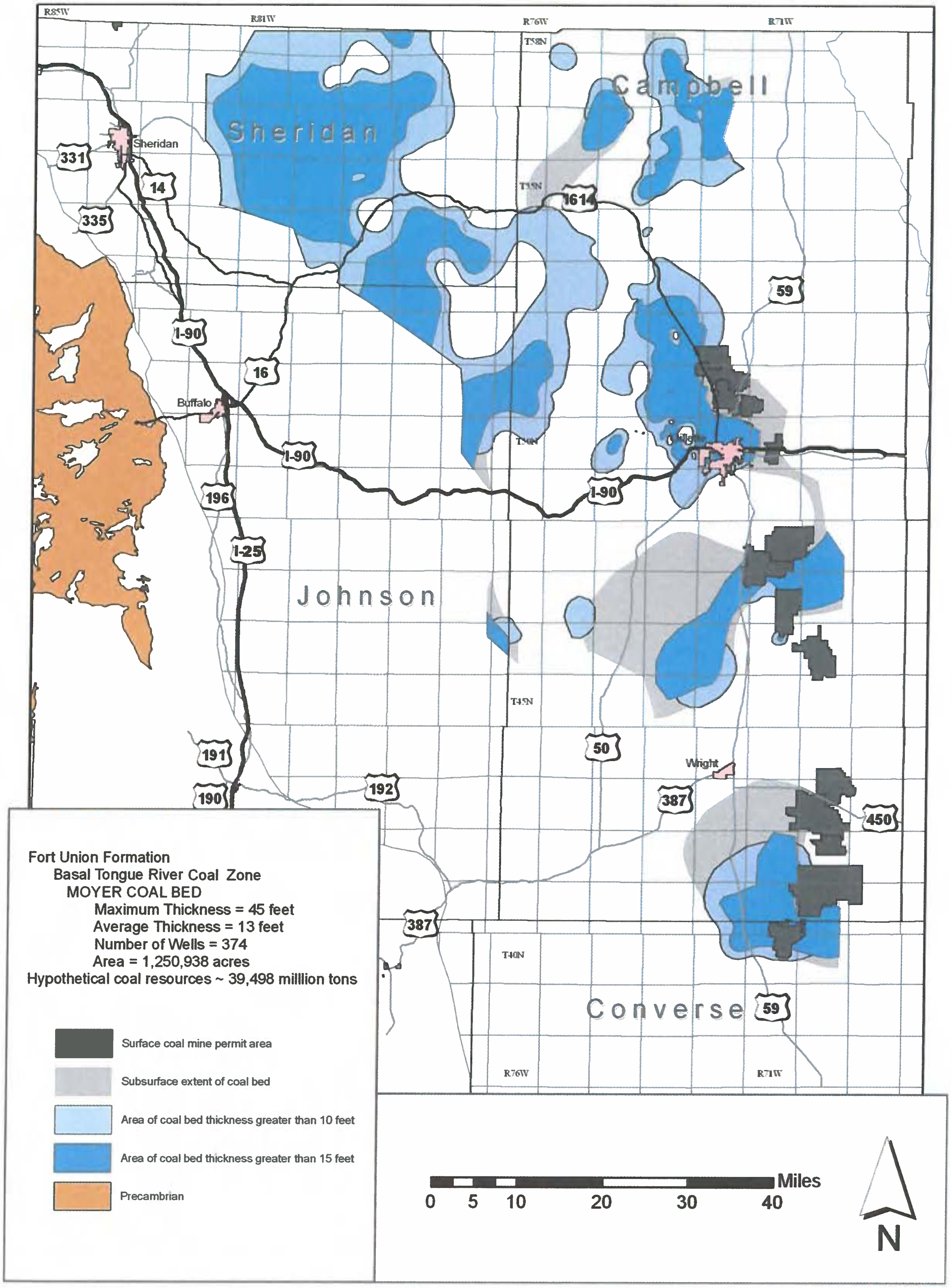

R85W
R81W
R76W
R71W
T58N
T55N
T50N
T45N
T40N
Sheridan
Campbell
Johnson
Converse
Sheridan
Buffalo
Gillette
Wright
331
14
335
I-90
16
196
I-25
191
190
192
1614
59
50
387
450
Fort Union Formation
Basal Tongue River Coal Zone
MOYER COAL BED
Maximum Thickness = 45 feet
Average Thickness = 13 feet
Number of Wells = 374
Area = 1,250,938 acres
Hypothetical coal resources ~ 39,498 milllion tons
Surface coal mine permit area
Subsurface extent of coal bed
Area of coal bed thickness greater than 10 feet
Area of coal bed thickness greater than 15 feet
Precambrian
Miles
0
5
10
20
30
40
N

Figure 2-32. Map of Moyer coal bed, Powder River Basin, Wyoming.

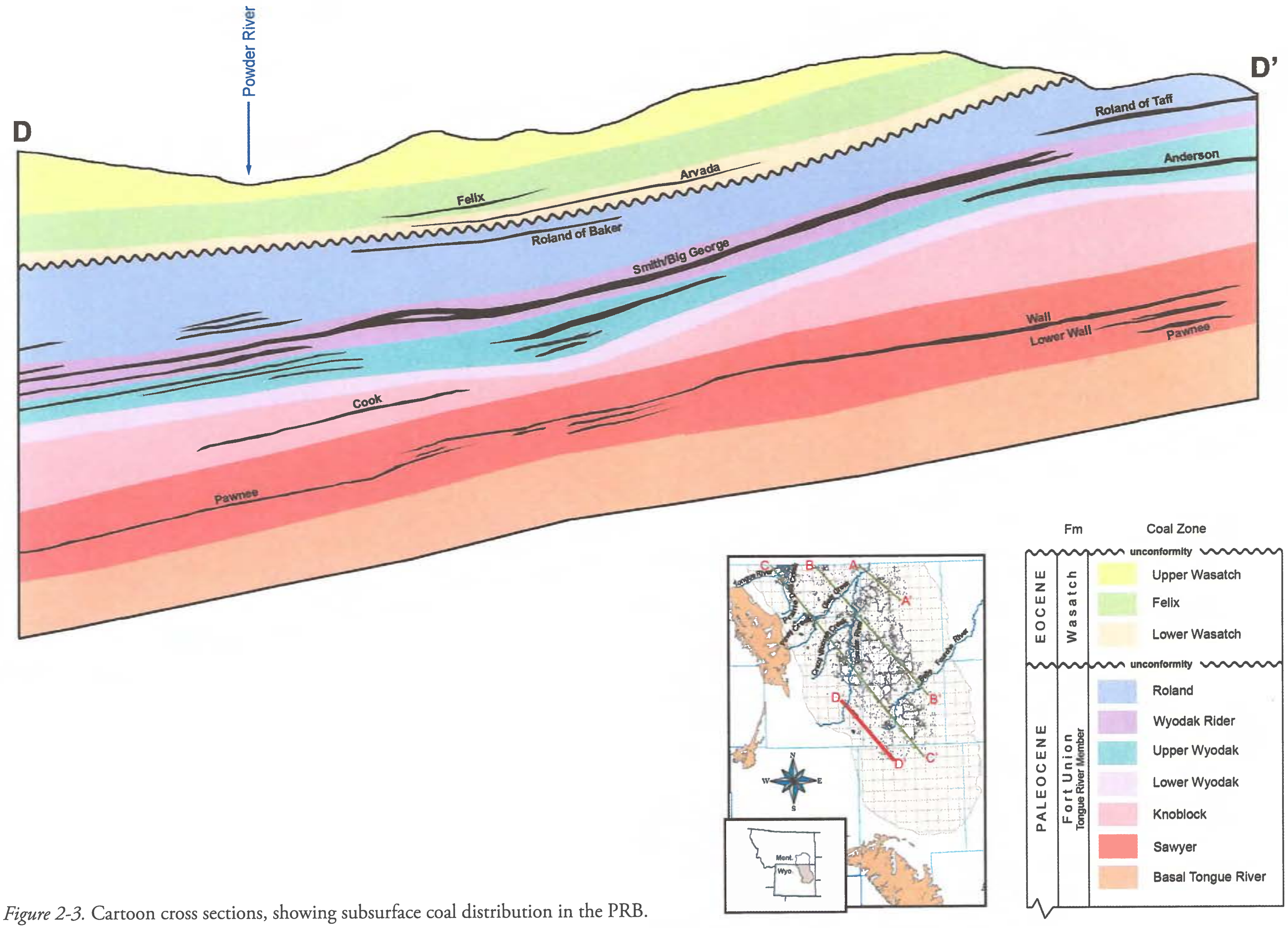
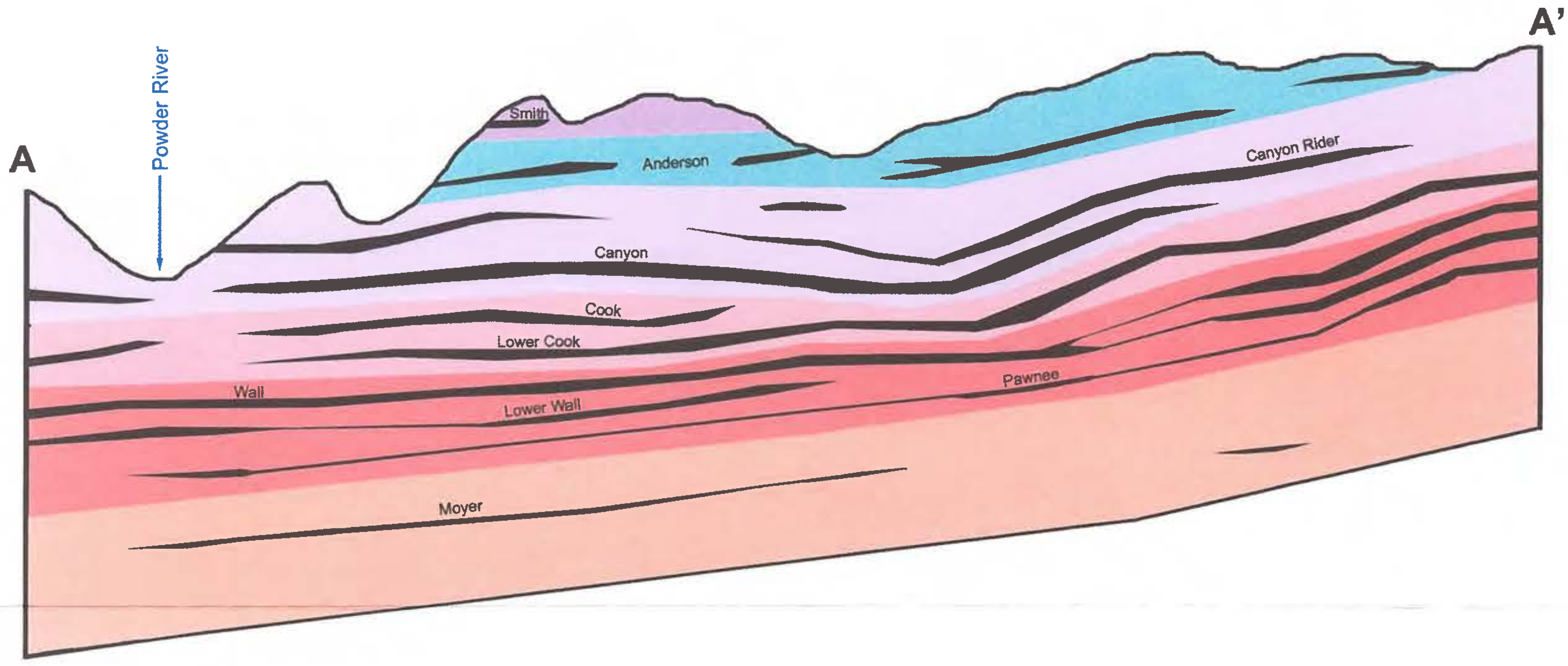
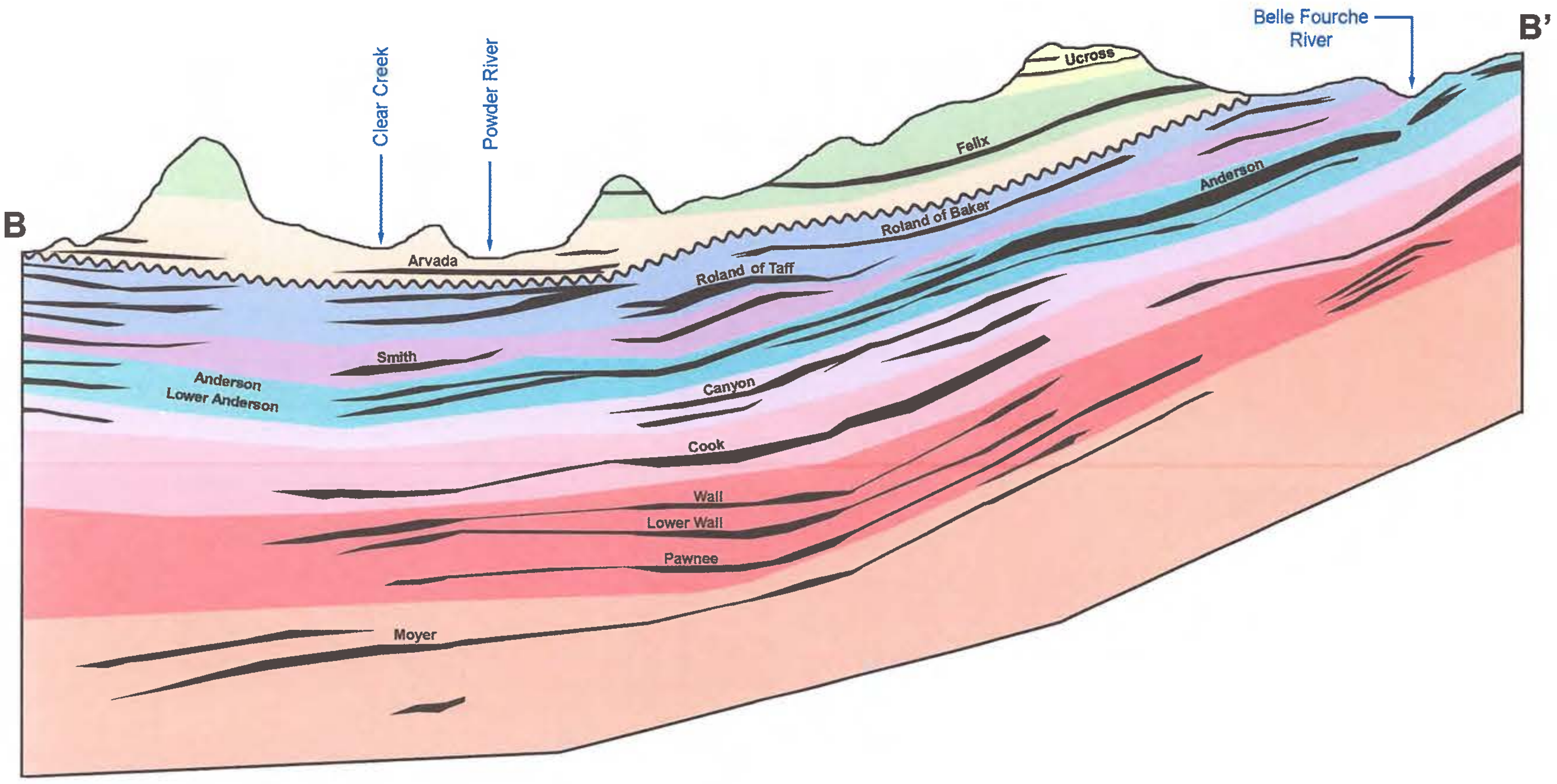


Figure 2-3. Cartoon cross sections, showing subsurface coal distribution in the PRB.


A
A'
Powder River
Smith
Anderson
Canyon Rider
Canyon
Cook
Lower Cook
Wall
Lower Wall
Pawnee
Moyer


B
B'
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Powder River
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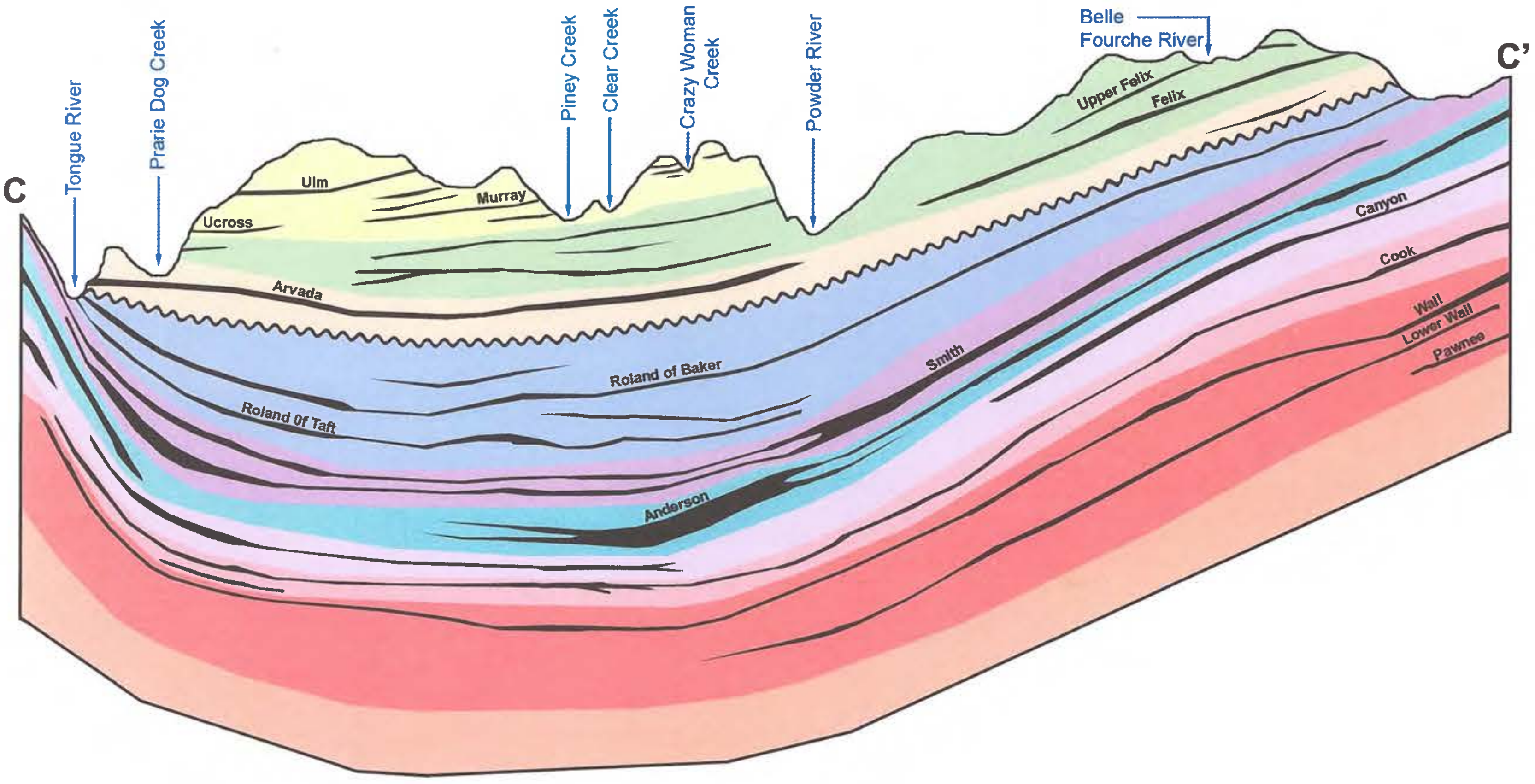
Pawnee
Moyer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APPENDIX 2A

geophysical well log interpretation

Scott Quillinan

Unique physical properties of coal allow the use of geophysical well logs to determine coal-seam top and base depths. Gamma-ray logs, density logs, neutron logs, and resistivity logs register natural radioactivity, density, and resistance to electric current flow in strata down-hole. Most of the well logs cited in this report were from CBNG wells, and some were from traditional oil and gas wells. Simultaneous gamma-ray/density logs in CBNG wells gave the most reliable picks.

Overview

Geophysical well logs record the natural radioactivity, density, and electrical resistivity of the rocks that a well penetrates. Several unique physical properties of coal allow the use of well logs to identify coal in the subsurface: low natural radioactivity, low density, and high resistance to electric current (**Table 2A-1**). Because non-coal rocks differ from coal in these properties, geophysical logs can be used to determine the presence and thickness of a coal seam in a coal-bearing sequence.

We used several types of geophysical logs to identify subsurface coal-seam top and base elevations for this report: gamma-ray, density, neutron, and resistivity logs. Some sets of well logs recorded a suite of measurements, making coal-seam distinction straightforward and accurate, while other well logs, with only one type of measurement over a coal-bearing interval, made coal-seam distinction difficult and less accurate. The combined gamma-ray/density log was generally the most common, accurate, and easiest log to interpret, whereas a resistivity log gave the greatest uncertainty (**Figure 2A-2**). Neutron logs are valuable, but have seldom been run in the PRB.

Coal seams identified and measured on well logs constitute most of the data acquired for this report. Most of that data was taken from CBNG well logs, some from conventional oil and gas well logs. The CBNG wells are closely spaced and their logs well calibrated

Table 2A-1. Geophysical log characteristic responses in coal and associated strata.
[Modified from Renwick (1981). Gamma-ray response in counts per second; density in grams per cubic centimeter; neutron in porosity units (volume percentage); resistivity in ohms per meter.]

Lithology	Geophysical log type			
	Gamma-ray	*Density*[1]	*Neutron*	*Resistivity*
Shale	high	high	high	low
Sandstone	low	high	low	intermediate
Coal	low	low	high	high
Pyrite in coal	low	high	high	high

[1] Gamma-ray logs plot low response to the left, high response to the right; coal plots to the left (as does pure sandstone). In order to read density logs in the same sense as corresponding gamma-ray logs, to match them, we reverse the density plot electronically so that the high back-scatter response of coal is read to the left as a low-density response and is calibrated as density (grams per cubic centimeter) rather than as counts-per-second of back-scattered radiation.

for coal identification, and several types of logs are run simultaneously (**Figure 2A-1**). Conventional oil and gas wells log a deeper interval but are not closely spaced, nor are their logs calibrated to easily identify coal seams; generally, only resistivity logs are run.

Although conventional oil and gas logs provided a picture of the entire Paleocene and Eocene coal-bearing sequence, we exercised caution in using them, for two reasons. First, other lithologies can be misidentified as coal seams when using only one type of log. For example, coarse quartz-rich sandstone emits extremely low gamma, mimicking a distinctive property of coal (**Table 2A-1**). Second, some log types used in conventional oil and gas exploration are simply not effective for coal-seam identification. Thus cautioned, we used the conventional oil and gas well logs solely to augment resolution on deep coal beds in support of data collected from thousands of CBNG well logs (**Figure 2A-3**).

Gamma-ray logging

The natural radioactive decay of certain elements in rocks releases measurable levels of gamma radiation. The gamma-ray log was introduced by Well Surveys, Inc. in 1939 as a technique to determine subsurface lithology beyond casing. Gamma rays are bursts of high-energy electromagnetic energy that penetrate even dense matter (**Figure 2A-4**). Gamma rays are emitted as a result of the breakdown of radioactive isotopes of uranium, thorium, and potassium. The most abundant of these elements is potassium, a component of micas, feldspars, and clay minerals. Strata in which these minerals are major constituents, such as shales and felsic volcanics, emit much higher levels of gamma radiation than strata, such as quartz-rich sandstone and coal, containing potassium-poor minerals.

The gamma-ray log gives a general measure of the shale and clay content of strata. Pure coal is distinguished by a remarkably low gamma value; shaley coals give a somewhat higher gamma value, and may be difficult to distinguish from sandstone. The non-

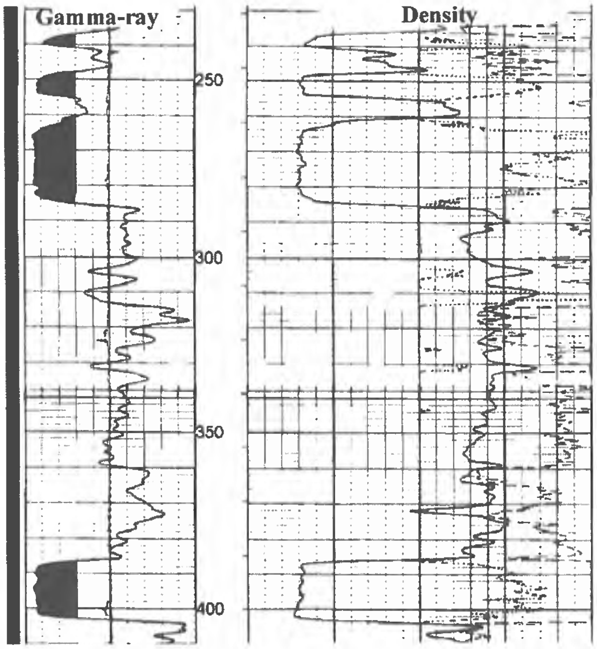

Figure 2A-1. Coal bed identification verified on corresponding gamma-ray and density logs.

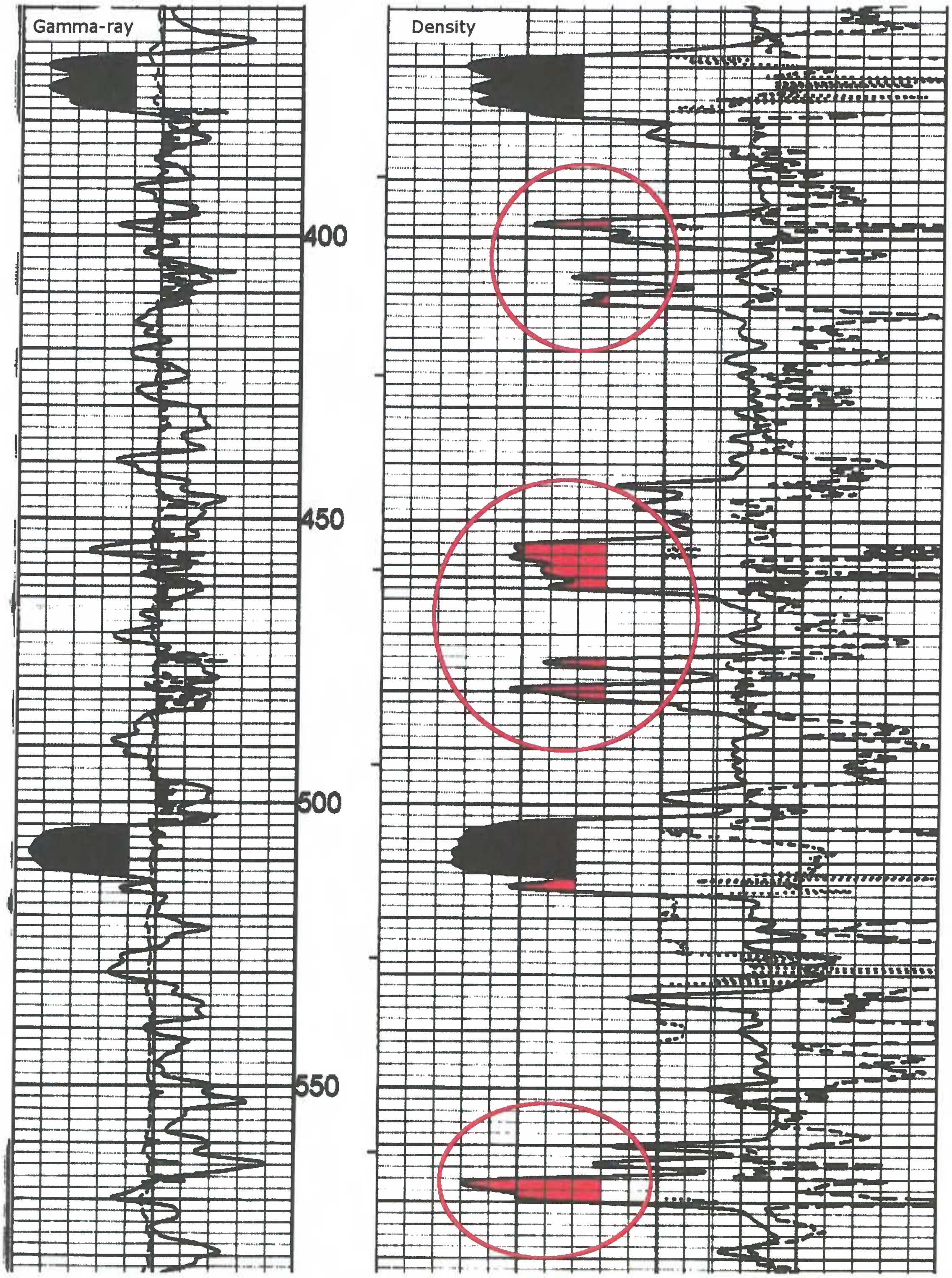

Figure 2A-2. Many sets of gamma-ray and density logs show discrepancies, and both logs are needed to identify coal with complete confidence. This set is unusual in that it is generally the gamma-ray log that shows spurious peaks (red).

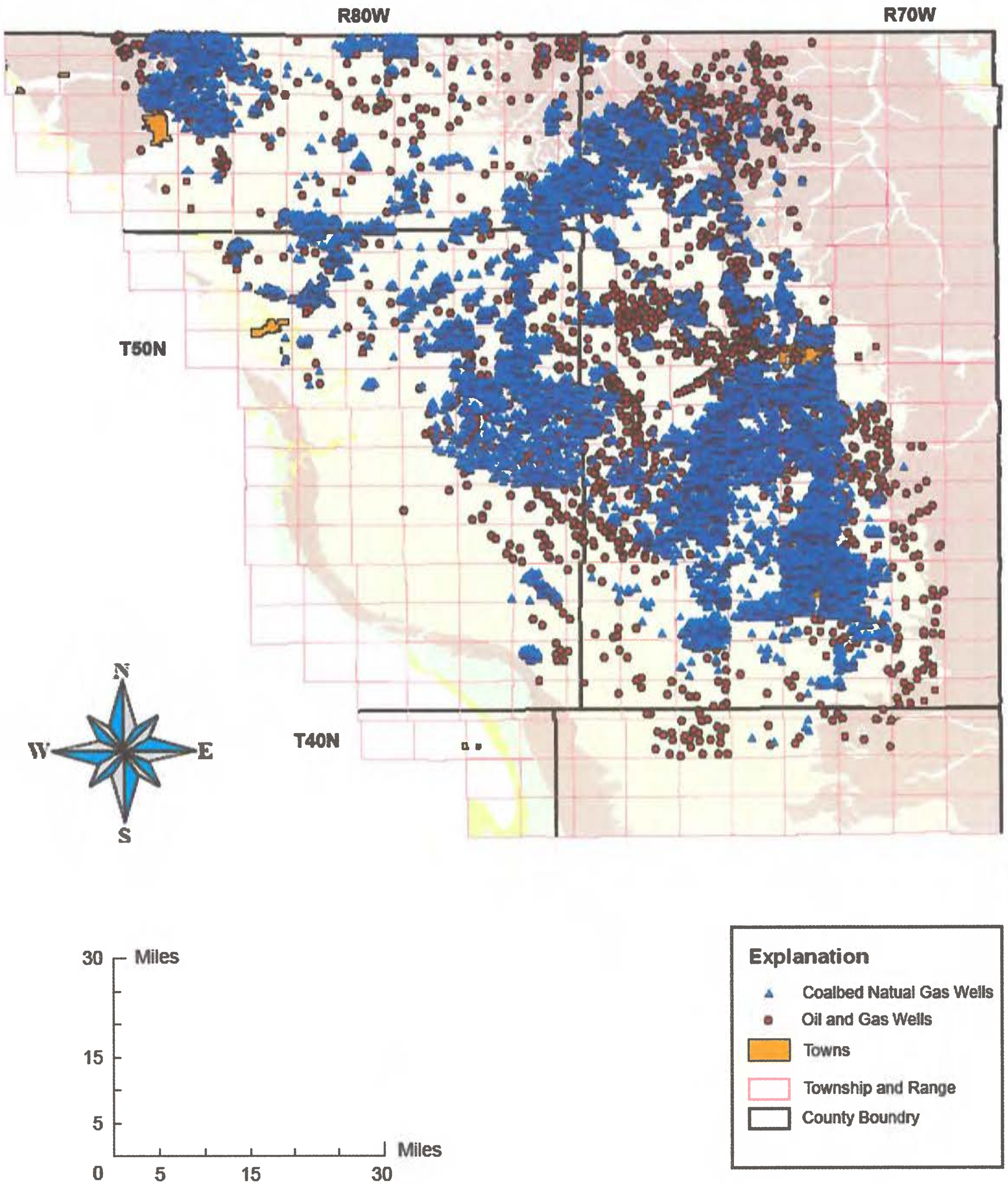

Figure 2A-3. Map showing density of CBNG wells and of conventional oil and gas wells in the WSGS Powder River Basin Coal Occurrence Database. Among these wells are those used in the coal bed correlations described in this chapter.

coal strata within the PRB coal-bearing formations generally consist of shales and other fine-grained sediments that are easily distinguished from coal seams on a gamma-ray log. The gamma-ray log is useful not only in detecting lithological boundaries, but also in detecting thin beds within a lithological unit (**Figure 2A-5**).

Density logging

The density log (scattered gamma-ray log, gamma-gamma log) was introduced in 1953 as a log that could record rock density in place. Density logging is based on the response of strata around a bore hole to incident gamma radiation. Dense rocks tend to absorb the emitted gamma-rays, whereas rocks with low bulk density reflect (back-scatter) more of the emitted gamma-rays. [High back-scatter is logged as low density: see **Table 2A-1**, footnote.] The density log was originally developed for the oil industry, to measure the bulk density of a rock reservoir and thus give a general estimate of formation porosity (**Figure 2A-6**).

Density logs are used in coal exploration in conjunction with gamma-ray logs. Coal is made up almost entirely of carbon and hydrogen, both of which are of lower atomic number than the aluminum, iron, and silicon in minerals generally associated with sandstones. As a result, coals send much greater back-scatter to the receiver than sandstone does. The density of coal is about 1.3 g/cm³, compared to the average

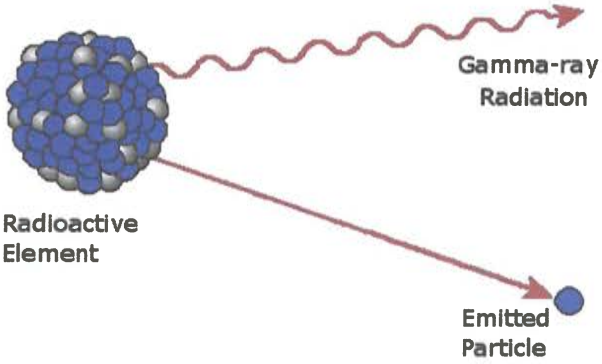

Figure 2A-4. Radioactive decay: an unstable atomic nucleus loses energy by emitting radiation in the form of a particle plus a quantum of electromagnetic energy (a gamma ray).

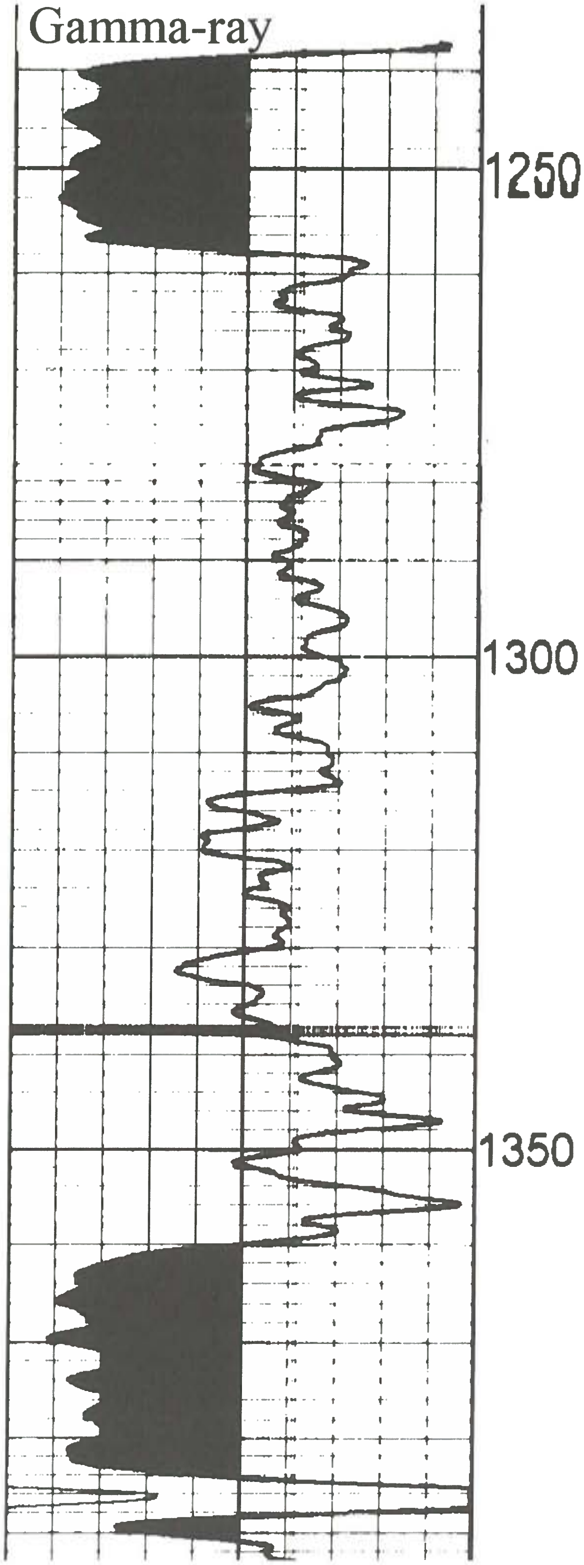

Figure 2A-5. Typical gamma-ray log showing low gamma-ray signature of coal beds (blackened in, left of center). A shale parting in the lower coal gives a high gamma-ray response, a peak that rises to the right and re-enters the log from the left.

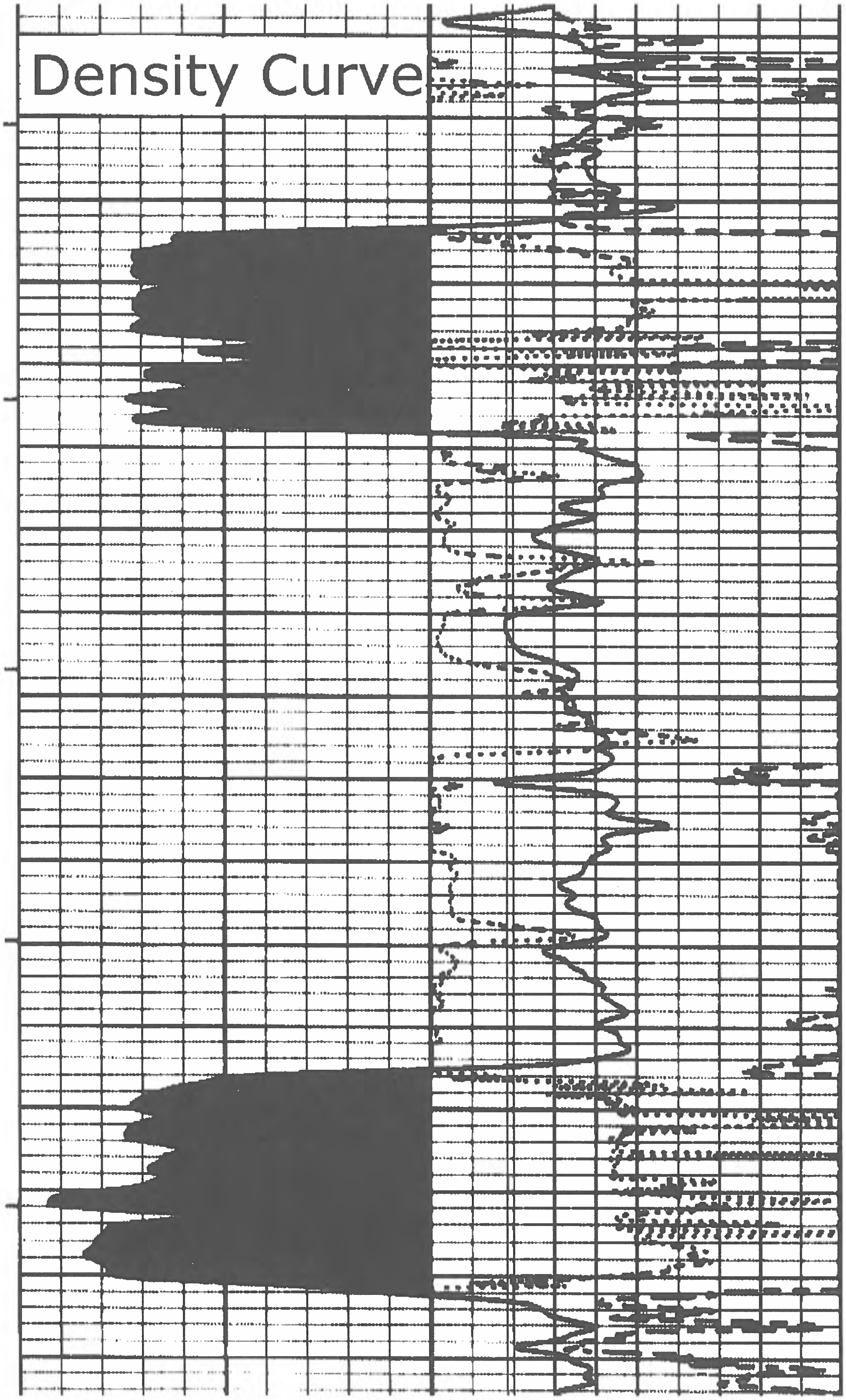

Figure 2A-6. Typical density log showing low-density signature of coal beds.

2.5 g/cm^3 of other sedimentary strata. Thus, coal and sandstone are distinguished from other lithologies on a gamma-ray log, and the coal is distinguished from the sandstone on the corresponding density log.

Neutron Logging

Well Surveys, Inc. introduced neutron logging in 1941, and Lane-Wells initiated the first commercial logging soon after. Neutron logging records the reduction in energy of neutrons passing through a rock-body. Of the chemical elements, hydrogen has the lowest mass and causes the greatest loss of the energy in incident neutrons. By slowing the neutrons, it also allows neutron capture by other elements. Thus, the response recorded on neutron logs depends mostly on the amount of hydrogen present. Most of the hydrogen in sedimentary rocks occurs as water. However, since coal is a hydrocarbon, hydrogen also occurs in the molecular structure of the coal. The neutron log response may be used to measure the total hydrogen present in the coal, which is related to coal rank and to the moisture content of the seam. If the interstitial water content is uniform over a coal-bearing interval, the neutron log can be calibrated to indicate the approximate amount of volatile matter in the coal (Ward 1984). Very few neutron logs have been run in the PRB. In a few instances, neutron logging has been done in conjunction with gamma-ray logging in conventional oil and gas wells, but it has very rarely been done in CBNG wells.

Resistivity Logging

By far the most common geophysical log used in oil and gas exploration is the resistivity (electrical) log (**Figure 2A-7**). The resistivity log records the response of rocks to incident elastic waves. The use of elastic waves to investigate bore holes was first proposed by Humble Oil and Refining Company in 1948: an experimental acoustic logger was built that could record reproducible elastic wave propagation down-hole. The resistivity log has three components: spontaneous potential (sp), resistivity, and conductivity. The spontaneous potential curve records changes in natural potential along an uncased borehole: small voltages developed between the mud and the formation water of an invaded bed and also across the shale-to-mud interface, augmented by an electrokinetic potential developed when the mud filtrate moves along the borehole toward a formation region of lower pressure. In resistivity logging, current and potential electrodes in the receiver make contact with the walls of the uncased hole and measure the resistivity of the surrounding strata. Induction logs make a continuous record of the conductivity of the strata traversed by a borehole, as a function of depth.

The resistance of rock strata to an electric current depends partly on mineralogy and partly on fluids in pore spaces. Generally, subbituminous and bituminous coal should be highly resistive, and shale, sandstone, and limestone much less resistive. But in actual well logging, geological conditions influence, and may distort, the resistance log response: not all high-resistivity beds are coal seams, nor do all coal seams show significant resistivity contrast with surrounding strata; water in pores or cleat fractures may reduce a formation's apparent resistivity; and coals may be difficult to distinguish from fresh-water sandstones and conglomerates (Ward 1984).

Acknowledgements

The author referred to Reeves (1978), Rice et al. (2000), Ward (1984), the Wyoming Department of Environmental Quality, and the Wyoming Oil and Gas Conservation Commission in preparing this work.

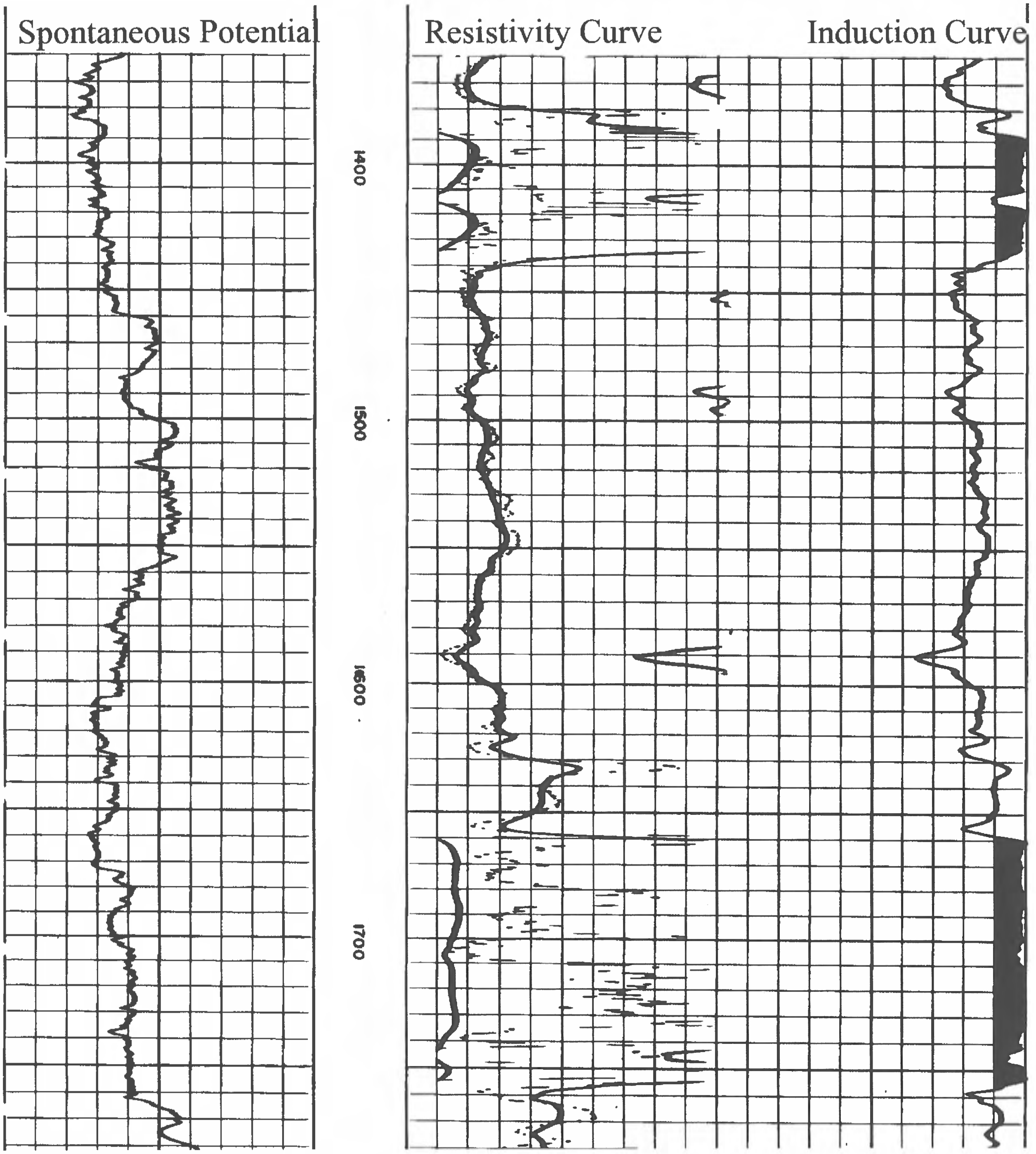

Figure 2A-7. Typical electrical log showing the high-resistivity and high-conductivity coal signature. The blackened-in areas show where resistivity and conductivity are high. The conductivity (induction) curve wraps around and enters the log from the left.

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CHAPTER 3

water production and quality

Keith E. Clarey and James E. Stafford

Groundwater

In the Powder River Basin (PRB) of Wyoming, groundwater resources are present within both the unconsolidated deposits and bedrock formations of the structural basin. Groundwater resources in the PRB include aquifers ranging in geologic age from Quaternary to Precambrian (**Figure 3-1**). Groundwater in the PRB varies widely in quantity and quality.

In outcrop areas, shallow groundwater in bedrock formations is typically unconfined. Deeper in the structural basin, groundwater is generally confined by low-permeability strata adjacent to the permeable aquifer beds (sandstone, coal, and limestone/dolomite beds). Confined (artesian) groundwater in some areas of the PRB flows at the surface from confined (artesian) wells, where confining (artesian) pressure is greater in pressure height than the ground surface elevation.

At present, data on aquifer recharge rates, groundwater flow rates, aquifer discharge rates, degree of subsurface inter-aquifer mixing, and total groundwater quantities available for development in the PRB are sparse relative to the great area and stratigraphic complexity of the basin. Our models of basin stratigraphy and of water quality, quantity, and distribution can be updated as more data are collected in the future – see Chapter 4, **Appendix 4A1**.

Within the PRB and on the flanks of the surrounding mountain uplifts, most of the water-saturated portions of the geologic bedrock formations and unconsolidated deposits will yield groundwater to wells. This chapter addresses the quantity and quality of the groundwater available from these geologic units. Many of the low-permeability geologic units in the PRB yield very low quantities of low-quality ground-

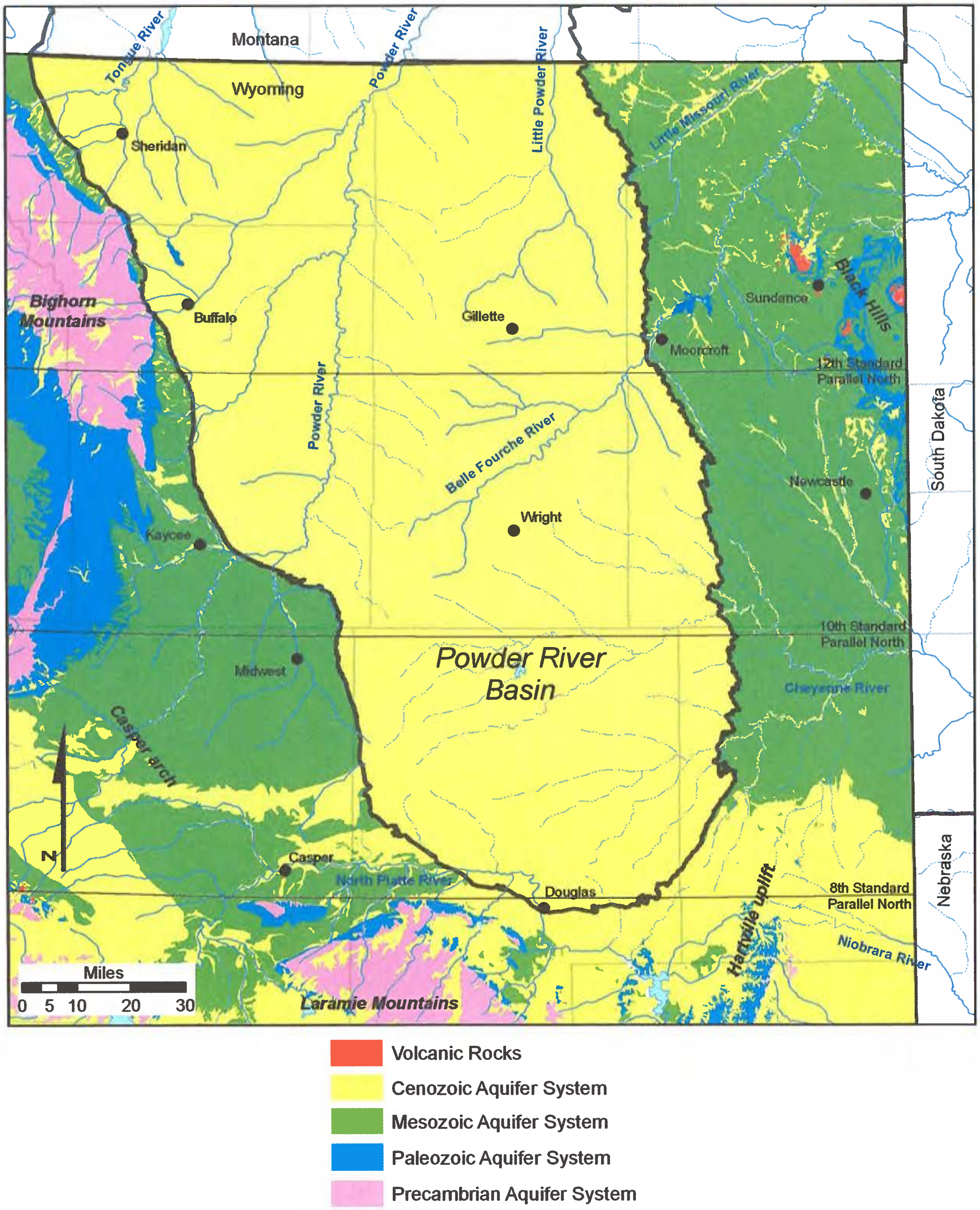


Figure 3-1. Major aquifer systems of the Powder River Basin, Wyoming.

water, which may not be adequate or economically viable for the desired water use.

For this project, we scanned more than 34,000 groundwater permits on file with the Wyoming State Engineer's Office (WSEO) for the southern PRB from December 2005 to December 2007. More than 55,000 groundwater permits on file with the WSEO are for locations in the PRB (**Figure 3-2**). Most of these groundwater permits are for wells; however, a small number of springs (**Figure 3-3**) with yields of 25 gallons per minute (gpm) or less used for domestic purposes and/or stock-watering are included. Most of the wells are less than 1,000 feet deep and yield less than 25 gpm to wells from sandstone or coal beds.

The well and water data collected during the course of this project were reported data and publicly available. Proprietary well and water data from coal bed natural gas (CBNG) operators (**Figure 3-4**) and private water wells were not available. Groundwater quality data included with Wyoming Pollutant Discharge Elimination System (WYPDES) Program permit applications to the Wyoming Department of Environmental Quality (WDEQ) are currently available only as hard copies in the Cheyenne offices of the WDEQ. We collected a representative number of WYPDES permit water quality data for this report.

Groundwater flow within the bedrock formations of the PRB is commonly structurally and stratigraphically controlled in parts of the geologic basin and surrounding Laramide uplifts. Aquifers are predominantly contained within an interstratified sequence of high- and low-permeability sedimentary beds. Groundwater is present in the open spaces of the geologic formations, and flow occurs where there are permeable, interconnected pathways and sufficient head pressure. The PRB aquifers are commonly heterogeneous and anisotropic in character on both local and regional scales.

Locally, groundwater is unconfined in outcrop areas along the margins of the PRB and in the shallow parts of the outcrop area of the Wasatch Formation. Shallow groundwater flow in the PRB is primarily controlled by topography and stream drainage patterns. In general, shallow groundwater (less than about 300 to 500 feet below ground surface) follows topography and is discharged to stream and river drainages. Regional groundwater flow also generally follows ground surface topography, and local stream drainages are superimposed on the structural basin. The Little Bighorn, Tongue, Powder, Little Powder, Little Missouri, Belle Fourche, Cheyenne, Niobrara, and North Platte rivers all drain the Wyoming PRB. The Niobrara and North Platte river drainages are not discussed in this report because they drain only very small areas along the southernmost basin margin. The other river drainages are discussed in the *Surface water* section of this chapter.

Deep regional groundwater in the PRB formations flows predominantly through permeable formations and fractures from aquifer recharge areas – formational outcrops located along the margins of the structural basin – toward the structural axis of the PRB, and down-gradient (downward in elevation) to the north-northwest into the Montana PRB. Discharge occurs along stream drainages as springs or as subcrop flow into overlying geologic units. The subcrop discharge flow of this groundwater is generally into alluvium along stream valleys, which helps maintain base flow in the streams.

In summary, local, topographically-controlled groundwater flow zones and outcrop areas are the primary areas of recharge to and discharge from the aquifers. Local groundwater flow, in areas where hills and uplands are higher than the local stream/river drainages, is dominated by these local topographic features. Local groundwater tends to flow downhill into nearby surface drainages. Complex groundwater-surface water to groundwater interaction occurs between 1) permeable beds of bedrock and unconsolidated deposits, and 2) surface water drainages, which are typically lined with alluvial deposits. The groundwater and surface water resources of the PRB of Wyoming are interconnected, as discharge of groundwater to the surface may occur from springs, subcrop discharge flow to overlying geologic units, and pumping wells.

Definitions

We use the following definitions in this report:

- *Aquifer* – A formation, group of formations, or part of a formation that contains sufficient water-saturated high-permeable material to yield

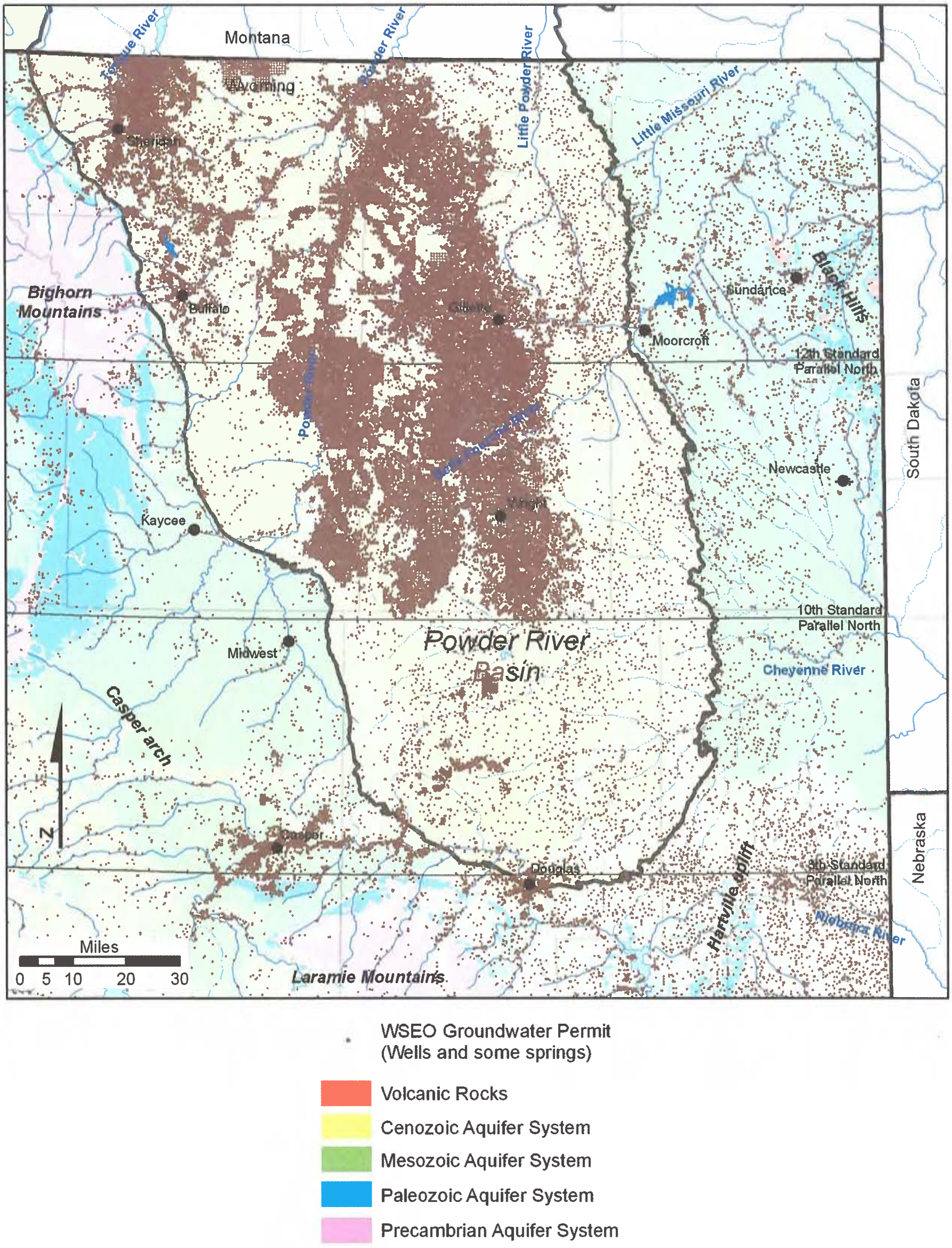


Figure 3-2. Map showing locations of wells in the Powder River Basin, Wyoming.

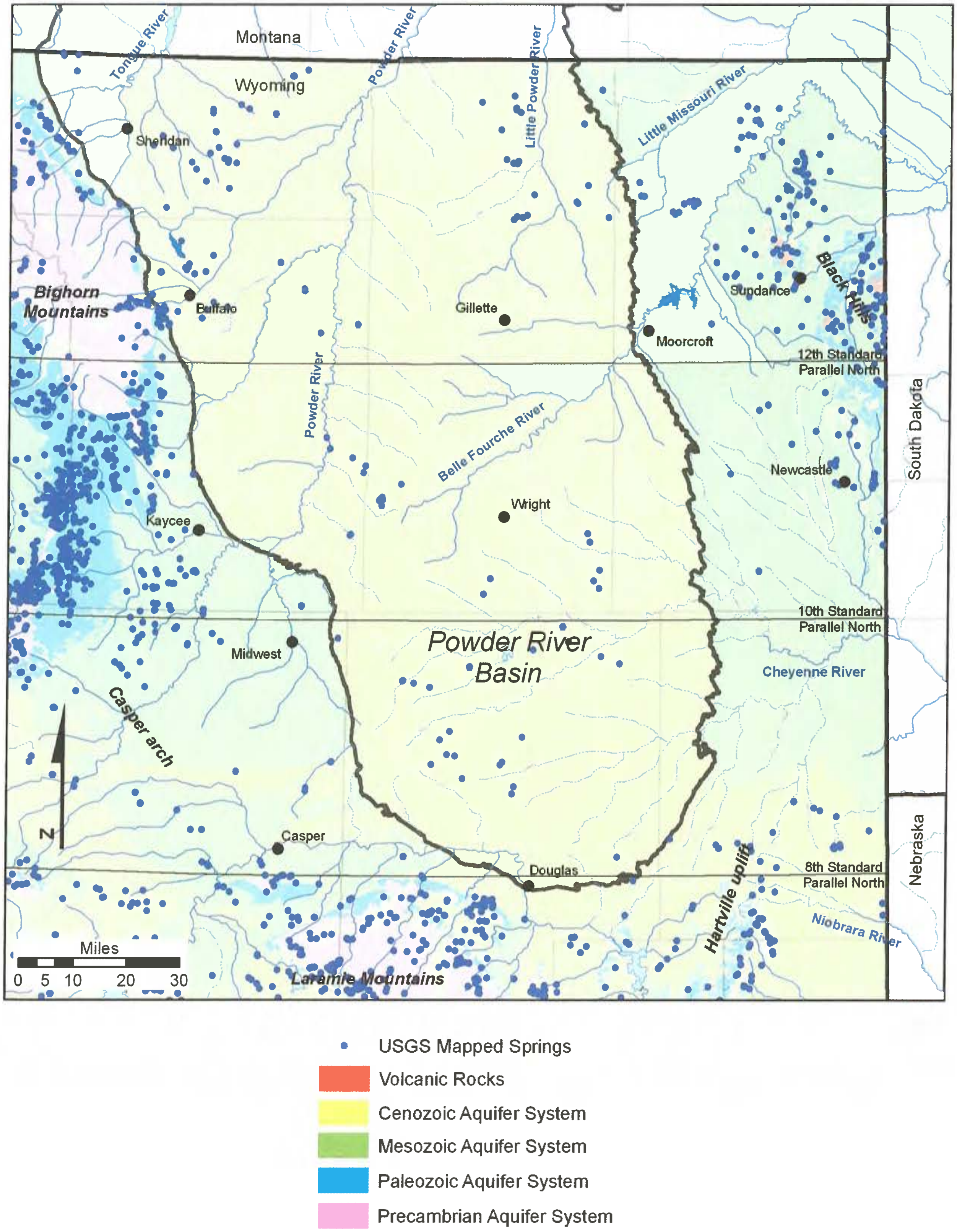


Figure 3-3. Map showing locations of springs in the Powder River Basin, Wyoming.

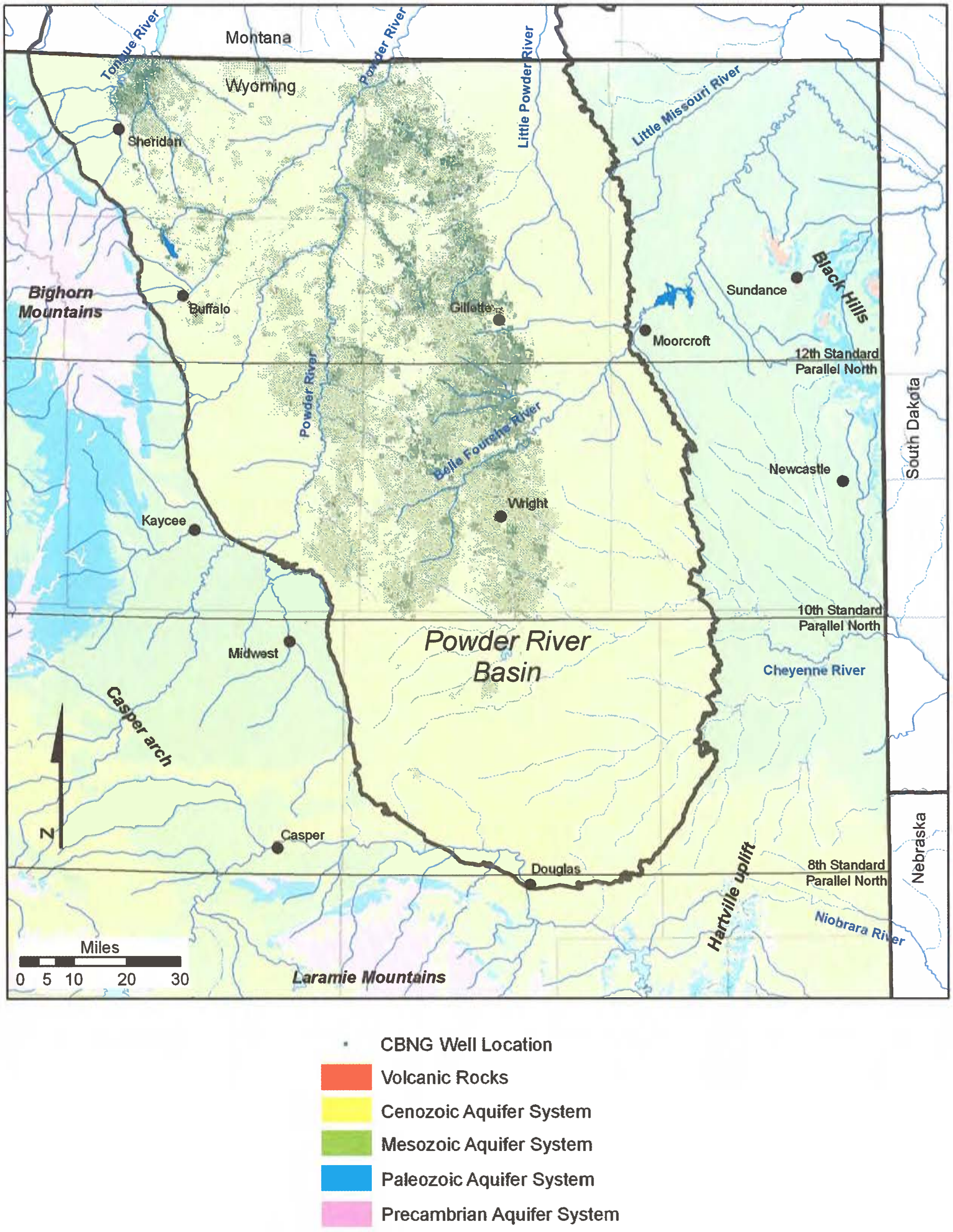


Figure 3-4. Map showing locations of CBNG wells in the Powder River Basin, Wyoming.

significant quantities of water to wells and springs (modified from Lohman et al., 1972).

- *Aquifer System* – A heterogeneous body of intercalated high-permeable and low-permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more high-permeable beds [aquifers] separated at least locally by low-permeable confining beds [aquitards] that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system (modified from Poland et al., 1972).

- *Confining Bed (or Unit)* – A formation, group of formations, or part of a formation that is defined as a body of "impermeable" material stratigraphically adjacent to an aquifer. In nature, however, the hydraulic conductivity of the confining bed may range from nearly zero to some value distinctly lower than that of an aquifer. Its conductivity relative to that of the aquifer it confines is specified or indicated by a suitable modifier such as "slightly permeable" or "moderately permeable." (modified from Lohman et al., 1972). *Aquitard* is a synonym.

In this report, we use the terms *aquifer* and *water-bearing bed/unit* as they are currently accepted by the USGS. In geohydrologic use, an individual water-bearing bed (or unit) is generally considered to be thinner and smaller than an aquifer. We also use the terms *aquitard* or *confining bed/unit* as accepted by the USGS. An aquitard is commonly considered thicker and more laterally extensive than an individual confining bed (or unit) in common geohydrologic usage. *Aquitard* is also an older geohydrologic term.

Aquifers and aquifer systems are generally anisotropic because of interbedded low-permeability confining beds or confining units (shale, claystone, mudstone, bentonite beds, etc.) present within the aquifer systems. Groundwater flow rates through aquifers and confining units range from very high to very low. A high flow rate through a gravel-rich, high-permeability deposit may exceed 100 centimeters per second (cm/s) (3.3 feet per second (fps) or 2.9 x 10^5 feet per day (ft/day)). A low flow rate within a clay-rich, low-permeability deposit may be less than 10^{-9} cm/s (3.3 x 10^{-11} fps or 2.9 x 10^{-7} ft/day). Flow rates encompass 11 to 12 orders of magnitude. The rate of water flow through an aquifer may be several orders of magnitude faster than the flow rate through an adjacent aquitard or confining bed/unit.

Confining beds (or units) are commonly considered impermeable to groundwater flow, but in reality, most confining beds seep water at low to very low flow rates. The terms *semi-confined* and *semi-confining* are appropriate for beds or formations with sufficient seepage from, or through, the confining unit to an adjacent aquifer.

Unconfined aquifers are water-saturated portions of geologic units wherein groundwater is under atmospheric pressure. The commonly-used term *water table* is the same as the geohydrologic terms *groundwater surface* or *potentiometric surface*. The term *water table* implies a flat, horizontal groundwater surface. However, the actual groundwater (potentiometric) surface is generally tilted or contoured like a topographic land surface.

The slope of the groundwater surface is defined as the *hydraulic gradient* and has both a direction and a magnitude. Hydraulic gradient is commonly expressed in feet of elevation change per foot of horizontal distance (ft/ft). The direction of slope from high to low elevation indicates the potential direction of groundwater flow, provided permeable interconnected pathways exist to allow such groundwater movement. Steep hydraulic gradients are common for low-permeability geologic units, and low-angle to nearly flat hydraulic gradients are common for high-permeability units.

The terms *perched groundwater* or *perched aquifer* refer to groundwater lying on top of a confining bed; this is the same concept as ponded (trapped) groundwater. Perched groundwater is located above deeper aquifers that may be either unconfined or confined, is generally unconfined, and is hydrologically separated from the deeper aquifers by a confining bed. The saturated thickness of perched groundwater ranges from a few inches to many feet.

Groundwater flows in aquifers as porous flow, conduit flow, fracture flow, or a combination of these.

Porous flow refers to water moving through interconnected, open, intergranular, or intercrystalline pore spaces within a rock unit (conglomerate, sandstone, siltstone, limestone, or dolomite bedrock; or unconsolidated mixtures of loose gravel, sand, silt, and clay). The size of the sediment grains or mineral crystals affects flow rate through pore spaces. Larger open pore spaces between larger grains/crystals generally have greater flow due to less friction resulting from a lower grain surface-area-to-volume ratio. In a mixed deposit with clay to gravel grain sizes, increased amounts of fine-grained matrix in the pore spaces reduces the permeability and flow rate.

Conduit flow refers to water moving through large discrete open spaces (such as pathways, pipes, cavities, channels, caves, or karstic zones) within a rock unit, generally limestone or dolomite. Conduits may form by the dissolution of soluble minerals in a rock unit or by subsurface sediment transport (piping) through a loosely consolidated formation.

Fracture flow refers to water moving through interconnected breaks within a geologic unit. The breaks result from structural deformation (folding, faulting, jointing in rocks, cleating in coal, across or along bedding planes) or physiochemical alteration (bedrock weathering or soil formation).

Gravity generally drives groundwater flow from areas of higher pressure (greater hydraulic head, higher elevation) to areas of lower pressure (lesser hydraulic head, lower elevation). However, groundwater flow as inferred from potentiometric surface maps will only occur if permeable pathways actually exist to allow the water to flow in the subsurface.

Pumping water from a well generally induces anthropogenic groundwater flow toward the well. During pumping, the water level in the pumping well lowers, correspondingly lowering the water pressure locally in the aquifer(s) surrounding the well (zone of influence).

Groundwater flow to a pumping well may be either laminar or turbulent. Most natural and anthropogenic groundwater flow is laminar – along a straight path through the aquifer and into the well. A few examples exist of turbulent flow in nature, where groundwater cascades and roils through a subsurface bedrock formation or an unconsolidated deposit. Wells are subject to anthropogenic turbulent flow when pumped at discharge rates higher than the maximum rate at which an aquifer will yield laminar-flowing water to the well. During turbulent flow, sediment may be mobilized within the aquifer and enter the pumping well, causing pebbly, sandy, silty, clayey, or muddy water to flow from the pump. In a pumping coal bed well, turbulent flow may yield abundant coal fines in the produced water.

Other groundwater-related definitions include the following.

Water table, an old term, refers to the groundwater surface within an unconfined aquifer under atmospheric pressure. In popular usage, the water table is the first occurrence of unconfined or confined groundwater below the ground surface; technically, this may be inaccurate.

A *potentiometric surface* is a surface that represents the static head pressure of groundwater; it replaces the older terms *piezometric surface* and *water table*. A synonym is *groundwater surface*. The potentiometric surface is expressed as elevation in feet above mean sea level (ft-msl).

Static head or *static water level* refers to the level of water in a well when the well and surrounding wells are not being pumped and the groundwater in the aquifer is at rest. Static head or level is commonly expressed in feet, as either depth below measuring point or depth below ground surface. Also, the static head or level may be converted to elevation in feet above mean sea level (ft-msl).

Drawdown is the lowering of the groundwater (potentiometric) surface by anthropogenic (pumping of wells) or natural (seasonal and annual variation, drought) means from a higher groundwater-level datum. Drawdown is expressed as feet of water-level change. A rise in groundwater level is the opposite of drawdown.

A *gaining stream* is a stream, or reach (part) of a stream, in which the discharge of groundwater from the geologic unit(s) underlying (or adjacent to) the stream adds to the surface water flow of the stream.

A *losing stream* is a stream, or reach (part) of a stream, in which the leakage of surface water into the geologic unit(s) underlying (or adjacent to) the stream recharges the groundwater and decreases the surface water flow of the stream.

Well yield is a measure of the rate of groundwater discharged (pumped or flowing) from a well and is expressed in gallons per minute (gpm).

In a hydrologic context, *porosity* is the proportion of open-space volume (pores, pipes, conduits, voids, or fractures through which water can move) with respect to the total volume of an earth material (soil, unconsolidated deposit, or bedrock), expressed as percentage.

Permeability is a measure of the amount of water flowing through the interconnected open spaces of an aquifer or aquitard, and is expressed in gallons per day per square foot (gpd/ft^2).

Specific capacity is the pumping discharge rate of a well divided by the number of feet of drawdown of the water level measured in the well during pumping, and is expressed in gallons per minute per foot of drawdown (gpm/ft).

Specific yield is defined as the drainable porosity, and is reported as the proportion (percent) of the water volume that will drain under gravity from a total volume of earth material (alluvium). Specific yield is calculated only for unconfined aquifers, such as alluvial deposits.

Transmissivity is the rate at which groundwater of the prevailing kinematic viscosity is moving through a unit width of the water-saturated part of the aquifer under a unit hydraulic gradient, and is expressed in gallons per day per foot (gpd/ft).

Total dissolved solids (TDS) is a measure of the concentration of dissolved chemical species (mineral salts, or ions). TDS is expressed in either milligrams per liter (mg/l) or parts per million (ppm).

Geochemical water type is an expression of the dominant cations and anions dissolved in the groundwater. For example, the Fort Union Formation coal beds generally have sodium-bicarbonate type water in the deep PRB.

Groundwater availability depends on the quantity, quality, depth, and intended use. Implicit in availability are economic constraints on development of groundwater resources. If the groundwater is not economically available for development, the resource will not be used. Groundwater quality depends primarily on the natural geochemistry of the water and various geologic factors. In addition, groundwater may also be contaminated or availability impaired by human activities.

More than 55,000 water, petroleum (oil and conventional gas), exploration, and CBNG wells have been constructed in the Wyoming PRB. More than 25,000 of these are CBNG wells. An unknown number of the 55,000 wells have connected various aquifers and water-bearing zones by perforating through confining beds (units). Some of these wells were improperly completed or incompletely plugged and abandoned, which has allowed water to leak through the well boreholes from one aquifer to another.

In general, groundwater quality decreases with depth and with distance from the outcrop areas of an aquifer. Also, the permeability of a formation generally decreases with depth because of compaction under lithostatic load and increased filling of pore spaces by mineral cement.

Previous groundwater studies

A bibliography and classified index of approximately 350 groundwater and related studies is available from the WSGS.

Aquifer Systems

The geohydrologic units in the Wyoming PRB are aquifers in unconsolidated sedimentary deposits and consolidated (lithified) bedrock formations ranging in age from Quaternary to Precambrian. We describe the aquifers as occurring in four major aquifer systems that correspond to the four geologic eras represented in the basin: the Cenozoic, Mesozoic, Paleozoic, and Precambrian aquifer systems (**Figure 3-1**).

The younger aquifer systems overlie the older aquifer systems at depth within the basin, and the older systems are exposed only in outcrop along the basin margins and along the mountain uplifts surrounding the basin. We discuss these aquifer systems and their aquifers in order from youngest to oldest.

The Cenozoic aquifer system (**Figure 3-5**) consists of the water-saturated parts of unconsolidated deposits and consolidated bedrock formations ranging in age from Quaternary (Holocene and Pleistocene Epochs)

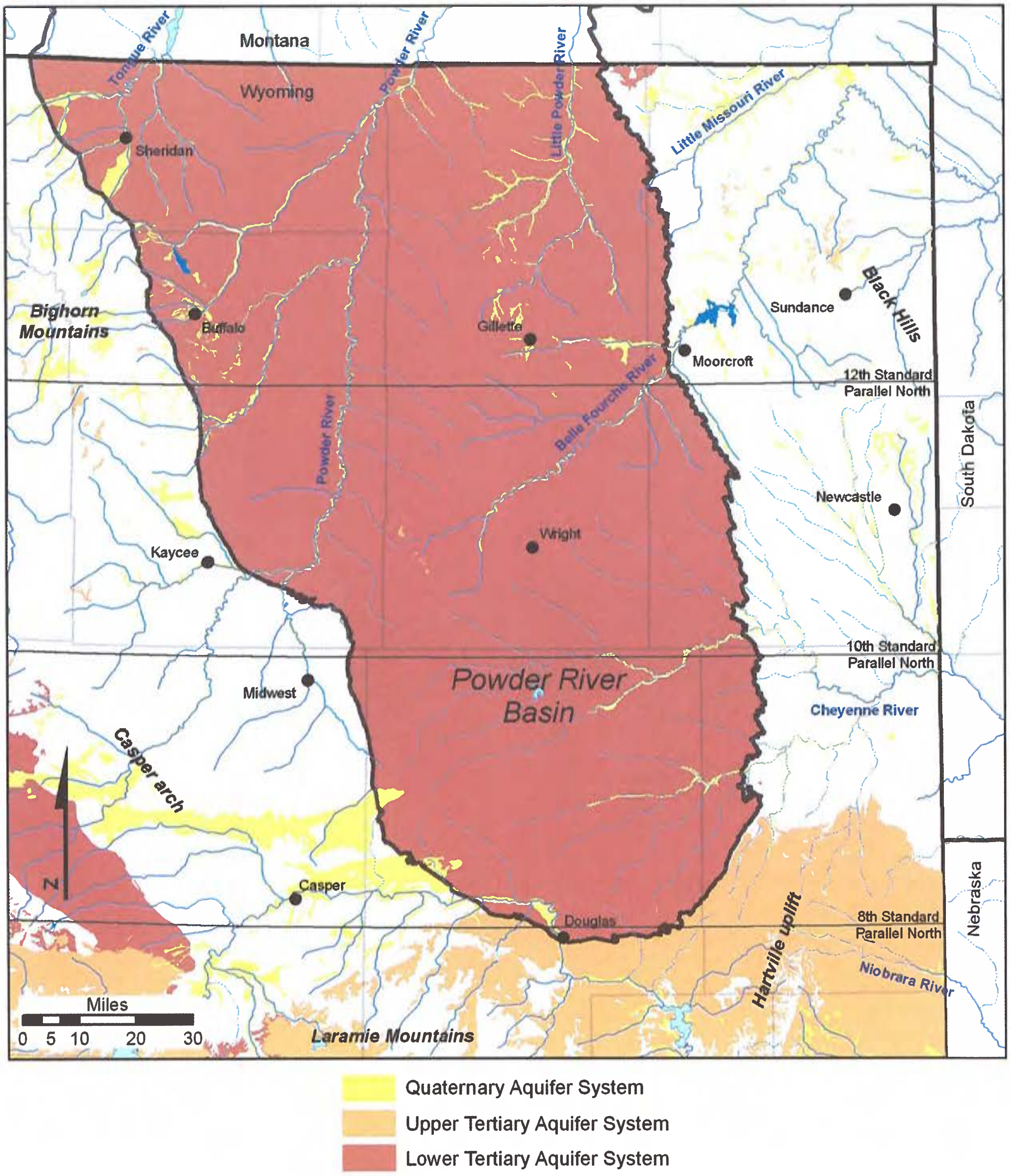


Figure 3-5. Cenozoic aquifer system, Powder River Basin, Wyoming.

to Tertiary (Pliocene, Miocene, Oligocene, Eocene, and Paleocene Epochs). The Cenozoic aquifer system is the most heavily used of the four major aquifer systems in the PRB. It consists of the upper and younger Quaternary aquifer system and the lower and older Tertiary aquifer system.

The Quaternary aquifer system in the PRB consists mostly of unconsolidated deposits: alluvial deposits, terrace deposits, clinker (scoria) areas, and eolian, lacustrine, and glacial deposits.

The Tertiary aquifer system generally underlies the Quaternary aquifer system. The upper Tertiary aquifer system is limited to a few remnant outcrops of the Oligocene White River Formation within the PRB, a few White River outcrops in the Black Hills area, and larger exposures of the Arikaree and White River formations along the southern and southeastern margins of the PRB. The lower Tertiary aquifer system comprises the Wasatch and Fort Union formations. The primary water-yielding beds in the Wasatch and Fort Union aquifers are the sandstone and coal beds. The outcrop area of the lower Tertiary aquifer system is the largest within the PRB. Most water wells in the PRB yield water from the Wasatch and Fort Union formations.

The Mesozoic aquifer system (**Figure 3-6**) consists of the water-saturated parts of the consolidated bedrock formations of Cretaceous, Jurassic, and Triassic age. This aquifer system is the second most used of the four major aquifer systems within the PRB. The Mesozoic aquifer system yields water mostly from sandstone beds in the Upper Cretaceous Lance Formation and Fox Hills Sandstone.

The Paleozoic aquifer system (**Figure 3-7**) consists of the water-saturated portions of the consolidated bedrock formations of Permian, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian ages. This aquifer system is the third most used of the four major aquifer systems within the PRB. The Paleozoic aquifer system is accessible along the basin margins and mountain flanks.

The Precambrian aquifer system (**Figure 3-8**) consists of the water-saturated parts of the bedrock formations ranging in age from Proterozoic to Archean. This aquifer system is the least used of the four major aquifer systems within the PRB. The Precambrian rock units – ancient crystalline crustal rocks – underlie all other geologic formations at depth in the basin and are exposed in the cores of the mountain uplifts surrounding the basin. The Precambrian aquifer system is accessed in the outcrop areas of mountain uplifts.

The lithologic descriptions below are summarized from Hodson et al., (1973), Feathers et al., (1981), and Love and Christiansen (1985). The Wyoming Statewide Framework Water Plan 2007 (WWC Engineering, 2007) provided state aquifer classifications. These sources are abbreviated in the descriptions below:

- (Feathers) – Feathers et al., 1981
- (Hodson) – Hodson et al., 1973
- (L&C) – Love and Christiansen, 1985
- (WWC) – WWC Engineering, 2007

Cenozoic Aquifer System

Quaternary

The Quaternary aquifer system (**Figure 3-5**) in the PRB consists mostly of unconsolidated deposits: alluvial deposits, terrace deposits, clinker (scoria) areas, and eolian, lacustrine, and glacial deposits. The water quality of the Quaternary aquifers is generally very good.

Alluvial deposits

Well yield	<25–1,000 gallons per minute (gpm)
Porosity	28–45%
Permeability	0.1–1,000 gallons per day per square foot (gpd/ft^2)
Well specific capacity	0.3–18 gpm per foot of drawdown (gpm/ft)
Transmissivity	15–64,000 gpd/ft
TDS	100–9,300 milligrams per liter (mg/l); generally from 300–500 mg/l
Geochemical water type	highly variable; calcium-sodium/sulfate and calcium-sodium/bicarbonate

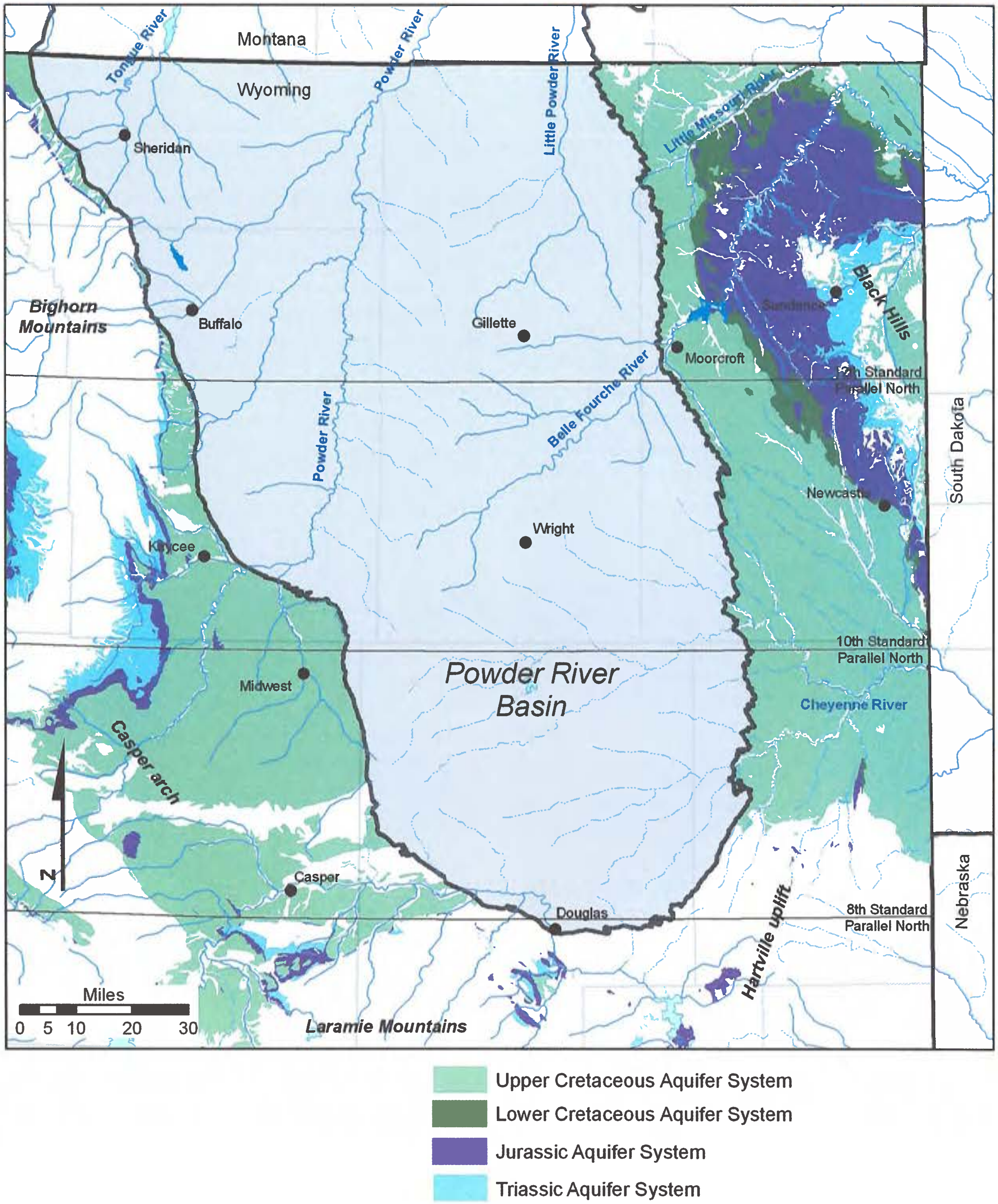


Figure 3-6. Mesozoic aquifer system, Powder River Basin, Wyoming.

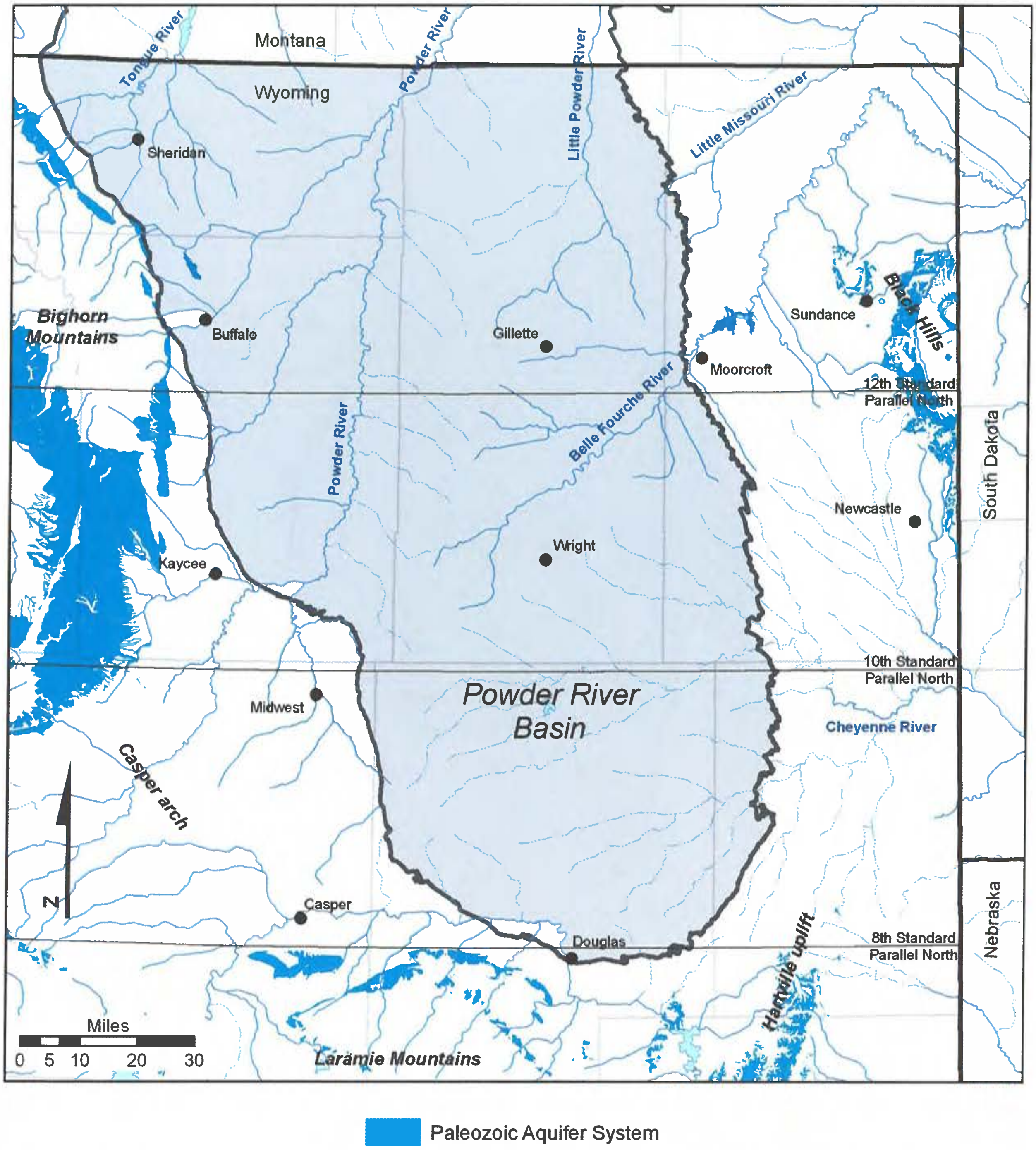
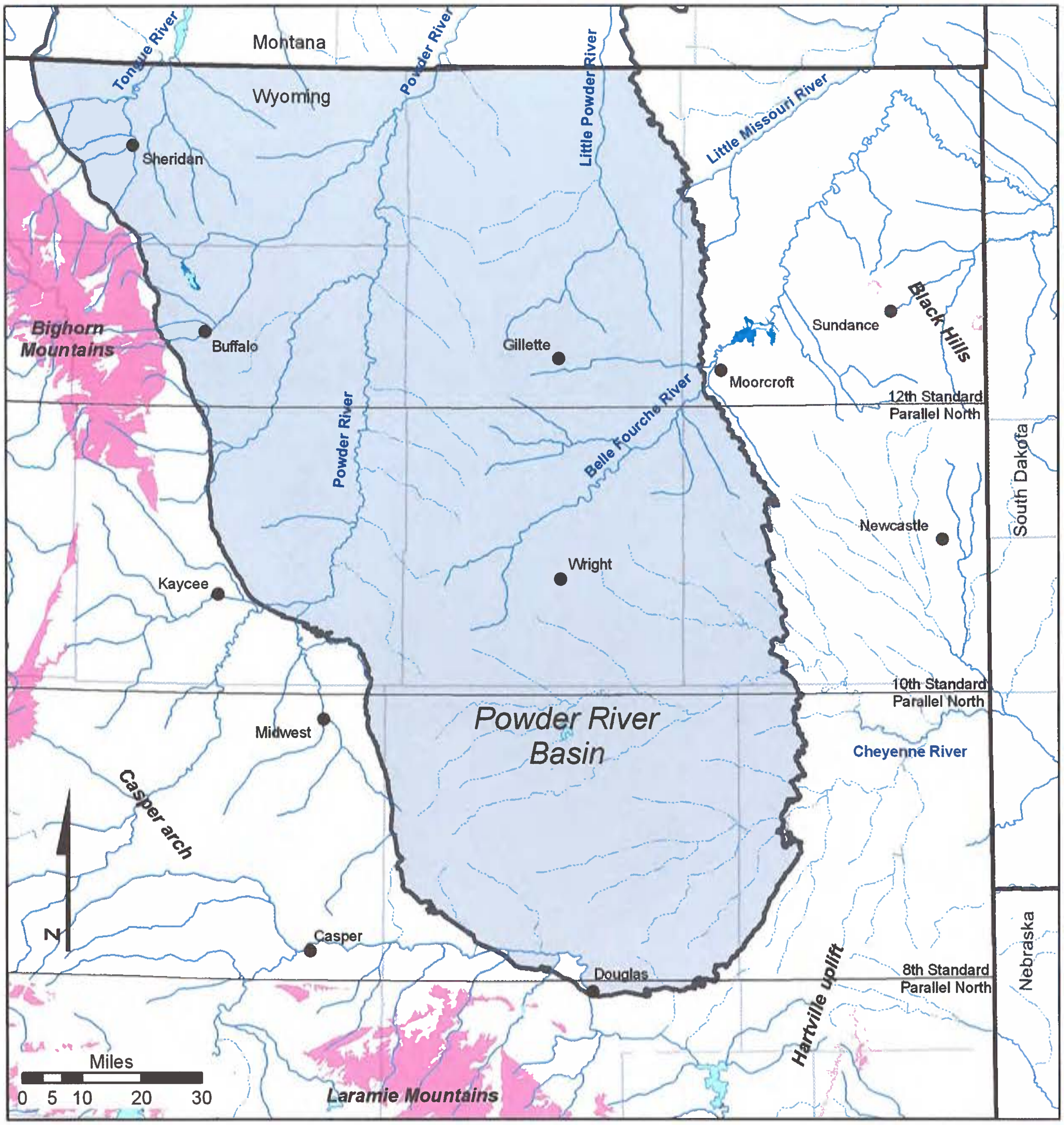


Figure 3-7. Paleozoic aquifer system, Powder River Basin, Wyoming.



🟪 Precambrian Aquifer System

Figure 3-8. Precambrian aquifer system, Powder River Basin, Wyoming.

The Holocene alluvial deposits consist of interbedded and unconsolidated mixtures of clay, silt, sand, and gravel. They are located along stream and river channels in the PRB. They are commonly less than 50 feet thick, although locally they may be more than 100 feet thick (Feathers, et al., 1981). The alluvial deposits unconformably overlie bedrock formations or older unconsolidated deposits.

Groundwater in the alluvial deposits is commonly connected hydrologically to local surface water stream flow, and is unconfined. Water quality in the alluvial deposits is similar to the surface water quality. Shallow groundwater flow generally flows as intergranular porous flow in this unconsolidated sediment, and flow direction generally follows topography.

Alluvial aquifers have specific yields ranging from 2 percent to 39 percent (Feathers). Specific yield is defined as the drainable porosity, and is reported as a proportion (percent) of the water volume that will drain under gravity from a total volume of earth material (alluvium). Specific yield is calculated only for unconfined aquifers, such as alluvial deposits.

In general, the large grain size of the alluvial deposits allows greater permeability and groundwater flow. The Wyoming Framework Water Plan (WWC) classifies the alluvial deposits as a major aquifer in areas where they are sufficiently permeable and water saturated.

Terrace deposits

The Holocene to Pleistocene terrace deposits consist of interbedded and unconsolidated mixtures of clay, silt, sand, and gravel, and are located above the present-day stream channel/flood plain levels in the PRB. The deposits are locally more than 100 feet thick (Feathers). Some of the older terrace deposits may be of Upper Tertiary (Pliocene) in age. Terrace deposits unconformably overlie bedrock formations or older unconsolidated deposits.

Because most terrace deposits are located at higher elevations than present-day stream levels, they are commonly drained of groundwater (Feathers, et al., 1981). Where sufficiently water-saturated, the terrace deposits generally exhibit aquifer properties similar to those of the alluvial deposits.

Eolian deposits

These Holocene to Pleistocene windblown deposits are located north of Casper in Natrona County and extend eastward into western Converse County. In this area along the southern margin of the PRB, the eolian deposits are generally less than 100 feet thick, but locally can be more than 100 feet thick. Small, unmapped eolian deposits located in other parts of the PRB range from 1 to 10 feet thick.

The sand dune deposits are oriented predominantly west-southwest to east-northeast, which corresponds to the present-day prevailing wind direction. Locally, the basal eolian deposits may contain shallow groundwater as perched and unconfined groundwater, especially where the permeable eolian deposits overlie weathered low-permeability bedrock strata (shale, mudstone, and claystone) of Tertiary to Cretaceous age. An actively-migrating sand dune may incorporate quantities of snow drifts on the lee-side of the dune during the winter season. During warmer summer months, this subsurface snow interbedded with sand gradually melts and provides groundwater to the eolian deposits.

Clinker (scoria) areas

Well yield	<25 to >2,000 gpm
Porosity	5% to >35%
Permeability	<3 million gpd/ft^2
Well specific capacity	<2,000 gpm/ft
Transmissivity	200 to >8,500 gpd/ft
TDS	<300 mg/l
Geochemical water type	calcium-sodium/sulfate

Clinker (scoria) is located along the outcrop areas of some coal beds of the Fort Union and Wasatch formations. The clinker zones correlate laterally with coal beds deeper in the basin. The coal beds and clinker (scoria) areas typically exhibit better aquifer properties than the sandstone and coal beds of the Tertiary formations. Lake De Smet initially formed where the thick Lake De Smet coal bed burned out and overlying strata fell into the void, forming a clinker depression that subsequently filled naturally with water.

Glacial deposits

Glacial deposits and glacial outwash are present locally along the mountain flanks in a very few areas. In outcrop areas where the glacial deposits are sufficiently permeable and water-saturated, the deposits yield small quantities of water to wells and springs. Where the glacial deposits are well-drained or less permeable due to a matrix with high clay content, very little to no groundwater is available to wells and springs.

Tertiary

The Tertiary aquifer system (**Figure 3-5**) underlies the Quaternary aquifer system and consists of the Upper Tertiary and Lower Tertiary aquifer systems. The water quality of the Tertiary aquifers is highly variable in the PRB, ranging from very good to poor.

The Upper Tertiary aquifer system is limited to a few remnant outcrops of the Oligocene White River Formation within the PRB, a few White River outcrops in the Black Hills area of Wyoming, and larger exposures of White River and other Oligocene and Miocene (Arikaree) rocks along the southern and southeastern margins of the PRB.

The Lower Tertiary aquifer system comprises the Wasatch and Fort Union formations. The primary water-yielding beds in the Wasatch and Fort Union aquifers are the sandstone and coal beds. The outcrop area of the Lower Tertiary aquifer system is the largest in the PRB (**Figure 3-5**). Most water wells constructed in the PRB yield water from the Wasatch and Fort Union formations.

The regional groundwater flow in the Lower Tertiary aquifer system is northward in most of the basin, and eastward in the southern PRB in the Cheyenne and Niobrara river drainages (Lobmeyer, 1985). The potentiometric surface elevations of the Tertiary aquifer system range from more than 5,200 feet above mean sea level in the southwestern PRB to 3,600 feet above mean sea level along the Wyoming/Montana border (Lobmeyer, 1985). The potentiometric pressures in the Lower Tertiary aquifer system are several hundred feet higher in elevation than the potentiometric pressures in the Upper Cretaceous aquifer system in the Wyoming PRB.

Arikaree Formation

[Lower Miocene and Oligocene rocks of Love, Christiansen, and Ver Ploeg (1993); Arikaree Formation in the Niobrara River Basin and Denver Basin]

Well yield	<1,000 gpm
Porosity	5–24%
Permeability	<1–300 gpd/ft^2
Well specific capacity	<232 gpm/ft
Transmissivity	<77,000 gpd/ft
TDS	261–532 mg/l
Geochemical water type	calcium to sodium bicarbonate

The upper Oligocene to lower Miocene Arikaree Formation consists of light-colored, soft, unconsolidated to consolidated, fine-grained, tuffaceous sandstone; pebble conglomeratic, medium- to coarse-grained sandstone in lenses; concretionary zones; and interbedded white tuffaceous claystone and siltstone lenses. As shown in **Figure 3-5**, the Arikaree Formation is present only along the southeastern margin of PRB and the northern flanks of the Hartville Uplift and Laramie Mountains. The Arikaree Formation is as much as 500 feet thick. The top and base of the Arikaree are stratigraphic unconformities.

Where the formation is sufficiently saturated, the Arikaree Formation is the most heavily used local aquifer for water wells in southern Converse and southern Niobrara counties. The Wyoming Framework Water Plan (WWC) classifies the Arikaree Formation as a major aquifer. The permeable sandstone and conglomeratic sandstone beds of the Arikaree Formation are included within the High Plains aquifer system of southeastern Wyoming.

White River Formation/Group

Well yield	<25 gpm; up to 300–500 gpm locally
Porosity	5%–24%
Permeability	0.0002–0.03 gpd/ft^2
Well specific capacity	<0.5 gpm/ft
Transmissivity	<50,000 gpd/ft
TDS	<1,000 mg/l
Geochemical water type	sodium/bicarbonate

The Oligocene White River Formation/Group consists of white to pale pink, unconsolidated to consolidated siltstone in the upper part of the unit, which overlies the lower part of claystone that locally contains channel lenses of fine- to coarse-grained sandstone and pebble conglomeratic sandstone. The White River Formation/Group ranges from 0 to 1,500 feet thick and, as shown in **Figure 3-5**, is present only along the southeastern margin of PRB, the flanks of the Hartville uplift and Laramie Mountains, and a few small remnants (Pumpkin Buttes in southwestern Campbell County) within the PRB (Feathers). There are also sparse outcrops on the flanks of the Bear Lodge Mountains. The top and base of the White River Formation/Group are unconformities.

The White River Formation/Group has highly variable yields. Fracturing of the unit increases the permeability of this relatively fine-grained, low-permeability formation. Where the formation is sufficiently permeable, thick, and water-saturated, the White River Formation/Group may yield a few hundred gpm to wells, especially along the northern flank of the Laramie Mountains in southern Converse County.

The water quality of the White River aquifer is generally very good. However, the reported TDS level for an area located about 12 miles west of Douglas (secs. 27 and 34, T. 33 N., R. 73 W., Converse County) was 4,500 mg/l with sodium/sulfate type water (Feathers).

The Wyoming Framework Water Plan (WWC) classifies the White River Formation as a marginal aquifer, and locally, where the formation has high yields to wells, as a major aquifer. The permeable sandstone and conglomeratic sandstone beds of the White River Formation are included within the High Plains aquifer system of southeastern Wyoming.

Wasatch Formation

Well yield	<25–500 gpm; sandstone bed 10–50 gpm; flowing wells locally
Porosity	<10% to 28–30%; 30–35% for the sand and coal beds, respectively (Hinaman, 2005); 26% sand and 10% coal
Permeability	0.01–65 gpd/ft^2
Well specific capacity	0.1–2 gpm/ft
Transmissivity	1–4,000 gpd/ft; average 500 gpd/ft
TDS	52–8,200 mg/l; average 1,000–1,300 mg/l
Geochemical water type	calcium-magnesium/sulfate to sodium/sulfate. and calcium-magnesium/bicarbonate to sodium/bicarbonate in shallow basin areas; sodium/bicarbonate to sodium/chloride in deep basin areas; selenium may exceed drinking water standard (0.01 mg/l)

The Eocene Wasatch Formation consists of drab, fine- to coarse-grained, lenticular sandstone interbedded with variegated claystone and shale, and numerous coal beds in the lower part. The formation contains coarser-grained sandstone in the southern and southwestern PRB, and conglomeratic sandstone in northwestern PRB. The Wasatch Formation is as much as 1,600 feet thick in the central PRB. As shown on **Plate 1**, the Wasatch has the greatest exposure of any geologic formation in the PRB. Water from the Wasatch Formation in its outcrop area (**Figure 3-5**) is used heavily for both domestic purposes and livestock watering. The top and base of the Wasatch Formation are generally unconformable, except in the central PRB, where the Wasatch conformably overlies the Fort Union Formation.

The Wasatch Formation is divided into two members along the northwestern basin margin between Buffalo and Sheridan. Both members are alluvial fans deposited off the eastern flank of the emergent Bighorn Mountains; both are conglomerates composed of clasts interbedded with drab sandstone and variegated claystone (L&C). The overlying Moncrief Conglomerate Member contains Precambrian clasts from the core of the Bighorns. The underlying Kingsbury Conglomerate Member, locally the base of the Wasatch Formation, contains Paleozoic clasts. Both members interfinger eastward with the undivided Wasatch Formation, which covers much of the Wyoming PRB.

The coal and sandstone beds in the Wasatch Formation are the main water-bearing zones in the formation. The rest of the formation consists of low-permeability, interbedded intervals of mixed shale, mudstone, clayey siltstone, and claystone. Some Wasatch wells have flowed water to the ground surface under locally confined (artesian) pressure. The Wyoming Framework Water Plan (WWC) classifies the Wasatch Formation as a major sandstone aquifer.

The Wasatch coal beds produce water predominantly of sodium/sulfate type in shallow basin areas and of sodium-bicarbonate type in deep basin areas.

Fort Union Formation

Well yield	<300 gpm (flowing wells from 1–60 gpm locally); coal beds generally yield 10–50 gpm; wells in the Tullock Member may yield uo to 200–300 gpm
Porosity	30–35%; 26% sand and 10% non-sand
Permeability	0.01 to >100 gpd/ft^2
Well specific capacity	0.1–2 gpm/ft
Transmissivity	1 to >5,000 gpd/ft
TDS	<300 to 2,300 mg/l; average 1,000–1,350 mg/l
Geochemical water type	calcium-sodium/sulfate; calcium-sodium/bicarbonate; and sodium/bicarbonate in coal beds

The Paleocene Fort Union Formation consists of a thick, nonmarine sedimentary sequence of fine- to medium-grained lenticular sandstone interbedded with siltstone, coal, and shale beds. The Fort Union Formation in the PRB consists of three members: the upper Tongue River Member, middle Lebo Shale Member, and lower Tullock Member. The Lebo Shale Member has greater shale content in the northern PRB, and the Tongue River Member has greater silt content in the southern basin (Feathers).

The Tongue River Member consists of thick interbeds of yellow sandstone; gray to brown mudstone, claystone, and shale; and thick coal beds. The Lebo Member consists mainly of predominantly dark gray claystone and shale with minor interbedded, concretionary sandstone. The Tullock Member consists of gray, soft sandstone, gray to brown carbonaceous shale, and thin coal beds. The Fort Union Formation ranges in total thickness from 1,100 to more than 2,500 feet in the PRB (Feathers). Clinker (scoria) zones of the Tongue River Member along the basin margins correlate with coal beds deeper in the basin (Feathers).

The coal seams and sandstone beds in the Fort Union Formation are the aquifers within the formation. The Fort Union sandstone beds are generally lenticular and discontinuous. The thick main coal beds are regionally extensive aquifers. The low-permeability confining beds consist of claystone, mudstone, and shale. The Fort Union aquifer has heterogeneous stratification; anisotropic groundwater flow; and leaky, low-permeability confining strata interbedded between the permeable sandstone and coal beds (Feathers; Hinaman, 2005). In some local areas, Fort Union coal beds directly overlie or underlie adjacent sandstone beds, allowing some degree of groundwater communication between coal and sandstone beds within the formation. Hinaman (2005) estimated the porosity of the Fort Union (all three members) with the sand beds as 30 percent and the coal beds as 35 percent. The Wyoming Framework Water Plan (WWC) classifies the Fort Union Formation as a minor aquifer.

The coal beds and clinker areas typically exhibit better aquifer properties than the sandstone beds of the Fort Union Formation. Typical aquifer properties of Fort Union clinker areas and associated coal beds include transmissivity of up to 3,000,000 gpd/ft, and well specific capacity of more than 2,000 gpm per foot of drawdown (Feathers).

In the PRB, intensive CBNG development in the Tongue River Member of the Fort Union Formation since 1997 and the associated pumping of more than 4.8 billion gallons of groundwater from this member between 1987 and 2007 has caused drawdown in the coal beds. In 2007, the measured drawdowns with respect to initial groundwater level in monitoring wells in Tongue River coal beds ranged from 200 to 300 feet in some areas, to more than 750 feet in other areas.

The drawdown measured in the coal beds of the Tongue River Member includes the cumulative effects of more than eight years of regional drought conditions from 1999 through 2007, ten years of large-scale CBNG development from 1997 through 2007, surface coal mine dewatering by pumping groundwater from wells from 1980 through 2007, pumping of public water supply wells, and pumping of other water wells constructed into the Tongue River Member. Therefore, although this drawdown did not result from CBNG development alone, CBNG pumping appears to be the cause of most of the drawdown measured in the Tongue River Member.

Because all but a few CBNG wells in the PRB tap the Fort Union Formation, the contour maps (**Figure 3-9** and **Figure 3-10**) of TDS and sodium adsorption ratio (SAR) in CBNG waters from the PRB (Surdam et al., 2007, Figures 18 and 19) closely represent the TDS and SAR distributions in Fort Union coal bed waters. These distributions show the following regional trends in Fort Union coal bed water chemistry:

- An increase in TDS content from approximately 300–500 mg/l in the eastern basin to 1,000–2,200 mg/l in the western basin, and an increase in TDS content from approximately 300–500 mg/l in the southeastern basin to 1,000–2,200 mg/l in the northwestern basin.

- This observed trans-basin increase in the TDS content of groundwater within the coal bed aquifers is attributed to increasing concentrations of sodium and bicarbonate due to the geochemical processes of cation exchange and bacterially-mediated sulfate reduction in the Fort Union coal beds (Bartos and Rice, 2001).

- An increase in the sodium adsorption ratio (SAR) from 4–8 in the southeastern and eastern PRB to 40–56 in the northwestern and northern PRB.

These distributions in each of 20 main coal beds in the Fort Union Formation are shown in Chapter 4, Figures 4-103 through 4-122 (TDS) and Figures 4-83 through 4-102 (SAR).

The Fort Union coal beds produce water that is predominantly sodium/sulfate type in shallow basin areas and sodium/bicarbonate type in deep basin areas. Some groundwater samples collected from Fort Union coal beds are sodium-calcium-magnesium/bicarbonate type.

The Lebo Shale Member of the Fort Union Formation is a low-permeability confining unit, except for the lower Lebo sandstone beds, which are included in the underlying Tullock Member aquifer. The Lebo Member is a leaky confining unit with relatively low overall permeability (Feathers). The lower sandstone beds of the Lebo Member constitute a minor aquifer in areas where they are sufficiently thick and water saturated.

The sandstone beds of the Tullock Member of the Fort Union Formation constitute a minor to marginal aquifer in areas where the beds are sufficiently thick, abundant, and water saturated. The Tullock Member directly overlies the Upper Cretaceous Lance Formation; the Cretaceous-Tertiary (K-T) boundary is therefore the base of the Fort Union Formation, which is the base of the Tullock Member. During 2007, new public water-supply wells were constructed into the Tullock aquifer south of Gillette to supplement the existing municipal water supply for the city.

Davis (1976) described the regional groundwater flow in the Fort Union Formation from the outcrop area in the eastern part of the PRB as generally flowing down structural dip into the basin axis, which is located along the western part of the PRB, and discharging to streams in the northwestern part of the Wyoming PRB to maintain the base flow of the Tongue River.

Based on local geohydrologic data in the Wyoming PRB, Davis and Rechard (1976) and Brown (1980) estimated the infiltration of water recharge into the

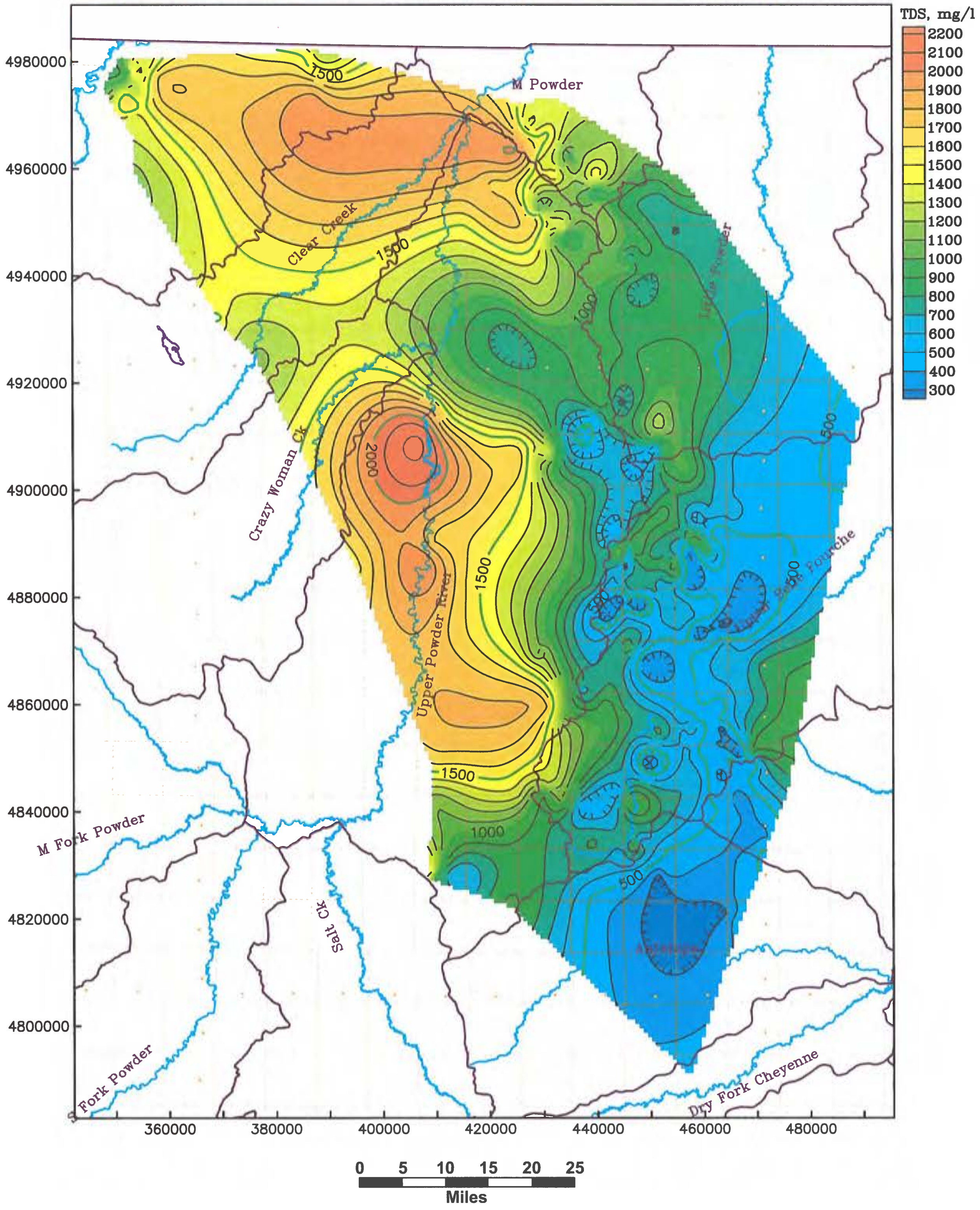
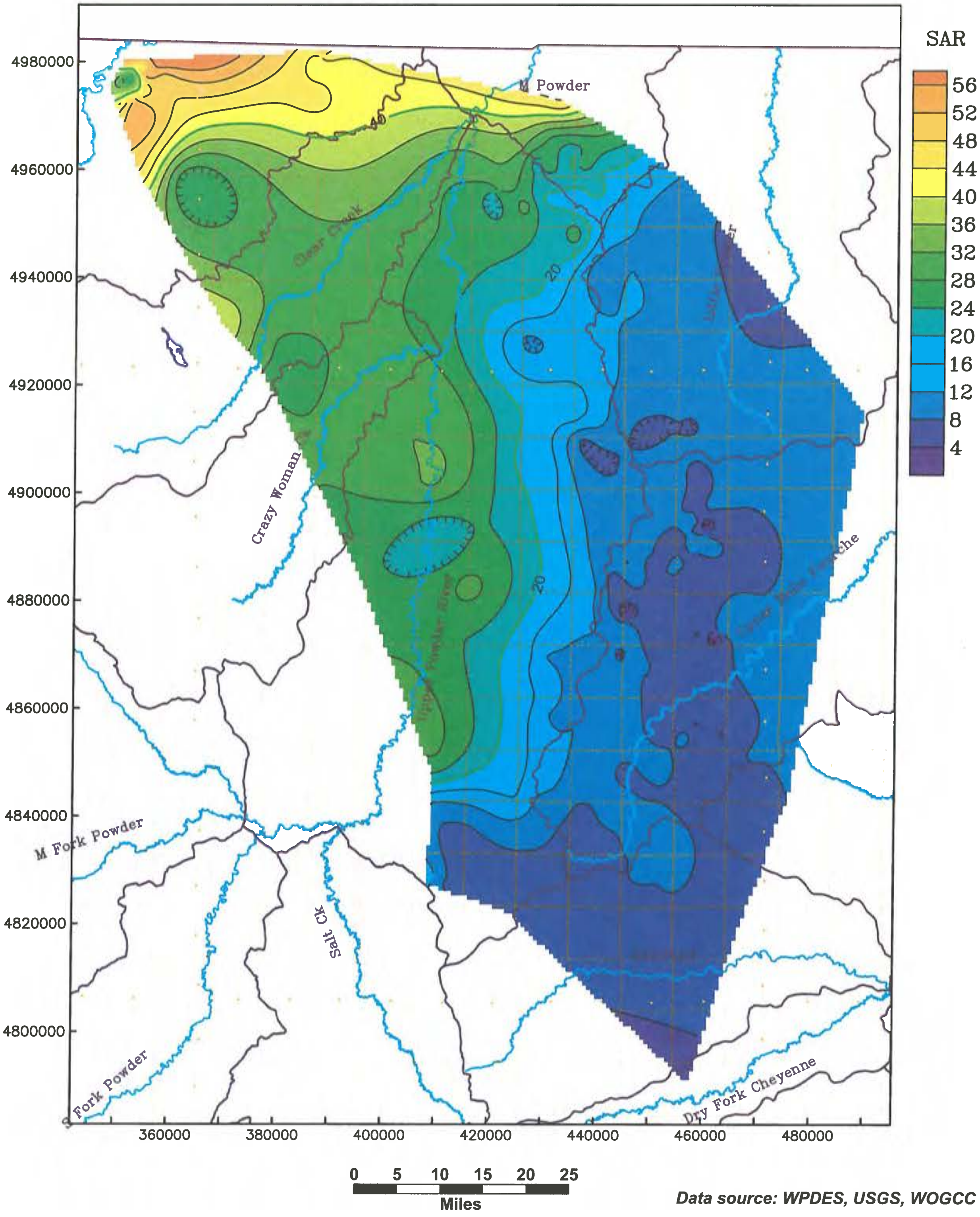


Figure 3-9. Contour map of TDS for CBNG produced water from the Fort Union Formation, Powder River Basin, Wyoming. [Salinity contour map of CBNG water from th Powder River Basin shows that TDS of CBNG produced water increases significantly in the west and northwest parts of the PRB, namely in the Upper Powder River, Crazy Woman Creek, Clear Creek, and Upper Tongue River drainages.] Reproduced from Surdam et al., 2007.



Data source: WPDES, USGS, WOGCC

Figure 3-10. Contour map of sodium adsorption ratio (SAR) for CBNG produced water from the Fort Union Formation, Powder River Basin, Wyoming. [Sodium adsorption ratio (SAR) contour map of CBNG produced water from the PRB. The SAR of the CBNG produced water increases from southeast to northwest across the basin.] Reproduced from Surdam et al., 2007.

Wasatch/Fort Union aquifers of the PRB to be approximately 0.15 inches of precipitation per year.

Mesozoic Aquifer System

The Mesozoic aquifer system (**Figure 3-6**) is divided into four units: the Upper Cretaceous, Lower Cretaceous, Jurassic, and Triassic aquifer systems. The Upper Cretaceous aquifer system in the PRB consists mostly of the water-saturated, permeable sandstone beds in the lower Lance Formation and the underlying Fox Hills Sandstone. Sandstone beds in some Upper Cretaceous formations underlying the Fox Hills Sandstone may locally yield small to moderate quantities of water to wells. The permeable sandstone beds of the Upper Cretaceous formations are part of the regional Great Plains aquifer system, which also includes permeable Lower Cretaceous rock units: the Muddy Sandstone (west)/Newcastle Sandstone (east) and the Cloverly Formation (west)/Inyan Kara Group – Fall River and Lakota formations (east).

The Upper Cretaceous aquifer system – the Lance and Fox Hills – is underlain in the Upper Cretaceous sequence by the regional, thick sequence of low-permeability confining beds that includes the Lewis, Pierre, Cody, and Mowry shales. This shale sequence acts as a regional seal for groundwater flow within the PRB, separating the groundwater above the sequence from the groundwater below it throughout the basin.

Regional groundwater flow in the Upper Cretaceous aquifer system is northward in most of the basin, and eastward in the southern PRB in the Cheyenne and Niobrara river drainages (Lobmeyer, 1985). The potentiometric surface elevation for the Upper Cretaceous aquifer system is more than 4,800 feet above mean sea level in the southwestern PRB to 3,200 feet above mean sea level along the Wyoming/Montana border (Lobmeyer, 1985). The potentiometric pressure in the Upper Cretaceous aquifer system is several hundred feet higher in elevation than the potentiometric pressure in the Lower Tertiary aquifer system.

Upper Cretaceous

Lance Formation	
Well yield	<350 gpm
Porosity	5–20%
Permeability	6–35 gpd/ft^2
Well specific capacity	0.5–2 gpm/ft
Transmissivity	170–2,100 gpd/ft
TDS	350–3,500 mg/l
Geochemical water type	variable geochemistry in outcrop areas and generally sodium/bicarbonate-sulfate in deep basin; fluoride above drinking water standard (2.0 mg/l)

The Upper Cretaceous Lance Formation consists of brown and gray, nonmarine, lenticular, fine- to medium-grained sandstone, which is interbedded with sandy siltstone and claystone, and thin coal beds locally. The lower Lance generally contains a higher percentage of sandstone beds than the upper Lance. The Lance Formation ranges in thickness from 500–1,000 feet in the northern PRB and to 1,600–3,000 feet in the southern PRB (Feathers). The Lance Formation is the stratigraphic equivalent of the Upper Cretaceous Hell Creek Formation in Montana.

The sandstone beds of the Lance Formation are the primary water-bearing zones in the formation, and groundwater flow is generally intergranular porous flow. The rest of the formation consists of low-permeability interbeds. The upper Lance has relatively low permeability and acts as a confining bed due to a predominance of clay- and silt-size sediment (Hinaman, 2005).

Many of the permeable sandstone beds in the lower Lance Formation and Fox Hills Sandstone are combined as a single aquifer (Hinaman, 2005). The combined Lance Formation/Fox Hills Sandstone thickness ranges from 700 feet in the northern PRB in Montana to 3,300 feet in the southern PRB (Connor, 1992). Groundwater in the Lance aquifer occurs under confined conditions (artesian pressure), with static water levels ranging from 500–1,000 feet below ground surface.

Some Lance Formation wells reportedly yield as much as 350 gpm with long intervals of well screens/perforations in the constructed water well and several hundred feet of water level drawdown during pumping (Feathers).

Locally, Lance Formation wells flow water to the ground surface under confined pressure. The lower Lance in the PRB is often the target of deep water wells where it is combined as an aquifer with the underlying Fox Hills Sandstone. The Wyoming Framework Water Plan (WWC) classifies the Lance Formation as a minor aquifer.

The combined lower Lance-Fox Hills aquifer supplies industry in the eastern and northeastern PRB and municipalities in the northeastern and southwestern PRB. The water quality of the Lance-Fox Hills aquifer ranges from good to poor in outcrop areas, with TDS levels of 350–3,500 mg/l of variable major ion chemistry, and of 1,000–3,500 mg/l in the central PRB of predominantly sodium/bicarbonate-sulfate type. High levels of fluoride (more than 2.4 mg/l, which exceeds the secondary federal drinking water standard of 2.0 mg/l) in Lance-Fox Hills groundwater were reported in the subsurface area of Campbell County (Feathers). The high fluoride content of Lance-Fox Hills groundwater requires blending of waters or treatment to meet public drinking water standards.

Fox Hills Sandstone

Well yield	85–1,700 gpm
Porosity	10–25%
Permeability	<34 gpd/ft^2
Well specific capacity	0.03–4.9 gpm/ft
Transmissivity	76–1,600 gpd/ft
TDS	<500–3,060 mg/l
Geochemical water type	variable geochemistry; generally sodium/bicarbonate-sulfate in deep basin; fluoride above drinking water standard (2.0mg/l) and also may show elevated levels of iron, manganese, sulfate, and SAR

The Upper Cretaceous Fox Hills Sandstone consists of light-colored, fine- and medium-grained sandstone with interbeds of thin, gray, sandy shale containing marine fossils. The Fox Hills Sandstone is 150–200 feet thick in the northern PRB, and thickens to 400–700 feet thick in the southern PRB (Feathers). The thickness of the Fox Hills Sandstone ranges from 125 to 200 feet in Crook and Weston counties and from 400 to 500 feet in Niobrara County, and is approximately 700 feet in the southwestern PRB (Hodson). The Fox Hills is the final (youngest) marine sedimentary deposit in the PRB.

Groundwater in the Fox Hills aquifer typically occurs under confined conditions (artesian pressure), with static water levels ranging from 500 to 1,000 feet below ground surface in deeper parts of the PRB. The sandstone beds in the Fox Hills Sandstone are the main water-yielding zones in the formation. The rest of the formation consists of low-permeability interbeds of thin sandy shale.

Wells constructed into the Fox Hills may yield as much as 350 gpm with several hundred feet of drawdown during pumping and long intervals of well screens/perforations in the completed water well (Feathers). Several Fox Hills wells located south of Rozet in Campbell County yield 200 gpm, and Fox Hills wells in the western PRB yield a maximum of about 100 gpm (Hodson, et al., 1973). Public water supply wells for Gillette constructed in the Fox Hills Sandstone have been pumped at discharge rates of 85–705 gpm (Wester-Wetstein and Associates, Inc., 1994).

In some areas of the PRB, wells constructed into the Fox Hills Sandstone flow water to the ground surface under confined pressure. One 2,000-foot-deep well located in SE¼SE¼ sec. 15, T. 56 N., R. 71 W., Campbell County, was reported to flow 75 gpm under a confined pressure of 54 pounds per square inch at shut-in pressure (Hodson). Shut-in pressure is the condition when a well is capped and any valves/openings are closed off, and the water (or gas) pressure is allowed to build to a maximum over time.

In the western PRB, groundwater in the Fox Hills Sandstone has TDS levels ranging from less than 500 mg/l to 3,060 mg/l, and water geochemistry varies from sodium/sulfate to calcium/sulfate types (HKM Engineering, 2002b). In the eastern PRB, TDS levels generally range from less than 1,000 mg/l to 2,000 mg/l without a dominant geochemistry type (Hodson).

High iron (up to 6.03 mg/l), sulfate (less than 100 to 1,780 mg/l), manganese, and fluoride levels, and an SAR from 1.9 to 39 (HKM Engineering, 2002b) generally render Fox Hills groundwater unsuitable for domestic use. Only where TDS and SAR are low is Fox Hills water suitable for irrigation. Groundwater from the Fox Hills is fair to poor for livestock watering (HKM Engineering, 2002b).

The Wyoming Framework Water Plan (WWC) classifies the Fox Hills Sandstone as a major sandstone aquifer.

Lewis Shale (Bearpaw Shale)

Well yield	<25 gpm
Porosity	<15–20%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the western PRB, the Upper Cretaceous Lewis Shale consists of gray marine shale with sandy shale and thin lenses of gray and brown, fine-grained, lenticular, concretion-rich sandstone beds (Feathers; L&C, 1985). The Lewis Shale is conformable with overlying and underlying marine formations in the PRB. In the western PRB, the Lewis is stratigraphically equivalent to the upper section of the Pierre Shale in the eastern PRB. The Lewis Shale also correlates northward with the Upper Cretaceous Bearpaw Shale in Montana. The Lewis is approximately 200 feet thick along the northwestern margin of the PRB and approximately 470 feet thick in the southwestern PRB (Feathers).

The Lewis Shale is a low-permeability confining bed and a regional, basin-wide confining bed system with the Pierre Shale in the PRB (Hodson; Feathers). Low-yielding shallow water wells have been constructed within and close to the outcrop areas of the Lewis Shale (Feathers). Well yields from sandstone beds in outcrop areas of the Lewis Shale are less than 10 gpm (Hodson). In outcrop areas, Lewis groundwater may be suitable for livestock watering and domestic use. The Wyoming Framework Water Plan (WWC) classifies the Lewis Shale as a major, low-permeability, regional confining unit (major aquitard).

Mesaverde Formation (Group)

Well yield	<25 gpm; <120 gmp locally in Natrona County
Porosity	15–21%
Permeability	<5 gpd/ft^2
Well specific capacity	0.1–0.2 gpm/ft
Transmissivity	<120 gpd/ft
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the western PRB, the Upper Cretaceous Mesaverde Formation consists of light-colored, massive to thin-bedded, fine- to medium-grained sandstone with interbedded gray marine shale (Feathers; L&C). North of the North Fork of the Powder River east of the Bighorn Mountains, the Mesaverde Formation consists only of the Parkman Sandstone Member (L&C).

The Mesaverde Formation is conformable with overlying and underlying marine formations in the PRB. The Mesaverde Formation in the western PRB is stratigraphically equivalent to the middle Pierre Shale in the eastern PRB. The Lewis Shale conformably overlies the 50-foot-thick Teapot Sandstone Member, the uppermost member of the Mesaverde Formation. The Mesaverde has a total thickness of 355 feet along the northwestern margin of the PRB and is approximately 900 feet thick in the southwestern PRB (Feathers). The 500-foot-thick Parkman Sandstone Member is the lowest member of the Mesaverde Formation in the central PRB (Feathers).

The Mesaverde Formation is considered a minor aquifer along the entire western margin of the PRB

(Feathers). The Wyoming Framework Water Plan (WWC) also classifies the Mesaverde Formation as a minor aquifer. In some areas, Mesaverde wells may flow at up to 4 gpm to the ground surface under confined pressure (Feathers).

Cody Shale

Well yield	<25 gpm; <120 gmp locally
Porosity	12–25%
Permeability	<8 gpd/ft^2
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<85 gpd/ft
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the western PRB, the Upper Cretaceous Cody Shale consists of dull, dark gray marine shale, limey shale near the base of the formation; gray siltstone; some bentonite beds; and interbedded lenticular, fine-grained, commonly shaly sandstone beds (Feathers; L&C). The Cody Shale is conformable with overlying and underlying marine formations in the PRB.

The Cody Shale correlates with the Steele Shale and underlying Niobrara Formation to the south. The upper part of the Cody Shale in the western PRB is equivalent to the lower part of the Pierre Shale in the eastern PRB. The lower part of the Cody Shale in the western basin is equivalent to the Niobrara Formation and the upper part of the underlying Carlile Shale in the eastern basin. See the stratigraphic chart in Chapter 1 (**Figure 1-3**) to visualize these relationships.

The 200-foot-thick Sussex Sandstone Member and the 200-foot- to 500-foot-thick Shannon Sandstone Member below it lie in the upper and middle Cody Shale in the central PRB. The Cody Shale is approximately 3,700 feet thick along the northwestern margin of the PRB, and ranges from 3,000 to 5,000 feet thick in the southwestern PRB (Feathers).

The Cody Shale is a confining bed along the entire western margin of the PRB, but sufficiently saturated sandstone beds in or near outcrops may yield water to wells (Feathers). Cody Shale wells may flow as much as 4 gpm to the ground surface under confined pressure (Feathers). In some areas, confined pressure Cody Shale wells flow low yields of water to the ground surface and wells may be pumped at flow rates less than 25 gpm. The Wyoming Framework Water Plan (WWC) classifies the Cody Shale as a major, low-permeability, regional confining unit (major aquitard).

Pierre Shale

Well yield	<12 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the eastern PRB, the Upper Cretaceous Pierre Shale consists of dark gray concretionary marine shale containing several bentonite beds, thin siltstone beds, lenticular carbonate beds, and sandstone beds; the Pierre contains the Great Sandstone bed (0–125 feet thick) in the northeastern PRB (Feathers; L&C). The Pierre Shale is conformable with overlying and underlying marine formations in the PRB.

The Lewis Shale, the Mesaverde Formation, and the upper part of the Cody Shale in the western PRB are stratigraphically equivalent to the Pierre Shale in the eastern PRB. Part of the Pierre Shale correlates with the Bearpaw Shale in Montana. The Pierre Shale is approximately 2,000 feet thick along the northeastern margin of the PRB and varies from 2,500–3,100 feet thick in the southeastern PRB (Feathers).

The Pierre Shale is a low-permeability confining bed (aquitard), but low-yielding wells have been constructed in the outcrop areas of the formation (Feathers). The Wyoming Framework Water Plan (WWC) classifies the Pierre Shale as a major, low-permeability, regional confining unit (major aquitard).

Steele Shale

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the extreme southwestern PRB, the Steele Shale is equivalent to the upper part of the Cody Shale. However, the Steele is poorly defined, limited in outcrop exposure, and mapped in areas southwest of the basin. The Niobrara Formation, which is equivalent to the lower part of the Cody Shale, conformably underlies the Steele Shale. The Wyoming Framework Water Plan (WWC) classifies the Steele Shale as a major low-permeability, regional confining unit (major aquitard).

Niobrara Formation

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Upper Cretaceous Niobrara Formation consists of gray to yellow marine shale, calcareous shale, and light-colored marl with numerous thin bentonite clay beds (Feathers; L&C). The Niobrara Formation is as much as 985 feet thick in Johnson County. It is equivalent to approximately the lower 1,000 or more feet of the undivided Cody Shale. The Niobrara Formation is conformable with overlying and underlying marine formations in the western PRB; in the eastern PRB, the Niobrara is conformable with the overlying Pierre Shale and unconformable with the underlying Carlile Shale. The Niobrara Formation conformably underlies the Pierre Shale in the eastern PRB. The Niobrara is 150–225 feet thick along the northeastern margin of the PRB and of 100–250 feet thick in the southeastern PRB (Feathers).

The Niobrara Formation is a low-permeability confining bed (Feathers). However, some low-yielding water wells have been constructed within the outcrop areas of the formation (Feathers). Niobrara Formation well yields are typically less than 25 gpm and water from the formation may prove suitable for livestock watering or domestic use. The Wyoming Framework Water Plan (WWC Engineering) classifies the Niobrara Formation as a major, low-permeability, regional confining unit (major aquitard).

Frontier Formation

Well yield	<50 gpm
Porosity	12–26%
Permeability	0.09–9 gpd/ft^2
Well specific capacity	<0.02 gpm/ft
Transmissivity	<150 gpd/ft
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Upper Cretaceous Frontier Formation consists of dark gray to black marine shale and gray, sandy shale with interbedded thin to massive bedded, fine- to medium-grained sandstone beds (Wall Creek sandstone beds). The base of the Frontier Formation conformably overlies the Mowry Shale and is conformably overlain by the Cody Shale in the western PRB. The Frontier Formation in the western PRB is the stratigraphic equivalent of the lower part of the lower Carlile Shale, Greenhorn Formation, and Belle Fourche Shale in the eastern PRB. The Frontier Formation is approximately 515 feet thick along the northwestern margin of the Wyoming PRB and approximately 900 feet thick in the southwestern PRB (Feathers).

The Frontier Formation is a minor aquifer in the southwestern PRB. Wells completed into the Frontier in some areas of Natrona County have flowing yields to the ground surface of 1 to 10 gpm under artesian (confining) pressure (Feathers).

Carlile Shale

Well yield	<25 gpm
Porosity	<15%
Permeability	0.02 gpd/ft^2
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	0.2–0.4 gpd/ft
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the eastern PRB, the Upper Cretaceous Carlile Shale is composed of dark-gray, marine shale and locally of sandy shale, with the middle Turner sandy member present in the northeastern PRB and the Sage Breaks Member at the top of the formation. The Carlile Shale is conformable with the underlying Greenhorn Formations and unconformable with the overlying Niobrara Formation. The lowest part of the Cody Shale and the uppermost part of the Frontier Formation in the western PRB are stratigraphically equivalent to the Carlile Shale. The Carlile Shale has a thickness of 500-700 feet along the northeastern margin of the PRB and 460-540 feet in the southeastern basin (Feathers, et al., 1981).

The Carlile Shale is a low-permeability confining unit, but some low-yielding wells have been constructed into the outcrop areas of the formation. Carlile Shale wells in outcrop areas may be suitable for livestock watering and domestic use. The Wyoming Framework Water Plan (WWC Engineering, 2007) classifies the Carlile Shale as a major, low-permeability, regional confining unit (major aquitard).

Greenhorn Formation

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the eastern PRB, the Upper Cretaceous Greenhorn Formation consists of gray concretionary shale, limey shale, limey sandstone, and marl containing light-colored, thin limestone beds. Part of the middle Frontier Formation in the western PRB is the stratigraphic equivalent of the Greenhorn Formation in the eastern basin. The Greenhorn Formation is conformable with the overlying and underlying marine formations in the PRB. It is 70–370 feet thick in the northeastern PRB and 30–70 feet thick in the southeastern basin (Feathers). The Greenhorn Formation is a low-permeability confining bed (aquitard).

Belle Fourche Shale

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the eastern PRB, the Upper Cretaceous Belle Fourche Shale consists of dark gray to black, soft, siliceous shale containing iron and limestone concretions and bedded bentonite. The Belle Fourche Shale is conformable with the overlying and underlying marine formations. It is 450–850 feet along the northeastern margin of the PRB and 400–850 feet thick in the southeastern basin (Feathers).

The Belle Fourche Shale is a low-permeability confining bed, but low-yielding shallow wells have been constructed in outcrop areas. The groundwater quality from this marine shale is generally low due to high TDS levels. Belle Fourche Shale wells in outcrop areas may be suitable for livestock watering or domestic use.

Mowry Shale	
Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin (estimated)

In the PRB, the Upper Cretaceous (formerly considered Lower Cretaceous) Mowry Shale consists of silver gray-weathering, hard, siliceous shale with abundant fish scales and bentonitic beds, and non-siliceous black shale beds at the base of the formation. The regionally extensive Mowry Shale is conformable with the overlying and underlying marine formations. The Mowry is approximately 525 feet thick along the northwestern margin of the PRB, 200–300 feet thick in the southwestern PRB, 180–230 feet thick in the northeastern basin, and approximately 220 feet thick in the southeastern PRB (Feathers). It thickens to the west and north in the PRB.

The Mowry Shale is a low-permeability confining bed. The Wyoming Framework Water Plan (WWC) classifies the Mowry as a major, low-permeability, regional confining unit (major aquitard). However, some low-yielding shallow wells with predominantly fracture flow have been constructed in the outcrop areas of the Mowry. In some areas of Natrona County, Mowry Shale wells show flowing yields to the ground surface of 2 gpm under artesian (confining) pressure and pumping well yields of up to 10 gpm (Feathers). The groundwater quality from this marine shale is generally low due to high TDS levels. Mowry Shale wells in outcrop areas may be suitable for livestock watering or domestic use.

Lower Cretaceous

Muddy Sandstone	
Well yield	<50 gpm
Porosity	5–20%
Permeability	<7 gpd/ft^2
Well specific capacity	0.1–1 gpm/ft
Transmissivity	7–875 gpd/ft; generally <150 gpd/ft
TDS	<300 mg/l in outcrop areas to >20,000 mg/l in deep basin
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin

In the western PRB, the Lower Cretaceous Muddy Sandstone is a light gray, fine-grained, lenticular sandstone with interbedded siltstone. The Muddy Sandstone conformably overlies, and is considered by Love and Christiansen (1985) to be the uppermost member of, the Thermopolis Shale. The Muddy Sandstone in the western PRB is the stratigraphic equivalent of the Newcastle Sandstone in the eastern basin. It is up to 40 feet thick along the northwestern margin of the PRB and approximately 6 feet thick in the southwestern PRB (Feathers).

The Muddy Sandstone is a minor aquifer. TDS levels in the Dakota aquifer, which includes the Muddy Sandstone, range from less than 300 mg/l to more than 20,000 mg/l.

Newcastle Sandstone	
Well yield	<50 gpm
Porosity	2–27%
Permeability	<11 gpd/ft^2
Well specific capacity	0.1–1 gpm/ft
Transmissivity	7–875 gpd/ft; generally <170 gpd/ft
TDS	<300 mg/l in outcrop areas to >20,000 mg/l in deep basin
Geochemical water type	calcium-magnesium-sodium/ bicarbonate-sulfate; sodium/ chloride in deep basin

Along the eastern margin of the PRB, the Lower Cretaceous Newcastle Sandstone consists of gray, fine- to medium-grained sandstone. Locally, the Newcastle is a conglomeratic, lenticular sandstone with interbedded siltstone, sandy shale, claystone, bentonite, and coal (lignite) beds. It was deposited in mixed continental, shallow, organic-rich lagoon, beach sand, and near-shore marine environments (Collier, 1923). The Newcastle Sandstone conformably overlies the Skull Creek Shale. The Muddy Sandstone in the western PRB is the stratigraphic equivalent of the Newcastle Sandstone in the eastern basin. The Newcastle is 0–60 feet thick along the northeastern margin of the PRB and 0-100 feet thick in the southeastern PRB (Feathers).

The Newcastle Sandstone is a minor aquifer. Many wells completed into the Newcastle Sandstone are located in outcrop areas but tap the formation where it is deeply buried, requiring excessive pumping lift (Feathers). TDS levels for the Dakota aquifer, which includes the Newcastle Sandstone, range from less than 300 mg/l to more than 20,000 mg/l.

Thermopolis Shale

Well yield	<25 gpm (outcrop areas)
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Lower Cretaceous Thermopolis Shale is a black marine shale sequence, with minor siltstone partings in the northwestern PRB. The Muddy Sandstone conformably overlies the Thermopolis Shale. The Thermopolis Shale in the western PRB is the stratigraphic equivalent of the Skull Creek Shale in the eastern basin.

The Thermopolis Shale conformably overlies the Cloverly Formation in the western PRB. The Thermopolis is approximately 175 feet thick along the northwestern margin of the PRB and approximately 200 feet thick in the southwestern PRB (Feathers). It is a low-permeability confining bed. The Wyoming Framework Water Plan (WWC) classifies the Thermopolis Shale as a major, low-permeability, regional confining unit (major aquitard).

Skull Creek Shale

Well yield	<25 gpm (outcrop areas)
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the eastern PRB, the Lower Cretaceous Skull Creek Shale is a black marine shale sequence with iron concretions. The Thermopolis Shale in the western PRB is the stratigraphic equivalent of the Skull Creek Shale in the eastern basin. The Skull Creek conformably overlies the Inyan Kara Group in the eastern PRB. It is 200–250 feet thick in the northeastern PRB and 160–200 feet thick in the southeastern basin (Feathers). The Skull Creek Shale is a low-permeability, regional confining unit. The Wyoming Framework Water Plan (WWC) classifies the Skull Creek-equivalent Thermopolis Shale as a major, low-permeability, regional, confining unit (major aquitard).

Cloverly Formation

Well yield	<100 gpm; up to 250 gpm locally
Porosity	11–18%
Permeability	0.4–4 gpd/ft^2
Well specific capacity	0.2 gpm/ft
Transmissivity	4–231 gpd/ft
TDS	<500 mg/l (outcrop areas); >20,000 mg/l in deep basin
Geochemical water type	sodium-potassium/bicarbonate-carbonate-sulfate-chloride

In the western PRB, the Lower Cretaceous Cloverly Formation consists of a rusty-colored sandstone at the top, which overlies variegated bentonitic claystone; interbedded dark shale and brown siltstone; and a basal fine- to coarse-grained, well-sorted sandstone 15–45 feet thick which locally includes a basal chert-pebble conglomerate bed. The Cloverly Formation unconformably overlies the Morrison Formation. It is approximately 150 feet thick along the northwestern basin margin and approximately 140 feet thick in the southwestern PRB (Feathers).

The Cloverly Formation is a minor aquifer. In some areas, confined pressure flowing Cloverly wells yield 1–40 gpm (Feathers).

Inyan Kara Group

Well yield	<150 gpm
Porosity	11–23%
Permeability	2–36 gpd/ft^2
Well specific capacity	0.01–14 gpm/ft
Transmissivity	1–900 gpd/ft
TDS	<500 mg/l (outcrop areas); >10,000 mg/l in deep basin
Geochemical water type	sodium-potassium/bicarbonate-carbonate-sulfate-chloride

The Lower Cretaceous Inyan Kara Group consists of rusty-colored to light gray, fine- to coarse-grained sandstone containing lenticular beds of chert-pebble conglomerate; shale; siltstone; and variegated bentonitic claystone. The Inyan Kara Group comprises the Fall River Formation and the unconformably-underlying Lakota Formation. A concentration of shale beds (Fuson Shale) at the top of the Lakota marks the unconformity.

The Fall River Formation is 95–150 feet thick in the northeastern PRB and 35–85 feet thick in the southeastern basin (Feathers). The Lakota Formation is 45–300 feet thick in the northeastern basin and 115–200 feet thick in the southeastern basin (Feathers). The Lakota Formation unconformably overlies the Morrison Formation. The Cloverly Formation in the western PRB is the stratigraphic equivalent of the Inyan Kara Group in the eastern PRB.

Wells completed into the Fall River Formation are also commonly completed into the underlying Lakota Formation. Together, the two formations are included in the Dakota aquifer. Both the Fall River Formation and Lakota Formation are minor aquifers; locally, artesian flowing wells yield 1–10 gpm from these two formations (Feathers). The Fuson Shale at the top of the Lakota Formation acts as a low-permeability confining unit separating these two aquifers of the Inyan Kara Group.

Jurassic

Morrison Formation

Well yield	<10 gpm (outcrop)
Porosity	11%
Permeability	5–74 gpd/ft^2
Well specific capacity	0.2 gpm/ft
Transmissivity	<160 to 260 gpd/ft
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Jurassic Morrison Formation consists of dull, variegated shale; siliceous claystone; white, nodular limestone; and some gray, lenticular, silty, fine-grained sandstone beds. The Morrison Formation conformably overlies the Sundance Formation; it unconformably underlies the Cloverly Formation in the western PRB and the Inyan Kara Group in the eastern basin. The Morrison Formation is approximately 185 feet thick in the northwestern PRB and 130–220 feet thick in the southwestern PRB (Feathers).

In the eastern PRB, the Morrison Formation consists of varicolored claystone containing thin beds of white, nodular limestone or gray, silty sandstone; and locally containing predominant gray, fine-grained sandstone. The Morrison Formation is 0–150 feet thick in the northeastern PRB and 150–220 feet thick in the southeastern PRB (Feathers).

The Morrison Formation is considered a low-yielding and low-permeability minor aquifer. In outcrop areas, low-yielding wells may be developed from sufficiently water-saturated Morrison sandstone beds. The Wyoming Framework Water Plan (WWC) classifies the Morrison Formation as a minor aquifer.

Sundance Formation

Well yield	<50 gpm (outcrop)
Porosity	14–20%
Permeability	<8–23 gpd/ft^2
Well specific capacity	<0.1 gpm/ft
Transmissivity	8–1,250 gpd/ft
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Jurassic Sundance Formation consists of greenish gray, glauconitic shale and sandstone, calcareous in part, with higher sand content at the base of the formation. The Sundance unconformably overlies the Gypsum Spring Formation. The Sundance is 280 feet thick in the northwestern PRB and of 300 feet thick in the southwestern PRB (Feathers).

A few Sundance water wells flow at surface discharge rates of as much as 2 gpm confined pressure. The Wyoming Framework Water Plan (WWC) classifies the Sundance Formation as a marginal to minor aquifer, depending on local aquifer properties.

In the eastern PRB, the Sundance Formation consists of greenish gray, glauconitic, silty and sandy shale with thin limestone beds and red and gray, thin to thick sandstone beds (including the Hulett Sandstone Member, 55–90 feet thick). The Sundance Formation is 300–400 feet thick along the northeastern margin of the PRB and 330–365 feet thick in the southeastern PRB (Feathers).

The Sundance Formation is considered a minor aquifer in Crook County; some artesian-flowing Sundance wells flow to ground surface as much as 5 gpm (Feathers). The Wyoming Framework Water Plan (WWC) classifies the Sundance Formation as a marginal to minor aquifer, depending on local aquifer properties.

Gypsum Spring Formation

Well yield	<25 gpm (outcrop)
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	>1,000 mg/l
Geochemical water type	calcium/sulfate

In the western PRB, the Jurassic Gypsum Spring Formation consists of interbedded red shale, red claystone, and dolomite with gray, thin-bedded limestone and gypsum. The Gypsum Spring Formation is bounded by unconformities. It is 120–185 feet thick in the northwestern PRB, thins to absence in southern Johnson County, and is absent in the southwestern PRB (Hodson; Feathers).

The low-permeability Gypsum Spring Formation lithologies are not an aquifer in the western PRB, although wells constructed in the formation yield a few gpm from solution cavities (conduit flow) in outcrop areas and generally yield a calcium/sulfate type water with TDS levels of more than 1,000 mg/l (Hodson; Feathers).

In the eastern PRB, the Gypsum Spring Formation consists of massive white gypsum with interbedded red shale and cherty limestone. The Gypsum Spring is 0–125 feet thick in the northeastern PRB, 125 feet thick in northern Crook County, and thins southward. The formation is absent from Weston County and the southeastern PRB (Hodson; Feathers). The low-permeability Gypsum Spring Formation confining bed in the eastern PRB may yield small quantities of a calcium/sulfate type water with TDS levels of more than 1,000 mg/l to shallow wells in outcrop areas (Hodson; Feathers).

Triassic

Chugwater Formation (or Group)

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium/sulfate

In the western PRB, the Triassic Chugwater Formation (or Group) consists of interbedded red siltstone, red claystone, red shale, and red fine-grained sandstone, with thin limestones including the Alcova Limestone Member in upper middle part of the formation in the northern PRB, and thin gypsum partings near the base of the formation (Hodson; L&C). The top of the Chugwater includes a unit of fine- and medium-grained sandstone (Hodson).

The Chugwater Formation is unconformably overlain by the Gypsum Spring Formation and conformably overlies the Goose Egg Formation in the western PRB. The Chugwater is equivalent to the upper part of the Triassic and Permian Spearfish Formation in the eastern PRB. It is 750–800 feet thick in the northwestern PRB and 700–800 feet in the southwestern PRB (Hodson; Feathers).

The Chugwater Formation shows generally poor porosity and low permeability; this unit is a confining bed (Feathers). In outcrop areas where the Chugwater Formation is sufficiently permeable and water saturated, the formation may yield small quantities of water to wells (Hodson). Chugwater wells produce low-quality groundwater. The Wyoming Framework Water Plan (WWC) classifies the Chugwater Formation as a major, low-permeability, regional confining unit (major aquitard).

Goose Egg Formation (or Group)

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	500 to >3,000 mg/l
Geochemical water type	calcium/sulfate and sodium/chloride

In the western PRB, the Triassic and Permian Goose Egg Formation (or Group) consists of interbedded red sandstone, red siltstone, white gypsum (deep subsurface anhydrite), subsurface halite, and purple to white dolomite and limestone. Locally in outcrop areas, the halite and gypsum beds have been removed by dissolution during weathering and have formed breccias and disturbed bedding within the formation exposures. Some of the evaporite minerals in the formation were locally flushed out by movement of groundwater and subsurface dissolution in the geologic past. In some subsurface areas, evaporite minerals remain within the Goose Egg Formation.

For a description of the Goose Egg Formation, see the Permian aquifer system below, as most of the Goose Egg is Permian. The Wyoming Framework Water Plan (WWC) classifies the Goose Egg Formation as a major, low-permeability, regional confining unit (major aquitard).

Spearfish Formation

Well yield	<25 gpm
Porosity	<15%
Permeability	6–8 gpd/ft^2
Well specific capacity	0.6 gpm/ft
Transmissivity	150–370 gpd/ft
TDS	<500 to >3,000 mg/l
Geochemical water type	calcium/sulfate; magnesium/bicarbonate; locally sodium/chloride

In the eastern PRB, the Triassic and Permian Spearfish Formation consists of interbedded red shale; red siltstone; and red, silty, fine-grained sandstone with white gypsum beds that are more abundant in the lower part of the formation. In the Newcastle area, the lower part of the Spearfish locally contains discontinuous beds of halite (rock salt) (Hodson). The Spearfish conformably overlies the Minnekahta Formation in the eastern PRB. It is 450–825 feet thick in the northeastern PRB, 825 feet thick in northwestern Crook County, 450 feet thick in the Newcastle area, and 550–600 feet thick in the southeastern PRB (Hodson; Feathers).

The Spearfish Formation is a minor aquifer in Crook County with well yields averaging 13 gpm in the outcrop areas (Feathers). In general, Spearfish wells yield less than 10 gpm and produce low-quality groundwater (Hodson).

Paleozoic Aquifer System

The Paleozoic aquifer system (**Figure 3-7**) is divided into the Permian, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian aquifer systems. The Pennsylvanian through Cambrian section in the PRB ranges in thickness from less than 1,000 feet to approximately 3,000 feet (Feathers), and contains several major aquifers.

The Permian aquifer system is generally a low-permeability confining bed composed of the lower Permian part of the Goose Egg Formation in the western PRB and the lower part of the Spearfish Formation, the Minnekahta Limestone, and the Opeche Shale in the eastern PRB.

The Pennsylvanian aquifer system includes the water-saturated parts of the Tensleep Sandstone, Amsden Formation, Casper Formation, Minnelusa Formation, and Hartville Formation. The Mississippian aquifer system includes the water-saturated parts of the Madison Limestone and Pahasapa Limestone (Black Hills). The Devonian aquifer system consists of the water-saturated parts of the Englewood Formation and Fremont Canyon Sandstone. The Devonian aquifer system is present along the southern margin of the PRB (Hodson; Sando and Sandberg, 1987). Groundwater flow occurs predominantly as porous flow through the sandstone and limestone beds, except in local areas where the permeability of the formations is sufficiently enhanced by fracture.

The Silurian aquifer system is almost completely absent from Wyoming. Small areas of thin Silurian rocks are present in the deep subsurface, sandwiched between Devonian and Ordovician strata in northeastern Wyoming along the state borders with Montana and South Dakota. Silurian formations in Wyoming thicken to the northeast into the Williston Basin of eastern Montana and western North Dakota. The Silurian aquifer system is not considered usable within Wyoming.

The Cambrian aquifer system includes an upper low-permeability confining bed consisting of the Gallatin Limestone, Gros Ventre Formation, and equivalent formations, and a lower minor aquifer zone composed of the basal Flathead Sandstone and Deadwood Formation. In general, the Cambrian aquifer system thins southward and eastward from the thickest section located in the northwestern PRB (Hodson, et al., 1973) and is absent along the southern basin margin (Sando and Sandberg, 1987). Groundwater flow is predominantly as porous flow through the sandstone and limestone beds, except in local areas where the Cambrian formations are sufficiently fractured to enhance groundwater flow through an interconnected fracture system.

Permian

Goose Egg Formation (or Group)

Well yield	<10 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	500 to >3,000 mg/l
Geochemical water type	calcium/sulfate and sodium/chloride

In the western PRB, the Triassic and Permian Goose Egg Formation (or Group) consists of interbedded red shale, red siltstone, white gypsum (anhydrite in the deeper basin), subsurface halite (rock salt), and purple to white dolomite and limestone. Locally in outcrop areas, the halite and gypsum (evaporite minerals) have been removed by dissolution during weathering, leaving breccias and disturbed bedding within the exposures of the Goose Egg. Some of the evaporite minerals in the formation have also been removed by dissolution in the subsurface, and flushed out by groundwater. Locally in subsurface areas, evaporite minerals remain in the Goose Egg Formation.

The Goose Egg Formation in the western PRB is equivalent to the lower part of the Spearfish Formation, the Minnekahta Limestone, and the Opeche Shale in the eastern PRB. The Goose Egg ranges in thickness from about 180 feet in the Buffalo-Lake De Smet area, to about 250 feet in central Johnson County, and to 350 feet in the southwestern basin (Hodson).

Because the porosity and permeability of the Goose Egg Formation is generally poor, this formation is a confining bed. In outcrop areas where the Goose Egg Formation is sufficiently permeable and water saturated, it may yield small quantities of water to wells. Low-yielding Goose Egg wells produce low-quality groundwater due to dissolved gypsum and anhydrite.

Spearfish Formation

Well yield	<25 gpm
Porosity	<15%
Permeability	6–8 gpd/ft^2
Well specific capacity	0.6 gpm/ft
Transmissivity	150–370 gpd/ft
TDS	<500 to >3,000 mg/l
Geochemical water type	calcium/sulfate and sodium/chloride

In the eastern PRB, the Triassic and Permian Spearfish Formation consists of red shale, red siltstone, and red, silty, fine-grained sandstone with white gypsum beds that are more abundant in the lower part of the formation. Locally in the Newcastle area, the lower Spearfish contains discontinuous beds of halite (rock salt) (Hodson). For a more complete description of the aquifer characteristics of the Spearfish Formation, see the formation description under the Triassic aquifer system above, as most of the Spearfish is Triassic.

Minnekahta Formation

Well yield	<10 gpm; flowing wells 12 gpm locally in Crook County
Porosity	5–20%
Permeability	33 gpd/ft^2
Well specific capacity	0.1 gpm/ft
Transmissivity	330 gpd/ft
TDS	<500 to >3,000 mg/l
Geochemical water type	calcium/sulfate

In the eastern PRB, the Permian Minnekahta Formation consists of gray, hard, thin-bedded, finely-crystalline limestone and dolomitic limestone. The Minnekahta conformably underlies the Spearfish Formation and conformably overlies the Opeche Formation. It is approximately 40 feet thick in the northeastern PRB and Black Hills, and 20–50 feet thick in the southeastern PRB (Hodson; Feathers).

The Minnekahta Formation is a minor aquifer in Crook County. Wells constructed into the Minnekahta Formation generally produce low-quality groundwater. The Wyoming Framework Water Plan (WWC) classifies the Minnekahta Formation as a minor aquifer.

Opeche Shale

Well yield	<10 gpm
Porosity	5–15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<0.1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<500 to >3,000 mg/l
Geochemical water type	calcium/sulfate

Along the eastern margin of the PRB, the Permian Opeche Shale consists of maroon, silty, shaly, fine-grained sandstone intercalated with red claystone, red soft shale, red siltstone, and white gypsum beds. The Opeche Shale unconformably overlies the Minnelusa Formation. The Opeche Shale in the eastern PRB is equivalent to the lower Goose Egg Formation in the western basin; Love and Christiansen (1985) considered it a member of the Goose Egg. The Opeche is 60–90 feet thick in the northeastern PRB, 70–120 feet in the Black Hills, and 25–100 feet in the southeastern basin (Hodson; Feathers).

The permeability of the Opeche Shale is generally low; the formation is a confining bed. Opeche wells commonly produce low-quality calcium/sulfate groundwater due to dissolved gypsum and anhydrite. The Wyoming Framework Water Plan (WWC) classifies the Goose Egg Formation (Opeche Shale) as a major, low-permeability, regional confining unit (major aquitard).

Pennsylvanian

Tensleep Sandstone

Well yield	<25 to >500 gpm
Porosity	0.4–24.3%
Permeability	<21 gpd/ft^2
Well specific capacity	<1 gpm/ft
Transmissivity	0.02–1,900 gpd/ft
TDS	200–500 mg/l generally; <2,000 mg/l locally
Geochemical water type	calcium/bicarbonate

In the western PRB, the Pennsylvanian Tensleep Sandstone consists of white to gray, fine- to medium-grained, massive, cross-bedded, quartzitic sandstone with interbedded thin limestone and dolomite beds. The limestone and dolomite beds are more common in the lower part of the formation, and sandstone beds are more common in the upper part (Hodson). The thickness of the Tensleep Sandstone increases southward along the western margin of the PRB, from about 50 feet in northern Sheridan County to approximately 250 feet at the Johnson/Sheridan county line, from about 275 feet at Lake De Smet to approximately 350 feet in central Johnson County, and finally up to 500 feet in Natrona County in the southwestern PRB (Hodson; Feathers). The Tensleep Sandstone is unconformable with the overlying Goose Egg Formation and conformable with the underlying Amsden Formation.

The Tensleep Sandstone is a major aquifer, with wells flowing up to 400 gpm under confined pressure in some areas along the western margin of the PRB (Feathers). The Wyoming Framework Water Plan (WWC) classifies the Tensleep Sandstone as a major limestone aquifer.

Amsden Formation

Well yield	<25 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l
Geochemical water type	sodium-calcium/sulfate and calcium-magnesium/sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Middle Pennsylvanian and Upper Mississippian Amsden Formation consists of red, green, and purple shale interbedded with cherty dolomite and sandstone. Locally, a brown sandstone bed lies at the base of the formation. The Amsden is 150–300 feet thick in the northwestern PRB and 0–200 feet thick in the southwestern basin (Feathers). It conformably underlies the Tensleep Sandstone and unconformably overlies the Madison Limestone. The low-permeability Amsden Formation is a confining bed, unless fractured. The Wyoming Framework Water Plan (WWC) classifies the Amsden Formation as a marginal aquifer.

Casper Formation

Well yield	<25 gpm generally; >1,000 gmp locally
Porosity	<10%–25%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l
Geochemical water type	sodium-calcium/sulfate and calcium-magnesium/sulfate; sodium/chloride in deep basin (estimated)

In the extreme southern and southwestern PRB, the Permian and Middle Pennsylvanian Casper Formation consists of gray, tan, and red, thick-bedded, fine-grained, limey sandstone underlain by interbedded sandstone and pink and gray limestone beds. The Casper Formation along the eastern flank of the Laramie Mountains may overlie and include some thin beds of the Devonian Fremont Canyon Sandstone (L&C). The Casper Formation is equivalent to part of the Amsden Formation and the Tensleep Sandstone.

Groundwater from the Casper aquifer is similar in properties and quality to groundwater from the Tensleep Sandstone. The Wyoming Framework Water Plan (WWC) classifies the Casper Formation as a major limestone aquifer.

Minnelusa Formation

Well yield	<900 gpm
Porosity	6–25%
Permeability	<0.1–18 gpd/ft^2
Well specific capacity	1–5 gpm/ft
Transmissivity	2–900 gpd/ft
TDS	<600 to >3,000 mg/l; >10,000 mg/l in deep basin areas
Geochemical water type	calcium-magnesium/bicarbonate in outcrop areas; calcium/sulfate to sodium/chloride in the deep basin areas; fluoride levels exceed drinking water standard (2.0 mg/l)

In the eastern PRB, the Permian and Pennsylvanian Minnelusa Formation consists of buff and red, fine- to coarse-grained, limey sandstone interbedded with limestone, dolomite, and shale. Locally the Minnelusa Formation contains gypsum and anhydrite crystals and beds, mostly at the top of the formation (Feathers). The Minnelusa Formation is stratigraphically equivalent to the Hartville Formation along the extreme south-southeastern margin of the PRB, and to the Tensleep Sandstone and upper part of the Amsden Formation in the western PRB (Hodson). The Minnelusa Formation is 600–800 feet thick in the northeastern PRB and approximately 1,000 feet thick in the southeastern basin (Feathers). It is bounded by unconformities.

Groundwater in the Minnelusa aquifer near outcrop areas along the eastern PRB is predominantly calcium-magnesium/bicarbonate type and has TDS levels generally less than 600 mg/l, but as high as 3,000 mg/l in some outcrop areas due to calcium sulfate enrichment from gypsum dissolution (Feathers). Deeper in the structural basin and farther from outcrop areas, the TDS level increases to more than 10,000 mg/l of the sodium/chloride type (Feathers). High levels of fluoride are also common in Minnelusa water (Feathers).

The sandstone beds in the upper Minnelusa Formation form a major aquifer – the middle part is a low-permeability confining bed, and the sandstone beds in the lower part are considered a minor aquifer. Locally in the eastern PRB, the Minnelusa Formation has sufficient confining pressure in some wells to yield water flows to ground surface of more than 200 gpm (Feathers). The Wyoming Framework Water Plan (WWC) classifies the Minnelusa Formation as a major limestone aquifer.

Hartville Formation

Well yield	<25 to >1,000 gpm
Porosity	<10%–25%
Permeability	<1 to >15 gpd/ft^2
Well specific capacity	<1 to >5 gpm/ft
Transmissivity	<1 to >500 gpd/ft
TDS	200–500 mg/l; >1,000 mg/l in deep basin areas
Geochemical water type	sodium-calcium/sulfate and calcium-magnesium/sulfate

In the Hartville uplift area along the extreme south-southeastern margin of the PRB, the Permian and Pennsylvanian Hartville Formation consists of interbedded gray, siliceous limestone; dolomite; shale; and sandstone. Locally, the top of the Hartville Formation is a 100-foot-thick gray, buff, tan, fine- to medium-grained sandstone known informally as the "Converse sand." A 100-foot-thick brown-red, quartz-rich sandstone of the Darwin Sandstone Member, occurs at the base of the formation (Hodson; Sando and Sandberg, 1987). The total thickness of the Hartville Formation varies from approximately 850 to 1,300 feet (Hodson). The Hartville is equivalent to the Minnelusa Formation, the Tensleep Sandstone, and the upper Amsden Formation in the basin, and the Casper Formation.

Based on a stratigraphic clarification and redefinition by Sando and Sandberg (1987), the basal part of the Hartville Formation has been redefined as the basal

Pennsylvanian Darwin Sandstone Member of the Hartville Formation. The Darwin Sandstone Member of the Hartville Formation correlates with basal sandstone members of the Casper Formation and the Amsden Formation north and west of the Hartville uplift (Sando and Sandberg, 1987). Older (Mississippian and Devonian) beds previously classified as the basal Mississippian part of the Hartville Formation (or the Guernsey Formation) now belong to the Fremont Canyon Sandstone, Englewood Formation, and Madison Limestone in the Hartville uplift area, according to Sando and Sandberg (1987). The lower part of the Hartville Formation formerly classified as Mississippian is no longer part of the formation. The stratigraphic name *Guernsey Formation* has been abandoned (Sando and Sandberg, 1987).

Where sufficiently water saturated and permeable, the sandstone beds (Converse and Darwin) at the top and base of the Hartville Formation constitute a major aquifer (Hodson; Feathers). Locally, the Hartville Formation has sufficient confined pressure in some wells to yield water flows to ground surface of a few hundred gpm and pumping well yields of more than 1,000 gpm (Hodson). The Wyoming Framework Water Plan (WWC) classifies the Hartville Formation as a major limestone aquifer.

Mississippian

In the PRB, the Mississippian formations generally thin to the southeast from the thickest section located in the northwestern PRB (Hodson). Groundwater flow is predominantly intercrystalline porous flow through the limestone and dolomite beds, except in local areas where the limestone beds have enhanced flow permeability as conduit flow due to dissolution features (including paleokarst) in the carbonate rocks and fracture flow from structural deformation (folding and faulting) and weathering.

Madison Limestone

Well yield	<600 to >1,200 gpm locally
Porosity	<10–30%
Permeability	<1 to >2,000 gpd/ft^2
Well specific capacity	0.5–50 gpm/ft
Transmissivity	<500 to 90,000 gpd/ft; >300,000 gpd/ft locally
TDS	<600 mg/l in outcrop areas; >3,000–5,000 mg/l in deep basin areas
Geochemical water type	calcium/sulfate and magnesium/bicarbonate in outcrop areas; sodium/chloride and calcium/sulfate in deep basin

In the western PRB, the Mississippian Madison Limestone consists of the upper Mission Canyon Limestone – blue-gray, massive limestone and dolomite – and the lower Lodgepole Limestone – gray, cherty limestone and dolomite, with local basal sandy dolomite. The Madison Limestone in the western PRB has a thickness of approximately 1,100 feet in the northwestern basin and 200–400 feet in the southwestern basin (Feathers).

Along the southern PRB margin, the Madison is approximately 158–260 feet thick in southern Natrona County and approximately 260–271 feet thick in southern Converse County (Sando and Sandberg, 1987). In the Hartville uplift area of northeastern Platte County, the Madison Limestone is about 53 feet thick (Sando and Sandberg, 1987). The Madison is bounded by unconformities. Commonly, a paleokarst dissolution feature has developed on and near the top of the formation.

In the western PRB, the Madison aquifer consists of the water-saturated part of the Madison Limestone. Aquifer properties of the Madison aquifer vary widely in the PRB, and follow the permeability of the carbonate beds. Intercrystalline and intergranular permeability of the Madison is locally enhanced by dissolution, paleokarst formation, and fracturing.

The highest yields from wells constructed into the Madison Limestone are in local areas where the formation is structurally deformed, folding and faulting having created fracture-flow zones in the formation (Huntoon, 1976). Fracture flow dominates porous and conduit flow for the high-yielding wells constructed into the Madison Limestone. Exploration techniques for additional high-yield wells into the Madison Limestone in the PRB should help identify fracture-zone trends associated with regional structures (anticlines and faults) (Huntoon, 1976). High-yield wells constructed into the Madison typically show several hundred of feet of drawdown during pumping (Feathers).

Madison permeability observed in or near outcrop areas along the Bighorn Mountains is significantly greater than the low permeability at depth. Therefore, the Madison aquifer should yield less water to wells in the deeper basin than to wells in or near outcrop (Huntoon, 1976).

The Wyoming Framework Water Plan (WWC) classifies the Madison Limestone as a major limestone aquifer.

Recharge to the Madison aquifer is predominantly through infiltration in the outcrop areas of the formation and pressure leakage from adjacent formations. Estimates of recharge to the Madison aquifer range from 8,000 to more than 100,000 acre-feet of water per year (Feathers). Huntoon (1976) estimated the total amount of annual water recharge along the eastern flank of the Bighorn Mountains to the Madison Limestone as approximately 180,000 acre-feet, and the total annual amount of recharge to the entire Paleozoic aquifer in the PRB (excluding the confining beds of the Goose Egg Formation, Gallatin Limestone, and the Gros Ventre Formation) along the eastern flank of the Bighorn Mountains as approximately 400,000 acre-feet, including the 180,000 acre-feet to the Madison.

In areas of the PRB with structural deformation (folds, faults, or joints), water from the Madison aquifer may mix with adjacent groundwater from overlying and underlying rock formations. This mixing may locally change the geochemical characteristics of the groundwater in the Madison aquifer.

Pahasapa Limestone

Well yield	<1,000 gpm
Porosity	<10–30%
Permeability	<1 to >20 gpd/ft^2
Well specific capacity	0.5–50 gpm/ft
Transmissivity	1,000–6,000 gpd/ft; >300,000 gpd/ft locally
TDS	<500 mg/l in outcrop areas
Geochemical water type	calcium/sulfate and magnesium/bicarbonate in outcrop areas; sodium/chloride and calcium/sulfate in deep basin

In the eastern PRB, the Lower Mississippian Pahasapa Limestone consists of massive fine-grained limestone and dolomitic limestone, locally cherty or cavernous (karstic) in outcrop areas. The Pahasapa Limestone unconformably underlies the Minnelusa Formation and conformably overlies the Englewood Limestone in the eastern and southern PRB (Feathers; Sando and Sandberg, 1987). The upper Madison Limestone in the western basin is equivalent to the Pahasapa in the eastern basin. The Pahasapa is 550–900 feet thick in the northeastern PRB and approximately 250 feet thick in the southeastern PRB (Feathers). On the Hartville uplift, the Madison Limestone equivalent thins to 52.5 feet thick (Sando and Sandberg, 1987).

Pahasapa Limestone wells in the eastern PRB have shown artesian pressure flows or pumping yields as great as 1,000 gpm (Feathers). The Wyoming Framework Water Plan (WWC) classifies the Madison (Pahasapa) Limestone as a major limestone aquifer.

Devonian

Jefferson Formation

Well yield	<25 gpm
Porosity	<20%
Permeability	<0.1 gpd/ft^2
Well specific capacity	<1 gpm/ft
Transmissivity	<1 gpd/ft
TDS	<500 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium/sulfate in outcrop areas; sodium/chloride in deep basin (estimated)

In the northwestern PRB, the Devonian Jefferson Formation consists of gray to dark gray, clayey to silty, thin-bedded dolomite interbedded with thin beds of dolomite (Sandberg, 1967). The formation is approximately 125 feet thick at the Wyoming/Montana state line and thins southward to zero thickness between Buffalo and Mayoworth in central Johnson County (Huntoon, 1976). The permeability of the Jefferson Formation is sufficient for low yields to wells. Groundwater in the formation is often interconnected with overlying and underlying aquifers (Huntoon, 1976). Little data exist for Jefferson Formation groundwater in the PRB area. Due to the thinness of the Jefferson in Wyoming and its stratigraphic proximity to higher-yielding Paleozoic aquifers, the Jefferson aquifer is not commonly a target aquifer, except in combination with other Paleozoic aquifers.

Englewood Formation

Well yield	<25 gpm
Porosity	15–18%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium/sulfate in outcrop areas; sodium/chloride in deep basin (estimated)

In the eastern, southern, and southeastern PRB, the Lower Mississippian and Late Devonian Englewood Formation consists of gray, thin-bedded limestone with gray, shaly limestone and local gray-white to reddish brown, fine- to medium-grained, quartz-rich sandstone. The Englewood Formation unconformably overlies the Whitewood Dolomite.

The Englewood is 30–60 feet thick in the northeastern PRB and 0–50 feet thick or more in the southeastern PRB. The Englewood Formation is about 33 feet thick in the Hartville uplift area (Sando and Sandberg, 1987).

The Englewood Formation is a minor aquifer where it is sufficiently saturated within outcrop areas and in shallow subsurface areas close to outcrop.

Fremont Canyon Sandstone

Well yield	<25 gpm
Porosity	<20%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium/sulfate in outcrop areas; sodium/chloride in deep basin (estimated)

The Devonian Fremont Canyon Sandstone consists of quartzitic and glauconitic sandstone. The Fremont Canyon Sandstone occurs along the northern flank of the Laramie Mountains and along the southwestern, southern, and southeastern margins of the PRB. Sando and Sandberg (1987) correlated the Fremont Canyon Sandstone from the Fremont Canyon area located in southern Natrona County, across the northern Laramie Mountains, and to the Hartville uplift in northern Platte County.

The Fremont Canyon Sandstone has often been confused with the Cambrian Flathead Sandstone and other Paleozoic formations during geologic field mapping and well-drilling in southeastern Wyoming. The Fremont Canyon Sandstone conformably underlies the Englewood Formation and nonconformably overlies the older Precambrian basement rocks. In the extreme southwestern to southeastern PRB, the Cambrian through Silurian formations were either not deposited or were eroded prior to deposition of the Fremont Canyon Sandstone.

Along the extreme southern PRB margin, the Fremont Canyon is 137–186 feet thick in southern Natrona County and thins eastward to 0–48 feet thick in southern Converse County (Sando and Sandberg, 1987). On the Hartville uplift, the Fremont Canyon Sandstone consists of brown-weathering, coarse- to very-coarse-grained, crossbedded, quartz-rich sandstone only 6 feet thick (Sando and Sandberg, 1987).

The Wyoming Framework Water Plan (WWC) does not classify the Fremont Canyon Sandstone as an aquifer; however, the formation may be considered a minor to major sandstone aquifer in local areas where it is sufficiently thick, water saturated, and fractured to enhance formation permeability. The aquifer properties of the Fremont Canyon Sandstone are similar to those of the Flathead Sandstone and some overlying Paleozoic formations.

Silurian

The Silurian aquifer system is almost completely absent from Wyoming. Thin units of Silurian rock are present in the deep subsurface, sandwiched between Devonian and Ordovician strata in northeastern Wyoming, along the Montana and South Dakota borders. The Silurian formations thicken to the northeast into the Williston Basin of eastern Montana and western North Dakota. The Silurian aquifer system is not considered a usable aquifer system within Wyoming.

Ordovician

The Ordovician aquifer system consists of the water-saturated parts of the Bighorn Dolomite in the northwestern and western PRB, the laterally-equivalent Whitewood Dolomite in the northeastern PRB, and the Winnipeg Formation in the eastern PRB.

From the thickest section in the northwestern PRB, the Ordovician aquifer system thins to the south and east in the basin. The Ordovician formations are absent along the southern basin margin. Groundwater flow in the Ordovician aquifer system is predominantly porous flow through the dolomite and sandstone beds, except in areas where permeability is enhanced by dissolution conduit flow or fracture flow.

Bighorn Dolomite

Well yield	<25 to >750 gpm
Porosity	<10–25%
Permeability	<1 to >20 gpd/ft^2 (estimated)
Well specific capacity	<0.5 to >50 gpm/ft (estimated)
Transmissivity	<500 to >10,000 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium/bicarbonate in outcrop areas; sodium/chloride in deep basin (estimated)

In the western PRB, the Ordovician Bighorn Dolomite consists of gray, massive, cliff-forming, siliceous dolomite and local dolomitic limestone. The carbonate units are generally thin-bedded at the top of the Bighorn and a fine- to coarse-grained sandstone commonly lies at the base of the formation. The Bighorn Dolomite is present in the Bighorn Mountains and the northern third of the PRB. The formation is located predominantly in the northwestern PRB. The Bighorn unconformably underlies the Madison Limestone and unconformably overlies the Gallatin Limestone. In the eastern PRB, the stratigraphic equivalent of the Bighorn Dolomite is the Whitewood Dolomite.

The Bighorn Dolomite is 400–500 feet thick in the northwestern PRB and is absent from the southwestern PRB (Feathers). The formation thins southward from about 430 feet thick in northern Sheridan County to about 150 feet in central Johnson County (Hodson). The Bighorn Dolomite is a minor aquifer for wells constructed into the narrow outcrop area of the formation along the eastern flank of the Bighorn Mountains. Well yields range from about 25 gpm to several hundred gpm through solution cavities and fractures in the formation in outcrop areas. The Wyoming Framework Water Plan (WWC) classifies the Bighorn Dolomite as a major limestone (carbonate) aquifer or a minor aquifer, depending on well yield.

Whitewood Dolomite

Well yield	<25 gpm
Porosity	10%–25%
Permeability	<0.1–11 gpd/ft^2
Well specific capacity	15 gpm/ft
Transmissivity	6,400 gpd/ft
TDS	<300 mg/l in outcrop areas
Geochemical water type	calcium-magnesium/bicarbonate in outcrop areas

In the eastern PRB, the Ordovician Whitewood Dolomite consists of buff-colored, massive-bedded, fossiliferous dolomite and local cherty dolomite. The Whitewood Dolomite is present in the Black Hills uplift and the northern third of the PRB. The formation is located predominantly in the northeastern PRB. The Whitewood conformably overlies the Winnipeg Formation. In the western basin, the stratigraphic equivalent of the Whitewood Dolomite is the Bighorn Dolomite. The Whitewood is 50–60 feet thick in the northeastern PRB and is absent from the southeastern basin (Feathers). In general, the Whitewood Dolomite thins southward and is probably absent south of Crook County (Hodson).

The Whitewood Dolomite is considered a minor aquifer in outcrop areas and areas where the formation is close to the ground surface in the northeastern PRB. Whitewood wells yield good-quality water in outcrop areas. The intercrystalline porous flow of the dolomite is locally enhanced by fracture.

Winnipeg Formation

Well yield	<25 gpm
Porosity	<10%–20%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium/sulfate in outcrop areas; sodium/chloride in deep basin (estimated)

In the eastern PRB, the Ordovician Winnipeg Formation consists of clayey siltstone (Roughlock Siltstone or Roughlock Member), shale and silty shale (Icebox Shale or Icebox Member), and a fine- to medium-grained sandstone (formerly Aladdin Sandstone, abandoned in 1958) near the base of the formation (Feathers). The Winnipeg Formation unconformably overlies the Deadwood Formation along the eastern margin of the PRB. It is 60–70 feet thick in the northeastern PRB and absent from the southeastern basin (Feathers).

Porosity and permeability of the Winnipeg Formation are low, and this formation is generally a confining bed for adjacent aquifers. Groundwater flow is primarily porous flow through the sandstone. Permeability is enhanced in fractured areas. In outcrop areas where the Winnipeg Formation is sufficiently permeable and water saturated, the formation may yield small quantities of water to wells.

Cambrian

Gallatin Limestone

Well yield	<10 gpm
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 mg/l in outcrop areas
Geochemical water type	calcium-magnesium/bicarbonate to calcium-magnesium/sulfate in outcrop areas

In the western PRB, the Upper Cambrian Gallatin Limestone consists of blue-gray and yellow mottled, hard limestone and mud-pebble, conglomeratic limestone interbedded with micaceous shale. The combined thickness of the Gallatin Limestone and underlying Gros Ventre Formation is approximately 645 feet in the northwestern PRB and 0–500 feet in the southwestern PRB (Feathers). The Gallatin Limestone is a low-permeability confining bed in the PRB. Groundwater permeability is locally enhanced by fracture. The Wyoming Framework Water Plan (WWC) classifies the Gallatin Limestone as a minor aquifer.

Gros Ventre Formation and equivalent lithologies

Well yield	<10 gpm in outcrop areas
Porosity	<15%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 to >10,000 mg/l (estimated)
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Upper and Middle Cambrian Gros Ventre Formation and equivalent lithologies, consist of green, soft, micaceous shale of the upper Park Shale Member; blue-gray, yellow mottled, hard, dense limestone of the middle Death Canyon Limestone Member; and green, soft, micaceous shale of the lower Wolsey Shale Member, grading downward into a basal, brown, medium- to coarse-grained sandstone.

The combined thickness of the Gallatin Limestone and Gros Ventre Formation is 645 feet in the northwestern PRB and 0–500 feet in the southwestern basin (Feathers). These two formations are low-permeability confining beds. Local groundwater permeability is enhanced where the formations are fractured. The Wyoming Framework Water Plan (WWC) classifies the Gros Ventre Formation and equivalents as a minor aquifer.

Flathead Sandstone

Well yield	<25 gpm
Porosity	<10–20%
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 mg/l in outrop areas
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the western PRB, the Cambrian Flathead Sandstone consists of tan to dull red, quartzitic sandstone and local conglomeratic sandstone, interbedded with green shale and siltstone. The Flathead Sandstone is in nonconformable contact with the underlying Precambrian basement rock units. The Flathead is approximately 345 feet thick in the northwestern PRB and approximately 90 feet thick in the southwestern basin (Feathers).

The Flathead Sandstone is considered a minor aquifer, and is only tapped by a few wells located in the outcrop areas. Local permeability is enhanced in fractured areas. Wells constructed into the Flathead Sandstone must be located within outcrop areas or areas where the formation is close to the ground surface. Wells in Flathead outcrop areas generally produce good-quality water. The Wyoming Framework Water Plan (WWC) classifies the Flathead Sandstone as either a major sandstone aquifer or a minor aquifer, depending on well yield.

Deadwood Formation

Well yield	<25 gpm
Porosity	13–20%
Permeability	2–18 gpd/ft^2
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<300 mg/l in outcrop areas
Geochemical water type	calcium-magnesium-sodium/bicarbonate-sulfate; sodium/chloride in deep basin (estimated)

In the eastern PRB, the Lower Ordovician and Upper Cambrian Deadwood Formation consists of red and brown, locally dolomitic or conglomeratic quartzitic sandstone, with interbeds of shale, siltstone, limestone, and dolomite. Glauconite is characteristically common in the lithologies of the Deadwood Formation (Sando and Sandberg, 1987). In the western PRB, the Gallatin Limestone and upper Gros Ventre Formation are partial equivalents of the Deadwood Formation. The Deadwood Formation is in nonconformable contact with the underlying Precambrian basement.

The Deadwood Formation is 300–500 feet thick in the northeastern PRB. The Deadwood Formation thins southward from 500 feet thick in northern Crook County to about 200 feet thick in the Newcastle area. It is generally absent from the southeastern basin. The Deadwood Formation is a minor aquifer in outcrop areas and areas where the formation is close to the ground surface. Local permeability is enhanced in fractured areas.

Precambrian Aquifer System

The Precambrian aquifer system consists of the water-saturated parts of the Proterozoic and Archean bedrock formations (**Figure 3-8**). Most of the rock units are of Archean age in northeastern Wyoming. The Precambrian rocks are exposed in the cores of the mountain uplifts surrounding the PRB and underlie all younger formations deeper in the basin. This aquifer system is the least used of the four major aquifer systems in the PRB. The Precambrian aquifer system is used where it occurs in the cores of the Laramide mountain uplifts.

Precambrian basement rocks are the oldest crustal rocks of the Rocky Mountain foreland area. Precambrian formations are exposed in the cores of the Bighorn Mountains, Laramie Mountains, Hartville uplift, and Black Hills. The metamorphic rocks of the Precambrian aquifer system comprise metasedimentary, metavolcanic, and metaplutonic rock types. Plutonic igneous rock types of Precambrian age are granite, quartz monzonite, granodiorite, diorite, gabbro, and diabase rocks.

Precambrian rocks	
Well yield	<25 gpm in outcrop areas
Porosity	<10–15% (fracture)
Permeability	<0.1 gpd/ft^2 (estimated)
Well specific capacity	<1 gpm/ft (estimated)
Transmissivity	<1 gpd/ft (estimated)
TDS	<100 mg/l in outcrop areas
Geochemical water type	calcium/sulfate to calcium-magnesium-sodium/bicarbonate in outcrop areas

Precambrian formations located in outcrop areas may yield small quantities of water to springs and shallow wells where these rock units are sufficiently weathered, fractured, or jointed. In general, the fracture permeability of Precambrian rock units decreases at depths more than 100 feet below ground surface.

Uses for water from Precambrian aquifers include domestic purposes, livestock watering, and campground water supply. Outside the outcrop areas, the Precambrian aquifer system is not usable in the PRB. The Wyoming Framework Water Plan (WWC) classifies Precambrian rock formations as a major, low-permeability, regional confining unit (major aquitard).

Groundwater use

Groundwater use in the PRB has been addressed by Feathers and by HKM Engineering (2002 a,b). HKM's reports for the Wyoming Water Development Commission Basin Planning Project cover the hydrologic basing draining the PRB north to the Yellowstone River in Montana (2002b – the Powder, Tongue, Little Powder, and Little Bighorn river basins), and those draining the PRB east to the Missouri River in the Dakotas (2002a – the Little Missouri, Belle Fourche, Beaver (Creek), Cheyenne, and Niobrara river basins). The groundwater addressed by the HKM reports underlies the Powder River Basin Drainage Area (PRBDA), as defined in the *Surface water* section of this chapter (**Figure 3-10**) – except that the PRBDA does not include the Niobrara river basin. **Table 3-1** and **Table 3-2** give estimates of the agricultural, municipal, domestic, industrial, recreational, and environmental uses of groundwater in the PRBDA. Annual groundwater use in the Wyoming PRB exceeds 150,000 acre-feet.

Agricultural use

Feathers reported that irrigation use of groundwater in the PRB at that time accounted for approximately 22,000 to more than 34,000 acre-feet per year to water some 37,272 acres of land. Feathers also reported that stockgrowers in the PRB used approximately 11,000 acre-feet of groundwater per year to water stock, most of it from low-yield wells in the shallowest aquifers in the basin. A more recent estimate of agricultural use of groundwater is 11,000–17,000 acre-feet per year in the Northeast Wyoming River Basin (HKM Engineering, Inc., 2002b). The combined totals range from 11,200 to 17,300 acre-feet per year for the PRB, excluding the North Platte river drainage. In the combined Northeast Wyoming and Powder-Tongue river basins, groundwater was used to irrigate 18,220 acres (WWC).

Municipal use

The total estimated municipal use in the PRB is 9,600 acre-feet per year, excluding the North Platte river drainage (HKM Engineering, Inc., 2002a, 2002b). Communities in the PRB area using only groundwater for water supply are Clearmont, Gillette, Hulett, Sundance, Upton, Van Tassell, and Wright. Bar Nunn, Casper, Dayton, Douglas, Edgerton, and Midwest use a combination of groundwater and surface water for public supply. Buffalo, Ranchester, and Sheridan use only surface water (WWC).

Domestic use

Wells with yields of 25 gpm or less may be permitted by the WSEO for domestic use. HKM Engineering, Inc. (2002a, 2002b) estimated domestic use of

Table 3-1. Northeast Wyoming River Basin Plan: the Little Missouri, Belle Fourche, Beaver (Creek), Cheyenne, and Niobrara river basins – Groundwater usea in acre-feet per year during dry, normal, and wet years (HKM Engineering, 2002a).

Agricultural		**Municipal**	**Domestic**	**Industrial**		**Recreation**	**Environmental**
				Oil and gas	other		
dry	*normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*
11,000	17,000	9,100	3,600	46,000	4,700	non-consumptive use	non-consumptive use

Table 3-2. Powder-Tongue River Basin Plan – Groundwater uses, acre-feet per year (HKM Engineering, 2002b)

Agricultural		**Municipal**	**Domestic**	**Industrial**	**Recreation**	**Environmental**
dry	*normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*	*dry, normal, wet*
200	300	500	4,400	68,000	non-consumptive use	non-consumptive use

groundwater in the PRBDA at 8,000 acre-feet per year.

Industrial use

Feathers reported that industrial uses of groundwater in the PRB at that time accounted for approximately 66,000 to 73,000 acre-feet per year, most of it groundwater extracted during oil production and reinjected as water flood for secondary recovery. More recent industrial use estimates are 50,700 acre-feet per year for the Northeast Wyoming River Basin (HKM Engineering, Inc., 2002a) and 68,000 acre-feet per year for the Powder-Tongue river basin (HKM Engineering, Inc., 2002b). Total annual industrial use of groundwater in northeastern Wyoming is estimated at 120,000 acre-feet.

Recreational use

Recreational use of groundwater is generally non-consumptive and is minimal in the PRB. Most recreational use of groundwater in the basin consists of seasonal watering of golf courses, athletic and school fields, community parks, historic sites, and Keyhole State Park. The spring-fed water supply of the Story fish hatchery is also a recreational use.

Environmental use

Groundwater is used in monitoring and remediating subsurface water contamination. Environmental use of groundwater in the PRB is non-consumptive.

Groundwater production

Groundwater co-produced with CBNG

CBNG production in the PRB during 2007 included approximately 638 million barrels of co-produced water, equivalent to 82,200 acre-feet per year, or 73.4 million gallons per day. **Table 3-3** shows the history of this tremendous outflow of water, and Chapter 6 discusses its prognosis and implications.

A smoothed production curve would show CBNG water production roughly doubling each year from the late 1980s through 2000, then increasing at 25 percent per year through 2002, then at near 10 percent per year through 2007. Chapter 6 discusses factors influencing this pattern.

Groundwater co-produced with oil and gas

Roughly, 50,000 acre-feet per year is co-produced with conventional oil and gas, much of which is reinjected (WWC).

Table 3-3. Summary of CBNG annual water production, Powder River Basin, Wyoming (1987–2007).

Year	Average produced water (barrels/ day)	Annual water production (acre-feet)	Average number of CBNG production wells	Average water production per well (barrels/day)	Average water production per well (gpm)
1987	55	2.57	3.8	14.5	0.4
1988	3	0.14	12.6	0.24	0.007
1989	1,400	66	19	73.7	2.2
1990	1,620	76	32	50.6	1.5
1991	4,989	235	49	102	3.0
1992	16,620	781	50	332	9.7
1993	16,930	796	79	214	6.2
1994	25,855	1,216	110	235	6.9
1995	47,780	2,248	132	362	10.6
1996	55,476	2,610	171	324	9.5
1997	123,659	5,818	305	405	11.8
1998	197,841	9,308	520	380	11.1
1999	429,667	20,214	1,091	394	11.5
2000	1,029,227	48,400	3,218	319	9.3
2001	1,421,000	66,900	6,546	217	6.3
2002	1,618,397	76,100	9,604	168	4.9
2003	1,562,071	73,500	11,633	134	3.9
2004	1,455,899	68,500	12,996	112	3.3
2005	1,526,882	71,800	14,757	103	3.0
2006	1,840,500	86,600	16,594	111	3.2
2007	1,747,495	82,200	17,315	101	2.9

Groundwater quality

We requested groundwater quality data from CBNG operators in the PRB and their consultants. The operators declined to release proprietary CBNG water quality data to the public because of potential legal and environmental issues. We therefore sought the publicly available CBNG water quality data reported as required by state and federal permitting regulations. **Appendix 4A** describes these data in detail. WDEQ-WQD-WYPDES discharge monitoring reports may record the water quality of mixtures of groundwater from several aquifers. In outfall samples, the mixtures may include surface water and precipitation/snowmelt water.

Potentiometric surface maps

The water-level measurement data needed for preparring a potentiometric surface contour map are compiled from available sources or collected from new field studies. The minimal data required to generate a potentiometric surface map are:

- The date and time of the water-level measurement
- The accurately surveyed well location (1-foot precision or better)
- The accurately surveyed measuring point elevation (0.1-foot to 0.01-foot precision), generally taken as the north side of the well casing, but may also be ground surface elevation or some other marked location on the wellhead
- The accurately measured depth to the water level in the well (0.1-foot to 0.01-foot precision) from the measuring point at the top of the well.

The precision of the well location survey, measuring point elevation survey, and well water level measurement is critical to the accuracy of a potentiometric surface map. Therefore, only well and water-level data that meet all accuracy criteria are used to generate these maps.

Variation in the potentiometric surface occurs in response to long-term and short-term climate factors and seasonal variations in groundwater recharge, flow, and discharge. Also, anthropogenic recharge (irrigation infiltration, pond infiltration, pipeline leakage) and anthropogenic discharge (well pumping) may cause local changes in the potentiometric surface. Ideally, a potentiometric surface map would be based on water levels recorded on a single day, without local precipitation, melting snow, or other recharge event providing water to the monitored wells. In practice, however, potentiometric surface maps are generated on the basis of accurate measurements of groundwater levels that may fluctuate widely over time.

Surface water

River basins and stream drainages

In this section, we define the Wyoming Powder River Basin Drainage Area (PRBDA) as that area of northeast Wyoming drained by the Powder, Cheyenne, Belle Fouche, Tongue, Little Missouri, and Little Big Horn rivers (**Figure 3-1**). The PRBDA is bounded on the west and south by the set of watershed divides within which the rivers and their tributaries begin, and on the north and east by the Wyoming state line, across which the rivers and several tributaries leave the state. Included within the PRBDA is the Powder River Basin (PRB), the structural and depositional basin that is the setting for most of this report. For this section, we define the PRB as that area of the structural and depositional basin underlain by the Fort Union Formation. (Notice the distinction between the Powder River Basin – the structural and depositional basin – and the Powder River basin – the drainage basin of the Powder River.)

River basins are topographic watersheds that define where surface water flows. Four major river basins together cover most of the drainage area in the Wyoming PRDA: the Powder River, Cheyenne River, Belle Fourche River, and Tongue River basins. The four major river basins and the Little Missouri River basin constitute the five river basins of this section. The Little Bighorn River drainage is insignificant in the PRBDA. The headwaters of all six basins are in Wyoming.

The Powder River basin is the largest of the four major river basins, and it includes several notable tributaries. The Powder River begins near Kaycee at the confluence of the Middle and North forks of the Powder River, both of which originate on the eastern slope of the southern Bighorn Mountains. A short distance downstream from its origin, the Powder River is met by its first two major tributaries, the South Fork Powder River and Salt Creek, which flow north and east from their origin on the Casper Arch. Just downstream from where the Powder River merges with Salt Creek near Sussex, it turns sharply north, and continues north into Montana. Before it enters Montana, the Powder River is met by two other notable tributaries. The first, Crazy Woman Creek, flows east off the flank of the Bighorn Mountains and meets the Powder River east of Buffalo. The second, Clear Creek, originates west of Buffalo and flows northeast to meet the Powder River near the Montana border. Not tributary in Wyoming, the Little Powder River begins north of Gillette, flows north out of Wyoming, and meets the Powder River a short distance into Montana. Powder River water flows into the Yellowstone River in Montana and ultimately into the Missouri River in North Dakota.

The Cheyenne River basin encompasses the second-largest drainage area in the PRBDA. It begins at the confluence of Antelope Creek and the Dry Fork Cheyenne River. Antelope Creek emerges from the east side of northern Pine Ridge, east of Midwest. The Dry Fork Cheyenne River begins on the southern end of Pine Ridge. Below where the two creeks meet to form the Cheyenne River, the river flows generally eastward and into South Dakota. Tributaries that it collects on its way to South Dakota include Black Thunder Creek, Lodgepole Creek, and Lance Creek. Black Thunder Creek and Lodgepole Creek drain southeast Campbell County and southwest Weston County, respectively, and meet the Cheyenne River in southern Weston County. Lance Creek drains central Niobrara County and eastern Converse County, and meets the Cheyenne River in northeast Niobrara County. Beaver Creek, another major tributary, begins in Wyoming, drains the southwest flank of the Black Hills, and merges with the Cheyenne

River in South Dakota. The Cheyenne River ultimately meets the Missouri River in South Dakota.

The Belle Fourche River basin is the third-largest drainage basin in the PRBDA. The Belle Fourche River begins near Pumpkin Buttes and flows northeast across Campbell County into Crook County, where it enters Keyhole Reservoir. Below the reservoir, the river continues northeast; then, just south of the Montana border, it makes a ninety-degree right turn and flows southeast around the Black Hills and into South Dakota. In South Dakota, the Belle Fourche meets the Redwater Creek (Redwater River after it crosses the border into South Dakota), which begins in Wyoming on the west side of the Bear Lodge Mountains. Notable creeks that intersect the Belle Fourche are Caballo and Donkey creeks in Campbell County and Raven and Inyan Kara creeks in Crook County. The Belle Fourche River meets the Cheyenne River and ultimately the Missouri River in South Dakota.

The fourth major drainage basin in the PRBDA is the Tongue River basin. The Tongue River begins in the northeastern Bighorn Mountains and flows a short distance northeast to the Montana border. One of it's two major tributaries, Goose Creek, drains the southern part of the Tongue River basin and meets the river north of Sheridan. The other tributary, Prairie Dog Creek, drains the eastern part of the basin and flows north, where it meets the Tongue River as the Tongue River meanders back into Wyoming near the Montana border. The Tongue River flows to the Yellowstone River in Montana, which flows ultimately into the Missouri River in North Dakota.

A minor drainage basin in Wyoming is the headwaters of the Little Missouri River basin in the northeastern PRB. The Little Missouri River flows to the northeast out of the state and ultimately meets the Missouri River in North Dakota. The Little Bighorn River basin, another minor drainage basin, begins in north central Wyoming in the far northwestern corner of the PRBDA. The Little Bighorn River flows north into Montana to the Bighorn River, which flows into the Yellowstone River, which meets the Missouri River in North Dakota.

Interstate river compacts

Belle Fourche River Compact, 1943

The Belle Fourche River begins in southwest Campbell County and flows northeast to Moorcroft and into Keyhole Reservoir. Below the reservoir, it flows northeast around the Black Hills, and just before reaching Montana turns sharply southeast and enters South Dakota.

The compact allows Wyoming to use unlimited amounts of water from the river for small stock ponds (less than 20 acre-feet in capacity). The compact also allocates ten percent of the river's unallocated flow to Wyoming.

Yellowstone River Compact, 1950

The Yellowstone River begins in the Absaroka Mountains of Park County and flows north into Yellowstone Lake. From the lake, the river flows north into Montana, then turns east and flows the entire width of Montana to its eastern border with North Dakota. Here, it flows into the Missouri River. Major tributaries of the Yellowstone River begin in Wyoming and meet it in Montana: the Clarks Fork River, the Bighorn River, the Tongue River, and the Powder River. The Powder River and the Tongue River drain the PRBDA.

The compact exempts stock reservoirs of 20 acre-feet or less. Water rights dated before 1/1/1950 are maintained, and regulation and control devices are exempted from the compact. The unappropriated flows of the Yellowstone's tributaries are allotted as percentages per river. Wyoming receives 40 percent of the Tongue River flow (Montana receives 60 percent) and 42 percent of the Powder River flow (Montana Receive 58 percent). Water from the Yellowstone River itself is not available to Wyoming's citizens, even though its headwaters are in the state, because it begins in a National Forest and flows out of the state through Yellowstone National Park, wherein water cannot be diverted.

Other drainages

The North Platte River drains such a small area along the southernmost margin of the PRBDA that no description of the North Platte River Decree, 1945 (2001) is warranted in this report. The Cheyenne River basin and the Little Missouri River basin are not part of any interstate compact.

Lakes, reservoirs, and ponds

The PRBDA has many lakes, ponds, and reservoirs, due to its low relative elevation and above-average precipitation (for Wyoming). The four major river basins in the PRBDA host 23 large reservoirs having more than 1000 acre-feet of storage. There are also approximately 3500 small reservoirs, lakes, and ponds. The number of ponds and reservoirs has increased in recent years due to coalbed natural gas produced water storage and disposal.

Within the PRBDA are more than 2500 mapped lakes, reservoirs, and ponds. Converse County has 238 of these bodies of water, Niobrara County has 22, Natrona County has 1, Weston County has 37, Crook County has 29, Campbell County has 1706, Sheridan County has 242, and Johnson County has 253. Many other lakes, ponds, and reservoirs in the PRB are unmapped, some because they have been constructed recently. Only four of the 23 large reservoirs – Lake De Smet, Healy Reservoir (Clear Creek drainage), Burlington Reservoir (Upper Belle Fourche drainage), and Betty Reservoir (Antelope Creek drainage) – are located in the PRB. The 23 large reservoirs, including Lake De Smet, have a combined storage capacity of more than 450,000 acre-feet.

The two major bodies of water in the PRBDA are Lake De Smet and Keyhole Reservoir. Lake De Smet, located in northern Johnson County, is a natural lake dammed to increase water storage and control inflow and outflow. Before the dam was constructed, Lake De Smet's water came from Shell Creek. Lake De Smet is now fed by canals that draw water from Rock Creek and Piney Creek, with an outlet canal to Piney Creek. The reservoir has a surface area of approximately 5 square miles and a volume of 210,000 acre-feet.

Keyhole Reservoir is located in southern Crook County in the channel of the Belle Fourche River. Several creeks empty into the reservoir, as does the river. Keyhole Reservoir has a surface area of approximately 14 square miles when full (much of it very shallow) and a total storage capacity of 193,000 acre-feet. Five of the 23 large reservoirs are located on the east and west forks of Big Goose Creek (southwest Sheridan and northwest Johnson counties): Sawmill Reservoir, Twin Lakes Reservoir, Dome Lake Reservoir, Park Reservoir, and Bighorn Reservoir together store 19,804 acre-feet of water. The South Fork of Piney Creek (western Johnson County) has three of the large on-channel reservoirs: Kearny Lake Reservoir, Willow Park Reservoir, and Cloud Peak Reservoir together store 14,288 acre-feet of water. Healy Reservoir and Tie Hack Reservoir store a combined 7575 acre-feet of water in the Clear Creek drainage (western Johnson County). Muddy Guard No. 2 Reservoir, near Crazy Woman Creek in Northeastern Johnson County, stores 1934 acre-feet. Dullknife Reservoir, located on the North Fork Powder River (western Johnson County), stores 5003 acre-feet. Of the other of the nine large reservoirs, seven are located in the Cheyenne River Basin, one in the Belle Fourche River Basin, and one in the Little Missouri River Basin.

Stream gaging stations (USGS)

There are 125 USGS stream gaging stations in the five river basins that drain the PRBDA. Some are located on the state line or directly across the border in Montana or South Dakota. Fifty-seven gages are located in the Powder River basin, 11 in the Cheyenne River basin, 20 in the Belle Fourche River basin, 36 in the Tongue River basin, and 1 in the Little Missouri River basin. Many of these gages are no longer operational or have recorded only a few years of data. Eighty-five gages have complete datasets (defined as more than 5 years of data, some of which was recorded after 1950). Of these 85 gages, 44 are located in the Powder River basin, 9 in the Cheyenne River basin, 13 in the Belle Fourche River basin, 18 in the Tongue River basin, and 1 in the Little Missouri River basin. These gages provide coverage of the main rivers and most of the major tributaries in the PRBDA. Sixteen of these gages are located on the main stems of the five rivers, the rest on tributaries. Thirty-four of the 85 gages are located in the PRB, most of them in the Powder River drainage.

Stream flow rates and hydrographs

Eight major rivers and creeks flow across the state line from the five river basins in the PRBDA. These eight outlets allow 850,000 acre-feet of water per year to leave Wyoming. The Powder River and Little Powder River flow at an average rate of 437 cubic feet per second (cfs) and 20 cfs, respectively, as they leave the state. The Cheyenne River averages 54 cfs, and

Beaver Creek averages 31 cfs. The two major waterways leaving the Belle Fourche River Basin are the Belle Fourche River at 86 cfs and the Redwater River at 33 cfs. The Tongue River flows at an average 430 cfs, and the Little Missouri River at 80 cfs.

Our database for stream flow and volume calculations comprised hydrographs from the 85 USGS stream gauging stations that have complete data sets. Hydrographs are graphs of stream flow rate over one year. Each hydrograph is keyed to the cross-sectional shape of the stream channel at the gauging station, so that the cross sectional area of the stream, as water level changes over time, can be computed. The product of the average flow rate (ft/sec) and the average cross-sectional area (ft^2) is the volume (ft^3/sec) of water passing the gauging station each second, generally converted to acre-feet per year.

Surface water quality data

There are many surface-water quality sampling sites in the PRBDA, each sampled one to dozens of times over the years, to give the 1,856 water quality samples cited in this report. The dates, parameters, and data gathered from these sites vary greatly. By watershed, there are 970 samples from the Powder River Basin, 100 from the Cheyenne River Basin, 417 from the Belle Fourche River Basin, 363 from the Tongue River Basin, and 6 from the Little Missouri Basin. The WSGS collected these data from the Bureau of Land Management, U.S. Forest Service, U.S. Geological Survey, Wyoming Department of Environmental Quality, Wyoming Water Resource Center, and U.S. Environmental Protection Agency. These data may be found on the WSGS website <http://www.uwyo.wsgs.edu>.

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CHAPTER 4

Modeling and visualization of coal/fluid distribution

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We used 3-D modeling to construct integrated, predictive geospatial representations of individual coal bed distributions and associated water quality distributions in the lower Tertiary rock/fluid system (i.e., the Tongue River Member of the Fort Union Formation and the Wasatch Formation) in the Wyoming Powder River Basin (PRB). The resultant models and visualizations – images on screen or on paper – allow ranchers, interested citizens, state agencies, and industry to predict the quality of water associated with individual coal beds within the lower Tertiary stratigraphic units in the PRB. A rapid and effective means of updating and maintaining the PRB water quality database is included in the models and is described in **Appendix 4A**.

The visualization of coal distribution and associated water chemistry is an effective way to study the characteristics of the coal/fluid systems in the PRB. We used Dynamic Graphic earthVision® software and Wyoming State Geological Survey in-house software to construct three-dimensional coal and water quality models that allow users to visualize coal distributions, coal volumes, and water quality associated with individual coal beds. We use 3-D visualizations to better understand the model results and, in this report, to illustrate the utility of the model. These models and visualizations encapsulate the summation, integration, and analysis of large quantities of data; establish data consistency and a protocol for recognizing significant data errors; and can continually evolve to incorporate new data.

Database

For the discussion in this chapter, we define the PRB as that area of the Wyoming basin north of the 10th Standard Parallel North and underlain by the Fort Union Formation (see Chapter 1, **Figure 1-1**). For the area of the basin south of the 10th Standard Parallel, little reliable data is available. We call the 26 coal beds delineated in Chapter 2, taken together, the *Tertiary coal bed assemblage.* These are the major coal beds in the Tongue River Member of the Fort Union Formation and the Washakie Formation, and together constitute the immense coal resource of the PRB. The 26 coal beds included in the 3-D coal distribution model are, in descending order, the Ulm, Buffalo Cameron, Murray, Ucross, Felix Rider, Upper Felix, Felix, Arvada, Unnamed, Upper Roland, Roland of Baker, Roland of Taff, Smith Rider, Smith/Big George, Lower Smith, Anderson Rider, Anderson, Lower Anderson, Canyon Rider, Canyon, Cook, Lower Cook, Wall, Lower Wall, Pawnee, and Moyer coals. The water quality parameters model includes all but the first four coal beds. A total of 45,326 coal top and bottom picks constitute the data used to generate the 3-D coal bed models, and gave the 22,663 coal thickness intervals used to construct the 3-D coal thickness models. After checking for quality, we used 374 sets of the CBNG water analyses to model water quality. Water quality parameters and chemical constituents modeled are specific conductance (SC); total dissolved solids (TDS); sodium adsorption ratio SAR); pH; alkalinity; and sodium ion (Na^+), potassium ion (K^+), magnesium ion (Mg^{2+}), calcium ion (Ca^{2+}), barium ion (Ba^{2+}), manganous ion (Mn^{2+}), ferrous ion (Fe^{2+}), chloride ion (Cl^-), bicarbonate ion (HCO_3^-), and sulfate ion (SO_4^{2-}) concentrations.

Modeling process

We created the 3-D models for this study using the earthVision® Workflow Manager program. Many visualization options are available for displaying scattered data (e.g., coal top and bottom picks) and property data (e.g., thickness or water analysis data) in the earthVision® 3-D Viewer. When a map (X-Y plot) of scattered data is initially displayed, the property data is automatically displayed (contoured) in the Z direction (in and out of the map) as colors corresponding to property value intervals. The minimum, maximum, range, and spatial distribution patterns of the data can be observed visually on this kind of 3-D display, and the missed picks or data errors can be seen clearly: spurious data points falling outside a specified range can be identified readily and eliminated so as not to distort the trend of the data.

Very thin coal layers (2 feet of coal thickness vs. 5,000 feet of model Z range) present a major challenge for 3-D coal distribution modeling. In order to represent coal geometry accurately, we tried several approaches to modeling the individual coal beds. Using only coal bed top and bottom picks in modeling resulted in erratic predictions of coal bed pinchouts, and introduced significant uncertainty in the distribution mapping and volume calculations. Hanging the thickness of a coal bed on the coal bed top or bottom in order to describe the coal bed pinchouts and shape also resulted in inaccurate predictions. To most accurately represent coal bed pinchouts and best describe the shapes of the coal beds, we obtained consistent and manageable results when we developed the single surface representing the average elevation of the coal bed (the mean of the top and bottom picks) at each location, then added and subtracted the half-difference at each location to give the top and bottom surfaces.

We gridded the top, bottom, thickness, and water chemistry data using a 2-D minimum-tension gridding program in the earthVision® software. Minimum-tension gridding techniques represent (honor) the value of the input data as closely as possible and also generate a plausible model for those grid nodes that are not on or adjacent to input data points. The gridding contour is smoothed to remove bias (the weight of individual extreme values).

Model results

For this project, we created the following 3-D models:

- A distribution model for 26 individual coal beds (where the coal is 5 feet thick or thicker)
- A coal bed thickness model for the 26 coal beds
- A sodium adsorption ratio (SAR) distribution model for 20 coals (those coal beds with sufficient data to construct a viable model)

- A salinity (TDS) distribution model for those 20 coal beds.

Visualizations generated from these models are available on the WSGS website <http://www.wsgs.uwyo.edu/GeoMap>.

In addition, we generated structure contour maps and isopach maps of the Fort Union, Lance, Fox Hills, Pierre/Bearpaw/Lewis Shale, Niobrara, Mowry, Muddy Sandstone, Lakota, Sundance, Chugwater Group, Goose Egg, Opeche Shale, Minnelusa, and Madison formations from the 3-D modeling: these maps appear in other chapters of this report.

Table 4-1 lists the maps and inclined views resulting from our modeling. Some examples of these results are presented in this report in order to illustrate the utility of the modeled constructions. All results for all aspects of the modeling are available on the WSGS website, <http://www.wsgs.uwyo.edu>. This is a partially interactive website, as described in **Appendix 4A1**.

Coal bed distribution model

Using the methods described above, we evaluated the spatial distributions of 26 coal beds in three dimensions (**Figure 4-1**). We then cut 37 north-south and 51 east-west cross sections through the spatial volume. For both the north-south and east-west cross sections, the slicing interval is 4,000 feet; there are N-S and E-W cross sections within 2,000 feet of any location in the PRB.

To demonstrate the utility of the 3-D distribution model and of the cross sections, we present an index map (**Figure 4-2**), five N-S cross sections (**Figures 4-3 a–e**), and five E-Wcross sections (**Figures 4-4 a–e**). The five N-S cross sections are equally spaced (about 19 miles apart); they begin in the south, and each subsequent section is farther north (the viewer is looking north). The five E-W cross sections are also equally spaced (about 20 miles apart); they begin in the east, and each subsequent section is farther west (the viewer is looking west).

The coal bed 3-D spatial model allows a user to isolate any individual coal bed from the combined volume (the Tertiary coal bed assemblage) and view its spatial character where it is 5 feet thick or thicker.

Table 4-1. Maps and displays created for the PRB project.

Twenty-six inclined views of 26 coal beds
Twenty-six inclined views of coal thickness for 26 coal beds
Twenty-six maps of coal thickness for 26 coal beds
Fifty-one east-west cross sections of the PRB Tertiary coal beds
Thirty-seven north-south cross sections of the PRB Tertiary coal beds
Twenty inclined views of SAR distribution in 20 coal beds
Twenty maps of SAR distribution in 20 coal beds
Twenty inclined views of TDS distribution in 20 coal beds
Twenty maps of TDS distribution in 20 coal beds
Fifteen combined water quality contour maps for SAR, TDS, pH, alkalinity, SC, NA^+, K^+, Mg^{2+}, Ca^{2+}, Ba^{2+}, Mn^{2+}, Fe^{2+}, Cl^-, HCO_3^-, SO_4^{2-}
Structure contour and isopach maps of the Fort Union Formation, Lance Formation, Fox Hills Sandstone, Pierre/Bearpaw/Lewis Shale, Niobrara Formation, Mowry Shale, Muddy Sandstone, Lakota Formation, Sundance Formation, Chugwater Group, Goose Egg Formation, Opeche Shale, Minnelusa Formation, and Madison Limestone
Two hundred twenty-nine Stiff diagrams from water analysis data
A table listing the volume and water storage capacity of each coal bed
A water-table elevation model for the PRB

It is now possible to visually examine the distribution and orientation of individual coal beds in detail. In the model, viewed strike is true, but viewed dip is increased by vertical scale exaggeration (**Figure 4-5** through **Figure 4-30**).

Coal thickness model

We evaluated the thicknesses of the 26 individual coal beds in the Tertiary coal bed assemblage. **Figures 4-31** through **Figure 4-56** show inclined views of coal bed thickness, and **Figures 4-57** through **Figure 4-82** show contoured map views of coal bed thickness. Using the model, a viewer can determine the thickness of any of the 26 Tertiary coal beds anywhere in the PRB, and can easily determine where

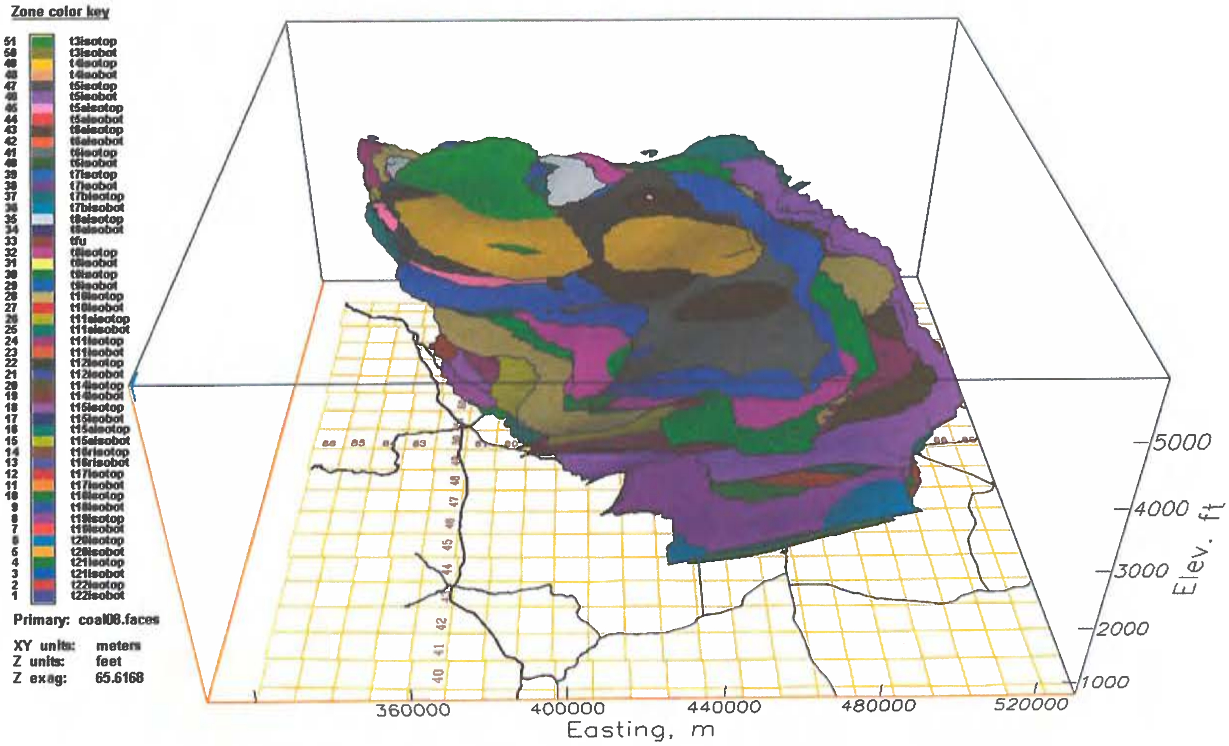


Figure 4-1. Spatial distributon of 26 coal beds, Powder River Basin, Wyoming.

the bed is thickest and where it thins to less than 5 feet thick.

Water chemistry data sets

We used three sources of water compositional data in this study. First is a CBNG water data set from the Wyoming Department of Environmental Quality (DEQ). The DEQ data set consists of 235 water analyses. Second is a PRB water data set from the USGS (provided by C. Rice at the Denver USGS office) consisting of 47 water analyses. Third is a CBNG water data set from the Wyoming Oil and Gas Conservation Commission (WOGCC) consisting of 92 water analyses. Because each water sample was tagged with sampling locality and depth, and our modeling gave us the depth of each major coal bed at any locality, we could tie the water analyses to individual coal beds. In addition, we used these same water data sets to evaluate the composite waters derived from the Tertiary coal bed assemblage. **Appendix 4A2** details the groundwater data collected for this report.

SAR distribution

With sufficient data, the regional variation of a chemical attribute of the water within a coal bed can be modeled spatially. Because sodium is a troublesome component of coal-produced waters in the PRB, an important water quality parameter is the sodium adsorption ratio (SAR):

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{\dfrac{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]}{2}}}$$

Our modeling makes it possible to determine the regional distribution of the SAR for water in 20 coal beds in the PRB (**Figure 4-83** through **Figure 4-102**). Both map and inclined views of these SAR distributions can be retrieved from the WSGS website. **Figures 4-83** through **Figure 4-102** show that significant vertical variation in SAR values may exist between coal beds at a given location. For example, at a location in the northwestern PRB, the water from the Felix coal has an SAR of 5 whereas the water from the Lower Smith coal has an SAR of 55 to 60 (**Figure 4-83** through **Figure 4-91**). The modeling also indicates that the SAR within a single coal

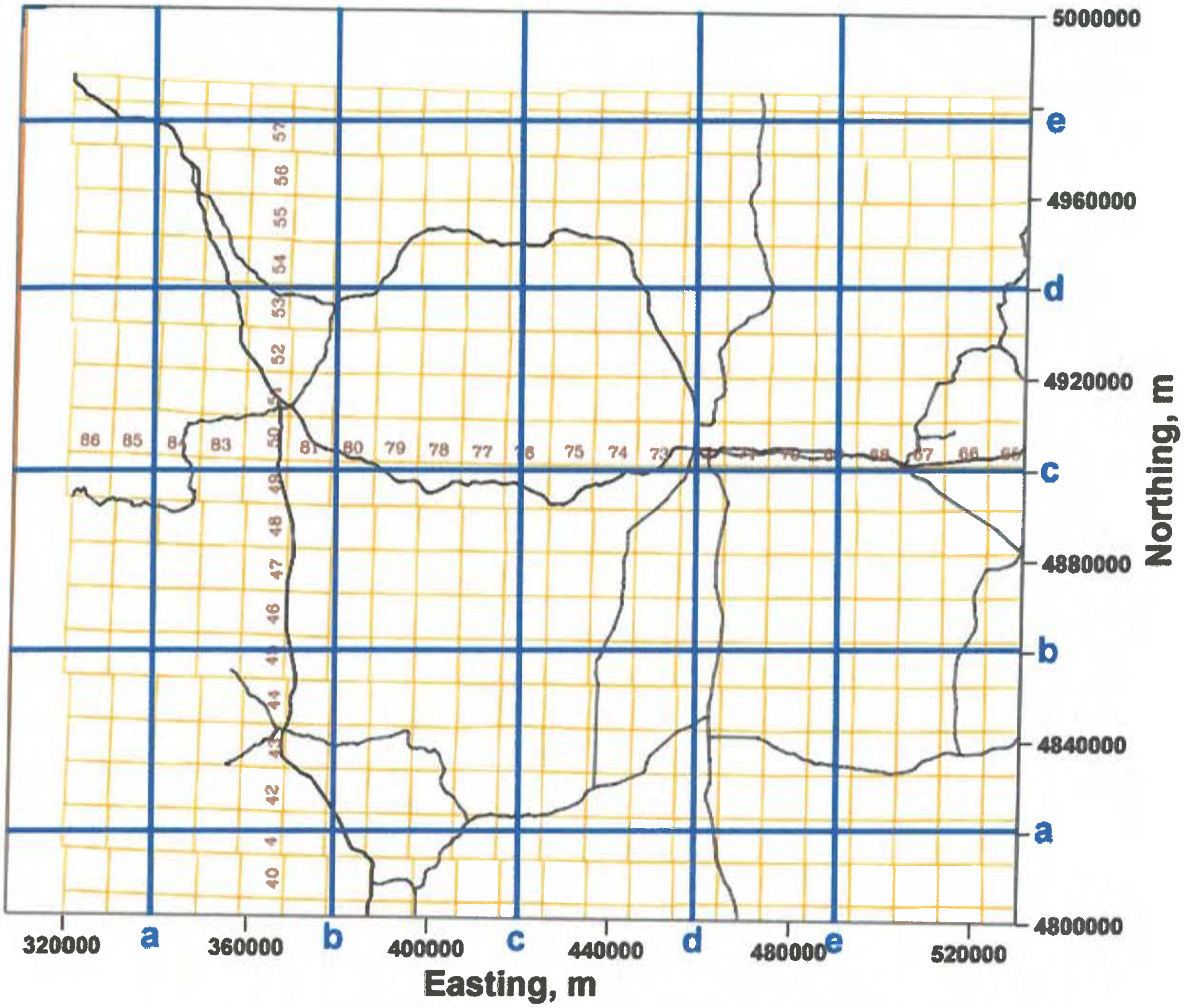


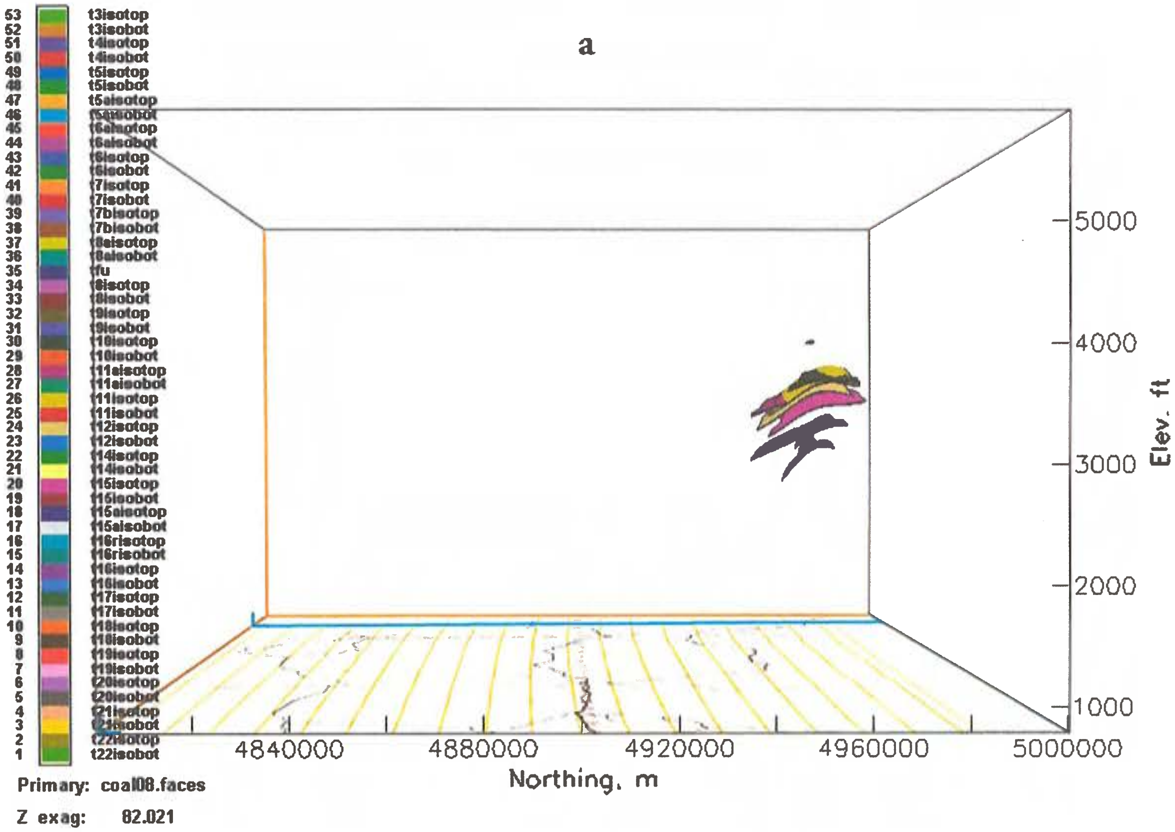
Figure 4-2. Index map of five representative north-south cross sections (blue vertical lines a through e) and five representative east-west cross sections (blue horizontal lines a through e), Figures 4-3a–e and 4-4a–e, Powder River Basin, Wyoming.

bed may vary substantially between locations. For example, the SAR of the Smith/Big George coal bed water varies from less than 5 in the southern PRB to more than 55 in the northern PRB (**Figure 4-90**).

Model of TDS

We here equate salinity with total dissolved solids (TDS), expressed in milligrams per liter (mg/l). Integrating the coal distribution model with salinity in the 20 coal beds allows us to examine regional salinity variation in detail (**Figure 4-103** through **Figure 4-122**). Some coal beds, such as the Felix, show uniformly low (less than 800 mg/l) and regionally homogeneous salinity (**Figure 4-103**). Others, such as the Smith/Big George, Anderson Rider, Canyon, Cook, Wall, Lower Wall, Pawnee, and Moyer, show stronger regional variation in salinity (**Figures 4-110**, **4-113**, **4-116**, **4-117**, **4-119**, **4-120**, **4-121**, and **4-122**). Generally, in the coal beds with substantial salinity differences (e.g., a range of 500 to 3,000 mg/l), salinity varies from low in the east (at shallow depths) to high in the west (deeper). **Figure 4-103** through **Figure 4-122** show the salinity of the water that can be derived from any of the Tertiary coal beds at any location in the PRB.

Figure 4-3, a–e. Five representative north-south cross sections through the study area, Powder River Basin, Wyoming.



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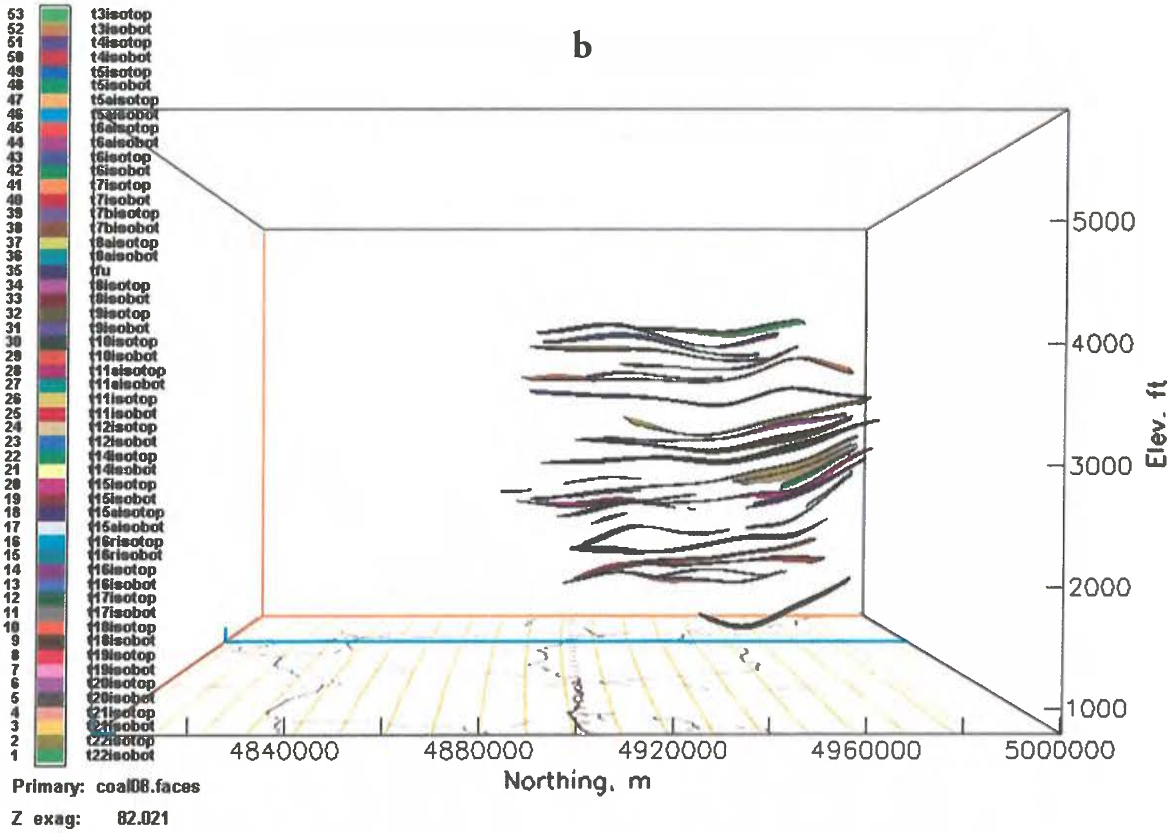
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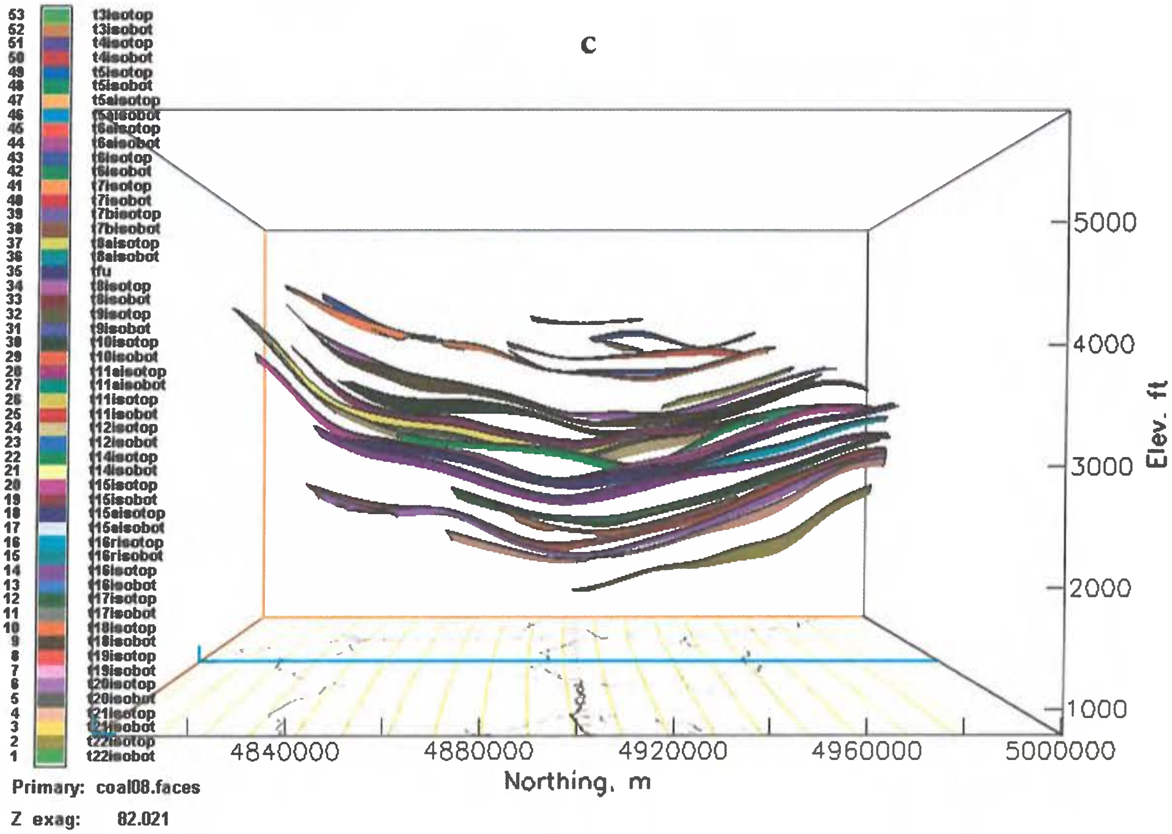
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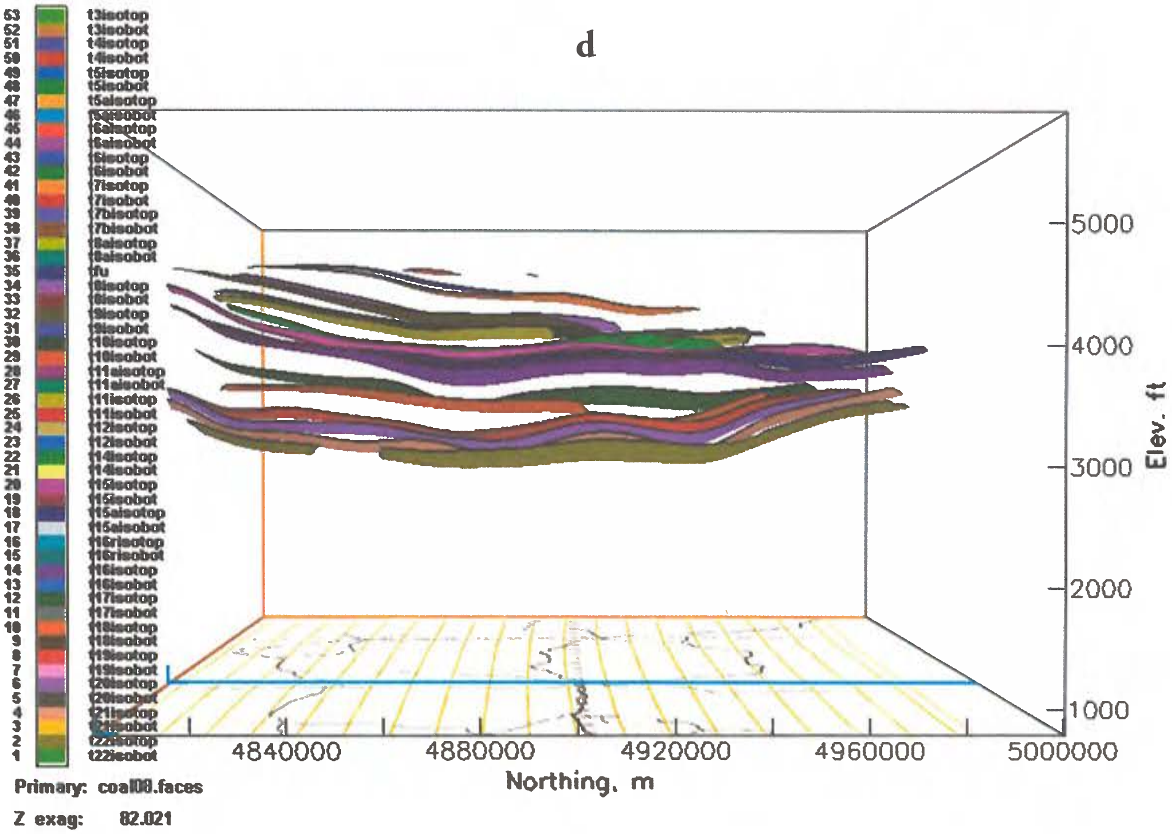
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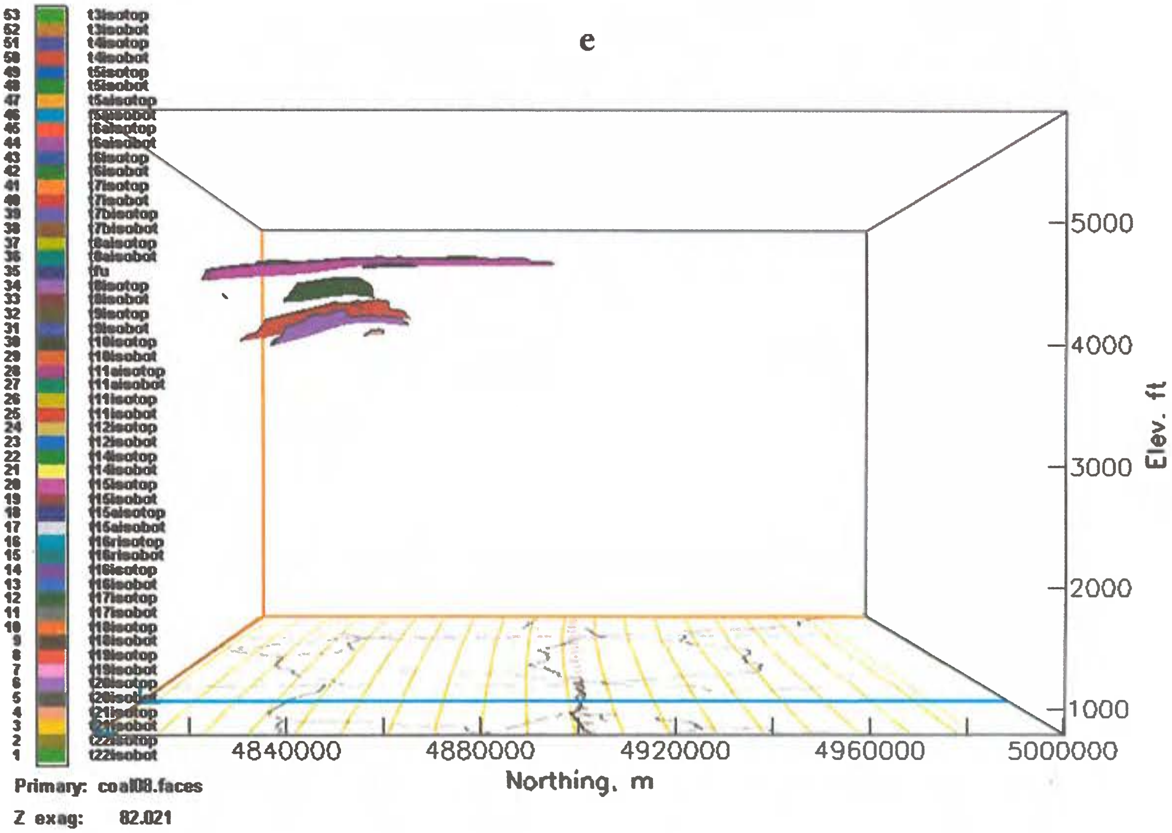
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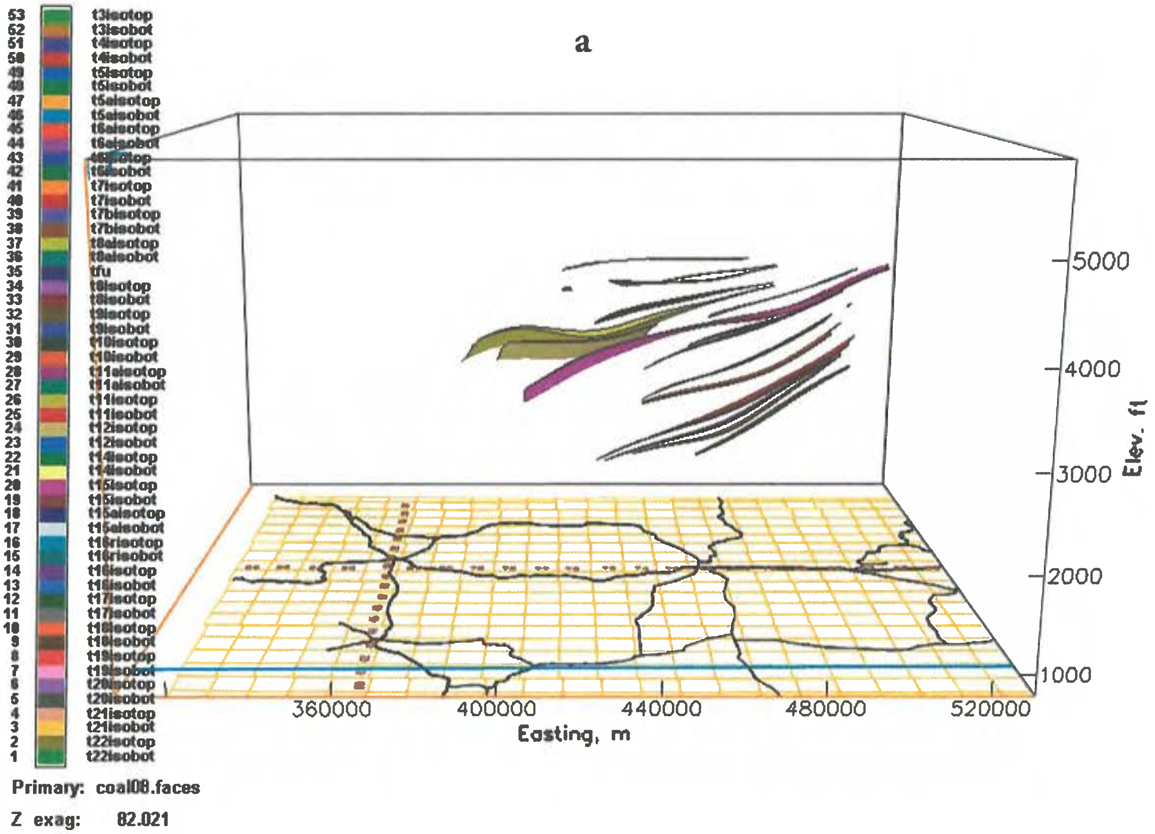
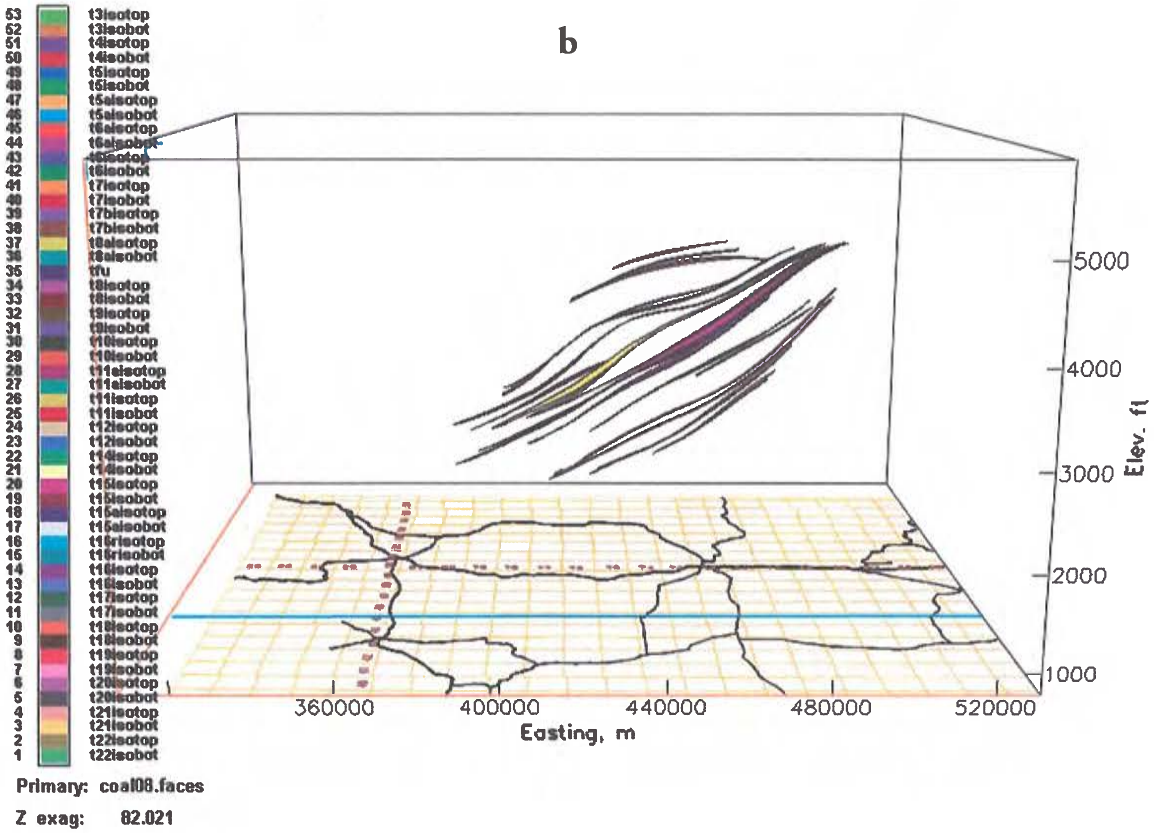
Figure 4-4 a–e. Five representative east-west cross sections through the study area, Powder River Basin, Wyoming.

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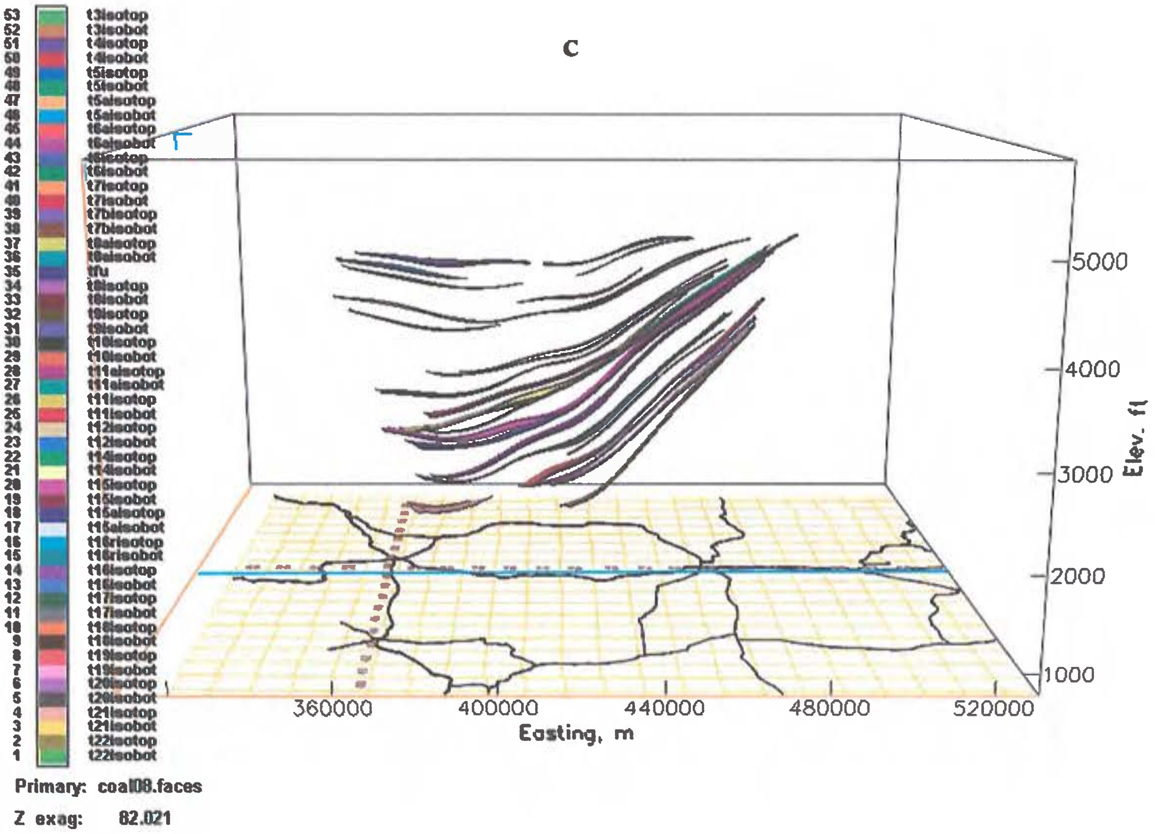
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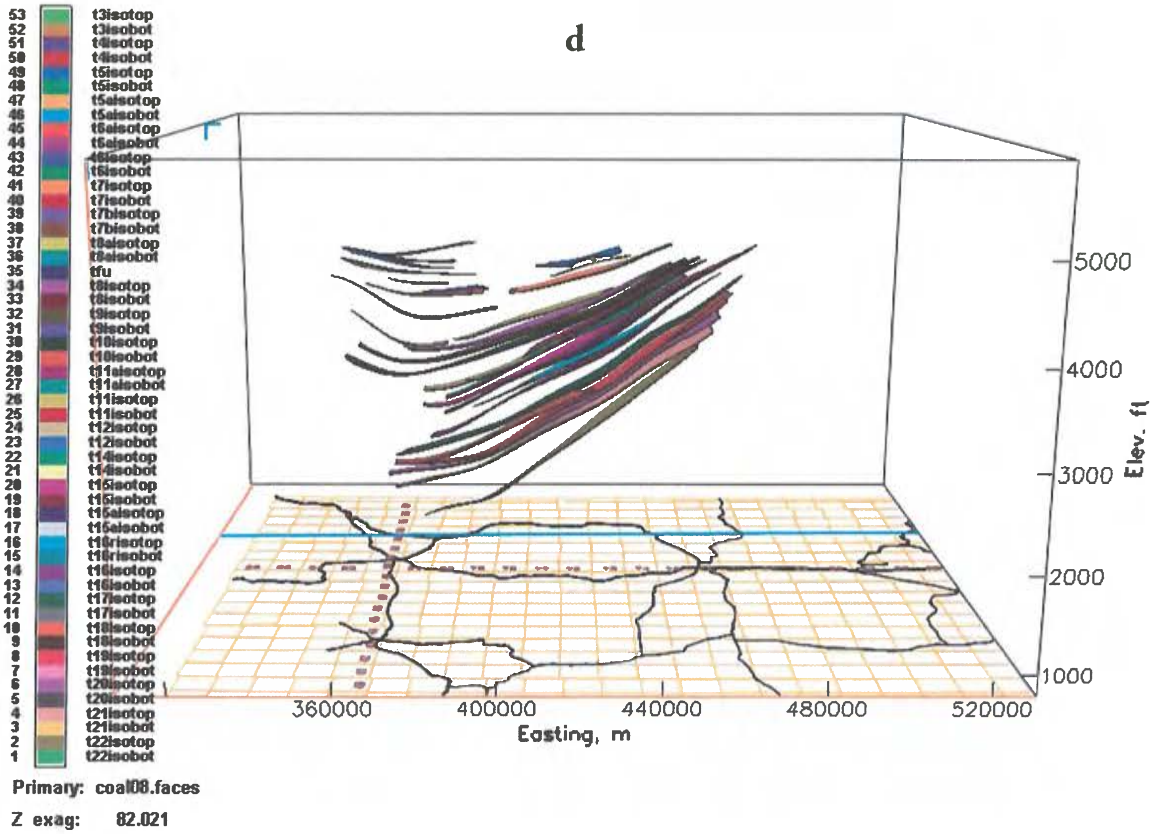

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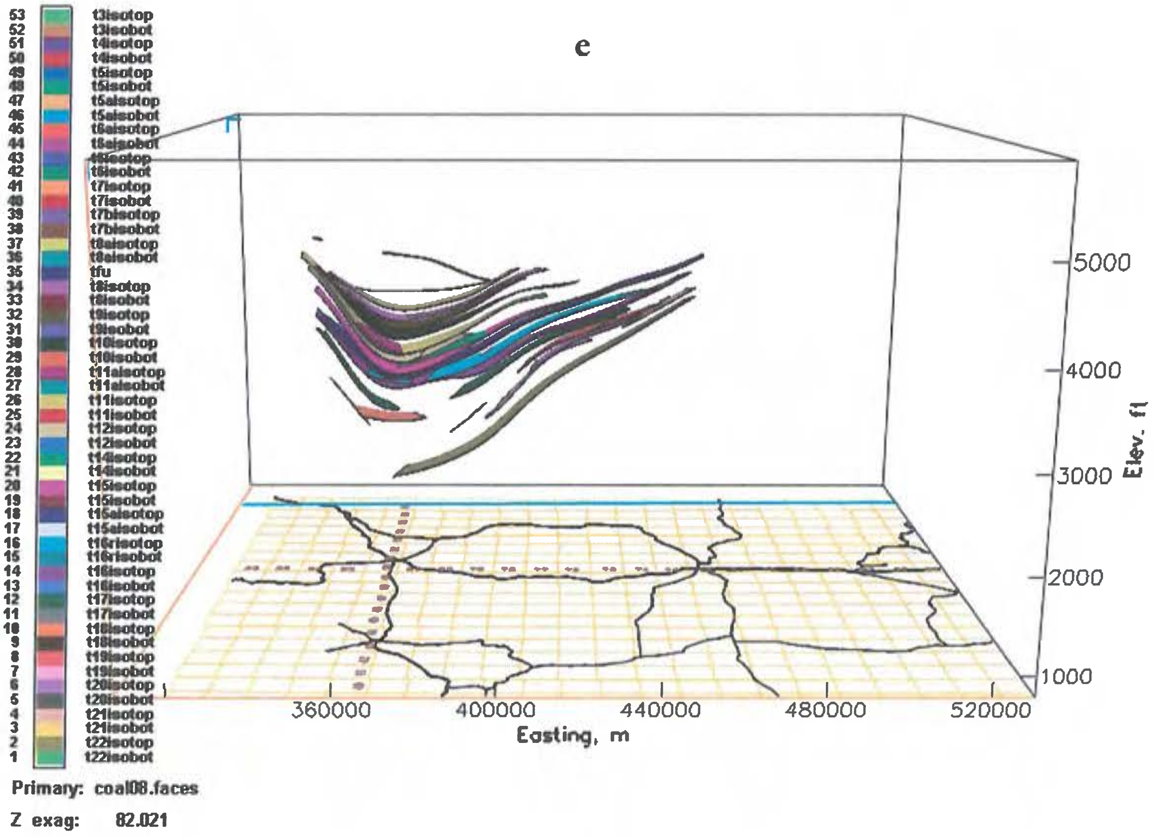

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Water chemistry

We also used the water analyses to determine regional trends in concentration of major chemical species in the coal bed waters. We combined chemical analyses of coal bed waters to generate maps of regional chemical variation for the whole Tertiary coal bed assemblage. To display these average trends in water composition, we constructed maps (**Figure 4-123** through **Figure 4-132**) showing the distribution of the following anions and cations in the Tertiary coal bed assemblage waters:

- Anions: chloride, Cl^- (**Figure 4-124**); bicarbonate, HCO_3^- (**Figure 4-125**); and sulphate, SO_4^{2-} (**Figure 4-123**)

- Cations: sodium, Na^+ (**Figure 4-127**); potassium, K^+ (**Figure 4-128**); magnesium, Mg^{2+} (**Figure 4-131**); calcium, Ca^{2+} (**Figure 4-126**); barium, Ba^{2+} (**Figure 4-132**); manganous, Mn^{2+} (**Figure 4-130**); and ferrous, Fe^{2+} (**Figure 4-129**)

In addition, we constructed maps of pH, SAR, alkalinity, TDS, and specific conductance in the Tertiary coal bed assemblage waters (**Figures 4-133** through **4-137**).

Stiff diagrams

To depict the water types characteristic of the Tertiary coal bed assemblage waters and the range of compositional variation in the waters, we constructed 229 Stiff diagrams. These diagrams show that 226 of the waters are $Na+K/HCO_3+CO_3$ waters. Some of these sodium-bicarbonate waters have very minor concentrations of Cl^- anions and Ca^{2+} and Mg^{2+} cations. **Figure 4-138** and **Figure 4-139** illustrate the range of compositional variation in the 226 Na^+/HCO_3^- samples. All 229 Stiff diagrams are on the WSGS website <http://www.wsgs.uwyo.edu/GeoMap>. The location of a water sample can be determined from the API number on the diagram. Of the 229 samples evaluated, only three vary significantly from the compositional range illustrated in **Figure 4-138** and **Figure 4-139**. These three samples are similar in cation composition to the other 226, but have SO_4^{2-} as the dominant anion (**Figure 4-140**). Two of the SO_4^{2-}-rich samples were collected near Gillette. At this time, we have no explanation for these three SO_4^{2-}-rich water samples.

Water storage potential

From the 3-D coal bed modeling, we could determine the regional distribution and the spatial variation in thickness of each of the 26 coal beds (where they are 5 feet thick or thicker) in the PRB. With this information, we calculated a minimum coal volume for each coal bed. Further, by assuming a fracture porosity, we estimated the water storage capacity in each coal bed and the total storage capacity of the Tertiary coal bed assemblage in the PRB.

The reported porosity of the Wasatch Formation sandstone/coal aquifer is 28 percent to 30 percent; of the Fort Union Formation sandstone/coal aquifer, 30 percent to 35 percent (another source gave 26 percent in sand, 10 percent in non-sand units, probably discounting fracture flow). These values were measured in relatively shallow wells that perforated coal subject to greater unroofing and therefore less compaction than coals in the deeper basin. We therefore assumed a conservative fracture porosity of 5 percent to 10 percent for all Wasatch and Fort Union coal beds, and calculated water storage capacities on that basis.

Table 4-2 shows the results of these calculations in both barrels and acre-feet of water, as well as the volume of the coal beds. The estimated 891 billion cubic meters of coal in the basin can store 36 million to 72 million acre-feet (at 5 percent to 10 percent fracture porosity), enough to cover Wyoming with 6–12 inches of water. It should be noted that (1) these estimates are based on a *static* storage model, for the model does not consider dynamic groundwater recharge; (2) similarly, these estimates are implicitly for coal beds confined within aquitards; and (3) these estimates are of water storage *capacity* only. **Table 4-2** provides useful estimates of the volume and water storage capacity of each of the 26 Tertiary coal beds, and of their combined storage capacity in the PRB.

Groundwater table map

We created a groundwater table (elevation) map of the PRB as part of this study (**Figure 4-141**). Because this study focuses on the groundwater volume, quality, and flow within the coal beds in the Fort Union and Wasatch formations, the map is based on15,326 wells 300 to 2,000 feet deep. **Figure 4-141** illustrates

Table 4-2. Coal volume and water storage capacity of 26 Tertiary coal beds, Powder River Basin, Wyoming.

Coal seam	Coal volume (m^3)	Water storage capacity			
		5% fracture porosity		10% fracture porosity	
		cubic meters (m^3)	acre-feet	cubic meters (m^3)	acre-feet
Ulm	$6.15 \bullet 10^{9}$	$0.31 \bullet 10^{9}$	$0.25 \bullet 10^{6}$	$0.62 \bullet 10^{9}$	$0.50 \bullet 10^{6}$
Buffalo Cameron	$10.08 \bullet 10^{9}$	$0.50 \bullet 10^{9}$	$0.40 \bullet 10^{6}$	$1.01 \bullet 10^{9}$	$0.82 \bullet 10^{6}$
Murray	$9.93 \bullet 10^{9}$	$0.50 \bullet 10^{9}$	$0.40 \bullet 10^{6}$	$0.99 \bullet 10^{9}$	$0.81 \bullet 10^{6}$
Ucross	$11.32 \bullet 10^{9}$	$0.57 \bullet 10^{9}$	$0.46 \bullet 10^{6}$	$1.13 \bullet 10^{9}$	$0.92 \bullet 10^{6}$
Felix Rider	$5.94 \bullet 10^{9}$	$0.30 \bullet 10^{9}$	$0.24 \bullet 10^{6}$	$0.59 \bullet 10^{9}$	$0.48 \bullet 10^{6}$
Upper Felix	$10.92 \bullet 10^{9}$	$0.55 \bullet 10^{9}$	$0.44 \bullet 10^{6}$	$1.09 \bullet 10^{9}$	$0.89 \bullet 10^{6}$
Felix	$31.47 \bullet 10^{9}$	$1.57 \bullet 10^{9}$	$1.28 \bullet 10^{6}$	$3.15 \bullet 10^{9}$	$2.55 \bullet 10^{6}$
Arvada	$14.20 \bullet 10^{9}$	$0.71 \bullet 10^{9}$	$0.58 \bullet 10^{6}$	$1.42 \bullet 10^{9}$	$1.15 \bullet 10^{6}$
Unnamed	$7.79 \bullet 10^{9}$	$0.39 \bullet 10^{9}$	$0.32 \bullet 10^{6}$	$0.78 \bullet 10^{9}$	$0.63 \bullet 10^{6}$
Upper Roland	$18.66 \bullet 10^{9}$	$0.93 \bullet 10^{9}$	$0.76 \bullet 10^{6}$	$1.87 \bullet 10^{9}$	$1.51 \bullet 10^{6}$
Roland of Baker	$39.19 \bullet 10^{9}$	$1.96 \bullet 10^{9}$	$1.59 \bullet 10^{6}$	$3.92 \bullet 10^{9}$	$3.18 \bullet 10^{6}$
Roland of Taff	$41.23 \bullet 10^{9}$	$2.06 \bullet 10^{9}$	$1.67 \bullet 10^{6}$	$4.12 \bullet 10^{9}$	$3.34 \bullet 10^{6}$
Smith Rider	$22.69 \bullet 10^{9}$	$1.13 \bullet 10^{9}$	$0.92 \bullet 10^{6}$	$2.27 \bullet 10^{9}$	$1.84 \bullet 10^{6}$
Smith/Big George	$99.74 \bullet 10^{9}$	$4.99 \bullet 10^{9}$	$4.04 \bullet 10^{6}$	$9.97 \bullet 10^{9}$	$8.09 \bullet 10^{6}$
Lower Smith	$19.57 \bullet 10^{9}$	$0.98 \bullet 10^{9}$	$0.79 \bullet 10^{6}$	$1.96 \bullet 10^{9}$	$1.59 \bullet 10^{6}$
Anderson Rider	$29.27 \bullet 10^{9}$	$1.46 \bullet 10^{9}$	$1.19 \bullet 10^{6}$	$2.93 \bullet 10^{9}$	$2.37 \bullet 10^{6}$
Anderson	$144.19 \bullet 10^{9}$	$7.21 \bullet 10^{9}$	$5.84 \bullet 10^{6}$	$14.4 \bullet 10^{9}$	$11.7 \bullet 10^{6}$
Lower Anderson	$68.69 \bullet 10^{9}$	$3.43 \bullet 10^{9}$	$2.78 \bullet 10^{6}$	$6.87 \bullet 10^{9}$	$5.57 \bullet 10^{6}$
Canyon Rider	$10.33 \bullet 10^{9}$	$0.52 \bullet 10^{9}$	$0.42 \bullet 10^{6}$	$1.03 \bullet 10^{9}$	$0.84 \bullet 10^{6}$
Canyon	$59.75 \bullet 10^{9}$	$2.99 \bullet 10^{9}$	$2.42 \bullet 10^{6}$	$5.98 \bullet 10^{9}$	$4.84 \bullet 10^{6}$
Cook	$58.07 \bullet 10^{9}$	$2.90 \bullet 10^{9}$	$2.35 \bullet 10^{6}$	$5.81 \bullet 10^{9}$	$4.71 \bullet 10^{6}$
Lower Cook	$16.33 \bullet 10^{9}$	$0.82 \bullet 10^{9}$	$0.66 \bullet 10^{6}$	$1.63 \bullet 10^{9}$	$1.32 \bullet 10^{6}$
Wall	$60.66 \bullet 10^{9}$	$3.03 \bullet 10^{9}$	$2.46 \bullet 10^{6}$	$6.07 \bullet 10^{9}$	$4.92 \bullet 10^{6}$
Lower Wall	$33.86 \bullet 10^{9}$	$1.69 \bullet 10^{9}$	$1.37 \bullet 10^{6}$	$3.39 \bullet 10^{9}$	$2.74 \bullet 10^{6}$
Pawnee	$31.712 \bullet 10^{9}$	$1.59 \bullet 10^{9}$	$1.29 \bullet 10^{6}$	$3.17 \bullet 10^{9}$	$2.57 \bullet 10^{6}$
Moyer	$28.84 \bullet 10^{9}$	$1.44 \bullet 10^{9}$	$1.17 \bullet 10^{6}$	$2.88 \bullet 10^{9}$	$2.34 \bullet 10^{6}$
Total*	**$890.57 \bullet 10^{9}$**	**$44.5 \bullet 10^{9}$**	**$36.1 \bullet 10^{6}$**	**$89.1 \bullet 10^{9}$**	**$72.2 \bullet 10^{6}$**

**Totals may show small errors due to rounding.*

the following aspects of the Tertiary groundwater system in the PRB:

- The direction of fluid flow in the subsurface mimics the direction of flow in surface streams.
- The major recharge area for groundwater in the Fort Union and Washakie formations in the PRB is the eastern flank of the Bighorn Mountains (**Figure 4-141**).
- The one significant groundwater flow divide in the PRB separates groundwater flow to the north from groundwater flow to the east.

Water and natural gas production

Chapter 6 of this report is a detailed study of water/gas ratios resulting from CBNG activity in each of the drainage basins in the PRB. The conclusions drawn in Chapter 6 are based on historical CBNG production data; but, by estimating future drilling activity in each of the drainage basins, it is possible to predict future water and gas production that will result from CBNG activities in the PRB.

Conclusion

The 3-D modeling of coal bed distribution and thickness in the Washakie Formation and the Tongue River Member of the Fort Union Formation in the PRB has greatly increased our ability to predict the spatial attributes of the 26 major Tertiary coal beds in the basin. These same coal beds have served area ranchers as essential aquifers for a century, and the CBNG industry as a tremendous source of gas for nearly two decades. In this study, we integrate water chemistry with the 3-D coal distribution model in order to assess the water chemistry of individual coal beds. This integration allows us to forecast regional patterns of variables such as sodium adsorption ratio and salinity in individual coal beds. Most important, as a result of integrating water chemistry and coal bed distribution, we can predict the depth of any individual coal bed, the thickness of that coal bed, and the composition of water in that coal bed in the subsurface beneath any location in the basin.

This 3-D modeling of coal bed distribution and volumes also allows us to estimate the amount of water any coal bed can store. Finally, the water table elevation map generated in this report vastly improves our understanding of the direction of subsurface fluid flow in the PRB and of major groundwater recharge areas.

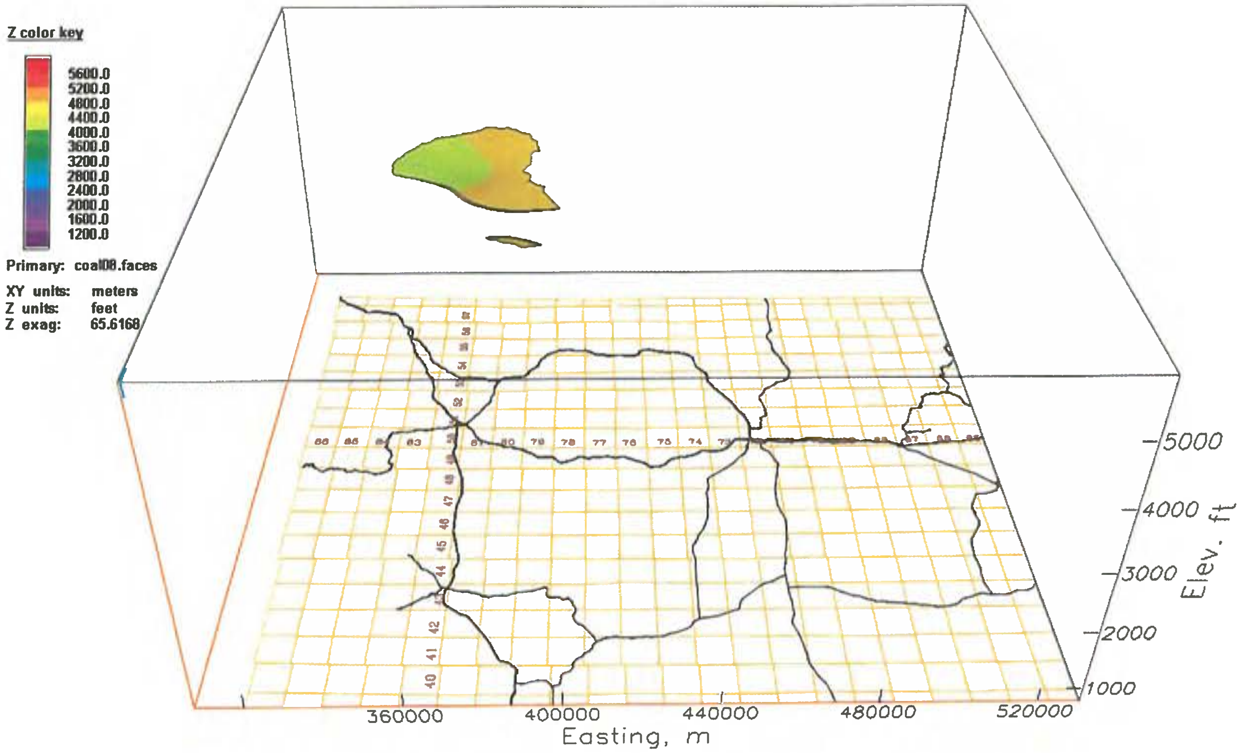


Figure 4-5. View generated by coal bed spatial model showing the distribution and orientation of the Ulm coal where it is 5 feet thick or thicker.

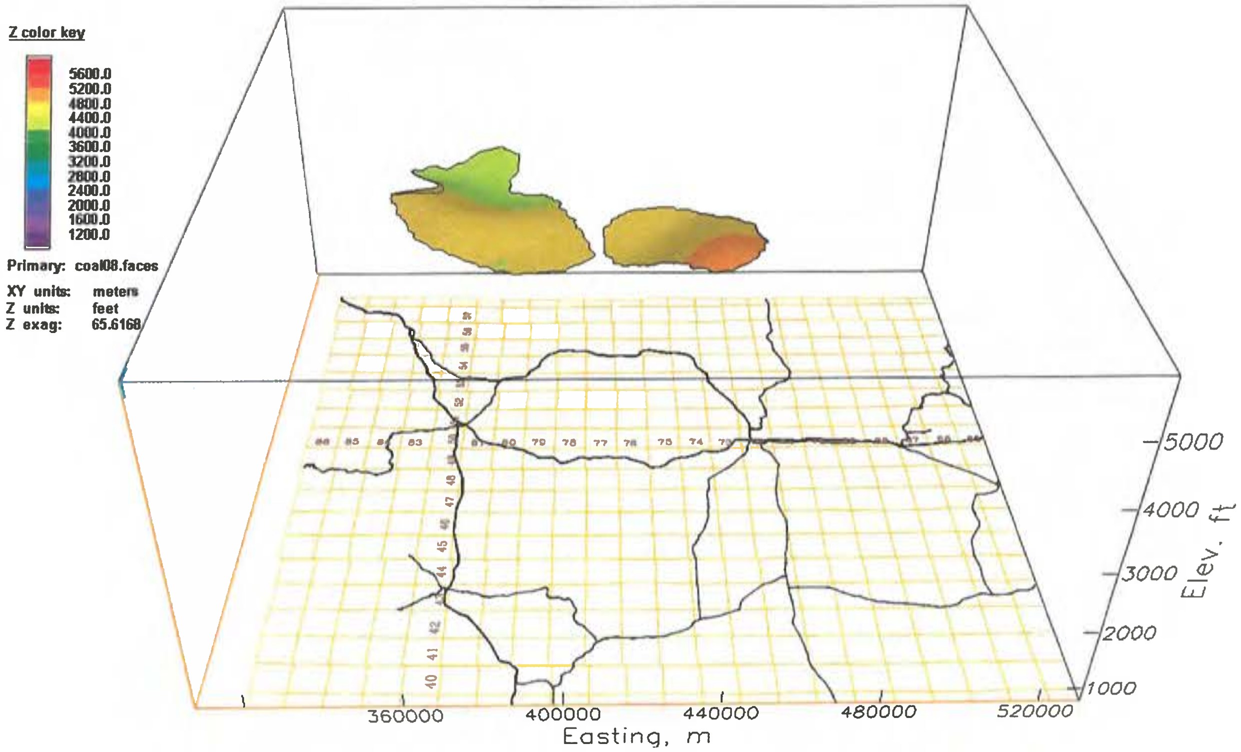


Figure 4-6. View generated by coal bed spatial model showing the distribution and orientation of the Buffalo Cameron coal where it is 5 feet thick or thicker.

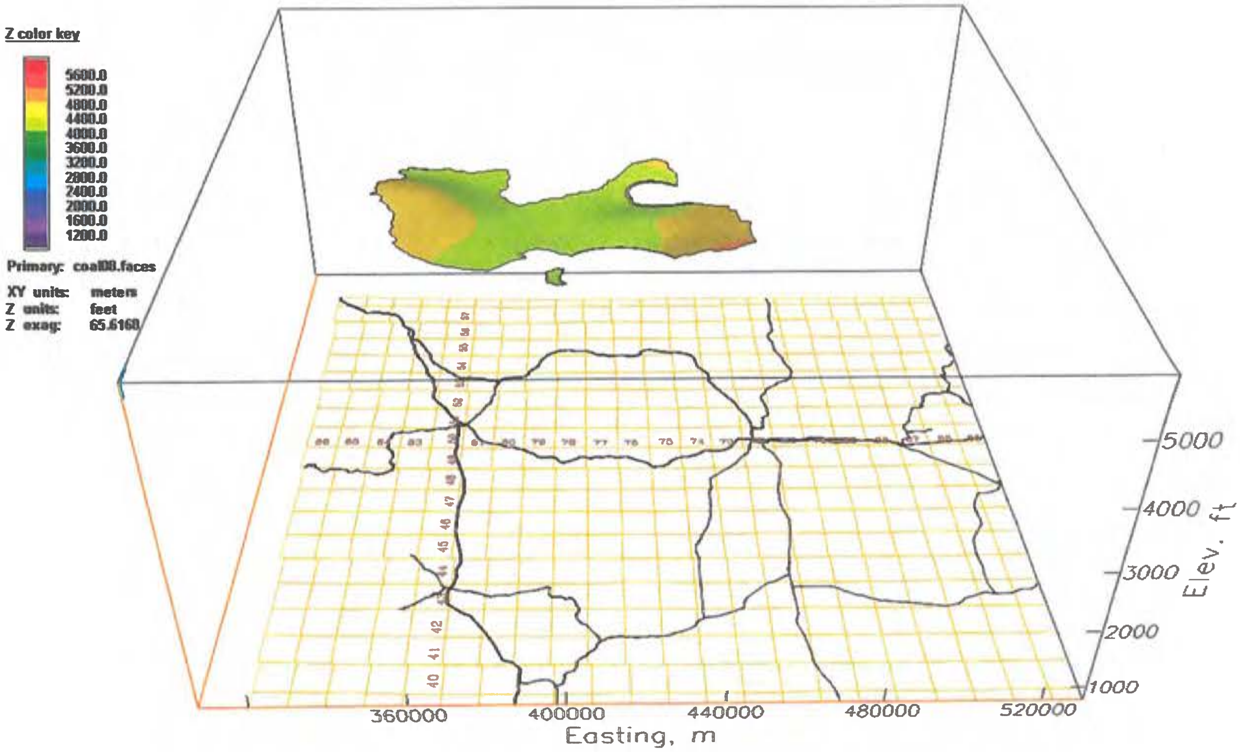


Figure 4-7. View generated by coal bed spatial model showing the distribution and orientation of the Murray coal where it is 5 feet thick or thicker.

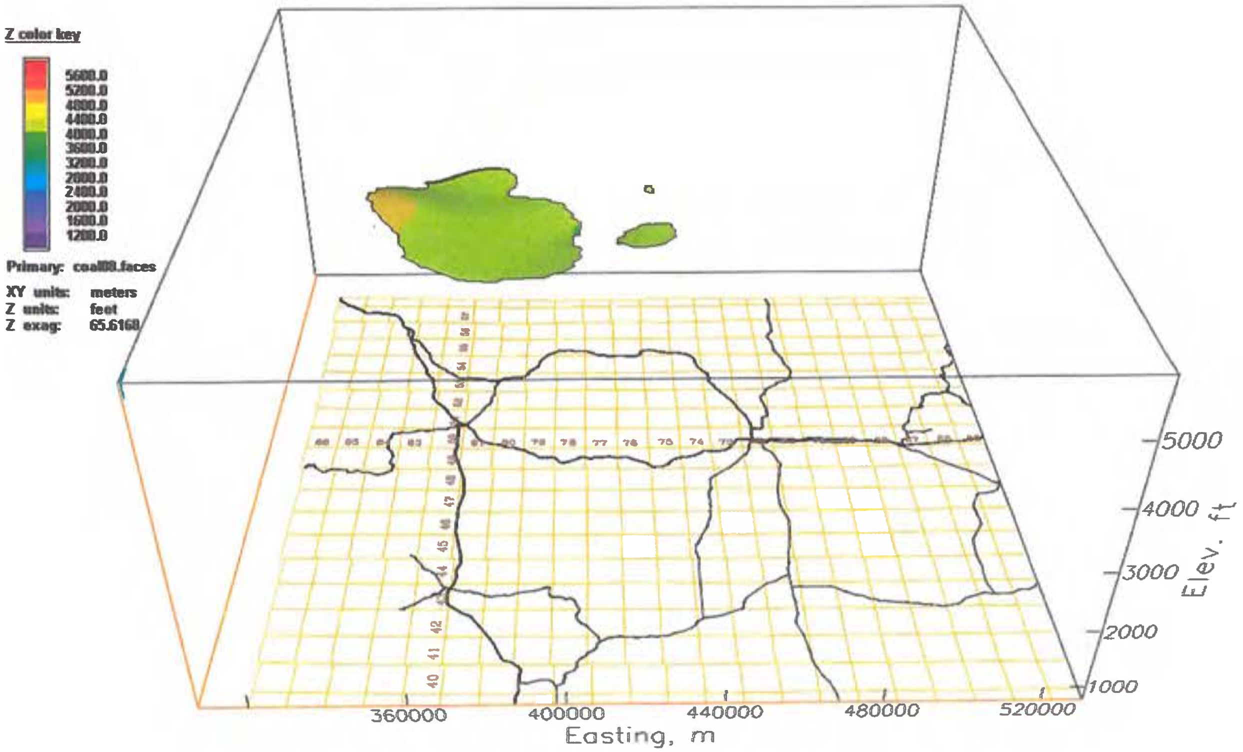


Figure 4-8. View generated by coal bed spatial model showing the distribution and orientation of the Ucross coal where it is 5 feet thick or thicker.

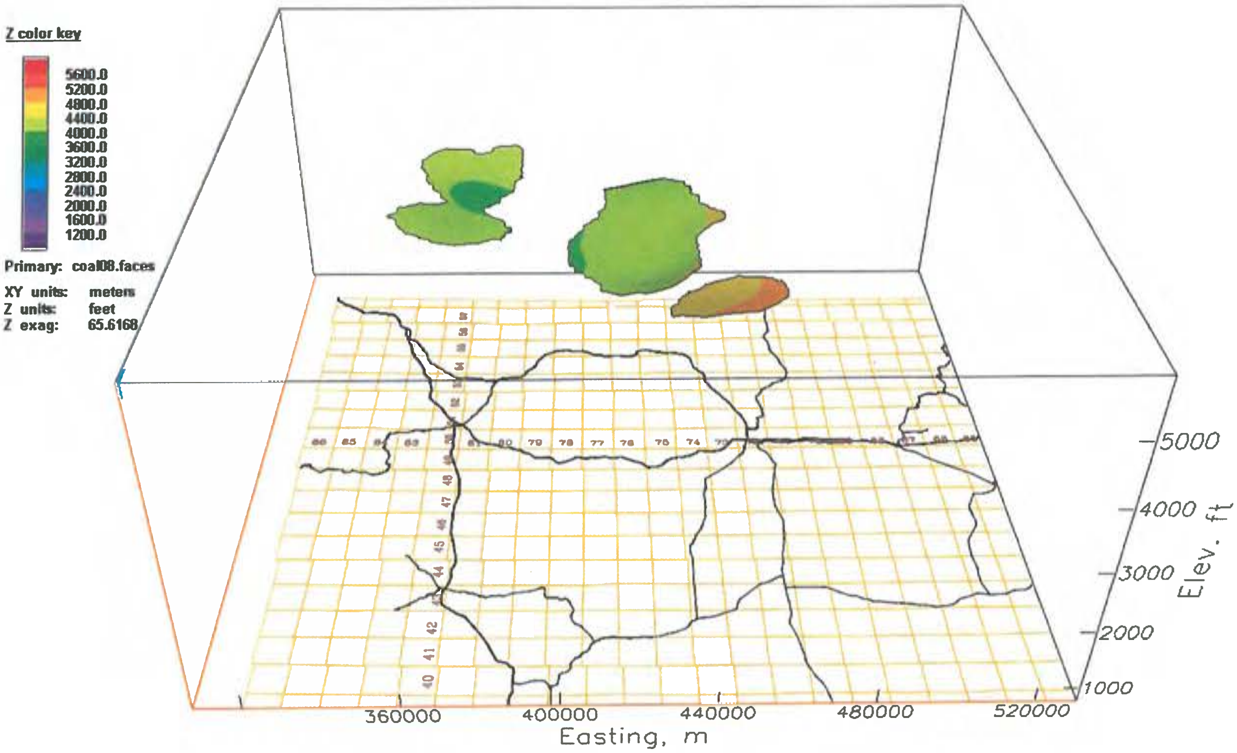


Figure 4-9. View generated by coal bed spatial model showing the distribution and orientation of the Felix Rider coal where it is 5 feet thick or thicker.

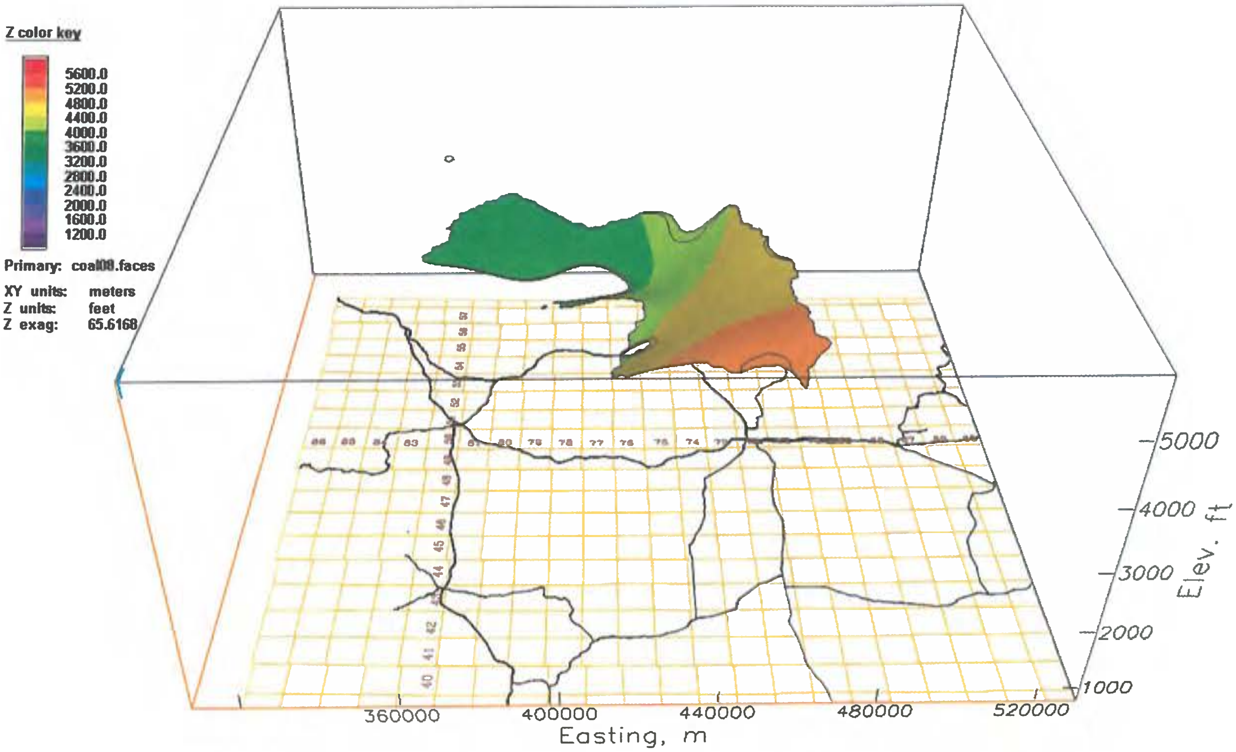


Figure 4-10. View generated by coal bed spatial model showing the distribution and orientation of the Upper Felix coal where it is 5 feet thick or thicker.

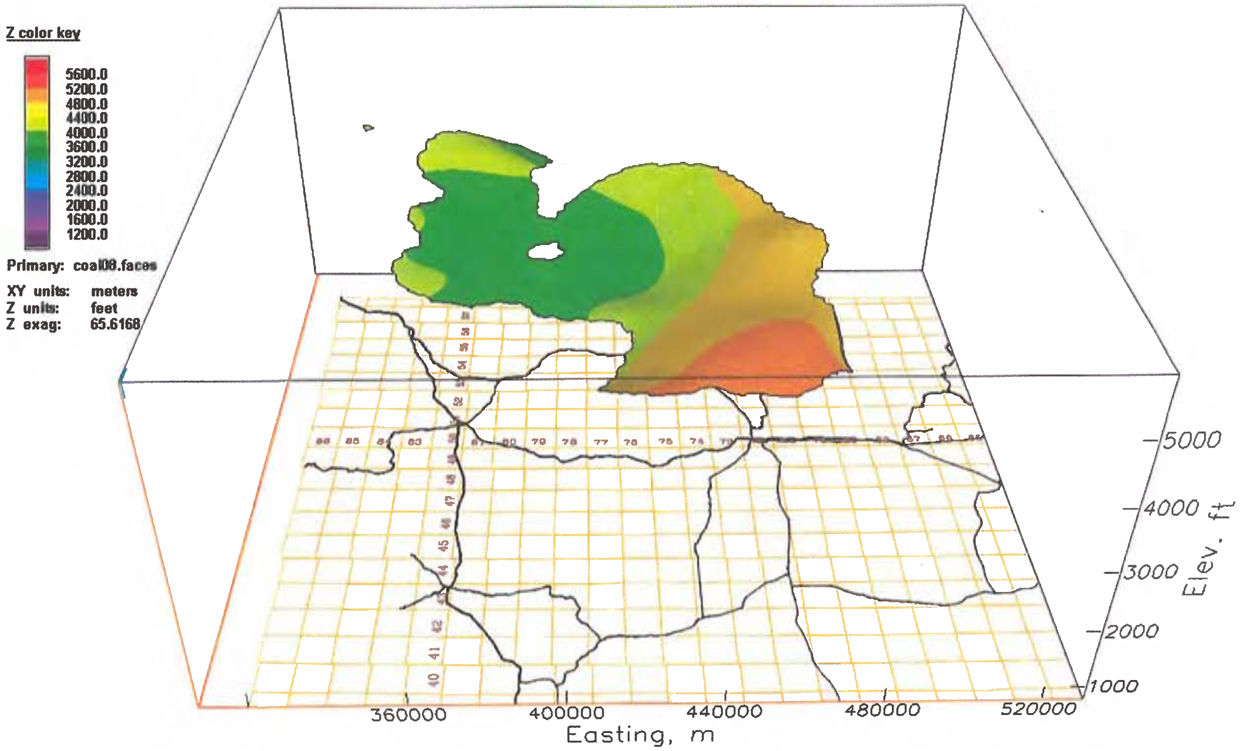


Figure 4-11. View generated by coal bed spatial model showing the distribution and orientation of the Felix coal where it is 5 feet thick or thicker.

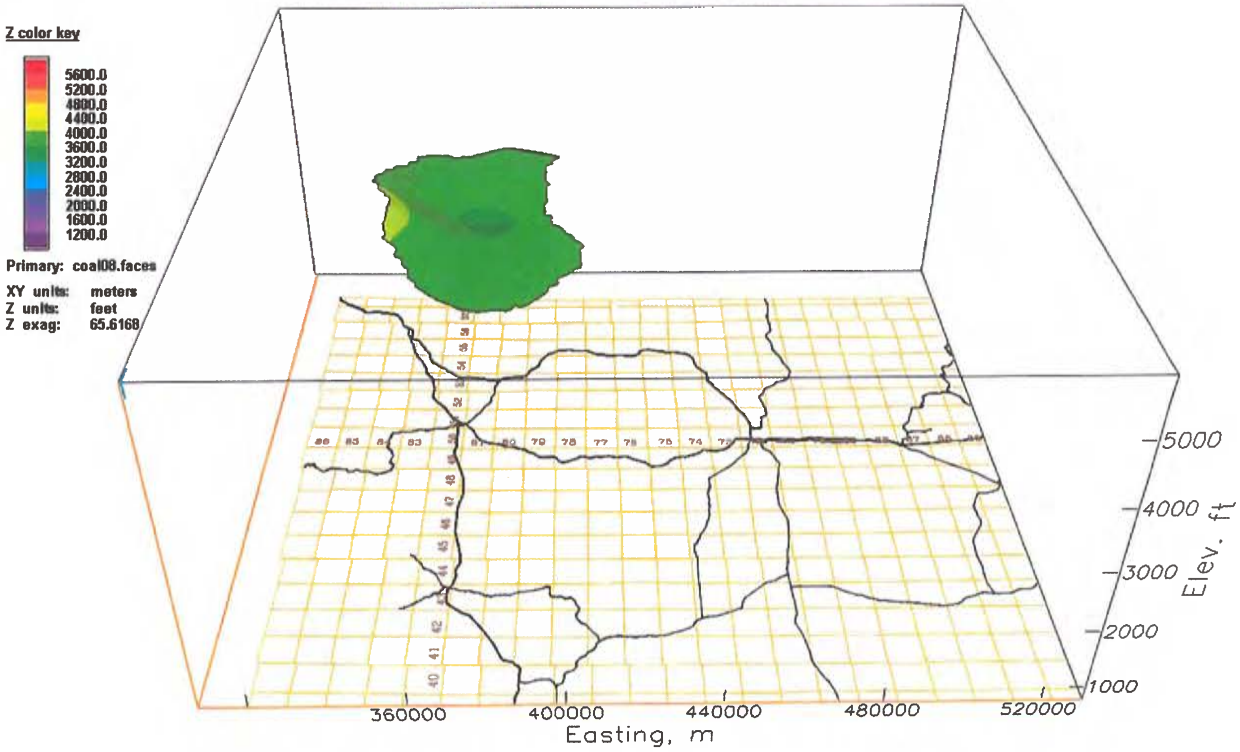


Figure 4-12. View generated by coal bed spatial model showing the distribution and orientation of the Arvada coal where it is 5 feet thick or thicker.

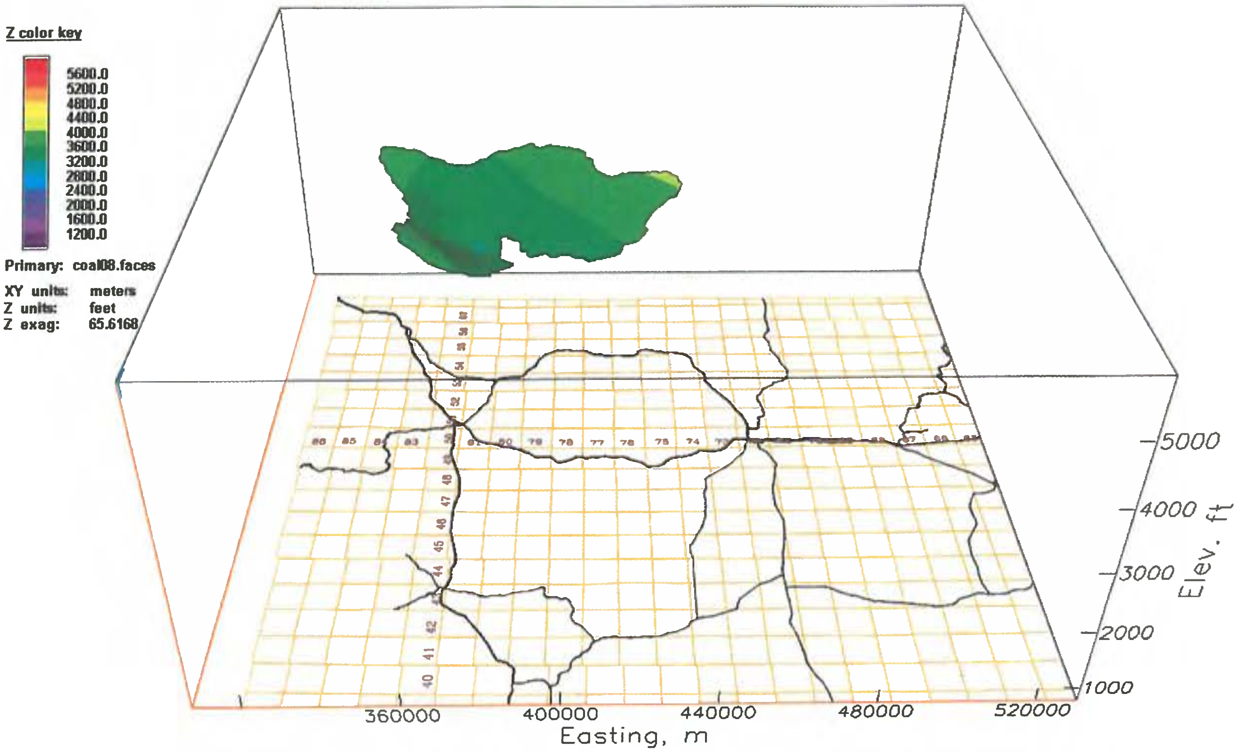


Figure 4-13. View generated by coal bed spatial model showing the distribution and orientation of the unnamed coal where it is 5 feet thick or thicker.

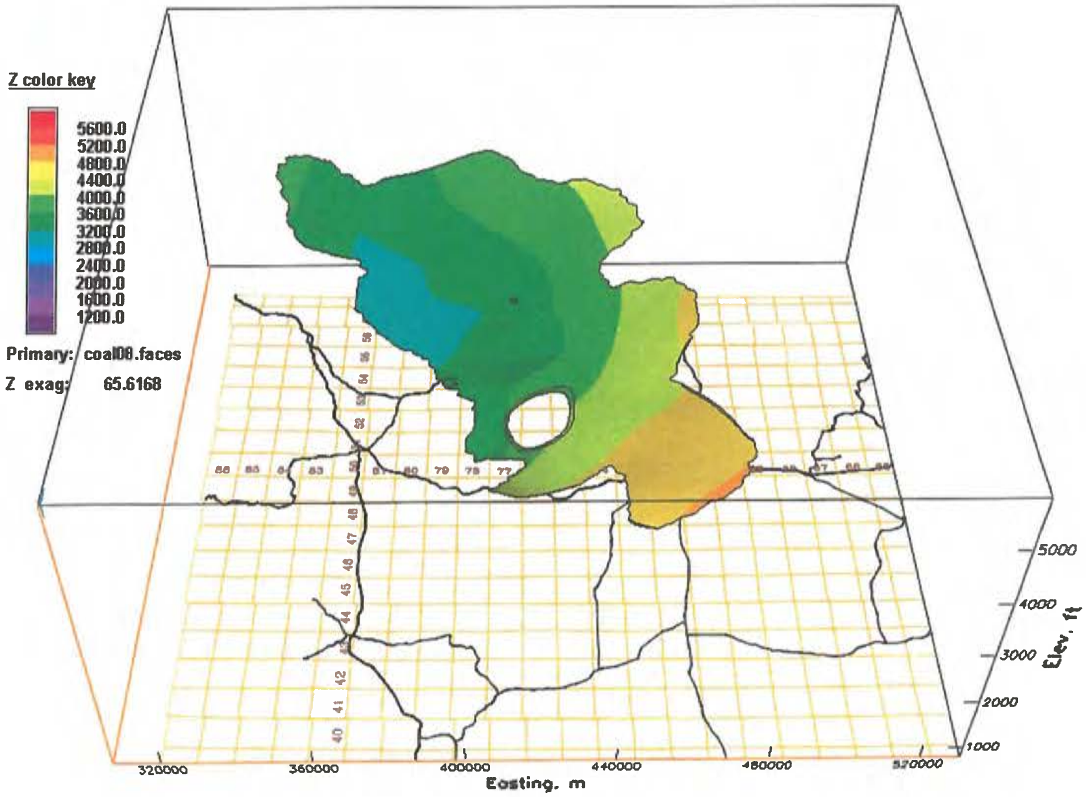


Figure 4-14. View generated by coal bed spatial model showing the distribution and orientation of the Upper Roland coal where it is 5 feet thick or thicker.

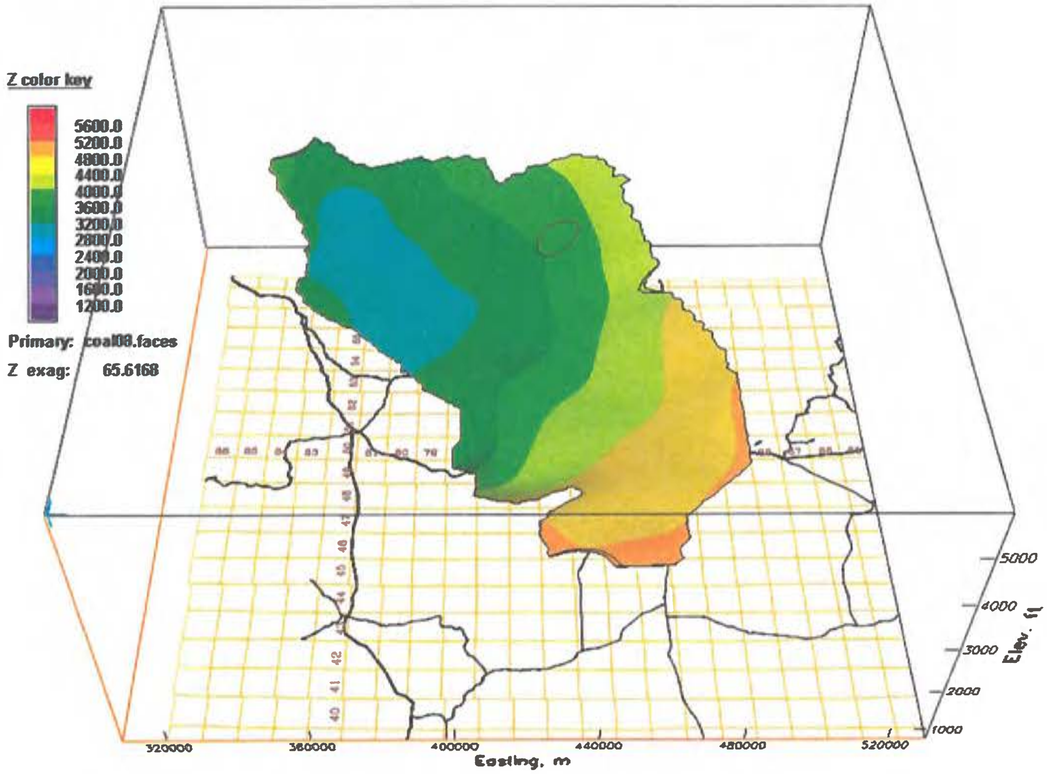


Figure 4-15. View generated by coal bed spatial model showing the distribution and orientation of the Roland of Baker coal where it is 5 feet thick or thicker.

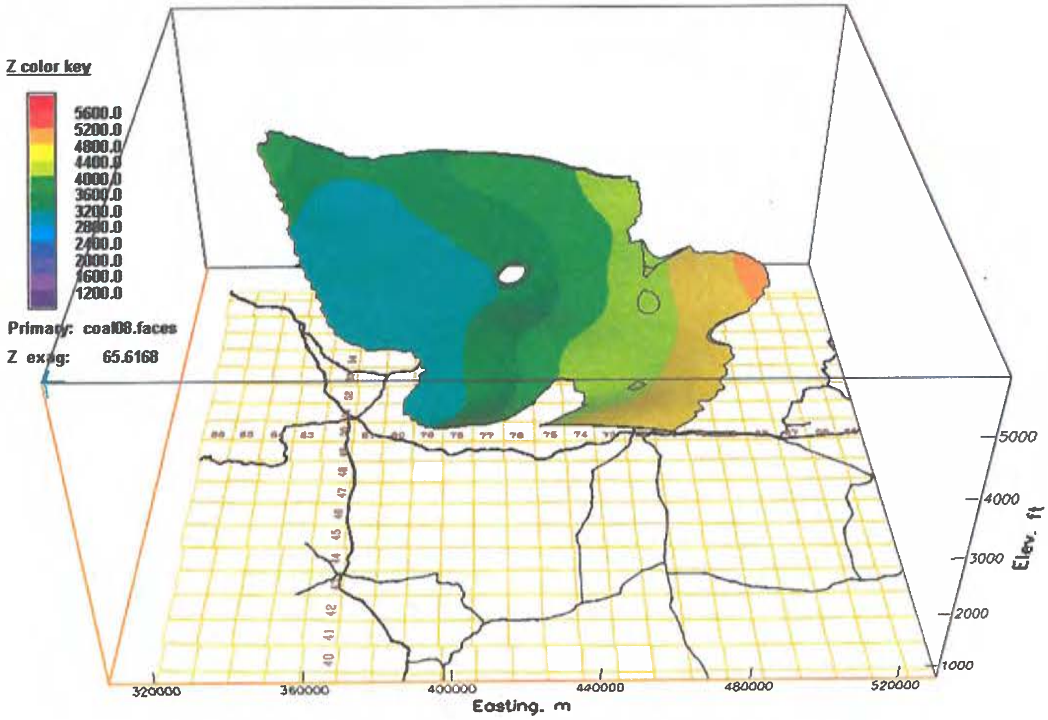


Figure 4-16. View generated by coal bed spatial model showing the distribution and orientation of the Roland of Taff coal where it is 5 feet thick or thicker.

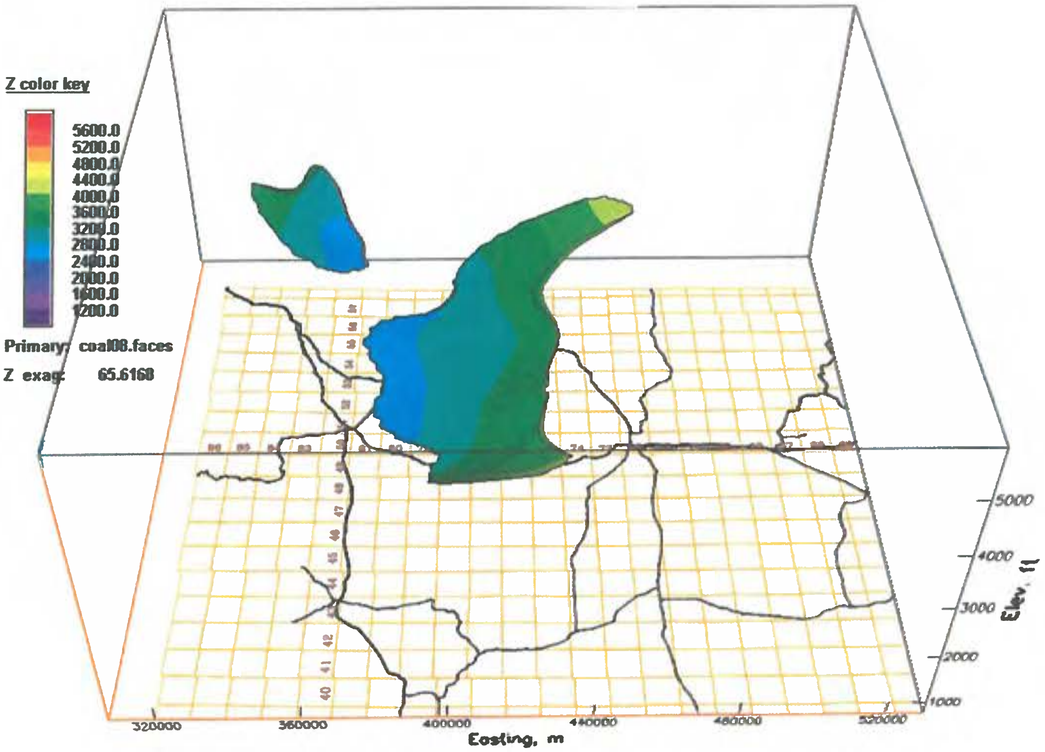


Figure 4-17. View generated by coal bed spatial model showing the distribution and orientation of the Smith Rider coal where it is 5 feet thick or thicker.

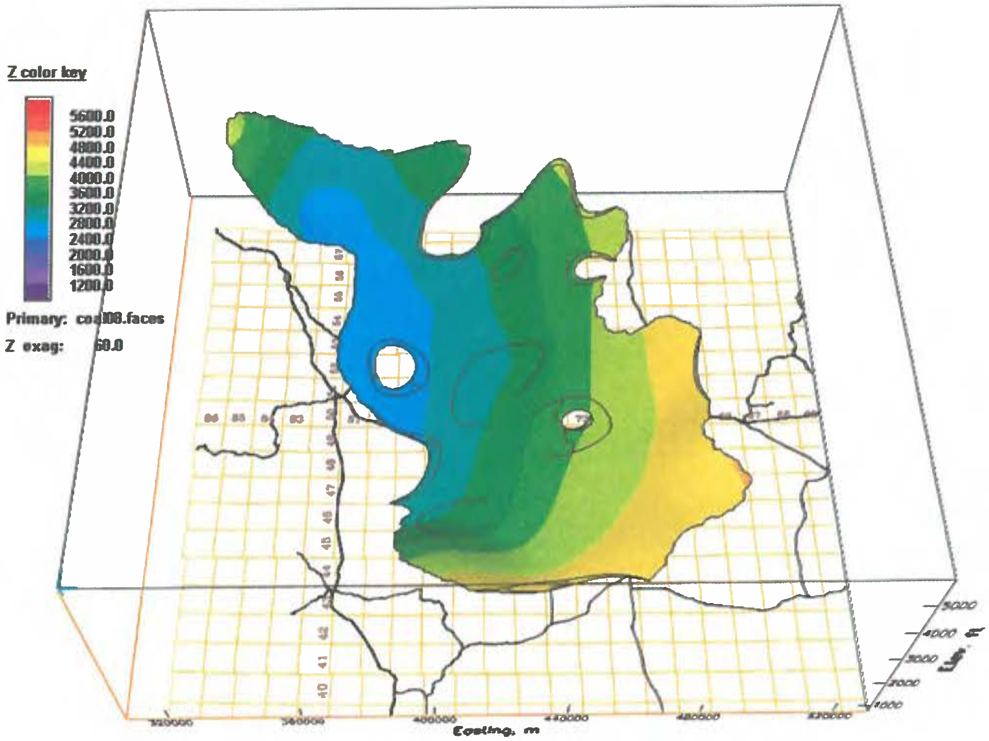


Figure 4-18. View generated by coal bed spatial model showing the distribution and orientation of the Smith/Big George coal where it is 5 feet thick or thicker.

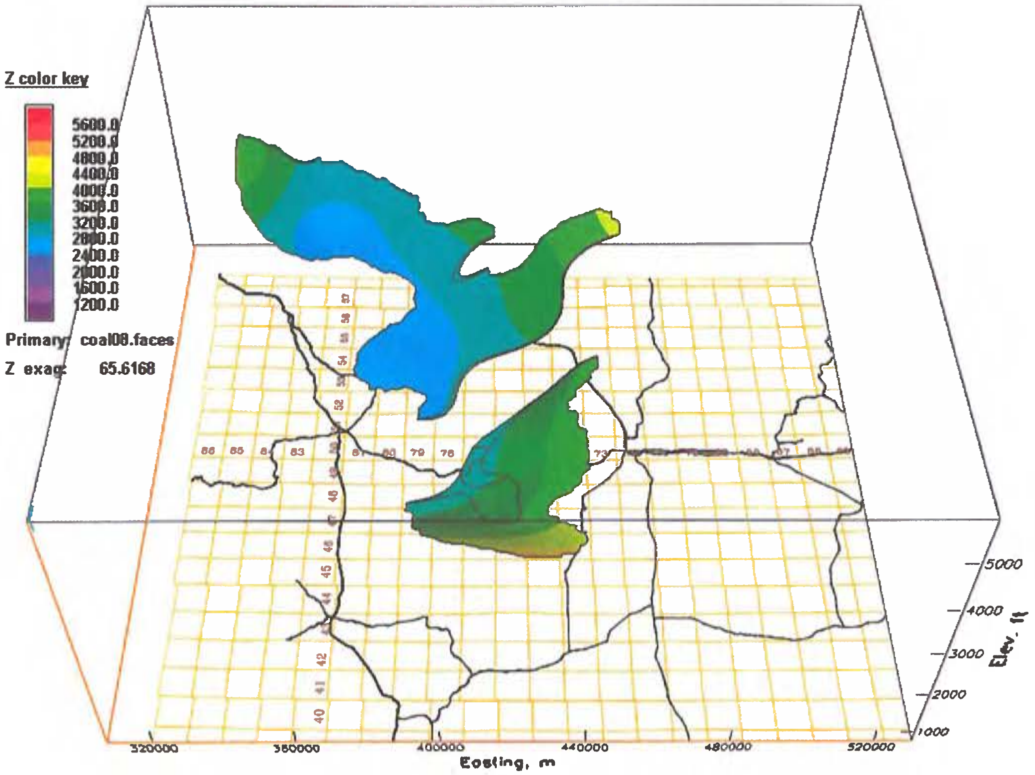


Figure 4-19. View generated by coal bed spatial model showing the distribution and orientation of the Lower Smith coal where it is 5 feet thick or thicker.

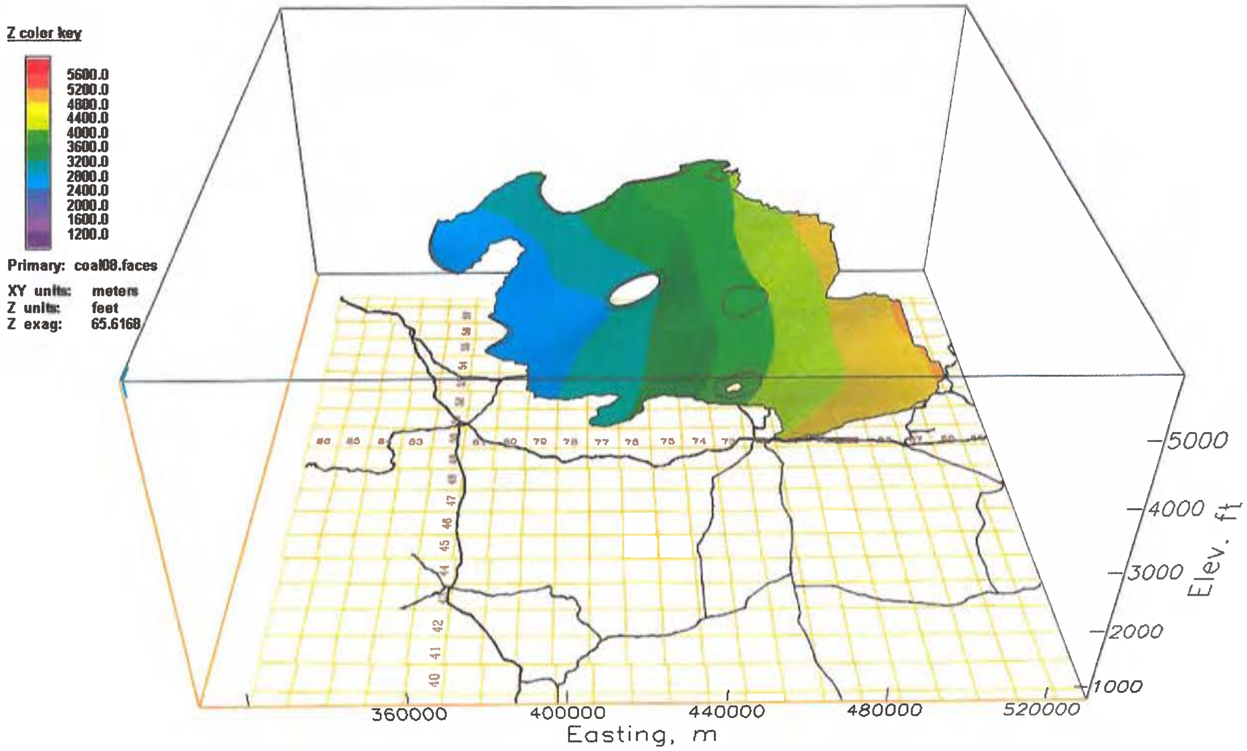


Figure 4-20. View generated by coal bed spatial model showing the distribution and orientation of the Anderson Rider coal where it is 5 feet thick or thicker.

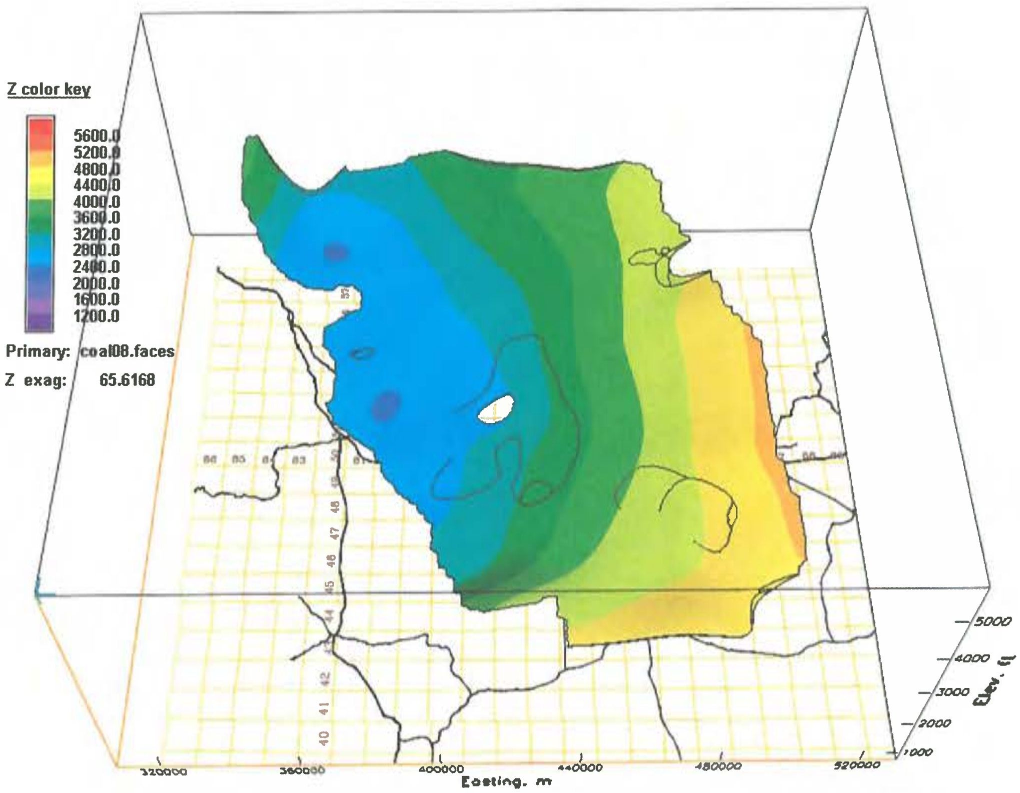


Figure 4-21. View generated by coal bed spatial model showing the distribution and orientation of the Anderson coal where it is 5 feet thick or thicker.

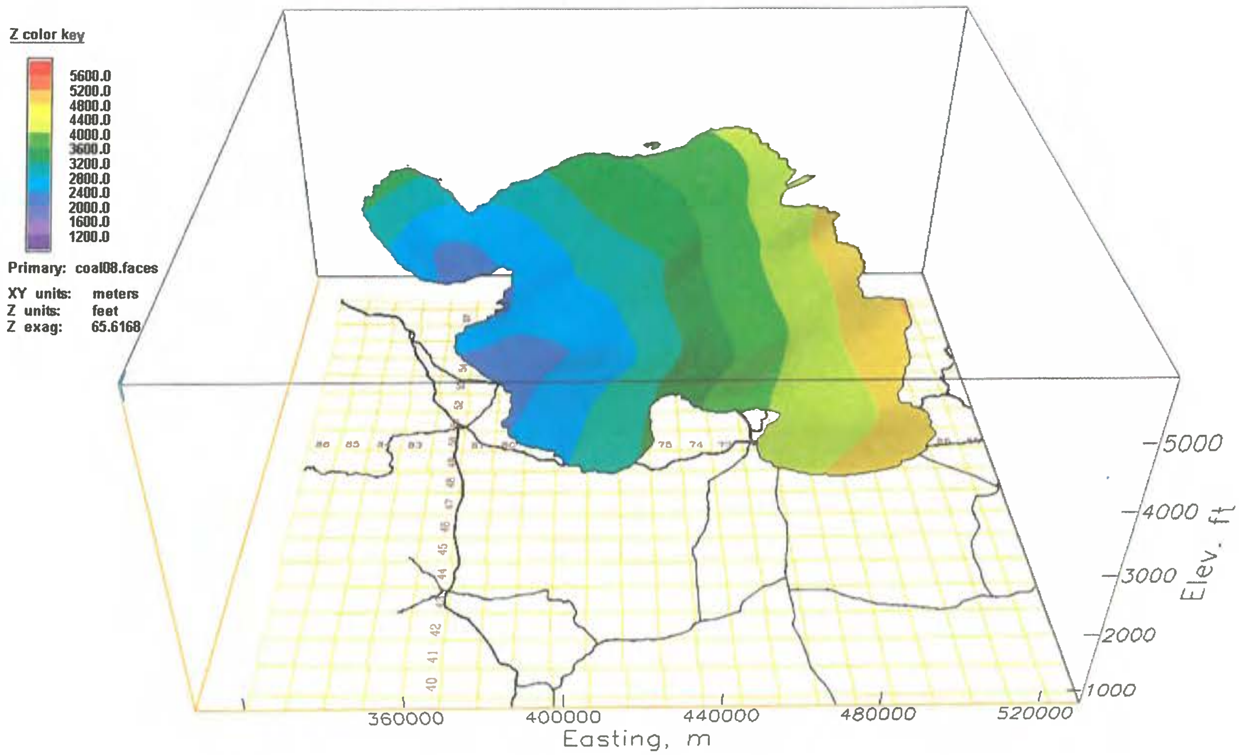


Figure 4-22. View generated by coal bed spatial model showing the distribution and orientation of the Lower Anderson coal where it is 5 feet thick or thicker.

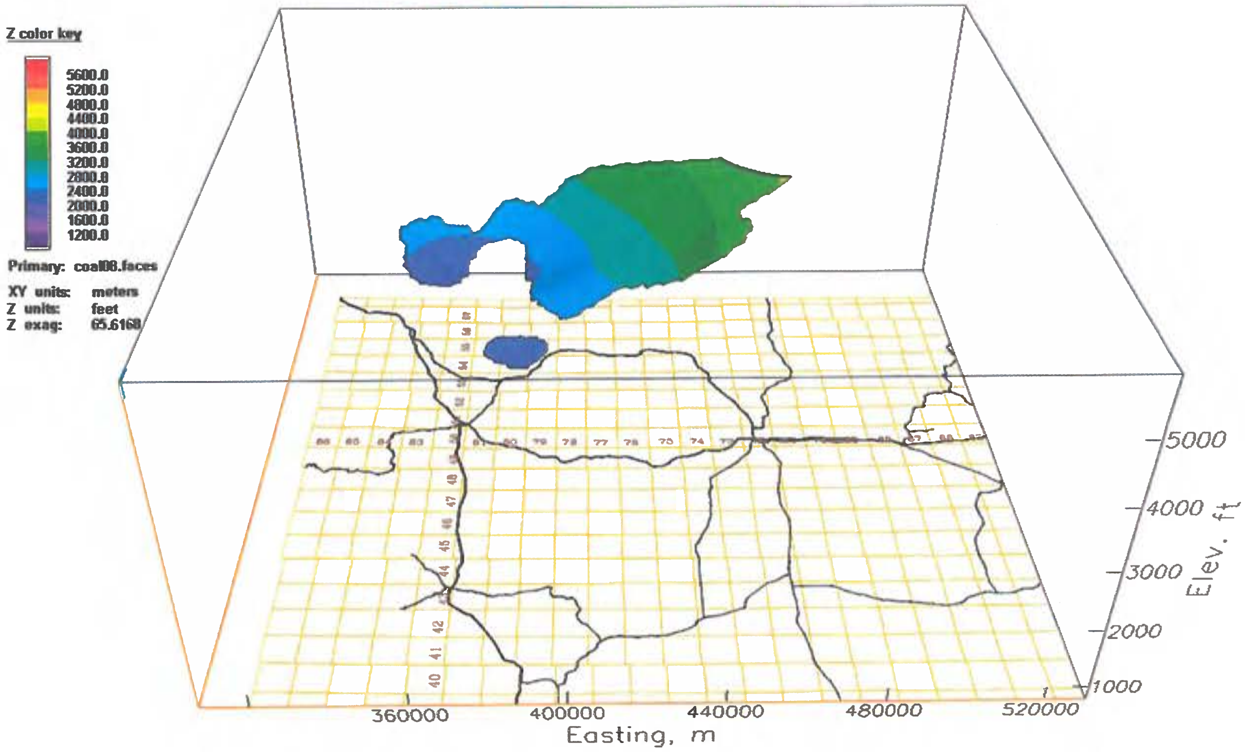


Figure 4-23. View generated by coal bed spatial model showing the distribution and orientation of the Canyon Rider coal where it is 5 feet thick or thicker.

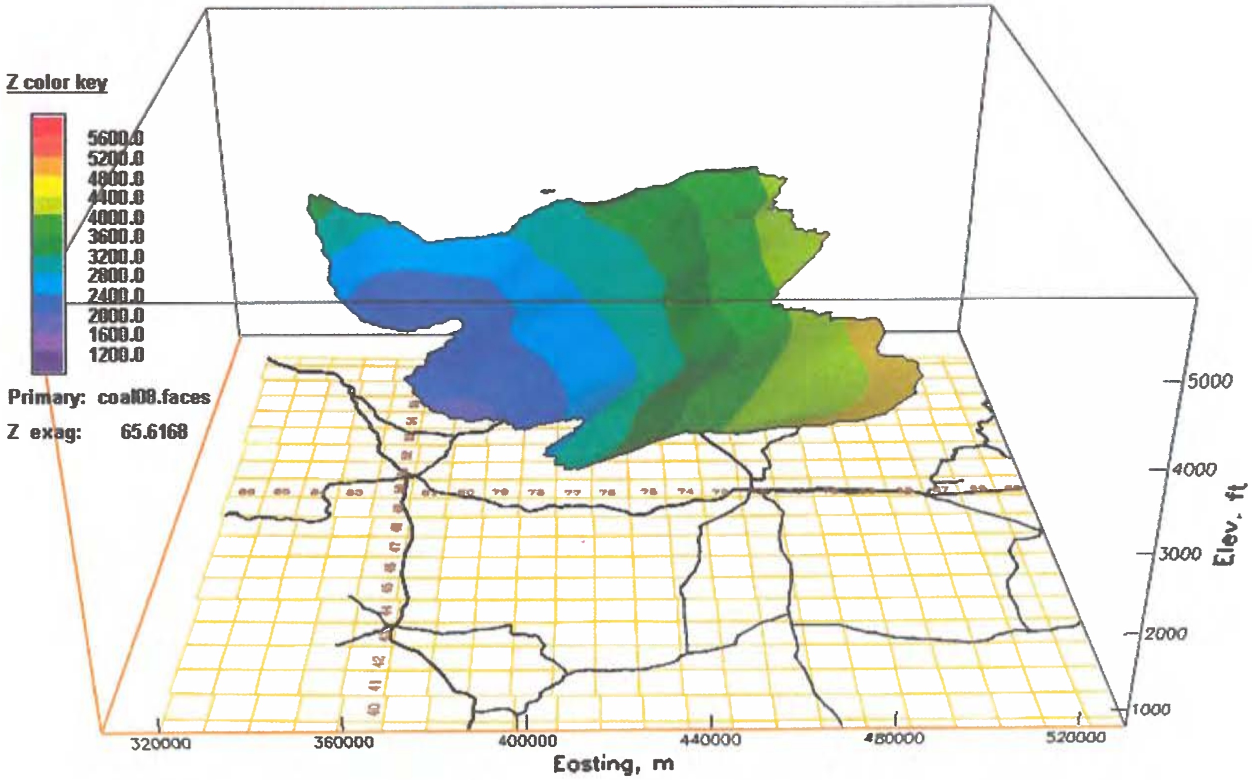


Figure 4-24. View generated by coal bed spatial model showing the distribution and orientation of the Canyon coal where it is 5 feet thick or thicker.

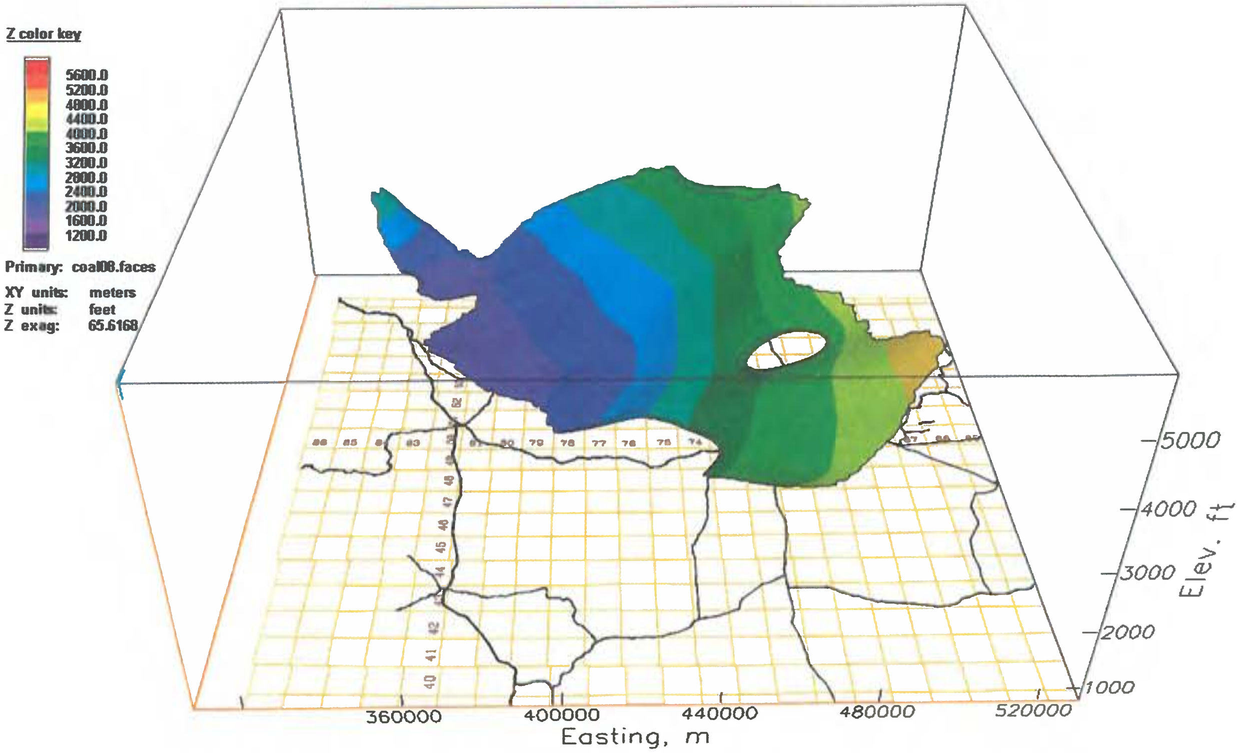


Figure 4-25. View generated by coal bed spatial model showing the distribution and orientation of the Cook coal where it is 5 feet thick or thicker.

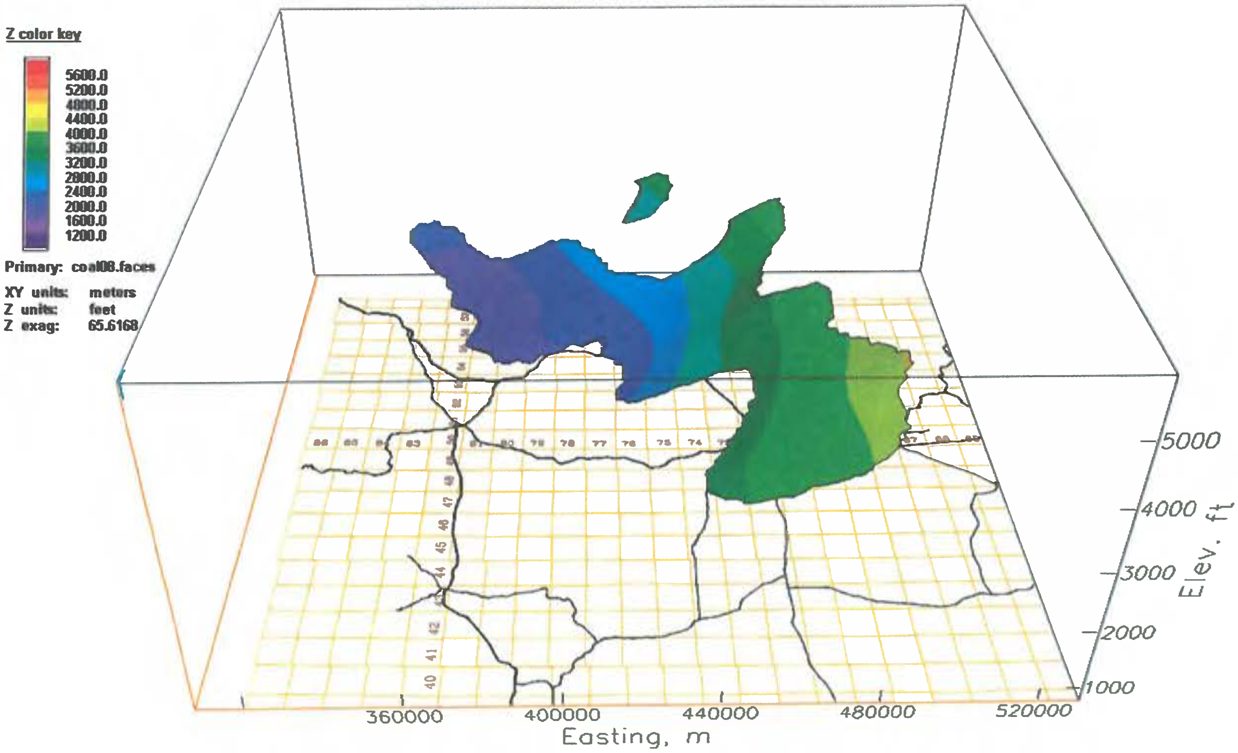


Figure 4-26. View generated by coal bed spatial model showing the distribution and orientation of the Lower Cook coal where it is 5 feet thick or thicker.

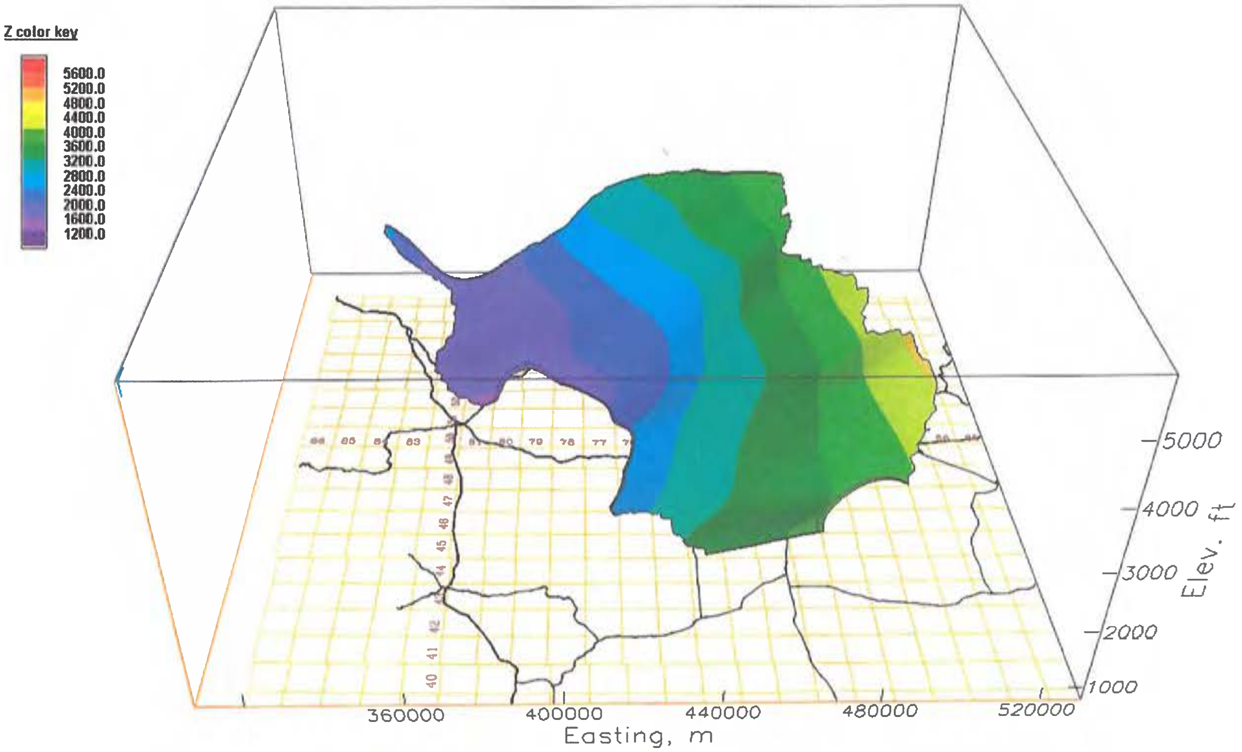


Figure 4-27. View generated by coal bed spatial model showing the distribution and orientation of the Wall coal where it is 5 feet thick or thicker.

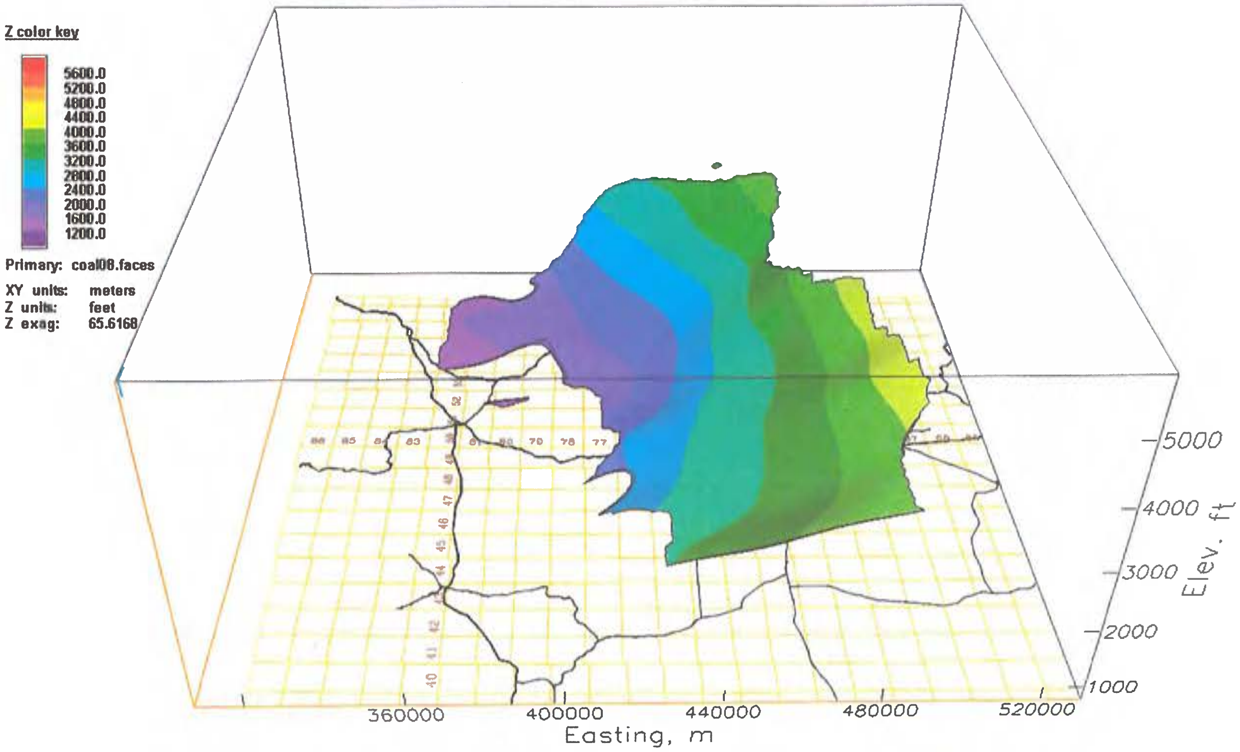


Figure 4-28. View generated by coal bed spatial model showing the distribution and orientation of the Lower Wall coal where it is 5 feet thick or thicker.

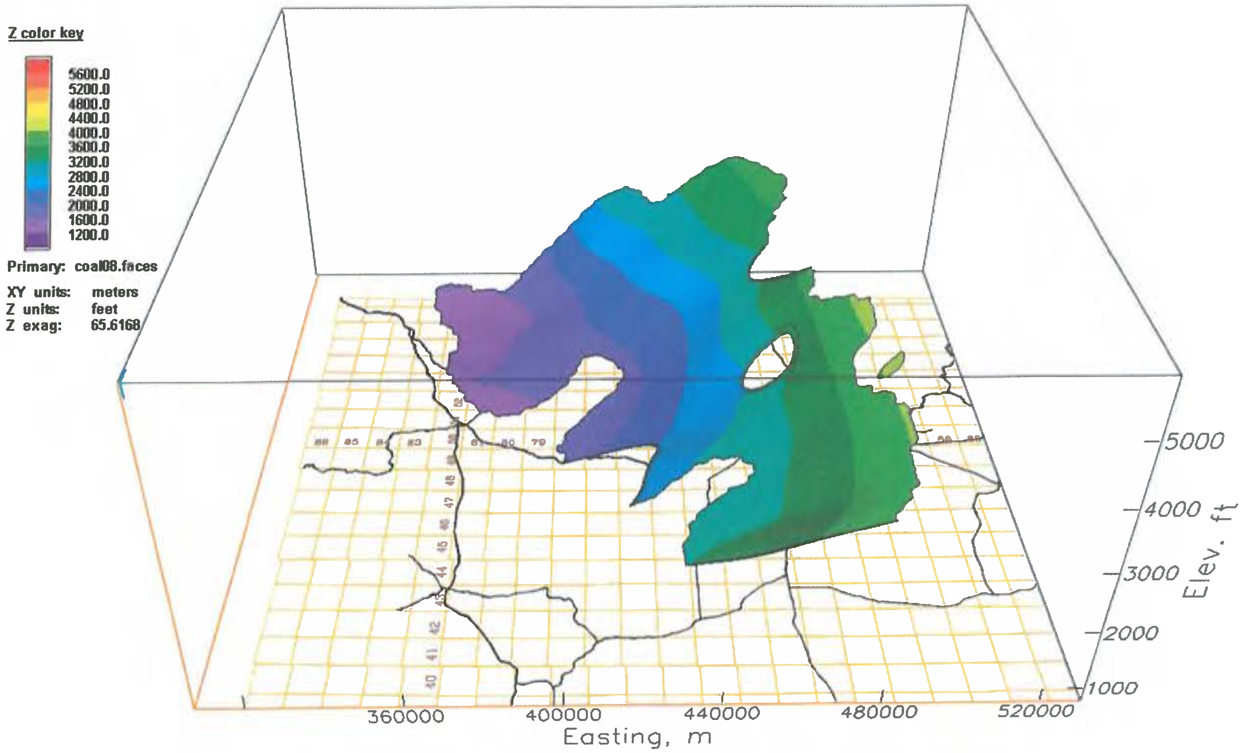


Figure 4-29. View generated by coal bed spatial model showing the distribution and orientation of the Pawnee coal where it is 5 feet thick or thicker.

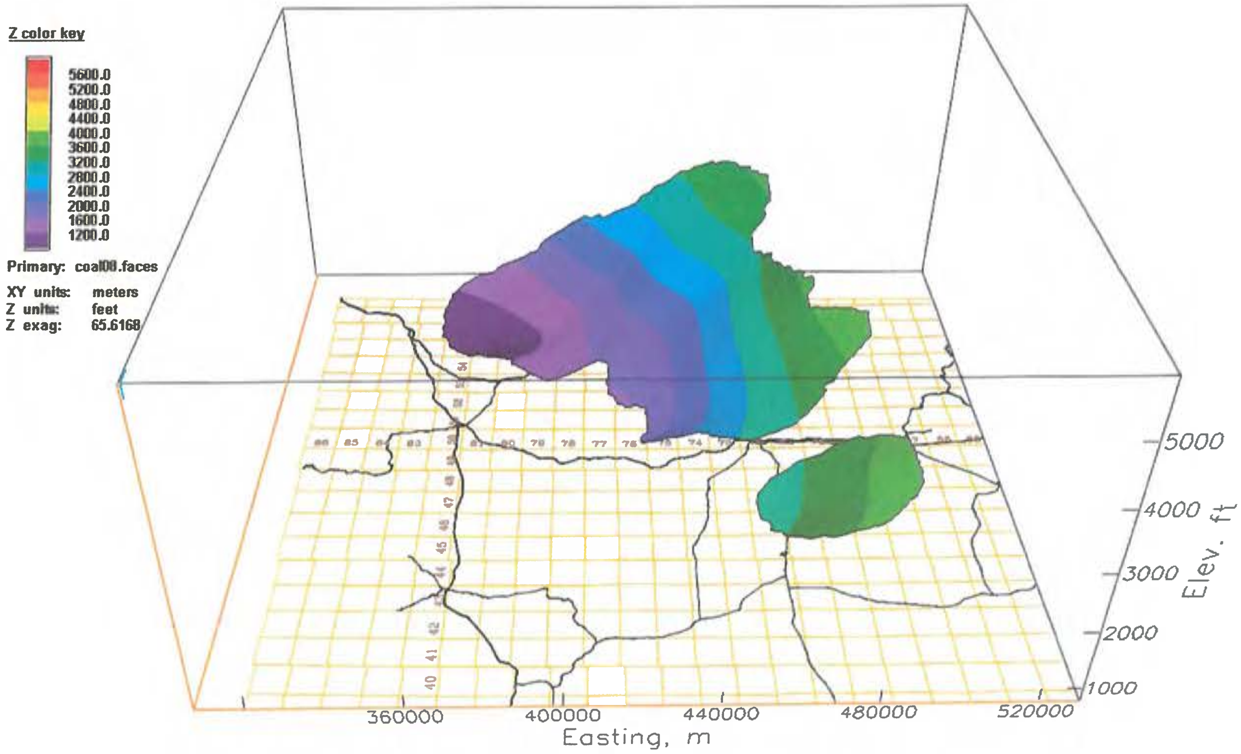


Figure 4-30. View generated by coal bed spatial model showing the distribution and orientation of the Moyer coal where it is 5 feet thick or thicker.

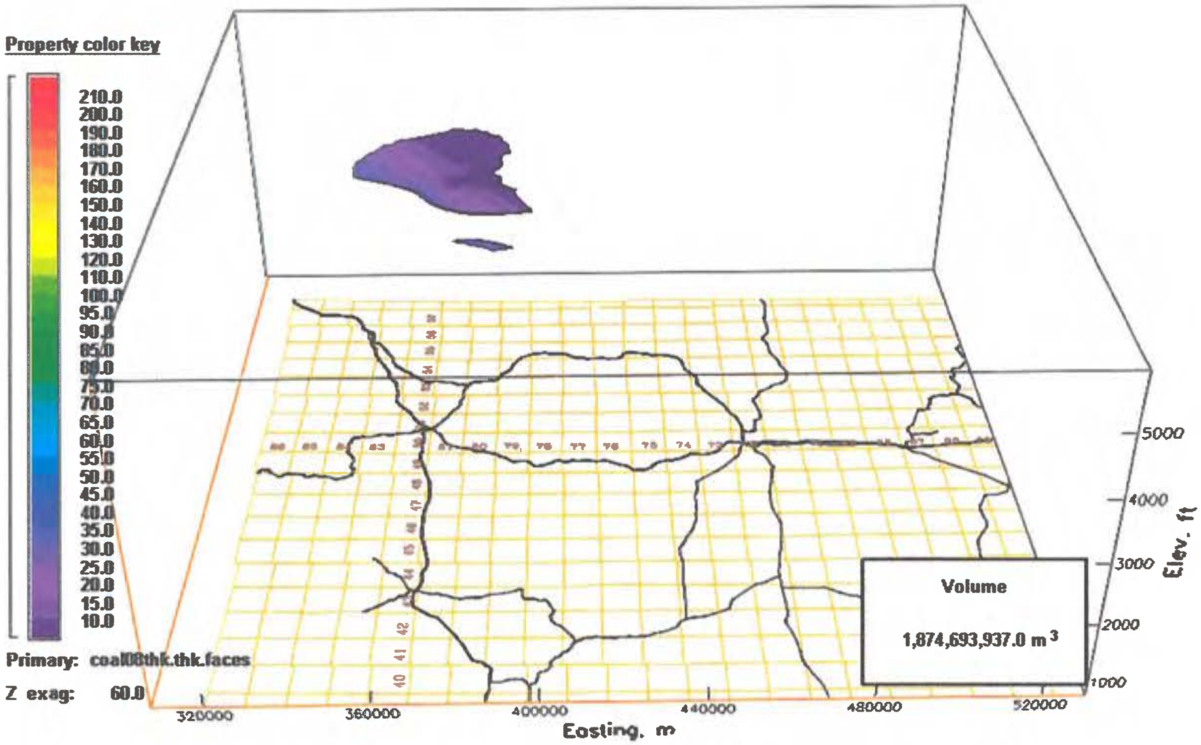


Figure 4-31. Inclined view of Ulm coal bed thickness (feet) generated by the coal thickness model.

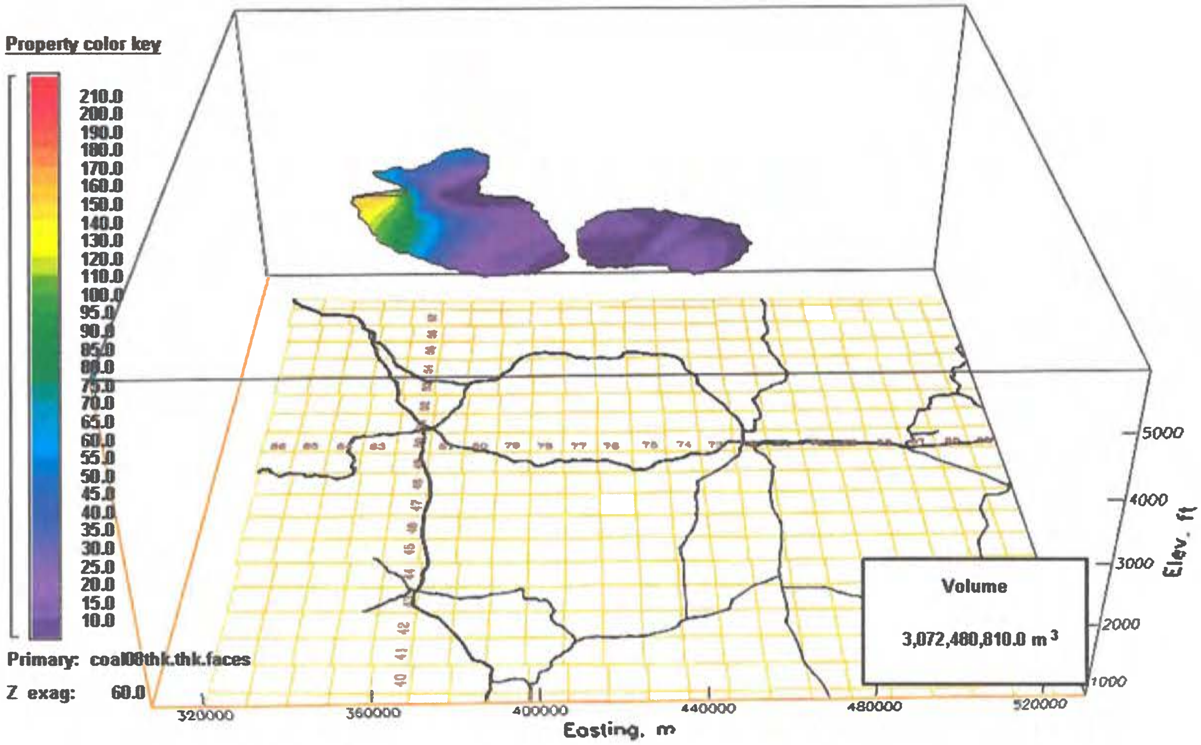


Figure 4-32. Inclined view of Buffalo Cameron coal bed thickness (feet) generated by the coal thickness model.

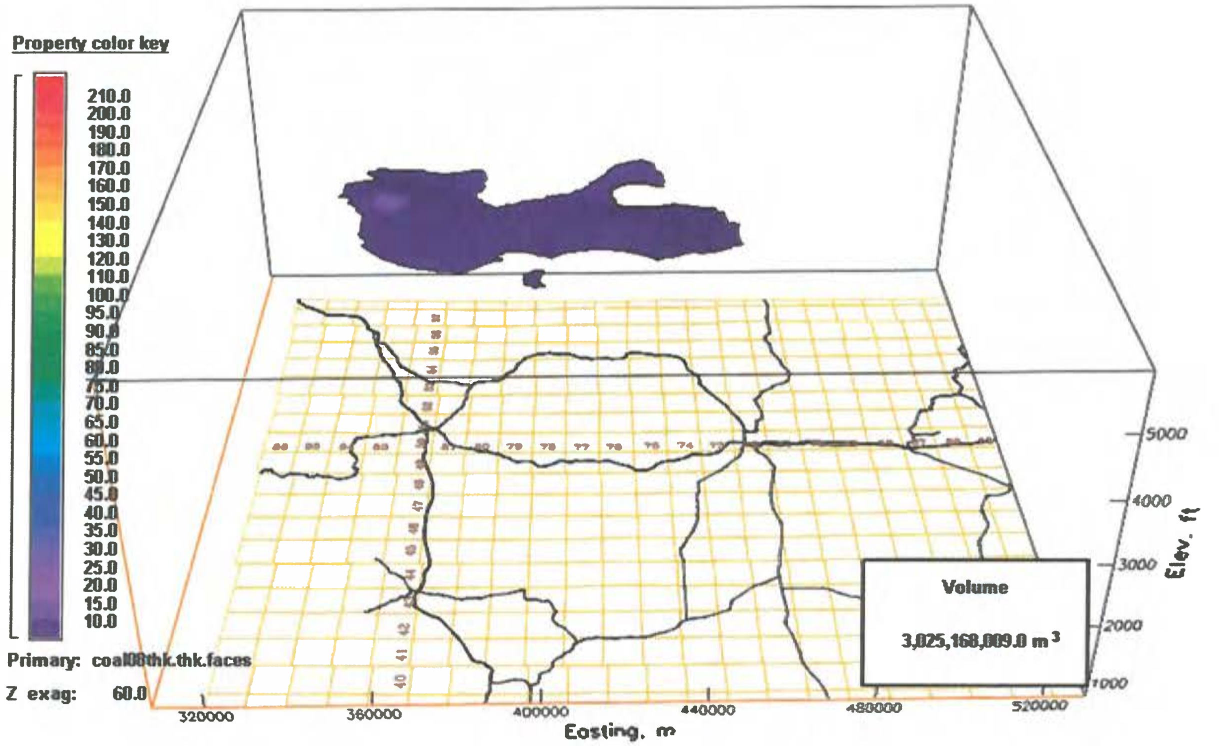


Figure 4-33. Inclined view of Murray coal bed thickness (feet) generated by the coal thickness model.

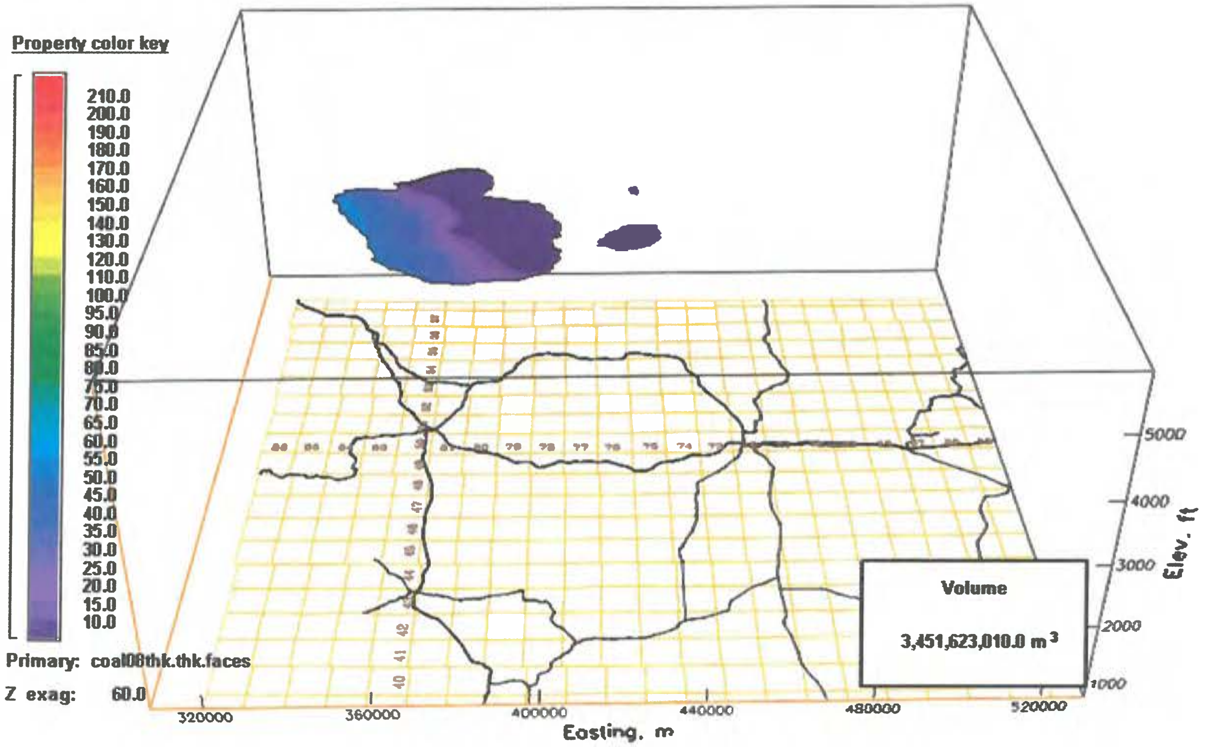


Figure 4-34. Inclined view of Ucross coal bed thickness (feet) generated by the coal thickness model.

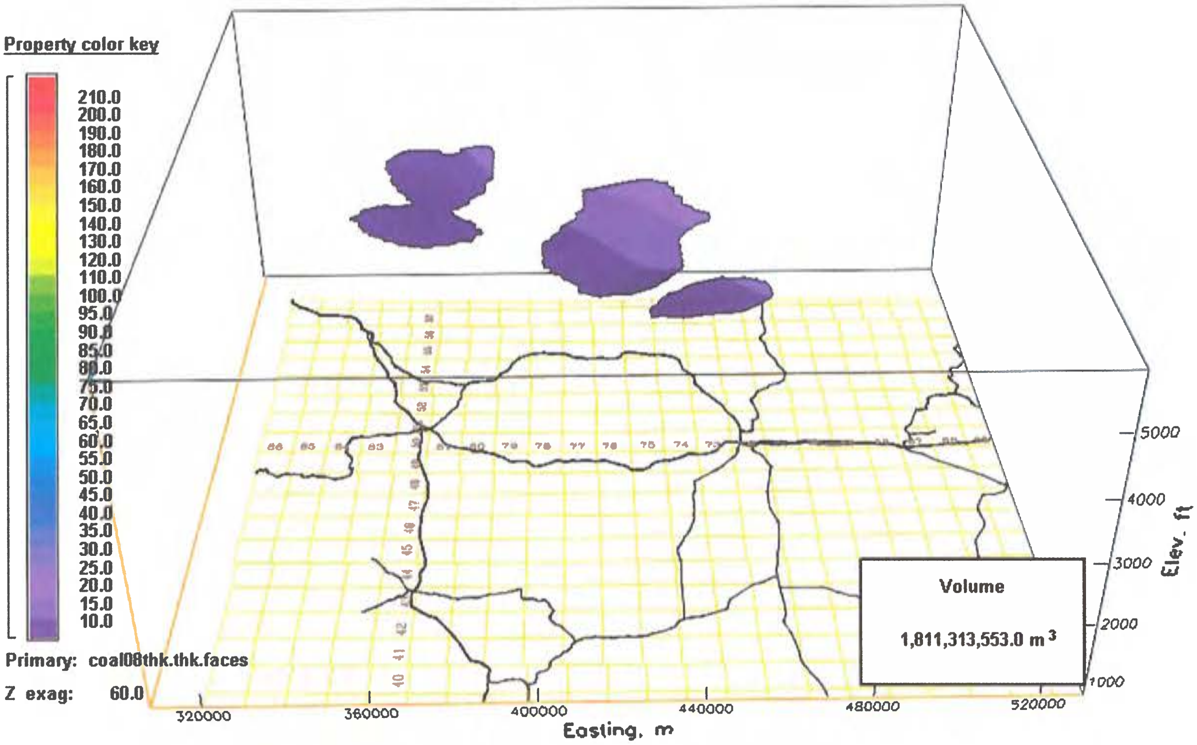


Figure 4-35. Inclined view of Felix Rider coal bed thickness (feet) generated by the coal thickness model.

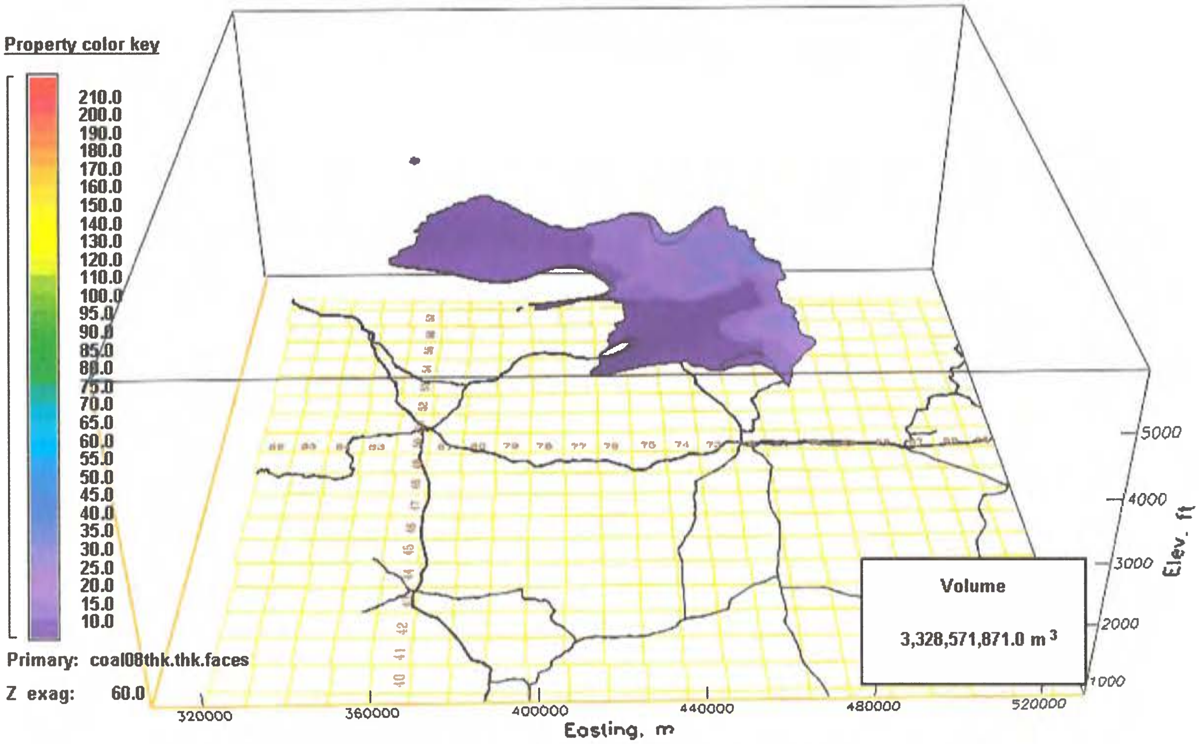


Figure 4-36. Inclined view of Upper Felix coal bed thickness (feet) generated by the coal thickness model.

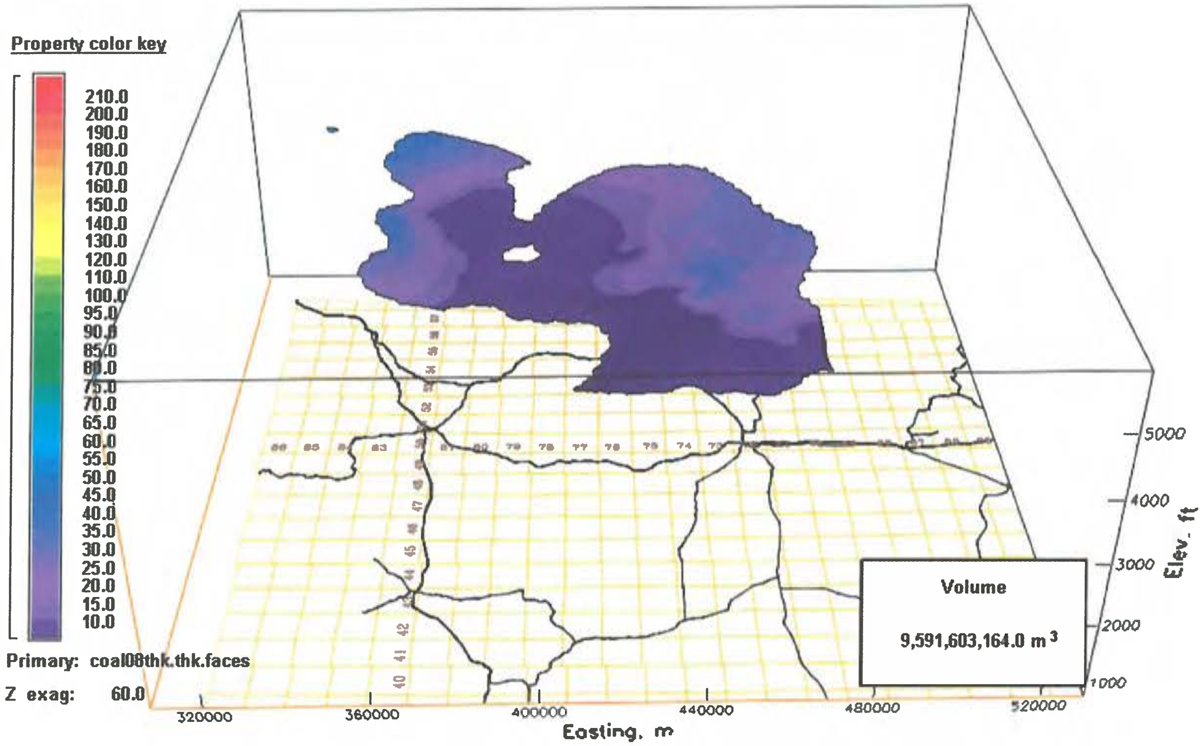


Figure 4-37. Inclined view of Felix coal bed thickness (feet) generated by the coal thickness model.

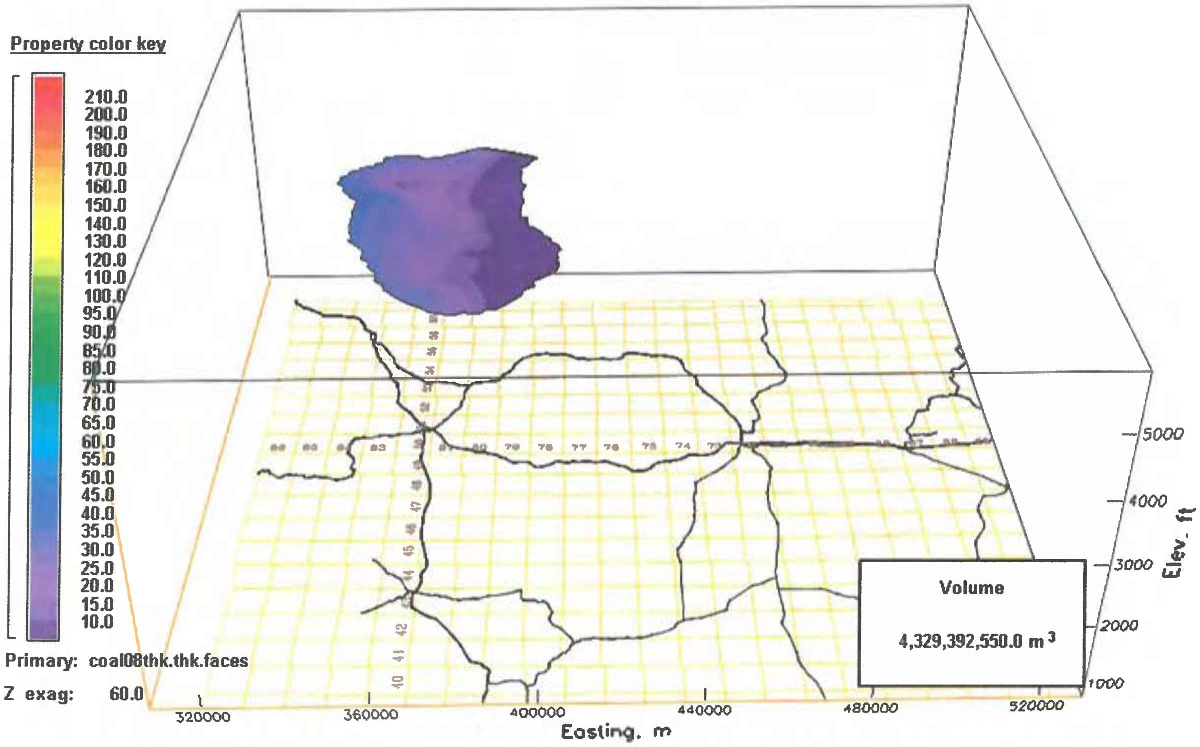


Figure 4-38. Inclined view of Arvada coal bed thickness (feet) generated by the coal thickness model.

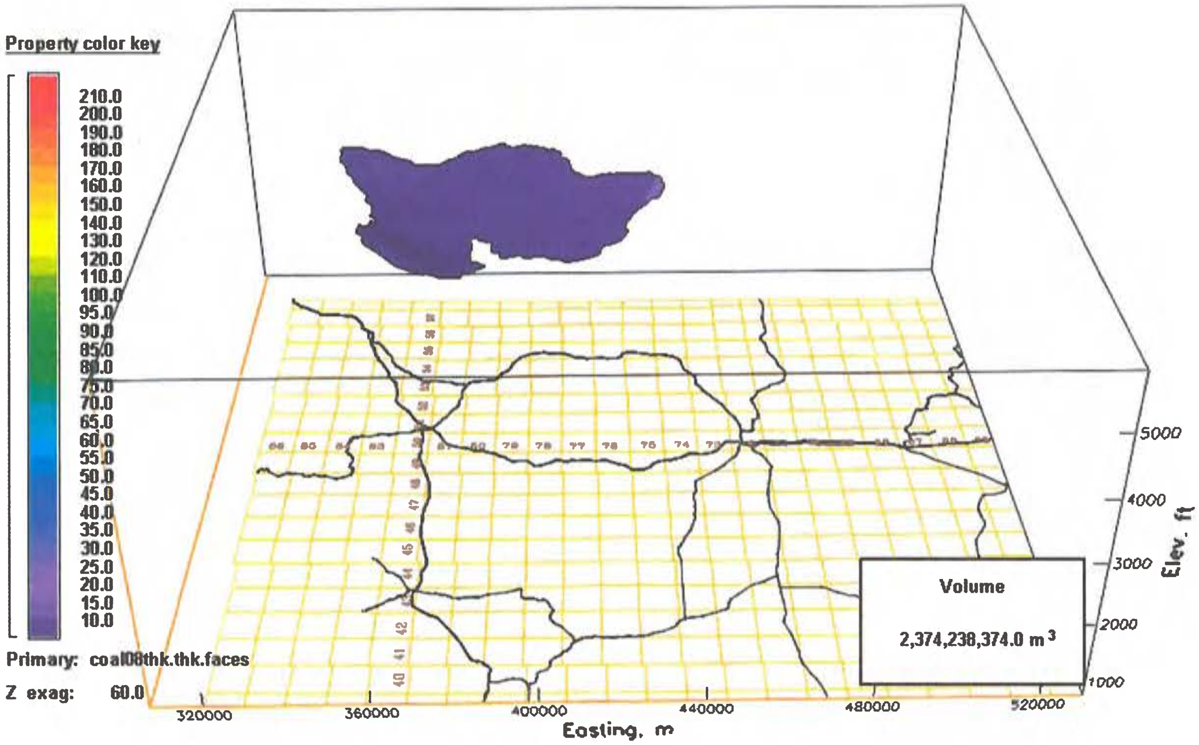


Figure 4-39. Inclined view of unnamed coal bed thickness (feet) generated by the coal thickness model.

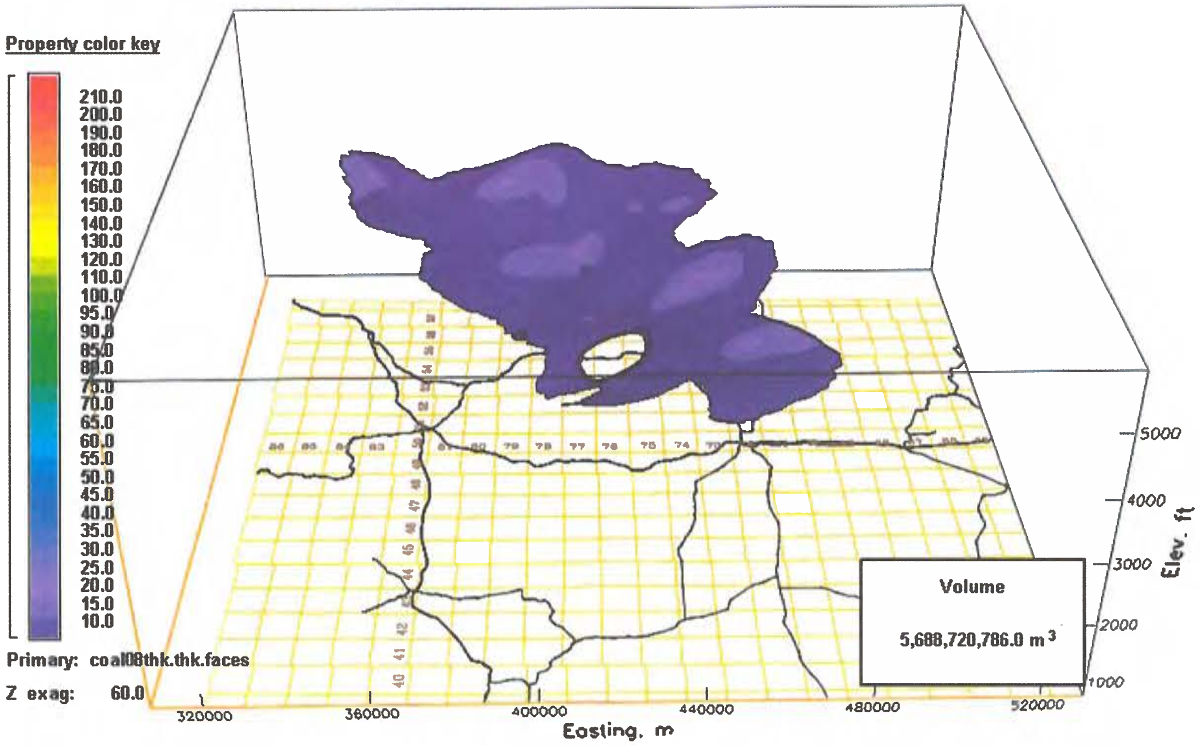


Figure 4-40. Inclined view of Upper Roland coal bed thickness (feet) generated by the coal thickness model.

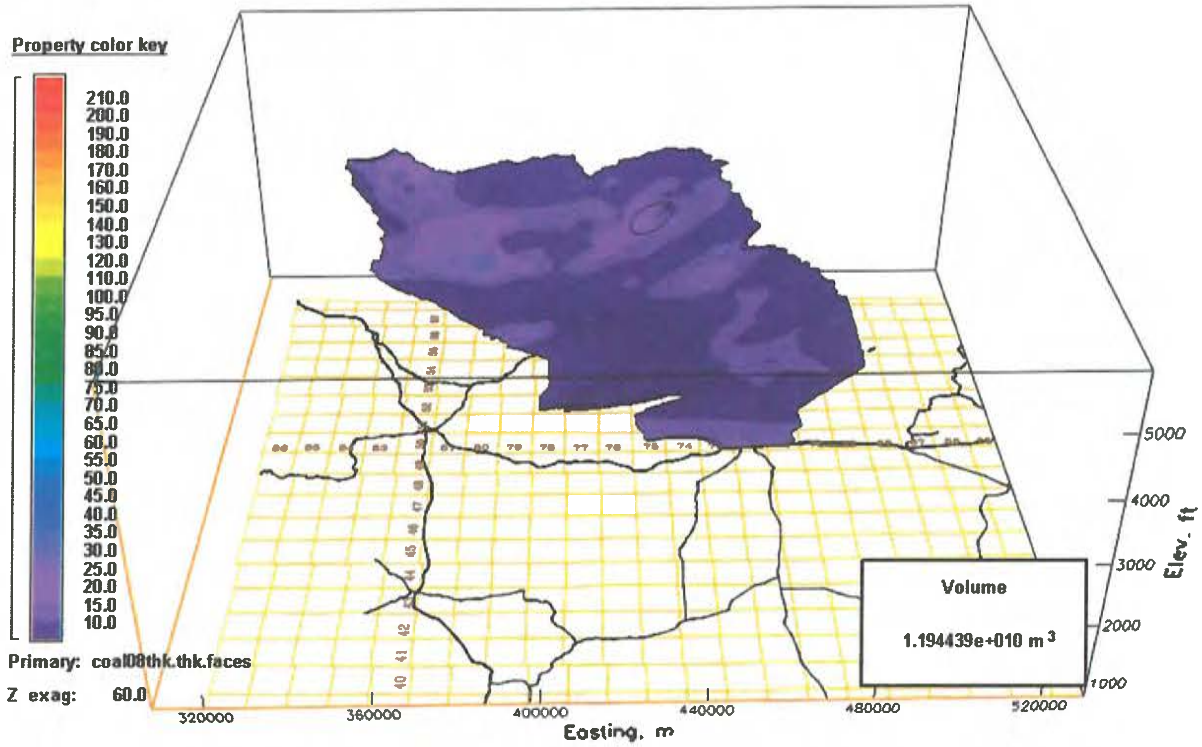


Figure 4-41. Inclined view of Roland of Baker coal bed thickness (feet) generated by the coal thickness model.

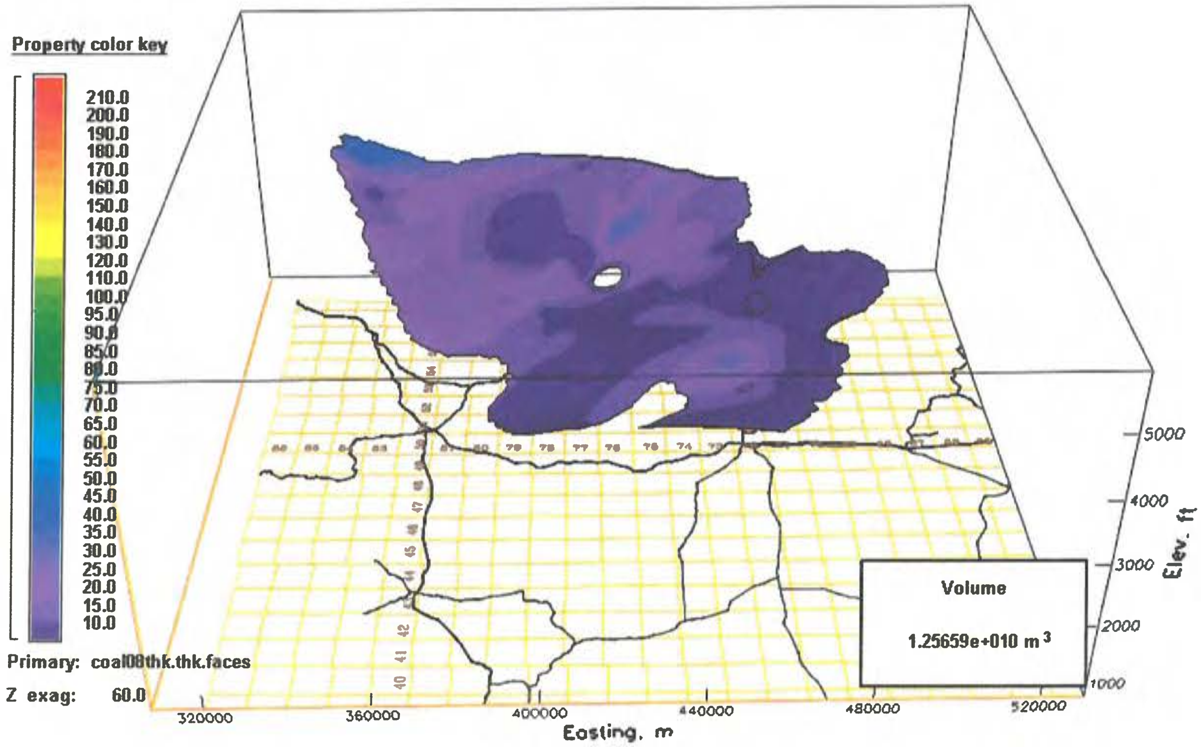


Figure 4-42. Inclined view of Roland of Taff coal bed thickness (feet) generated by the coal thickness model.

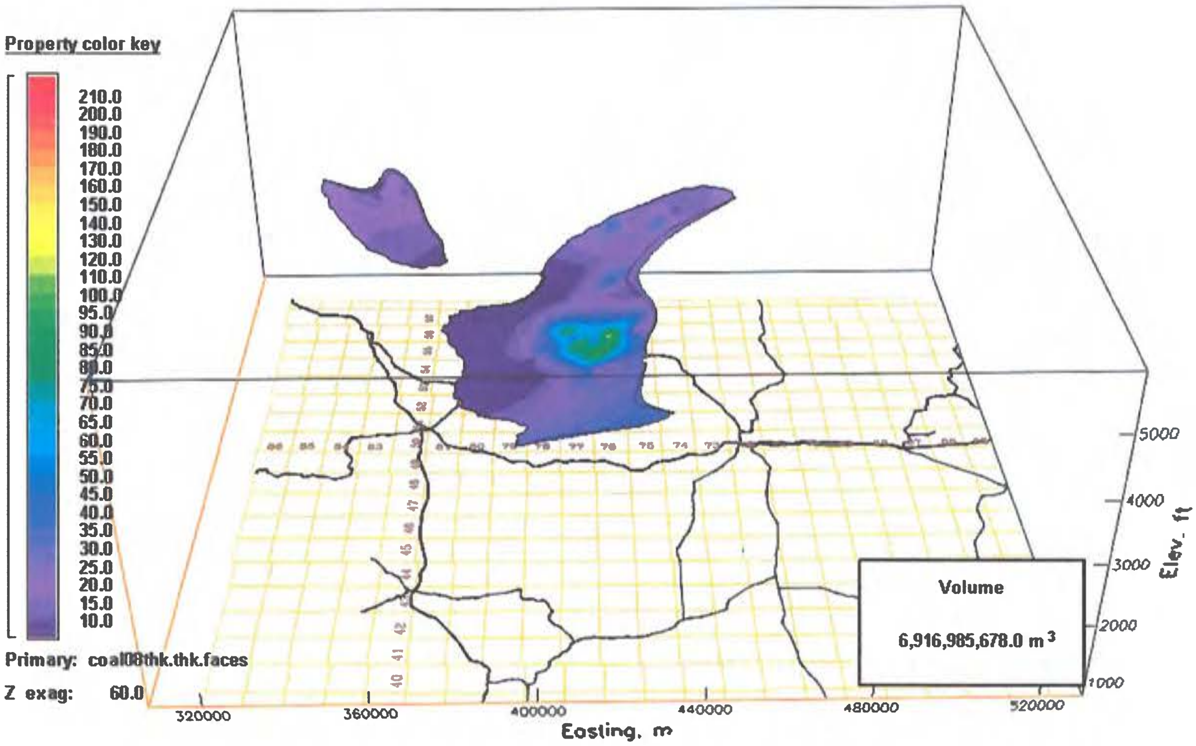


Figure 4-43. Inclined view of Smith Rider coal bed thickness (feet) generated by the coal thickness model.

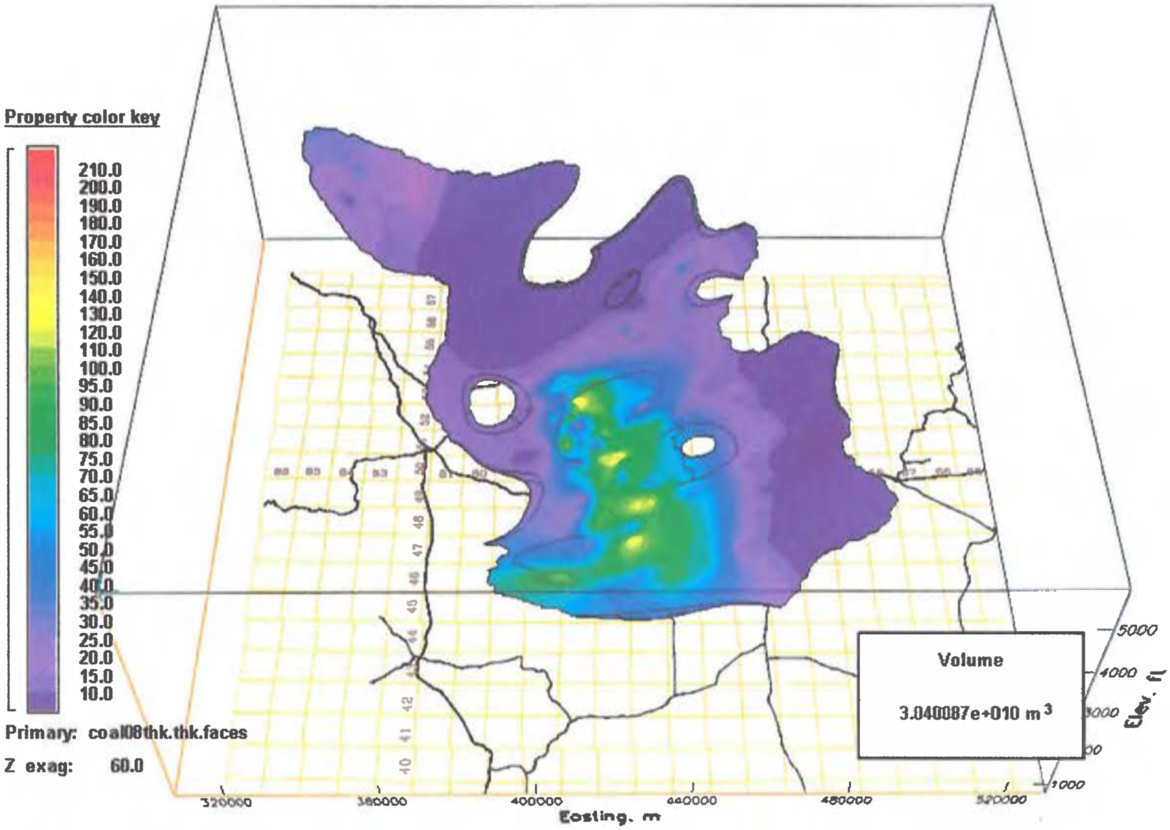


Figure 4-44. Inclined view of Smith/Big George coal bed thickness (feet) generated by the coal thickness model.

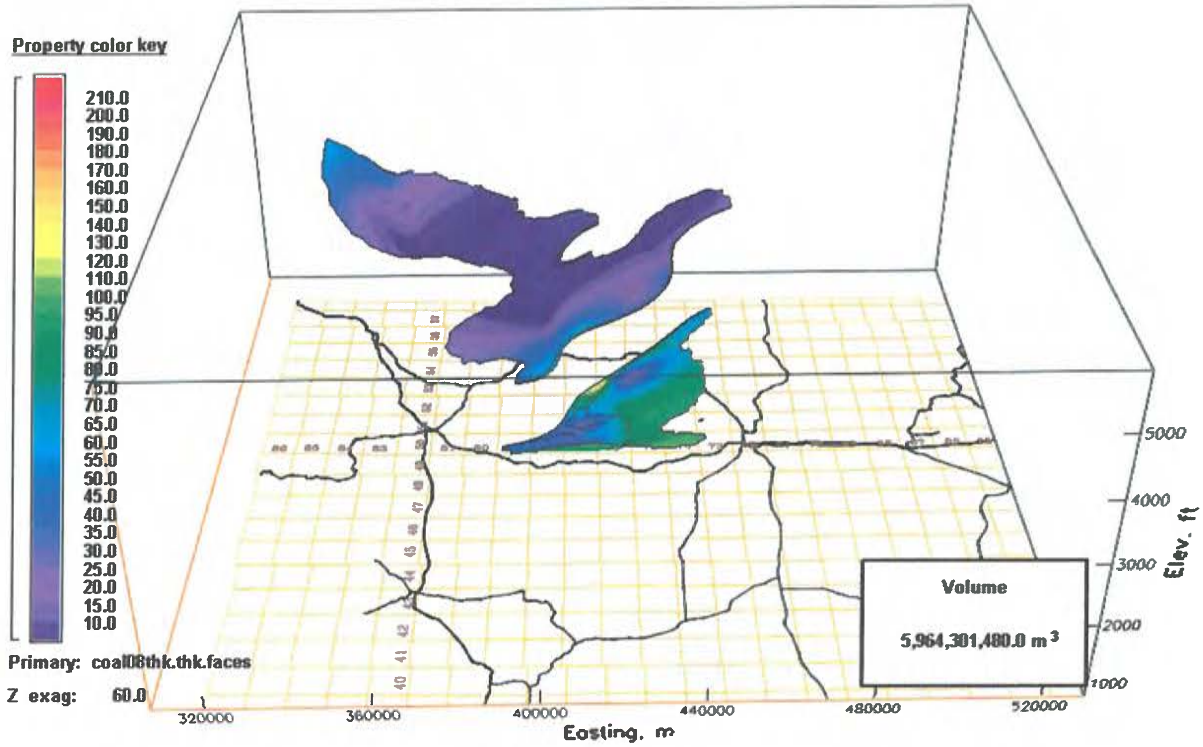


Figure 4-45. Inclined view of Lower Smith coal bed thickness (feet) generated by the coal thickness model.

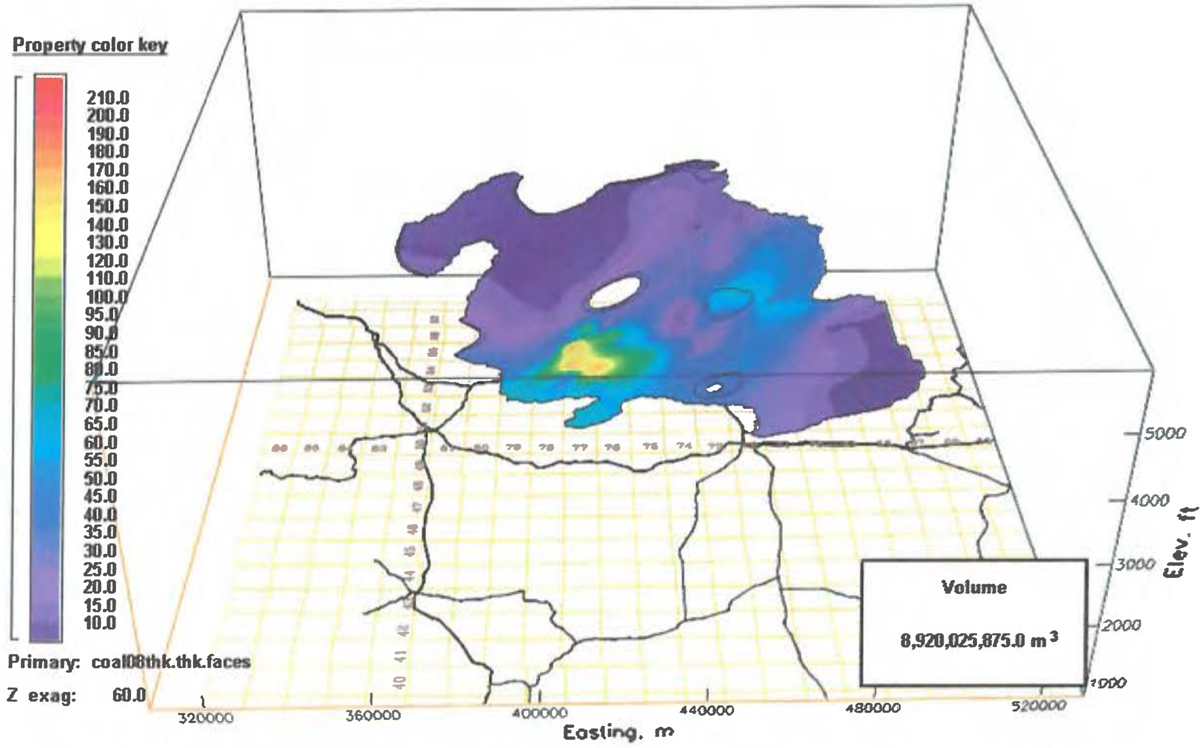


Figure 4-46. Inclined view of Anderson Rider coal bed thickness (feet) generated by the coal thickness model.

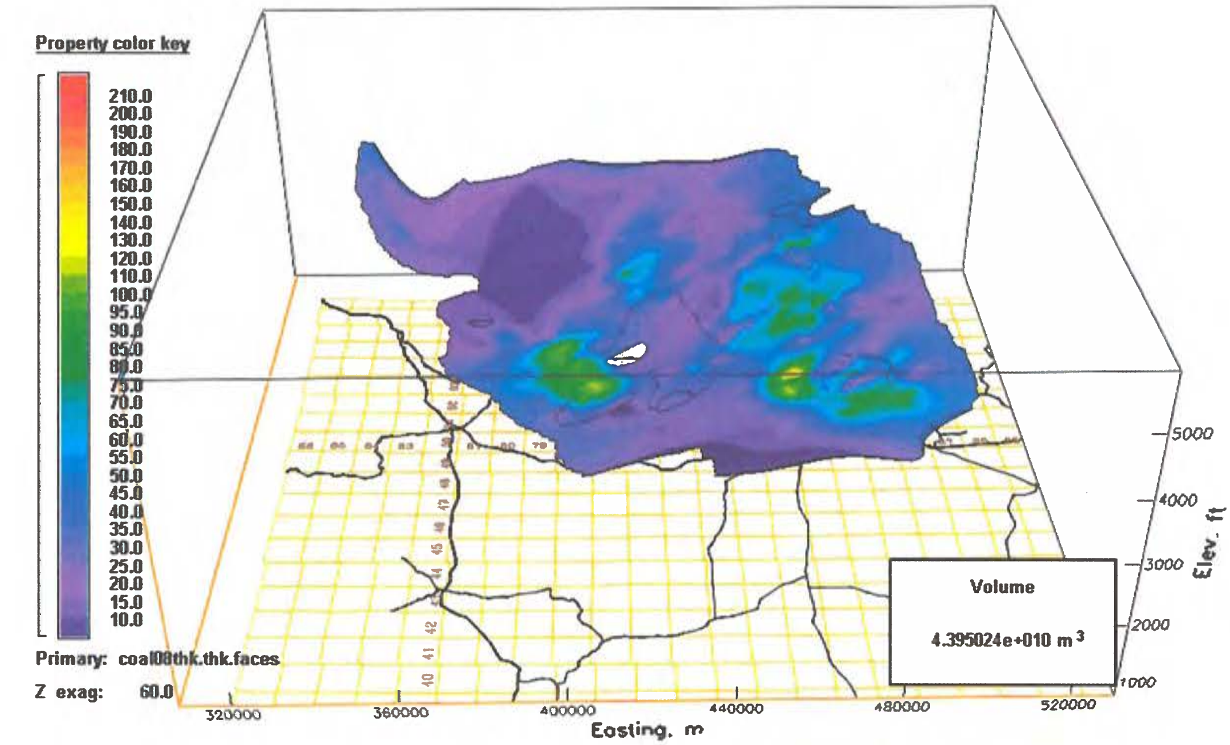


Figure 4-47. Inclined view of Anderson coal bed thickness (feet) generated by the coal thickness model.

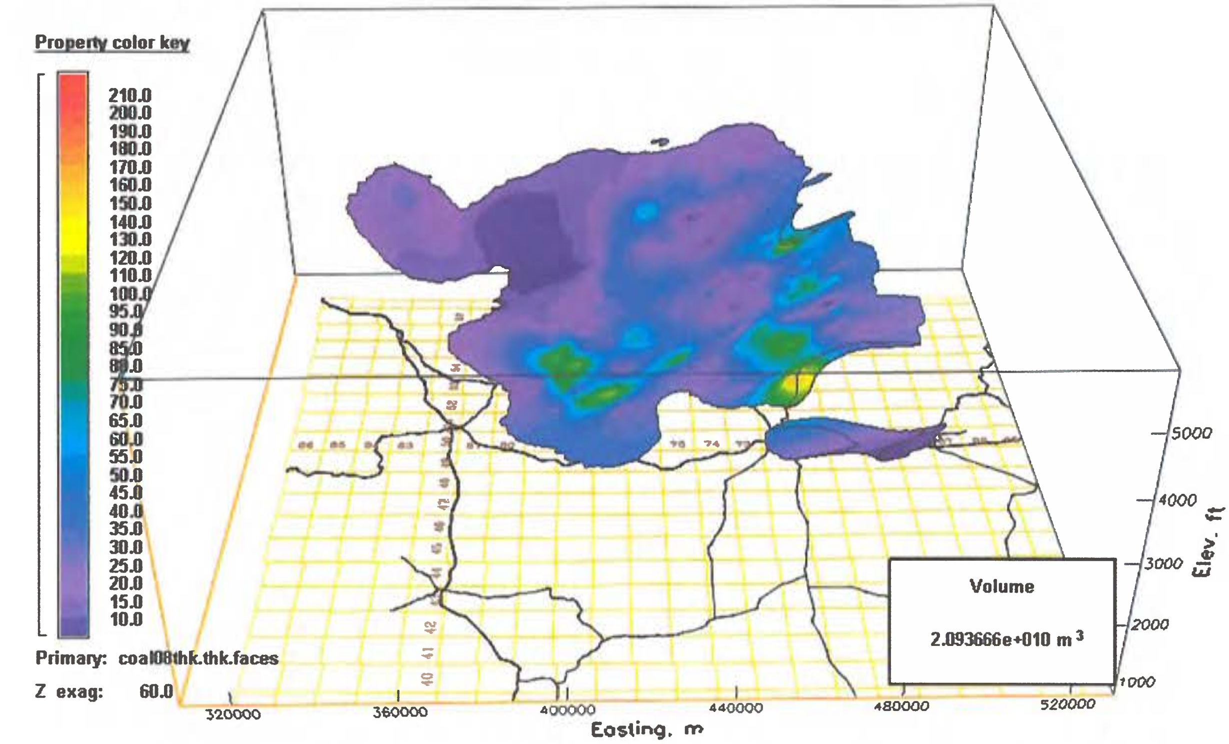


Figure 4-48. Inclined view of Lower Anderson coal bed thickness (feet) generated by the coal thickness model.

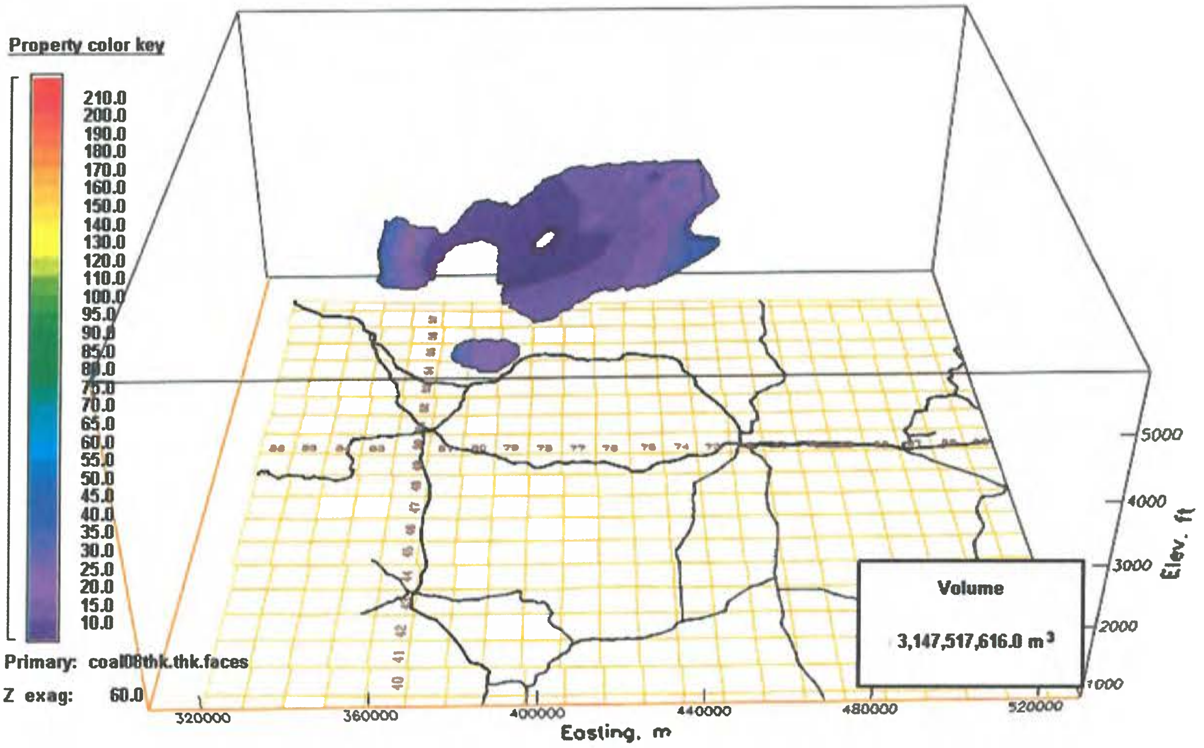


Figure 4-49. Inclined view of Canyon Rider coal bed thickness (feet) generated by the coal thickness model.

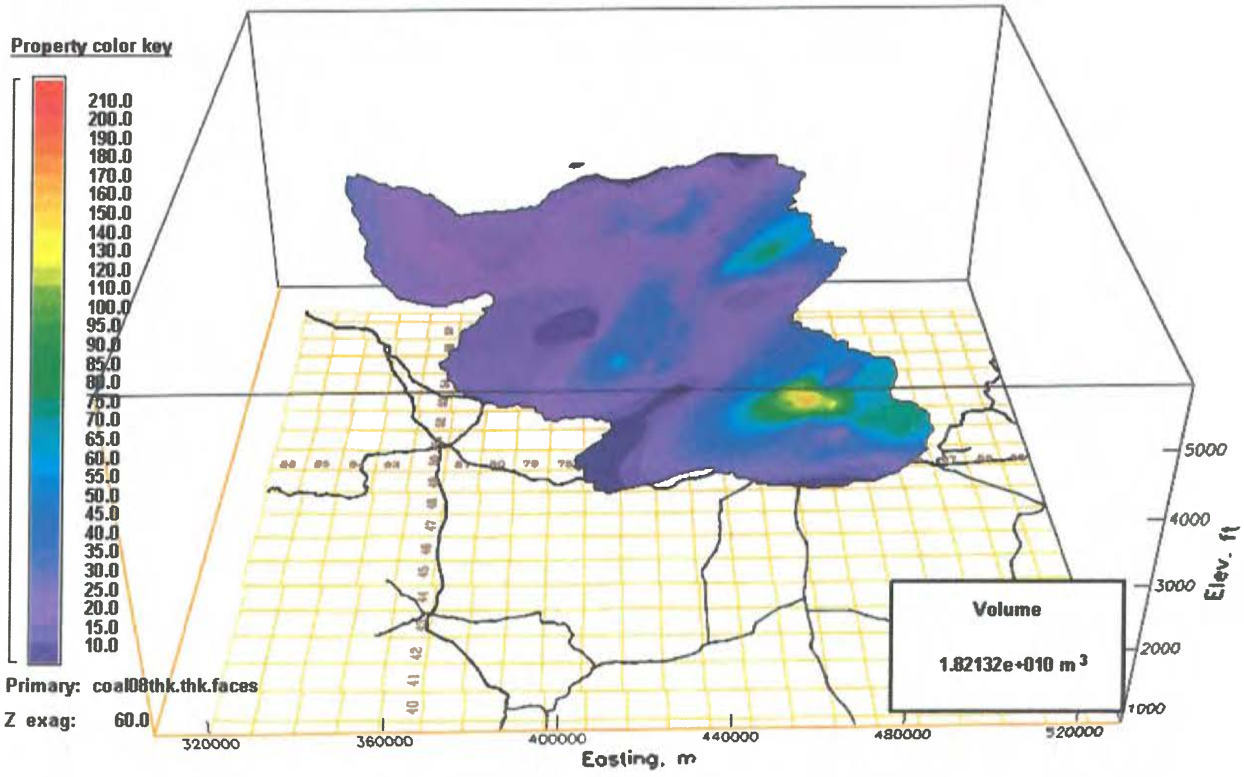


Figure 4-50. Inclined view of Canyon coal bed thickness (feet) generated by the coal thickness model.

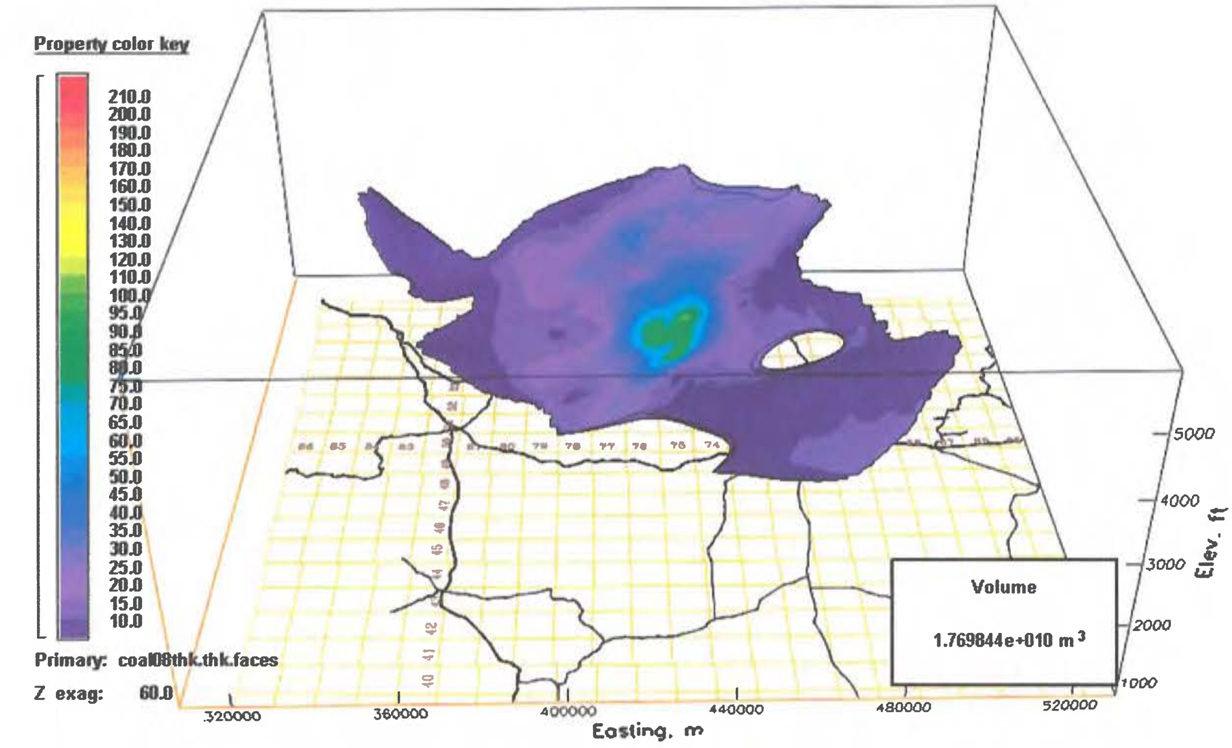


Figure 4-51. Inclined view of Cook coal bed thickness (feet) generated by the coal thickness model.

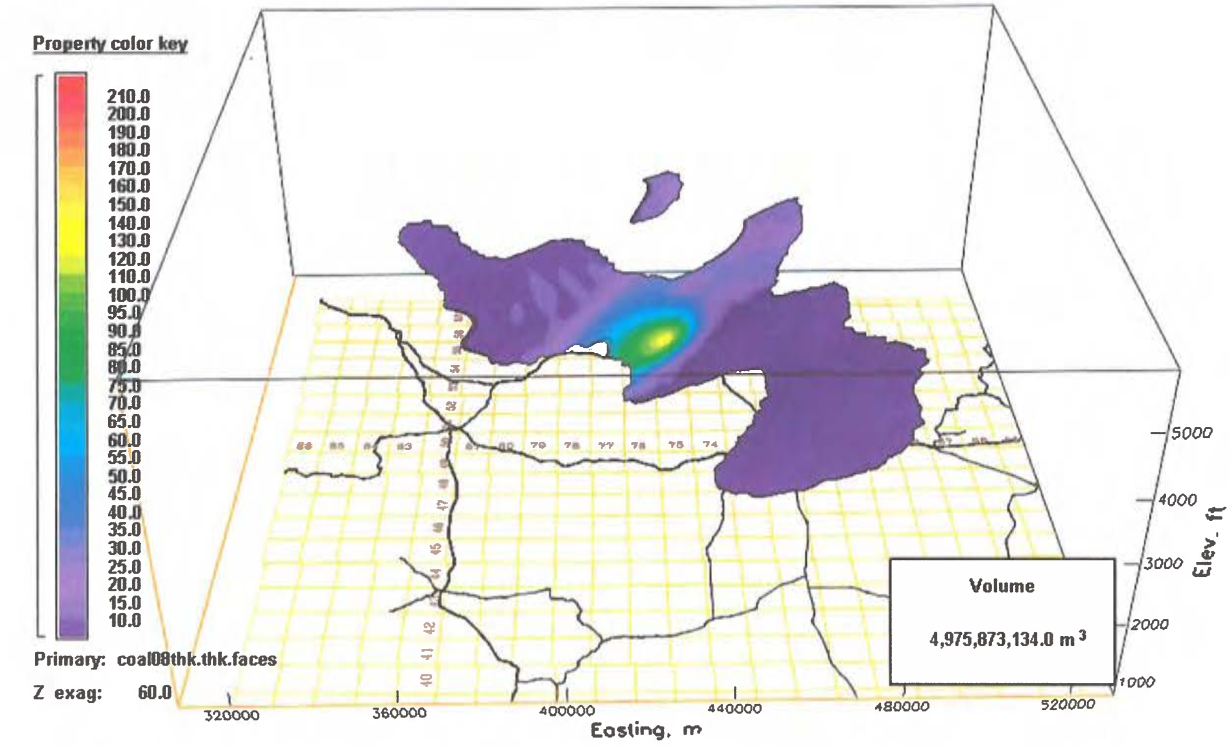


Figure 4-52. Inclined view of Lower Cook coal bed thickness (feet) generated by the coal thickness model.

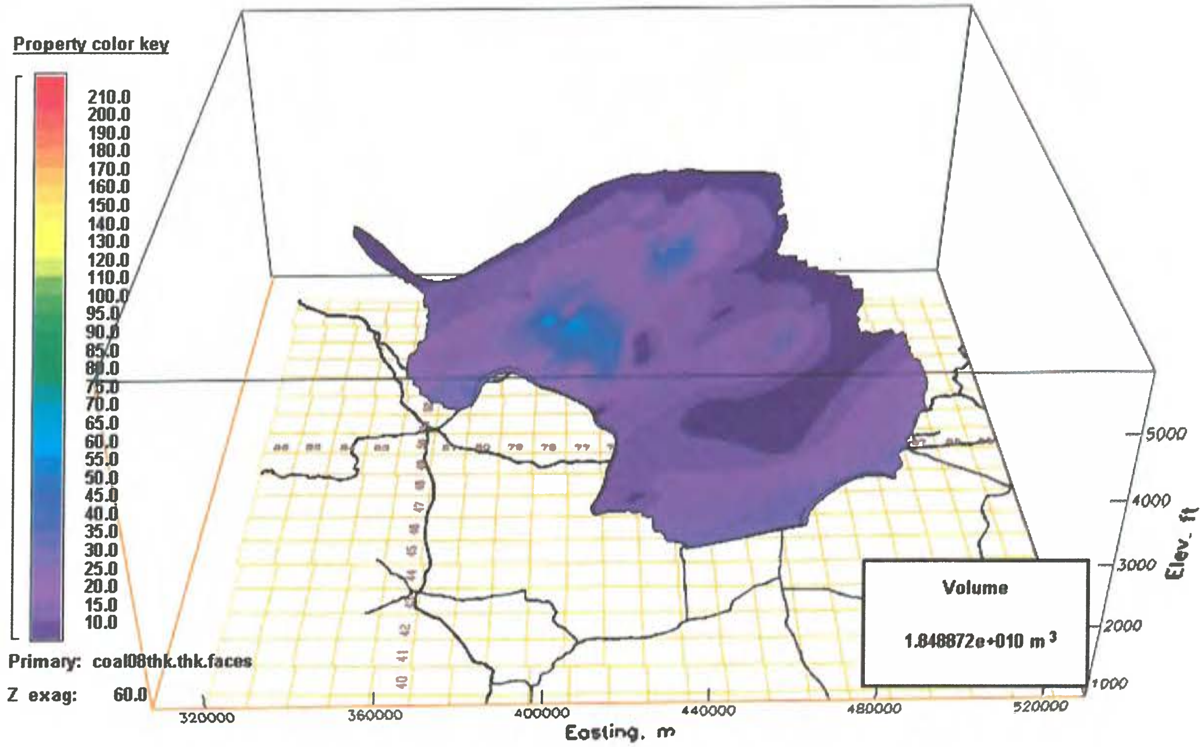


Figure 4-53. Inclined view of Wall coal bed thickness (feet) generated by the coal thickness model.

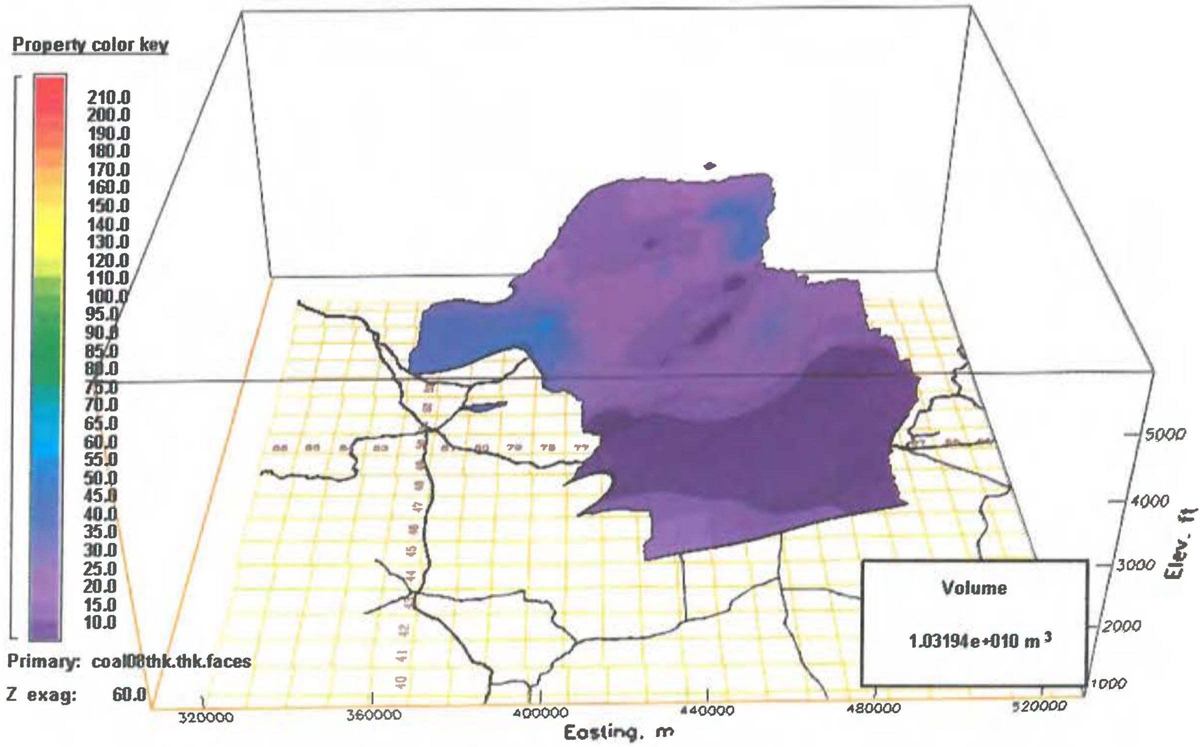


Figure 4-54. Inclined view of Lower Wall coal bed thickness (feet) generated by the coal thickness model.

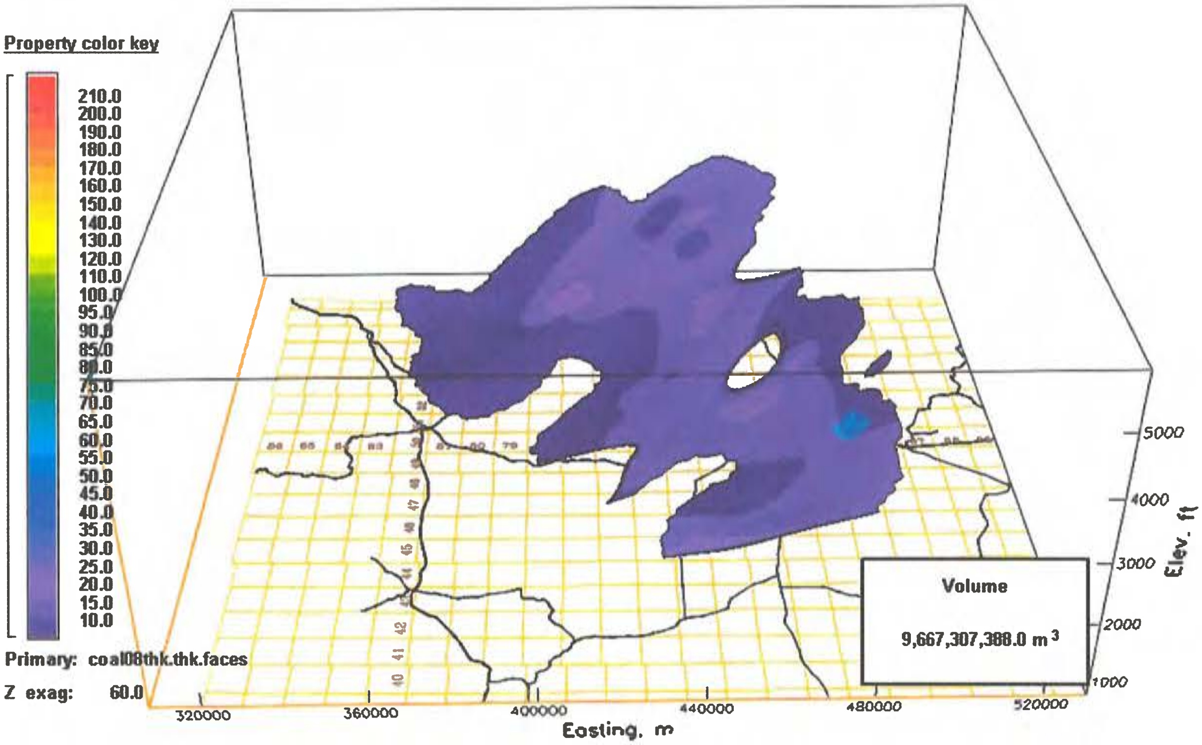


Figure 4-55. Inclined view of Pawnee coal bed thickness (feet) generated by the coal thickness model.

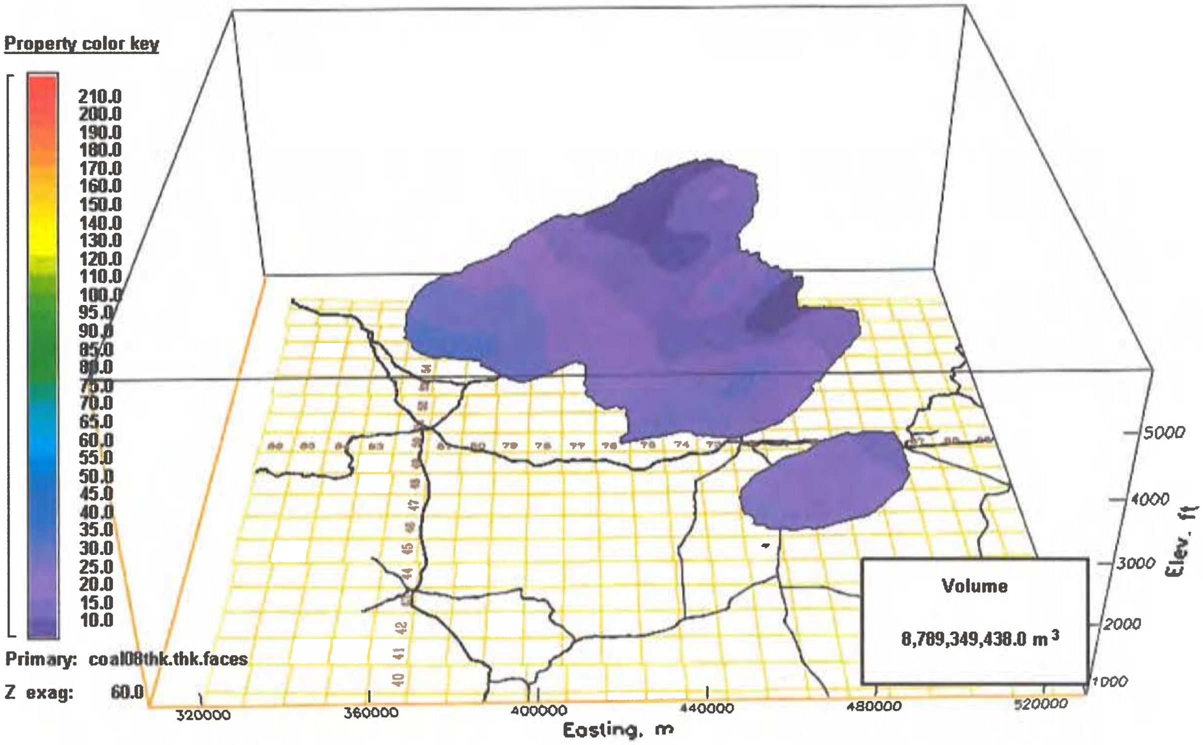


Figure 4-56. Inclined view of Moyer coal bed thickness (feet) generated by the coal thickness model.

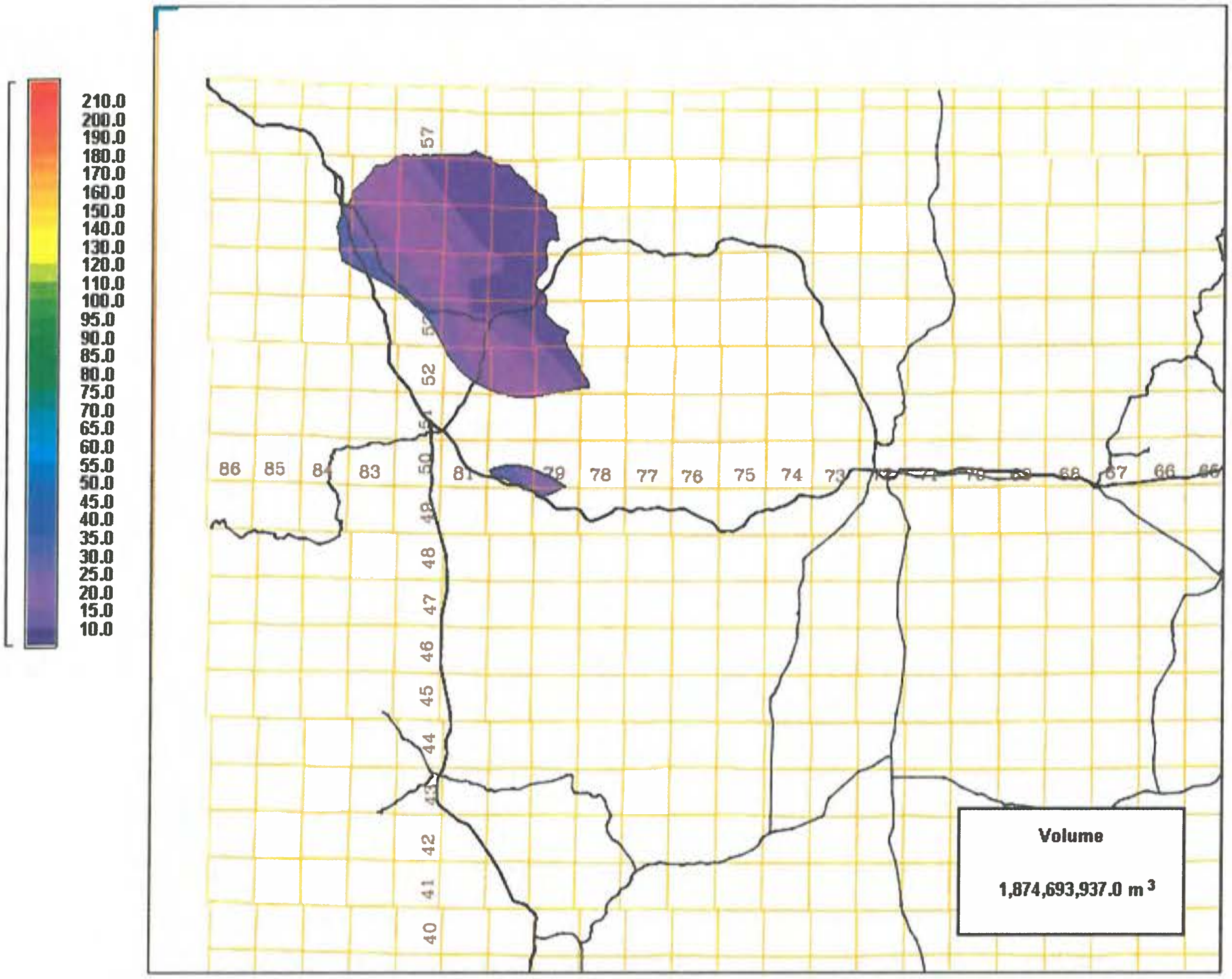


Figure 4-57. Contoured map view of Ulm coal bed thickness (feet) generated by the coal thickness model.

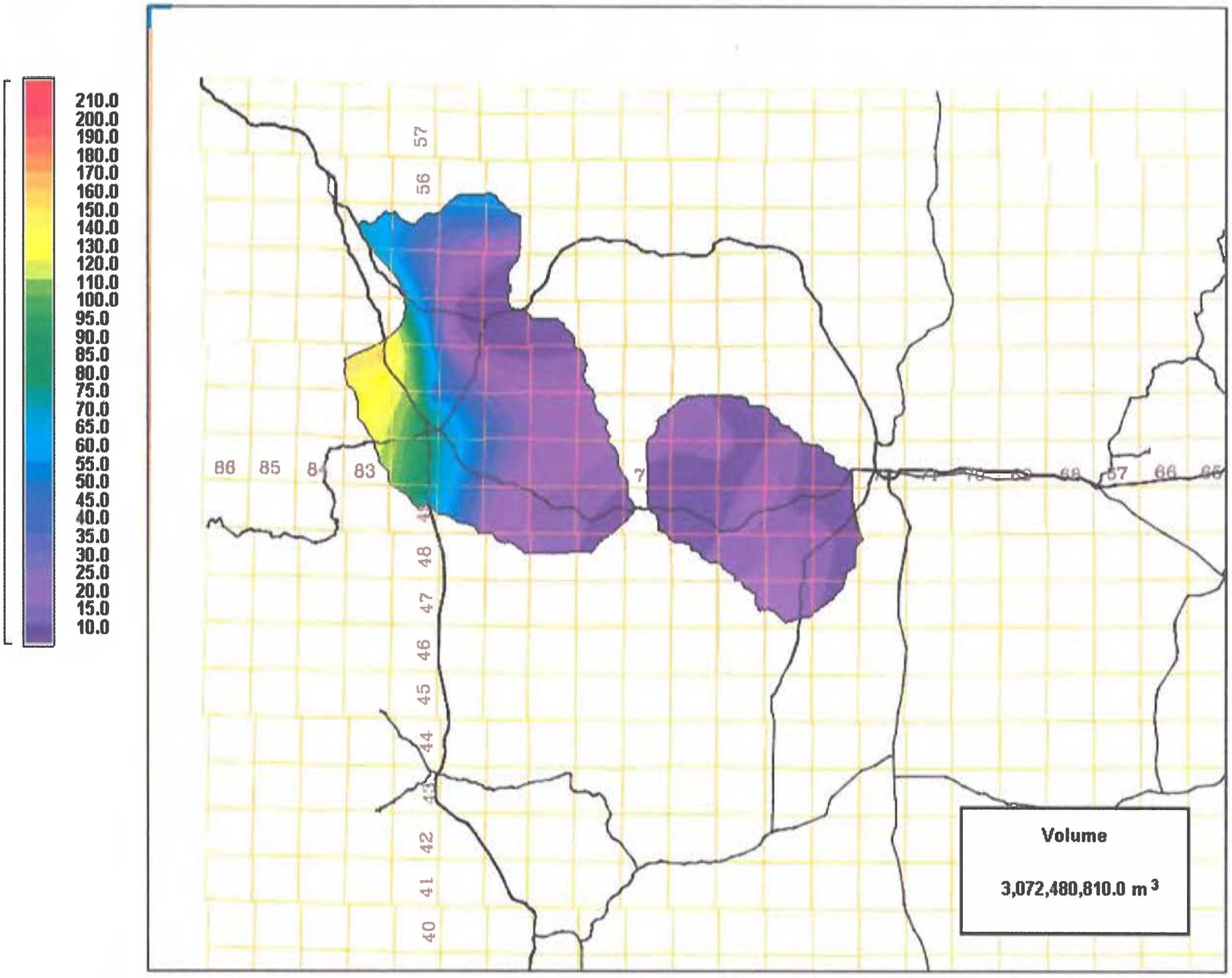


Figure 4-58. Contoured map view of Buffalo Cameron coal bed thickness (feet) generated by the coal thickness model.

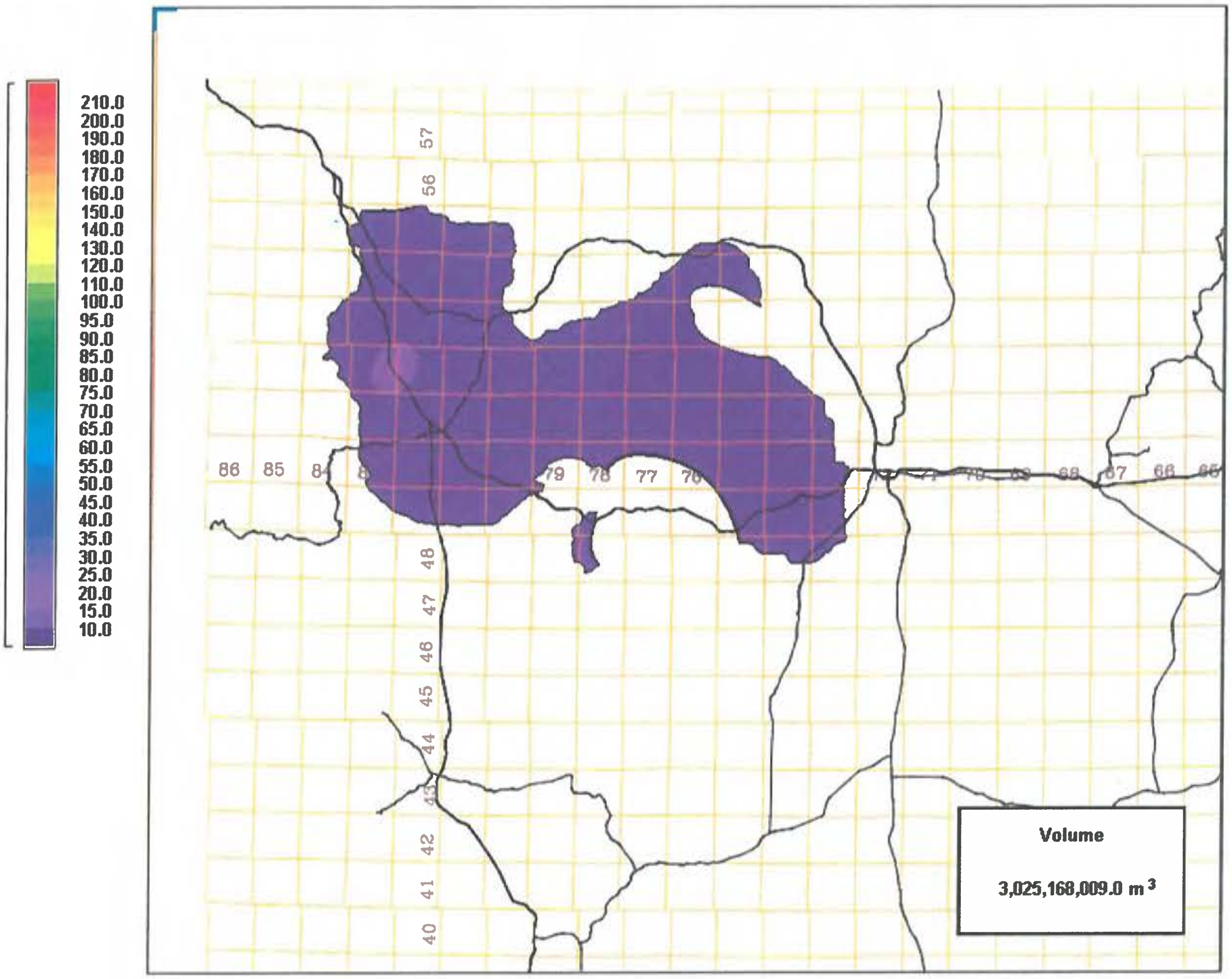


Figure 4-59. Contoured map view of Murray coal bed thickness (feet) generated by the coal thickness model.

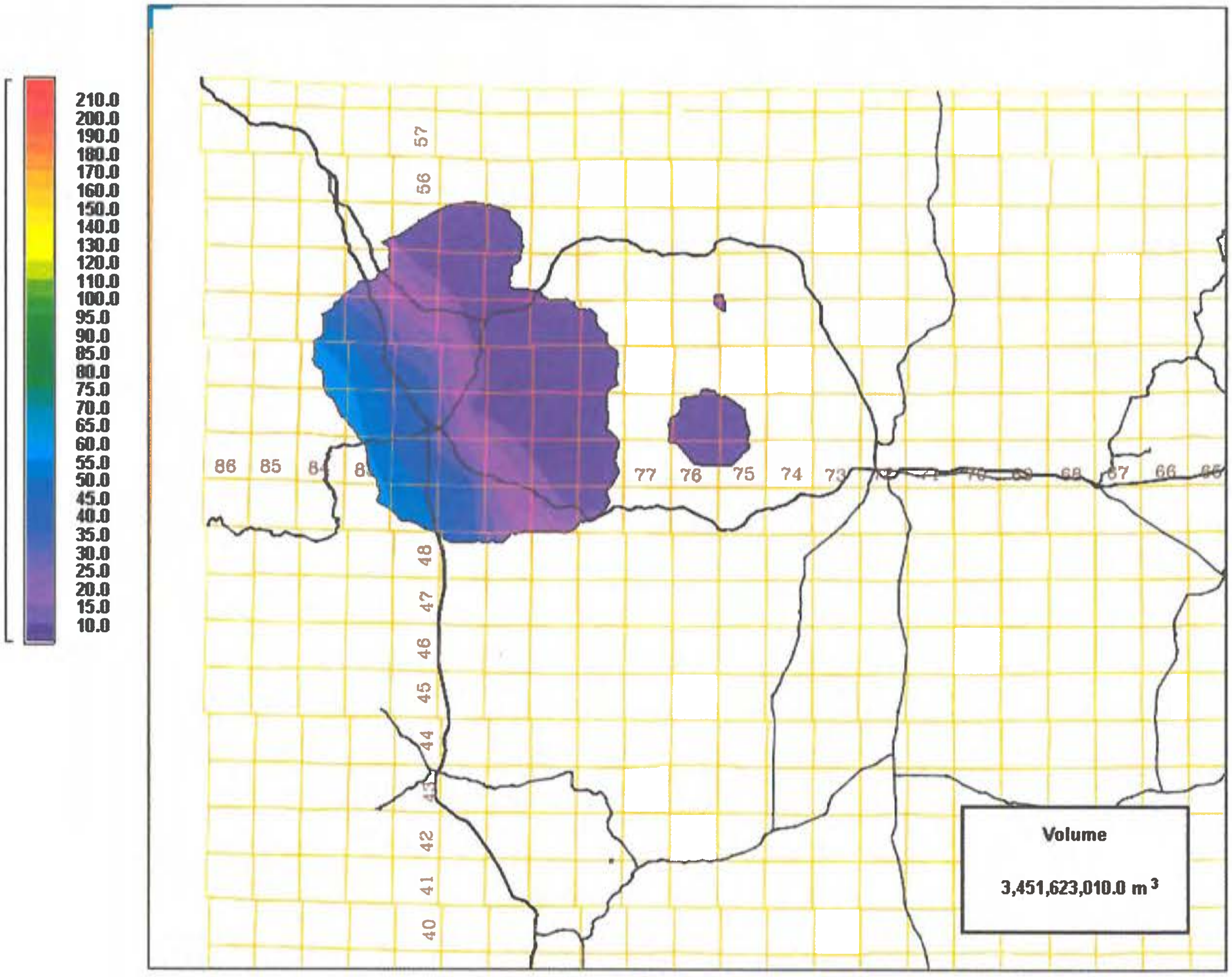


Figure 4-60. Contoured map view of Ucross coal bed thickness (feet) generated by the coal thickness model.

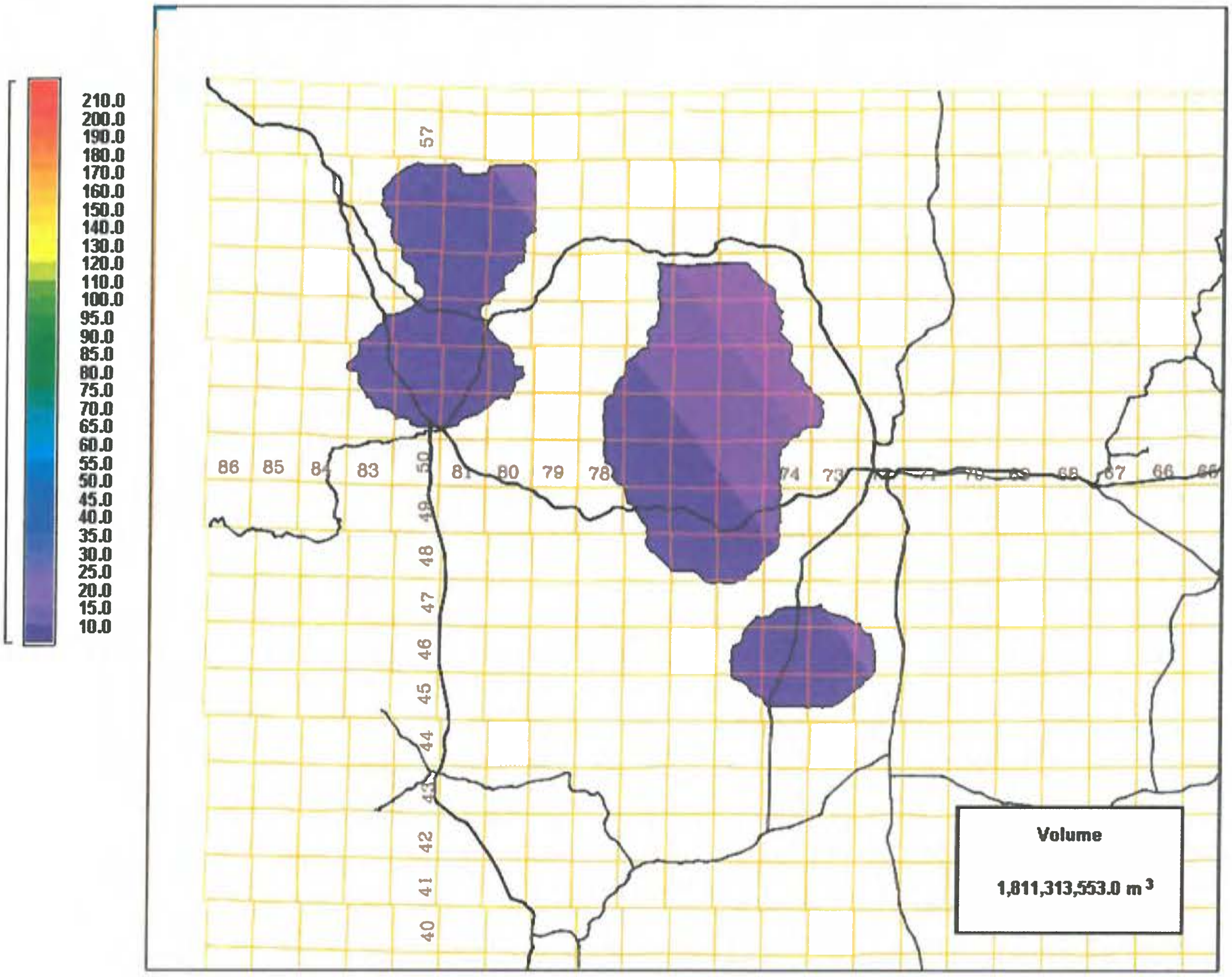


Figure 4-61. Contoured map view of Felix Rider coal bed thickness (feet) generated by the coal thickness model.

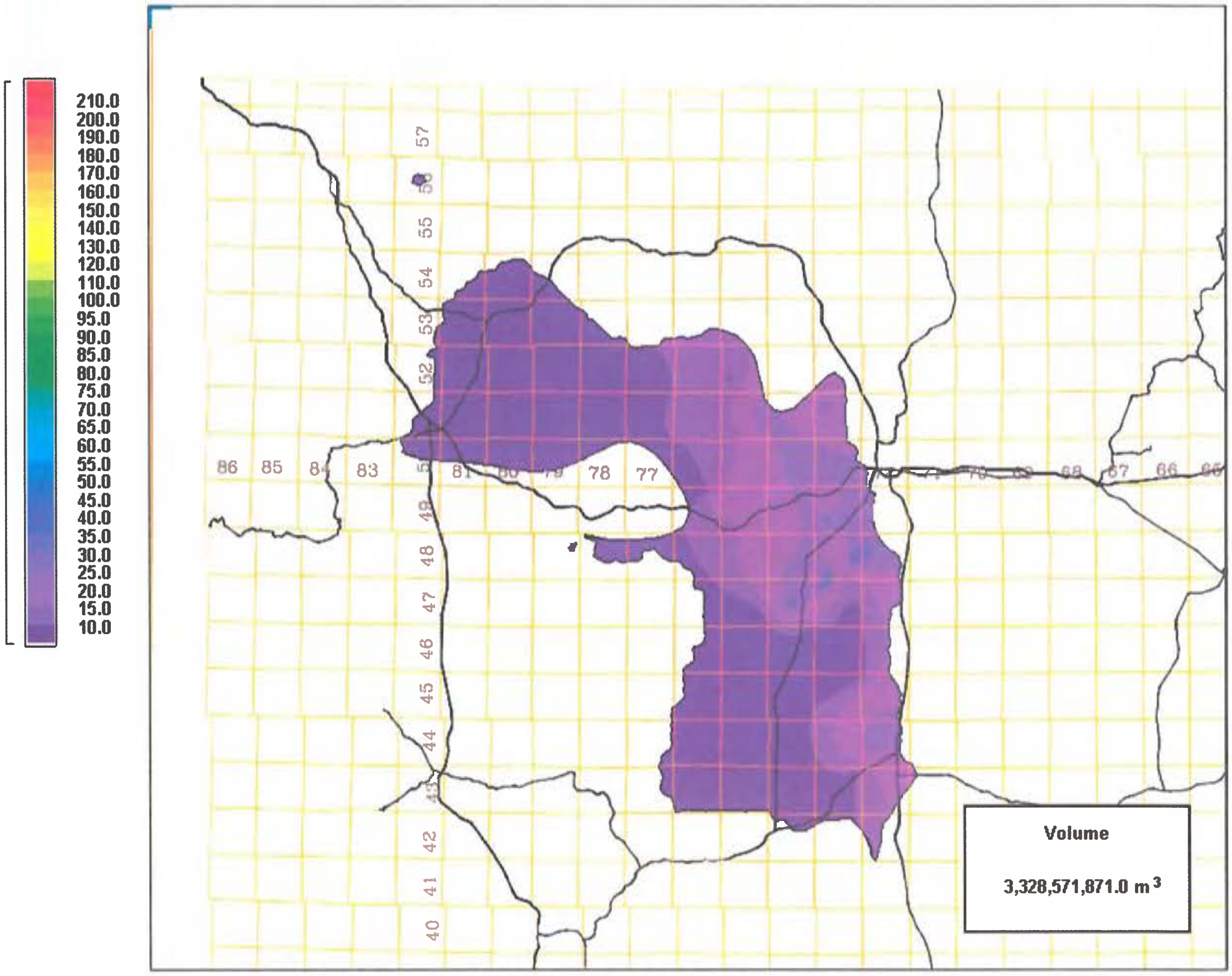


Figure 4-62. Contoured map view of Upper Felix coal bed thickness (feet) generated by the coal thickness model.

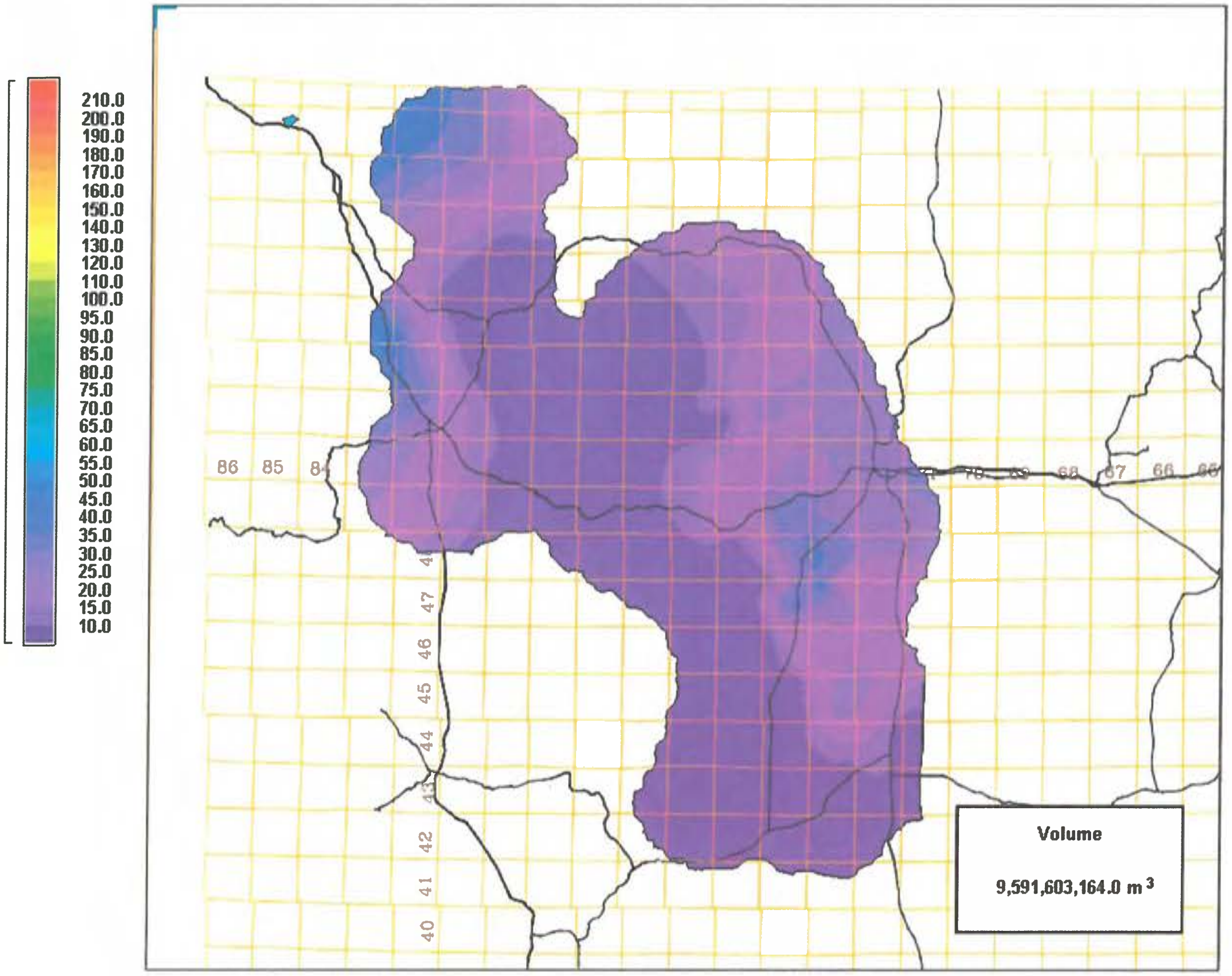


Figure 4-63. Contoured map view of Felix coal bed thickness (feet) generated by the coal thickness model.

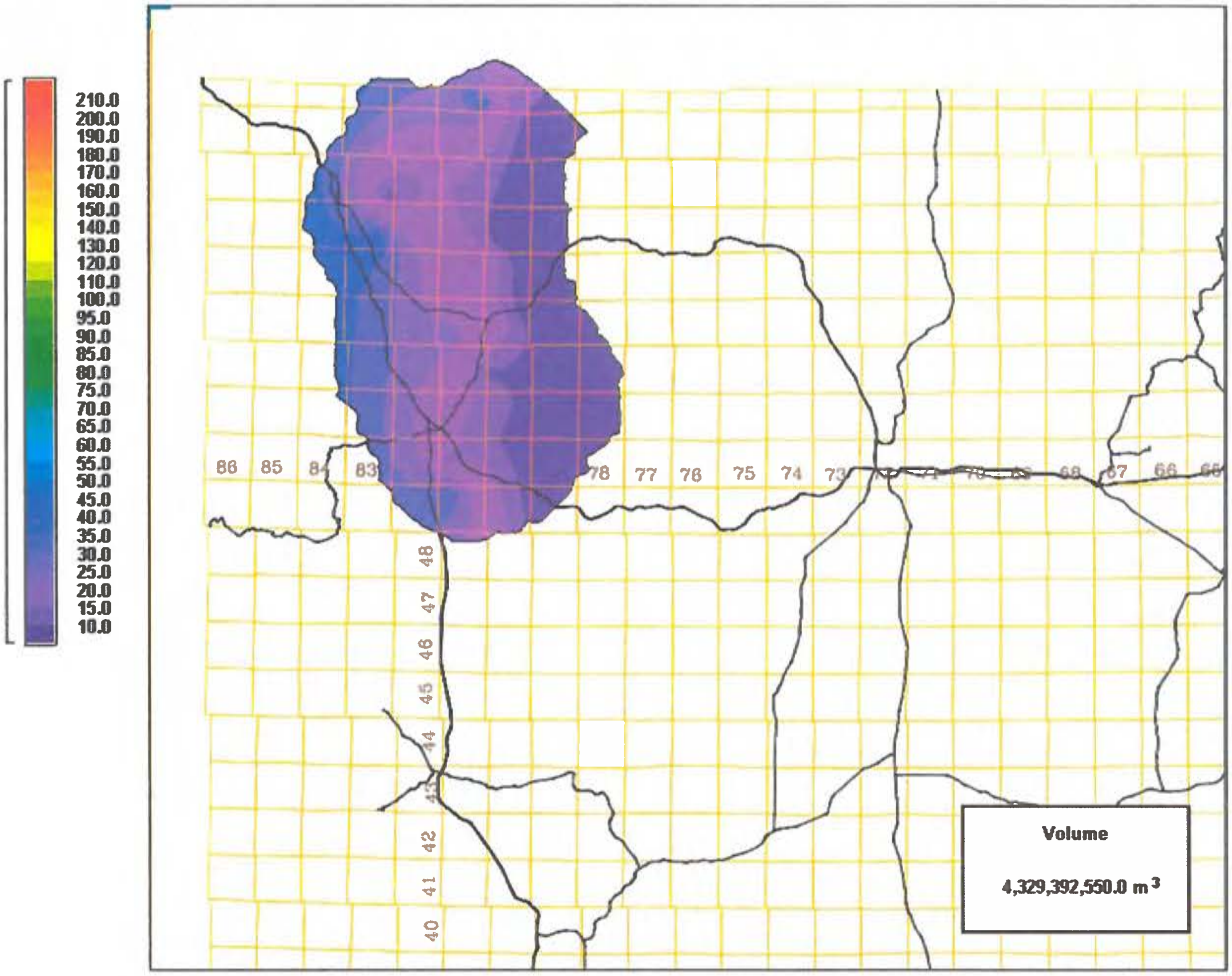


Figure 4-64. Contoured map view of Arvada coal bed thickness (feet) generated by the coal thickness model.

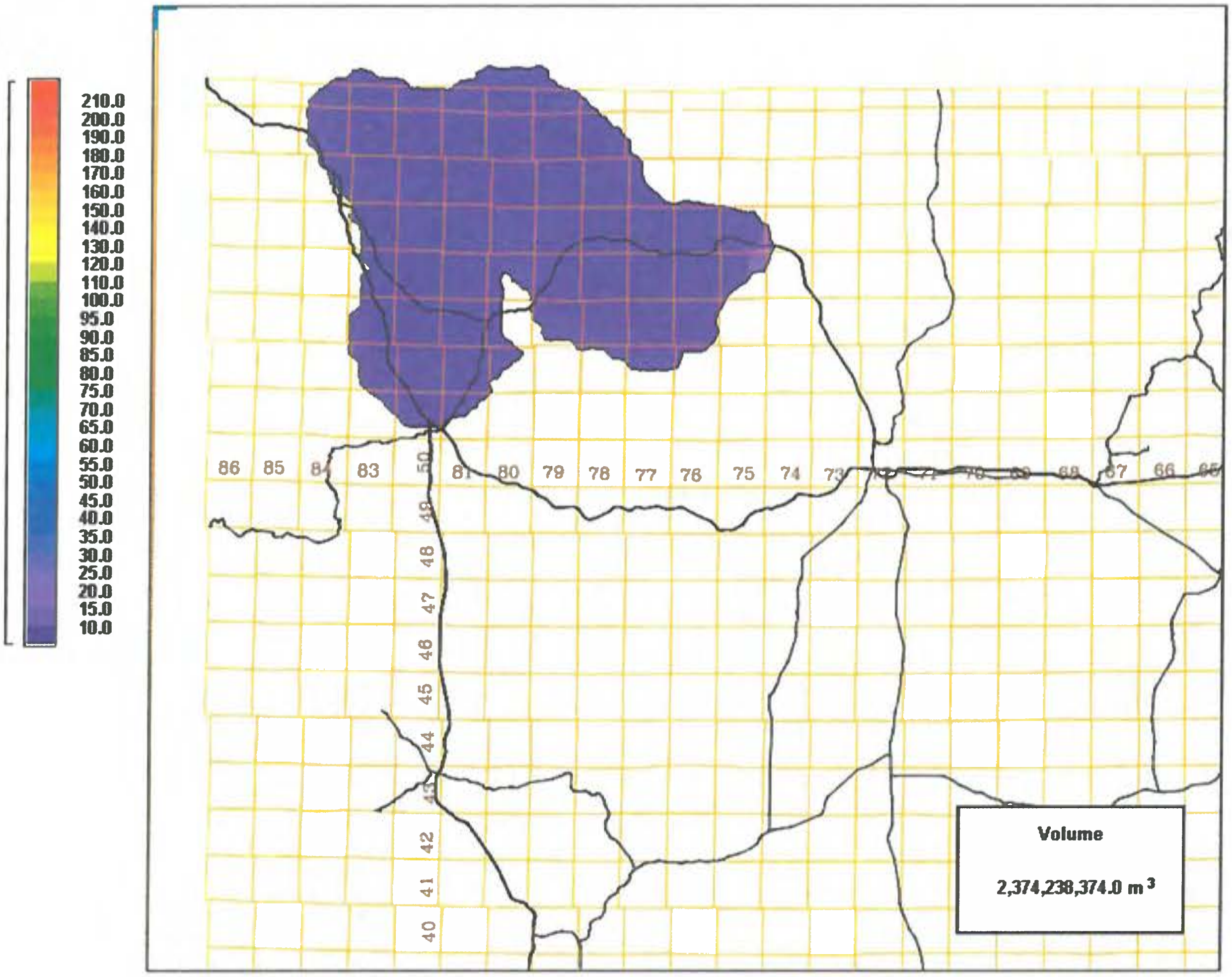


Figure 4-65. Contoured map view of unnamed coal bed thickness (feet) generated by the coal thickness model.

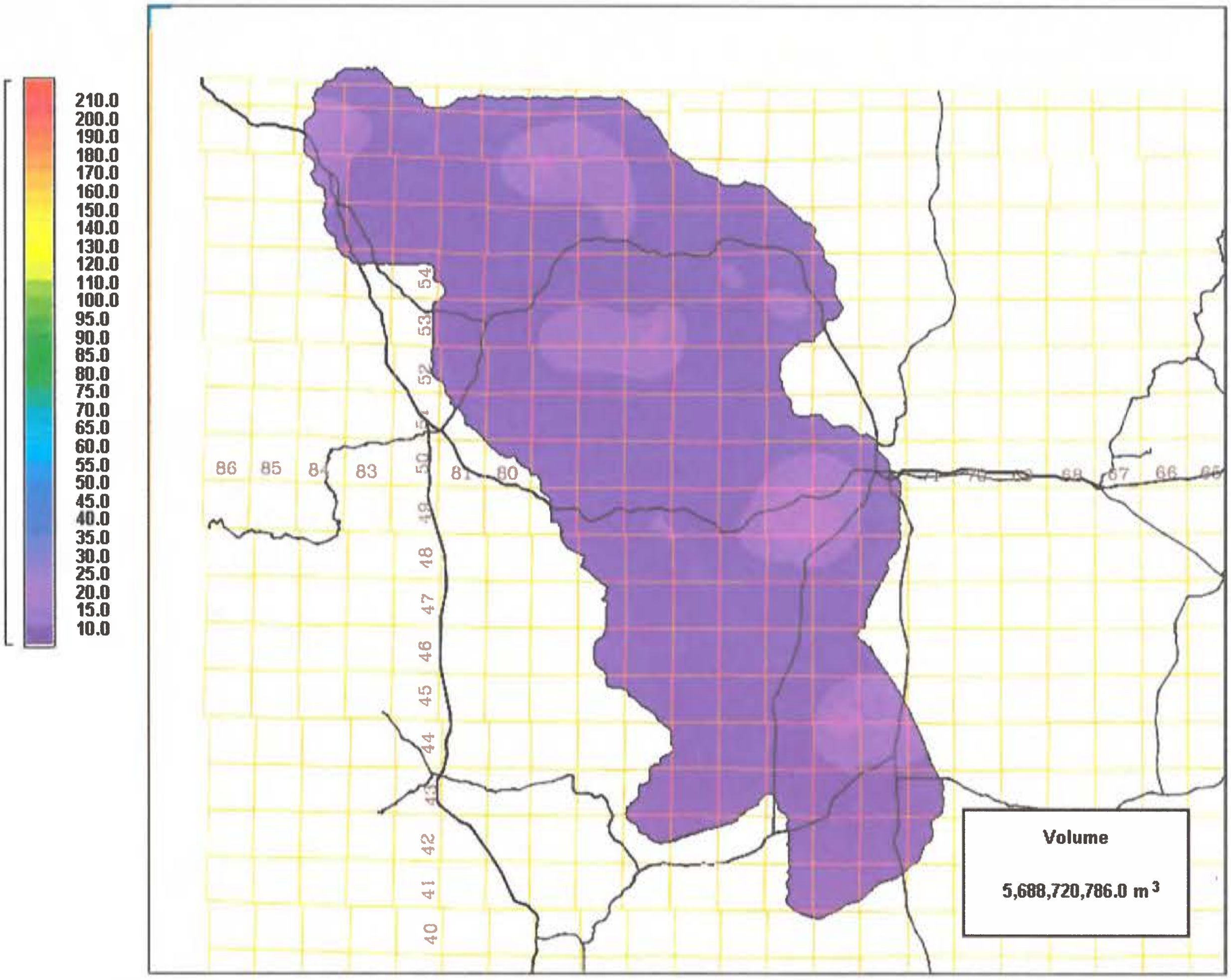


Figure 4-66. Contoured map view of Upper Roland coal bed thickness (feet) generated by the coal thickness model.

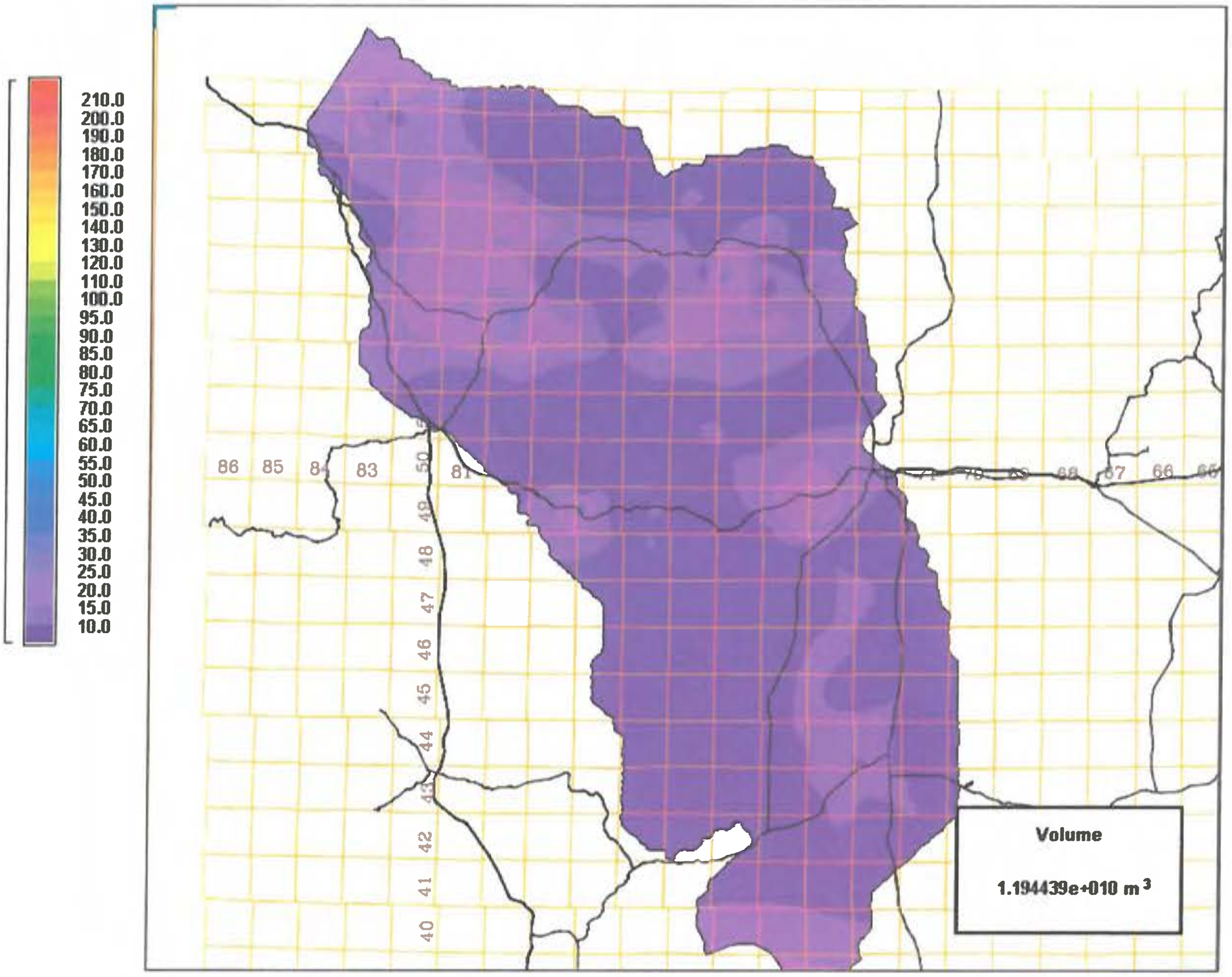


Figure 4-67. Contoured map view of Roland of Baker coal bed thickness (feet) generated by the coal thickness model.

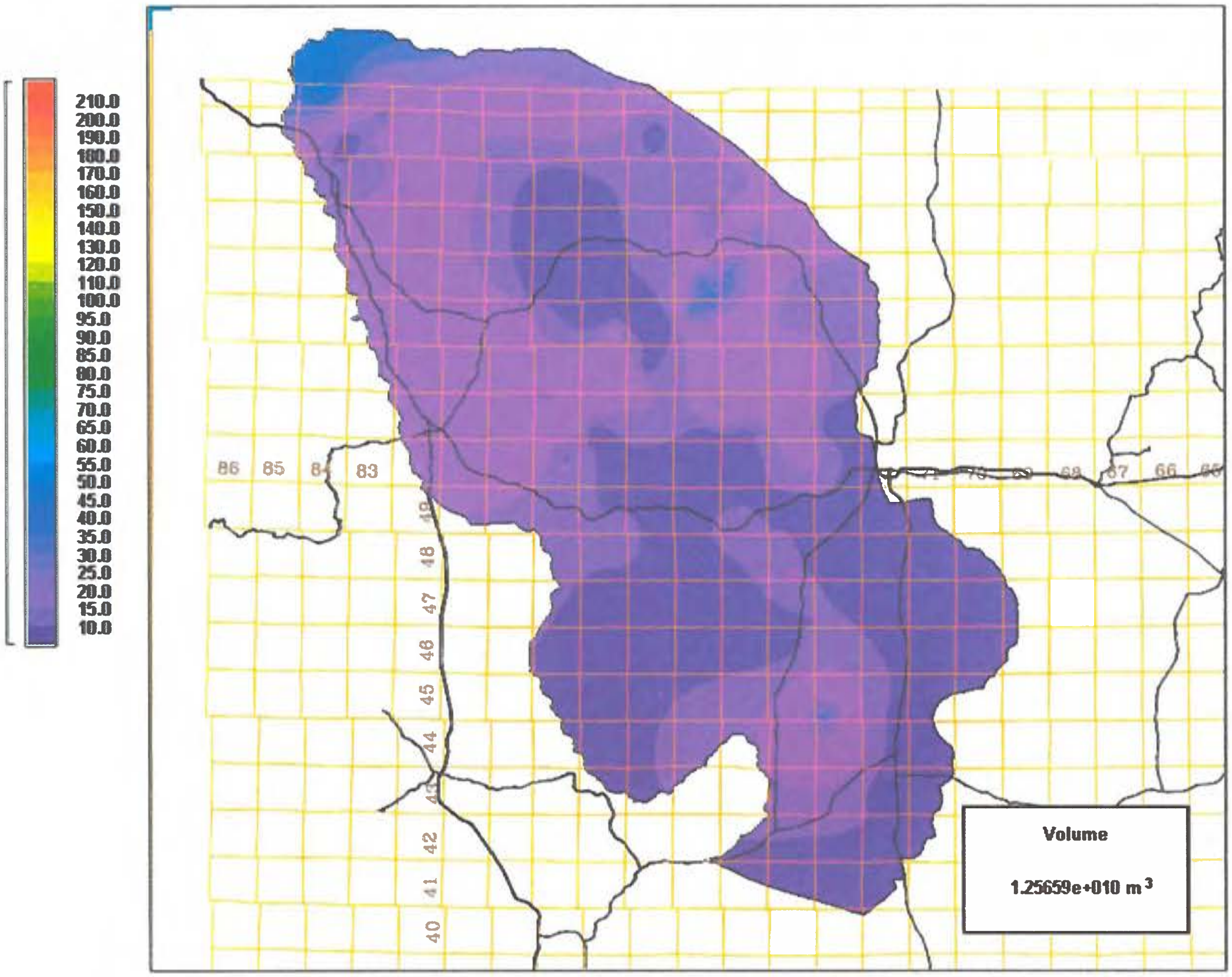


Figure 4-68. Contoured map view of Roland of Taff coal bed thickness (feet) generated by the coal thickness model.

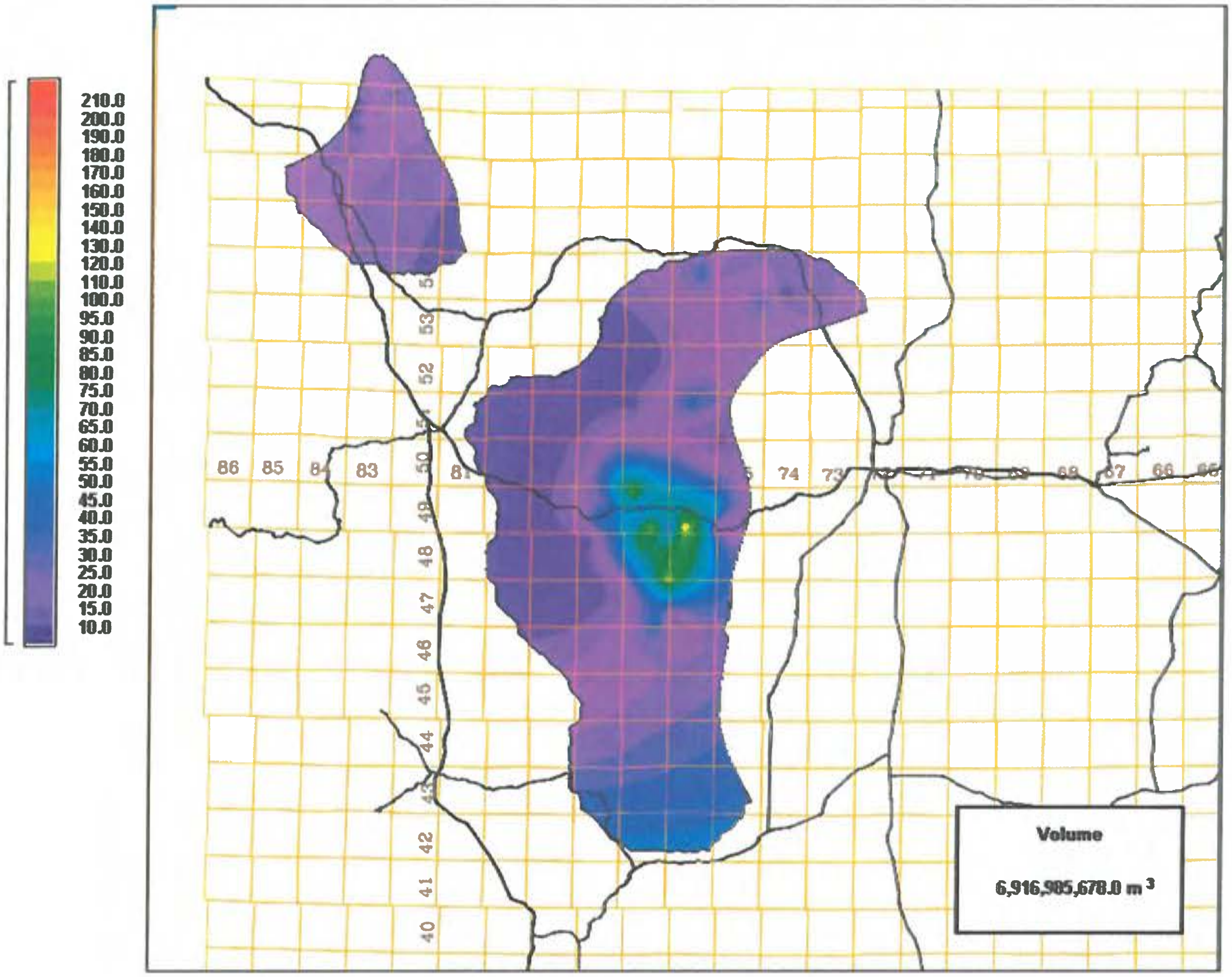


Figure 4-69. Contoured map view of Smith Rider coal bed thickness (feet) generated by the coal thickness model.

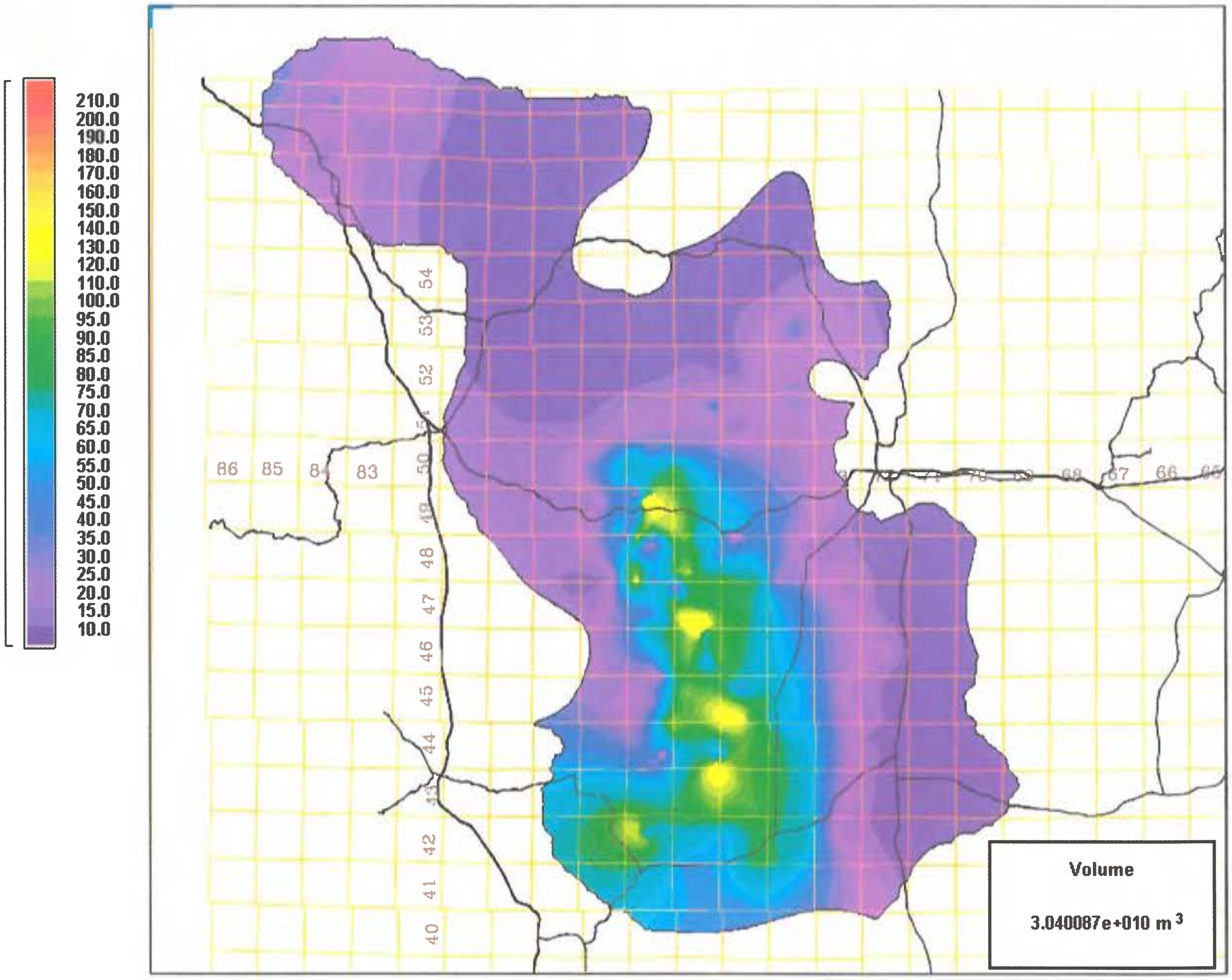


Figure 4-70. Contoured map view of Smith/Big George coal bed thickness (feet) generated by the coal thickness model.

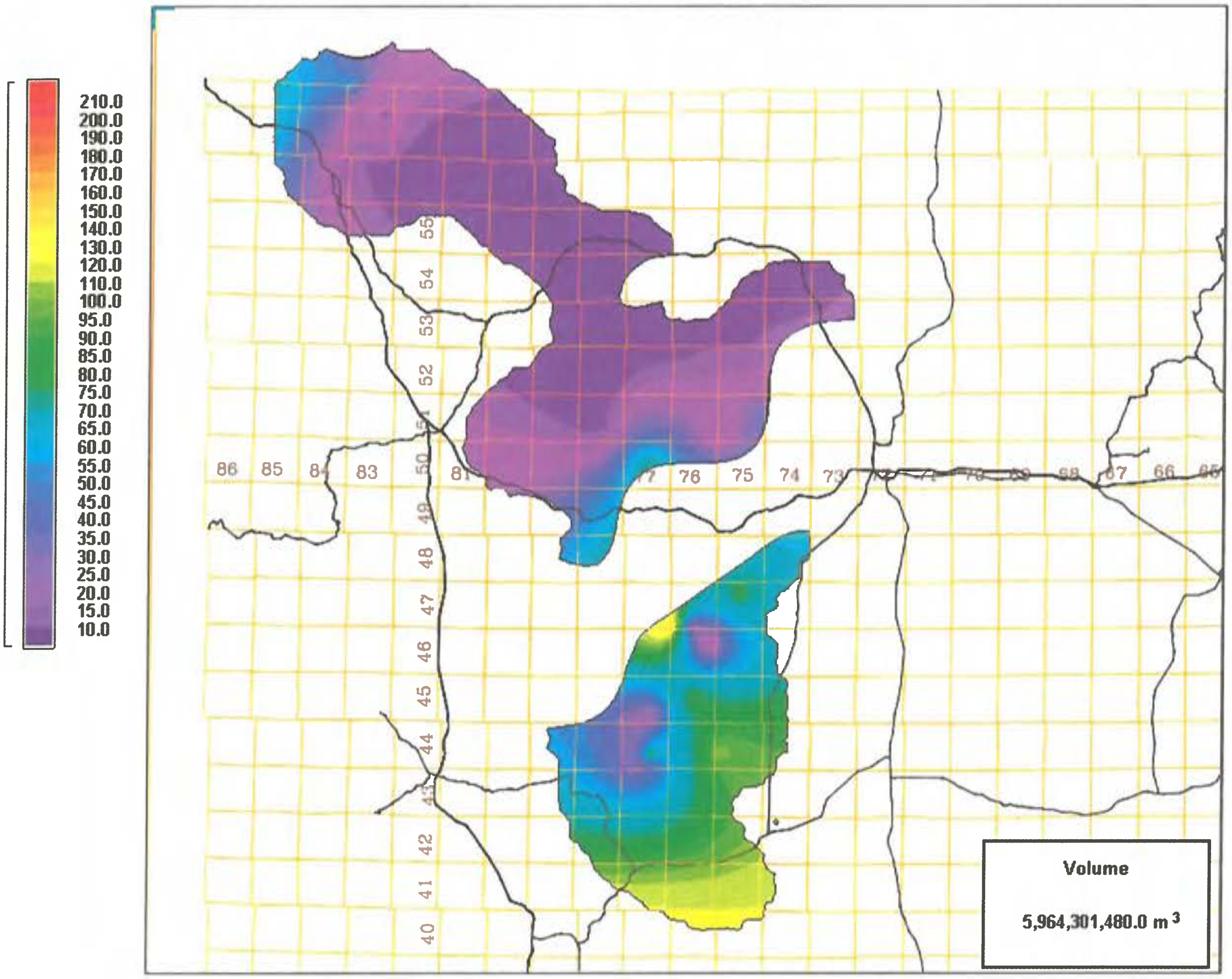


Figure 4-71. Contoured map view of Lower Smith coal bed thickness (feet) generated by the coal thickness model.

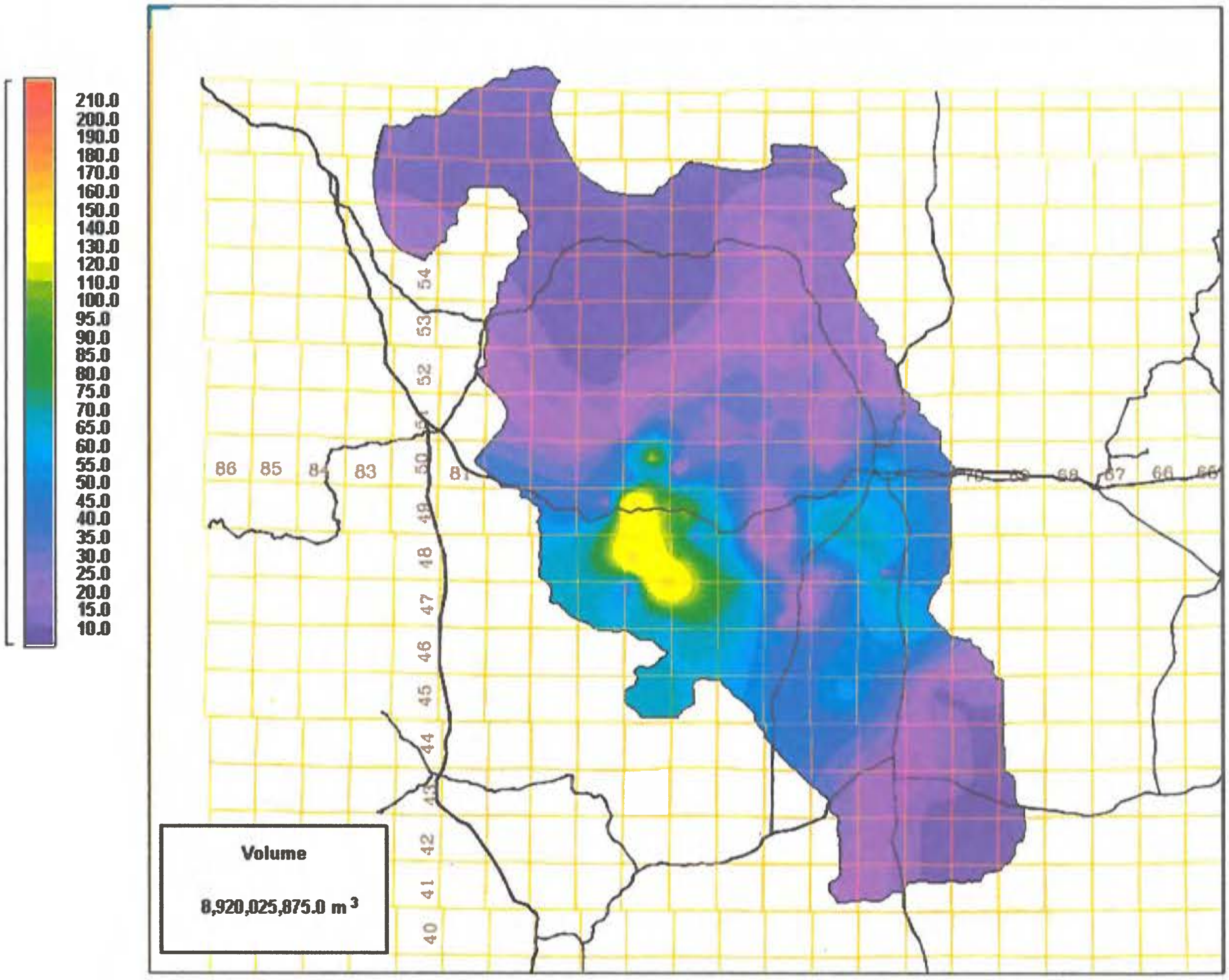


Figure 4-72. Contoured map view of Anderson Rider coal bed thickness (feet) generated by the coal thickness model.

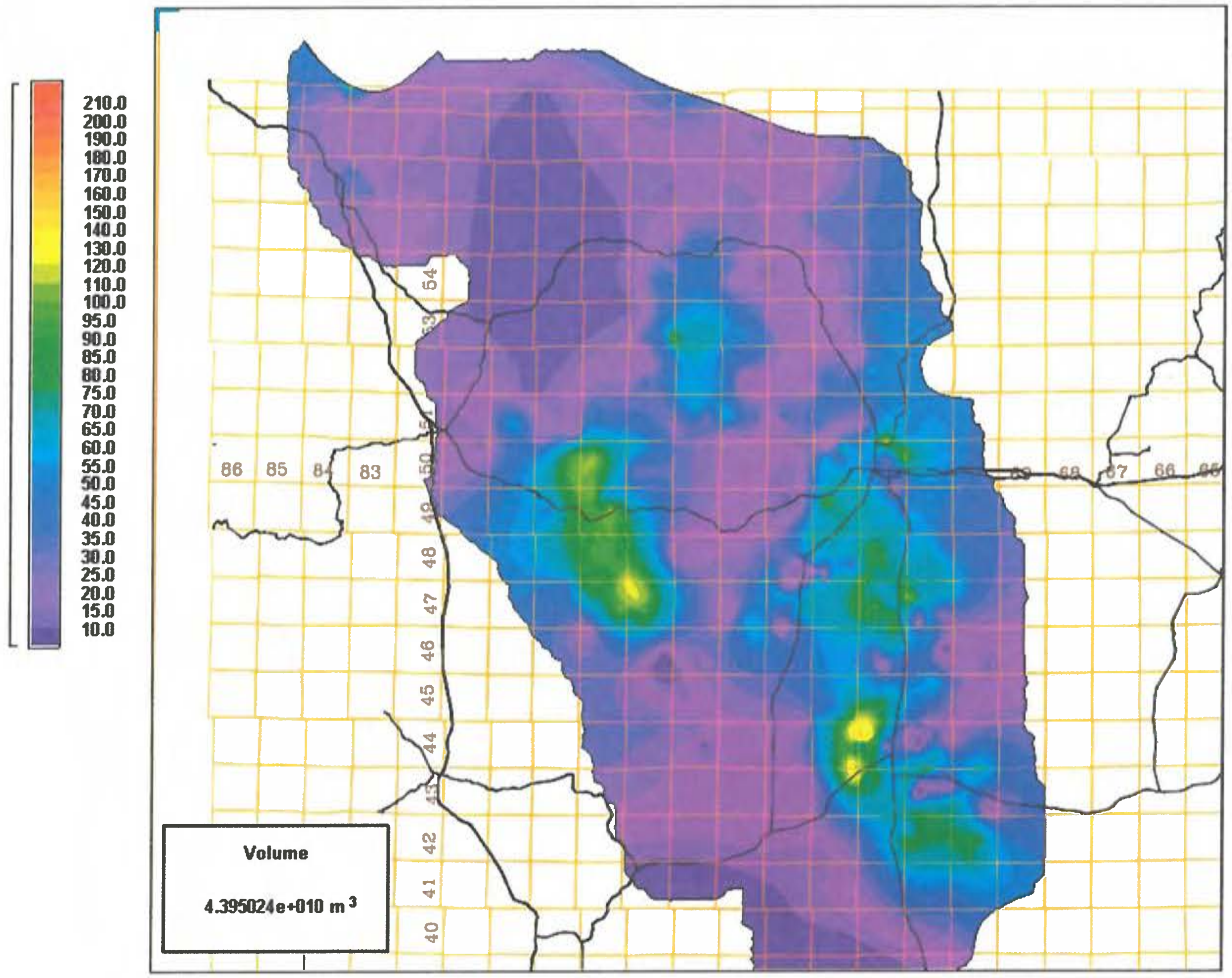


Figure 4-73. Contoured map view of Anderson coal bed thickness (feet) generated by the coal thickness model.

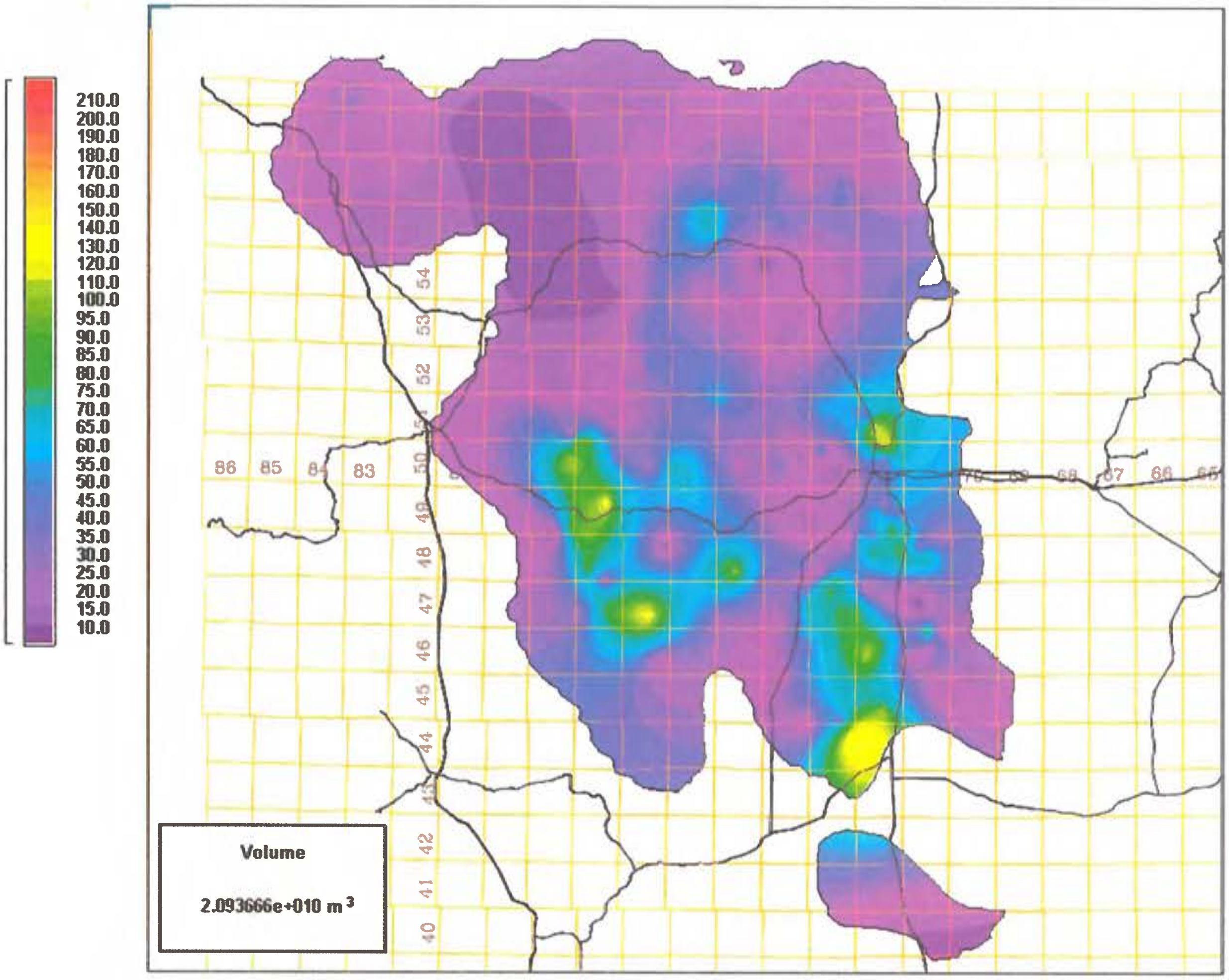


Figure 4-74. Contoured map view of Lower Anderson coal bed thickness (feet) generated by the coal thickness model.

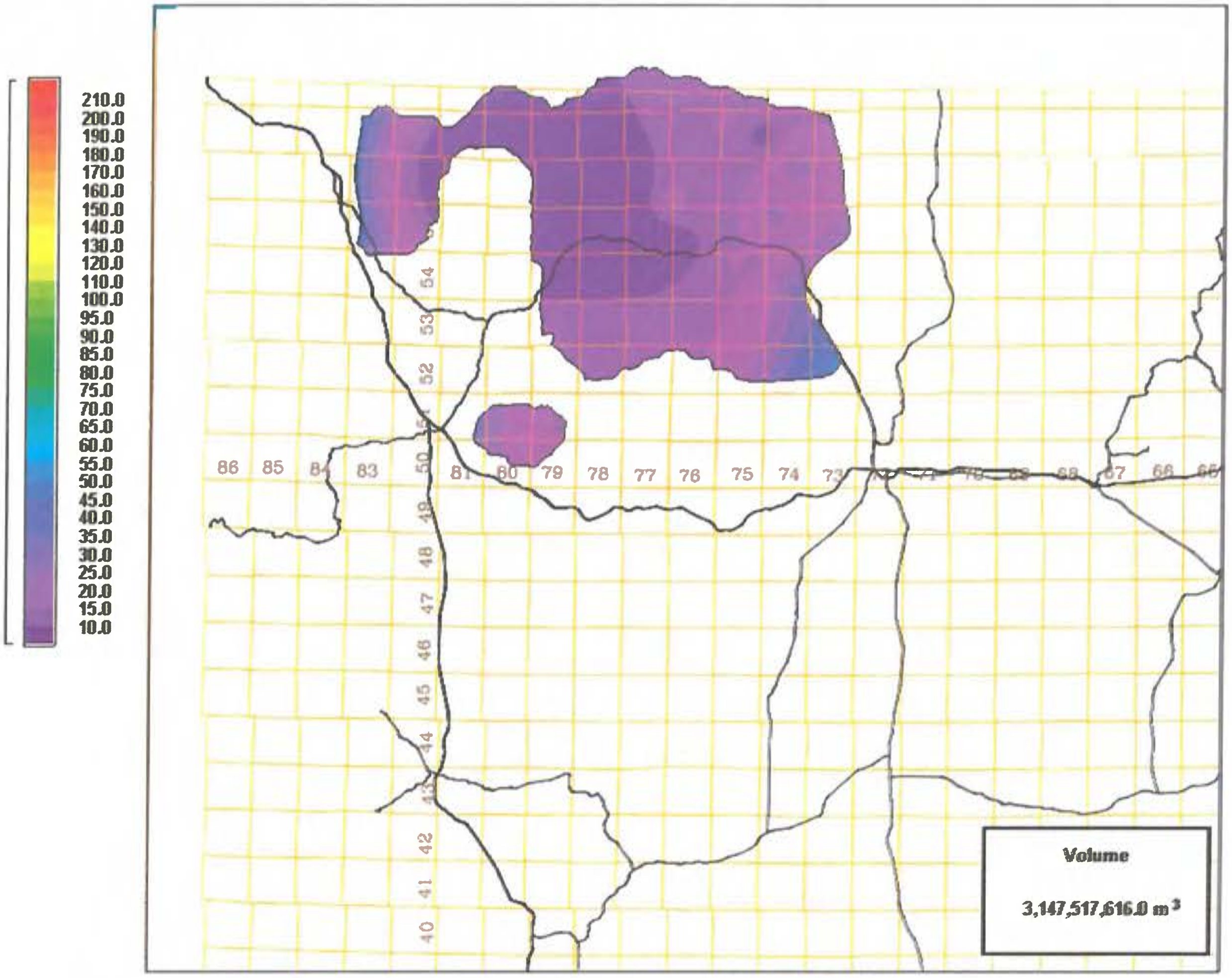


Figure 4-75. Contoured map view of Canyon Rider coal bed thickness (feet) generated by the coal thickness model.

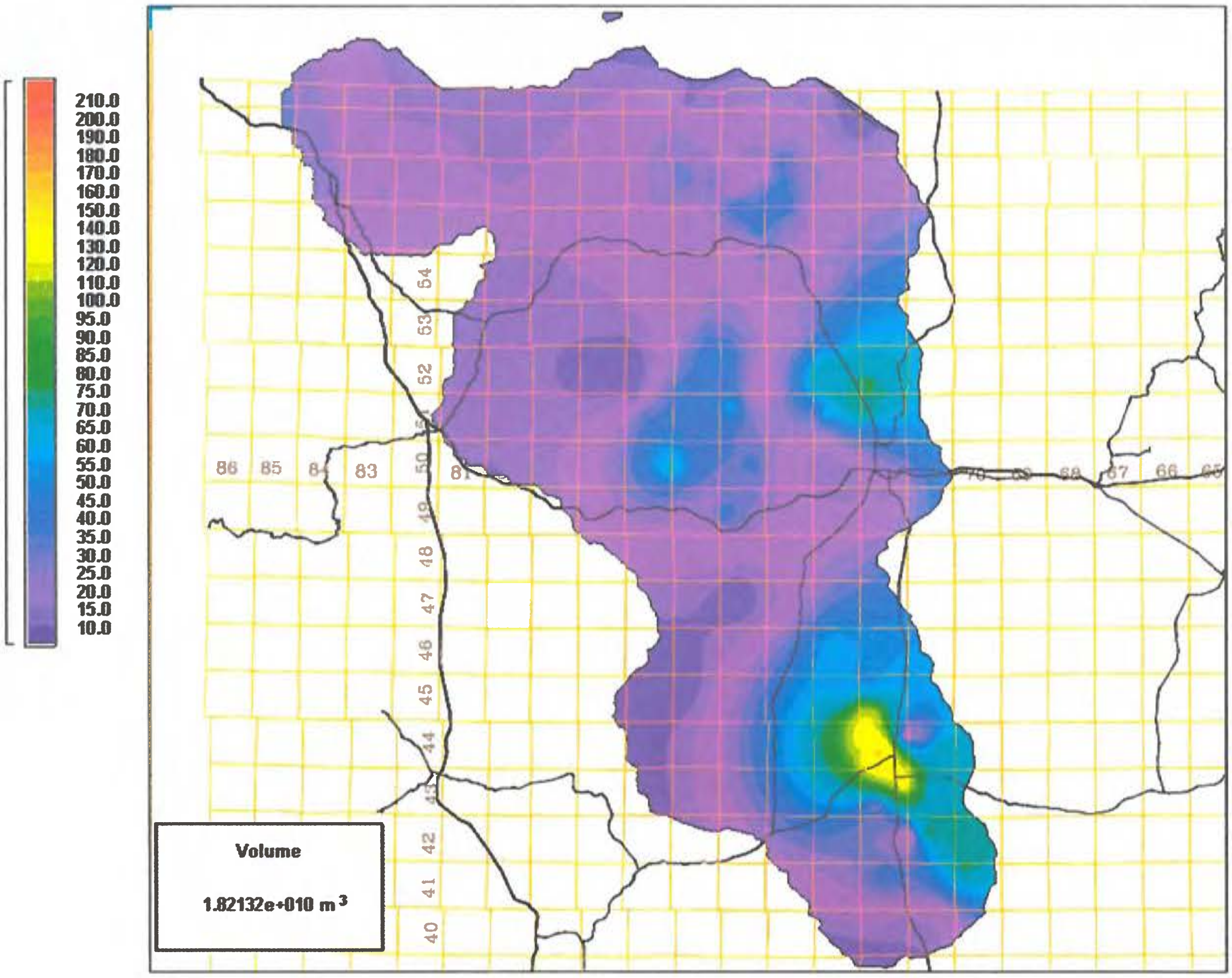


Figure 4-76. Contoured map view of Canyon coal bed thickness (feet) generated by the coal thickness model.

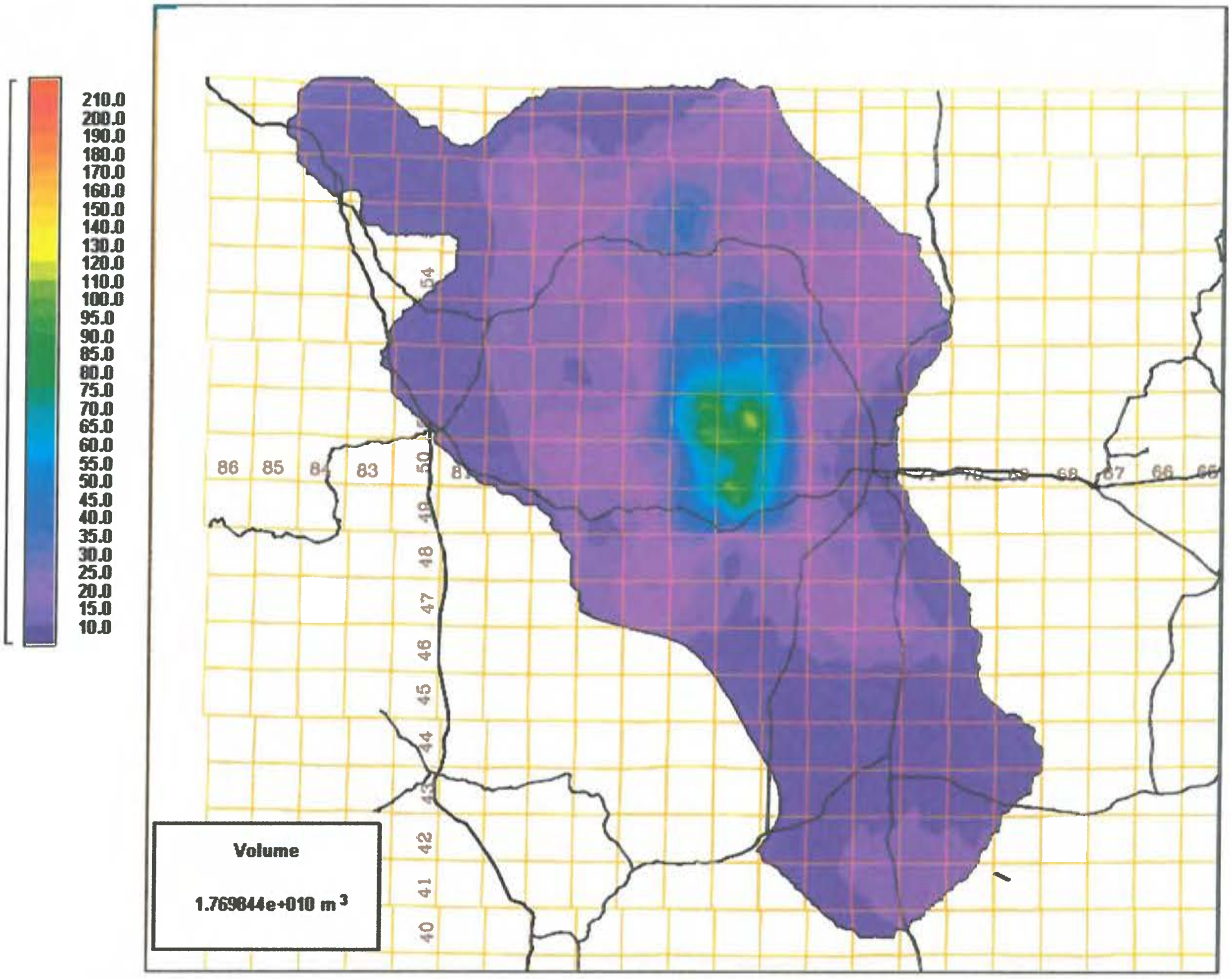


Figure 4-77. Contoured map view of Cook coal bed thickness (feet) generated by the coal thickness model.

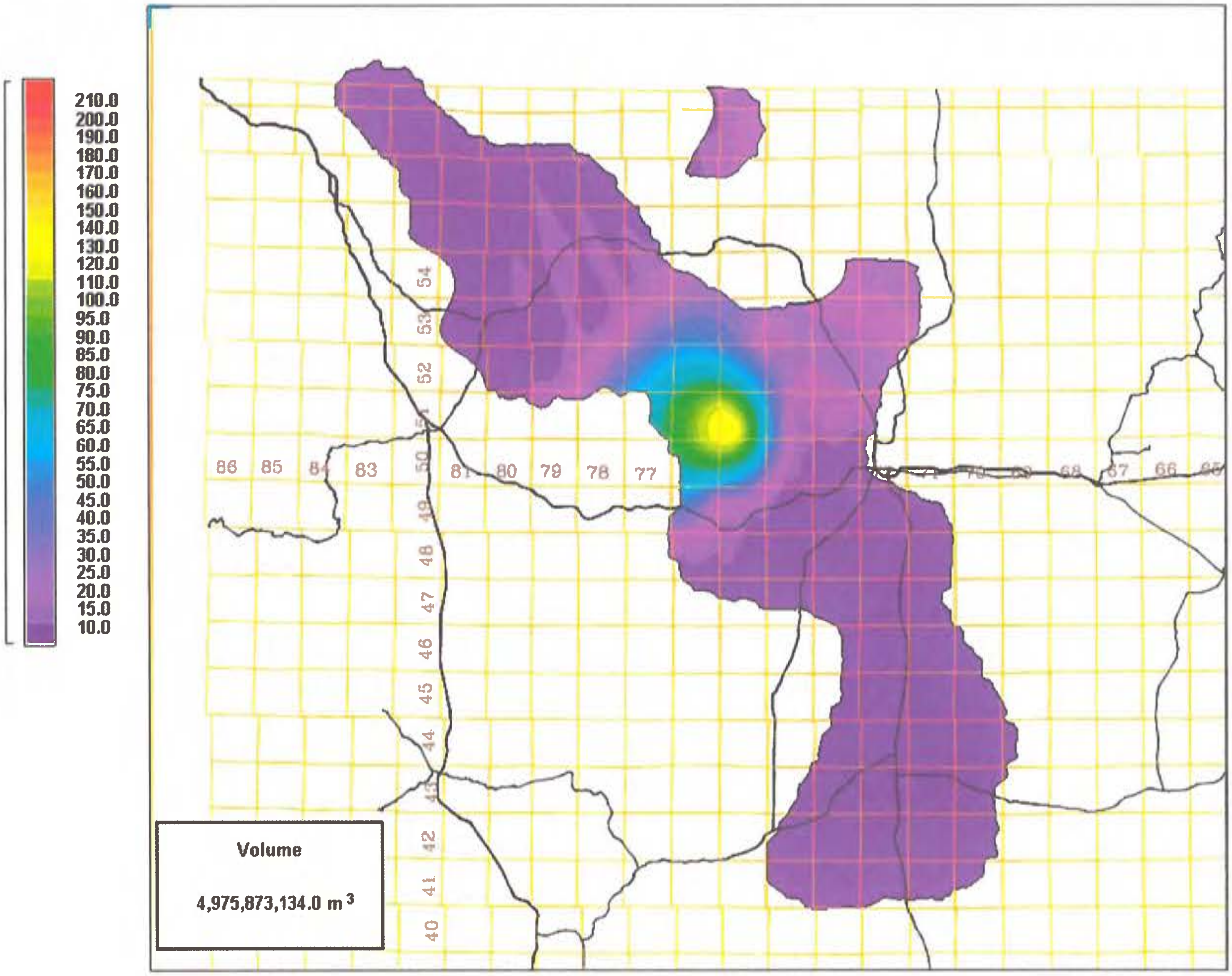


Figure 4-78. Contoured map view of Lower Cook coal bed thickness (feet) generated by the coal thickness model.

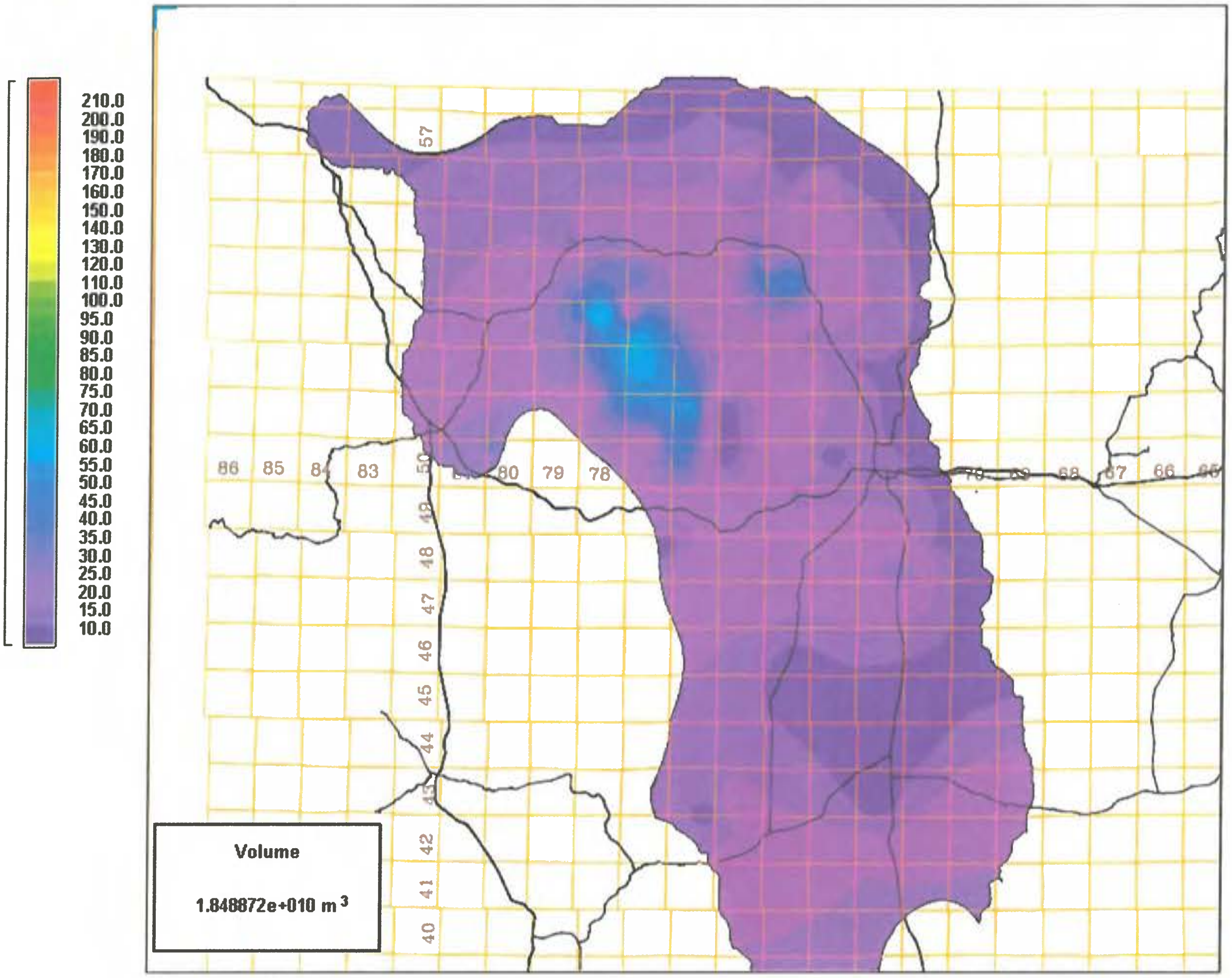


Figure 4-79. Contoured map view of Wall coal bed thickness (feet) generated by the coal thickness model.

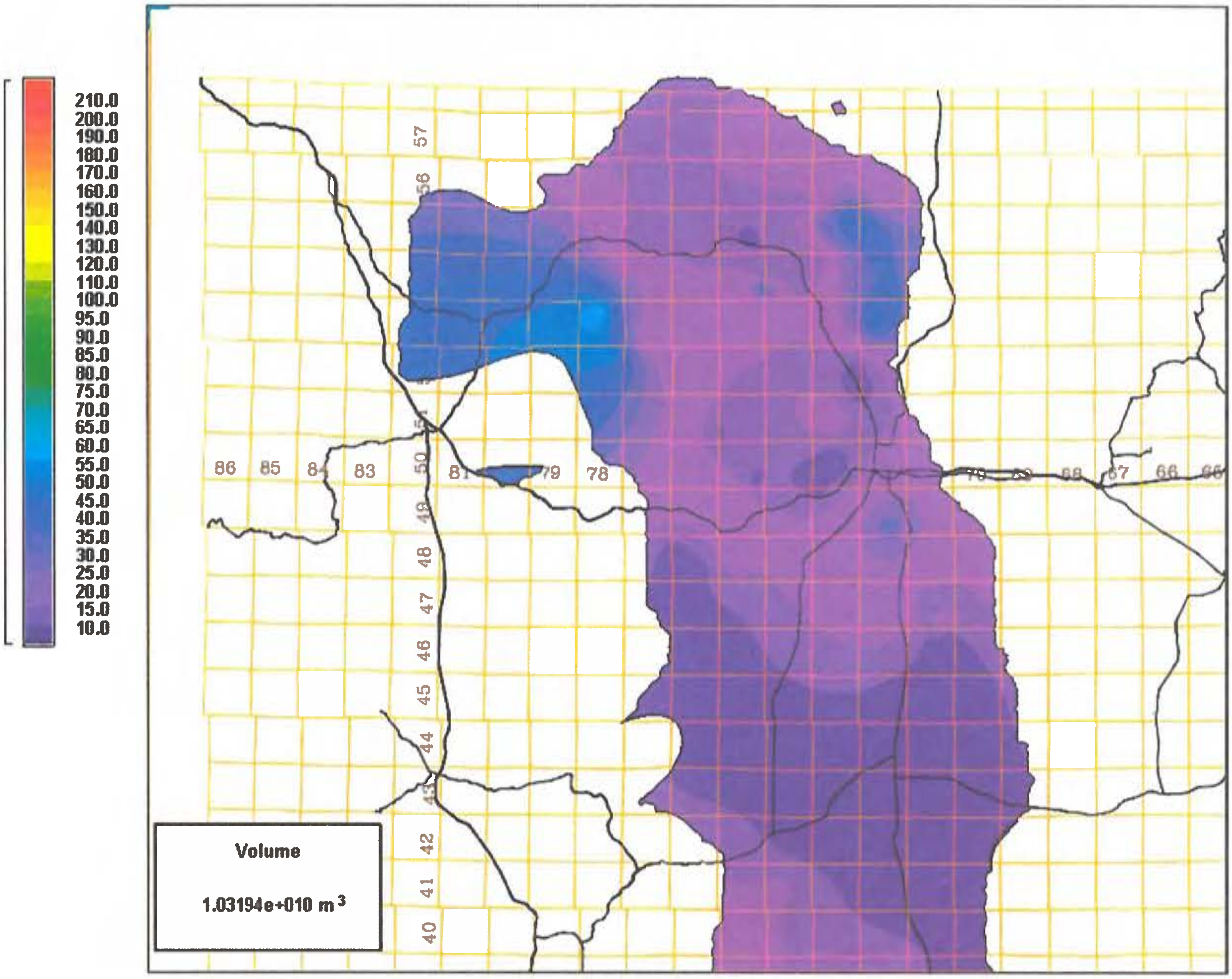


Figure 4-80. Contoured map view of Lower Wall coal bed thickness (feet) generated by the coal thickness model.

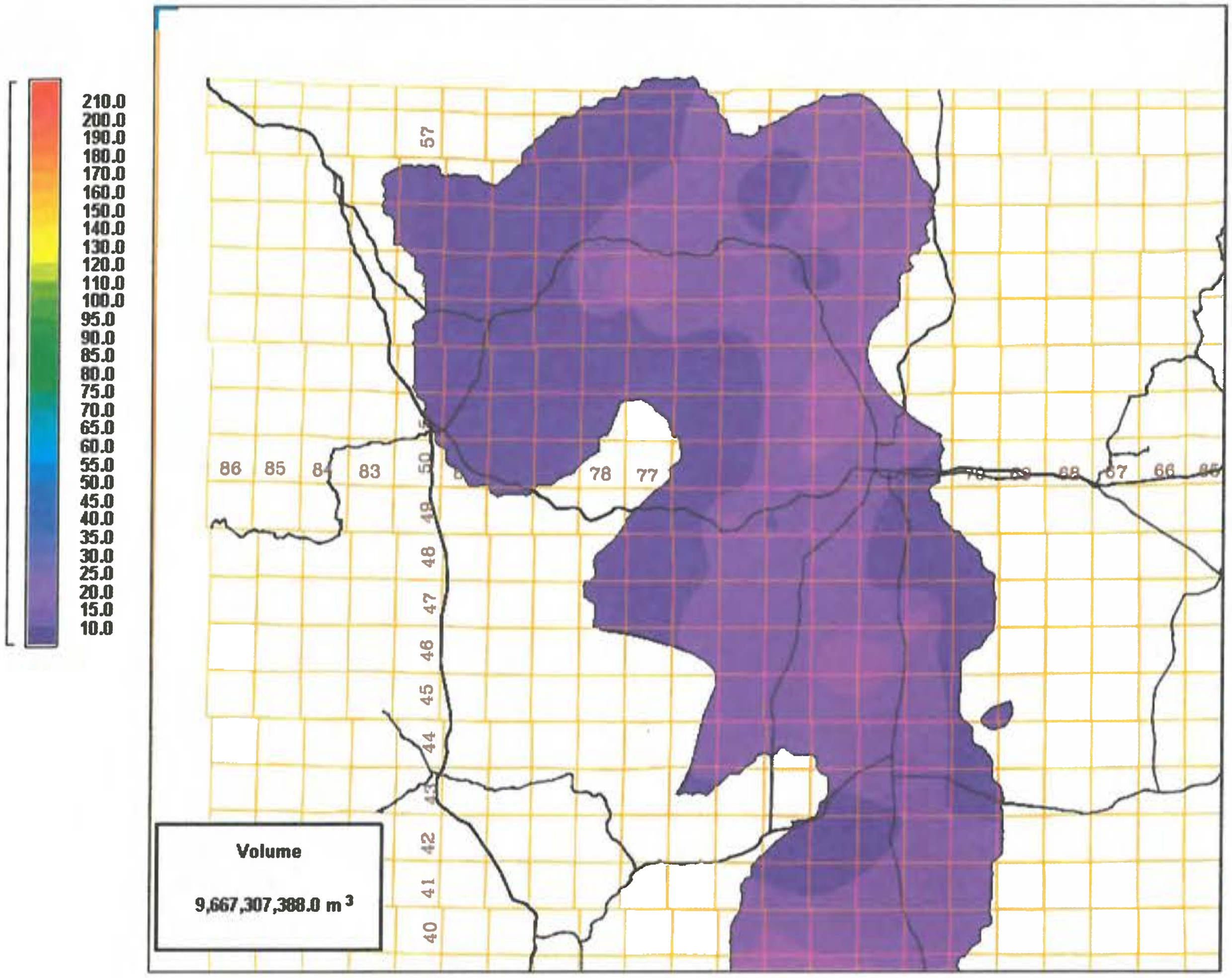


Figure 4-81. Contoured map view of Pawnee coal bed thickness (feet) generated by the coal thickness model.

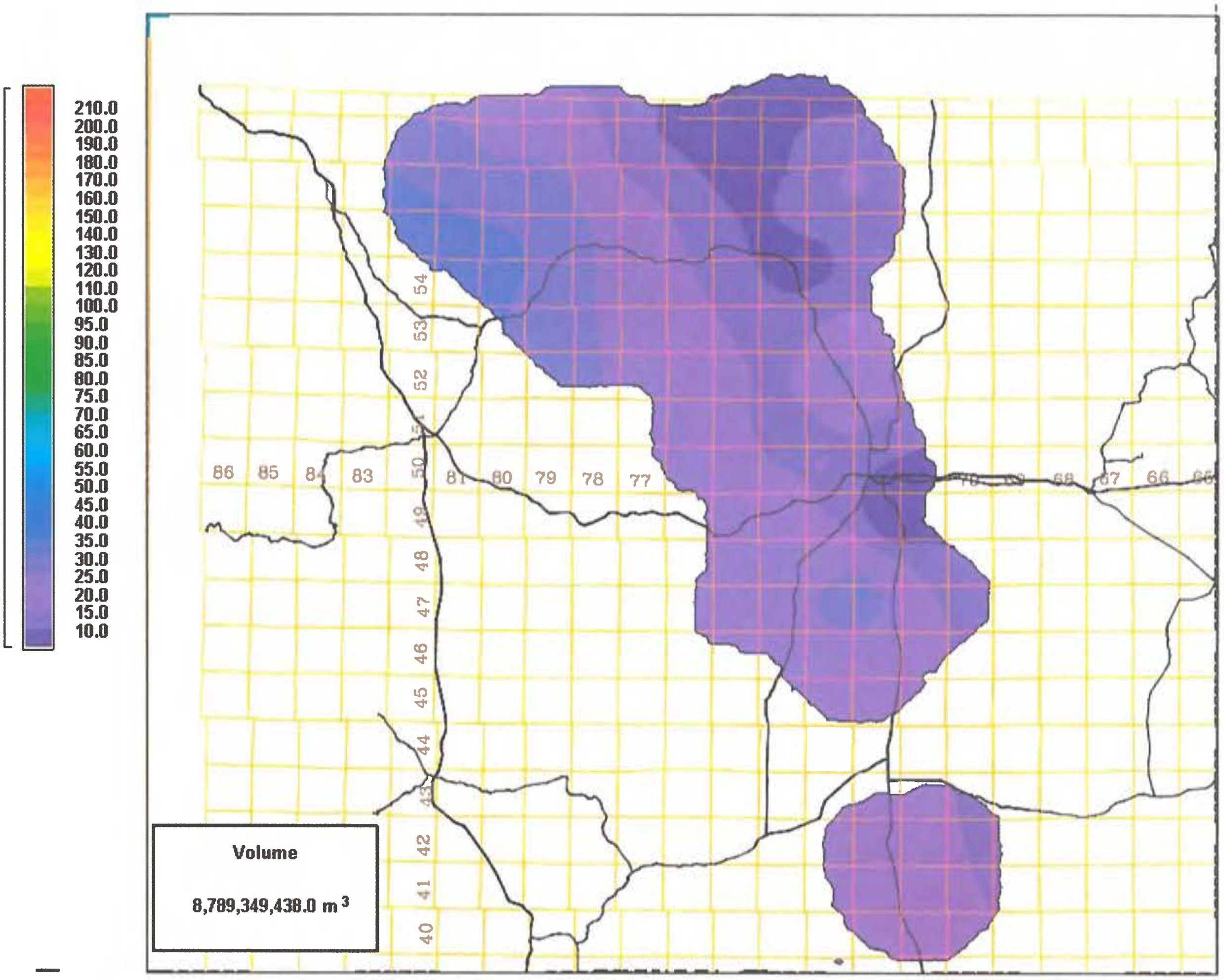


Figure 4-82. Contoured map view of Moyer coal bed thickness (feet) generated by the coal thickness model.

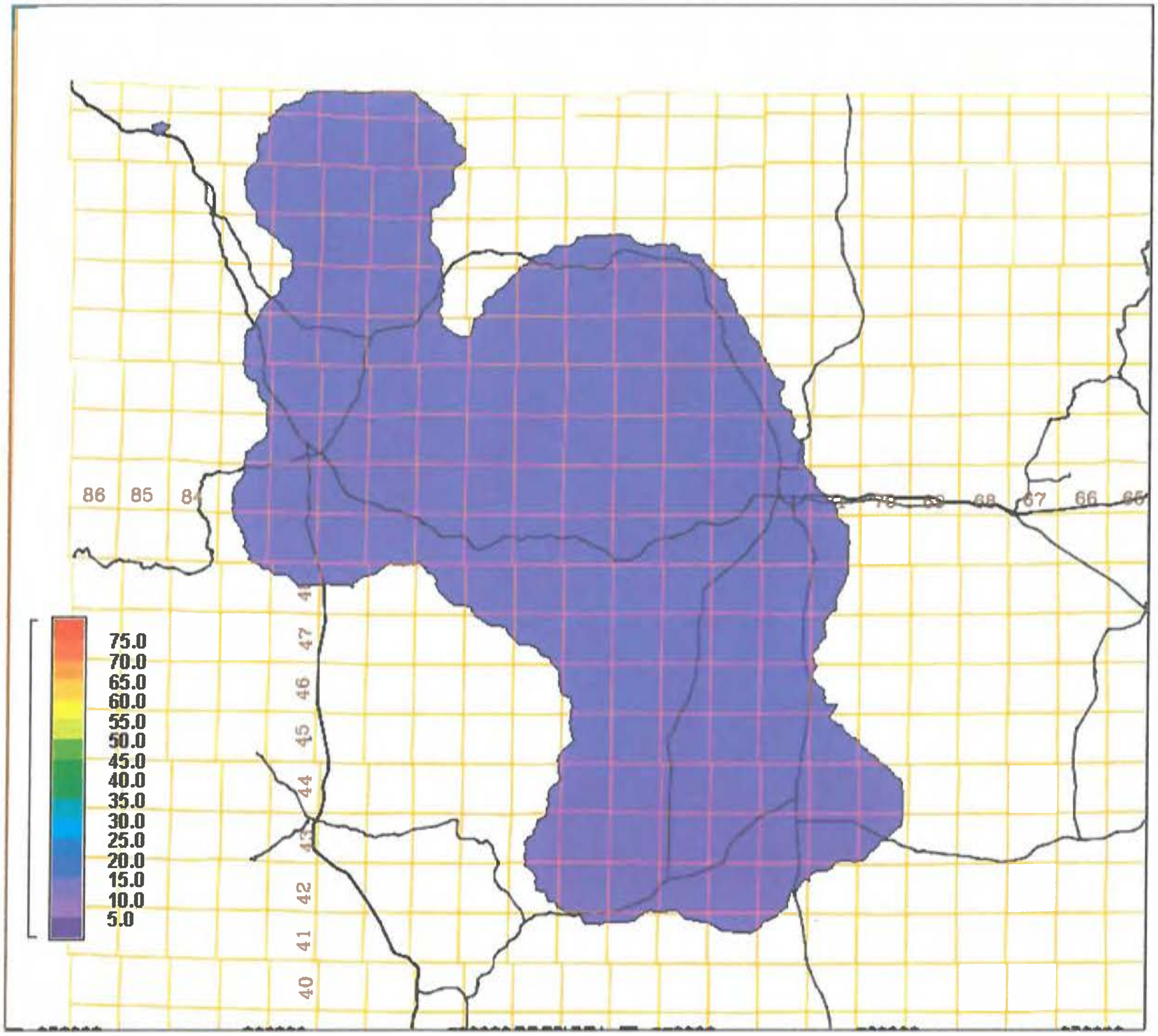


Figure 4-83. Regional distribution of sodium adsorption ratio (SAR) of water from the Felix coal bed, Powder River Basin, Wyoming.

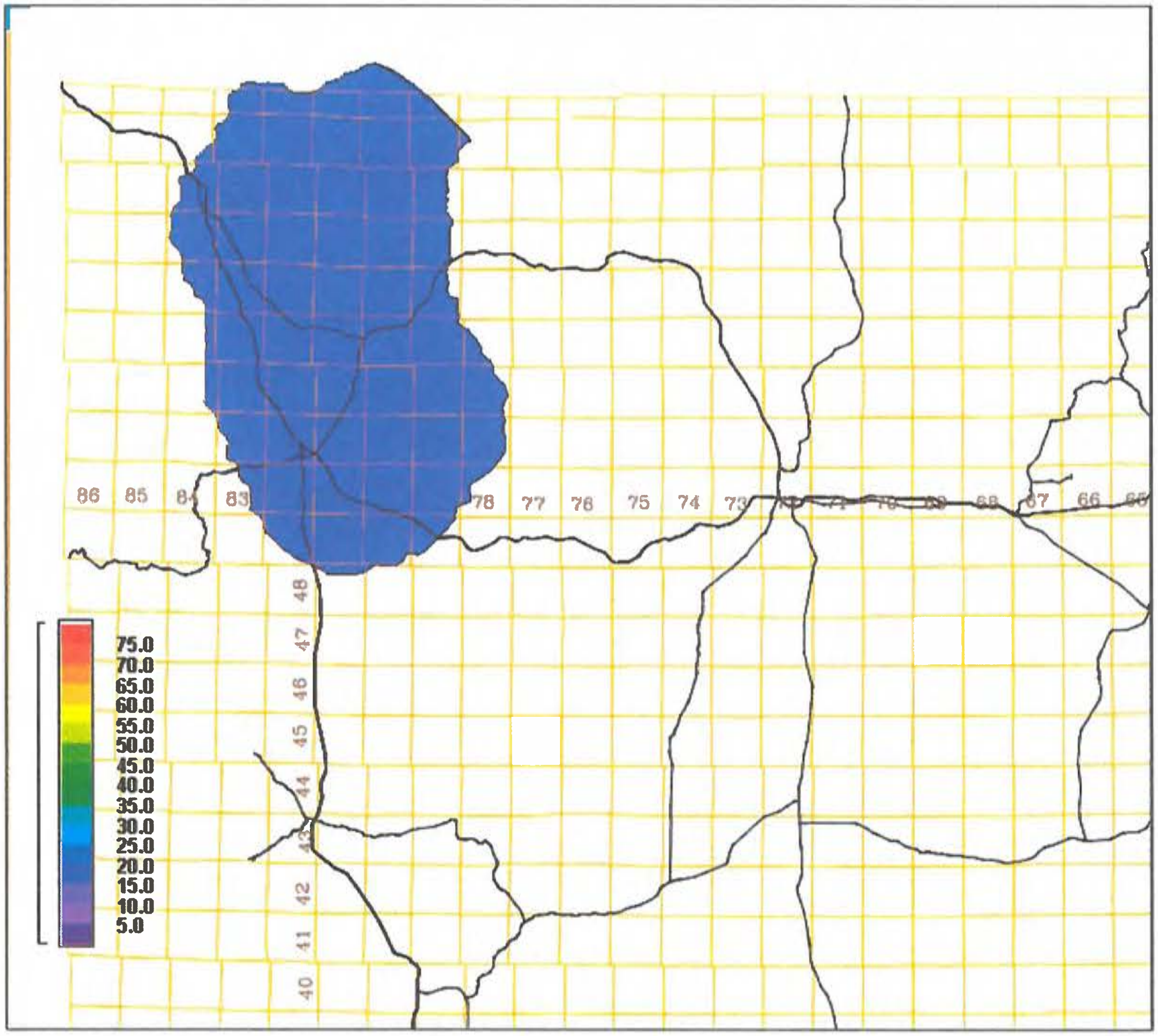


Figure 4-84. Regional distribution of sodium adsorption ratio (SAR) of water from the Arvada coal bed, Powder River Basin, Wyoming.

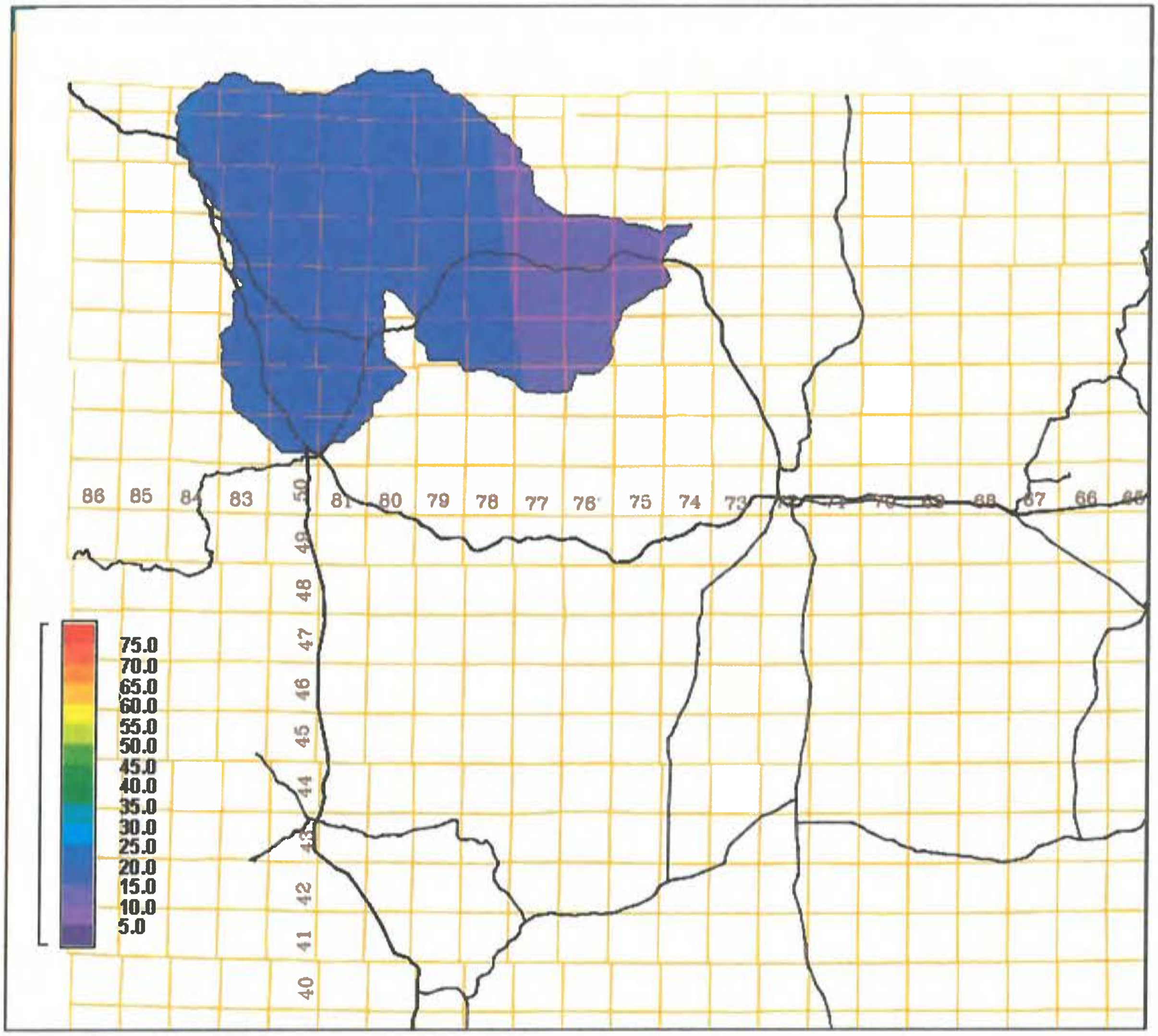


Figure 4-85. Regional distribution of sodium adsorption ratio (SAR) of water from the unnamed coal bed, Powder River Basin, Wyoming.

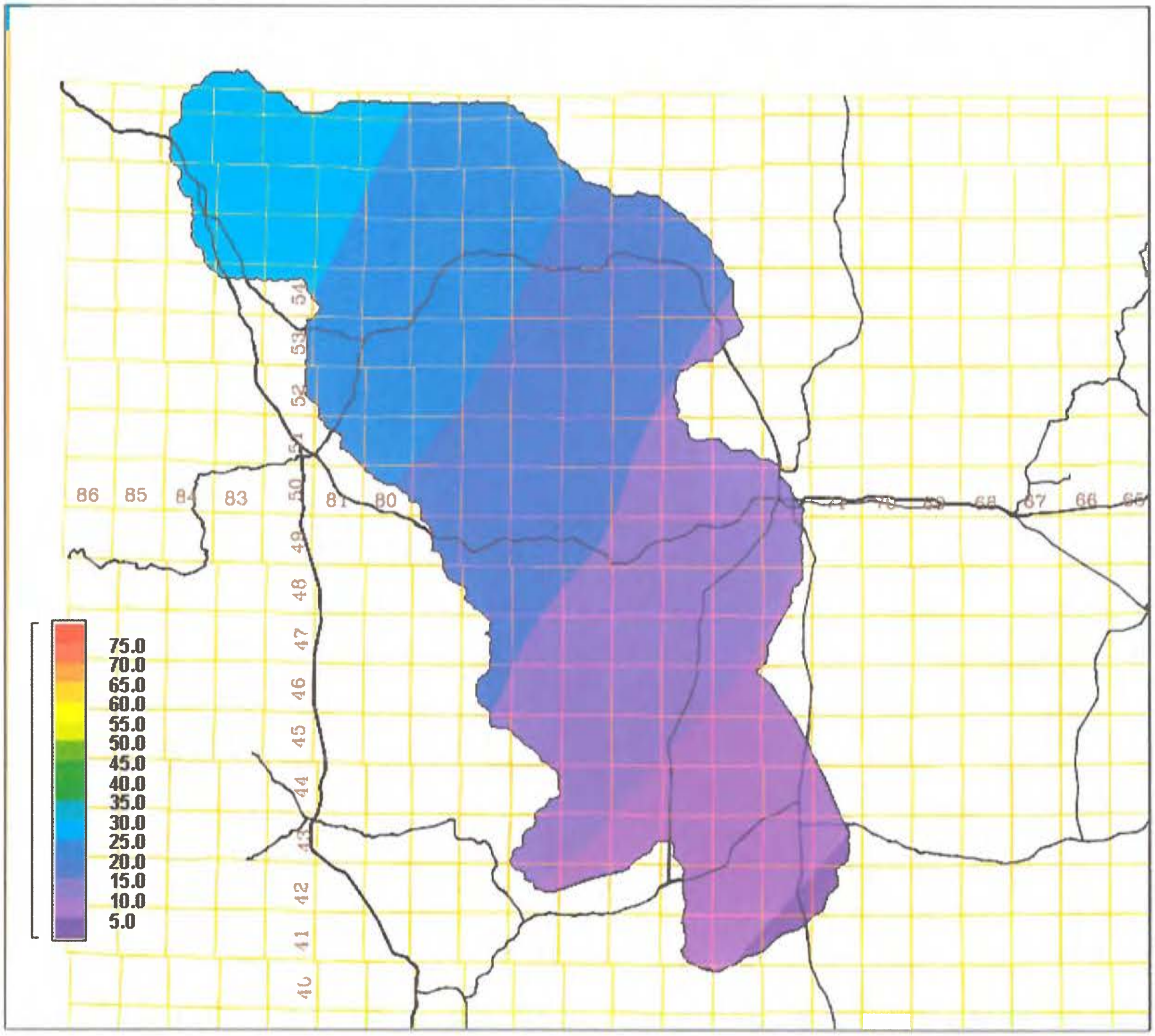


Figure 4-86. Regional distribution of sodium adsorption ratio (SAR) of water from the Upper Roland coal bed, Powder River Basin, Wyoming.

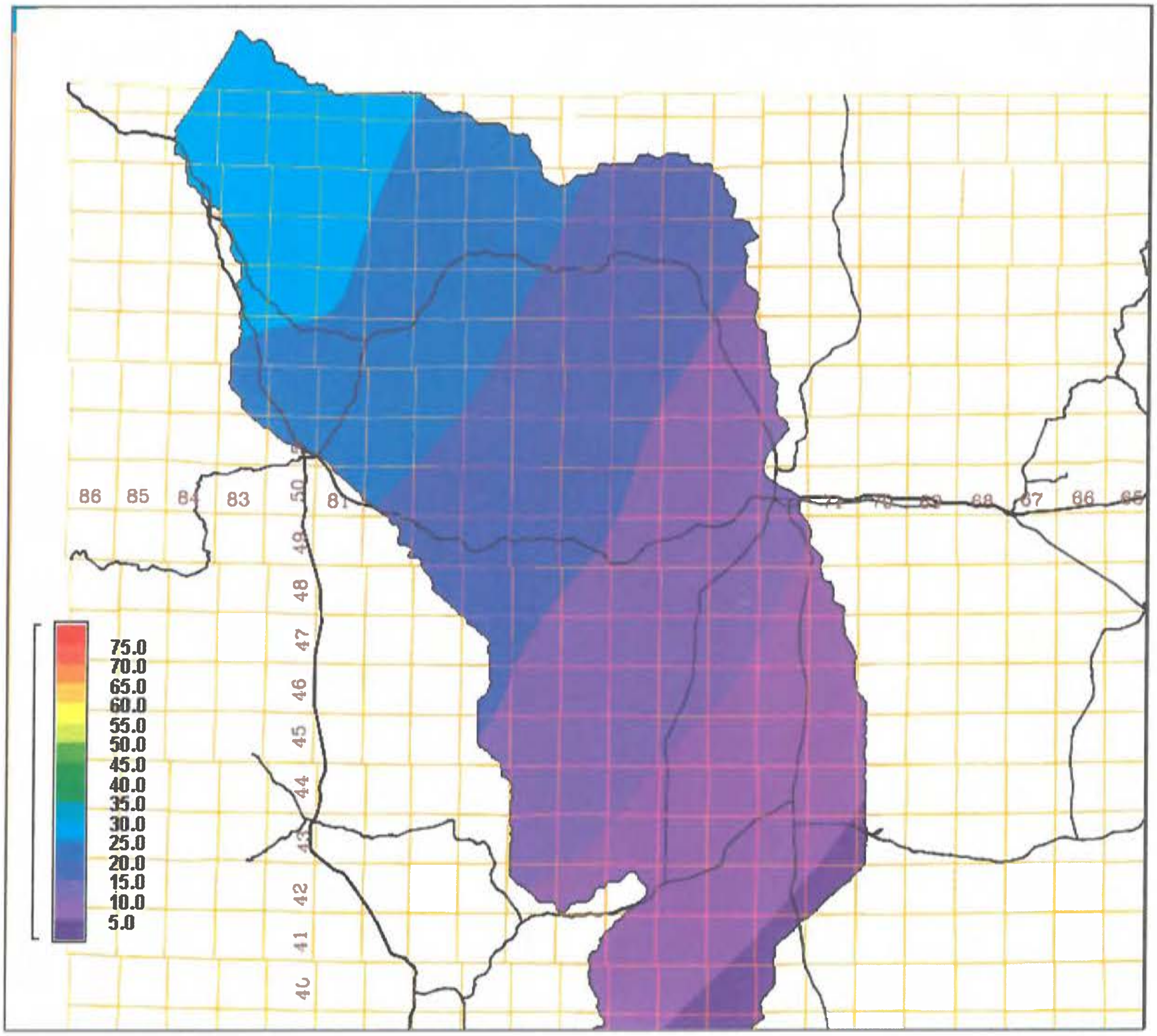


Figure 4-87. Regional distribution of sodium adsorption ratio (SAR) of water from the Roland of Baker coal bed, Powder River Basin, Wyoming.

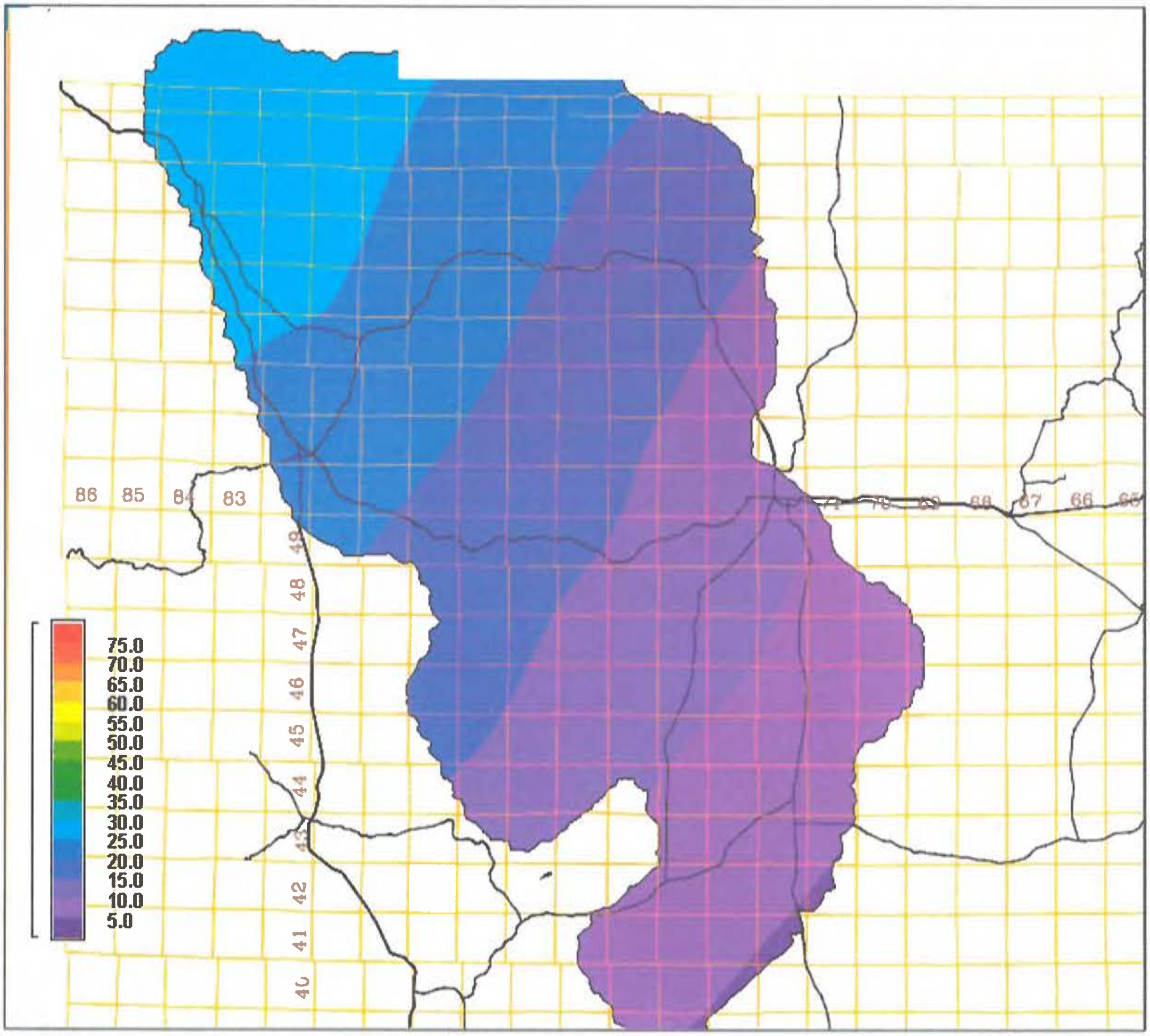


Figure 4-88. Regional distribution of sodium adsorption ratio (SAR) of water from the Roland of Taff coal bed, Powder River Basin, Wyoming.

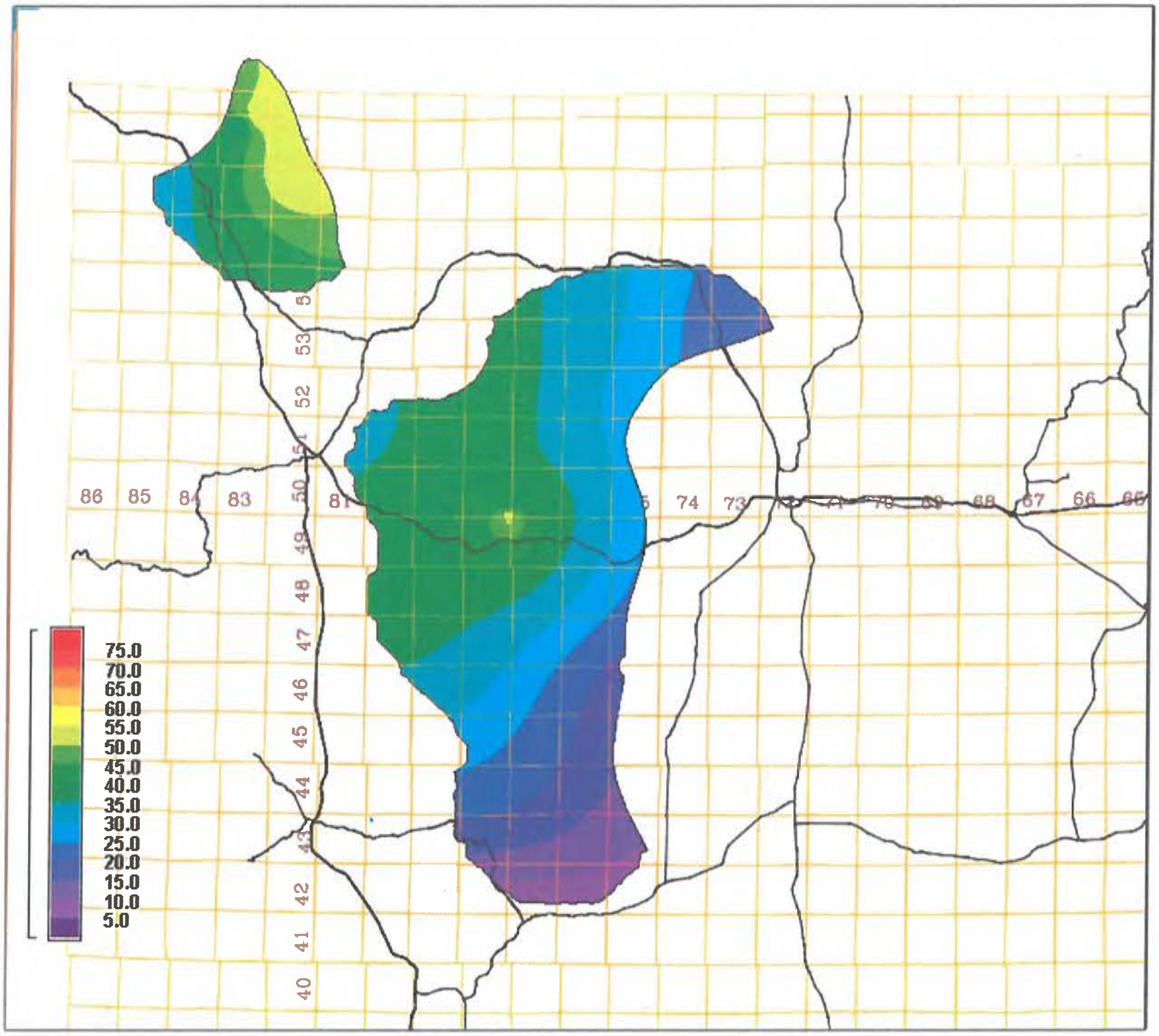


Figure 4-89. Regional distribution of sodium adsorption ratio (SAR) of water from the Smith Rider coal bed, Powder River Basin, Wyoming.

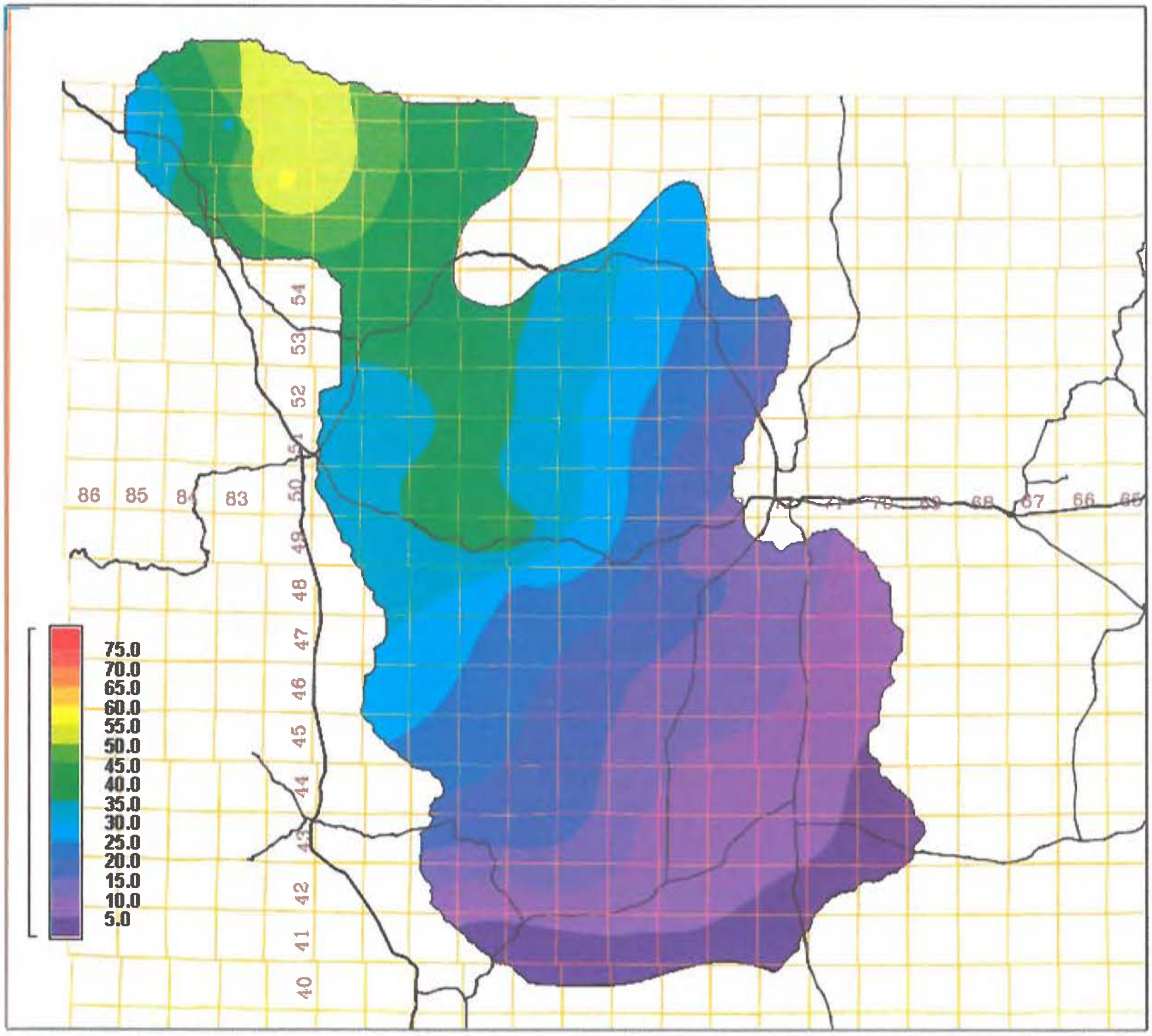


Figure 4-90. Regional distribution of sodium adsorption ratio (SAR) of water from the Smith/Big George coal bed, Powder River Basin, Wyoming.

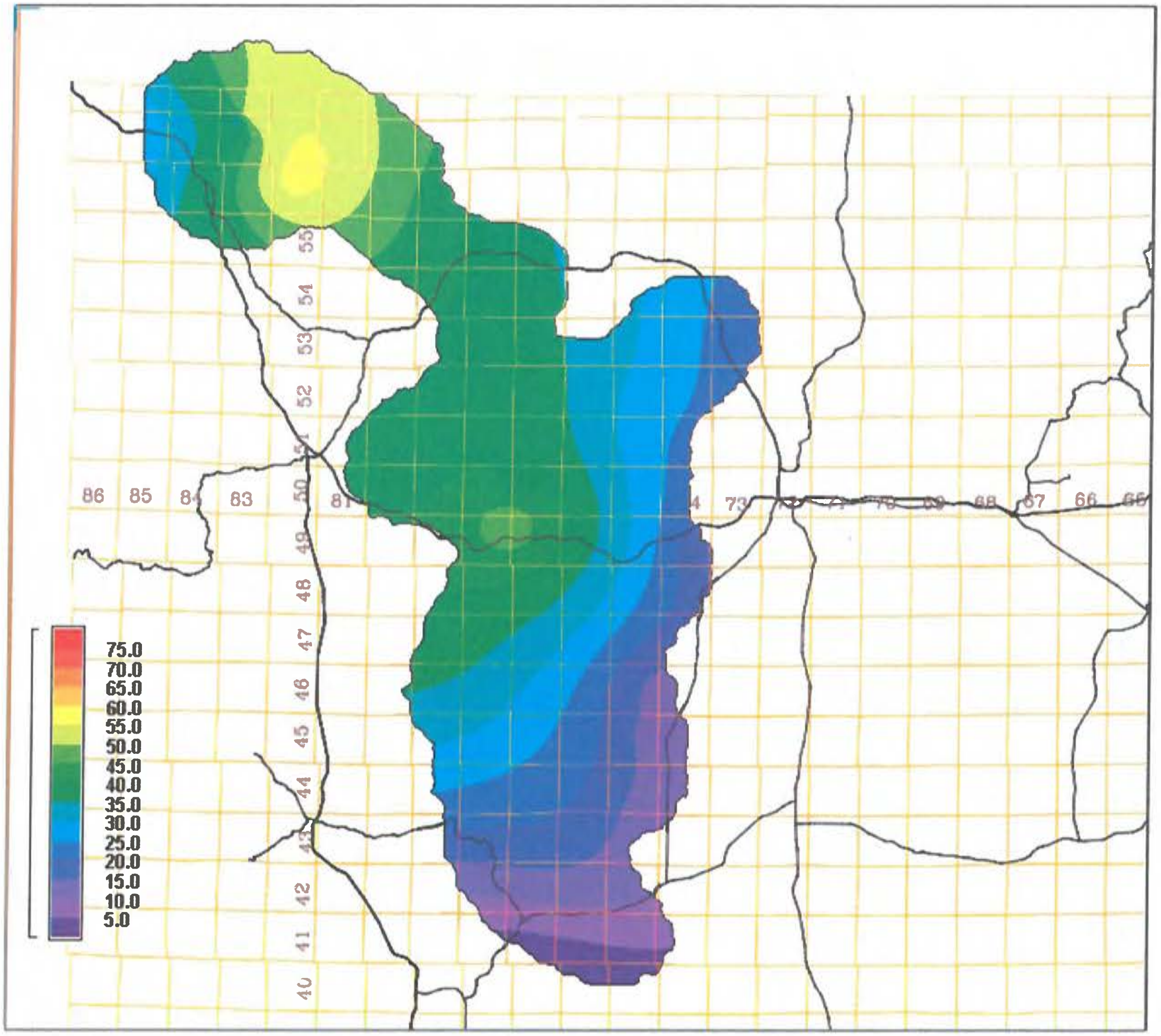


Figure 4-91. Regional distribution of sodium adsorption ratio (SAR) of water from the Lower Smith coal bed, Powder River Basin, Wyoming.

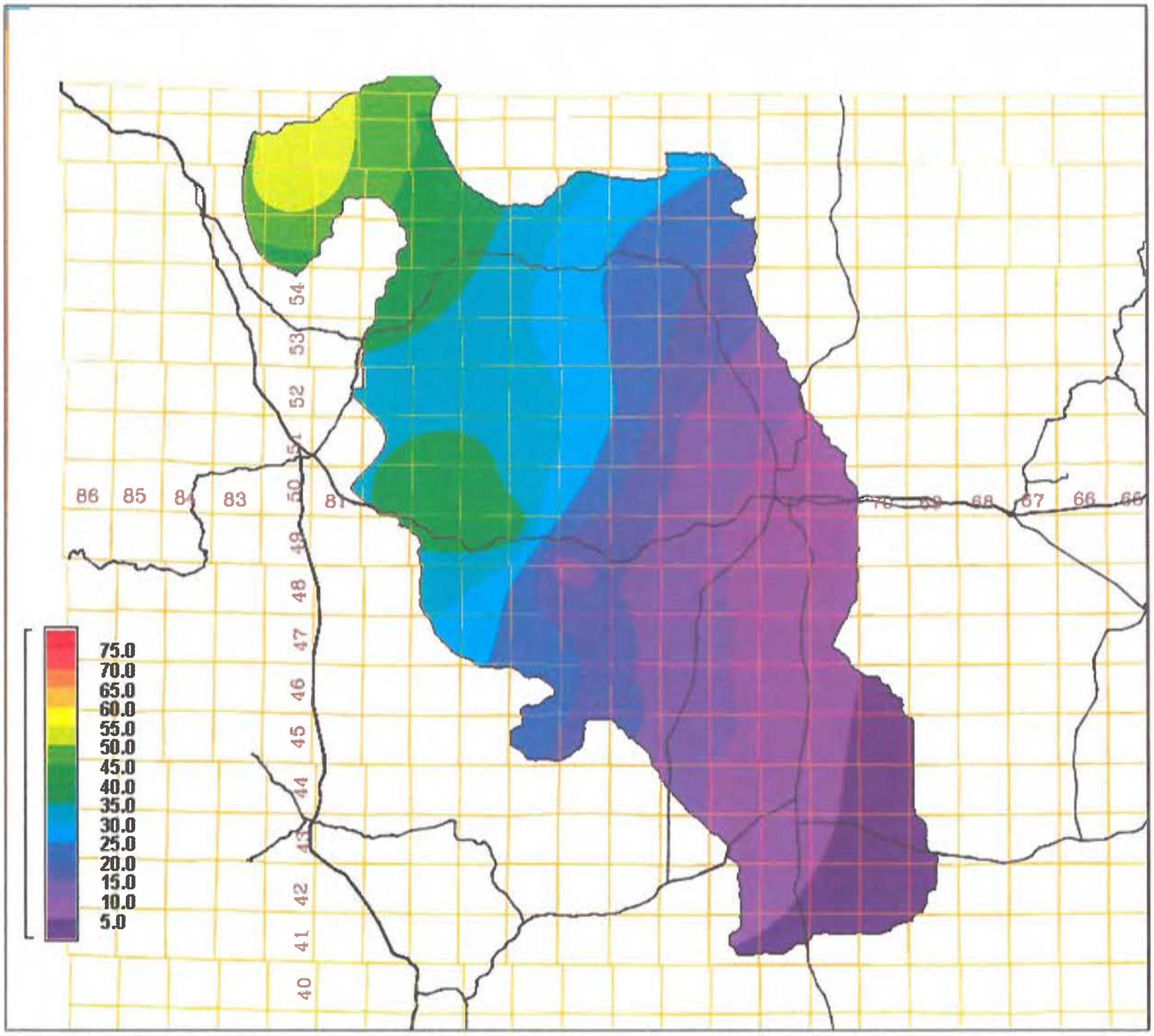


Figure 4-92. Regional distribution of sodium adsorption ratio (SAR) of water from the Anderson Rider coal bed, Powder River Basin, Wyoming.

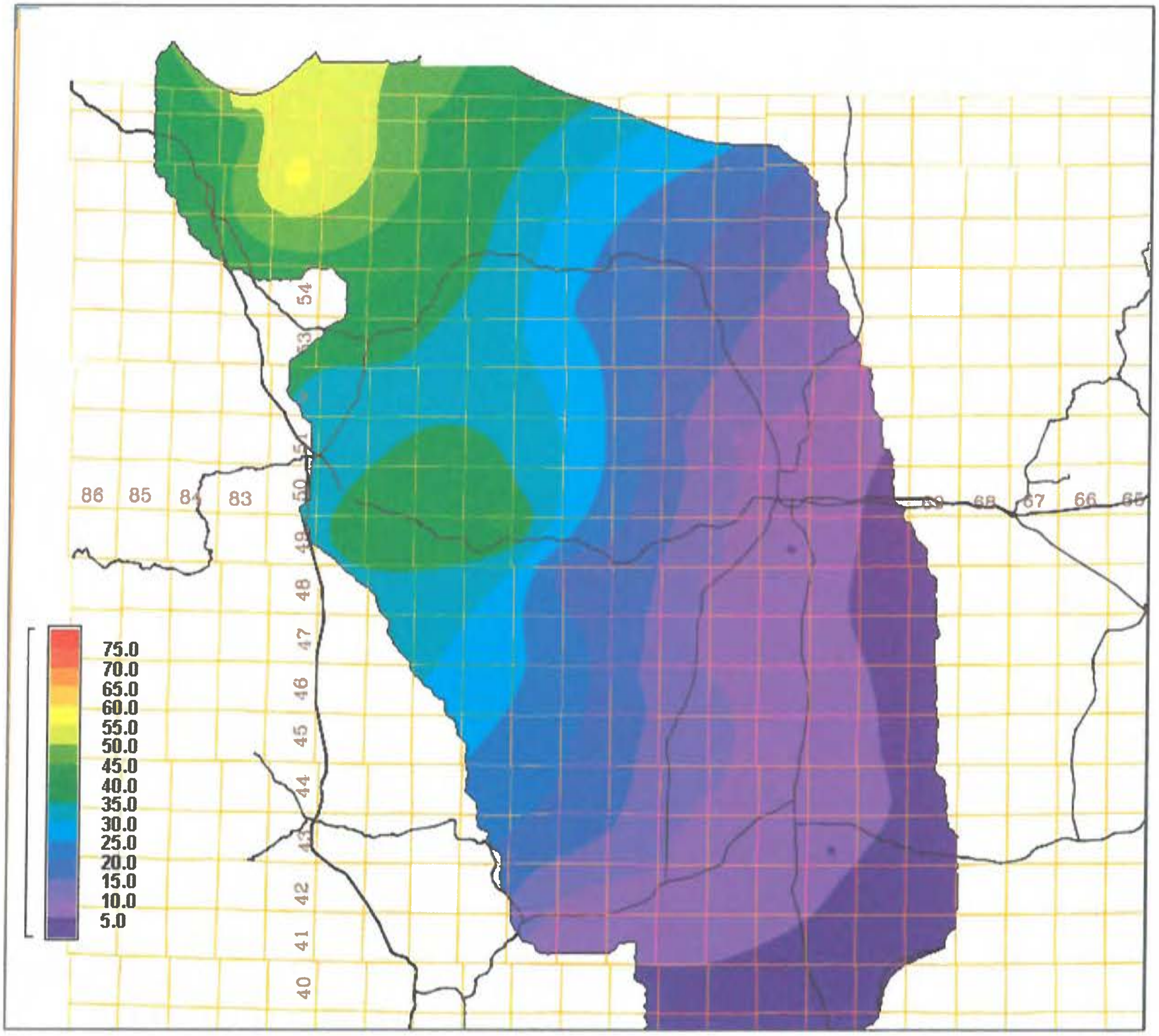


Figure 4-93. Regional distribution of sodium adsorption ratio (SAR) of water from the Anderson coal bed, Powder River Basin, Wyoming.

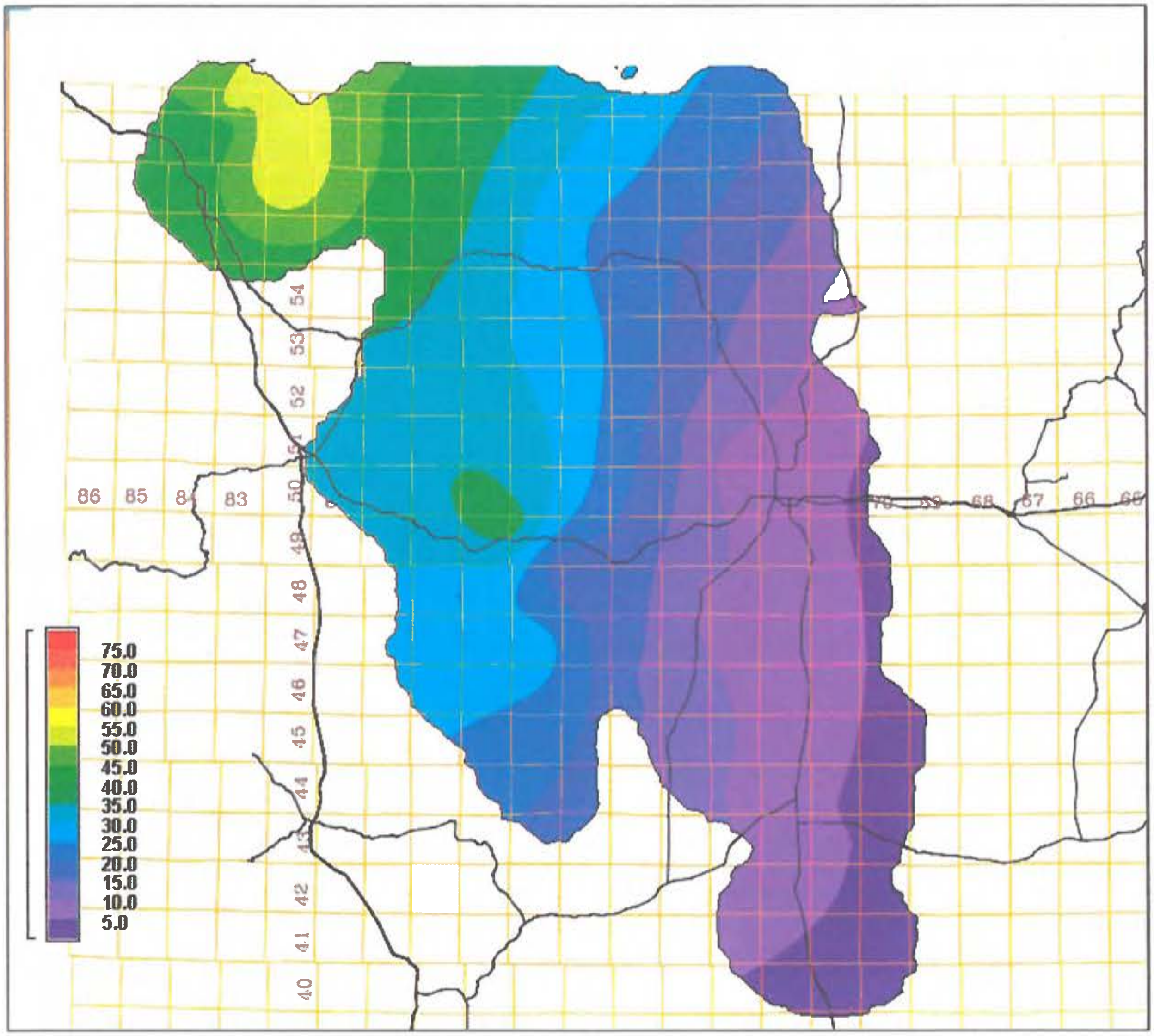


Figure 4-94. Regional distribution of sodium adsorption ratio (SAR) of water from the Lower Anderson coal bed, Powder River Basin, Wyoming.

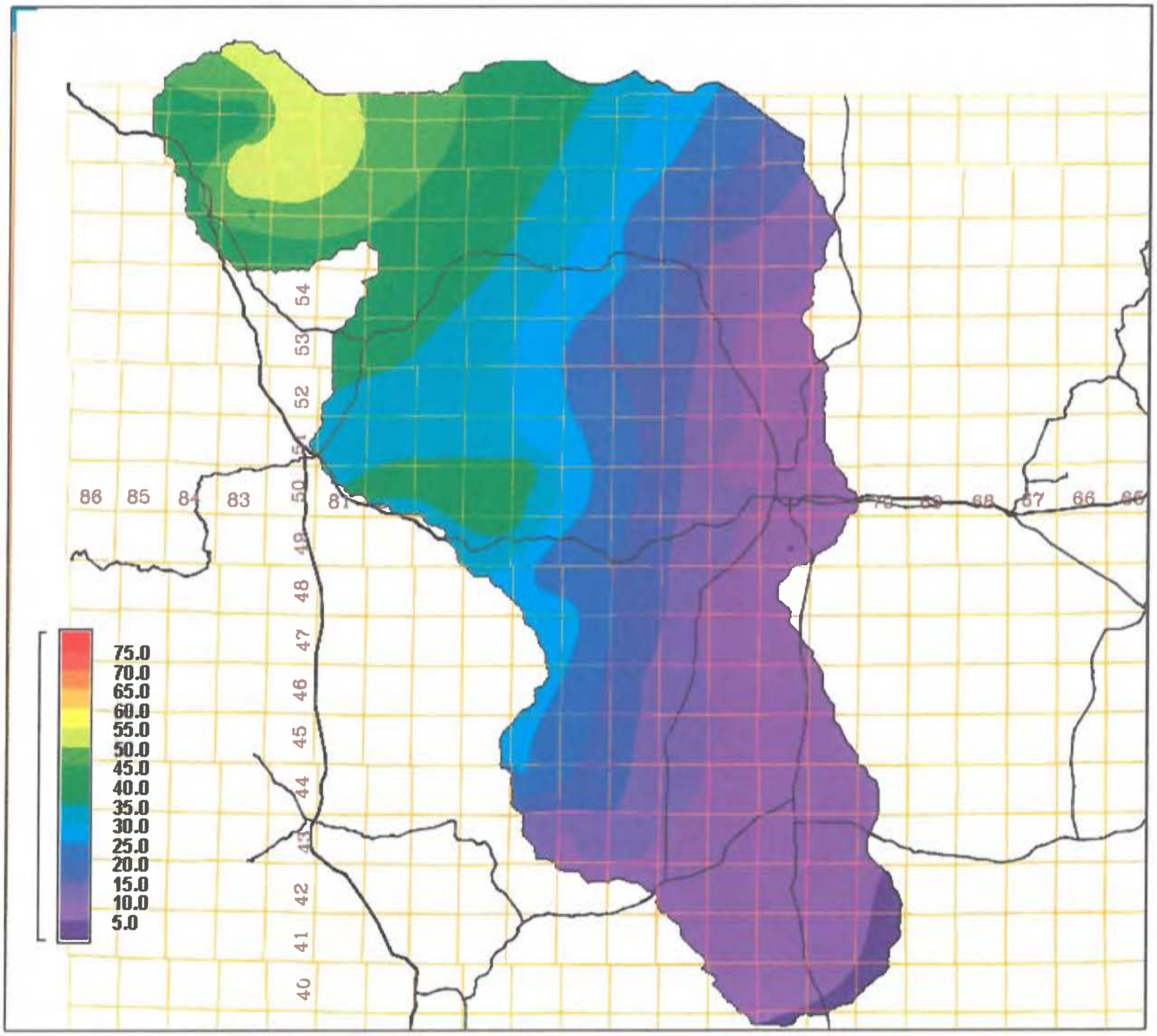


Figure 4-95. Regional distribution of sodium adsorption ratio (SAR) of water from the Canyon coal bed, Powder River Basin, Wyoming.

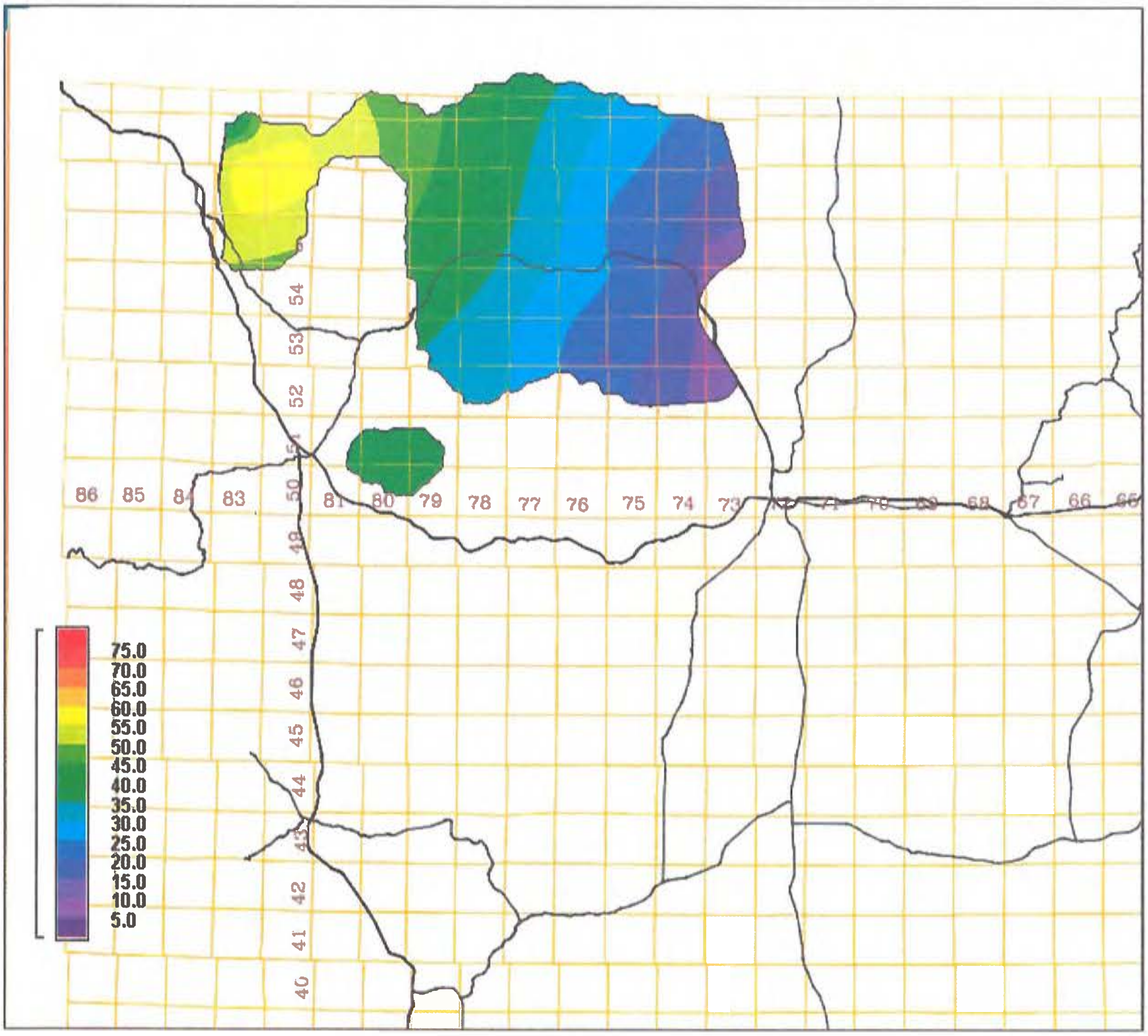


Figure 4-96. Regional distribution of sodium adsorption ratio (SAR) of water from the Canyon Rider coal bed, Powder River Basin, Wyoming.

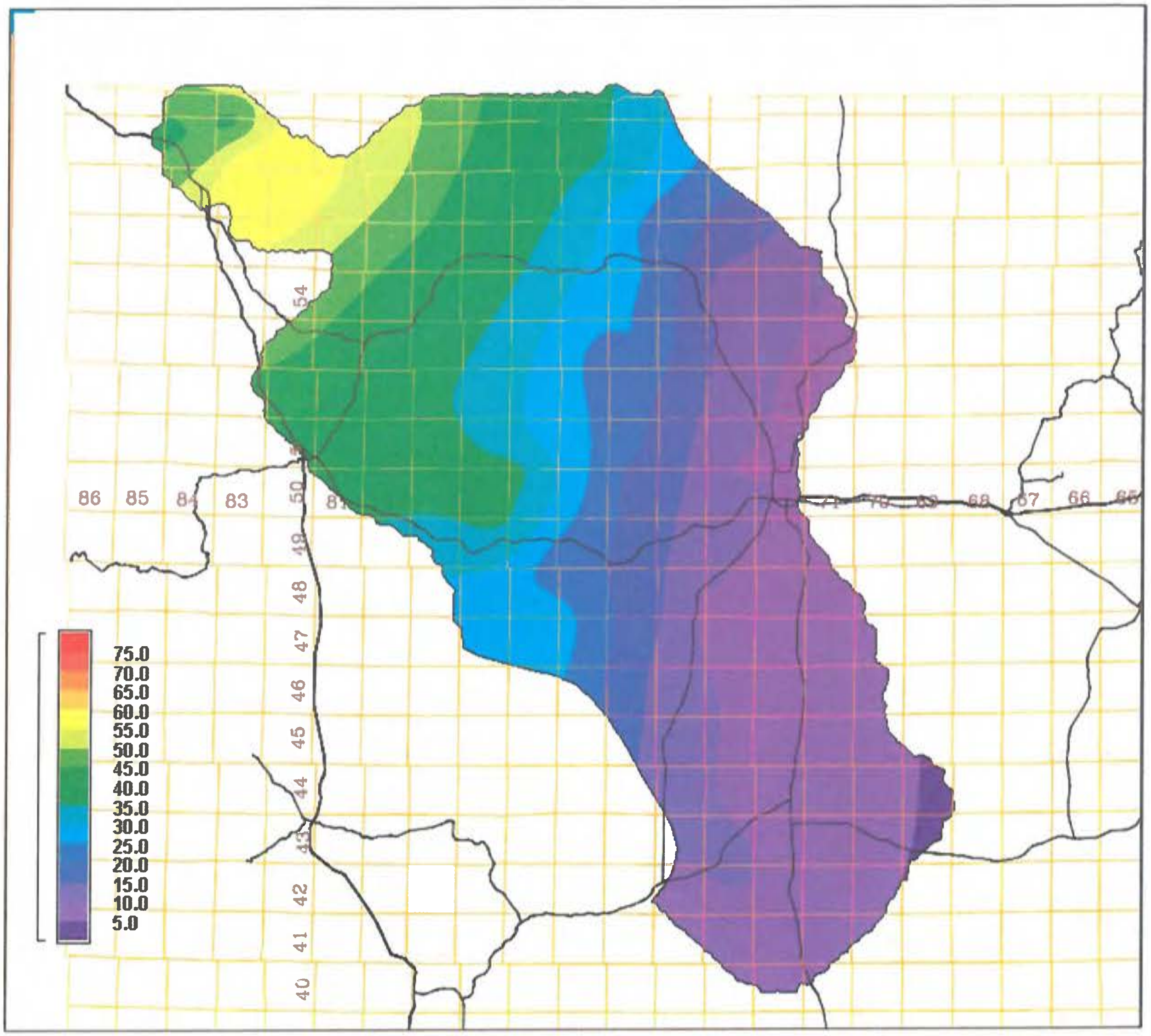


Figure 4-97. Regional distribution of sodium adsorption ratio (SAR) of water from the Cook coal bed, Powder River Basin, Wyoming.

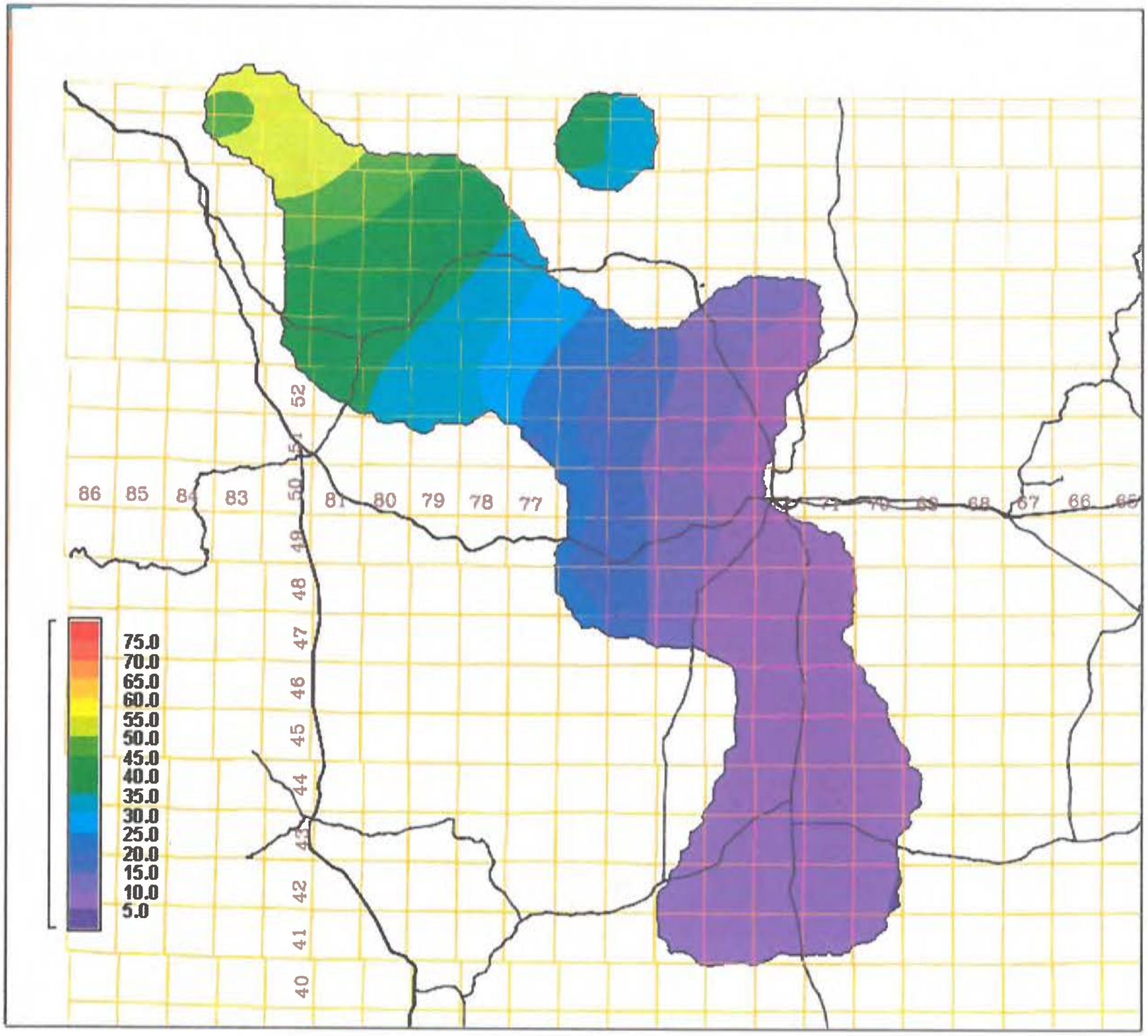


Figure 4-98. Regional distribution of sodium adsorption ratio (SAR) of water from the Lower Cook coal bed, Powder River Basin, Wyoming.

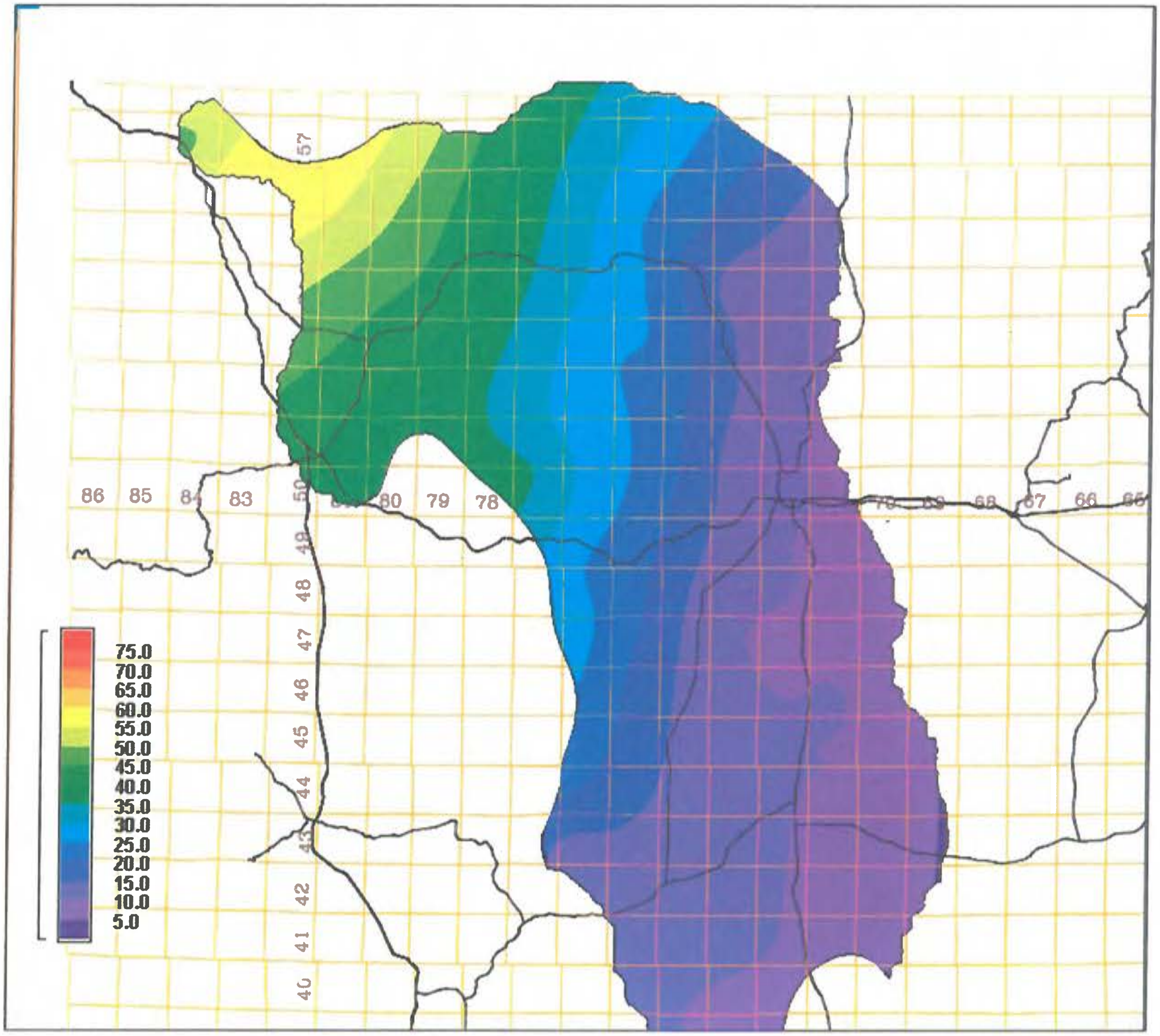


Figure 4-99. Regional distribution of sodium adsorption ratio (SAR) of water from the Wall coal bed, Powder River Basin, Wyoming.

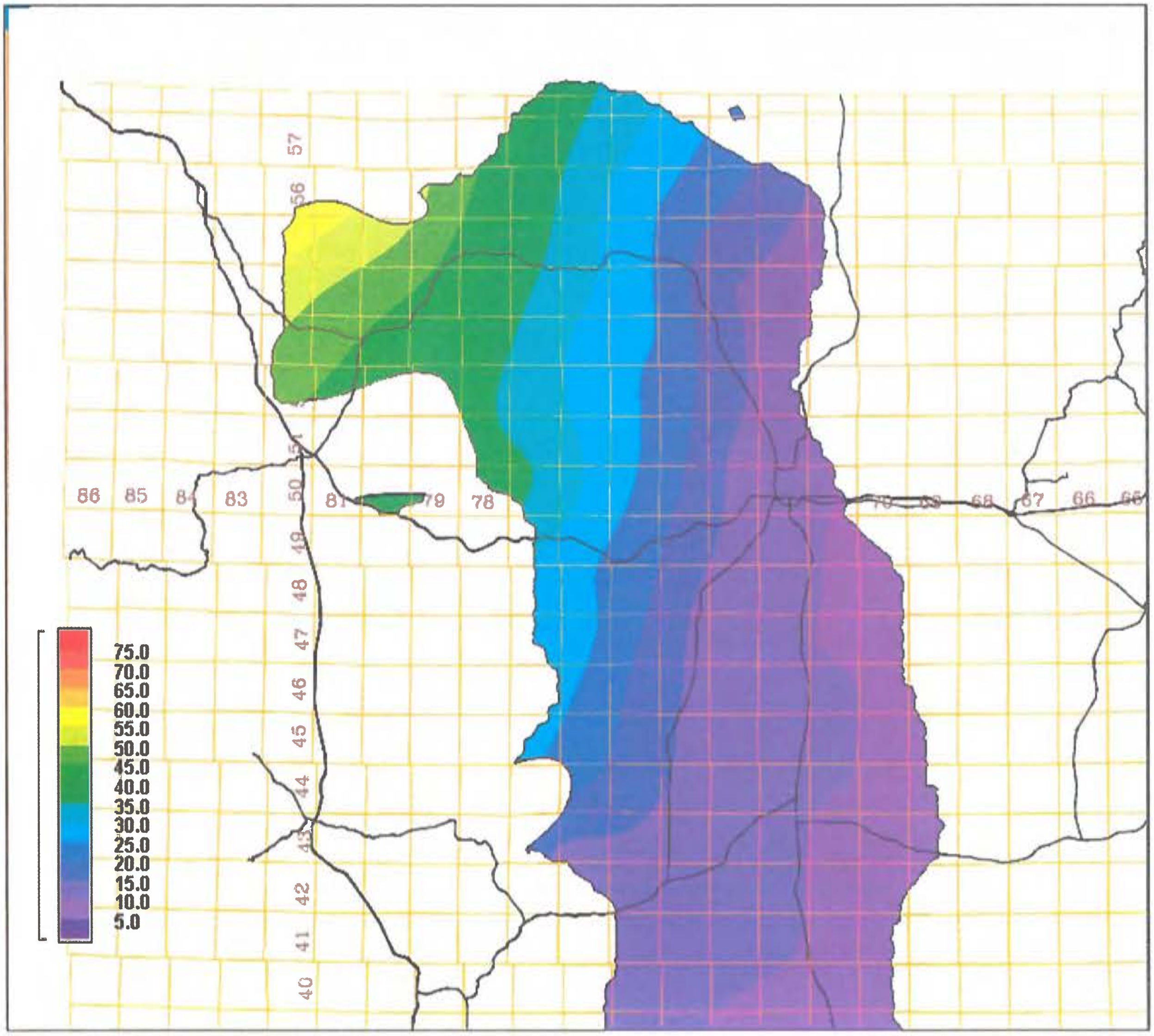


Figure 4-100. Regional distribution of sodium adsorption ratio (SAR) of water from the Lower Wall coal bed, Powder River Basin, Wyoming.

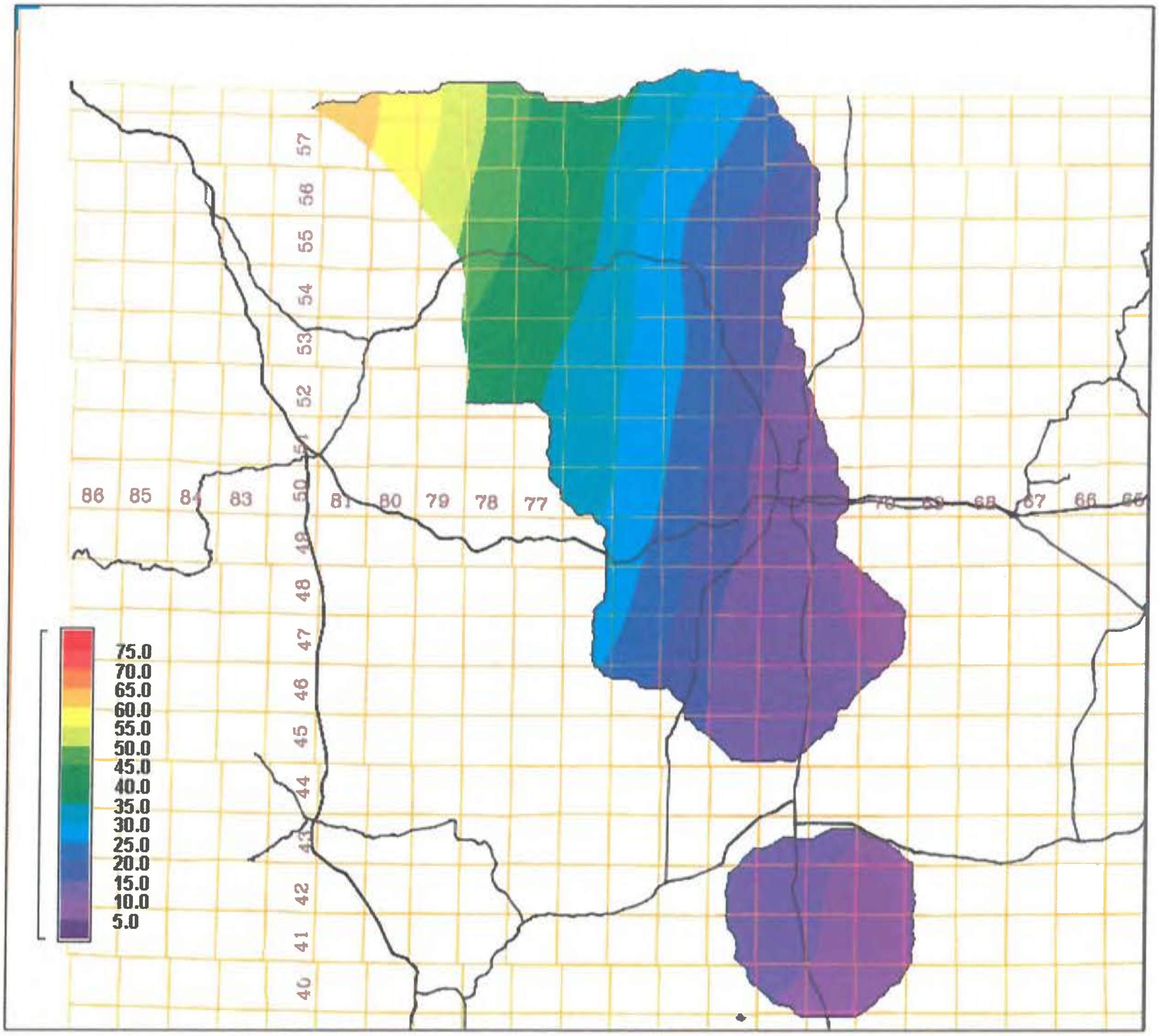


Figure 4-101. Regional distribution of sodium adsorption ratio (SAR) of water from the Moyer coal bed, Powder River Basin, Wyoming.

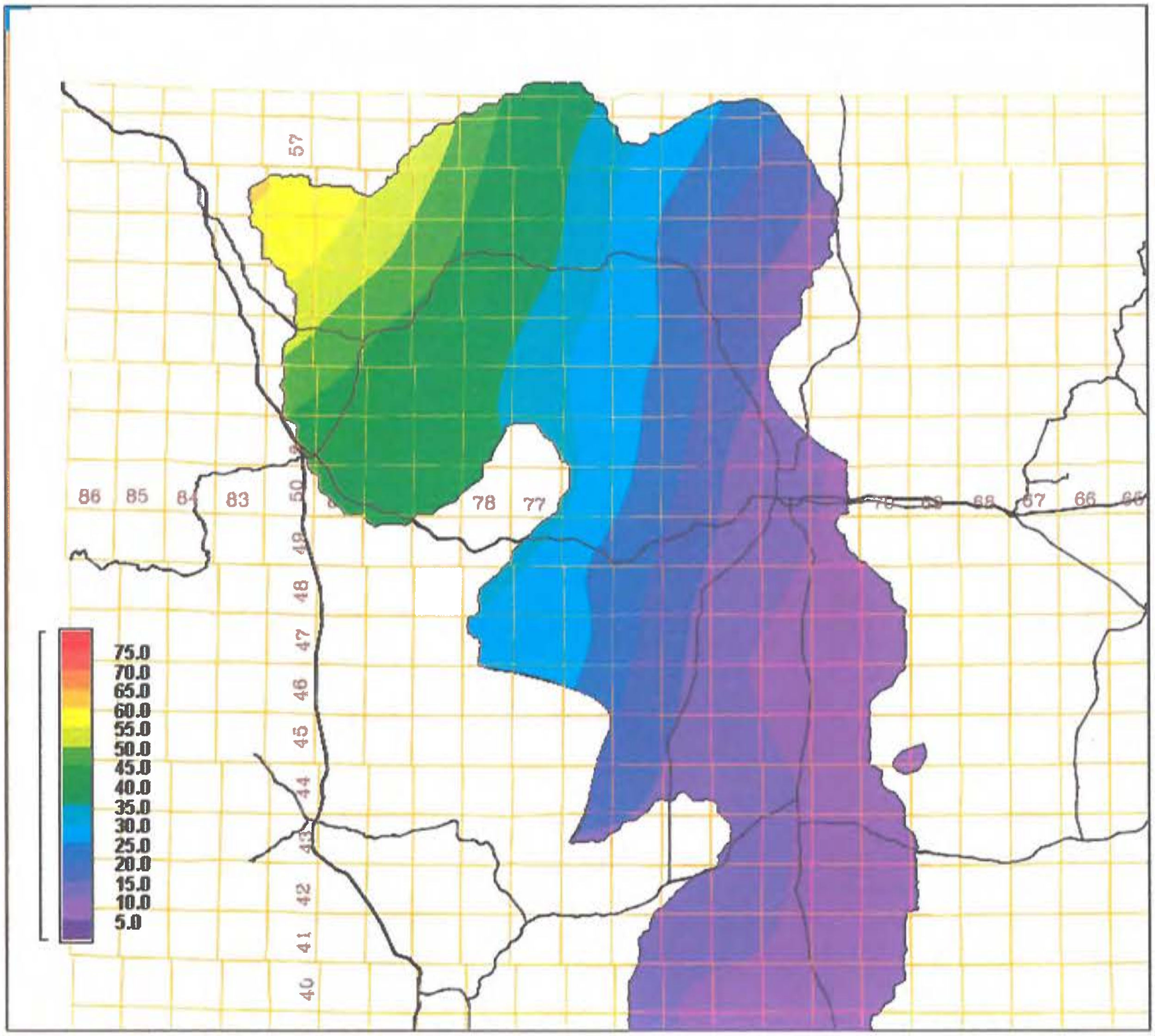


Figure 4-102. Regional distribution of sodium adsorption ratio (SAR) of water from the Pawnee coal bed, Powder River Basin, Wyoming.

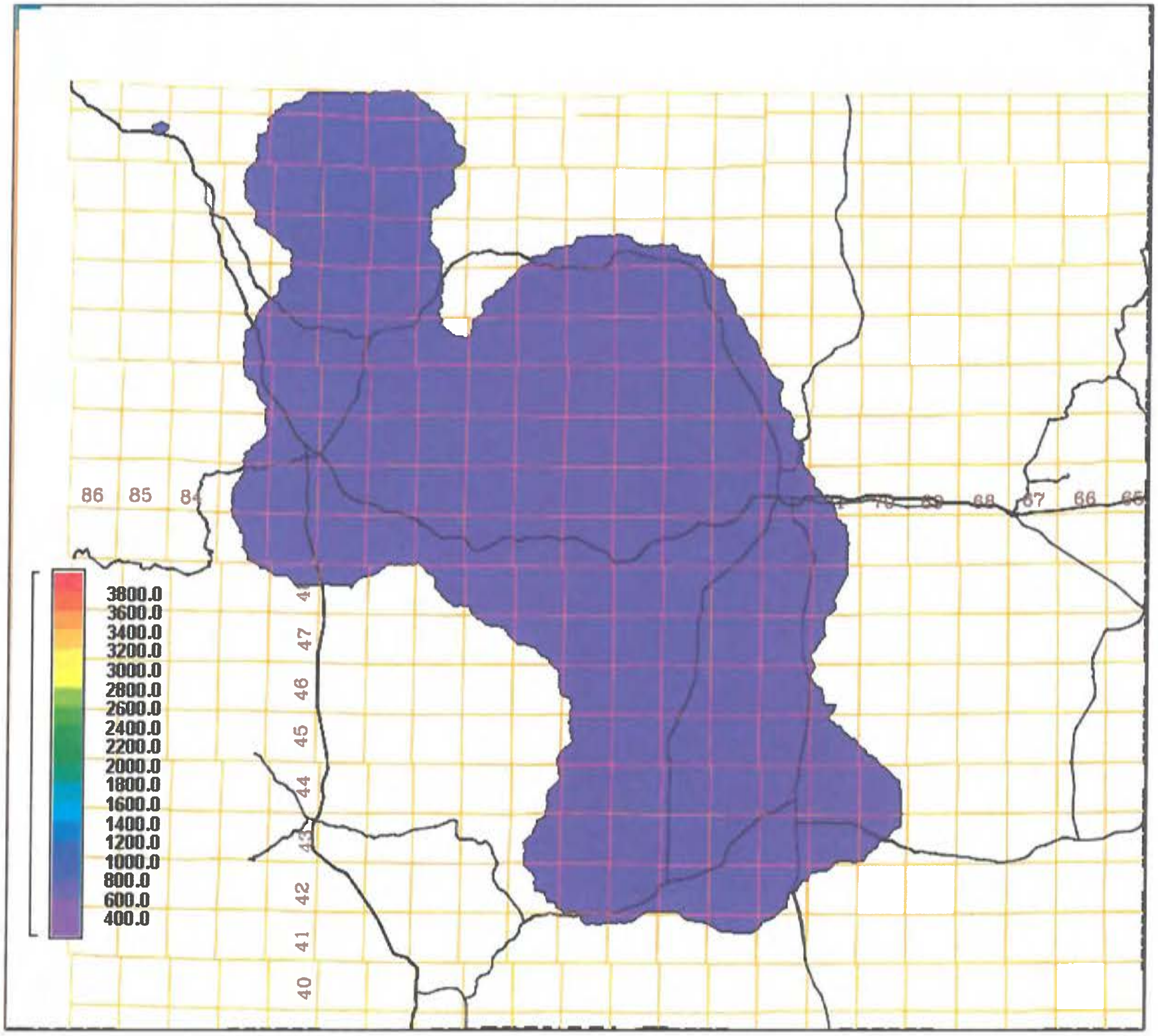


Figure 4-103. Regional distribution of TDS (mg/l) content of water from the Felix coal bed, Powder River Basin, Wyoming.

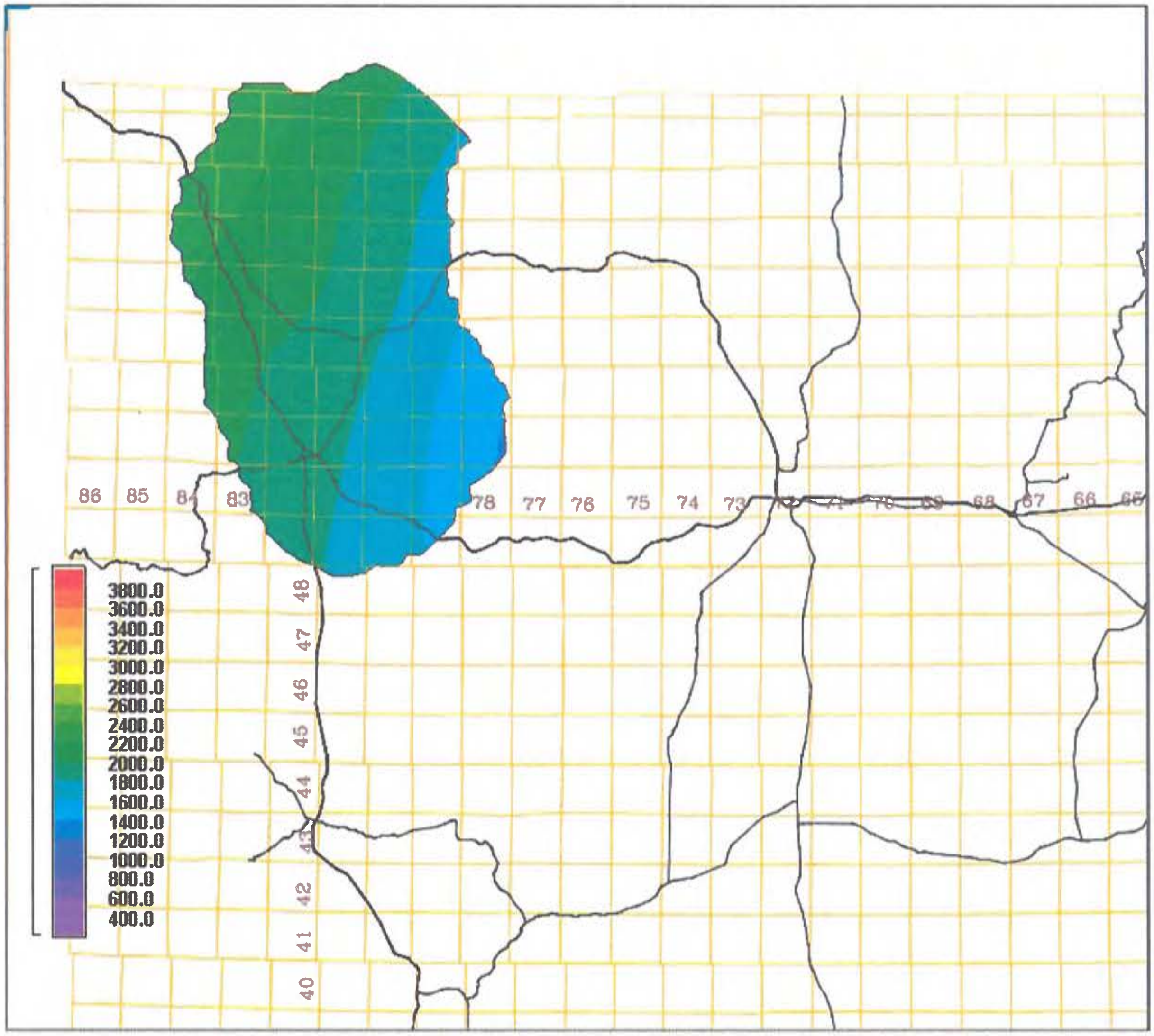


Figure 4-104. Regional distribution of TDS (mg/l) content of water from the Arvada coal bed, Powder River Basin, Wyoming.

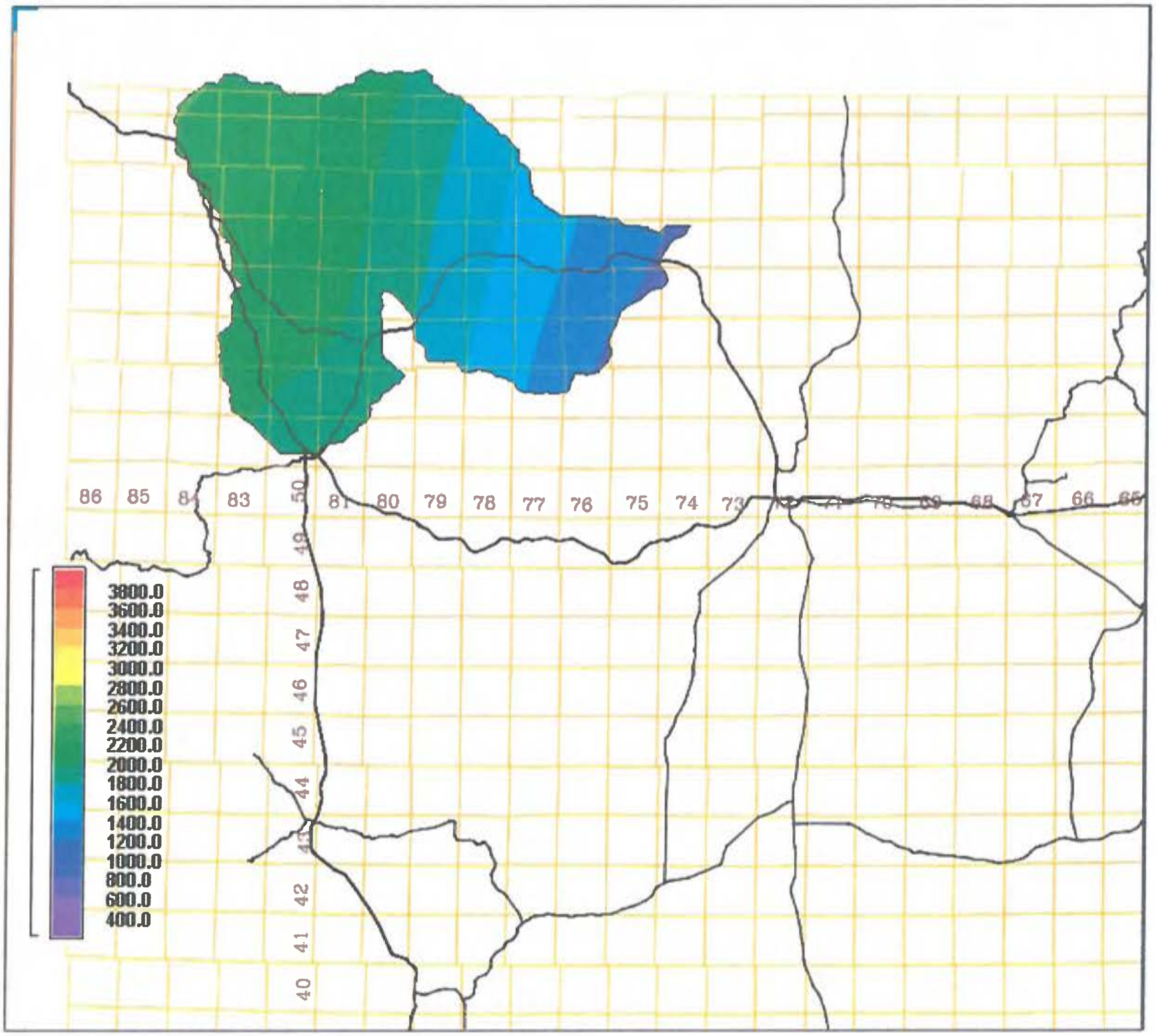


Figure 4-105. Regional distribution of TDS (mg/l) content of water from the unnamed coal bed, Powder River Basin, Wyoming.

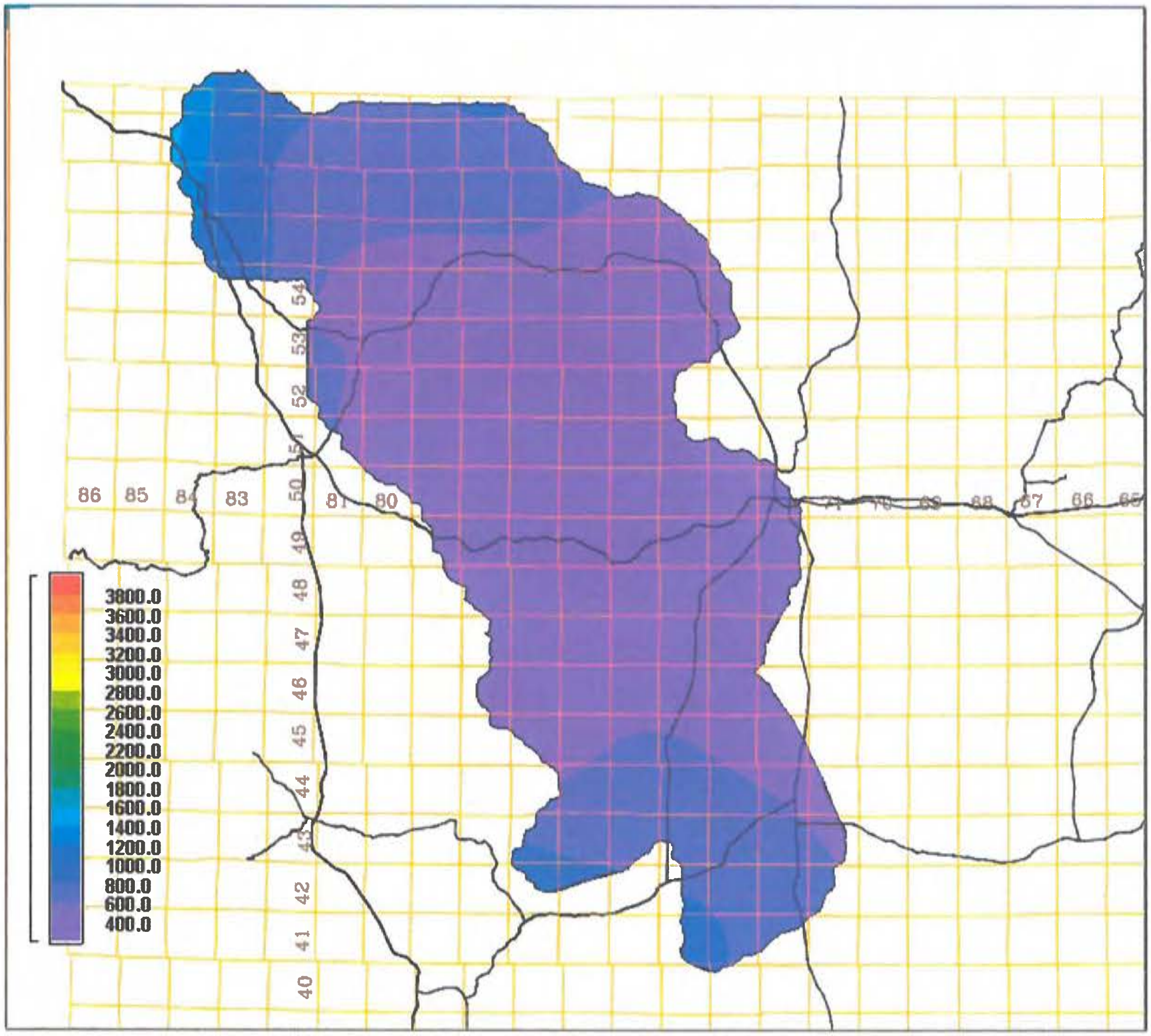


Figure 4-106. Regional distribution of TDS (mg/l) content of water from the Upper Roland coal bed, Powder River Basin, Wyoming.

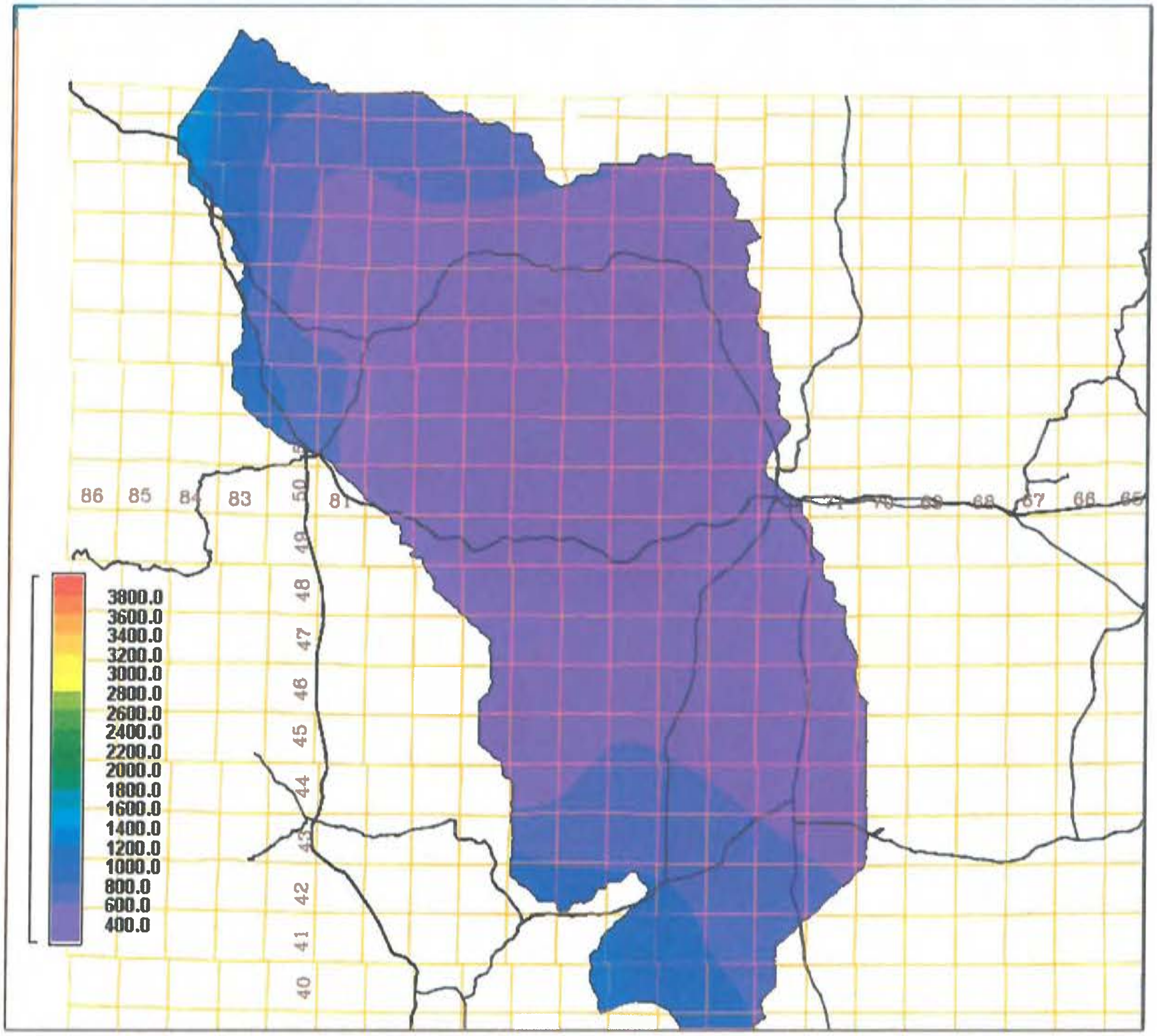


Figure 4-107. Regional distribution of TDS (mg/l) content of water from the Roland of Baker coal bed, Powder River Basin, Wyoming.

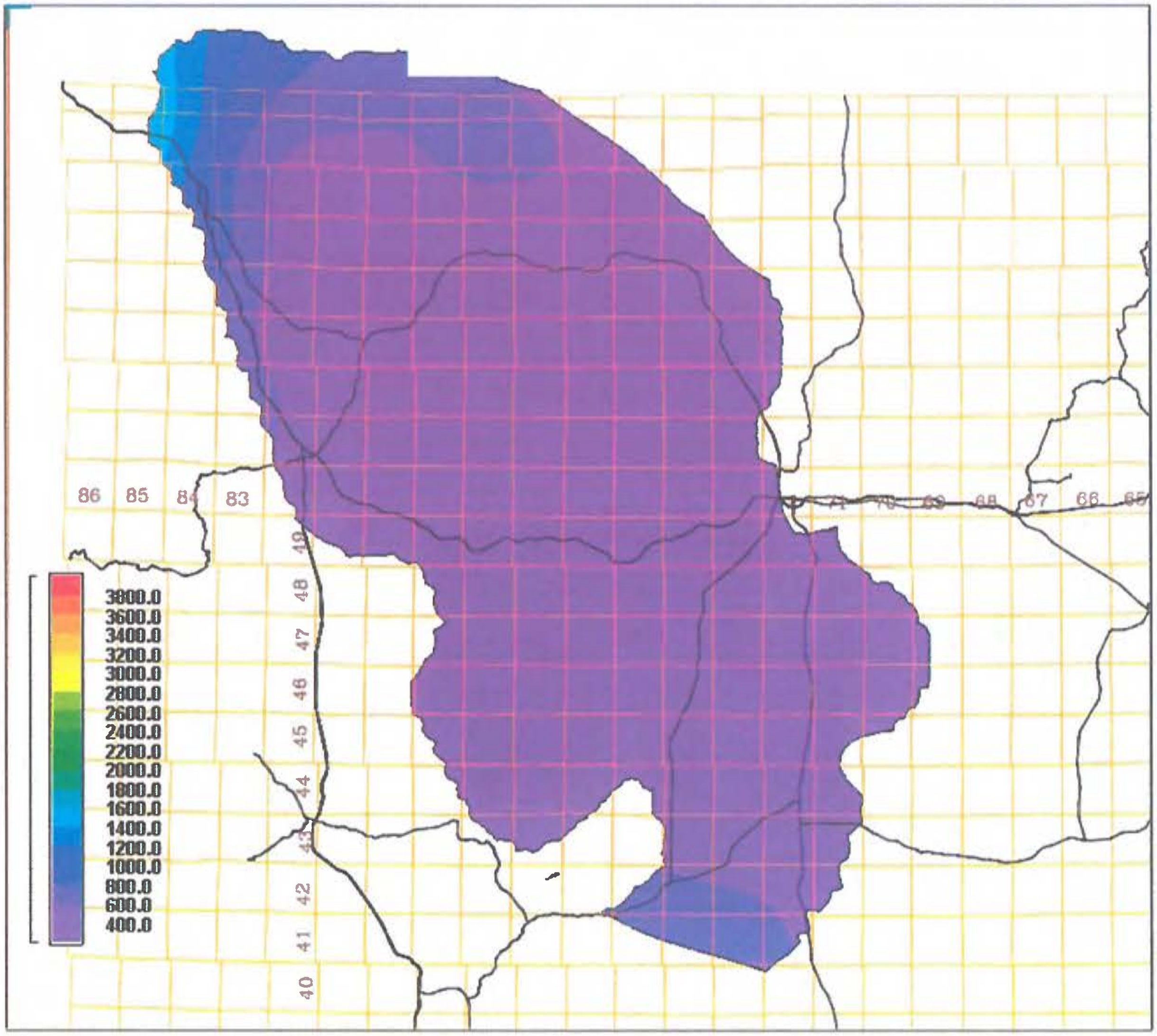


Figure 4-108. Regional distribution of TDS (mg/l) content of water from the Roland of Taff coal bed, Powder River Basin, Wyoming.

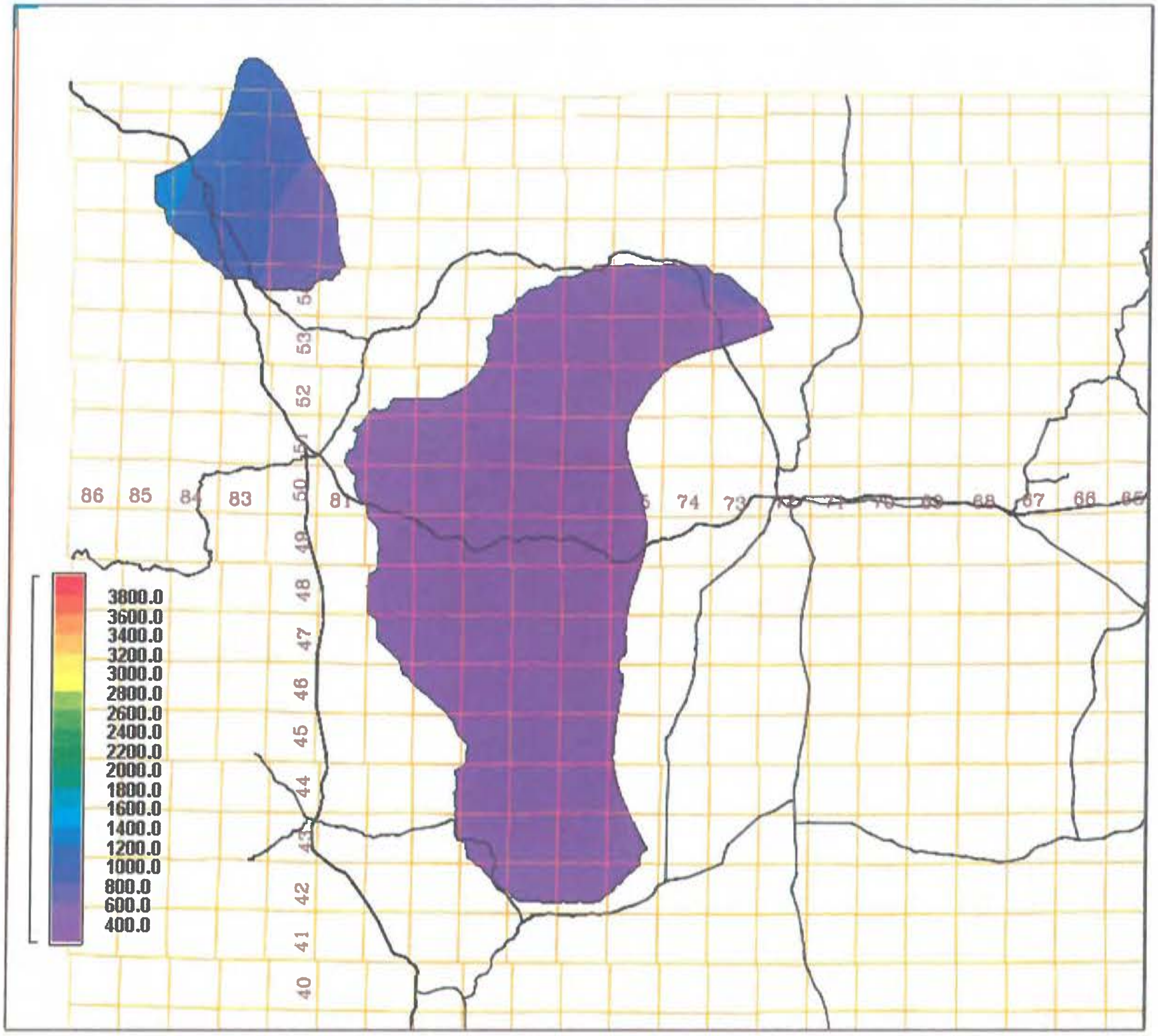


Figure 4-109. Regional distribution of TDS (mg/l) content of water from the Smith Rider coal bed, Powder River Basin, Wyoming.

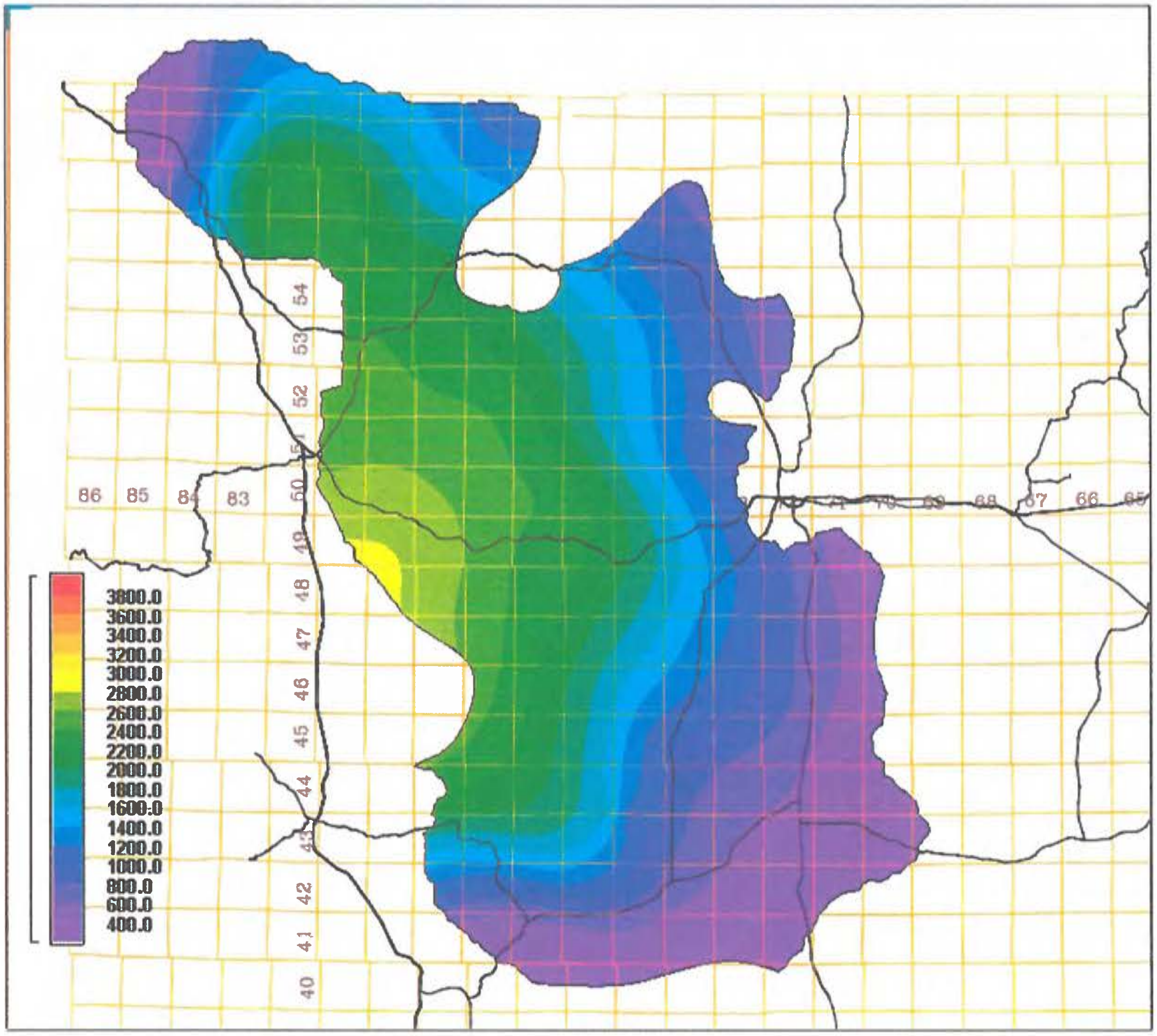


Figure 4-110. Regional distribution of TDS (mg/l) content of water from the Smith/Big George coal bed, Powder River Basin, Wyoming.

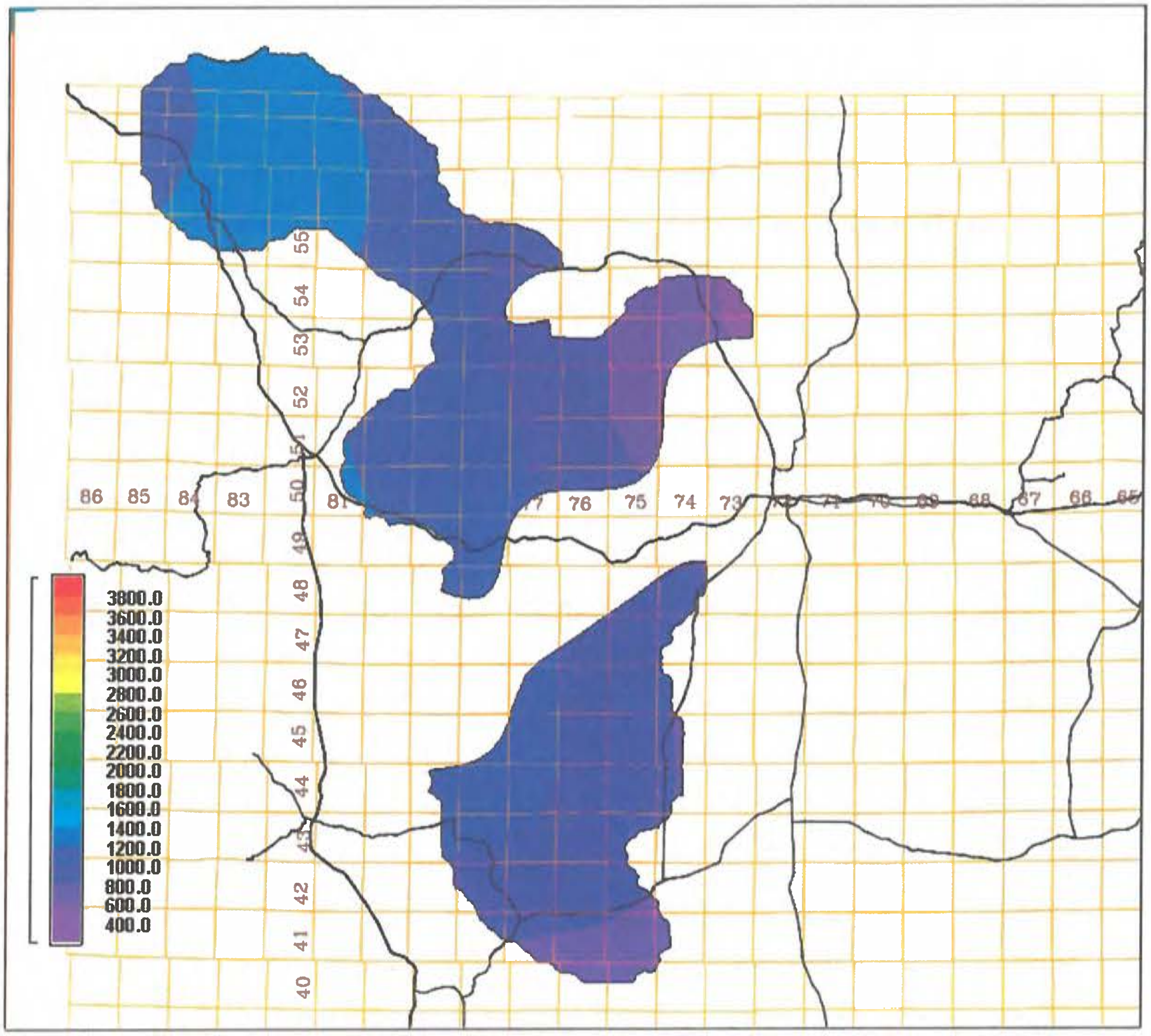


Figure 4-111. Regional distribution of TDS (mg/l) content of water from the Lower Smith coal bed, Powder River Basin, Wyoming.

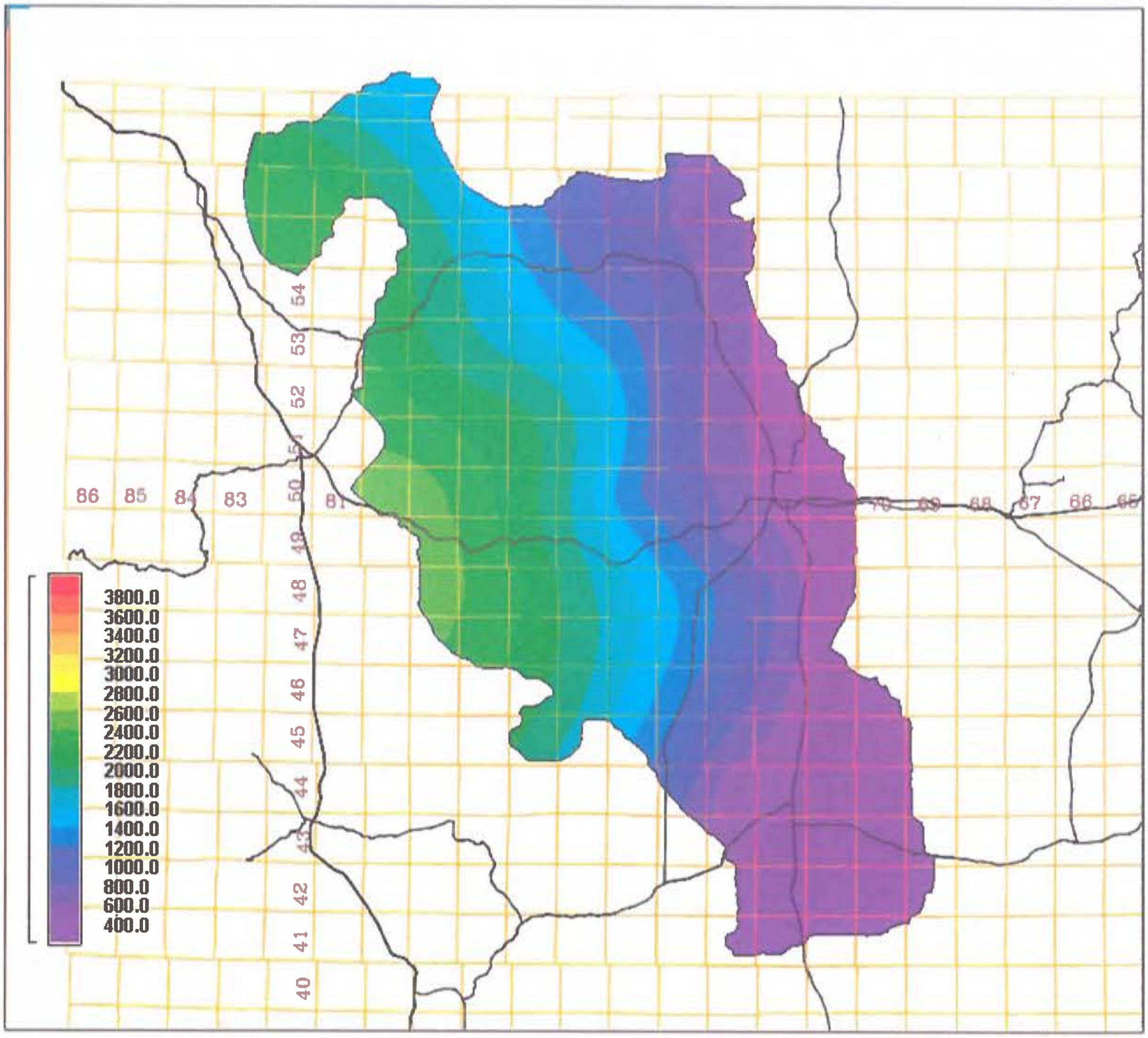


Figure 4-112. Regional distribution of TDS (mg/l) content of water from the Anderson Rider coal bed, Powder River Basin, Wyoming.

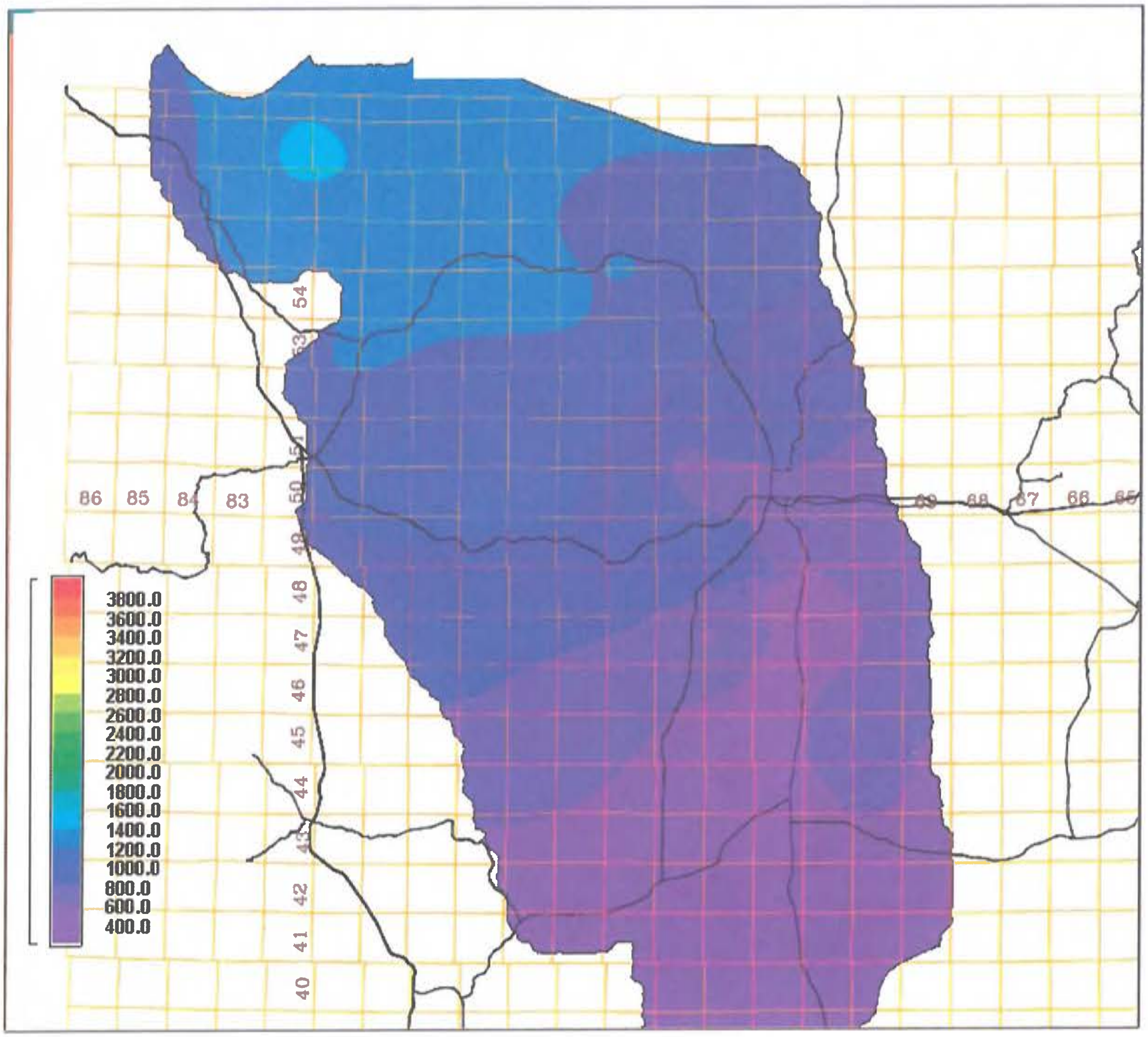


Figure 4-113. Regional distribution of TDS (mg/l) content of water from the Anderson coal bed, Powder River Basin, Wyoming.

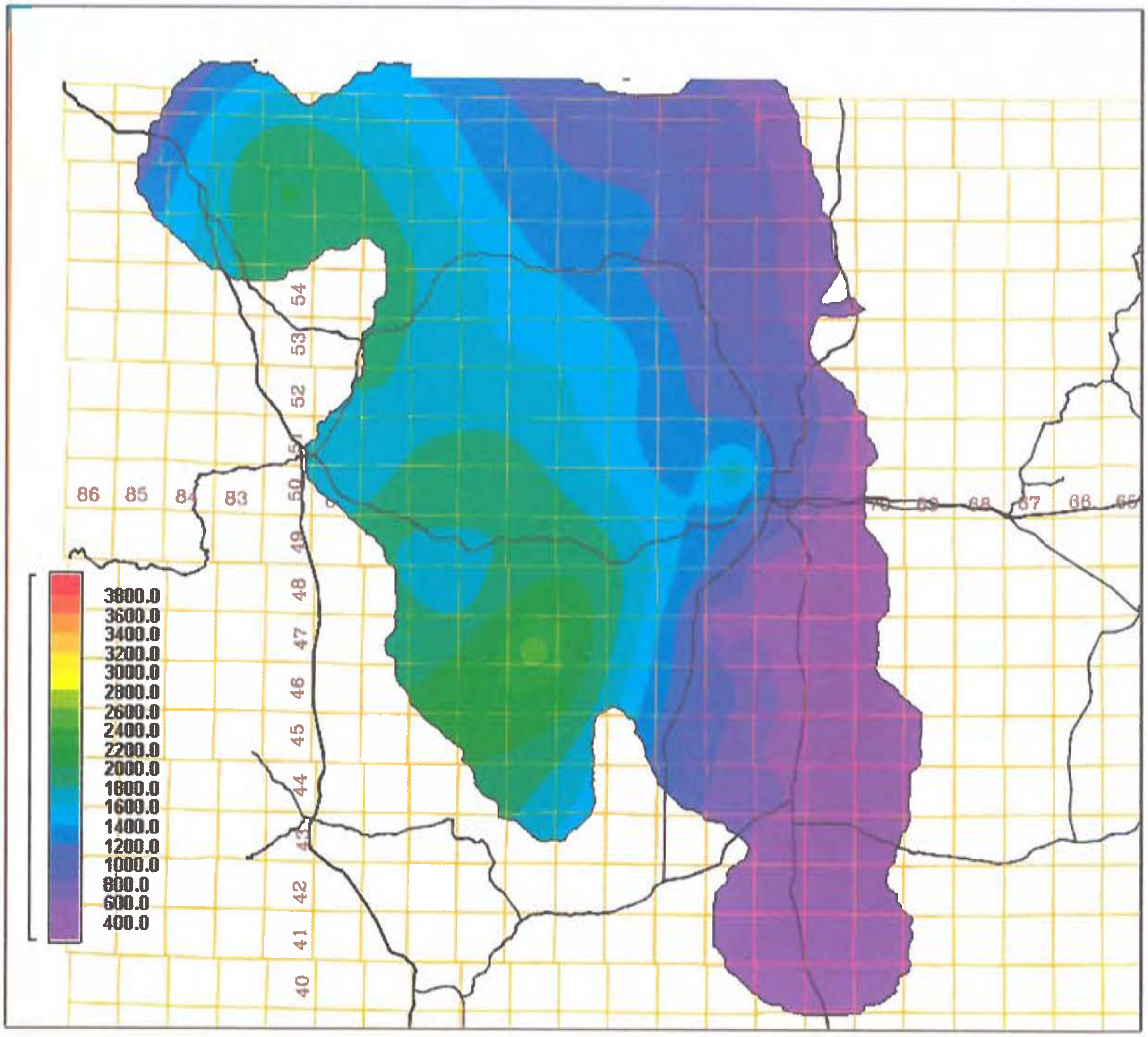


Figure 4-114. Regional distribution of TDS (mg/l) content of water from the Lower Anderson coal bed, Powder River Basin, Wyoming.

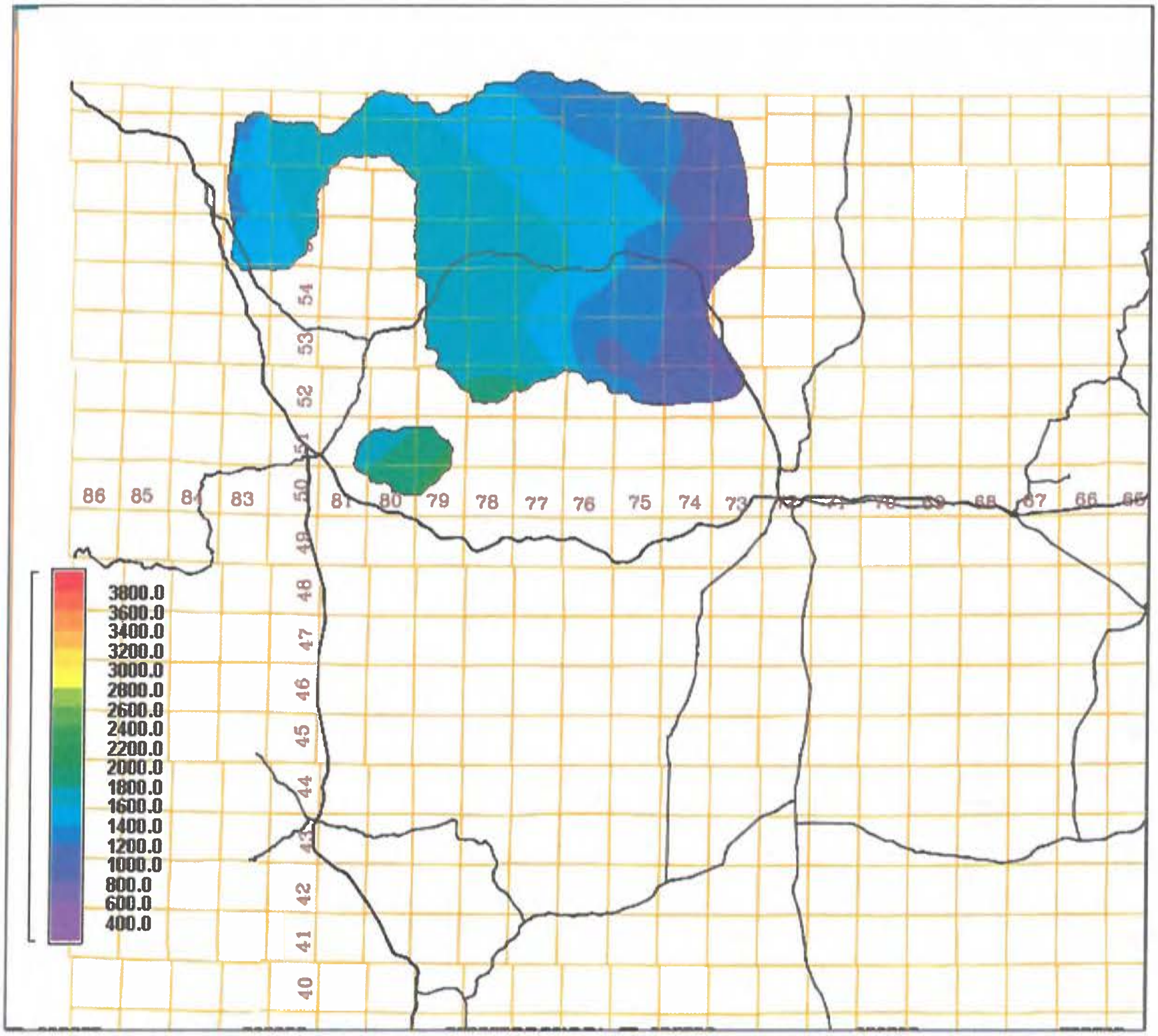


Figure 4-115. Regional distribution of TDS (mg/l) content of water from the Canyon Rider coal bed, Powder River Basin, Wyoming.

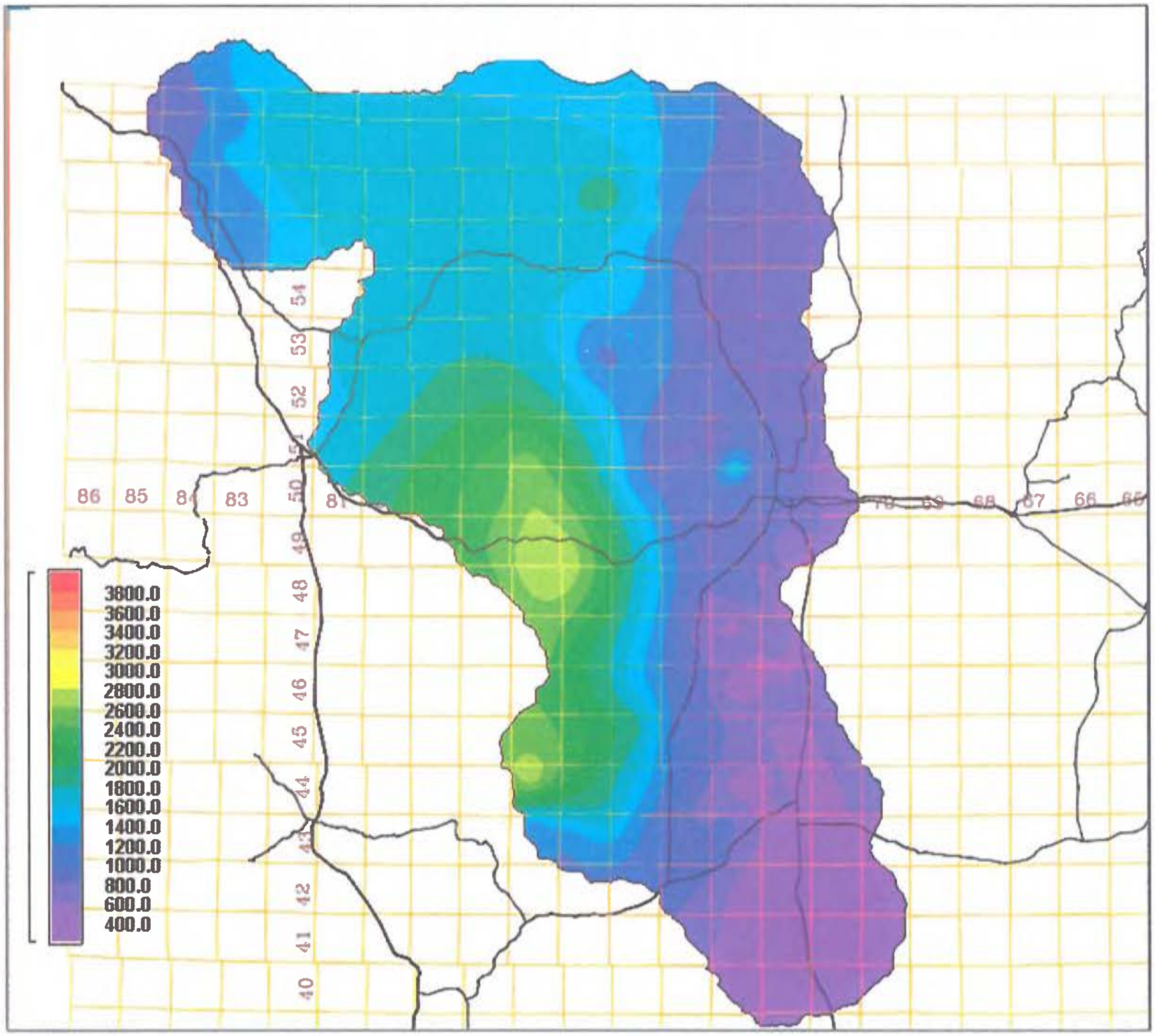


Figure 4-116. Regional distribution of TDS (mg/l) content of water from the Canyon coal bed, Powder River Basin, Wyoming.

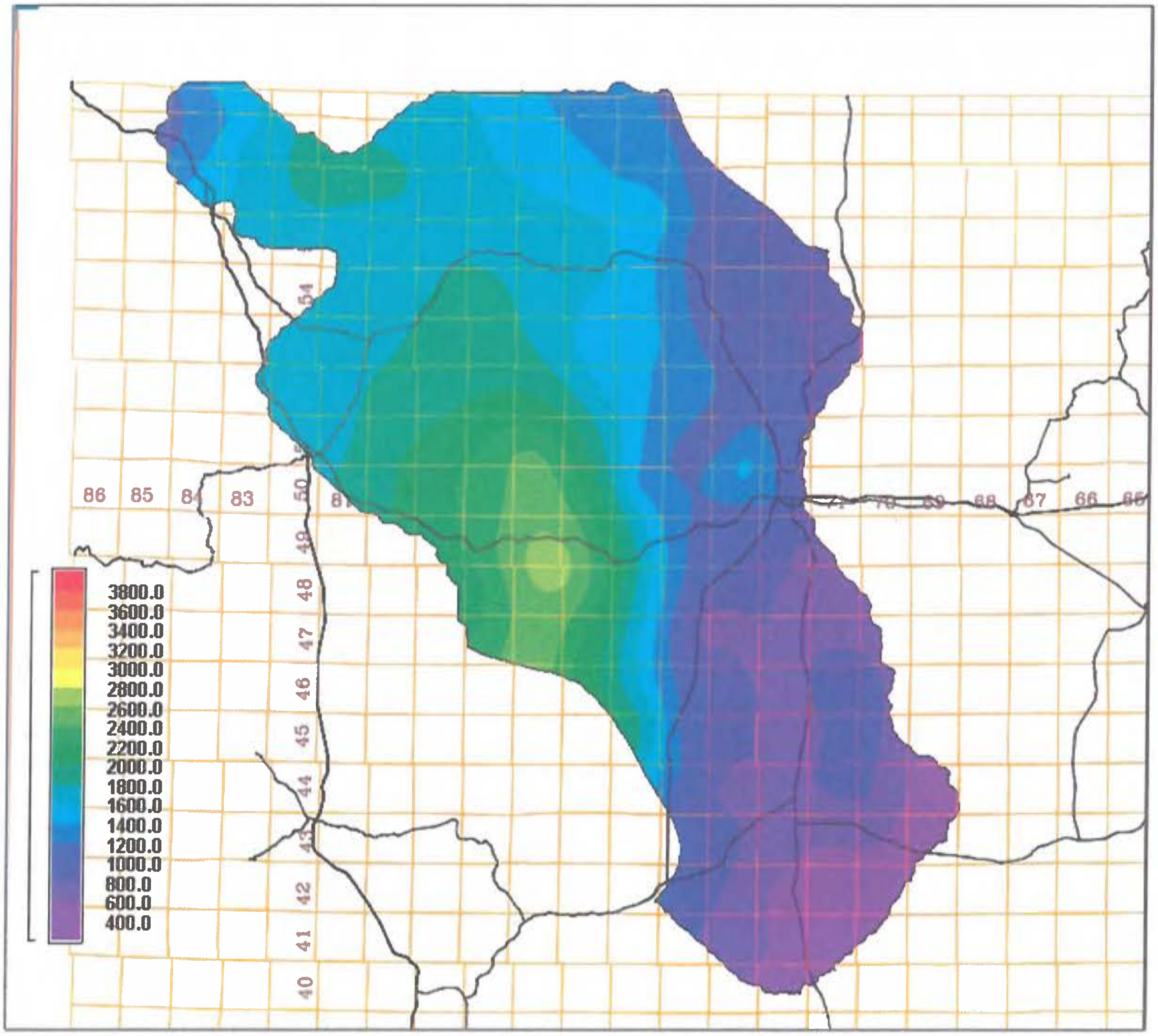


Figure 4-117. Regional distribution of TDS (mg/l) content of water from the Cook coal bed, Powder River Basin, Wyoming.

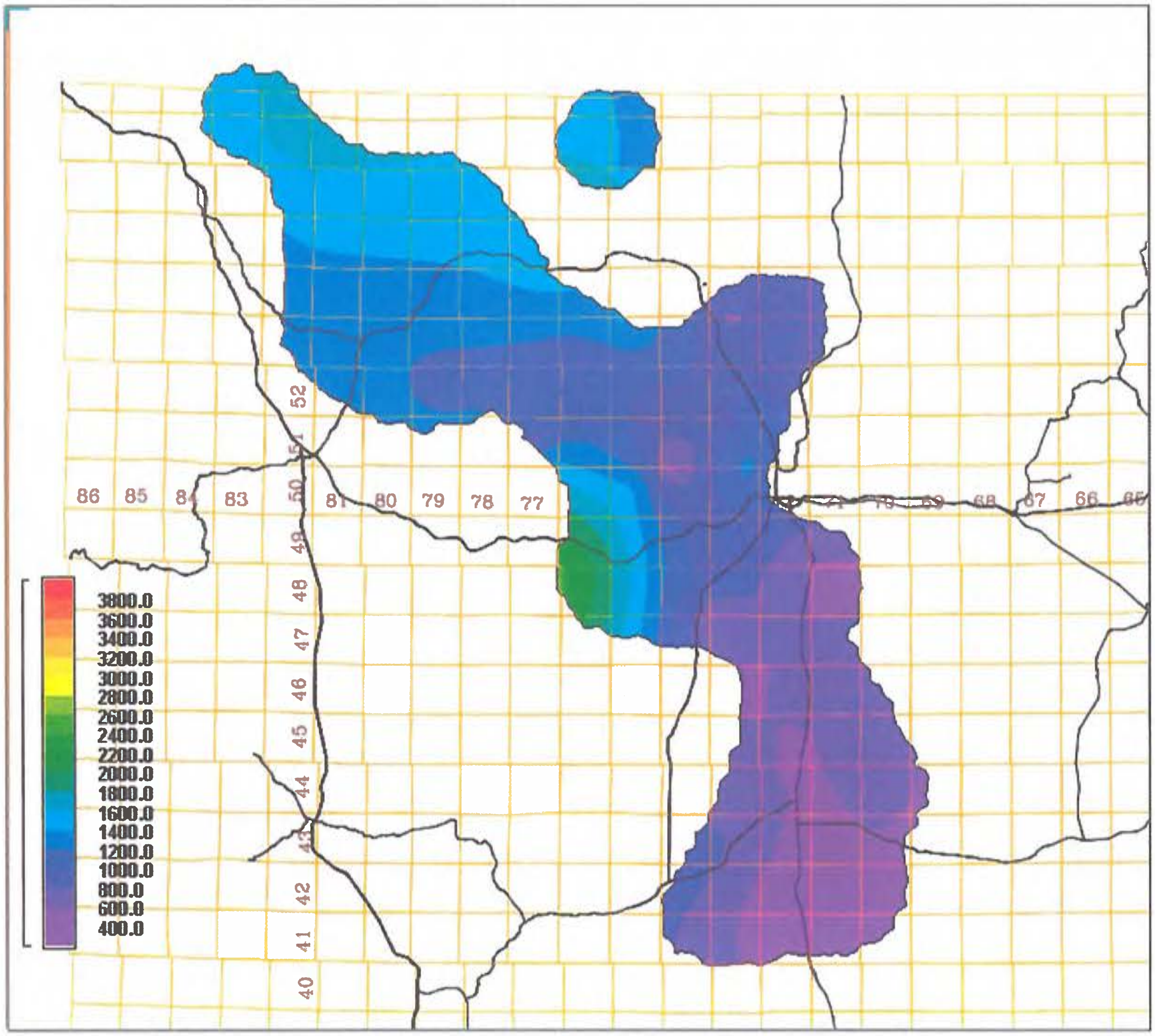


Figure 4-118. Regional distribution of TDS (mg/l) content of water from the Lower Cook coal bed, Powder River Basin, Wyoming.

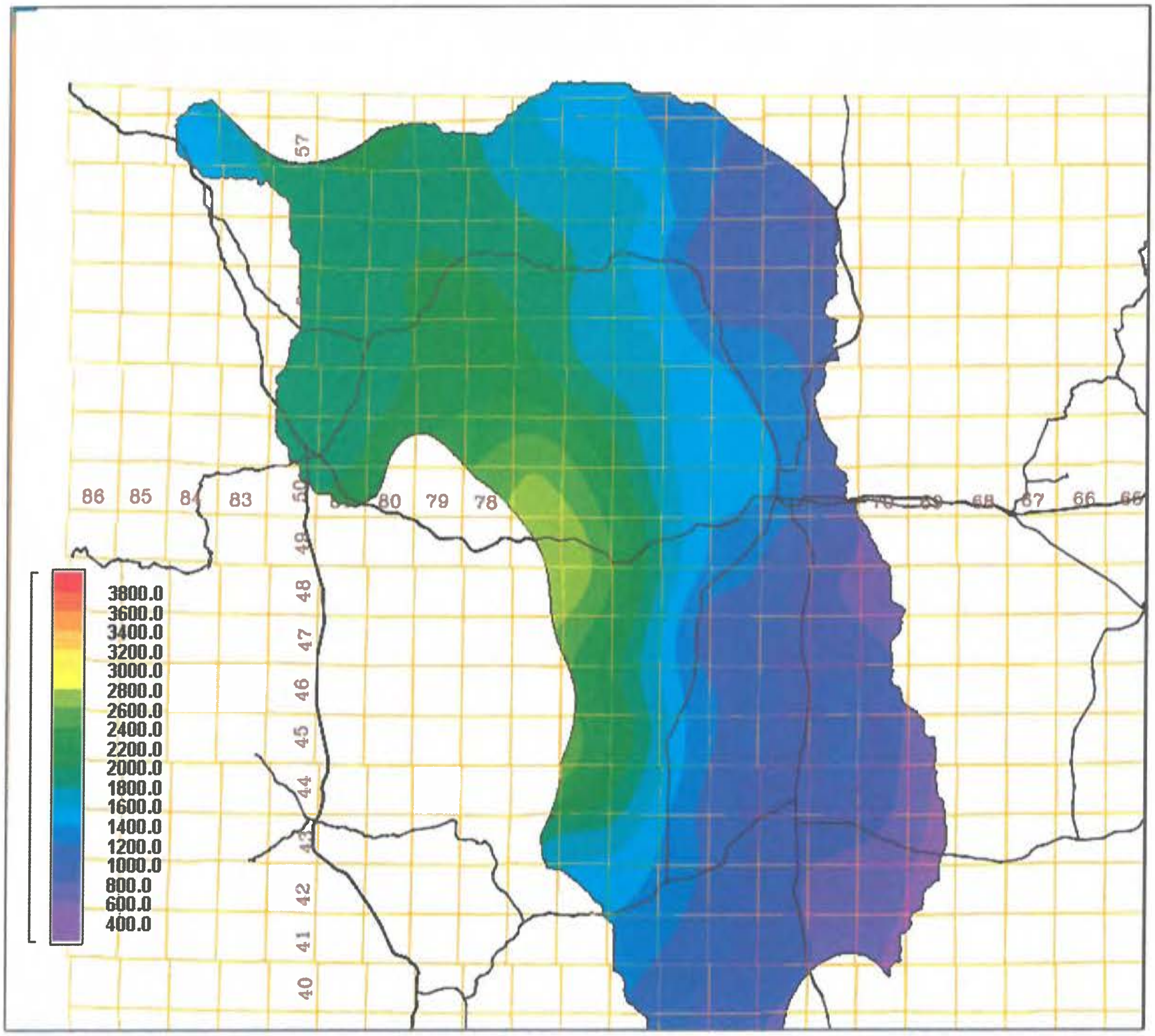


Figure 4-119. Regional distribution of TDS (mg/l) content of water from the Wall coal bed, Powder River Basin, Wyoming.

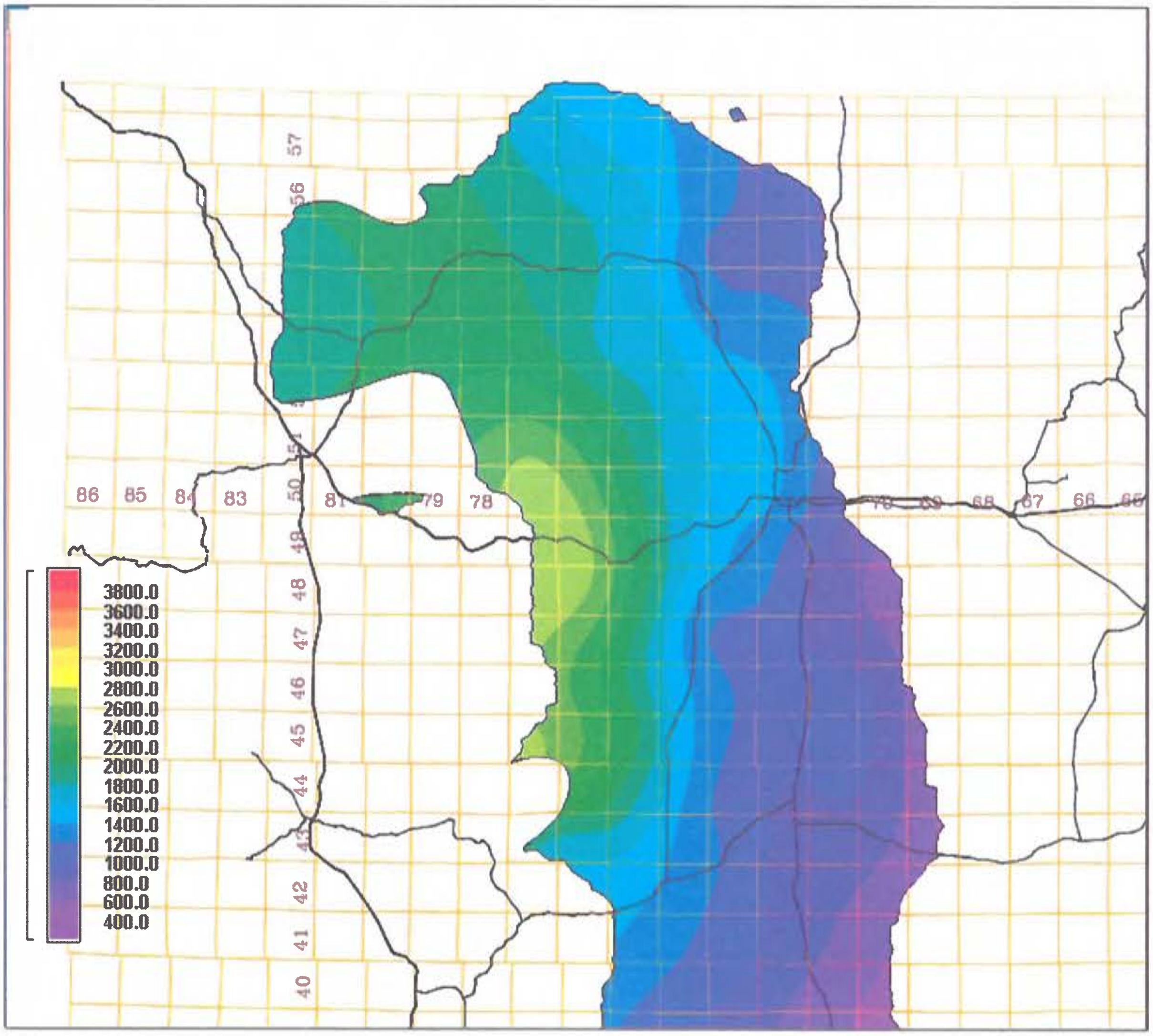


Figure 4-120. Regional distribution of TDS (mg/l) content of water from the Lower Wall coal bed, Powder River Basin, Wyoming.

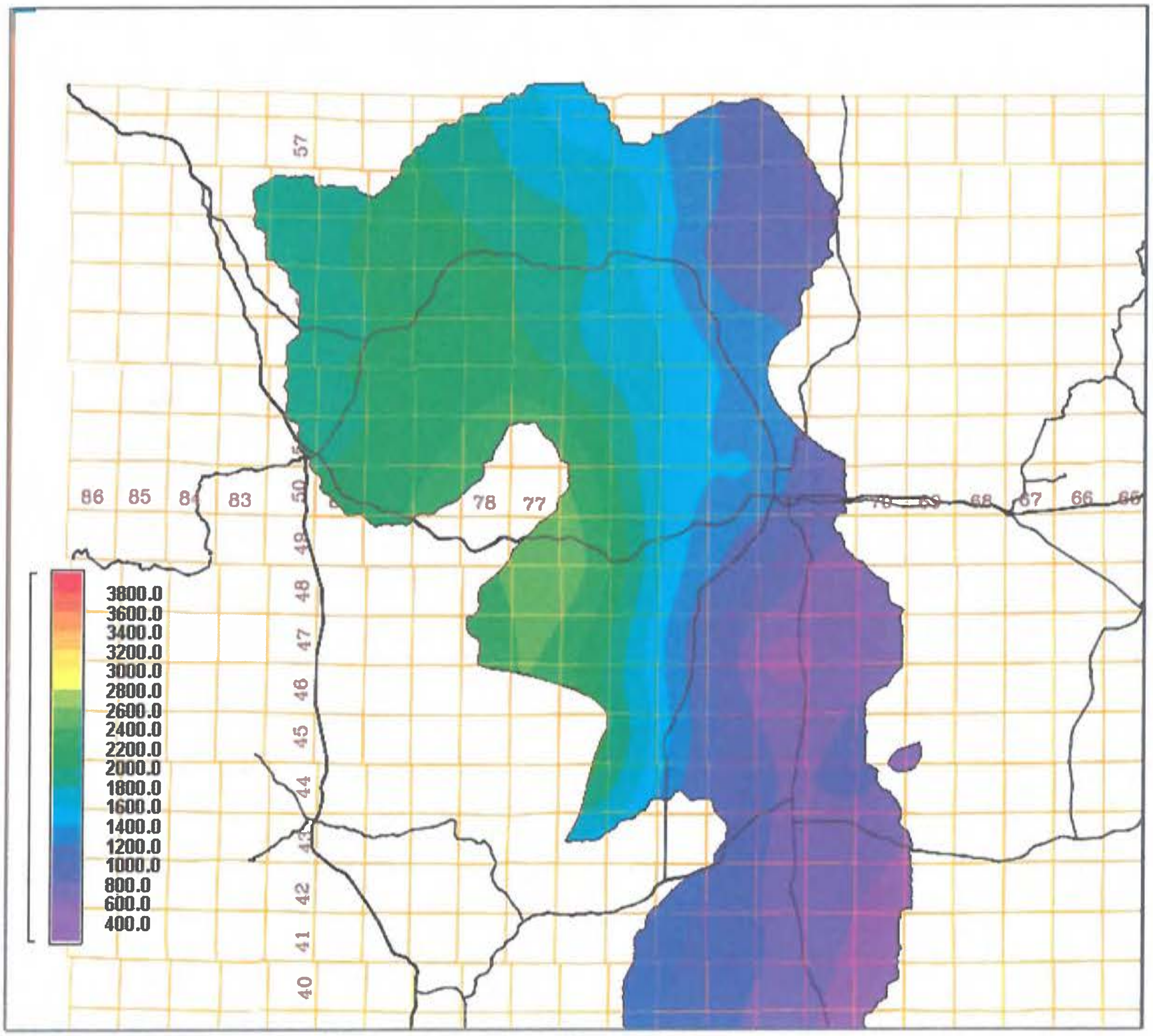


Figure 4-121. Regional distribution of TDS (mg/l) content of water from the Pawnee coal bed, Powder River Basin, Wyoming.

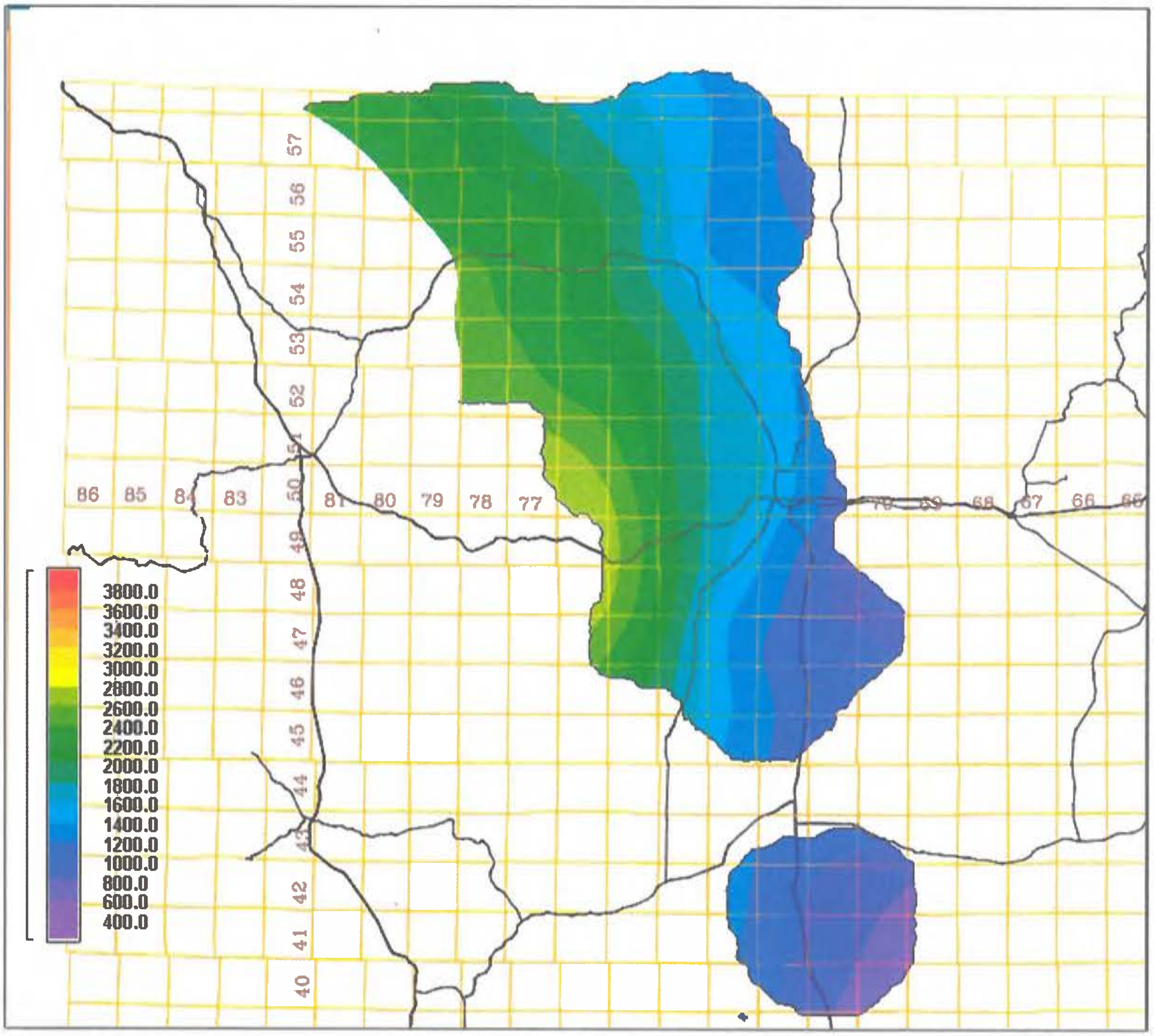


Figure 4-122. Regional distribution of TDS (mg/l) content of water from the Moyer coal bed, Powder River Basin, Wyoming.

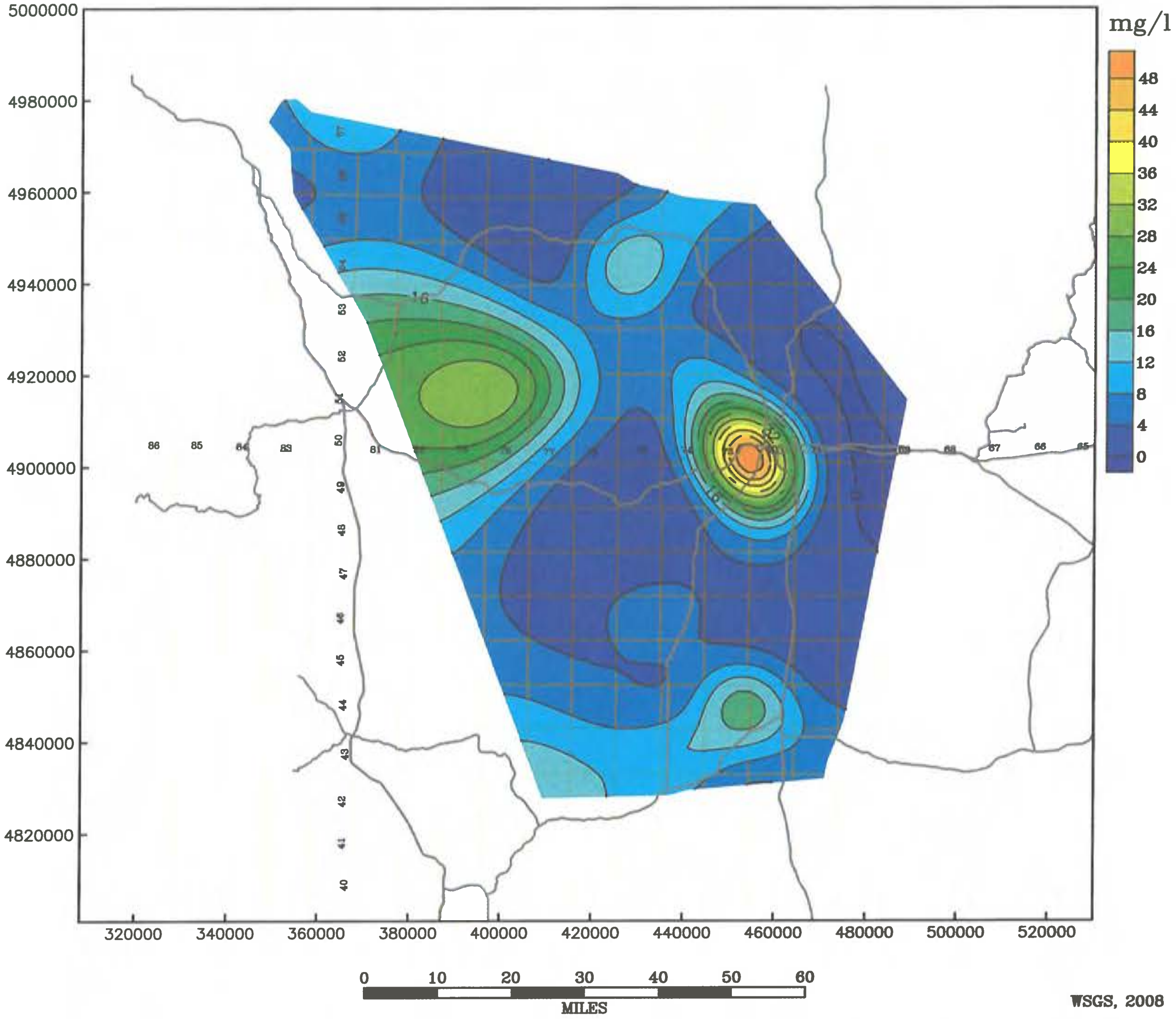


Figure 4-123. Map showing distribution of sulfate ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

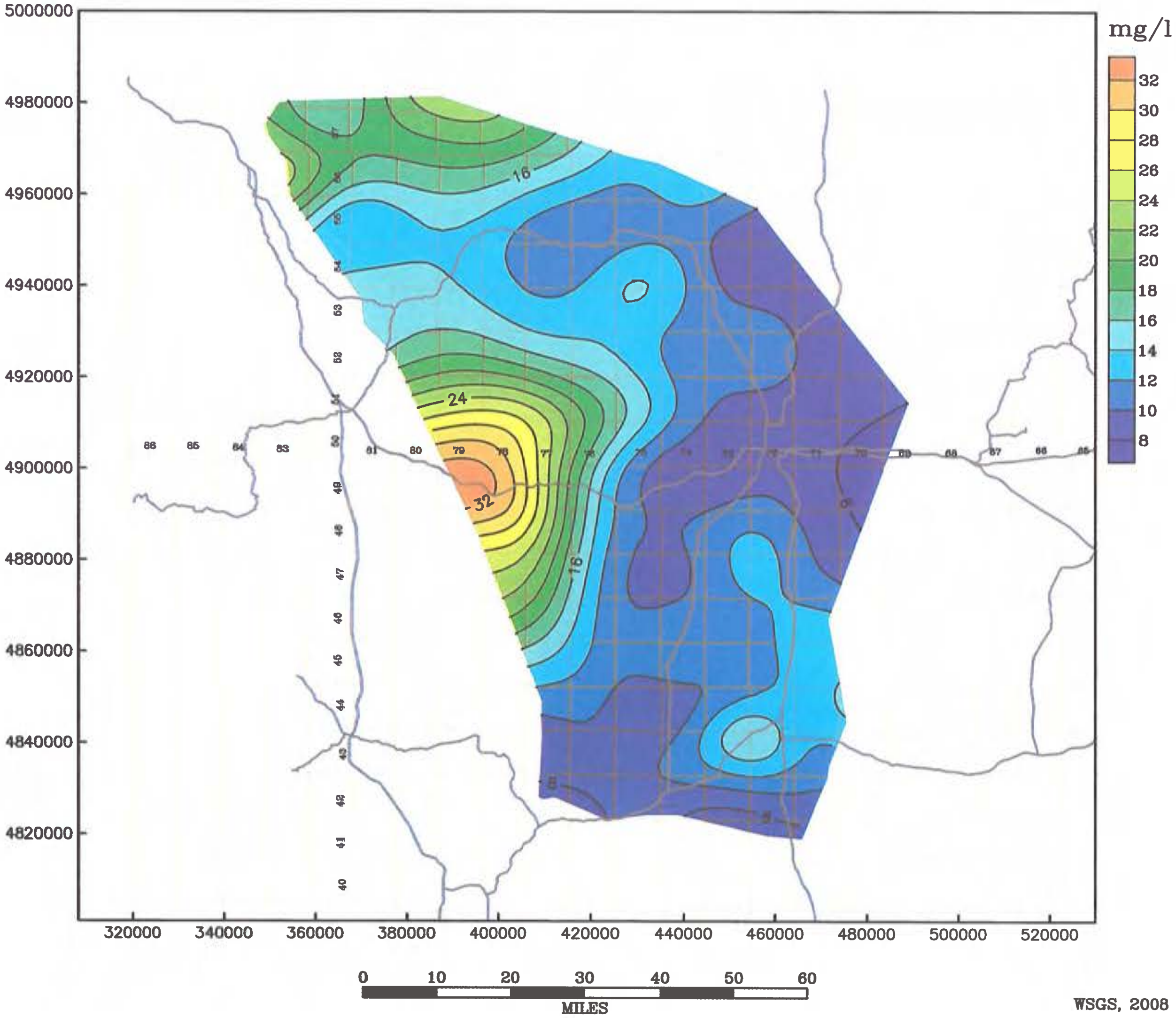


Figure 4-124. Map showing distribution of chloride ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

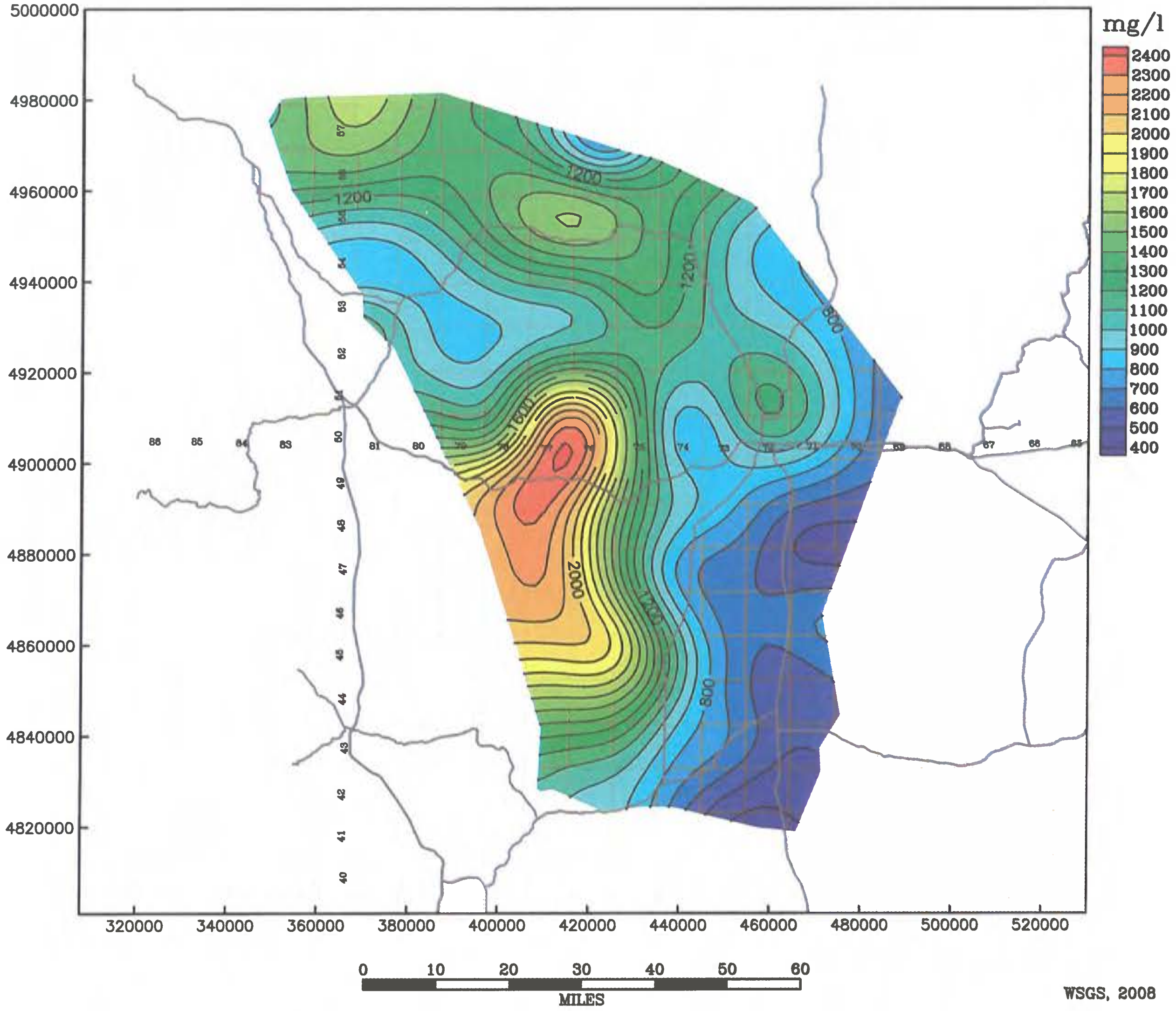


Figure 4-125. Map showing distribution of bicarbonate ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

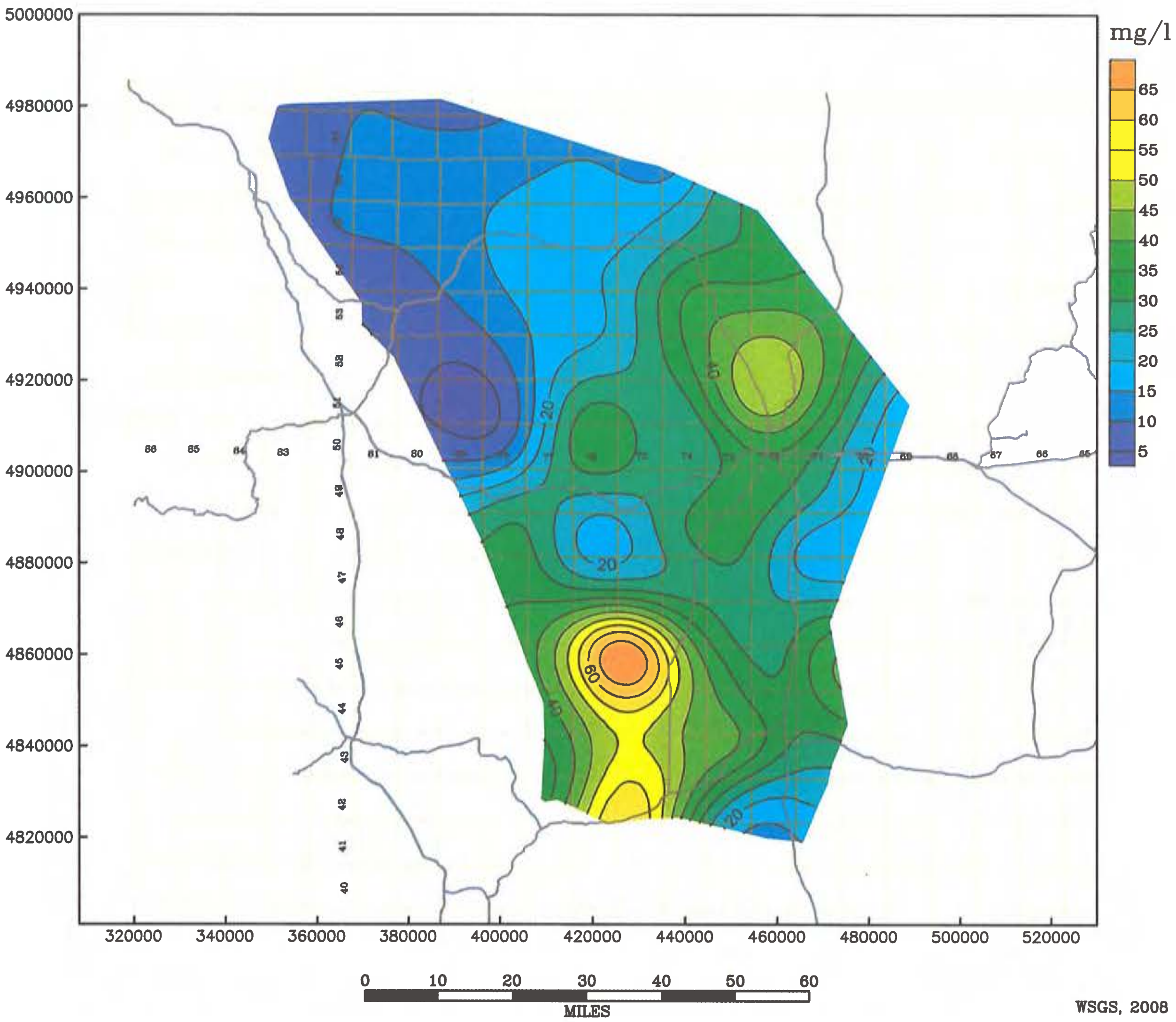


Figure 4-126. Map showing distribution of calcium ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

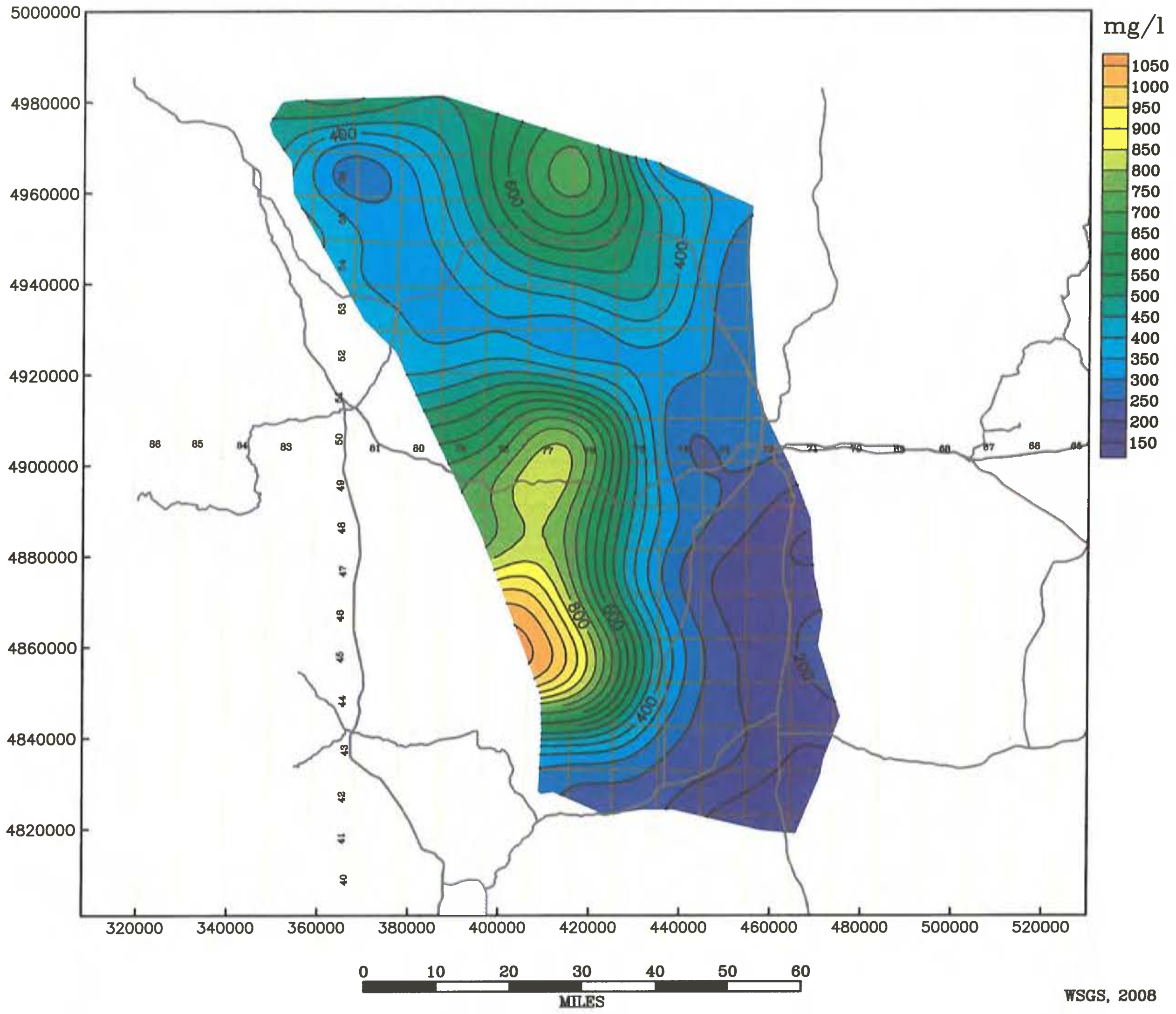


Figure 4-127. Map showing distribution of sodium ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

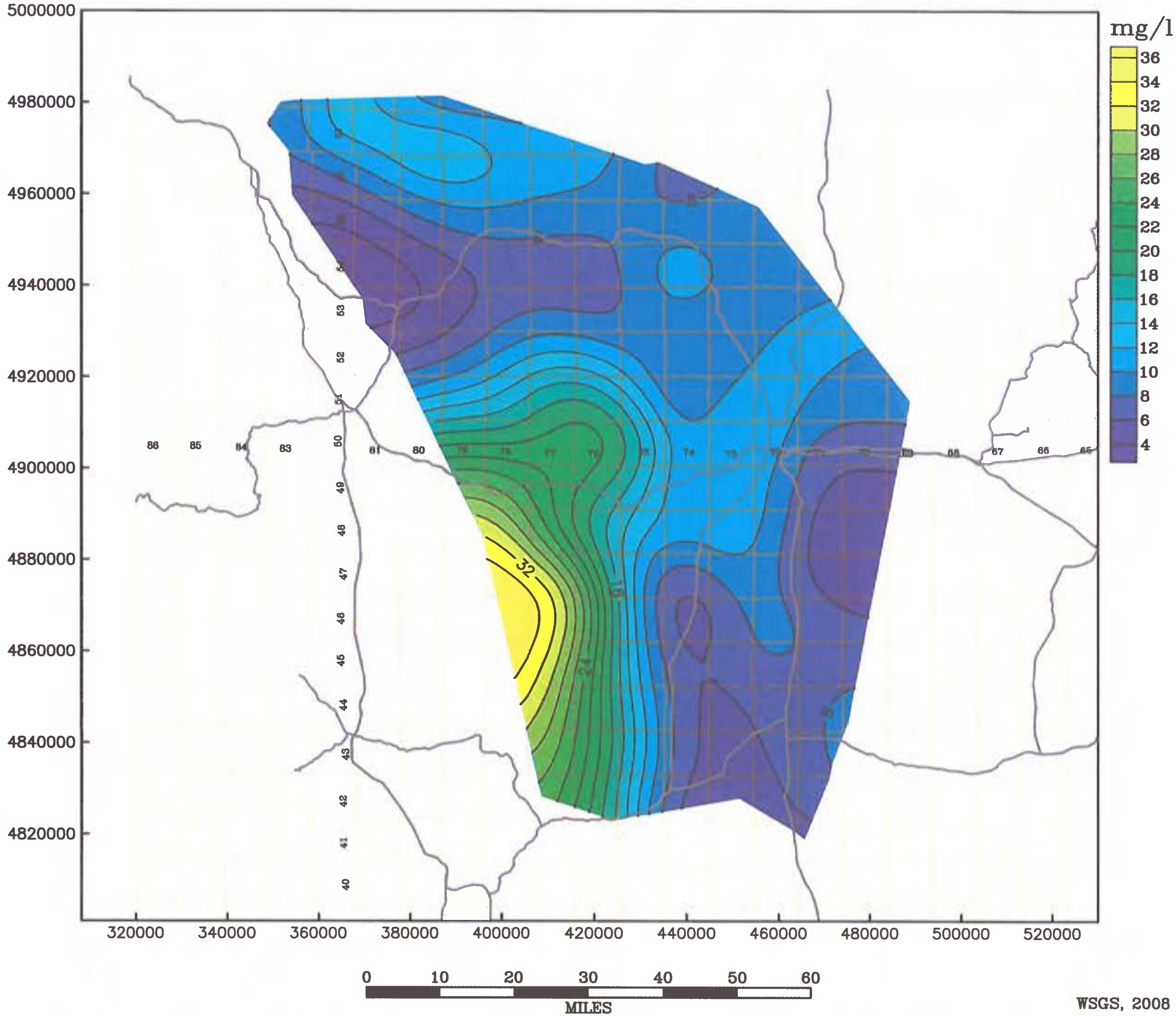


Figure 4-128. Map showing distribution of potassium ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

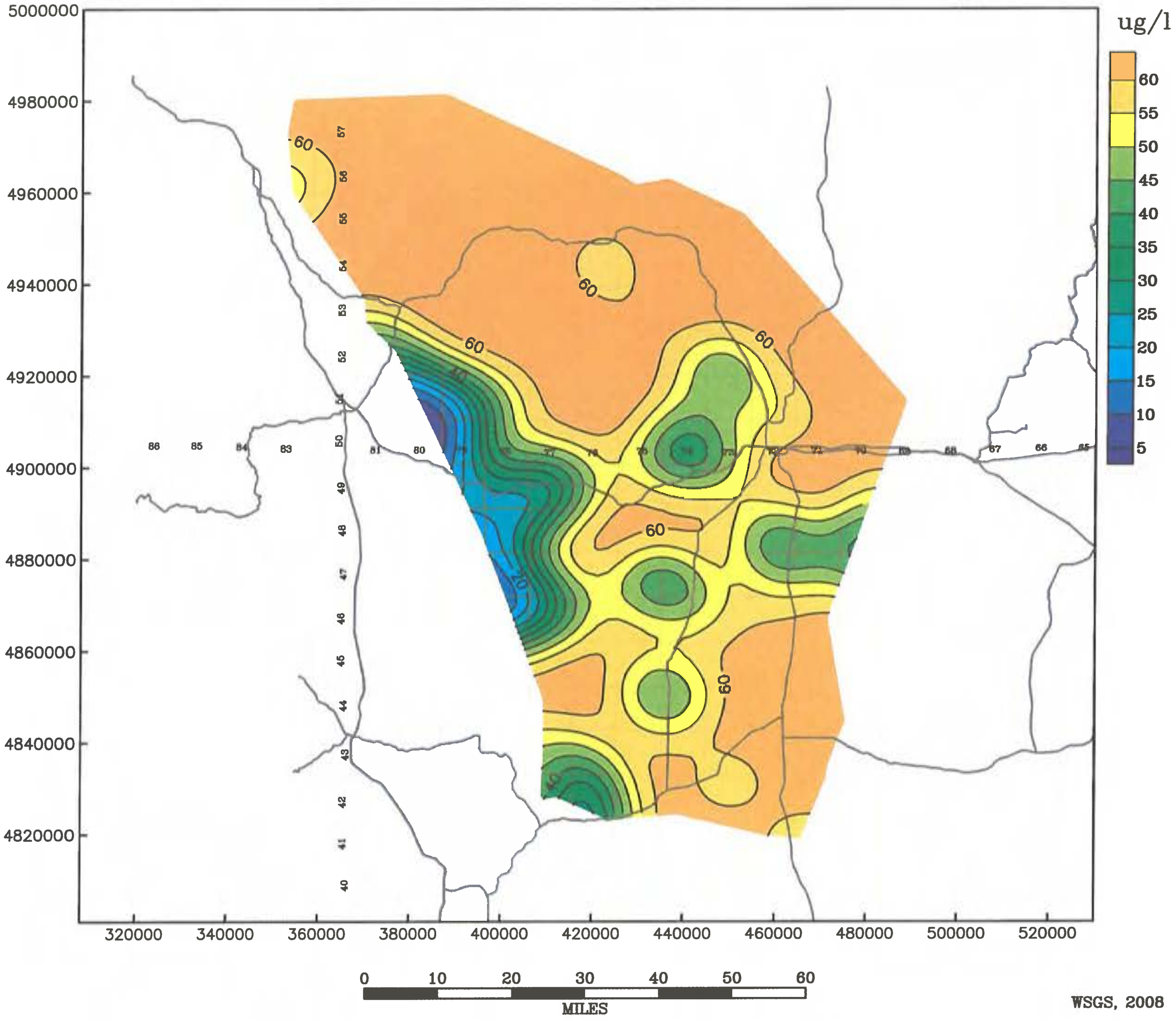


Figure 4-129. Map showing distribution of ferrous ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

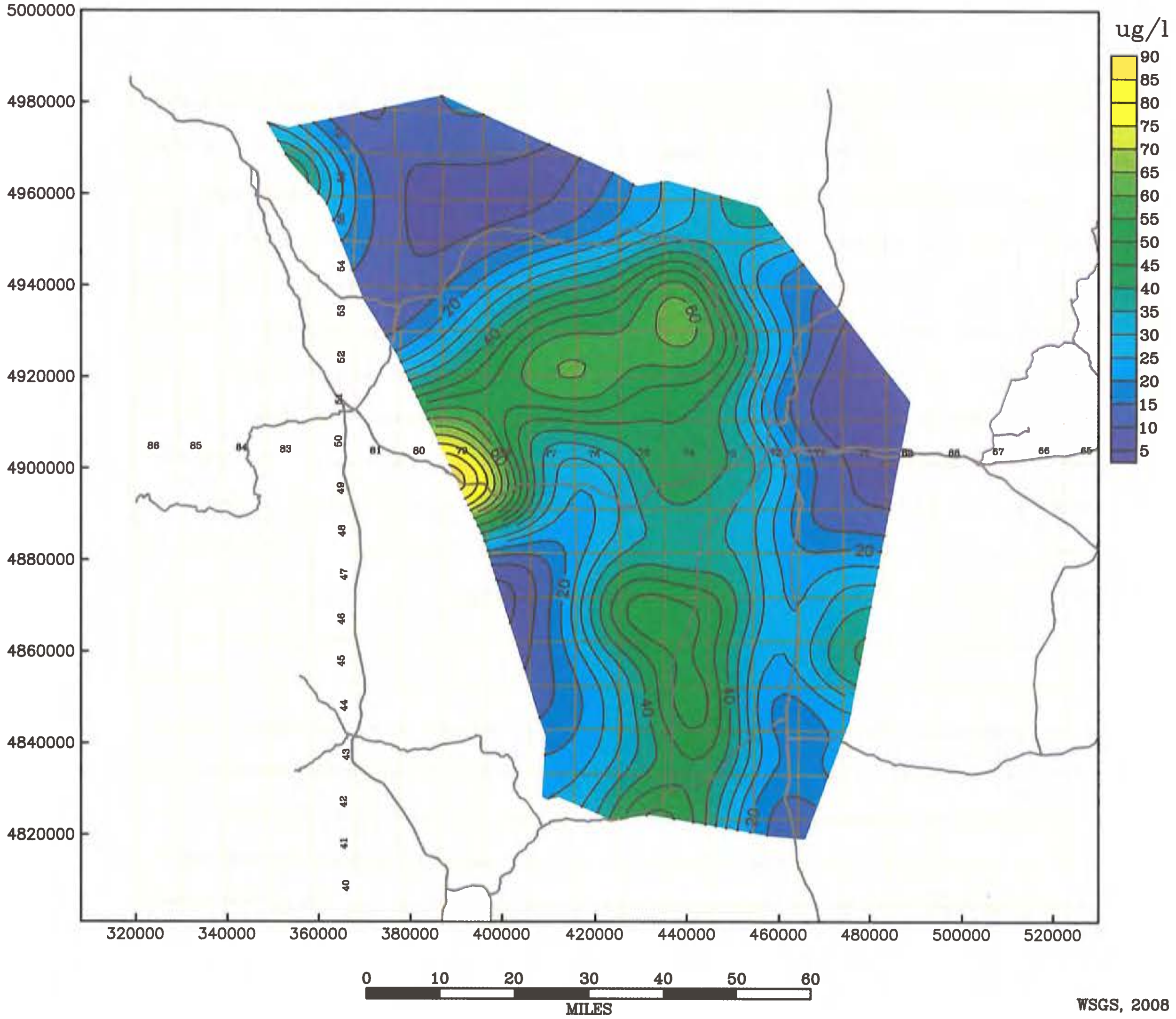
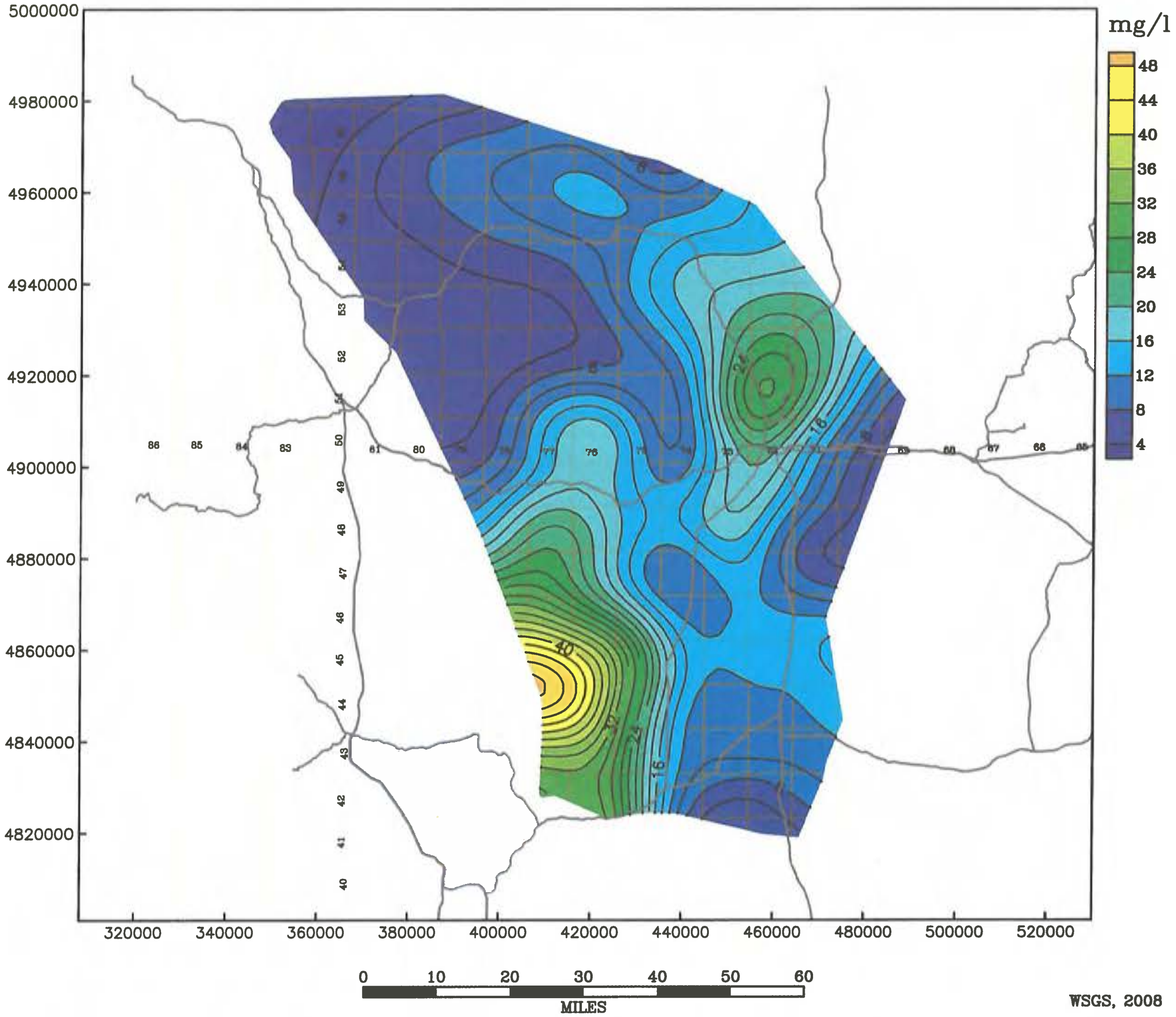


Figure 4-130. Map showing distribution of manganous ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.



WSGS, 2008

Figure 4-131. Map showing distribution of magnesium ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

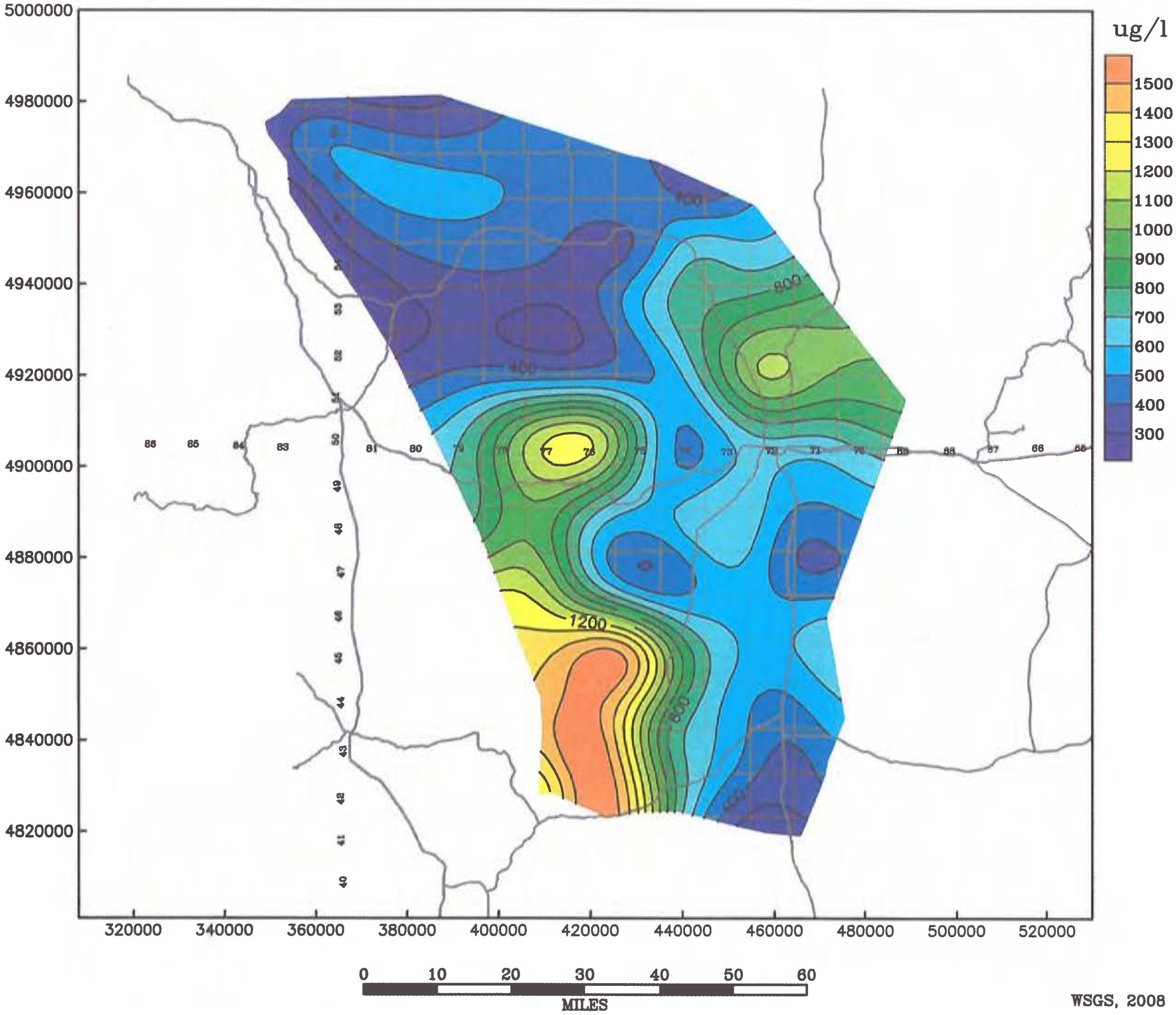


Figure 4-132. Map showing distribution of barium ion concentration in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

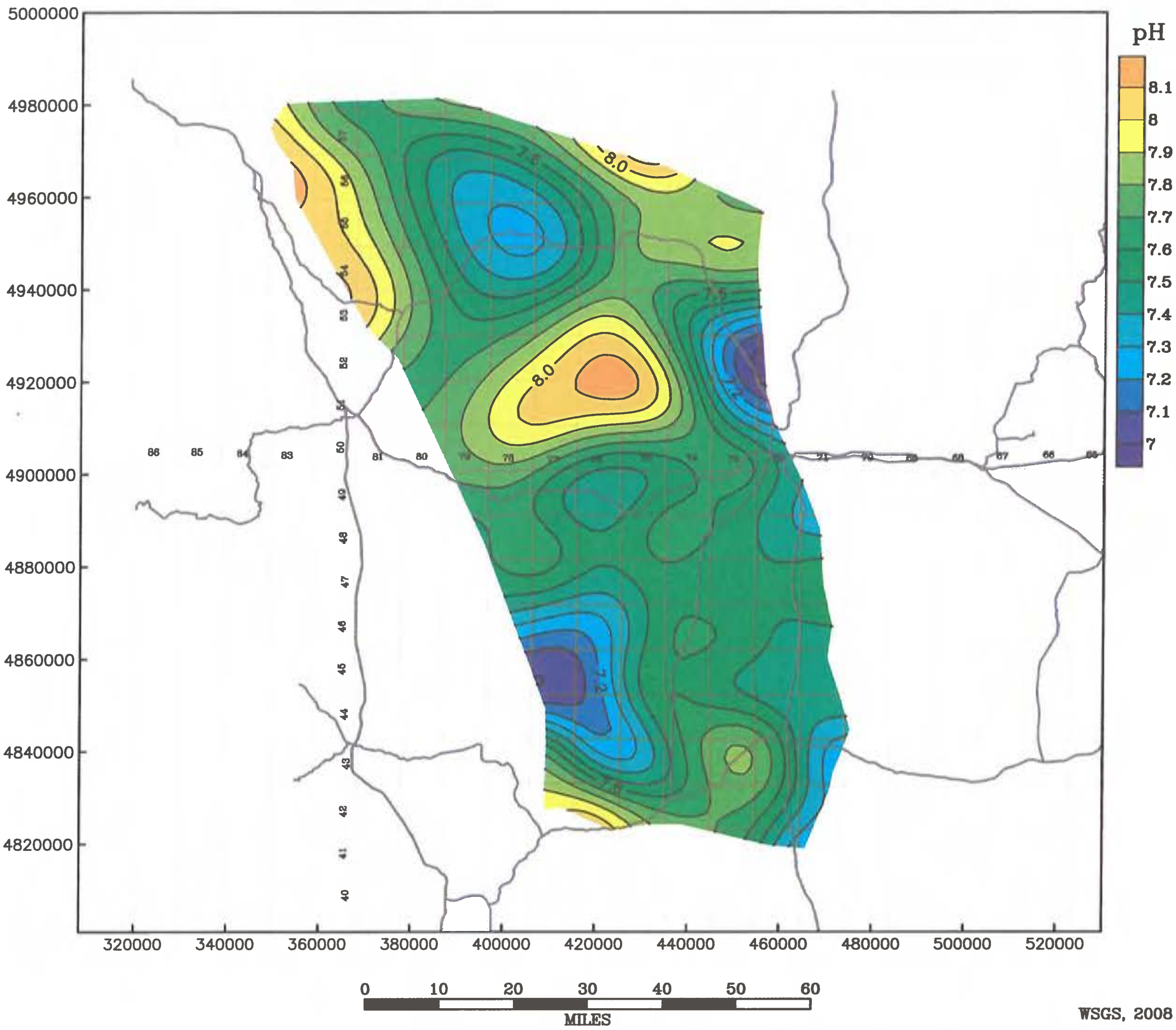


Figure 4-133. Map showing distribution of pH values of the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

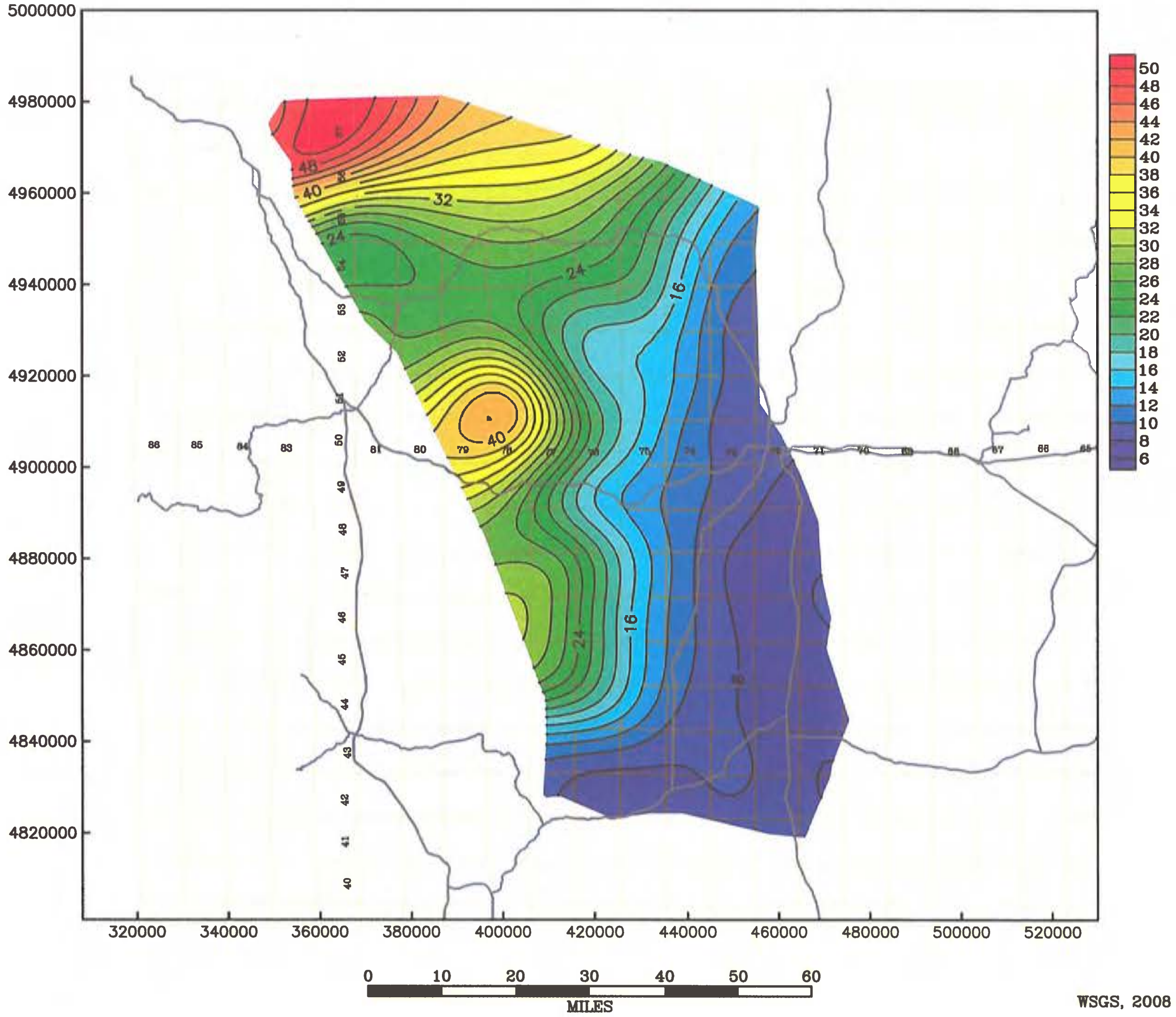


Figure 4-134. Map showing sodium adsorption ratio (SAR) in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

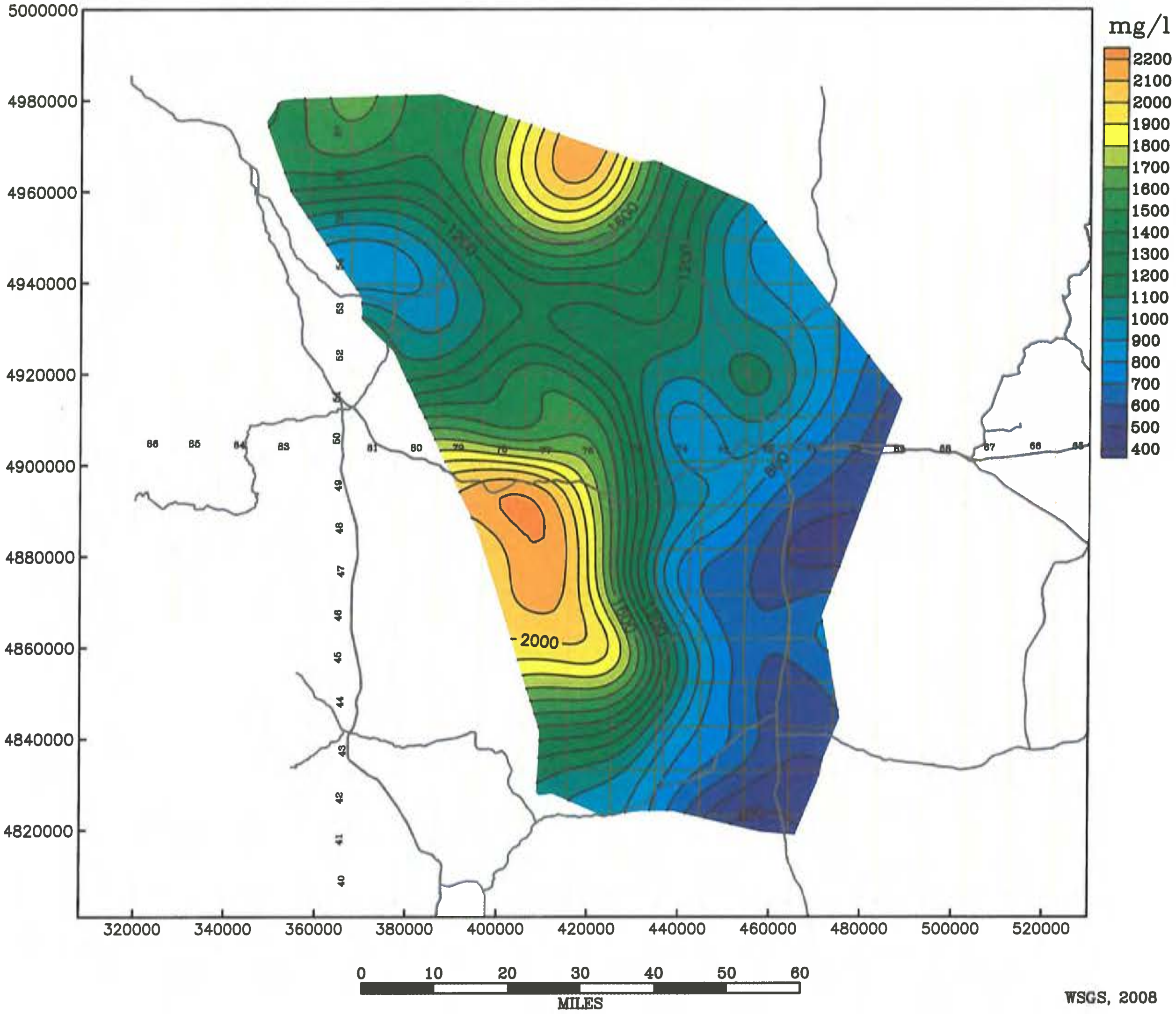


Figure 4-135. Map showing alkalinity contour in the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

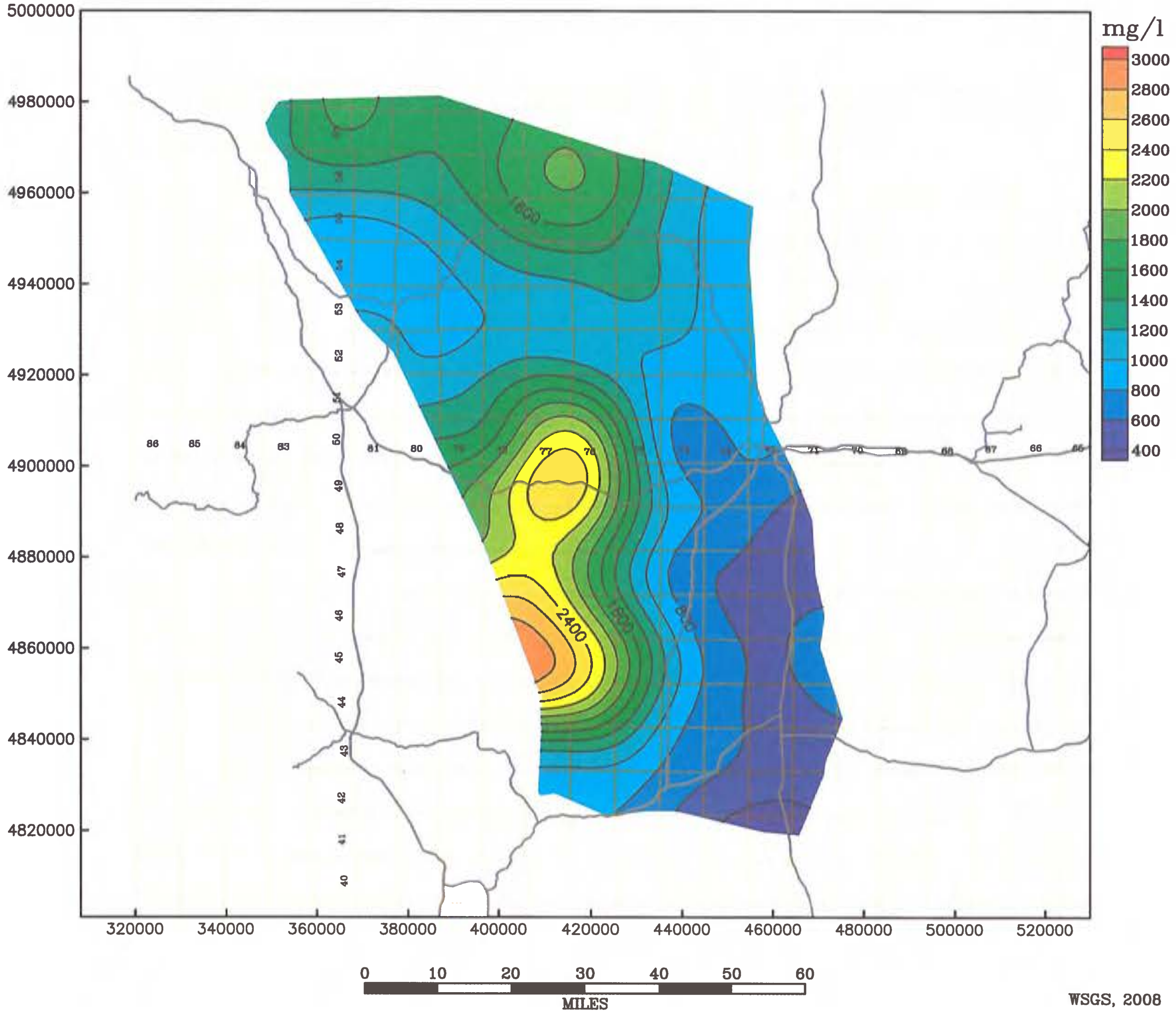
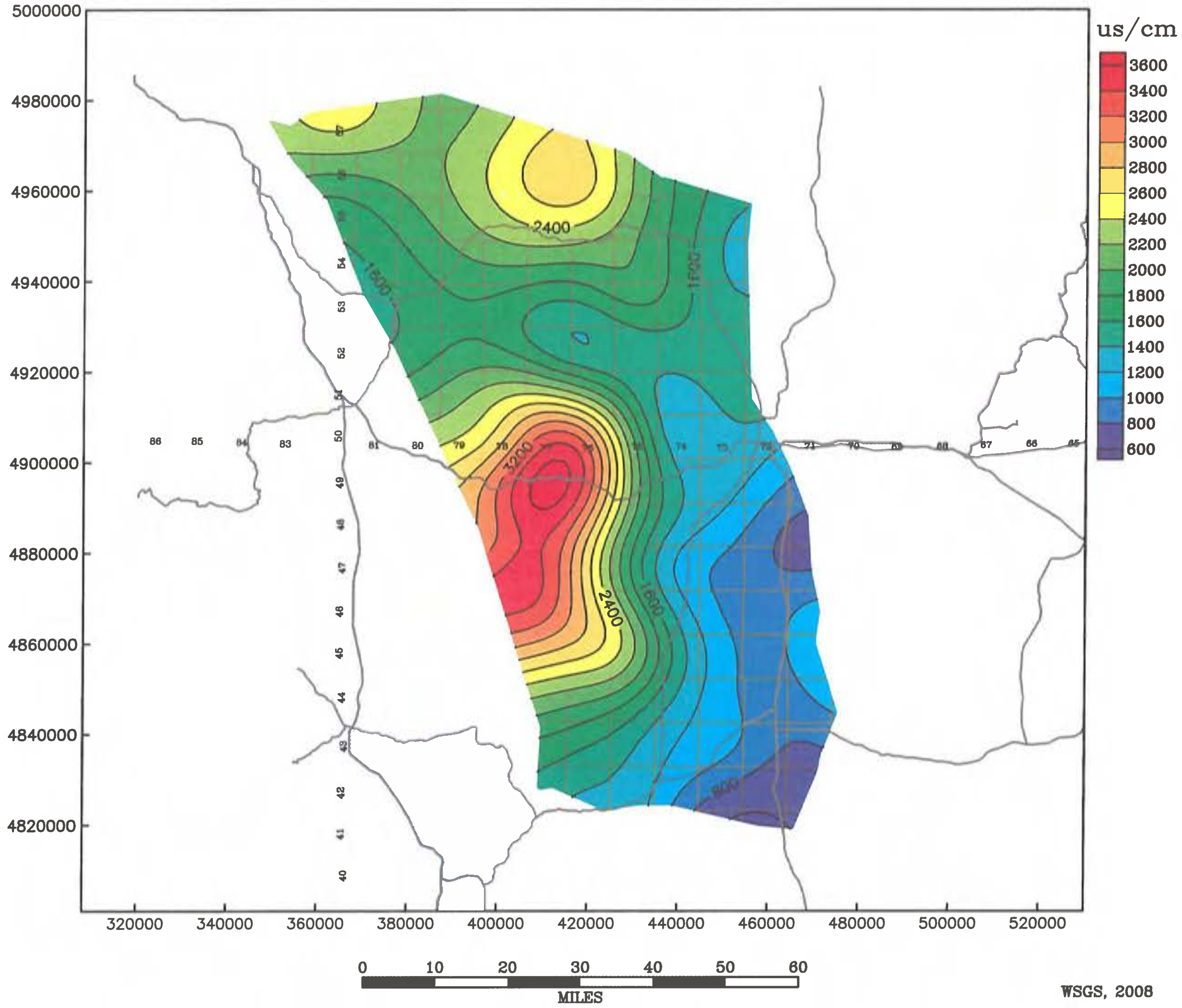


Figure 4-136. Map showing total dissolved solids (TDS) content (mg/l) of the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.



WSGS, 2008

Figure 4-137. Map showing specific conductance (micro-siemens per centimeter) of the Tertiary coal bed assemblage waters, Powder River Basin, Wyoming.

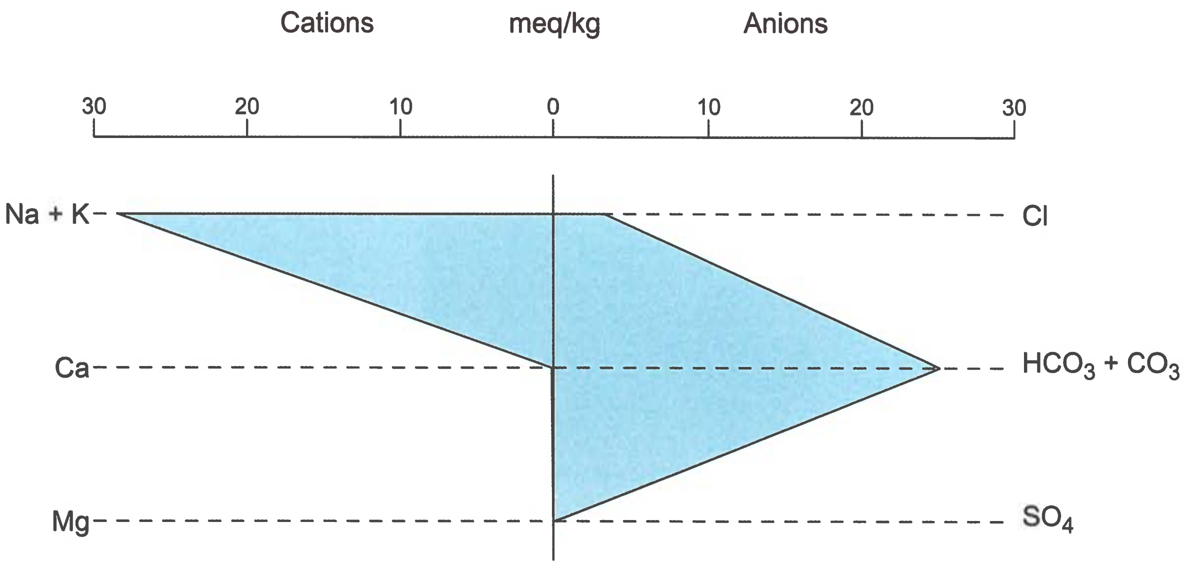


Figure 4-138. One of 226 Stiff diagrams showing cation and anion composition of typical Tertiary coal bed assemblage water (water sample 3320428).

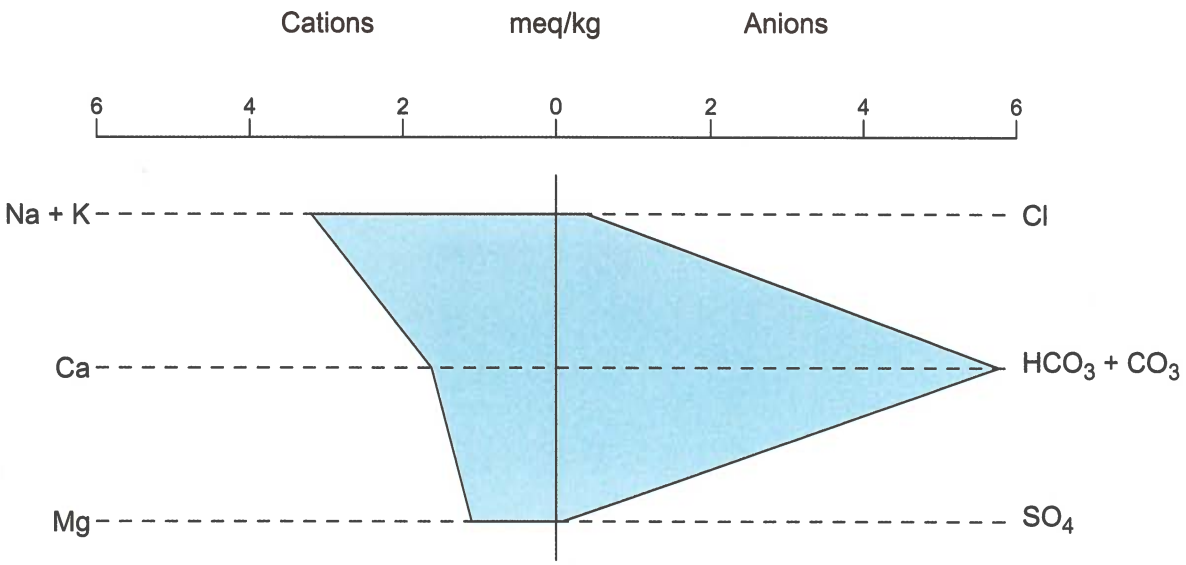


Figure 4-139. One of 226 Stiff diagrams showing cation and anion composition of typical Tertiary coal bed assemblage water (water sample 928032).

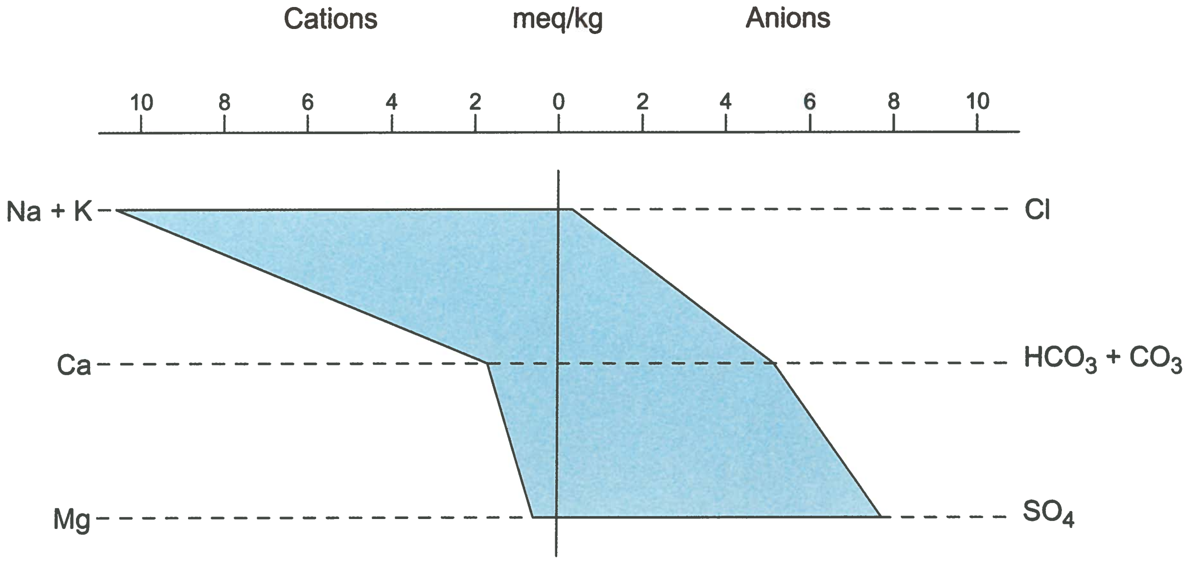
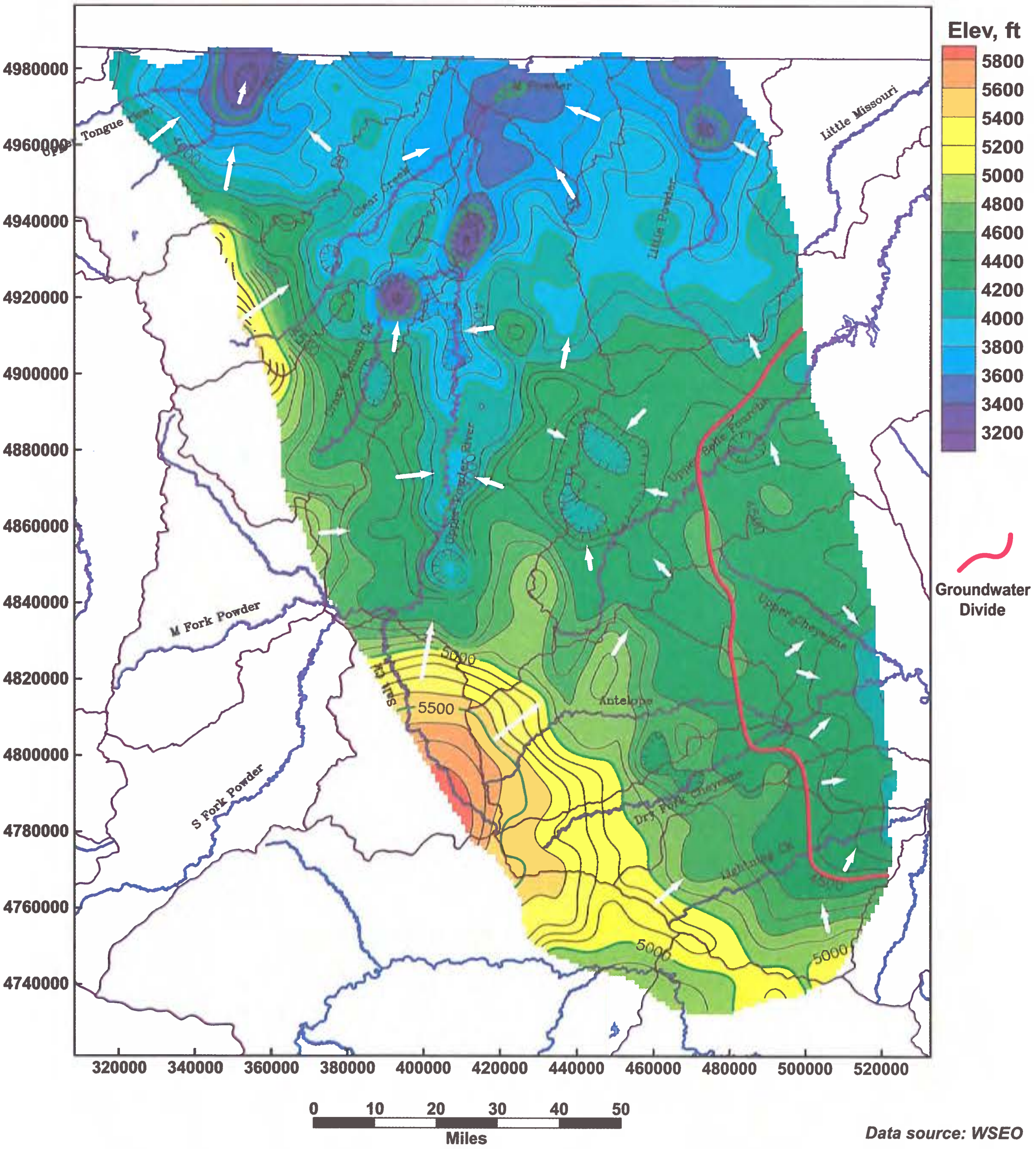


Figure 4-140. Stiff diagram showing cation and anion composition of non-typical Tertiary coal bed assemblage water (water sample 538892). Sample 538892 was one of three water samples with SO_4^{2-} as the primary anion.



Data source: WSEO

Figure 4-141. Contour map of the groundwater table, Powder River Basin, Wyoming.

APPENDIX 4A1

accessing and using the data model

Scott Parrill

Why an interactive model?

Often, paper reports are written, published, and placed on a shelf. While these reports offer many benefits, they also have their limitations. In the interest of increasing the value of this report to future investigations, we created an interactive mapping service (IMS) to allow anyone with a web browser and an internet connection to interactively view the data model.

Through the IMS, a user can generate custom images of any specific geographic area of interest. For example, a paper report may contain maps only of the Sheridan area, the Gillette area, and the entire Powder River Basin. A reader interested in the area near Wright is limited to the information on the map of the entire basin. However, through the IMS, a user can generate a map showing the specific area of interest near Wright.

Additionally, the IMS allows users to combine data sets in ways not published in a paper report. For example, a paper report may contain a map showing the distribution of the coal deposits in the Powder River Basin and another map showing the location of the oil and gas wells used to log the coal deposits. The paper report may not contain a map showing the oil and gas wells overlain on the coal deposits. With the IMS, a user can generate a custom map showing exactly that.

The IMS also can directly connect to the data model and retrieve interactive background images within software packages that support ESRI's ArcXML® protocol. (Support for other protocols may be added in the future but had not been tested at the time this report went to press.) Once a connection to the IMS is established, the user can overlay additional data on the model to investigate and display relationships outside the scope of this report. For example, a user can connect to the IMS service using ESRI's ArcDesktop® and overlay wildlife habitat information. Thus, the IMS allows this report to directly benefit a greater range of sciences and cross-disciplinary work.

The technology used to implement the IMS provides a two-dimensional (X-Y), top-down view of the data model with links to static images displaying information in the Z-axis and it does not allow the end user direct access to the underlying data behind the model. Nevertheless, the interactive nature of the IMS allows greater flexibility in applying results of this report to future studies.

Using the Model

This data model is accessible with a web browser at <http://www.wsgs.uwyo.edu/GeoMap>.

When the model is first loaded, it will display a map image of the entire state of Wyoming. Using the "Zoom In", "Zoom Out", and "Pan" tools, the user can alter the scale of the map image. The user can also alter the data display by checking and unchecking the associated items in the table of contents. This allows the user to customize the view within the limitations of the data in the model. Information about individual features is accessed with the "Identify" tool; this includes viewing cross sections or other Z-axis-related data. Cross sections will appear as a hyper-link in the "Results" window generated by an "Identify" action. Click on the link to view the cross section image.

Users cannot overlay their own data over the model or change the symbology used in the model when viewing it in a web browser, but they can explore the data with no need for additional software. To overlay additional data, the user must connect to the data model with ESRI's ArcDesktop® or similar software. Please consult the documentation for the specific software you are using to determine how to connect to the IMS service.

Data sets in the model include the following:

- Structure contours and isopach maps for the Fort Union Formation, Lance Formation, Fox Hills Sandstone, Pierre Shale, Niobrara Formation, Mowry Shale, Muddy Sandstone, Lakota Formation, Sundance Formation, Chugwater Group, Goose Egg Formation, Opeche Shale, Minnelusa Formation, and Madison Limestone
- Incline views and maps of coal beds, coal thickness, SAR distributions, and TDS distributions for the coal beds described in Chapter 2
- Water quality contour maps of SAR, TDS, pH, alkalinity, SC, HCO_3^-, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, K^+, Fe^{2+}, and Mn^{2+} for five coal beds
- Stiff diagrams for water analysis data from the Powder River Basin coal beds
- East-west and north-south cross sections of the Powder River Basin coal beds
- Maps and incline views of 26 coal beds
- Bedrock geology of the Powder River Basin
- Location of calculated hydrographs with links to stream flow data in the Power River Basin
- Location of water quality sample sites in the Powder River Basin, with links to sampling data
- Watershed drainages and applicable interstate water compacts
- Location, hydrologic unit code, USGS site number, and USGS station name of stream gauges in the Powder River Basin
- Scanned PDFs of Wyoming State Engineer's Office (WSEO) groundwater permits for the Powder River Basin

We encourage first-time users to view the help files and browse the *Introduction to IMS Services at the WSGS* document available at <http://www.wsgs.uwyo.edu/GeoMap/intro.pdf> for further information regarding use of the service.

We are constantly working to improve the function of this service: please contact us at 307-766-2286 or wsgs-info@uwyo.edu with comments and suggestions, or to report a problem.

APPENDIX 4A2

collection of groundwater data

Scott Quillinan

The Wyoming State Geological Survey (WSGS) collected groundwater quality data for this report from three sources: the Wyoming Department of Environmental Quality (235 data points), the United States Geological Survey (47 data points), and the Wyoming Oil and Gas Conservation Commission (92 data points). A data point is defined as a water quality analysis associated with a specific coal bed at a specific location (well). The 374 data points collected represent groundwater from the major CBNG target coals in the Wyoming Powder River Basin. **Table 4A2-1** lists the chemical constituents, calculated water-quality parameters, reporting units, and detection limits required by the DEQ and used in this report.

Wyoming DEQ

The National Pollutant Discharge Elimination System (NPDES), a program administered by the U.S. Environmental Protection Agency, requires that a permit be obtained for every point source discharging pollutants into waters of the United States. In Wyoming, the DEQ Water Quality Division is responsible for issuing these permits, under the program name WYPDES. The DEQ issues permits to all facilities where water is released or discharged to the environment within the state.

Thus, surface discharge of produced water from CBNG wells requires a WYPDES permit. Documen-

Table 4A2-1. Chemical constituents, calculated water-quality parameters, reporting units, and detection limits used in this report. [From Wyoming DEQ website. mg/l, milligrams per liter; µg/l, micrograms per liter]

Parameter	Required detection limits and required units
Alkalinity, total	1 mg/l as $CaCO_3$
Aluminum, dissolved	50 µg/l
Arsenic, total recoverable	1 µg/l
Barium, total recoverable	100 µg/l
Bicarbonate	10 mg/l
Cadmium, dissolved	5 µg/l
Calcium, dissolved	50 µg/l, report as mg/l
Chlorides	5 mg/l
Copper, dissolved	10 µg/l
Dissolved solids, total (TDS)	5 mg/l
Fluoride, dissolved	100 µg/l
Hardness, total	10 mg/l as $CaCO_3$
Iron, dissolved	50 µg/l
Lead, dissolved	2 µg/l
Magnesium, dissolved	100 µg/l, report as mg/l
Manganese, dissolved	50 µg/l
Mercury, dissolved	1 µg/l
pH	0.1 pH units
Radium 226, total recoverable	0.2 pCi/l
Radium 228, total recoverable**	0.2 pCi/l
Selenium, total recoverable	5 µg/l
Sodium adsorption ratio (SAR)	Calculated as unadjusted ratio
Sodium, dissolved	100 µg/l, report as mg/l
Specific conductance (SC)	5 micromhos/cm
Sulfates	10 mg/l
Zinc, dissolved	50 µg/l

tation required with a permit application includes a water quality analysis that is representative of the "coal formation(s) and the same approximate depth(s) as proposed" in the application. Samples from commingled coal seams are acceptable. A water analysis must include the following:

- Detection limits
- Each chemical constituent reported in the chemical state given in Table 1
- Quarter/quarter section, township, and range of the sample collection location
- Time and date of sample collection
- Time and date of analysis for each parameter
- Analyst's initials for each parameter
- Detection limit for each parameter as achieved by the laboratory
- WYPDES permit number and outfall number, where the sample was collected

For this report, the WSGS searched WYPDES permit files both online and at the Cheyenne DEQ offices. The WSGS collected water quality analyses from permits on which the applicant stated that the water sample was obtained from a specific coal bed at a specific location. These analyses and locations were compared with CBNG well data online at the WOGCC website. Where a WYPDES water analysis matched a CBNG well and specific coal bed, the data was deemed valid and placed into our database. This process yielded 235 water quality data points assigned to specific coals in the Wyoming PRB.

USGS

The WSGS obtained the USGS data from Open-File Report 00-372 (Rice, Ellis, and Bullock, 2000). USGS personnel collected samples from specific coal beds in CBNG wells during 1999 and 2000. The USGS analyzed the samples at their labs at the Denver Federal Center. The USGS data set comprises 47 samples collected and analyzed using strict sampling, collection, and analysis protocols.

WOGCC

The WSGS gathered information supplied to the WOGCC by the operators of 132 CBNG wells and posted on the WOGCC website. Sampling and sample analysis protocols are outlined in the WOGCC Water Sample Guide, available on their website. The WSGS checked the information to confirm that sample analysis data for each well could be tied to water produced from specific coals. Ninety-two of these sample points qualified as valid groundwater samples from specific coal beds.

References

Rice, C.A., Ellis, W.S., and Bullock, J.H., 2000, Water co-produced with coal bed methane in the Powder River Basin, Wyoming – Preliminary compositional data [paper edition]: United States Geological Survey Open-File Report 00-372, 20p.

Wyoming Department of Environmental Quality website, <http://deq.state.wy.us>

Wyoming Oil and Gas Conservation Commission website, <http://wogcc.state.wy.us>

CHAPTER 5

desalination project feasibility

Ronald C. Surdam, Keith E. Clarey, Ramsey D. Bentley,
James E. Stafford, and Zunsheng Jiao

Since 1997, coalbed natural gas (CBNG) development in Wyoming's Powder River Basin (PRB) has increased dramatically, resulting in both the generation of a huge energy resource and a set of serious environmental and regulatory impacts. The most serious impacts caused by CBNG development relate directly to production of the copious quantities of groundwater required to recover the natural gas. Not only are the thick coals in the PRB rich in natural gas, they are also an important regional aquifer system. In order to extract the absorbed natural gas from the coals, the formation pressure must be reduced by the production of groundwater from wells.

Importantly, the existing data[1] strongly suggest that during the next five years, CBNG activity in the PRB will expand west into deeper coals, the quality of water produced from the coal will deteriorate, and the volume of water produced per well will increase significantly (**Figure 5-1**). For example, the data show that the salinity of water produced from deeper wells in the west, when compared to that of water produced from the initial CBNG wells in the eastern

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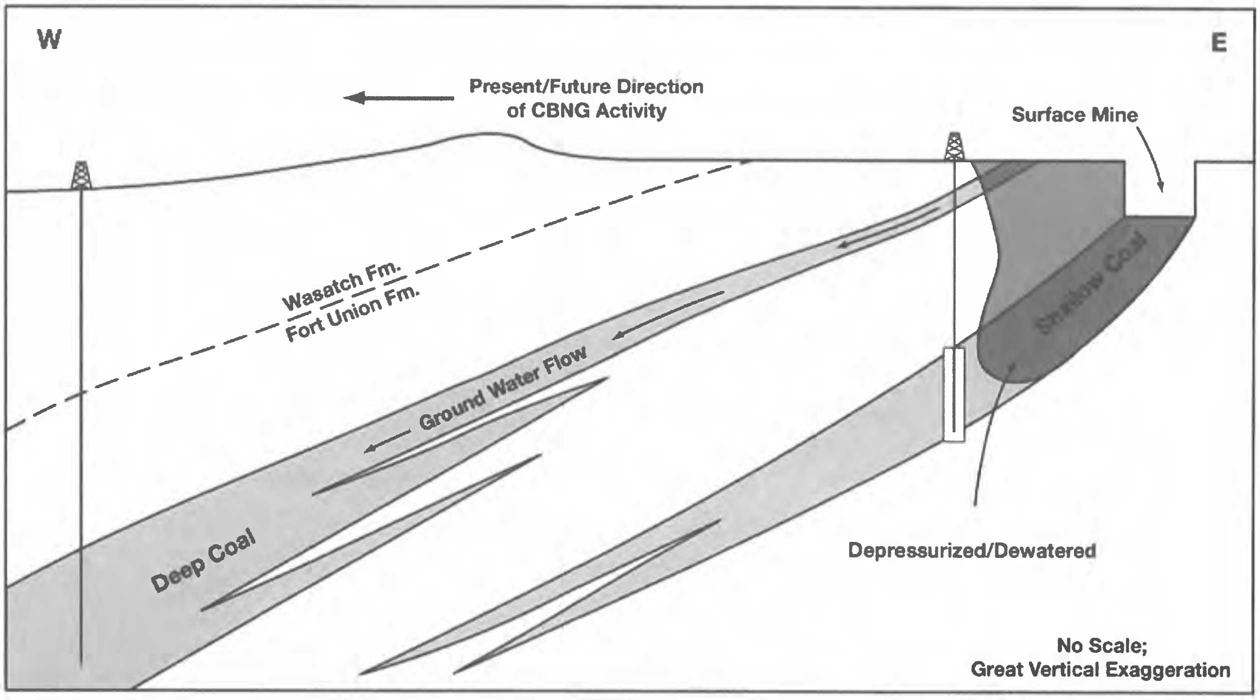
[1] Data were obtained from various coalbed methane producers, from the National Pollution Discharge Elimination System (NPDES) and Wyoming Pollution Discharge Elimination System (WYPDES) permits issued and maintained by the Wyoming Department of Environmental Quality (DEQ), from the Water Resources Data System (WRDS), from the U. S. Bureau of Land Management (BLM) Casper Field Office, from the U. S. Geological Survey (USGS) Energy Program, from the USGS National Water Information System (NWIS), and from the Wyoming Oil and Gas Conservation Commission (WOGCC).



Modified from Ayers (2002)

Figure 5-1. Early CBNG wells were located in depressurized strata adjacent to surface mines. Currently, CBNG activity is moving to the west and exploiting deeper and thicker coal beds in the Powder River Basin, such as the Big George.

part of the basin, will increase from approximately 500 to 3,500 milligrams per liter (mg/L), considered brackish, (**Figure 5-2**); the sodium adsorption ratio (SAR) will increase from 2-6 to 30-50 milliequivalents per liter (meq/L), (**Figure 5-3**); and the ratio of barrels of water to million cubic feet (MCF) of produced gas will increase from 2 to more than 2,000 (**Figure 5-4**). Therefore, all stakeholders in the PRB have focused on the collection and disposal of the water during CBNG activities. Consequently, a very contentious atmosphere has emerged concerning CBNG development, particularly with respect to the handling of the produced water. Most recently, the non-degradation ruling regarding waters entering the State of Montana will surely exacerbate the combative nature of the discussion of CBNG-produced water in both Montana and Wyoming.

Most of the disagreement among stakeholders in the PRB would disappear if the CBNG-produced water was treated and put to beneficial use. At present, much of the produced water is discharged into ephemeral streams or stored in fenced, lined or unlined, off-channel reservoirs for disposal by evaporation and/or infiltration into the alluvium. To many stakeholders in the arid Powder River Basin, this "preferred" water disposal procedure constitutes a waste of an important water resource. In order to alleviate the concerns of many stakeholders and prevent the waste of an important Wyoming resource, we must increase the beneficial use of CBNG-produced water in the PRB. In most cases, both the SAR and salinity of the produced water must be significantly decreased to accomplish this goal. Without SAR and salinity reduction, municipalities, agriculture, and industry will not be able to use the water in beneficial ways, and the discharge of waters produced from the deeper "Big George" coal seam into natural drainages will not be allowed in the future.

The SAR of the produced water is very important in evaluating potential problems related to discharging water onto soil because of how sodium affects clay minerals. Most soils found in Rocky Mountain Laramide structural basins are derived from Tertiary and Mesozoic shale beds that are rich in clay minerals, particularly smectites. These smectite-rich soils typically have exceptionally high water-absorbing and cation exchange capacities. If sodium-rich waters are applied to smectite-rich soils, sodium replaces

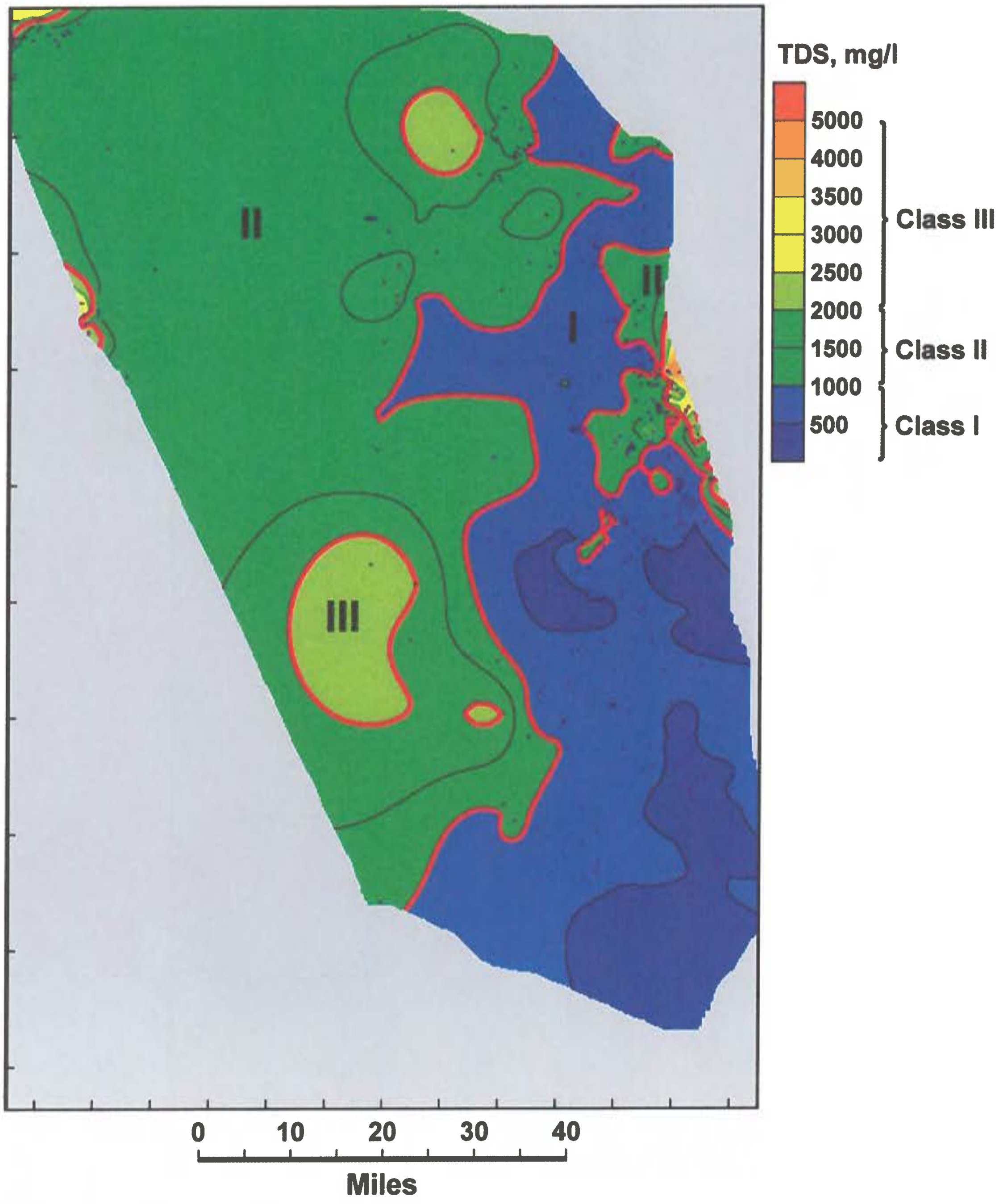


Figure 5-2. Contour map of water salinity from CBNG wells in the Powder River Basin, Wyoming. The total dissolved solids level (TDS) of the produced water is expressed in mg/L. Class I, II, and III are from the Wyoming Department of Environmental Quality water salinity classification.

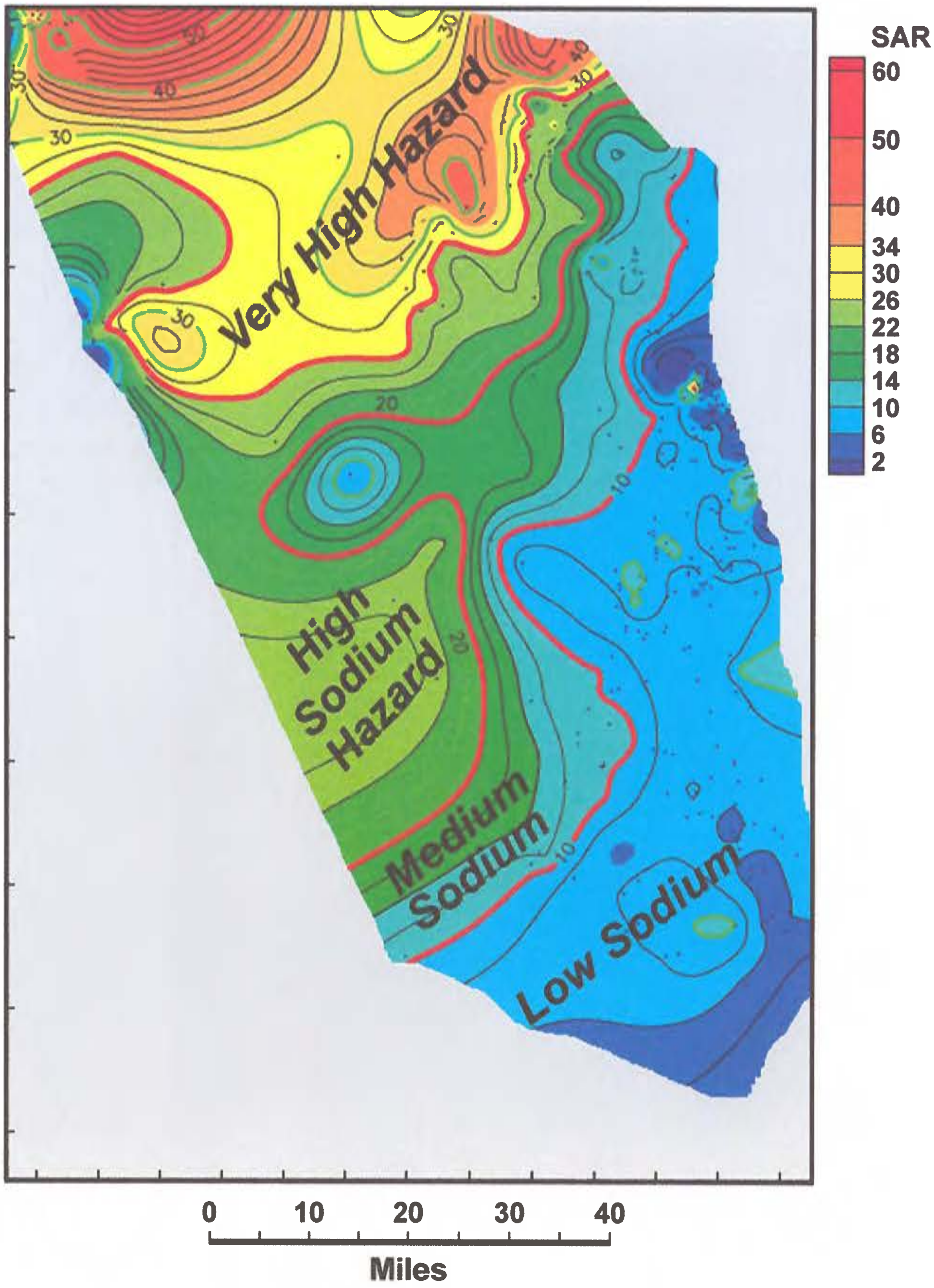


Figure 5-3. Contour map of sodium adsorption ratio (SAR) from water produced during CBNG activities in the Powder River Basin. The sodium hazard classification shown in this figure is from the Wyoming Department of Environmental Quality.

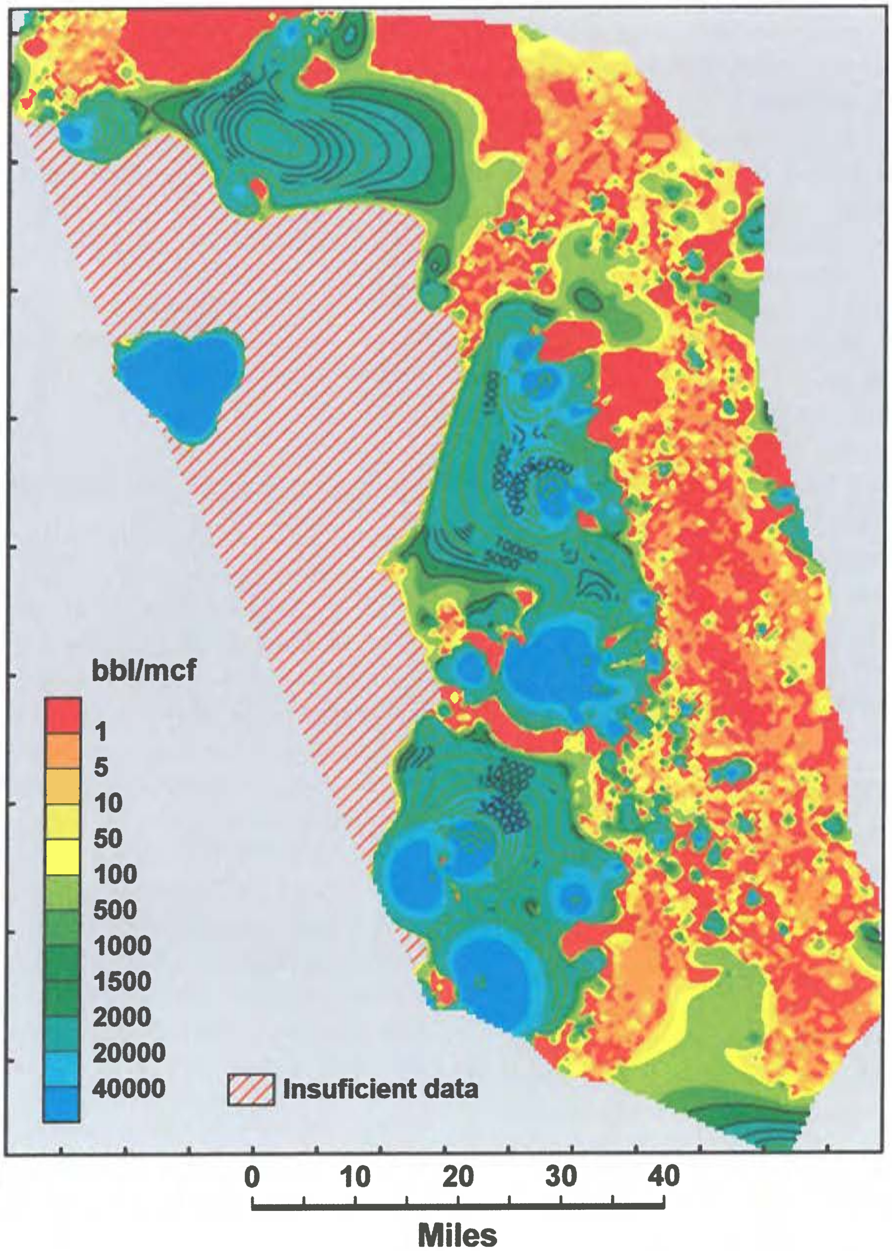


Figure 5-4. Map showing the ratio of cumulative water/gas production from CBNG wells in the Powder River Basin. The ratio is based on the number of barrels of water produced to recover one million cubic feet of gas. The Wyoming Oil and Gas Conservation Commission provided the data for this figure.

calcium in the clay mineral and the water absorption and swelling capacity of the clay increases significantly, resulting in a low permeability, expanded greasy soil. As this soil dries, it becomes brick-like and mud-cracked. In addition, the shale-derived soils contain abundant sulfates derived from the oxidation of sulfides (i.e., pyrite) in the Tertiary and Mesozoic shale beds. In those portions of sodium-rich soils subjected to evaporative pumping in the vadose zone, the mineral mirabilite ($NaSO_4$•10 H_2O) forms. With drying of the soil, the mirabilite dehydrates to form thenardite ($NaSO_4$) which forms the white evaporitic surface layer that is prevalent in topographic lows subjected to wet-dry cycles in Rocky Mountain Laramide structural basins. The end result of the application of relatively high SAR water on clay-rich soils is the deterioration of soil structures and a significant reduction of water penetration through the soils, which drastically decreases plant production and accelerates soil erosion. In addition, the uses of untreated brackish water in municipalities, agriculture, and industry are limited.

In summary, CBNG production in Wyoming benefits the state, but also generates relatively large quantities of moderate to low quality groundwater. The current water permitting system adds both time and monetary burdens to the growth and sustainability of the CBNG industry. Various methods of CBNG-production water discharge, treatment, and storage are currently being used. However, the prospective use and value of this available groundwater resource is largely lost to Wyoming's residents because the produced water is simply surface discharged or evaporated away. Collection and treatment of CBNG water for reuse has the potential to become an additional source of revenue for the state, help alleviate some of the permitting burden on the CBNG industry, and eliminate surface water and groundwater degradation. This document examines future CBNG water production, desalination plant data, uses for treated water, and piping costs, and outlines three specific desalination cost/location/use scenarios.

This report will address ways to economically, effectively, and efficiently optimize the beneficial use of water produced during PRB CBNG operations in the future.

Produced water and related issues

The accompanying chart (**Table 5-1**) shows the previous five years of annual CBNG water production in the PRB. The number of producing wells has increased almost fourfold during this time period, while water production has only increased by approximately 30%. Not all of this produced groundwater is of a quality that requires treatment. As is typical of CBNG wells, initial water production exceeds natural gas production; subsequently, water production declines as the potentiometric surface elevation in the coalbed aquifer is lowered by pumping groundwater from CBNG production wells. As CBNG development progresses in the PRB, additional wells will go into production and total CBNG water production will remain relatively high, but is anticipated to decline over time.

A gradual decline in total CBNG water production is desirable, but the amount of water in need of disposal

Table 5-1. Summary of annual CBNG water production in the PRB of Wyoming.

Production year	Produced water (barrels per day)	Average number of CBNG production wells	Average production per well (barrels per day)
2000	1,029,227	3,218	319
2001	1,421,000	6,546	217
2002	1,618,397	9,604	168
2003	1,562,071	11,633	134
2004	1,455,899	12,996	112

Wyoming State Geological Survey compilation based on Wyoming Oil and Gas Conservation Commission data, December 2005.

will remain relatively high for a considerable period of time. The projected economic production life of an individual CBNG well is currently unknown, but CBNG development in the PRB is expected to continue for another 25 years or more. In addition, current CBNG development is progressing westward into the "Big George" coal seam, which is located deeper in the PRB. The "Big George" coal bed has been shown to produce larger quantities of higher-salinity groundwater than current production wells do.

Presently, disposal of CBNG-produced groundwater is problematic at best. The highly variable quality of CBNG-produced groundwater complicates permitting by the Wyoming Department of Environmental Quality (WDEQ) and the Wyoming State Engineer's Office (WSEO). Costs of permitting are high and time-consuming for operators, the WDEQ, and the WSEO. The proposed desalination scenarios would streamline or omit permitting. Most of the CBNG-produced groundwater of moderate to low quality could be collected and transmitted by pipeline to a water treatment plant. The brackish saline groundwater would be treated and then made available for a variety of beneficial uses. Questions about the suitability of various CBNG-produced waters for use in variable circumstances (for example, SAR in relation to irrigation) would be greatly reduced or eliminated. Some of the treated water could also be made available for municipal use.

Projected plant costs and capabilities

Initially, Streeter (1972) discussed desalination of the public groundwater supply for the City of Gillette. Since then, desalination technology has greatly improved, especially during the past decade. The cost of desalinating brackish water, such as saline groundwater, is half that of desalinating seawater. This lower treatment cost is due to the fact that brackish waters have less than half the salinity of seawater. Currently, there are approximately 1,500 brackish water desalination plants operating in the United States, generating approximately 1 billion gallons of treated water per day (Texas Water Development Board, December 2005). A list of Texas communities that operate brackish water reverse osmosis (RO) desalination plants can be found in **Table 5-2**.

Reverse osmosis is the most common treatment process used for desalinating brackish groundwater. Reverse osmosis plants can be constructed in modules, have an approximate 90% recovery rate, use less energy, are simpler to construct, and screen out more biological components than other treatment options. These plants use high pressure pumps to force saline water through membrane tubes that screen out most non-water molecules. With proper maintenance, desalination plants can function for decades. The electrical power required to operate a desalination plant could easily be supplied by inexpensive and clean Wyoming coal. Close proximity to coal mines in the PRB and the use of trucks instead of trains to transport coal could further reduce operating costs. Operating large-scale desalination also reduces total capital facility costs and per barrel operating costs. **Table 5-3** illustrates the estimated capital cost of one to three plants divided by half the play's lifetime production and the total play lifetime production. **Table 5-4** shows the estimated per-barrel operating capital costs of different capacity RO plants.

Beneficial use of treated water

The treated CBNG-produced groundwater resource has a near limitless number of valuable uses in an arid to semi-arid region such as Wyoming. A 600,000-barrel-per-day (BPD) capacity desalination plant produces a flow of water approximately equivalent to the average flow of Salt Creek or Crazy Woman Creek (approximately 69 acre-feet per day). Treated water can be used by nearby, growing, high-use municipalities such as Gillette, where water demand is currently between 4.4 and 13.6 million gallons per day (GPD) (105,000 BPD and 325,000 BPD) (City of Gillette, Wyoming, December 2005). Treated low-salinity groundwater could be discharged into river basins to supplement irrigation or discharged into surface waters of the Tongue, Powder, Belle Fourche, or North Platte river basins.

Treated water from a 600,000-BPD desalination plant could provide approximately 13% of the 217,000 acre-feet per year (4,600,000 BPD) of the North Platte River water allocated for irrigation use (Nebraska *v.* Wyoming, 2001). Low-salinity water is also desirable for use in dust suppression at surface coal mines, for electrical generation in future or existing power plants, and in proposed coal-to-liquids

Table 5-2. Texas cities and towns with desalination plants (> 1 MGD capacity).

Plant Name	County	Design Capacity (MGD)	Use	Source	Startup Year	Process	Blending	Disposal Method
City of Abilene	Taylor	8.000	DW	SW	2004	RO	No	EP
SWRA	Cameron	6.750	DW	GW	2004	RO	Yes	DSW
Lake Granbury SWATS	Hood	6.000	DW	SW	2003	RO	Yes	DSW
City of Fort Stockton	Pecos	6.000	DW	GW	1996	RO	Yes	Sewer
Horizon	El Paso	2.200	DW	GW	2001	RO	Yes	LA/IRR/EP
City of Primera	Cameron	2.000	DW	GW	2005	RO	Yes	DSW
City of Robinson	McLennan	1.800	DW	SW	1994	RO	Yes	DSW
City of Brady	McCulloch	1.500	DW	GW	2005	RO	Yes	DSW
City of Raymondville	Hidalgo	1.000	DW	GW	2004	RO	No	DSW
Windermere Water System	Travis	1.000	DW	GW	2003	RO	Yes	Sewer
City of Kenedy	Karnes	0.720	DW	GW	1995	RO	Yes	DSW
City of Seadrift	Calhoun	0.520	DW	GW	1998	RO	Yes	DSW
City of Seymour	Baylor	0.500	DW	GW	2000	RO	Yes	DSW
Valley MUD #2	Cameron	0.500	DW	GW	2000	RO	Yes	LA/DSW
City of Electra	Wichita	0.500	DW	GW	1999	RO	No	LA/IRR
City of Tatum	Rusk	0.290	DW	GW	1999	RO	Yes	Sewer
The Cliffs	Palo Pinto	0.200	DW	SW		RO	No	DSW
Holiday	Aransas	0.150	DW	GW	1998	RO	Yes	DSW
Study Butte Terlingua Water System	Brewster	0.140	DW	GW	2000	RO	No	DSW
River Oaks Ranch	Hays	0.140	DW	GW	1987	RO	No	EP
City of Beckville	Panola	0.140	DW	GW	2004	RO	Yes	Sewer
Midland Country Club	Midland	0.110	IRR/ DW	GW	2004	RO	No	Yes
City of Laredo	Webb	0.100	DW	GW	1998	RO	No	Sewer

DW=Drinking Water; GW=Groundwater; IND=Industrial; SW=Surface Water; RO=Reverse Osmosis; EP=Evaporation Pond; IRR=Irrigation; LA=Land Application; DSW=Discharged to surface water.

Source: A Desalination Database for Texas. Texas Bureau of Economic Geology, prepared for Texas Water Development Board, Scott W. Tinker, John A. Jackson, Katherine G. Jackson, October 2005.

Table 5-3. Typical estimated capital costs of desalination plants.

Total project plant capital	Capital cost per 1,000 barrels at 22 billion lifetime barrels produced	Capital cost per 1,000 barrels at 44 billion lifetime barrels produced
$50 million	$2.27	$1.14
$100 million	$4.55	$2.27
$150 million	$6.82	$3.41

Wyoming State Geological Survey compilation based on Wyoming Oil and Gas Conservation Commission data, December 2005.

Table 5-4. Treatment plant estimated cost by processing capacity.

Processing capacity (barrels per day)	Plant capital cost	Processing cost per 1,000 barrels at 44 billion lifetime barrels produced
600,000	$50 million	$63.00
360,000	$35 million	$65.10
180,000	$20 million	$67.20

Texas Water Development Board, December 2005.

conversion plants. Coal mines in the PRB currently use between 200 and 800 acre-feet of water per year (4,250 to 17,000 BPD) (HKM Engineering, 2002) for dust suppression. A potential coal-to-liquids conversion plant is estimated to use 1,200 acre-feet of water per year (25,500 BPD), and a new electric generation plant will use approximately 23,000 to 34,000 acre-feet of water per year (495,000 to 725,000 BPD) (Purcell, 2001). An area of especially high demand is the Front Range urban development zone in Colorado, where water supply prices range from $3,000 to $10,000 or more per acre-foot, or $0.38 to $1.28 per barrel (Wyoming State Water Plan FAQ, January 2006). **Table 5-5** compares the demand for various water uses to the volume of treated water made available for use.

Out of every 10 barrels (420 gallons) of water processed, it is estimated that one barrel (42 gallons) of brine concentrate with a total salinity ranging from 10,000 to 15,000 mg/L, or parts per million (ppm), of total dissolved solids (TDS) is produced (Texas Water Development Board, December 2006). This level of brine concentrate salinity is approximately one-third to one-half that of seawater. Approximately 10% of the influent entering the treatment plant is produced as concentrated high-salinity effluent water.

Disposal of high-salinity water

During the desalination process, approximately 90% of the influent water received at the water treatment plant would be treated to very low salinity levels and then made available for beneficial use. The dissolved constituents removed by water treatment are concentrated into the remaining 10% of the influent water volume, which leaves the plant as brine concentrate. Brine concentrate resulting from the desalination process will require disposal, or could generate revenue if used in industrial processes.

This study has not investigated disposal options and associated costs for high-salinity effluent (brine concentrate) produced by the desalination plant. Each 600,000-BPD treatment plant would produce an estimated 60,000 BPD (2.5 million GPD) of brine concentrate. The estimated costs and methods of disposal would need to be addressed by an engineering feasibility study during the initial phase of any proposed desalination project to ensure project viability.

Disposal methods for the RO treatment effluent may include lined surface evaporation ponds, heated evaporation tanks, subsurface injection into deep formations with similar or higher salinities, and other methods. Either existing underground injection control (UIC) wells or future permitted UIC wells may be available for effluent disposal in deep formations located in the PRB. Alternatively, some of the effluent water may be suitable for use in water-flood enhanced oil recovery. In addition, the predominantly sodium bicarbonate-type groundwater produced from PRB coal beds and concentrated during RO treatment may constitute a desirable chemical plant feedstock.

The number of available subsurface geologic formations in the PRB that can be used for injection of fluids via UIC wells is limited. The paucity of such formations in the PRB has placed serious constraints on the potential for reinjecting the large volumes of water currently produced by CBNG activities. As such, the available formations suitable as fluid injection UIC wells in the PRB might be best used for effluent disposal of high-salinity water generated by desalination plants. Additional treatment methods for concentration of the high-salinity effluent may be required before injection and disposal.

Table 5-5. Water use comparison.

Consumptive use	Average water demand (BPD)	Percent of water demand generated by a 600,000-BPD plant
Gillette municipal system	214,285	252%
North Platte River irrigation allocation	4,600,000	13%
Coal dust suppression	10,627	5081%
Coal-fired power plant	608,480	89%
Coal-liquid conversion	25,507	2117%

City of Gillette, December 2005; Nebraska v. Wyoming, 2001; and Wyoming State Water Plan, January 2006.

Also, a preliminary review of existing oil fields in the PRB has identified several older oil field reservoirs that could be used for injection and disposal of the estimated quantity of produced effluent. One 600,000-BPD treatment plant is expected to produce approximately 22 million barrels of high-salinity effluent per year (at a rate of 60,000 BPD), or a total of approximately 660 million barrels over a 30-year operating period. Based on petroleum and water production data from the Wyoming Oil and Gas Conservation Commission, the estimated 660 million barrels of effluent could be injected into several PRB oil fields with a sufficient volume of available reservoir space. This alternative method of effluent disposal must be investigated further with an engineering feasibility and cost estimate study.

Logistics

Please refer to the accompanying map for plant and pipeline locations (**Plate 2**). Proposed sites for desalination plants were selected based on several parameters. Proximity to produced water sources would help reduce gathering costs. Proximity to existing pipeline corridors, power supplies, roadways, and railroad lines would help reduce permitting costs. Further, proximity to usage or storage points of desalinated water, including municipalities, would also help reduce overall costs. The potential water treatment plant sites are approximately located and the proposed sites may be adjusted for location onto state-owned land and/or closer to CBNG water production centers.

Potential desalination plant sites are: A) near Gillette; B) near Pine Tree Junction (southern end of CBNG play); and C) Dead Horse (near the Big George coal area).

Proposed underground transmission pipelines include: 1) Gillette to Keyhole Reservoir; 2) Gillette to Pine Tree Junction, 3) Pine Tree Junction to Douglas, 4) Pine Tree Junction to Casper, 5) Dead Horse to Lake De Smet, 6) Dead Horse to Gillette, and 7) Dead Horse to Pine Tree Junction.

Several combinations of multiple treatment plant sites and transmission pipeline routes are possible.

Transmission pipeline calculations

The following pipeline calculations are based on operating one desalination plant with a capacity for treating a total of 600,000 BPD of CBNG-produced water. The salinity of the CBNG-produced water before treatment is expected to range from 500 to 10,000 mg/L of TDS. The plant would produce 375 barrels of treated water per minute (15,750 gallons per minute (gpm)), which is 90% of the total influx of 600,000 BPD, or 17,500 gpm of CBNG-produced water at the plant. The maximum recommended flow velocity within a water pipeline is approximately 3 feet per second to avoid excessive head losses.

- An influent flow rate of 17,500 gpm is converted to 417 barrels per minute, 2,339 ft^3/minute, or 39.0 ft^3/second.

- An effluent flow rate of 15,750 gpm of treated good-quality water is converted to 375 barrels per minute, 2,106 ft^3/minute, or 35.1 ft^3/second. This quantity of treated water would be available for beneficial use, including drinking water.

- The water treatment plant would also produce an effluent waste stream of 1,750 gpm (41.7 barrels per minute or 234 ft^3/minute) of concentrated brine water (10% of the influent) for disposal. This brine concentrate flow rate would require a 16-inch-diameter pipeline and have a flow rate of 2.8 feet per second at 1,750 gpm from the plant. A disposal method for this brine concentrate effluent would need to be developed.

An underground 48-inch-diameter steel pipeline would be required with an internal pipeline volume calculated to be 12.57 ft^3 per linear foot of pipeline. A pipeline this size is capable of flowing 17,500 gpm at a flow velocity of 3.1 feet/second and 15,750 gpm at a flow velocity of 2.8 feet/second.

A water transmission pipeline construction project will likely need to include permitting, an environmental impact statement (EIS), pipeline alignment, land access agreements, engineering design and construction supervision, public bidding for a piping contractor, and construction of the pipeline. The pipeline project would probably require approximately one year to obtain the necessary permits/access/alignment, conduct the EIS, and prepare the engineering design. It would also require approximately one more year to construct the pipeline, depending on the amount of manpower provided by the construction contractor and the final design, alignment, and length of the pipeline.

For example, the engineering and construction of a 48-inch-diameter steel pipeline for a distance of 70 miles has an estimated total pipeline cost of $83.2 million. The estimated unit cost is $225 per linear foot in 2007 dollars, which includes an increase of $25 per linear foot from the estimated current piping cost of $200 per linear foot in 2006 dollars.

Estimated plant and pipeline costs

Each 600,000-BPD desalination plant is estimated to cost $50 million. Calculated pipeline costs are estimated at $225 per linear foot (see discussion in the previous section). This cost estimate is based on engineering and constructing a 48-inch-diameter steel underground pipeline capable of carrying the estimated plant yield of 540,000 BPD of treated water. Two 600,000-BPD capacity plants would be needed to treat the amount of CBNG groundwater currently produced by CBNG operations in the PRB of Wyoming. Estimated project engineering and construction costs follow.

- 600,000-BPD capacity desalination water treatment plants cost $50 million each.
- Optimal underground 48-inch-diameter steel water transmission pipeline costs are as follows:
  1) $39 million for the Gillette to Keyhole Reservoir pipeline;
  2) $72 million for the Gillette to Pine Tree Junction pipeline;
  3) $78 million for the Pine Tree Junction to Douglas pipeline;
  4) $78 million for the Pine Tree Junction to Casper pipeline;
  5) $44 million for the Dead Horse to Lake De Smet pipeline;
  6) $43 million for the Dead Horse to Gillette pipeline; and
  7) $69 million for the Dead Horse to Pine Tree Junction pipeline.

Obviously, the estimated costs for engineering and constructing pipelines are relatively high. Therefore, minimizing overall length of pipeline distances is critical to controlling total project cost.

Plant sites and pipeline scenarios

Following are three scenarios that represent the most viable options for cost and/or desired uses based on the many possible combinations from the above pipeline locations. These scenarios focus on the most probable beneficial uses of treated water and site the desalination plants near the heaviest CBNG-produced water zones. All scenarios use the largest plant capacity due to the beneficial economics of lower per-barrel operating costs and the significantly lower pipeline costs associated with fewer locations. The first and last scenarios are relatively low-cost options that focus on localized use and reservoir storage. The second scenario is a higher-cost option developed to specifically supply additional water to the North

Platte River to help satisfy requirements of the 2001 Modified Decree with Nebraska.

Cost-per-barrel estimates are the sum of per-barrel operating costs and per-barrel capital costs. The operating costs come from typical reported per-barrel estimates. The per-barrel capital costs are calculated from the total scenario capital cost divided by half of the total number of barrels the play will produce in its lifetime. The disposal of brine concentrate effluent from each desalination plant has not been addressed.

Dead Horse-Gillette-Keyhole
Plant Locations: Dead Horse (1 plant), Gillette (1 plant)

Pipelines: Dead Horse to Gillette (1 pipeline at $43 million), Gillette to Keyhole Reservoir (1 pipeline at $39 million)

Treatment Capacity: 1,200,000 BPD

Total Cost: $182 million = $100 million (2 plants) + $82 million (2 pipelines)

Possible Add-ons: For enhanced capacity, another desalination plant at Dead Horse and another pipeline to Gillette could be added. This would add 600,000 BPD in treatment capacity and $93 million in additional piping and plant costs.

Cost per Barrel: $0.09 per barrel (includes operating, plant, and pipe capital)

Other Options: The treated water could be discharged into Donkey Creek, which flows into the Belle Fourche River and Keyhole Reservoir. This option would eliminate $39 million from the total cost and provide a much greater outflow capacity.

Treated Water Uses: Treated water produced in the Gillette area could generate revenue if sold to electric-power generation plants or coal companies for dust suppression. Non-revenue generating options include providing water to the Gillette water municipality for public consumption or putting water into the Belle Fourche River Basin for irrigation or recreation/storage in the reservoirs.

Obstacles: The 1943 water compact for the Belle Fourche River Basin between Wyoming and South Dakota ensures that almost all unappropriated river water belongs to South Dakota. Since this scenario includes storing water in Keyhole Reservoir, a negotiated deal would have to be reached concerning who owns the transferred groundwater to ensure that treated water is not claimed for use by another. Moving groundwater from the Tongue/Powder River Basin to the Belle Fourche River Basin could be considered a trans-basin diversion, and downstream states (Montana, North Dakota, and South Dakota) might contest this groundwater transfer if they consider themselves to be losing available surface water.

Summary: This is a lower cost option that assumes industrial water use near Gillette and storage of extra desalinated water in Keyhole Reservoir. Gillette is an ideal location for desalination plants because of accessibility, revenue possibility, and reservoir storage. Locating plants in the "Big George" coal area provides for nearby treatment of the largest quantities and lowest qualities of water in the basin.

Dead Horse-Pine Tree Junction-North Platte River
Plant Locations: Dead Horse (2 plants)

Pipelines: Dead Horse to Pine Tree Junction. (2 pipelines at $69 million each), Pine Tree Junction to Casper/Douglas (2 pipelines at $78 million each)

Treatment Capacity: 1,200,000 BPD

Total Cost: $394 million = $100 million (2 plants) + $294 million (4 pipelines)

Possible Add-ons: Another desalination plant in the Dead Horse area and another 2 pipelines. This would add 600,000-BPD in treatment capacity and $197 million in additional piping and plant costs.

Cost per Barrel: $0.10 per barrel (includes operating, plant, and pipe capital)

Other Options: Relocating one or both plants from Dead Horse to Pine Tree Junction decreases the number of nearby CBNG well locations, however piping costs are reduced by $69 million per plant by placing the plants in Pine Tree Junction instead of Dead Horse. A half scenario with one plant at Dead Horse and two pipes to Casper would cost less and has potential to help mitigate Wyoming's water debt to Nebraska for half the cost.

Treated Water Uses: Water treated in this scenario would serve to boost Wyoming's water supply to Nebraska via the North Platte River to meet compact requirements. The additional water could also be used for irrigation or recreation in the reservoirs. This would allow North Platte River irrigators to have a larger, more consistent supply of water.

Obstacles: Although transferring treated groundwater to the North Platte River Basin under the Modified Decree would benefit the state of Nebraska, the other states listed in Scenario 1 may take issue with the transfer of groundwater from a river basin that flows into their states.

Summary: This is a fairly costly option, and possible interstate concerns about trans-basin movement of treated groundwater may need to be overcome to render this scenario feasible. However, the higher cost of this project may well be worth it in the long run because it addresses the need to help supply additional water to the North Platte River Basin. Locating plants in the "Big George" coal area provides for nearby treatment of the largest anticipated quantities and lowest qualities of CBNG-produced water in the PRB.

Dead Horse-De Smet

Plant Locations: Dead Horse (1 plant), near Lake De Smet (1 plant)

Pipelines: Dead Horse to Lake De Smet (1 pipeline at $44 million)

Treatment Capacity: 1,200,000 BPD

Total Cost: $144 million = $100 million (2 plants) + $44 million (1 pipeline)

Possible Add-ons: Constructing an additional plant in the Dead Horse area adds 600,000 BPD in capacity and $94 million in additional piping and plant costs.

Cost per Barrel: $0.08 per barrel (includes operating, plant, and pipe capital)

Other Options: One of the plants could be moved farther northwest, near Sheridan, to be closer to CBNG-produced groundwater from the Tongue River Basin. This would include adding a short pipeline segment estimated to cost approximately $35 to $45 million more.

Treated Water Uses: The treated water could be stored in Lake De Smet. From there it could be used for irrigation, piped to the Buffalo/Story/Sheridan area for public water supply use, or discharged into the Clear Creek drainage, which has a confluence with the Powder River near the Wyoming-Montana border.

Obstacles: Because the groundwater remains within the same river basin in this scenario, no interstate compact issues would exist. However, assurances would be needed to confirm adequate storage space in Lake De Smet for the quantity of treated water.

Summary: This option does not offer any immediate revenue-generating options, but it is relatively inexpensive, provides for transfer of treated water to a manageable reservoir, and keeps the groundwater within the same river drainage basin. Placing a desalination plant near Lake De Smet also reduces piping costs and favorably situates it to take advantage of the growing CBNG production near the lake. Locating plants in the "Big George" production area provides for nearby treatment of the largest quantity of lowest quality CBNG-produced water in the PRB.

Interstate river compacts

Parts of the greater Powder River geologic basin in Wyoming are located within the Little Bighorn, Tongue, Powder, Little Powder, Belle Fourche, Cheyenne, and North Platte river basins. Water in the Yellowstone River Basin, which includes the Little Bighorn, Tongue, Powder, and Little Powder river basins in Wyoming, is part of the Yellowstone River Compact of 1950, signed with the states of Montana and North Dakota (W.S. Title 41, Chapter 12, Article 6). Water in the Belle Fourche River Basin is part of the Belle Fourche River Compact of 1943, signed with the state of South Dakota (W.S. Title 41, Chapter 12, Article 2).

The City of Gillette and Keyhole Reservoir are located within the Belle Fourche River Basin, and potential transfer of groundwater from the Tongue, Powder, and Little Powder River Basins may be considered a trans-basin water diversion under the terms of the 1950 compact. Article X of the Yellowstone River Compact states: "No water shall be diverted from the Yellowstone River basin without the unanimous consent of all the signatory states." However, Article II (g) of the 1950 compact states: "The terms 'divert' and 'diversion' mean the taking or removing of water from the Yellowstone River or any tributary thereof when the water so taken or removed is not returned directly into the channel of the Yellowstone River or of the tributary from which it is taken." The quoted definitions in Article II (g) appear to apply only to surface water located within the Yellowstone River Basin. In addition, the Yellowstone River Compact never specifically refers to groundwater. It is our understanding that the WSEO has investigated the 1950 compact and determined that the Yellowstone River Compact only applies to surface water within the Yellowstone River Basin. This WSEO determination may be challenged by Montana or North Dakota.

Although groundwater is not specifically mentioned in either the Yellowstone River or Belle Fourche River interstate compacts, any diversion of groundwater from the Tongue/Powder/Little Powder River Basins to the Belle Fourche River Basin may be considered a trans-basin diversion by the Wyoming Attorney General's Office (WAGO), WSEO, Montana, or North Dakota. The same may be true of diverting groundwater from the Lower Yellowstone River Basin to the North Platte River Basin. Legal and regulatory issues for potential trans-basin groundwater diversions would need to be clearly determined by the State of Wyoming prior to planning, design, or construction of any water system crossing the major surface water divides. The WAGO and WSEO will determine the legal, administrative, and water rights issues for the state of Wyoming.

Other treatment options

Another option, which would eliminate the expense of large treatment plants and long pipelines, is the use of mobile truck-mounted or skid-mounted RO units. These portable desalination units could be placed at water outfall locations when and where needed, and then moved to new locations as necessary. Treated water could be used near the portable treatment unit for irrigation, stock reservoirs, or dust suppression. These smaller desalination units are offered by various companies and produce anywhere from 500 GPD to more than 100,000 GPD (from 10 BPD to more than 2,500 BPD). The downside of this option is that the per-barrel operating cost is much higher than that of large-scale RO plants because portable units require a portable power source. Also, a method of disposal for the high-salinity effluent from the RO units would need to be established.

Future water supply alternatives

CBNG-related production of groundwater will decrease with time as profitable CBNG production gradually declines in the PRB. As a result, any infrastructure projects completed in Wyoming constructed specifically to treat and beneficially use CBNG-produced water will likely require an alternative water supply at some time in the future. A reconnaissance-level investigation of potential alternative water resources in the Gillette area of the PRB was conducted to help identify possible water supplies for use as CBNG-produced water supply declines.

Surface water

Potential surface water resources present in the Powder River Basin area of Wyoming include the Tongue, Powder, Little Powder, Little Missouri, Belle Fourche, Cheyenne, and North Platte River Basins. The question has been asked: "How much unappropriated surface water is available in the Tongue River and Powder River drainage basins?" **Table 5-6**, based on information contained in the Wyoming Water Development (WWDC) River Basin Plans (HKM Engineering, 2002a and 2002b), summarizes the surface water resources available for use in Wyoming.

The preceding data are for dry years only. For normal and wet years, the quantity of available surface water for beneficial use in Wyoming increases in these river basins. The data for dry years was selected to identify the minimum amount of surface water that may be available in the future. Due to the highly seasonal nature of stream discharge in this area of Wyoming, water storage would be a requirement for year-round use of these surface water supplies.

Under the terms of the Yellowstone River Compact of 1950, the unappropriated or unused total divertible flow, after needs for supplemental supply for existing rights are met, is allocated to Wyoming and Montana as Tongue River (60% to Wyoming and 40% to Montana,) and Powder River and Little Powder River (42% to Wyoming and 58% to Montana). Currently, some of the tributary streams in both

Table 5-6. Annual remaining allocation of surface water for the state of Wyoming.

Drainage basin	Total annual allocation of available surface water flow for dry years	
Tongue River	40,000 acre-feet	310 million barrels
Powder River	74,000 acre-feet	574 million barrels
Belle Fourche River	2,500 acre-feet	19 million barrels

WWDC River Basin Plans, HKM Engineering, 2002a and 2002b.

the Tongue River and Powder River drainage basins are fully appropriated during dry years (Sue Lowry, WSEO, personal communication, 2006).

The Belle Fourche River and Keyhole Reservoir have an agreement for unappropriated river flow of 10% to Wyoming and 90% to South Dakota. The entire quantity of the Keyhole storage water (10%) for current use in Wyoming is contracted by the Crook County Irrigation District (WSEO personal communication from Sue Lowry, 2006). Keyhole Reservoir and the Belle Fourche River Basin in Wyoming are regulated under the Belle Fourche River Compact of 1943. The Belle Fourche River Compact also states that no reservoir located in the Belle Fourche River drainage basin which is built solely to use water allocated to Wyoming shall have a capacity in excess of 1,000 acre-feet.

Groundwater

With an anticipated decline in total CBNG water production in the PRB over time, contingency (replacement) well water may be needed for future use as feed water for the desalination plants. Each plant can treat approximately 600,000 BPD (17,500 gpm) and two plants could treat up to 1.2 million BPD (35,000 gpm). If we assume that there is no CBNG-produced water available for the desalination plants in the PRB, what kind of wells (depths and aquifers) and associated costs are projected for replacement groundwater supply?

For this study, potential aquifers in the Gillette area of Campbell County were investigated (Littleton, 1950; Wyoming Water Planning Program, 1977). Potential wells for construction in this area may include those listed in **Table 5-7**.

Groundwater produced from the aforementioned aquifers will likely require some degree of water treatment for municipal or industrial use.

Potential deeper aquifers in the Gillette area include the Lower Cretaceous-age Cloverly/Inyan Kara Group (Fall River Sandstone and Lakota Sandstone members), the Jurassic-age Sundance Formation (sandstone beds), and the Mississippian-age Madison Limestone (limestone/dolomite) with potential well depths ranging from 8,100 to 10,700 feet in the Gillette area of Campbell County. Beneath the City of Gillette, the top of the Madison Limestone is present at a depth of approximately 10,000 feet below ground surface with relatively poor water quality. The Madison Limestone is approximately 700 feet thick in this area and the total well depth for constructing a Madison aquifer well near Gillette would be approximately 10,700 feet.

The estimated cost for drilling a relatively deep water well in Wyoming averaged approximately $250 per foot in 2005. Well drilling costs are estimated to increase at a rate of 10% to 20% per year for diesel fuel, steel, transportation, labor, and cement. Assuming a 20% increase from 2005 costs, it would likely cost up to $300 per foot for well construction in 2006. It is estimated that a 2,000-foot deep water well would cost approximately $600,000 in 2006 dollars to construct. The cost for each deep water well constructed into the Inyan Kara/Cloverly to Madison aquifers (8,100 to 10,700 feet deep) near Gillette is estimated to range from $2.4 million to $3.2 million in 2006 dollars.

Due to increased well depth, lower water quality, and associated higher costs for construction of water supply wells into the deeper aquifers in the Gillette area, the sandstone beds of the Wasatch, Fort Union, and Lance/Fox Hills are the most practical aquifers for future development of an alternative groundwater supply in the Powder River Basin. The Wasatch and Fort Union aquifers are currently being used by the City of Gillette, CBNG operators, surface coal mine operators, and other local well owners. The Fox Hills

Table 5-7. Potential wells in the Gillette area for replacement groundwater supply.

	Wasatch Formation	Fort Union Formation	Lance Formation
Well depths	182-355 ft.	900-1,200 ft.	2,000-4,000 ft.
Cost per well	$55,000-$107,000	$270,000-$360,000	$600,000-$1.35 million
Well yields	60-100 gpm	50-150 gpm	325-400+ gpm (950 gpm enlargement on 1 well)
Static water levels	60-80 feet below ground	400-450 feet below ground	450-824 feet below ground
Water quality	1,200-2,000 mg/L TDS	300-500 mg/L TDS	850-1,400 mg/L TDS

Littleton, 1950; Wyoming Water Planning Program, 1977.

Sandstone also has good potential for construction of a future well field to supply replacement groundwater to desalination plants following a decline in CBNG water production.

Conclusion

With a combination of state funds (i.e., bonding and capital, and per-barrel water treatment fees charged to industry), the cost of a treatment/pipeline project could be promptly repaid. The amount of time and money spent on the water permitting process could be substantially reduced. High salinity groundwater would no longer be considered a pollutant to be disposed of or a roadblock to future CBNG production. Treated CBNG-produced water could become a valuable commodity and a useful water resource for the region.

In brief, the issues associated with CBNG-produced water in Wyoming will continue to grow and become more contentious as the development moves deeper and farther to the west in the PRB. In this report, the WSGS has explored an option for CBNG water treatment that overcomes the most significant challenges facing CBNG development. The basic premise is to treat all water produced during CBNG activities to drinking water standards. In this way, beneficial use of the water is optimized and the waste of the water resource is minimized. The proposed treatment (i.e., desalination) is based on available and well-tested technology. The adoption of such a plan depends on a cooperative partnership between the CBNG industry and the State of Wyoming. For the plan to work, the cost of such a project would have to be shared between industry and the state. The results of the project would greatly benefit both partners.

Acknowledgements

The authors would especially like to thank the Wyoming Water Development Commission for supporting this desalination project feasibility study as part of a comprehensive investigation of the Powder River Basin. We would also like to thank the following organizations and individuals for contributing information to this report: the City of Gillette; coalbed natural gas operators; Mark Stacy, P.G., of Lidstone and Associates, Inc.; the Texas Water Development Board; Rich Allen, P.E., of Trihydro Corporation; the U.S. Bureau of Land Management; the U.S. Geological Survey; the Water Resources Data System; the Wyoming Department of Environmental Quality; the Wyoming Oil and Gas Conservation Commission; the Wyoming State Engineer's Office; and the Wyoming Water Development Commission.

Applicable conversions

1 barrel = 42 gallons

1 acre-foot = 7,758.36 barrels = 325,851 gallons = 43,560 cubic feet

1 acre-foot per year = 21.26 barrels per day = 892.9 gallons per day

1 cubic foot = 7.48 gallons of water

$\text{SAR}=[\text{sodium}]/(([\text{calcium}]+[\text{magnesium}])/2)^{1/2}$

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CHAPTER 6

an evaluation of coal bed natural gas production trends

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In this study, we evaluated production histories of the first ten years of coal bed natural gas (CBNG) development in the Powder River Basin (PRB). We then used this evaluation to predict future gas and water production as CBNG activity moves to the west in the PRB over the next decade. CBNG wells more than two years old with water/gas ratios greater than 2 have produced 4.6 percent of the gas and 38 percent of the water in the PRB to date. Water/gas ratios for the first 10 years of CBNG development in the PRB (22,111 wells two years old or older) averaged 1.83 barrels of water per thousand cubic feet (MCF) of gas produced. The predicted water/gas ratio for future CBNG development in the Upper, Middle, and Little Powder River and Upper Tongue River drainages is less than 3 barrels/MCF. In stark contrast, the Clear Creek and Crazy Woman Creek drainages have projected water/gas ratios greater than 300 barrels/MCF. From now until 2020, CBNG development in the Clear Creek and Crazy Woman Creek drainages is predicted to supply only 0.15 percent of the total gas extracted in the PRB, but will produce 20 percent of the water (130 billion gallons).

We recommend that all CBNG wells with water/gas ratios greater than 3 after two years of production be reviewed. Barring extenuating circumstances, these wells should be regulated as water wells. Finally, the observations outlined in this study support a moratorium on CBNG activity in the Clear Creek and Crazy Woman Creek drainages.

Introduction

This study was initiated to determine if there is information available that would further optimize the gas production and minimize water production in the CBNG play in Wyoming's Powder River Basin (PRB). An improved understanding of production characteristics could make the CBNG development more resource-responsible, particularly with respect to water management. Historically, water production has been the most contentious aspect of the CBNG development in the PRB. In order to avoid further conflict, we make every effort in this report to maximize observation and minimize speculation. Now is an ideal time to examine CBNG production characteristics because it is possible to retrieve ten years of production data from most of the drainage basins in the PRB.

General observations

CBNG well number 531860 exhibits an ideal water-gas production profile (**Figure 6-1**): the well produces substantial amounts of water in the first one to two years; gas production peaks in the first one to two years; and well life ends with a steep decline in both water and gas production lasting three years or more. The productive life of a typical CBNG well is somewhere between five and ten years.

It is important to note that the described production scenario (**Figure 6-1**) applies to typical CBNG wells, but many notable exceptions exist. For example, out of 22,211 CBNG wells at least two years old in the PRB, 338 produced only gas (**Figure 6-2**). These wells are shown in red in **Figure 6-2** and occur in close proximity to the open pit coal mines along the eastern margin of the basin (shown in purple on **Figure 6-2**). Conversely, 851 wells produced only water after two or more years of "production"(**Figure 6-3**). Most of these water-rich wells appear to occur along NW-SE, or NE-SW linears (**Figure 6-3**). Between the gas-only and water-only wells shown in **Figure 6-2** and **Figure 6-3**, there is a wide variety of water-gas production profiles, with the ideal profile shown in Figure 1 somewhere near the middle of the production spectrum for CBNG wells in the PRB.

Figure 6-4 presents a summary of the water/gas production histories of 22,211 CBNG wells two years old or older in the PRB. As of March 2007, these wells produced approximately 2.3 trillion cubic feet (TCF) of gas, and approximately 4.2 billion barrels of water. The average water/gas production ratio for the more than 22,000 CBNG wells is 1.83 barrels (bbls) of water per thousand cubic feet (MCF) of produced gas. Other important observations that can be derived from **Figure 6-4** pertain to wells that have produced for more than two years with water/gas ratios greater than 10 (4,135 wells, or 18.6 percent of wells). These wells have produced 37.1 billion cubic feet (BCF) of gas (1.64 percent of total gas production), and more than 1.1 billion bbls of water (26.5 percent of total water produced). In addition, CBNG wells with water/gas ratios greater than 5 (5,761 wells, or 25.9 percent of wells) have produced 105.6 BCF of gas (4.7 percent of total gas production) and more than 1.5 billion bbls of water (38.1 percent of total water produced), while CBNG wells with water/gas ratios greater than 3 have produced slightly more than 233 BCF of gas (10.3 percent of total gas production) and slightly more than 2 billion bbls of water (49.8 percent of total water produced).

In summary, eliminating all wells with water/gas ratios greater than 10 would have saved 25 percent or more of the total water produced, while reducing total gas production by only 1.6 percent. If wells with water/gas ratios greater than 5 could have been avoided, it would have saved 38 percent of the total water produced, while eliminating just 4.7 percent of total gas production. Given this information, it should be possible to save significant amounts of produced water by eliminating CBNG wells with high water/gas ratios and allowing development of the gas play to proceed more responsibly. Most importantly, this management action would substantially reduce animosity directed at the CBNG play in the PRB.

Future production

Most of the wells shown in **Figure 6-4** are located in the eastern part of the basin, and the CBNG play in the PRB is currently moving into the western part of the basin. Specifically, the play is moving from the Dry Fork of the Cheyenne River, Antelope Creek, and Upper Belle Fourche River drainage west and north into the Little, Middle, and Upper Powder River drainages and the Upper Tongue River, Clear Creek, and Crazy Woman Creek drainages (**Figure 6-5**). Of the total number of CBNG wells slated

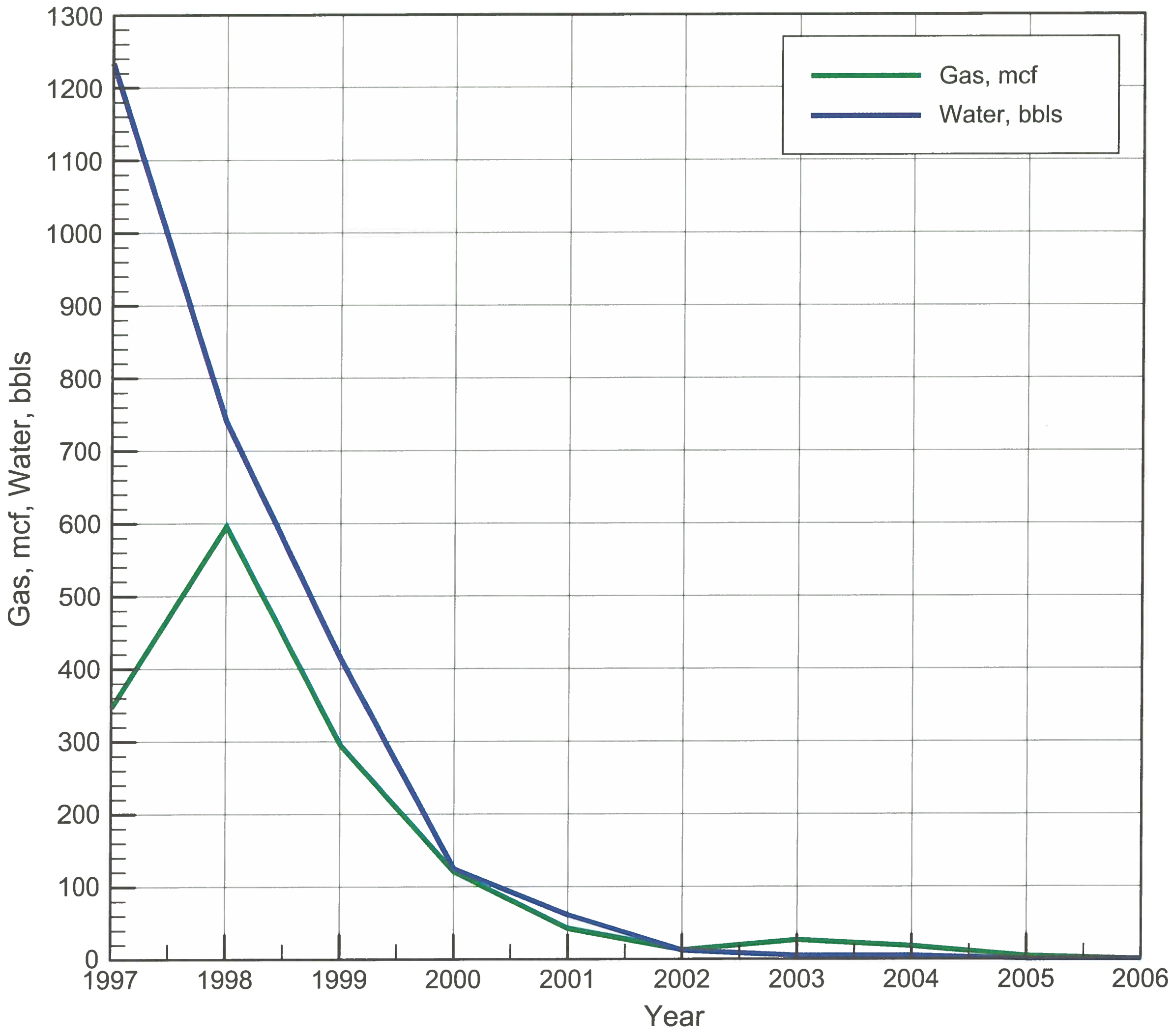


Figure 6-1. Annual gas and water production curves of the CBNG well Thielen 20-41. Note that the well produces substantial amounts of water in the first two years, and gas production peaks in the second year.

for the PRB, half have been drilled so far. Estimates of future drilling activity in the drainages shown in Figure 5 can be determined from approved and pending environmental documents, BLM permitting activity, Wyoming Oil and Gas Conservation Commission (WOGCC) records, and Wyoming Department of Environmental Quality (DEQ) and State Engineer's Office estimates. For three time periods, 2007–2010, 2011–2015, and 2016–2020, we assigned CBNG wells to each of the drainage basins (**Figure 6-5**) in order to fill out the remaining wells to be drilled (approximately half of the total wells predicted for CBNG development in the PRB). For 2007–2010, we assigned approximately 12,300 wells; for 2011–2015, we assigned approximately 16,400 wells; and for 2016-2020, we assigned approximately 13,000 wells.

Fortunately, in the Upper Tongue River; Clear Creek; Crazy Woman Creek; and Little, Middle, and Upper Powder River drainages, we have enough CBNG activity and production history data to determine typical CBNG well performance for each of the basins. For each drainage basin cited above, we determined cumulative gas and water production for CBNG wells more than two years old. For each basin, we then divided total production by the number of wells two years old or older to calculate the average (typical) CBNG well performance profile. Using the typical well performance in each basin and the num-

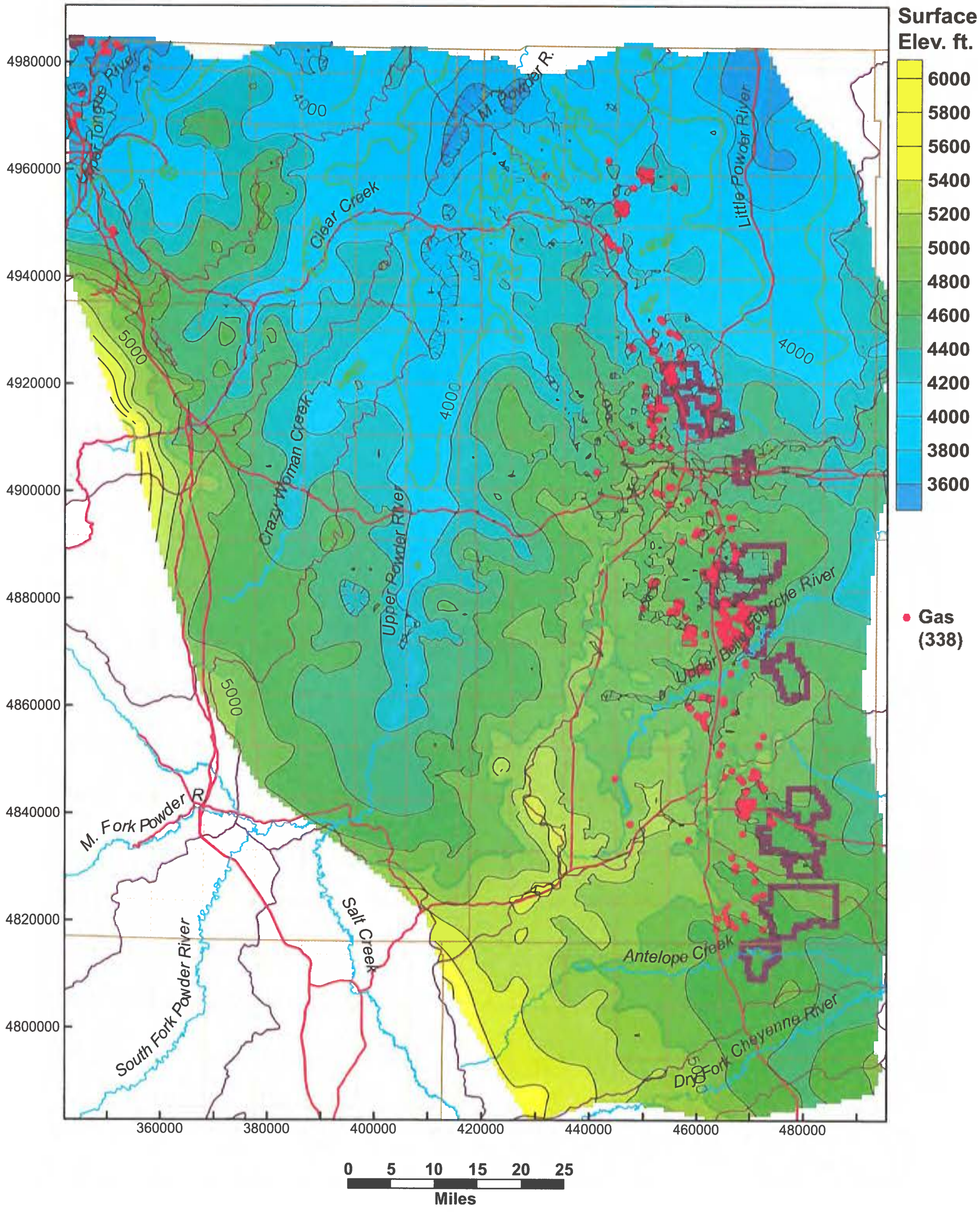


Figure 6-2. CBNG wells more than two years old that have produced only gas (red dots). These wells are located near the open pit coal mines along the eastern margin of the basin (shown by the polygons outlined in purple).

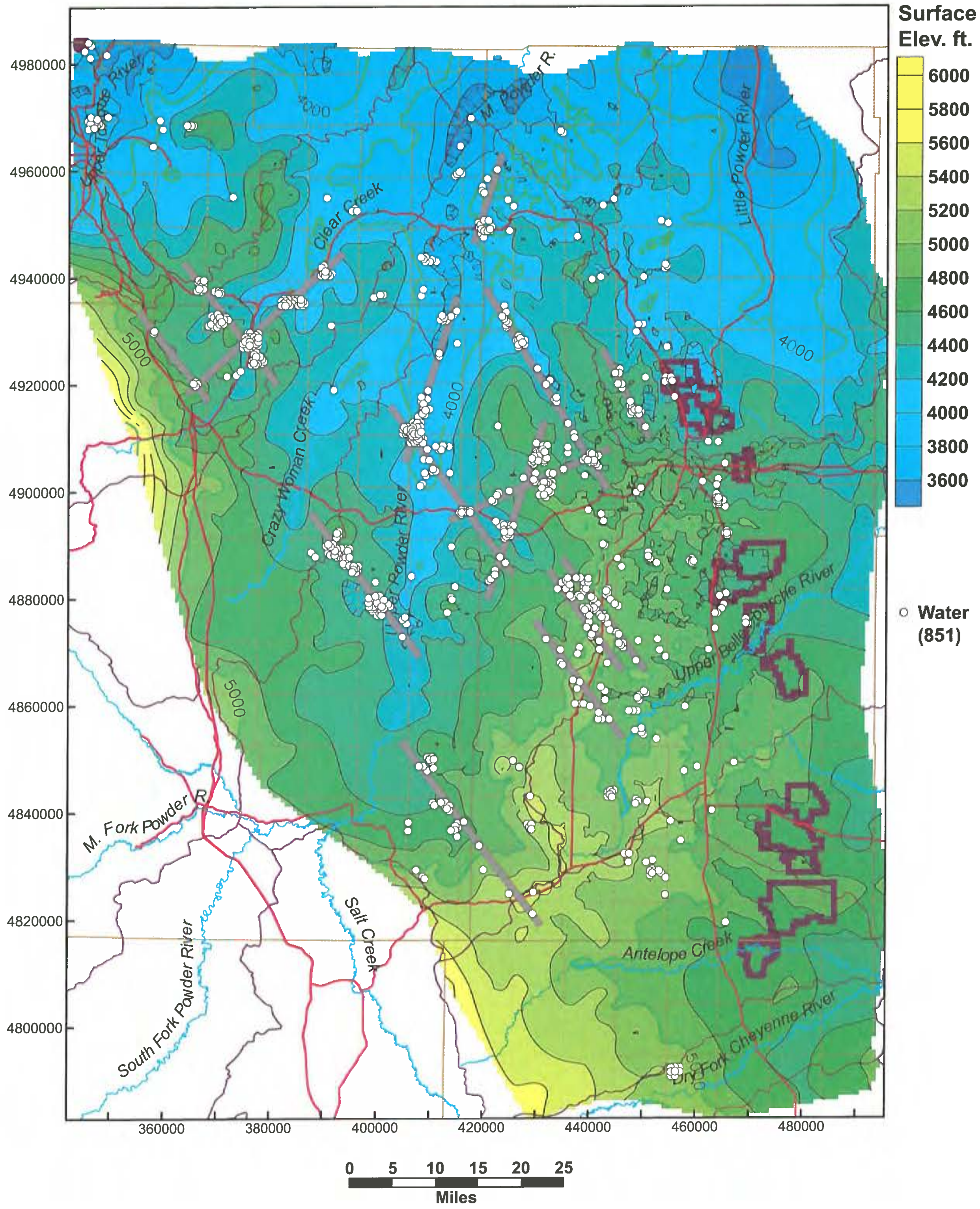


Figure 6-3. CBNG wells more than two years old that have produced only water (white dots). Most of these wells appear to occur along NW-SE and NE-SW lineaments (i.e., faults or fracture zones shown in gray).

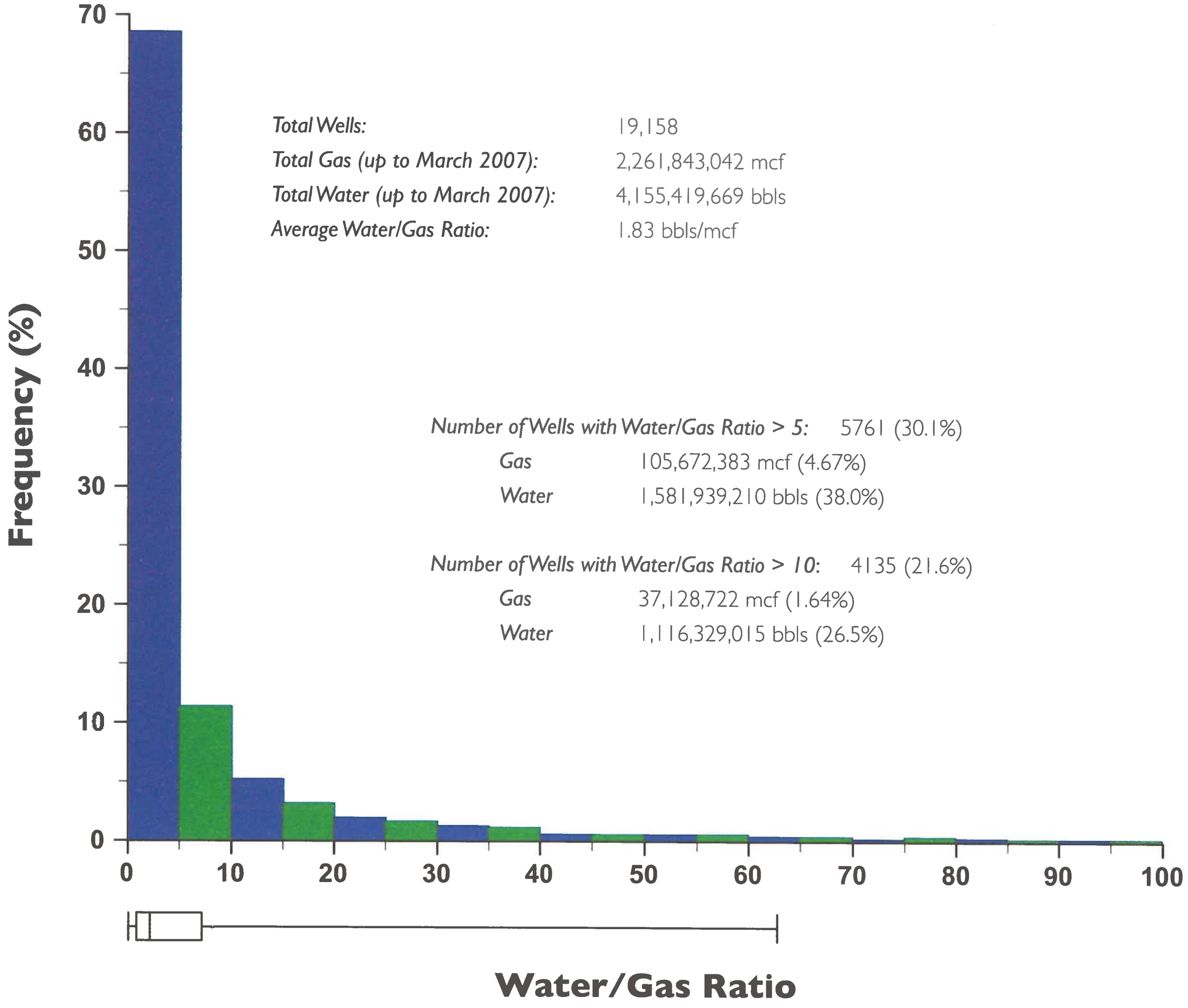


Figure 6-4. Histogram of the water/gas production ratios of 19,158 CBNG wells in the Powder River Basin. The average water/gas ratio is 1.83 bbls/mcf. Note that there are 4,135 wells with a water/gas ratio greater than 10. These wells have produced only 3.7 billion cubic feet of gas (1.64 percent of total gas production), but more than 1.1 billion barrels of water (26.5 percent of total water production).

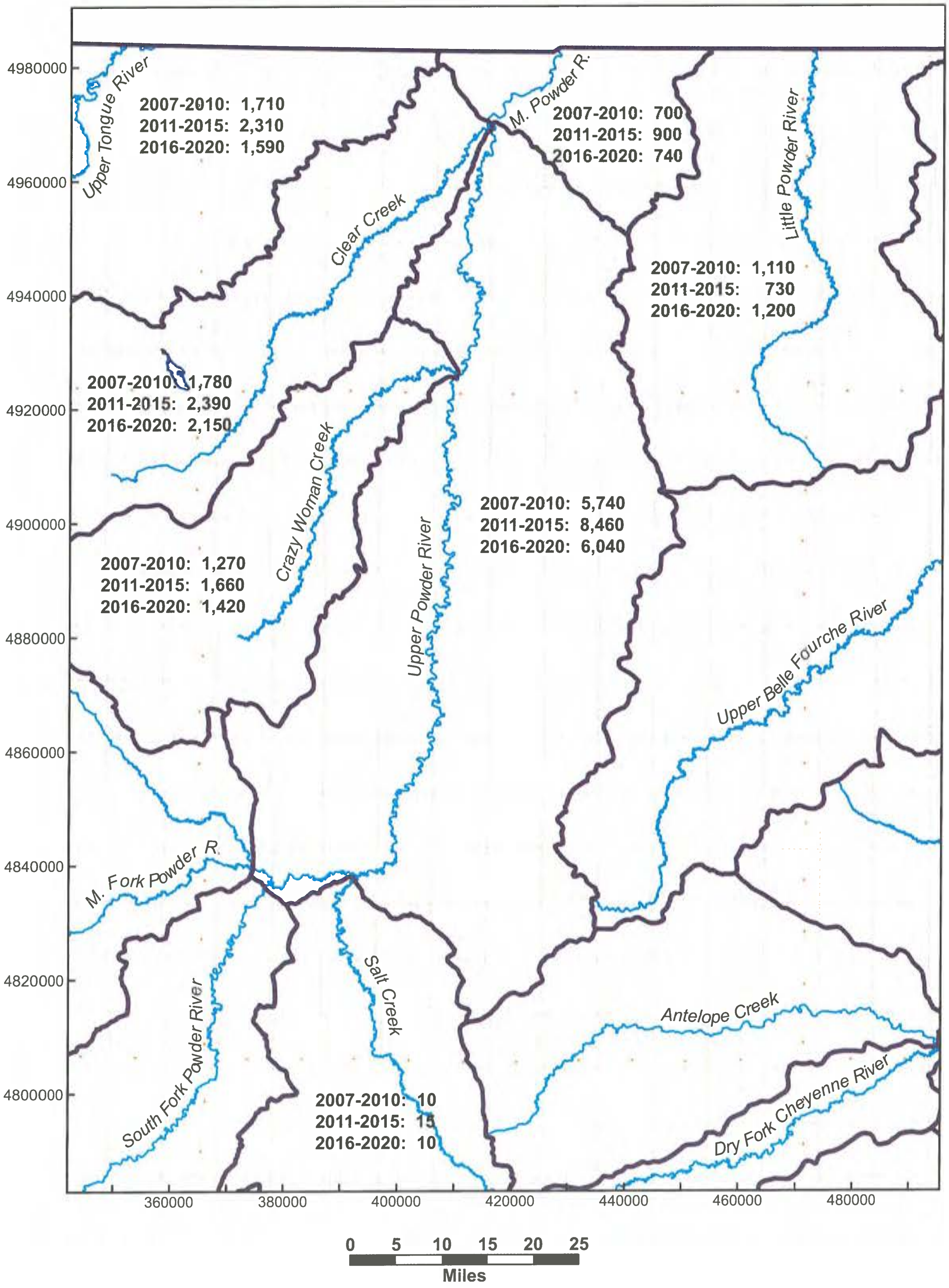


Figure 6-5. An estimated 41,900 wells will be drilled from 2007 to 2020. Predicted well numbers are: 6,320 wells in the Clear Creek drainage; 4,350 wells in the Crazy Woman Creek drainage; 3,040 wells in the Little Powder River drainage; 2,340 wells in the Middle Powder River drainage; 20,240 wells in the Upper Powder River drainage; and 5,610 wells in the Upper Tongue River drainage.

Table 6-1. Data reported for 2006.

Drainage	Producing wells	Gas rate (MCF/day)	Gas production (MCF)	Water rate (BBLS/day)	Water production (BBLS)
Clear Creek	392	1	120,007	67	5,914,600
Crazy Woman Creek	120	0	459	73	3,188,758
Little Powder River	2,756	25	24,923,454	65	64,133,193
Middle Powder River	1,324	41	22,045,429	88	47,266,610
Upper Powder River	7,103	56	159,305,798	111	318,025,559
Upper Tongue River	2,529	51	51,387,090	80	80,609,682
Total	**14,224**		**257,782,237**		**519,138,402**

Table 6-2. Estimated new wells in individual drainage basins (2007–2020).

Drainage	2006	2007–2010 (estimated new wells)	2011–2015 (estimated new wells)	2016–2020 (estimated new wells)	Total
Clear Creek	392	1,780	2,390	2,150	6,712
Crazy Woman Creek	120	1,270	1,660	1,420	4,470
Little Powder River	2,756	1,110	730	1,200	5,796
Middle Powder River	1,324	700	900	740	3,664
Upper Powder River	7,103	5,740	8,460	6,040	27,343
Upper Tongue River	2,529	1,710	2,310	1,590	8,139
Total	**14,224**	**12,310**	**16,450**	**13,140**	**56,124**

Table 6-3a. Predicted values for 2007–2008, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	759	145,664	30,014,402	445	1,125	279,587	54,035,104
Crazy Woman Creek	318	414	152,110	18,870,325	318	707	165,031	44,705,059
Little Powder River	278	2,482	50,083,717	116,766,767	278	2,209	41,217,744	98,112,545
Middle Powder River	175	1,234	27,502,895	49,613,170	175	1,144	24,876,777	44,451,093
Upper Powder River	1,435	7,117	213,317,676	470,588,391	1,435	7,132	213,834,188	472,146,638
Upper Tongue River	428	2,451	52,191,659	96,667,851	428	2,372	49,622,061	91,540,339
Total	**3,078**	**14,457**	**343,393,721**	**782,520,905**	**3,078**	**14,689**	**329,995,388**	**804,990,778**

Table 6-3b. Predicted values for 2009–2010, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	1,492	356,722	77,010,847	445	1,858	373,865	99,406,294
Crazy Woman Creek	318	1,001	226,785	63,099,441	318	1,294	240,510	71,182,892
Little Powder River	278	1,935	34,766,097	85,527,850	278	1,661	30,370,689	74,989,882
Middle Powder River	175	1,055	22,245,888	40,479,061	175	965	20,297,290	37,414,100
Upper Powder River	1,435	7,146	214,436,762	473,237,127	1,435	7,161	214,908,429	473,933,909
Upper Tongue River	428	2,294	47,383,461	87,989,463	428	2,216	45,926,146	85,383,742
Total	**3,078**	**14,922**	**319,415,716**	**827,343,788**	**3,078**	**15,155**	**312,116,929**	**842,310,818**

Table 6-3c. Predicted values for 2011–2012, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,258	386,858	118,137,869	478	2,291	398,913	120,300,125
Crazy Woman Creek	332	1,602	251,835	79,902,590	332	1,617	252,474	81,178,923
Little Powder River	146	1,256	25,312,071	59,061,839	146	1,125	21,052,388	50,099,361
Middle Powder River	180	800	18,798,746	34,978,603	180	885	18,944,966	35,266,024
Upper Powder River	1,692	7,432	219,236,453	490,408,565	1,692	7,689	228,454,757	518,218,942
Upper Tongue River	462	2,172	45,411,253	84,213,219	462	2,207	46,543,451	86,472,467
Total	**3,290**	**15,600**	**309,397,217**	**866,702,685**	**3,290**	**15,813**	**315,646,950**	**891,535,843**

Table 6-3d. Predicted values for 2013–2014, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,324	405,857	120,300,125	478	2,357	407,400	124,384,275
Crazy Woman Creek	332	1,617	255,525	81,178,923	332	1,646	256,203	82,487,027
Little Powder River	146	1,125	17,952,674	50,099,361	146	862	15,840,887	38,990,007
Middle Powder River	180	885	19,091,452	35,266,024	180	895	19,199,949	35,657,839
Upper Powder River	1,692	7,689	239,209,038	518,218,942	1,692	8,203	247,626,991	550,116,772
Upper Tongue River	462	2,207	47,529,808	86,472,467	462	2,276	48,171,920	89,185,144
Total	**3,290**	**15,846**	**324,444,354**	**891,535,843**	**3,290**	**16,238**	**331,503,349**	**920,821,064**

Table 6-3e. Predicted values for 2015–2016, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,390	407,931	125,994,667	430	2,342	397,620	124,770,554
Crazy Woman Creek	332	1,660	256,436	82,886,380	284	1,612	234,591	80,780,180
Little Powder River	146	730	14,389,988	34,107,648	240	824	15,847,354	38,229,390
Middle Powder River	180	900	19,286,081	35,802,922	148	868	18,976,389	34,713,601
Upper Powder River	1,692	8,460	253,805,441	559,427,808	1,208	7,976	246,306,572	529,384,124
Upper Tongue River	462	2,310	48,594,933	90,079,863	318	2,166	46,736,863	86,489,884
Total	**3,290**	**16,450**	**336,740,811**	**928,299,288**	**2,628**	**15,788**	**328,499,388**	**894,367,733**

Table 6-3f. Predicted values for 2017–2018, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	2,294	380,085	121,625,454	430	2,246	369,985	118,617,173
Crazy Woman Creek	284	1,564	232,478	76,555,078	284	1,516	222,379	73,546,798
Little Powder River	240	918	18,892,299	44,636,029	240	1,012	21,108,064	48,958,138
Middle Powder River	148	836	18,040,579	32,874,108	148	804	17,103,068	31,458,685
Upper Powder River	1,208	7,492	228,946,030	477,009,716	1,208	7,008	208,692,831	440,357,171
Upper Tongue River	318	2,022	42,011,165	77,059,977	318	1,878	37,894,199	70,529,631
Total	**2,628**	**15,126**	**308,502,635**	**829,760,362**	**2,628**	**14,464**	**285,390,525**	**783,467,596**

Table 6-3g. Predicted values for 2019–2020, assuming a 5-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	2,198	367,741	115,684,872	430	2,150	366,968	113,342,483
Crazy Woman Creek	284	1,468	220,134	72,224,802	284	1,420	219,361	70,902,807
Little Powder River	240	1,106	22,617,630	52,577,316	240	1,200	23,654,775	56,067,367
Middle Powder River	148	772	16,408,690	30,366,494	148	740	15,857,444	29,437,958
Upper Powder River	1,208	6,524	192,839,567	416,937,539	1,208	6,040	181,203,885	399,402,359
Upper Tongue River	318	1,734	35,214,080	65,737,500	318	1,590	33,448,460	62,003,022
Total	**2,628**	**13,802**	**267,667,842**	**753,528,524**	**2,628**	**13,140**	**254,750,893**	**731,155,997**

Table 6-3h. Average gas production rate (MCF/ day) for a well with a 5-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year
Clear Creek	0.651	1.107	0.6376	0.1417	0.0488
Crazy Woman Creek	1.3791	0.1334	0.6376	0.1417	0.0488
Little Powder River	46.9815	98.1607	71.4302	48.6643	33.4347
Middle Powder River	29.3269	88.6184	88.7794	65.7555	52.2013
Upper Powder River	46.9501	108.6936	126.8044	99.2566	72.8505
Upper Tongue River	39.1008	99.4465	86.6365	56.3998	37.1553

Numbers based on 330 production days per year

Table 6-3i. Average water production rate (MCF/ day) for a well with a 5-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year
Clear Creek	77.2799	198.5543	189.9167	185.12	147.8781
Crazy Woman Creek	132.9672	266.7362	189.9167	83.4593	83.4593
Little Powder River	132.8737	206.5325	139.333	116.6724	112.5097
Middle Powder River	103.1554	174.1944	134.0363	103.4272	87.9295
Upper Powder River	188.1022	327.9139	229.48	146.6293	109.787
Upper Tongue River	75.5467	198.4408	137.4231	100.8445	78.5875

Numbers based on 330 production days per year

Table 3j. Predicted cumulative gas and water production (2006–2020).

Drainage	Average Rate (MCF/day/ well)	Average Rate (bbls/day/ well)	2006–2020		Percentage of total production	
			Cumulative gas (MCF)	Cumulative water (bbls)	% Gas	% Water
Clear Creek	0.51722	159.7498	5,165,203	1,469,538,843	0.11	11.98
Crazy Woman Creek	0.46812	151.30774	3,186,311	982,689,983	0.07	8.01
Little Powder River	59.73428	141.58426	378,029,832	912,356,693	8.17	7.44
Middle Powder River	64.9363	120.54856	298,675,645	555,046,292	6.46	4.52
Upper Powder River	90.91104	200.38248	3,262,124,417	7,107,413,562	70.53	57.94
Upper Tongue River	63.74778	118.16852	678,066,548	1,240,434,252	14.66	10.11
Total			**4,625,247,955**	**12,267,479,625**	**100**	**100**

Table 6-4a. Predicted values for 2007–2008, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	798	123,788	26,912,947	445	1,204	272,031	53,502,147
Crazy Woman Creek	318	426	149,269	18,053,476	318	731	162,718	44,944,486
Little Powder River	278	2,758	40,021,403	130,437,088	278	2,760	40,082,950	130,566,584
Middle Powder River	175	1,367	21,976,958	44,558,486	175	1,409	23,222,755	47,007,311
Upper Powder River	1,435	7,828	170,539,436	395,298,237	1,435	8,552	196,533,619	473,719,174
Upper Tongue River	428	2,704	39,994,611	80,507,346	428	2,878	45,724,519	91,941,108
Total	**3,078**	**15,879**	**272,805,465**	**695,767,579**	**3,078**	**17,534**	**305,998,592**	**841,680,809**

Table 6-4b. Predicted values for 2009–2010, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	445	1,609	357,415	78,934,652	445	2,015	376,390	103,724,812
Crazy Woman Creek	318	1,037	226,997	64,090,938	318	1,342	241,283	72,504,887
Little Powder River	278	2,762	40,127,736	130,653,946	278	2,764	40,158,249	130,727,100
Middle Powder River	175	1,452	24,470,816	48,891,593	175	1,494	25,395,207	50,345,573
Upper Powder River	1,435	9,277	226,859,018	528,599,545	1,435	10,002	250,596,333	563,666,089
Upper Tongue River	428	3,053	50,716,341	99,859,152	428	3,227	53,965,985	105,669,610
Total	**3,078**	**19,189**	**342,758,324**	**951,029,826**	**3,078**	**20,844**	**370,733,447**	**1,026,638,071**

Table 6-4c. Predicted values for 2011–2012, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	2,452	389,585	124,318,333	478	2,889	407,445	146,152,492
Crazy Woman Creek	332	1,662	252,802	81,555,084	332	1,982	258,360	91,245,367
Little Powder River	146	2,634	38,140,450	125,031,589	146	2,504	33,898,273	116,128,849
Middle Powder River	180	1,542	26,177,442	51,751,892	180	1,590	26,904,961	53,092,047
Upper Powder River	1,692	10,984	272,000,441	605,874,707	1,692	11,965	296,282,556	653,146,285
Upper Tongue River	462	3,437	56,551,961	111,057,764	462	3,646	59,250,741	117,516,086
Total	**3,290**	**22,710**	**393,512,682**	**1,099,589,370**	**3,290**	**24,576**	**417,002,336**	**1,177,281,125**

Table 6-4d. Predicted values for 2013–2014, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	3,326	420,502	159,222,638	478	3,762	428,487	171,262,225
Crazy Woman Creek	332	2,302	266,330	100,058,669	332	2,622	271,928	109,050,871
Little Powder River	146	2,375	30,815,351	111,138,719	146	2,245	28,718,888	82,629,654
Middle Powder River	180	1,637	27,480,614	54,217,461	180	1,685	28,196,521	52,724,399
Upper Powder River	1,692	12,947	316,288,107	681,931,809	1,692	13,929	337,902,196	691,569,075
Upper Tongue River	462	3,855	61,633,551	122,809,429	462	4,064	63,633,540	124,312,872
Total	**3,290**	**26,441**	**436,904,455**	**1,229,378,725**	**3,290**	**28,307**	**459,151,561**	**1,231,549,097**

Table 6-4e. Predicted values for 2015–2016, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	478	4,199	435,521	185,031,016	430	4,590	432,673	196,547,069
Crazy Woman Creek	332	2,942	277,081	118,194,671	284	3,214	260,390	124,901,773
Little Powder River	146	2,116	27,284,956	100,376,874	240	2,080	27,552,550	100,519,455
Middle Powder River	180	1,732	28,902,583	57,112,070	148	1,748	28,797,425	57,007,294
Upper Powder River	1,692	14,910	356,617,134	761,047,883	1,208	15,408	358,246,311	769,558,785
Upper Tongue River	462	4,273	65,602,461	132,818,005	318	4,338	65,878,569	132,697,387
Total	**3,290**	**30,172**	**479,119,737**	**1,354,580,519**	**2,628**	**31,378**	**481,167,917**	**1,381,231,763**

Table 6-4f. Predicted values for 2017–2018, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	4,575	416,368	182,130,805	430	4,560	407,188	192,357,656
Crazy Woman Creek	284	3,181	258,510	124,587,574	284	3,147	248,644	118,467,097
Little Powder River	240	2,043	29,435,355	105,152,741	240	2,005	30,590,485	101,548,786
Middle Powder River	148	1,721	27,911,986	57,351,481	148	1,694	27,045,768	53,977,315
Upper Powder River	1,208	15,181	344,166,542	667,948,906	1,208	14,954	328,593,083	693,847,841
Upper Tongue River	318	4,229	61,428,802	139,318,198	318	4,119	57,580,145	118,299,616
Total	**2,628**	**30,929**	**463,617,564**	**1,276,489,706**	**2,628**	**30,479**	**444,465,314**	**1,278,498,312**

Table 6-4g. Predicted values for 2019–2020, assuming a 10-year well life.

Drainage	2007				2008			
	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)	New producing wells	Total producing wells	Gas production (MCF)	Water production (BBLS)
Clear Creek	430	4,545	405,537	190,401,323	430	4,530	405,295	189,010,322
Crazy Woman Creek	284	3,114	246,633	117,544,454	284	3,080	246,094	116,621,812
Little Powder River	240	1,968	30,925,805	98,274,981	240	1,930	30,450,651	91,015,058
Middle Powder River	148	1,667	26,424,152	53,069,004	148	1,640	25,888,905	52,241,523
Upper Powder River	1,208	14,727	317,185,627	680,763,410	1,208	14,500	306,892,564	674,453,343
Upper Tongue River	318	4,010	55,205,490	114,255,777	318	3,900	53,800,407	111,042,879
Total	**2,628**	**30,030**	**430,393,243**	**1,254,308,950**	**2,628**	**29,580**	**417,683,914**	**1,234,384,937**

Table 6-4h. Average gas production rate (MCF/ day.well) for a well with a 10-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year	Sixth year	Seventh Year	Eighth year	Ninth Year	Tenth year
Clear Creek	0.651	1.107	0.6376	0.1417	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488
Crazy Woman Creek	1.3791	0.1334	0.6376	0.1417	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488
Little Powder River	46.9815	98.1607	71.4302	48.6643	33.4347	27.9208	26.7805	24.4414	27.0595	34.8496
Middle Powder River	29.3269	88.6184	88.7794	65.7555	52.2013	41.35	30.5283	43.2075	44.098	9.696
Upper Powder River	46.9501	108.6936	126.8044	99.2566	72.8505	62.9887	38.6838	55.1791	52.4208	15.8309
Upper Tongue River	39.1008	99.4465	86.6365	56.3998	37.1553	27.1891	24.2364	23.5669	26.8303	31.6677

Numbers based on 330 production days per year

Table 6-4i. Average water production rate (MCF/day.well) for a well with a 10-year life.

Drainage	First year	Second year	Third year	Fourth Year	Fifth year	Sixth year	Seventh Year	Eighth year	Ninth Year	Tenth year
Clear Creek	77.2799	198.5543	189.9167	185.12	147.8781	147.8781	83.4593	83.4593	83.4593	83.4593
Crazy Woman Creek	132.9672	266.7362	189.9167	83.4593	83.4593	83.4593	83.4593	83.4593	83.4593	83.4593
Little Powder River	132.8737	206.5325	139.333	116.6724	112.5097	95.2756	116.2186	107.296	158.8428	247.7238
Middle Powder River	103.1554	174.1944	134.0363	103.4272	87.9295	74.8851	67.9157	68.4097	111.4427	61.2452
Upper Powder River	188.1022	327.9139	229.48	146.6293	109.787	81.3762	68.3664	88.6435	121.863	132.356
Upper Tongue River	75.5467	198.4408	137.4231	100.8445	78.5875	72.8778	71.9433	65.2971	65.7261	45.8129

Numbers based on 330 production days per year

Table 6-4j. Predicted cumulative gas and water production (2006-2020).

Drainage	Average Rate (MCF/day/ well)	Average Rate (bbls/day/ well)	2006–2020		Percentage of total production	
			Cumulative gas (MCF)	Cumulative water (bbls)	% Gas	% Water
Clear Creek	0.28301	128.0464	5,398,231	2,005,423,037	0.09	12.12
Crazy Woman Creek	0.25846	117.38352	3,367,498	1,305,009,915	0.06	7.88
Little Powder River	43.97232	143.32781	493,126,556	1,618,334,618	8.26	9.78
Middle Powder River	49.35613	98.66412	390,841,523	780,614,061	6.54	4.72
Upper Powder River	67.96585	149.45175	4,238,008,765	9,159,450,648	70.95	55.34
Upper Tongue River	45.22293	91.24998	842,354,212	1,682,714,911	14.10	10.17
Total			**5,973,096,786**	**16,551,547,190**	**100**	**100**

ber of CBNG wells that will be drilled in each basin in the future, we can predict future gas and water production for each basin (**Table 6-1, Table 6-2, Tables 6-3a through 6-3j**, and **Tables 6-4a through 6-4j**). **Table 6-1** presents real data from 2006; **Table 6-2** shows the estimated number of new wells in each drainage basin; **Tables 6-3a through 6-3j** show predicted performance assuming a 5-year well life; and **Tables 6-4a through 6-4j** show predicted performance assuming a 10-year well life.

Future production scenarios

A difficult task in constructing the future gas and water production scenarios shown in **Table 6-3** and **Table 6-4** was determining how to build production scenarios for existing wells into the equation. To do this, we started the tables in 2006 with reported production figures. **Table 6-3** represents predicted production scenarios for CBNG activities in the noted drainage basins for 2006 through 2020, assuming that a typical well will have a 5-year production life. **Table 6-4** represents predicted production scenarios for CBNG activities in the noted drainage basins for 2006 through 2020, assuming that a typical well will have a 10-year production life.

Figure 6-6 assumes a 5-year production life for CBNG wells and shows that the greatest gas production will occur in the Upper Powder River drainage (3 x 10^8 MCF/year). The Upper Tongue River, Little Powder River, and Middle Powder River drainages will produce 2 x 10^7 to 4 x 10^7 MCF/year, while the Clear Creek and Crazy Woman Creek drainages will produce only 3 x 10^5 MCF/year. In other words, from 2006 to 2020, the Clear Creek and Crazy Woman Creek drainages will produce three orders of magnitude less gas than the Upper Powder River drainage. If wells produce for 10 years instead of 5, the gas production versus time curves for the period 2006–2020 change only slightly (**Figure 6-7**).

Figure 6-8 shows predicted water production scenarios for six of the PRB drainage basins from 2006 to 2020, based on a 5-year CBNG well life expectancy. The Upper Powder River drainage basin will produce between 4 and 5 billion barrels of water from 2006 to 2020. The Upper Tongue River, Middle Powder River, and Little Powder River drainages will each produce approximately 40 to 80 million barrels of water each year; the Clear Creek drainage will average 150 million barrels of water per year; and the Crazy Woman Creek drainage will produce 100 million barrels of water per year (**Figure 6-8**). Extending CBNG well life expectancy to ten years changes the water production scenarios for each drainage basin only slightly.

With the data shown in **Figure 6-6** through **Figure 6-9**, we can predict the water/gas ratio for each of the western and northern drainages in the PRB. The water/gas ratio is one of the most important parameters to consider when designing management strategies that maximize gas production while minimizing water production. For wells in the Upper, Middle and Little Powder River drainages from 2006–2020 (the second half of the PRB CBNG play), the water/gas ratio will be less than 3. In stark contrast, the water/gas ratio for the Crazy Woman Creek and Clear

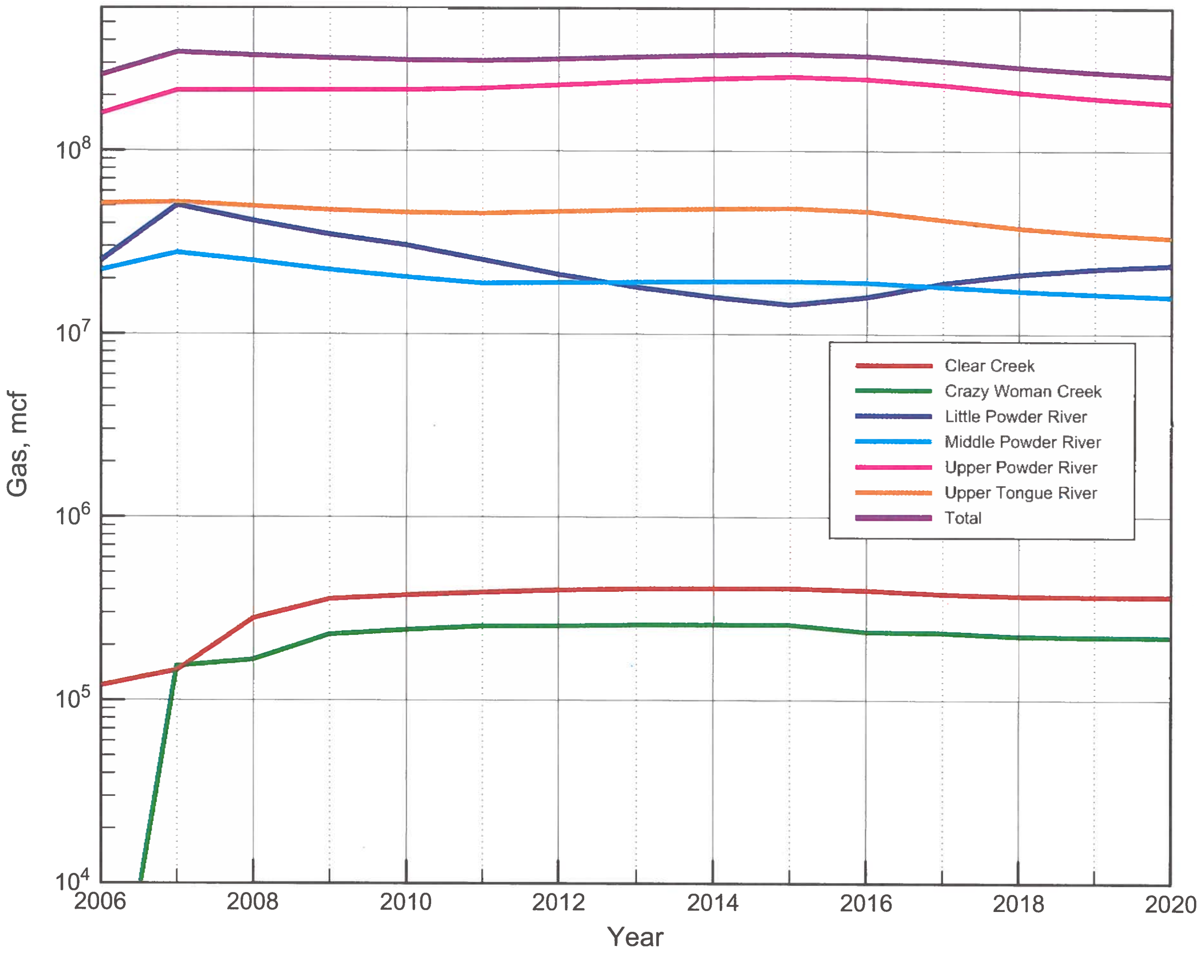


Figure 6-6. Plot of the estimated yearly gas production for each drainage. Well life is assumed to be 5 years. Note that the yearly gas production from the Upper Powder River drainage is three orders of magnitude higher than the yearly gas production from the Clear Creek and Crazy Woman Creek drainages. The yearly gas productions of the Upper Tongue River, Middle Powder River, and Little Powder River drainages are two orders of magnitude higher than the yearly gas productions of the Clear Creek and Crazy Woman Creek drainages.

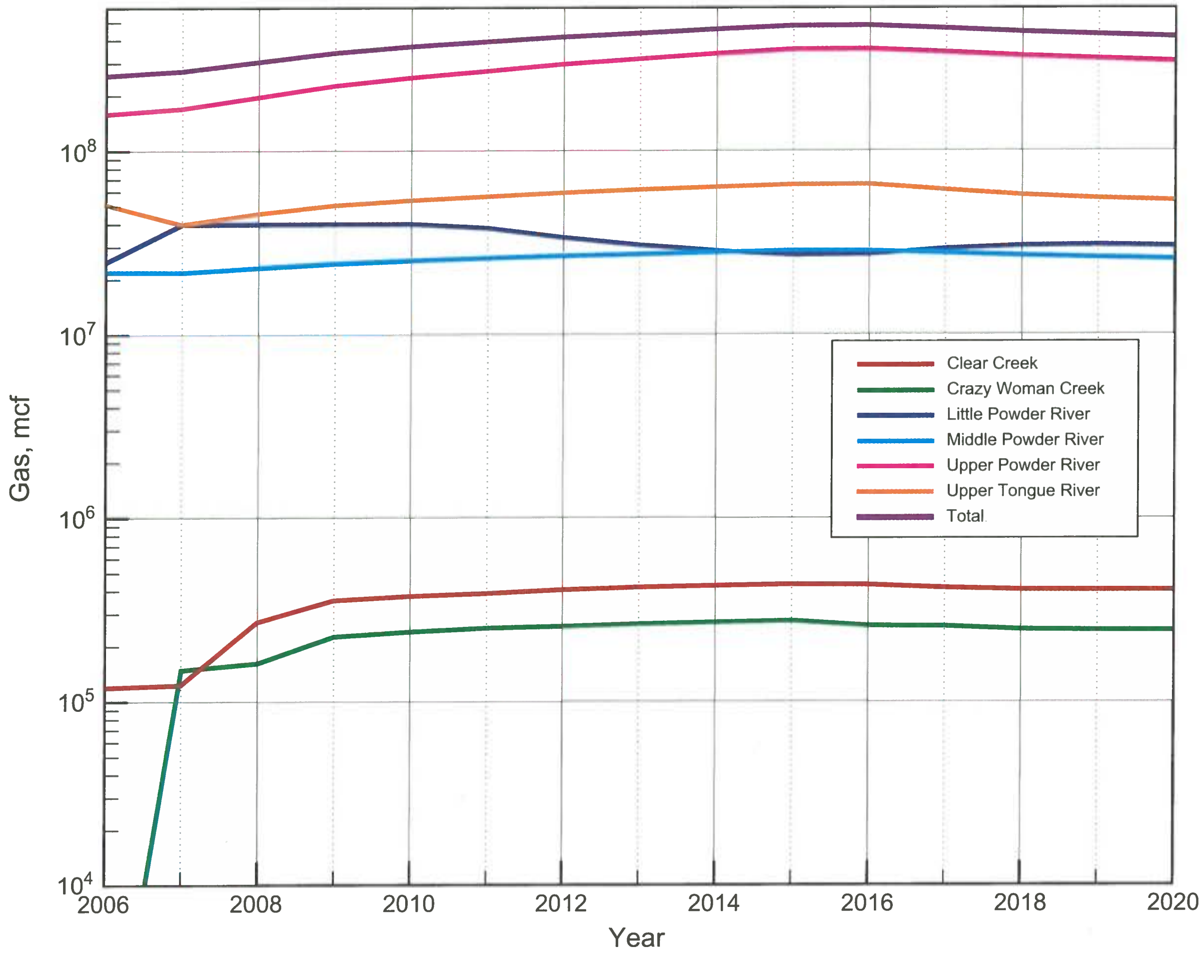


Figure 6-7. Plot of the estimated yearly gas production for each drainage. Well life is assumed to be 10 years. Note that the yearly gas production from the Upper Powder River drainage is three orders of magnitude higher than the yearly gas productions of the Clear Creek and Crazy Woman Creek. The yearly gas production of the Upper Tongue River, Middle Powder River, and Little Powder River drainages is two orders magnitude higher than the yearly gas production of the Clear Creek and Crazy Woman Creek drainages.

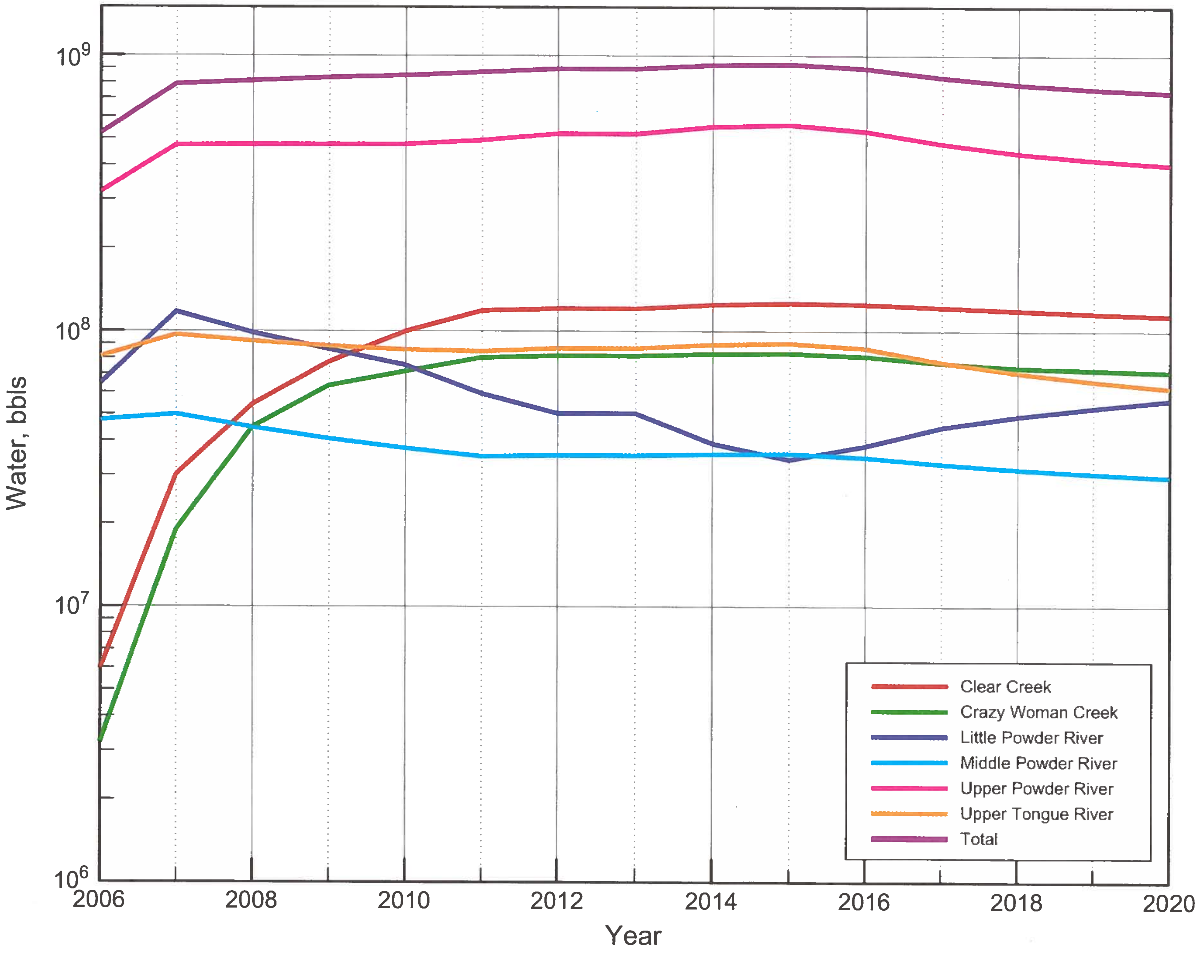


Figure 6-8. Plot of estimated yearly water production for each drainage. Well life is assumed to be 5 years. Clear Creek and Crazy Woman Creek drainages are predicted to produce more water than the Little and Middle Powder River drainages, but two orders of magnitude less gas (Figure 6).

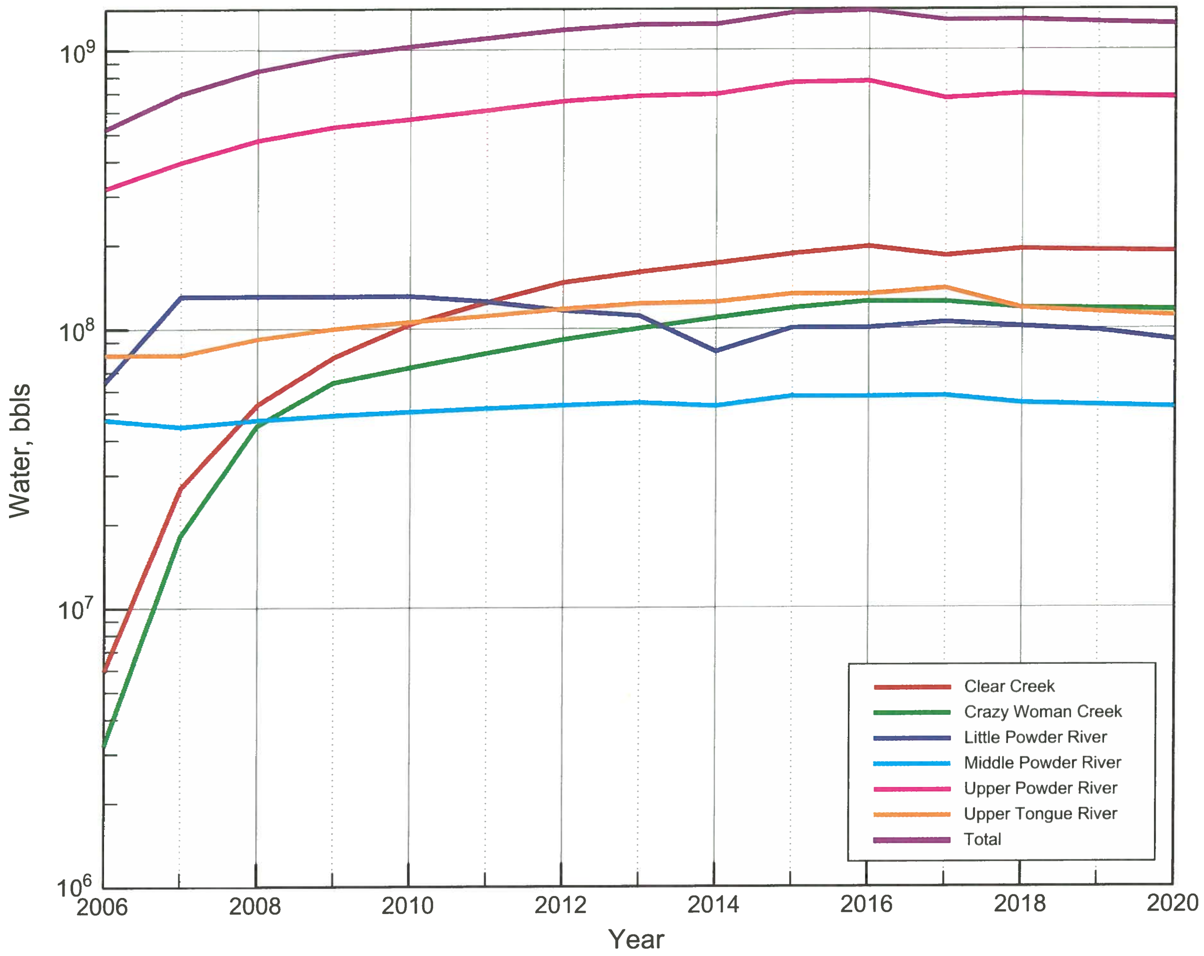


Figure 6-9. Plot of estimated yearly water production for each drainage. Well life is assumed to be 10 years. Clear Creek and Crazy Woman Creek drainages are predicted to produce more water than the Little and Middle Powder River drainages, but two orders of magnitude less gas (Figure 6).

Creek drainages will be 300 or greater, two orders of magnitude higher than the ratios for the other drainages (**Figure 6-10**).

Current CBNG well estimates for the years 2007–2020 (**Figure 6-5**) indicate that approximately 11,000 wells (25 percent of all new wells) will be drilled in the Crazy Woman Creek and Clear Creek drainages. These wells will produce approximately 9,000,000 MCF of gas (0.15 percent of total gas produced from 2007–2020), and approximately 3.3 billion barrels of water (20 percent of the water CBNG development will produce from 2007–2020). **Figure 6-11** shows water/gas ratio versus time for a well life expectancy of 10 years. The only substantial difference between **Figure 6-10** and **Figure 6-11** is that a 10-year well life results in a water/gas ratio greater than 300 for the Crazy Woman Creek and Clear Creek drainages, a water/gas ratio greater than three but less than 4 for the Little Powder River drainage, and water/gas ratios near 2 for the other drainages (**Figure 6-11**).

A number of rock/fluid characteristics differ between the Clear Creek and Crazy Woman Creek drainages, and the Upper, Middle, and Little Powder River and Upper Tongue River drainages. First, the Clear Creek and Crazy Woman Creek drainages cross that part of the PRB where the gas-producing coal beds are buried most deeply (**Figure 6-12**).

Next, the potentially productive coal beds in the Clear Creek and Crazy Woman Creek drainages are thinner than those in the other, more productive basins, and the targeted stratigraphic section is more sandstone-rich.

Also, a preliminary map of the groundwater table (elevation) based on wells 300 to 2,000 feet deep (approximately 15,326 wells) demonstrates that: 1) the Clear Creek and Crazy Woman Creek drainages are spatially associated with very high groundwater recharge rates (**Figure 6-13**); and 2) CBNG activity has already lowered the water table substantially in these two drainages (**Figure 6-14**).

Finally, the distribution of CBNG wells more than two years old that have produced water and no commercial quantities of gas appears to be strongly influenced by linear elements in the PRB. These wells typically occur along NW-SE and NE-SW linear trends, perhaps suggesting a relationship between regional fracture systems (i.e., NW-SE and NE-SW faults) and high rates of groundwater flow (**Figure 6-15**).

All of the geologic factors discussed above help explain why existing wells, and probably future wells, in the Clear Creek and Crazy Woman drainages have such consistently high water/gas ratios.

Other important observations

Groundwater quality research in the targeted coal-rich stratigraphic interval of the PRB clearly shows that the salinity, or total dissolved solids (TDS), of produced water increases as you move west across the basin (**Figure 6-16**). The sodium adsorption ratio (SAR) of the groundwater also increases to the west. It is apparent that groundwater quality consistently declines from east to west in the PRB (**Figure 6-16**, **Figure 6-17**). Lastly, no significant relationship appears to exist between the depth of a CBNG well and the elevation of the water table (**Figure 6-18**). This observation suggests that the groundwater system associated with the coal-rich stratigraphic interval of the PRB should be considered a regional hydrologic system with substantial connectivity. A different classification of the hydrologic system (i.e., as a series of discontinuous perched water tables) would require additional observations and substantial evidence.

Conclusions

The following observations should be considered in future management strategies for CBNG development in the PRB.

The vast majority of commercial CBNG wells in the PRB produce substantial amounts of gas within two years of well completion (**Figure 6-1**). However, a significant number of CBNG wells (851) in the PRB have existed for more than two years and have produced no reportable gas.

CBNG wells more than 2 years old with water/gas ratios greater than 10 have produced 1.64% of the gas and 26.5% of the water in the PRB to date. CBNG wells more than 2 years old with water/gas ratios greater than 5 have produced 4.67% of the gas and 38% of the water in the PRB to date.

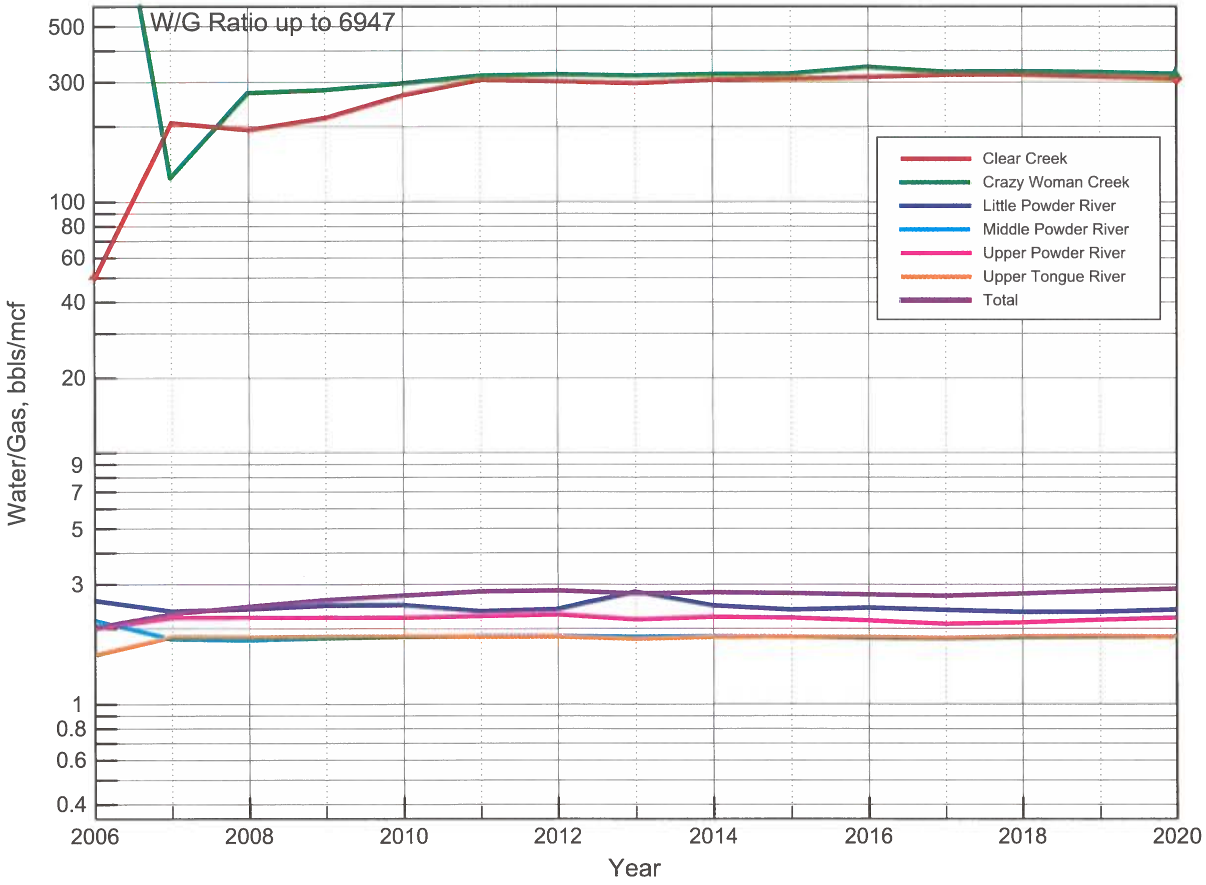


Figure 6-10. Plot of the estimated water production/gas production ratios for each drainage in the Powder River Basin. Well life is assumed to be 5 years. The average water/gas ratio is approximately 2.8. The water/gas ratios in the Little, Middle, and Upper Powder River and Upper Tongue River drainages are close to this average. The water/gas ratios in the Clear Creek and Crazy Woman Creek drainages are 100 times higher than the average water/gas ratio.

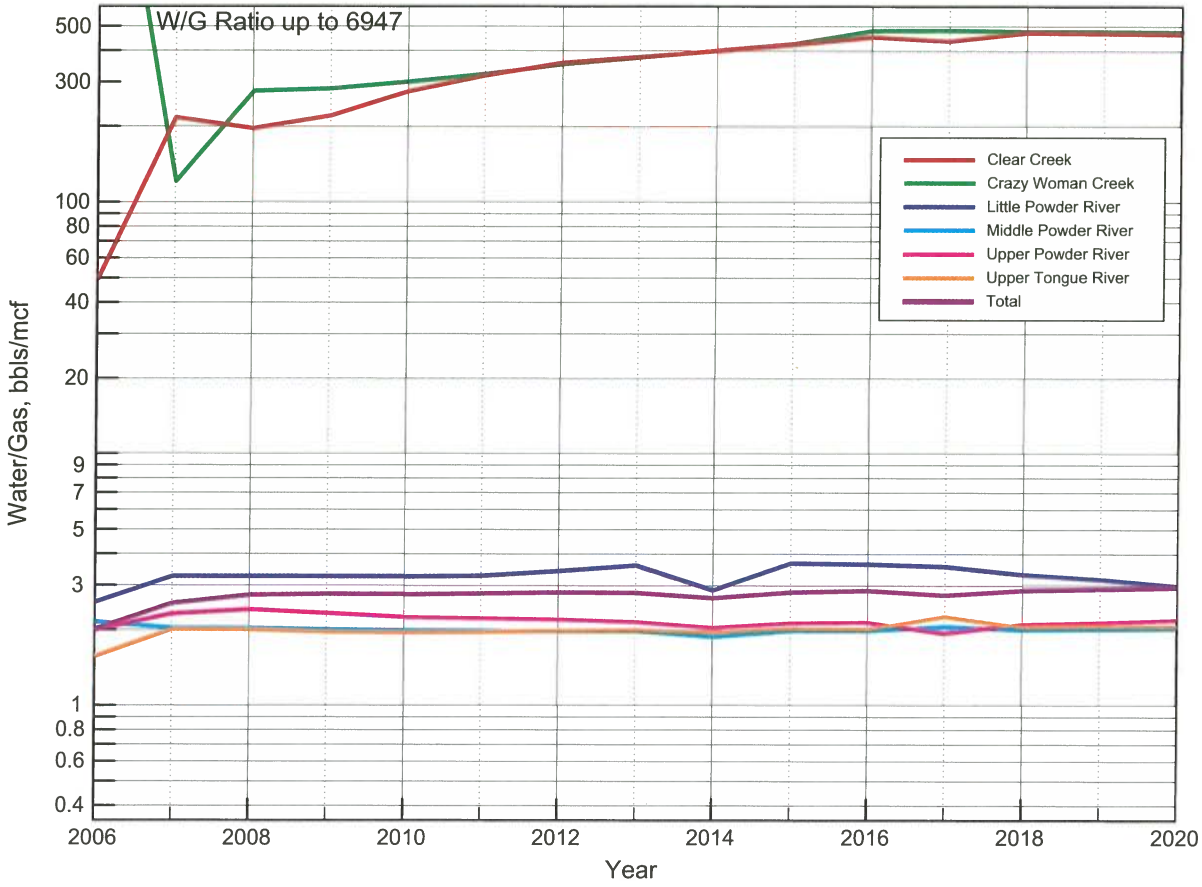


Figure 6-11. Plot of the estimated water production/gas production ratios for each drainage in the Powder River Basin. Well life is assumed to be 10 years. The average water/gas ratio is approximately 2.8. The water/gas ratios in the Little, Middle, and Upper Powder River and Upper Tongue River drainages are close to this average. The water/gas ratios in the Clear Creek and Crazy Woman Creek drainages are 100 times higher than the average water/gas ratio.

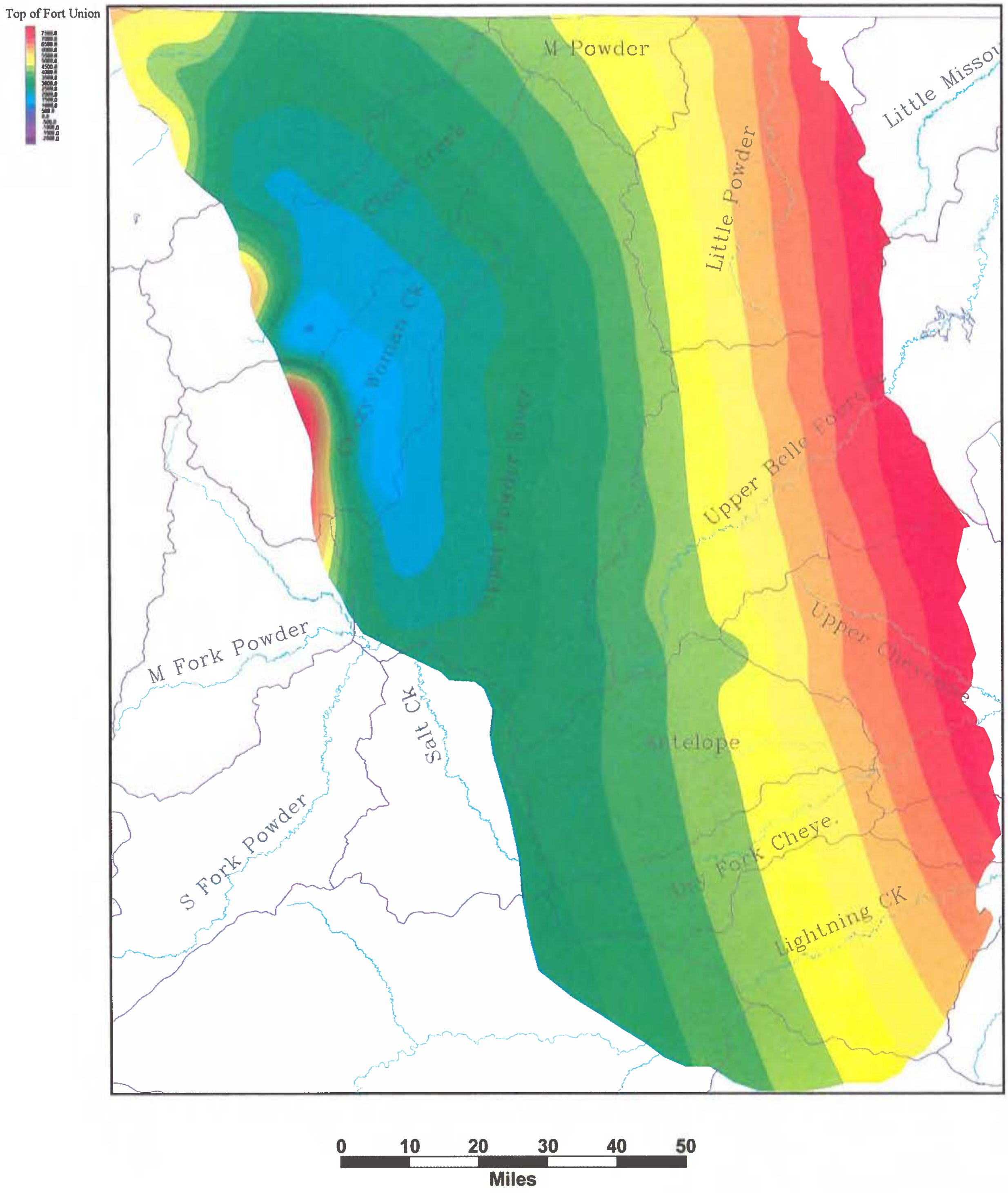
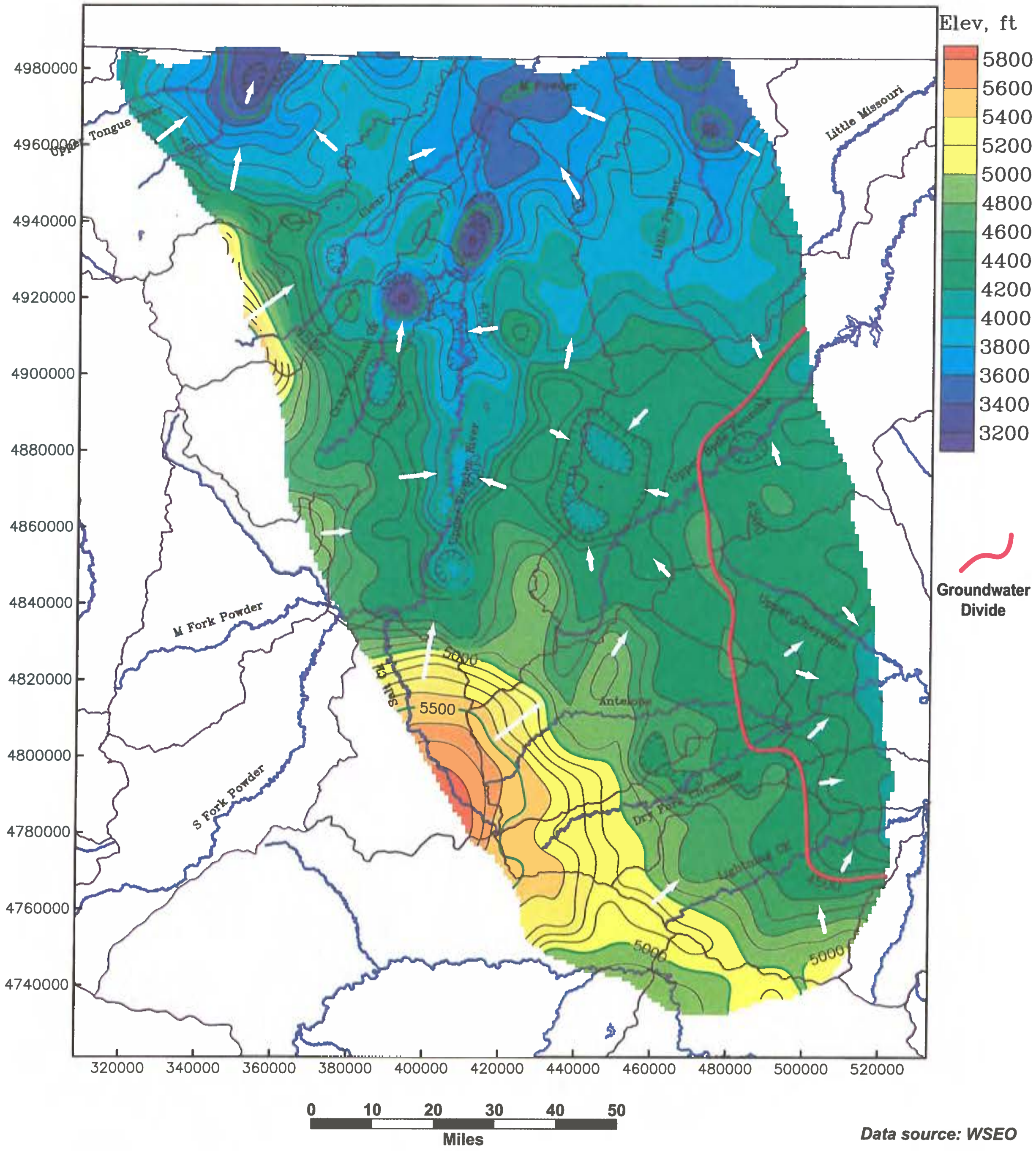


Figure 6-12. Structure contour map of the top of the Fort Union Formation, Powder River Basin. Note that the deepest portion of this asymmetric basin is located within the Clear Creek and Crazy Woman Creek drainages.



Data source: WSEO

Figure 6-13. Contour map of the groundwater table (elevation) based on wells 300 to 2,000 feet deep (approximately 15,326 wells) shows the directions of groundwater flow (white arrows) and relative flow rate (length of the arrows).

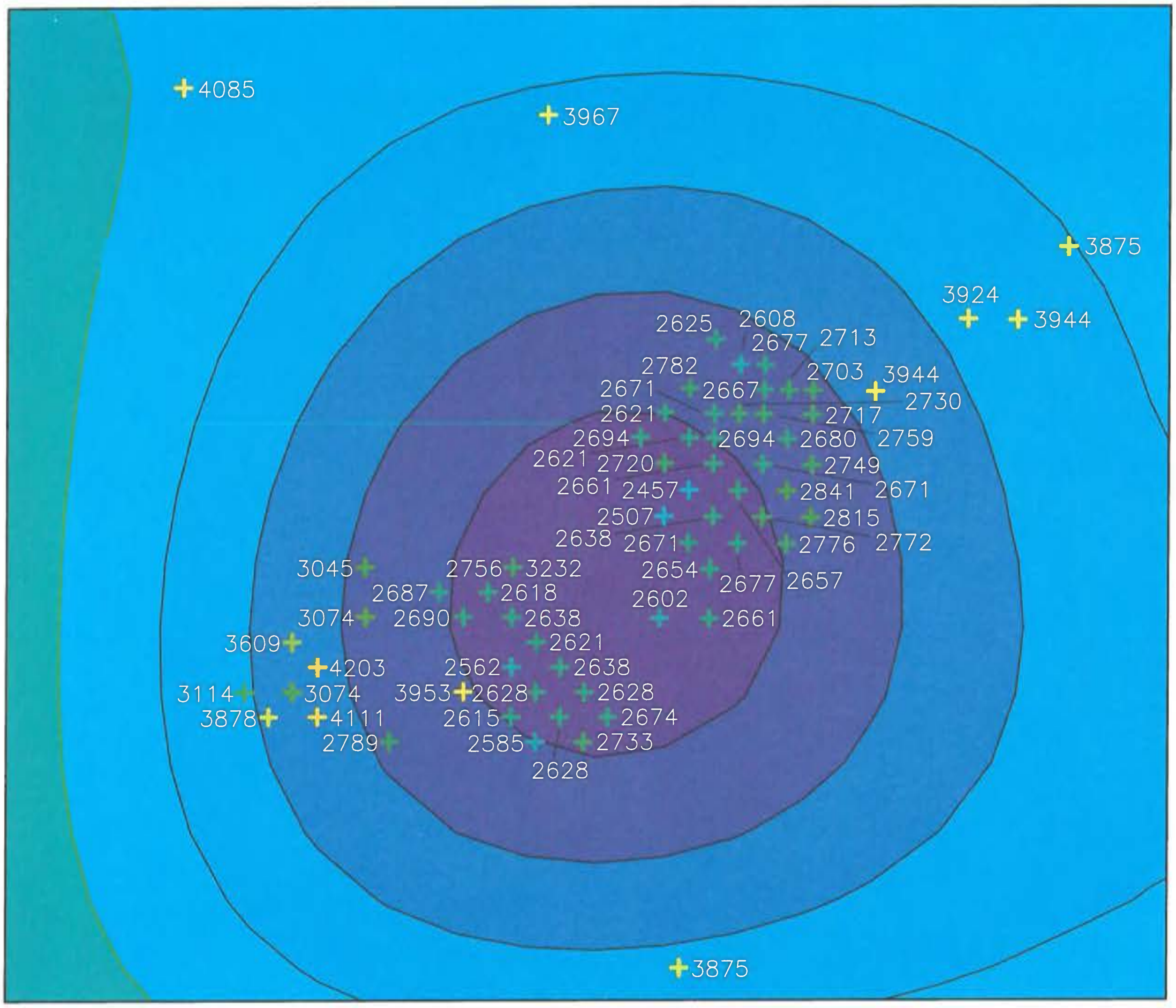


Figure 6-14. Contour map of the groundwater table (elevation) based on 67 wells within the Crazy Woman Creek drainage shows that CBNG activity has already lowered the groundwater table significantly. Numbers indicate the elevation of the water table in feet.

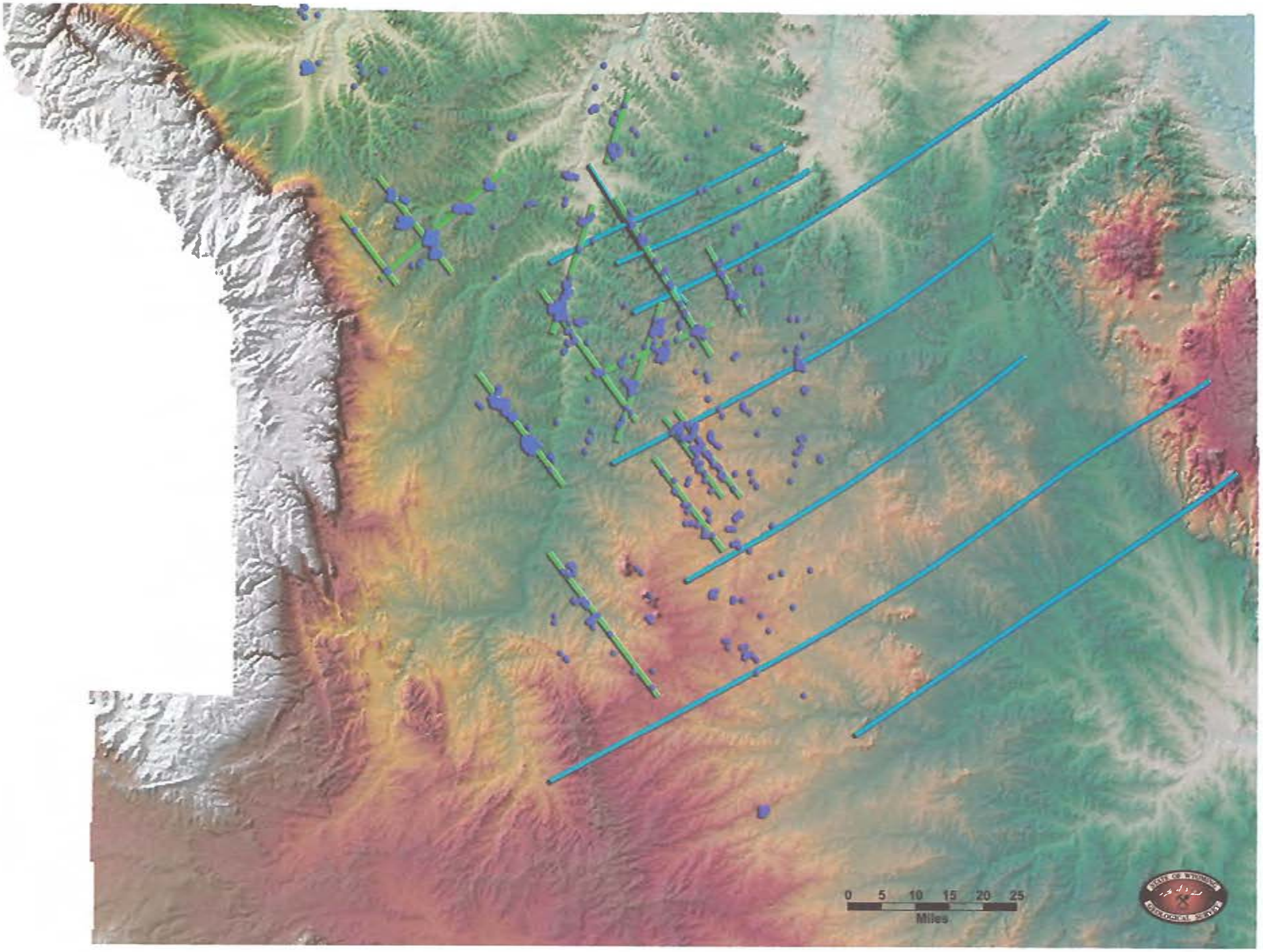


Figure 6-15. The distribution of CBNG wells more than 2 years old that have produced significant amounts of water but no commercial quantities of gas appear to be strongly influenced by regional faults or fracture zones (blue and green lines) in the Powder River Basin.

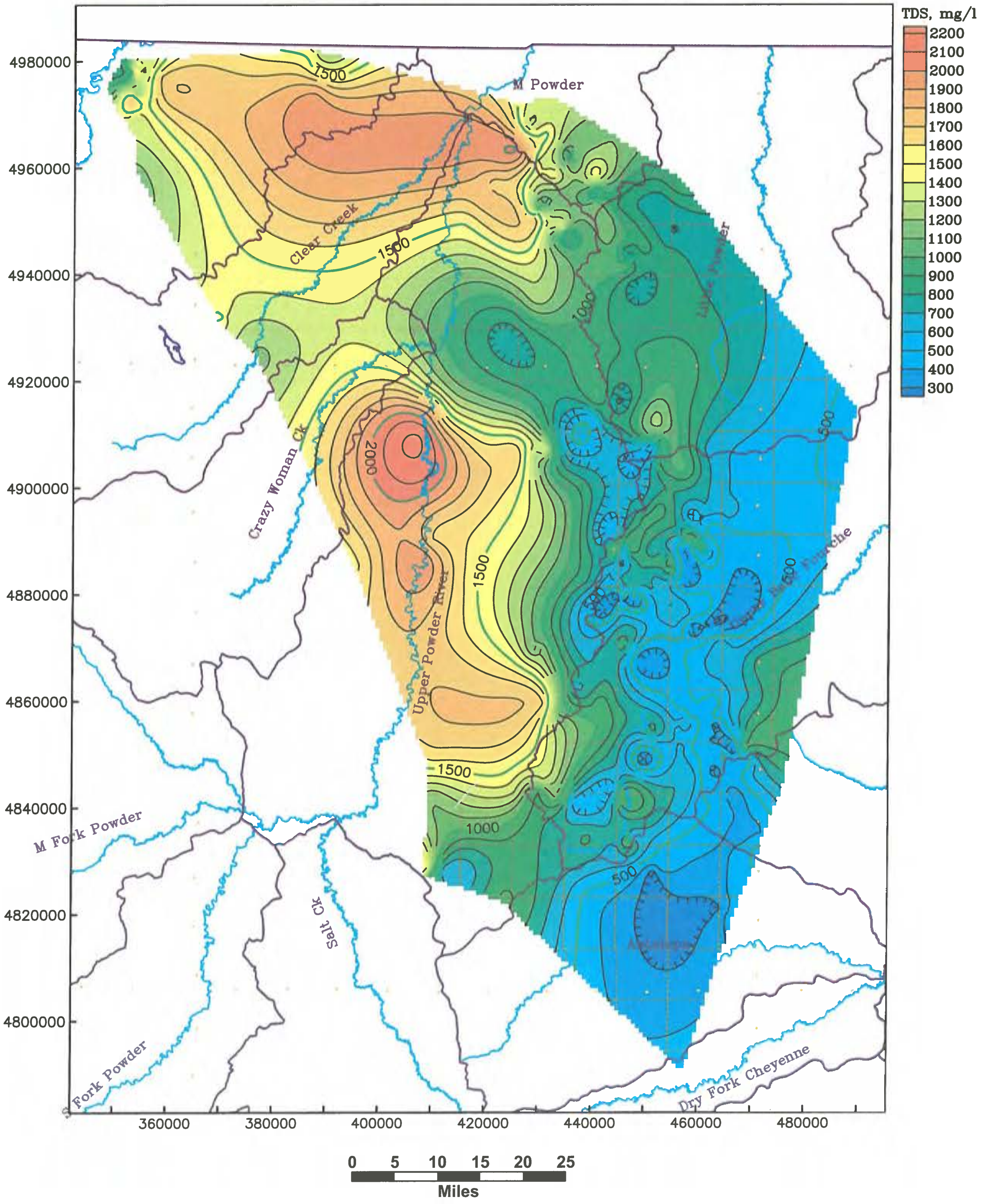
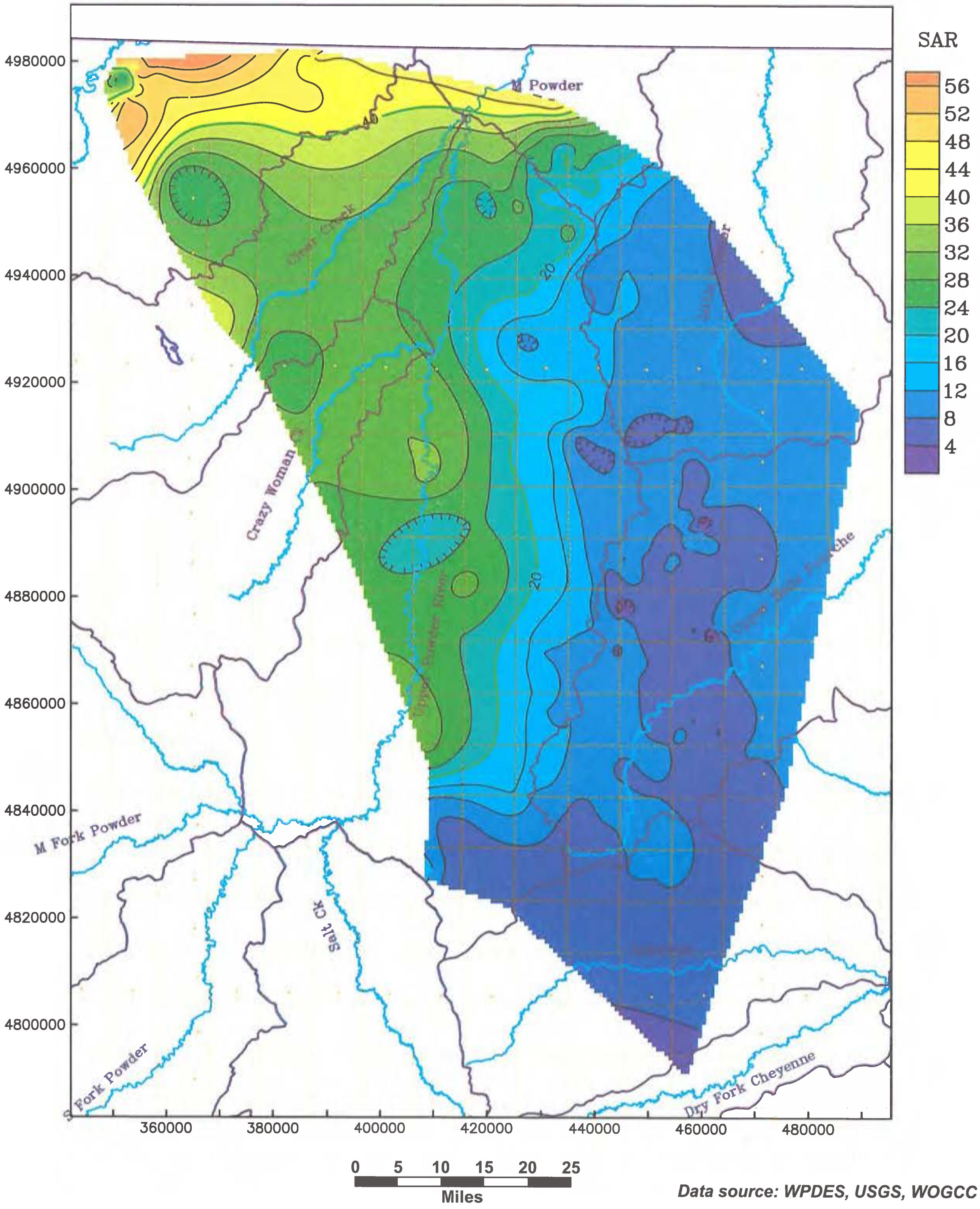


Figure 6-16. Salinity contour map of the CBNG water from the Powder River Basin shows that the salinity, or total dissolved solids, of the CBNG produced water increases significantly in the west and northwest parts of the Powder River Basin, namely in the Upper Powder River, Crazy Woman Creek, Clear Creek, and Upper Tongue River drainages.



Data source: WPDES, USGS, WOGCC

Figure 6-17. Sodium adsorption ratio (SAR) contour map of the CBNG produced water from the Powder River Basin. The sodium absorption ratio of the CBNG produced water increases from southeast to northwest across the basin.

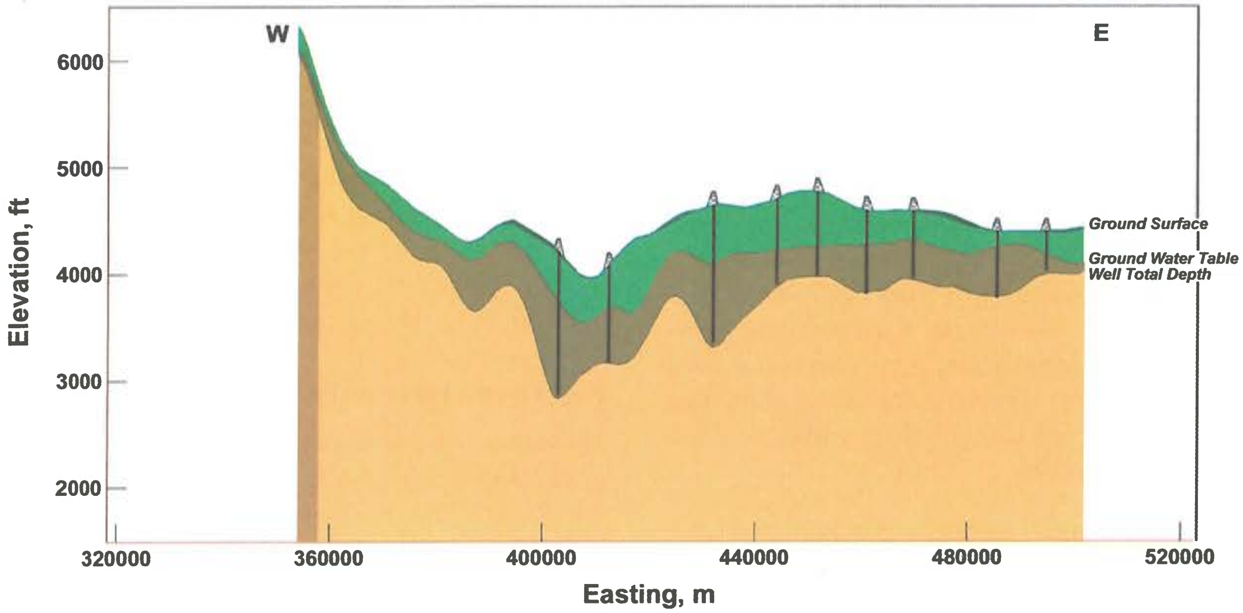


Figure 6-18. An east-west cross section of the ground surface elevation, groundwater table, and total well depth through the northern Powder River Basin shows that there is no significant relationship between the depth of the CBNG wells and the elevation of the groundwater table.

Water/gas ratios for the first half of CBNG development in the PRB (22,211 wells more than two years old) averaged 1.83 barrels of water for every MCF of gas produced.

Based on the first 10 years (1997-2007) of CBNG development in the PRB, we can evaluate future CBNG production trends. Future CBNG development in the Upper, Middle, and Little Powder River and Upper Tongue River drainages has a predicted water/gas ratio of less than 3. Conversely, the Clear Creek and Crazy Woman Creek drainages have projected water/gas ratios greater than 300.

During the second half of CBNG development in the PRB, 25% of the new wells will probably be drilled in the Clear Creek and Crazy Woman Creek drainages; these areas will contribute only 0.15% of gas produced during this period, but will account for 20% of the water produced. As the CBNG play moves from east to west in the PRB, most of the targeted coal-rich section will lie in the lowest/deepest structural part of the basin.

The targeted Fort Union Formation coals are relatively thick in the Upper Powder River drainage (the "Big George" coal), whereas the stratigraphic interval targeted in the Clear Creek and Crazy Woman Creek drainages contains thinner coals and more sandstones.

Groundwater flow rates are highest along the western margin of the PRB. Already, CBNG activity in the Upper Tongue River, Upper Powder River, Crazy Woman Creek, and Clear Creek drainages has measurably lowered the elevation of the water table.

Regional linears and associated fracture patterns appear to significantly affect groundwater flow patterns in the PRB. Groundwater quality (based on TDS and SAR) declines from east to west in the PRB. Preliminary research suggests that the best model for the groundwater associated with the Fort Union coal beds is a regional groundwater system characterized by substantial hydrologic connectivity.

Recommendations

The data and information in this report strongly support Wyoming State Engineer Patrick Tyrrel's recommendation to the Coalbed Methane Task Force concerning the regulation of CBNG wells, after a reasonable amount of time, based on water/gas ratios. The observations outlined in this study suggest that the Wyoming State Engineer's Office should review every CBNG well drilled in the PRB with a water/gas ratio greater than 3 after two years of production. These CBNG wells should be discouraged unless the operator can do all of the following: 1) document special circumstances that have prevented the well from producing commercial quantities of gas; 2) quantify any decrease in water elevation in the well as a result of 2 or more years of water production (document any decrease in water table elevation); and 3) demonstrate that there are commercial quantities of gas in the perforated and completed coal intervals in the well. If the operator cannot do all of the above, we suggest the well be regulated as a water well rather than a CBNG well.

This report strongly supports a moratorium on all CBNG activity in the Clear Creek and Crazy Woman Creek drainages. Historically, these areas have very little commercial gas, yet have produced immense quantities of water. Predicted production trends based on projected CBNG wells indicate that these areas will contribute only 0.15% of gas produced in the future, yet will account for 20% of future produced water. A moratorium on future CBNG activity in these two drainages would save 3.3 billion barrels of water (130 billion gallons).

Implementing these changes would be a positive step in developing a strategy to minimize both produced water and animosity toward future CBNG development, and would place regulation of CBNG activity in the PRB on a sound, scientifically-supported path.

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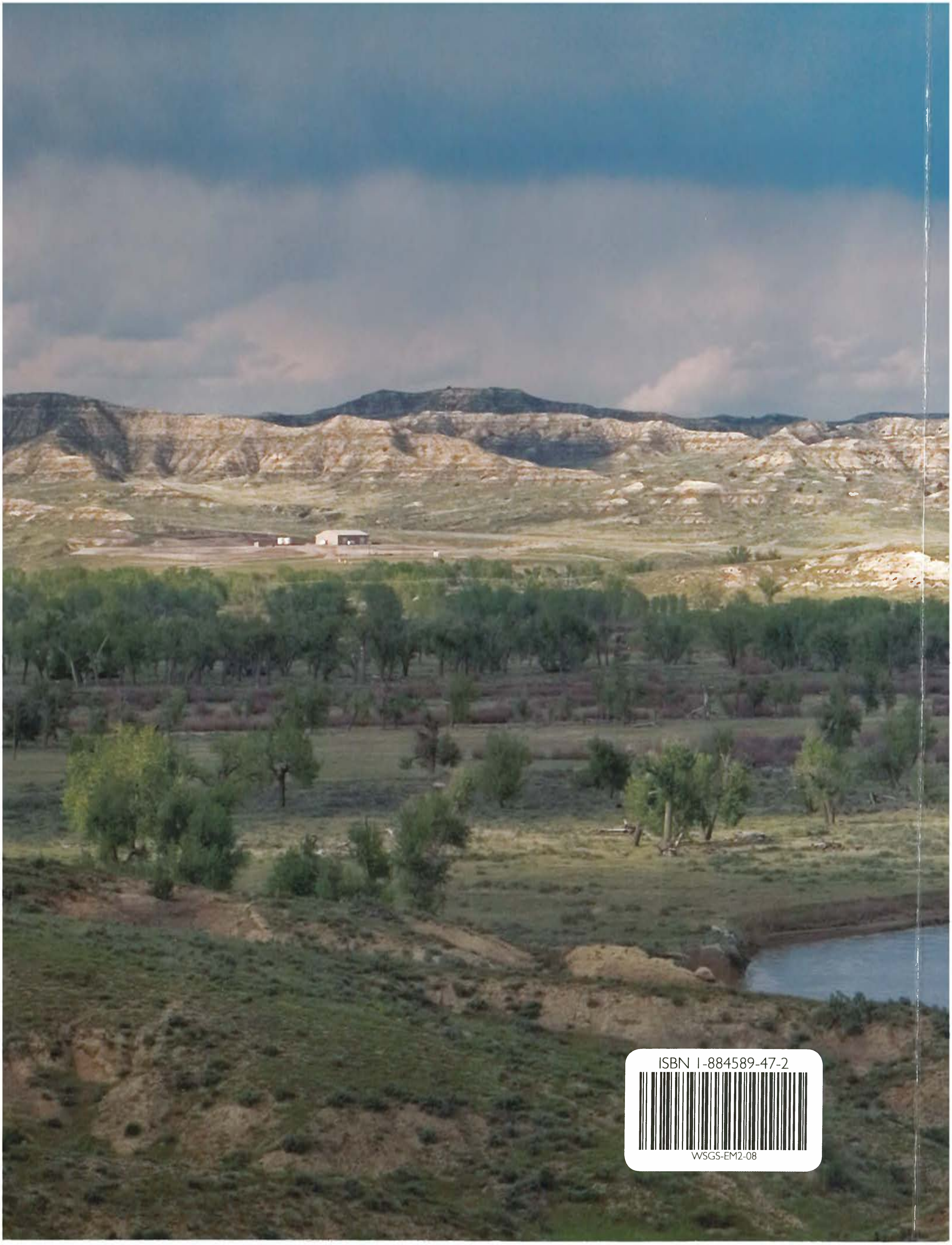

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