Chapter PG

GILLETTE COALFIELD, POWDER RIVER BASIN: GEOLOGY, COAL QUALITY, AND COAL RESOURCES

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STRUCTURAL AND STRATIGRAPHIC SETTING

The Gillette coalfield (fig. PG-1) contains the Fort Union Formation (Paleocene) that includes, from bottom to top, the Tullock, Lebo, and Tongue River Members. The Tongue River Member is mainly mapped in the northern part of the coalfield (see fig. PG-1) Mapel, 1973; Law, 1974, 1975, 1978; Kent and Berlage, 1980; Love and others, 1990).

The Eocene Wasatch Formation, which was interpreted by Dobbin and Barnett (1927) as unconformably overlying the Fort Union Formation, is in the western part of the coalfield. An erosion surface is at the bottom of the thick channel sandstone beds immediately above the Wyodak-Anderson coal zone. The contact between these formations is not delineated in the subsurface because they have basically the same lithology and are difficult to correlate in the absence of the channel sandstone. The surface contact between the Wasatch and Fort Union Formations is placed above the Roland coal bed above the channel sandstone. These rocks dip 2-3 degrees westward.

The Gillette coalfield boundary (see fig. PG-1) approximately follows the area defined by the U.S. Geological Survey (for example, Keefer and Schmidt, 1973; Denson and Keefer, 1974) to include early mining activity, as revised by Jones (1990; 1991).

In this study, the Gillette coalfield (see fig. PG-1) is delineated by the surface contact line of the Wyodak-Anderson coal and associated coal/clinker burn line on the east (Heffern and Coates, 1997; Boyd and ver Ploeg, 1997), the closest coordinate (T. 54 N. and T. 53 N.) to the northernmost mine on the north (fig. PG-

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2), the closest coordinate (T. 39 N. and T. 38 N.) to the southernmost mine on the south, and the closest coordinate (R. 74 W. and R. 73 W.) to the mines on the west.

The coal beds of the Wyodak-Anderson coal zone of the Tongue River Member of the Fort Union Formation are mined at the surface in the Gillette coalfield. These coal beds are variously identified by the mine operators as the Smith, Anderson, Wyodak, and Canyon.

Clinker exists along the easternmost outcrops of the Wyodak-Anderson coal zone (see fig. PG-3). Clinker is an orange-red rock produced from the burning of coal and related rocks due to spontaneous combustion. Approximately a 250-square-mile area of clinker covers the eastern boundary of the Gillette coalfield from east of Gillette, Wright, and Rochelle Hills (Heffern and Coates, 1997). The clinker in the Rochelle Hills east of Wright was dated as being from 700,000 to 18,000 years before present from downdip to updip toward the burn line using fission-track ages of zircon grains (Coates and Naeser, 1984; Heffern and Coates, 1997).

The coal beds of the Wyodak-Anderson coal zone exist as merged or split, or as an individual bed. The coal beds of the Wyodak-Anderson coal zone merge to form a single bed as much as 145 ft thick. They pinch out into mudstone, siltstone, and sandstone.

The coal beds of the Wyodak-Anderson coal zone are commonly broken up by pinch outs along a north-south direction and commonly split westward or basinward. Coal pinch outs produced pod-like to lenticular-shaped beds.

DEPOSITIONAL SETTING

The coal beds are interbedded with carbonaceous shale, mudstone, siltstone, limestone, and sandstone. The depositional environments of these rocks types were interpreted by Budai and Cummings (1987).

The Wyodak-Anderson coal zone is split by floodplain mudstone, siltstone, silty sandstone, and associated fluvial channel sandstone as seen in the highwall at the Antelope coal mine (fig. PG-4). The coal zone is overlain by vertically stacked and multi-erosional sandstone deposited in fluvial channels, as seen in the highwall at the Belle Ayr coal mine (figs. PG-5 and PG-6). This fluvial channel sandstone grades laterally into floodplain and crevasse-splay mudstone, siltstone, and silty sandstone as exhibited in the highwall of the Cordero Rojo coal mine (figs. PG-7 and PG-8). The fluvial channel sandstone is thick and crossbedded and has a deep erosional base as seen in the highwall of the Buckskin coal mine (figs. PG-9 and PG-10)

The vertical and lateral variations, thickness, distribution, and shape of the Wyodak-Anderson coal beds reflect their deposition in raised mires formed in meandering and anastomosed fluvial systems (figs. PG-11, PG-12, and PG-13; Warwick and Stanton, 1986, 1988).

WYODAK ANDERSON COAL ZONE—GILLETTE COALFIELD

GILLETTE COALFIELD STRUCTURAL CROSS SECTION A-A'

- The north-south oriented structural cross section A-A' (fig. PG-14) is 80 mi long. The Wyodak-Anderson coal zone shows merging, splitting, and resplitting of as many as two to eight coal beds. The cross section was drawn using data from 185 drill holes, which are not labeled on the cross section.

- Coal beds are interbedded with, and split by, mudstone (shown in green), which was deposited in floodplains and floodplain lakes, and sandstone (shown in yellow), which was deposited in fluvial channels.

- The coal beds commonly pinch out into these fluvial mudstone and sandstone deposits.

- Coal beds are lenticular in the southern part of the cross section and in the middle and southern subareas of the Gillette coalfield.

- Coal beds in the northern part of the cross section, in the northern subarea of the Gillette coalfield, display pod and lenticular geometry.

- The lenticular coal beds in the southern part of the cross section split and merge, forming a zigzag pattern.

- The peat deposits (precursor of coal) accumulated in interchannel raised mires. The areal size and shape of the peat in these mires was influenced by the types and patterns of surrounding streams.

- Merging and diverging fluvial channels of anastomosed streams yielded small, isolated, interchannel mires that produced pod-shaped peat deposits (figs. PG-15 and PG-16).

- Lateral migration and avulsion, or shift of fluvial channels of meandering streams (fig. PG-17) created widespread mires on interchannel and abandoned fluvial deposits that produced lenticular peat deposits.

- A combination of raised mires, confinement of the fluvial channels by peat deposits, local and regional subsidence, and rain-fed mires controlled the accumulation of thick coal beds and kept the ash content low.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone consist of intervals more than 300 ft thick. The intervals include interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION B-B’

- The west-east oriented structural cross section B-B’ (fig. PG-18) is more than 8 mi long. The Wyodak-Anderson coal zone, an interval as much as 350 ft thick, contains merging and splitting coal beds that dip to the west. The cross section was drawn using data from 20 drill holes, which are not labeled on the cross section.

- The coal beds merge toward the east to form a bed more than 100 ft thick.

- Toward the west, coal beds are interbedded with, and split by, mudstone (shown in green), which was deposited in floodplains and floodplain lake (fig. PG-16), and by sandstone (shown in yellow), which was deposited in fluvial channels and crevasse splays.

- The peat deposits accumulated in interchannel raised mires, which encroached and occupied abandoned fluvial-channel and floodplain deposits. The peat deposits formed in these mires produced low-ash and low-sulfur coal.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are as much as 400 ft thick and more than 400 ft thick, respectively. They are composed of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION C-C’

- The west-east oriented structural cross section C-C’ (fig. PG-19) is 12 mi long. The Wyodak-Anderson coal zone, as much as 400 ft thick, contains merging and splitting coal beds that dip westward. The cross section was drawn using data from 20 drill holes, which are not labeled on the cross section.

- The coal beds merge eastward to form a bed about 200 ft thick.

- Toward the west, coal beds are interbedded with, and split by, mudstone (shown in green), which was deposited in floodplains and floodplain lakes, and by sandstone (shown in yellow), which was deposited in fluvial channels and crevasse splays.

- The coal beds merge, split, and pinch out, to form a zigzag pattern. This pattern yields a discontinuous distribution of coal.

- The peat deposits accumulated in interchannel raised mires, which are adjacent to abandoned fluvial channel and floodplain deposits. Raised mires formed coal with low-ash and low-sulfur contents.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are as much as 300 ft thick and more than 500 ft thick, respectively. The rocks consist of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION D-D'

- The west-east oriented structural cross section D-D' (fig. PG-20) is 15 mi long. The Wyodak-Anderson coal zone, as much as 450 ft thick, contains coal beds that merge, split, pinch out, and dip to the west. The cross section was drawn using data from 17 drill holes, which are not labeled on the cross section.

- The coal beds merge into a bed more than 100 ft thick and pinch out eastward into fluvial-channel sandstone (shown in yellow).

- The coal beds are interbedded with, and split by, mudstone (shown in green), which was deposited on floodplains and in floodplain lakes, and by sandstone (yellow), which was deposited in fluvial channels.

- The peat deposits accumulated in interchannel raised mires flanked by deposits of a fluvial-channel complex.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are as much as 450 ft thick and about

400 ft thick, respectively. The rocks are composed of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION E-E'

- The west-east oriented structural cross section E-E' (fig. PG-21) is 13 mi long. The Wyodak-Anderson coal zone, more than 200 ft thick, contains a merged coal bed that dips westward. The cross section was drawn using data from 15 drill holes, which are not labeled on the cross section.

- The merged coal bed is about 80 ft thick.

- The coal bed is interbedded with, and split by, mudstone (shown in green) that was deposited on floodplains and in floodplain lakes.

- The peat deposits accumulated in interchannel raised mires.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are more than 750 ft thick, and are composed of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION F-F'

- The west-east oriented structural cross section F-F' (fig. PG-22) is more than 15 mi long. The Wyodak-Anderson coal zone, more than 125 ft thick, contains merging and splitting coal beds that dip westward. The cross section was drawn using data from 15 drill holes, which are not labeled on the cross section.

- The coal beds merge westward into a single bed that is about 130 ft thick.

- To the east the coal beds are interbedded with, and split by, mudstone (shown in green) that was deposited on floodplains and in floodplain lakes.

- The peat deposits accumulated in interchannel raised mires.

- The undifferentiated Fort Union rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are more than 400 ft thick and 1,100 ft thick, respectively. The intervals are composed of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION G-G’

- The west-east oriented structural cross section G-G’ (fig. PG-23) is 13 mi long. The Wyodak-Anderson coal zone, more than 100 ft thick, contains coal beds that merge, split, pinch out, and dip westward. The cross section was drawn using data from 20 drill holes, which are not labeled on the cross section.

- The coal beds merge to form a bed about 90 ft thick.

- The coal bed is interbedded with, and split by, mudstone (shown in green) that was deposited on floodplains and in floodplain lakes.

- The peat deposits accumulated in interchannel raised mires.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are more than 600 ft thick and 500 ft thick, respectively. The intervals are composed of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION H-H'

- The west-east oriented structural cross section H-H' (fig. PG-24) is 17 mi long. The Wyodak-Anderson coal zone, more than 100 ft thick, contains coal beds that merge, split, pinch out, and dip westward. The cross section was drawn using data from 16 drill holes, which are not labeled on the cross section.

- The coal beds merge eastward into a single bed that is about 80 ft thick.

- The coal bed is interbedded with, and split by, mudstone (shown in green) that was deposited on floodplains and in floodplain lakes.

- The peat deposits accumulated in interchannel raised mires.

- The rocks above and below the Wyodak-Anderson coal zone are more than 600 ft thick and 350 ft thick, respectively. They are composed of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

GILLETTE COALFIELD STRUCTURAL CROSS SECTION I-I'

- The west-east oriented structural cross section I-I' (fig. PG-25) is 8 mi long. The Wyodak-Anderson coal zone contains as many as four coal beds in an interval more than 300 ft thick that dip westward. The cross section was drawn using data from 17 drill holes, which are not labeled on the cross section.

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- The coal beds are as much as 35 ft thick.

- The coal beds are interbedded with, and split by, mudstone (shown in green), which was deposited in floodplain lakes, floodplains, and crevasse splays, and sandstone (shown in yellow), which was deposited in fluvial channels.

- The peat deposits accumulated in interchannel raised mires and low-lying swamps.

- The undifferentiated Fort Union and Wasatch rocks above and Fort Union rocks below the Wyodak-Anderson coal zone are more than 200 ft thick and 400 ft thick, respectively. The rocks consist of interbedded fluvial-channel sandstone, and overbank, floodplain, and lacustrine mudstone.

COAL QUALITY

COAL QUALITY—SUBAREAS

- The Gillette coalfield may be divided from north to south into three subareas (see figure PG-2) based on the quality of the Wyodak-Anderson coal.

- The northern subarea from north to southeast of the city of Gillette contains coal with a total average heat value of produced coal of 8,326 Btu/lb (Resource Data International, Inc., 1998).

- The central subarea south of the city of Gillette and to the east of the town of Wright contains coal with a total heat value of produced coal of 8,445 Btu/lb (Resource Data International, Inc., 1998).

- The southern subarea east-southeast of the town of Wright contains coal with a total heat value of produced coal of 8,764 Btu/lb (Resource Data International, Inc., 1998).

- The higher value of Btu/lb in coal of the southern subarea may have been caused by deeper burial of the peat deposits that formed the Fort Union coal.

GILLETTE COALFIELD, WYODAK-ANDERSON COAL QUALITY

Coal from the Wyodak-Anderson coal zone is produced from 19 mines in the Gillette coalfield, Wyoming. This coal is utilized for out-of-state electric power generation in power plants in 26 states. Wyodak-Anderson coal is sometimes blended with higher sulfur coals to produce a compliant fuel.

Coal in the Wyodak-Anderson coal zone in the Gillette coalfield in the Powder River Basin, Wyoming, is considered to be ‘clean coal’. This coal zone (see chapter PS in this CD-ROM) for a description of the coal zone) contains low-contaminant, compliant, subbituminous apparent rank coal. Analyses of the coal have the following arithmetic mean values (on an as-received basis): **moisture—**27.47%, **ash**—7.45%, **total sulfur**—0.48%, **heat value**—8,220 (Btu/lb), **lb SO_2 per million Btu**—1.25, and **moist, mineral-matter-free Btu**—8,910. Arithmetic mean values (on a whole coal, parts per million, and remnant moisture basis) of elements of environments concern for the Wyodak-Anderson coal zone are: **antimony**—0.72, **arsenic**—2.3, **beryllium**—0.35, **cadmium**—0.39, **chromium**—7.0, **cobalt**—2.3, **lead**—2.9, **manganese**—22, **mercury**—0.17, **nickel**—5.0, **selenium**—1.4, and **uranium**—1.5.

Summary data for the 18 variables mentioned in the previous paragraph were calculated for the Wyodak-Anderson coal zone using all available data. However, some of the coal quality data in this basin is proprietary. This type of data, along with public data, is used for the summary table (table PG-1), but is not shown on location maps or graphic displays. The locations of public data points used in the summary are shown on figure PG-26.

A common problem in statistical summaries of trace-element data arises when element values are below the limits of detection. This results in a censored distribution. To compute unbiased estimates of censored data for the elements in this table, we adopted the protocol of reducing all 'less than' values by 50 percent to generate a real value for these data. Summary statistics of range (minimum and maximum value) and arithmetic means were generated using the modified data. Moisture values are reported on an as-received basis (ASTM, 1996, designation D388-6). Because no equilibrium moisture values are available for this report, apparent ranks can not reliably be determined.

Between 1974 and 1994, the U.S. Geological Survey analyzed samples of coal for contents of major-, minor-, and trace-elements. Prior to performing the analyses most of the coal samples were dried at room temperature and humidity for up to 80 hours. However, some samples may have been dried only long enough to allow grinding (to less than 100 mesh). Moisture content in the above mentioned samples is unknown, although moisture contents were probably similar to that which would remain after air-dry loss determination (ASTM Standards, 1991, D3302). Since the actual moisture content of the samples analyzed between 1974 and 1994 is unknown, the elemental analysis of the samples cannot be converted to any other moisture basis. In addition, these analyses can only provide an approximation of load factors (such as, grams of mercury per trillion Btu).

For graphic display of public analytical data, data points were color keyed to show the values of the 17 variables, moisture and calorific value (Btu/lb) are not shown. When more than one analysis was available per location, the analytical values were weight averaged on thickness. For ash and total sulfur (figs. PG-27 and PG-28), the values are keyed to low, medium, and high, following guidelines established in U.S. Geological Survey Circular 891 (Wood and others, 1983). For calorific value as represented by moist, mineral-matter-free Btu (apparent rank) (fig. PG-29), apparent rank designations established in ASTM (1994) were utilized. For pounds of SO_2 per million Btu (fig. PG-30), values are keyed according to the Environmental Protection Agency's Phase I, Phase II, and non-compliant limits for sulfur emission from coal fired power plants.

No guidelines have been established for elements of environmental concern (also referred to as 'hazardous air pollutants' or 'HAPs'). Analytical values for these elements (figs. PG-31 through PG-42) are coded based on the following parameters: (1) each element of environmental concern was ranked from the lowest to the highest value for all data in the northern Rocky Mountains and Great Plains region; and (2) quartiles were established for each element. Low represents those values that are less than the .25 quartile (also known as the lower quartile or the 25th percentile). Medium represents those values that are within the .25 to .75 quartile (or between the 25th to 75th percentile). High represents those values that are in the upper .25 quartile (or greater than the 75th percentile).

COAL RESOURCES—WYODAK-ANDERSON COAL ZONE GILLETTE COALFIELD

RESOURCE ESTIMATES—AN OVERVIEW

- Coal resources are calculated using the specific gravity of the coal calculated from apparent coal rank, which is the weight of coal per unit volume, net coal thickness, and areal extent of the coal.

- Resource tables for the Wyodak-Anderson coal zone in the Gillette coalfield include coal and overburden thickness categories from Wood and others (1983), which are based on apparent coal rank. Additional categories have been added to provide more detail in this area. Resources are also reported by county, Federal coal and surface ownership categories, and 7.5-minute quadrangle.

- Following USGS published guidelines (Wood and others, 1983); coal resource estimates are divided into measured, indicated, and inferred categories according to relative abundance and reliability of data.

- Where data are widely spaced, a hypothetical resource may be extrapolated.

- Measured resources are tonnage estimates of coal in the coal zone within a radius of 0.25 mi of a control point where the net thickness of coal is measured.

- Indicated resources are tonnage estimates of coal that is within a radius of 0.25-0.75 mi of a control point where the net thickness of the coal is measured.

- Inferred resources are tonnage estimates of coal that is within a radius of 0.75-3 mi of a control point where the net thickness of the coal is measured.

- Hypothetical resources are tonnage estimates of coal that is beyond a radius of 3 mi of a control point where the net thickness of coal is measured.

- These resource categories assume a high to low degree of geologic certainty. A statistical method, which measures levels of uncertainty (confidence limits) for the Wyodak-Anderson resource estimates in the Gillette coalfield, is also included in this study.

- Resource estimates are reported in millions of short tons with two significant figures.

WYODAK-ANDERSON COAL RESOURCES

The lateral extent (study limit) of the Wyodak-Anderson coal zone in the Gillette coalfield is based on the Wyodak-Anderson coal outcrop and Wyodak-Anderson clinker to the east from published maps by Kent and Berlage (1980), and Heffern and others (1993; and unpublished data, undated). The eastern boundary was generalized in some areas to include small areas containing Wyodak-Anderson coal that were outside of the main boundary. The contact of Cretaceous and Tertiary rocks (Love and Christiansen, 1985) was used in some areas where mapped coal outcrop was not available. The northern, southern, and western boundaries of the study area were delineated by the closest Township and Range lines (T54-53N, T39-38 N, R 74-73 W respectively) outside of the active Gillette coalfield mine areas. The total study area is about 1,026,000 acres (415,208 hectares) in size.

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Wyodak-Anderson coal resources in the Gillette coalfield, Powder River Basin, Wyoming were calculated using several software packages and custom programs. Details of the methodology used are given in Ellis and others (1999, in press).

To calculate the Wyodak-Anderson coal resources in the Gillette coalfield data was compiled in a StratiFact* (GRG Corporation, 1996) relational database. The coal beds in the Wyodak-Anderson coal zone, including the Smith, Anderson, Canyon, Werner, Upper Werner, Swartz, and Sussex beds (see the explanation of coal bed nomenclature in chapter PS of this CD-ROM), were correlated in the database. A custom program was used to calculate net coal thickness at each data point (drill hole or measured section) location.

The net coal thickness and overburden were gridded, and isopach maps were produced using EarthVision* (Dynamic Graphics, Inc., 1997) software. The grids were made using an isopach grid option (special handling of 0 values and terminated data) with a grid spacing of 200 x 200-meters.

The spatial parameters for querying the coal resources (for example, 7.5-minute quadrangle map area (fig. PG-43; U.S. Geological Survey National Mapping Division unpublished data, undated), Federal coal and surface ownership (fig. PG-44; Biewick and others, 1998), reliability, coal thickness (fig. PG-45), and overburden categories (fig. PG-46)) were created on individual layers as ARC/INFO* (ESRI, 1998a) polygon coverages. The coverages were unioned to make one polygon coverage with many attributes for each polygon. The polygons in the union coverage were edited in ARC/INFO* and ArcView* (ESRI, 1998b).

Coal resources were calculated using the EarthVision* (EV) volumetrics tool, which calculates tonnages in each polygon in the union coverage using the net coal thickness grid, the area of each polygon, and a conversion factor of 1,770 short tons per acre-ft for subbituminous rank coal (Wood and others, 1983). Data from the EV volumetrics report and the union coverage polygon attribute table were combined in Excel* (Microsoft, 1997) spreadsheet software. Data for polygons containing Wyodak-Anderson clinker (fig. PG-47) (Heffern and others, 1993; Boyd and others, 1997; Heffern unpublished data, undated), Wyodak-Anderson mine or lease areas (fig. PG-47) (Bureau of Land Management, 1996) or areas of net coal less than 2.5 ft in thickness were deleted from the data set. Lease areas may include public and/or state leases in addition to Federal leases. Resource tables were created using data from the remaining polygons (tables PG-2 through PG-4). The final resource area (fig. PG-47) (area that met all coal resource criteria) was about 892,000 acres (360,980 hectares) in area.

*Commercial Software package.

CONFIDENCE LIMITS FOR RESOURCE CALCULATIONS

A confidence interval is a statistic designed to capture uncertainty associated with a point value estimate. In this study we computed 90-percent confidence intervals on the volume (total resource in millions of short tons) of coal in the Wyodak-Anderson coal zone in the measured, indicated, inferred, and hypothetical categories.

The three main potential sources of error that might bias the confidence intervals are preferential sampling, measurement errors, and model fitting. The probabilistic interpretation of a confidence interval is based upon a random sample, which does not apply in this situation, because there is preferential sampling in those areas deemed to be minable. Measurement error can be caused by an error in recording the coal bed thickness or in the definition of coverage areas. Modeling fitting variability and bias result from the choice of models and fitting procedures.

Confidence limits for coal resources of the Wyodak-Anderson coal zone in the Gillette coalfield were calculated by J.H. Schuenemeyer and H.C. Power, University of Delaware. The data set that they used contained net coal measurements from 2,009 locations. This data set only included locations that contained Wyodak-Anderson coal (no 0 values) and data that were representative of the entire coal zone (no terminated holes).

The confidence limits were derived through a complex series of steps. These steps included modeling coal thickness trends and removing the coal thickness trends using a nonparametric regression algorithm called loess (with span=0.5), using residual thickness to compute a semivariogram, and fitting the semivariogram to a spherical model. Parameter estimates were sill=393.98 ft^2, nugget=299.14 ft^2, and range=1.69 miles. Standard deviations of coal thickness were obtained from the semivariogram model. Differences in point densities were compensated for by calculating sample size, called a pseudo *n*, within each reliability category and calculating the variability of volume for each of the reliability categories. Volumes of Wyodak-Anderson coal were then calculated at a 90-percent confidence interval with measurement error. Some of the parameters used and results of the confidence interval calculations are shown in tables PG-4 and PG-5. A detailed description of the methodology used is given in Schuenemeyer and Power (in press) and in Ellis and others (1999, in press).

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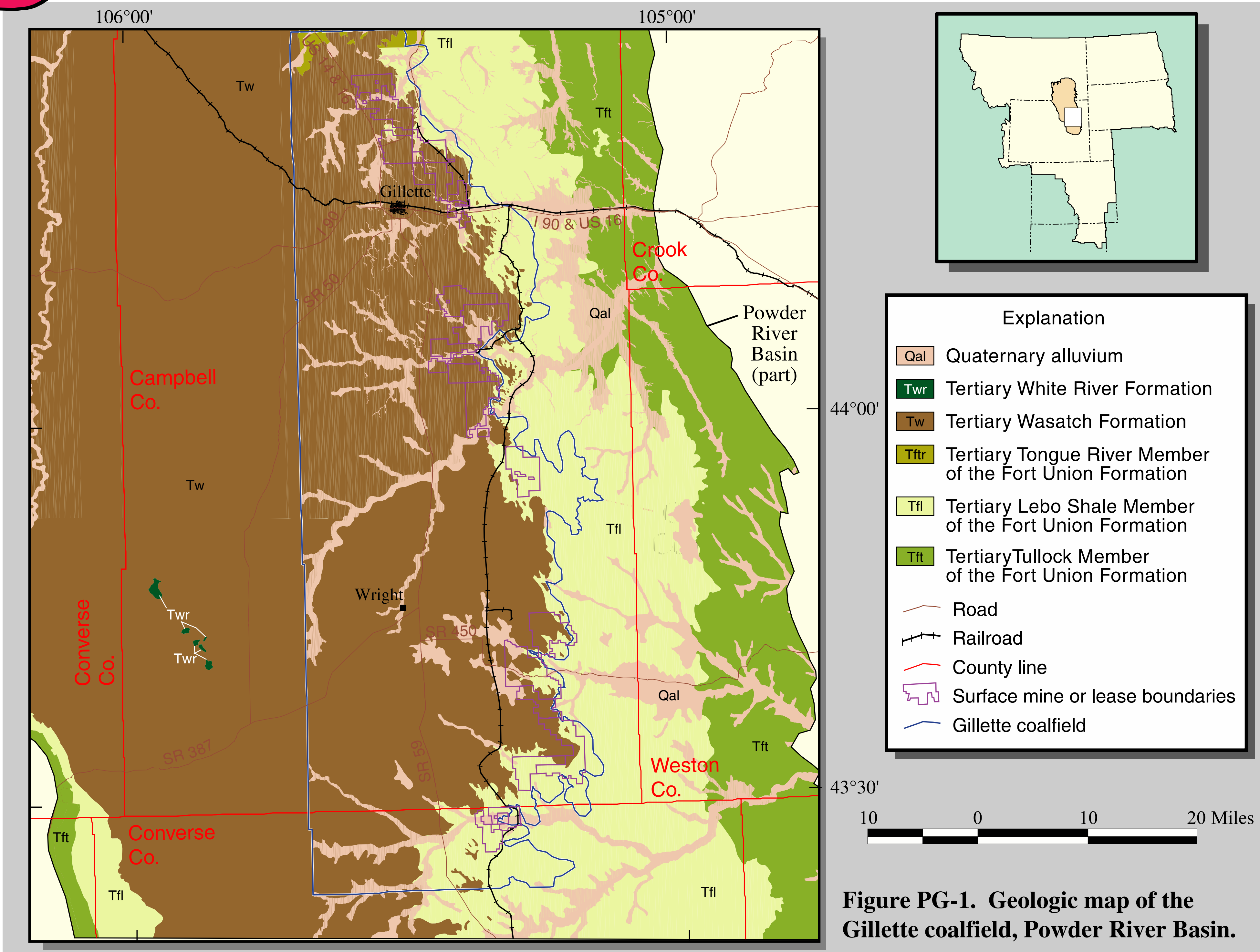

Figure PG-1. Geologic map of the Gillette coalfield, Powder River Basin.

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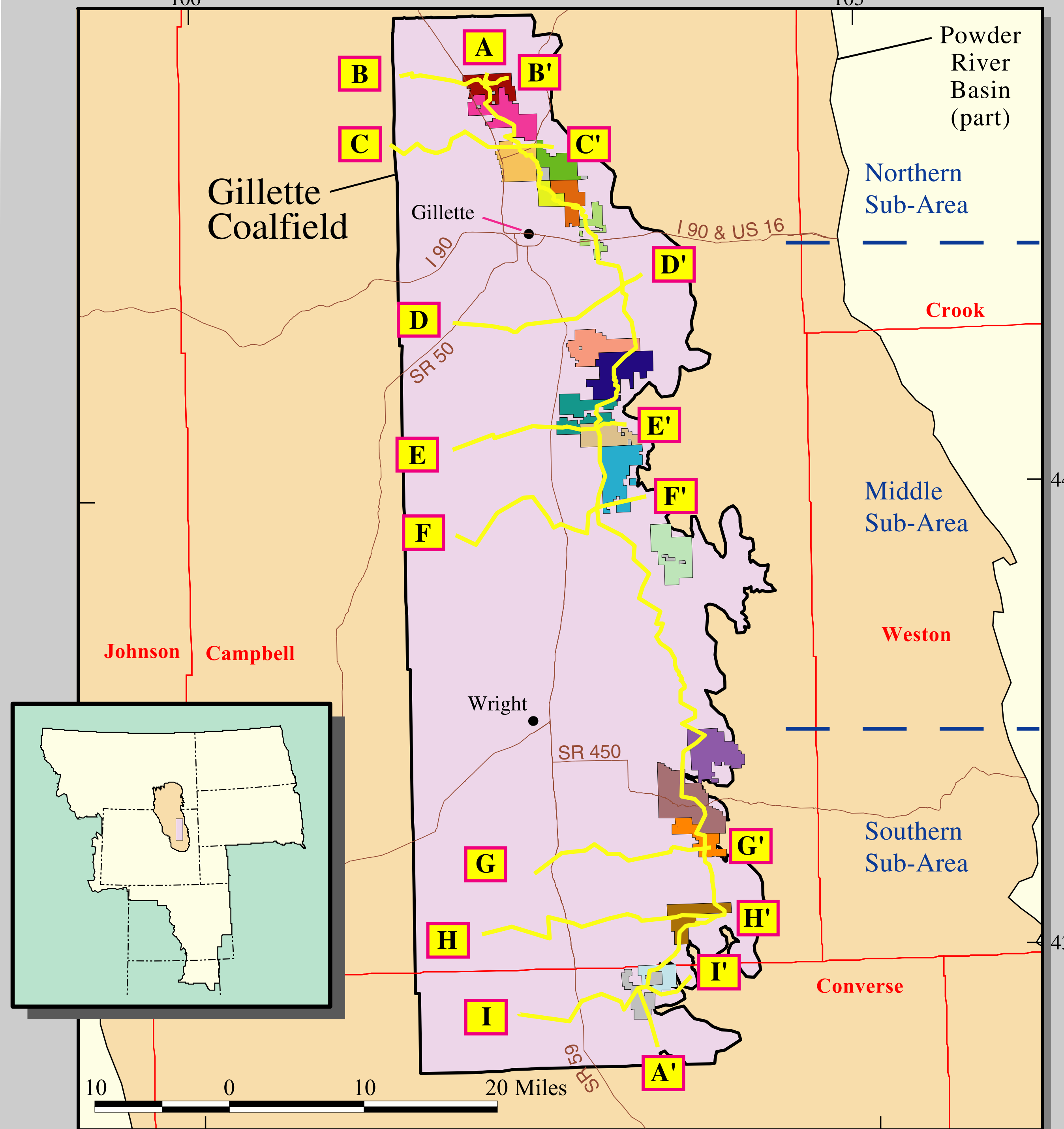

Figure PG-2. Index map showing locations of Gillette coalfield cross sections and mines.

Standby, operating, and proposed coal mines

- Buckskin
- Rawhide
- Dry Fork
- Eagle Butte
- Fort Union
- Clovis Point
- Wyodak
- Rocky Butte
- Caballo
- Belle Ayr
- Caballo Rojo
- Cordero
- Coal Creek
- Jacob's Ranch
- Black Thunder
- Rochelle
- North Antelope
- Antelope
- BLM or state lease

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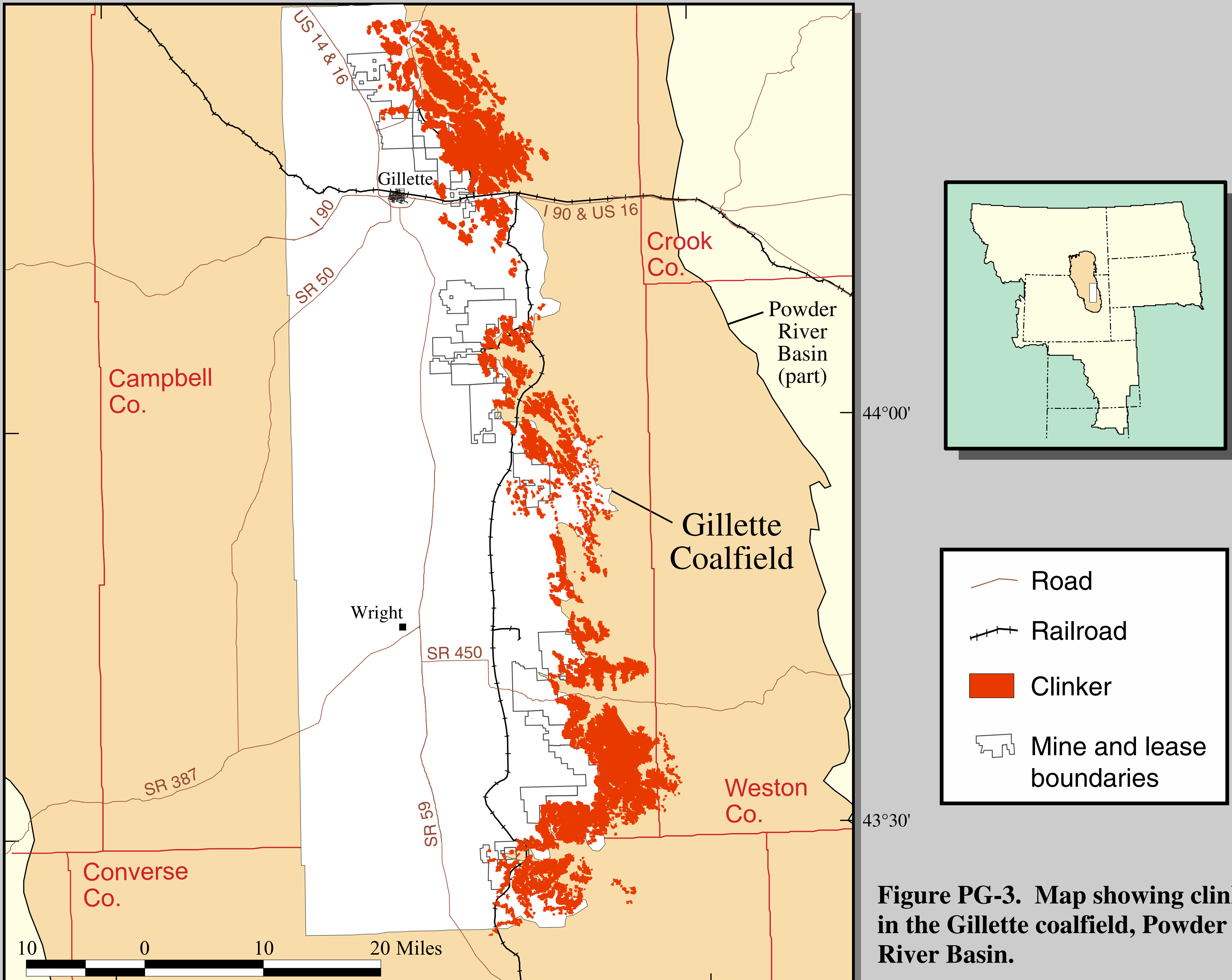

Figure PG-3. Map showing clinker in the Gillette coalfield, Powder River Basin.

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Figure PG-4. Fluvial channel sandstone above the Wyodak–Anderson coal zone. Photograph by R.M. Flores.

Figure PG-5. Vertically stacked, multierosional, fluvial sandstone above the Wyodak-Anderson coal zone. Photograph by R.M. Flores.

Figure PG-6. Stacked fluvial channel sandstone containing crossbeds. Photograph by R.M. Flores.

Figure PG-7. Crevasse-splay sandstone, siltstone, and mudstone above the Wyodak–Anderson coal zone. Photograph by R.M. Flores

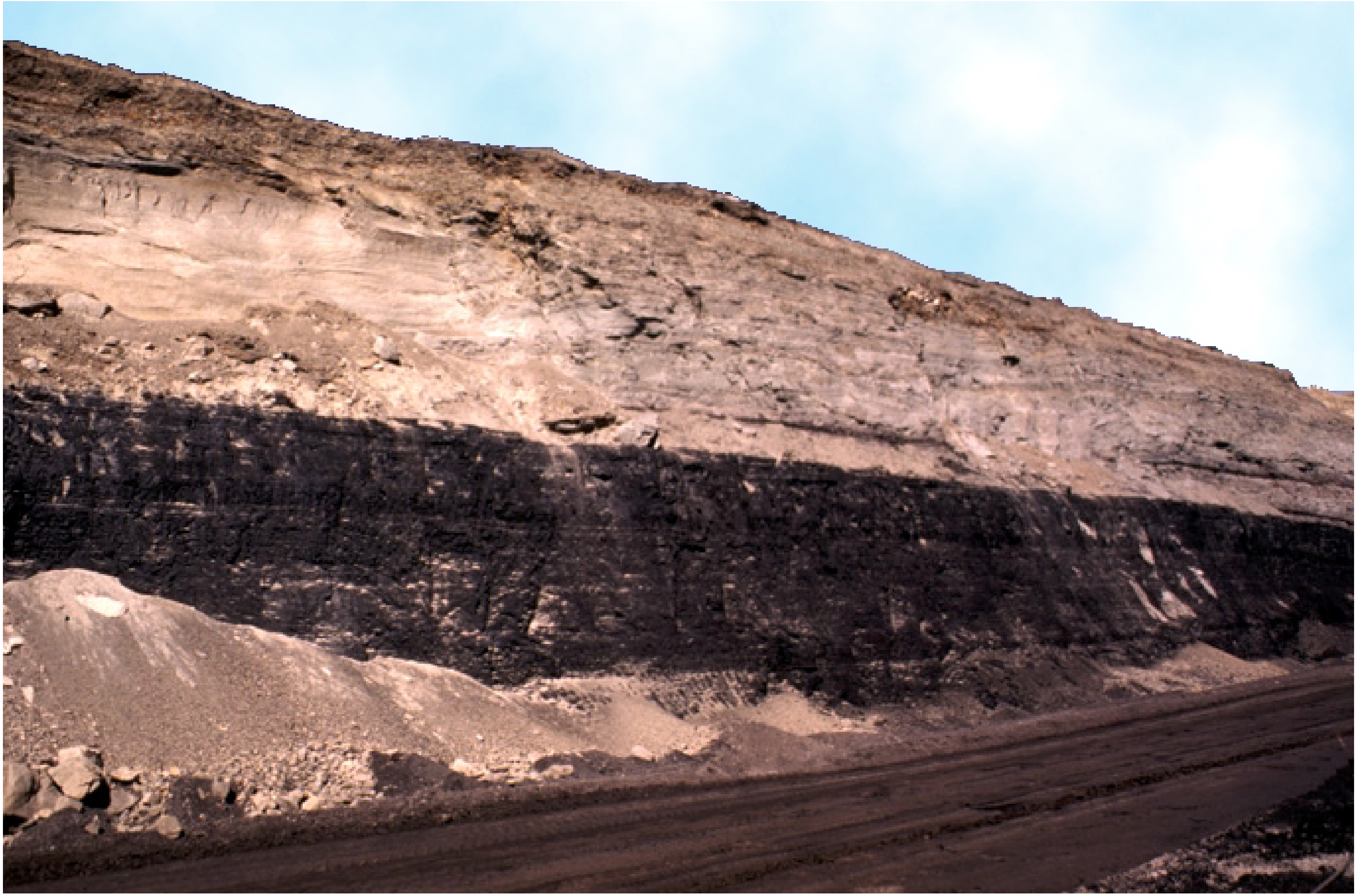

Figure PG-8. Crevasse channel sandstone lateral to crevasse-splay sandstone, siltstone, and mudstone above the Wyodak–Anderson coal zone. Photograph by R.M. Flores.

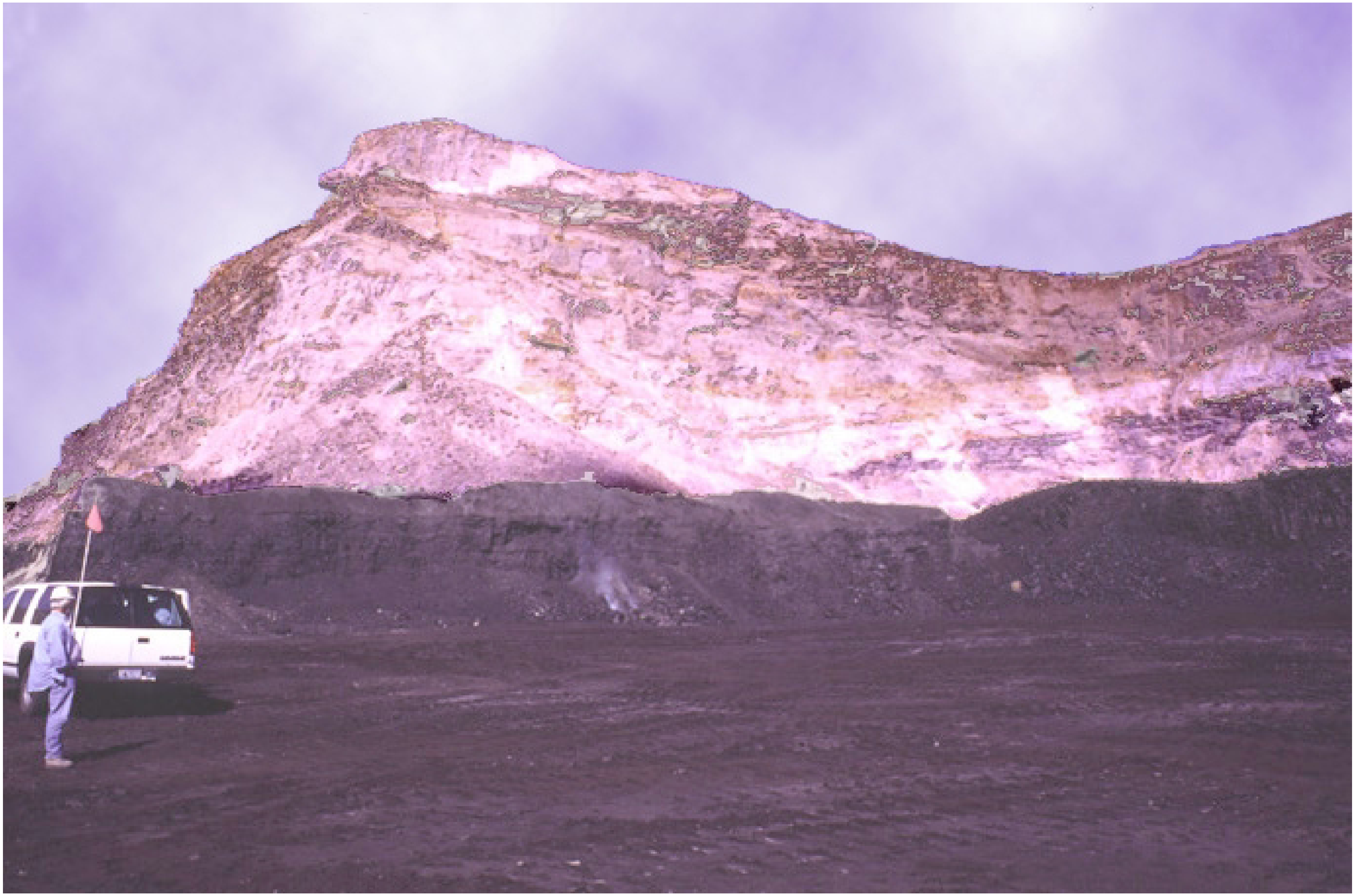

Figure PG-9. Thick fluvial channel sandstone with deep erosional base above the Wyodak–Anderson coal zone. Photograph by R.M. Flores.

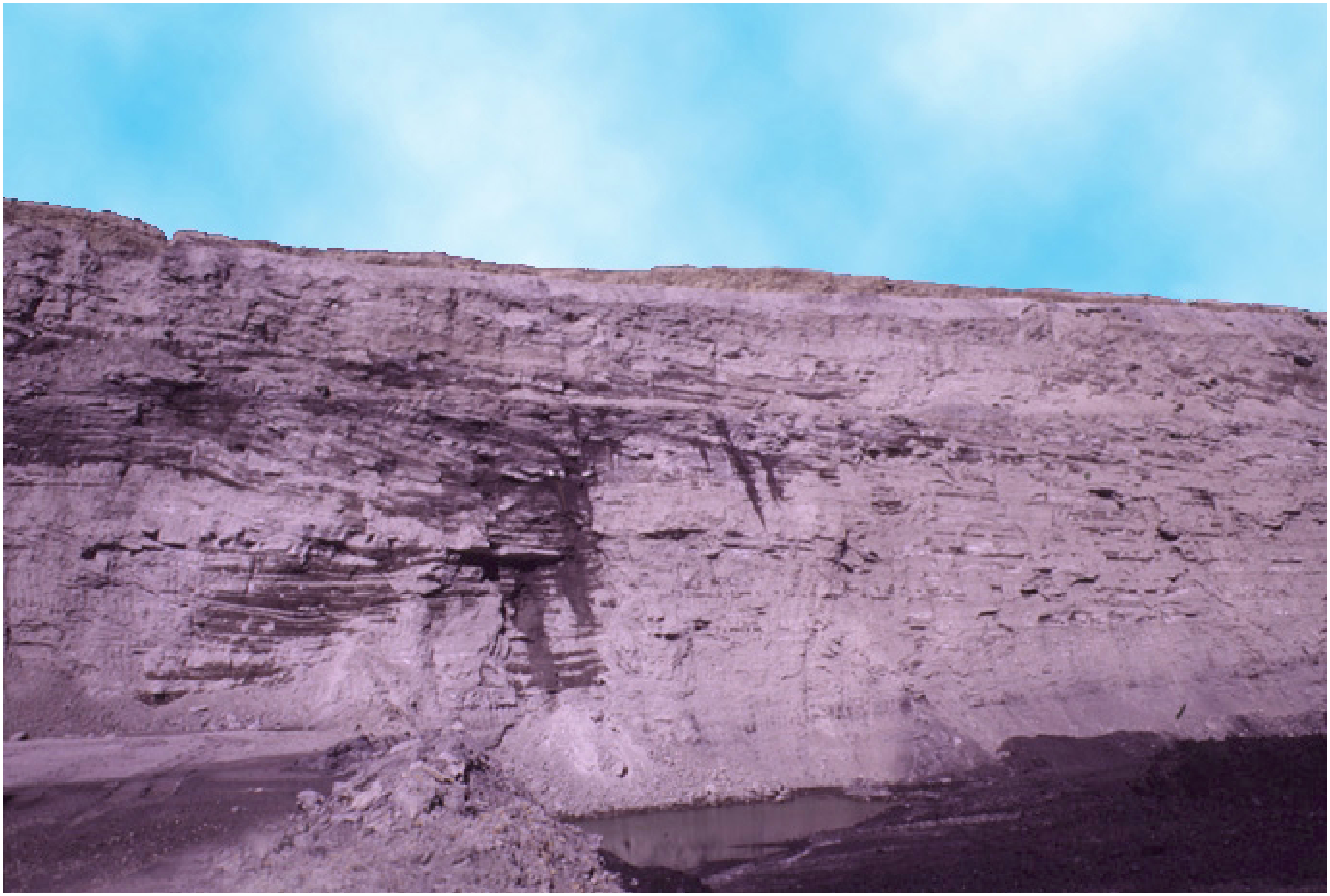

Figure PG-10. Lateral accretion units in the fluvial channel sandstone. Photograph by R.M. Flores.

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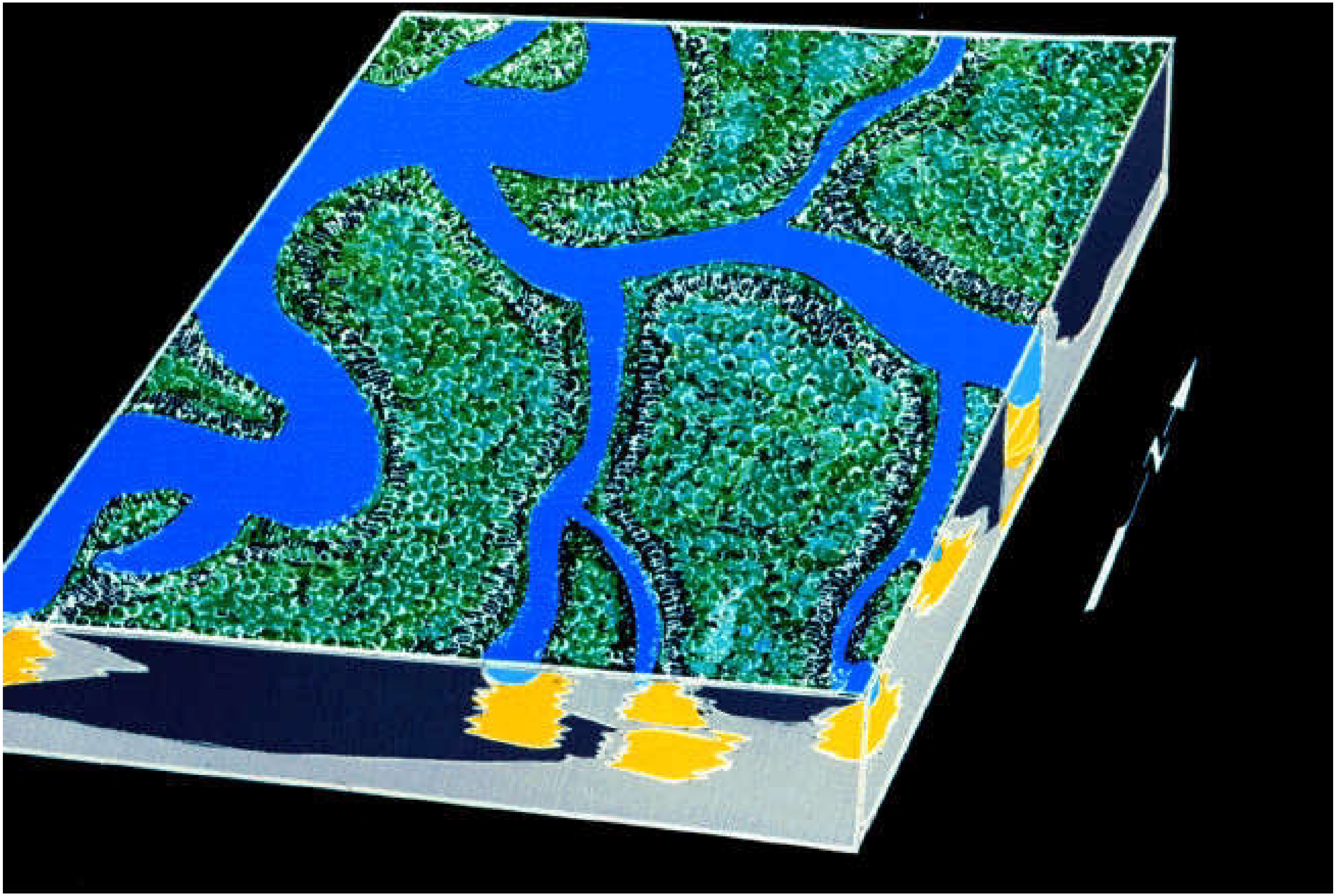

Figure PG-11. Depositional model of anastomosed streams for the Wyodak–Anderson coal zone in the Gillette coalfield. Adapted from Flores and others (1989).

Figure PG-12. A peat deposit near the margin of a raised mire in Central Kalimantan, Borneo, Indonesia. Photograph by C. Blaine Cecil.

Figure PG-13. A river channel at the edge of a raised mire in Sumatra, Indonesia. Photograph by C. Blaine Cecil.

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Figure PG-14. Gillette coalfield structural cross section A-A'.

Figure PG-15. Modern analog of a peat forming, raised swamp in the Atchafalaya River Basin, Louisiana. Photograph by R.M. Flores.

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Figure PG-16. Modern analog of a peat-forming swamp in the Atchafalaya River Basin, Louisiana. Photograph by R.M. Flores.

Figure PG-17. Lateral migration of a fluvial channel caused by avulsion and abandonment of the Santee River in South Carolina. Photograph by C. Conner.

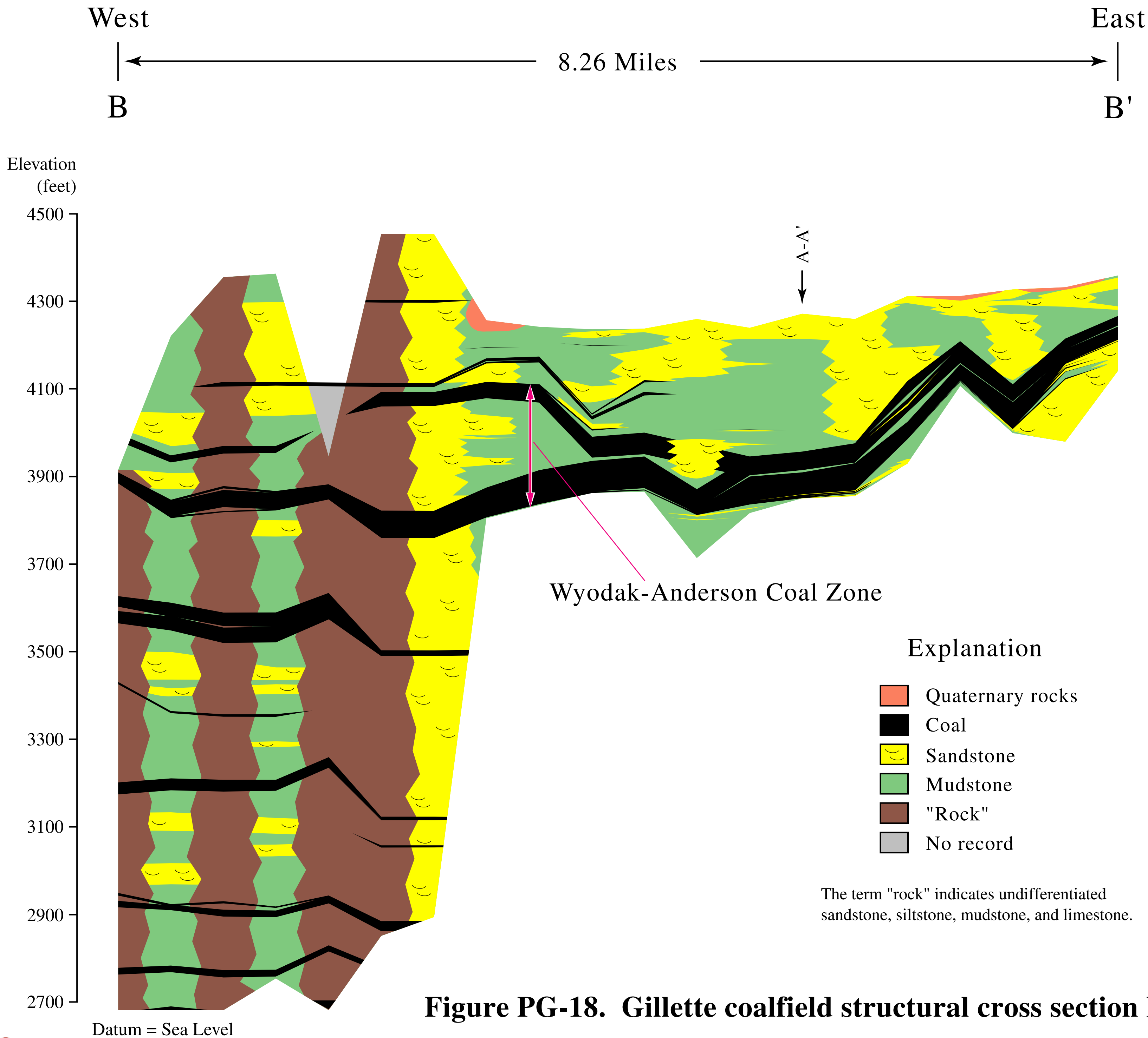

Figure PG-18. Gillette coalfield structural cross section B-B'.

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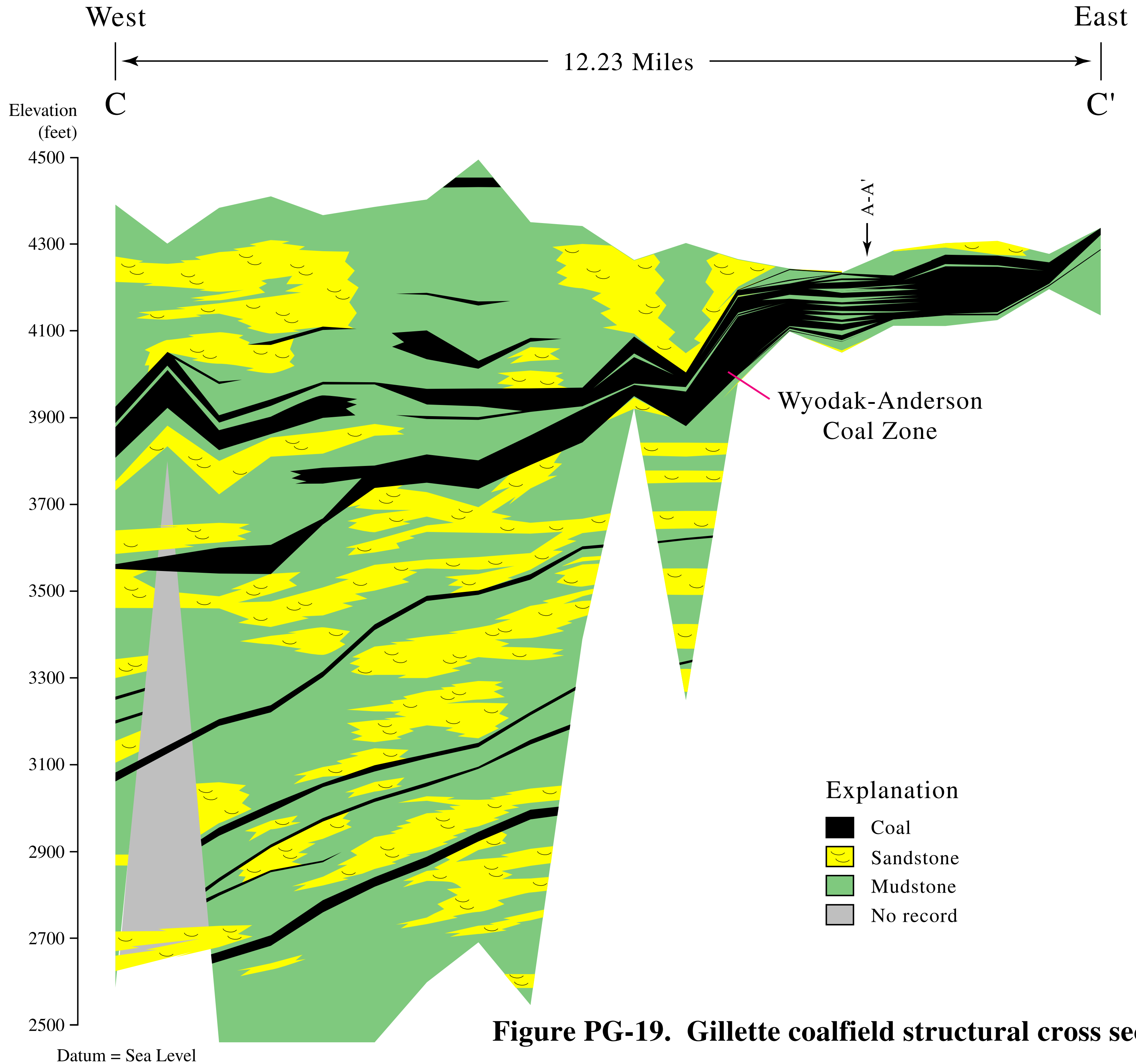

Figure PG-19. Gillette coalfield structural cross section C-C'.

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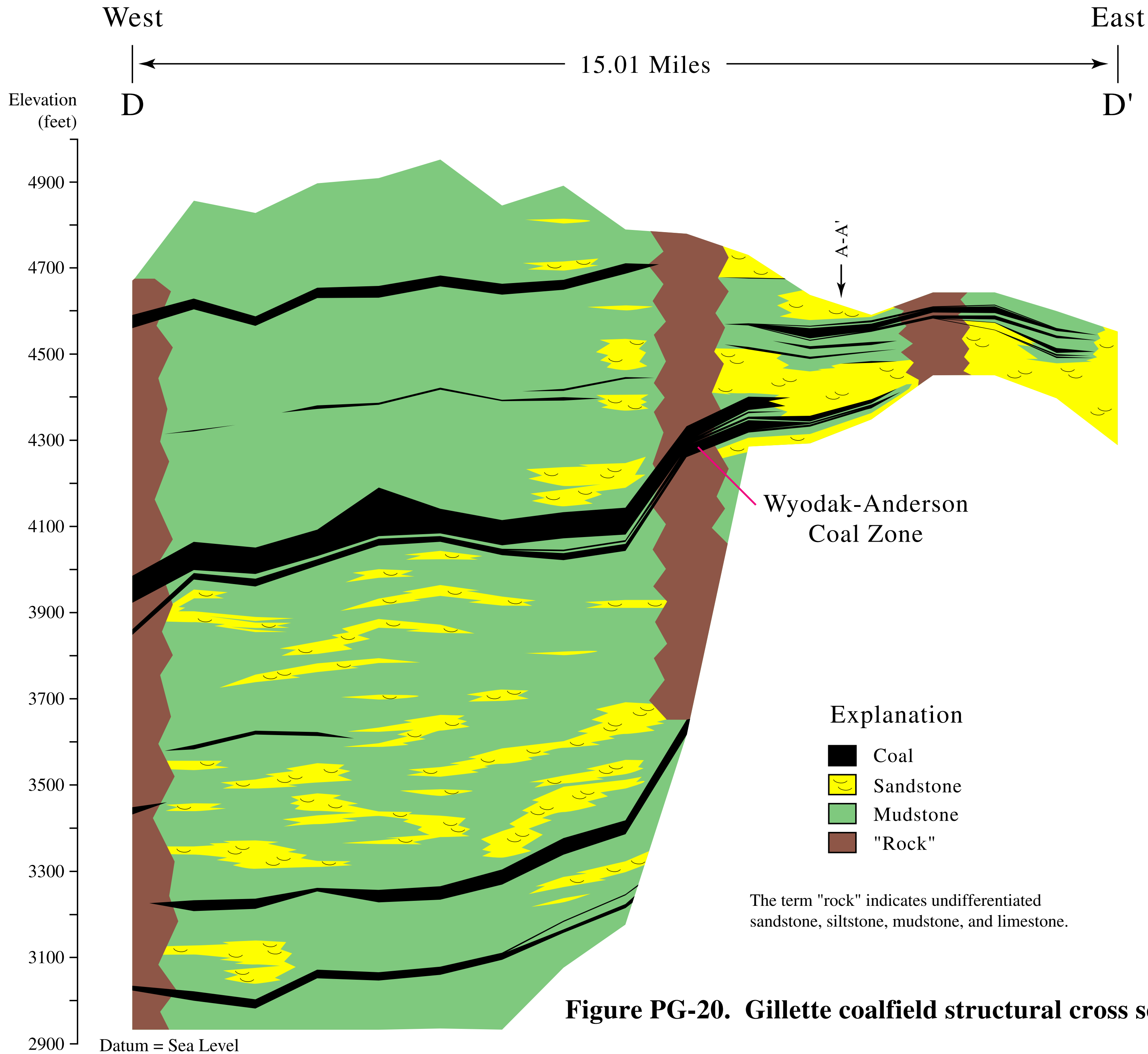

Figure PG-20. Gillette coalfield structural cross section D-D'.

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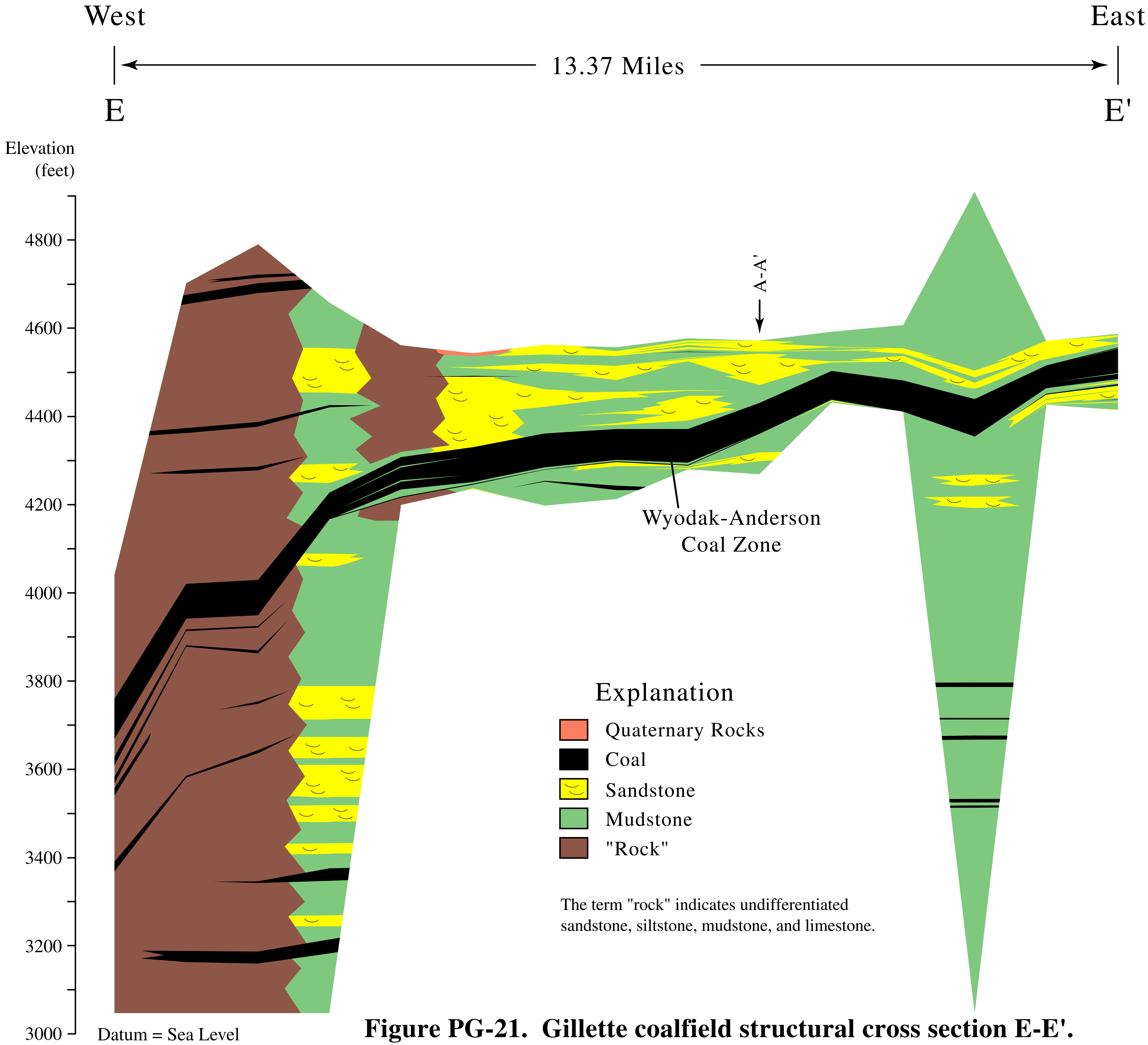

Figure PG-21. Gillette coalfield structural cross section E-E'.

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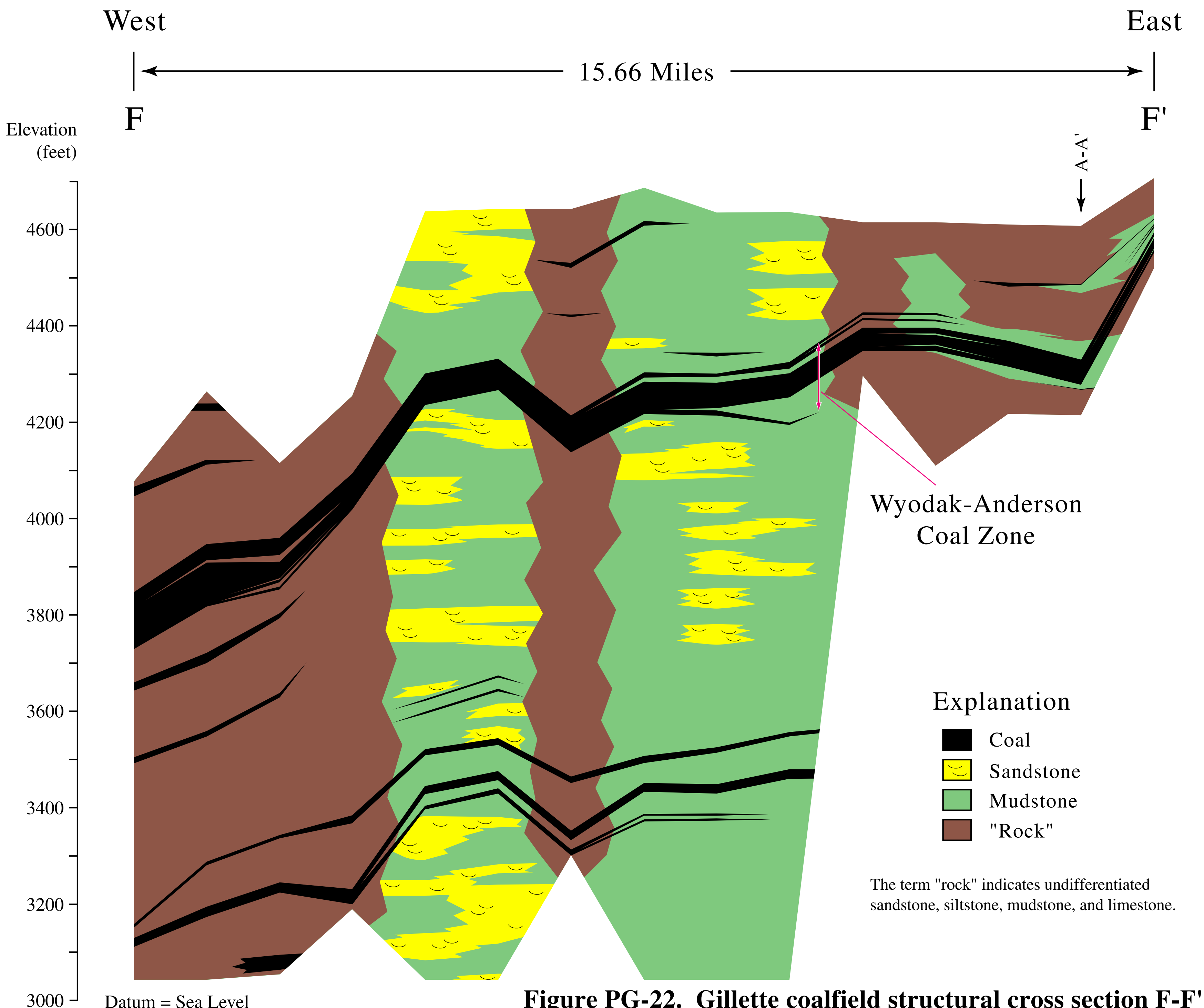

Figure PG-22. Gillette coalfield structural cross section F-F'.

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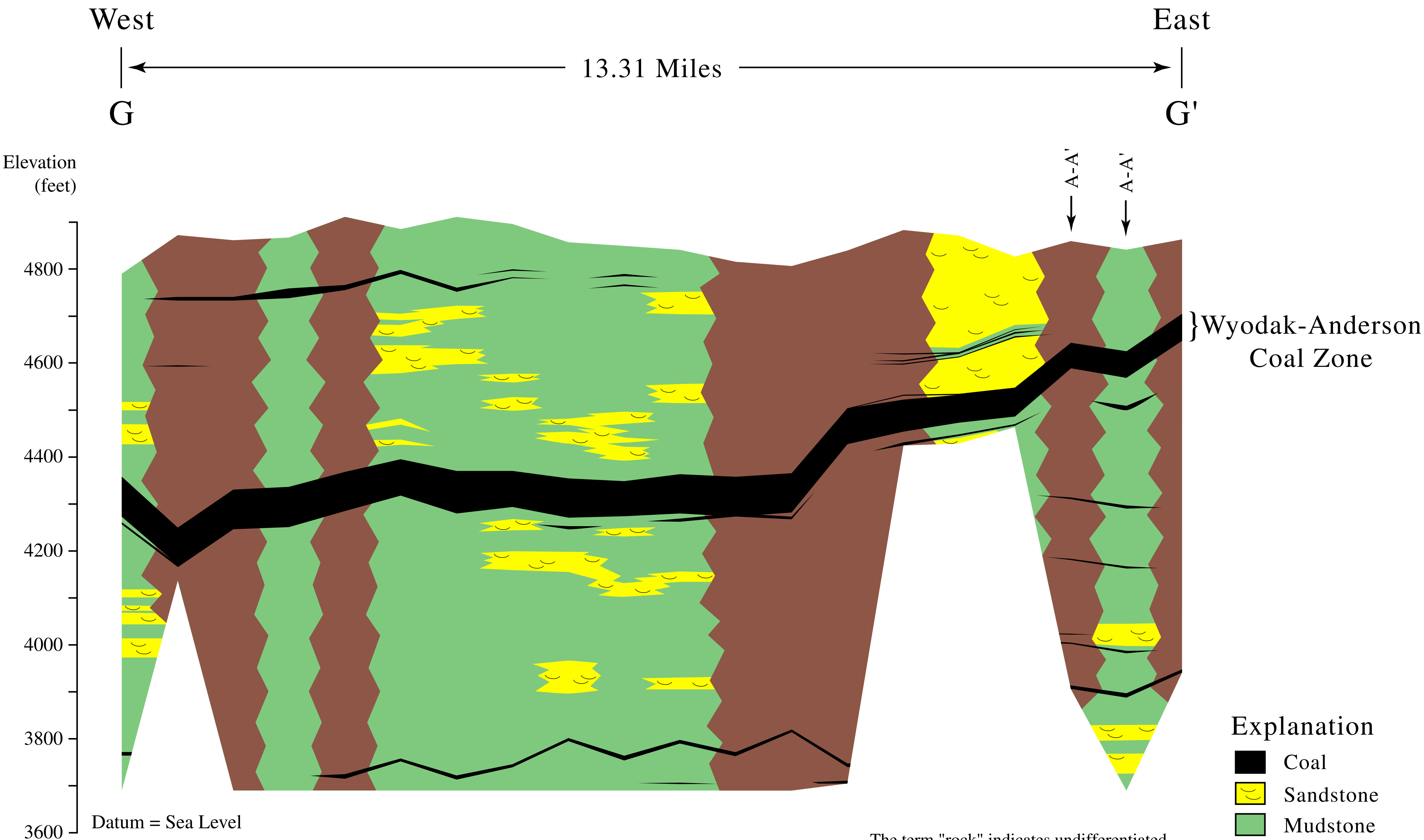

Figure PG-23. Gillette coalfield structural cross section G-G'.

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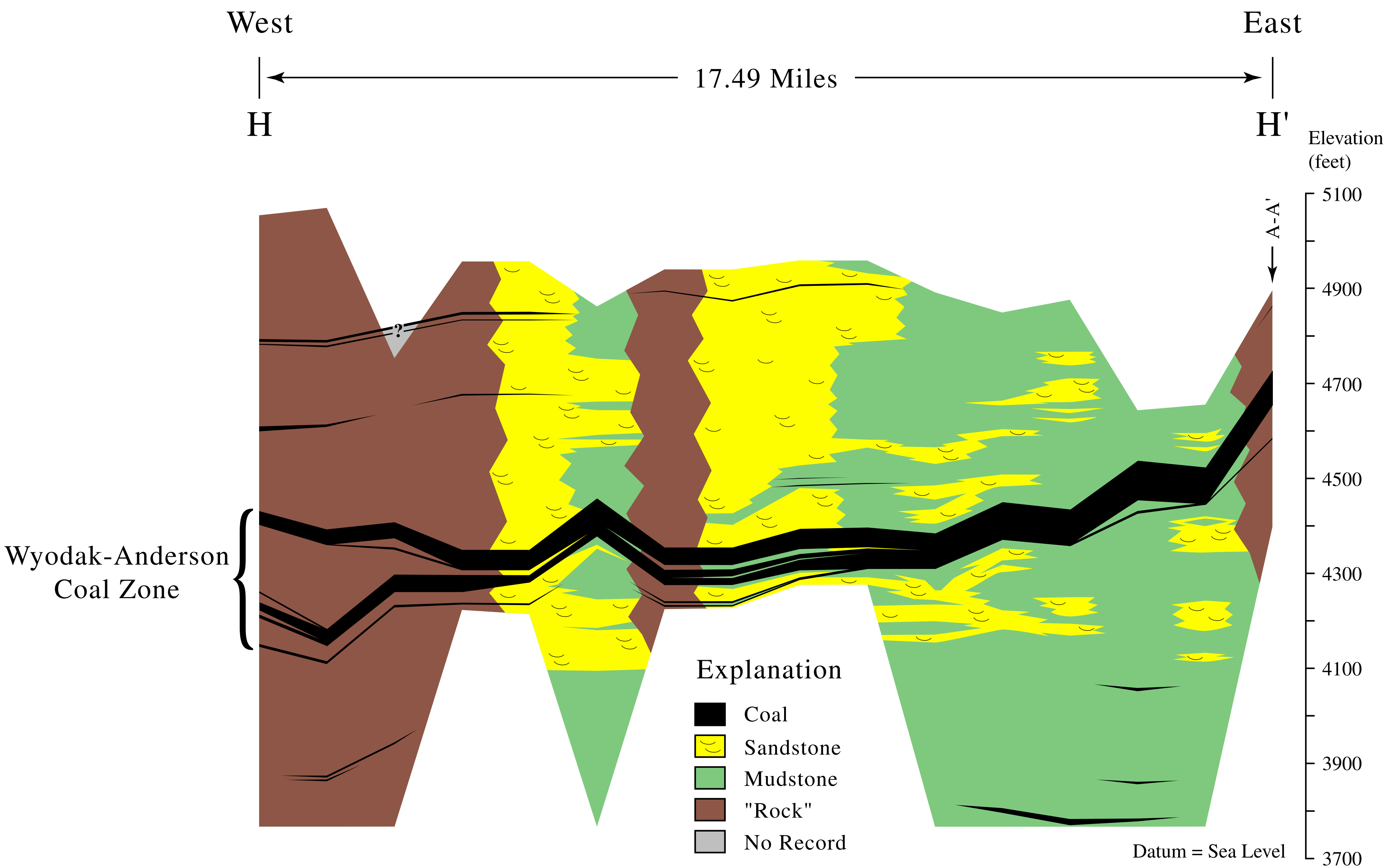

The term "rock" indicates undifferentiated
sandstone, siltstone, mudstone, and limestone.

Figure PG-24. Gillette coalfield structural cross section H-H'.

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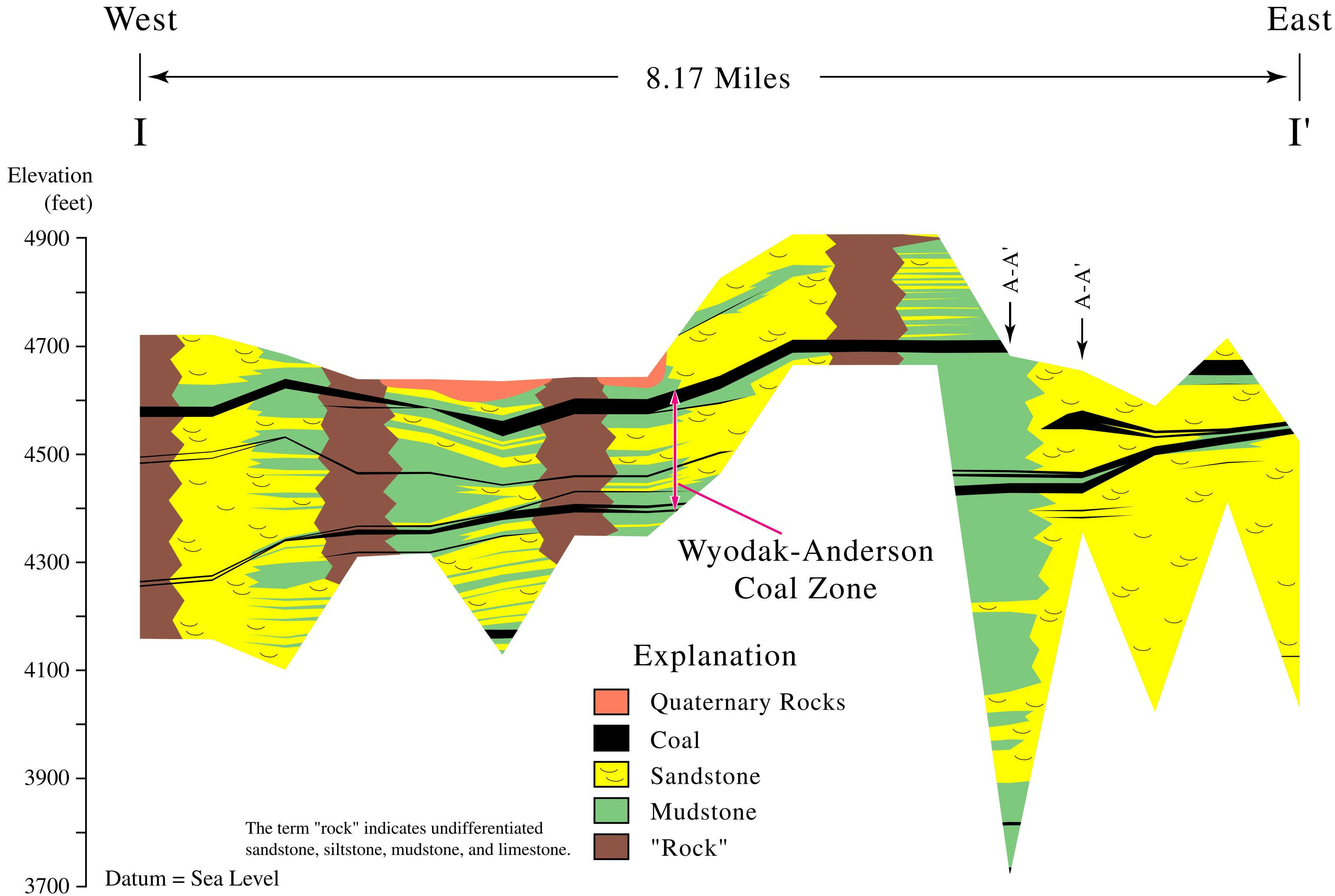

Figure PG-25. Gillette coalfield structural cross section I-I'.

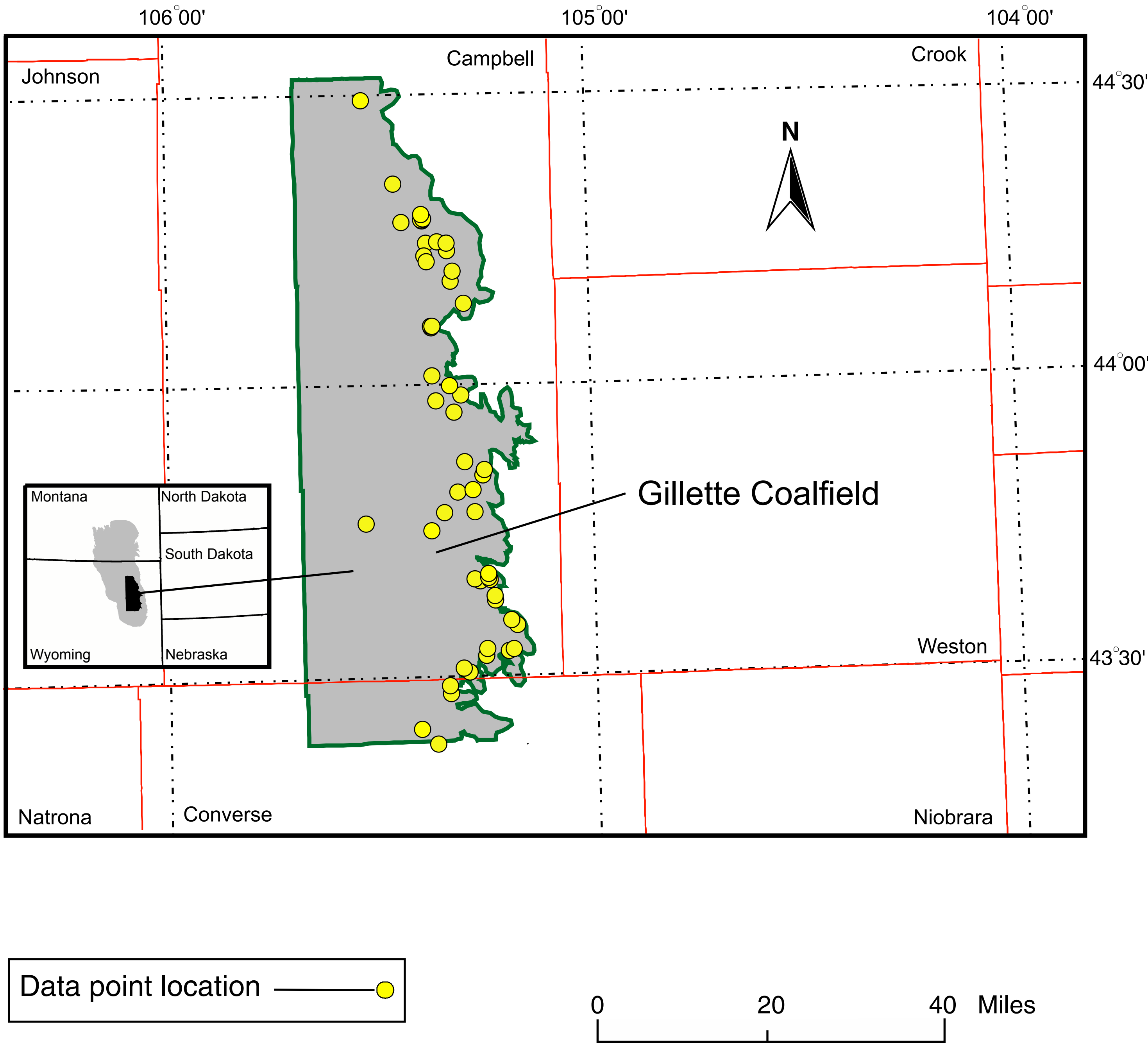

Figure PG-26. Index map showing coal quality data distribution in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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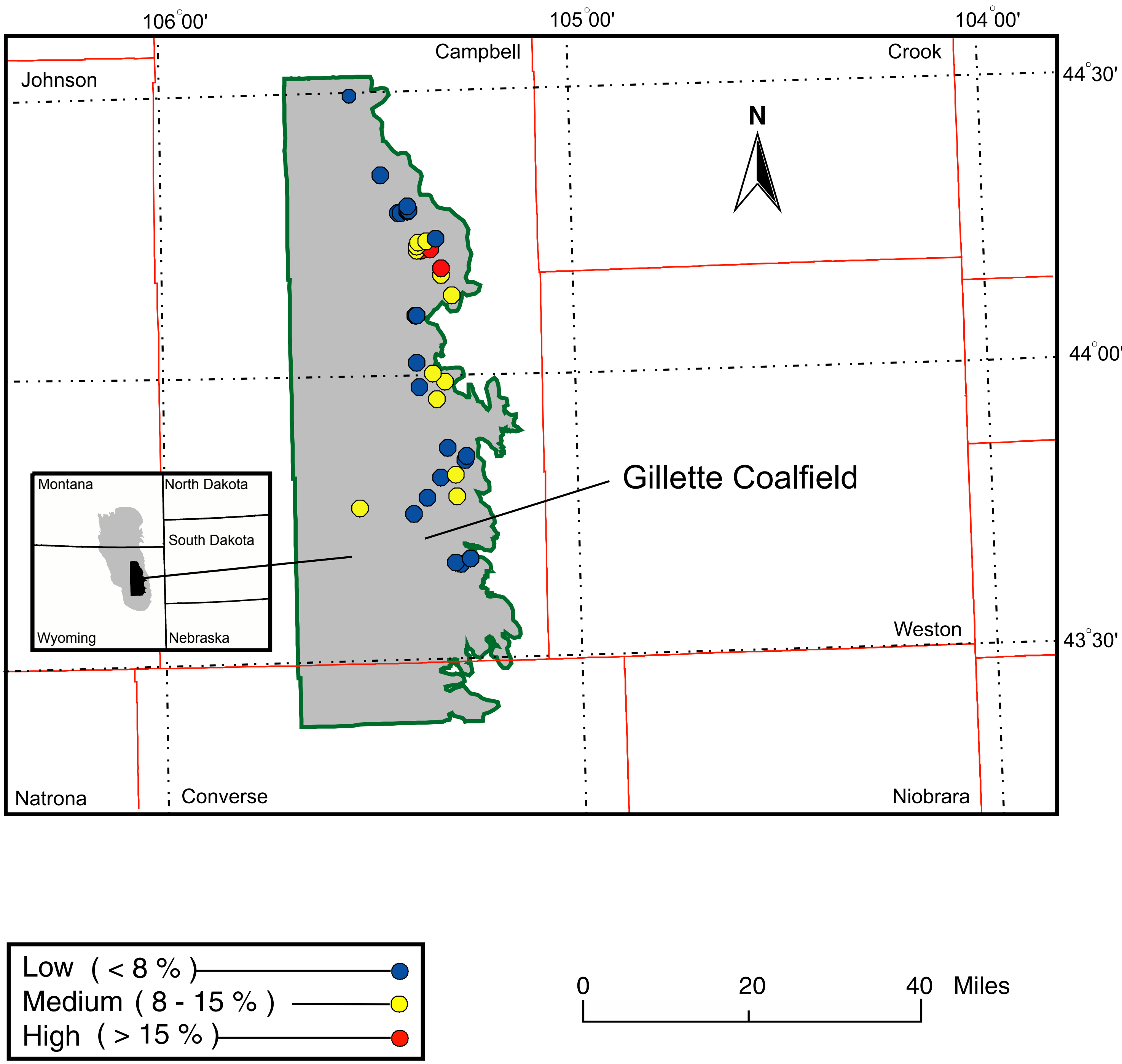

Figure PG-27. Ash yield in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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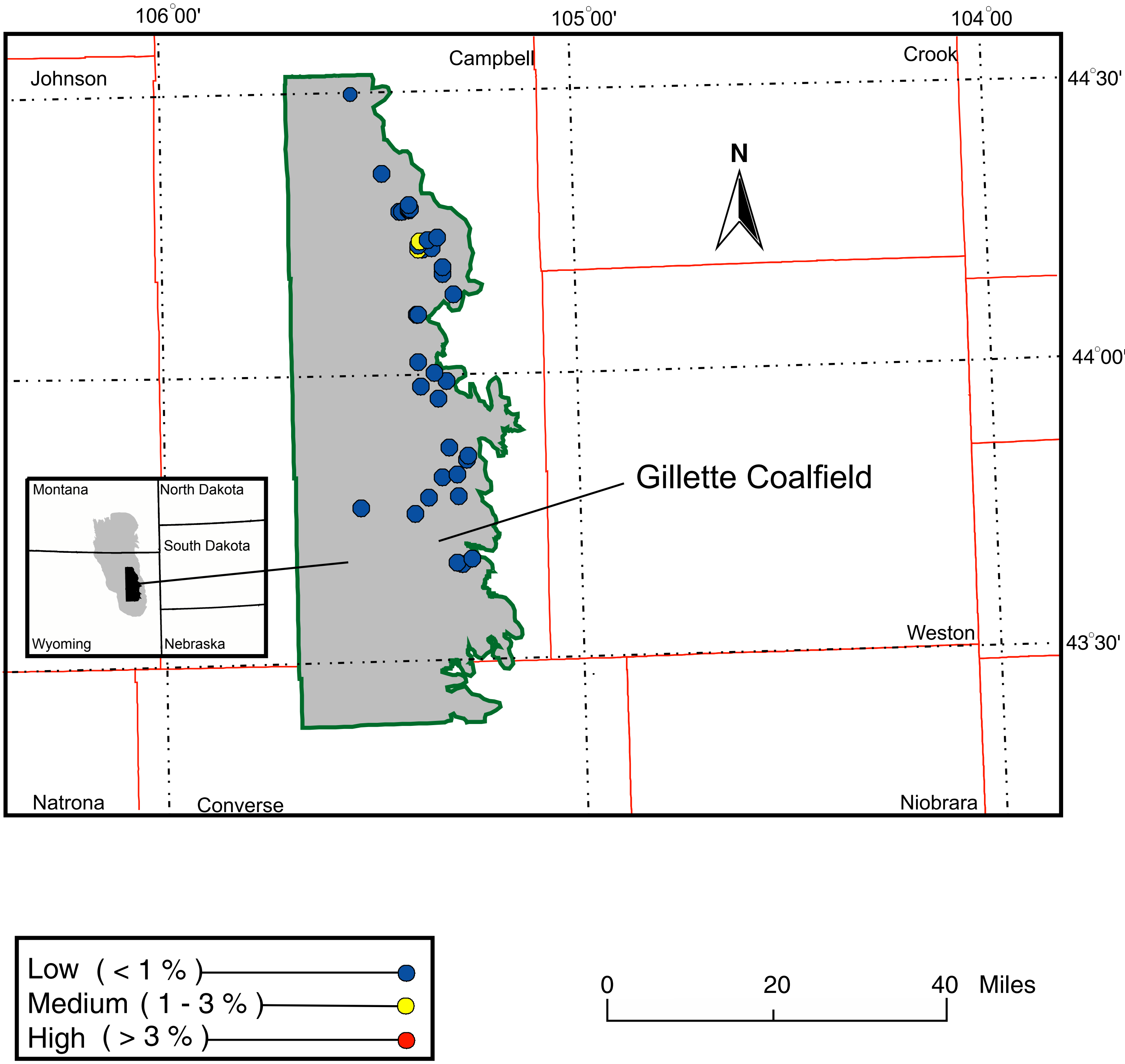

Figure PG-28. Sulfur content in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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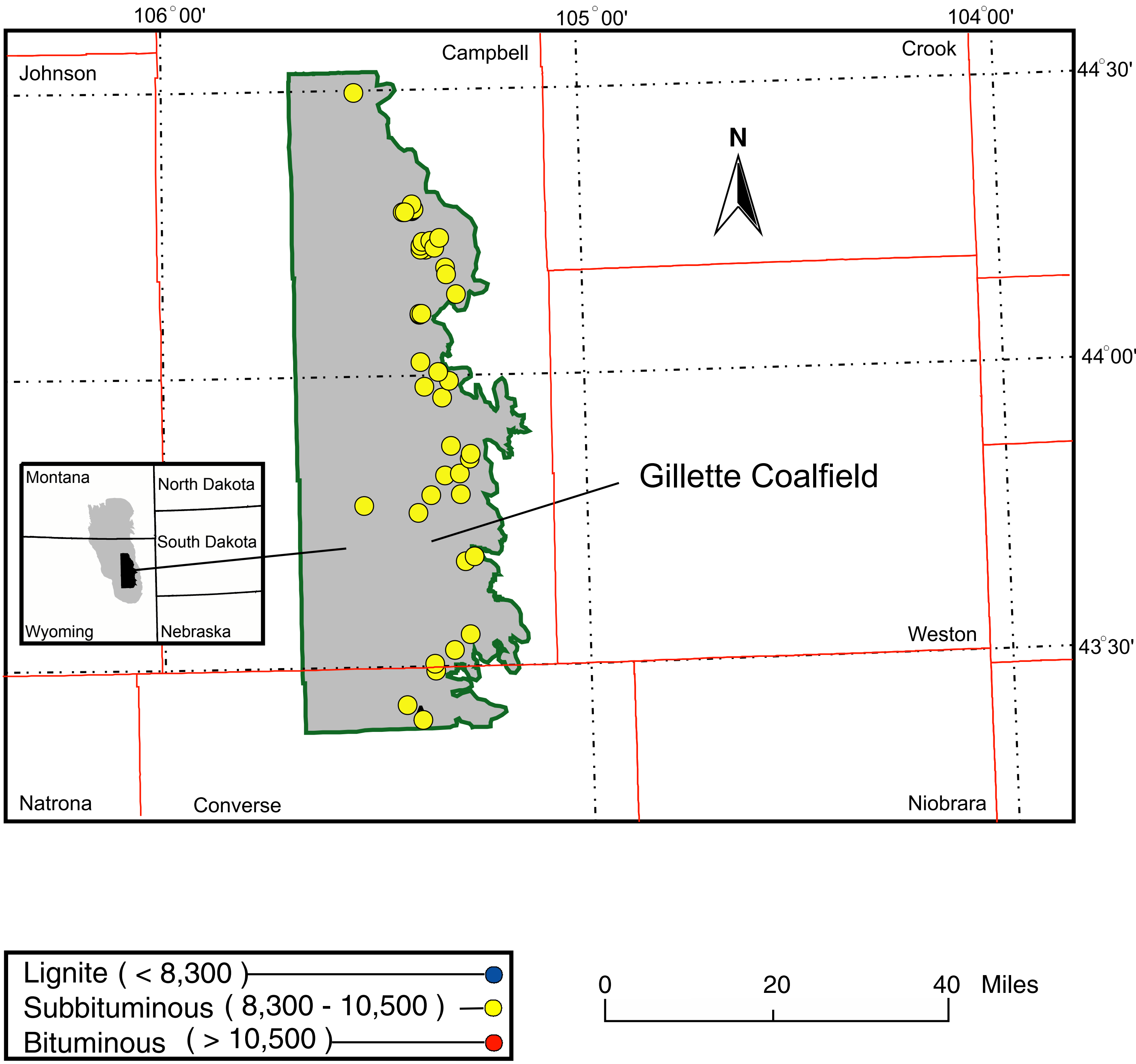

Figure PG-29. Moist-mineral-matter free Btu/lb in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

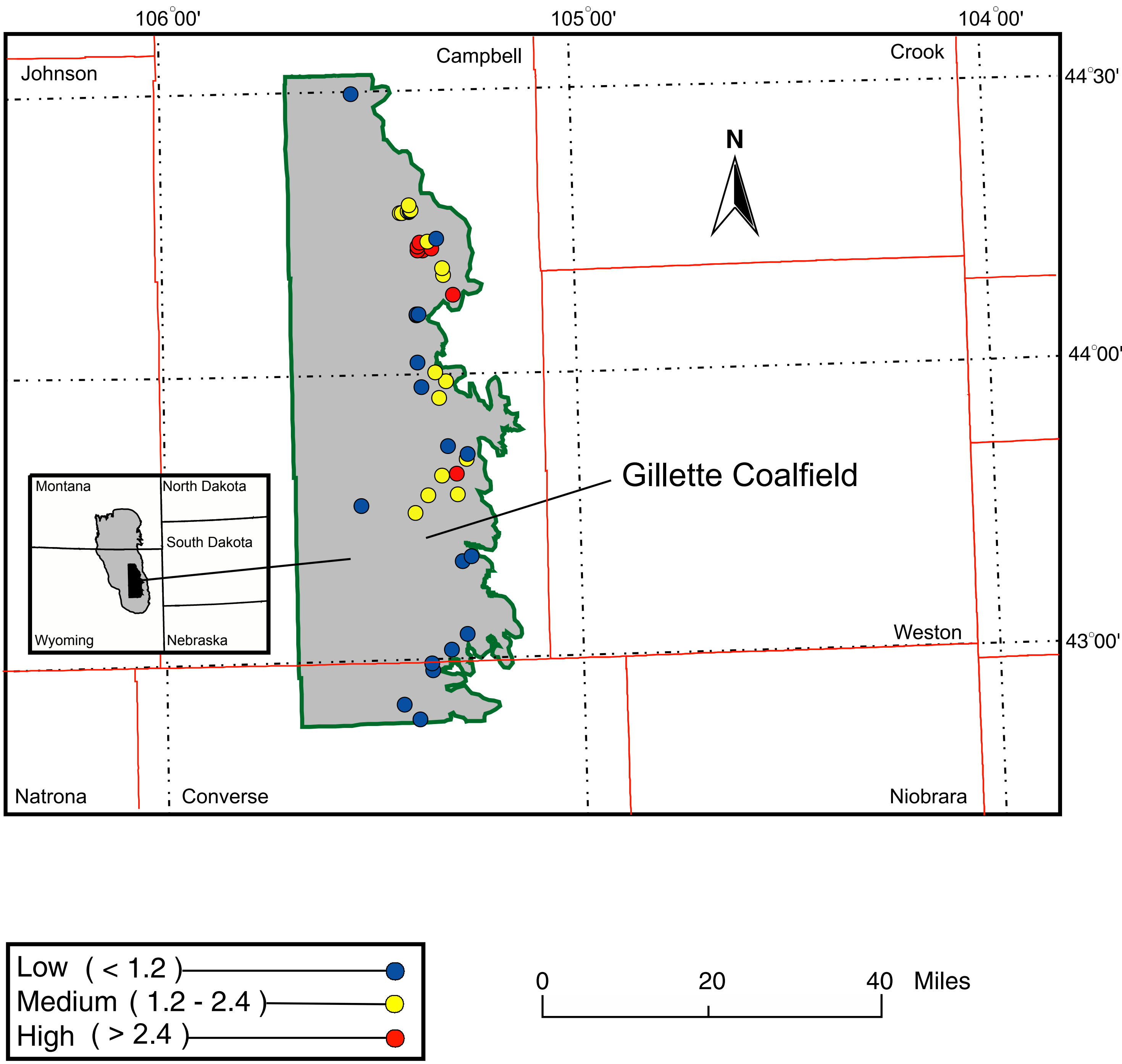

Figure PG-30. Pounds of sulfur dioxide per million Btu in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

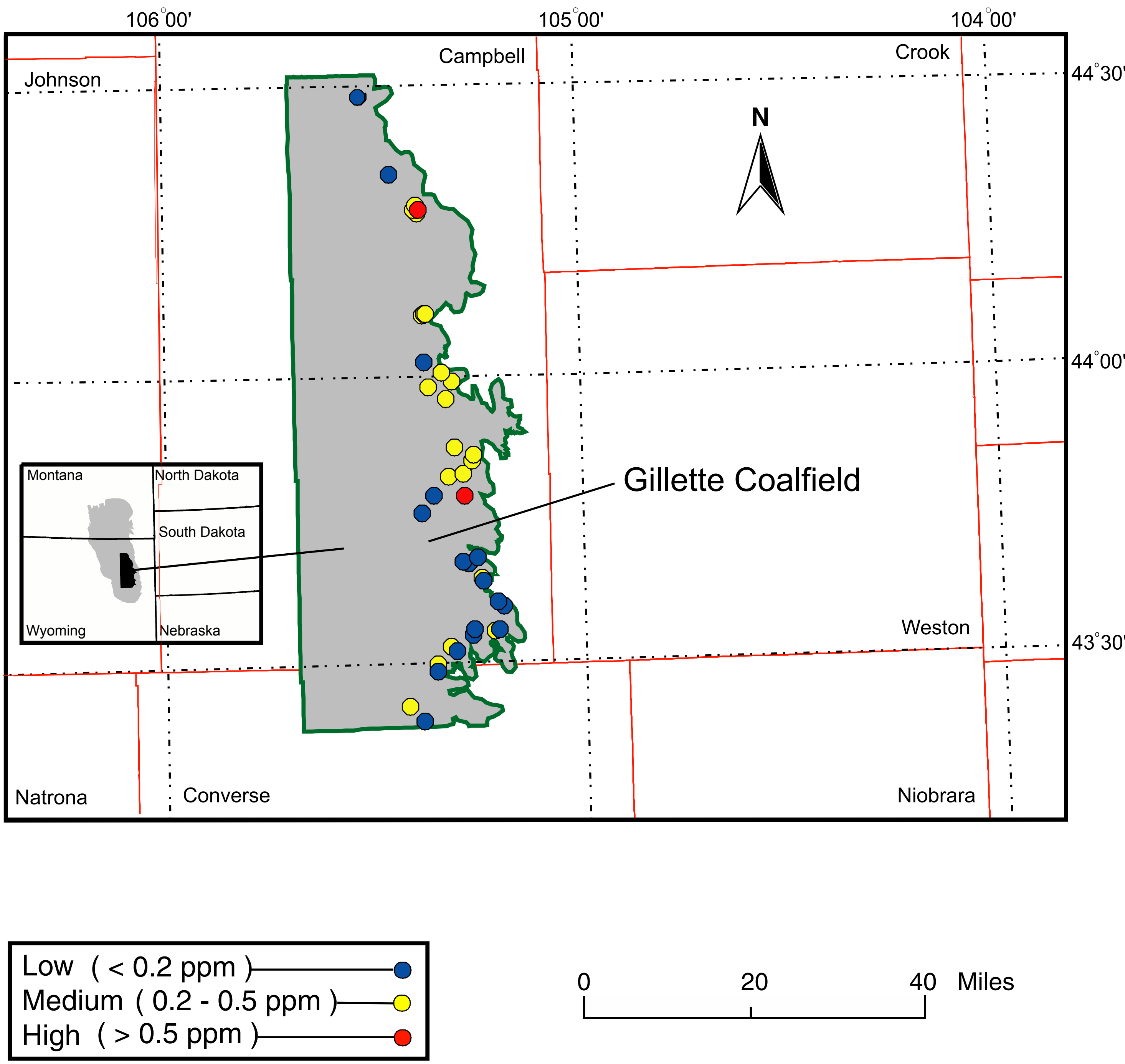

Figure PG-31. Antimony concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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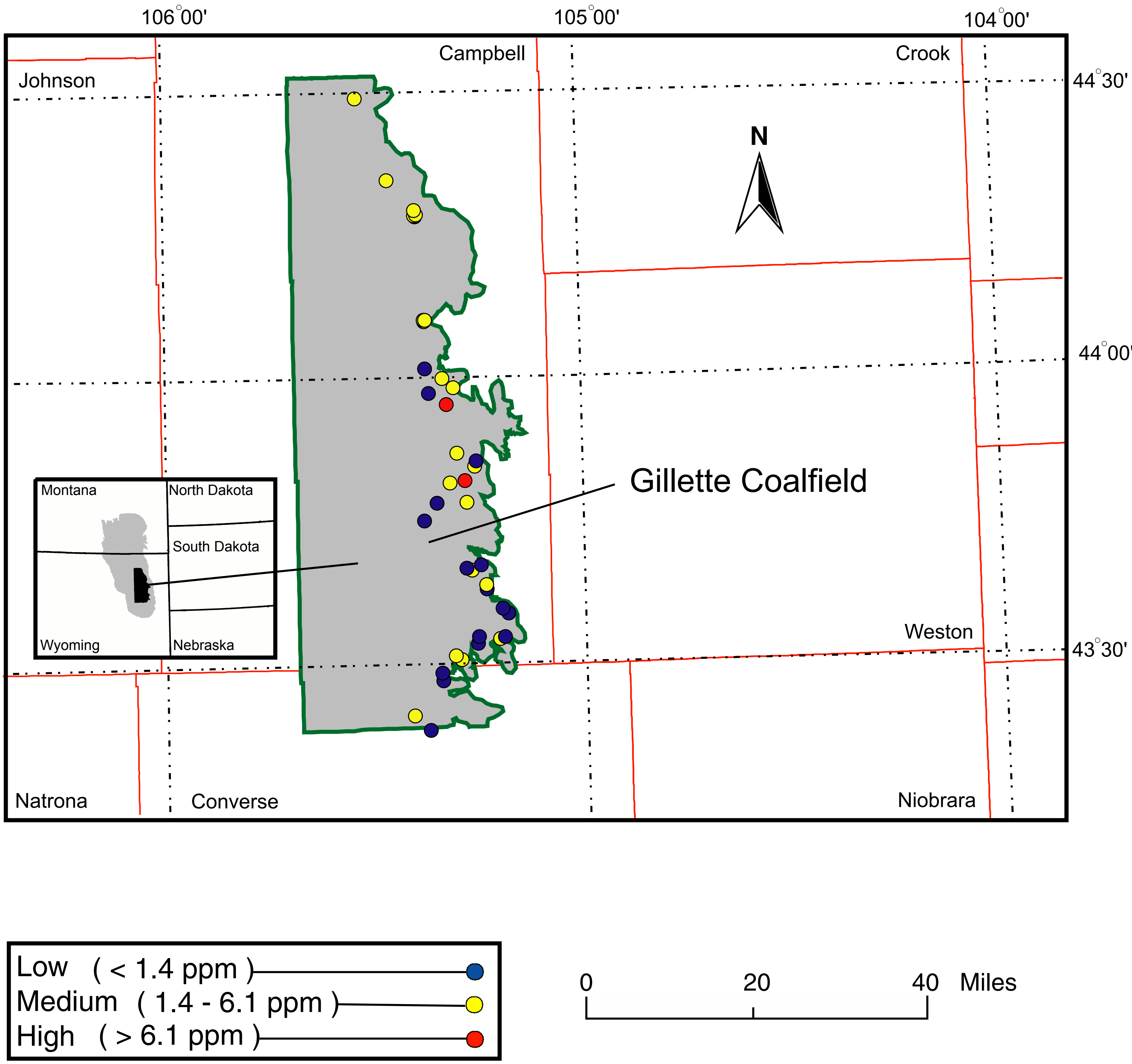

Figure PG-32. Arsenic concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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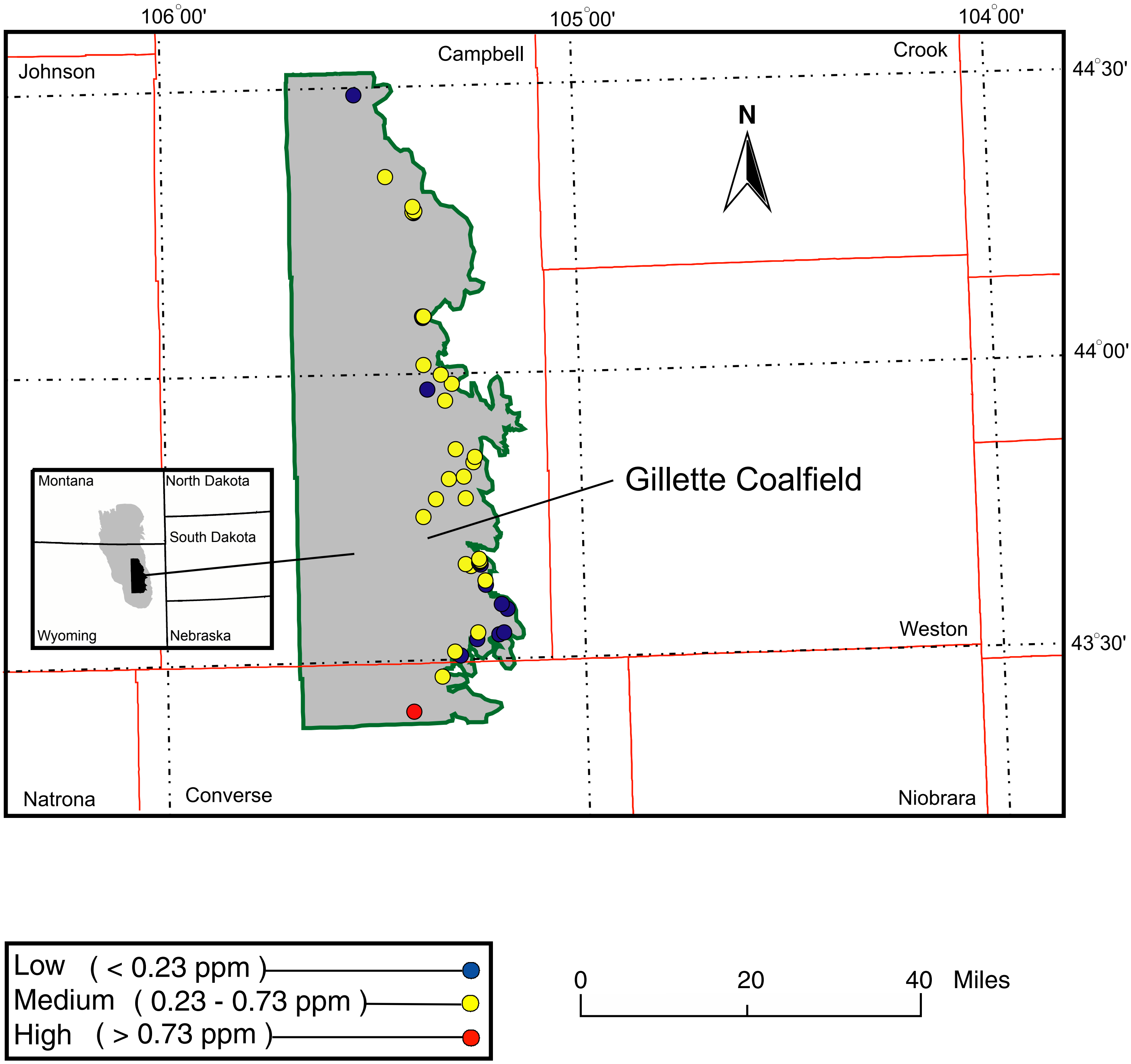

Figure PG-33. Beryllium concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

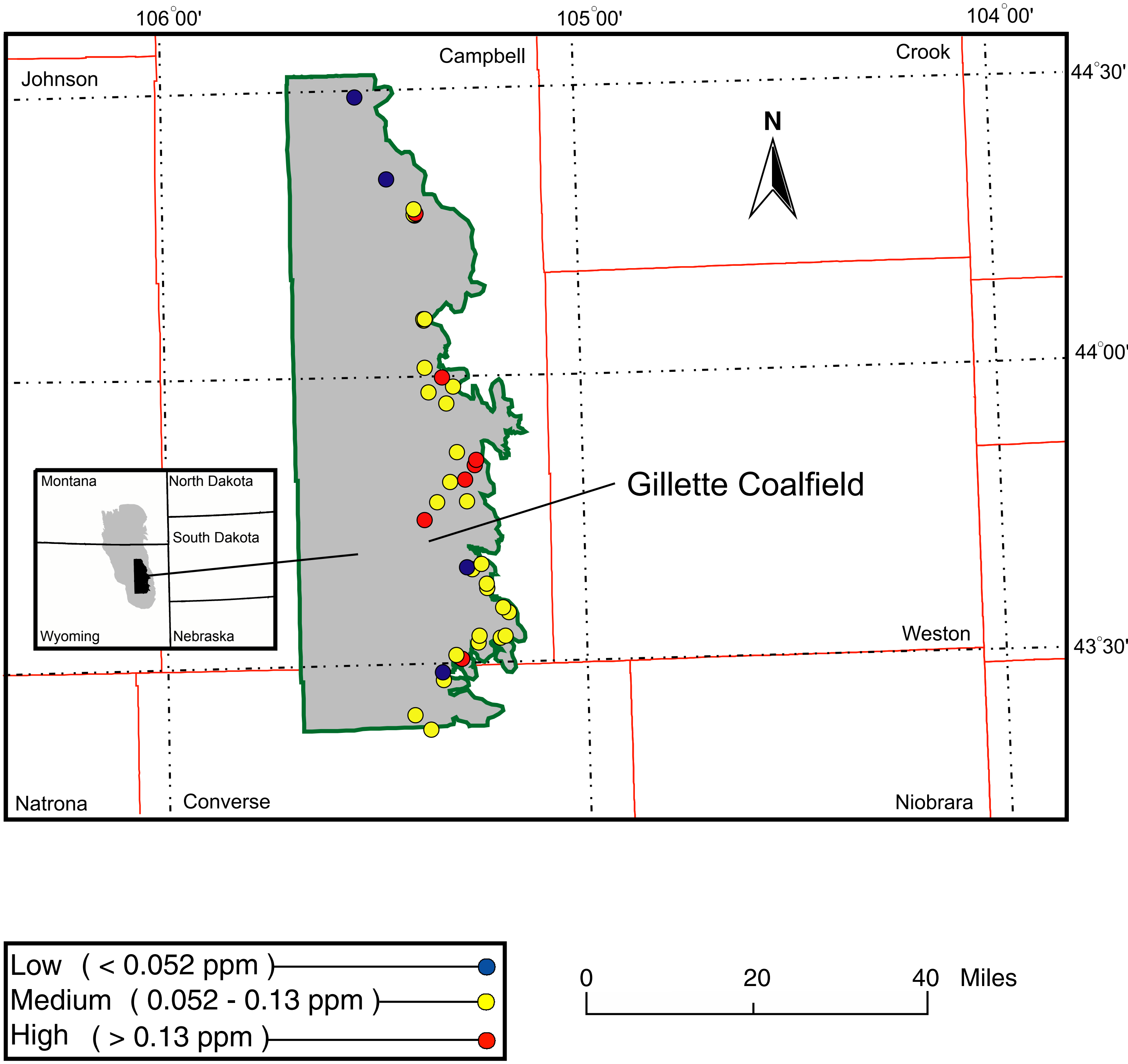

Figure PG-34. Cadmium concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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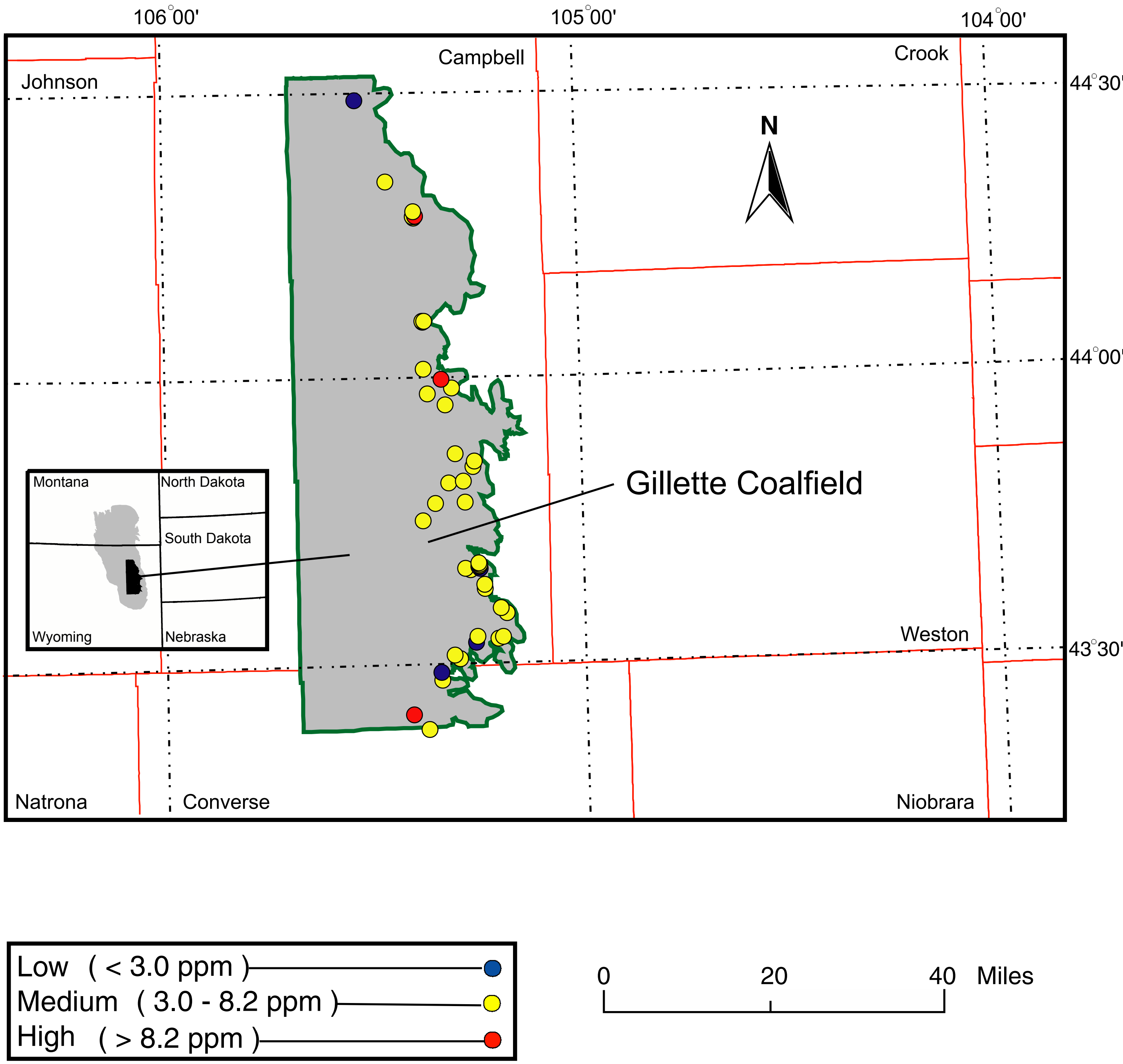

Figure PG-35. Chromium concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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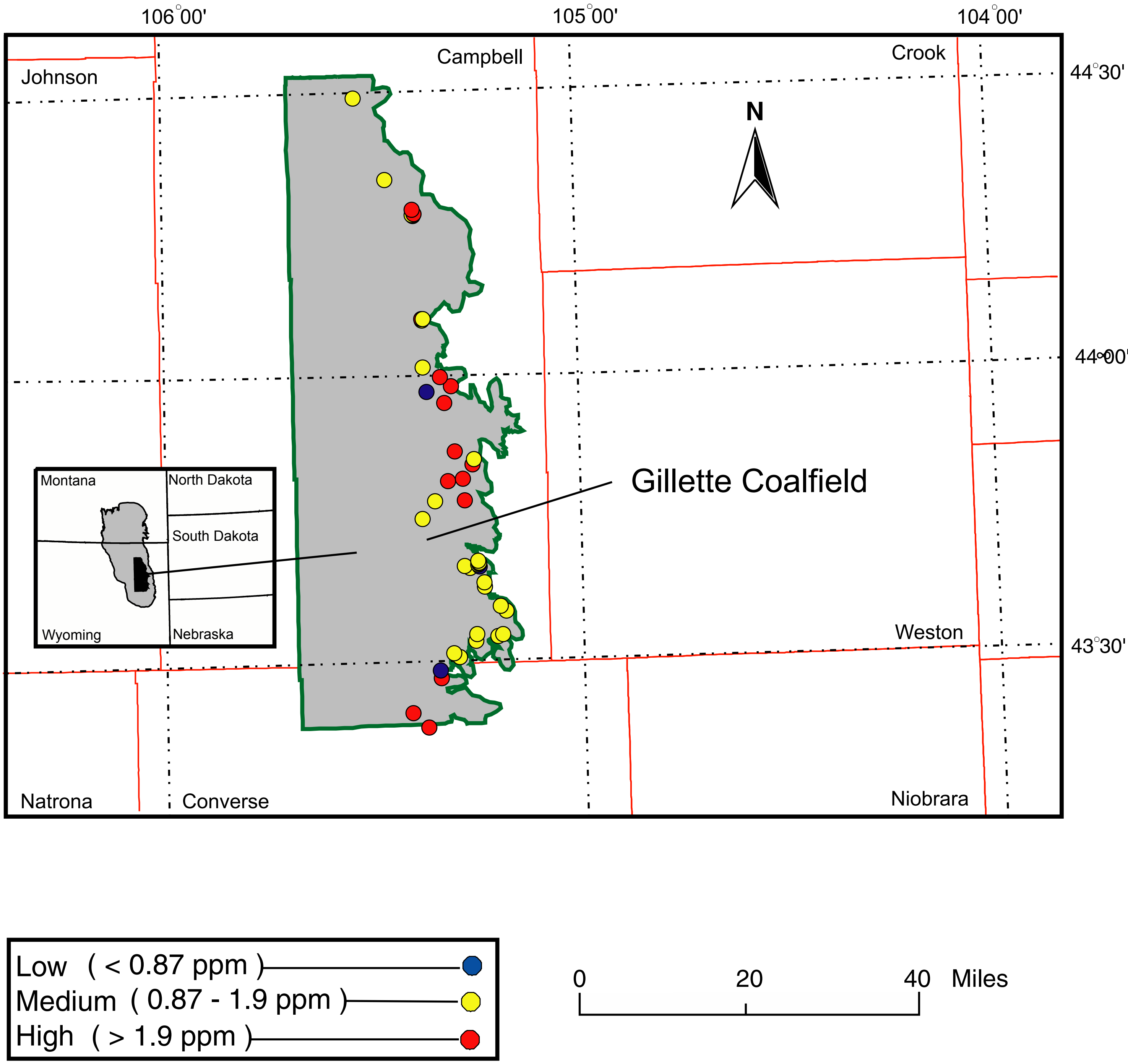

Figure PG-36. Cobalt concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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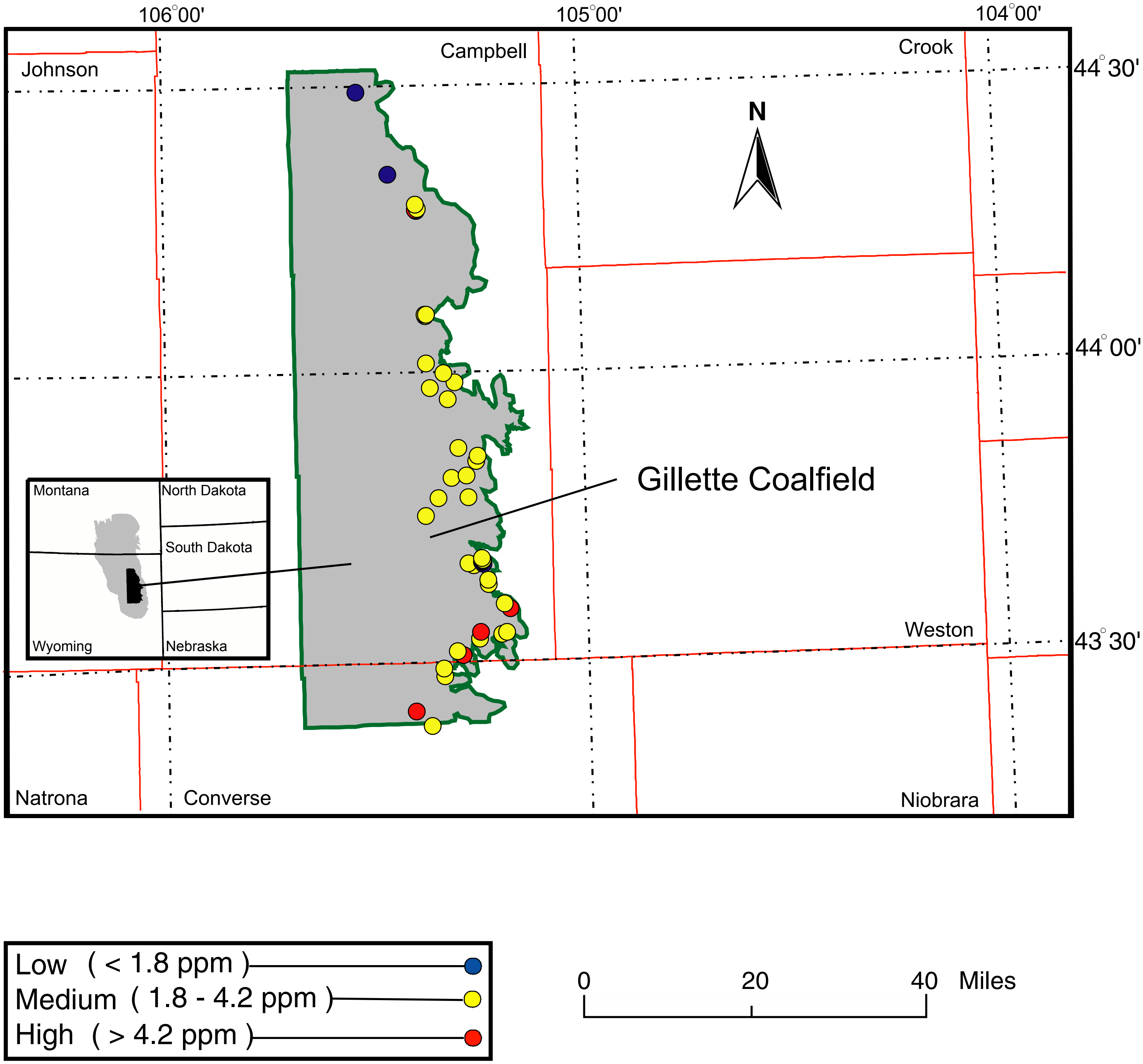

Figure PG-37 Lead concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

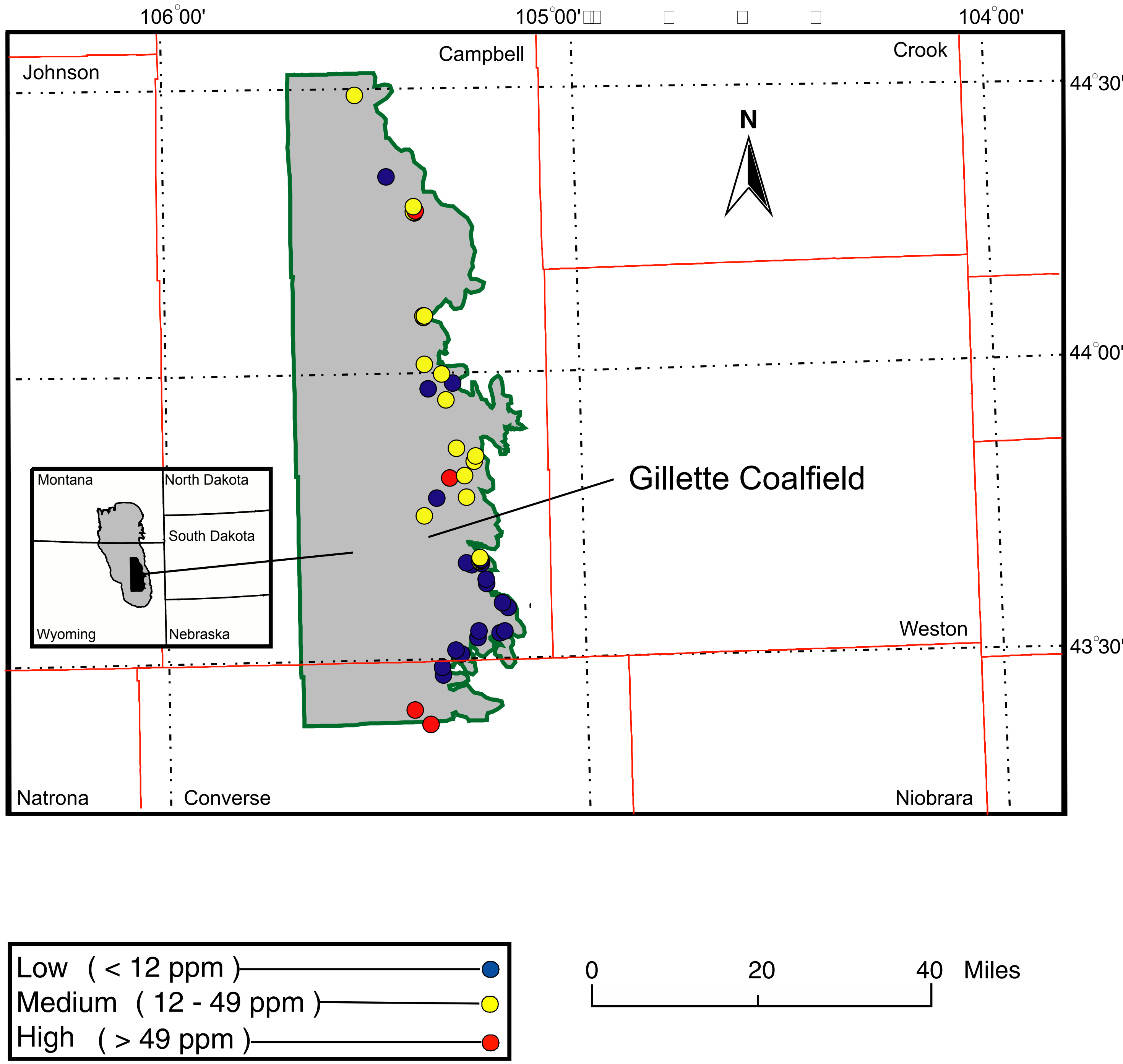

Figure PG-38. Manganese concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

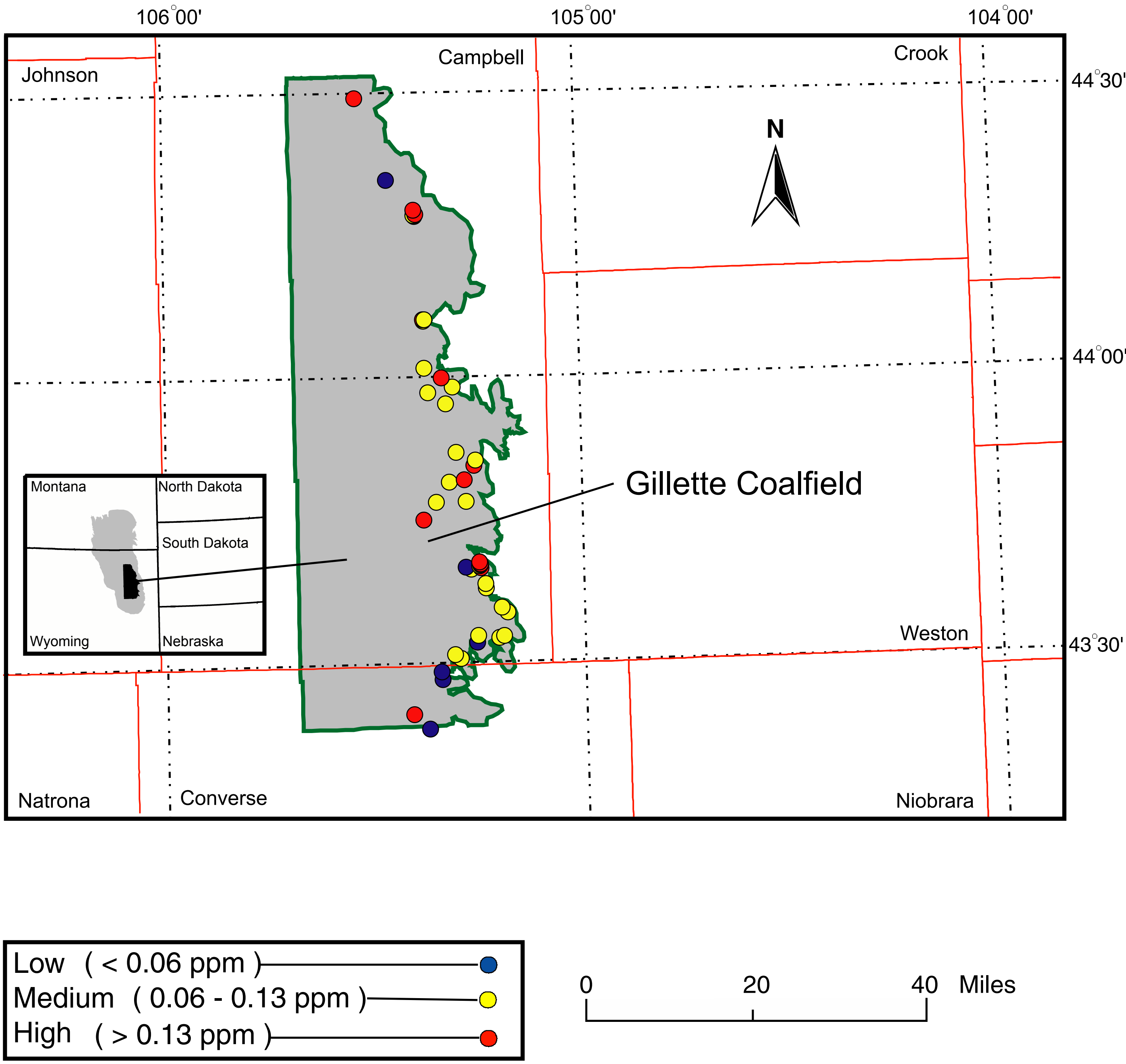

Figure PG-39. Mercury concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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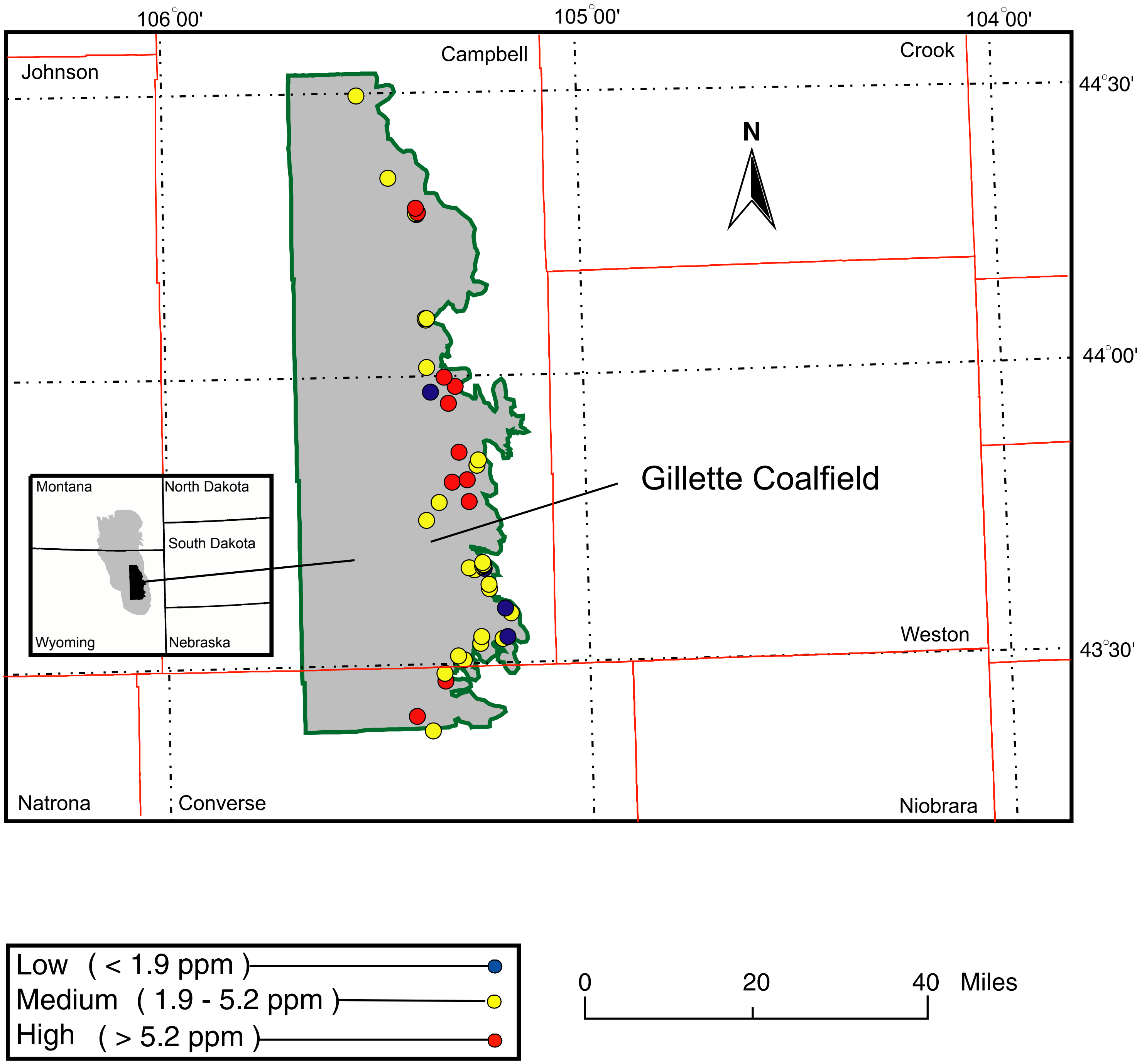

Figure PG-40. Nickel concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

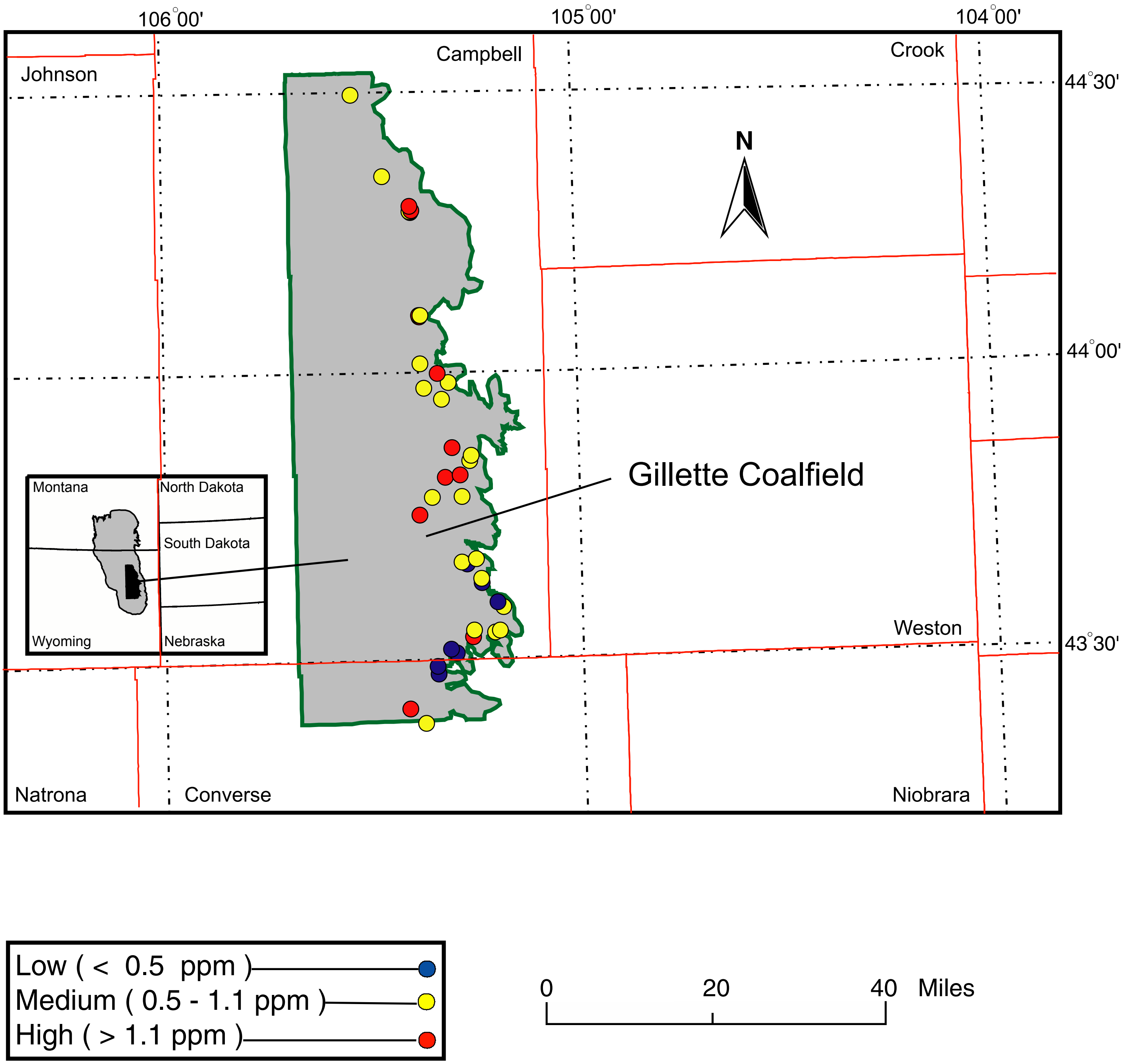

Figure PG-41. Selenium concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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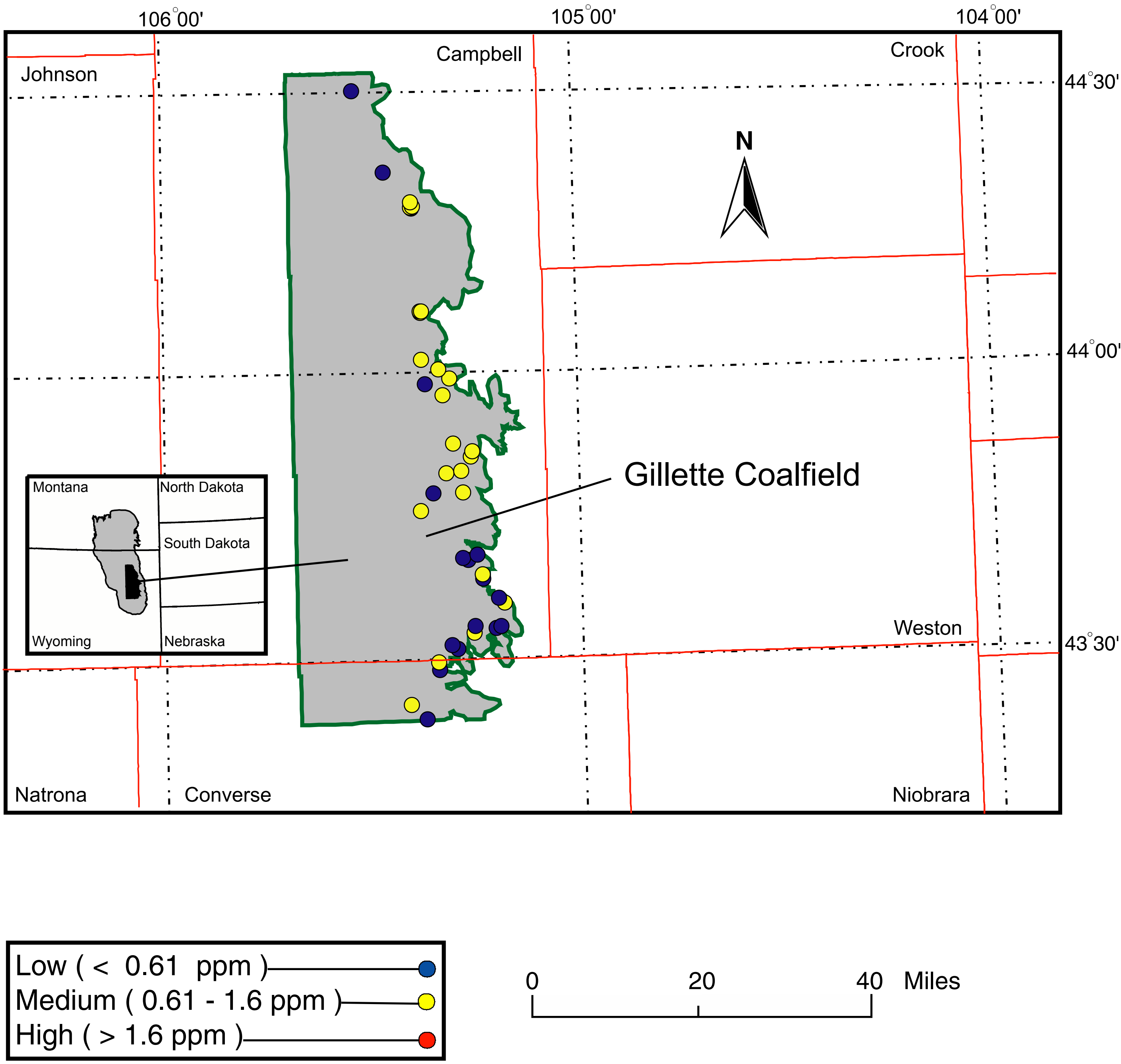

Figure PG-42. Uranium concentration in the Wyodak-Anderson coal zone, Gillette coalfield, Powder River Basin, Wyoming.

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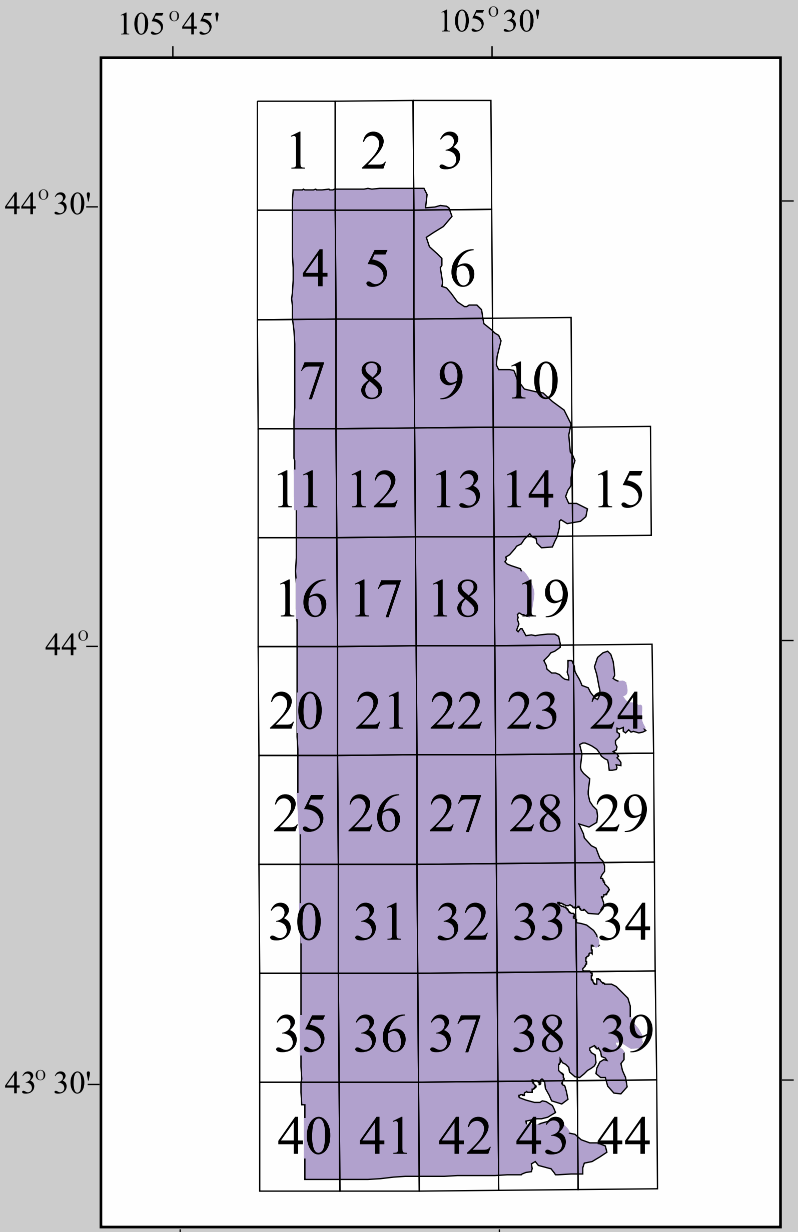

Key to 7.5-minute quadrangle maps

1 WILDCAT
2 CALF CREEK
3 WESTON SW
4 ORIVA NW
5 RAWHIDE SCHOOL
6 MOYER SPRINGS
7 ORIVA
8 GILLETTE WEST
9 GILLETTE EAST
10 FORTIN DRAW
11 FOUR BAR J RANCH
12 APPEL BUTTE
13 THE GAP
14 COYOTE DRAW
15 COON TRACK CREEK
16 PLEASANTDALE
17 SCAPER RESERVOIR
18 THE GAP SW
19 SADDLE HORSE BUTTE
20 PEPSSON DRAW
21 THREEMILE CREEK RESERVOIR
22 EAGLE ROCK
23 NEIL BUTTE
24 ROUGH CREEK
25 GREASEWOOD RESERVOIR
26 ROCKY BUTTE GULCH
27 RENO JUNCTION
28 HILIGHT
29 OPEN A RANCH
30 BAKER SPRING
31 RATTLESNAKE DRAW
32 LITTLE THUNDER RESERVOIR
33 RENO RESERVOIR
34 PINEY CANYON NW
35 TURNERCREST
36 RENO FLATS
37 TECKLA SW
38 TECKLA
39 PINEY CANYON SW
40 MACKEN DRAW
41 COAL DRAW NORTH
42 BETTY RESERVOIR
43 DUGOUT CREEK NORTH
44 COAL BANK DRAW

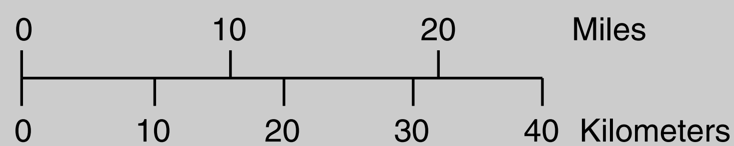

Figure PG-43. Location of 7.5-minute quadrangle maps in the Wyodak-Anderson study limit of the Gillette coalfield.

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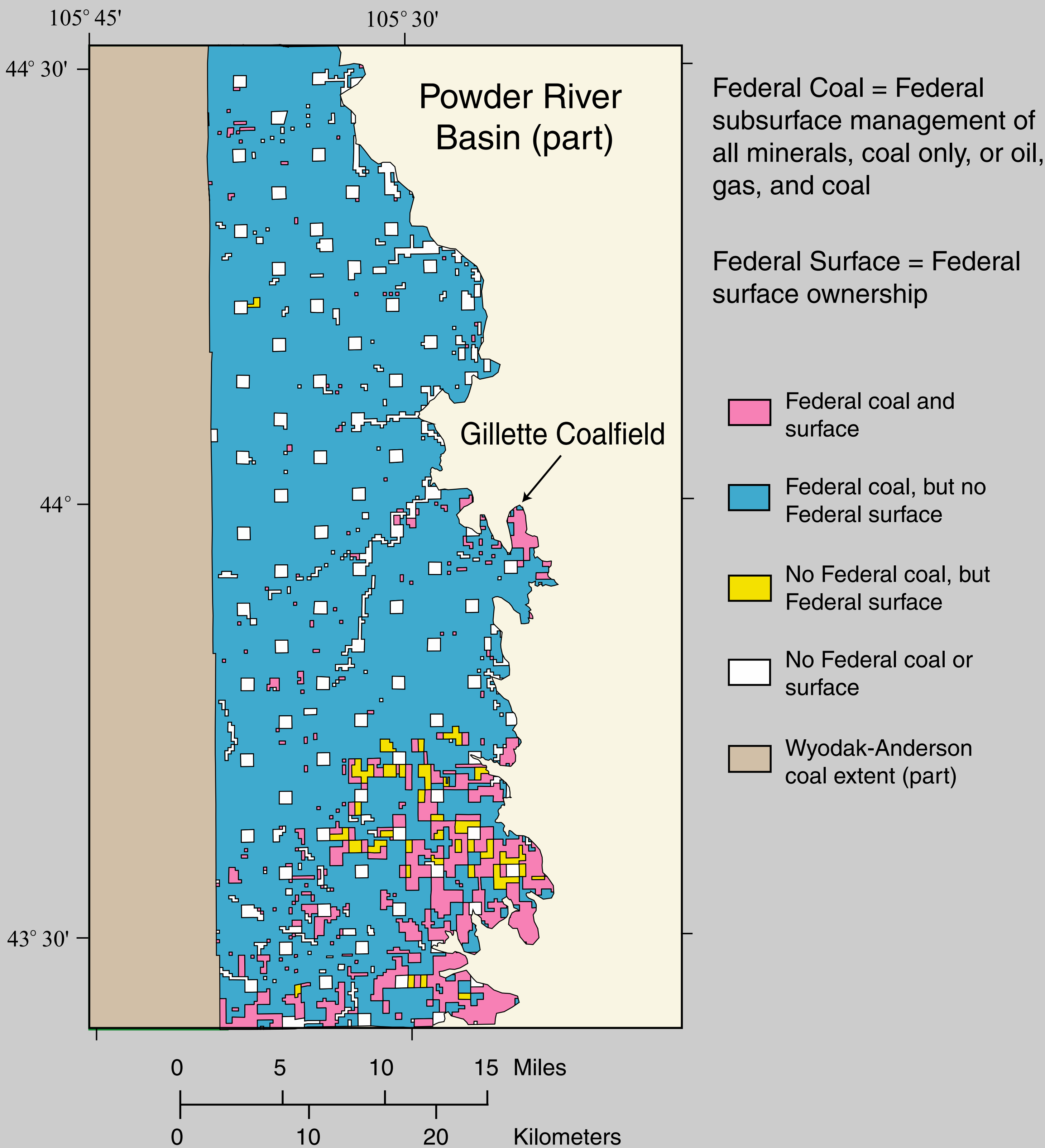

Figure PG-44. Federal coal and Federal surface ownership in the Gillette coalfield.

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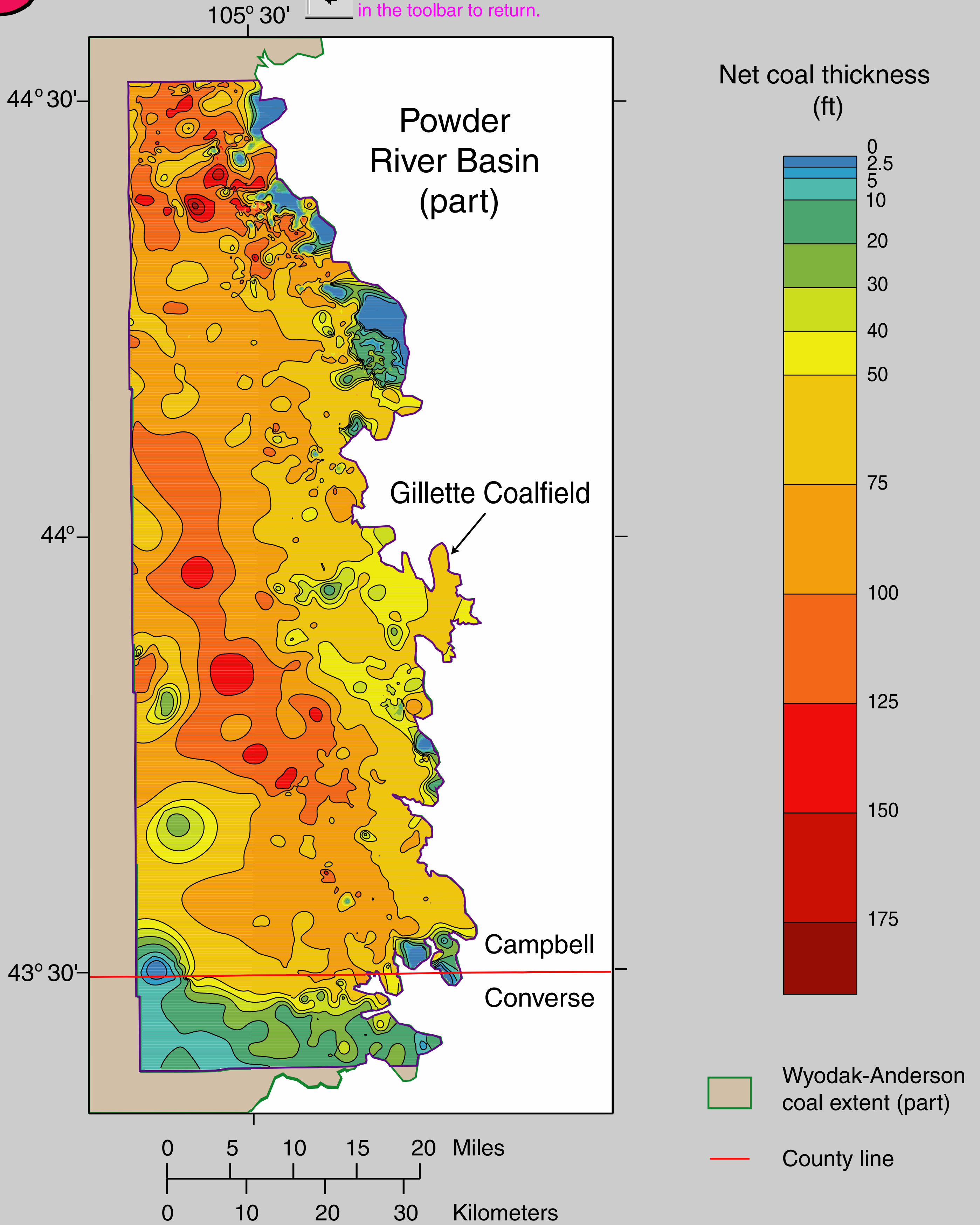

Figure PG-45. Wyodak-Anderson net coal isopach map for the Gillette coalfield.

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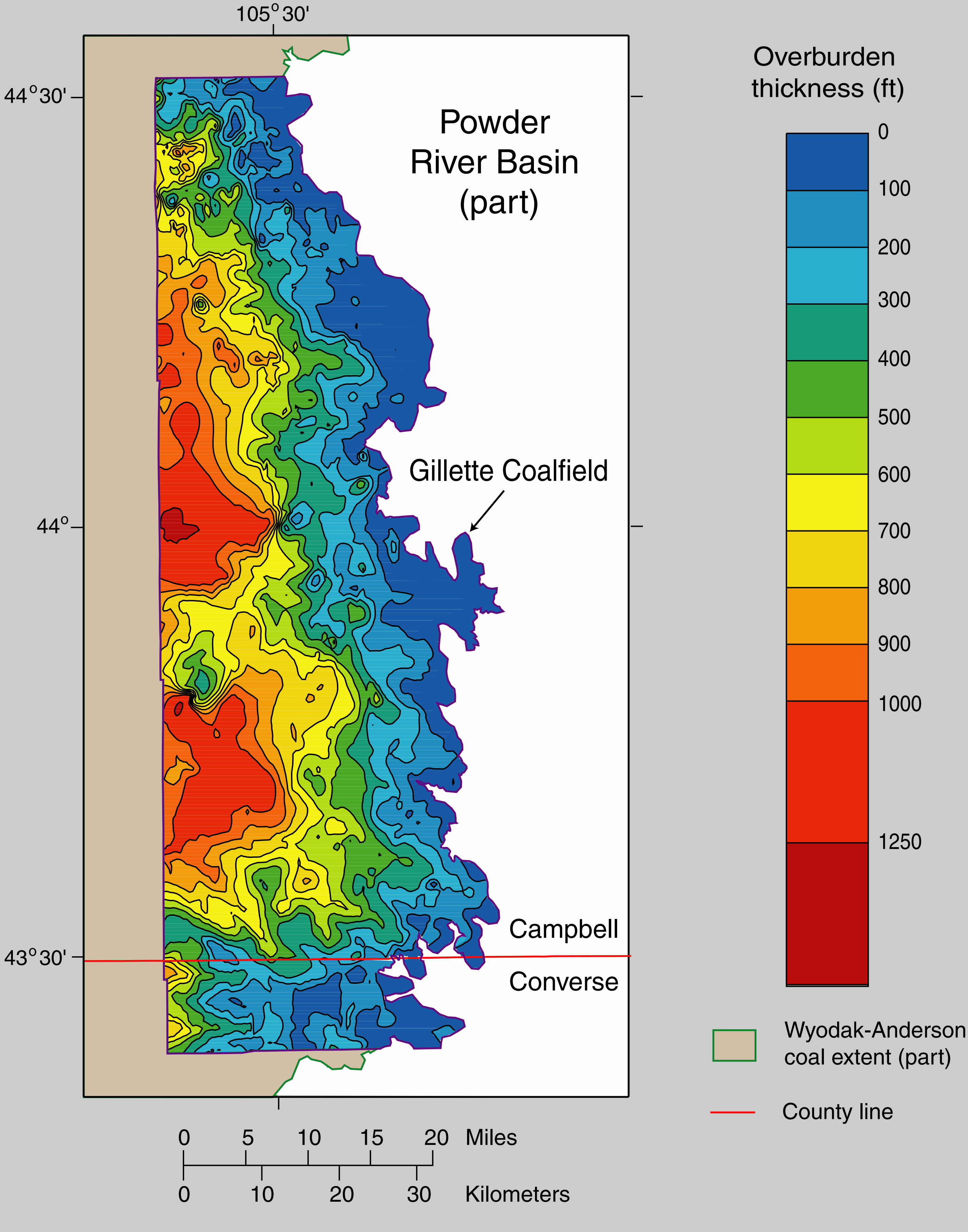

Figure PG-46 Wyodak-Anderson overburden isopach map for the Gillette coalfield.

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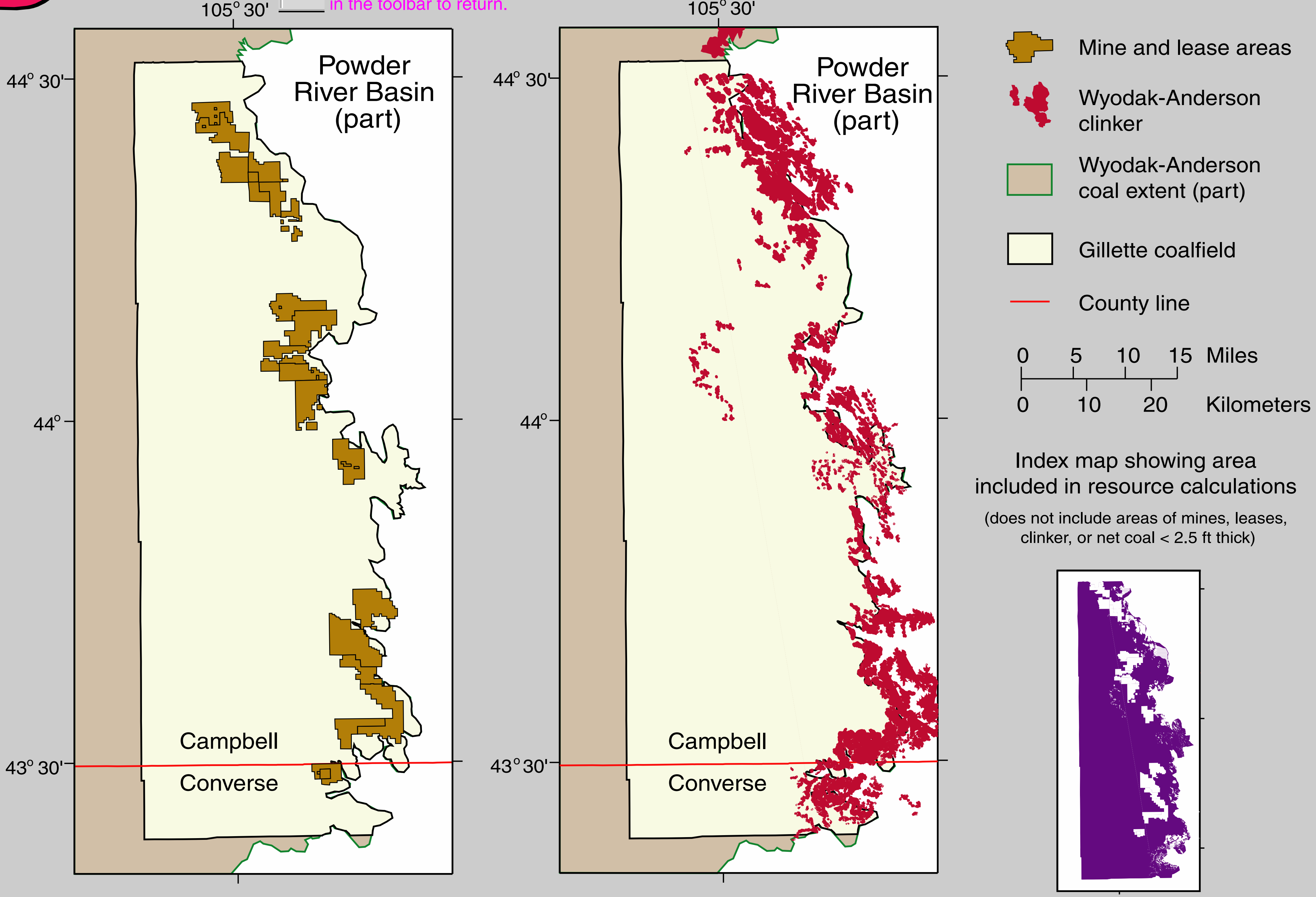

Figure PG-47. Wyodak-Anderson mine and lease areas, clinker, and resource area in the Gillette coalfield.

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Table PG-1. Summary data for Wyodak-Anderson coal zone in the Gillette coalfield, Powder River Basin, Wyoming. Modified from unpublished U.S. Geological Survey coal quality database (USCHEM), February, 1992; Bragg and others (1994); and data from proprietary source(s)

Variable	Number of samples	Range		Mean
		Minimum	Maximum	
Moisture [1]	108	14.50	42.30	27.47
Ash [1]	87	3.50	25.06	7.45
Total Sulfur [1]	87	0.20	1.16	0.48
Heat Value [2]	85	3,740	9,950	8,220
lb SO_2 [3]	85	0.44	3.27	1.25
MMMFBtu [4]	85	4,580	10,560	8,910
Antimony [5]	49	0.01L	17	0.72
Arsenic [5]	62	0.20L	19	2.3
Beryllium [5]	64	0.078L	3.3	0.35
Cadmium [5]	56	0.007L	3.0	0.39
Chromium [5]	65	0.59L	50	7.0
Cobalt [5]	65	0.38L	27	2.3
Lead [5]	66	0.50L	17	2.9
Manganese [5]	66	0.18	210	22
Mercury [5]	66	0.006L	27	0.17
Nickel [5]	66	0.71L	35	5.0
Selenium [5]	56	0.08L	16	1.4
Uranium [5]	61	0.11L	12	1.5

[1] Values are in percent and on an as-received basis.
[2] Value is in British thermal units (Btu).
[3] Value is in pounds per million Btu and on an as-received basis.
[4] Value is in British thermal units on a moist, mineral-matter-free basis.
[5] Values are in parts per million (PPM) on a whole coal and remnant moisture basis and 'L' denotes less than value shown.

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Table PG-2. Wyodak-Anderson coal resources in the Gillette coalfield, reported by county, overburden thickness (fig. PG-46), net coal thickness (fig. PG-45), and reliability categories. Resources are reported in millions of short tons (MST) with two significant figures. Zeros (0) indicate that no coal resources were calculated within those categories. The table does not include resources in mine or lease areas, or areas containing Wyodak-Anderson clinker. Columns will not sum due to independent rounding

County	Overburden thickness	Net coal thickness	Reliability categories (distance from data point)				Grand total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
CAMPBELL	0-100 ft	2.5-5 ft	0.94	6.5	2.1	0.099	9.6
		5-10 ft	4.7	23	10	0.45	39
		10-20 ft	32	100	50	0.74	190
		20-30 ft	48	110	80	0	240
		30-40 ft	95	320	180	0	600
		40-50 ft	190	690	360	140	1,400
		50-100 ft	570	1,800	1,800	280	4,400
		100-150 ft	190	240	56	0	480
		150-200 ft	0	5.1	0	0	5.1
	0-100 ft total		1,100	3,300	2,500	420	7,400
	100-200 ft	2.5-5 ft	0.11	0.43	0.11	0	0.65
		5-10 ft	0.58	0.96	1.6	0	3.1
		10-20 ft	4.8	14	6.4	0	25
		20-30 ft	2.8	28	15	0	46
		30-40 ft	24	110	27	0	160
		40-50 ft	100	460	86	0	650
		50-100 ft	880	2,600	950	0	4,500
		100-150 ft	380	660	5.8	0	1,000
		150-200 ft	28	56	0	0	84
	100-200 ft total		1,400	4,000	1,100	0	6,500

Table PG-2. Wyodak-Anderson coal resources, Gillette coalfield, Powder River Basin—continued

County	Overburden thickness	Net coal thickness	Reliability categories (distance from data point)				Grand total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
CAMPBELL	200-300 ft	10-20 ft	2.5	0.97	0	0	3.5
		20-30 ft	2.9	25	2.8	0	31
		30-40 ft	5.7	78	27	0	110
		40-50 ft	84	390	130	0	600
		50-100 ft	1,300	4,500	1,100	0	6,900
		100-150 ft	510	860	88	0	1,500
		150-200 ft	0	11	0	0	11
	200-300 ft total		1,900	5,800	1,400	0	9,100
	300-400 ft	5-10 ft	0.16	0.21	0	0	0.37
		10-20 ft	1.3	4.9	18	0	25
		20-30 ft	1.0	3.8	50	0	55
		30-40 ft	9.4	10	96	0	120
		40-50 ft	48	170	80	0	300
		50-100 ft	1,600	5,300	1,700	0	8,600
		100-150 ft	380	1,000	270	0	1,700
		150-200 ft	11	20	0	0	31
	300-400 ft total		2,100	6,500	2,200	0	11,000
	400-500 ft	5-10 ft	0.6	4.0	3.9	0	8.4
		10-20 ft	0.72	2.2	5.3	0	8.3
		20-30 ft	1.4	6.9	0.97	0	9.3
		30-40 ft	4.7	22	32	2.0	61
		40-50 ft	7.0	19	100	17	150
		50-100 ft	1,400	4,600	2,800	0	8,800
		100-150 ft	610	1,600	390	0	2,600
		150-200 ft	3.0	11	0	0	14
	400-500 ft total		2,000	6,300	3,400	19	12,000

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Table PG-2. Wyodak-Anderson coal resources, Gillette coalfield, Powder River Basin—continued

County	Overburden thickness	Net coal thickness	Reliability categories (distance from data point)				Grand total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
CAMPBELL	500-1,000 ft	5-10 ft	0	1.3	2.7	0	4.0
		20-30 ft	9.1	12	0	0	21
		30-40 ft	11	15	1.6	0	27
		40-50 ft	20	63	260	86	430
		50-100 ft	2,800	13,000	19,000	380	35,000
		100-150 ft	1,500	5,800	10,000	90	18,000
	500-1,000 ft total		4,400	19,000	29,000	560	53,000
	1,000-1,500 ft	20-30 ft	8.2	26	52	0	86
		30-40 ft	0.37	48	300	0	340
		40-50 ft	0	1.4	390	19	410
		50-100 ft	57	450	5100	540	6,100
		100-150 ft	92	850	4200	35	5,200
	1,000-1,500 ft total		160	1,400	10,000	590	12,000
CAMPBELL total			13,000	46,000	50,000	1,600	110,000
CONVERSE	0-100 ft	2.5-5 ft	0.091	0.79	0	0	0.88
		5-10 ft	0.58	4.5	2.3	0	7.4
		10-20 ft	32	200	47	0	270
		20-30 ft	47	200	140	0	390
		30-40 ft	19	100	14	0	130
		40-50 ft	9.6	60	39	0	110
		50-100 ft	27	28	49	0	100
	0-100 ft total		140	590	290	0	1,000
	100-200 ft	2.5-5 ft	0.13	0.82	0	0	0.95
		5-10 ft	0.63	4.1	15	0	20
		10-20 ft	30	120	110	1.8	260
		20-30 ft	44	190	120	0	360
		30-40 ft	21	110	36	0	170
		40-50 ft	8.3	70	12	0	90
		50-100 ft	44	110	6.4	0	160
	100-200 ft total		150	610	300	1.8	1,100

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Table PG-2. Wyodak-Anderson coal resources, Gillette coalfield, Powder River Basin—continued

County	Overburden thickness	Net coal thickness	Reliability categories (distance from data point) Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	Grand total (MST)
CONVERSE	200-300 ft	5-10 ft	0.13	5.3	31	0	37
		10-20 ft	16	67	110	1.1	200
		20-30 ft	12	29	36	0	76
		30-40 ft	11	62	29	0	100
		40-50 ft	7.8	82	73	0	160
		50-100 ft	59	170	30	0	260
	200-300 ft total		110	410	310	1.1	830
	300-400 ft	5-10 ft	1.3	3.4	41	3.5	49
		10-20 ft	0	1.8	45	0.75	47
		20-30 ft	0	5.7	31	0	36
		30-40 ft	0	0.31	44	0	44
		40-50 ft	5.2	14	17	0	37
		50-100 ft	50	160	54	0	260
	300-400 ft total		56	180	230	4.3	470
	400-500 ft	5-10 ft	1.2	11	42	1.5	56
		10-20 ft	0	0	17	0	17
		20-30 ft	0	0	3.3	0	3.3
		50-100 ft	0	7.6	0	0	7.6
	400-500 ft total		1.2	18	62	1.5	83
	500-1,000 ft	5-10 ft	4.3	31	70	0	110
		10-20 ft	0	0	2.2	0	2.2
	500-1,000 ft total		4.3	31	72	0	110
CONVERSE total			450	1,800	1,300	8.6	3,600
Grand total (MST)			14,000	48,000	51,000	1,800	110,000

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Table PG-3. Wyodak-Anderson coal resources in the Gillette coalfield, Wyoming, reported by county (fig. PG-47) and by Federal coal and surface ownership (fig. PG-44). Coal resources are reported in millions of short tons (MST) with two significant figures. Resources were not calculated for areas containing net coal less than 2.5 ft thick, in mine or lease areas, or in areas containing mapped clinker. Column will not sum due to independent rounding

County	Federal ownership	Total (MST)
CAMPBELL	No Federal coal or Federal surface ownership	9,000
	No Federal coal, but Federal surface ownership	1,900
	Federal coal, but no Federal surface ownership	94,000
	Federal coal and Federal surface ownership	5,900
CAMPBELL total		110,000
CONVERSE	No Federal coal or Federal surface ownership	340
	No Federal coal, but Federal surface ownership	30
	Federal coal, but no Federal surface ownership	2,400
	Federal coal and Federal surface ownership	810
CONVERSE total		3,600
Grand total (MST)		110,000

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Table PG-4. Wyodak-Anderson coal resources in the Gillette coalfield, Wyoming, reported by 7.5-minute quadrangle map area (fig. PG-43) in each county. Coal resources are reported in millions of short tons (MST) and with two significant figures. Resources were not calculated for areas containing coal less than 2.5 ft thick, in mine or lease areas, or in areas containing mapped clinker. Column will not sum due to independent rounding

County	7.5-minute quadrangle map	Total (MST)
CAMPBELL	APPEL BUTTE	5,000
	BAKER SPRING	1,900
	BETTY RESERVOIR	110
	CALF CREEK	1,000
	COAL BANK DRAW	1.0
	COAL DRAW NORTH	85
	COON TRACK CREEK	74
	COYOTE DRAW	1,400
	DUGOUT CREEK NORTH	52
	EAGLE ROCK	4,200
	FORTIN DRAW	370
	FOUR BAR J RANCH	2,600
	GILLETTE EAST	2,400
	GILLETTE WEST	5,000
	GREASEWOOD RESERVOIR	2,100
	HILIGHT	3,500
	LITTLE THUNDER RESERVOIR	5,800
	MACKEN DRAW	2.9
	MOYER SPRINGS	510
	NEIL BUTTE	2,200
	OPEN A RANCH	450
	ORIVA	2,900
	ORIVA NW	3,300
	PEPSSON DRAW	2,800
	PINEY CANYON NW	110
	PINEY CANYON SW	500
CAMPBELL	PLEASANTDALE	2,900
	RATTLESNAKE DRAW	4,000
	RAWHIDE SCHOOL	4,300
	RENO FLATS	4,300
	RENO JUNCTION	6,000
	RENO RESERVOIR	3,100
	ROCKY BUTTE GULCH	6,400
	ROUGH CREEK	1,400
	SADDLE HORSE BUTTE	390
	SCAPER RESERVOIR	5,900
	TECKLA	3,700
	TECKLA SW	4,900
	THE GAP	3,900
	THE GAP SW	3,200
	THREEMILE CREEK RESERVOIR	6,400
	TURNERCREST	1,200
	WESTON SW	55
	WILDCAT	590
CAMPBELL total		110,000
CONVERSE	BETTY RESERVOIR	1,600
	COAL BANK DRAW	36
	COAL DRAW NORTH	1,000
	DUGOUT CREEK NORTH	730
	MACKEN DRAW	200
CONVERSE total		3,600
Grand total (MST)		110,000

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Table PG-5. Data used for computation of confidence intervals within reliability categories for the Wyodak-Anderson coal zone in the Gillette coalfield. Volume refers to the calculated resource in millions of short tons (MST). Rows will not sum due to independent rounding. NA, not applicable

Parameter	Reliability category				Entire area
	Measured	Indicated	Inferred	Hypothetical	
Area (in square meters)	416,538,074	1,530,925,727	1,602,753,691	60,295,123	3,610,512,615
Percent of area	12	42	44	2	100
Acres (area x 0.0002471)	102,929	378,300	396,049	14,899	892,177
SD (standard deviation (in ft) from semivariogram model)	19.65	23.33	26.33	26.33	NA
Acre feet (acres x SD)	2,022,084	8,825,319	10,426,851	392,255	NA
Volume standard deviation (MST)	125	854	3,945	694	5,618
Pseudo *n*	819	334	22	1	NA

Table PG-6. Estimates of uncertainty (calculated with measurement error) for Wyodak-Anderson coal resources in the Gillette coalfield, Powder River Basin, Wyoming. To show detail, resources are reported in millions of short tons (MST) with 4 significant figures

Parameter	Reliability category				Entire area
	Measured	Indicated	Inferred	Hypothetical	
Total calculated resource (MST)	13,520	48,160	51,260	1,597	114,500
Lower 90% confidence limit (MST)	13,310	46,760	44,770	455.0	105,300
Upper 90% confidence limit (MST)	13,730	49,570	57,750	2,739	123,800