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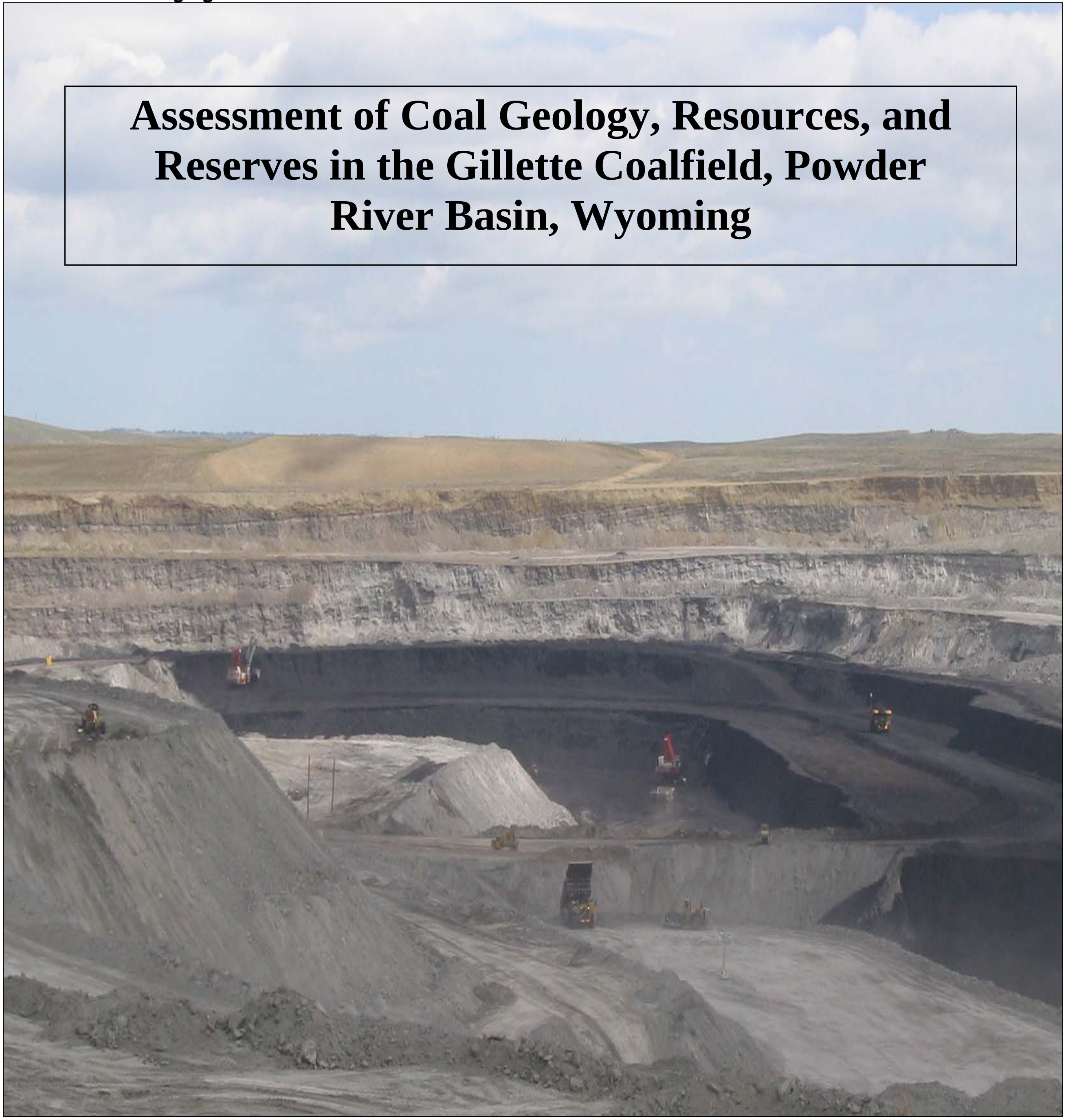

Assessment of Coal Geology, Resources, and Reserves in the Gillette Coalfield, Powder River Basin, Wyoming

Open-File Report 2008-1202

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
square feet (ft^2)	0.929	square meters (m^2)

Density		
pounds (lbs)	0.4536	kilograms (kg)
short tons (2,000 lbs)	0.90718474	Metric tons (2,204.6 lbs)
millions of short tons (mst)	1,000,000	short tons
billions of short tons (bst)	1,000,000,000	short tons
trillions of short tons (tst)	1,000,000,000,000	short tons

Area		
acre-ft	1,770	short tons of subbituminous coal

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By James A. Luppens[1], David C. Scott[2], Jon E. Haacke[2], Lee M. Osmonson[2], Timothy J. Rohrbacher[2],and Margaret S. Ellis[2]

Abstract

The Gillette coalfield, within the Powder River Basin in east-central Wyoming, is the most prolific coalfield in the United States. In 2006, production from the coalfield totaled over 431 million short tons of coal, which represented over 37 percent of the Nation's total yearly production. The Anderson and Canyon coal beds in the Gillette coalfield contain some of the largest deposits of low-sulfur subbituminous coal in the world. By utilizing the abundance of new data from recent coalbed methane development in the Powder River Basin, this study represents the most comprehensive evaluation of coal resources and reserves in the Gillette coalfield to date. Eleven coal beds were evaluated to determine the in-place coal resources. Six of the eleven coal beds were evaluated for reserve potential given current technology, economic factors, and restrictions to mining. These restrictions included the presence of railroads, a Federal interstate highway, cities, a gas plant, and alluvial valley floors. Other restrictions, such as thickness of overburden, thickness of coal beds, and areas of burned coal were also considered.

The total original coal resource in the Gillette coalfield for all eleven coal beds assessed, and no restrictions applied, was calculated to be 201 billion short tons. Available coal resources, which are part of the original coal resource that is accessible for potential mine development after subtracting all restrictions, are about 164 billion short tons (81 percent of the original coal resource).

Recoverable coal, which is the portion of available coal remaining after subtracting mining and processing losses, was determined for a stripping ratio of 10:1 or less. After mining and processing losses were subtracted, a total of 77 billion short tons of coal were calculated (48 percent of the original coal resource).

Coal reserves are the portion of the recoverable coal that can be mined, processed, and marketed at a profit at the time of the economic evaluation. With a discounted cash flow at 8 percent rate of return, the coal reserves estimate for the Gillette coalfield is10.1 billion short tons of coal (6 percent of the original resource total) for the 6 coal beds evaluated.

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Introduction and Objectives

The recently completed U. S. Geological Survey (USGS) National Coal Resource Assessment (NCRA) represented the first National digital coal assessment of in-place coal *resources*. However, in-place estimates do not, by themselves, provide all the information needed for resource planning. Estimates of that portion of the in-place coal resources that are economically recoverable (*reserves*) are equally important. There is often confusion concerning the use of the terms resources and reserves. Although the two terms are frequently used interchangeably, there are significant differences. Coal resources include those in-place tonnage estimates determined by summing the volumes for identified and undiscovered deposits of coal of a minimum thickness of 14 inches (1.2 ft) or more thick for anthracite and bituminous coal; and 30 inches (2.5 ft) or more thick for lignite and subbituminous coal) and less than 6,000 ft deep (Wood and others, 1983). To be classified as reserves, the coal must be considered economically producible at the time of classification, but facilities for extraction need not be in place and operative (Wood and others, 1983).

Traditional coal reserve estimates have typically used average mining percentages to obtain volume estimates of recoverable coal. Those estimates were very general but did not take into consideration the amount of coal that cannot be mined because of environmental concerns, site-specific geologic factors, coal loss owing to mining and preparation technology, or economic constraints. More recently, published studies by the USGS have indicated that application of site-specific restrictions to estimates of available coal resources significantly reduces the amount of coal that is considered recoverable (Ellis and others, 2002).

Since the NCRA study, the methodology used by the USGS for determining coal resources and reserves has been refined, taking advantage of improvements in computer hardware as well as geologic and mining model software. As a result, the scope of coal resource assessments, and especially coal reserve assessments, has grown in size from 7.5-minute topographic quadrangles to entire coalfields or basins. Thus, the current generation of U.S. coal assessments is not only a refinement of the coal resources but also the systematic determination of the coal reserve base on a regional basis in all the major coal provinces in the United States. Regional estimates of coal reserves will provide a meaningful appraisal of the amount of coal that is realistically recoverable in the foreseeable future.

The first U.S. coal basin to be evaluated in this current USGS assessment program is the Powder River Basin (PRB) in north-central Wyoming and south-east Montana (fig. 1). The PRB was subdivided into three regional areas to keep the databases and modeled areas to a more manageable size and to permit a more timely publication of assessment results.

This report summarizes coal resources and reserves for the Gillette coalfield within the Powder River Basin in east-central Wyoming (fig. 2). The coalfield covers an area of about 2,000 square miles (mi^2) and is the single most important coalfield in the United States. In light of the PRB importance, and in particular the Gillette coalfield, reliable coal resource and reserve estimates of the region are essential for use in making local, State, and Federal energy and land-use policy decisions for the foreseeable future. Additionally, this information can aid planners in determining the possible socio-economic effects on the region as coal resources are developed and eventually approach depletion.

Previous coal availability and recoverability studies in the United States. have relied heavily on reinterpretation of existing data. With the development of coalbed methane (CBM) gas in the State of Wyoming, especially in the Gillette coalfield, substantial volumes of new data from drill holes are now available. The interpretation of these new data provides an unprecedented view of the coal resources and reserves in the Gillette coalfield.

The primary objectives of this assessment were to:

1) Improve geological assurance by updating the current stratigraphic database with information obtained from recently completed CBM and oil and gas well data.
2) Develop a more comprehensive in-place coal resource computer model with the geological assurance to support regional reserve estimates.
3) Complete an economic surface mining evaluation that was customized to the environmental and technological restrictions in the coalfield and derive a regional estimate of coal reserves.

Technical terms used in this report requiring additional explanation are *italicized* when used for the first time and their definitions can be found in the Glossary section.

Previous Coal Resource Calculations in the Gillette coalfield

A number of previous studies have estimated coal resources and reserves in the PRB as well as the Gillette coalfield. These studies have included different coal beds, or coal zones, and boundaries. There have been different purposes for which resources have been calculated, as well as differences in criteria, such as variations in coal thickness and *overburden* categories, used for those calculations.

The earliest published estimate of coal resources in the Gillette coalfield was by Dobbin and others (1927). They estimated the tonnage to be 14.4 billion short tons (bst). The area included in their coalfield designation was about 3,000 mi^2. However, they were limited to outcrop measurements for their calculation because little subsurface data were available at that time.

Berryhill and others (1950) provided a calculation of total original reserves of subbituminous coal in Wyoming by township, overburden thickness, and coal bed thickness. Coal tonnage estimates given for 86 townships entirely or partly within the Gillette coalfield totaled about 45 bst. Their estimate was made for all coal beds more than 2.5 ft thick and overburden less than 2,000 ft. Those estimates were the sum of *measured*, *indicated*, and *inferred* reserve tonnages.

Trent (1986) published an estimate of 225 bst of non-leased, Federal coal within the Gillette coalfield. Included were all coal beds greater than 5 ft thick at depths of less than 3,000 ft. No resources were included for leased Federal coal, State coal, privately owned coal, or lands encompassed by coal prospecting permits and preference right lease applications.

Ayers (1986) provided an estimate of 1.06 trillion short tons (tst) of coal in the Tongue River Member of the Fort Union Formation within the Wyoming part of the Powder River Basin. He included all coal beds greater than 2 ft thick to a depth of 3,000 ft.

Ellis and others (1999) reported an estimate of 110 bst of coal within the Gillette coalfield. Their resource estimate was limited to the Wyodak- Anderson coal zone, as defined by the Fort Union Coal Assessment Team (1999). That estimate was derived from stratigraphic data interpreted from geophysical logs from about 2,000 drill-hole locations. Using total coal thickness, resources were calculated for all coal beds more than 2.5 ft thick in the Wyodak-Anderson coal zone. *Parting* material and coal within active lease areas were not included in the resource calculations.

Glass (2001) published an estimate of 1.03 tst of coal for the Wyoming part of the Powder River Basin, which included coal beds of any thickness and to all depths, even greater than 6,000 ft. The remaining strippable reserve base for the Wyodak coal bed was reported to be 17.9 bst, using a 200-ft cut-off depth for overburden. This is the largest reserve base for any single coal bed in Wyoming.

Ellis and others (2002) estimated the original coal resource in the Gillette coalfield, for five coal beds in the coalfield, to be 136.1 bst. Coal resources were calculated for an area of the Gillette coalfield encompassing about 1,500 mi^2. The estimates showed that the *available resource* already defined represents about 89 percent of the *original resource*. They also estimated the *recoverable* *resource* already defined to represent about 80 percent of the original coal resource and the economically recoverable resource to represent about 17 percent of the original resource, or 23 bst at the then current sales price of $6.00 per ton.

Comparison of the previous resource estimates shows the usefulness of periodically recalculating coal resources and reserves when more data become available. Economic coal recoverability calculations in the current report are a significant refinement of previous coal resource studies in the coalfield. Coal resource estimates in this report include data about how much of the total coal resource (1) has already been mined, (2) could be produced using specific mine models, and (3) could be produced at a profit using current market values. These more specific resource calculations add to the body of knowledge available for State and Federal agencies to determine the amount of coal that could actually be produced within the Gillette coalfield, thereby contributing to decisions regarding energy policy and future land use.

Previous and Current Coal Mining

Coal mining in the PRB began in 1883 near the towns of Glenrock and Douglas, Wyoming, (fig. 1). The development of railroad lines in 1886 and 1887 influenced growth in coal mining activity. The first mines were underground, with the Inez Mine near Douglas and the Deer Creek Mine near Glenrock, each producing about 13,000 short tons of coal in 1888 (Gardner and Flores, 1989). The Cole Creek, Buffalo Fuel Company, and Dietz Mines opened soon after. By 1925, 17 additional underground mines opened in Sheridan County. In 1905, mines in Sheridan County were producing about 550,000 tons of coal annually (Trumbull, 1905). The first surface mine, the Peerless Mine near Gillette, Wyoming, opened in 1924 (Gardner and Flores, 1989), and a 90-ft-thick bed was mined. Soon after, the Wyodak Coal and Manufacturing Company opened a large surface mine and produced about 33,600 short tons of coal in 1925. By the mid-1900's, advancements in strip mining equipment and mining techniques made strip mining much more profitable. Most underground mines closed or the companies switched from underground to surface mining methods.

Prior to 1950 most coal was used for locomotive fuel, with minor amounts used as fuel for power plants, sugar factories, cement plants, and local heating (Mapel, 1958). In the 1960s, because of the national need for additional electrical energy, power plants were built adjacent to producing coal mines. At that time, coal utilization shifted from railroad fuel to fuel for power generation.

The Gillette coalfield contains 13 active surface coal mines, all producing from the Tongue River Member of the Fort Union Formation. Year 2006 production from all of the mines in the coalfield contributed about 37 percent (431 mst) of the total U.S. coal production of 1.161 bst (Energy Information Agency, 2007). In 2006, nine of the ten coal mines with the largest production in the U.S. were located in the Gillette coalfield, making it one of the most important coalfields in the nation (Energy Information Agency, 2007).

Other Energy Commodities

Energy commodities currently being developed in the Powder River Basin, in addition to coal, include conventional oil and gas and CBM. Although CBM is a gas, it is discussed separately below because there are potential conflicts and concerns specific to the development of that resource that do not apply to conventional oil and gas development. Uranium is also currently mined in the southern PRB, by in-situ leaching of roll-front deposits in the Wasatch Formation.

PRB oil and gas development began in 1887, with the discovery of an oil and gas field near Moorcroft, Wyoming (Ellis and others, 2002). According to the Wyoming Oil and Gas

Conservation Commission (WOGCC), 1,931 oil and gas wells were reported within the Gillette coalfield as of May, 2007 (Wyoming Oil and Gas Conservation Commission, 2007). Current infrastructure for production and transport of oil and gas in the area includes roads, pipelines, pump houses, separators, and several gas-processing plants. Generally, there is little conflict between coal development and conventional oil and gas development in the PRB. Conventional oil and gas development is primarily from stratigraphic units below the extractable coal seams. Additionally, conventional oil and gas development that might impact coal recovery is primarily in the central part of the basin, whereas current coal mining is along the basin margins. Where oil and gas development and coal mining occur in the same areas, mining is confined to areas outside a specific buffer distance from wells, pipelines, and other oil and gas related structures.

CBM development in the coalfield began in the early 1980s and, as of May, 2007 more than 8,265 wells had been drilled (Wyoming Oil and Gas Conservation Commission, 2007). The production life of a CBM well is estimated to be from about 10 to 12 years, although production from multiple seams can extend the life of the well by an additional 10 to 30 years (De Bruin and others, 2004).

To produce CBM, a large volume of groundwater is pumped from the coal bed. The groundwater can be discharged to holding ponds for consumption by livestock, discharged to existing drainage systems, released into the atmosphere through the use of misting towers, or re-injected into another stratigraphic unit. Concerns regarding possible contamination of existing surface water, the quality of water in holding ponds, the production of saline crust on the ground surface, the lowering of the water table, and possible contamination or depletion of groundwater in existing aquifers, have all been examined in the PRB by Rice and others (2000).

Conflicts have arisen between coal mining and CBM development. One conflict involves the ownership of CBM, whether it belonged to the owner of the oil and gas estate or the owner of the coal estate. The U.S. Supreme Court resolved this issue in 1999, when they ruled that CBM in Wyoming is part of the oil and gas estate. In addition, the court specified the owner of the CBM leases has the right to gain access and to develop their estate, and owners of the land surface should be adequately compensated for damage to their property resulting from CBM extraction. The Bureau of Land Management (BLM) has established Conflict Administration Zones to guide development of CBM leases in the path of near-term coal mining. In these zones, standard guidelines offer a process to settle conflicts and schedule development of each resource under a Federal mineral estate.

Geologic Setting of the Powder River Basin and Gillette Coalfield

The PRB covers about 22,000 mi^2 in northeastern Wyoming and southeastern Montana (fig. 1). Near the west edge of the basin, the axis trends northwest-southeast and is markedly asymmetrical with steep dips on the west side and gentle dips on the east. The Eocene Wasatch Formation (fig. 3) covers about one-third of the PRB, mostly in Wyoming, with the underlying Paleocene Fort Union Formation (fig. 3) exposed along the basin boundaries in Wyoming and throughout most of the basin in Montana. Within the Wyoming part of the PRB, the Wasatch Formation contains coal beds that have heat values, agglomeration characteristics, and fixed carbon and volatile matter content that place them as subbituminous C in apparent rank. In general, Fort Union Formation coals range from subbituminous C to subbituminous A in apparent rank. The low rank coal (subbituminous C) is located primarily in the shallower part of the basin (surface to 1,000 ft of depth), the middle coal rank (subbituminous B) is at an intermediate depth in the basin (1,000 to 1,400 ft of depth), and the high rank coal (subbituminous A) is in the deeper part of the basin (greater than 1,400 ft of depth) (Stricker and others, 2007).

The Eocene Wasatch Formation conformably overlies the Paleocene Fort Union Formation in the center of the basin and unconformably overlies it along the basin margins (fig. 3). The boundary between the two formations is generally placed above the Roland coal bed (fig. 4) (Fort Union Coal Assessment Team, 1999). Rocks in the Fort Union Formation lie unconformably on the Upper Cretaceous Lance Formation (fig. 3). The Fort Union Formation in Wyoming is made up of three members, from upper to lower: the Tongue River Member, the Lebo Member, and the Tullock Member (fig. 3). The Fort Union Formation contains some of the thickest and most extensive deposits of low-sulfur subbituminous coal in the world (Molnia and Pierce, 1992), most of which is from the Wyodak-Anderson coal zone in the Tongue River Member (Fort Union Coal Assessment Team, 1999). The Wyodak-Anderson coal zone is equivalent to the following coal beds discussed in this report (from younger to older): Roland, Smith, Anderson Rider, Anderson, Dietz, Canyon, and Werner (fig. 4, table 1).

The Gillette coalfield encompasses an area of about 2,000 mi^2 in the south-central part of the PRB in Campbell County, Wyoming (figs. 1, 2). The very southern part of the coalfield extends into Converse County, Wyoming. The east boundary of the Gillette coalfield is the Anderson (Wyodak) coal outcrop, east of which the coal has burned in most areas to produce an extensive plateau of clinker capping an escarpment 300 to 700 ft high (Kent and Berlage, 1980; Coates and Heffern, 1999; Heffern and Coates, 1999, 2004). In areas where outcrop and clinker information was not available and where coal beds assessed for this study were not present in drill holes, the coalfield boundary was defined using the contact between the Wasatch Formation and the Fort Union Formations as mapped by Kent and Berlage (1980) and Boyd and Ver Ploeg (1997). The north and south boundaries of the coalfield were delineated by the closest township lines that contained all areas of active mining as of 2007. The west boundary, at R. 74 W., is one township west of the west boundary used for the earlier coal resource assessment of the coalfield by Ellis and others (1999).

Within the Gillette coalfield, Ellis and others (1999) reported that rocks dip 2 to 3 degrees to the west; however, our investigations show that the beds dip between 0.5 and 1.0 degrees to the west. Individual coal beds within the Tongue River Member are as much as 200 ft thick. These beds merge, split, and are cut out by channels within short distances (Ellis and others, 1999). The named coal beds assessed in this report, from younger to older, are the Felix Rider, Felix, Roland, Smith, Anderson Rider, Anderson, Dietz, Canyon, Werner, Gates, and Pawnee (fig. 4).

The Gillette coalfield was divided into three separate geographic regions, referred to in this report as the north mining area, middle mining area, and south mining area (fig. 5). Areas were generally delineated on the basis of coal quality. The north mining area includes the Buckskin, Rawhide, Eagle Butte, Dry Fork, and Wyodak mines. Middle mining area mines include the Caballo, Belle Ayr, Cordero Rojo, and Coal Creek. The south mining area includes the Jacobs Ranch, Black Thunder, North Antelope/Rochelle, and Antelope mines.

Coal Bed Nomenclature

Prior to this report, correlation of individually named coal beds across the entire PRB was difficult, because the coal beds commonly split, merge, and pinch out (Flores and others, 1999a [Chapter PF]). In addition, prior to this study the distance between data drill holes used in the correlation process was sometimes large, thus creating uncertainty in correctly correlating individual coal beds from one drill hole to the next. Previous reports relied on drill hole data that were up to ten or more miles apart. However, with the recent drilling and development of CBM in the PRB, data from over 10,000 new drill holes in the Gillette coalfield alone are now available. Utilizing the more closely spaced coalbed methane drill holes, it was possible to more confidently define coal bed correlations, determine split lines, and outline paleo-channels.

Many different names for individual coal beds have been used over the past 25 years (table 1). A report by Kent and others (1980), covering the northern part of the Gillette coalfield that falls within the Spotted Horse coalfield of Olive (1957), established a coal bed nomenclature system that has become the standard for much of the PRB in Wyoming. They retained certain existing coal bed nomenclature and revised other nomenclature by introducing new coal-bed names. In descending order, these names are Felix, Arvada, Roland (Baker, 1929), Smith, Anderson, and Canyon. Kent and others (1980) also recognized the Swartz coal bed of McKay and Mapel (1973) as occurring between the Smith and Anderson coal beds in certain areas and used the name Wyodak in the sense of Mapel (1973), which refers to a 90 ft thick coal bed exposed by surface mining about 5 miles east of the town of Gillette, Wyoming. Cross sections by Pierce and others (1990) extended the nomenclature of Kent and others (1980) into the southwestern part of the Gillette coalfield.

Names of coal beds below the Canyon coal (i.e., Cook, Wall, Pawnee, and Cache) were not retained by Kent and others (1980) in the Spotted Horse coalfield because those names originated many miles to the north in Montana and direct correlations were not warranted in their view. Also, previous workers had used the name “Wall” to represent different beds in different coalfields.

Flores and others (1999a) defined a coal zone known as the Wyodak-Anderson in the PRB, which includes many named coal beds in the upper part of the Tongue River Member of the Fort Union Formation. Coal beds in this zone are from younger to older are the Smith, Roland, Badger, School, Sussex, Big George, Wyodak, Anderson, Dietz, Canyon, and Werner. Some of these beds are splits of other beds or are stratigraphically equivalent to other beds. Additionally, many of the beds are found only in certain parts of the basin.

Because of mining economics, resources and reserves must be based on individual coal beds, not coal zones. Zones contain both *interburden* and *parting*. The partings can vary from a few inches to many feet in thickness. The amount of interburden and partings can significantly affect the economics of coal mining. Therefore, coal zones such as the Lower and Upper Wyodak had to be separated into distinct coal beds, where interburden or partings could be quantified separately to determine the actual thickness of coal for each bed. For this assessment, the individual correlated coal beds comprising the Wyodak-Anderson zone included the Smith, Anderson Rider, Anderson, Dietz, Canyon, and Werner. Table 1 compares the coal bed names used in this report and the various equivalent names previously used within the Gillette coalfield.

Study Methodology

The methodology for calculating coal resources and reserves in the Gillette coalfield involved three basic phases that are shown on a flow chart in figure 6. The first phase began with data collection and editing. A report by Ellis and others (2002) was used as a foundation for the development of a database. This was followed by an intense data collection process involving the acquisition of recently generated geologic information. The second phase involved correlating individual coal beds, subsequent geologic modeling of those beds and resource allocation to determine land use, technologic and *legal unsuitability* areas within the coalfield. The third phase involved completing a mining economics evaluation to determine economically recoverable coal resources (reserves).

Data Collection

The original database from Ellis and others (2002), with 2,555 drill holes, was used as a foundation for the current assessment. Data points were deleted where the original geophysical logs could not be found to verify the coal interval picks or the reliability of the location or original logs quality was suspect. After this initial data integrity check, only 1,267 of the original drill holes were kept.

As of 2005, approximately 7,600 oil and gas wells and 14,500 new CBM wells had been completed in the Gillette coalfield area. The first step of the data collection effort was the addition of 1,124 data points from the BLM (2005) that were added to the 1,267 drill holes remaining in the original database. The BLM data primarily consisted of coal test holes in the eastern part of the coalfield and scattered oil and gas wells in the western part of the coalfield.

Then, a preliminary map of the overburden depth to the top of the Anderson coal bed was generated. On the basis of this overburden map, additional drill hole logs were selected for data entry at a spacing of about ¼ mile for areas of less than 500 ft of overburden, ½ mile for areas of 500 to1,000 ft of overburden, and one mile for areas of overburden greater than 1,000 ft in depth. Additional drill-hole logs were also added in areas of particularly difficult correlations. Data within a three mile wide buffer zone were added around the Gillette coalfield to extend stratigraphic correlations and minimize the edge effect when modeling the coal beds.

The drill hole geophysical logs selected for data entry were downloaded as TIFF images from the WOGCC web site (Wyoming Oil and Gas Conservation Commission, 2007). USGS personnel completed data entry for a total of 6,623 logs. This data entry effort was augmented by the WSGS (*http://www.wsgs.uwyo.edu*), which contributed 1,196 additional data points. All data were entered into the Stratifact® database program (GRG Corporation, 1998). The final database used for this assessment totaled 10,210 data points (table 2).

These new data consisted of both oil and gas logs and CBM well logs. Because the well logs displayed a very wide range in quality and resolution, the interpretation was often challenging. Gamma-ray logs were available for most of the wells and constituted the basis for most of the lithology interpretation. Traditionally, oil and gas wells were logged primarily for detail in deep formations with the upper (coal bearing) intervals not logged or minimally gamma logged through the surface casing. Log data in older wells usually consisted of only spontaneous potential, resistivity and conductivity logs, making the identification of coal beds more difficult. The most reliable log suite consisted of natural gamma, gamma-gamma density, and resistivity traces. However, many CBM wells were logged with gamma only, either in open hole or through steel drill pipe or casing. Additionally, many of the CBM wells were only logged with gamma to the top of the target coal.

Given the sizable task of data entry for over 6,000 wells, it was immediately apparent that in order to keep the assessment on schedule a compromise needed to be made regarding the amount of lithologic detail. Because the primary focus of this report was to determine coal resources and reserves rather than conducting a comprehensive geological study, detailed non-coal lithology types were not critical to the results of the evaluation. Therefore, it was decided to code all lithology as either coal or rock. Parting intercepts within coal beds and interburden between coal beds were also coded as rock. Intervals with no geophysical log, such as the upper part of an oil well or CBM well that was not logged to the bottom, were entered as “No Log.” However, if the methane producing interval was available from production records for those CBM wells not completely logged, that interval was entered as coal.

Coal Bed Correlations

Once all the new drill hole data entry was completed, the graphical interface to the StratiFact database was a critical tool for managing the interpretation of the large volume of new information. With the graphics program, on-screen, cross sections were selected, edited and correlated, and automatic, real-time database updates were performed Both linear and circular cross sections were constructed to correlate coal beds across the Gillette coalfield. Circular cross sections to verify closure were especially valuable when coal beds either split or thinned adjacent to sand channels. In this process, the beginning and ending drill holes of the cross section are the same, assuring that the coal beds do not cross each other. Figures 7 and 8 show that with new data and circular cross sections, previous correlations can be verified or refined. As seen in figure 7, there is a 9.0 mile gap between drill holes API 524358 and API 533013. Both drill holes contain thick coal beds. Therefore, both coals were assumed to be the Upper Wyodak coal bed. In this study, nine new drill holes were added between those two drill holes, (fig. 8), showing the revised correlations.

Current coal bed nomenclature, along the eastern margin of the Gillette coalfield, was used as a basis for correlating and naming coal beds to the west. Guidelines were established regarding which nomenclature would be used when two named beds merge into a single bed. The general correlation guidelines used for this assessment are:

- Two named beds are considered to have merged into a single named bed when the intervening parting was less than 2.0 ft thick. The following exceptions have been made for modeling purposes:
    - In individual holes, coal beds split by partings as much as 5 ft thick are considered to be merged if nearby surrounding holes indicate the beds have merged into a single bed.
    - In individual holes, coal beds with no partings or partings less than 2.0 ft thick are considered to be split into two beds if surrounding holes show the coal has split into two beds.
- The upper bed's name will be used for the merged bed with two exceptions:
    - A rider name becomes the main bed name; e.g. Felix merged with Felix Rider becomes Felix.
    - In the west-central part of the coalfield, the very thick Canyon (the lower bed) merges with the very thin Anderson and retains the Canyon name.

Geologic Modeling

The first step of phase two of the assessment (fig. 6) was the creation of digital coal models. Subsequent to coal bed correlations, preliminary coal isopach maps were created using the single bed mapping software Surfer® (Golden Software, 2002) to help decide which coal beds would be included in the geological model. The basic criterion for inclusion was a minimum areal continuity of two or more townships. Eleven coal beds were selected and digital models for each bed were constructed. The integrated, multi-bed modeling program PC/Cores® (Mentor Consultants, 2005) was used to product the geologic model grids.

This modeling program was designed for coal or mineral evaluations and is more effective because of its capability to grid multiple beds at one time. The multiple gridding software allows for a considerable reduction in time when compared to other programs that grid only one parameter at a time. Use of a sophisticated modeling package is especially effective for situations like the Gillette coalfield, where a significant number of the drill holes in and around existing mines and the CBM development wells did not penetrate coal beds below the Anderson or Canyon. The upper intervals of many oil and gas wells were not logged.

The time required to produce all the required grids using a program that generates grids one parameter at a time can be significant considering that for each coal bed, grids must be made for coal thickness, parting thickness, coal height (coal plus parting), and roof and floor structures. Then, to calculate the overburden and interburden grids for each seam, the roof grids for each coal bed must be individually subtracted from the surface grid or the floor grid for the next stratigraphically higher coal bed. In cases where the drill holes were not deep enough, or an interval was not logged, a zero coal thickness is assigned to each coal bed affected. To mitigate these false zeros, each coal bed isopach must be edited manually, an especially time-consuming given the number of coal beds modeled and the prevalence of shallow drill holes in the Gillette coalfield.

Most multiple bed modeling programs are highly automated with a subroutine that utilizes the individual coal bed structure grids to check for drill holes too shallow to penetrate a given bed. This feature produces more accurate digital models without the need for extensive manual editing. The PC/Cores program code was modified to allow correlations to pass through the sections of the drill holes that were not geophysically logged to reduce the generation of false zero thickness values.

The geologic models were gridded at a resolution of 150 meters (about 500 ft) with a total of about 383,000 cells in a single grid. To verify coal bed correlations and coal bed areal distributions, preliminary roof and floor contour maps for each modeled bed were generated to check for “bull’s eye” anomalies. A routine within the PC/Cores modeling program was used to identify suspect locations by comparing collar elevations to the digital elevation model (DEM) of the earth’s surface. A number of location errors were resolved using this technique.

Once the editing was completed, the final geologic model was created and all the grids necessary for determination of the in-place coal resource volumes were generated. A copy of the in-place coal resources model was modified to generate the grids necessary for the reserve evaluation. The need for a second model was dictated by the fact that only six of the eleven coal beds modeled were to be included in reserve analysis.

The basic assumptions used to qualify coal beds for potential reserve evaluation were to include: (1) coal beds above the Anderson or Canyon 5 ft or greater with significant areal extent and (2) coal beds below the Anderson or Canyon 5 ft or greater (U.S. Bureau of Land Management, 1986) with significant areal extent and an incremental *stripping ratio* of 4:1 or less. The minimum thickness of at least 5 ft and the maximum incremental stripping ratio of 4:1 criteria for beds below the Anderson or Canyon were selected on the basis of current mining practices at existing mines in the Gillette coalfield.

Coal beds between and above the Anderson or Canyon that met the criteria are the Roland, Smith, Dietz, and Anderson Rider. Because the Felix bed is so high stratigraphically, its sub-crop was not reached until the Anderson-Canyon approached its 10:1 stripping ratio, the maximum ratio that was used for the reserves analysis. Furthermore, limited quality data that indicates that the Felix bed has lower Btu content and higher ash and sulfur contents, Therefore, it was decided to exclude the Felix bed from the reserve analysis based on its stratigraphic position combined with poorer coal quality The 4:1 stripping ratio criterion essentially eliminated all coal resources below the Anderson or Canyon. There are areas where the Werner coal bed does meet the criteria of the 5 ft minimum thickness and the 4:1 incremental stripping ratio, but these areas are of relatively limited extent except for an area near the town of Gillette (fig. 5). Because a significant portion of the Werner underlies the buffer around Gillette, it was decided not to include the Werner in the regional reserves evaluation.

A final set of grids from both the coal resources and reserves models (thickness, parting thickness, and roof and floor structures) for each coal bed were converted in PC/Cores to a generic

ASCII grid format. These ASCII grids were then exported to the software program ArcView® (ESRI, 2001a) to begin the last step in phase two of the assessment which is the modeling of the *restrictions to mining*.

Coal Bed Geology of the Gillette Coalfield

Nine cross sections were constructed (fig. 9, index map; and figs. 10, 11, 12, 13, 14, 15, 16, 17, and 18, cross sections) that illustrate the stratigraphic relationships for the coal beds that were assessed. Except for the Felix Rider and Felix coal beds, which are in the Wasatch Formation, the remaining coal beds are within the Tongue River Member of the Fort Union Formation. The following descriptions of the eleven coal beds (fig. 4) that were assessed in the Gillette coalfield are discussed from youngest to oldest.

Summary data for the coal bed thicknesses and depths were derived from the statistical summaries from the coal bed digital models. Coal resources were classified according to geologic assurances of existence (Woods and others, 1983). The degree of assurance increases as the nearness to points of control, abundance, and quality of geologic data decreases and is often presented as *reliability categories*. Coal resource reliability maps were constructed from the digital models for each coal bed assessed. Since most of the new data were CBM well logs which primarily targeted the Anderson and Canyon beds, there is a progressive decrease in geologic assurance for coal beds below the Canyon.

Felix and Felix Rider coal beds

The Felix Rider and Felix coal beds are stratigraphically within the Wasatch Formation. The Felix Rider coal bed was identified in 2,253 well logs and has a maximum thickness of 36 ft with an overall average thickness of 7 ft. The Felix Rider (fig. 19) is less continuous than the Felix. It is present mostly in the central part of the Gillette coalfield and to a lesser extent in a smaller area in the southern part of the coalfield. Contiguous areas where the Felix Rider thickness exceeds 5 ft are limited. Overburden depth for the Felix Rider ranges from near zero feet at subcrop to about 700 ft (fig.20) along the western edge of the coalfield. The coal resource reliability map for the Felix bed is shown in figure 21.

The Felix coal bed is the uppermost coal bed modeled in this study. The Felix coal (fig. 22) was identified in 3,350 well logs and has a maximum thickness of 54 ft with an overall average thickness of 14 ft. Because of its relatively high stratigraphic position, the Felix bed is restricted to the western half of the Gillette coalfield. There is a significant area where the Felix coal exceeds 5 ft in thickness, but the bed thins to the west and south, and around the town of Gillette. Overburden depth of the Felix (fig. 23) ranges from near zero feet at its subcrop to over 700 ft along the western edge of the coalfield. The Felix splits into upper and lower beds primarily in the west central part of the coalfield. When split, the lower bed retains the Felix name and the upper bed is referred to as the Felix Rider (although it is sometimes locally the bed of greater thickness). The coal resource reliability map for the Felix bed is shown in figure 24.

Roland coal bed

The Roland coal bed is stratigraphically the highest coal bed within the Tongue River Member of the Fort Union Formation and it is generally considered to be the boundary between the Fort Union and Wasatch Formations (Flores and others, 1999a). The Roland (fig. 25) was identified in 5,886 well logs and has a maximum thickness of 52 ft with an average thickness of 10 ft. This coal bed is lenticular in shape and is continuous throughout much of the Gillette coalfield. There are two significant areas where the Roland coal exceeds a thickness of 5 ft. The Roland crops out along its eastern extent except north of the city of Gillette, where it rapidly pinches out. Maximum overburden depth is about 1,175 ft along the western edge of the coalfield (fig. 26). In the northern part of the coalfield, interburden between the Anderson coal bed and the Roland becomes very thin. However, the Roland was not observed to merge with the Anderson coal bed in any cross-sections. The coal resource reliability map for the Roland bed is shown in figure 27.

Smith coal bed

The Smith coal bed (fig. 28) was identified in 4,418 well logs and has a maximum thickness of 142 ft along the western edge of the Gillette coalfield and has an overall average thickness of 25 ft. The Smith is continuous throughout the west-central part of the coalfield. The northern, eastern, and southern limits of the coal bed are characterized by a gradual thinning and then pinching out. To the northwest, interburden between the Smith and the next lowest bed (Anderson) becomes very thin; however, the Smith does not merge with the Anderson in any drill holes. The Smith coal bed thickens dramatically to the west and is equivalent to the Big George coal bed along the southwestern part of the coalfield. Previous to this study, the Big George was generally considered to be equivalent to the Anderson coal bed (figs. 7 and 8). Overburden depth ranges from about 10 ft along its eastern extent to over 1,400 ft along the western edge of the coalfield (fig. 29). The coal resource reliability map for the Smith bed is shown in figure 30.

Anderson and Anderson Rider coal beds

The Anderson Rider coal bed is a minor upper split of the Anderson coal bed and is only present along the southeastern margin of the coalfield. The Anderson Rider ranges in thickness from about 1 ft to just over 20 ft (fig. 31) west of the Jacobs Ranch and Black Thunder coal mines and has an average thickness of 8 ft. Overburden of the Anderson Rider ranges in depth from subcrop along the eastern margin of the coalfield to 545 ft in depth southeast of the town of Wright (fig. 32). The coal resource reliability map for the Anderson bed is shown in figure 33.

The Anderson coal bed (fig. 34) was identified in 7,800 well logs and has a maximum thickness of 202 ft with an average thickness of 45 ft. The Anderson coal bed is the principal CBM production target in the Gillette coalfield. The Anderson coal bed is the thickest and most contiguous of the coal beds evaluated in the coalfield, and is distributed throughout the coalfield except in the western and southwestern parts, where it thins rapidly and pinches out. The Anderson coal bed contains up to 6 distinct partings that range from 1 to 4 ft thick and consist mostly of mudstone.

Guidelines discussed in the methodology section of this report were used to separate the Main Wyodak coal zone of Molnia and others (1999) into the Smith, Anderson Rider, Anderson, Dietz, and Canyon coal beds entirely on the basis of parting thicknesses. In areas in the western part of the coalfield, the separation between the Anderson, Dietz, and Canyon coal beds becomes very significant. Interburden between the coal beds ranges from 2 ft to over 400 ft in the southwestern and northwestern parts of the coalfield. Overburden depth ranges from subcrop along the eastern edge of the coalfield to about 1,600 ft along the western edge of the coalfield (fig. 35). The coal resource reliability map for the Anderson bed is shown in figure 36.

Dietz coal bed

The Dietz coal bed, a lower split of the Anderson coal bed, was identified in 824 well logs and has a maximum thickness of 36 ft with an average thickness of 8 ft (fig. 37). Dietz resource areas greater than 5 ft are limited to several small areas in the east and central and northwestern portions of the Gillette coalfield. Overburden depth ranges from subcrop along the eastern margin of the coalfield to over 1,600 ft along the western part of the coalfield (fig. 38). The coal resource reliability map for the Dietz bed is shown in figure 39.

Canyon coal bed

The Canyon coal bed was identified in 4,022 well logs and reaches a maximum thickness of about 140 ft, and has an overall average thickness of 26 ft (fig. 40). The Canyon is also one of the principal CBM production targets in the Gillette coalfield. The Canyon and Anderson beds merge into a single thick Anderson coal bed in three large areas of the eastern part of the coalfield (fig. 40). The Canyon is truncated in the southwest by a major channel system that also impacts the Anderson coal bed. Overburden depth ranges from subcrop along the eastern margin of the coalfield to about 1,700 ft along the western part of the coalfield (fig. 41). The coal resource reliability map for the Canyon bed is shown in figure 42.

Werner coal bed

The Werner coal bed was identified in 1,322 well logs and has a maximum thickness of 75 ft with an average thickness of 9 ft along the western margin of the Gillette coalfield (fig. 43). The Werner is very discontinuous in the Gillette coalfield with only small, isolated areas where thicknesses exceed 5 ft, except for an area near the town of Gillette. Overburden ranges from about 100 ft along its eastern extent to a maximum of over 1,800 ft along the western margin of the coalfield (fig. 44). The coal resource reliability map for the Werner bed is shown in figure 45.

Gates coal bed

The Gates coal bed was identified in 471 well logs and has a maximum thickness of 101 ft with an average thickness of 13 ft along the western margin of the Gillette coalfield (fig. 46). This coal bed is predominately in the north and west-central parts of the coalfield. The coal bed does not crop out in the coalfield and thins considerably to the east and south. Overburden ranges from a minimum of 250 ft along its eastern extent to a maximum of over 1,900 ft along the western margin of the coalfield (fig. 47). The coal resource reliability map for the Gates bed is shown in figure 48.

Pawnee coal bed

The Pawnee coal bed is the deepest coal bed evaluated in this study. The Pawnee was identified in 437 well logs and has a maximum thickness of 48 ft with an overall thickness of 14 ft (fig. 49). Although the Pawnee is relatively contiguous over the western and northwestern portions of the Gillette coalfield, only one significant area in excess of 5 ft in thickness is present southwest of the town of Gillette. In some areas, the Pawnee merges with the Gates coal bed or is separated from it by only 10 to 20 ft of interburden (fig. 12, 13 and 14). Overburden ranges from 81 ft along subcrop to a maximum of almost 2,000 ft along the western margin of the coalfield (fig. 50). The coal resource reliability map for the Pawnee bed is shown in figure 51.

Although there are more coal beds in the Gillette coalfield deeper than the Pawnee, they are too deep to be extracted by conventional surface mining techniques. Furthermore, stratigraphic control on those deeper coal beds was very limited. For these reasons, no deeper coals were evaluated for this assessment.

Influence of Paleochannel Geometry upon Coal Bed Distribution

The significant increase in new subsurface data for this assessment has resulted in a much better definition of the location of paleochannels and coal bed spatial geometry within the Gillette coalfield. The improvements in the channel and coal bed definition can be seen by comparing the isopach maps of the Anderson bed from Ellis and others (2002) and the current assessment (fig. 52).

While the focus of this assessment does not include a detailed discussion of the geology of the Gillette coalfield, it is informative to address the influence of channel geometry upon the spatial distribution of the assessed coal beds. The coal beds of the Gillette coalfield originated as peat deposits that accumulated in interchannel raised mires flanked by deposits of a fluvial-channel complex (Ellis and others, 1999). The lenticular coal bodies of the Wyodak-Anderson coal zone are laterally split by and pinch out into sandstone which was deposited in the adjacent fluvial channels (Flores and others, 1999a).

The location of significant channels can be inferred from the map showing the location of data points (fig. 5). The lack of extensive CBM production drilling is often indicative of a thinning or absence of the thick Wyodak coal zone targets (Smith, Anderson Rider, Anderson, Canyon, and Werner coal beds of this report). These channel areas can also be observed readily for the Anderson and Canyon coal beds by the individual isopach maps (figs. 34 and 40). The generalized locations of these channel areas were defined by areas where the coal beds were less than 10 ft thick or absent (fig. 53). Drill holes deep enough to have penetrated the expected Anderson bed, but with explicit “no Anderson interval” present, are also displayed in figure 53, with a red dot symbol.

The most dominant fluvial system is a north-south trending channel along the western margin of the Gillette coalfield. This distributary-like channel complex is at least 6 miles wide (fig. 53) and significantly impacts the three most important Wyodak-Anderson zone coal beds (Smith, Anderson, and Canyon). All east-west cross sections (figs. 12, 13, 14, 15, 16, 17, and 18) as well as the coal bed isopach maps (figs. 28, 34, and 40) illustrate the influence of this channel on the laterally adjacent coal beds. For example, the Canyon bed splits off the Anderson bed approaching the channel and both beds pinch out along the eastern margins of the distributary channel. The isopach map of the Anderson-Canyon interburden (fig. 54) illustrates an increase in thickness towards the channel, the apparent source of the interburden sediments. In another example, a structural high in the Smith coal bed over the distributary channel is owing to differential compaction and the coal bed thickens rapidly west of the channel. The Smith coal bed is thickest west of the channel where it is commonly referred to as the “Big George” coal bed Ashley, (2005). Ashley (2005) also found that structural highs in the Smith (his Big George coal) bed were indicative of the presence of an underlying Anderson “no-coal zone” (fig. 17). The distribution of relatively minor coal beds of the Anderson-Wyodak coal zone including the Dietz and the Werner are also largely controlled by channel geometry as illustrated by cross section N-S-2 (fig. 11).

There are also several secondary channels that impact the coal beds but to a lesser degree than the major north-south channel shown in figure 53. Two of these secondary channel areas can be seen on cross section N-S-2 (fig. 11). One of these secondary channels is an east-west trending channel that roughly bisects the Gillette coalfield (fig. 53). This channel complex is bounded below and above by the Canyon and Anderson coal beds, respectively. Isopach maps of the Anderson and Canyon beds illustrate the effects of the channel on bed thickness and areal extent (figs. 34 and 40). Locally, both the Anderson and Canyon coal beds are absent, but the lack of extensive drilling in the channel area made it impossible to define the “no coal” areas completely. The significant effects of the channel complex on the interburden interval between the Anderson and Canyon beds can be seen in figure 54. The Anderson-Canyon interburden map as well as north-south digital coal bed model cross sections shown in figs. 55 and 56 show that there are two channels that merge westward into a single wider channel. The structural separation between the Anderson and Canyon beds is accentuated owing to differential compaction over the sand-rich channel complex. Locally, the maximum interburden thickness exceeds 250 ft, but, typically, the interval is less than 200 ft thick. The increased sand content in these channel areas may cause at least minor increases in both highwall and spoil pile stability problems during mining.

The other secondary channel trends southeast-northwest under the town of Gillette and impacts the Anderson coal bed and especially the Canyon coal bed in the northern third of the coalfield (fig. 53). Isopach maps of the Anderson and Canyon beds illustrate the effects of this channel on bed thickness and areal extent (figs. 34 and 40). Except for a local "no coal" area in the Canyon bed, the principal effects on both coal beds are local thinning and fluctuations in the interburden interval. The Anderson-Canyon interburden map, as well as north-south cross sections from the digital coal bed models (figs. 57 and 58) illustrate the coal bed geometry. The reason for the sudden increase in the interburden thickness can be seen on the NW-SE cross section (fig. 58). The trend of increasing Anderson-Canyon interburden thickness northward suggests the presence of another significant channel complex in that direction.

There are additional relatively narrow channels throughout the coalfield that are typically less than 1,000 ft wide. Definition of these small channels would have required additional drilling with less than the ¼ mi spacing used for this assessment. An example of these relatively small channels can be seen at API drill-hole number 526745 on cross section E-W-5 (fig. 16). The red-colored "no coal" holes in figure 53 also suggest the presence of at least several narrow channels in the areas of thicker Anderson and Canyon coals east of the major channel on the west side of the coalfield, such as in T.47 N., R. 74 W. Similar small channels have been described by Ashley (2005). These channels may be similar to a channel on the west side of the Dry Fork mine just north of the town of Gillette. A north-south trending channel, from about 300 to 900 ft wide, cuts through a 75 to 100 ft section of the Anderson-Canyon coal bed interval (Western Fuels-Wyoming, Inc., 2000). It is expected that these small channels will have minimal impact on the overall recovery of coal resources in the Gillette coalfield, except perhaps in areas immediately adjacent to the major distributary channel at the western edge of the coalfield where these small channels appear to be more numerous.

Channel complexes not only impact the thickness and areal extent of the coal beds but also can influence coal quality. Typically, ash content increases when approaching channel margins where ash-bearing thin clastic lamina and partings in the coal beds are more numerous. Higher ash contents also result in lower Btu contents. A relationship between channels and coal quality is expected and is confirmed by the distribution of partings the Canyon coal bed (fig. 59). The volume of parting material is concentrated in and adjacent to the east-west and southeast-northwest channel complexes. Unfortunately, insufficient coal quality data are available in these channel areas to quantify the anticipated impacts on the coal quality. However, inferences can be made from observing average coal quality variations from producing coal mines in and adjacent to the east-west channel. The Coal Creek mine is within a channel area, the Cordero Rojo mine is just north of the channel, and the Belle Ayr mine is the furthest away from the channel (fig. 53). The average ash and Btu contents for the first half of year 2007 production period for the Belle Ayr, Cordero Rojo, and Coal Creek mines were 4.57% ash, 8,542 Btu; 5.31% ash, 8,428 Btu; and 5.67% ash, 8,336 Btu, respectively (Platts, 2007). While certainly not conclusive, these averages do support the trend of improved coal quality away from the channels.

One of the most important findings of this assessment was the influence of the major north-south distributary channel on long-term, deeper surface mining in the Gillette coalfield. From the

2002 assessment of this area (Ellis and others, 2002), it appeared that the thick Anderson coal bed was continuous throughout the coalfield. The comparison of the Upper Wyodak (Anderson) coal bed isopach map from the 2002 study and the current Anderson isopach (fig. 52), as well as the comparison of the significant changes in coal bed correlations (figs. 7 and 8), illustrate the important interpretational revisions of this assessment. The Anderson and Canyon beds pinch out along the eastern margin of the major north-south channel complex. The Smith bed extends over the major channel and thickens rapidly to over 60 ft to the west, but east of the channel, where the Anderson and Canyon beds are thinning and pinching out, the Smith bed is only 20 ft or less thick (figs. 13, 15, 16, 17, and 18). Thus, there are areas along the eastern margin of the major channel where no thick coal beds are present, causing a rapid increase in the cumulative stripping ratio and thus effectively creating an economic barrier to down-dip surface mining.

In summary, the thickest and typically best quality coal bed was formed in the interchannel basinal areas farthest removed from the higher energy channel environments. Coal that formed near the channels was contaminated by sediments supplied from the channel environment. It is not surprising that essentially all the current mines are located in the shallow areas of the thickest, highest quality coal resources. This is a good example of the mining practice called “high grading,” where the most economically attractive resources are selectively mined first. Through time, however, continued production forces exploitation of deeper, thinner, and often lower quality coal resources as long as economic conditions are favorable.

Resource Allocation Planning

Following the PC/Cores geologic digital modeling for the evaluated coal beds, the next step of phase two of the assessment involved importing the files into a geographic information system (GIS). This GIS system was used to allocate coal resources to the various restrictions to mining (previous mining, towns, sensitive environmental areas, railroads, and so on) in order to determine the amount of available coal.

ArcView® and the ArcView Spatial Analyst® extension (Environmental Systems Research Institute, Inc., 2000a, 2000b) were used to perform the various GIS analyses and ultimately calculate the area’s coal resource numbers. In addition, ArcGIS® (Environmental Systems Research Institute, Inc., 2006) was occasionally used to project digital coverages, shapefiles, or grids to the assessment area’s base map projection. The geographic referencing base of the digital data used for the GIS analysis is the Universal Transverse Mercator (UTM) map projection, using the following parameters: map units= meters; zone=13; datum=NAD27; and spheroid = Clarke 1866.

USGS coal resource assessments do not have a standard grid cell size that is used for all GIS analyses. For this GIS assessment, a grid cell size of 30 meters (about 100 ft) was chosen because it matches the cell size of USGS digital elevation model (DEM) data sets that are currently available for most of the United States. and therefore facilitates GIS integration of the DEM data sets with other model grids (USGS, 2007). Consequently, all grids used within the GIS analysis were either originally created with a grid cell size of 30 meters or resampled to 30 meters from another cell size. In the case of the digital coal model grids, the cell size was resampled from 150 meters to 30 meters.

The first task in the GIS analysis involved creating ArcView readable grids from the ASCII files of the coal, parting, and overburden isopach grids that were created by the digital coal models. These ArcView grids were used to create a total thickness (coal plus parting) grid and an aerial extent grid for each coal bed to be evaluated. The next task then involved creating a group of grids that categorized the Gillette coalfield, with each grid representing one specific theme. These grid themes consisted of mined out areas, environmental and societal (*land-use*) restrictions, *technical restrictions*, overburden-to-coal bed ratios, counties, coal ownership, mining areas, resource reliability categories, and coal bed depth. The grid themes for mined out areas, land-use restrictions, and coal ownership were derived from digital information obtained from the Wyoming BLM. The grid theme for the counties was developed from a digital file of Wyoming county lines obtained from the Wyoming Spatial Data Clearinghouse (*http://wgiac2.state.wy.us*). The other grid themes were developed independently for this evaluation.

The grid of environmental restrictions includes buffer zones that surround or lie adjacent to the restrictions (fig. 60). The location and width of these buffers are usually mandated by State or Federal regulations, but specifications presented in the Buffalo Resource Management Plan (BLM, 2001), such as additional buffers around the town of Gillette, Wyoming, were also used in this evaluation. Each restriction buffer measures hundreds or, in the case of the extra-jurisdictional buffer around the town of Gillette, thousands of feet in width at the surface, as discussed in the following section on factors affecting coal resources.

One of the improvements in the methodology for this assessment was revising the technique for defining surface restrictions at depth. Previous economic assessments used a simple “cookie cutter” approach when applying regulatory surface buffers (such as a 300-ft buffer around an inhabited house) below the surface. The surface buffers were simply projected straight downward through the coal beds to be evaluated. However, the restriction areas actually increase with depth when surface mining operations are considered owing to the setback distance required in order to maintain a safe mining pit highwall angle. Consequently, the area that is affected by a restriction becomes larger, the deeper a coal bed lies beneath the surface. For instance, a circular restriction at the surface having a diameter of 600 ft encompasses an area of about 282,600 ft^2, or approximately 6.5 acres. At a depth of 200 ft, however, this same restriction has a diameter of 858 ft encompassing an area of about 577,900 ft^2, or approximately 13 acres, while at a depth of 500 ft the restriction has a diameter of 2,144 ft and encompasses an area of about 3,608,400 ft^2, or approximately 83 acres. Figure 61 illustrates the effect of depth on overall land-use restriction size.

The technical restrictions grids consisted of a grid of areas where coal beds are less than 2.5 ft (30 in) thick and a grid of areas where coal beds are less than 5 ft thick. For this evaluation, coal resources of less than 2.5 ft in thickness are not considered to represent viable resources, whereas coal resources greater than 2.5 ft thick but less than 5 ft thick are not considered to represent currently minable resources or potential reserves.

The grid of mined out areas accounted for all previous mining within the coalfield, including those mines shown in figure 60. The counties grid contained locations of two counties within the Gillette coalfield (Campbell and Converse). The coal mineral ownership grid divided the coalfield into Federal, State, and private ownership categories, while the mining areas grid divided the coalfield into the north, middle, and south area categories. The resource reliability grid divided the coalfield area into measured, indicated, inferred, and *hypothetical* coal resources, whereas the coal bed depth grid divided the coalfield into three categories of depth (less than 500 ft, 500 ft to 1,000 ft, and greater than 1,000 ft).

Once all the individual theme grids were generated, the next step was to apply these grids to the coal resources of the eleven coal beds to be evaluated. First, the individual theme grids were combined into one composite themes grid which was used with the coal bed areal extent grids to define the coalfield’s resources on a bed by bed basis according to all the various categories. Next, areas within each coal bed that represented *previously mined coal* and restrictions (land-use and technical) were removed. The remaining areas contain coal resources that were still available for mining, with each area assigned a mining ratio for subsequent use by the USGS CoalVal program (McIntosh and others, 2005).

A critical step in the allocation of coal for potential mining is defining all the various regions within the coalfield. For the Gillette coalfield, regions are based on a combination of local tax districts (counties), land and mineral rights ownership, mining areas, and mining ratios. The CoalVal program is used to calculate the cost of extraction and recovery potential for the coal resources assigned to each individual region.

For this assessment of the Gillette coalfield, coal resources were allocated to separate stripping ratio areas for six of the eleven evaluated coal beds (fig. 62). These coal beds (Roland, Smith, Anderson Rider, Anderson, Dietz, and Canyon) are either currently being mined or represent potentially minable resources within the foreseeable future. These stripping ratios represent ratios for the coal resource that exist before any mining takes place. However, areas where these coal beds are less than 5 ft thick are considered technically restricted for surface mining. Consequently, separate PC/Cores models were produced for these coal beds that excluded areas where the coal resources were less than 5 ft thick and no mining potential was allocated to them.

Factors Affecting Extraction of Coal Resources

There are many factors that can affect the availability of coal for mining. About 90% of the coal in the Gillette coalfield is Federally owned and must be leased in order to be mined. A four-step coal screening process, defined in the 43 Code of Federal Regulations (CFR) 3420.1-4 regulations (Office of the Federal Register, 2003), determines which areas of Federal coal are acceptable for leasing. Table 3a shows coal-leasing unsuitability criteria listed in the Code of Federal Regulations, Title 43 Subpart 3461.5 (43 CFR 3461.5). These 20 specific legal criteria are used to determine if an area is unsuitable for leasing and surface mining. The criteria were established by the Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Public Law 95-87, 1977). The unsuitability criteria involve consideration of land use, scenic areas, natural areas, historic sites, wildlife habitats, flood plains, alluvial valley floors, and other special lands. Although the 20 unsuitability criteria were developed for Federally owned lands, many of the criteria would also be applicable to State-owned and privately owned lands. For example, areas containing threatened or endangered plant or animal species are protected from destruction wherever they occur. Municipal watersheds are likewise protected from detrimental actions regardless of who owns the land. It is important to understand that not all criteria listed in tables 3a and 3b affect development within the Gillette coalfield.

Other potential restrictions to mining exist in addition to the coal-leasing unsuitability criteria given in table 3a. Restrictions to mining vary with location and local land-management regulations. Thus, different study areas can have different mining restrictions and availability considerations. This report reflects assumptions concerning restrictions to mining that are based on local practices in the PRB and specifically to those practices within the Gillette coalfield. In addition, the BLM in Casper, Wyoming, provided guidance concerning restrictions to mining and the distances to be buffered around specific features and also provided files that delineate many of the features and the buffer distances used for the study. Because required buffer distances can change through time, distances were selected that were considered the maximum amount likely to be required by future regulations. A more detailed determination of restrictions and other availability considerations would be necessary as part of leasing and mine-planning phases of property development.

Figure 60 shows the areas within the Gillette coalfield that were affected by restrictions. In some cases, an area that was originally declared unavailable for coal mining could have a mitigation measure that would permit mining.

The following is a detailed discussion of potential mining restrictions for the Gillette coalfield. Table 3b lists other potential mining restrictions that were considered for the Gillette coalfield. All buffer restrictions refer to distances at the surface.

Federal Land Systems

There are no Federal lands systems that are unsuitable for coal leasing in the Gillette coalfield. The southern part of the coalfield does contain a part of the Thunder Basin National Grassland that includes scattered Federal lands under the jurisdiction of the U.S. Forest Service (USFS), although it is not part of a National Forest. The same unsuitability criteria and land-use conflicts discussed in this report apply to coal mining on the Thunder Basin National Grassland. Where the mineral ownership is Federal, the BLM develops coal-leasing and mining stipulations in cooperation with the USFS. Federal subsurface coal ownership is shown in figure 63.

Railroads

There are two main railroad routes through the Gillette coalfield (fig. 63). The generally east-west route in the northern part of the coalfield is a rail line of the Burlington Northern Santa Fe Railway. The north-south route in the eastern part of the coalfield is a combination of rail lines of both the Burlington Northern Santa Fe Railway and the Union Pacific Railroad. This combination of railroad lines is referred to in this report as the “Joint Line.” In addition to the main rail lines, a number of additional railroad spur lines serve the existing coal mines. However, because these spur lines can be moved as the mining operations progress, they are not considered to restrict mining.

Although it is conceivable that the main lines of the existing rail routes could also be relocated to allow mining to proceed, it is assumed that these main rail lines would not be moved and are restrictions to mining. The total restricted width for each main rail line, including the right-of-way and a 100 ft buffer along each side, is 600 ft.

Roads

County roads (mostly gravel) cross many areas throughout the Gillette coalfield. These roads are not considered to restrict mining because it is assumed that they could be easily relocated or temporarily blocked off to allow mining to proceed. In addition, a number of State and U.S. highways, including an interstate highway (Interstate Highway 90), are present within the coalfield. For this study, it is assumed that all of these highways would also be relocated to allow for mining, except for Interstate Highway 90. This interstate is considered to be a restriction to mining and its total restricted width is 450 ft, including the highway right-of-way and a 100 ft buffer on each side.

Dwellings and Buildings

Individual dwellings and buildings that exist within the Gillette coalfield, outside of the incorporated areas of Gillette and Wright, are not considered restrictions to mining. These individual structures could probably be purchased by a coal company, which could then move or raze them in order to proceed with mining.

Alluvial Valley Floors

All areas identified as alluvial valley floors by the State program delegated to enforce SMCRA, where mining would interrupt, discontinue, or preclude farming, are unsuitable for surface coal mining and thus are deemed to be restrictions. In addition, areas outside alluvial valley floors where mining would materially damage the quantity or quality of water supplying alluvial valley floors are unsuitable for mining; however, this analysis did not cover those areas.

Airports

The Campbell County airport is about two miles north of the city of Gillette. The airport grounds are completely within the Gillette restriction buffer and so it does not represent an additional area of restriction.

Archaeological Areas

No major archaeological areas that would prevent mining are known in the coalfield. There are several minor archaeological sites and also several minor historic sites within the coalfield. A mitigation plan would be developed before coal mining disturbed these areas. Therefore, coal within these known sites was not excluded from this resource study.

Areas of Clinker

In the eastern part of the Gillette coalfield there are many areas along the coal outcrop where coal has burned in-place and produced overlying clinker (fig. 2). Some of these areas extend as much as several miles down dip from the coal outcrop. Because near-surface coal beneath areas containing clinker is either burned or compromised in quality, areas containing clinker were excluded from consideration for resource assessment even though deeper coal may not be affected. Thus, the eastern limit for the Gillette coalfield assessment area is, in some places, down dip from (west of) the actual outcrop of the coal.

Coalbed Methane Wells

The rapid growth in CBM production within the Gillette coalfield has resulted in the placement of thousands of wells, along with their accompanying pipeline infrastructure, throughout the coalfield. Designating all of these wells and their extensive gas delivery systems as being restrictive to mining would effectively exclude most of the coalfield from resource consideration. As stated previously, the expected lifetime of CBM wells producing from a single coal bed is 10 to 12 years.   The BLM has designated Conflict Administration Zones to minimize conflicts between coal mines and CBM wells in the path of projected near-term mining. For the purpose of this study, it is assumed that coal within any part of the coalfield will be mined after the CBM operations have ceased operating in that area. Therefore, CBM facilities are not considered a restriction to mining.

Hilight Gas Plant

The Hilight gas plant is located approximately 7 miles northeast of the town of Wright and connects to several major pipelines for gas and crude oil, as well as to a pipeline for gas-processing-plant products. This installation, with a 100-ft buffer, is considered a restriction to mining.

Oil and Oil-Related Gas Wells

Two major oil and gas fields (Hilight and Kitty) are located within the Gillette coalfield. Hundreds of additional oil and gas wells are also located throughout the remainder of the coalfield.

Resolution of land-use conflicts between coal mining and oil and gas field development will depend on economic conditions, regulations, and negotiations between oil developers and coal developers. An area around a major cluster of active wells might be eliminated from mining activities until these wells are no longer actively producing, or mining activities might proceed around individual active wells that are given a buffer zone. Conversely, specific wells might be plugged and then re-established after mining. For this study, it was assumed that the wells will no longer be actively producing when mining operations reach them and thus they are not considered to be restrictions to mining.

Pipelines

There is a network of underground oil and gas pipelines throughout the Gillette coalfield. Probably most, if not all, of these pipelines would be moved so that surface mining could proceed. However, moving and restoring them would represent an added economic cost to mining. In any case, pipelines were not considered to be restrictions to mining for this study.

Power Lines

All power lines within the coalfield could be moved to accommodate surface mining operations. Thus, power lines are not considered a restriction to mining in the Gillette coalfield.

Power Plants

Electrical power-generating facilities of the Wyodak Plant and the Neil Simpson Plant lie a few miles to the east of the town of Gillette, near the outcrop of the Anderson/Canyon coal. Since this area lies completely within the Gillette restriction buffer, it does not represent an additional restricted area.

Rivers, Lakes, and Streams

The Belle Fourche River is the most significant body of flowing water within the Gillette coalfield. However, throughout its course within the coalfield, it is a shallow, slow moving, meandering stream as is the case with all of the other larger creeks in the coalfield. Therefore, surface mining operations could temporarily relocate the courses of these streams and then return them to their pre-mining locations during mine reclamation. Only the parts of the watercourses that have been designated by the State Land Quality Division as alluvial valley floors significant to farming would need to be preserved with no modification. There are no major lakes present within the Gillette coalfield. Shallow lakes and small ponds that do exist could either be temporarily moved during mining or simply reformed after the mining operations ceased.

Towns

The municipalities of Gillette and Wright are located within the Gillette coalfield and are permanent restrictions to mining. In addition to the actual incorporated area, the mining restriction for each municipality includes a buffer that extends well beyond the municipality limits. The boundaries of each town buffer are taken from the Buffalo Resource Management Plan Update (BLM, 2001) developed by the BLM for potential coal development areas within the PRB of Wyoming.

State Lands

There are no State parks, forests, or specially designated State lands within the Gillette coalfield. Therefore, there are no State lands that are considered to be restrictions to mining for this study.

Coal Reserve Evaluation

The third and final phase in the resource assessment is the economic evaluation of the available resources calculated in phase two (fig. 6). This phase begins by selecting the available resources information for each evaluated bed, parsing them into stripping ratio increments, and importing these data into a coal resource evaluation program named CoalVal, developed by the USGS (Plis and others, 1993; Suffredini and others, 1994; McIntosh and others, 2005). This program is used to calculate recoverable coal resources, operating costs, and a discounted cash flow (DCF) at a given rate of return (ROR) for all the recoverable coal. That portion of the recoverable coal that is economically minable at or below the current sales price of coal is designated as reserves.

Mine Model Designs

In the evaluation of the Gillette coalfield by Ellis and others (2002), mine models assumed truck-shovel recovery methods. The standardized mine size was 20 million tons per year, a single set of averaged coal quality values, and estimated market price per ton were used for the entire coalfield.

Several significant assumptions made by Ellis and others (2002) were modified for this assessment. These modifications include: (1) the standardized mine model size was re-evaluated and increased to a 35 million ton per year operation with a 20 year mine life, (2) pit highwall designs were re-evaluated and the overall highwall angle adjusted to reflect Mine Safety and Health Administration (MSHA) permits for the deeper surface mines, (3) average coal quality was recalculated by mining area (fig. 5), and (4) new mine models were created using truck-shovel pre-stripping and adding dragline final stripping, with associated cast blasting.

Mine plans in recently filed State mining permits and discussions with operators in the south mining area indicated that mining progress for several mines could be impacted by the Joint Line within 10 to 12 years. Two 2006 coal Lease-By-Applications (LBAs) confirmed that coal mining companies were planning to develop new mining pits west of the Joint Line. Permitting and construction start-up of a new rail loadout system west of the railroad in 2007 emphasized that mining in that area was imminent. Mining west of the railroad would require a deep *box cut* to begin to recover the coal resources. However, leaving the Joint Line intact produced two new restrictions to mining. One restriction accounted for the amount of coal resources affected beneath the Joint Line right-of-way (ROW) and a second estimated the amount of coal resources affected by the box cut development west of the Joint Line for overburden storage and mine facilities (fig. 64).

For the Gillette coalfield, the thick Anderson and Canyon bed sequence dominates the economic evaluation. These two beds are generally very close to each other with little or no separation by parting or interburden material. Additional coal beds had to meet the following criteria to be evaluated for mining as previously explained earlier in the report. First, the minimum minable coal bed thickness was 5 ft and beds stratigraphically below the Anderson and Canyon bed sequence had to have an incremental stripping ratio of 4:1 or less (fig. 62). This stripping ratio criterion eliminated all beds below the Canyon. Six beds with significant areal extent and exceeding 5 ft thick were evaluated for potential recovery and reserves. In addition to the Anderson and Canyon beds, the Roland, Smith, Anderson Rider, and Dietz coal beds were included in the mine models.

As coal mining of the Anderson/Canyon coal beds progresses westward, the Anderson Rider bed in the South Mining Area is next to be added to the total minable coal thickness followed by the Roland bed. Although the Roland is stratigraphically higher than the Smith bed, the Smith attains minimum minable thickness farther down-dip (west) than the Roland (figs. 62 and 64). The addition of 5 or more ft of Roland coal extends the 3:1 and 4:1 ratio area westward, where the Smith bed becomes a minable bed with an additional 5 or more ft of coal bed thickness. The addition of the Smith bed helps extend the 5:1 and 6:1 total ratios westward.

For this study, the mining ratio is an accumulative value of tonnage for all the coal beds 5 ft thick or greater down through the coal. Therefore, all coal beds within a given ratio were modeled with the same operating costs per ton on a mining area basis. Utilizing individual bed coal quality averages will yield different total costs for modeling parameters such as taxes and royalties, which are sensitive to differences in coal quality characteristics.

Mine Model Assumptions

One of the most significant developments in the overburden removal process has been the evolution from predominantly truck-shovel operations to the use of large draglines in concert with truck-shovel pre-stripping. This more cost effective overburden removal system takes advantage of the efficiencies of draglines and the flexibility of the truck-shovel operation to strategically place the spoils near final reclamation grade. Eighteen truck-shovel dragline models and eight truck-shovel box cut models were developed in CoalVal for this evaluation. The coal truck dump, near-pit primary crusher and overland conveying system were moved and extended early in the 3:1 ratio model, again late in the 4:1 ratio model, early in the 7:1 ratio model, and late in the 9:1 ratio model. These moves and extensions were justified on the basis of reduced haul truck capitalization, truck operating costs, and reduced labor costs as shown in table 4, where the coal haul trucks and labor increased from the 3:1 to the 6:1 ratio model (even with a coal dump/crusher move and overland conveyor extension late in the 4:1 ratio model).

Equipment and staffing cost data and productivities obtained from the Society of Mining Engineers (1973), Society of Mining Metallurgy and Exploration, Inc. (1992a, 1992b), U.S. Bureau of Mines (1987), Caterpillar, Inc. (2006), and Western Mine Engineering, Inc. (2007) as well as industry reports, such as Hill and Associates (2006), and reviews of mining assumptions from coal companies within the Gillette coalfield were used to construct truck-shovel and dragline/truck-shovel overburden removal mine models in CoalVal. The models were developed by waste to coal effective ratios, from <1:1 to 10:1, for a mining operation recovering 35 mst of coal per year. The dragline operation uses cast-blasting to move a portion of the overburden into its final location across the open pit rather than using mining equipment. This is accomplished by drilling angled blast holes (55 to 65 degrees from horizontal) and detonating enough explosives to cast the material 200 plus ft. Cast-blasting is more cost effective than moving the same volumes by the dragline or dozers. For these studies, the cast-blasting volume of the dragline bench was considered to equal the volume of re-handled waste by the dragline. The stripping ratio and *effective stripping ratios* are essentially equivalent for this assessment.

The mine models were designed to assume that new, optimally sized equipment would be purchased and operated on a 24 hours-per-day, 7 days-per-week schedule. Ten holidays were scheduled for all equipment operations except for the dragline. The amount of stripping and coal production equipment was determined from truck-haulage simulations and from shovel and from reported dragline productivities existing in Gillette coalfield mines. The amount of support equipment needed was determined by the required stripping and coal production equipment. Production staffing was determined for all equipment necessary for the mine operations. Maintenance staffing was based on field observations and regression analysis of the amount of mobile production equipment (trucks, dozers, graders, etc,) and electrically operated equipment (draglines, shovels, and drills) in use. Mine management and supervision staffing were determined using ratios of salaried mine staffing to wage staffing based on current Gillette coalfield mining operations.

When a surface mine is started, a box cut is typically excavated immediately downdip from the subcrop. The overburden material from the box cut is normally placed outside the pit area (out-of-pit overburden dump) on land that is not underlain by coal. This dump is either re-contoured to blend with the original ground surface or is strategically placed for use in final pit reclamation. Occasionally, box cuts must be made away from the outcrop where there is considerable overburden depth. These pit developments take much more time and incur greater costs to reach coal production. Furthermore, the out-of-pit overburden dump is typically placed on coal resources adjacent to box cuts. The affected coal resources under these dumps would be sterilized for future mining, or else expensive double handling the overburden would be required if the underlying was recovered.

A new box cut would be needed to access the coal west of the Joint Line. This box cut would be a challenge both economically and logistically. The projected time required to open a box cut using truck-shovel equipment, would vary from more than one year for a 3:1 ratio box cut to nearly three years for a box cut at a 9:1 ratio. Such operations would require additional equipment separate from the mining operations east of the Joint Line. During development of the new box cut, coal production would have to continue in the pits east of the Joint Line, as no coal is being produced from the new box cut would not be producing any coal. This need for the additional equipment also exacerbates the financial impacts of the new box cut. Given the long lead times necessary for box cut development, a major timing challenge would be to develop the pit and be ready to begin coal production west of the Joint Line just as coal production was completed east of the Joint Line. When the dragline overburden removal operations east of the Joint Line were finished, the equipment would have to be moved across the railroad to begin overburden removal in the next cut after the box cut. Because coal production would have to continue east of the Joint Line until the box cut was ready for coal production, back-filling the eastern pit with spoil from the box cut pit would not be possible, leaving an out-of-pit overburden dump as the only feasible option.

The standardized coal pit was designed to be 10,600 ft long by 200 ft wide with haulage ramps from the truck-shovel pre-benching operation located at the ends of the pit. This long, straight highwall allowed enough pit length to inventory in-pit coal, to be served by three coal haulage ramps, and to schedule coal mining operations and dragline operations with a minimum amount of conflict. No cross-pit haulage with highwall ramps was used. The truck-shovel pit design assumes 200 ft wide, 70 ft high benches, with a 55 degree slope angle. Dozers are used to push the upper 15 to 20 ft of overburden to the overburden removal shovel. The dragline stripping operation assumes a 200 ft wide, 140 ft high bench, and 55 degree highwall with ramp access from both ends of the pit. Access for the coal haulage was by three ramps, one on each end of the pit and one ramp entering in the center of the pit.

Overburden, interburden, and parting densities ranged from 3,200 lbs per bank cubic yards (BCY) to 2,700 lbs per BCY (data obtained from Gillette coal mines) so an average of 2,950 lbs per BCY was used for waste calculations and a density of 80.965 lbs per cubic ft or 2,186.1 lbs per BCY was used for coal (swell factors of 16 percent for overburden, interburden, and parting, and

26 percent for coal were used). The coal density analysis is an average from more than 900 core samples of the Smith, Anderson, and Canyon coal beds in the PRB (Stricker and others, 2007). Equipment availability was determined using the Society of Mining, Metallurgy, and Exploration Inc. (1992a and 1992b), Caterpillar, Inc. (2006), and Western Mine Engineering, Inc. (2007) reference books, mine observations in the Gillette coalfield, and meetings with mine personnel.

To help illustrate the level of details and fundamental concepts of mine planning used for the mine models, a comparison of the 3:1 ratio model to the 6:1 ratio model is provided in table 4. The coal production is constant at 35 millions tons per year, yet at a 6:1 ratio, twice as much overburden must be removed (210 million BCY versus 105 million BCY) to uncover the same amount of coal. The first truck-shovel pre-strip bench operation was required in the 3:1 ratio model. By the 6:1 ratio model four pre-stripping benches are required. Because of the additional benches and longer haul distances, the equipment and staffing increases by more than 5.5 times. The dragline and associated stripping dozer operation is always scheduled to remove the 140 ft of overburden/interburden directly above the Anderson coal bed. This schedule allows the dragline and its associated equipment and manning to remain constant from model to model. Coal haulage and reclamation equipment and associated manning show modest increases in the 6:1 model owing to longer coal haul distances and increased reclamation volumes because of the increased overburden volumes.

In 2006, the average estimated effective ratio for the mines in the south mining area was about 3:1 with an average productivity of 44.4 tons per man-hour (not including temporary staffing). Productivity for the 3:1 model used in this study is 48.4 tons per man-hour (including fill-in staffing). Total employment in the 6:1 model is 627 employees with 25 tons per man-hour productivity. It is obvious that there are significant increases in mining costs at greater depths. Furthermore, it can be seen from table 4 that most of the increase in mining costs is associated with the truck-shovel overburden removal operations.

All mining assumptions, such as production rates, coal recoverability, equipment and man-power scheduling, blasting costs, salaries, wage burden rates, taxation, haulage rates, equipment sizes, capitalization costs, maintenance costs, and manpower requirements, are inputs into the CoalVal mine models. CoalVal mine model reports are then generated to produce the operating cost per ton by bed and by ratio.

Coal Quality

Coal quality is a major factor in its marketability and is an important input parameter in CoalVal cost calculations. Quality parameters such as increased ash or lower heat British thermal unit (Btu) content negatively impact the operating and maintenance costs at coal-fired power plants. Government restrictions to reduce potentially hazardous air pollutants (HAPs) such as sulfur place a premium on fuels that are lower in those regulated HAPs. According to the Clean Air Act, the regulatory standard for sulfur dioxide emissions from coal-fired power plants is 1.2 pounds of SO_2 per million Btu (Public Law 101-549, 1990).

In the Gillette coalfield, coal is relatively low in total sulfur content and most of the minable coal contains less than 1.2 pounds SO_2 per million Btu. Coal quality is an important component for the economic evaluation. At the present time, all mine production is from the Anderson and Canyon beds. Within the next 10 years the Anderson Rider bed may be mined followed by the Roland, Smith, and Dietz, As these other beds are produced, it is assumed they would be blended with the then more abundant and highest quality Anderson and Canyon beds (table 5). These assumptions produce two scenarios for coal production, mining high quality coal at the present time and a slightly lower quality, blended coal in the future.

In-Place Coal Quality

In-place coal quality varies significantly within the Gillette coalfield. The north, middle and south mining areas (fig. 5) were defined on the basis of variations in coal quality which permitted estimates of sales price using averaged coal quality data for each area. From table 5, the in-place coal quality trends by bed may be observed. For each bed, moisture is generally lowest in the south mining area and increases to the north. The Btu is highest in the south mining area and lowest in the north mining area. This trend is expected because the Btu content is inversely proportional to the moisture content. Sulfur and ash generally increase from the south mining area to the north mining area with the exception of higher sulfur and ash contents in the Canyon bed in the middle mining area. The Anderson Rider bed contains the lowest quality coal with lower Btu and much higher sulfur and ash contents. The blended coal quality was determined by weighting the individual bed's quality by the associated in-place resource tones. This procedure was followed for each mining area (table 5).

Reliable, publicly available, in-place coal quality data (moisture, Btu, sulfur, ash) for the Gillette coalfield are very limited, particularly for beds other than the Anderson and Canyon. Several publications from the U.S. Bureau of Mines (1975a and 1975b), the USGS (Bragg and others (1997), Ellis (2002), Stricker and others (2007), and public data from the BLM have provided enough quality data to obtain trends and averages by mining area. Although more data are available for the Anderson and Canyon beds, there are still not sufficient public data to develop detailed coal quality models for the Gillette coalfield. A review of all the available data was completed to arrive at reasonable in-place coal quality average by bed by mining area. These coal quality averages were then reviewed with coal industry geologists in the Gillette area.

Coal Recovery

Coal quality dilution from outside the coal bed is kept to a minimum by careful cleaning of the top of the coal bed with rubber tired dozers, front-end loaders, and graders. Dilution at the base of the coal bed is minimized by using coal loading shovels. Coal quality at the top and base of the coal beds is often higher in ash and sulfur content. Some mining operations are able to improve produced coal quality from thicker coal beds by cleaning the top and/or by leaving the bottom few feet of coal unmined (this floor coal may provide a better running surface for the haul trucks than the clay below the coal bed). In these cases, gains in quality (and eliminating dilution) compensate for slightly lowered recovery rates. No dilution tons were added to the in-place coal resources in this study.

The loss of coal at the top and base of the mined coal bed is minimal and is affected by the coal hardness, bed thickness, and position of the coal bed in the stratigraphic column. In general, as bed thickness increases, the recovery percentage also increases. Beds in the upper portion of the stratigraphic column, which are mined by truck-shovel only, experience losses from only the top and base of the coal bed. In the truck-shovel/dragline operation, lower beds near and at the base of the mining sequence experience the use of a large "fender" or rib of coal that is left undisturbed to hold back the low-wall overburden dump (spoil) on the up-dip side of the coal pit. Recovery reports from Gillette coalfield mines indicate that the greatest amount of coal lost during mining comes from that large fender of coal on the spoil side of the pit. That coal left in-place for controlling spoil stability may actually account for 90 to 95 percent of the total coal lost in some operations.

Sales Price Estimates

After in-place coal quality is estimated on a bed by bed basis, the blended coal quality of the produced coal quality can be estimated. This estimate was accomplished by determining the quality of the sold coal and sales prices by producing mine from January through December 2006 (Platts, 2007). The mine production and sold quality data were determined by mining area. Because those data are not reported by bed, there is no way to determine average coal quality separately for the Anderson or Canyon coal beds. Therefore, the reported coal quality and sales prices by mining area for quality and price within each mining area for the Anderson and Canyon are averages of the two beds (table 5).

Regression analyses were run comparing historical coal quality and sales prices. The derived equations were run using the predicted blended coal quality to estimate the future sales prices. The primary component of the regression equation was the Btu factor; however, sulfur and ash were also factored into the analyses. The results in table 5 show estimates of the sales prices for the blend of evaluated beds by mining area.

Estimating the Bid Cost/ton for Federal Lease by Applications

Although Federal Lease by Application (LBA) lease bids have many variables such as proximity to a neighboring mine, stripping ratio, and ultimately estimated mining costs, the bid values from the last seven LBA sales correlate well to coal quality. Regression analyses were run on the lease bid cost per ton verses coal quality by mining area. Coal quality by bed was then entered into the derived equation from the regression analysis to estimate future bid costs per ton. These data were then entered into CoalVal as a land acquisition component of the economic evaluation.

Coal Reserve Calculations

The economic evaluation to determine coal reserve estimates was performed using the program CoalVal. This program delineates recoverable resources and generates mine operating costs and a discounted cash flow (DCF) analysis to calculate the break-even price required to cover costs at a specified rate of return (ROR). All resource blocks with a break-even price at or less than the current estimated market price are considered coal reserves by definition. CoalVal mine models for the Gillette coalfield were developed on a stripping ratio basis from <1:1 to 10:1 ratios (fig. 62). The 10:1 ratio model was chosen to be the final mining model because the location is close to the large north-south trending sand channel that will limit westward stripping in the Gillette coalfield. Depth to coal for the 10:1 ratio model varies from about 800 ft to more than 1,200 ft.

Data Input

The in-place tons of coal and partings for all resource blocks modeled in phase 2 were imported into CoalVal on coal bed, mining area, and stripping ratio basis. The appropriate restrictions to mining and previously mined resources were subtracted from the in-place resources. CoalVal was used to calculate the *recoverable resources* for each coal bed by mine model for the three mining areas. The average coal quality for the three mining areas and county tax tables were imported into the applicable resource areas in CoalVal. Other sold coal quality, estimated sales prices, taxes, and estimated resource acquisition costs were then entered into the tax tables in CoalVal.

Operating and Discounted Cash-Flow Costs

To increase the usefulness of the assessment results, both operating costs and DCF costs by mining ratio and by mining area were calculated. Operating costs were developed for the recoverable resources in order to understand how resource areas compared by mining ratio and by bed. These costs are a better indication of mining performance than DCF cost comparisons, which contain a blend of factors that vary between mining operations. These operating cost comparisons were then used to compare economic models to existing mines.

Operating costs were divided into: (1) direct costs, which included payroll and burden, fuel and lube, explosives, operating supplies, repair parts and supplies, utilities, rentals, professional services, reclamation provision, general expenses, and blending and loadout costs; (2) indirect costs, which included depreciation, depletion, amortization, overhead, property and sales taxes; and (3) royalties, LBA or land acquisition, and taxes.

The DCF analysis in CoalVal calculates a price where the net present value (NPV) of the revenue matches the net present value of all expenditures. The NPV is discounted by a rate of return (ROR) that compensates investment for the time value of money and risk. The ROR was set at 8 percent in this study on the basis of Energy Information Administration recommendations for a weighted cost of capital in other energy exploration industries (T.K. Lee, EIA, written communication, 2004). At 8 percent, the DCF-ROR as defined by Barnes (1980) is “the rate of return that makes the present worth of future generated cash flow over the life of a project equal to the present worth of all after-tax investments” or “the rate of return that makes the present worth of positive or negative after-tax cash flow for an investment equal to zero” (Stermole, 2000). CoalVal can be used to run sensitivity analysis on a range of ROR values, but higher ROR will require higher market prices for the NPV of revenue to match investments.

Data from the DCF cost per ton calculation of all of the recoverable resources (in increments from the lowest cost to the highest cost) were used to develop *cost curve* for the Gillette coalfield. This cost curve, using a January 1, 2007, sales price, was used to extrapolate the amount of reserves should the sales price increase/or decrease while the costs remain constant.

Once the CoalVal mining models are constructed, costs can be easily updated. A subroutine in CoalVal can use a variety of cost indices from the U.S. Department of Labor’s Bureau of Labor Statistics website (*www.bls.gov*.). These indices can be weighted by the user as appropriate to revise costs and generate an updated costs curve.

Resource Assessment Results

The incorporation of the data from over 8,000 additional drill holes during the current assessment has resulted in a substantial refinement in the coal geology of the Gillette coalfield. The improvements from this additional control can be observed readily from a comparison of the isopach maps of the Upper Wyodak (Anderson) coal bed from the study of Ellis and others (2002) and the Anderson coal bed in the current assessment (fig. 52).

Quantifying the total effects on resource estimates between the two assessments is not straightforward because of differences between the two studies. The differences include the size of the areas assessed, significant modifications in coal bed correlations, modified methodologies for restrictions, and revised mining models. However, it was possible to make at least a reasonable comparison of original resources for the two most important coal beds from both studies by utilizing the area in the report by Ellis and others (2002) to gain a sense of the magnitude of any changes in the resource estimates. The Upper Wyodak and Lower Wyodak/Werner in the 2002 study correlated to the Anderson and Canyon beds respectively in the current assessment. Total original resources for the two beds for the area in the 2002 study and the current assessment were about 125 bst and 105 bst respectively. Therefore, results of the current assessment for these two beds are 20 bst (about 16 percent) less than the 2002 study.

Gillette Coalfield Resources Evaluation

Special GIS resource allocation planning (RAP) scripts were used to apply appropriate density values to the coal and parting isopach grids in order to calculate the tonnage of coal and the tonnage of parting material contained within each area. Finally, other RAP scripts were used to apply the original, remaining, and available coal and parting tonnages to the grids of coal ownership, county boundaries, mining areas, reliability categories, depth to coal, and mining ratios to create an even more detailed breakdown of the study area's coal resources.

The final step in the GIS resource allocation process was to convert all the grid data to tabular form. One last RAP script was used to place all of the coal and parting tonnage and acreage numbers for each categorized area, per coal bed, in an ArcView Spatial Analyst value attribute table, which was subsequently exported out of ArcView as a dBASE (.dbf) file.

Original resources (coal plus parting) were calculated for coal resources greater than 2.5 ft thick with no restrictions taken out. *Remaining resources* were calculated using the volume of that original resource minus the volume of coal and parting that had been previously mined. Land use (environmental) and technical restrictions were then calculated and subtracted from the remaining resource to determine *available resources*.

The eleven coal beds evaluated in the Gillette coalfield (Felix Rider, Felix, Roland, Smith, Anderson Rider, Anderson, Dietz, Canyon, Werner, Gates, and Pawnee) contained 201 bst of original coal resources (figs. 65 and tables 6, 7, and 8). The majority of these resources, 185 bst (83 percent of the total) are on Federal lands (table 6). About 6 bst (3 percent) of the total original coal resources has already been mined in the Gillette coalfield. Approximately 31 bst (16 percent) of the original coal resource is affected by restrictions (too thin, land use, and technical). About 4.2 bst of the total 31 bst of restricted coal resources lies under the Joint Line right-of-way and associated area required for box cut development. The subtraction of all the restrictions to mining leaves 165 bst (81 percent) of the total original resource available for development in the Gillette coalfield.

Coal resource reliability categories for the original coal resources for the 11 assessed coal beds are summarized in table 8. About 91 percent of the total original resources can be classified as measured or indicated reflecting the overall substantial improvement in geologic confidence provided by the additional data included in this assessment. Since most of the new data were from CBM drilling, table 8 shows a significant decrease in overall coal resource reliability for beds below the Anderson/Canyon development targets.

Six of the 11 coal beds modeled for in-place resources (Roland, Smith, Anderson Rider, Anderson, Dietz, and Canyon) were also evaluated for coal reserve potential. The criteria used for inclusion of a bed for the reserves analysis are discussed in the section on geologic modeling. Table 9 shows available resources greater than 2.5 ft thick by stripping ratio. The emergence of the Smith coal bed as the dominant coal bed in the deeper areas west of the major north-south channel can be seen by the resources in the greater than 10:1 ratio category (table 9).

Gillette Coalfield Reserves Evaluation

A total of 165 bst of original minable coal resources (2.5 ft thick or greater) was found in the six coal beds included in the reserves evaluation (table 10). A total of 74 bst of restricted resources was estimated. This amount includes 50 bst of resource that was not evaluated because the mining ratio exceeds 10:1. The amount of recoverable resources totaled 77 bst or about half of the total original minable resources. The Anderson bed (45 bst) and the Canyon bed (19 bst), which are the beds currently being mined, provide the majority of the recoverable resource tons.

Once the amount of recoverable resources was established, the next step of the reserves analysis was the completion of the mining economics evaluation. Since most of the present and new mining in the foreseeable future will be conducted in the Anderson bed, it is used as an example to illustrate the variation in costs by ratio and mining area. The results of the operating and the DCF costs per ton for the Anderson bed are provided in tables 11 and 12 respectively.

Direct and indirect operating costs are stripping ratio dependent, while acquisition costs, royalties, and taxes are mining area dependent and not contingent on the ratio (table 12). The direct costs do not change from area to area for the same stripping ratio but progressively increase with higher ratios owing to the need for more equipment and manning. Indirect costs containing amortization costs also remain the same from area to area but increase as the stripping ratio increases owing to the addition of capital equipment. Acquisition costs, royalties, and taxes will increase from the north area to the south area, because sales price and LBA bonus bid costs increase from north to south; however, acquisition costs, royalties, and taxes remain constant from ratio to ratio within the same mining area.

There is a trend for mining costs to be lower in the northern area that can be attributed to several factors. First, mining costs in the middle and southern areas are higher because overburden removal is adversely affected by the location of the Joint Line. Eliminating the need in the northern mining area for the amortization of deep, expensive box cuts west of the Joint Line results in lower indirect mining costs. The impact of the box cut can be readily seen by examining the difference in costs in table 11 east and west of the Joint Line for ratio models of 3:1 or more in the middle and southern mining areas. For example, the operating costs for the 5:1 ratio resources in the south mining area west of the Joint Line are about a dollar per ton greater ($10.84 per ton versus $11.84 per ton) than those unaffected by the Joint Line. The impacts on DCF costs are greater. For the same area, the DCF costs for the 5:1 ratio resources in the south area west of the Joint Line are nearly six dollars per ton greater ($14.50 per ton versus $20.20 per ton) than those unaffected by the Joint Line (table 13).

Secondly, decreasing coal quality from the south to north mining areas, as shown on table 5, also results in lower sales prices in the respective mining areas. The lower sales prices generated lower royalties, acquisition costs, severance and ad valorem taxes. These reductions in turn result in a trend towards lower total operating and DCF costs per ton northward (tables 11 and 12).

Once the DCF costs per ton are determined for all the recoverable resources, the final step in the economic evaluation is determining what portion of those resources can be considered coal reserves (total tons at or below current estimated sales price). To derive a reserve estimate for the Gillette coalfield, a composite cost curve was developed for the total recoverable resources by incremental DCF costs (fig. 66). The DCF costs utilized an 8 percent ROR. Increments of $0.50 per ton, from $5.00 per ton to $60.00 per ton, were chosen to enable the construction of a smooth cost curve.

With a January 2007 sales price of $10.47 per ton for the Anderson and Canyon beds in the south mining area (Platts, 2007), an estimated 10.1 bst of the total 77 bst of recoverable resources are considered as coal reserves (fig. 66). Because a coal reserve estimate is based on a single reference point in time, the use of cost curves is particularly useful. From the cost curve, the relationship between sales price and estimated reserves can readily be demonstrated. As of March, 2008, the sales price for the Gillette coalfield had increased to $14.00 per ton (Platts, 2008). If it is assumed that operating costs remained essentially unchanged over the past year since the reserve study was completed, there would be approximately 18.5 bst of reserves (fig. 66).

The bar **c**harts in figures 67 and 68 summarize the results of the Gillette coalfield coal resources and reserves assessment by tonnages and percentages for the six coal beds included in the economic evaluation. Two key points from the bar graphs need to be emphasized. First, the 77 bst of recoverable resources, which are only 47 percent of the original resources, represent the total estimated amount of coal that could be produced by current surface mining technologies. The significant amount of coal impacted by all the restrictions to mining and mining losses precludes recovery of all of the original in-place coal resources. These recoverable resources would be equivalent to coal resource categories included in the U.S. Energy Information Administration's (EIA) estimated recoverable reserves database (ERR) (Energy Information Agency, 1997). The ERR, which is updated by the EIA periodically, is currently the only published national summary of potentially recoverable coal in the United States. Estimated recoverable reserves are the quantities of the demonstrated reserve base (DRB) coal that may be recoverable, based on regional estimates of coal resource accessibility and mining recovery rates. It is especially important to understand that "the reserve base may encompass those parts of a resource that have a reasonable potential for becoming economically recoverable within planning horizons that extend beyond those which assume proven technology and current economics" (Energy Information Agency, 1997). Thus, the ERR not only includes those resources that currently are classified as reserves, but also recoverable resources that may be mined in the future.

The second point that needs to be stressed is that the volume of estimated coal reserves are even a much smaller subset of the original resources (6 percent) than recoverable resources. The relationship of original resources to reserves is consistent with previous USGS coal assessments which typically found the reserve fraction to be less than 20 percent. This finding emphasizes the need to avoid use of the terms resource and reserves interchangeably and why the determination of reserves is not a one time or static process.

Typically, as a basin matures through time, resources become progressively more expensive to produce. Sale prices generally increase over the long term and operating costs follow accordingly as long as demand is steady. With continued favorable sales prices as well as productivity and technological advances in mining that positively affect economics, resources once considered to be subeconomic may be elevated to the status of reserves. Therefore, reserve studies should be considered a cyclic process and models should be adjusted periodically using the most recent data and reassessed utilizing the most current recovery technology and economics.

Conclusions

This assessment of the Gillette coalfield in the PRB in Wyoming marks a departure from previous assessments where the information relied almost exclusively upon existing data. The tremendous amount of CBM development in the PRB over the last ten years has provided a wealth of new, publicly available data, especially in the Gillette coalfield. Because the Gillette coalfield is the single most important coalfield in the United States in terms of yearly coal production, incorporating as much of those data as practical was warranted. Some of the key results of this assessment are:

- The original database was expanded from about 2,391 to 10,210 data points. The increased data control significantly improved the geological interpretation, including revision of coal bed correlations and definition of framework channels that controlled coal areal extent, thickness, and quality.
- The new geologic coal bed models not only provide a more robust assessment of recoverable coal resources but will also facilitate other resource planning, such as developing CBM and evaluating the environmental impacts of energy-related production.
- The methodology for assessing the restrictions to mining was improved over the previous "cookie cutter" approach to allow for safety setbacks needed to maintain stable highwalls in the mined coal beds rather than simple surface-only expressions around identified buffers.
- While still very significant, improved definition of paleo fluvial systems and a more realistic methodology for assessing mining restrictions have resulted in reduced estimates of the total amount of recoverable coal from previous the estimates by Ellis and others (2002).

- An additional relatively deep box cut will be required in the southern half of the Gillette coalfield to recover coal resources west of the Joint Line. The need for this additional box cut will result in a significant increase in overall mining costs for coal resources in that area.

Eleven coal beds in the Gillette coalfield were evaluated for in-place coal resources. Six of those 11 coal beds met the criteria for inclusion in the economic analysis to derive an estimate of coal reserves in the Gillette coalfield. A summary of the resources in those six beds is shown in figure 65.

Results of the economic assessment of coal resources in the Gillette coalfield, Wyoming, indicate that there is a total of 165 bst of original coal resources for the six coal units assessed (fig. 67). Of these original coal resources, 51 percent (84 bst) of the coal resource is available and 47 percent (77 bst) is recoverable (figs. 67 and 68). Most importantly, only 10.1 bst (6 percent) of the original coal resources for the six beds can be classified as reserves at the current average estimated sales price of $10.47 per ton (as of January, 2007). This reserves estimate will change depending on changes in current sales prices (assuming mining costs remained steady) as shown on the cost curve in figure 66.

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Glossary

The present study includes determinations of original, available, recoverable, and economically recoverable (reserves) resources. This terminology has been used in many USGS coal studies (see Carter and Gardner, 1989; Eggleston and others, 1990; Molnia and others, 1999; Osmonson and others, 2000). The following definitions were applied in this resource evaluation:

- **Available resource** is the amount of the original resource that is accessible for mine development under current regulatory and land-use constraints. This resource is the original coal minus previously mined coal and coal that cannot be mined owing to land use and technical restrictions.
- **Box cut** is the initial pit developed when opening a surface coal mine.
- **Cost curve** is a graph of the costs of production as a function of total quantity produced. Discrete quantities are ordered from lowest to highest cost.
- **Dilution** is contamination of the coal bed during the mining operation with non-coal or poorer quality coal, subsequently lowering the initial coal bed quality.
- **Effective stripping ratio** is the total volume of waste material (overburden, interburden, re-handled waste, and mined parting material) divided by the total recoverable tons of coal.
- **Interburden** is non coal material that lies between two coal beds.
- **Original resource** is the total amount of coal 2.5 ft thick or greater in the ground prior to mining.
- **Parting** is thin layers of non coal material within a coal bed. Typically, parting material contains higher ash and lower carbonaceous material than the surrounding coal.
- **Previously mined coal i**s coal that has already been extracted.
- **Recoverable resource** is the amount of the available resource that is left after mining losses and cleaning losses are subtracted. The economics of extraction and coal cleaning are not considered in the recoverable resource determination.
- **Reliability categories** are based on the distance from points of measurement and (or) sampling. The measured, indicated, inferred, and hypothetical resource categories, as defined, indicate the relative reliability of tonnage estimates as related to distance from points of thickness control of particular parts of a coal deposit (Wood and others, 1983).
    - **Measured—**Tonnage estimates computed by projection of thicknesses of coal for a radius of ¼ mile (0.4 km) from a point of measurement.
    - **Indicated—**Tonnage estimates computed by projection of thicknesses of coal for a radius of ¼ to ¾ mile (0.4 to 1.2 km) from a point of measurement.
    - **Inferred—**Tonnage estimates computed by projection of thicknesses of coal for a radius of ¾ to 3.0 miles (1.2 to 4.8 km) from a point of measurement.
    - **Hypothetical—**Tonnage estimates computed by projection of thicknesses of coal for a radius beyond 3.0 miles (48. km) from a point of measurement.

- **Remaining resource** is the amount of coal left after subtracting mined out resources from the original resource total.
- **Reserve** is the amount of the recoverable resource that can be mined at a profit at the time of the economic evaluation. Reserves are affected by the mine location, coal bed characteristics, coal quality, mining methods, and any cleaning of the coal.
- **Resource** is a naturally occurring concentration or deposit of coal in the Earth's crust, in such forms and amounts that economic extraction is currently or potentially feasible.
- **Restrictions to mining are** land use, technical limitations, and legal unsuitability that would prohibit mining:
  - **Land use restrictions** are constraints placed upon mining by societal policies to protect those surface features or entities that could be affected by mining. Since laws and regulations can be modified or repealed, the restrictions, including industrial and environmental restrictions, may change. Land use restrictions include railroads, cities and towns, airports, and interstate highways.
  - **Technical restrictions** are constraints, relating to economics and safety, placed upon mining by the state of technology or prescribed by law. These restrictions can change with advances in science or modifications in the law. In this report, geological factors are included as technologic restrictions. Technical restrictions include coal between 2.5 ft and 5.0 ft thick and clinker areas.
  - **Legal unsuitability criteria** are constraints used to determine if an area can be mined by surface mining methods. These include, but are not limited to, federal land systems, dwellings, and alluvial valley floors.
- **Stripping (Mining) Ratio** is the most influential economic factor in the evaluation and planning of open pit coal mines. It represents the ratio of the volume of overburden and/or interburden (waste) that must be removed to gain access to a unit amount of coal. For this assessment, the ratio is expressed as cubic yards of overburden to tons of coal. The stripping ratio can be approximated by dividing the total thickness of waste by the total thickness of coal. For example, given two coal beds each 5 ft thick at 50 and 105 ft in depth, the total waste and coal thicknesses would be 100 and 10 ft respectively. A simple ratio would be 10:1, but a stripping ratio would be 9.1:1 (in cubic yards to a ton of coal).

FIGURES 1-68

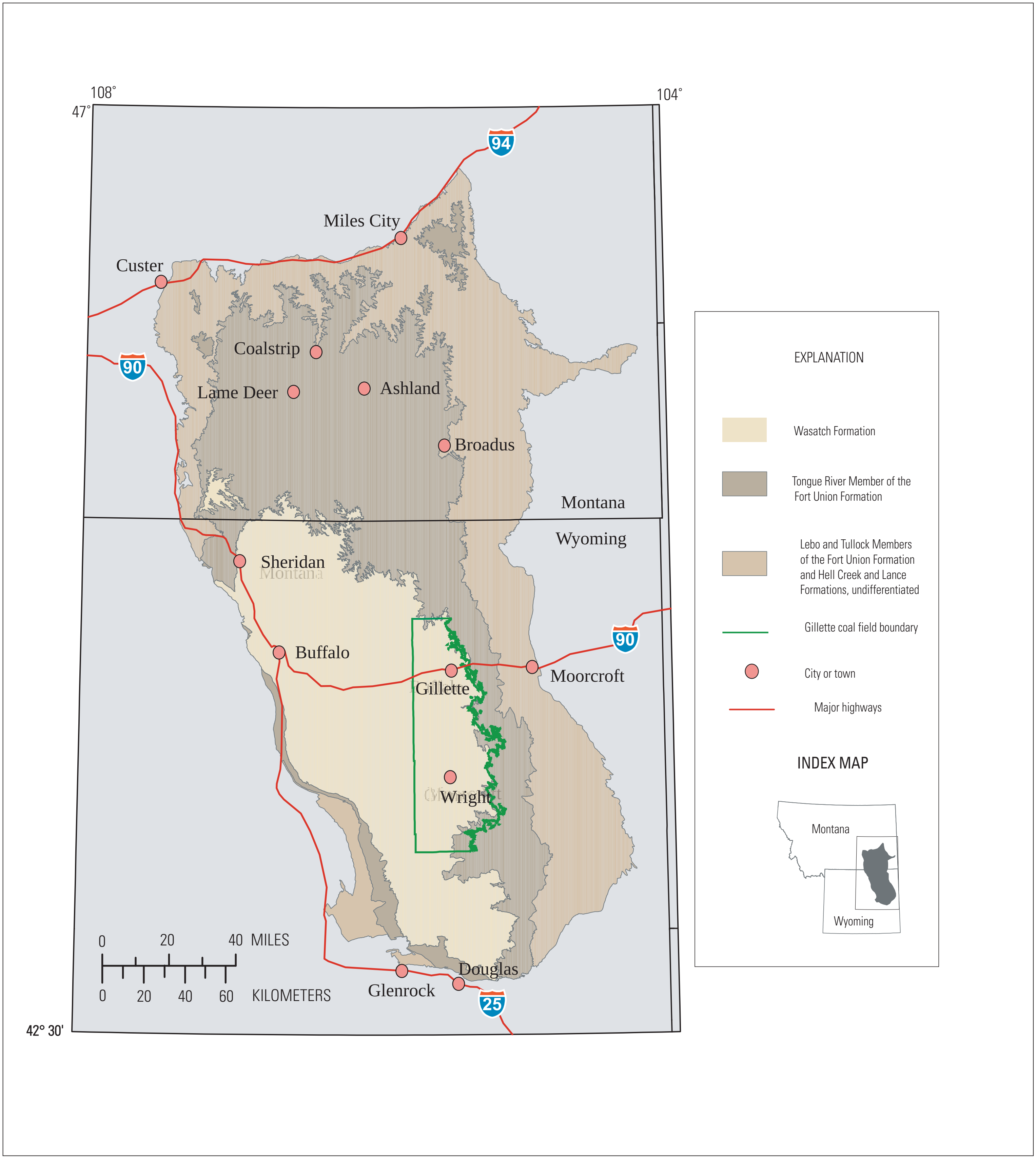


Figure 1. Generalized geologic map of the Powder River Basin, Montana and Wyoming, and the location of the Gillette coalfield, Wyoming. (Ellis and others, 2002).

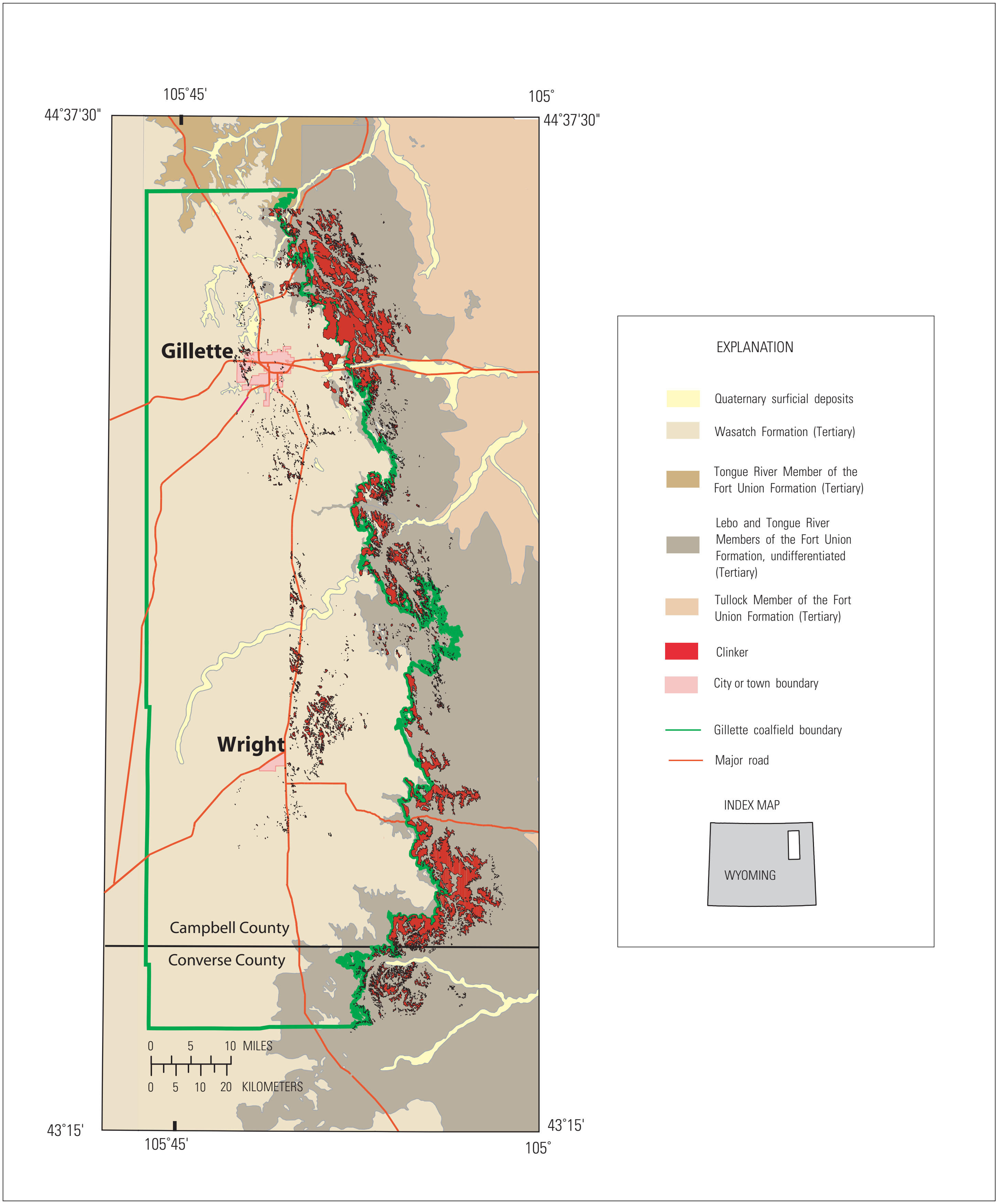


Figure 2. Geologic map modifed from Ellis and others (2002) showing Tertiary and younger rocks, major roads, and towns, and counties in the Gillette coal field, Wyoming. (Clinker mapped by Heffern and others, 1993).

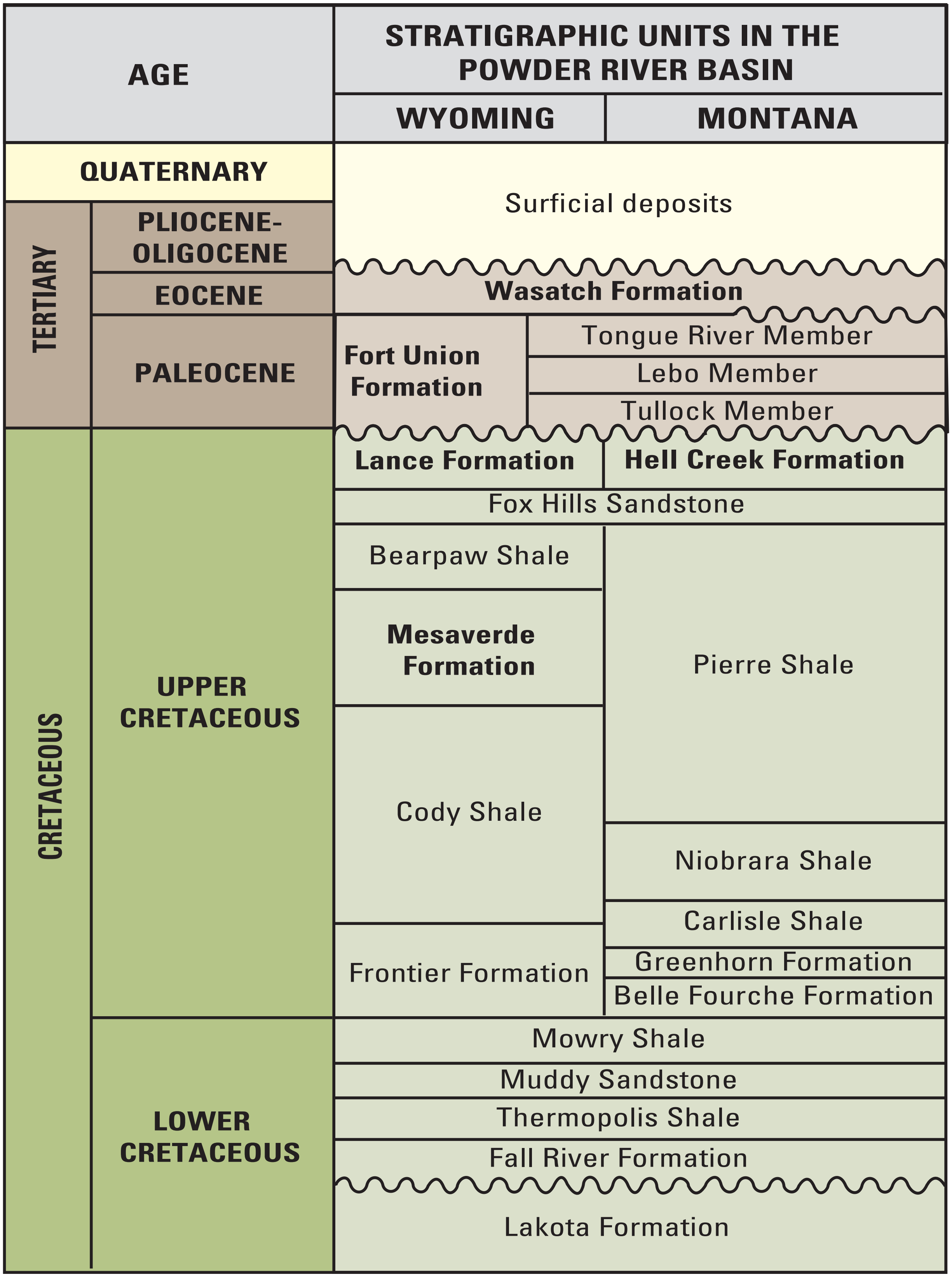
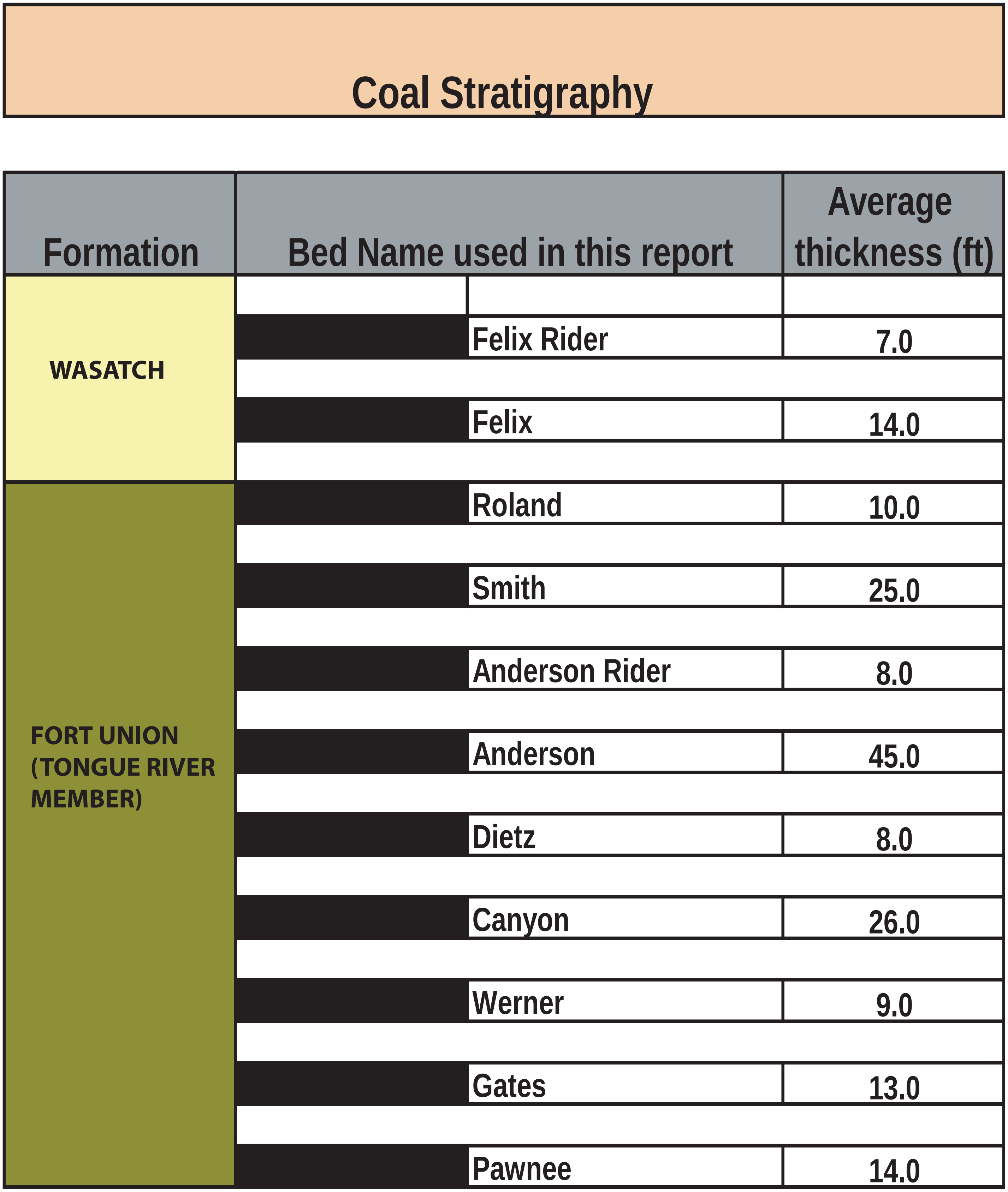


Figure 3. Generalized stratigraphic column for the Powder River Basin and Gillette coalfield, Wyoming. (Ellis and others, 2002).



Coal Stratigraphy

Formation	Bed Name used in this report	Average thickness (ft)
WASATCH	Felix Rider	7.0
	Felix	14.0
FORT UNION (TONGUE RIVER MEMBER)	Roland	10.0
	Smith	25.0
	Anderson Rider	8.0
	Anderson	45.0
	Dietz	8.0
	Canyon	26.0
	Werner	9.0
	Gates	13.0
	Pawnee	14.0

Figure 4. Coal stratigraphy in the Gillette coalfield showing names used in this report. (Modified from the Wyoming Geological Survey , 2007).

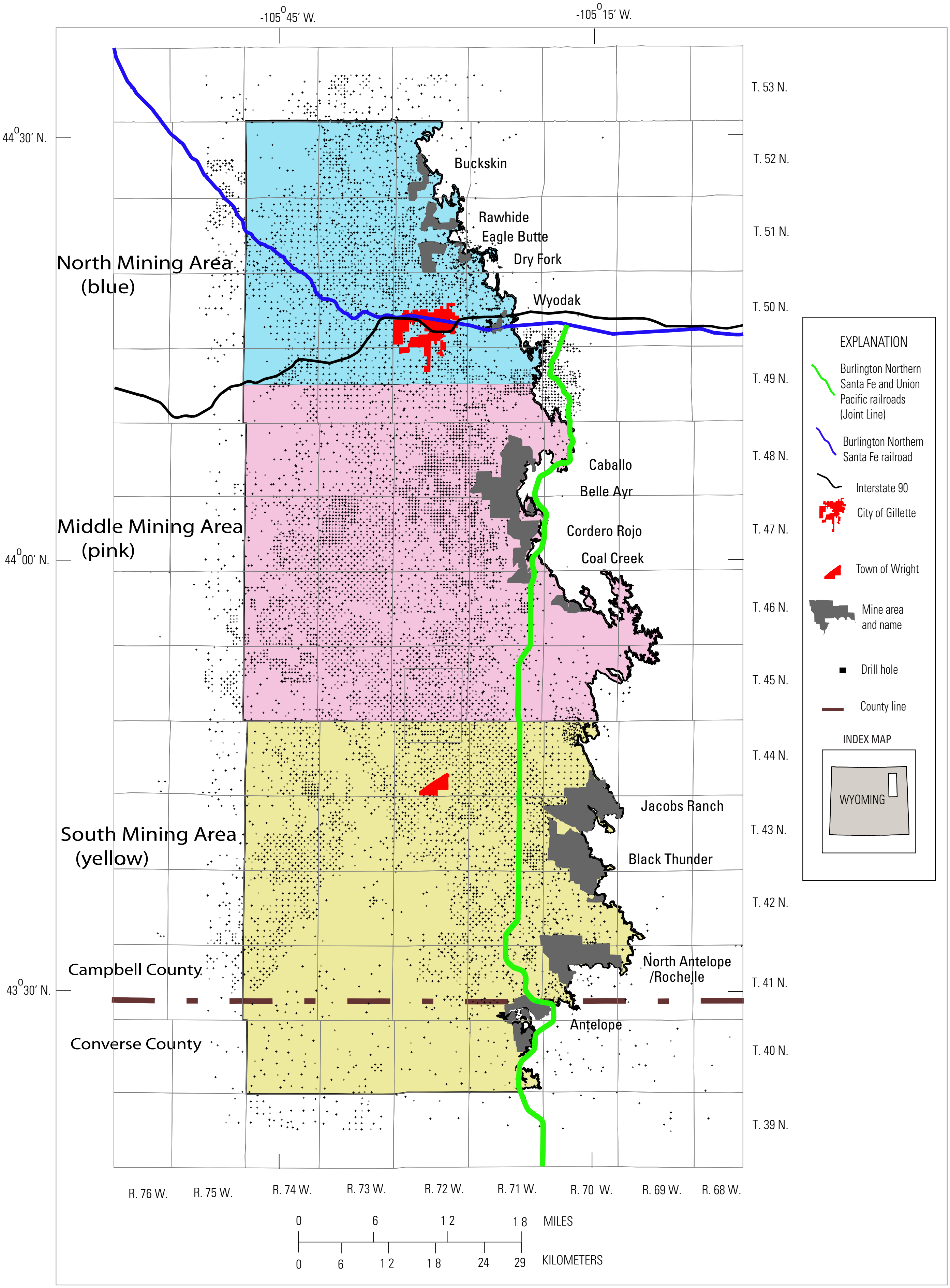


Figure 5. Map showing location of drill holes, mines, and mining areas in the Gillette coalfield, Wyoming.

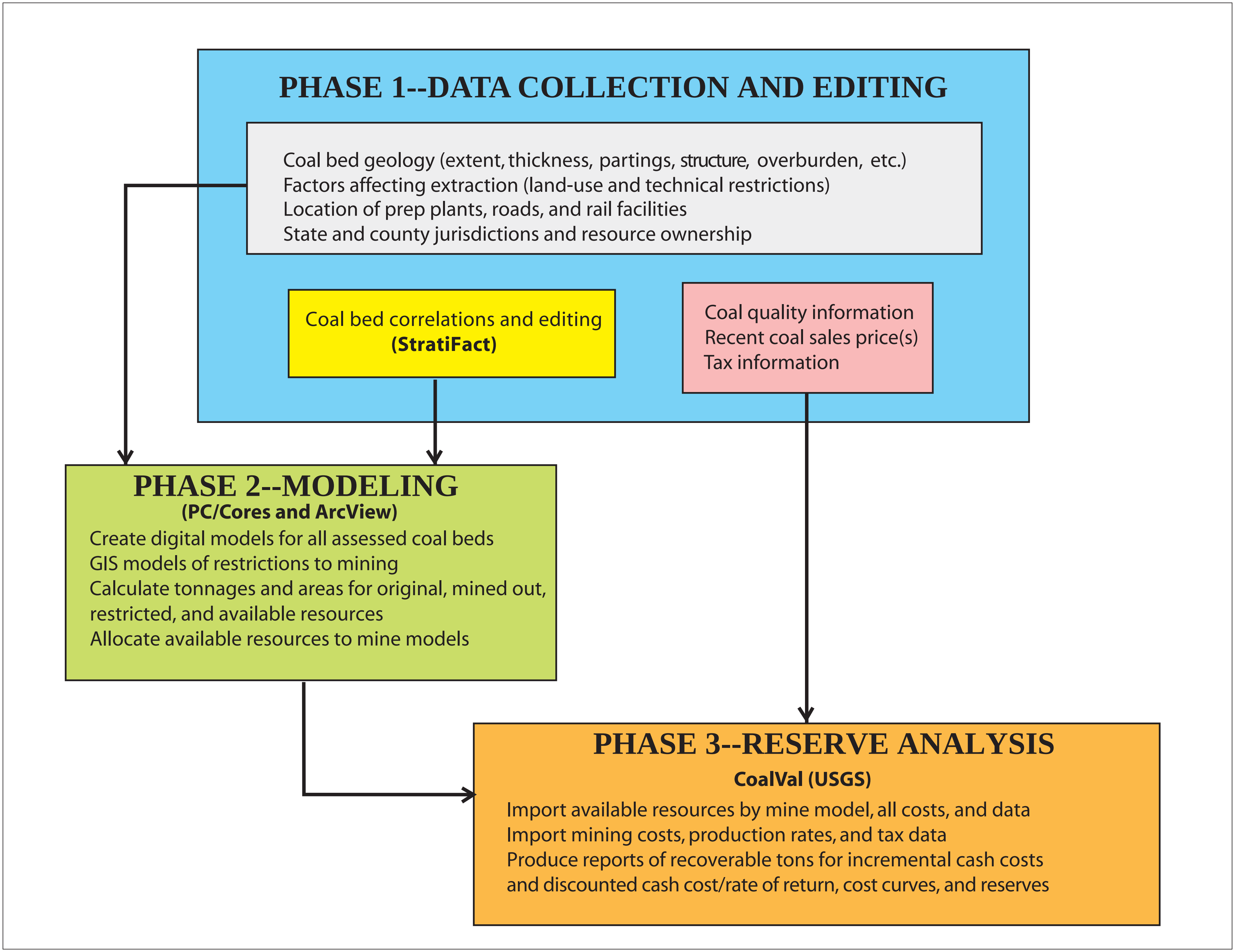


Figure 6. Flow chart showing generalized methodology used during this coal resource evaluation.

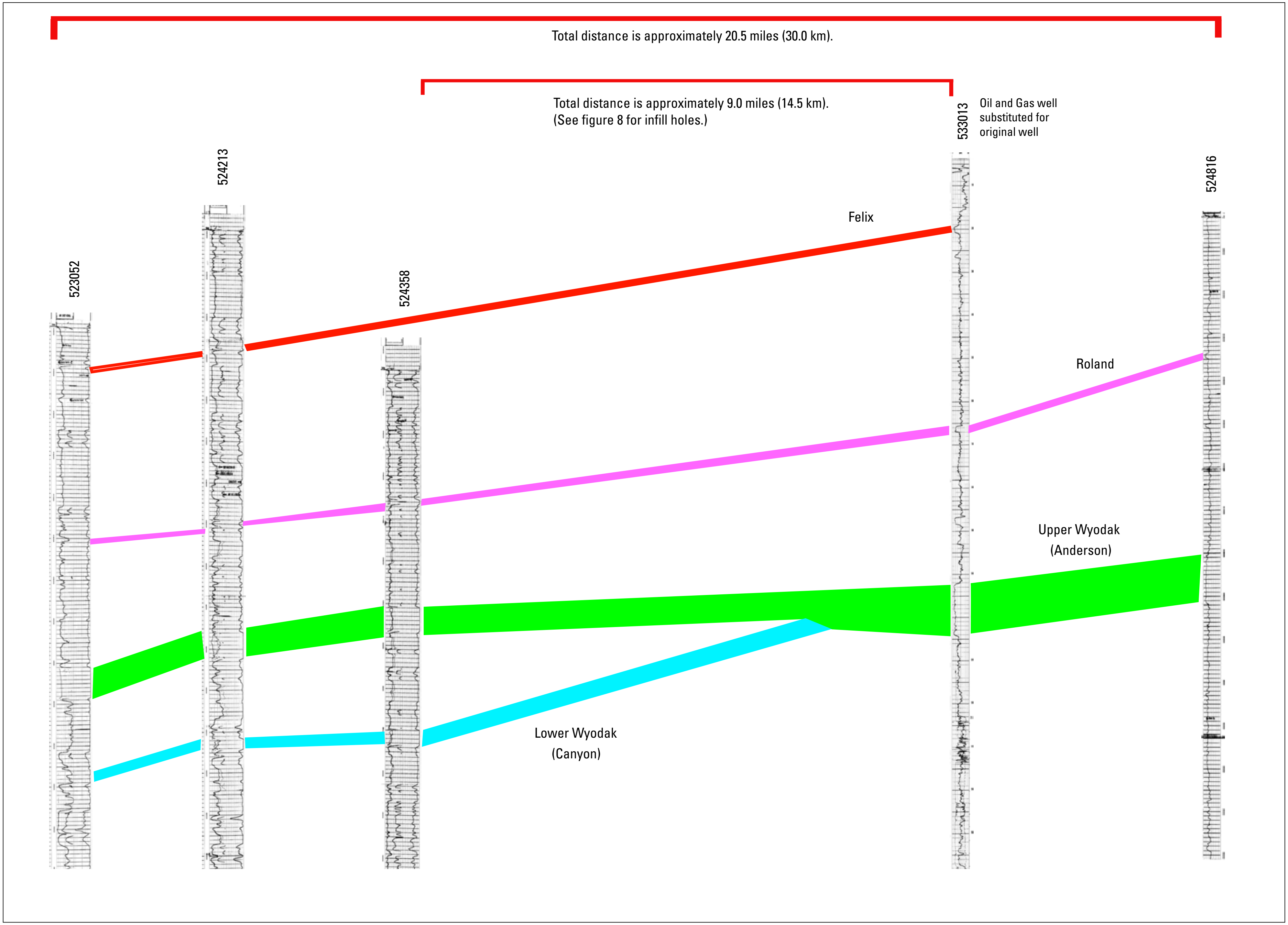


Figure 7. Cross section showing correlations used in the 1959-D publication (Molnia and Pierce, 1992). The numbers above the drill holes indicate API numbers. The location of this section is shown on figure 9.

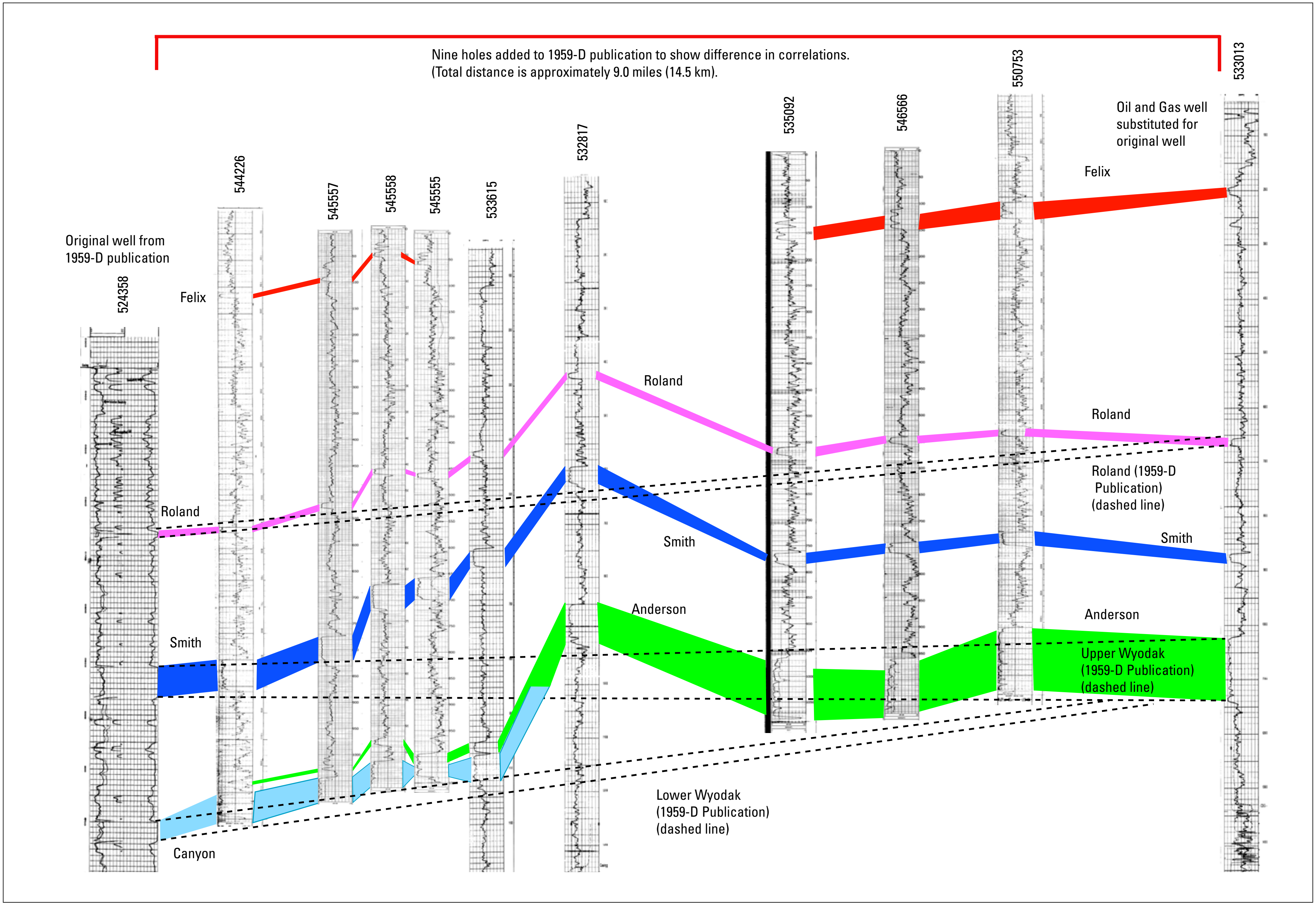


Figure 8. Cross section showing comparison of coal bed correlations made in this report to the 1959-D publication (Molnia and Pierce, 1992). Colored sections represent correlations made in this report. Dashed lines represent correlations made in the 1959-D publication. The numbers above the drill holes indicate API numbers. The location of this section is shown on figure 9.

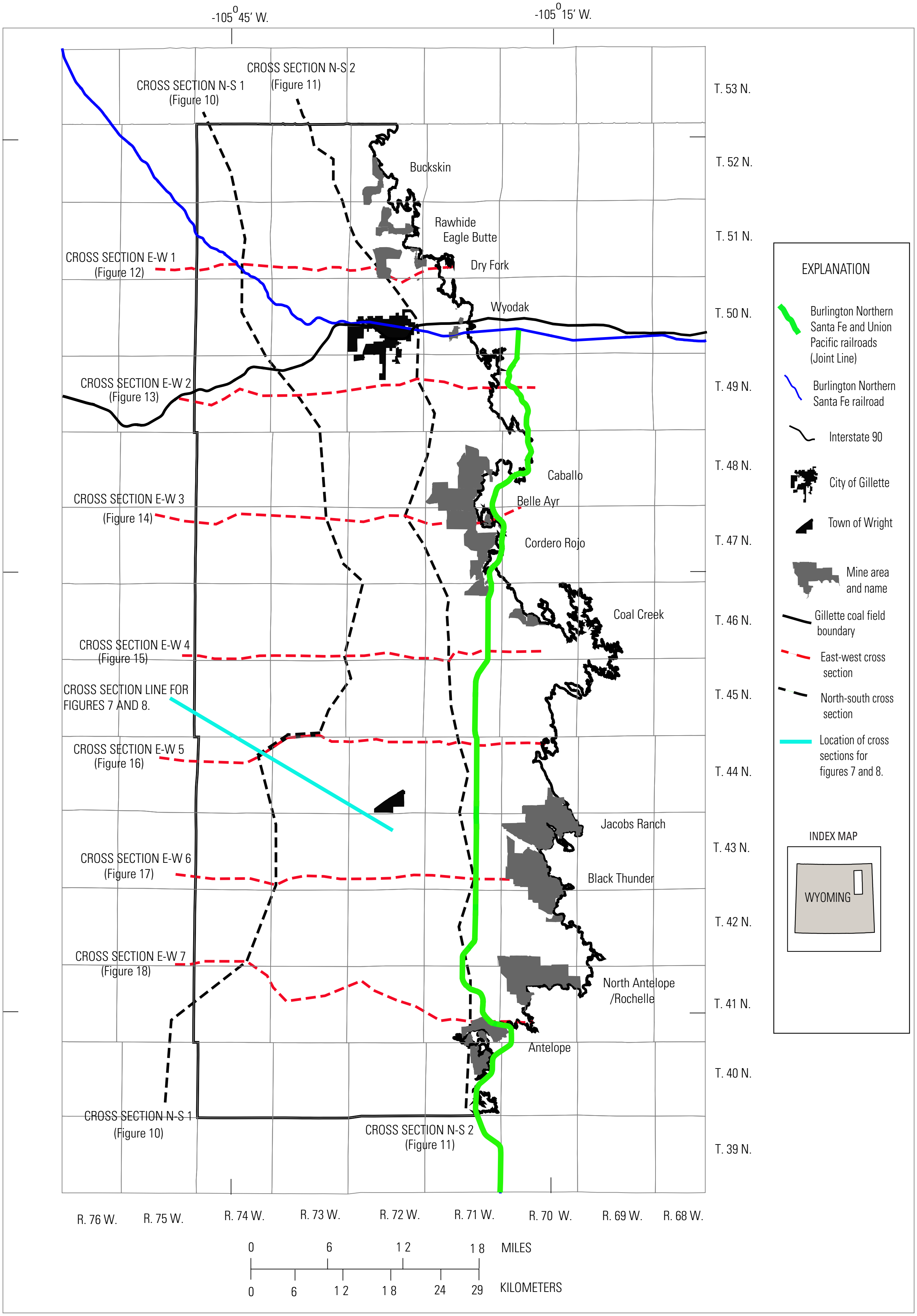


Figure 9. Index map showing locations of east-west and north-south cross sections and section from figures 7 and 8 (1959-D) in the Gillette coalfield, Wyoming.

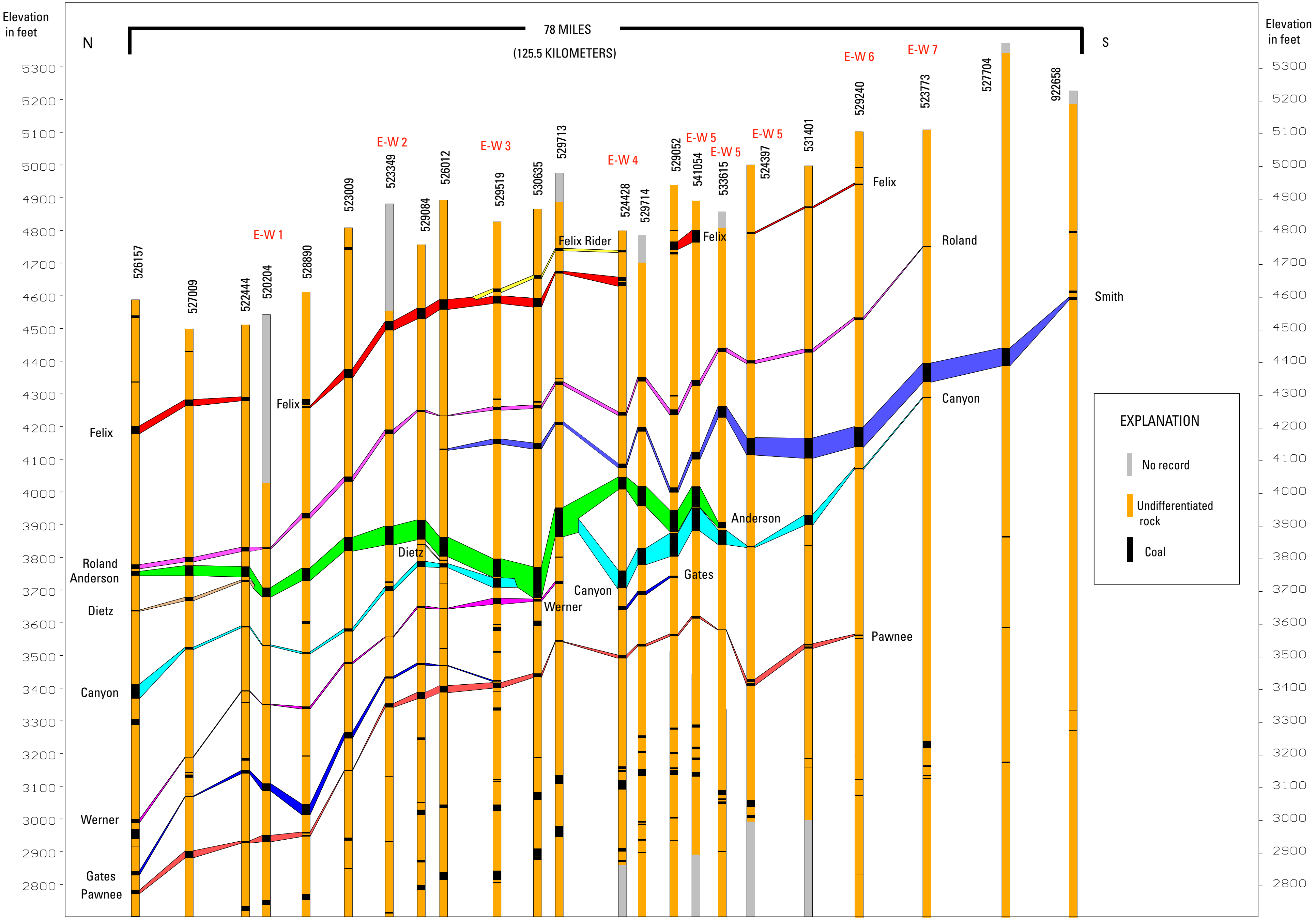


Figure 10. North-south stratigraphic cross section N-S 1 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on east-west cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” or a “9” denote API numbers.

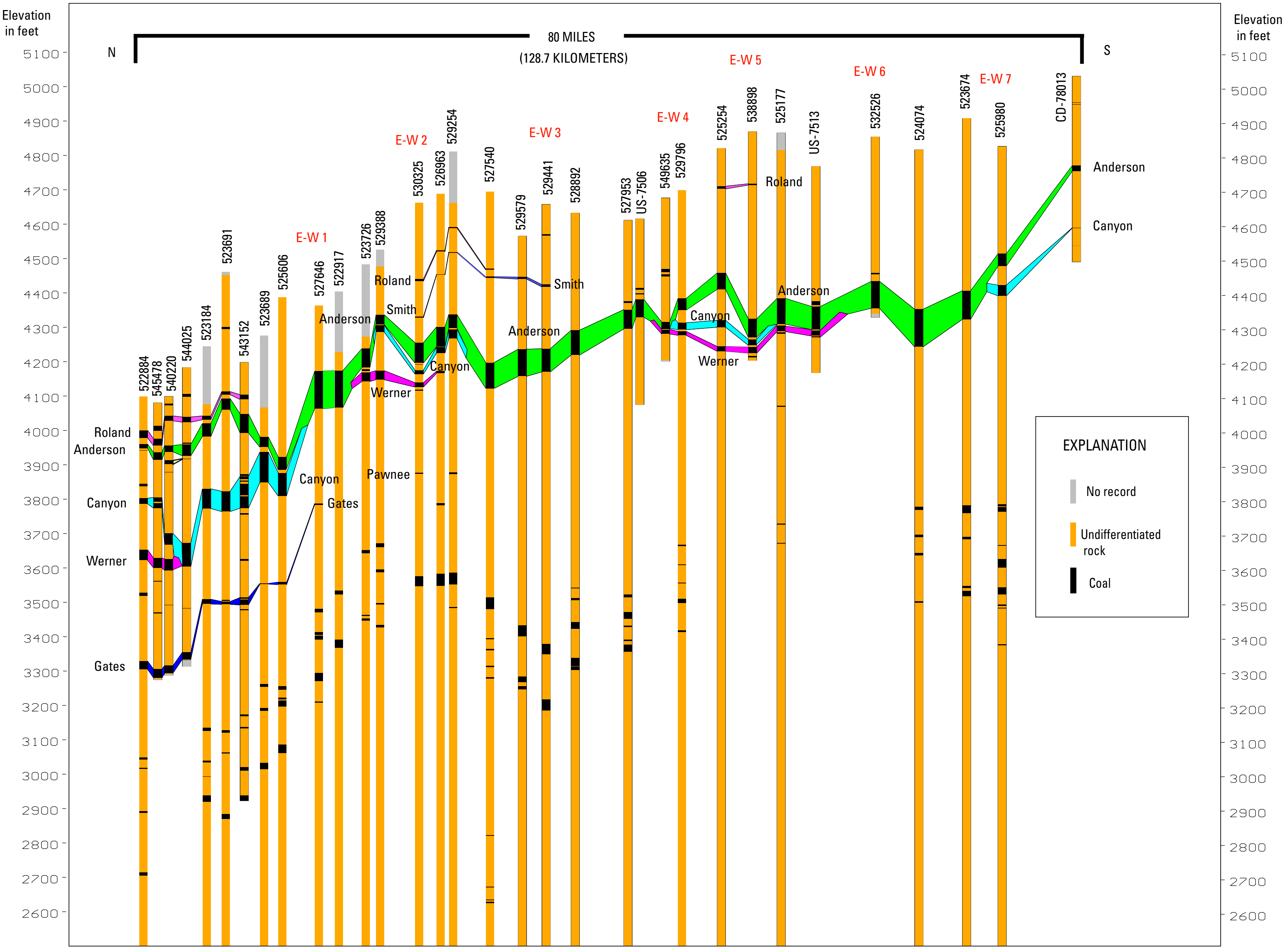


Figure 11. North-south stratigraphic cross section N-S 2 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on east-west cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill hole numbers beginning with “US” and “CD” denote U.S. Government drill holes.

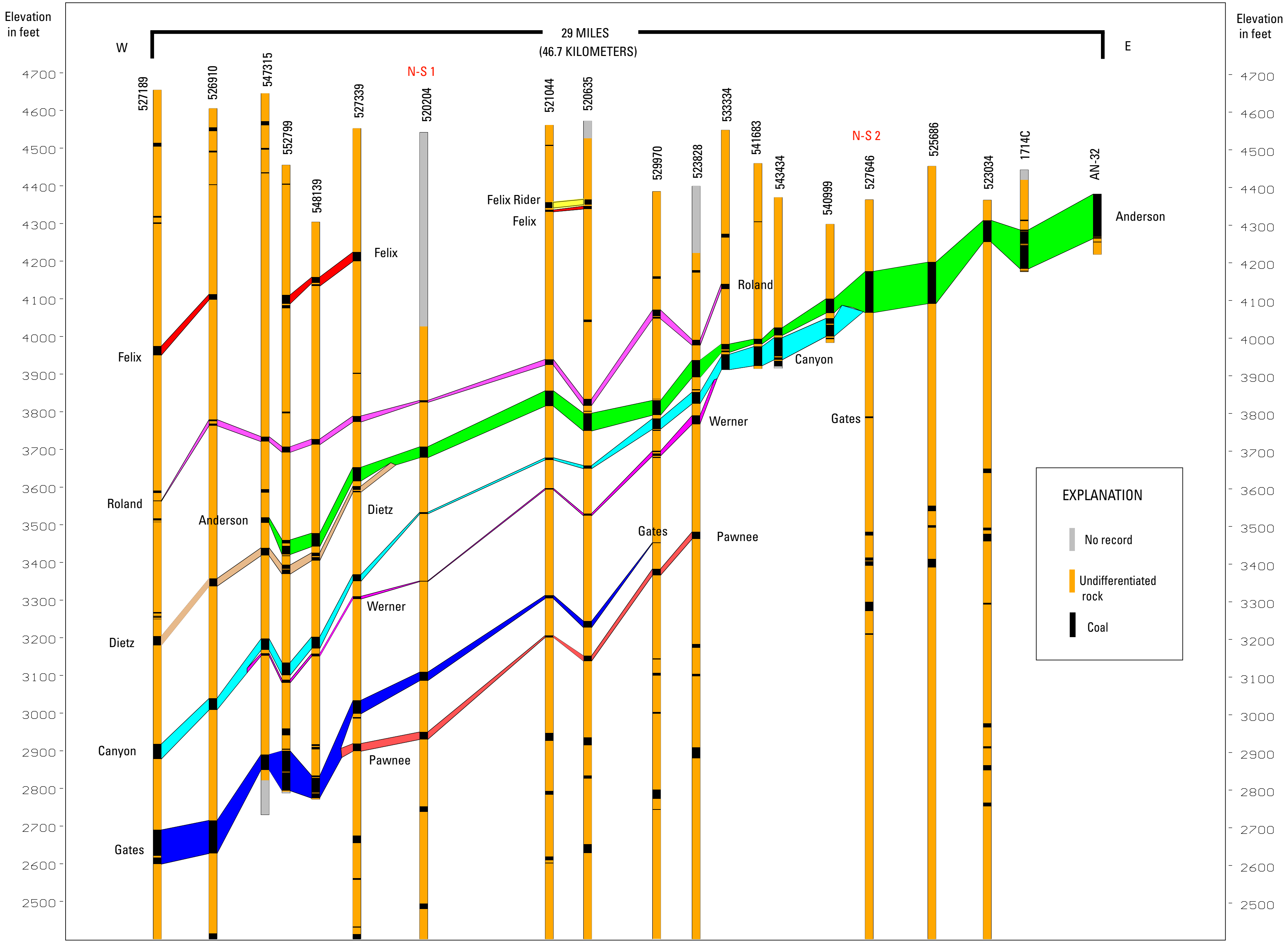


Figure 12. East-west stratigrapic cross section E-W 1 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill hole number AN-32 is a U.S. Government drill hole; drill hole number 1714C is a CITGO drill hole.

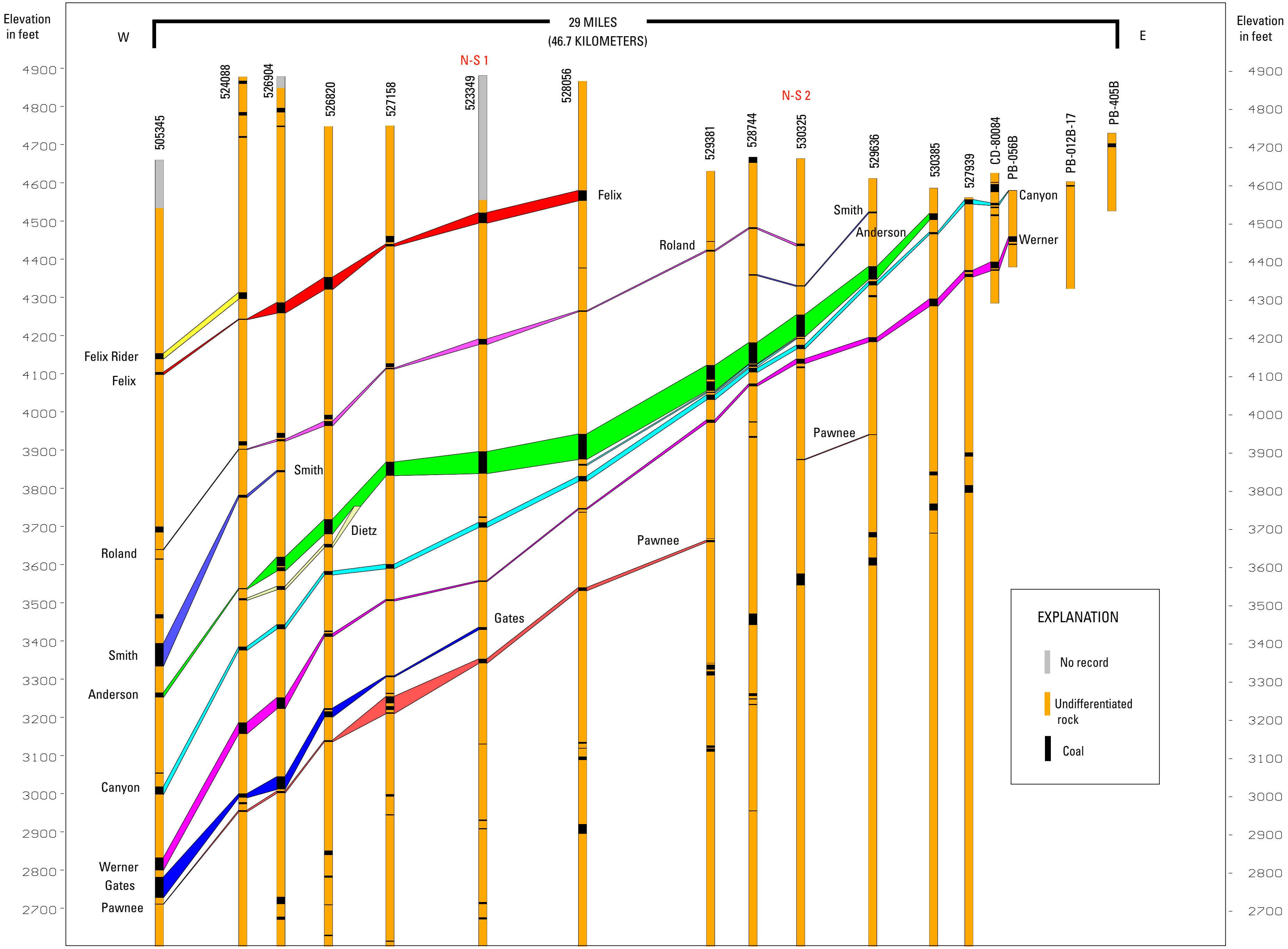


Figure 13. East-west stratigraphic cross section E-W 2 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill holes beginning with a “PB” denote Peabody drill holes; drill holes beginning with a “CD” denote U.S. Government drill holes.

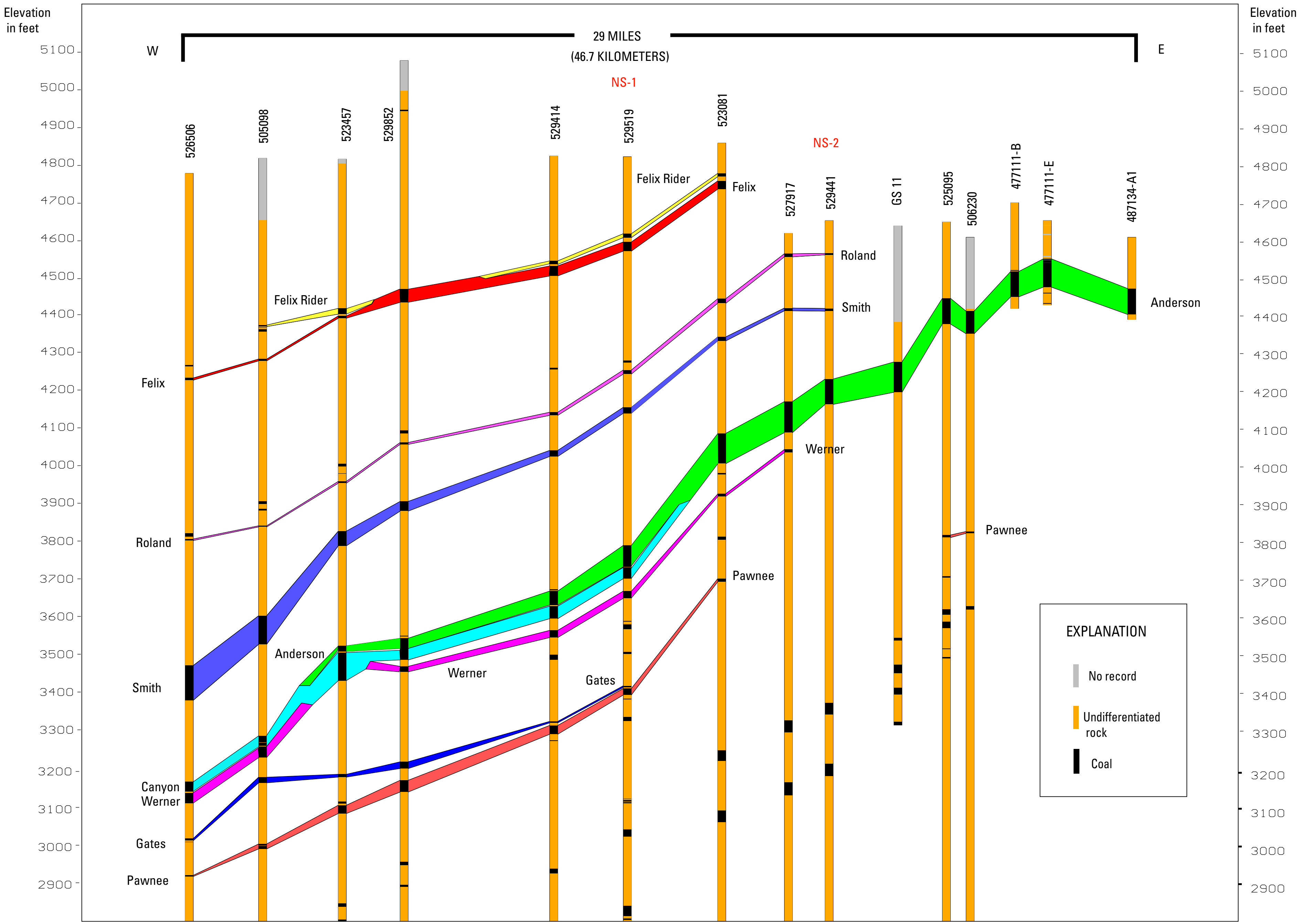


Figure 14. East-west stratigraphic cross section E-W 3 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill hole number GS 11 is a U.S. Government drill hole; drill holes 477111-B and 47711-E are Caballo Rojo drill holes; drill hole 487134-A1 is an Amax drill hole.

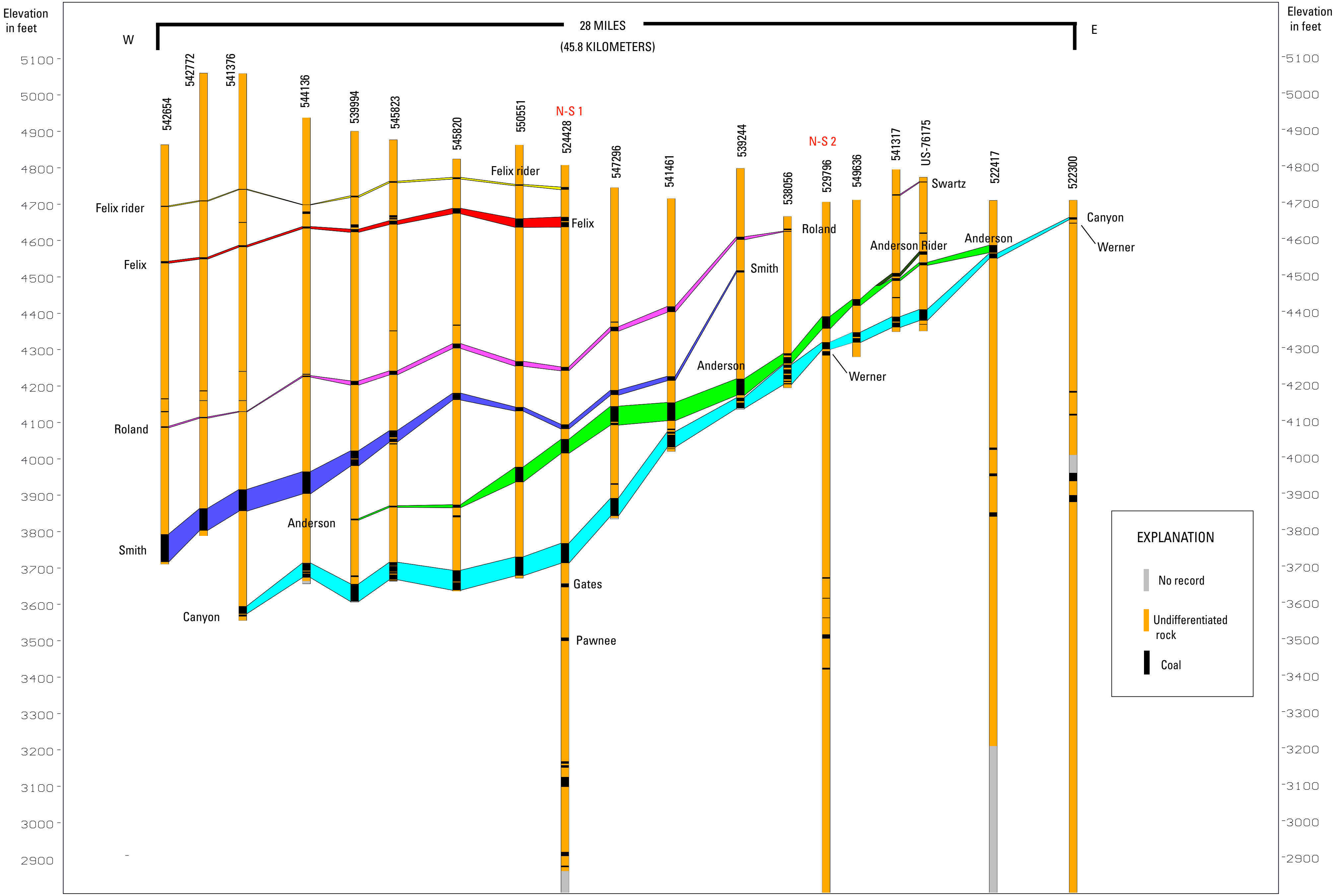


Figure 15. East-west stratigraphic cross section E-W 4 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill hole US-76175 is a U.S. Government drill hole.

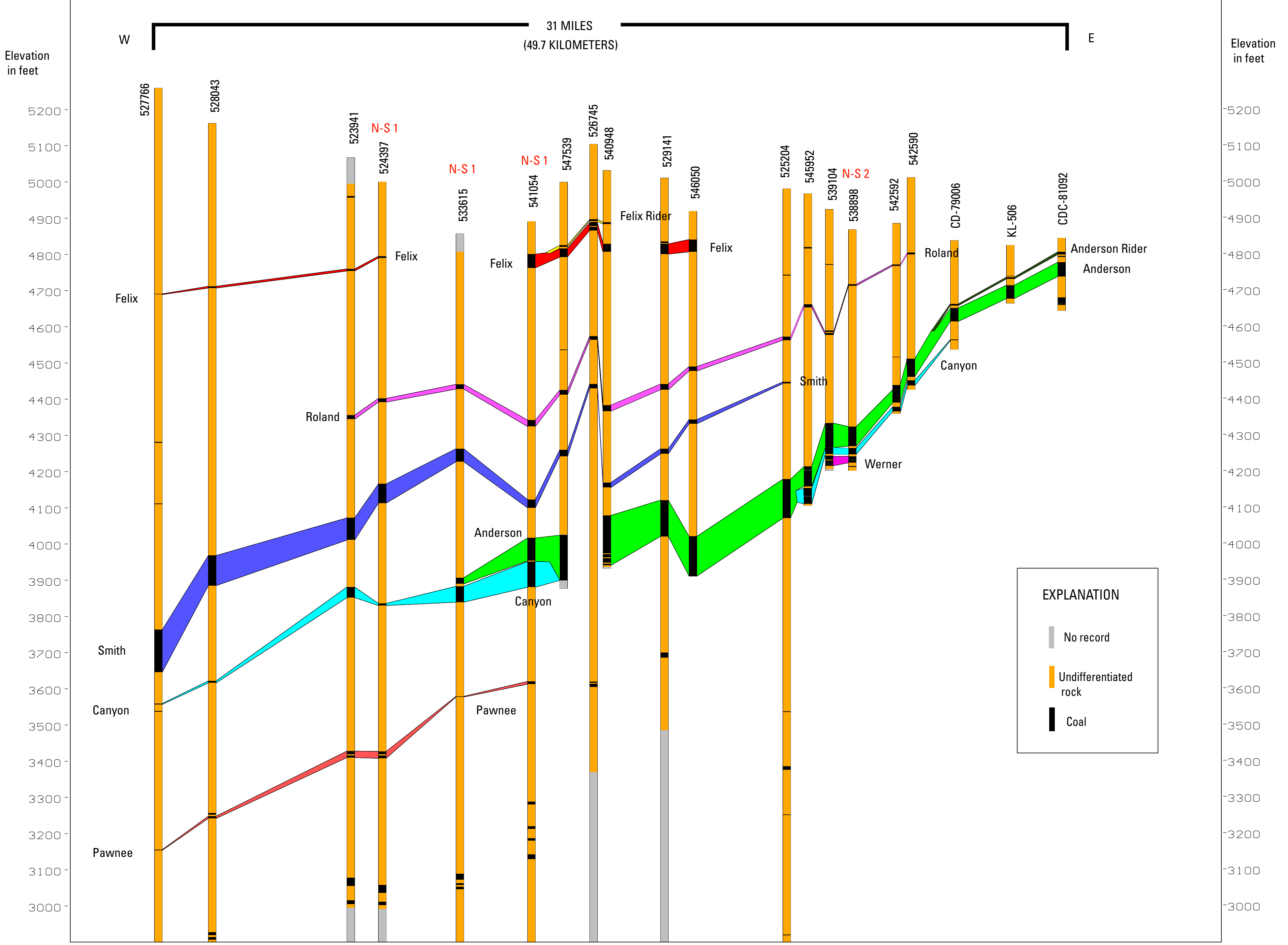


Figure 16. East-west stratigraphic cross section E-W 5 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a "5" denote API numbers. Drill hole number KL-506 is a Neil Butte Co. drill hole; drill holes CDC-79006 and CDC-81092 are U.S. Government drill holes.

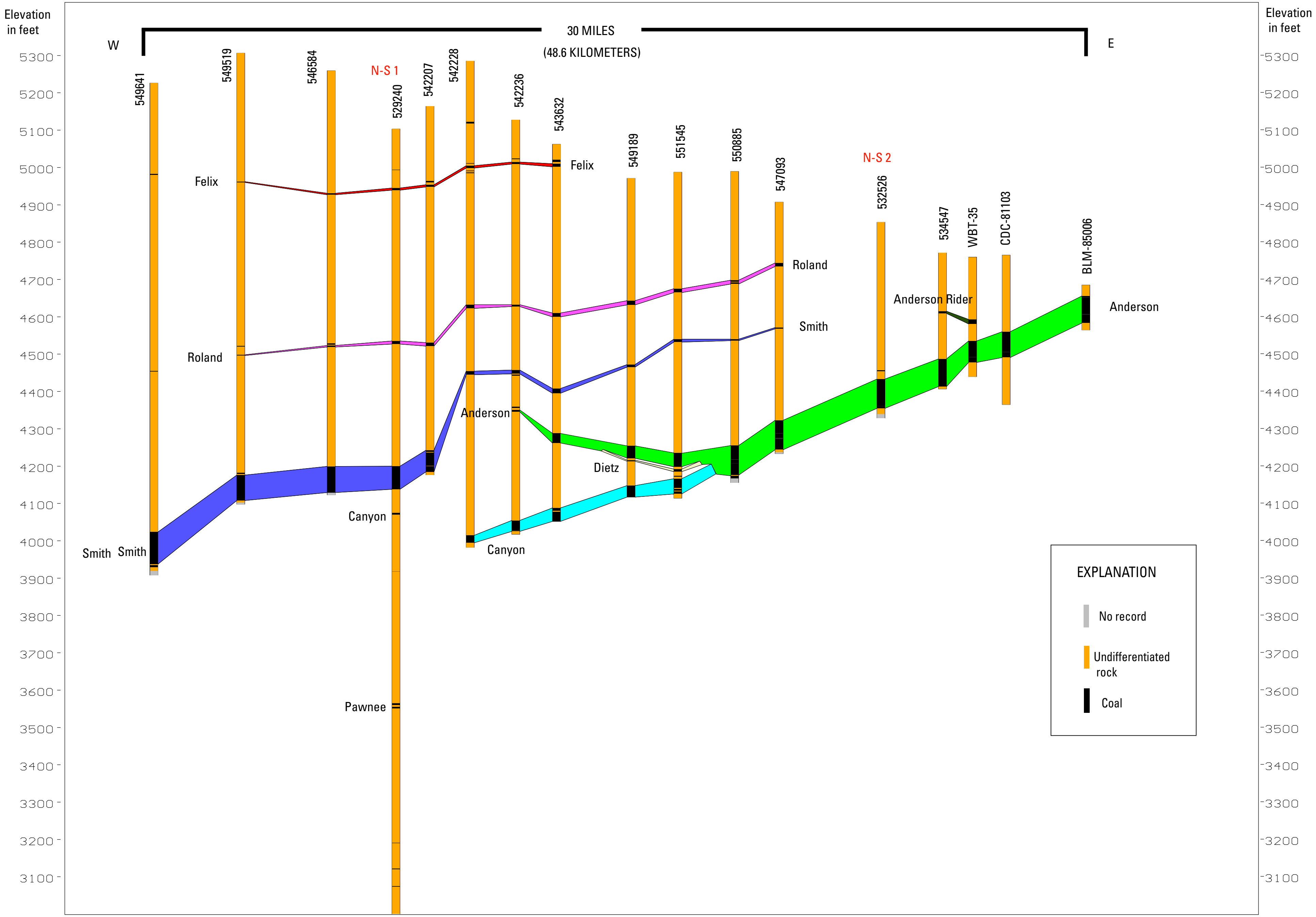


Figure 17. East-west stratigraphic cross section E-W 6 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill holes CDC-81103 and BLM-85006 are U.S. Government drill holes; drill hole WBT-35 is a Black Thunder drill hole.

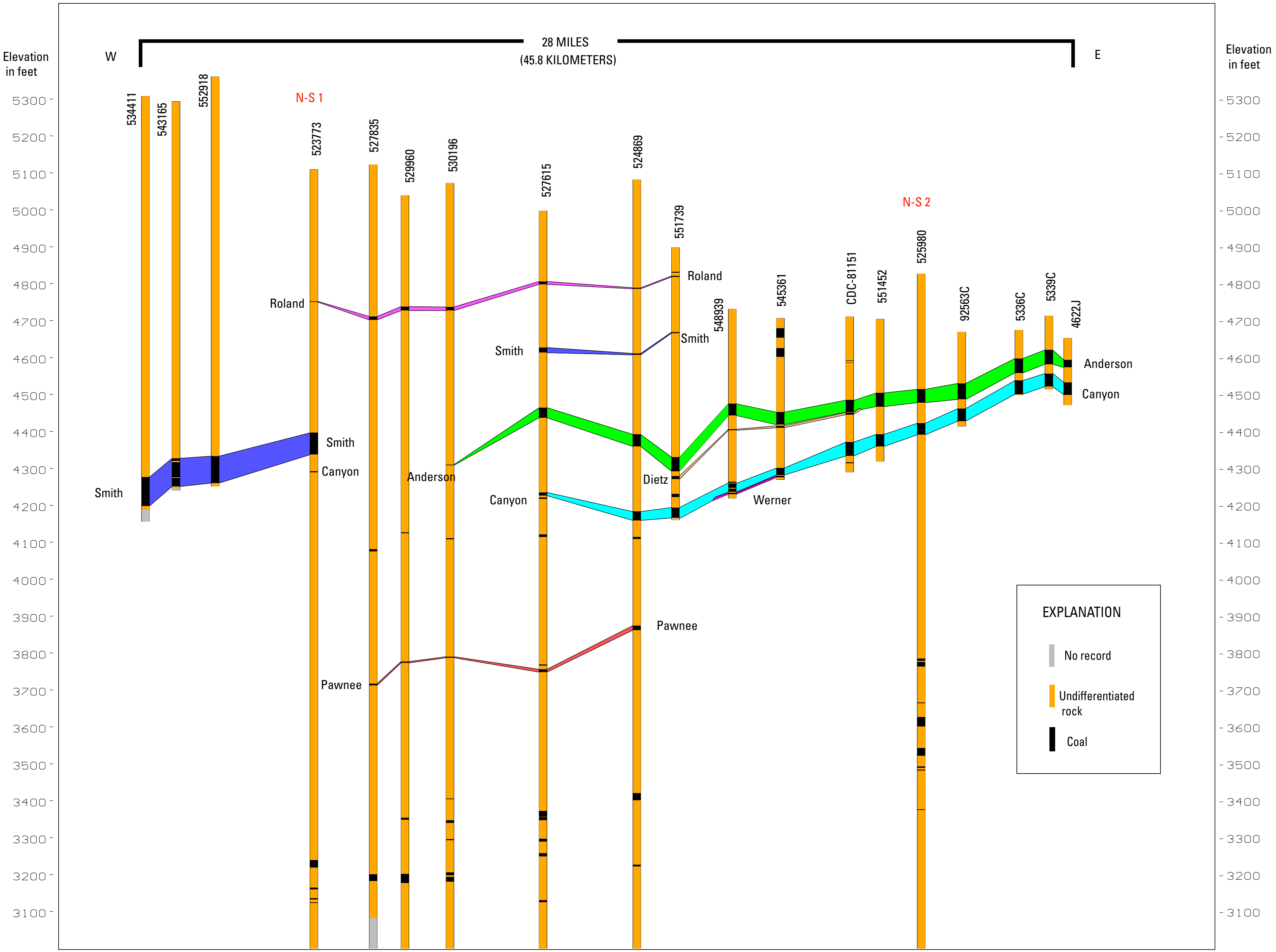


Figure 18. East-west stratigraphic cross section E-W 7 showing correlation of coal beds assessed in the Gillette coalfield. See figure 9 for location of cross section. Drill holes labeled in red are also shown on north-south cross sections (i.e. drill hole is common to both east-west and north-south cross sections). Drill hole numbers beginning with a “5” denote API numbers. Drill hole CDC-81151 is a U.S. Government drill hole; drill holes 92563C, 5336C, 5339C, and 4622J are Powder River Coal Company drill holes.

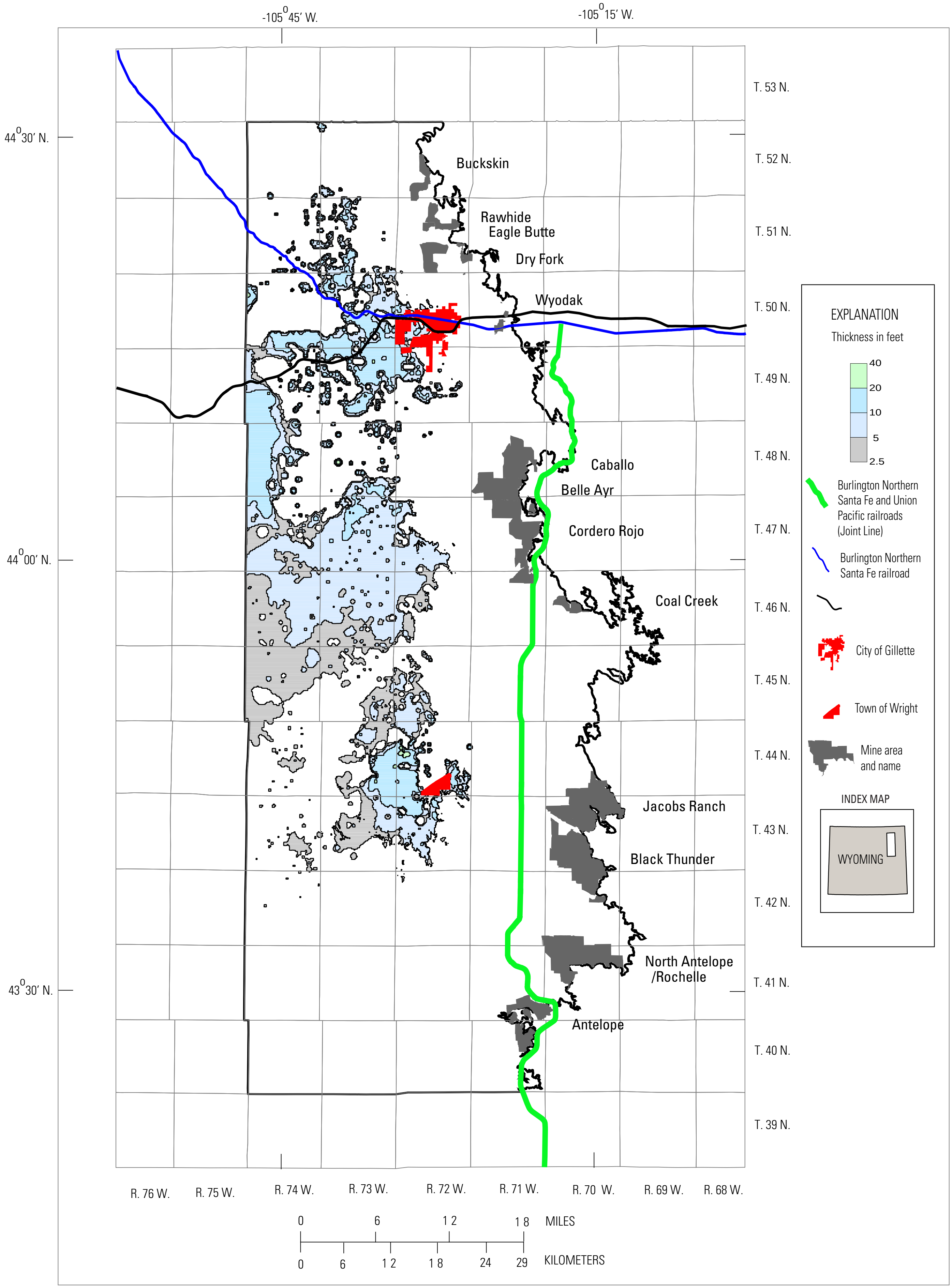


Figure 19. Isopach map of the Felix Rider coal bed showing extent of resources greater than 2.5 ft thick.

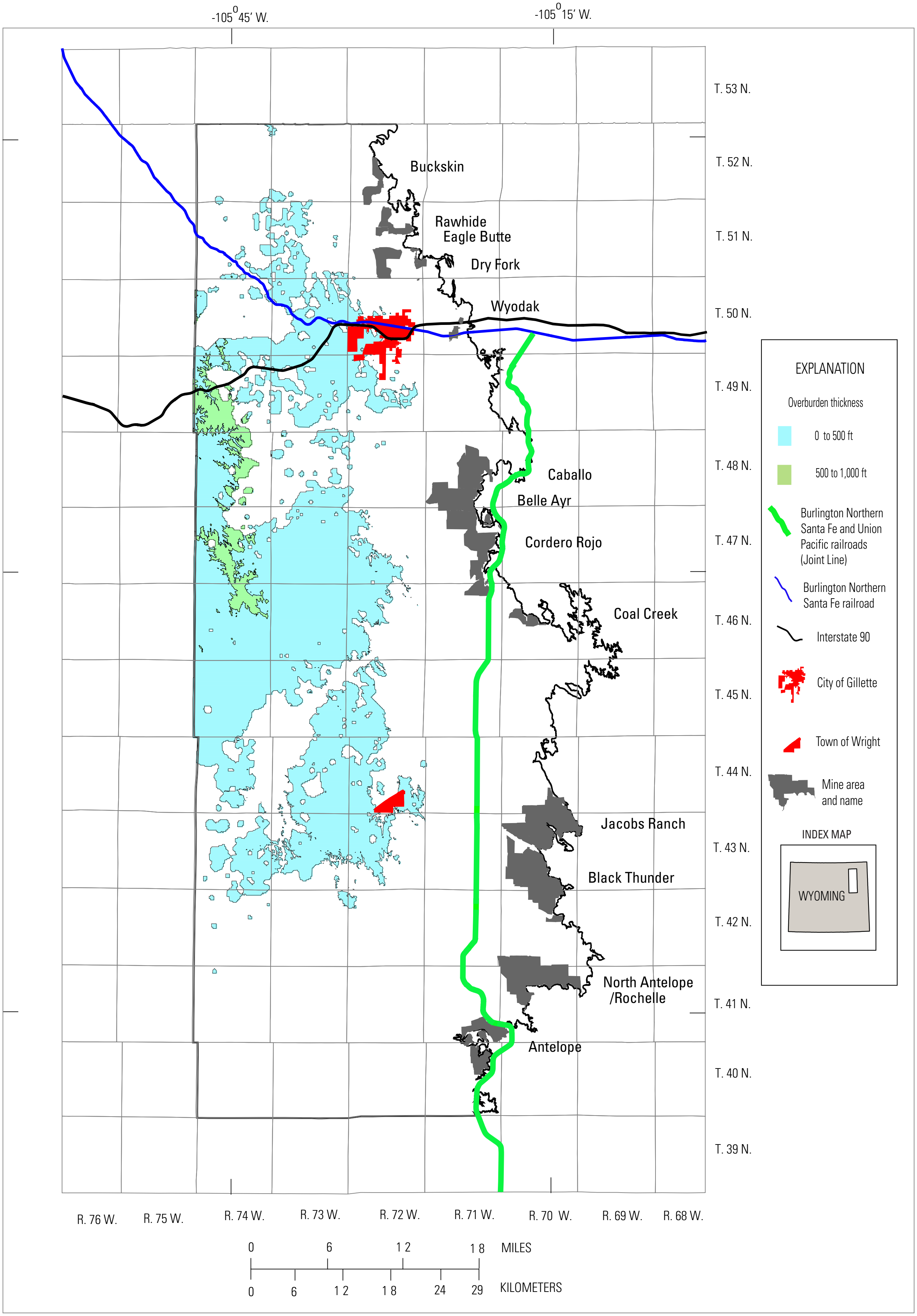


Figure 20. Map showing overburden thickness for the Felix Rider coal bed.

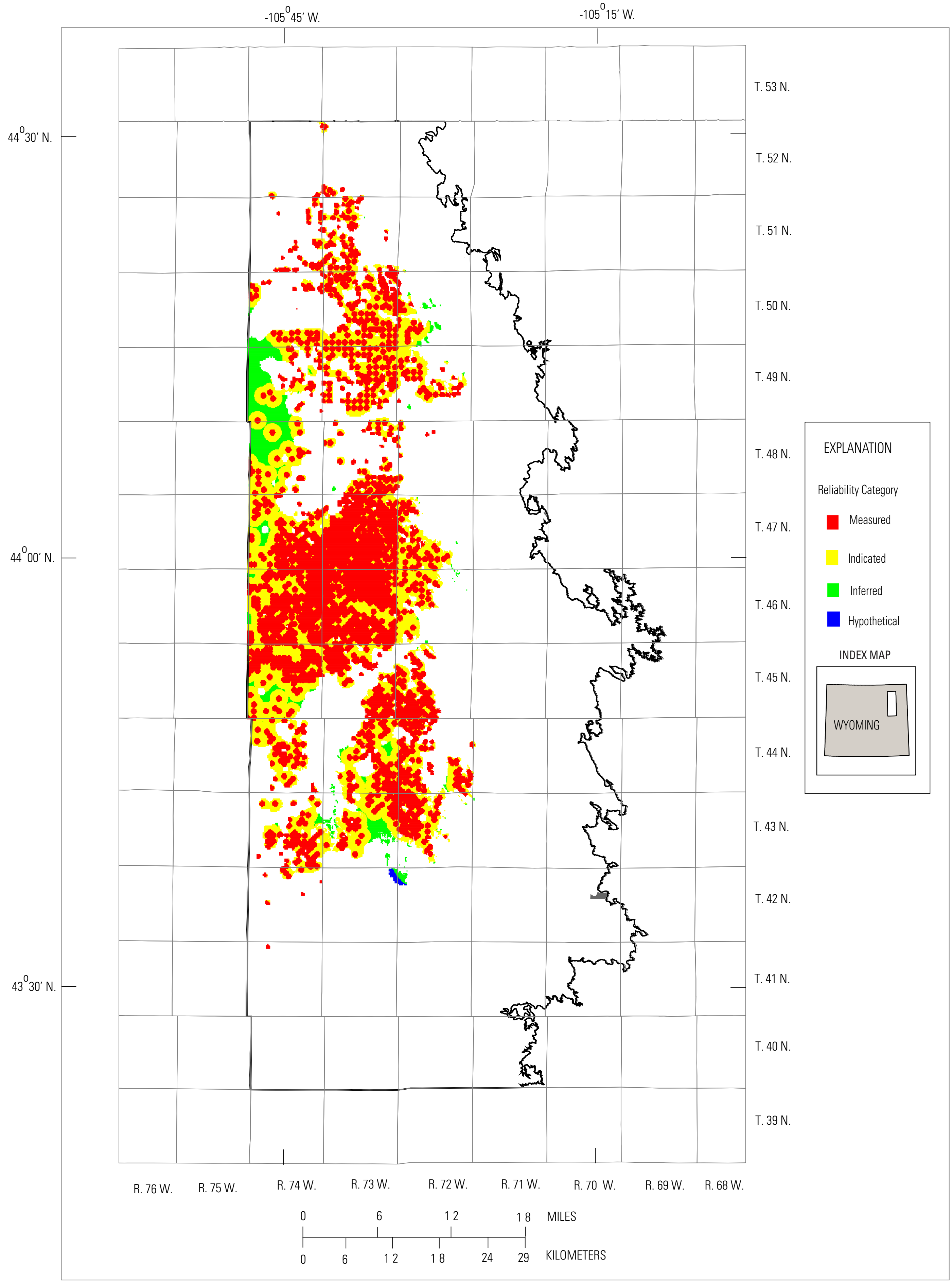


Figure 21. Map showing coal resource reliability categories for the Felix Rider coal bed.

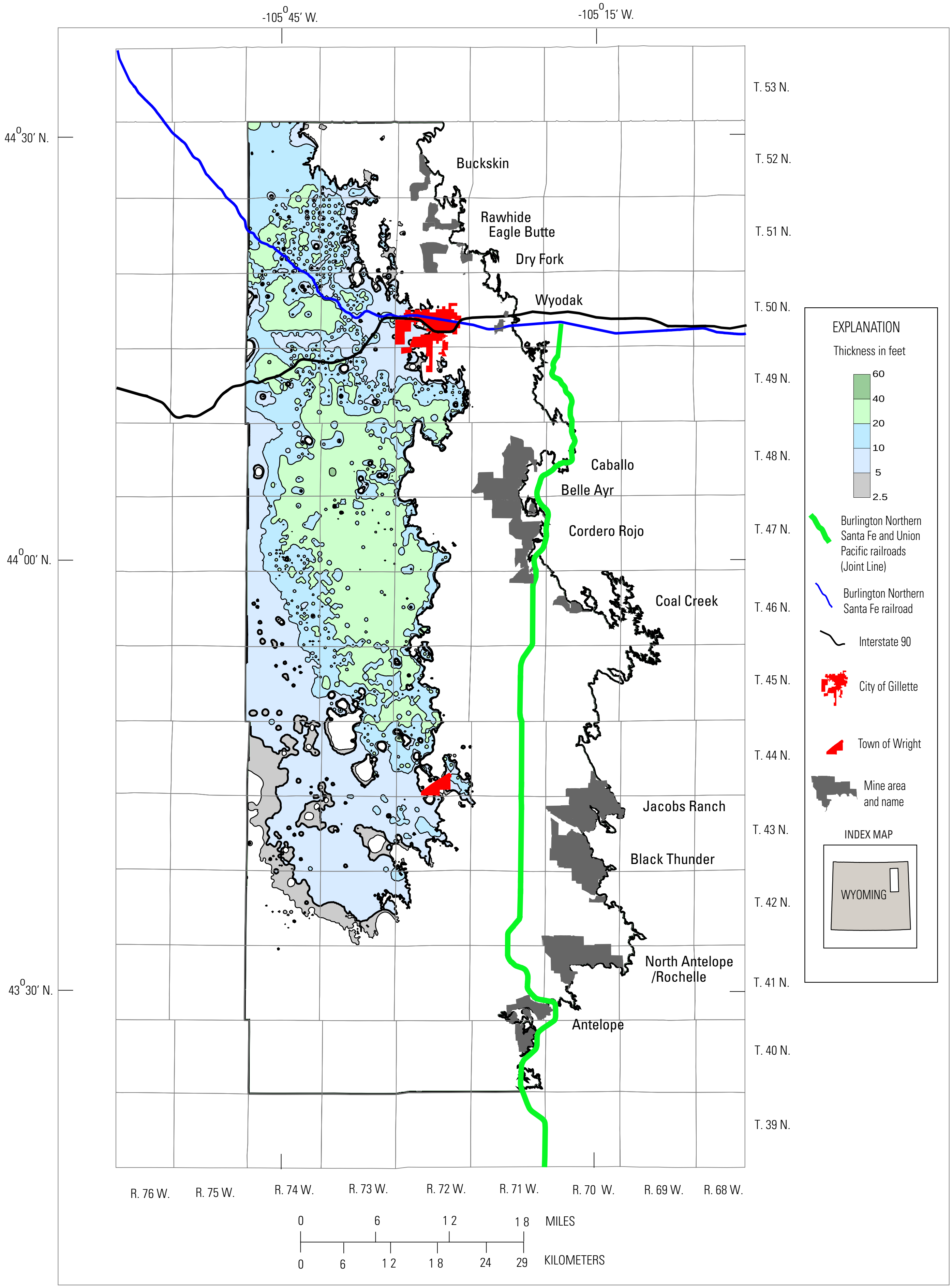


Figure 22. Isopach map of the Felix coal bed showing extent of resources greater than 2.5 ft thick.

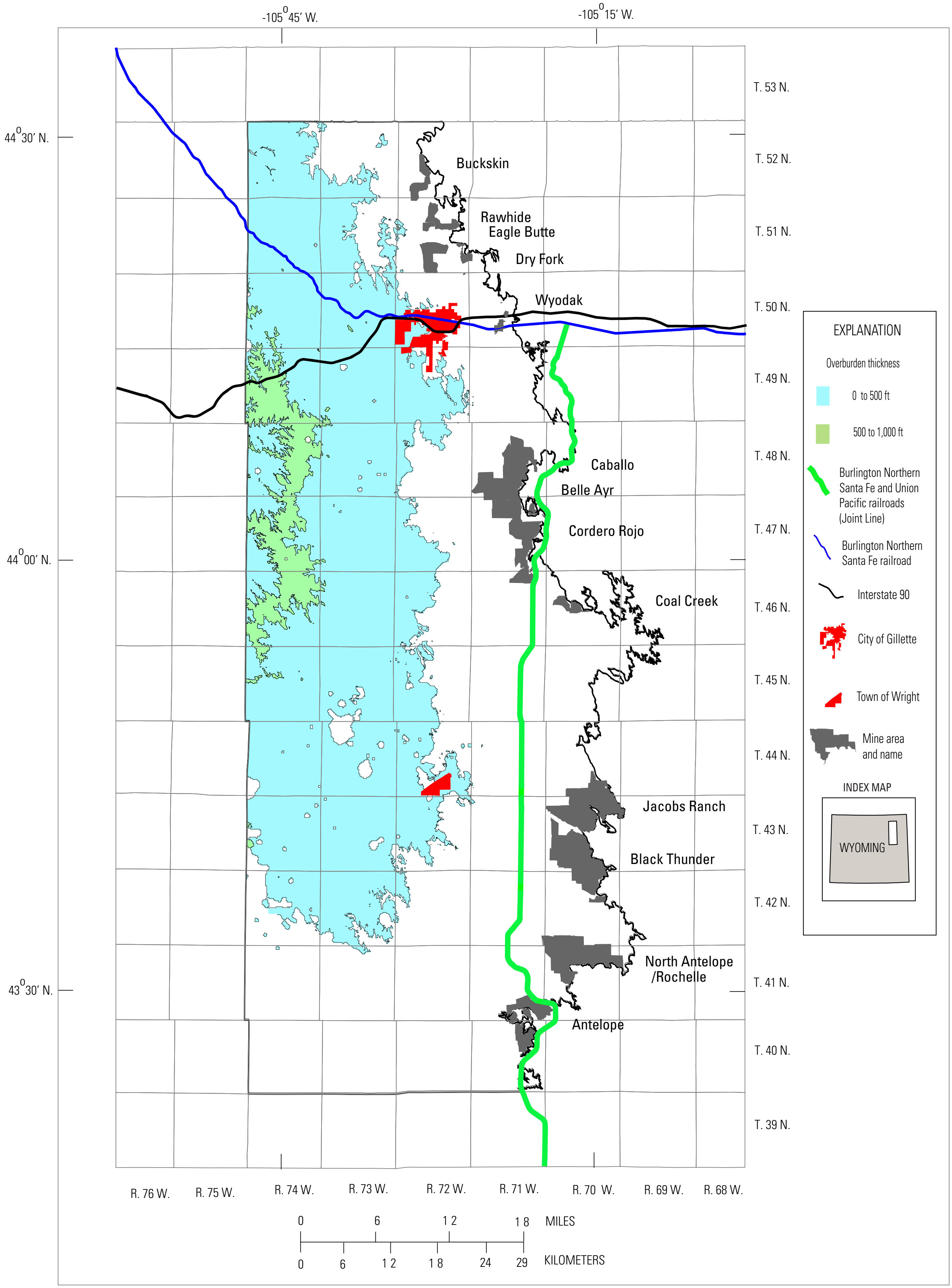


Figure 23. Map showing overburden thickness for the Felix coal bed.

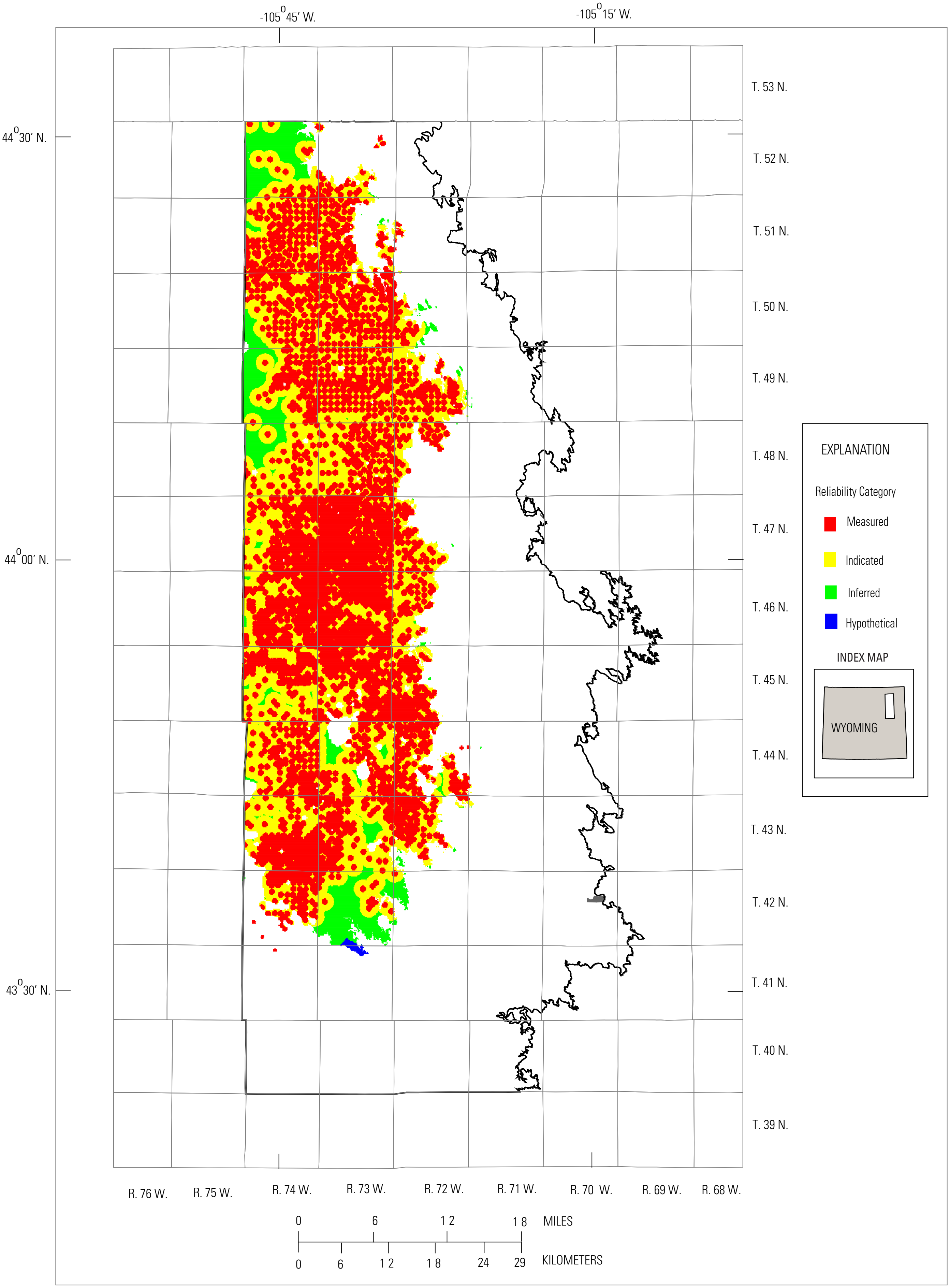


Figure 24. Map showing coal resource reliability categories for the Felix coal bed.

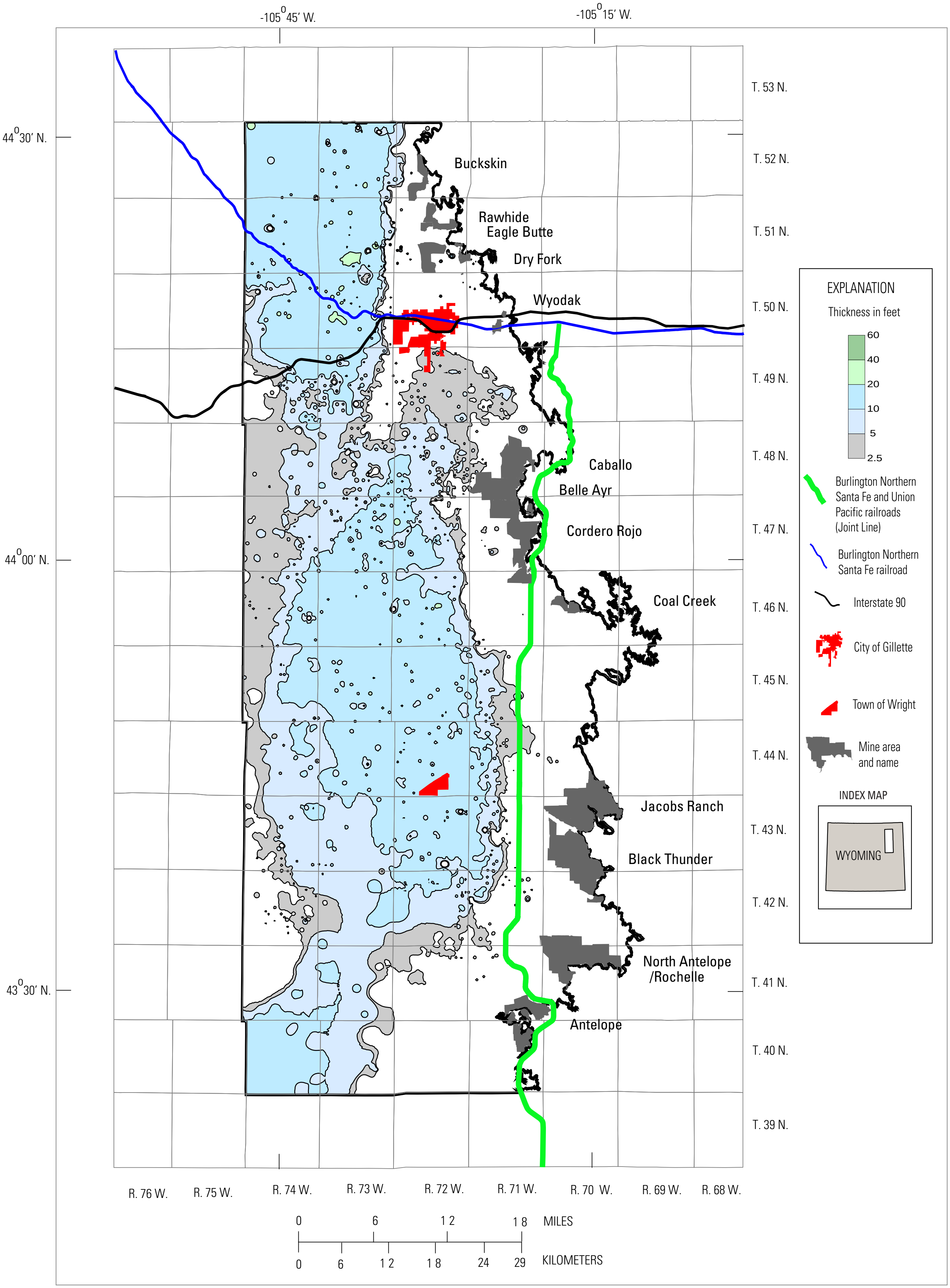


Figure 25. Isopach map of the Roland coal bed showing extent of resources greater than 2.5 ft thick.

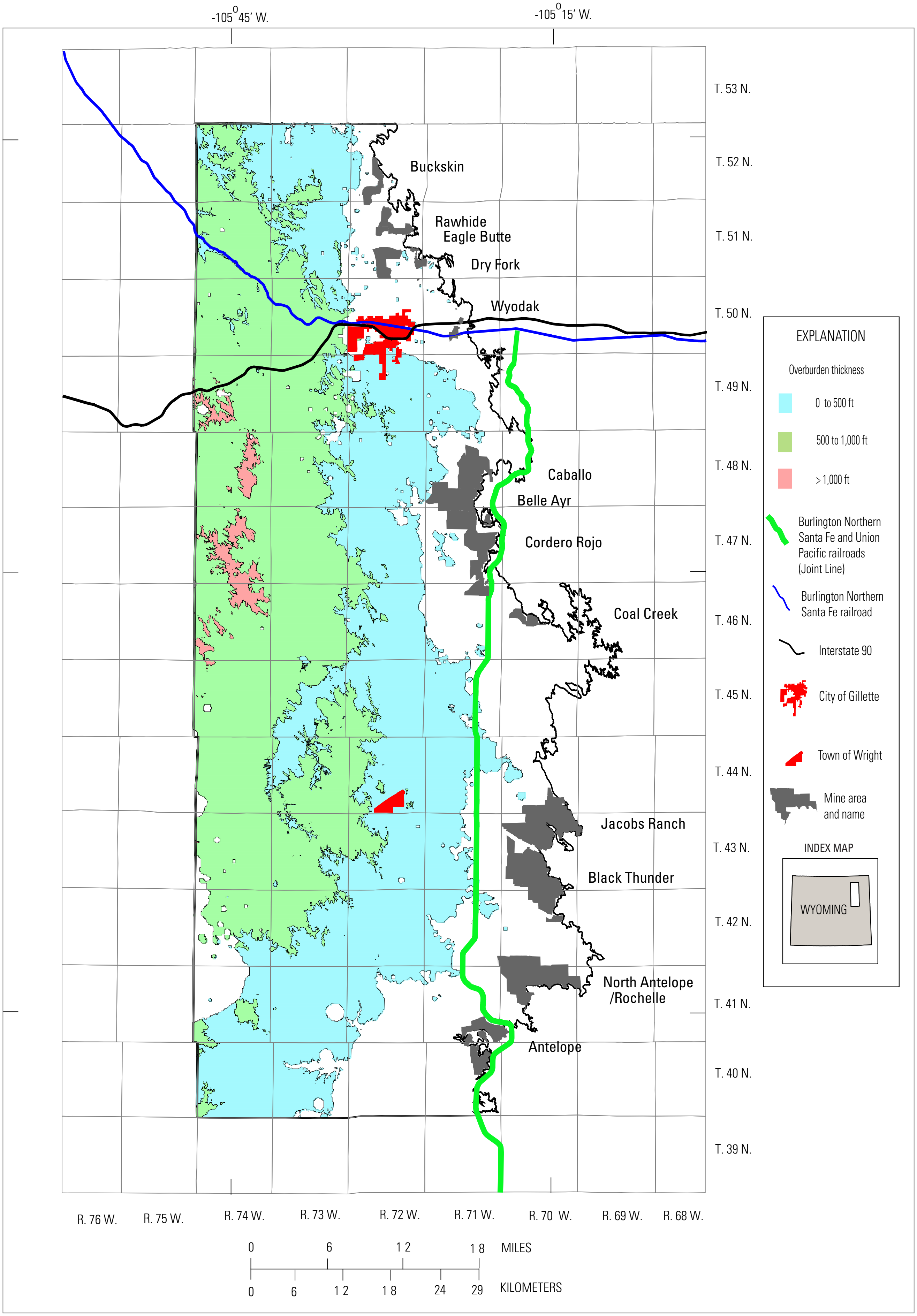


Figure 26. Map showing overburden thickness for the Roland coal bed.

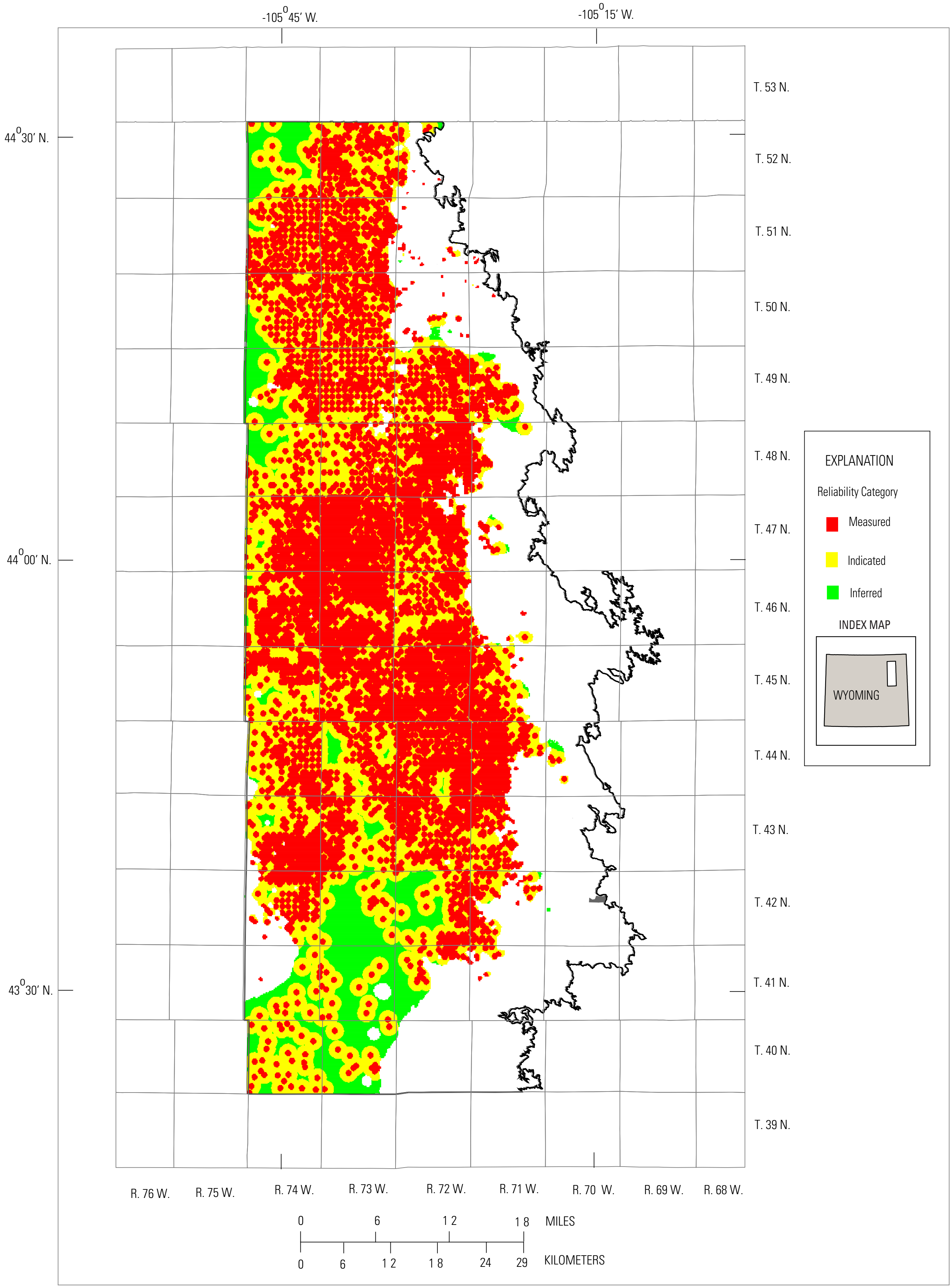


Figure 27. Map showing coal resource reliability categories for the Roland coal bed.

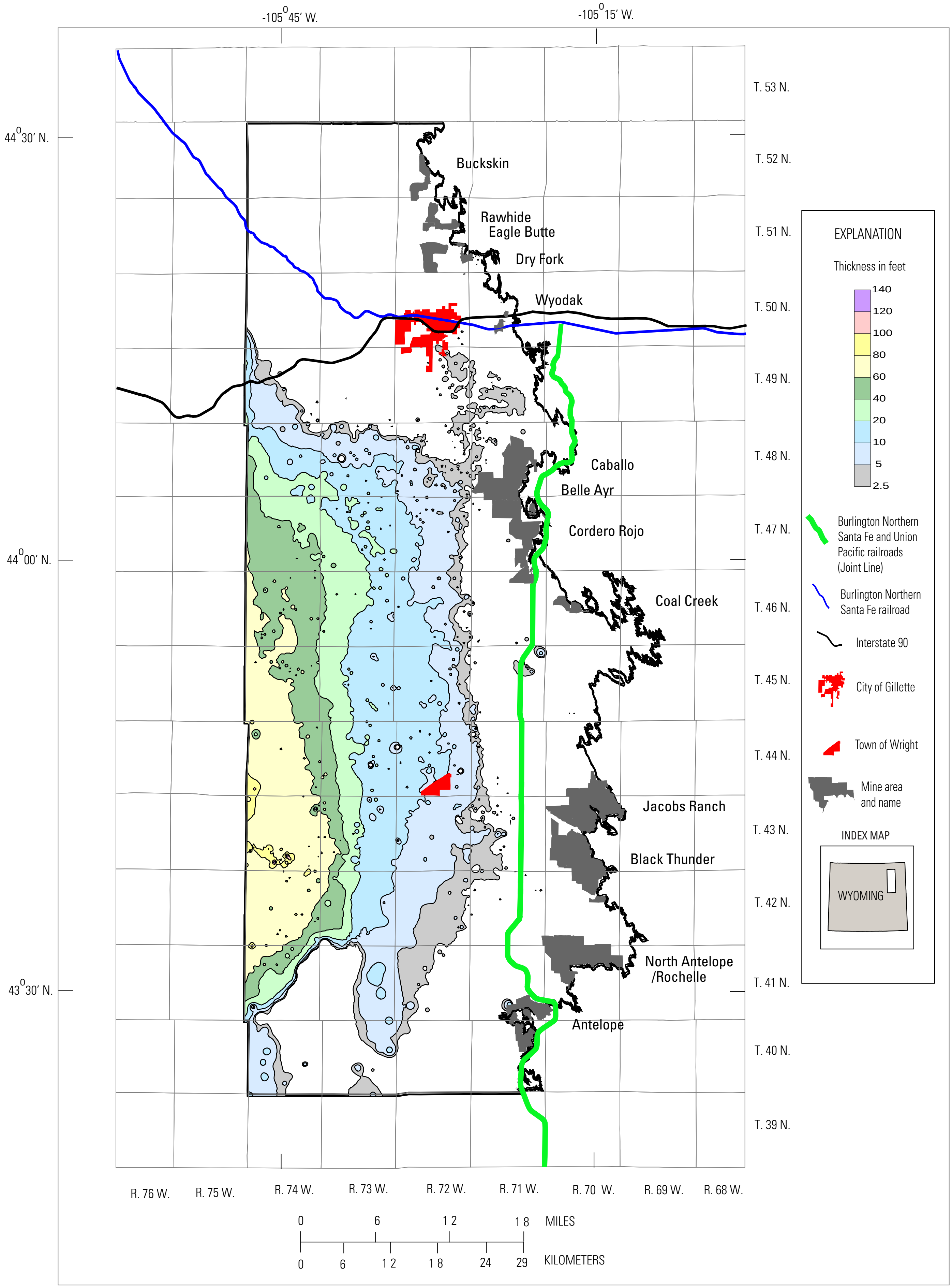


Figure 28. Isopach map of the Smith coal bed showing extent of resources greater than 2.5 ft thick.

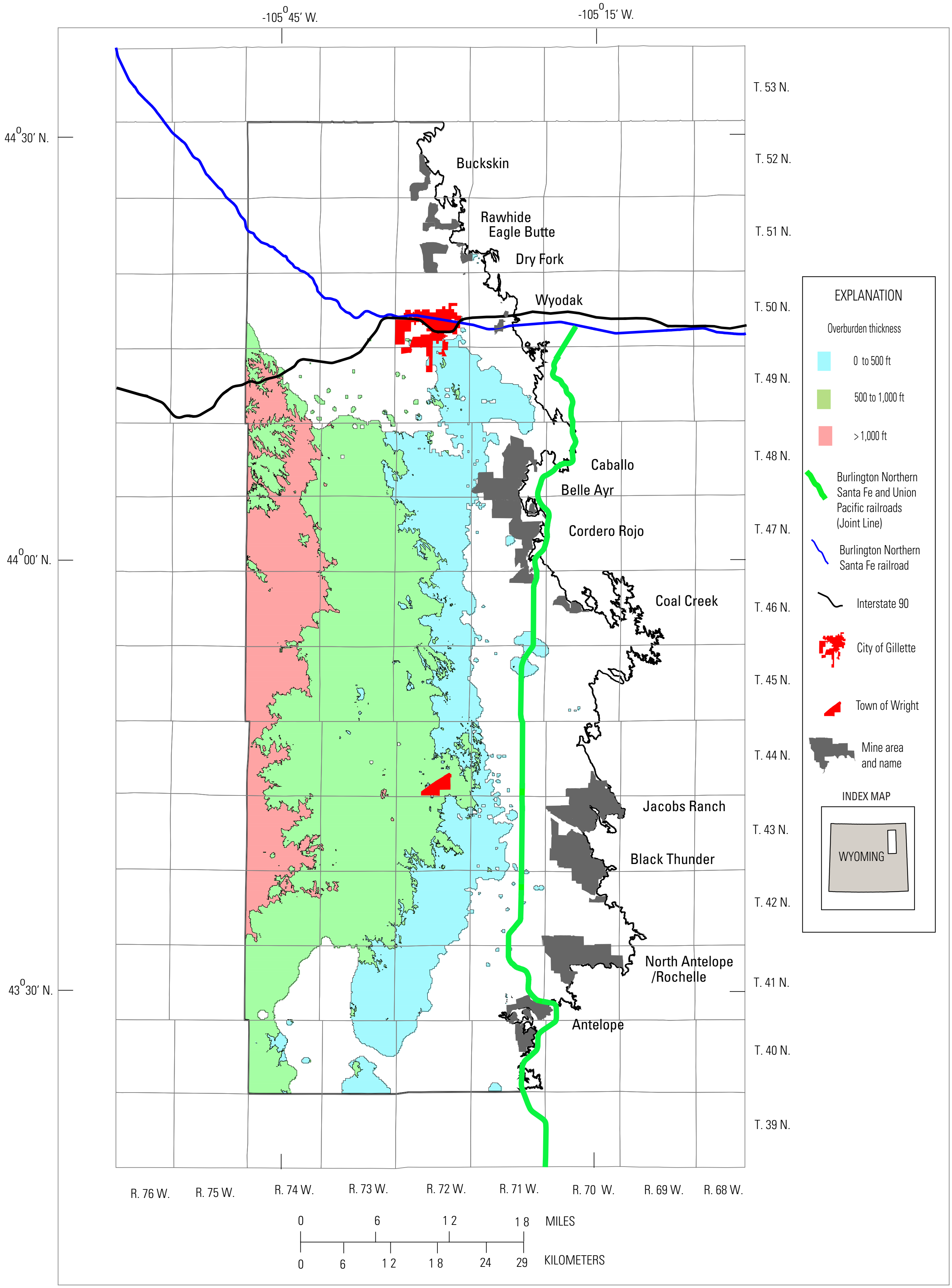


Figure 29. Map showing overburden thickness for the Smith coal bed.

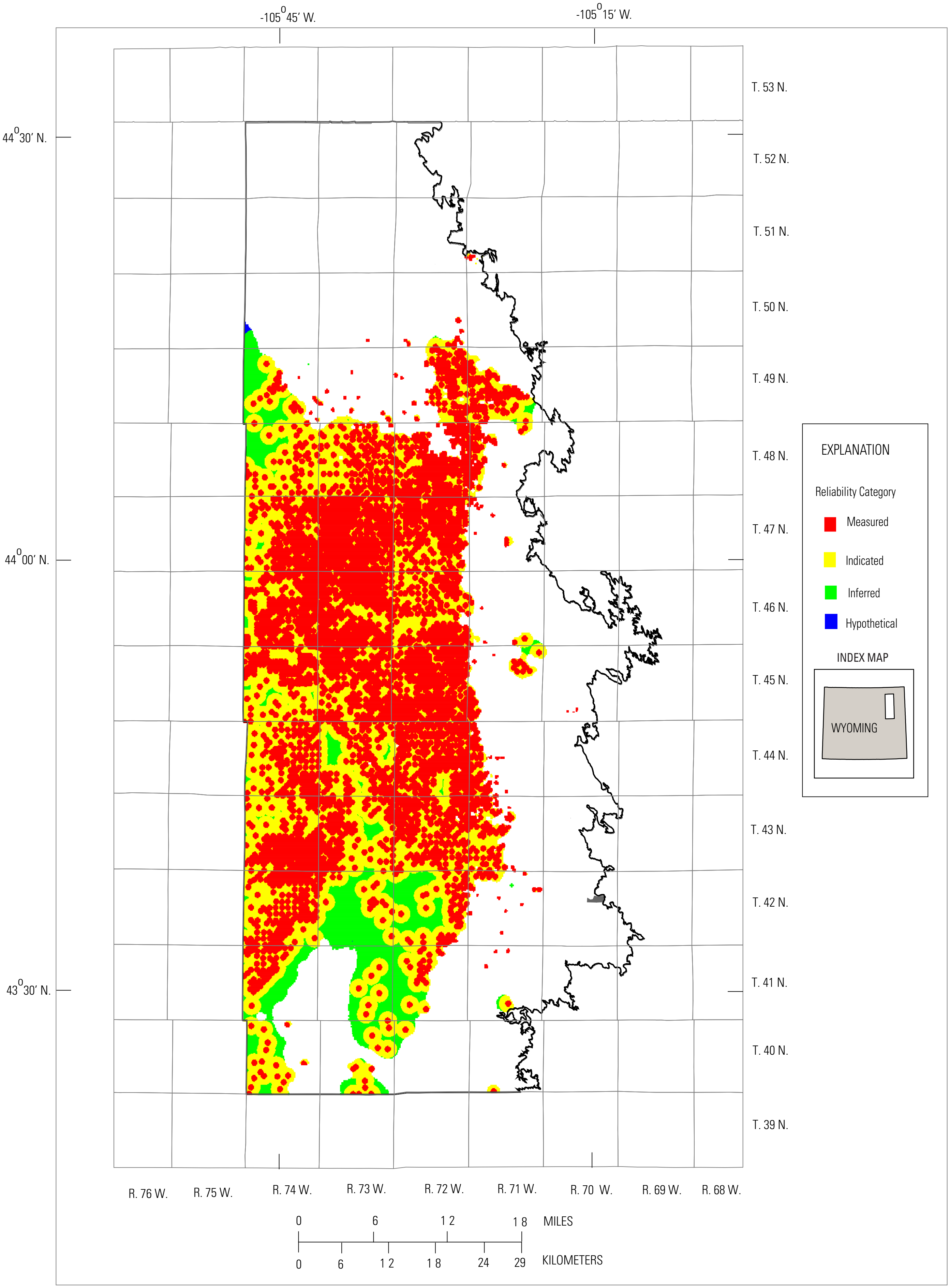


Figure 30. Map showing coal resource reliability categories for the Smith coal bed.

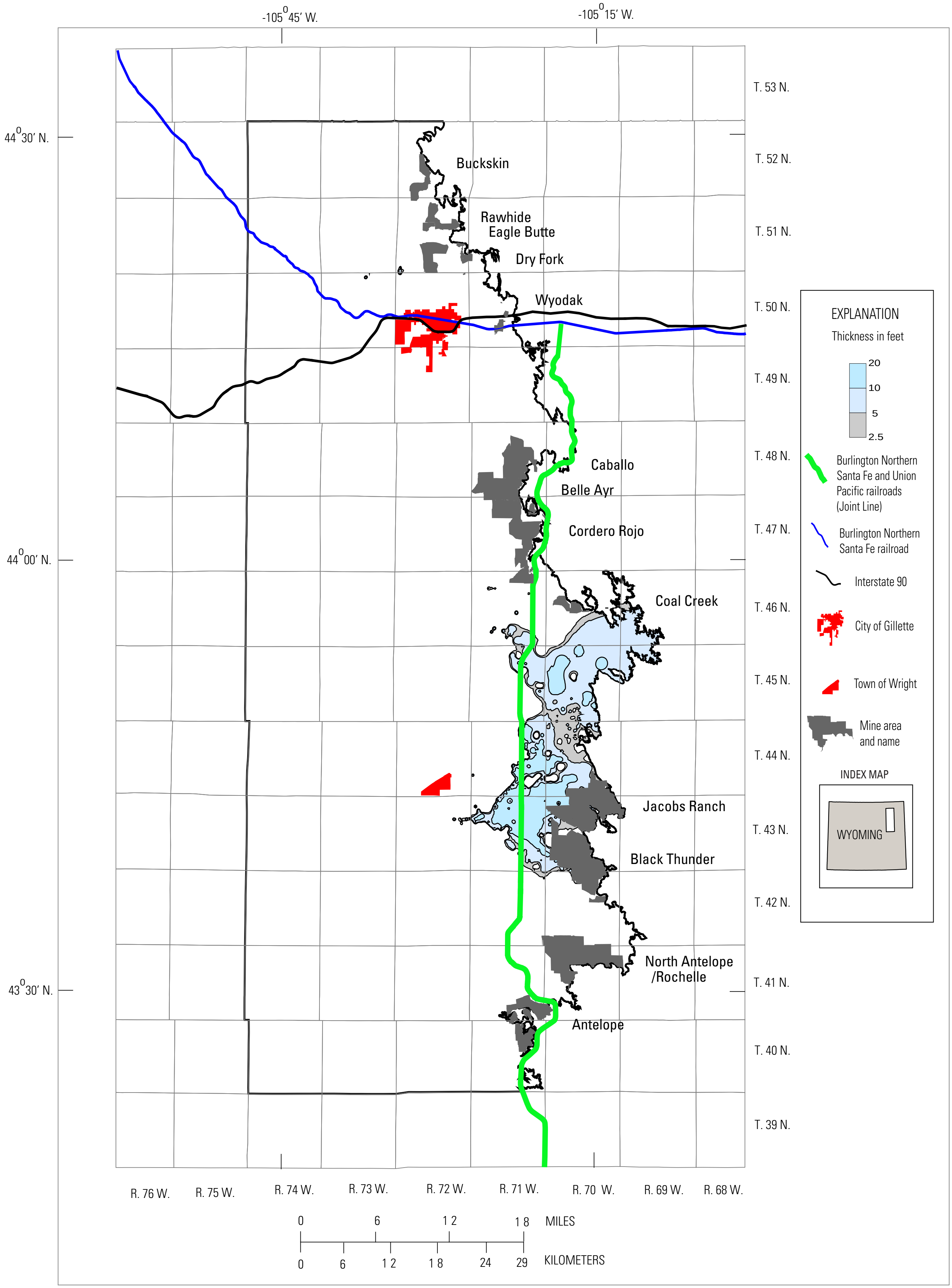


Figure 31. Isopach map of the Anderson Rider coal bed showing extent of resources greater than 2.5 ft thick.

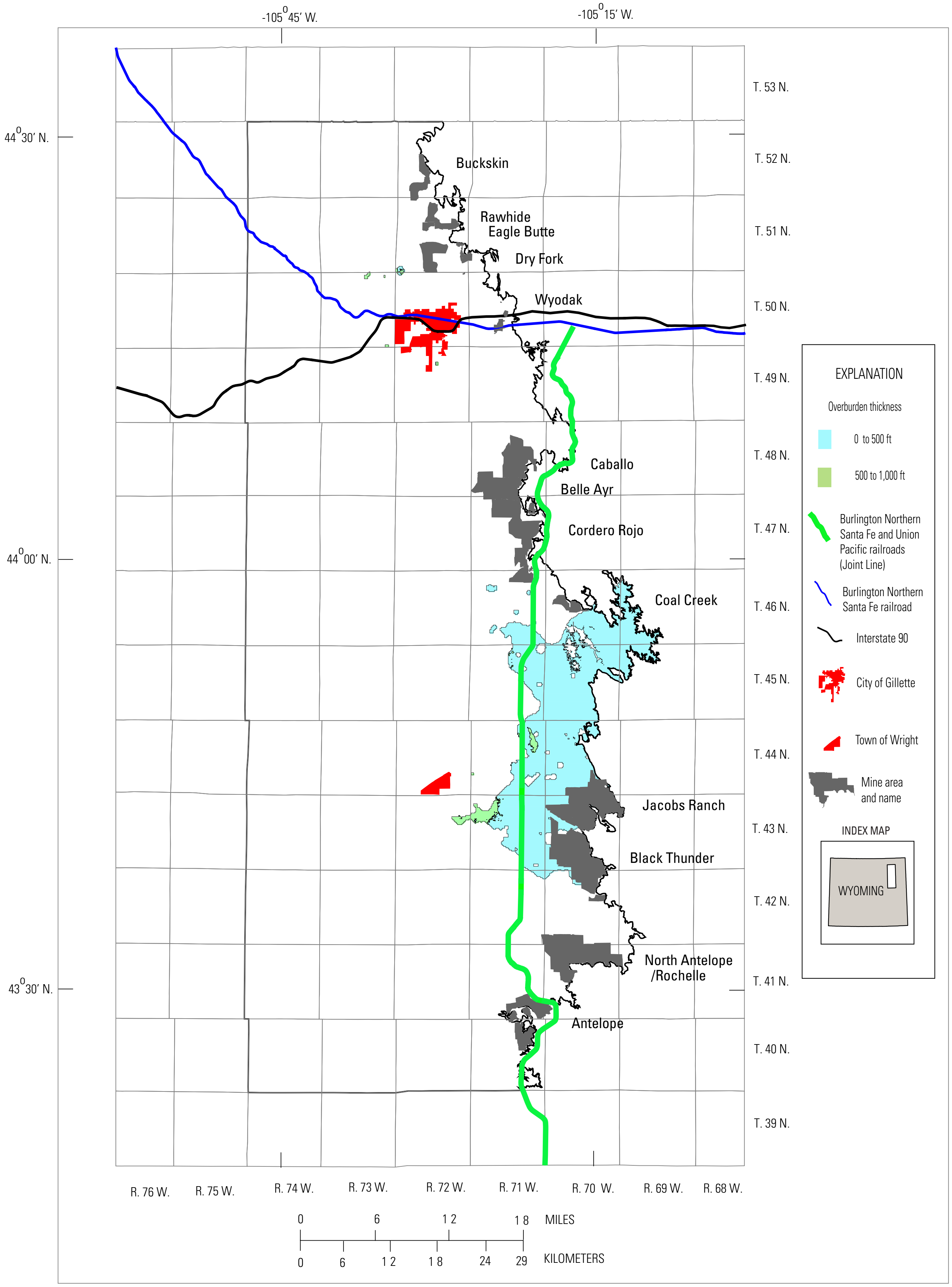


Figure 32. Map showing overburden thickness for the Anderson Rider coal bed.

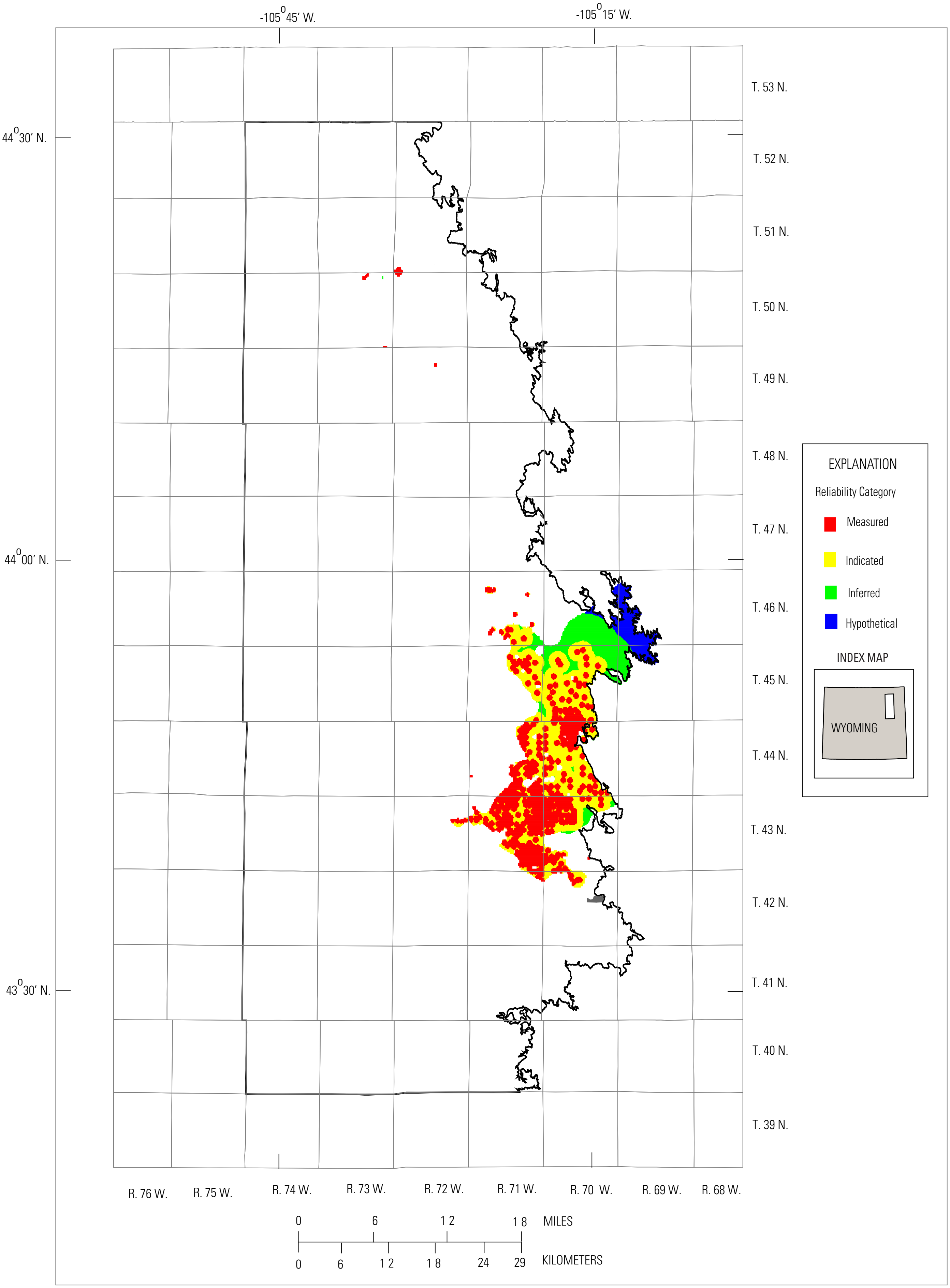


Figure 33. Map showing coal resource reliability categories for the Anderson Rider coal bed.

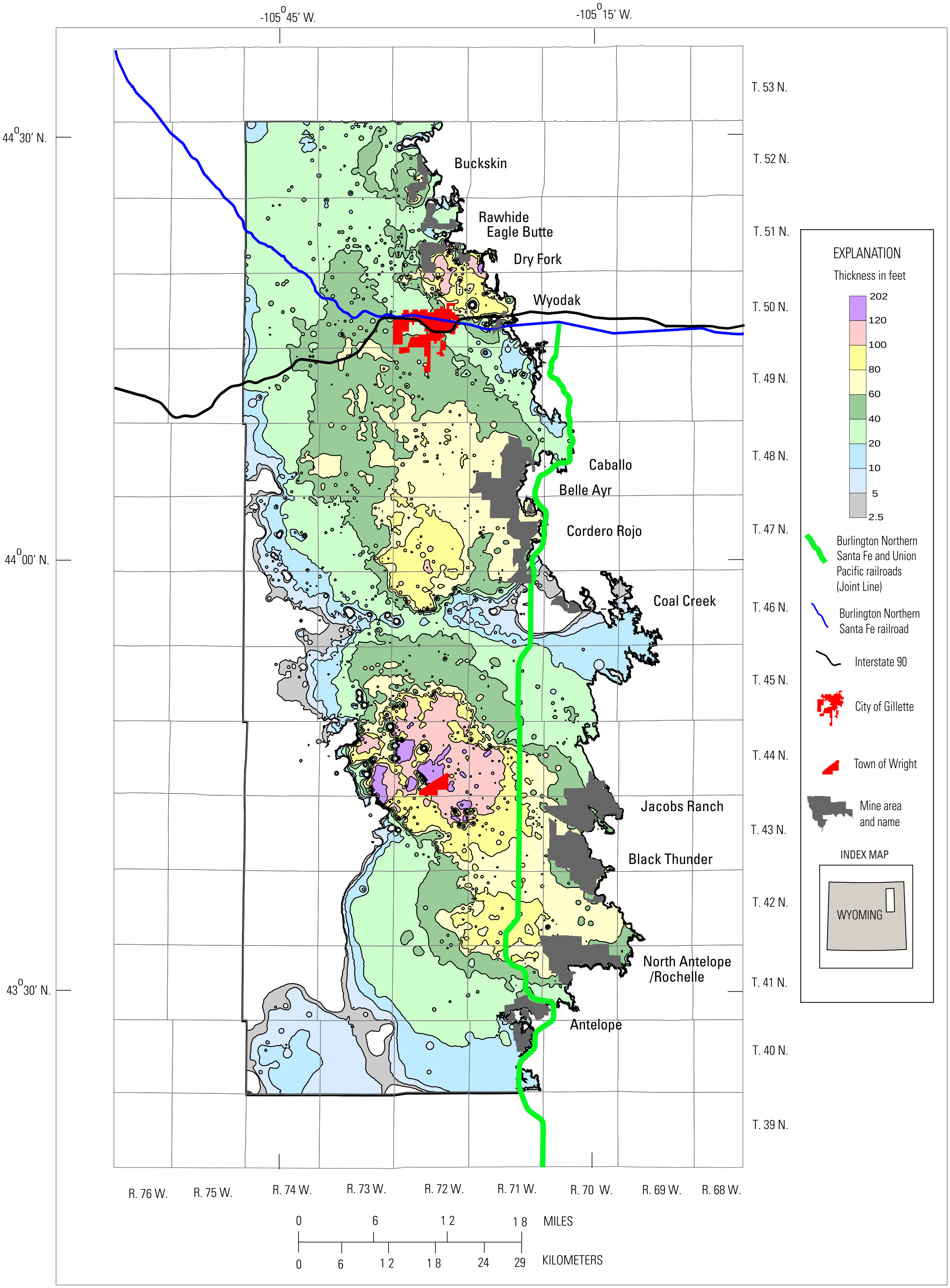


Figure 34. Isopach map of the Anderson coal bed showing extent of resources greater than 2.5 ft thick.

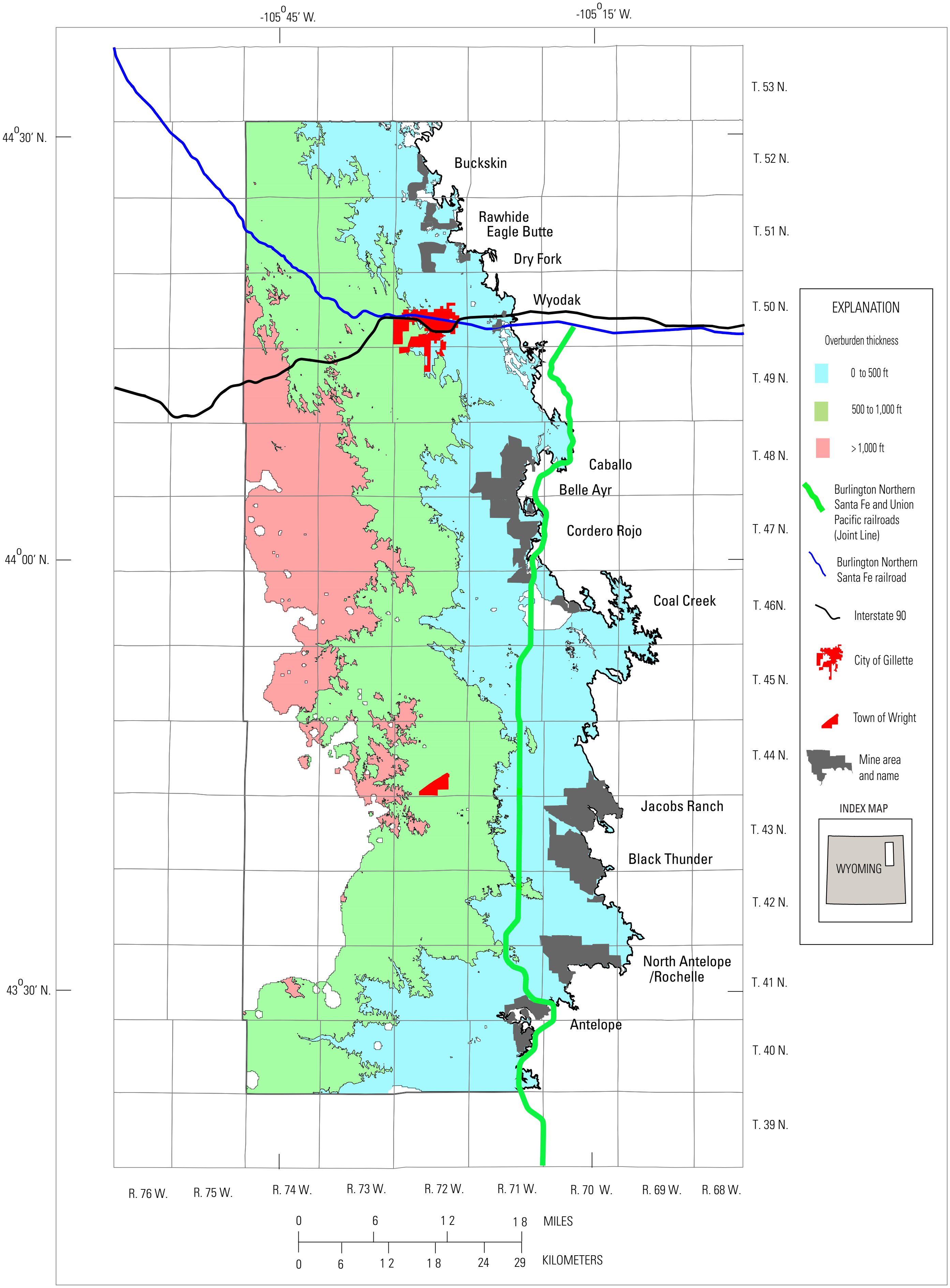


Figure 35. Map showing overburden thickness for the Anderson coal bed.

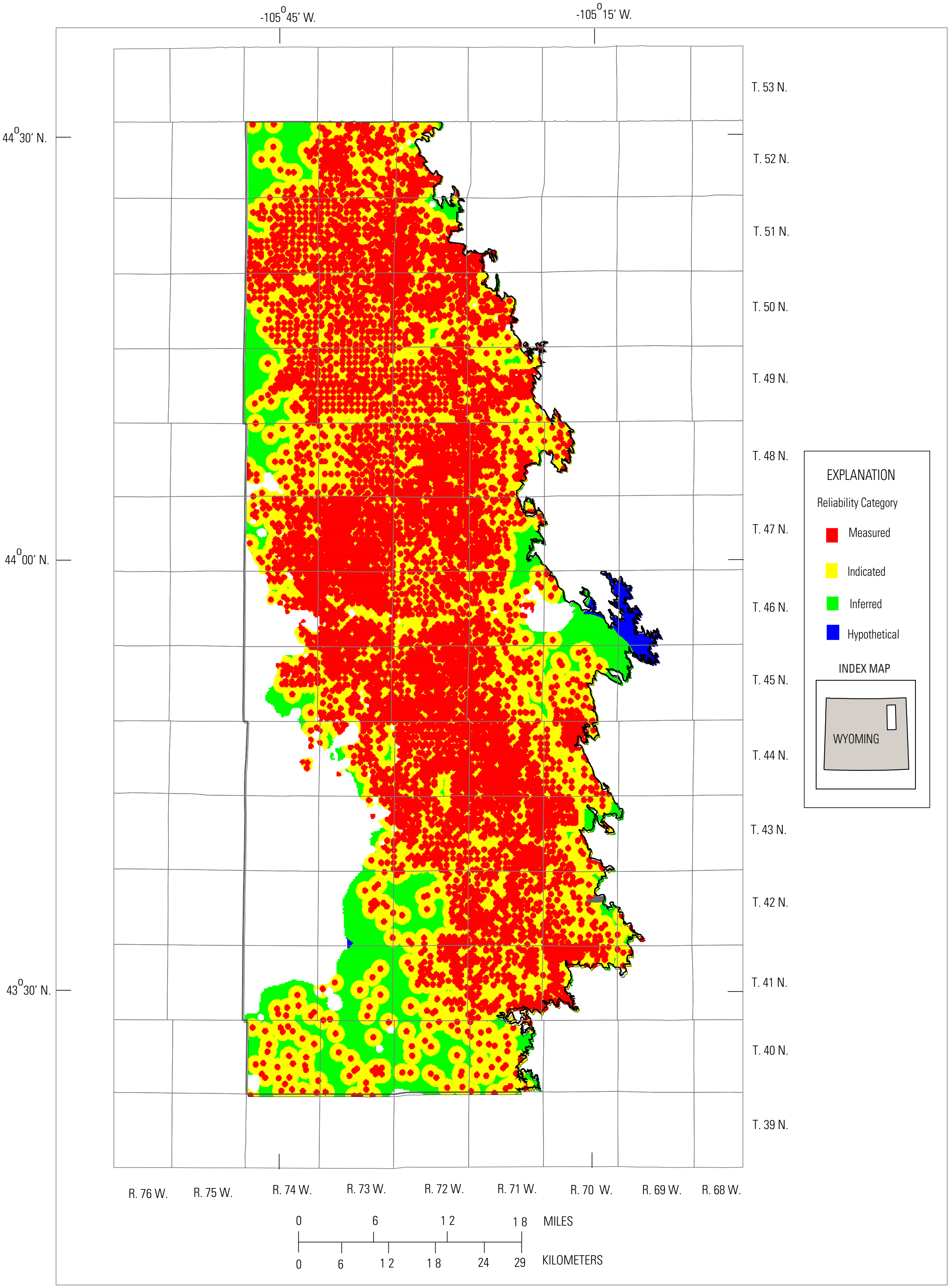


Figure 36. Map showing coal resource reliability categories for the Anderson coal bed.

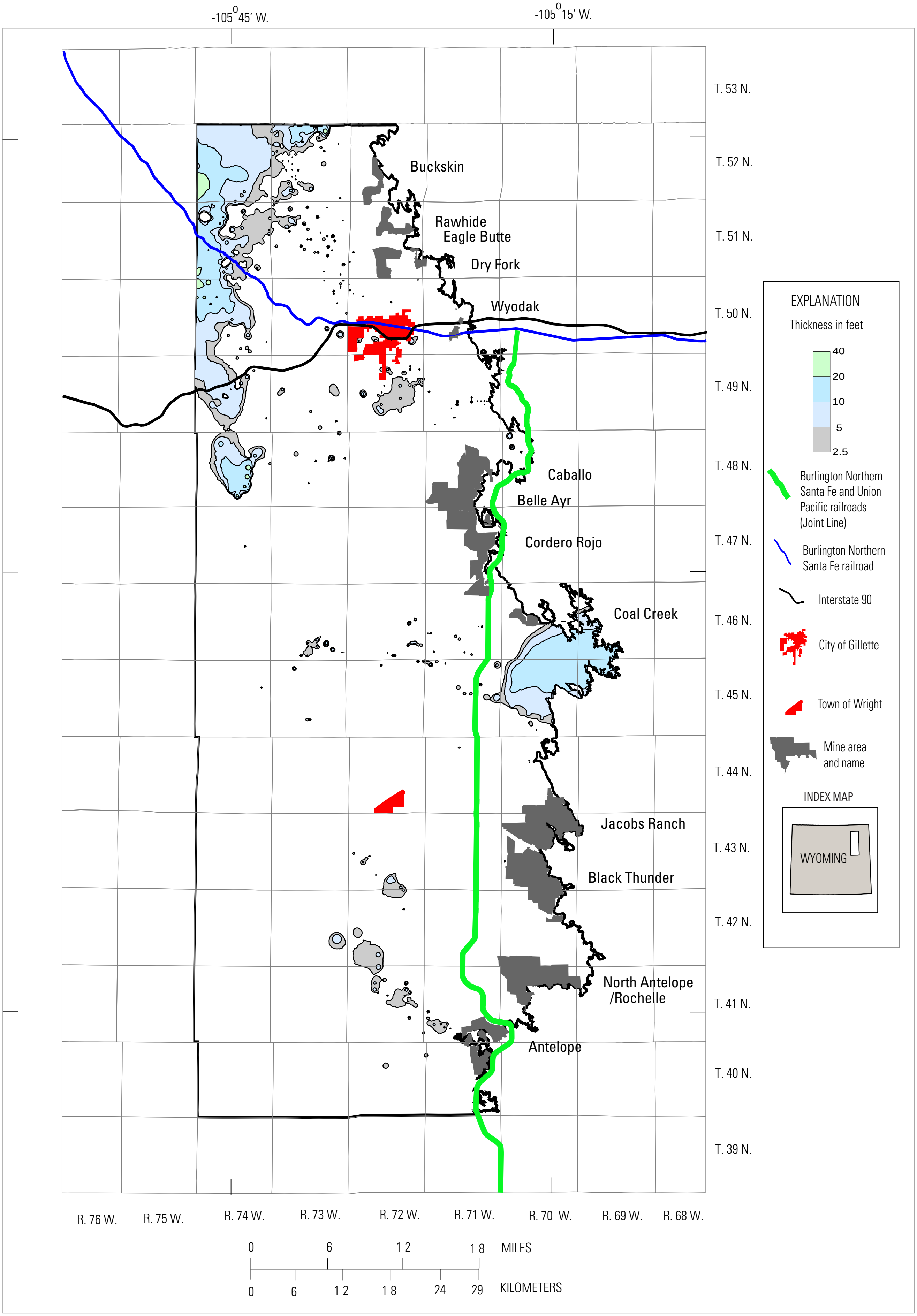


Figure 37. Isopach map of the Dietz coal bed showing extent of resources greater than 2.5 ft thick.

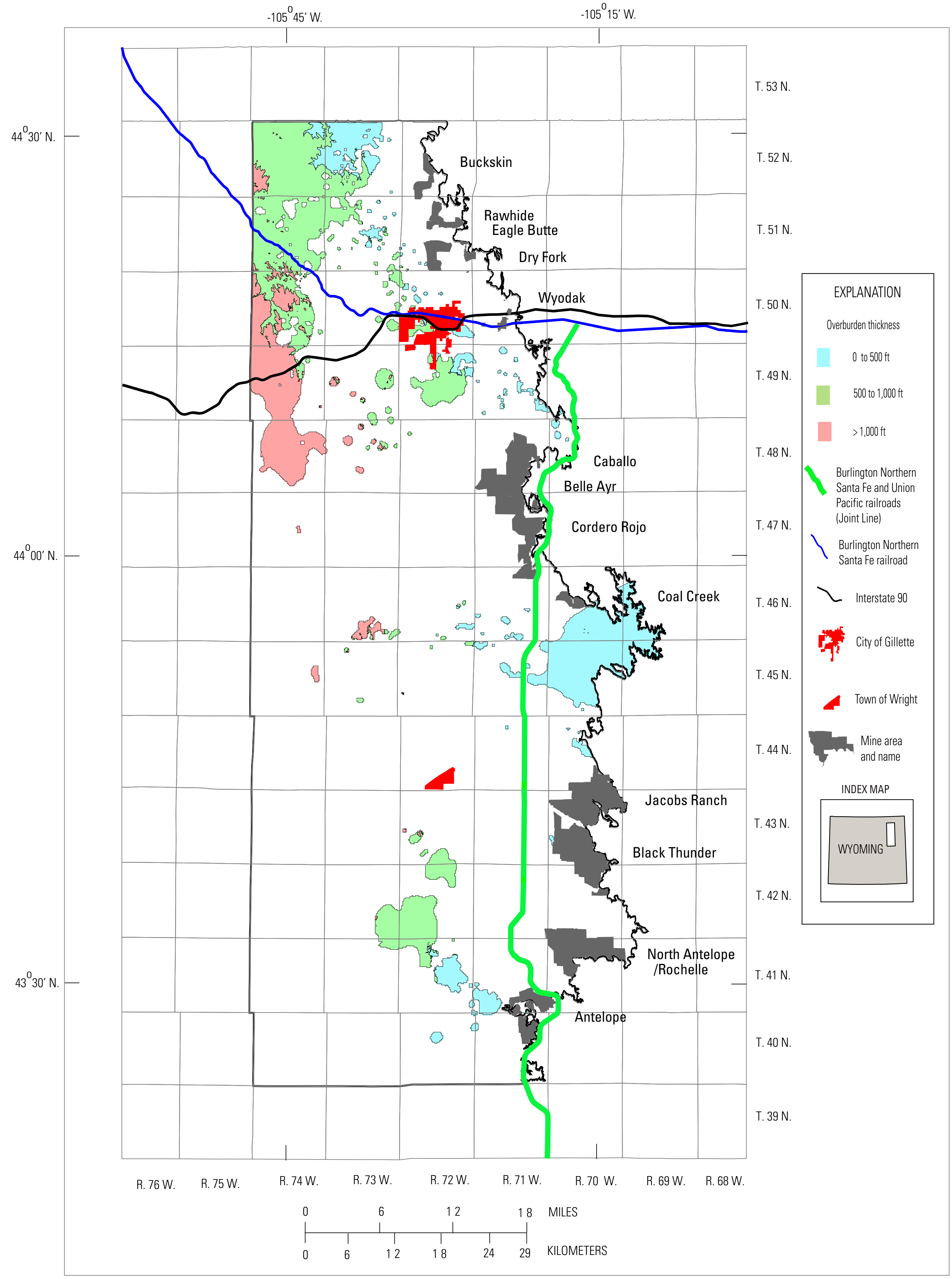


Figure 38. Map showing overburden thickness for the Dietz coal bed.

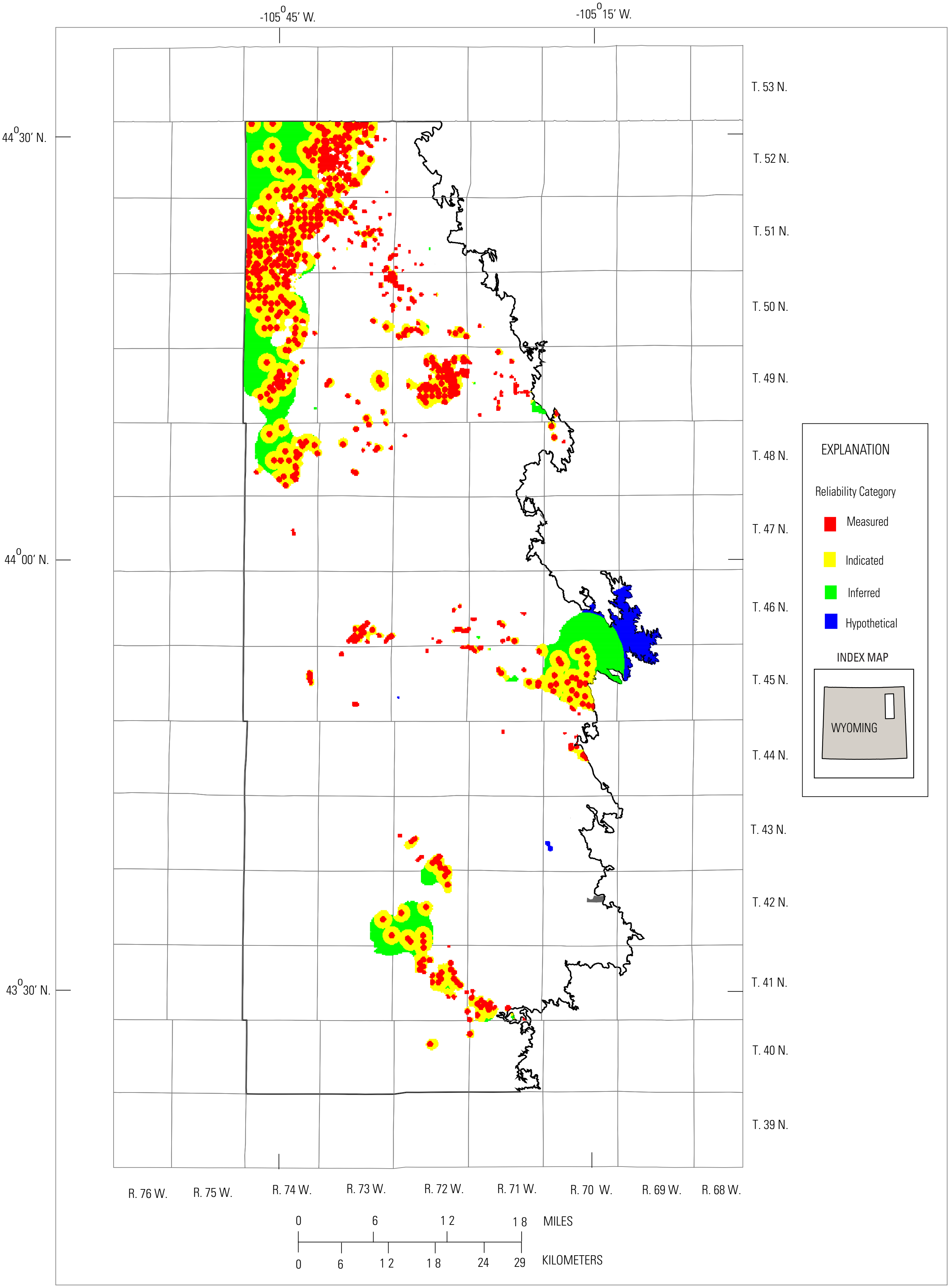


Figure 39. Map showing coal resource reliability categories for the Dietz coal bed.

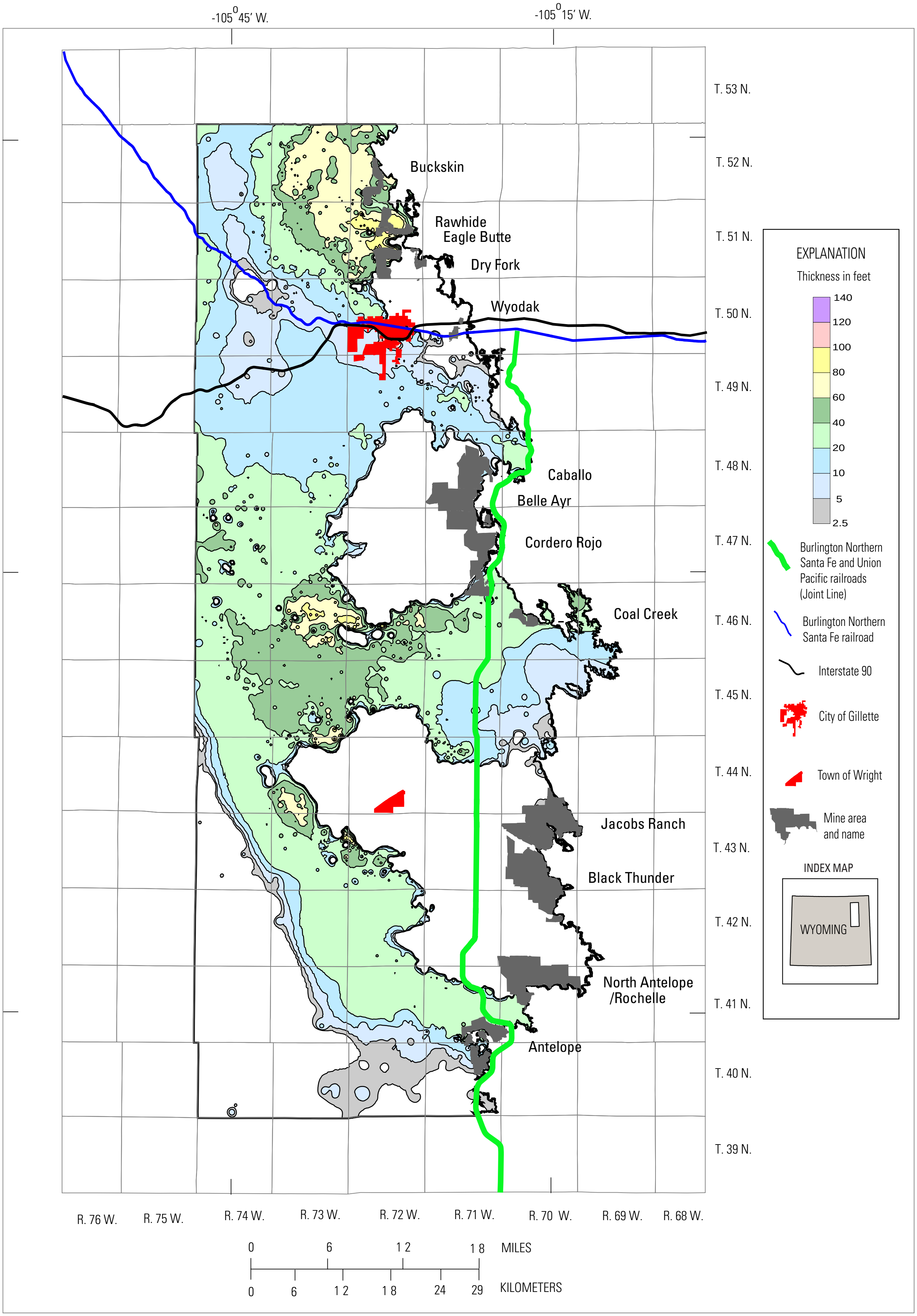


Figure 40. Isopach map of the Canyon coal bed showing extent of resources greater than 2.5 ft thick.

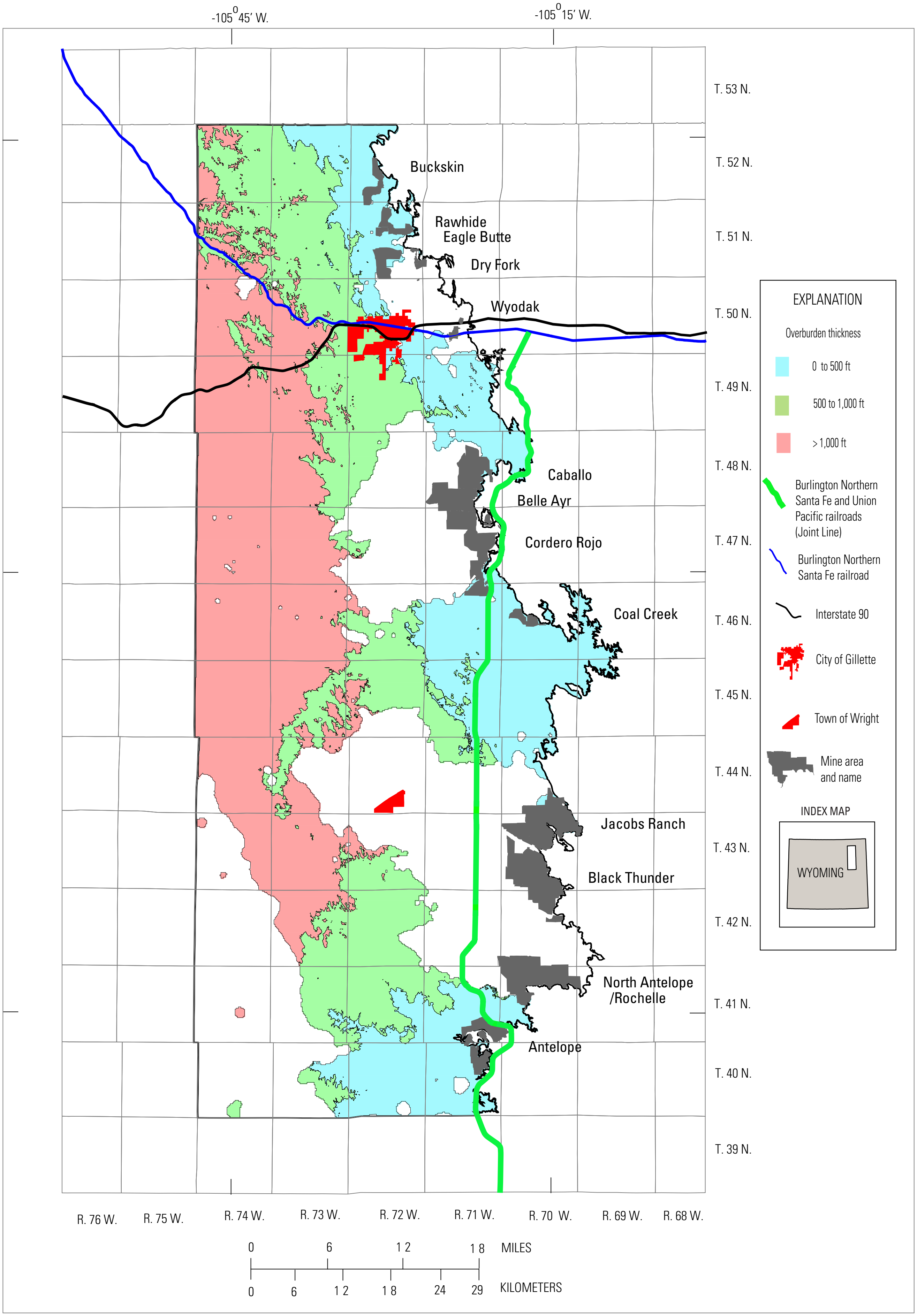


Figure 41. Map showing overburden thickness for the Canyon coal bed.

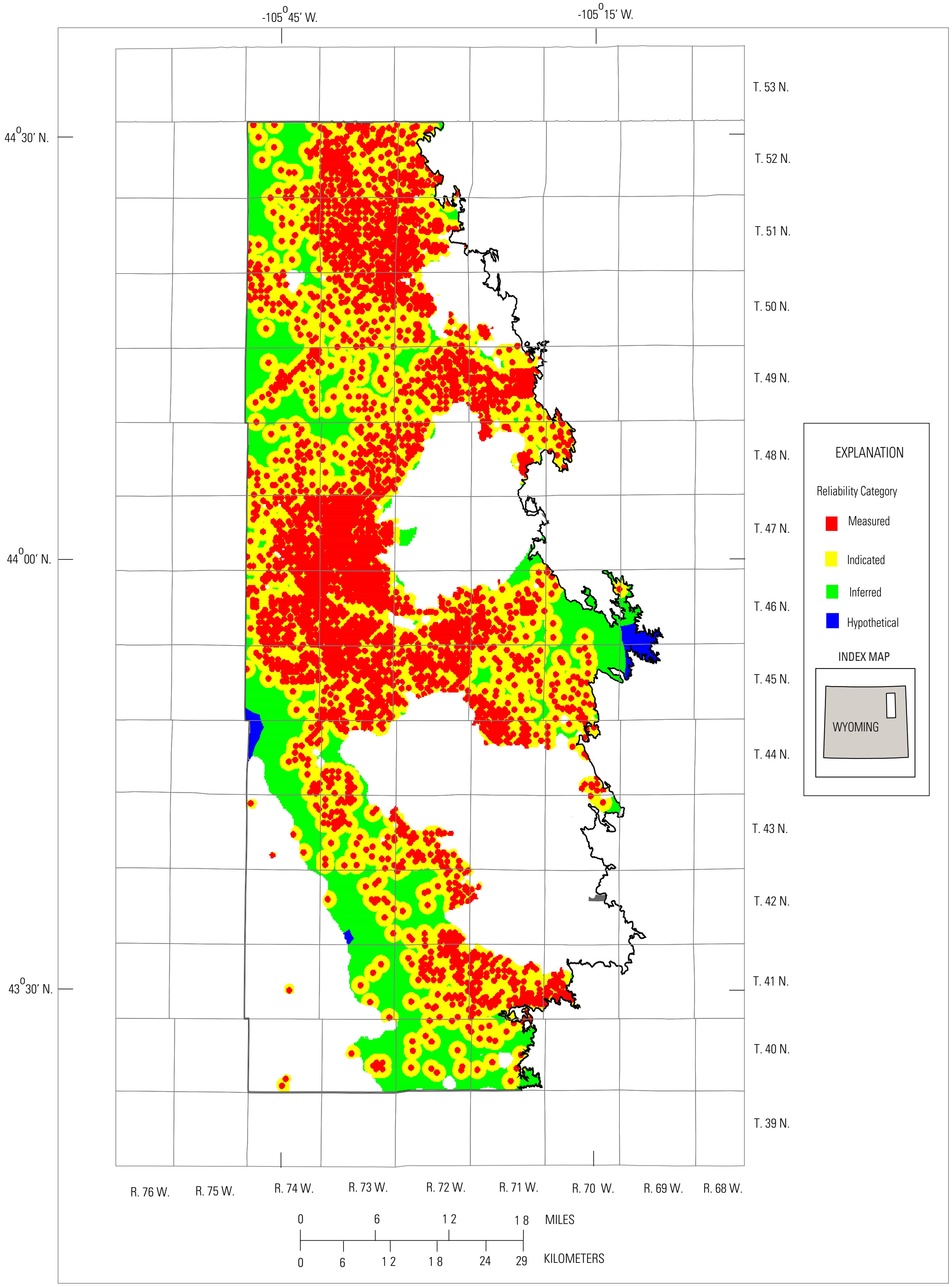


Figure 42. Map showing coal resource reliability categories for the Canyon coal bed.

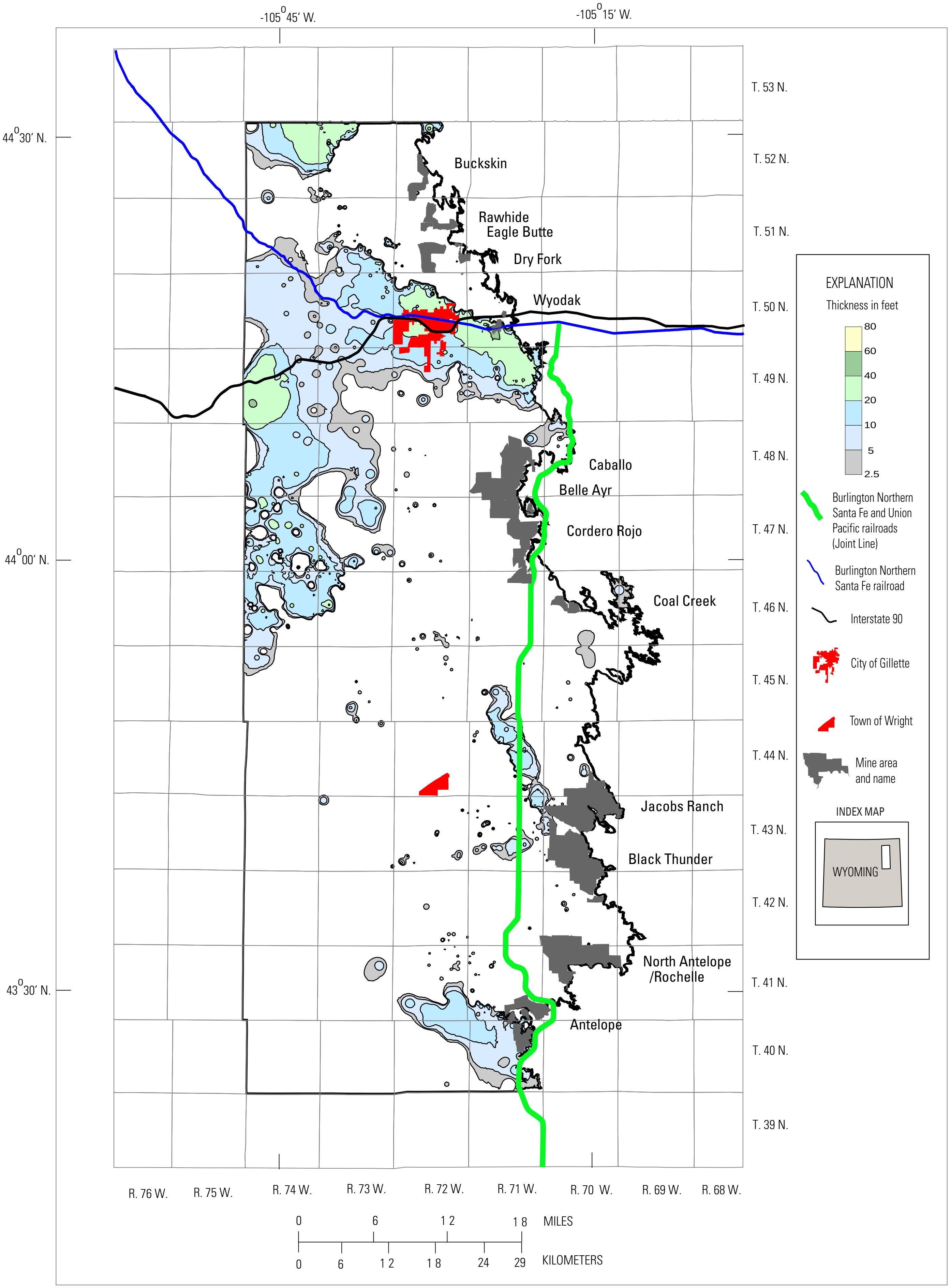


Figure 43. Isopach map of the Werner coal bed showing extent of resources greater than 2.5 ft thick.

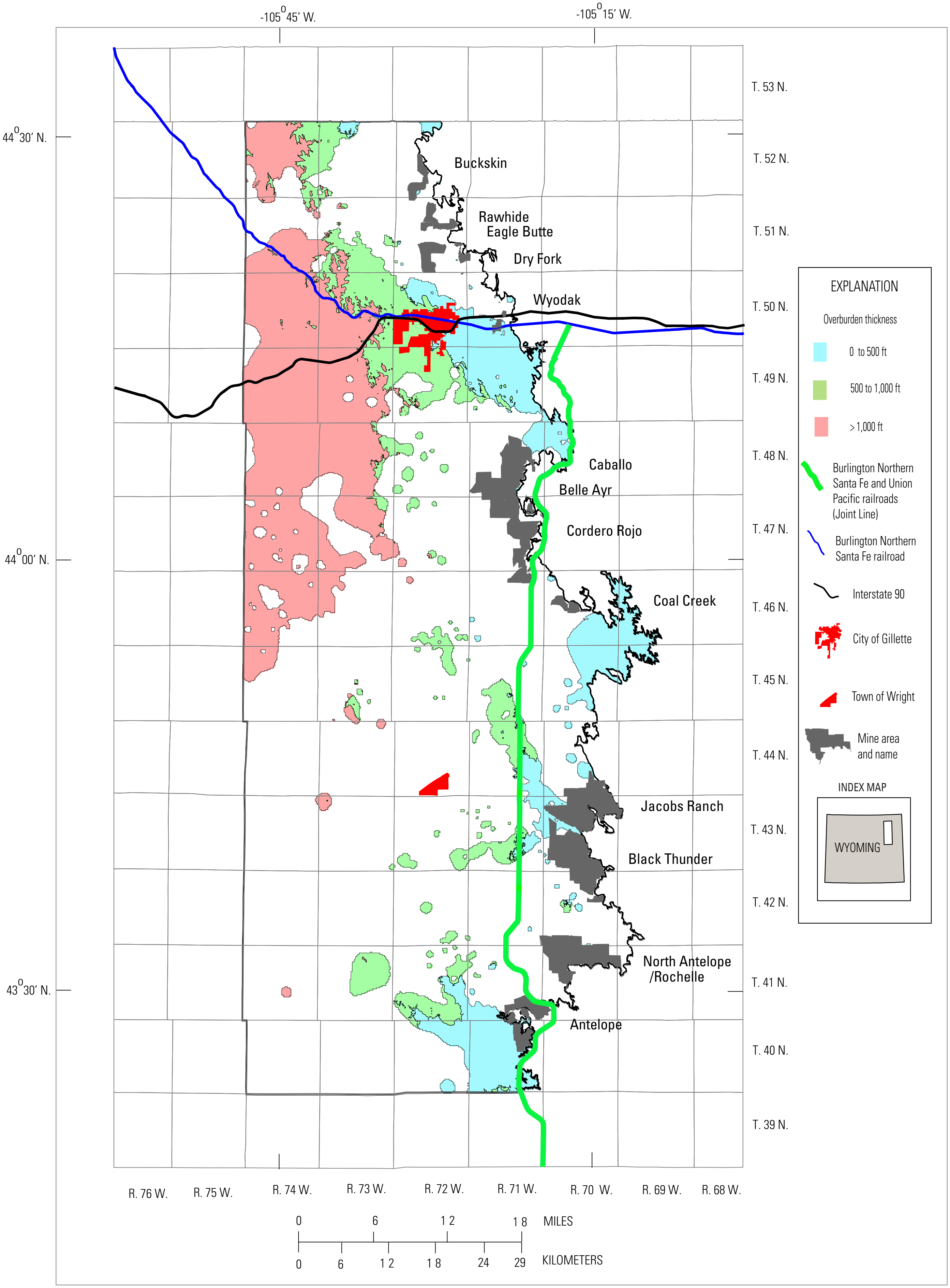


Figure 44. Map showing overburden thickness for the Werner coal bed.

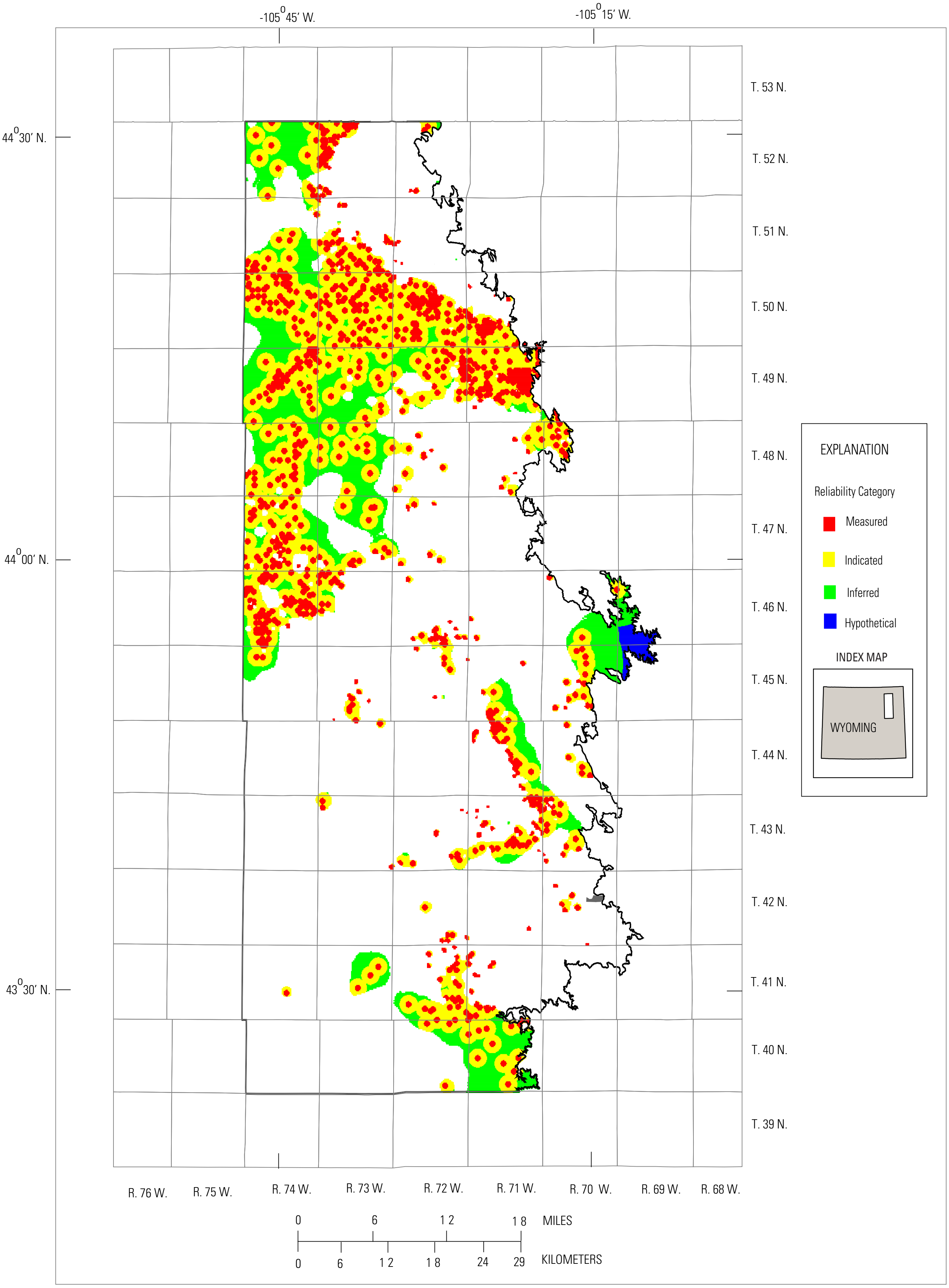


Figure 45. Map showing coal resource reliability categories for the Werner coal bed.

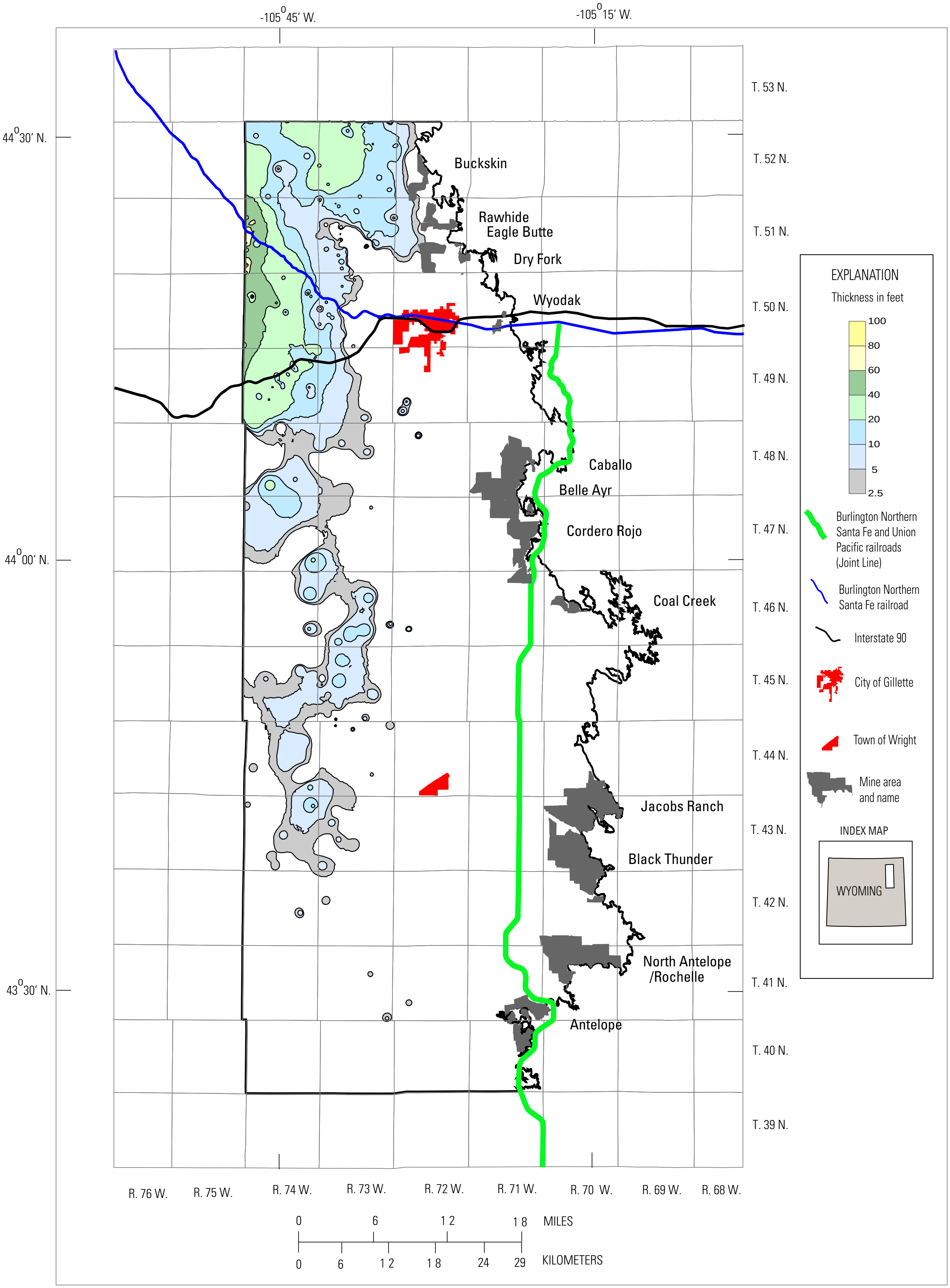


Figure 46. Isopach map of the Gates coal bed showing extent of resources greater than 2.5 ft thick.

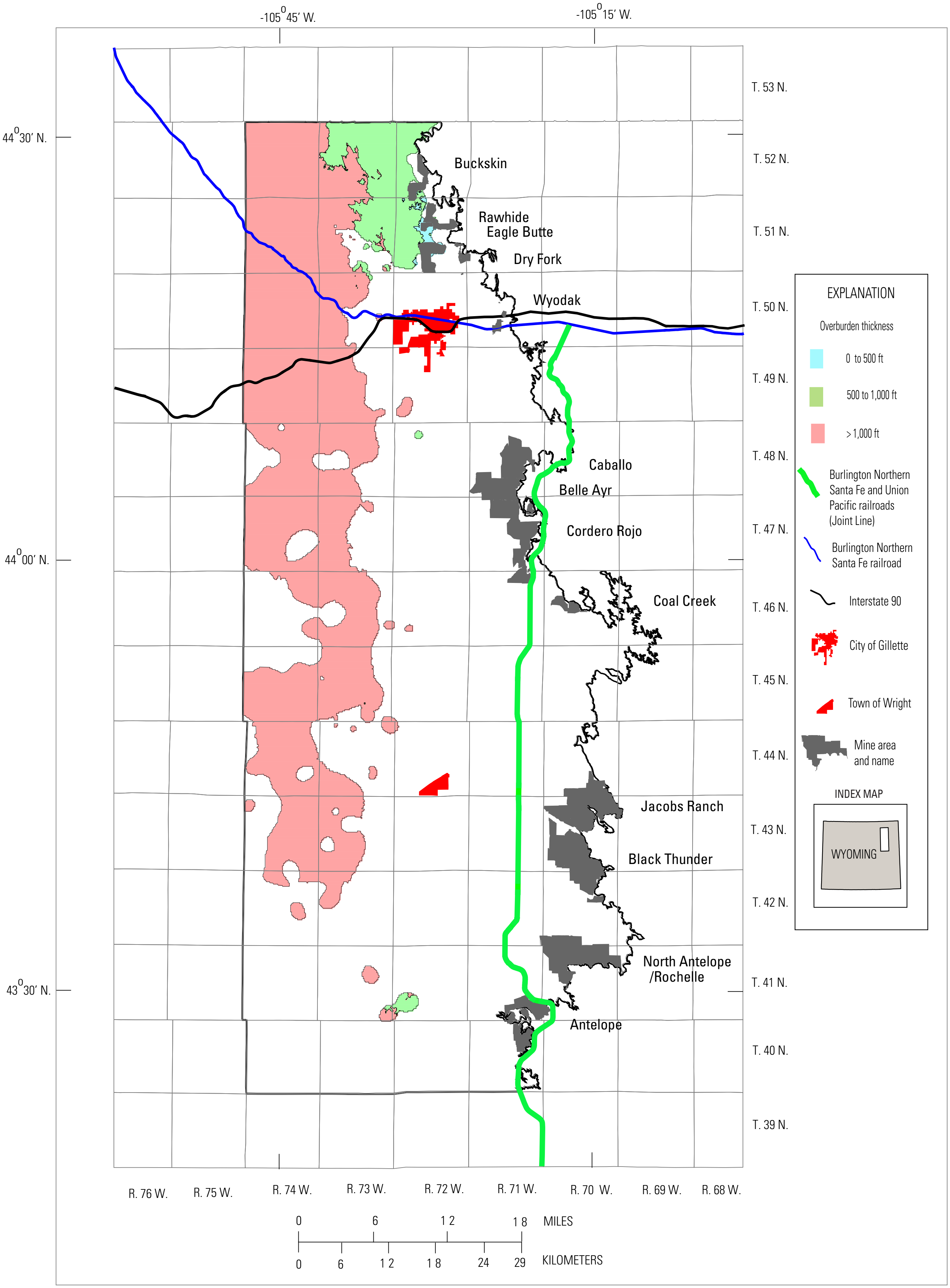


Figure 47. Map showing overburden thickness for the Gates coal bed.

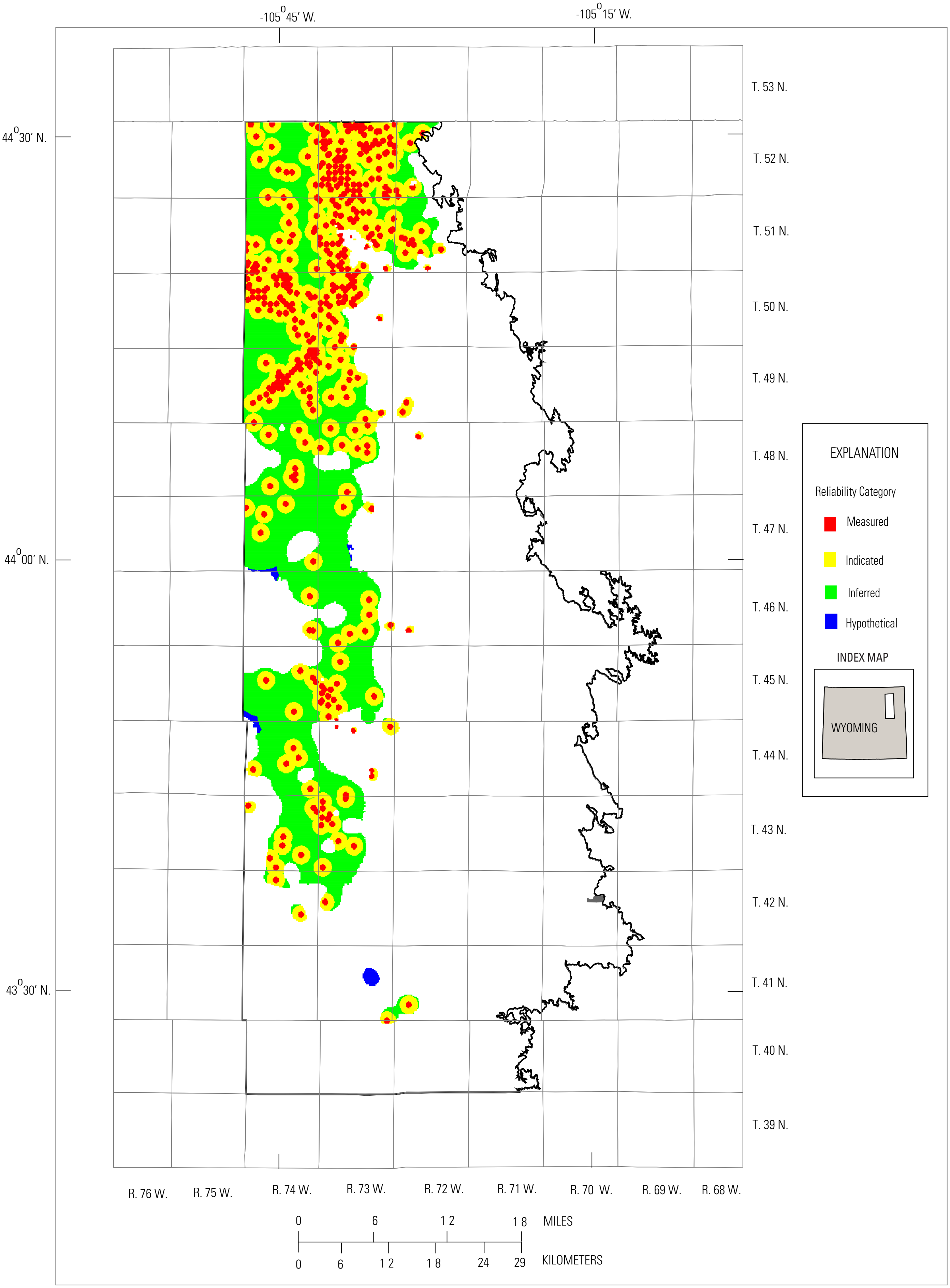


Figure 48. Map showing coal resource reliability categories for the Gates coal bed.

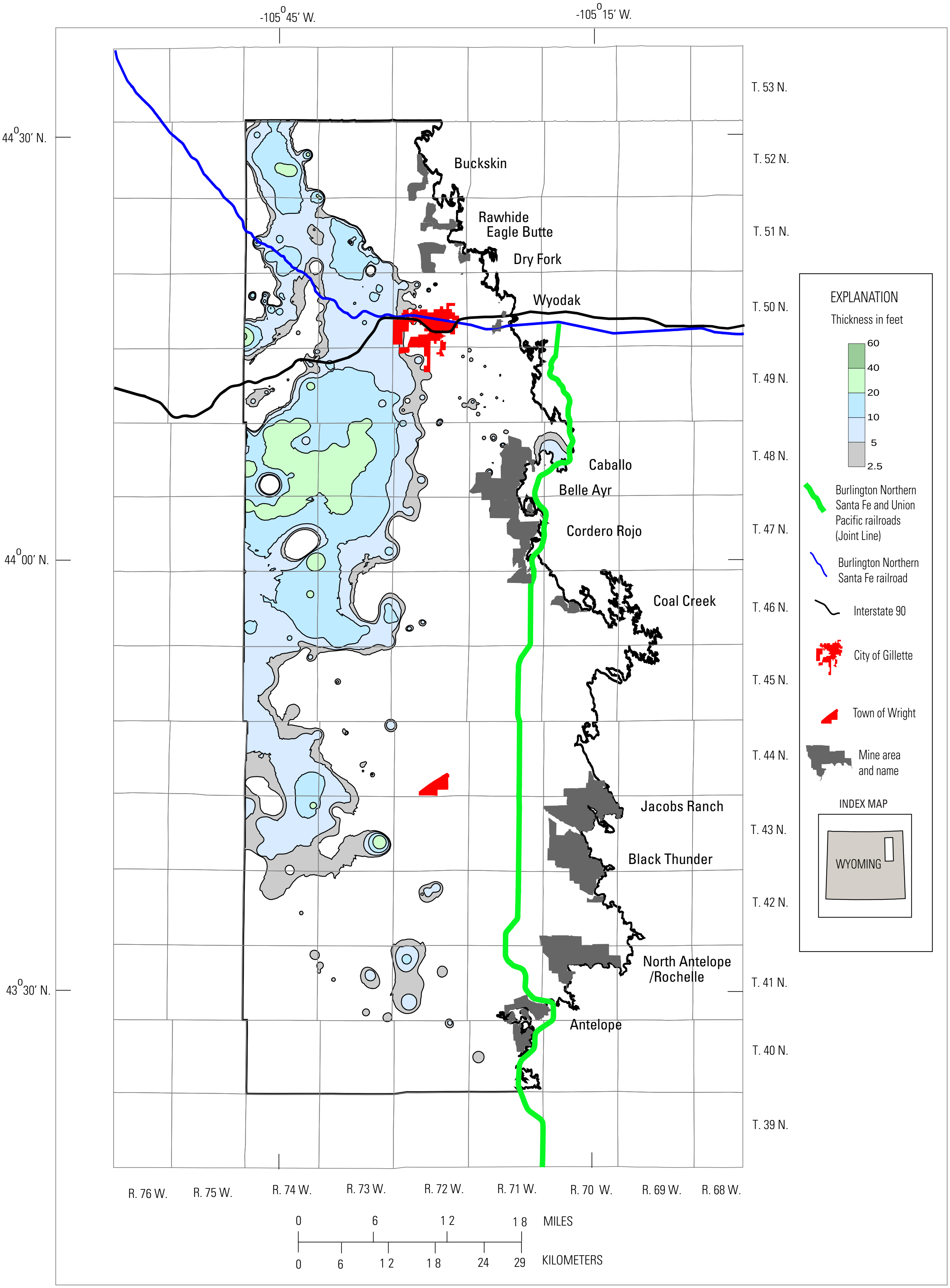


Figure 49. Isopach map of the Pawnee coal bed showing extent of resources greater than 2.5 ft thick.

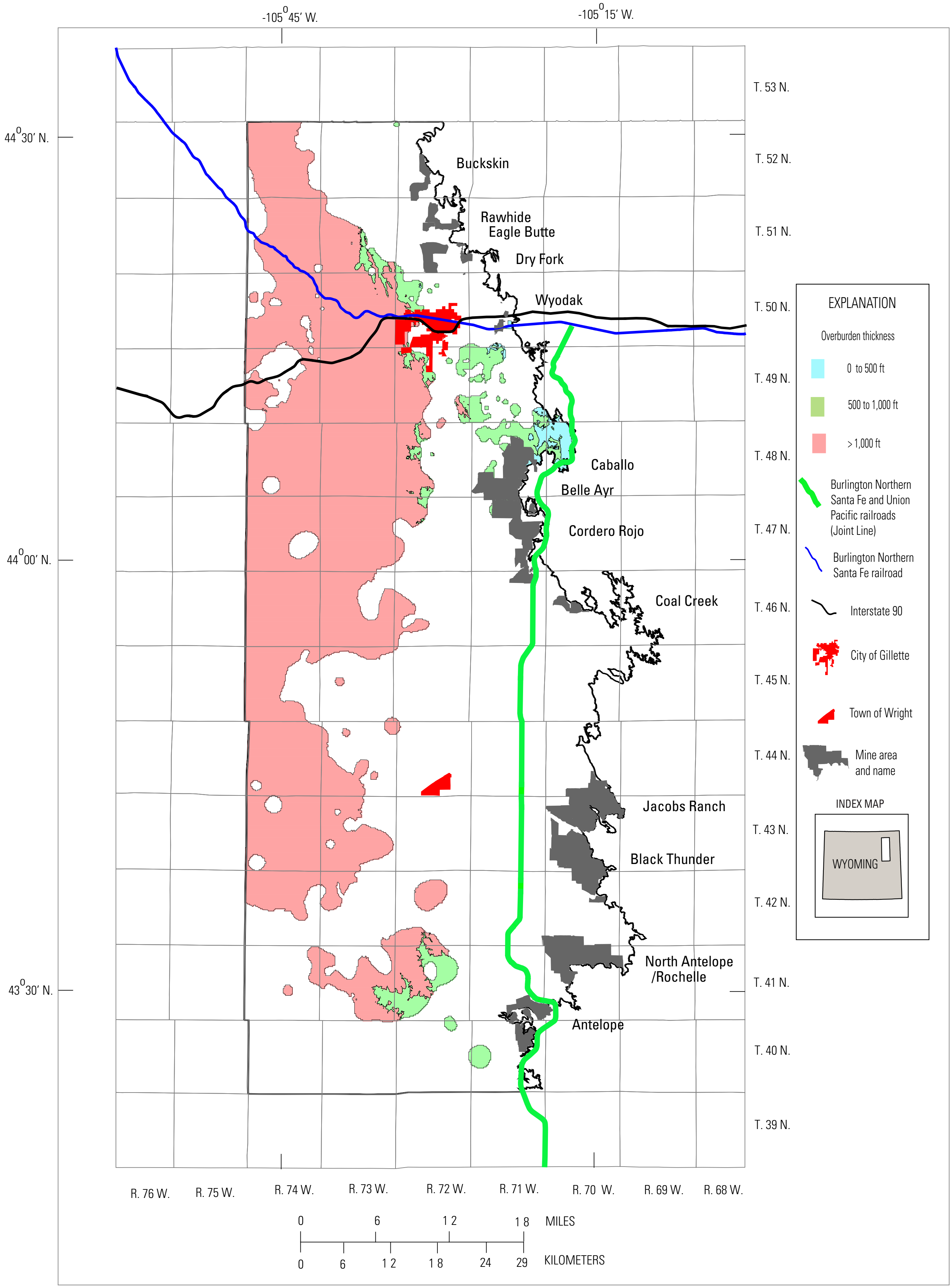


Figure 50. Map showing overburden thickness for the Pawnee coal bed.

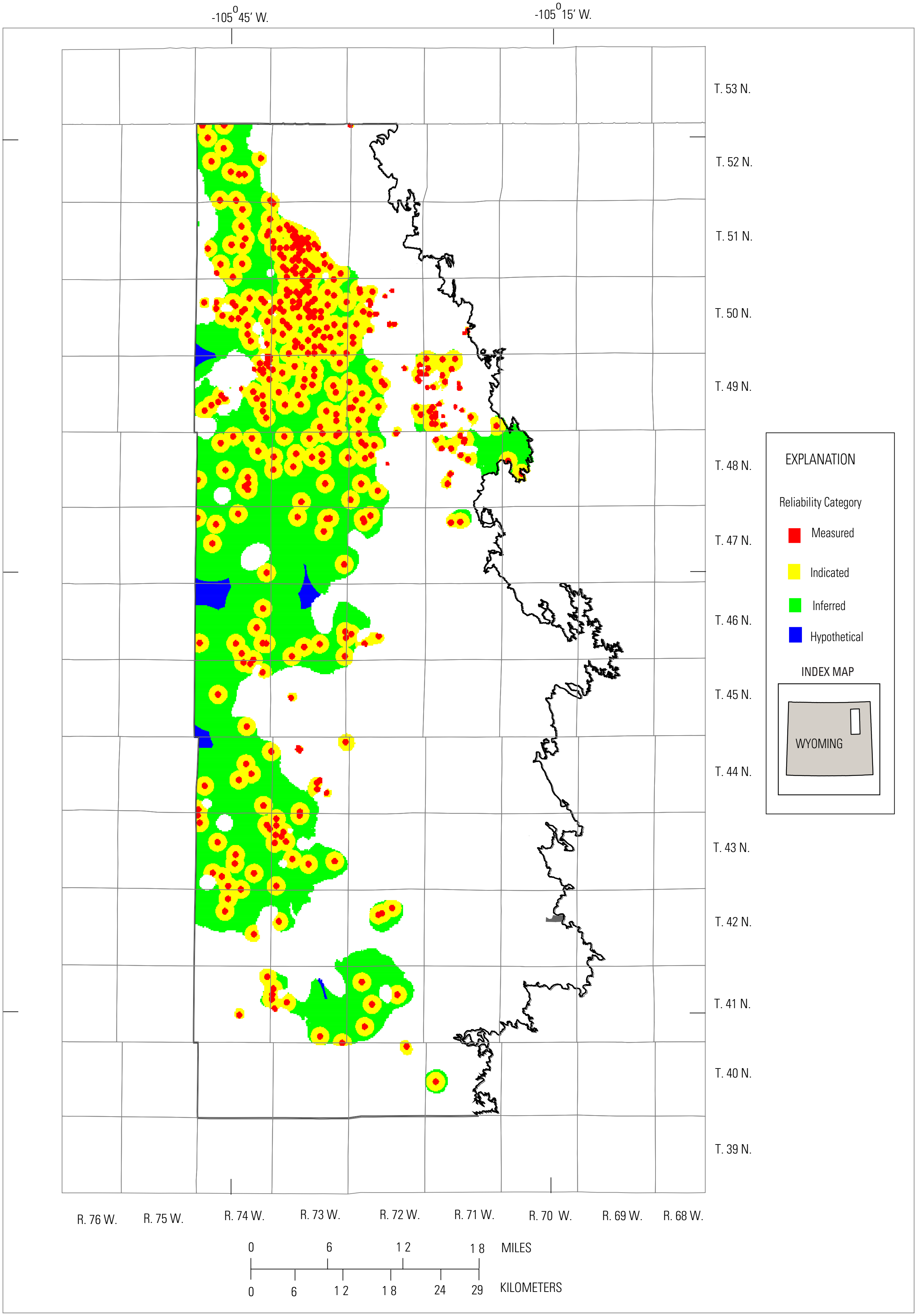


Figure 51. Map showing coal resource reliability categories for the Pawnee coal bed.

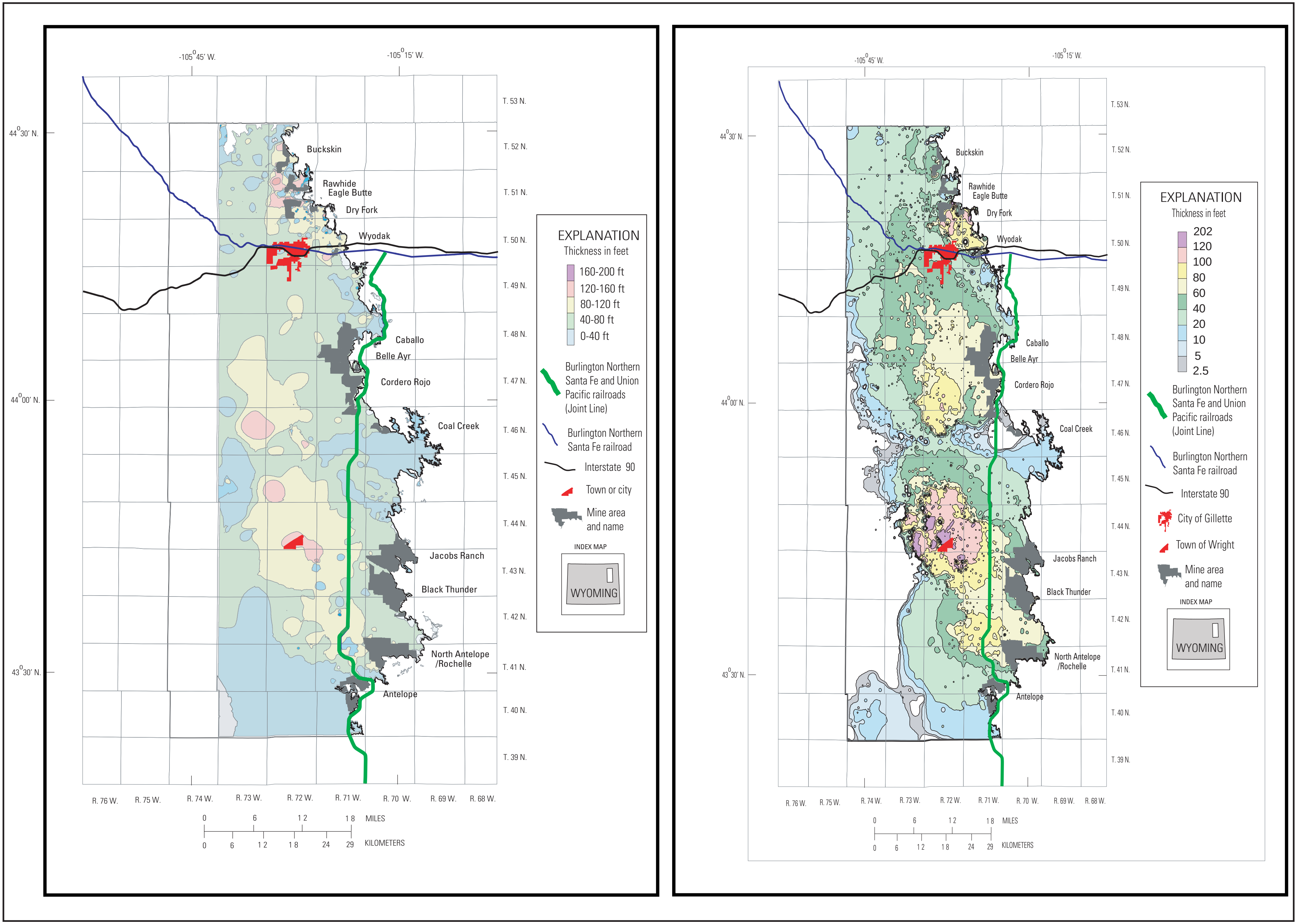


Figure 52. Comparison of the Upper Wyodak coal bed of Ellis and others (2002) (left figure) to the Anderson coal bed of this report (right figure).

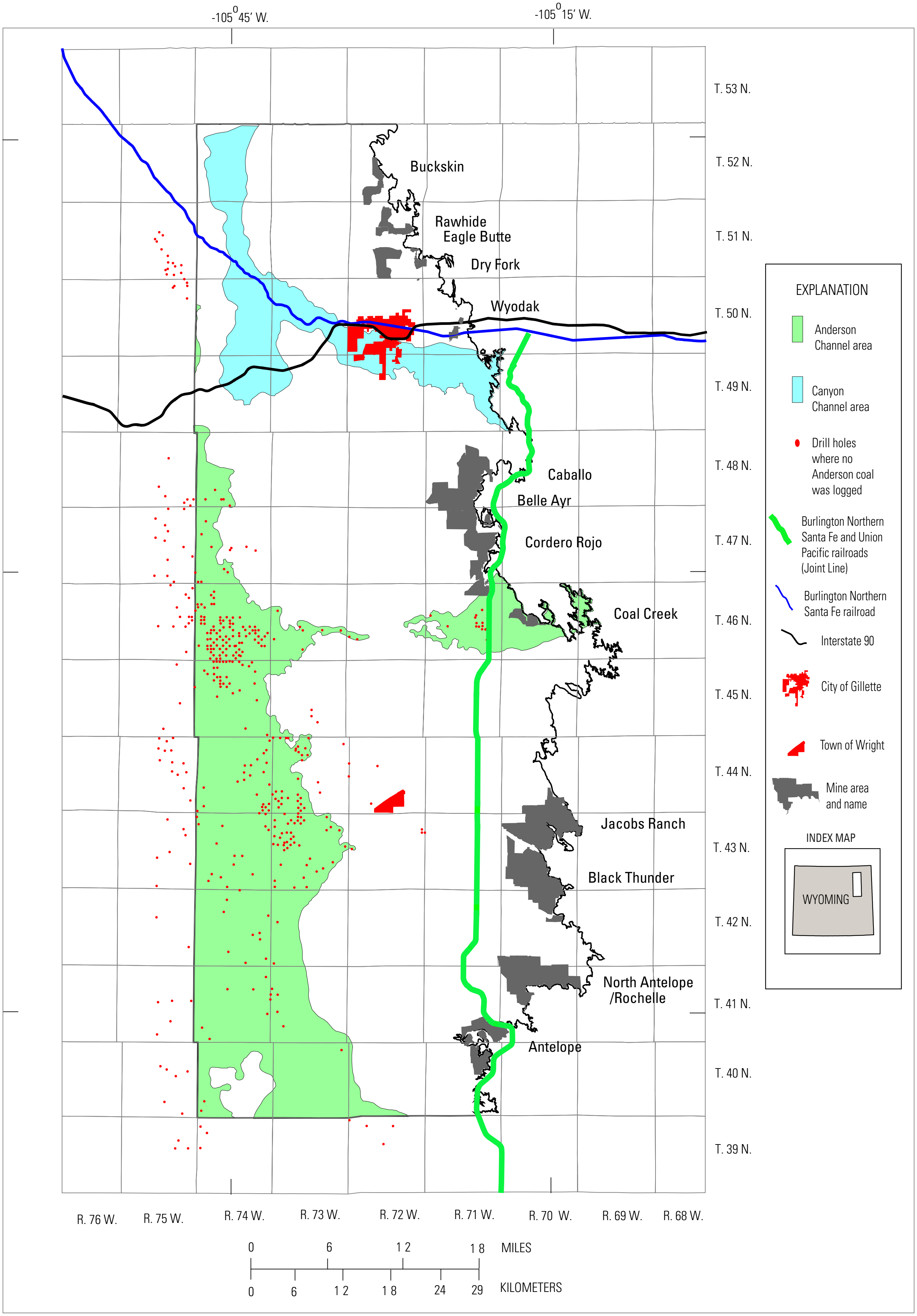


Figure 53. Map showing paleo channels associated with the Anderson and Canyon coal beds.

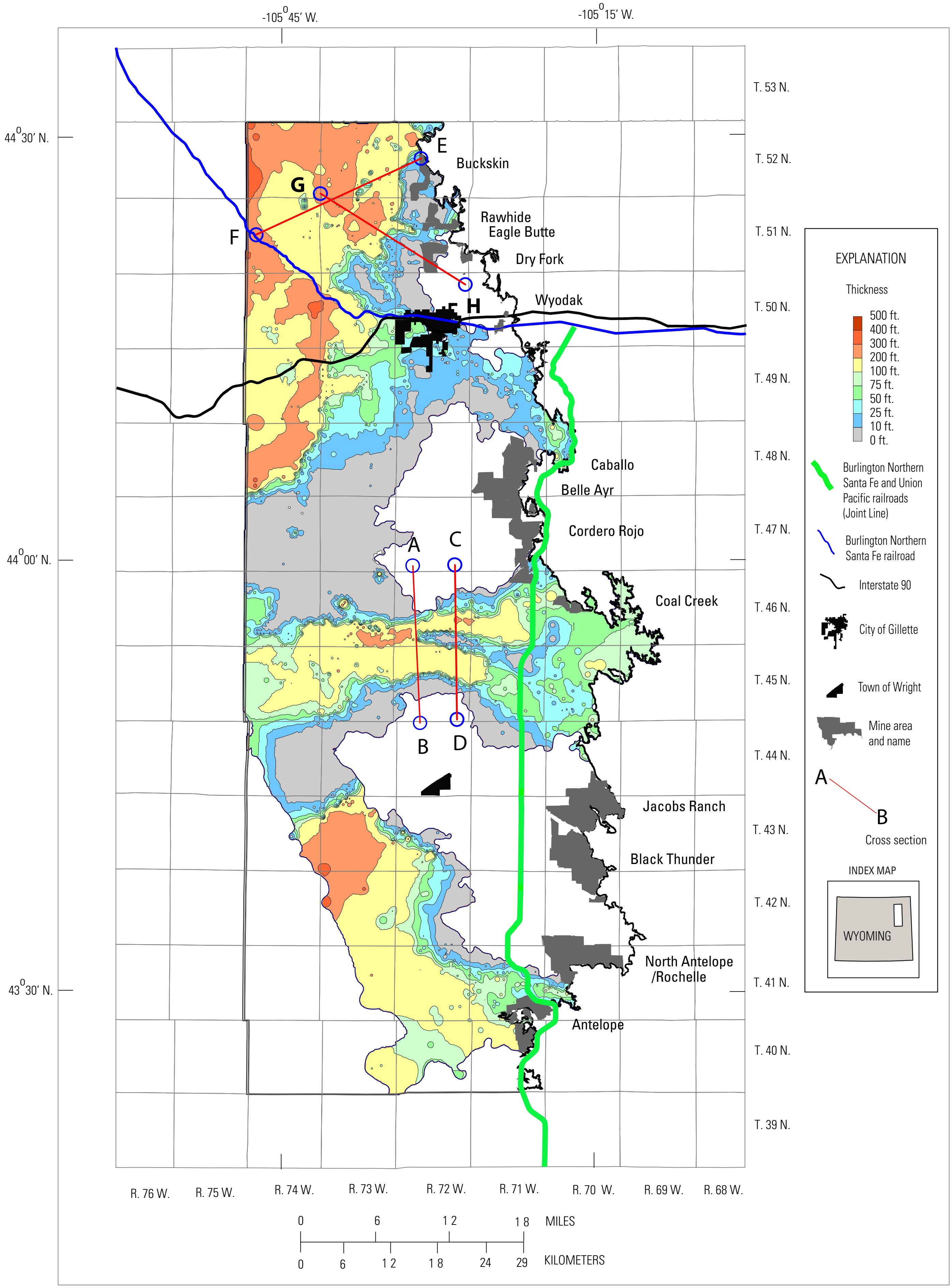


Figure 54. Isopach map of interburden between the the Anderson and Canyon coal beds and location of cross sections for figures 55-58.

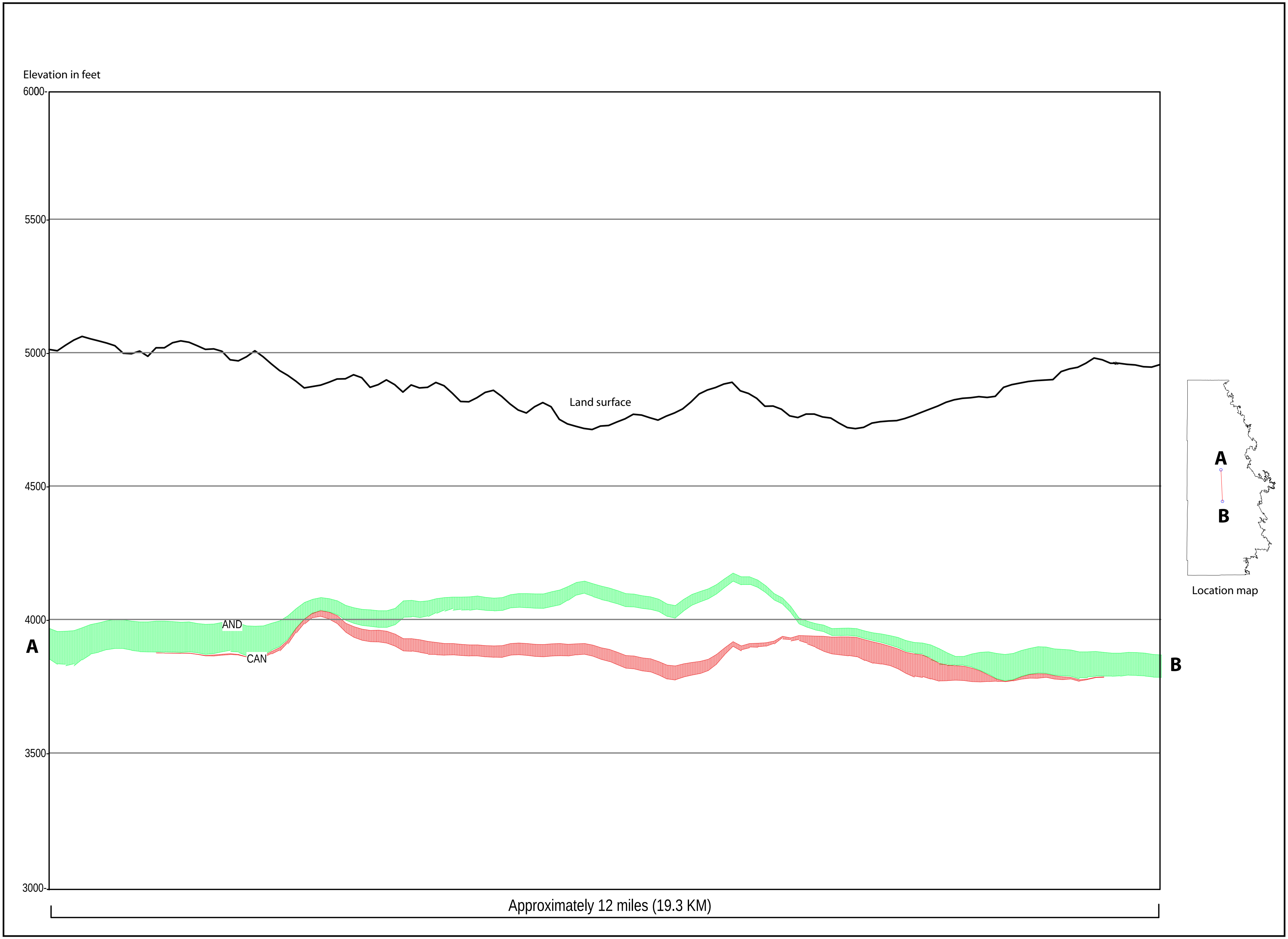


Figure 55. North-south cross section A-B through the Anderson (AND) and Canyon (CAN) coalbeds showing a single east-west paleo channel. Line of section shown in figure 54.

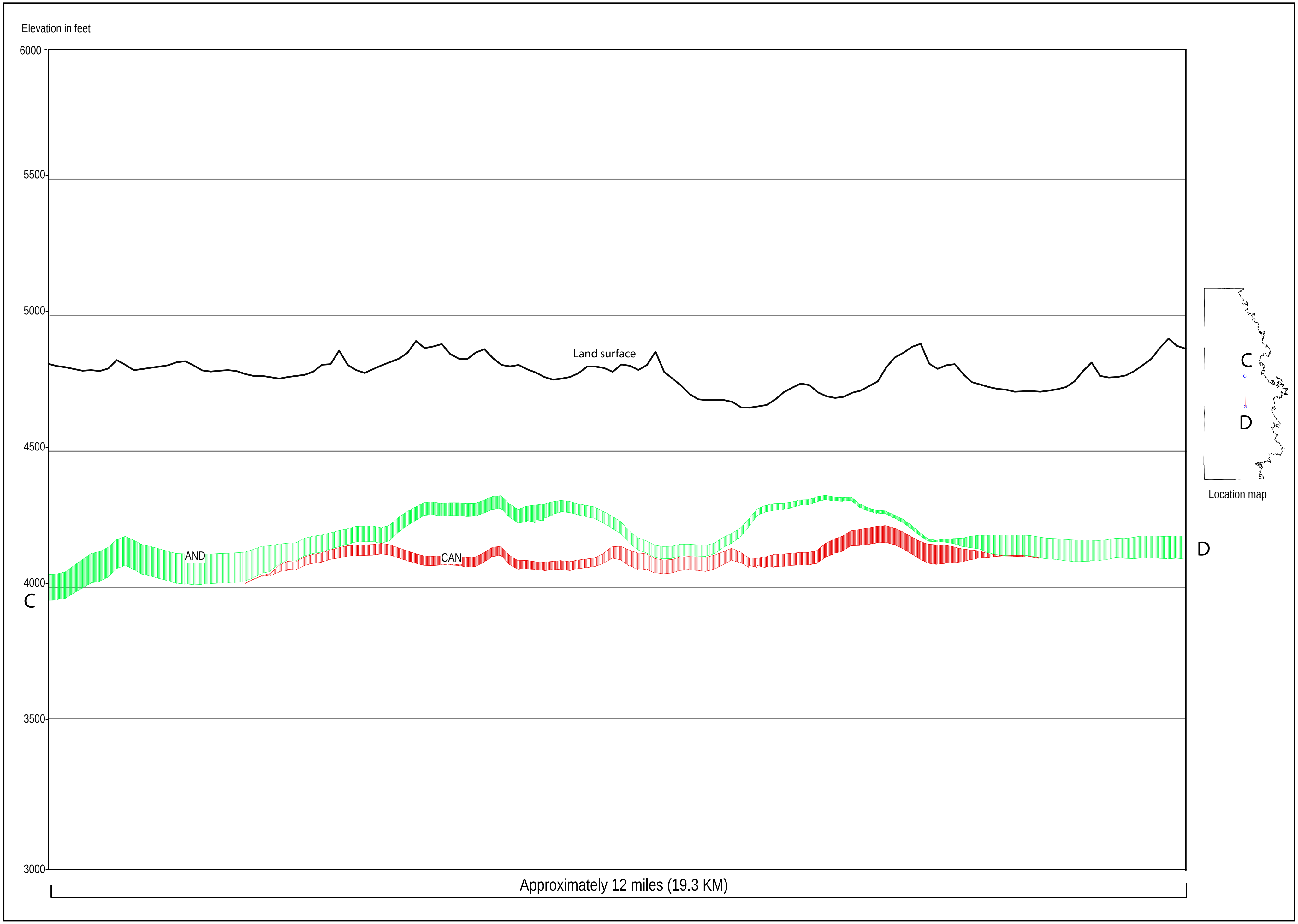


Figure 56. North-south cross section C-D through the Anderson (AND) and Canyon (CAN) coalbeds showing multiple paleo channels. Line of section shown in figure 54.

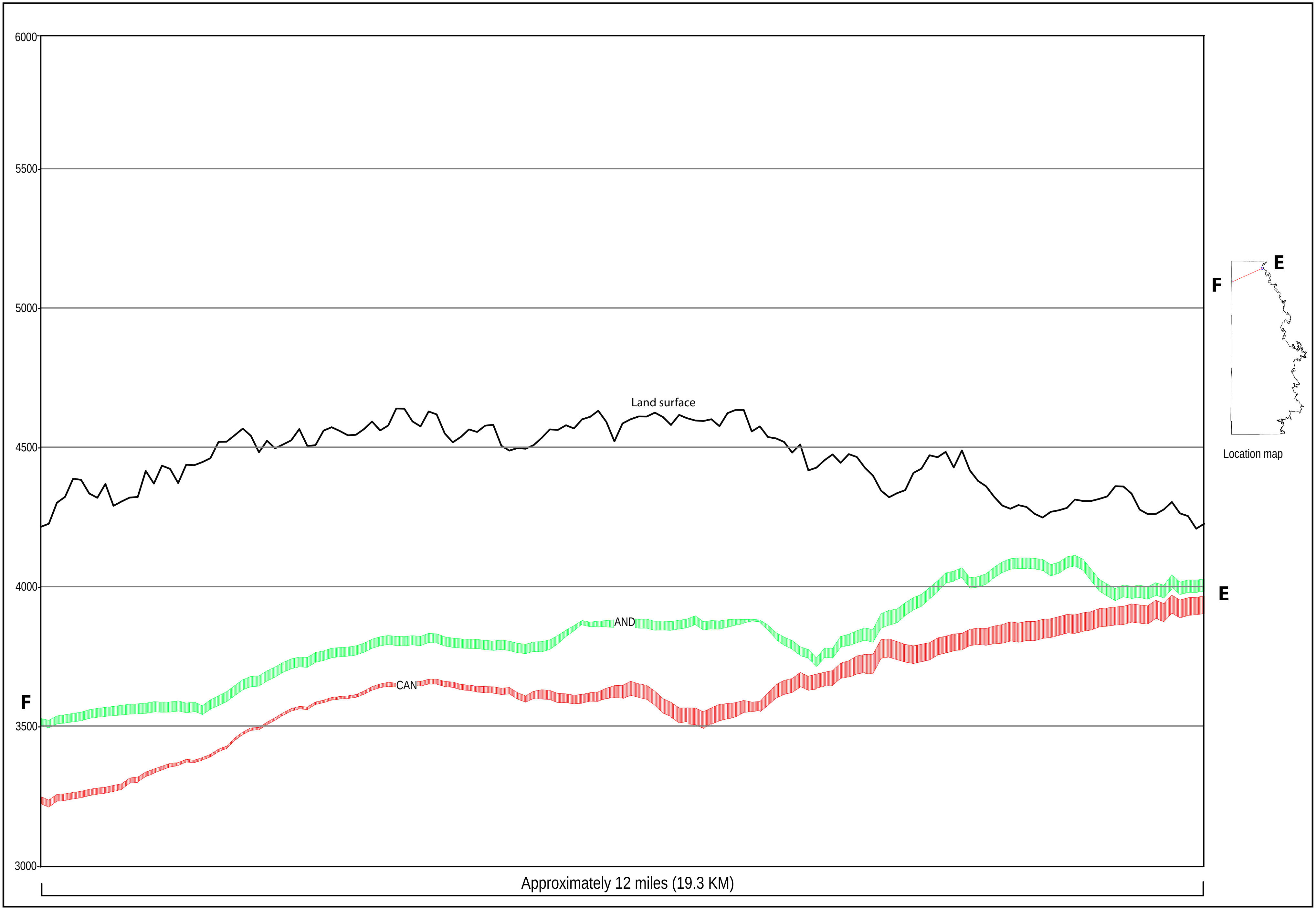


Figure 57. Northeast-southwest section E-F through the Anderson (AND) and Canyon (CAN) coal beds across the east-west channel showing variations in coal bed and interburden thicknesses in the channel areas.

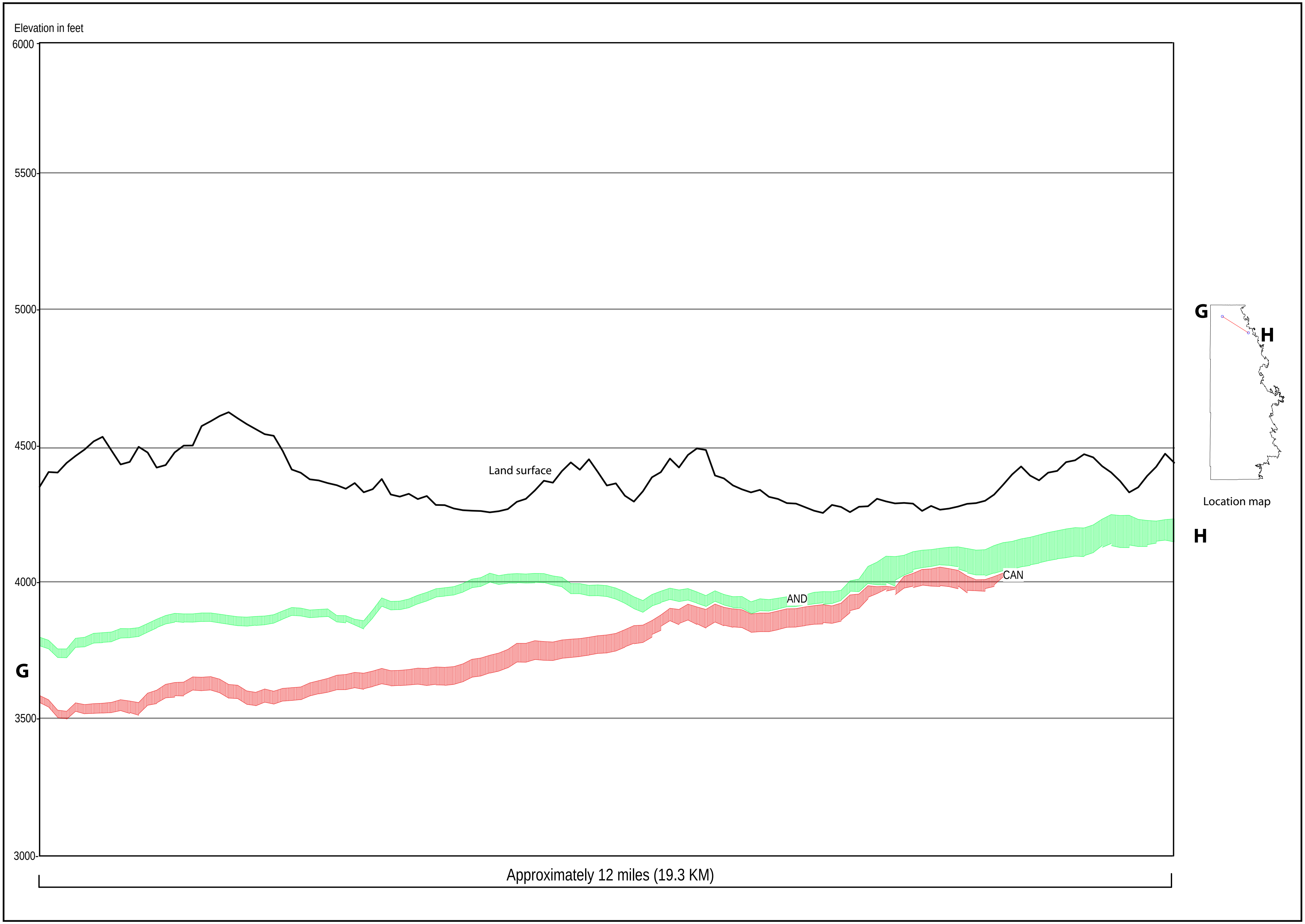


Figure 58. Southeast-northwest cross section G-H through the Anderson (AND) and Canyon (CAN) coal beds across the east-west channel showing a rapid increase in the interburden between the beds.

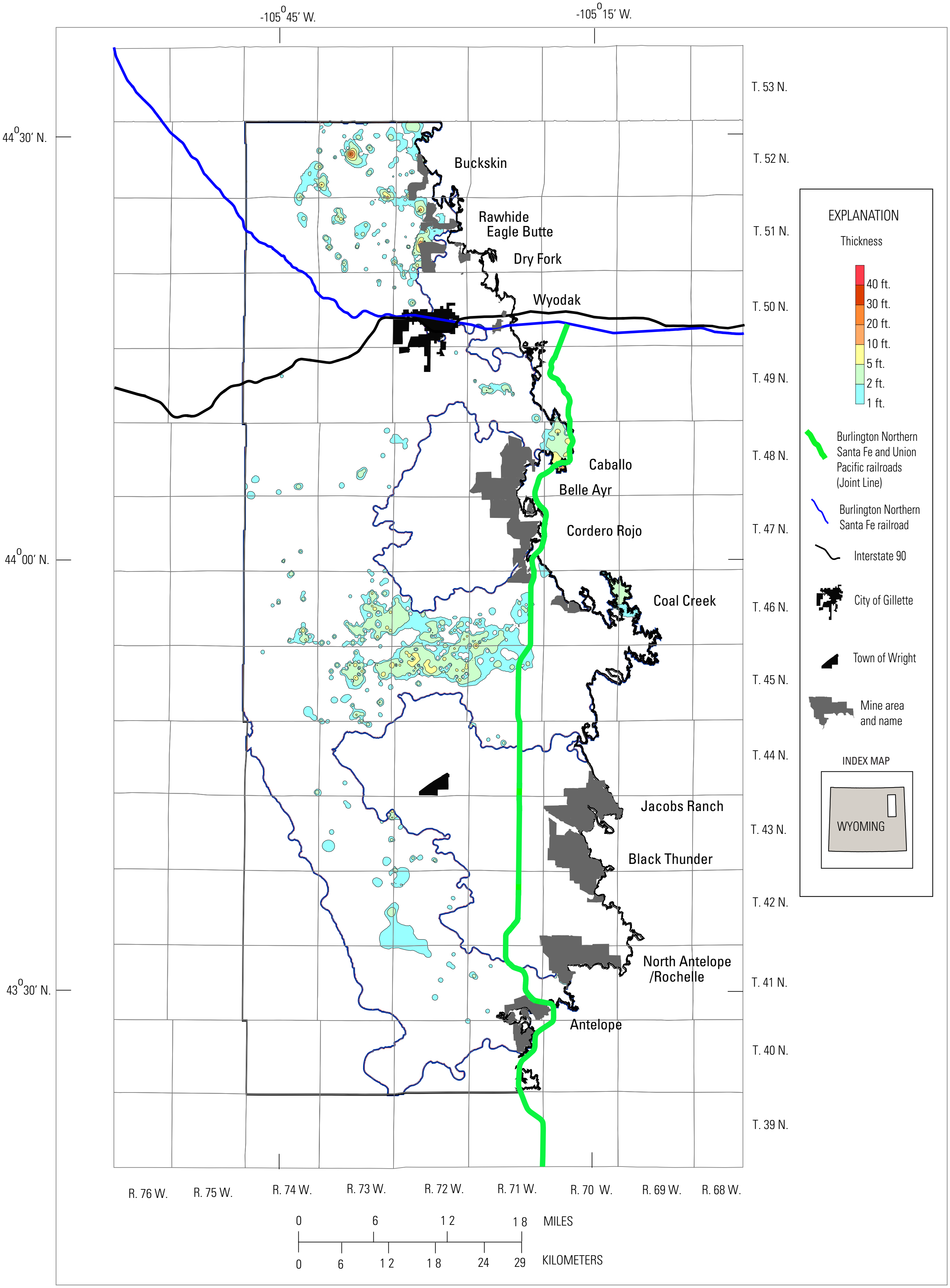


Figure 59. Total parting isopach map for the Canyon coal bed.

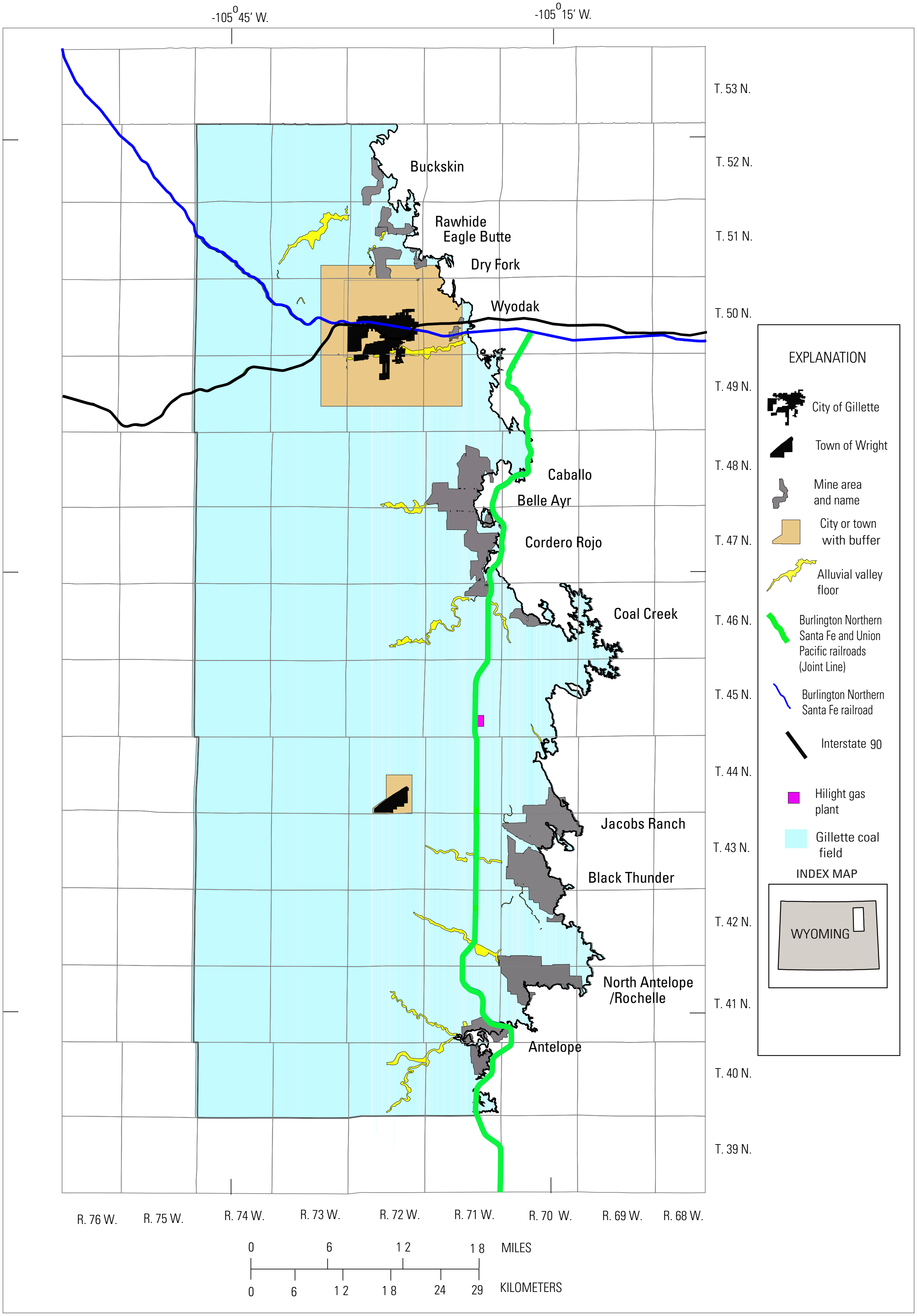


Figure 60. Land use restriction map in the Gillette coalfield, Wyoming.

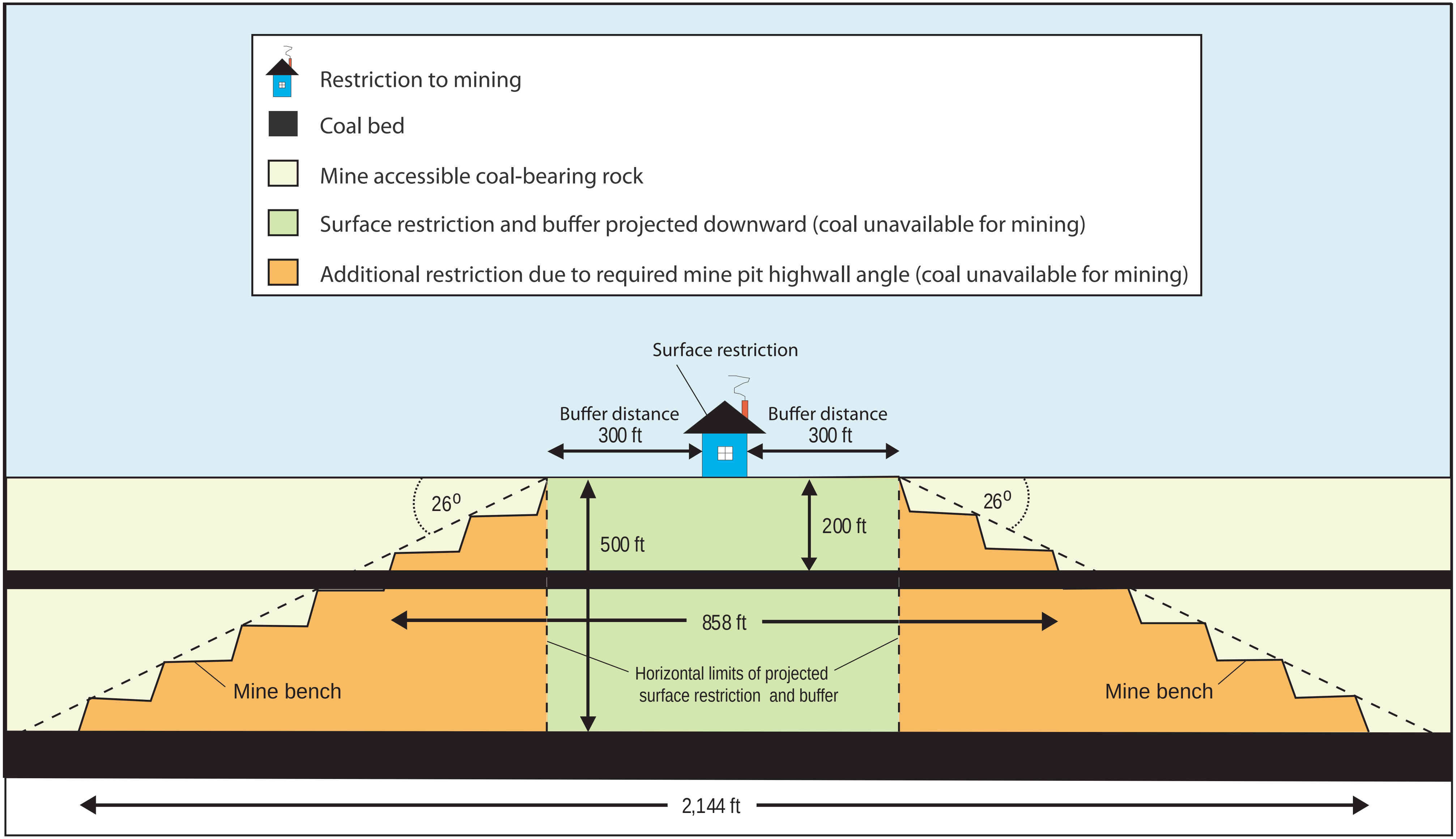


Figure 61. Illustration showing the effect of coal bed depth upon restricted resource due to mine pit highwall setback requirements (not to scale).

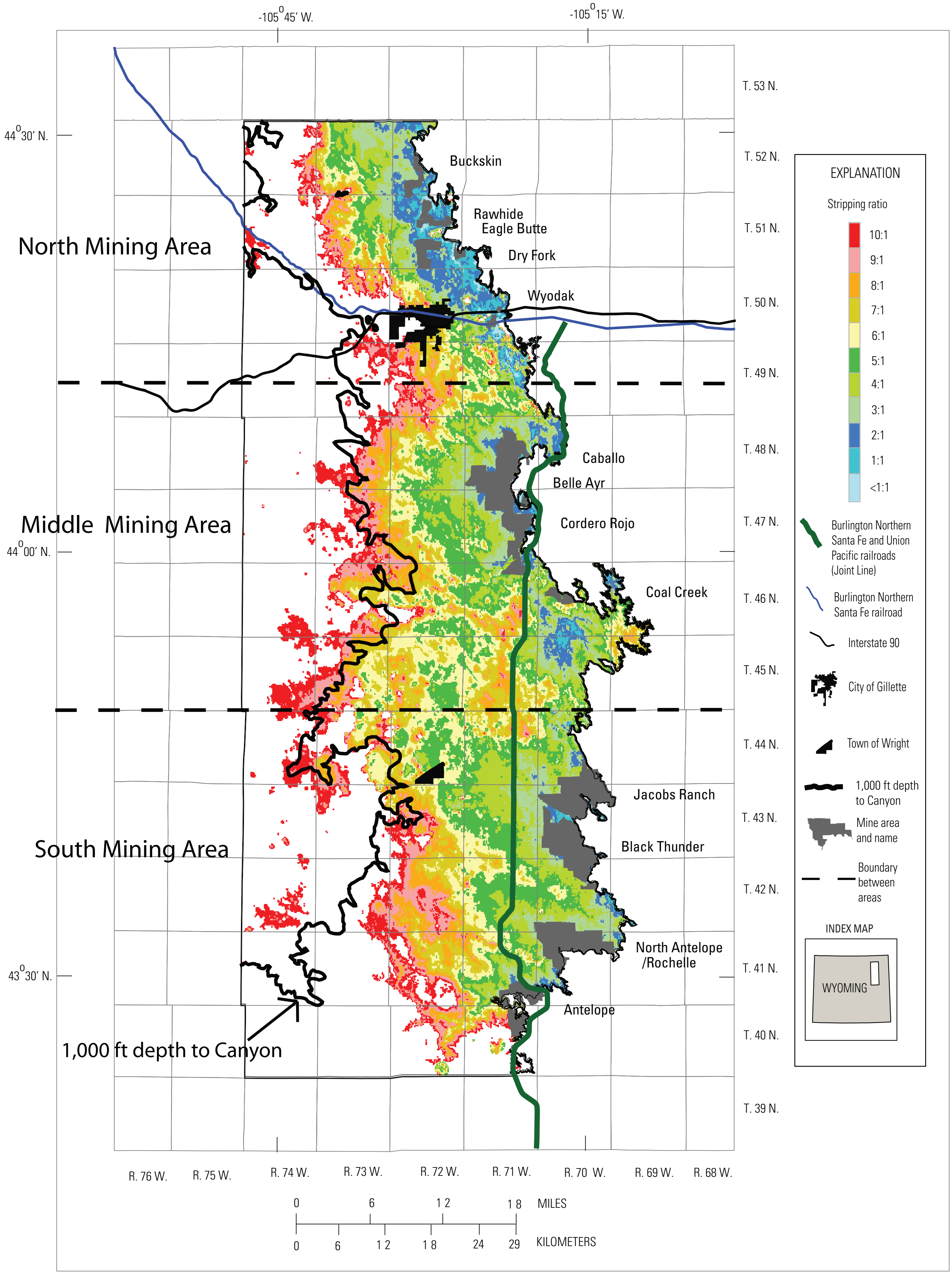


Figure 62. Map showing the stripping ratio for the six coal beds for which reserves were calculated. Waste rock includes the volume of overburden above the uppermost coal bed, volume of rock between coal beds, and volume of partings within the coal bed. Coal includes all coal from the top of the Roland coal bed to the bottom of the Canyon coal bed.

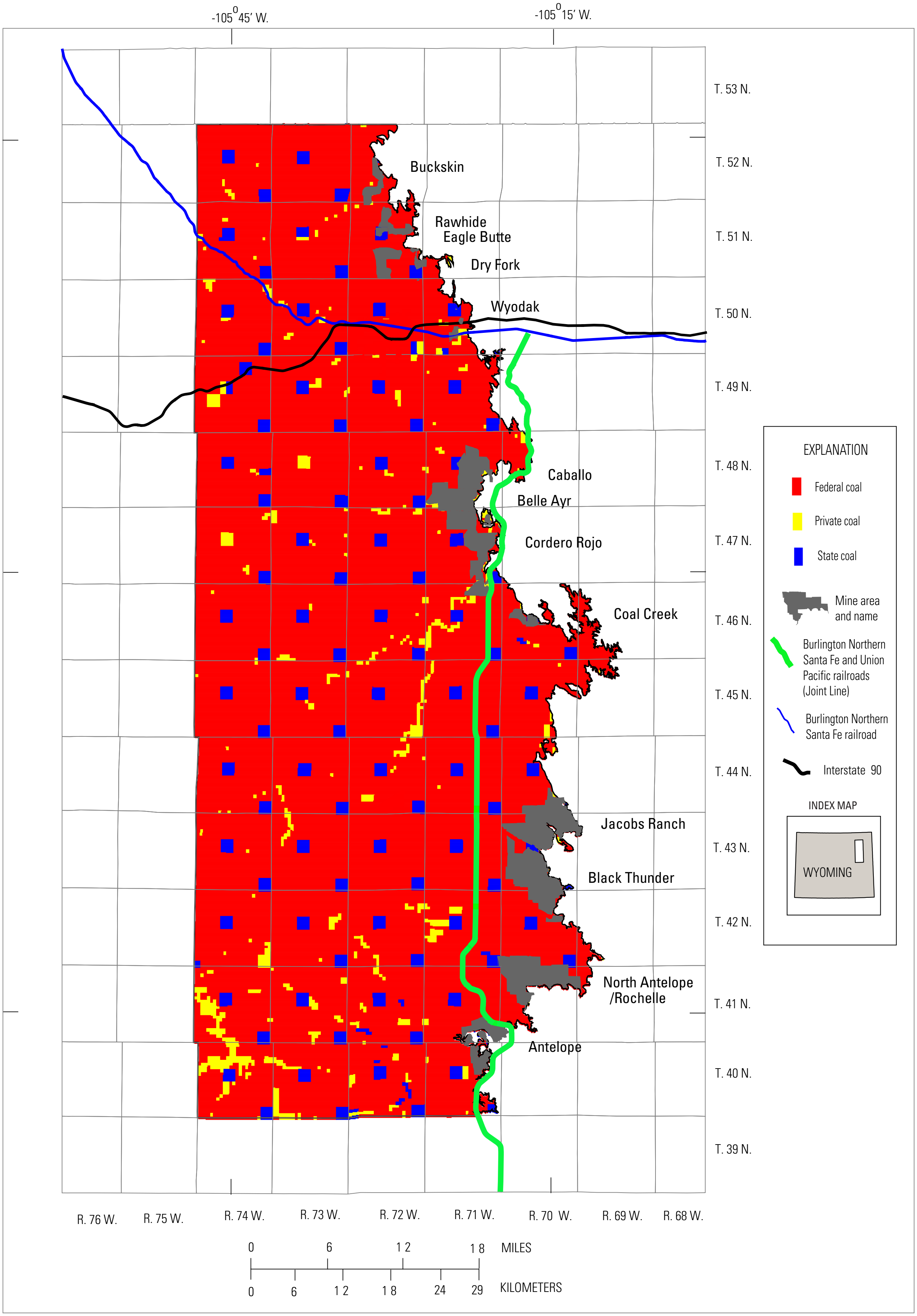


Figure 63. Map showing coal ownership in the Gillette coalfield, Wyoming.

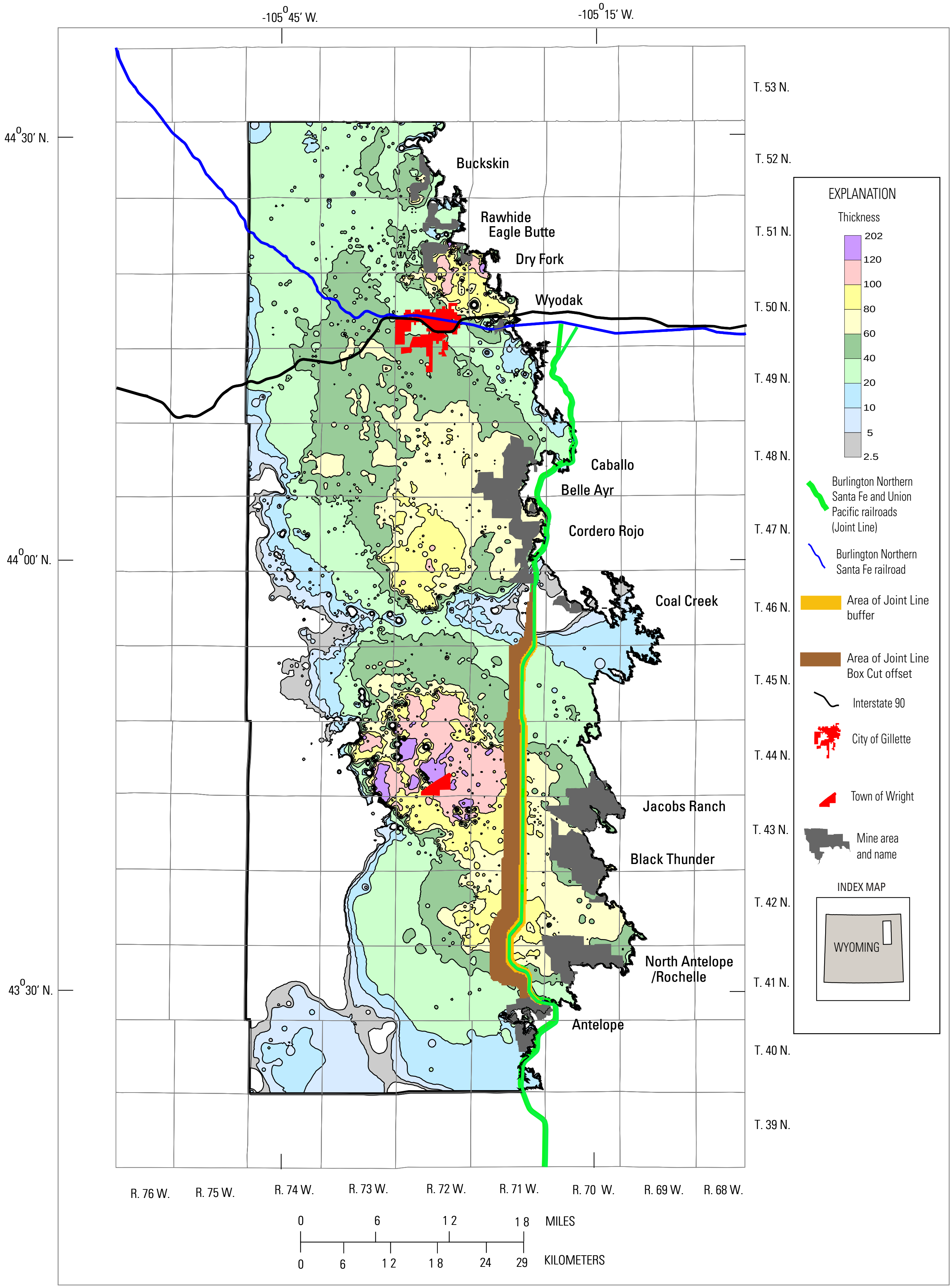


Figure 64. Isopach map of the Anderson coal bed showing railroads and coal affected by the boxcut and adjacent raiload buffer.

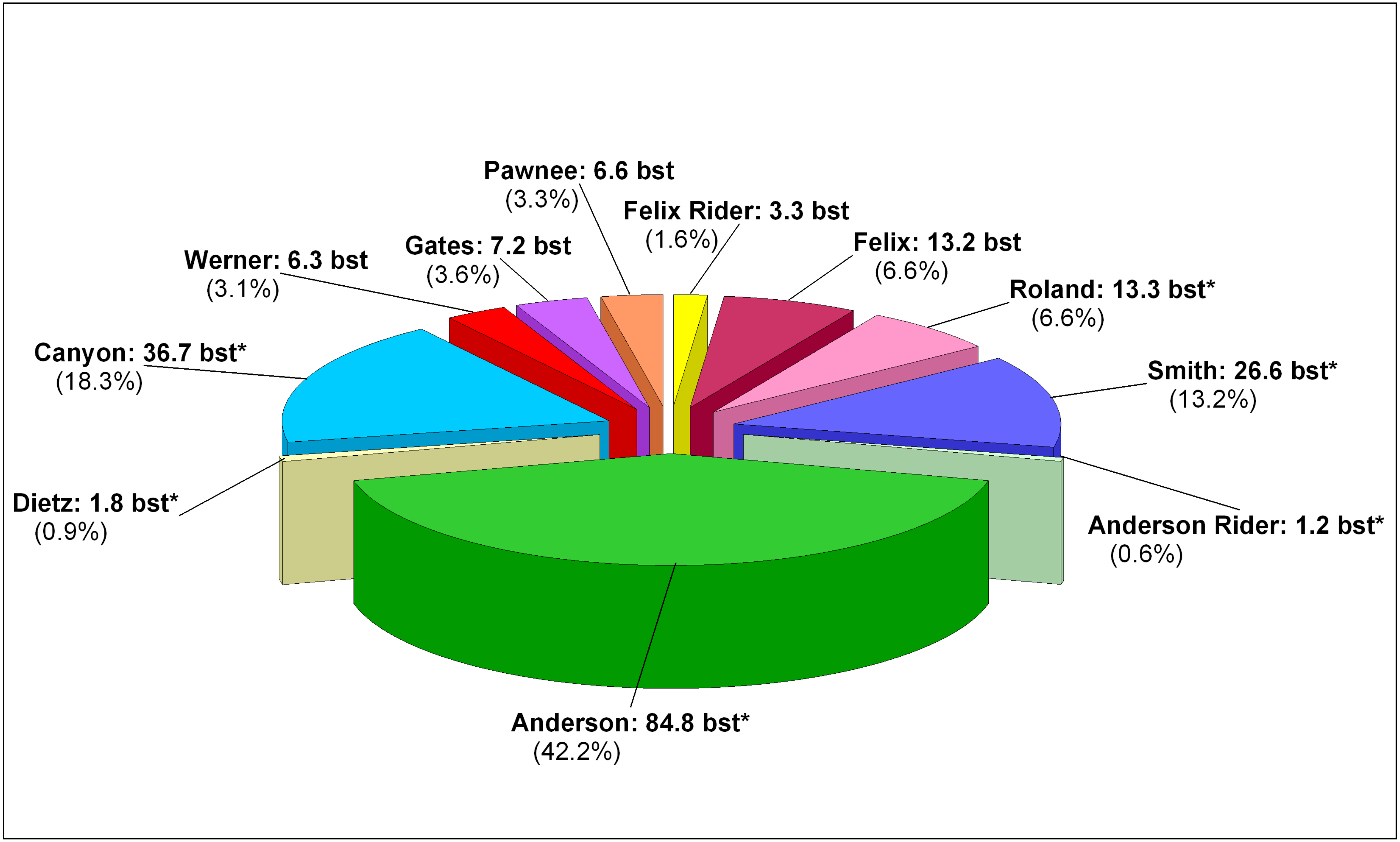


Figure 65. Pie chart showing billions of tons and percentages for original resources (201 bst) in the Gillette coalfield. The beds marked with an asterisk were included in the reserve analysis.

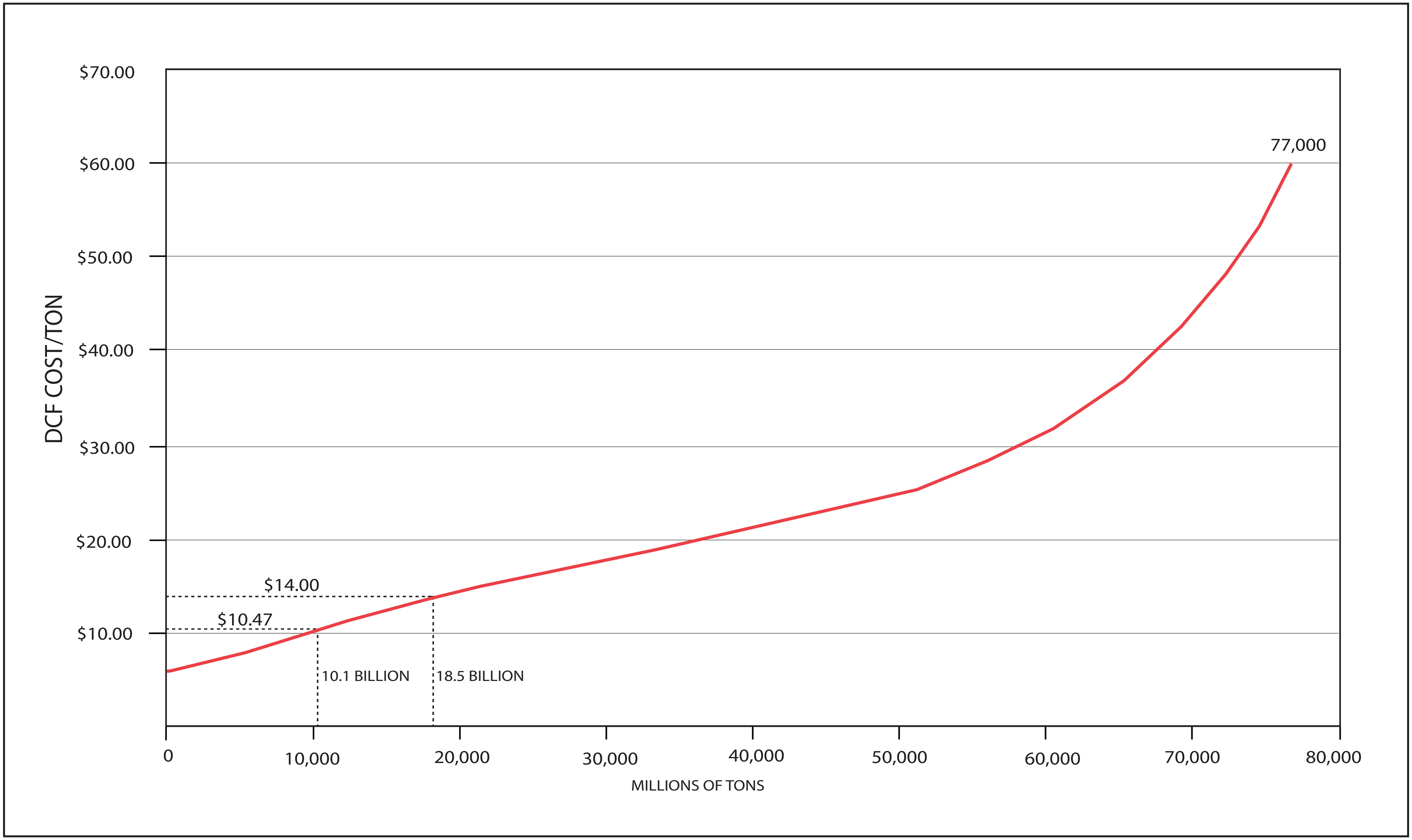


Figure 66. Cost curve showing reserve estimates at $10.47/ton (as of January, 2007) and $14.00/ton (as of March, 2008) for the Gillette coalfield.

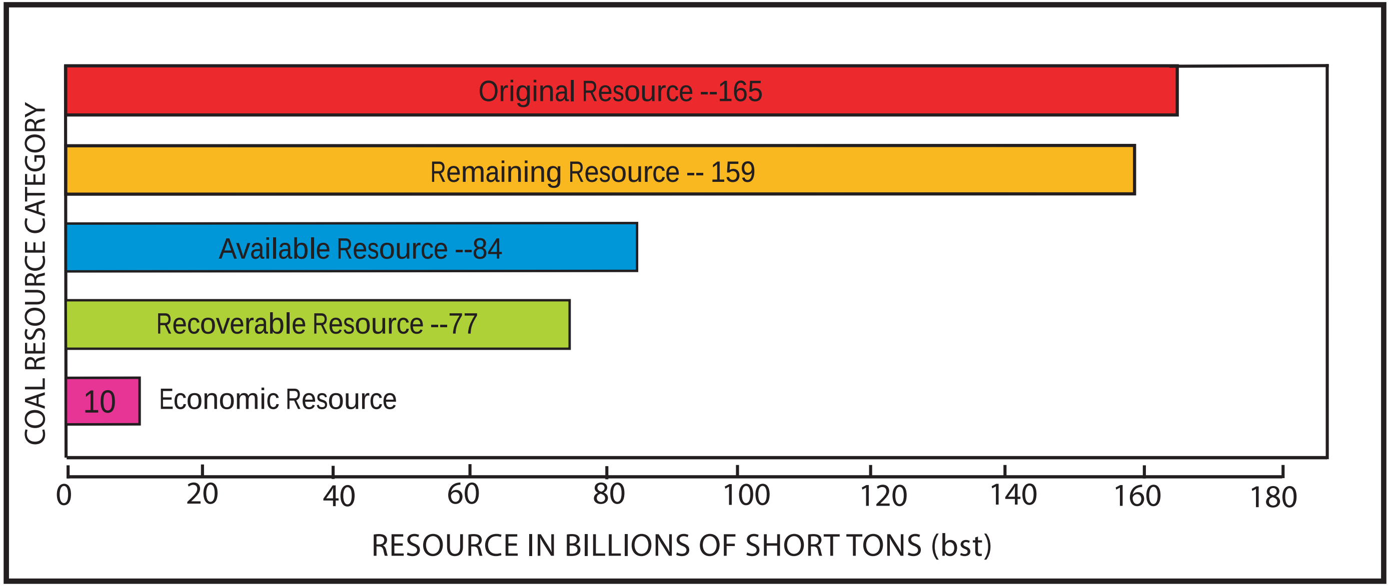


Figure 67. Bar graph showing resources in different resource categories for the six coal beds included in the reserve evaluation (5.0 ft thick or greater, 10:1 stripping ratio or less) of the Gillette coalfield, reported in short tons (at a sales price of $10.47 as of January, 2007). This reserves estimate would nearly double to 18.5 bst if the market price were $14 as shown on the cost curve in figure 66.

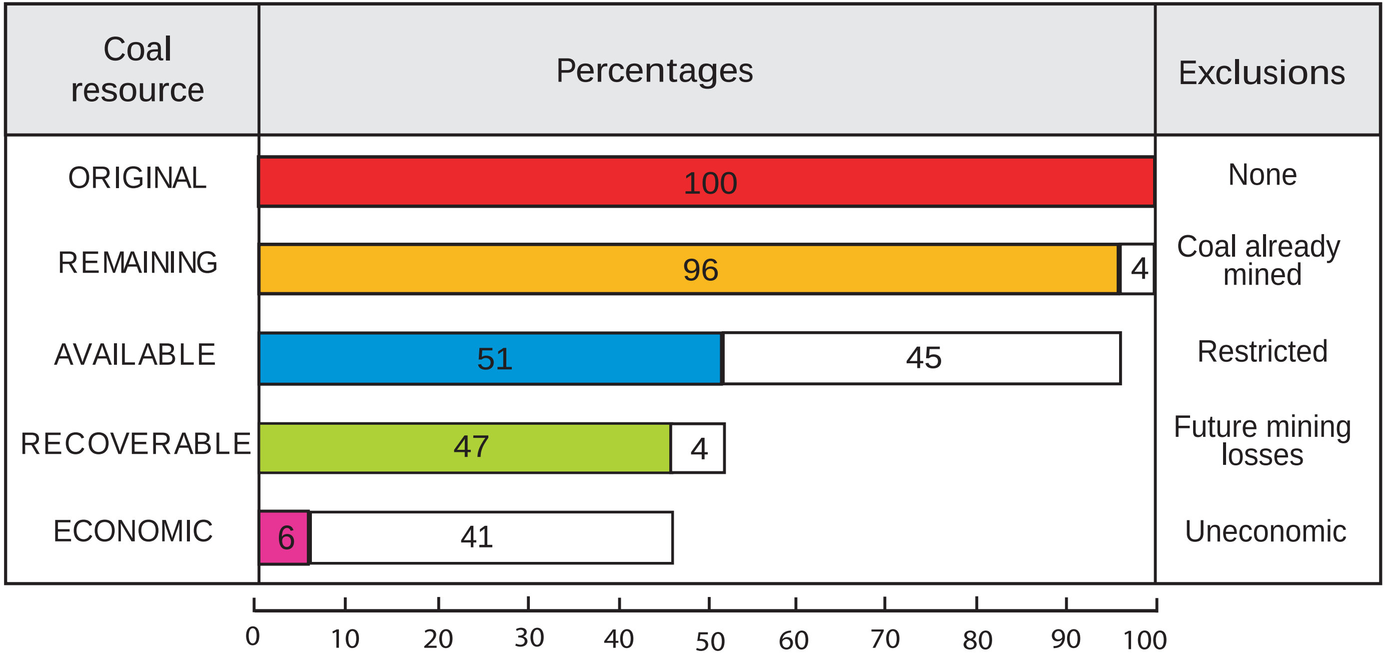


Figure 68. Bar graph showing Gillette coalfield coal resource analysis results for the six coal beds from figure 67, reported as percentages of original resources (at sales price of $10.47 as of January, 2007). Percent of remaining resources are shown in colored bars; excluded resources from the previous category are shown in white bars.

TABLES 1-13

Table 1. Names used in different publications for coal beds and zones in the area of the Gillette coalfield. The beds in the Wyodak-Anderson coal zone are listed from upper to lower; however, many of the beds are only in certain parts of the coalfield, stratigraphically equivalent, or split of other beds.

Formation Name	Kent and others, 1980a	Pierce and others, 1990	Fort Union Coal Assessment Team, 1999, and Glass, 1999	Molnia and others, 1997, 1999, and Osmonson, 2000	Ellis and others, 2002	This report 2007
Wasatch		Felix				Upper Felix/Felix
Fort Union (Tongue River Member)	Smith	Roland/ Badger	Roland	Wyodak Rider	Wyodak Rider	Roland
	Upper Wyodak	Wyodak or upper Wyodak (Anderson-Canyon)	Wyodak-Anderson coal zone= Smith (Swartz), Badger, School, Sussex, Big George, Wyodak, Anderson, Dietz, Canyon, Werner	Main Wyodak	Upper Wyodak	Smith
						Anderson Rider, Anderson
						Dietz
	Canyon				Canyon	Canyon
	Werner	Lower Wyodak		Lower Wyodak Cook	Lower Wyodak/ Werner	Werner
	Gates/ Kennedy	Upper Kennedy		Wall	Gates/ Kennedy	Gates
						Pawnee

Table 2. Data source and numbers of drill holes for the Gillette coalfield.

Data Source	Gillette coalfield area	Three mile buffer	Total
Original database of Ellis and others (2002)	1,207	60	1,267
U.S. Bureau of Land Management	1,124	0	1,124
Wyoming State Geological Survey	1,121	75	1,196
New data entry-coal bed methane (USGS)	5,134	330	5,464
New data entry-oil and gas (USGS)	939	220	1,159
TOTALS	**9,525**	**685**	**10,210**

Table 3a. Coal leasing unsuitability criteria from Code of Federal Regulations (43 CFR 3461.5). Bold type denotes a criterion considered as a restriction applying to the Gillette coalfield.

Federal land systems
Rights-of-way and easements (e.g., **railroads)**
Dwellings, **roads**, cemeteries, and public buildings
Wilderness study areas
Lands with outstanding scenic quality
Lands used for scientific study
Historic lands and sites
Natural areas
Critical habitat for threatened or endangered plant and animal species
State listed threatened or endangered species
Bald or golden eagle nests
Bald and golden eagle roost and concentration areas
Federal lands containing active falcon cliff nesting site
Habitat for migratory bird species
Fish and wildlife habitat for resident species
Floodplains
Municipal watersheds
National resource waters
Alluvial valley floors
State or Indian tribe proposed criteria

Table 3b. Other factors considered as potential restrictions to coal mining in the Gillette coalfield. Bold type denotes a factor considered as a restriction applying to the Gillette coalfield.

Airports
Archaeological areas
Areas of clinker
Coalbed methane wells
Hilight gas plant
Oil and oil-related gas wells
Pipelines
Power lines
Power plants
Rivers, lakes, and streams
Towns

Table 4. Equipment and manning comparisons for 3:1 versus 6:1 stripping ratio mine models for the Gillette coalfield. Abbreviations: Overburden (ob); Horse Power (hp); Cubic Yards (cy); Dragline (DL); Rubber Tired (Rbtrd); Gallon (gal); Bank Cubic Yards (bcy); Front End Loader (FEL); Ammonium Nitrate Fuel Oil (ANFO).

Yearly Coal Production		**3:1 ratio mine model 35,000,000 tons per year**		**6:1 ratio mine model 35,000,000 tons per year**	
Yearly Stripping Production		**3:1 ratio mine model 105,000,000 tons per year**		**6:1 ratio mine model 210,000,000 tons per year**	
Pre-Stripping Operation	**Staff Position**	**Equipment Amount**	**Number of Staff**	**Equipment Amount**	**Number of Staff**
Shovel-73cy-ob	Shovel Operator-ob	1	3	4	16
	Shovel Helper		3		16
Dozer-ob 850 hp	Dozer Operator	1	3	4	16
Drill-ob-9”x35’ rods	Drill Operator	1	3	4	16
Trucks-ob-270 cy	Truck Driver	5	13	28	112
Truck-Powder/ANFO	Blaster-ob	1	1	4	4
Truck-Blasters Flatbed	Blaster-Helper	1	1	4	4
Grader-24’, 500 hp	Grader Operator	2	7	5	19
Water Truck 20K gal	Truck Driver-Water	2	7	5	18
Trucks-270 cy Spare		3		8	
Equipment Monitor System		1		2	
Subtotal		**18**	**41**	**68**	**221**
Dragline Operation	Staff Position	**Equipment Amount**	**Number of Staff**	**Equipment Amount**	**Number of Staff**
DL-112 cy, 400’ boom	Dragline Operator	1	4	1	4
Truck-Shift ¾ ton 4WD	Dragline Oiler/Operator	1	4	1	4
Dozer-DL, 850 hp	Dozer Operator-Dragline	1	4	1	4
Drill-DL, 9”x60’ rods	Drill Operator-Dragline	2	8	2	8
Truck-Blasting Powder	Blaster-Dragline/ob	1	1	1	1
Truck-Blasters Flatbed	Blaster Helper	1	1	1	1
Dozer-Bench Prep-850 hp	Dozer Operator-Dragline	6	24	6	24
Backhoe-13 cy, 700 hp	Backhoe Operator-DL	1	4	1	4
Subtotal		**14**	**50**	**14**	**50**
Coal Loading Operations	Staff Position	**Equipment Amount**	**Number of Staff**	**Equipment Amount**	**Number of Staff**
Shovel-97 cy-Coal	Shovel Operator-Coal	1	4	1	4
	Shovel Helper		4		4
Dozer-Coal Rbtrd	Dozer Operator	1	4	1	4
Drill dsl-Coal-6”x25’ rods	Drill Operator	1	3	1	3
Trucks-Coal-380 ton	Truck Driver	5	18	7	27
FEL-31 cy-Coal/ob	FEL Operator	2	7	2	7
Truck-Blasters Flatbed	Blaster-Coal	1	1	1	1
FEL-Skid Steer, 75 hp	Blaster Helper	1	1	1	1
Coal Belt System-Dump		1		1	
Overland Conveyor		1		2	
Subtotal		**14**	**42**	**17**	**51**
Reclamation Operations	Staff Position	**Equipment Amount**	**Number of Staff**	**Equipment Amount**	**Number of Staff**
Dozer-reclamation-850 hp	Dozer Operator	2	6	3	12
Scraper-31cy-700 hp	Scraper Operator	2	6	2	8
Subtotal		**4**	**12**	**5**	**20**
Aux Equip. and Maint.	Mechanics, etc.		124		195
Total Wage Staffing			269		537
Management/Supervision	Technical Support		66		92
Total Mine Staffing			335		629

Table 5. Estimated in-place quality for the coal beds included in the reserve evaluation, the weighted average of the sold coal quality, and market price by mining area for the Gillette coalfield.

In-Place Coal Quality by Pod - Gillette Coalfield							Estimated sold quality and market price as a weighted blend of all mined beds				
Mining Area	Coal Bed	Average Bed Thickness	% Moisture	Btu/lb	% Sulfur	% Ash	% Moisture	Btu/lb	% Sulfur	% Ash	Price/ton (U.S. dollars, January, 2007)
North Mining Area	Roland	15	30.00	8,000	0.50	6.30	30.04	8,203	0.39	6.29	$6.48
	Anderson	36	30.10	8,122	0.55	6.87					
	Dietz	12	29.00	7,950	0.90	8.00					
	Canyon	53	30.50	8,367	0.24	4.55					
Middle Mining Area	Roland	12	29.00	8,100	0.50	6.30	29.06	8,459	0.35	5.86	$7.75
	Smith	17	28.00	8,600	0.25	5.20					
	Anderson Rider	9	27.00	7,800	1.05	11.70					
	Anderson	52	29.60	8,500	0.35	5.10					
	Dietz	13	29.00	7,950	0.90	8.00					
	Canyon	31	29.20	8,550	0.30	5.00					
South Mining Area	Roland	11	28.00	8,200	0.50	6.30	26.67	8,807	0.28	5.43	$9.57
	Smith	22	27.00	8,800	0.25	5.00					
	Anderson Rider	11	26.00	7,900	1.00	10.50					
	Anderson	65	27.00	8,875	0.27	4.60					
	Dietz	6	29.00	7,950	0.90	8.00					
	Canyon	35	26.25	8,925	0.20	4.70					

In-Place Coal Quality References:

Roland: Data from Bragg and others, 1997, Ellis, 2002, and Stricker and others, 2007.
Smith: Data from U.S. Bureau of Mines, 1975a and b, and Stricker and others, 2007.
Anderson Rider: Data from U.S. Bureau of Mines, 1975a and b, Bragg and others, 1997, Ellis, 2002, and Stricker and others, 2007.
Anderson: Data from U.S. Bureau of Mines, 1975a and b, Bragg and others, 1997, Ellis, 2002, Glass and Lyman, 2007, Johnson, 2007, and Stricker and others, 2007.
Dietz: Data from Bragg and others, 1997, and Ellis, 2002.
Canyon: Data from U.S. Bureau of Mines, 1975a and b, Glass and Lyman, 2007, Johnson, 2007, and Stricker and others, 2007.

Table 6. Original coal resources greater than or equal to 2.5 ft thick, reported in millions of short tons, by subsurface coal ownership categories for the Gillette coalfield. Resource includes coal plus partings. (Columns may not sum exactly owing to rounding).

Coal bed	Coal ownership	Original Resources > than 2.5 ft thick	Previously mined	Land Use restrictions	Technical restrictions	Available resources	Percent of original resource
Felix Rider	Federal	3,077	0	354	542	2,181	70.9
	State	169	0	19	33	117	69.1
	Private	57	0	11	8	37	65.9
	Total	**3,303**	**0**	**384**	**584**	**2,336**	**70.7**
Felix	Federal	12,256	0	650	274	11,332	92.5
	State	717	0	33	8	676	94.3
	Private	244	0	31	1	212	86.5
	Total	**13,217**	**0**	**714**	**284**	**12,220**	**92.5**
Roland	Federal	12,256	0	682	897	10,675	87.1
	State	692	0	35	47	610	88.2
	Private	385	0	40	27	319	82.7
	Total	**13,333**	**0**	**757**	**971**	**11,604**	**87.0**
Smith	Federal	24,812	1	150	405	24,257	97.8
	State	1,189	0	5	26	1,158	97.4
	Private	628	0	4	22	602	95.9
	Total	**26,629**	**1**	**158**	**453**	**26,016**	**97.7**
Anderson Rider	Federal	1,164	108	82	160	814	69.9
	State	55	3	0	11	41	74.9
	Private	11	1	0	0	7	81.4
	Total	**1,230**	**112**	**83**	**171**	**863**	**70.2**
Anderson	Federal	77,865	5,010	12,724	2,544	57,586	74.0
	State	4,663	141	854	206	3,461	74.2
	Private	2,272	207	551	38	1,476	65.0
	Total	**84,800**	**5,359**	**14,129**	**2,788**	**62,523**	**73.7**
Dietz	Federal	602	1	3	62	536	89.0
	State	775	0	56	140	579	74.7
	Private	448	0	20	49	379	84.5
	Total	**1,825**	**1**	**79**	**251**	**1,494**	**81.9**
Canyon	Federal	33,965	801	2,864	794	29,506	86.9
	State	1,898	81	231	57	1,530	80.6
	Private	867	27	230	13	598	69.0
	Total	**36,730**	**909**	**3,324**	**863**	**31,634**	**86.2**
Werner	Federal	5,808	0	1,720	370	3,719	64.0
	State	229	0	108	11	110	47.9
	Private	215	0	124	8	84	38.8
	Total	**6,252**	**0**	**1,952**	**389**	**3,912**	**62.6**
Gates	Federal	6,692	0	879	424	5,390	80.5
	State	330	0	46	19	264	80.0
	Private	174	0	66	9	99	57.0
	Total	**7,196**	**0**	**991**	**452**	**5,753**	**77.9**
Pawnee	Federal	6,161	0	660	442	5,059	82.1
	State	340	0	33	22	285	83.9
	Private	140	0	20	11	109	78.2
	Total	**6,640**	**0**	**712**	**475**	**5,453**	**82.1**
Total beds	Federal	184,657	5,921	20,768	6,913	151,055	83.2
	State	11,057	225	1,420	580	8,831	79.9
	Private	5,441	235	1,097	186	3,922	72.1
	Total	**201,155**	**6,382**	**23,283**	**7,681**	**163,808**	**81.4**

Table 7. Original coal resources greater than or equal to 2.5 ft thick, reported in millions of short tons by overburden depth for the Gillette coalfield. Resource includes coal plus partings. (Columns may not sum exactly owing to rounding).

Coal bed	Overburden thickness in ft	Original Resources > 2.5 ft thick	Previously mined	Land Use restrictions	Technical restrictions	Available resources	Percent of original resource
Felix Rider	0 to 500 ft	3,081	0	379	551	2,151	69.8
	500-1,000 ft	222	0	5	33	184	83.0
	> 1,000 ft	0	0	0	0	0	0.0
	Total	**3,303**	**0**	**384**	**584**	**2,336**	**70.7**
Felix	0 to 500 ft	12,018	0	673	281	11,065	92.1
	500-1,000 ft	1,199	0	41	3	1,154	96.3
	> 1,000 ft	0	0	0	0	0	0.0
	Total	**13,217**	**0**	**714**	**284**	**12,219**	**92.5**
Roland	0 to 500 ft	6,401	0	351	445	5,605	87.6
	500-1,000 ft	6,794	0	406	474	5,914	87.0
	> 1,000 ft	138	0	0	52	85	62.0
	Total	**13,333**	**0**	**757**	**971**	**11,604**	**87.0**
Smith	0 to 500 ft	1,403	1	37	387	978	69.7
	500-1,000 ft	15,434	0	106	54	15,274	99.0
	> 1,000 ft	9,792	0	16	12	9,764	99.7
	Total	**26,629**	**1**	**159**	**453**	**26,016**	**97.7**
Anderson Rider	0 to 500 ft	1,197	112	82	168	835	69.8
	500-1,000 ft	32	0	1	3	28	88.5
	> 1,000 ft	0	0	0	0	0	0.0
	Total	**1,230**	**112**	**83**	**171**	**863**	**70.2**
Anderson	0 to 500 ft	36,242	5,360	7,806	2,038	21,039	58.1
	500-1,000 ft	40,118	0	6,110	669	33,340	83.1
	> 1,000 ft	8,440	0	213	81	8,146	96.5
	Total	**84,800**	**5,359**	**14,129**	**2,788**	**62,524**	**73.7**
Dietz	0 to 500 ft	603	1	3	62	536	89.0
	500-1,000 ft	775	0	56	140	579	74.7
	> 1,000 ft	448	0	21	49	379	84.5
	Total	**1,825**	**1**	**79**	**251**	**1,494**	**81.9**
Canyon	0 to 500 ft	9,700	909	1,473	610	6,697	69.1
	500-1,000 ft	12,015	0	1,603	181	10,232	85.2
	> 1,000 ft	15,015	0	249	61	14,705	97.9
	Total	**36,730**	**909**	**3,324**	**852**	**31,634**	**86.2**
Werner	0 to 500 ft	1,695	0	884	103	708	41.8
	500-1,000 ft	1,347	0	699	89	560	41.5
	> 1,000 ft	3,210	0	369	196	2,645	82.4
	Total	**6,252**	**0**	**1,952**	**389**	**3,912**	**62.6**
Gates	0 to 500 ft	4	0	0	3	1	28.9
	500-1,000 ft	774	0	69	26	680	87.8
	> 1,000 ft	6,418	0	922	423	5,072	79.0
	Total	**7,196**	**0**	**991**	**452**	**5,753**	**79.9**
Pawnee	0 to 500 ft	19	0	4	7	8	40.4
	500-1,000 ft	123	0	37	48	38	31.1
	> 1,000 ft	6,498	0	670	420	5,407	83.2
	Total	**6,640**	**0**	**712**	**475**	**5,453**	**82.1**
Total beds	0 to 500 ft	72,363	6,383	11,692	4,655	49,623	68.6
	500-1,000 ft	78,833	0	9,132	1,720	67,983	86.2
	> 1,000 ft	49,959	0	2,460	1,294	46,203	92.5
	Total	**201,155**	**6,382**	**23,283**	**7,681**	**163,808**	**81.4**

Table 8. Original coal resources greater than or equal to 2.5 ft thick, reported in millions of short tons by reliability category for the Gillette coalfield. Resource includes coal plus partings. Reliability categories are based on distance from data point. Measured: < 1/4 mile; Indicated: 1/4-3/4 mile; Inferred: 3/4-3 miles; Hypothetical: > 3 miles. (Columns may not sum exactly owing to rounding).

Coal bed	Reliability category	Original Resources > 2.5 ft thick	Previously mined	Land Use restrictions	Technical restrictions	Available resources	Percent of original resource
Felix Rider	Measured	2,192	0	250	349	1,594	72.7
	Indicated	922	0	123	206	593	64.3
	Inferred	189	0	11	28	149	78.9
	Hypothetical	0	0	0	0	0	0
	Total	**3,303**	**0**	**384**	**584**	**2,336**	**70.7**
Felix	Measured	8,490	0	457	138	7,894	93.0
	Indicated	4,026	0	222	114	3,691	91.7
	Inferred	700	0	35	31	634	90.6
	Hypothetical	0	0	0	0	0	0
	Total	**13,217**	**0**	**714**	**284**	**12,219**	**92.5**
Roland	Measured	8,253	0	559	528	7,165	86.8
	Indicated	4,066	0	195	354	3,518	86.5
	Inferred	1,013	0	3	88	291	90.0
	Hypothetical	0	0	0	0	0	0
	Total	**13,333**	**0**	**757**	**971**	**11,604**	**87.0**
Smith	Measured	15,819	1	105	255	15,458	97.7
	Indicated	9,416	0	33	149	9,233	98.1
	Inferred	1,392	0	20	49	1,324	95.1
	Hypothetical	1	0	0	0	0	0
	Total	**26,629**	**1**	**158**	**453**	**26,016**	**97.7**
Anderson Rider	Measured	611	65	60	109	375	61.4
	Indicated	396	42	21	46	286	72.2
	Inferred	151	4	1	011	135	89.2
	Hypothetical	71	0	0	4	67	94.9
	Total	**1,230**	**112**	**83**	**171**	**863**	**70.2**
Anderson	Measured	56,289	2,807	10,077	2,046	41,358	73.5
	Indicated	24,631	2,058	3,878	662	18,033	73.2
	Inferred	3,738	493	174	73	2,998	80.2
	Hypothetical	142	0	0	7	135	95.2
	Total	**84,800**	**5,359**	**14,129**	**2,788**	**62,524**	**73.7**
Dietz	Measured	603	1	3	62	536	84.0
	Indicated	774	0	55	140	579	69.0
	Inferred	448	0	21	49	379	81.3
	Hypothetical	0	0	0	0	0	0
	Total	**1,825**	**1**	**79**	**251**	**1,494**	**81.9**
Canyon	Measured	19,066	528	2,010	358	16,170	84.8
	Indicated	13,553	265	1,162	404	11,721	86.5
	Inferred	4,013	115	152	96	3,650	91.0
	Hypothetical	0	0	0	0	0	0
	Total	**36,730**	**909**	**3,324**	**863**	**31,634**	**86.2**
Werner	Measured	2,045	0	753	87	1,205	59.0
	Indicated	3,180	0	1,012	194	1,975	62.1
	Inferred	1,027	0	187	108	731	71.3
	Hypothetical	0	0	0	0	0	0
	Total	**6,252**	**0**	**1,952**	**389**	**3,912**	**62.6**

Table 8--continued. Original coal resources greater than or equal to 2.5 ft thick, reported in millions of short tons by reliability category for the Gillette coalfield. Resource includes coal plus partings. Reliability categories are based on distance from data point. Measured: <1/4 mile; Indicated: 1/4-3/4 mile; Inferred: 3/4-3 miles; Hypothetical: > 3 miles. (Columns may not sum exactly owing to rounding).

Coal bed	Reliability category	Original Resources > 2.5 ft thick	Previously mined	Land Use restrictions	Technical restrictions	Available resources	Percent of original resource
Gates	Measured	1,373	0	194	40	1,139	83.0
	Indicated	3.171	0	479	166	2,256	79.7
	Inferred	2,651	0	318	245	2,088	78.7
	Hypothetical	0	0	0	0	0	0
	Total	**7,196**	**0**	**991**	**452**	**5,753**	**79.9**
Pawnee	Measured	731	0	185	47	499	68.3
	Indicated	2,685	0	432	182	2,070	77.1
	Inferred	3,119	0	95	241	2,783	89.2
	Hypothetical	106	0	0	5	101	95.3
	Total	**6,640**	**0**	**712**	**475**	**5,453**	**82.1**
Total beds	Measured	115,475	3,402	14,654	4,019	93,396	80.9
	Indicated	66,821	2,363	7,612	2,620	54,225	81.2
	Inferred	18,441	612	1,017	1,021	15,792	85.6
	Hypothetical	418	0	0	21	395	94.5
	Total	**201,155**	**6,382**	**23,283**	**7,681**	**163,808**	**81.4**

Table 9. Original resources greater than or equal to 2.5 ft thick, reported in millions of short tons by stripping ratio for the Gillette coalfield. Resource includes coal plus partings. (Columns may not sum exactly owing to rounding).

Stripping ratio	Coal bed name						
	Roland	Smith	Anderson Rider	Anderson	Dietz	Canyon	Total
≤1:1	0	0	0	386	0	134	520
>1:1-2:1	1	0	17	2,072	21	820	2,931
>2:1-3:1	8	0	93	4,762	82	1,446	6,391
>3:1-4:1	131	14	301	6,549	110	2,126	9,231
>4:1-5:1	376	107	428	9,298	147	2,194	12,550
>5:1-6:1	1,070	525	176	12,850	96	2,816	17,533
>6:1-7:1	1,416	853	99	11,140	73	3,373	16,954
>7:1-8:1	1,181	876	81	8,563	76	3,270	14,047
>8:1-9:1	885	871	29	5,525	51	2,636	9,997
>9:1-10:1	801	1,153	6	4,172	29	2,580	8,741
10:1-11:1	966	2,891	0	3,529	72	3,079	10,537
>11:1	6,498	19,339	0	15,954	1,068	12,256	55,115
TOTAL	**13,333**	**26,629**	**1,230**	**84,800**	**1,825**	**36,730**	**164,547**

Table 10. Resources greater than or equal to 2.5 ft thick, reported by bed, for restrictions, recovery rates, mining losses, and recoverable resources for the Gillette coalfield (reported in millions of tons. (Columns may not sum exactly owing to rounding). Note: The >10:1 ratio numbers do not equal the >10:1 ratio in table 9 because of CoalVal rounding functions and no restrictions were taken out in table 9.

Bed Name	Original Resources	Mined out	Restrictions				Available Resources (≤ 10:1 ratio)	Recovery Rate (in %)	Mining Losses	Recoverable Resources
			Coal between 2.5 and 5.0 ft thick	Land Use	Technical	>10:1 Ratio				
Roland 13,333		0	668	757	2	5,560	6,044	88.7	683	5,361
Smith	24,629	1	453	158	1	19,213	6,804	93.4	449	6,355
Anderson Rider	1,230	112	91	83	81	0	863	88.7	98	766
Anderson 84,800		5,359	225	14,129	2,563	13,068	49,455	91.9	4,006	45,449
Dietz 1,825		1	251	79	0	899	595	85.6	86	509
Canyon 36,730		909	269	3,324	594	11,435	20,199	91.9	1,636	18,563
Total Beds	**164,547**	**6,382**	**2,257**	**18,530**	**3,241**	**50,175**	**83,960**		**6,957**	**77,003**

Table 11. Operating costs per ton for the Anderson coal bed by mining area and ratio in the Gillette coalfield. All costs reported in U.S. dollars (as of January, 2007).

Total Operating Costs by Mining Area	Mining Ratio									
	1:1	2:1	3:1	4:1	5:1	6:1	7:1	8:1	9:1	10:1
North Mining Area										
Direct and Other Costs:	1.90	2.96	3.95	4.86	6.34	7.86	9.72	11.25	13.89	17.53
Indirect Costs:	0.36	0.41	0.53	0.59	0.77	0.91	1.15	1.32	1.61	1.99
Acquisition, royalties, taxes	3.03	3.04	3.05	3.05	3.07	3.08	3.09	3.1	3.13	3.16
Total Operating Cost/ton by ratio	5.29	6.43	7.53	8.52	10.18	11.85	13.96	15.68	18.63	22.60
Middle Mining Area										
Direct and Other Costs:	1.90	2.97	3.95 / 3.96	4.87 / 4.87	6.34 / 6.35	7.86 / 7.86	9.72 / 9.70	11.25 / 11.24	13.89 / 13.89	17.53 / 17.53
Indirect Costs:	0.36	0.41	0.53 / 0.96	0.59 / 1.31	0.77 / 1.74	0.91 / 2.13	1.15 / 2.52	1.31 / 3.51	1.61 / 4.53	1.99 / 5.64
Acquisition, royalties, taxes	3.37	3.38	3.39	3.39	3.41	3.42	3.43	3.44	3.47	3.50
Total Operating Cost/ton by ratio	5.63	6.77	7.87/8.32	8.86/9.58	10.52/11.50	12.19/13.41	14.30/15.85	16.02/18.19	18.19/21.89	23.02/26.67
South Mining Area										
Direct and Other Costs:	1.90	2.97	3.95 / 3.97	4.87 / 4.87	6.34 / 6.35	7.86 / 7.86	9.72 / 9.70	11.25 / 11.24	13.89 / 13.89	17.53 / 17.53
Indirect Costs:	0.36	0.41	0.53 / 0.98	0.59 / 1.31	0.77 / 1.74	0.91 / 2.13	1.15 / 2.52	1.32 / 3.51	1.61 / 4.53	1.99 / 5.64
Acquisition, royalties, taxes	3.71	3.72	3.73	3.73	3.75	3.76	3.77	3.78	3.81	3.84
Total Operating Cost/ton by ratio	5.97	7.11	8.21 / 8.66	9.20 / 9.92	10.84 / 11.84	12.53 / 13.75	14.64 / 15.99	16.36 / 18.53	19.31 / 22.23	23.36 / 27.01

Cells with two numbers (9.48 / 10.20) indicate the operating costs in areas not affected by the Joint Line versus areas affected by the Joint Line.

Note: Direct costs do not change from area to area for the same ratio; Indirect costs which include amortization remain the same from mining area to mining area, but increase as the ratio increases owing to the addition of capital equipment; Acquisition costs, royalties, and taxes will increase from the north mining area to the south mining area because sales price and LBA costs increases from north to south – however, acquisition costs, royalties, and taxes remain constant from ratio to ratio within the same mining area.

Table 12. Discounted cash flow costs/ton by mining area and ratio for the Anderson coal bed in the Gillette coalfield. All costs are reported in U.S. dollars (as of January, 2007). Abbreviations: Discounted Cash Flow (DCF); Rate of Return (ROR).

DCF at 8 percent ROR By Area	Stripping Ratios									
	1:1	2:1	3:1	4:1	5:1	6:1	7:1	8:1	9:1	10:1
North Mining Area	5.40	6.60	8.30	9.80	12.30	14.70	18.20	20.90	25.40	31.00
Middle Mining Area	6.70	7.80	9.40 / 16.20	10.80 / 17.60	13.30 / 19.00	15.70 / 22.80	18.65 / 27.10	22.60 / 33.80	26.10 / 42.90	31.70 / 52.78
South Mining Area	7.70	8.90	10.60 / 16.30	12.00 / 18.30	14.50 / 20.20	16.80 / 24.00	20.60 / 28.20	24.40 / 34.90	28.10 / 44.60	33.50 / 54.60

Cells with two numbers (10.60 / 16.30) indicate the DCF costs in areas not affected by the Joint Line versus areas affected by the Joint Line.

Table 13. Cumulative resources by incremental discounted cash flow (DCF) cost and coal bed in the Gillette coalfield (reported in millions of short tons and U.S. dollars (as of January, 2007). Note: A value of "zero" indicates less than 0.5 million short tons.

Coal Bed	**Mining Area**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Less Than**	**Total Resource**
		$6	**$7**	**$8**	**$9**	**$10**	**$12**	**$14**	**$16**	**$18**	**$20**	**$25**	**$30**	**$40**	**$50**	**<$60**
Roland	North		0	6	102	242	251	413	536	539	636	755	867	1,004	1,004	1,004
	Middle				1	25	52	206	441	469	835	1,418	1,964	2,305	2,305	2,661
	South					5	8	28	57	168	447	804	1,076	1,269	1,269	1,696
	Total GCF				104	271	311	647	1,033	1,176	1,918	2,978	3,907	4,578	4,578	5,361
Smith	Middle				2	30	43	66	182	333	491	1,106	1,768	2,369	2,709	3,648
	South						18	31	52	84	94	433	648	900	1,247	2,706
	Total GCF				2	30	61	97	234	417	586	1,538	2,416	3,268	3,956	6,355
Anderson Rider	Middle		13	57	59	231	237	242	308	374	375	411	411	411	411	411
	South			9	123	237	268	300	317	335	343	346	354	354	354	354
	Total GCF		13	66	182	468	506	542	625	708	718	757	766	766	766	766
Anderson	North	462.2	992.2	992.2	1,742.1	2,303.2	2,303.2	2,807.6	3,108.5	3,108.5	3,342.1	3,628.7	3,907.9	4,069.6	4,069.6	4,069.6
	Middle		135	617	617	1,804	1,804	6,793	8,808	8,808	11,857	15,341	18,588	20,652	21,061	21,266
	South			108	408	408	4,050	4,125	5,482	7,079	7,194	13,558	16,297	18,136	19,321	20,114
	Total GCF	462	1,128	1,717	2,767	4,515	8,157	13,725	17,398	18,996	22,393	32,527	38,793	42,857	44,451	45,449
Dietz	North				10		28	38	43	47	51	56	92	92	92	92
	Middle		18	87	166	173	267	270	359	411	411	411	411	411	411	411
	South						0	0	1	1	3	6	7	7	7	7
	Total GCF		18	87	175	173	295	309	403	459	465	472	509	509	509	509
Canyon	North		400	1,115	2,272	3,155	3,155	3,886	4,331	4,331	4,622	4,853	5,133	5,356	5,356	5,356
	Middle			315	315	667	1,066	1,371	1,601	1,601	2,754	4,599	6,461	7,736	8,383	9,272
	South			4	49	55	171	246	294	395	422	782	1,409	2,184	2,967	3,936
	Total GCF		400	1,434	2,636	3,877	4,392	5,503	6,226	6,327	7,798	10,234	13,003	15,276	16,705	18,563
TOTALS	**North**	**462**	**1,392**	**2,113**	**4,126**	**5,700**	**5,736**	**7,144**	**8,018**	**8,025**	**8,652**	**9,293**	**10,000**	**10,521**	**10,521**	**10,521**
	Middle	**0**	**166**	**1,076**	**1,160**	**2,930**	**3,470**	**8,949**	**11,699**	**11,996**	**16,723**	**23,286**	**29,603**	**33,884**	**35,279**	**37,668**
	South	**0**	**0**	**121**	**580**	**705**	**4,515**	**4,730**	**6,203**	**8,061**	**8,503**	**15,928**	**19,790**	**22,850**	**25,165**	**28,814**
	Total	**462**	**1,558**	**3,305**	**5,866**	**9,335**	**13,721**	**20,823**	**25,920**	**28,082**	**33,878**	**48,506**	**59,393**	**67,254**	**70,965**	**77,003**