Preliminary Report on Methodology for Calculating Coal Resources of the Wyodak-Anderson Coal Zone, Powder River Basin, Wyoming and Montana

By

Margaret S. Ellis, Gregory L. Gunther[1], Romeo M. Flores,
Gary D. Stricker, Allan M. Ochs[1], and John H. Schuenemeyer

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[1]Contractor for the U.S. Geological Survey, Denver, Colorado

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ABSTRACT

The National Coal Resource Assessment of the Wyodak-Anderson coal zone includes reports on the geology, stratigraphy, quality, and quantity of coal. The calculation of resources is only one aspect of the assessment. Without thorough documentation of the coal resource study and the methods used, the results of our study could be misinterpreted. The task of calculating coal resources included many steps, the use of several commercial software programs, and the incorporation of custom programs. The methods used for calculating coal resources for the Wyodak-Anderson coal zone vary slightly from the methods used in other study areas, and by other workers in the National Coal Resource Assessment.

The Wyodak-Anderson coal zone includes up to 10 coal beds in any given location. The net coal thickness of the zone at each data point location was calculated by summing the thickness of all of the coal beds that were greater than 2.5 ft thick. The amount of interburden is not addressed or reported in this coal resource assessment. The amount of overburden reported is the amount of rock above the stratigraphically highest coal bed in the zone. The resource numbers reported do not include coal within mine or lease areas, in areas containing mapped Wyodak-Anderson clinker, or in areas where the coal is extrapolated to be less than 2.5 ft thick.

The resources of the Wyodak-Anderson coal zone are reported in Ellis and others (1998). A general description of how the resources were calculated is included in that report. The purpose of this report is to document in more detail some of the parameters and methods used, define our spatial data, compare resources calculated using different grid options and calculation methods, and explain the application of confidence limits to the resource calculation.

INTRODUCTION

The National Coal Resource Assessment is a project by the U.S. Geological Survey begun in 1995. It is an assessment of coal in the United States that has the highest potential for development within the next 20-30 years. For the purpose of the assessment, five study regions were identified within the United States. These regions are the Appalachian Basin, the Illinois Basin, the Gulf Coast, the Rocky Mountains and Colorado Plateau, and the Northern Rocky Mountains and Great Plains (figure 1). Within these regions, coal was prioritized and the coal beds and zones with the highest potential for development were designated as assessment units. Efforts were made to standardize the assessment of coal in all of the regions. The characteristics of the coal, stratigraphy, and available data, as well as the types and nature of the mine areas and technology employed in different areas is, however, unique; therefore the methodology employed for each study was modified as necessary.

Early in the National assessment it was determined that resources would be calculated using standard resource reporting categories from Wood and others (1983). The computer software used, data modeling options, and methods for calculating resources were to be determined by the workers in each study area. This report explains some of the options considered in determining the methods employed for Northern Rocky Mountains and Great Plains Region studies, with examples from the study of the Wyodak-Anderson coal zone in the Powder River Basin of Wyoming and Montana. Additional methods considered and employed in other regions in the National Coal Resource Assessment are reported in Tewalt (1998), Roberts and others (1998) and Roberts and Biewick (in press). Methods for calculating and reporting coal resources vary because of considerations resulting from different mining methods, restrictions, and geology in each study area, as well as the availability of software and the expertise of individual workers.

ACKNOWLEDGEMENTS

Many individuals and organizations contributed to this study. Much of the data for the study was obtained from the U.S. Geological Survey National Coal Resource Data System (NCRDS), the Office of Surface Mining, the Bureau of Land Management, the Wyoming Geological Survey, and the

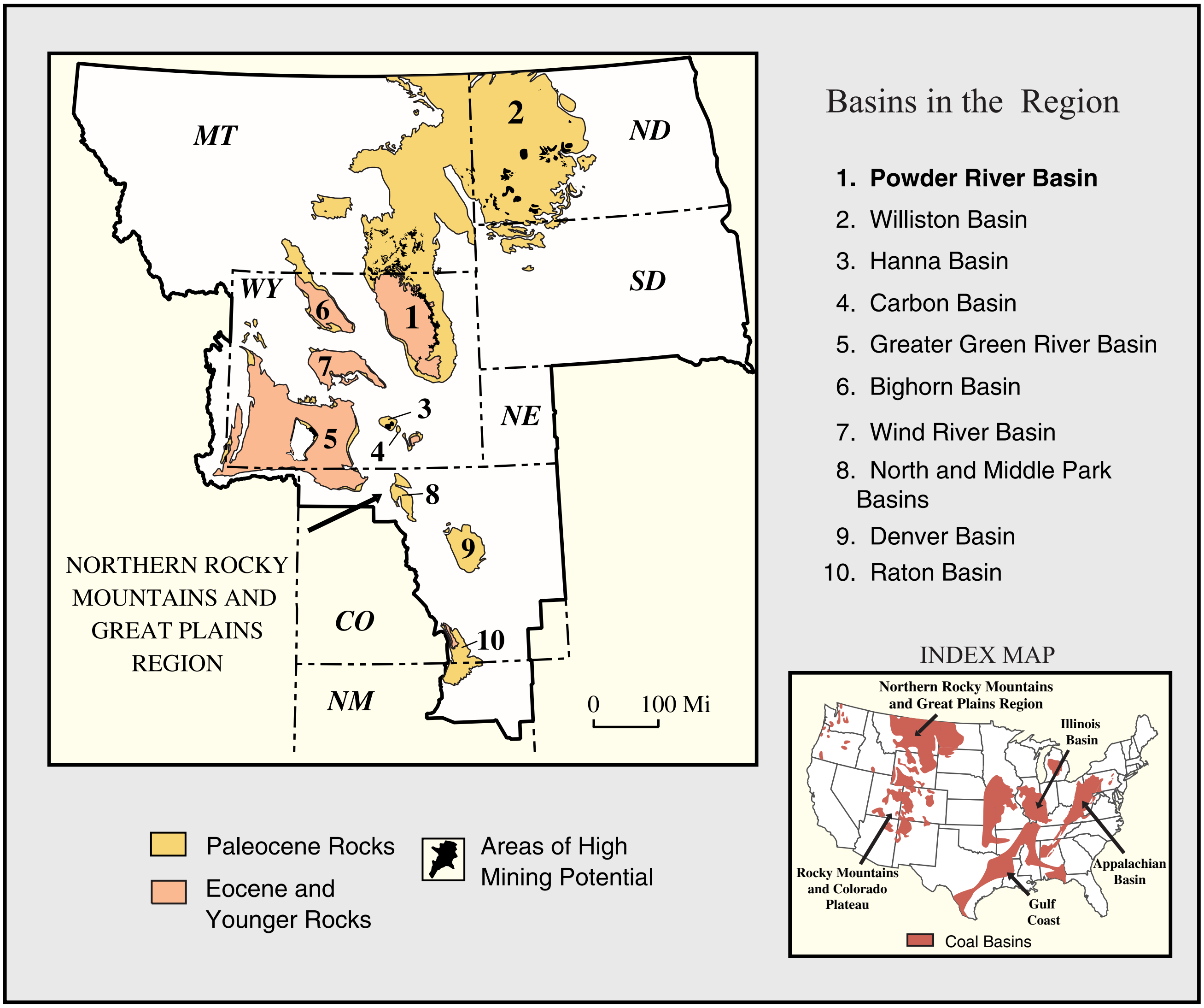

Figure 1. Index map of the Northern Rocky Mountains and Great Plains Region showing sedimentary basins, the outcrop of Paleocene, and Eocene and younger rocks, and areas of high mining potential.

Montana Bureau of Mines and Geology. Some other agencies and companies supplied information for this study, however they cannot be acknowledged due to the proprietary status of the data.

Workers who supplied and correlated data for the Wyodak-Anderson coal zone include Daniel Vogler (Wyoming Geological Survey); Edith Wilde (Montana Bureau of Mines and Geology); and Peter Warwick, Ronald Johnson, Frances Wahl Pierce, and Carol Molnia (U.S. Geological Survey). Additional workers that entered data and produced digital coverages were Gerald Forney, Timothy Gognat, James Hunsicker, Gregory Rossi, Scott Kinney, Kathy Yates, Thomas Taber, Gregory Rossi, Scott Kinney, and Paul Hagen.

Several custom programs were used in various steps of the resource study. These programs were written and supplied by Colin Treworgy of the Illinois State Geological Survey (ismarc program) and by Dorsey Blake and Gary Stricker of the U.S. Geological Survey (evrpt and parting/split programs respectively).

POWDER RIVER BASIN AND WYODAK-ANDERSON COAL

The Powder River Basin is in the central part of the Northern Rocky Mountains and Great Plains Region, in Wyoming and Montana (figure 1). More than 30% of the nation's 1996 total coal production of 1.06 billion short tons was produced from 14 Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains Region (Energy Information Agency, 1997). Coal that is being studied in this region is within the Powder River, Williston, Hanna, Carbon, and Greater Green River Basins. The greatest amount of coal production in the region is from mines in Wyoming, Montana, and North Dakota (figure 2). Coal production in Wyoming accounted for approximately 25% of total National coal production for 1997 (Energy Information Agency, 1998), with the highest coal production from the Wyoming part of the Powder River Basin, which is mainly Wyodak-Anderson coal.

For this study we are assessing the late Paleocene Wyodak, Anderson, and stratigraphically equivalent coal beds in the upper Fort Union Formation. The Fort Union Formation is exposed along the margin of the Powder River Basin, and is overlain by exposures of the Eocene Wasatch Formation, in the central part of the basin (figure 1). The Powder River Basin is an asymmetrical structural basin, with an axis trending northwest southeast along the western part of the basin. Fort Union rocks dip an average 20-25° to the east along the western margin of the basin and have an average dip of 2-5° to the west along the eastern margin of the basin. The Powder River Basin covers more than 12,000 square miles (31,080 square kilometers) and the Fort Union Formation is more than 6,000 ft (1,830 m) thick along the basin axis.

The upper part of the Fort Union Formation contains Wyodak-Anderson net coal that is more than 200 ft (61 m) thick. Beds included in the coal zone are the Anderson, Dietz, Canyon, Monarch, Werner, Wyodak, Smith, Swartz, Sussex, School, and Badger. The coal zone is more than 600 ft (183 m) thick, measured from the top of the uppermost coal to the base of the lowermost coal. The coal beds merge into a single coal bed as much as 202 ft (62 m) thick in the west-central part of the basin, and as much as 120 ft (37 m) thick in the eastern part of the basin. The coal beds are laterally discontinuous, and beds characteristically pinch-out, merge, and/or split within short distances. The lateral variability of the coal beds is shown in the cross section in figure 3.

Depositional setting controlled the thickness and lateral continuity of the Wyodak-Anderson coals. The depositional environments of the Fort Union Formation were mainly fluvial systems consisting of braided and meandering streams in the center of the basin and alluvial fans along the western basin margin. Coals accumulated in peat mires or swamps formed in fluvial floodplains, abandoned fluvial channels, and inter-channel environments (Flores, 1986).

OVERVIEW OF METHODOLOGY

The methods used in performing the coal resource calculations for the Wyodak-Anderson coal zone required many steps and a number of software packages and custom programs. A brief description of the steps involved, parameters selected, and software used for this study is given in Ellis and others (1998).

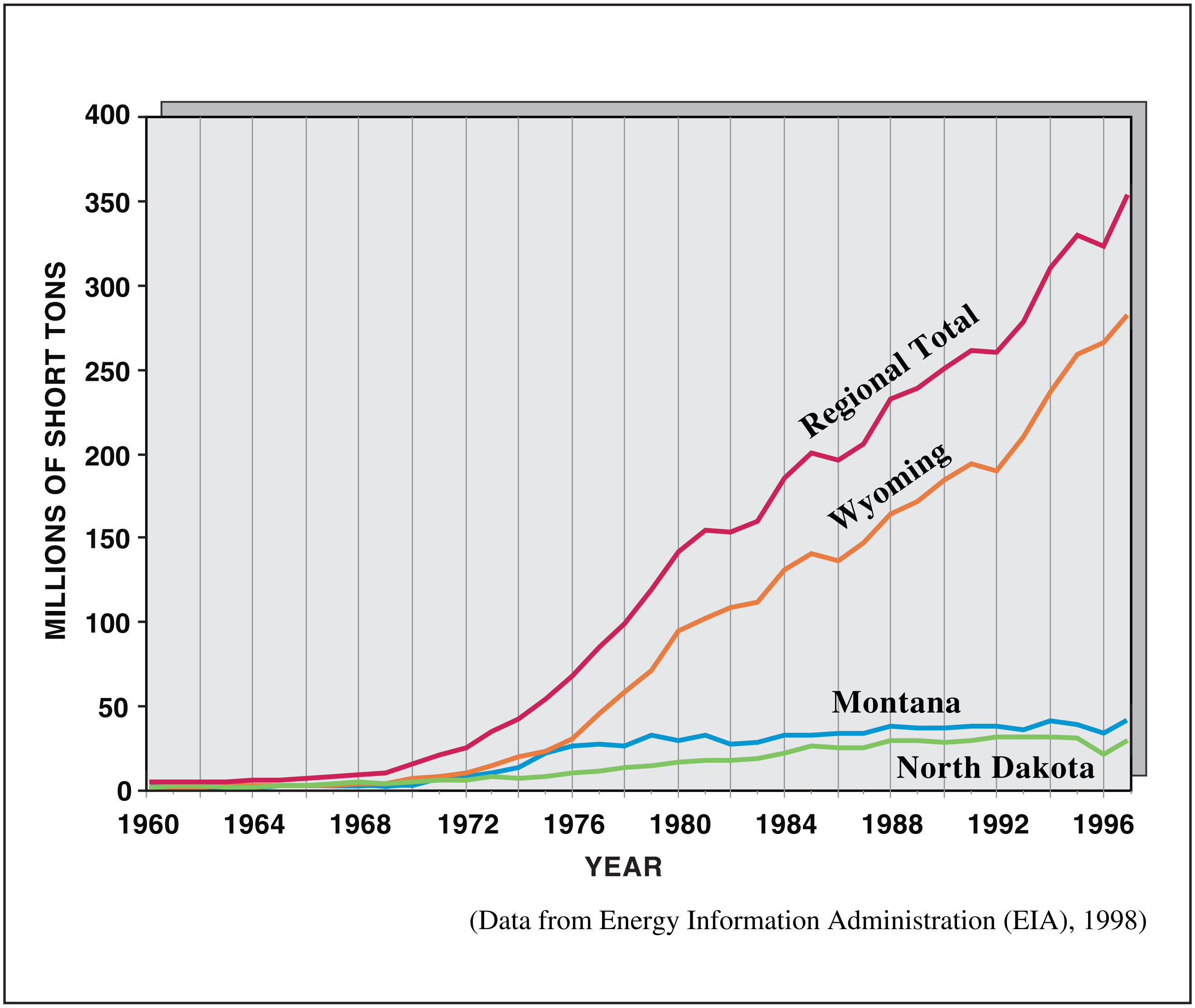

Figure 2. Production of all coal in Wyoming, Montana, and North Dakota from 1960 to 1997.

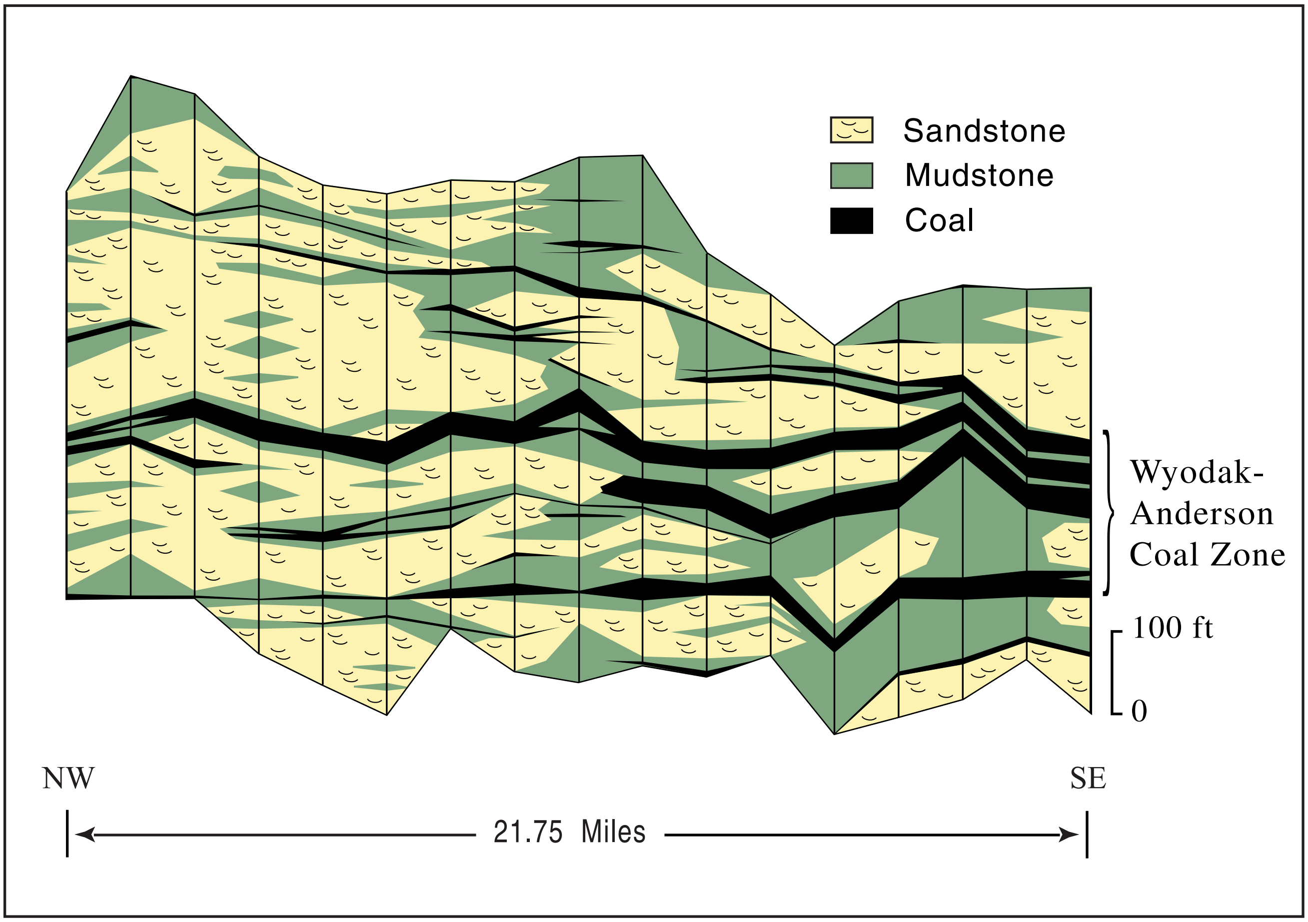

Figure 3. Generalized cross section showing the type of lateral and horizontal variation found in Wyodak-Anderson coal in the Powder River Basin of Wyoming and Montana. The cross section is located about three miles north of Gillette, Wyoming.

The parameters and methods used for resource calculation could have a significant influence on the amount of resources calculated. As part of the Powder River Basin Wyodak-Anderson coal assessment we tested different methods to see what influence, if any, the methods would have on our calculations.

The methods that were used for the resource study involve the use of Stratifact (GRG Corp., 1996) as a relational database in which to compile all of our data and establish coal zone correlations, a USGS custom "parting/split" program to calculate net coal at each data point location, and EarthVision (Dynamic Graphics Inc., 1997) to create the net coal and overburden isopach maps. In EarthVision (EV), the grid spacing, grid options, and editing of the grid or the isopach lines affect the coal thickness used for resource calculations. The coal thickness and overburden isopach maps are imported into ARC/INFO (ESRI, 1998a) and combined with other spatial data layers. The combined spatial data (union coverage) contains polygons with many attributes. This coverage is used for eliminating specific areas from resource calculations and for reporting coal resources by categories.

Resources can be calculated in ARC/INFO, using the attribute of the net thickness and area of each polygon in the union coverage, or the union coverage can be imported into EarthVision and the resources can be calculated for each polygon using the net coal thickness grid. In this report both options were tested. The first option is referred to as the ARC/INFO method, and the second option is referred to as the EarthVision method. The following chapters describe options for gridding and calculating coal resources, and compare resource calculations resulting from the two different methods.

GRID SPACING AND GRID OPTIONS (EarthVision)

Data files were imported into EV in fixed ASCII format, with locations in decimal degrees of latitude and longitude. The data fields were defined and the file was projected to a standardized projection for the Wyodak-Anderson study area. The projection for the study area is Lambert Conformal Conic, Clarke 1886 spheroid, with a first standard parallel of 33 degrees, a second standard parallel of 45 degrees, a central meridian of 106 degrees west, an origin of 0 degrees, 0 false easting, and 0 false northing.

There are two grid options in EV, the isopach grid and the normal minimum tension (NMT) grid. The isopach grid option allows for special handling of thickness data that does not represent the entire coal zone (the drill holes did not penetrate the entire zone). In our data set there were 792 data points that fit this criteria, and were therefore considered to be "terminated". To indicate the points that were terminated, a negative sign was assigned to the coal thickness values in the data set. This negative coal thickness value is treated as a "greater than" value when using the isopach gridding.

The NMT gridding has special "0" handling, but does not compensate for terminated data. To test the isopach and NMT grid options, we therefore used two separate data sets. The data set used for the NMT grids did not contain data from terminated holes. This data set contained 4,622 data points with a z range of 0 to 284 ft (0 to 87 m) thick. The data set used for isopach gridding contained data from terminated holes (negative values) and consisted of 5,414 data points with net coal values (z) that ranged from –169 to 284 ft (-52 to 87 m) thick.

Data points were not evenly distributed throughout the study area; therefore, grids and isopach maps generated strictly from the original data did not accurately depict the character of the coal. It was necessary to add interpretive points to the data set based on geologic knowledge, field experience, and additional measured sections. These interpretive points included adding "0" values in areas along the coal extent where the coal was known to pinch-out (depositional "want" areas), or where the coal was eroded away (erosional "want" areas). The addition of interpretive data to the data sets allowed us to grid the data using several different grid spacings and both the isopach and NMT grid options without having to edit every isopach map.

When calculating grids, we found that it was best to grid first with a grid range from 0 to 285 to determine where the program placed 0 values. A second grid was then produced with a z range of 1 to 285 to avoid having the program interpolate or extrapolate the grid nodes to 0 values in areas where the data points were widely spaced. We used the second grid to calculate resources. When calculating resources in EV, the values of the grid nodes are used for the coal thickness. There must be at least one grid node in a polygon for resources to be calculated in the polygon. Because many of the polygons in our union coverage were very small and therefore contained few grid nodes, by not gridding to 0, we eliminated the possibility of calculating 0 short tons in the small polygons.

To choose the grid spacing and grid option (isopach vs. NMT) that was appropriate for our study, we considered the grid reports and the associated graphics (net coal isopach maps). Considerations used for choosing the appropriate grid were: a grid that honored (used) as many of the data points as possible and produced a small average absolute z error, as shown in the grid report; a grid that produced an isopach map with a reasonable level of detail; and a grid spacing that was small enough to allow at least one grid node value within each union coverage polygon. Because the size of the union polygons was a consideration, we created grids based on their spacing in meters (grid spacing) rather than the number of columns and rows in the grid (grid size).

The EV grid reports included in the Appendix of this report provide information on how the grids with different grid spacings represented the data. All of the grids were produced using the same grid range (a box defined just outside of the Wyodak-Anderson study limit) and 4 multiple data points (the number of closest surrounding data points that the grid algorithm uses in determining the value of each grid node.) We began by testing the default EV grid size of 81 by 123 (columns and rows) that equates to a grid spacing of 3,520 by 3,606 m (1,073 by 1,099 ft) (map A. on fig. 4). Grid spacings of 1,000 by 1,000 m, 800 by 800 m, 500 by 500 m, and 300 by 300 m were tested. Grid ranges of both 0 to 285 and 1 to 285 were run, however only the grid reports for the z range of 1 to 285 are included in the Appendix. Highlighted areas in the grid reports indicate the number of data points in the data set, the number of data points used to produce the grid, and the average absolute z error of the grid. Isopach maps were generated using different grid spacings and using different grid options.

The results of our testing led to the selection of the 300 by 300-m and 500 by 500-m isopach grids as most representative of our study area. The 300 by 300-m isopach and NMT grids both honored over 98% of the data points, using 5,324 out of 5,414 (98%) data points for the isopach grid and 4,615 out of 4,622 (99.8%) data points for the NMT grid. The average absolute grid error was .5% for the isopach grid and .4% for the NMT grid. The isopach and NMT grid isopach maps look very similar in their general configuration. Maps in figure 5 show isopach maps created using the isopach (A.) and NMT (B.) grid options with 300 by 300-m grid spacing. Because isopach maps created using the two grid options were so similar and there were many terminated holes in our data set, we used the isopach grid option for the creation of the net coal coverage in ARC/INFO and for the calculation of volumetrics in EV. To determine what effect using the different grid options would have on the coal resources; we calculated volumetrics using the both the 300 by 300-m isopach grid and the 300 by 300-m NMT grid. The results are shown in table 1.

As an example of how grid spacing affects isolines on net coal isopach maps, figure 4 shows isopach maps created using the 3,520 by 3,606-m (EV default) grid spacing (map A.) and the 300 by 300-m grid spacing (map B.). The default grid spacing creates an isopach map that has very little detail. The difference between the isopach maps created using 500 by 500-m and the 300 by 300-m grid spacing is very slight. We decided to use the 500 by 500-m isopach grid for creating the net coal isopach coverage in ARC/INFO because it had the same general configuration as the smaller spaced grid, yet it had fewer very small polygons that would be a problem in the union coverage.

DIGITAL SPATIAL DATA (ARC/INFO)

Layers of digital information were created and made into ARC/INFO coverages for use in various aspects of the resource assessment. The coverages were used for creating graphics, for determining areas with specific characteristics for research purposes, and, by combining the layers into a single coverage, for including or excluding areas from resource calculations, and reporting coal resources using complex queries.

The areal extent of all of the layers of information for the Powder River Basin study was limited to the area of a box with boundaries just outside of the Powder River Basin. This box is not listed in our description of ARC/INFO coverages below. It is a tool used for clipping large coverages to a

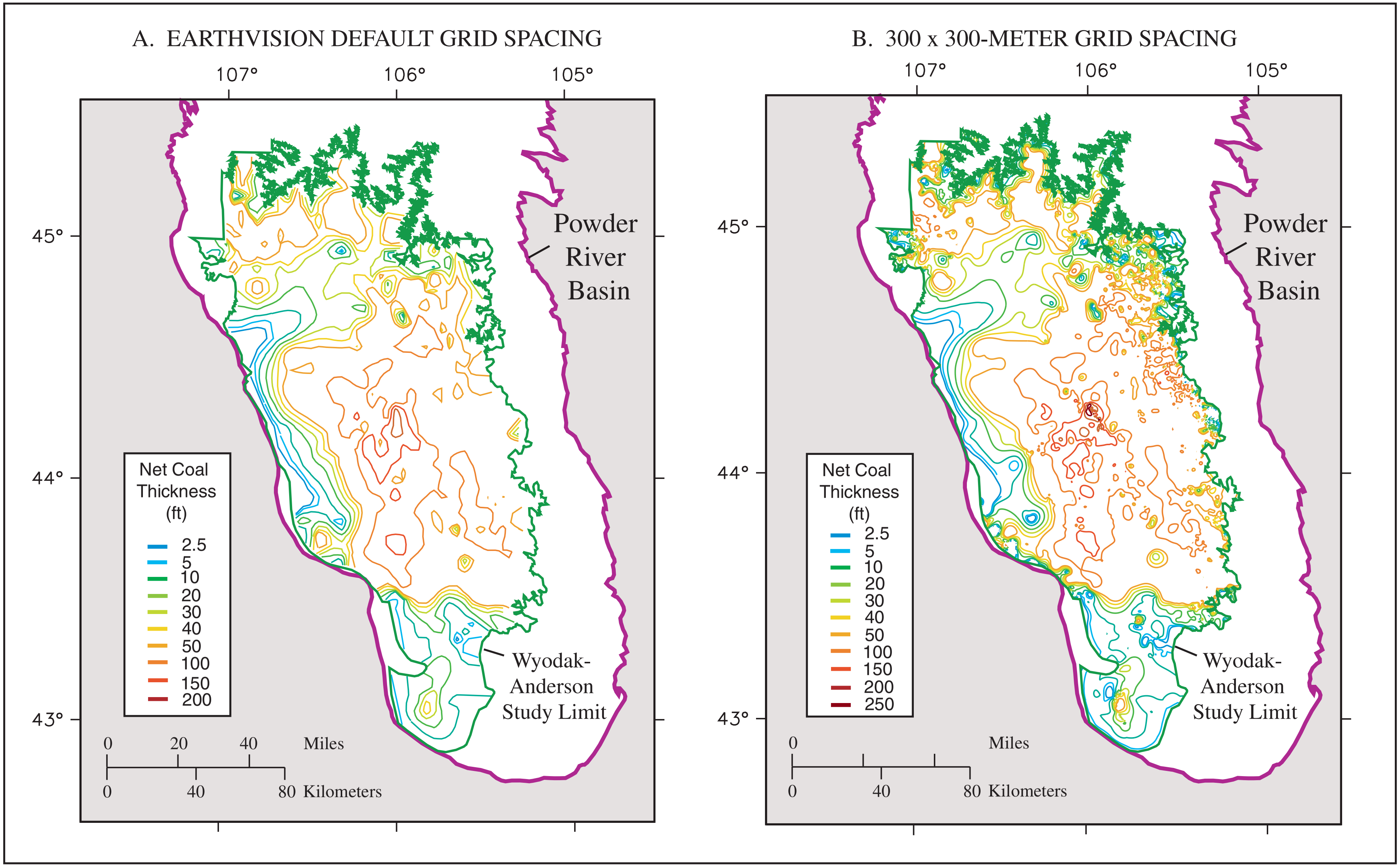

Figure 4. Isopach maps of net coal in the Wyodak-Anderson coal zone showing the difference between the isolines created using the 3,520 by 3,606-m EarthVision default grid spacing (A.) and the 300 by 300-m grid spacing (B.). Both maps were produced from grids created using the isopach grid option in EarthVision.

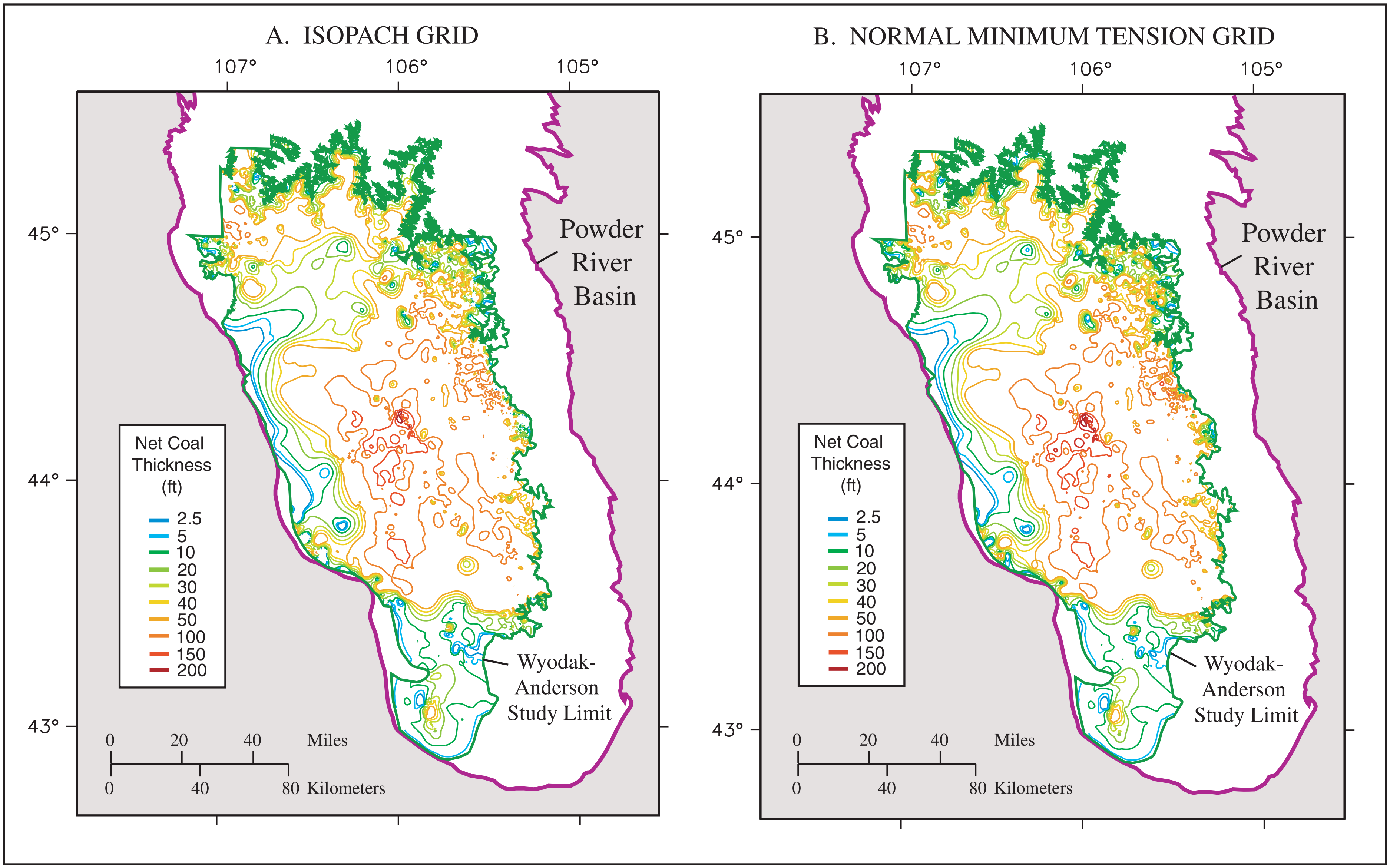

Figure 5. Isopach maps of net coal in the Wyodak-Anderson coal zone showing the differences between the isolines created using grids produced using the isopach grid option (A.) versus the normal minimum tension grid option (B.). Both maps were produced from grids with 300 by 300-meter grid spacing.

manageable size. All of the layered data were stored in the same projection used for the grid files and other files produced in EV. The layers of information (ARC/INFO coverages) that were used for this study, their use, the sources of information, and a general description of how the coverages were created are listed below.

State Boundary -- The state boundary coverage shows the boundary of Wyoming and Montana (figure 6) in the Powder River Basin area. The boundary is used for creating graphics and for reporting coal resources within each state (tables 1, 2, and 3). The coverage was created from a National state coverage from the U.S. Geological Survey National Mapping Division (1997). The original coverage was at a scale of 1:2,000,000 and was in Albers projection, with a first standard parallel of 29 degrees and 30 minutes, a second standard parallel of 45 degrees and 30 minutes, a central meridian of 96 degrees west longitude, and an origin of 23 degrees north latitude. The projection had 0 false northing and 0 false easting. We clipped-out parts of the state polygons for Montana, Wyoming, North Dakota, South Dakota, Nebraska, Colorado, and New Mexico using a polygon of the Northern Rocky Mountain and Great Plains region that we had digitized. The clipped coverage was projected to Lambert Conformal Conic with a central meridian of 107 degrees west longitude. This coverage is used for our regional studies. The Powder River Basin state coverage was created from the regional coverage by projecting the coverage to Lambert Conformal Conic with a central meridian of 106 degrees west longitude and clipped it to the Powder River Basin study area.

Counties -- The county coverage shows the location and extent of counties in the Powder River Basin area (figure 6). The original national coverage was obtained from the U.S. Geological Survey National Mapping Division (1997). The coverage was at a scale of 1:100,000 and was in Albers projection. The coverage was projected and clipped for use on a regional scale, and projected and clipped again for use in the Powder River Basin study area (as described above). The coverage is used for graphics and for reporting coal resources in tables.

Powder River Basin Boundary -- The Powder River Basin boundary is defined by the contacts of Tertiary/Cretaceous formations (figure 6). The coverage was digitized from 1:500,000 scale State maps of Montana (Ross and others, 1955) and Wyoming (Love and Christiansen, 1985). The northeast boundary was generalized (modified from Ross and others, 1955) along the Miles City Arch, a northwest, southeast trending arch east of the town of Miles City, Montana. The Powder River Basin boundary was used for creating graphics and for clipping some of the other coverages.

Wyodak-Anderson Study Limit -- This coverage shows the approximate lateral extent of the Wyodak-Anderson coal zone (figure 7). The boundary was created using published maps by Kent and Berlage (1980), Bryson and Bass (1973), Robinson and Culbertson (1984), Warren (1959), Baker (1929), Love and Christiansen (1985), and Ross and others (1955) and unpublished geologic maps by Romeo Flores and by William Culbertson of the U.S. Geological Survey. The boundary was generalized in some areas, to include small areas outside of the main boundary, and was refined by eliminating areas along the boundary where Wyodak-Anderson clinker had been mapped. This boundary was used for creating graphics and for clipping other coverages, including the net coal isopach map, the overburden isopach map, and the union coverage used for resource calculation.

Tribal Lands -- The tribal land coverage shows the boundary of the Northern Cheyenne and Crow Indian Reservations (figure 6). The coverage was generated from a land use and Federal land coverage in the Powder River Basin area, published by Biewick and others (1998). The coverage was used for graphic display and was also included in the union coverage to exclude the tribal lands from reported resource calculations.

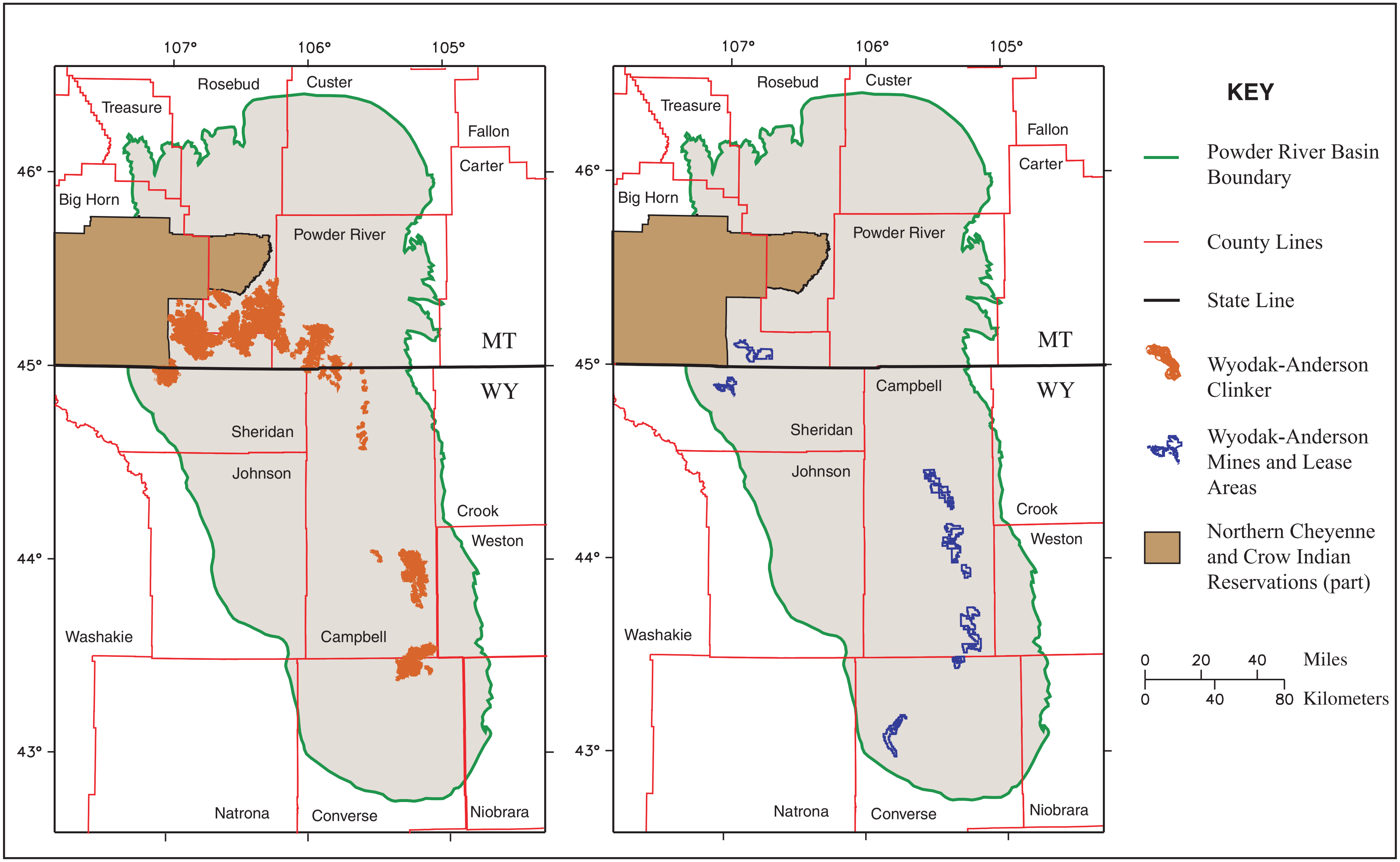

Figure 6. Maps showing the Montana/Wyoming state boundary, counties, the Powder River Basin boundary, tribal lands, and Wyodak-Anderson coal zone clinker, mines, and lease areas.

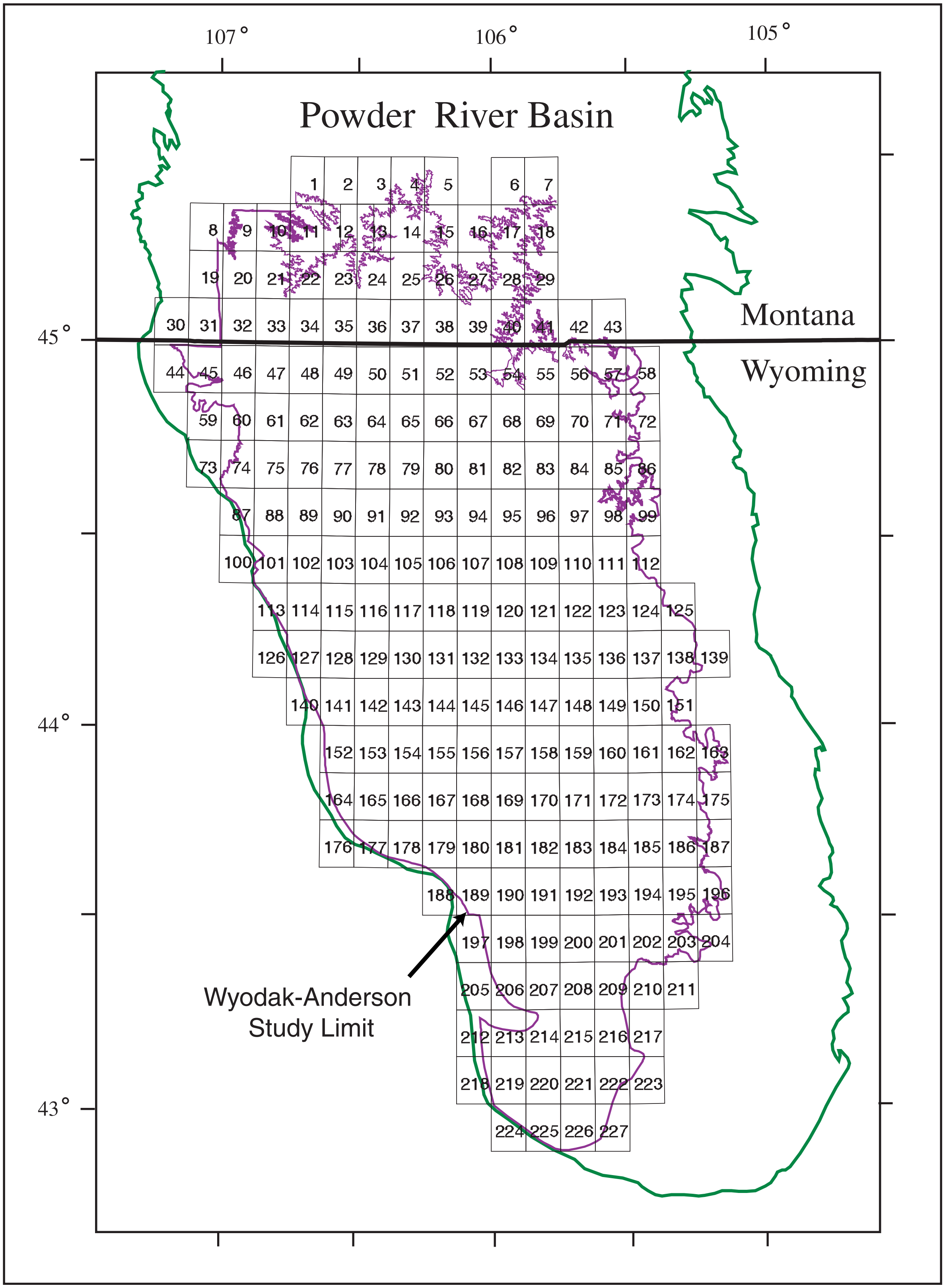

Figure 7. Map showing the location of 7.5-minute quadrangle maps in the study area. Quadrangle index numbers and names are shown on Table 1.

Clinker --The clinker coverage shows areas of mapped Wyodak-Anderson clinker in the Powder River Basin area (figure 6). Our sources for this coverage are Daddow, 1986, Boyd and Van Ploeg, 1997, Heffern and others, 1993, Heffern, unpublished maps, and Kanizay, 1978. In the clinker areas, we do not have detailed information on how much of the Wyodak-Anderson coal is burned. Because of this, we used this coverage to eliminate all of the clinker polygon areas from our coal resource calculations.

Mines and Lease Boundaries--This coverage shows all of the Wyodak-Anderson mine areas and lease boundaries (figure 6). The boundaries came from several sources, including the Bureau of Land Management (1996), Kennecott Energy and others (not dated), and Dunrud and Osterwald (1980). The coverage is used for graphic displays and for clipping out areas where we did not want to report coal resource calculations. Coal resources in mine or lease areas were not reported because much of the proprietary data that we used was within those areas and information on the boundaries for mined out areas was incomplete.

7.5-minute Quadrangle Maps --The quadrangle coverage shows the location of all of the 7.5-minute quadrangle maps within the Wyodak-Anderson coal extent (figure 7 and table 4). The coverage was created by projecting and clipping an existing national coverage obtained from the U.S. Geological Survey National Mapping Division (1997). The scale of the original coverage was 1:24,000. The polygons were numbered sequentially from the upper left-hand corner to the lower right corner (left to right and top to bottom) and the names of the quadrangles were added to the polygon attribute table, using the numbering of the polygons to join the files. The coverage was used for reporting coal resources within each quadrangle area.

Point Locations --Two point coverages were created, one with all of the data points and the other with only the public data points included. The point data were obtained from our Powder River Basin stratigraphic database. The point coverage with all of the data was used to create the polygons for the reliability categories (described below). The point coverage containing only the public data was used for graphic display.

Reliability Categories --The reliability coverage consists of areas defined by categories described in Wood and others (1983). Reliability categories are areas within specific distances from a data point location (see figure 8, which shows the reliability circles around public (nonproprietary) data points). To create the reliability circles, we created buffer zones in ARC/INFO around each of the data points at distances of ¼ mile, ¾ mile, and 3 miles. We then clipped the coverages using the Wyodak-Anderson coal extent boundary. Attributes to be used for reporting coal resource tonnages were added to the polygon attribute table. The reliability categories are: 0 to ¼ mile for measured, ¼ to ¾ mile for indicated, ¾ mile to 3 mile for inferred, and greater than 3 miles for hypothetical.

Federal Coal Ownership --This coverage shows Federal coal and Federal surface ownership (figure 9). The coverage was created from a land status and Federal mineral ownership coverage by Biewick and others (1998). The coverage was projected and clipped to our study area. We added an item to the polygon attribute table and generalized the attributes of the polygons into 4 categories: 1.) Federal coal yes and Federal surface yes (YY), 2.) Federal coal yes and Federal surface no (YN), 3.) Federal coal no and Federal surface yes (NY), and 4.) Federal coal no and Federal surface no (NN). Polygons in the coverage were then grouped on the basis of these four categories. The coverage was used for reporting coal resources by Federal ownership categories.

Digital Elevation Model (DEM) -- The DEM coverage is a representation of the topographic surface within the area of the Powder River Basin (figure 10). The Digital Elevation Model was obtained from the U.S. Geological Survey Global Land Information System (GLIS) (1997). Elevations in the DEM have a 500 by 500-m grid spacing. The DEM coverage was used for creating the overburden isopach map (as described below) and was also used for creating graphics.

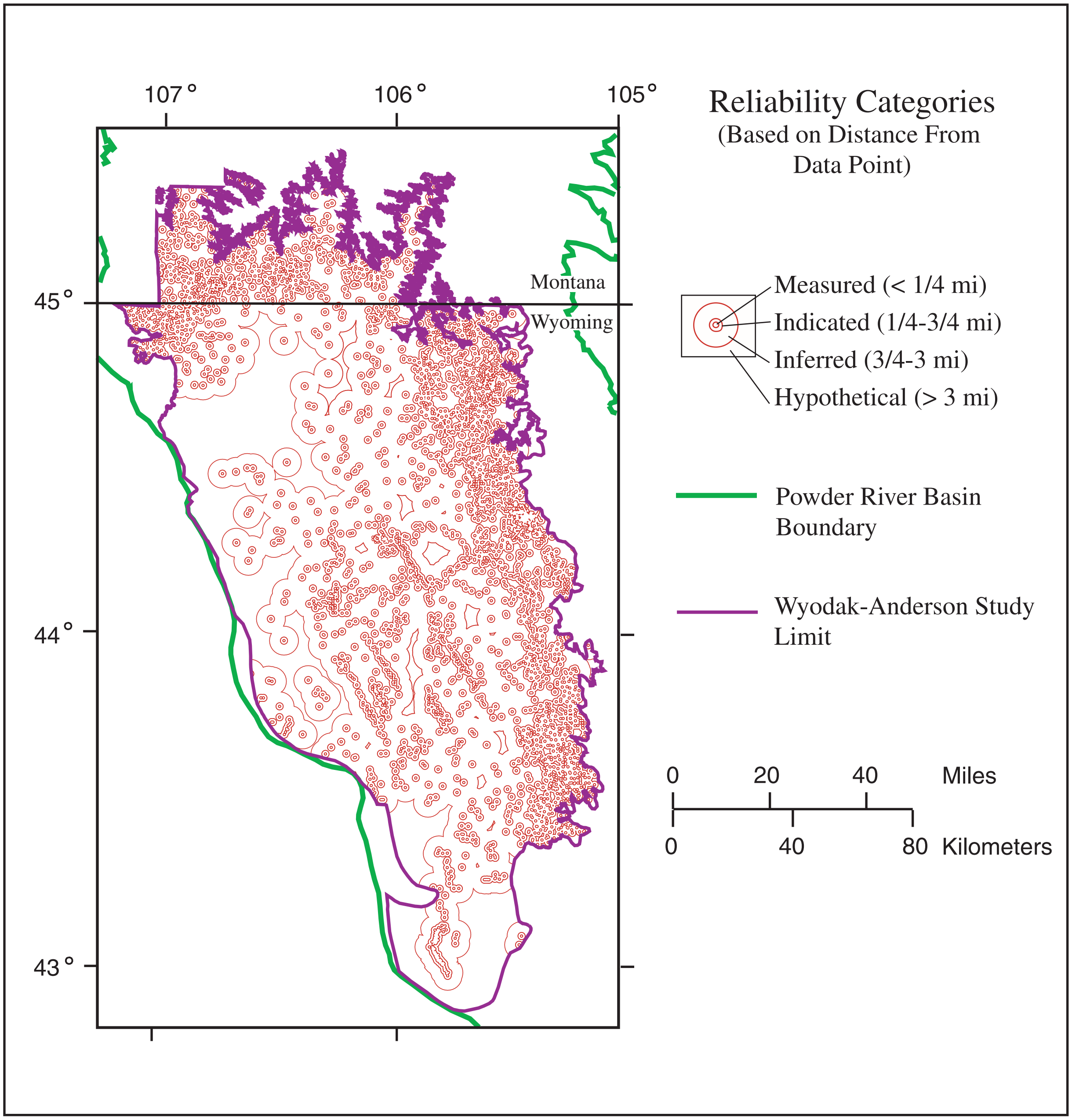

Figure 8. Map showing coal resource reliability categories in the Wyodak-Anderson study area, Powder River Basin, Wyoming and Montana. Only the areas around non-confidential (public) data points are shown on the map.

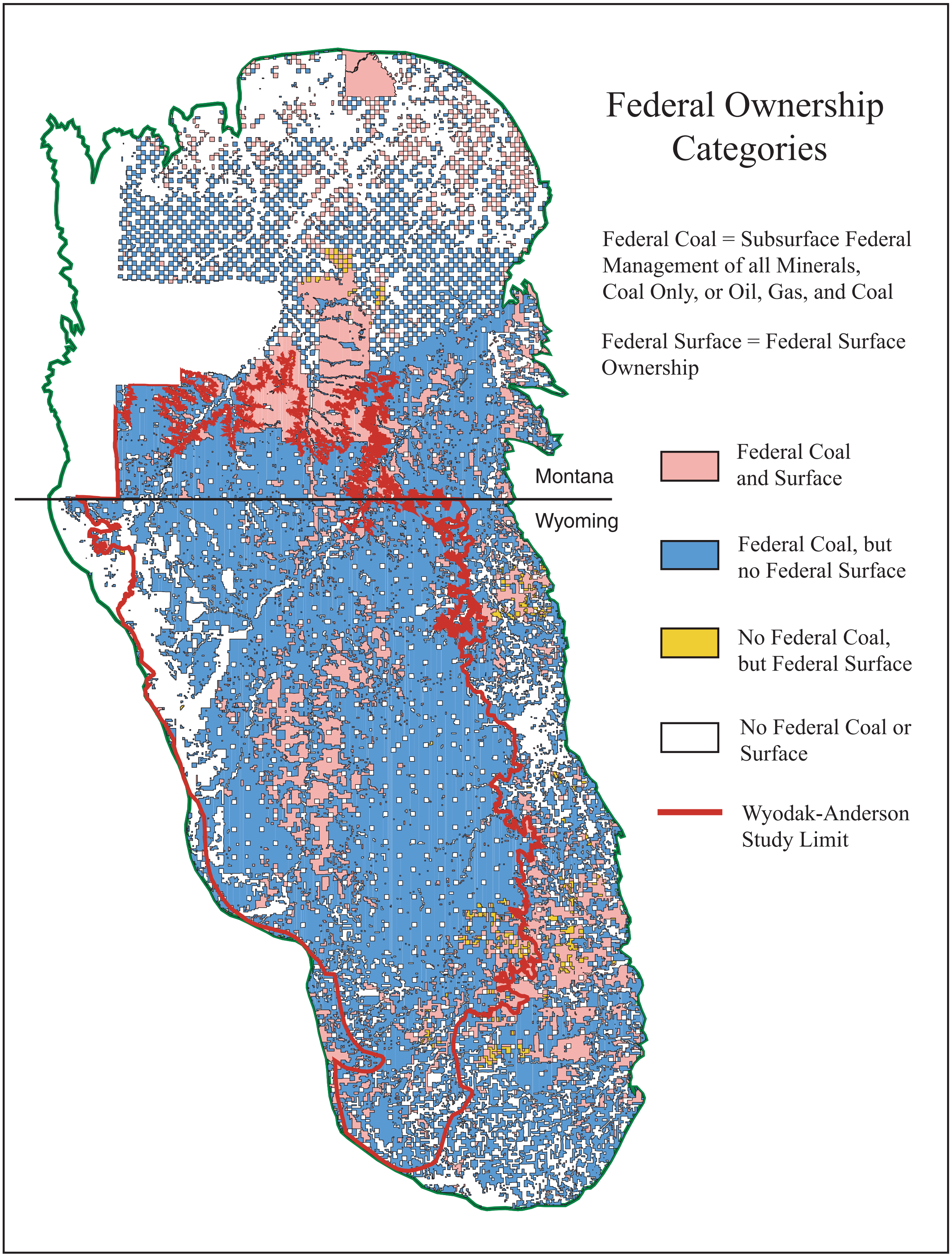

Figure 9. Map showing Federal ownership categories in the Powder River Basin.

Overburden -- The overburden coverage shows polygons for overburden categories. Figure 11 shows an overburden map with detailed overburden categories. Overburden categories used for reporting coal resources of surface-minable, subbituminous (or lignite) coal are 0 to 100 ft, 100 to 200 ft, 200 to 300 ft, 300 to 400 ft, 400 to 500 ft, and greater than >500 ft. The overburden coverage is used for graphics and for reporting coal resources in tables. The overburden coverage was created by using a Digital Elevation Model (DEM) for the gridded topographic surface, creating a gridded surface for the elevation of the top of the Wyodak-Anderson coal zone (with the same grid spacing), and subtracting the two grids to get an overburden thickness grid. The overburden is measured from the topographic surface to the top of the uppermost coal bed in the Wyodak-Anderson coal zone. The overburden thickness grid was used to create an overburden isopach map, with a constant contour interval. The isopach map was saved as an output file. This file was used to generate a polygon coverage in ARC/INFO, by applying the same AML (Arc Macro Language) utilized for generating the net coal thickness coverage described below. As in the coal thickness coverage, the resulting coverage was queried, the polygons in each query set were labeled with text for the reporting categories, and the coverage was simplified by removing the lines between polygons that had the same text labels. A detailed overburden isopach map is shown in figure 11.

Net Coal -- The net coal coverage contains polygons with thickness attributes of 0 to 2.5 ft, 2.5 to 5 ft, 5 to 10 ft, 10 to 20 ft, 20 to 30 ft, 30 to 40 ft, 40 to 50 ft, 50 to 100 ft, 100 to 150 ft, 150 to 200 ft, 200 to 250 ft, and 250 to 285 ft. Within EV, the 500 by 500-m net coal isopach grid was multiplied by 100 and the grid was made into an unlabelled isopach map with a constant contour interval of 250 ft. The map was saved as an ASCII file and modified using a custom program (ismarc). The ASCII file was then generated into a polygon coverage using an AML (ARC Macro Language) program in ARC/INFO. The AML clipped the contour lines to the Wyodak-Anderson coal extent and assigned coal thickness values to the resulting polygons (attributed as the mean of the values of the contour lines bounding each polygon). The thickness values were then divided by 100 to calculate back to the correct net coal thickness for the polygons. An item was added to the polygon attribute table for the polygon coverage, and text labels were assigned to the polygons for the coal thickness categories listed above. The polygons in the coverage were then grouped based on the text labels. This ARC/INFO coverage was used in the union coverage for reporting resources by coal thickness categories in Ellis and others (1998). An additional net coal isopach map was produced in EV from a grid clipped to the Wyodak-Anderson study limit. This map is used for graphic display (figure 12). For our comparison of resources calculated using the isopach and NMT grid options, we created separate net coal thickness coverages. These coverages were each combined with the other layered information to make separate union coverages, which were used with the appropriate grids in EV to calculate coal resources.

UNION COVERAGE

Coverages included in the ARC/INFO union coverage are: state, county, tribal land, clinker, mines and lease boundaries, 7.5-minute quadrangle maps, reliability, federal ownership, overburden, and net coal. The coverages were combined to create a union coverage with many attributes for each polygon. When the coverages were unioned, coverages that had many of the same boundaries (federal ownership, counties, states, 7.5-minute quadrangles) produced thin polygons (slivers) where the coverages did not match exactly. The overburden and net coal thickness coverages were the last to be added to the unioned coverage. After combining of all of the coverages, the coverage was clipped to the Wyodak-Anderson coal extent. Slivers in the coverage were removed by eliminating polygons that were less than 25,000 square meters in area. Additional problematic polygons were edited manually in ArcView (ESRI, 1998b). Text fields that aid in the production of coal resource tables were added to the final unioned coverage. A portion of the union coverage, in the Sheridan area of the Powder River Basin, is shown in figure 13. This figure illustrates the complexity of the coverage. Two union coverages were created with all layers of information identical except for coal thickness. One union

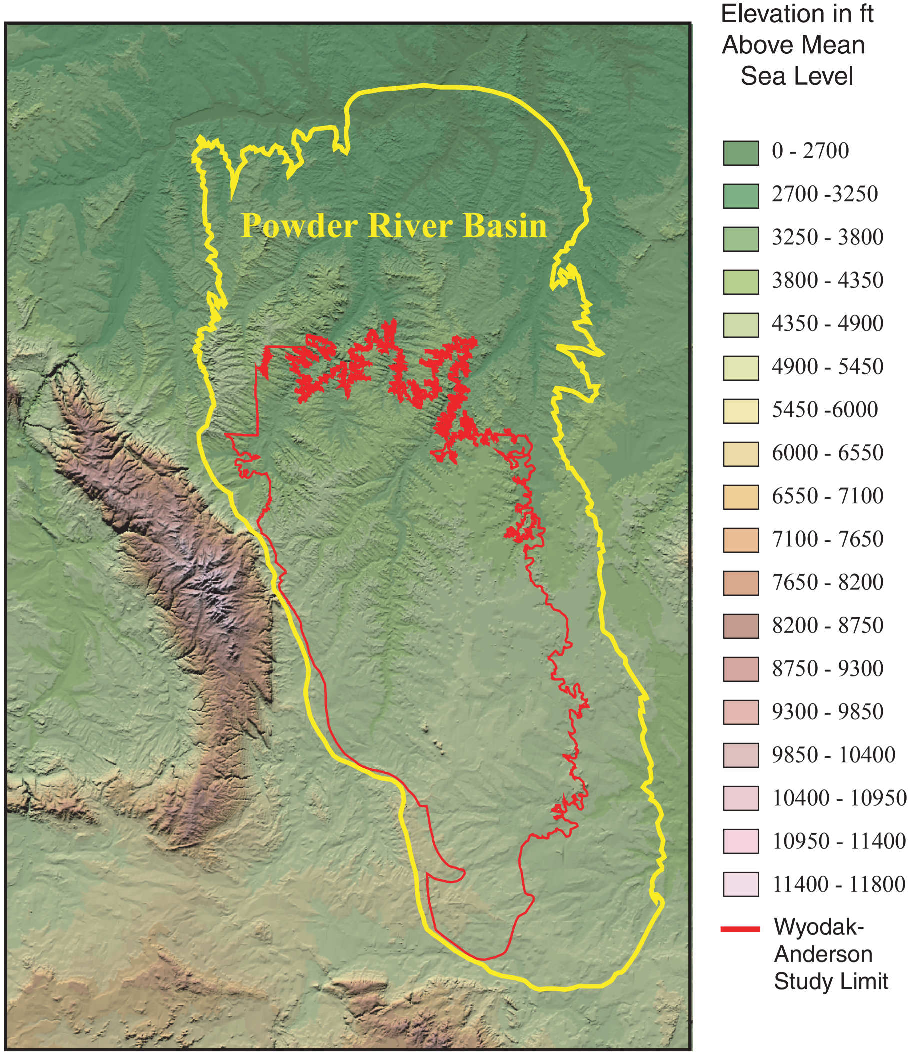

Figure 10. Shaded relief map of the Powder River Basin and vicinity showing topography generated from the DEM (Digital Elevation Model).

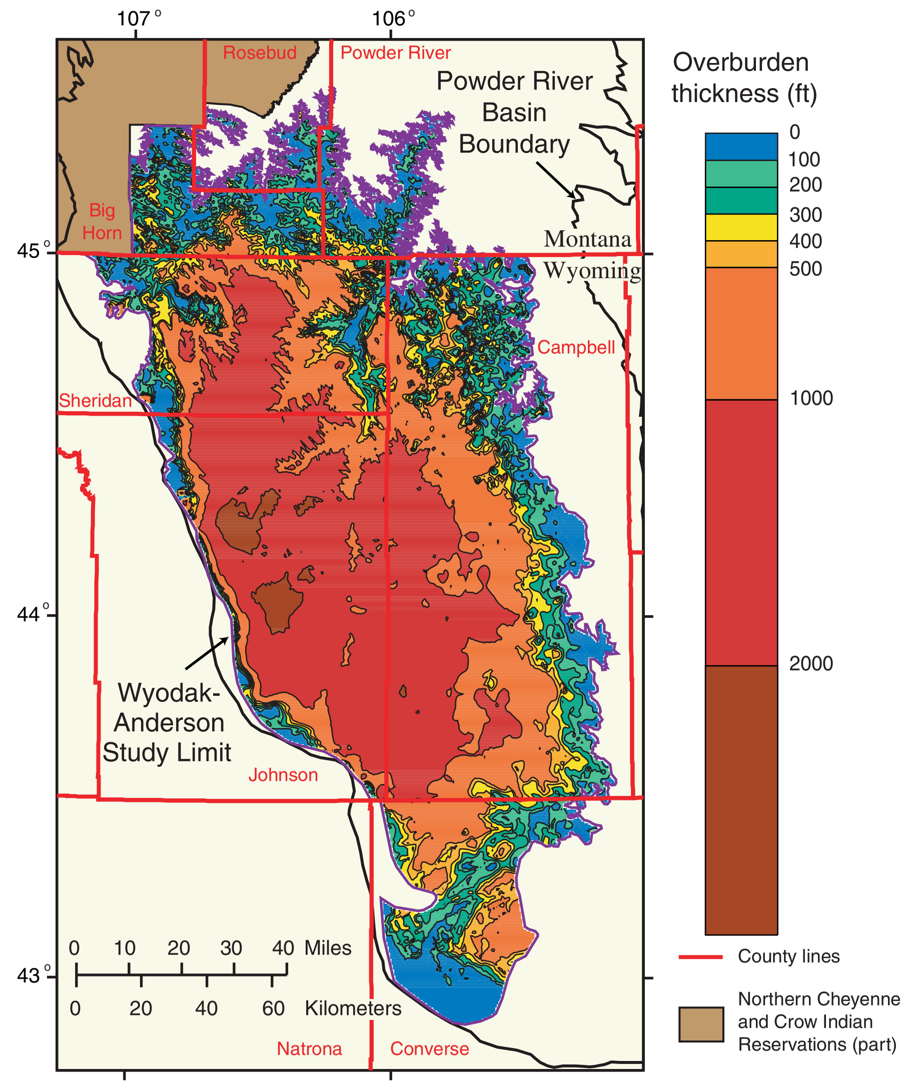

Figure 11. Map of the Wyodak-Anderson study limit in the Powder River Basin showing overburden thickness. The overburden thickness is measured from the surface to the top of the uppermost coal in the Wyodak-Anderson coal zone.

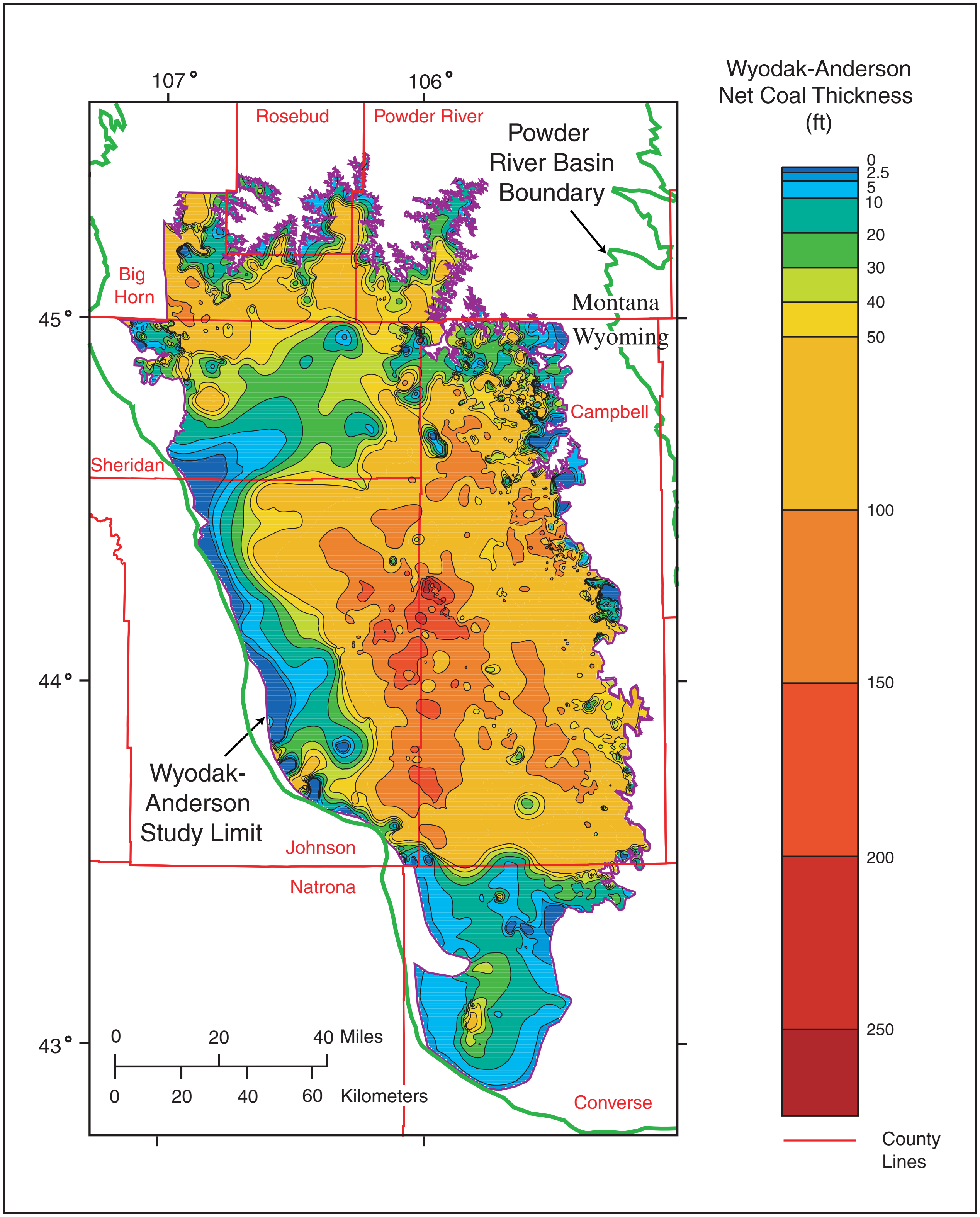

Figure 12. Net coal isopach map of the Wyodak-Anderson coal zone in the Powder River Basin, Wyoming and Montana.

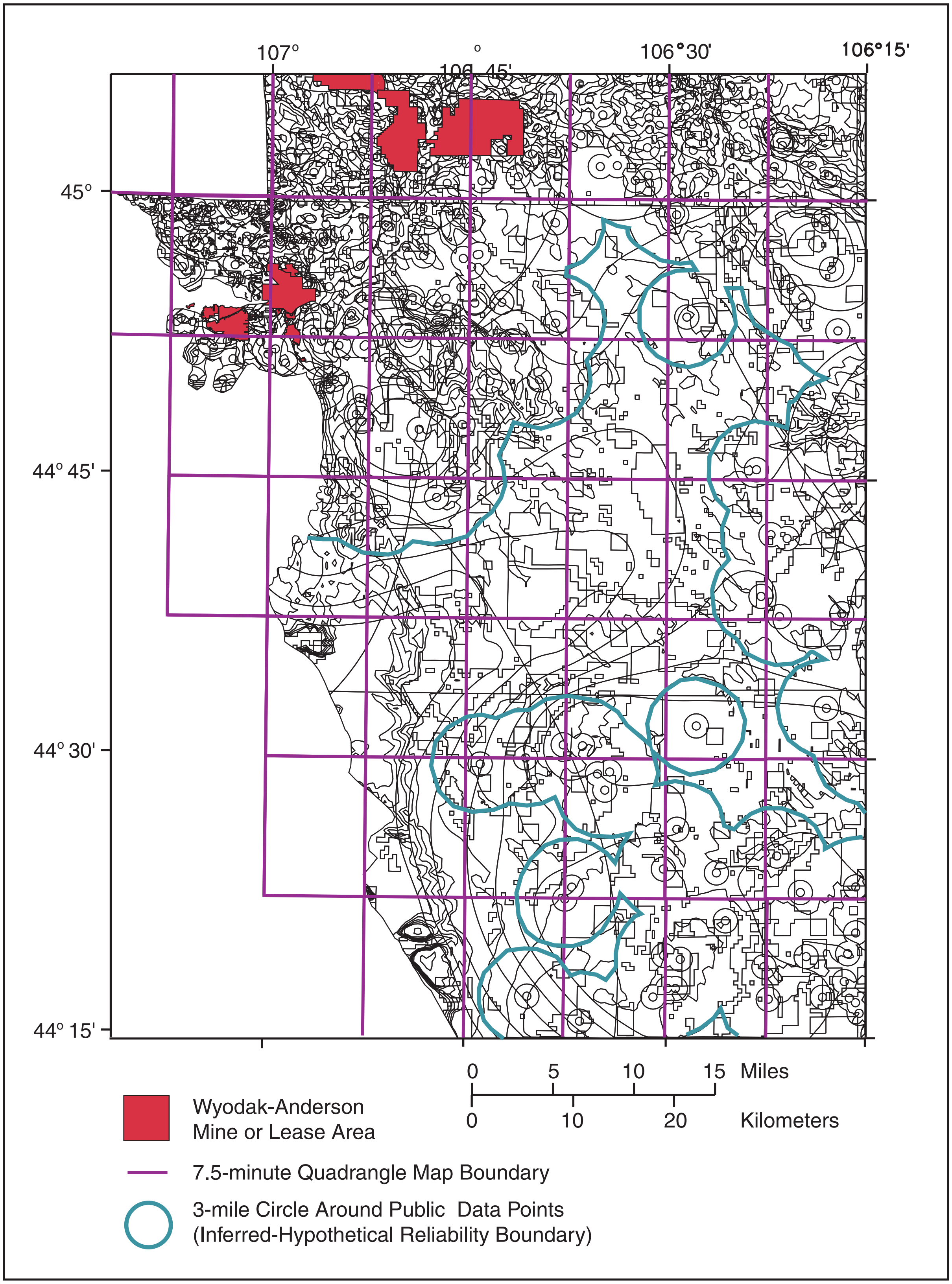

Figure 13. Map showing union coverage polygons used for the study of the Wyodak-Anderson coal zone in a portion of the study area near Sheridan, Wyoming. The mine and lease areas, 7.5-minute quadrangles, inferred-hypothetical reliability boundary are shown in color for a reference. (The coverage is too complex to effectively show each layer in a different color.)

coverage contained polygons created in EV using the isopach gridding option and the other used the polygons created using the NMT grid option. Coal resources were calculated in EV using the two union coverages and various coal thickness grids to compare the results (tables 2 through 6).

COMPARISON OF RESOURCE CALCULATIONS

For the calculation of coal resources, we tested two methods for calculating volumetrics, the ARC/INFO method and the EarthVision (Dynamic Graphics Inc., 1997) method. The ARC/INFO (ESRI, 1998a) method involved using information from the union coverage polygon attribute table to calculate the amount of short tons of coal in each polygon. The calculations could be performed in ARC/INFO, ArcView, or in relational database software or spreadsheet software. The method we used was to import the polygon attribute table(s) from the union coverage(s) into Excel (Microsoft, 1997). In Excel, we created several new calculated fields. First, we calculated the acres in each polygon by multiplying the area (in square meters) by .0002471 acres per square meter. The next field was acre-ft, which was calculated by multiplying the acres in each polygon by the mean thickness value of each polygon. The mean thickness value of polygons with attribute values of 0 to 2.5 ft was 1.25 ft, 2.5 to 5 ft was 3.75 ft, 5 to 10 ft was 7.50 ft, 10 to 20 ft was 15 ft, 20 to 30 ft was 25 ft, 30 to 40 ft was 35 ft, 40 to 50 ft was 45 ft, 50 to 100 ft was 75 ft, 100 to 150 ft was 125 ft, 150 to 200 ft was 175 ft, 200 to 250 was 225 ft, and greater than 250 ft was 275 ft. To calculate the amount of short tons of coal in each polygon, the acre-ft value was multiplied by a density conversion factor of 1,770 short tons of subbituminous coal per acre-ft (Wood and others, 1983). The polygons in areas where resources were not to be reported (Wyodak-Anderson clinker areas, mines, and lease areas, tribal land, and areas containing less than 2.5 ft of coal) were then deleted from the data set. Tables reporting coal resources by category were created using the Excel pivot table tool.

The EV method uses a combination of ARC/INFO and EV to calculate volumetrics. The polygons from the ARC/INFO union coverage were imported into EV, and the volumetrics were calculated using the area of the union coverage polygons and the grid values from the net coal thickness grid. For the comparison of coal resources calculated using different grid sizes and grid options, we imported several different coverages. To avoid problems resulting from grids created using coarse grid spacings, we used the formula processor in EV to add grid nodes to the 1,000 by 1,000-m, 800 by 800-m, and 500 by 500-m isopach and NMT grids. This operation retained the values of the coarse grids, but added grid nodes at the same spacing as the 300 by 300-m grid.

Each union coverage was brought into EV using the utility import, polygons were labeled using the polygon id, and the union coverage was saved as a polygon file. The polygon file was then selected and the projection of the data was defined in the file header. Resources were then calculated with the EV volumetrics tool, using the unioned polygon and the unclipped detailed coal thickness grid. Although calculations were performed using several different grids, the 300 by 300-m isopach grid was used for the final resource calculations. In the volumetrics utility, a 0 layer was added; the constant yield, to convert from acre-ft to short tons, was assigned as 1770; volumetrics were assigned as short tons; and the measurement was determined to be in acre-ft.

As a result of calculation, the EV volumetrics report contains header information, the polygon id, positive area, and the amount of short tons for each polygon. To modify the report, we ran it through a custom program (evrpt) to strip off the headers and calculate the net coal thickness within each polygon. The information from the volumetrics report was then merged with the union coverage polygon attribute table.

To create tables reporting resource calculations by category and combinations of attributes, we exported the ARC/INFO polygon attribute table into a spreadsheet (Excel) software program. The file was modified to include additional text fields to aid in the creation of resource tables and the tables were created using the pivot table tool. Final resource tables are included in Ellis and others, 1999. Comparisons of resource calculations performed using different grid spacings, grid options, and methods are shown in tables 1, 2, 3, 5 and 6.

Table 1. Comparison of EV coal resource calculations of the Wyodak-Anderson coal zone using 300 by 300-m isopach versus 300 by 300-m NMT grid options, reported by state and county. Resources are reported in millions of short tons (MST) rounded to three significant figures. Percentages are rounded to two significant figures. Columns will not sum to match the total due to independent rounding.

State	County	Isopach Grid Option Total (MST)	NMT Grid Option Total (MST)	Percent Difference in Unrounded MST[1]
Montana	BIG HORN	28,500	28,200	1.02%
	POWDER RIVER	10,900	10,900	0.29%
	ROSEBUD	2,790	2,650	5.1%
Montana Total		42,300	41,800	1.1%
Wyoming	CAMPBELL	282,000	282,000	0.11%
	CONVERSE	15,300	15,200	0.21%
	JOHNSON	159,000	159,000	0.22%
	SHERIDAN	52,300	52,100	0.29%
Wyoming Total		509,000	508,000	0.16%
Grand Total		551,000	550,000	0.24%

1. Percent difference in unrounded MST = (to calculate a positive percentage) subtracted the unrounded total of millions of short tons calculated using the NMT grid option from the unrounded total of millions of short tons calculated using the isopach grid option, divided by the unrounded total of millions of short tons using the isopach grid option, and multiplied the fraction by 100 to get a percentage representative of how much more MST were calculated using the isopach grid than using the NMT grid.

Table 2. Comparison of EV coal resource calculations of the Wyodak-Anderson coal zone using net coal thickness grids with different grid spacings reported by state and county. All of the grids were created using the EV isopach grid option. Resources are reported in millions of short tons (MST) with three significant figures. Percent is rounded to two significant figures. Columns will not sum to match the totals due to independent rounding.

State	County	Coal Resources in Millions of Short Tons (MST)				Maximum Percent Difference in Unrounded MST[1]
		300 by 300-m Grid Spacing	500 by 500-m Grid Spacing	800 by 800-m Grid Spacing	1,000 by 1,000-m Grid Spacing	
Montana	BIG HORN	28,500	28,600	28,600	28,700	0.41%
	POWDER RIVER	10,900	11,000	11,000	10,900	1.3%
	ROSEBUD	2,790	2,810	2,780	2,800	0.89%
Montana Total		42,300	42,400	42,400	42,400	0.41%
Wyoming	CAMPBELL	282,000	284,000	282,000	284,000	0.71%
	CONVERSE	15,300	15,200	15,400	15,200	0.89%
	JOHNSON	159,000	159,000	159,000	159,000	0.32%
	SHERIDAN	52,300	51,800	52,500	51,800	1.3%
Wyoming Total		509,000	510,000	509,000	510,000	0.30%
Grand Total		551,000	553,000	551,000	553,000	0.29%

1. Percent difference in unrounded MST = (to calculate a positive percentage) subtracted the smallest total of unrounded total of millions of short tons from the largest total of unrounded total of millions of short tons, divided by the largest unrounded total of millions of short tons, and multiplied the fraction by 100 to get a percentage representative of the maximum percent difference in millions of short tons calculated using the four different grid spacings.

Table 3. Comparison of average net coal thickness and total coal resources for the Wyodak-Anderson coal zone calculated using EarthVision (EV) versus ARC/INFO (ARC) methods, reported by state and county. The calculations for the EV method used a 300 by 300-m coal thickness isopach grid. Net coal thickness and percent are rounded to two significant figures. Resources are reported in millions of short tons (MST) with three significant figures. Resources will not sum to match totals due to independent rounding.

State	County	Data	Total	Percent Difference in Unrounded MST [5.]
Montana	BIG HORN	Average of EV net coal thk [1.]	55	
		Average of ARC net coal thk [2.]	58	
		Sum of EV MST [3.]	28,500	
		Sum of ARC MST [4.]	30,900	7.7%
	POWDER RIVER	Average of EV net coal thk [1.]	33	
		Average of ARC net coal thk [2.]	37	
		Sum of EV MST [3.]	10,900	
		Sum of ARC MST [4.]	12,200	11%
	ROSEBUD	Average of EV net coal thk [1.]	22	
		Average of ARC net coal thk [2.]	24	
		Sum of EV MST [3.]	2,790	
		Sum of ARC MST [4.]	3,070	9.1%
Montana Average of EV coal thk [1.]			41	
Montana Average of ARC coal thk [2.]			44	
Montana Sum of EV MST [3.]			42,300	
Montana Sum of ARC MST [4.]			46,200	8.6%
Wyoming	CAMPBELL	Average of EV net coal thk[1.]	63	
		Average of ARC net coal thk [2.]	65	
		Sum of EV MST [3.]	282,000	
		Sum of ARC MST [4.]	286,000	1.3%
	CONVERSE	Average of EV net coal thk [1.]	15	
		Average of ARC net coal thk [2.]	16	
		Sum of EV MST [3.]	15,300	
		Sum of ARC MST [4.]	16,200	5.6%
	JOHNSON	Average of EV net coal thk [1.]	67	
		Average of ARC net coal thk [2.]	68	
		Sum of EV MST [3.]	159,000	
		Sum of ARC MST [4.]	161,000	1.0%
	SHERIDAN	Average of EV net coal thk [1.]	35	
		Average of ARC net coal thk [2.]	36	
		Sum of EV MST [3.]	52,300	
		Sum of ARC MST [4.]	55,100	5.1%
Wyoming average of EV net coal thk [1.]			52	
Wyoming average of ARC net coal thk [2.]			54	
Wyoming sum of EV MST [3.]			509,000	
Wyoming sum of ARC MST [4.]			518,000	1.8%

Table 3. Continued.

Montana and Wyoming	Total	Percent Difference in Unrounded MST [5.]
Total average of EV net coal thk [1.]	50	
Total average of ARC net coal thk [2.]	52	
Total sum of EV MST [3.]	551,000	
Total sum of ARC MST [4.]	564,000	2.3%

[1.] EV coal thk = net coal thickness calculated from the short tons and the positive area from the EV volumetrics.

[2.] ARC coal thk = net coal thickness of the polygons. Represented by the mean value between the contour lines produced in EV and imported into ARC/INFO to produce the net coal isopach coverage. The level of detail decreases with increased coal thickness. Polygon categories for calculations (and corresponding thickness ranges) in ft are 2.5 to 5 (3.75), 5 to 10 (7.5), 10 to 20 (15), 20 to 30 (25), 30 to 40 (35), 40 to 50 (45), 50 to 100 (75), 100 to 150 (125), 150 to 200 (175), 200 to 250 (225), 250 to 300 (275).

[3.] EV MST = coal resources (in millions of short tons) taken from the number of short tons from the EV volumetrics report divided by 1,000,000.

[4.] ARC MST = coal resources (in millions of short tons) calculated from the area of the polygons (in square meters) multiplied by .0002471 acres per square meter to calculate acres, acres multiplied by ARC coal thk to calculate acre-ft, acre-ft multiplied by 1,770 short tons of subbituminous coal per acre-ft to calculate short tons, and short tons divided by 1,000,000 to calculate millions of short tons.

[5.] Percent difference in unrounded MST = (to calculate a positive percentage) subtracted the unrounded total of millions of short tons calculated using the EV method from the unrounded total of millions of short tons calculated using the ARC/INFO method, divided by the unrounded total of millions of short tons using the ARC/INFO method, and multiplied the fraction by 100 to get a percentage representative of how much more MST were calculated using the ARC/INFO method than using the EV method.

Table 4. Key to 7.5-minute quadrangle maps in the study area. Map locations are shown in figure 7.

Number	7.5-minute Quadrangle Map	Number	7.5-minute Quadrangle Map
1	COOK CREEK BUTTE	56	CORRAL CREEK
2	CLUBFOOT CREEK	57	HOMESTEAD DRAW
3	BIRNEY DAY SCHOOL	58	ROCKY BUTTE
4	GREEN CREEK	59	HULTZ DRAW
5	KING MOUNTAIN	60	SHERIDAN
6	THREEMILE BUTTES	61	WYARNO
7	SONNETTE	62	JONES DRAW
8	SPRING CREEK RANCH	63	S R SPRINGS
9	KIRBY	64	SHULER DRAW
10	TAINTOR DESERT	65	GARDNER GULCH
11	BIRNEY SW	66	FAWN DRAW
12	BIRNEY	67	CABIN CREEK SE
13	BROWNS MOUNTAIN	68	KLINE DRAW
14	POKER JIM BUTTE	69	RESERVOIR CREEK
15	FORT HOWES	70	HOMESTEAD DRAW SW
16	GOODSPEED BUTTE	71	WHITE TAIL BUTTE
17	PHILLIPS BUTTE	72	ROCKY BUTTE SW
18	HODSDON FLATS	73	BEAVER CREEK HILLS
19	BAR V RANCH NE	74	BIG HORN
20	HALF MOON HILL	75	BUFFALO RUN CREEK
21	TONGUE RIVER DAM	76	VERONA
22	SPRING GULCH	77	ULM
23	LACEY GULCH	78	CLEARMONT
24	STROUD CREEK	79	LEITER
25	HAMILTON DRAW	80	ARVADA
26	OTTER	81	ARVADA NE
27	REANUS CONE	82	LAREY DRAW
28	SAYLE	83	SPOTTED HORSE
29	BLOOM CREEK	84	RECLUSE
30	LITTLE BEAR CREEK	85	PITCH DRAW
31	BAR V RANCH	86	OLIVER DRAW
32	PEARL SCHOOL	87	STORY
33	DECKER	88	BANNER
34	HOLMES RANCH	89	HORSE HILL
35	PINE BUTTE SCHOOL	90	UCROSS
36	FORKS RANCH	91	JULIO DRAW
37	QUIETUS	92	ARPAN BUTTE
38	BEAR CREEK SCHOOL	93	JEWELL DRAW
39	SAYLE HALL	94	LARIAT
40	BRADSHAW CREEK	95	CROTON
41	MOORHEAD	96	TRUMAN DRAW
42	THREE BAR RANCH	97	WILDCAT
43	BAY HORSE	98	CALF CREEK
44	RANCHESTER	99	WESTON SW
45	MONARCH	100	STONE MOUNTAIN
46	ACME	101	LAKE DE SMET WEST
47	BAR N DRAW	102	LAKE DE SMET EAST
48	CEDAR CANYON	103	BUFFALO NE
49	O T O RANCH	104	FREDRICK DRAW
50	ROUNDUP DRAW	105	FLOATE DRAW
51	BOX ELDER DRAW	106	MITCHELL DRAW
52	CABIN CREEK NW	107	LIVINGSTON DRAW
53	CABIN CREEK NE	108	ECHETA
54	BLACK DRAW	109	TWENTYMILE BUTTE
55	DEAD HORSE LAKE	110	ORIVA NW

Table 4. Continued.

Number	7.5-minute Quadrangle Map	Number	7.5-minute Quadrangle Map
111	RAWHIDE SCHOOL	165	FOURMILE RESERVOIR
112	MOYER SPRINGS	166	SOLDIER CREEK
113	NORTH RIDGE	167	FORT RENO
114	BUFFALO	168	FORT RENO SE
115	BUFFALO SE	169	NORTH BUTTE
116	PINE GULCH	170	SAVAGETON
117	BEAR DRAW	171	GREASEWOOD RESERVOIR
118	SOMERVILLE FLATS WEST	172	ROCKY BUTTE GULCH
119	SOMERVILLE FLATS EAST	173	RENO JUNCTION
120	CARR DRAW	174	HILIGHT
121	JEFFERS DRAW	175	OPEN A RANCH
122	ORIVA	176	KAYCEE NE
123	GILLETTE WEST	177	FIGURE 8 RESERVOIR
124	GILLETTE EAST	178	SUSSEX
125	FORTIN DRAW	179	HOUSE CREEK
126	KLONDIKE RANCH	180	DRY FORK RANCH
127	T A RANCH	181	ROLLING PIN RANCH
128	TA RANCH NE	182	SOUTH BUTTE
129	CRAZY WOMAN RANCH	183	BAKER SPRING
130	PLOESSERS DRAW	184	RATTLESNAKE DRAW
131	JUNIPER DRAW	185	LITTLE THUNDER RESERVOIR
132	LASKIE DRAW	186	RENO RESERVOIR
133	MORGAN DRAW	187	PINEY CANYON NW
134	SCOTT DAM	188	LINCH
135	FOUR BAR J RANCH	189	TAYLOR RANCH
136	APPEL BUTTE	190	ARTESIAN DRAW
137	THE GAP	191	PINE TREE
138	COYOTE DRAW	192	TURNERCREST
139	COON TRACK CREEK	193	RENO FLATS
140	PURDY RESERVOIR	194	TECKLA SW
141	TRABING	195	TECKLA
142	BROWN RANCH	196	PINEY CANYON SW
143	BOON	197	SAWMILL CANYON
144	BOWMAN FLAT	198	ROSS
145	NEGRO BUTTE	199	ROSS FLAT
146	BOGIE DRAW	200	MACKEN DRAW
147	DOUBLE TANKS	201	COAL DRAW NORTH
148	PLEASANTDALE	202	BETTY RESERVOIR
149	SCAPER RESERVOIR	203	DUGOUT CREEK NORTH
150	THE GAP SW	204	COAL BANK DRAW
151	SADDLE HORSE BUTTE	205	GILLAM DRAW EAST
152	ANTELOPE DRAW	206	MARSH DRAW
153	ELAINE DRAW	207	THOMPSON DRAW
154	PROVENCE RANCH	208	BEAR CREEK
155	HOE RANCH	209	COAL DRAW SOUTH
156	THE NIPPLE	210	ALTA CREEK
157	FATS DRAW	211	DUGOUT CREEK SOUTH
158	WAGS PINNACLE	212	SEVEN L CREEK EAST
159	PEPSSON DRAW	213	FLY DRAW
160	THREEMILE CREEK RESERVOIR	214	SOUTH FORK RESERVOIR
161	EAGLE ROCK	215	SUICIDE HILL
162	NEIL BUTTE	216	RED HILL
163	ROUGH CREEK	217	PATSY DRAW
164	DRY CREEK RESERVOIR	218	BEAUCHAMP RESERVOIR

Table 4. Continued.

Number	7.5-minute Quadrangle Map
219	GUMBO HILL
220	COAL HILL
221	HOLDUP HOLLOW
222	WHIPPLE HOLLOW
223	BOBBY DRAW
224	GLENROCK NW
225	HYLTON RANCH
226	LEUENBERGER RANCH
227	GILBERT LAKE

Table 5. Comparison of EV coal resource calculations of the Wyodak-Anderson coal zone using 300 by 300-m isopach versus 300 by 300-m NMT grid options, reported by coal thickness categories. Resources are reported in millions of short tons (MST) rounded to three significant figures. Percentages are rounded to two significant figures. Columns will not sum to match the totals due to independent rounding.

Net Coal Thickness Categories	Isopach Grid Option Total (MST)	NMT Grid Option Total (MST)	Percent Difference in Unrounded MST[1]
2.5-5 ft	1,040	1,080	3.5%
5-10 ft	6,030	6,380	5.5%
10-20 ft	16,600	17,600	5.8%
20-30 ft	23,100	23,000	0.78%
30-40 ft	26,000	25,500	1.7%
40-50 ft	34,500	34,400	0.29%
50-100 ft	259,000	258,000	0.65%
100-150 ft	147,000	147,000	0.23%
150-200 ft	33,000	33,000	0.032%
200-250 ft	3,580	3,580	0.0055%
250-300 ft	607	607	0.00050%
Grand Total (MST)	551,000	550,000	0.24%

1. Percent difference in unrounded MST = (to calculate a positive percentage) subtracted the unrounded total of millions of short tons calculated using the NMT grid option from the unrounded total of millions of short tons calculated using the isopach grid option, divided by the unrounded total of millions of short tons using the isopach grid option, and multiplied the fraction by 100 to get a percentage representative of how much more MST were calculated using the isopach grid than using the NMT grid.

Table 6. Comparison of coal resources for the Wyodak-Anderson coal zone calculated using EV versus ARC/INFO methods, reported by coal thickness categories. The EV method used a 300 by 300-m isopach grid for the resource calculations. Resources are reported in millions of short tons (MST) and rounded to three significant figures. Percent is rounded to two significant figures. Resources will not sum to match the totals due to independent rounding.

Net Coal Thickness Category	Total Resource EarthVision Method (MST)	Total Resource ARC Method (MST)	Percent Difference in Unrounded MST[1]
2.5-5 ft	1,040	960	7.8%
5-10 ft	6,029	6,040	0.22%
10-20 ft	16,600	17,000	2.6%
20-30 ft	23,100	23,400	1.2%
30-40 ft	26,000	26,000	0.11%
40-50 ft	34,500	34,100	1.3%
50-100 ft	259,000	261,000	0.78%
100-150 ft	147,000	156,000	5.6%
150-200 ft	33,000	35,000	5.8%
200-250 ft	3,580	3,660	2.2%
250-300 ft	607	636	4.7%
Grand Total (MST)	551,000	564,000	2.3%

1. Percent difference in unrounded MST = (to calculate a positive percentage) subtracted the smallest unrounded total of millions of short tons from the largest unrounded total of millions of short tons, divided by the largest unrounded total of millions of short tons, and multiplied the fraction by 100 to get a percentage representative of how much more MST were calculated using one method verses the other.

CONFIDENCE LIMITS

A confidence interval is a statistical assessment of the uncertainty associated with a point estimate. In this study, we computed 90-percent confidence intervals on the volume of coal in the Wyodak-Anderson coal zone in the measured, indicated, inferred, and hypothetical categories.

The three main potential sources of error that might bias the confidence interval are preferential sampling, measurement errors, and model fitting. The probabilistic interpretation of a confidence interval is based upon a random sample; which is not the case for the Wyodak-Anderson coal zone in the Powder River Basin, because there is preferential sampling in the areas where coal is considered to be minable. Measurement error can be caused by an error in recording coal bed thickness or defining coverage areas. Model fitting variability and bias result from the choice of models and fitting procedures.

Confidence limits for coal resources of the Wyodak-Anderson coal zone were calculated by John Schuenemeyer and Helen Power (University of Delaware), using a data set containing net coal measurements from 4,462 drill hole locations. The data set did not include data from terminated drill holes, data points with coal less than 2.5 ft thick, or EarthVision interpretive points.

Confidence limits were derived through a complex series of steps. These steps included modeling coal thickness trends and removing the trends by using a nonparametric, regression algorithm called loess. Residual thickness was then used to compute a semivariogram and the semivariogram was fitted to an exponential model to determine measurement error. Standard deviations of coal thickness were calculated from the semivariogram model. Differences in point densities were compensated for by calculating a pseudo n (described in 5. below) within each reliability category and calculating the variability of volume for each of the reliability categories. Resources (in millions of short tons (MST)) were then calculated for the coal within different reliability categories at a 90-percent confidence interval with measurement error. Parameters used and the results of confidence limit calculations are shown in table 7.

A detailed description of the methodology is given in Schuenemeyer and Power (in press). The following steps were used for calculating the confidence limits for the Wyodak-Anderson coal zone.

1. We investigated large-scale changes in coal zone thickness and found that coal was thicker in the center of the study area. This trend was partially removed (R^2=0.49), using a nonparametric regression algorithm called loess, utilizing the Splus software program (Mathsoft Inc., 1998). The resulting residual thicknesses were used in subsequent analyses.
2. A study of spatial variation was performed using variograms and other geostatistical tools to determine and model spatial correlation. An empirical omnidirectional semivariogram was computed on residual thicknesses. This semivariogram provided information on changes in the variability of residual thicknesses as a function of distance between drill holes. Neither geometric nor zonal anisotropy was found to exist to any significant degree.
3. The semivariogram was fitted to an exponential model using a nonlinear least squares procedure. The fitted values were sill=529.75 ft, nugget=212.04 ft, and range=2.357 ft. Since the measurement error appeared excessively large, an exogenously supplied value of s_M = 4.33 ft was used. The choice of a value for measurement error is not critical, because only the sampling plus measurement error is reported.
4. Values of the standard deviations of thicknesses (s_h) were obtained at 0.25, 0.75, and 3.00 miles from the exponential model described above. These corresponded to circles generated by the reliability categories of measured, indicated, and inferred respectively (Wood and others, 1983). The standard deviation values for the measured, indicated, and inferred reliability categories are 18.88 ft, 23.19 ft, and 27.02 ft. The square root of the sill plus nugget effects of 26.89 ft is used for the hypothetical category.
5. An estimate of the variability of the volume V (total resource in millions of short tons (MST)) of a given reliability category, including measurement error, is $s_C^2 = (kA)^2(s_h^2 + \hat{\sigma}_\varepsilon^2)/n^*$, where k is the coal density in short tons per acre-ft, A is the area of the reliability category in meters squared, s_h^2 is the estimated variance of the thickness at distance h (taken from the semivariogram model), and n^* (pseudo n) is the number of pseudo data points. This latter number, $n^* = A/(\pi r^2)$ with r equal to the radius of the reliability category (0.25 mi, 0.75 mi, or 3.00 mi). This n^* was computed because of the clustered nature of the drilling and the fact that the indicated and inferred categories do not contain data points. It is a conservative estimate of the minimum number of data points influencing the calculation of coal volume for the area within each reliability category. For the hypothetical category, n^*=1.
6. The 90% confidence interval estimate on V for a given category is $V \pm 1.645 s_c$.
7. The estimate of uncertainty on the total volume V_T was obtained by summing estimates of variance across the four reliability categories and pairwise covariation, assuming a dependence of 1.0.

The following table (table 7) shows the parameters used and the results of the confidence interval calculations for the Wyodak-Anderson coal zone at a 90 percent confidence level. Total coal resources for the Wyodak-Anderson coal zone, calculated independently and rounded to four significant figures is 550,700 million short tons. The lower and upper confidence limits at a 90% confidence interval for the Wyodak-Anderson coal are 459,300 and 642,100 million short tons respectively.

Table 7. Wyodak-Anderson confidence limits parameters and results. Resources are reported in millions of short tons (MST) with four significant figures. Resources will not sum to match the totals for the entire area due to independent rounding.

Parameter	Reliability Category				Entire Area
	Measured	Indicated	Inferred	Hypothetical	
Area (in meters^2)	1,488,759,443	5,670,020,546	11,140,313,431	3,612,068,158	21,911,161,578
Percent of Area	7	26	51	16	100
Acres (=Area x .0002471)	367,880	1,401,092	2,752,831	892,561	5,414,365
Standard Deviation (SD) (in ft, from semivariogram model)	18.38	22.78	26.67	26.89	
Acre-ft (Acres x SD)	6,759,910	31,921,428	73,423,804	24,000,492	
Volume (MST)	43,670	167,700	303,700	35,610	550,700
Pseudo n					
n*= Minimum Number of Points in Category Area	2,928	1,239	152	1	
Estimates of Uncertainty With Measurement Error Included	Reliability Category				Entire Area
	Measured	Indicated	Inferred	Hypothetical	
Volume SD (MST)	227	1,634	10,675	43,028	55,564
Half Interval Width (90 % confidence interval)	374	2,688	17,560	70,781	91,403
Lower 90 % Confidence Limit (MST)	43,300	165,000	286,100	0	459,300
Upper 90 % Confidence Limit (MST)	44,050	170,400	321,200	106,400	642,100
% Error ((Half interval width / Volume) * 100)	0.86	1.60	5.78	198.75	16.60

(Coal density =1,770 short tons/acre-ft of subbituminous coal, n=4,462, measurement error standard deviation=4.33 ft, sill=529.75 ft^2, nugget=212.04 ft^2, range=2.357 mi (from exponential semivariogram model))

CONCLUSION

Although the methods used by the USGS for calculating coal resources in different study areas vary, it appears that the methods tested here did not have a great effect on the total amount of resources calculated. According to our comparisons of calculations using different parameters and methods (tables 2 through 6), the greatest difference resulted from the use of ARC/INFO volumetrics calculations versus EarthVision calculation methods. In our study, as shown in table 5, more resources were calculated using the ARC/INFO method (2.3% more overall, 1.8% more in Wyoming and 8.6% more in Montana.)

Table 5 also shows that the average coal thickness values used in the ARC/INFO method are consistently higher than the thickness values used in the EarthVision method. The ARC/INFO method assigns one value (the mean of the bounding isoline values to the entire polygon, whereas the EarthVision method uses many thickness values within each polygon. Coal resource values are ordinarily rounded to two significant figures. Upon examining the amount of short tons calculated using the two methods, we found that after rounding the resource values there was very little difference between totals derived via the two methods.

The resource calculations reported by county for different grid spacings, using the EarthVision method and the isopach grid option, were very similar (table 4). The maximum percent difference by county was 1.3% in Powder River County in Montana and Sheridan County in Wyoming. The percent difference in the resource totals for the entire area was only 0.29%.

The difference in calculations using the isopach grid option versus the NMT grid option (table 2) was only 0.24% overall, with a maximum difference of 5.1% in Rosebud County, Montana. The percent difference by county was generally less than 1%.

The results of our study show that although various parameters and methods may be used by different workers in the National Coal Resource Assessment nation-wide, the products resulting from these decisions show only minor differences in total resource values. The character of the data being modeled and personal preference, knowledge, and skills should determine how the resources are calculated in different areas. Because the studies differ in many ways, it is particularly important for each of the National Coal Resource studies to document the methods used, and what the resource numbers represent.

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APPENDIX

The following EV grid reports show all thickness values in feet and all x values, y values, and grid spacings in meters. Items of particular interest for selecting the appropriate grid for use in our study are shown in bold type. The negative coal thickness values shown in the isopach grid reports indicate that there was information used from drill holes that terminated before the entire Wyodak-Anderson coal zone interval was penetrated. Negative thickness is treated as a “greater than” value in the EV isopach gridding option.

Default Grid Spacing (3,520 x 3,606 m) Isopach Grid:

Net coal thickness mean value:	47.79927	
Standard deviation of Net coal thickness:	54.63241	
Number of data points:	**5414**	
Number of points outside of study boundary:	0	
Number of null data points:	0	
Number of invalid points:	0	
Number of points with comments attached:	54	
Number of faults:	0	
Number of points used as multiple data points:	2139	
Number of points used for grid:	**3206**	
Range of X values:	-91438.23	68419.46
Range of Y values:	5053588	5340636
Range of net coal thickness values:	-169	284
Range of grid X values:	-145000	140525
Range of grid Y values:	5020000	5464276
Range of grid net coal thickness values:	1	249.5273
Mean net coal thickness value in grid:	16.17833	
Standard deviation of net coal thickness value in grid:	28.89987	
Number of null nodes in grid:	0	
Average absolute Z error of net coal thickness:	12.24746	**(3.446739%)**
Standard deviation of Z error (net coal thickness):	14.14046	
Maximum Z error:	113.1543	(31.84442%)
Maximum error of X, Y, and Z values:	175.7812	5191852 51

Default Grid Spacing (3,520 X 3,606 m) NMT Grid:

Net coal thickness mean value:	62.81982
Standard deviation of Net coal thickness:	41.69276
Number of data points:	**4622**
Number of points outside of study boundary:	0
Number of null data points:	0
Number of invalid points:	0
Number of points with comments attached:	72
Number of faults:	0
Number of points used as multiple data points:	1952

Number of points used for grid:	**2670**		
Range of X values:	-91438.23	68419.46	
Range of Y values:	5053588	5340636	
Range of net coal thickness values:	0	284	
Range of grid X values:	-145000	140525	
Range of grid Y values:	5020000	5464276	
Range of grid net coal thickness values:	1	249.5275	
Mean net coal thickness value in grid:	16.70028		
Standard deviation of net coal thickness value in grid:	28.86244		
Number of null nodes in grid:	0		
Average absolute Z error of net coal thickness:	11.98783	**(3.289279%)**	
Standard deviation of Z error (net coal thickness):	14.26603		
Maximum Z error:	113.1543	(31.04782%)	
Maximum error of X, Y, and Z values:	175.7812	5191852	51

Many of the data points in the Powder River Basin are very closely spaced. The default grid spacing of 3,520 by 3,606 meters was so large that many of the data points were not used in creating the grids. With the default grid spacing, 3,206 out of 5,414 (59%) points were used for the isopach grid, and 2,670 out of 4,622 (58%) data points were used for the NMT grid. The average absolute z error was relatively high, about 3.4% for the isopach gridding and 3.3% for the NMT gridding. The isopach grid and the NMT grid isopach maps look very similar in their general configuration. Both isopach maps contain contours that appear to lack detail. The isopach gridding option used more data points to create the grid. Because the grids produced applying the default grid spacing used only about 50 percent of the data points, these grids were considered unacceptable. An isopach map created using the default grid spacing is shown in map A. on figure 4.

1,000 x 1,000-m Grid Spacing Isopach Grid:

Net coal thickness mean value:	47.79927		
Standard deviation of Net coal thickness:	54.63241		
Number of data points:	**5414**		
Number of points outside of study boundary:	0		
Number of null data points:	0		
Number of invalid points:	0		
Number of points with comments attached:	54		
Number of faults:	0		
Number of points used as multiple data points:	397		
Number of points used for grid:	**4948**		
Range of X values:	-91438.23	68419.46	
Range of Y values:	5055261	5340636	
Range of net coal thickness values:	-169	284	
Range of grid X values:	-145000	137000	
Range of grid Y values:	5020000	5461000	
Range of grid net coal thickness values:	1	273.6533	
Mean net coal thickness value in grid:	16.76521		
Standard deviation of net coal thickness value in grid:	29.0988		
Number of null nodes in grid:	0		
Average absolute Z error of net coal thickness:	6.074759	**(1.277415%)**	
Standard deviation of Z error (net coal thickness):	9.96925		
Maximum Z error:	110.1821	(23.16936%)	
Maximum error of X, Y, and Z values:	38742.17	5218148	195.1

1,000 x 1,000-m Grid Spacing Normal Minimal Tension Grid:

Net coal thickness mean value: 62.81982
Standard deviation of Net coal thickness: 41.69276
Number of data points: **4622**
Number of points outside of study boundary: 0
Number of null data points: 0
Number of invalid points: 0
Number of points with comments attached: 72
Number of faults: 0
Number of points used as multiple data points: 354
Number of points used for grid: **4268**
Range of X values: -91438.23 68419.46
Range of Y values: 5053588 5340636
Range of net coal thickness values: 0 284
Range of grid X values: -145000 138000
Range of grid Y values: 5020000 5462000
Range of grid net coal thickness values: 1 273.6533
Mean net coal thickness value in grid: 17.49016
Standard deviation of net coal thickness value in grid: 29.19929
Number of null nodes in grid: 0
Average absolute Z error of net coal thickness: 5.730798 **(1.242115%)**
Standard deviation of Z error (net coal thickness): 9.842724
Maximum Z error: 114.4404 (24.80426%)
Maximum error of X, Y, and Z values: 40488.47 5218509 0

The 1,000 by 1,000-m grid spacing was still relatively coarse, and although it used more points than the default grid spacing, it still used only 4,948 out of 5,414 (91%) data points for the isopach grid and 4,268 out of 4,622 (92%) points for the NMT grid. The average absolute z error of 1.3% for the isopach grid, and 1.2% for the NMT grid, was less than half of the average z error produced using both of the grid options and the default grid spacing,

The isopach grid and NMT grid isopach maps looked very similar and both honored just over 90% of the data. Although the grids produced using the 1,000 by 1,000-m grid were more accurate than those produced using the default grid spacing, we determined that a higher level of accuracy was preferable. Smaller grid sizes were therefore tested.

800 x 800-m Grid Spacing Isopach Grid:

Net coal thickness mean value: 47.79927
Standard deviation of Net coal thickness: 54.63241
Number of data points: **5414**
Number of points outside of study boundary: 0
Number of null data points: 0
Number of invalid points: 0
Number of points with comments attached: 54
Number of faults: 0
Number of points used as multiple data points: 233
Number of points used for grid: **5112**
Range of X values: -91438.23 68419.46
Range of Y values: 5053588 5340636
Range of net coal thickness values: -169 284

Range of grid X values:	-145000	137400	
Range of grid Y values:	5020000	5461600	
Range of grid net coal thickness values:	1	280.7725	
Mean net coal thickness value in grid:	21.59612		
Standard deviation of net coal thickness value in grid:	31.2261		
Number of null nodes in grid:	0		
Average absolute Z error of net coal thickness:	5.258592	**(1.061217%)**	
Standard deviation of Z error (net coal thickness):	9.294349		
Maximum Z error:	98.57388	(19.89284%)	
Maximum error of X, Y, and Z values:	41957.84	5218820	3.3

800 x 800-m Grid Spacing NMT Grid:

Net coal thickness mean value:	62.81982		
Standard deviation of Net coal thickness:	41.69276		
Number of data points:	**4622**		
Number of points outside of study boundary:	0		
Number of null data points:	0		
Number of invalid points:	0		
Number of points with comments attached:	72		
Number of faults:	0		
Number of points used as multiple data points:	207		
Number of points used for grid:	**4415**		
Range of X values:	-91438.23	68419.46	
Range of Y values:	5053588	5340636	
Range of net coal thickness values:	0	284	
Range of grid X values:	-145000	137400	
Range of grid Y values:	5020000	5461600	
Range of grid net coal thickness values:	1	280.7725	
Mean net coal thickness value in grid:	21.88455		
Standard deviation of net coal thickness value in grid:	31.35258		
Number of null nodes in grid:	0		
Average absolute Z error of net coal thickness:	4.937365	**(1.030353%)**	
Standard deviation of Z error (net coal thickness):	9.09726		
Maximum Z error:	96.8564	(20.21246%)	
Maximum error of X, Y, and Z values:	46637.77	5217112	142

We created new grids with grid spacings of 800 by 800 m. These grids used more data points than the previous grids. The isopach grid used 5,112 out of 5,414 (94%) data points and the NMT grid used 4,415 out of 4,622 (96%) data points. The average absolute grid error was 1.1% for the isopach grid and 1.0% for the NMT grid. The isopach grid and the NMT grid isopach maps look very similar in their general configuration. The average absolute z error was slightly higher for the isopach grid, and although it used 697 more data points than the NMT grid, it used a smaller percentage of data points to produce the final grid. Because over 200 data points were still not being used to create these grids, we continued to test grids with smaller grid spacings.

500 x 500-m Grid Spacing Isopach Grid:

Net coal thickness mean value: 47.79927
Standard deviation of Net coal thickness: 54.63241
Number of data points: **5414**
Number of points outside of study boundary: 0
Number of null data points: 0
Number of invalid points: 0
Number of points with comments attached: 54
Number of faults: 0
Number of points used as multiple data points: 86
Number of points used for grid: **5259**
Range of X values: -91438.23 68419.46
Range of Y values: 5053588 5340636
Range of net coal thickness values: -169 284
Range of grid X values: -145000 137000
Range of grid Y values: 5020000 5461000
Range of grid net coal thickness values: 1 274.9012
Mean net coal thickness value in grid: 17.15658
Standard deviation of net coal thickness value in grid: 29.54831
Number of null nodes in grid: 0
Average absolute Z error of net coal thickness: 3.613605 **(0.7492247%)**
Standard deviation of Z error (net coal thickness): 7.461863
Maximum Z error: 99.39446 (20.6079%)
Maximum error of X, Y, and Z values: 40368.98 5218378 132.6

500 x 500-m Grid Spacing NMT Grid:

Net coal thickness mean value: 62.81982
Standard deviation of Net coal thickness: 41.69276
Number of data points: **4622**
Number of points outside of study boundary: 0
Number of null data points: 0
Number of invalid points: 0
Number of points with comments attached: 72
Number of faults: 0
Number of points used as multiple data points: 60
Number of points used for grid: **4562**
Range of X values: -91438.23 68419.46
Range of Y values: 5053588 5340636
Range of net coal thickness values: 0 284
Range of grid X values: -145000 137000
Range of grid Y values: 5020000 5461000
Range of grid net coal thickness values: 1 274.9018
Mean net coal thickness value in grid: 17.94645
Standard deviation of net coal thickness value in grid: 29.6714
Number of null nodes in grid: 0
Average absolute Z error of net coal thickness: 3.313015 **(0.7053525%)**
Standard deviation of Z error (net coal thickness): 6.931679
Maximum Z error: 84.64108 (18.02038%)
Maximum error of X, Y, and Z values: 41957.84 5218820 3.3

The grids produced with the 500 by 500-m grid spacing used many more data points than the grids produced with coarser grid spacings. The 500 by 500-m grids used 5,259 out of 5,414 (97%) data points using the isopach grid option and 4,562 out of 4,622 (99%) data points using the NMT grid option. Many of the data points in the Powder River Basin are very closely spaced, especially in the areas of active mining. The average absolute z error was 0.7% for the grids produced using both grid options. This is considerably less z error than in the previous grids tested. The isopach grid and the NMT grid isopach maps look very similar in their general configuration. It was decided that the level of detail using this grid spacing was acceptable for use in making the polygons for the net coal isopach coverage in ARC/INFO.

In testing the grids with 500 by 500-m grid spacing, we found that although the net coal thickness polygon coverages created using both grid options were satisfactory; we had problems using the 500 by 500-m grid when calculating volumetrics in the EarthVision program. As explained previously, in order to calculate volumetrics in EarthVision there must be at least one grid node within a polygon. The 500 by 500-m grid was not fine enough to meet this criteria. We therefore tested smaller grids using 300 by 300-m grid spacing.

300 x 300-m Grid Spacing Isopach Grid:

Net coal thickness mean value: 47.79927
Standard deviation of Net coal thickness: 54.63241
Number of data points: **5414**
Number of points outside of study boundary: 0
Number of null data points: 0
Number of invalid points: 0
Number of points with comments attached: 54
Number of faults: 0
Number of points used as multiple data points: 21
Number of points used for grid: **5324**
Range of X values: -91438.23 68419.46
Range of Y values: 5053588 5340636
Range of net coal thickness values: -169 284
Range of grid X values: -145000 137000
Range of grid Y values: 5020000 5460700
Range of grid net coal thickness values: 1 285
Mean net coal thickness value in grid: 18.5292
Standard deviation of net coal thickness value in grid: 29.25462
Number of null nodes in grid: 0
Average absolute Z error of net coal thickness: 2.302457 **(0.4728865%)**
Standard deviation of Z error (net coal thickness): 5.775553
Maximum Z error: 98.81242 (20.29061%)
Maximum error of X, Y, and Z values: 41199.53 5219040 5

300 x 300-m Grid Spacing NMT Grid:

Net coal thickness mean value: 62.81982
Standard deviation of Net coal thickness: 41.69276
Number of data points: **4622**
Number of points outside of study boundary: 0
Number of null data points: 0
Number of invalid points: 0
Number of points with comments attached: 72
Number of faults: 0

Number of points used as multiple data points:	7		
Number of points used for grid:	**4,615**		
Range of X values:	-91,438.23	68,419.46	
Range of Y values:	5,053,588	5,340,636	
Range of net coal thickness values:	0	284	
Range of grid X values:	-145,000	137,000	
Range of grid Y values:	5,020,000	5,460700	
Range of grid net coal thickness values:	1	285	
Mean net coal thickness value in grid:	22.02523		
Standard deviation of net coal thickness value in grid:	29.49223		
Number of null nodes in grid:	0		
Average absolute Z error of net coal thickness:	2.12727	**(0.4420943%)**	
Standard deviation of Z error (net coal thickness):	5.544803		
Maximum Z error:	98.7226	(20.51677%)	
Maximum error of X, Y, and Z values:	41,199.53	5,219,040	5

The 300 by 300-m isopach and NMT grids both honored over 98% of the data points, using 5,324 out of 5,414 (98%) data points for the isopach grid and 4,615 out of 4,622 (99.8%) data points for the NMT grid. The average absolute grid error was .5% for the isopach grid and .4% for the NMT grid. The isopach grid and NMT grid isopach maps looked very similar in their general configuration and did not differ significantly from the isopach maps created using the 500 by 500-m grid spacings. Because the 300 by 300-m grid contained more data points it was used for the coal resource calculations in EV.