Chapter PD

DECKER COALFIELD, POWDER RIVER BASIN, MONTANA: GEOLOGY, COAL QUALITY, AND COAL RESOURCES

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INTRODUCTION

The Decker coalfield is located about 16 mi northeast of Sheridan, Wyoming, and as defined here, covers about 1,100 square miles in parts of Big Horn, Powder River, and Rosebud Counties, Montana (fig. PD-1). Access through the coalfield is primarily restricted to one State highway and a network of secondary roads. The coalfield is between the Tongue and Powder Rivers, and most of the field is dissected by small, intermittent or perennial streams, including the Otter Creek and Hanging Woman Creek drainages (fig. PD-2). The Decker coalfield includes all or parts of fifty 7.5’ quadrangles (fig. PD-3) and is bounded on the south by the Montana state line, on the west and northwest by the Crow and Northern Cheyenne Indian Reservations, respectively, and on the north and east by the main outcrop line of the Canyon coal bed or the contact between unburned coal and clinker of the Canyon coal bed. The extent of the Canyon coal bed as used in this study is based on published maps of Baker (1929), Warren (1959), Bryson and Bass (1973), and Robinson and Culbertson (1984).

The Decker coalfield includes parts of the historically defined Northward Extension of the Sheridan coalfield (Baker, 1929), the Moorhead coalfield (Bryson and Bass, 1973), and the Birney-Broadus coalfield (Warren, 1959), as well as a more areally restricted Decker coalfield (Decker area) described in studies by Matson and Blumer (1973). Most of the coal in the Decker coalfield is federally owned (fig. PD-4). Coal mining has taken place in the Decker area since the early 1900’s, although historic production was primarily from small wagon mines producing coal locally for domestic use (Baker, 1929). Currently there are three operating surface mines in the coalfield: the Spring Creek, East Decker, and West Decker mines (fig. PD-1). From

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1995 to 1997, the combined production from these 3 mines has been about 20 million short tons per year (Resource Data International, Inc., 1998).

The Anderson-Canyon coal zone has been selected for resource assessment in the Decker coalfield primarily because there is continuing coal production from certain beds within this coal zone in Montana, as well as significant production from equivalent coal deposits in Wyoming. The Anderson-Canyon coal zone is considered to be stratigraphically equivalent to the Wyodak-Anderson coal zone as described by Flores and Bader (Chapter PS in this CD-ROM). For the purposes of this study, however, local coal-bed terminology as applied in Montana is adhered to in this chapter.

Although coal beds in the Anderson-Canyon coal zone extend into the Crow and Northern Cheyenne Indian Reservations, no assessment of the coal resources on tribal lands is included in this report. Also, part of the Decker coalfield extends into Custer National Forest (fig. PD-4), and Section 522 (e) (2) (b) of the Surface Mining Control and Reclamation Act of 1977 [SMCRA; Public Law 95-87 (30 U.S.C. 1201 et seq.)] strictly prohibits surface coal mining within the boundaries of Custer National Forest. Although we have included coal resource information for areas within the National Forest, the reader should take into account the limitations of coal resource development as constrained by SMCRA.

GEOLOGIC OVERVIEW AND COAL STRATIGRAPHY

Bedrock exposures in the Decker coalfield consist of Tertiary strata in the Fort Union Formation and the overlying Wasatch Formation (fig. PD-5). The contact between the formations is placed at the top of the Roland coal bed of Baker (1929).

The structural dip of exposures in this area is generally less than 5 degrees with dip orientations varying from southeasterly in the western part of the coalfield to southwesterly in eastern areas of the coalfield. Although dips as steep as 72 degrees have been recorded (Galyardt and Murray, 1981), these steeper dips typically reflect structural attitudes associated with high-angle normal faults (Matson and Blumer, 1973), which are prevalent in the southern and western parts of the coalfield (fig. PD-5). These predominantly northeast-trending faults range in length from 1 to 6 miles, with offsets of as much as 300 ft; however, the average maximum offset is more on the order of 120-150 ft or less (see, for example, Matson and Blumer, 1973; Robinson and Culbertson, 1984).

The Fort Union Formation is Paleocene in age and the Wasatch Formation is Eocene in age; both formations are coal-bearing. The maximum thickness of the Wasatch Formation in the Decker coalfield is approximately 400 ft, whereas the maximum thickness of the coal-bearing section of the Fort Union alone is about 2,300 ft (Culbertson, 1987). The total Fort Union thickness may reach 3,500-3,600 ft in areas underlying the Wasatch Formation just east of the Tongue River Reservoir (Lewis and Roberts, 1978). Fort Union and Wasatch Formation rock types are similar to one another, and characterized by interbedded sandstone, siltstone, mudstone, carbonaceous shale and coal. Thin lenses of resistant limestone are present locally within the Fort Union Formation. Clinker deposits, formed by the natural burning of coal beds and the resultant baking or fusing of rocks overlying the burning coal, are present in both formations throughout much of the coalfield (see, for example, Heffern and others, 1993).

The Fort Union Formation is subdivided into three members (ascending order): the Tullock, Lebo, and Tongue River Members. The principal coal beds in this area are

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present in the Tongue River Member, which is the only member of the Fort Union Formation that crops out in the Decker coalfield (fig. PD-5). The Anderson-Canyon coal zone is in the upper part of the Tongue River Member, and the coal zone is defined as the interval of coal and associated clastic rocks between the top of the Anderson coal bed and the base of the Canyon coal bed. In areas where the Canyon coal bed splits, the base of the zone is placed at the base of the lower Canyon coal bed. Based on available drill-hole data, the coal zone ranges from 158 to 500 ft in thickness where the complete zone is preserved within the coalfield. Coal beds within the zone include the Anderson, Dietz 2, Dietz 3, Kirby, Cox, and Canyon coal beds (fig. PD-6) as well as local, unnamed coal beds that are distributed randomly throughout the coalfield. Our coal-bed terminology, particularly pertaining to the Anderson and Dietz 2 and Dietz 3 beds, is consistent with that of Culbertson (1987). However, alternative nomenclature is still widely used by other agencies and mine operators, and a brief summary of additional naming conventions for coal beds in this zone is included here (fig. PD-6). We've adopted Culbertson's nomenclature primarily to maintain consistency with his other USGS reports pertaining to coal in this area (see, for example, Culbertson and others, 1979; Culbertson, 1980).

The Anderson, Dietz 2, and Dietz 3 coal beds are the targets of coal production in the Decker coalfield. Although coal is not currently produced from the Canyon coal bed in this area, there has been production from an equivalent coal bed (Monarch bed) at the Big Horn mine in the Sheridan coalfield of Wyoming. There is no reported production of the other coal beds (Kirby and Cox beds) in the coal zone. Coal-bed thickness in the Anderson-Canyon coal zone is quite variable, and this variability is often the result of merging and splitting of individual beds within the zone, particularly in regard to the Anderson and Dietz 2 and Dietz 3 coal beds. For example, in the Spring Creek mine (fig. PD-1) and areas just south of the mine, the Anderson, Dietz 2, and Dietz 3 beds have merged to form a single bed as much as 88 ft thick at some locations. North and west of the Spring Creek mine area, this thick coal bed splits into two beds comprised of a single Anderson coal bed (as much as 34 ft thick), and a coalesced Dietz 2 and Dietz 3 coal bed as much as 54 ft thick (Cole and Sholes, 1980). However, southeast of the Spring Creek mine, in and near the Decker mines (fig. PD-1), the Anderson and Dietz 2 coal beds form a single bed (from 42 to 57 ft in thickness) while the Dietz 3 coal bed has split into a single bed from 15 to 21 ft in thickness (Cole and Sholes, 1980). Additionally, in eastern parts of the East Decker coal mine, the Anderson, Dietz 2 and Dietz 3 coal beds form three individual beds, and just east of the mine, the Dietz 2 and Dietz 3 coal beds split rapidly into 4 individual coal beds. This splitting and merging of coal beds is characteristic of all coal beds within the Anderson-Canyon zone and, for that matter, most or all the coal beds within the Tongue River Member of the Fort Union Formation.

Maximum net coal thickness (excluding partings) for individual coal beds in the Anderson-Canyon zone, where not coalesced with one another, is about 35-37 ft for the Anderson coal bed, 20-25 ft for both the Dietz 2 and Dietz 3 coal beds, and about 30-33 ft for the Canyon coal bed. The Kirby coal bed, which is only present in the northwestern part of the coalfield, is generally less than 10 ft thick, while the Cox coal bed in eastern areas of the coalfield is usually less than 5 ft thick. Each of these coal beds thicken and thin locally within the coalfield.

A series of 6 cross sections, derived from drill-hole data, is used to depict our interpretations of coal-bed continuity in the subsurface throughout the Decker coalfield. Two cross sections (fig. PD-7) show interpretations of coal-bed continuity using natural-gamma (NG) log profiles (figs. PD-8 and PD-9), whereas the remaining four lines of cross section (fig. PD-10) represent more "idealized" stratigraphic and structural reconstructions (figs. PD-11 through PD-14) based on drill-hole lithologic records. In all cross sections, the datum is mean sea level, and the horizontal distribution of drill-hole control points along each line of section is scaled to approximate the relative map distance between drill holes.

Many of the cross sections traverse faulted areas, and interpretations of fault displacement are shown where applicable. Faults shown in the cross sections are based on Robinson and Culbertson (1984), or they are inferred from observations of stratigraphic offset between drill holes along the lines of section. Coal-bed offset as depicted in the cross sections is very diagrammatic in that the actual structural attitude of the beds in the vicinity of the faults is not indicated. In some areas, where the distance between control points (drill holes) is significant, the displacement along the faults is highly inferred.

Natural-gamma log profiles (figs. PD-8 and PD-9) were constructed using reduced natural-gamma geophysical logs. Each control point displays "mirrored" images of the natural-gamma log recorded at that drill hole. This type of geophysical log measures the natural radioactivity emitted by all rocks in a manner similar to a very sensitive Geiger counter. Typically, coal beds in the study area are very low in natural radioactivity, and mirror imaging NG logs at each control point is used to highlight this characteristic. This type of geophysical log is extremely useful in determining the presence and thickness of coal beds penetrated by drill holes. Coal-bed names for coal above and below the Anderson-Canyon coal zone as shown on the natural-gamma log profiles are modified from data of W.C. Culbertson in the U.S. Geological Survey National Coal Resources Data System (NCRDS).

Cross section GP1-GP1' (fig. PD-8) traverses approximately 35 mi of the Decker coalfield, from an area near the Decker mines to just south of Quietus (fig. PD-7). Just to the west of the Decker coal mine, and within the Spring Creek coal mine, the Anderson, Dietz 2 and Dietz 3 beds merge into a single bed. However, these coal beds split rapidly to the west and east from this area. Additionally, in areas east of the East Decker mine, the Dietz 2, and Dietz 3 beds split into multiple beds, and in this report, are included within the broader Dietz subzone. Some of the coal beds within the Dietz subzone pinchout farther east. Near the town of Quietus, a single Dietz coal bed is all that remains of the subzone. In contrast to the Dietz beds, the Anderson and Canyon coal beds are essentially continuous along the cross section.

Cross section GP2-GP2' (fig. PD-9) traverses approximately 30 mi of the Decker coalfield, beginning south of the Spring Creek mine near the Montana-Wyoming state line, and extending north to an area just south of Kirby, near the boundary separating the Crow and Northern Cheyenne Indian Reservations (fig. PD-7). In this line of section the Anderson, Dietz 2, and Dietz 3 coal beds comprise a single coal bed in the area extending from the south end of the cross section (near the state line) to just north of the Spring Creek mine, where the bed splits into an Anderson bed and a merged Dietz 2 and 3 coal bed. Farther north, the Dietz 2 and Dietz 3 coal beds split into individual beds, and the Kirby coal bed becomes a constituent of the coal zone as well. Faults locally offset the overall northward structural rise of the coal zone, and faulting is particularly prevalent in the northern parts of the cross section. Additionally, the Anderson-Canyon zone thickens toward the north.

The restored stratigraphic/structural panels (figs. PD-11 through PD-14) were also constructed using drill-hole information, and they include interpretations of the lateral distribution of coal beds and associated rocks (for example, sandstone and mudstone) along each line of section. Lithologic data are from NCRDS, and in certain instances, no differentiation of rock types between coal beds was available. In these cases, the coal-bed correlations are maintained, and all other rock types are included in the general category of "rock."

Cross section A-A' (fig. PD-11) covers about 54 mi from west to east across the southern part of the Decker coalfield, extending from the Decker coal mine areas to the eastern limit of the Anderson-Canyon coal zone (fig. PD-10). Interpretations of sandstone and mudstone highlight the build up of ancient river deposits (sandstone) within the Anderson-Canyon coal zone in the west-central and eastern parts of the study area. Interbedded mudstone represents ancient floodplain deposits, which were sites of fine-grained sediment deposition and coal-bed mire development. Note that in areas where the Anderson, Dietz 2, and Dietz 3 beds merge (western part of the cross section) the predominant lithology associated with the coal beds is mudstone. There is an increase in sandstone in areas where the Dietz 2 and Dietz 3 coal beds have split to form the Dietz subzone, suggesting that the course of ancient rivers influenced the geometry and distribution of coal deposits. Fault offsets along the line of section locally disrupt the overall eastward structural rise of the Anderson-Canyon coal zone. Also note the interpreted continuity of primary coal beds across the width of the coalfield.

Cross section B-B' (fig. PD-12) traverses about 23 mi in the Decker coalfield, and extends from near Kirby to areas south and west of the Spring Creek coal mine (fig. PD-10). Note the overall northward structural rise of the Anderson-Canyon coal zone, which is disrupted by fault offset in the northern part of the cross section. Although lithologic information on rocks associated with the coal beds is sparse, there is an apparent buildup of ancient river deposits (sandstone) in areas where the

Anderson has split from the Dietz 2 and Dietz 3 coal beds; intervening sandstone deposits reflect disruption of peat accumulation by ancient rivers, resulting in the development of two coal beds. This is in contrast to areas near the Spring Creek mine where all three coal beds have merged into a single bed, and the surrounding rock is characterized by mudstone.

Cross section C-C' (fig. PD-13) covers approximately 27 miles in the central part of the Decker coalfield, east of the areas of active coal mining (fig. PD-10). In this area, a single Dietz coal bed is all that remains of the Dietz 2 and Dietz 3 beds and their correlative splits included in the Dietz subzone. At the northern end of the cross section, the Dietz coal bed merges with the Anderson to form a single bed that is 58 ft thick. Also note that the Canyon coal bed splits into upper and lower Canyon beds in the south-central part of the cross section. Along this line of section, much of the coal interburden is composed of mudstone (floodplain deposits), and only minor buildup of ancient river sandstones is observed in localities near the north, central, and southern limits of the cross section.

Cross section D-D' (fig. PD-14) extends for 26 miles from north to south near the eastern limit of the Decker coalfield (fig. PD-10). Much of the cross section includes areas where only the Dietz and Canyon coal beds are present. Through most of this area, the Dietz coal beds are included within the Dietz subzone, which merges locally with the Anderson coal bed near the southern end of the cross section. Along this cross section, coal beds dip gently southward to a point of abrupt structural rise at the extreme south end of the cross section. Both the Anderson and Dietz subzone coal beds outcrop intermittently along the section. Extensive river deposits of sandstone are well developed in southern areas of the traverse, with floodplain mudstone deposits becoming increasingly abundant northward along the line of section. The Anderson coal bed and Dietz subzone coal beds converge in areas where interburden is composed primarily of floodplain mudstone, and split northward where ancient river courses (sandstone) disrupted continuous peat accumulation.

COAL QUALITY

The principal coal beds in the Anderson-Canyon coal zone (Anderson, Dietz 2, Dietz 3, and Canyon coal beds) are primarily subbituminous in apparent rank (see, for example, Matson and Blumer, 1973; Fine and others, 1980), although sample analyses from these coal beds in the central part of the Decker coalfield indicate that the apparent rank may vary locally from lignite A to subbituminous C (Affolter and others, 1979). For purposes of resource calculations, we considered the coal beds to be subbituminous.

Matson and Blumer (1973) report that heat-of-combustion values (on an as-received basis) for the Anderson coal bed range from 6,594 to 9,850 Btu/lb, typical ash yields from 3.0 to 9.1 percent (locally exceeding 27 percent), and total sulfur content from 0.1 to 0.9 percent. Their reported as-received analyses for the Dietz coal beds, based on data from the individual beds or where the two beds have merged, indicate heat-of-combustion values ranging from 6,019 to 9,561 Btu/lb, ash yields from 2.5 to 14.1 percent, and total sulfur content from 0.1 to 2.4 percent, with most sulfur values being less than 1.0 percent. As-received analyses for the Canyon bed indicate heat-of-combustion values ranging from 6,646 to 9,113 Btu/lb, ash yields ranging from 3.2 to 10.7 percent (locally exceeding 30 percent), and total sulfur content varying from 0.1 to 2.5 percent, although more typical total sulfur values are less than 1.0 percent.

For comparison, chemical analyses of shipped coal from the Spring Creek (merged Anderson, Dietz 2 and Dietz 3 beds) and the Decker coal mines (merged Anderson and Dietz 2 beds and the Dietz 3 bed) covering the period from January 1989 to January 1998, indicate heat-of-combustion values ranging from 8,382 to 11,600 Btu/lb (unweighted mean = 9,420 Btu/lb), ash yields ranging from 3.20 to 41.0 percent (unweighted mean = 4.37 percent), and total sulfur content ranging from 0.21 to 1.18 percent (unweighted mean = 0.36 percent). The total tonnage of coal shipped in this time frame was about 142.5 million tons (Resource Data International, Inc., 1998).

TOTAL, NET COAL THICKNESS (ISOPACH) MAP

The total, net coal isopach map (fig. PD-15) is an interpretation of cumulative, net coal thickness for coal beds within the Anderson-Canyon coal zone in the Decker coalfield. At each drill hole or outcrop data point, net coal thickness (excluding partings) is measured for each coal bed within the zone, and then these individual coal thicknesses are summed to derive a cumulative value of total net coal within the coal zone at that data point. These total coal thickness values for all data points are then contoured by a computer modeling program to develop maps showing lines of equal total, net coal thickness. The isopach map reflects the distribution of the cumulative (summed) coal thickness for all coal beds within the Anderson-Canyon zone rather than the thickness of any individual coal bed except in areas stratigraphically below the Dietz 3 coal bed (or merged Dietz 2 and Dietz 3 coal beds), where thickness values reflect the thickness of the Canyon (or lower Canyon) coal bed alone.

Approximately 400 data points (drill-hole and outcrop locations) were used in the calculation of the total, net coal isopach map of the Anderson-Canyon coal zone. This total includes limited confidential data from mine operators and data from wells in northern Wyoming (near the Montana state line) which helped to define isopach trends along the southern boundary of the coalfield. Only public (non-proprietary) data points are shown in the total coal isopach map (fig. PD-15).

Because the isopach map for the Anderson-Canyon coal zone is based on cumulative coal thickness values, the following factors, either individually or collectively, can account for variations in the total, net coal thickness as seen on the map: (1) thickening or thinning of individual coal beds within the zone, (2) reduction in the number of coal beds because of lateral pinchout, and (3) reduction in the number of coal beds because of erosion in stratigraphically lower horizons nearing the outcrop limits of the coal zone, and (4) reduction of the total coal in clinker areas where coal has been lost because of natural burning. Therefore, thickness variations exhibited by apparent "thinning or thickening" trends in the total coal isopach map actually reflect variations in the total coal accumulation influenced by all or some of the factors listed above.

Areas of thicker coal accumulation are shown by warmer (yellow and red) color shades, whereas minimal coal accumulation areas are highlighted by cool (blue) shades (fig. PD-15). Based on the total, net coal isopach map, the thickest total coal accumulation in the Anderson-Canyon coal zone is concentrated in Tps. 8 and 9 S., Rs. 38 to 40 E., adjacent to active mines and in the area where the Anderson, Dietz 2, and Dietz 3 coal beds have typically merged into a single coal bed (figs. PD-8 and PD-9).

OVERBURDEN THICKNESS (ISOPACH) MAP

The overburden isopach map (fig. PD-16) represents the thickness of rock overlying the top of the Anderson-Canyon coal zone. The areal extent of overburden is constrained by the Anderson coal-bed outcrop (or the contact between the Anderson coal bed and adjacent clinker deposits), the Montana-Wyoming state line, and tribal lands along the western boundary of the coalfield. Areas between the Anderson and Canyon coal-bed outcrops (or clinker contacts), which define the top and base of the coal zone, respectively, contain exposed rocks of the Anderson-Canyon coal zone. These areas of "exposed coal zone" are shaded gray on the overburden map (fig. PD-16). The overburden interpretation was derived by subtracting an elevation grid (with faults) representing the top of the Anderson-Canyon coal zone (that is, the top of the Anderson coal bed) from a Digital Elevation Model (DEM) grid of topographic elevation, resulting in the calculation of a grid of thickness values that could then be contoured as overburden thickness isopachs. Because strata included in the Anderson-Canyon coal zone may extend from tens to hundreds of feet stratigraphically below the top of the zone (Anderson coal bed), the overburden as shown (fig. PD-16) actually represents a minimum overburden thickness. Thicker overburden is highlighted by green and yellow colors, whereas minimal overburden thickness is represented by blue shades.

COAL RESOURCES

Coal resource estimates for the Anderson-Canyon coal zone are reported in tables PD-1 through PD-3. In table PD-1, resources are tabulated by county, total, net coal thickness categories, and overburden categories. Table PD-2 includes a summary of coal resources reported by 7.5' quadrangle and overburden category, and table PD-3 includes a summary of coal resources reported by county and Federal surface and subsurface ownership criteria. It is important to note that these resource estimates are not comparable to 'reserve' estimates, and therefore, do not reflect in any way the amount of coal that can be economically produced at the present time.

The quantification of coal resources in the Decker coalfield follows a scheme of resource calculation reported in Wood and others (1983). The basic quantification formula is as follows: $R = A \times T \times C$,

where

R is the coal resource estimate (in short tons)

A is the area underlain by coal (in acres)

T is the cumulative (total) net coal thickness (in feet; excluding partings) based on isopach grids, and

C is a weight/unit volume (density) conversion factor (in short tons/acre-foot).

All resources are reported in millions of short tons and are reported in accordance with criteria established by Wood and others (1983). Coal tonnages were calculated for coal beds greater than 2.5 ft in thickness using an average density (*C*) for subbituminous coal of 1,770 short tons per acre-foot. Tonnage values are rounded to two significant figures and the tabulated totals may not equal the sum of the components because of independent rounding. Areas for which resource estimates are not reported include the Spring Creek and East and West Decker coal mines, the CX Ranch coal lease, tribal lands (Crow and Northern Cheyenne Indian Reservations), areas beneath the Tongue River Reservoir, and areas underlying clinker of the Anderson, Dietz 2, and Dietz 3 (or Dietz) coal beds.

Reported reliability categories (table PD-1) include measured, indicated, inferred, and hypothetical coal resources. Measured resources occur within a 0.25-mile radius of a data point, indicated resources within the area between 0.25 miles and 0.75 miles from a data point, and inferred resources are present within a radius from 0.75 miles to 3 miles surrounding a data point. Hypothetical resources are present in areas more than 3 miles beyond a data point (Wood and others, 1983).

Overburden categories, excluding the exposed zone category (see, for example, table PD-1), represent the thickness of overburden above the top of the Anderson-Canyon coal zone. Because the coal zone may extend from tens to hundreds of feet stratigraphically below the top of the zone, the reported overburden categories represent only a minimum overburden thickness; overburden to deeper horizons in the zone may actually be greater than the minimum overburden category as reported. The exposed zone category in the Anderson-Canyon coal zone resource tables represents areas of the coalfield where the complete coal zone is not present because of erosion or natural burning of the coal beds.

Confidence limits and estimates of uncertainty for total coal resources in the Anderson-Canyon coal zone are shown in table PD-4 and table PD-5, respectively. A confidence interval is a statistic designed to capture uncertainty associated with a point estimate. Confidence limits reported here are based on total, net coal thickness measurements from 366 drill-hole and outcrop locations. From these data, we computed 90-percent confidence intervals on the volume of coal in the Anderson-Canyon coal zone in the measured, indicated, inferred, and hypothetical categories. In this case, volume refers to the calculated resource in millions of short tons (MST).

The confidence limits were derived through a complex series of steps. These steps included modeling coal thickness trends and removing the trends using a nonparametric regression algorithm called loess (with span = 0.5), and using residual thickness to compute a semivariogram and fitting the semivariogram to a spherical model. Parameter estimates were sill = 239.85 ft^2, nugget = 18.99 ft^2, and range = 6.59 miles. Standard deviations of coal thickness were obtained from the semivariogram model. Differences in point densities were compensated for by calculating sample size, called pseudo *n*, within each reliability category and calculating the variability of volume for each of the reliability categories. The volume of coal in the Anderson-Canyon coal zone was then calculated at a 90-percent confidence interval with measurement error. A description of the methodology used is given in Schuenemeyer and Power (1998) and Ellis and others (1999).

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

SOURCES OF DATA

DRILL-HOLE DATA

The following is a list of published drilling reports that contain most of the drill-hole information used in this study, although additional point data were collated from the

U.S. Geological Survey National Coal Resources Data System (NCRDS), unpublished field logs, and from a limited set of proprietary records.

Culbertson, W.C., Gaffke, T.M., and Correia, G., 1980, Coal exploratory holes drilled in 1978-79 in the Birney 1° x 1/2° quadrangle, Big Horn and Rosebud Counties, Montana, for coal beds in the Tongue River Member of the Paleocene Fort Union Formation: U.S. Geological Survey Open-File Report 80-55, 68 p.

Hansen, W.B., and Culbertson, W.C., 1985, Correlated lithologic logs and analyses from 1982 coal drilling in Big Horn, Prairie, Rosebud, and Treasure Counties, Montana: U.S. Geological Survey Open-File Report 85-738, 125 p.

Kirschbaum, M.A., Correia, G.A., and McPhillips, M., 1982, Coal exploratory drilling during 1979 in western Powder River County, Montana: U.S. Geological Survey Open-File Report 82-748, 141 p.

Matson, R.E., 1971, Strippable coal in the Moorhead coal field, Montana: Montana Bureau of Mines and Geology Bulletin 83, 18 pages with plates.

Matson, R.E., and Blumer, J.W., 1973, Quality and reserves of strippable coal, selected deposits, southeastern Montana: Montana Bureau of Mines and Geology Bulletin 91, 135 pages with plates.

U.S. Bureau of Land Management and U.S. Geological Survey, 1977, Hanging Woman Creek Study Area; Resource and potential reclamation evaluation: EMRIA Report No. 12, 309 p.

U.S. Bureau of Land Management, U.S. Bureau of Reclamation, and U.S. Geological Survey, 1977, Bear Creek Study Area; West Moorhead coalfield; Resource and potential reclamation evaluation: U.S. Department of the Interior EMRIA Report No. 8, 148 pages with appendices.

U.S. Geological Survey and Montana Bureau of Mines and Geology, 1976, Preliminary report of coal drill-hole data and chemical analyses of coal beds in Campbell, Converse, and Sheridan Counties, Wyoming; and Big Horn, Richland, and Dawson Counties, Montana: U.S. Geological Survey Open-File Report 76-450, 382 p.

_____ 1977, Geophysical logs for Big Horn, Fallon, and Powder River Counties, Montana; Chapter A of preliminary report of 1977 coal drilling in eastern Montana and northeastern Wyoming: U.S. Geological Survey Open File Report 77-721-A, 77 p.

_____ 1977, Geophysical logs for Big Horn County, Montana; Chapter B of preliminary report of 1977 coal drilling in eastern Montana and northeastern Wyoming: U.S. Geological Survey Open File Report 77-721-B, 126 p.

_____ 1977, Geophysical logs for Powder River and Dawson Counties, Montana; Chapter C of preliminary report of 1977 coal drilling in eastern Montana and northeastern Wyoming: U.S. Geological Survey Open File Report 77-721-C, 79 p.

_____ 1977, Preliminary report on 1976 drilling of coals in Campbell and Sheridan Counties, Wyoming; and Big Horn, Dawson, McCone, Richland, Roosevelt, Rosebud, Sheridan, and Wibaux Counties, Montana: U.S. Geological Survey Open-File Report 77-283, 403 p.

_____ 1980, Coal drilling during 1978 in Big Horn, Daniels, Dawson, Musselshell, Richland, Roosevelt, Rosebud, Valley, and Yellowstone Counties, Montana: U.S. Geological Survey Open-File Report 80-267, 271 p.

_____ 1981, Coal drilling during 1979 in Beaverhead, Big Horn, Dawson, Fallon, Garfield, McCone, Musselshell, Powder River, Prairie, Roosevelt, Rosebud, and Wibaux Counties, Montana: U.S. Geological Survey Open-File Report 81-314, 622 p.

_____ 1982, Coal drilling during 1980 in Big Horn, Dawson, McCone, Powder River, Prairie, Richland, Rosebud, and Treasure Counties, Montana: U.S. Geological Survey Open-File Report 82-026, 256 p.

GEOLOGIC MAP DATA

Baker, A.A., 1929, The northward extension of the Sheridan coal field, Big Horn and Rosebud counties, Montana: U.S. Geological Survey Bulletin 806, pp. 15-67, with plates.

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Figure PD-1. Index map showing the Decker coalfield and vicinity, southeast Montana.

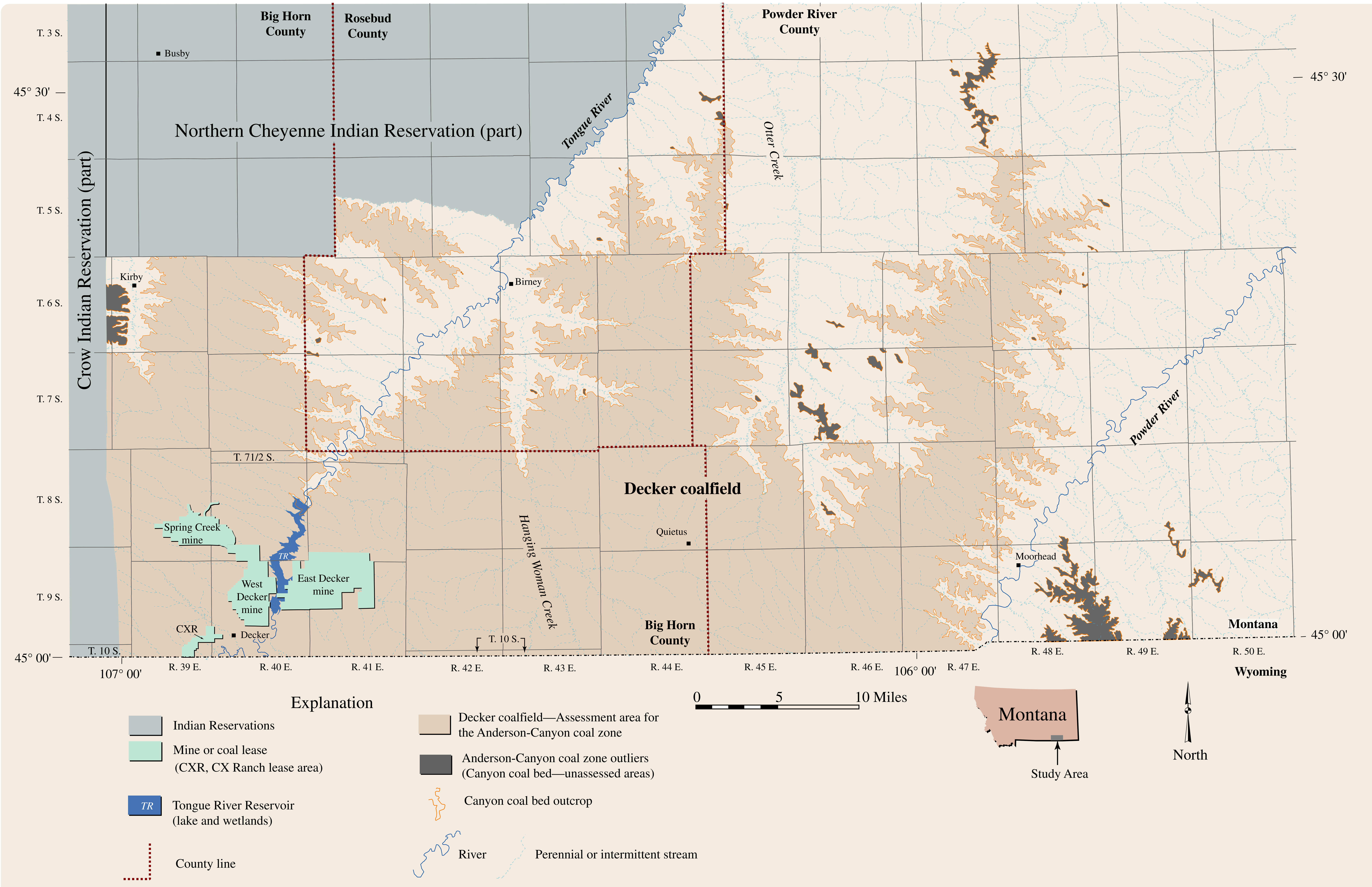

Figure PD-2. Map showing regional drainage pattern, Decker coalfield and vicinity, southeast Montana.

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Figure PD-3. Index map showing 7.5' and 30' x 60' quadrangle maps in the Decker coalfield, southeast Montana.

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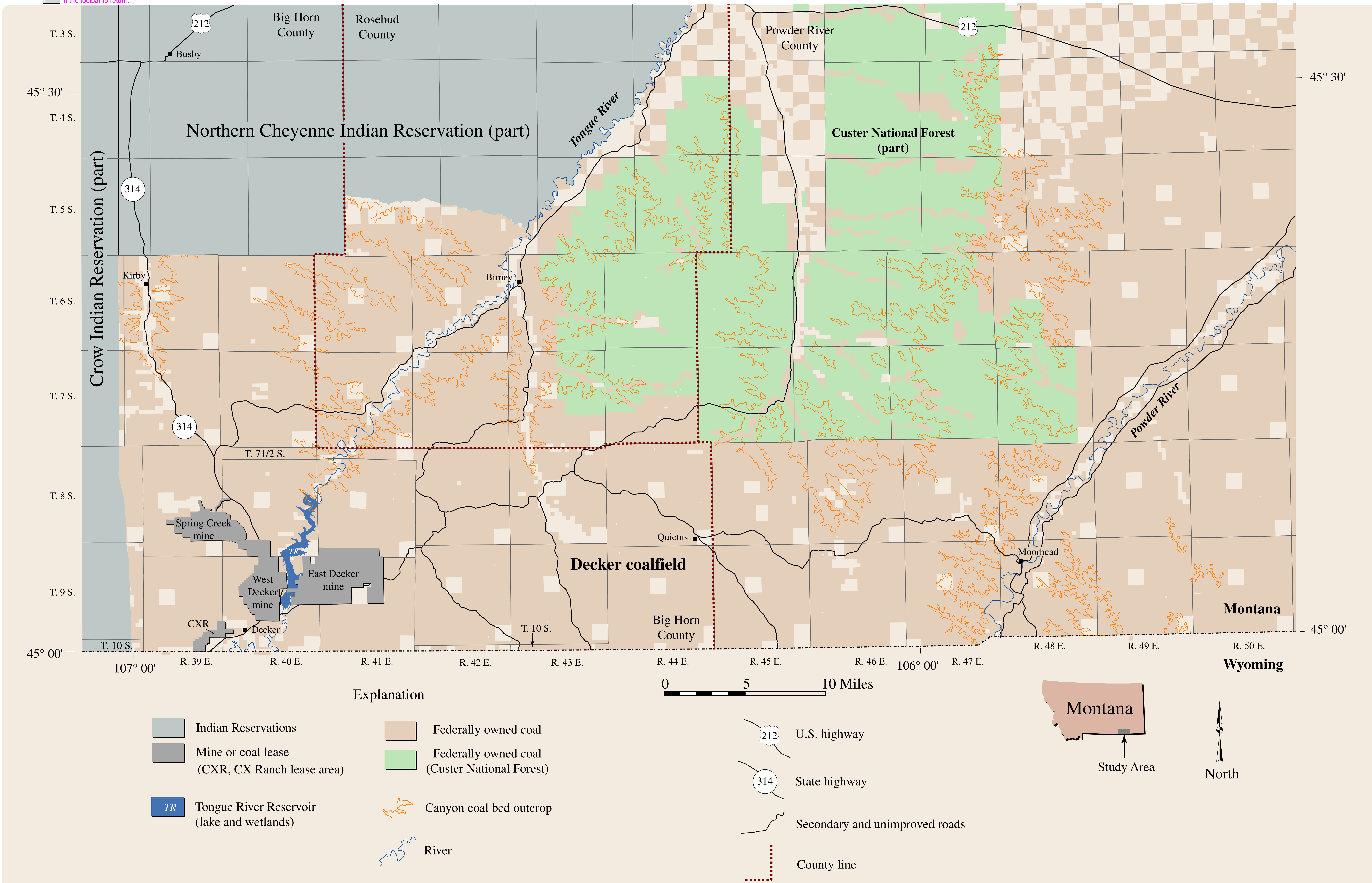

Figure PD-4. Map showing the distribution of Federally owned coal, Decker coalfield and vicinity, southeast Montana.

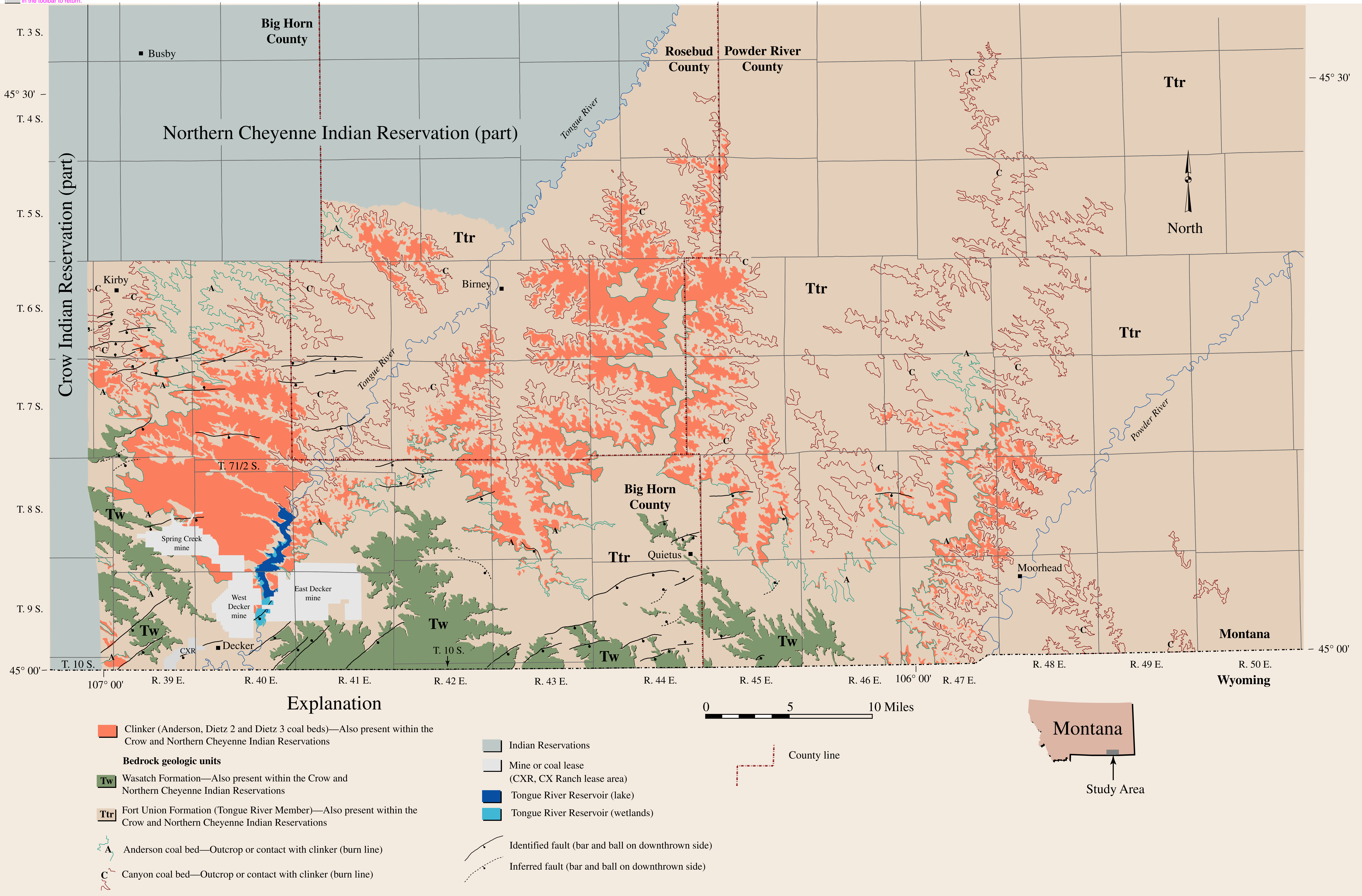

Figure PD-5. Map showing generalized bedrock geology, Decker coalfield and vicinity, southeast Montana. Geology based on Baker (1929), Warren (1959), Bryson and Bass (1973), McKay (1976), and W.C. Culbertson (USGS, unpublished mapping, 1970-1987). Fault locations and displacement modified from Robinson and Culbertson (1984).

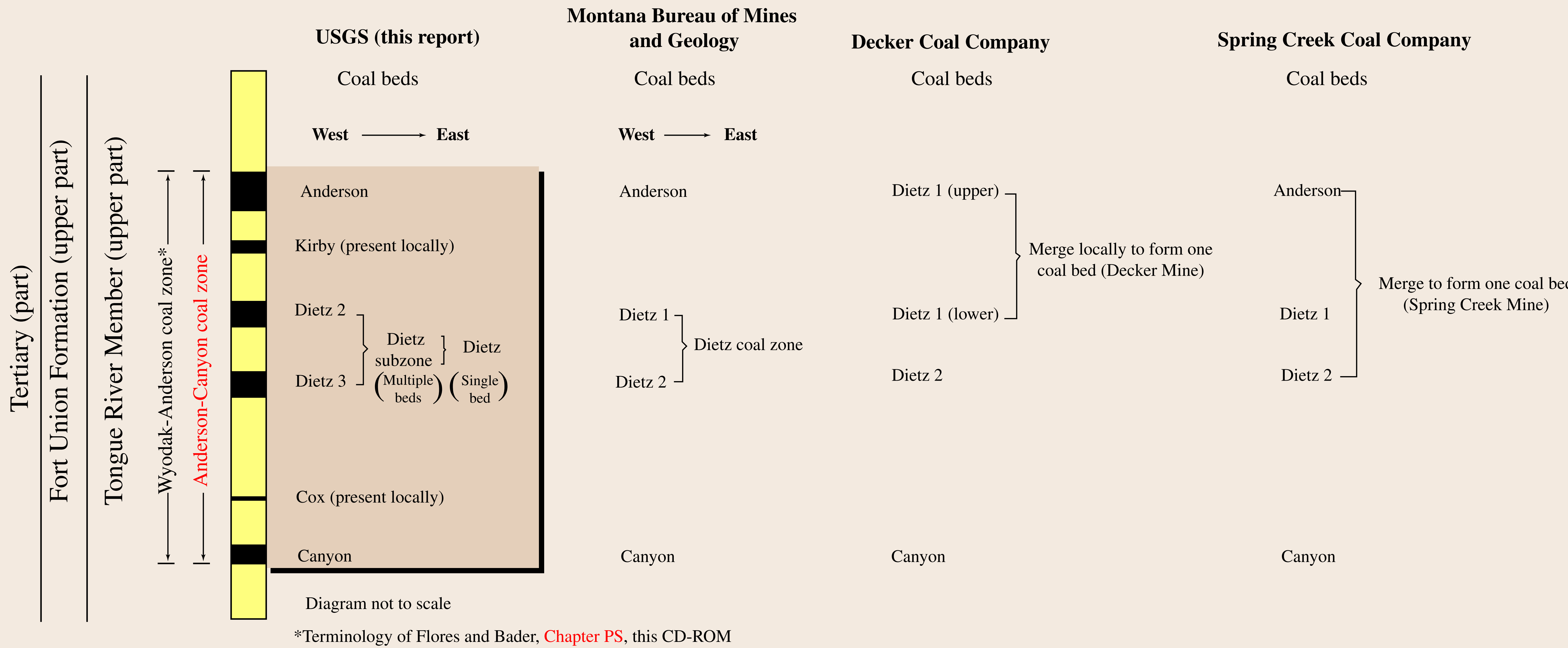

Figure PD-6. Chart showing coal-bed nomenclature for the Anderson-Canyon coal zone, Decker coalfield, Montana. Coal-bed designations based on Sholes and Cole (1981), Culbertson (1987) and terminology of local mine operators.

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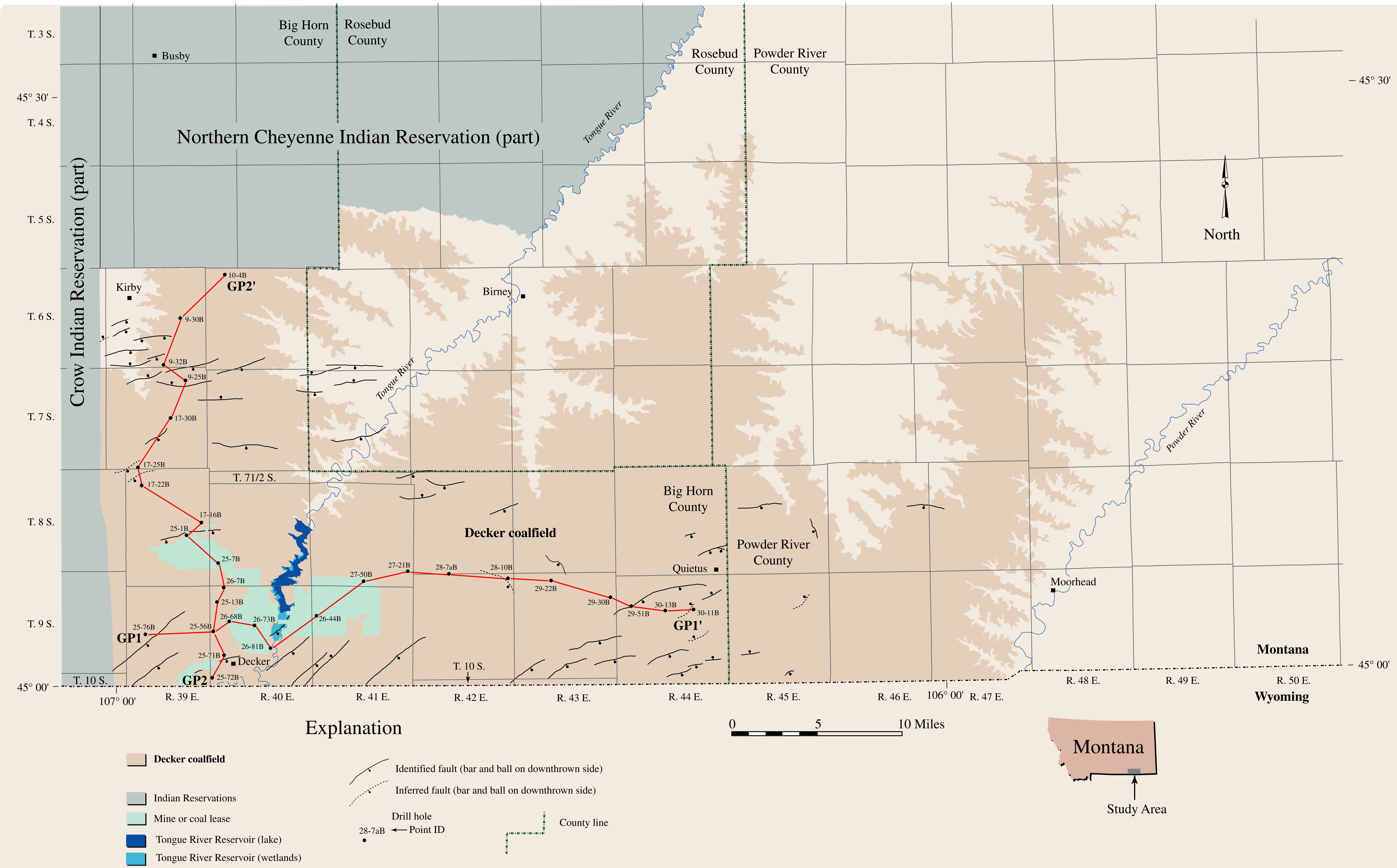

Figure PD-7. Index map showing the location of cross sections GP1-GP1' and GP2-GP2' (natural-gamma log profiles), Decker coalfield, southeast Montana.

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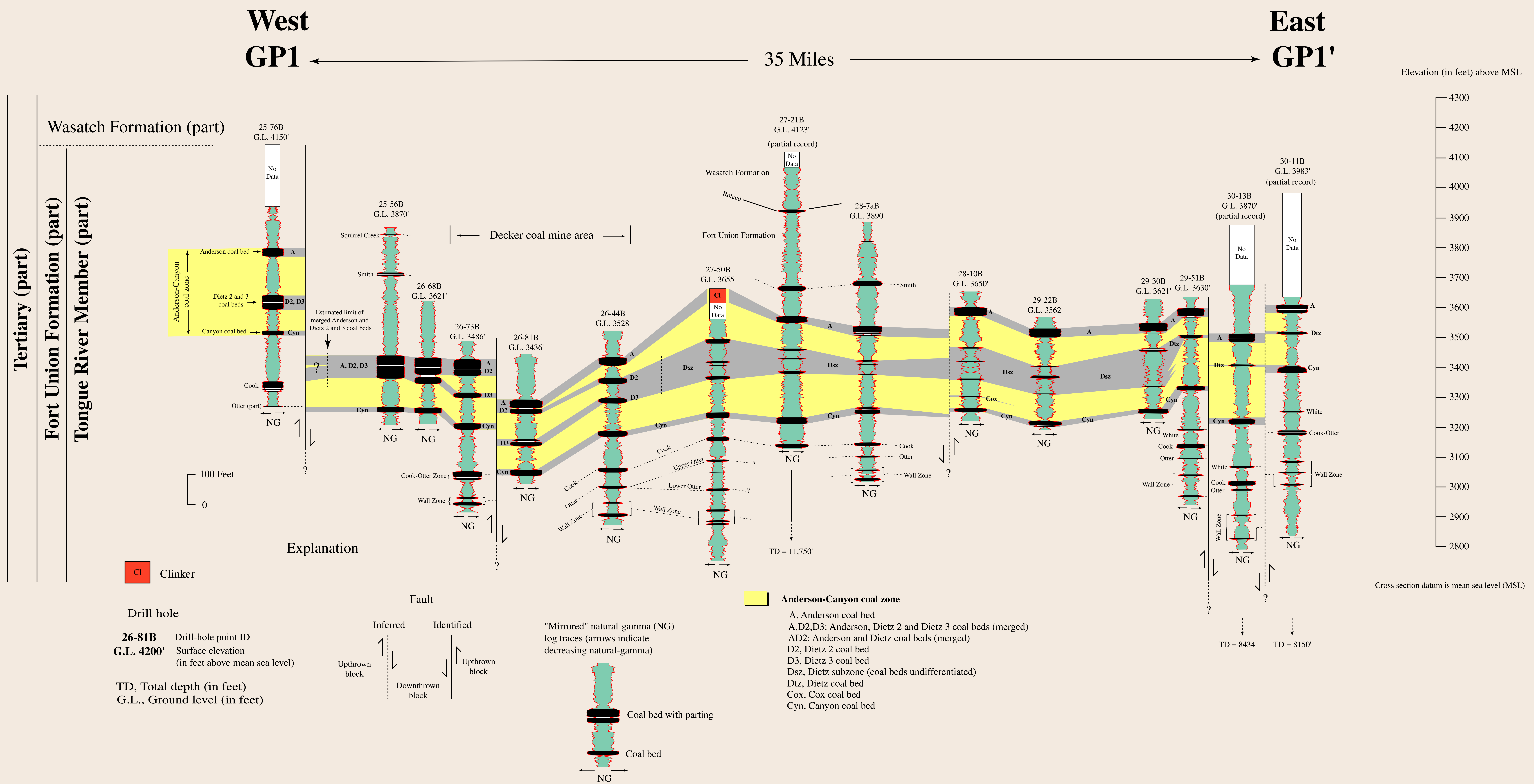

Figure PD-8. Cross section GP1-GP1' showing natural-gamma log profiles and coal-bed correlations in drill holes penetrating the Anderson-Canyon coal zone, Decker coalfield, southeast Montana. Fault displacement as shown is diagrammatic. Coal-bed terminology modified from Culbertson (1987).

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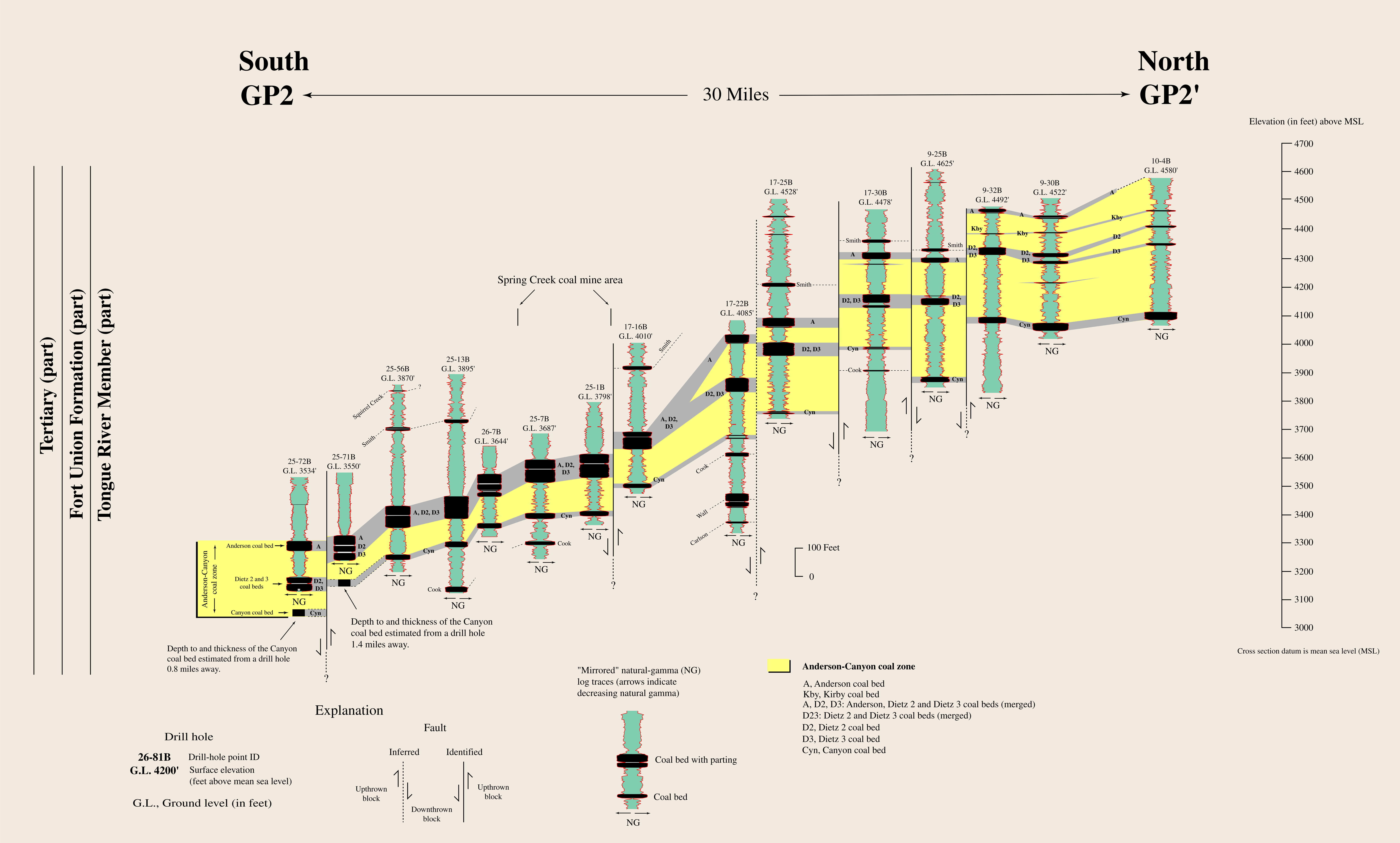

Figure PD-9. Cross section GP2-GP2' showing natural-gamma log profiles and coal-bed correlations in drill holes penetrating the Anderson-Canyon coal zone, Decker coalfield, southeast Montana. Fault displacement as shown is diagrammatic. Coal-bed terminology modified from Culbertson (1987).

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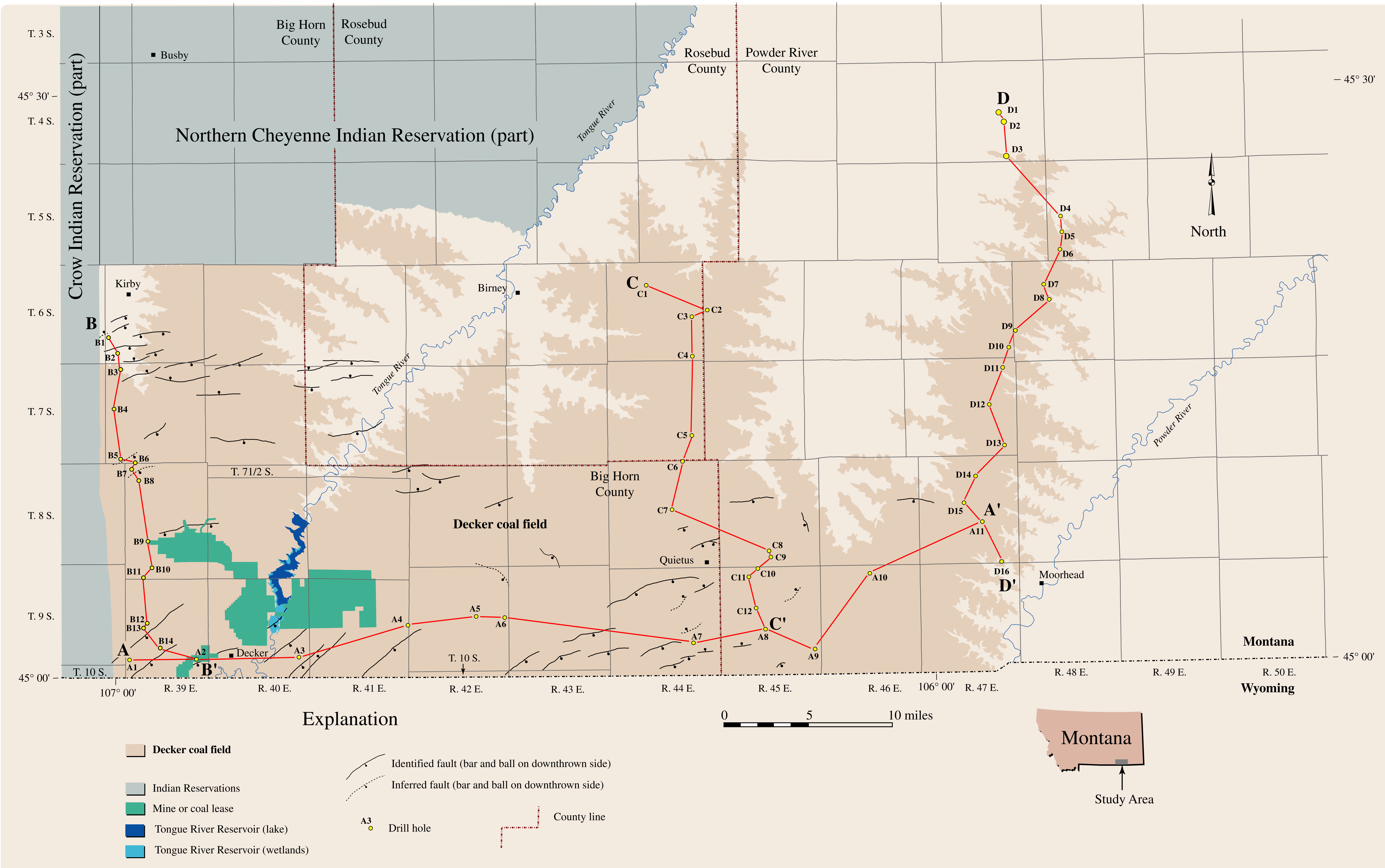

Figure PD-10. Index map showing the location of restored stratigraphic/structural cross sections A-A', B-B', C-C', and D-D', Decker coalfield, southeast Montana.

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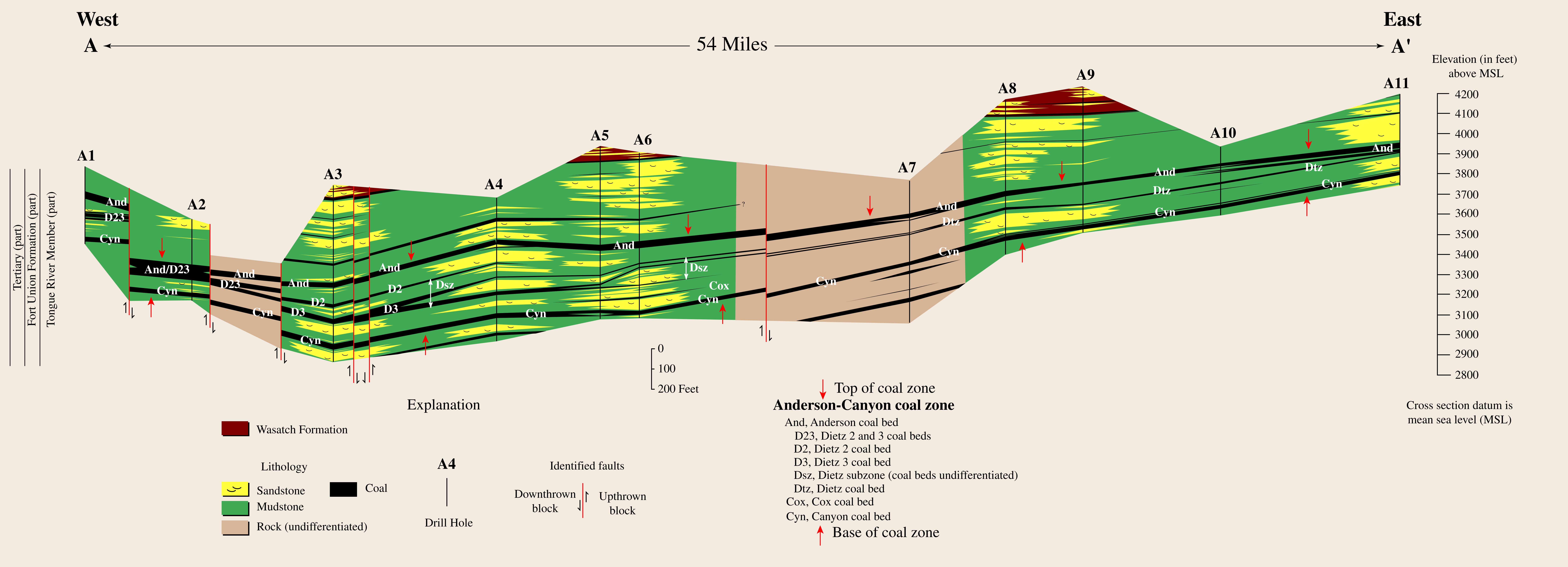

Figure PD-11. Restored stratigraphic/structural cross section A-A' showing coal-bed correlations in the Anderson-Canyon coal zone, Decker coalfield, southeast Montana. Displacement along faults as shown is diagrammatic. Fault location and relative displacement modified from Robinson and Culbertson (1984).

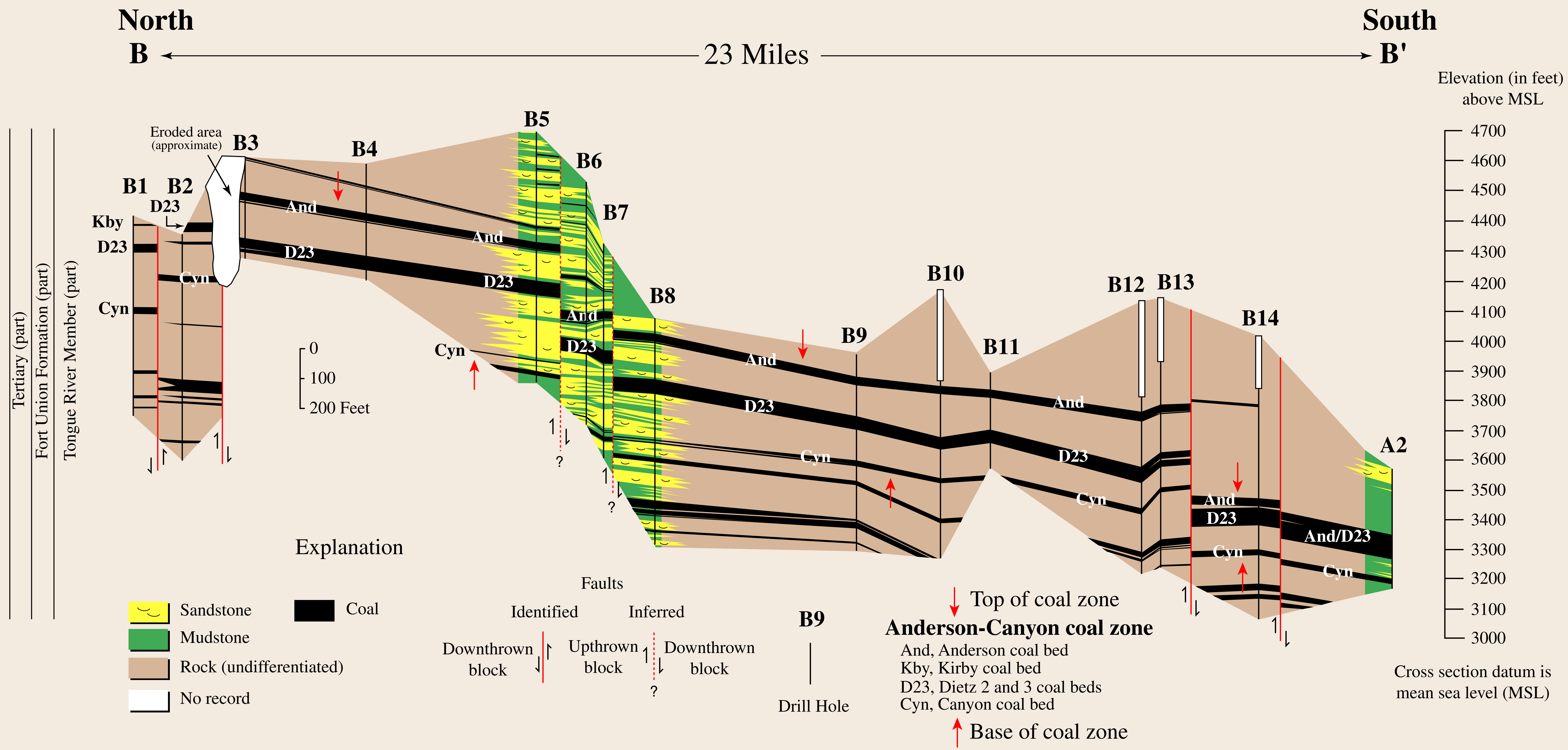

Figure PD-12. Restored stratigraphic/structural cross section B-B' showing coal-bed correlations in the Anderson-Canyon coal zone, Decker coalfield, southeast Montana. Displacement along faults as shown is diagrammatic. Fault location and relative displacement modified from Robinson and Culbertson (1984). The eroded area as shown is diagrammatic and approximately located.

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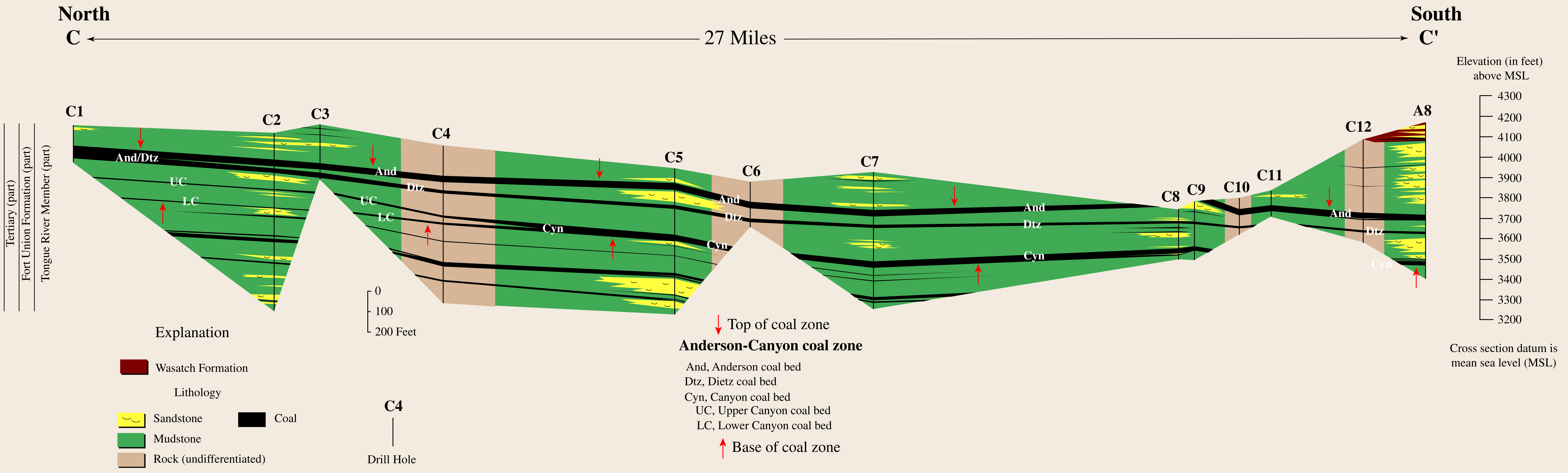

Figure PD-13. Restored stratigraphic/structural cross section C-C' showing coal-bed correlations in the Anderson-Canyon coal zone, Decker coalfield, southeast Montana.

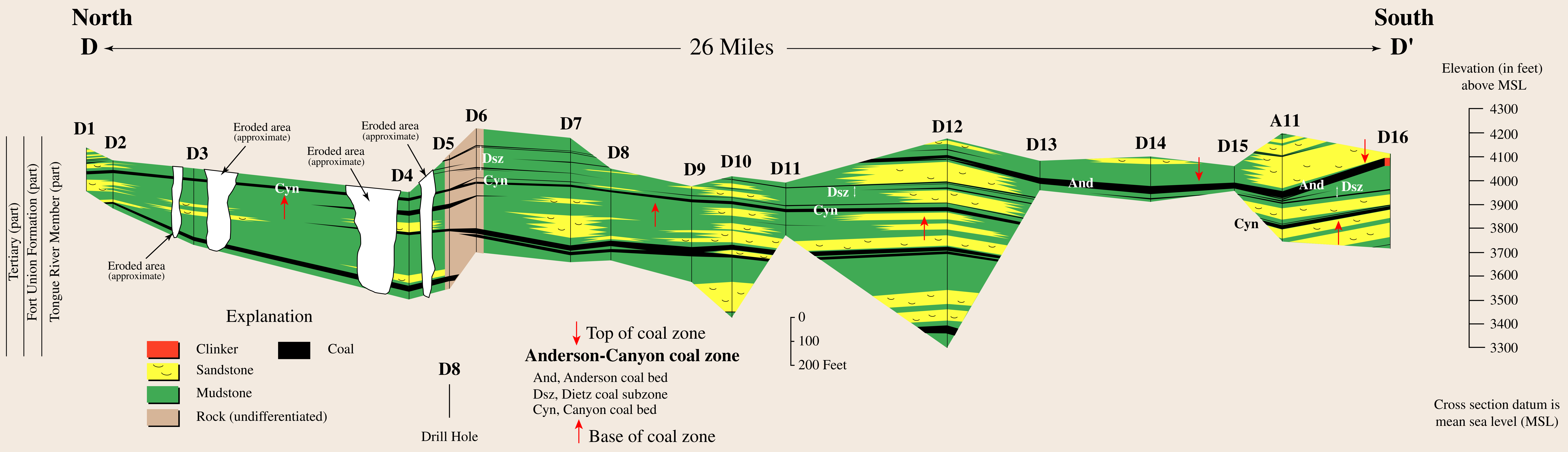

Figure PD-14. Restored stratigraphic/structural cross section D-D' showing coal-bed correlations in the Anderson-Canyon coal zone, Decker coalfield, southeast Montana. Eroded areas as shown are diagrammatic and approximately located.

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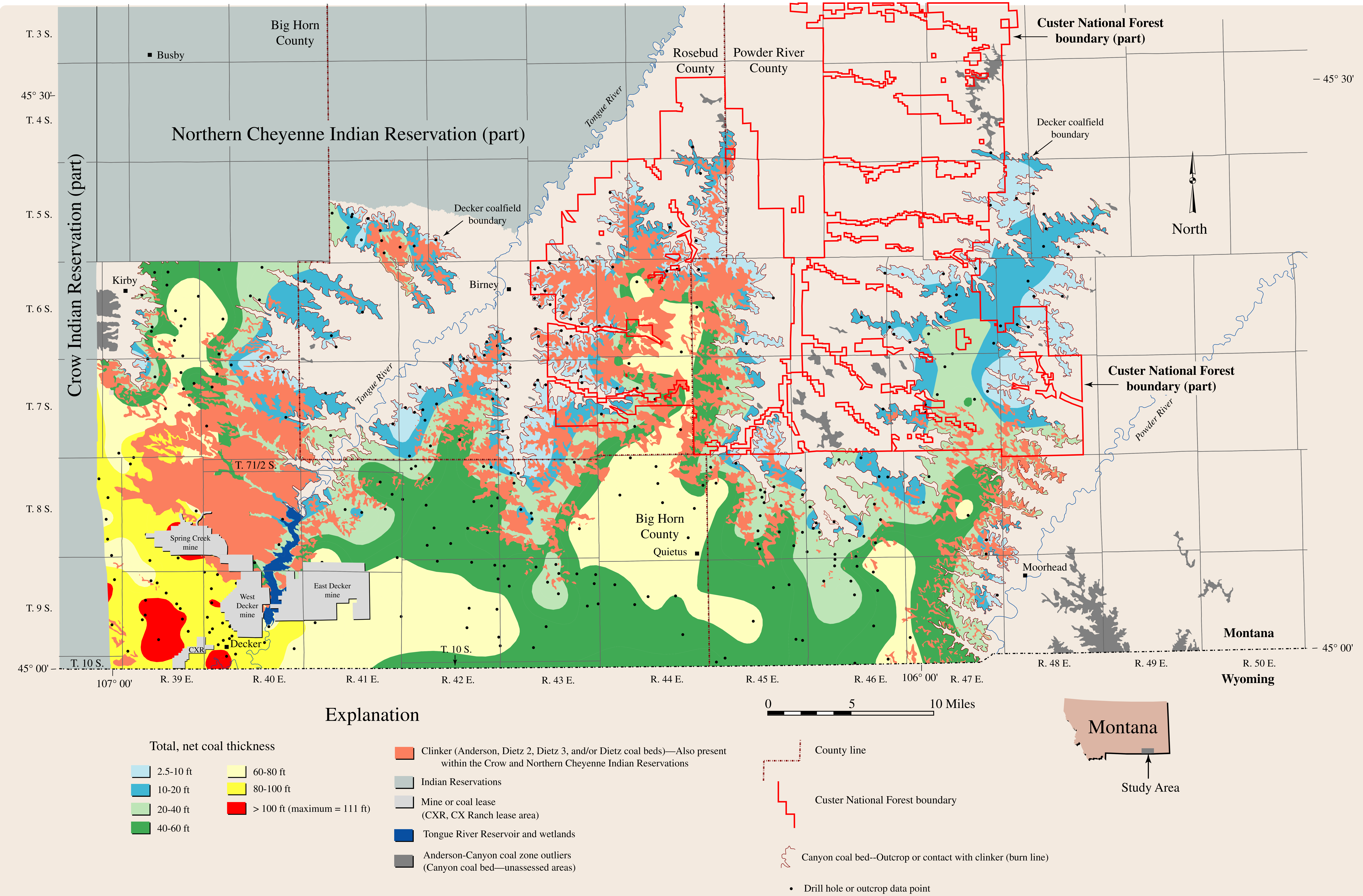

Figure PD-15. Map showing the total, net coal thickness in the Anderson-Canyon coal zone, Decker coalfield, southeast Montana.

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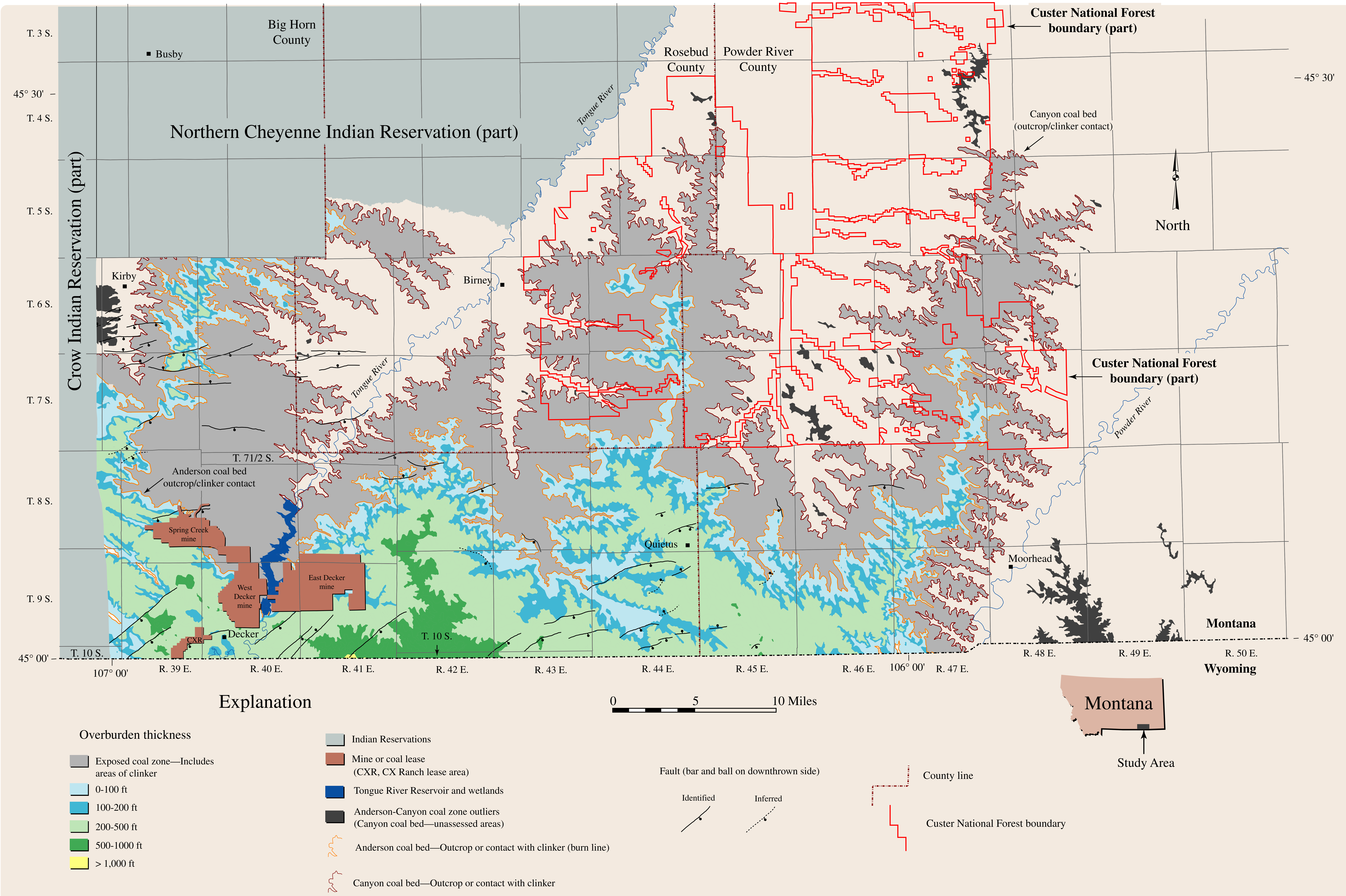

Figure PD-16. Map showing the thickness of overburden above the Anderson-Canyon coal zone, Decker coalfield, southeast Montana. Fault location and relative displacement modified from Robinson and Culbertson (1984).

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Table PD-1. Total, net coal resources in the Anderson-Canyon coal zone in the Decker coalfield, Montana, reported by county, overburden thickness, total, net coal thickness, and reliability categories. Resources are shown in millions of short tons (MST) and with two significant figures. Zeros (0) indicate that no coal resources were calculated within those categories. The table does not include resources in mine or coal lease areas, areas underlying clinker of the Anderson and/or Dietz coal beds, and areas underlying the Tongue River Reservoir and associated wetlands. Columns may not sum because of independent rounding

County	Minimum overburden thickness	Total, net coal thickness	Reliability categories (distance from data point)				Total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
BIG HORN	Exposed zone	2.5-5 ft.	0	1.3	0.86	0	2.2
		5 –10 ft.	2.9	15	20	0	38
		10-20 ft	20	47	140	0	210
		20-30 ft	55	170	260	1.8	490
		30-40 ft	40	230	310	4.6	590
		40-50 ft	55	260	400	13	730
		50-100 ft	92	630	1,100	1.2	1,800
	Exposed zone total		260	1,400	2,200	21	3,900
	0-100 ft.	10-20 ft	2.4	2.0	26	0	30
		20-30 ft	11	50	41	0	100
		30-40 ft	6.7	72	130	0	210
		40-50 ft	10	210	360	0	570
		50.100 ft	320	1,300	1,900	0	3,500
		100-150 ft	0	3.0	6.7	0	9.7
	0-100 ft. total		350	1600	2500	0	4,400
	100-200 ft	10-20 ft	0	0	2.3	0	2.3
		20-30 ft	0	14	16	0	29
		30-40 ft	0	26	53	0	79
		40-50 ft	5.9	120	290	0	420
		50-100 ft	330	1,800	2,000	0	4,200
		100.0-150 ft	16	92	46	0	150
	100-200 ft total		360	2,100	2,500	0	4,900

Table PD-1. Total, net coal resources, Anderson-Canyon coal zone—continued

County	Minimum overburden thickness	Total, net coal thickness	Reliability categories (distance from data point) Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	Total (MST)
BIG HORN	200-300 ft	30-40 ft	0	5.0	32	0	37
		40-50 ft	7.3	59	290	3.3	360
		50-100 ft	400	1,900	3,100	0	5,400
		100-150ft	68	160	81	0	310
	200-300 ft total		470	2,100	3,500	3.3	6,100
	300-400 ft	30-40 ft	0	2.7	12	0	14
		40-50 ft	2.0	29	210	32	270
		50-100 ft	280	1,700	2,600	0	4,600
		100-150 ft	17	130	120	0	270
	300-400 ft total		300	1,900	2,900	32	5,100
	400-500 ft	40-50 ft	0	0	40	50	89
		50-100 ft	120	880	1,600	0	2,600
		100-150 ft	1.3	180	170	0	360
	400-500 ft total		120	1,100	1,800	50	3,100
	500-1000 ft	40-50 ft	0	0	0.74	0	0.74
		50-100 ft	54	270	1,800	71	2,200
		100-150 ft	22	100	86	0	210
	500-1000 ft total		76	380	1,900	71	2,400
	1000-1500 ft	50-100 ft	0	0	2.3	10	12
	1000-1500 ft total		0	0	2.3	10	12
BIG HORN total			1,900	11,000	17,000	190	30,000
POWDER RIVER	Exposed zone	2.5-5 ft	2.2	11	39	0.23	53
		5-10 ft	11	54	130	4.4	200
		10-20 ft	65	330	530	23	950
		20-30 ft	100	420	480	86	1,100
		30-40 ft	64	320	500	100	980
		40-50 ft	20	140	430	55	640
		50-100 ft	14	110	530	24	680
	Exposed zone total		280	1400	2,600	290	4,600

Table PD-1. Total, net coal resources, Anderson-Canyon coal zone—continued

County	Minimum overburden thickness	Total, net coal thickness	Reliability categories (distance from data point)				Total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
POWDER RIVER	0-100 ft	2.5-5 ft	0	0.22	1.0	0	1.3
		5-10 ft	0	0.091	3.9	0	4.0
		10-20 ft	0	24	33	0	57
		20-30 ft	0	21	100	4.3	130
		30-40 ft	10	82	220	36	340
		40-50 ft	8.7	83	370	34	490
		50-100 ft	70	370	710	45	1,200
	0-100 ft total		88	580	1,400	120	2,200
	100-200 ft	2.5-5 ft	0	0	0.16	0	0.16
		5-10 ft	0	0	2.8	0	2.8
		10-20 ft	0	3.2	4.1	0	7.3
		20-30 ft	0	1.5	11	2.4	15
		30-40 ft	0	3.4	88	6.9	99
		40-50 ft	0.81	43	270	1.5	320
		50-100 ft	53	230	770	27	1,100
	100-200 ft total		54	290	1,100	38	1,500
	200-300 ft	5-10 ft	0	0	0.33	0	0.33
		10-20 ft	0	0	0.24	0	0.24
		30-40 ft	0	0	49	0.68	49
		40-50 ft	4.5	55	250	0	310
		50-100 ft	28	170	760	23	980
	200-300 ft total		33	230	1,100	24	1,300
	300-400 ft	30-40 ft	0	0	11	0	11
		40-50 ft	18	77	180	0	280
		50-100 ft	7.5	110	700	0	810
	300-400 ft total		26	190	890	0	1,100
	400-500 ft	40-50 ft	9.7	21	24	0	55
		50-100 ft	14	100	370	0	490
	400-500 ft total		24	130	400	0	540

Table PD-1. Total, net coal resources, Anderson-Canyon coal zone—continued

County	Minimum overburden thickness	Total, net coal thickness	Reliability categories (distance from data point)				Total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
POWDER RIVER	500-1000 ft	50-100 ft	1.0	9.7	3.9	0	15
	500-1000 ft total		1.0	9.7	3.9	0	15
POWDER RIVER total			510	2,800	7,600	470	11,000
ROSEBUD	Exposed zone	2.5-5 ft.	3.6	11	17	0	32
		5-10 ft.	29	99	90	0	220
		10-20 ft	41	210	340	14	610
		20-30 ft	23	170	210	0	410
		30-40 ft	16	55	130	0	200
		40-50 ft	1.9	58	90	0	150
		50-100 ft	0.81	57	290	0	350
	Exposed zone total		110	670	1,200	14	2,000
	0-100 ft	10-20 ft	0	2.6	8.9	0	11
		20-30.0 ft	2.5	2.8	20	0	25
		30-40 ft	2.2	7.7	24	0	34
		40-50 ft	0	31	99	0	130
		50-100 ft	46	260	640	0	950
	0-100 ft total		51	300	790	0	1,100
	100-200 ft	10-20 ft	0	0	0.36	0	0.36
		30-40 ft	0	0	0.78	0	0.78
		40-50 ft	0	0	12	0	12
		50-100 ft	12	84	150	0	250
	100-200 ft total		12	84	170	0	260
	200-300 ft	40-50 ft	0	0	0.87	0	0.87
		50-100 ft	2.3	18	13	0	33
	200-300 ft total		2.3	18	13	0	34
ROSEBUD total			180	1,100	2,100	14	3,400
Grand total (MST)			2,600	14,000	27,000	680	45,000*

* Of this total, approximately 3,500 MST are estimated to be present within Custer National Forest

Table PD-2. Total, net coal resources in the Anderson-Canyon coal zone reported for 7.5' quadrangles in the Decker coalfield, Montana. Coal resources are reported in millions of short tons (MST) rounded to two significant figures. Zeros (0) indicate that no coal resources were calculated within those categories. Overburden categories based on Wood and others (1983), and overburden is measured from the ground surface to the top of the uppermost coal bed (minimum overburden). Reported resources do not include areas within active coal mines or coal leases, areas underlying clinker of the Anderson and/or Dietz coal beds, or areas overlain by the Tongue River Reservoir and associated wetlands. Columns may not sum because of independent rounding

7.5-minute quadrangle map	Minimum overburden						Total (MST)
	Exposed zone	0.0-100 ft	100-200 ft	200-500 ft	500-1000 ft	> 1000 ft	
Acme	18	10	13	140	1.8	0	180
Bar N Draw	0	0	7.9	170	0	0	170
Bar V Ranch	43	76	44	170	0	0	340
Bar V Ranch NE	10	200	210	280	0	0	710
Bear Creek School	320	500	420	1,500	11	0	2,800
Birney	91	0	0	0	0	0	91
Birney Day School	4.2	0	0	0	0	0	4.2
Birney SW	160	3.2	0.36	0	0	0	170
Black Draw	20	42	9	0	0	0	71
Bloom Creek	130	0	0	0	0	0	130
Box Elder Draw	0	0	1.8	130	0	0	130
Bradshaw Creek	580	340	170	62	0	0	1,200
Browns Mountain	81	0.81	0	0	0	0	82
Cabin Creek NE	38	37	53	47	0	0	180
Cabin Creek NW	0	0	2.5	150	3.2	0	160
Cedar Canyon	0	0	0	7.7	120	12	140
Clubfoot Creek	2.3	0	0	0	0	0	2.3
Cook Creek Butte	97	0	0	0	0.0	0	97
Decker	140	66	160	1,400	30	0	1,800
Forks Ranch	250	720	680	1,200	13	0	2,900
Fort Howes	160	0	0	0	0	0	160
Goodspeed Butte	55	0	0	0	0	0	55
Green Creek	74	0	0	0	0	0	74

Table PD-2. Total, net coal resources by 7.5' quadrangle, Anderson-Canyon coal zone—continued

7.5-minute Quadrangle map	Minimum Overburden						Total (MST)
	Exposed Zone	0.0-100 ft.	100-200 ft.	200-500 ft.	500-1000 ft.	> 1000 ft.	
Half Moon Hill	670	670	400	470	0	0	2,200
Hamilton Draw	630	720	600	600	0	0	2,600
Hodsdon Flats	220	0	0	0	0	0	220
Holmes Ranch	38	170	250	1,700	720	0	2,900
King Mountain	29	0	0	0	0	0	29
Kirby	730	510	350	190	0	0	1,800
Lacey Gulch	480	410	260	240	2.2	0	1,400
Monarch	5.8	0	0	0	0	0	5.8
Moorhead	4.3	0	0	0	0	0	4.3
OTO Ranch	0	0	0	16	120	0	140
Otter	480	71	47	25	0	0	620
Pearl School	58	260	600	3,400	310	0	4,600
Phillips Butte	540	78	11	0.57	0	0	630
Pine Butte School	26	200	270	1,800	1,100	0	3,400
Poker Jim Butte	480	600	230	34	0	0	1,300
Quietus	57	360	890	2,300	0	0	3,600
Reanus Cone	260	28	3.9	0	0	0	290
Roundup Draw	0	0	0	132.44	0.74	0	130
Sayle	770	330	100	6.3	0	0	1,200
Sayle Hall	550	650	590	870	0	0	2,700
Sonnette	78	0	0	0	0	0	78
Spring Creek Ranch	32	0	0	0	0	0	32
Spring Gulch	620	160	91	62	0	0	930
Stroud Creek	330	340	160	130	0	0	970
Taintor Desert	670	240	64	7.6	0	0	980
Threemile Buttes	34	0	0	0	0	0	34
Tongue River Dam	340	13	0	0	0	0	350
Grand Total (MST)	10,000	7,800	6,700	17,000	2,500	12	45,000*

* Of this total, approximately 3,500 MST are estimated to be present within Custer National Forest

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Table PD-3. Total, net coal resources in the Anderson-Canyon coal zone, Decker coalfield, Montana, reported by county and by Federal coal and surface ownership. Coal resources in areas underlying clinker of the Anderson and/or Dietz coal beds, areas within active coal mines or leases, and areas underlying the Tongue River Reservoir and associated wetlands are not included in the resource total. Coal resources are reported in millions of short tons (MST) with two significant figures. Column will not sum due to independent rounding

County	Federal Ownership	Total (MST)
BIG HORN	No Federal coal or Federal surface ownership	3,100
	No Federal coal, but Federal surface ownership	5.8
	Federal coal, but no Federal surface ownership	25,000
	Federal coal and Federal surface ownership	2,000
BIG HORN Total		30,000
POWDER RIVER	No Federal coal or Federal surface ownership	700
	No Federal coal, but Federal surface ownership	1.5
	Federal coal, but no Federal surface ownership	7,200
	Federal coal and Federal surface ownership	3,400
POWDER RIVER total		11,000
ROSEBUD	No Federal coal or Federal surface ownership	150
	No Federal coal, but Federal surface ownership	1.1
	Federal coal, but no Federal surface ownership	1,500
	Federal coal and Federal surface ownership	1,800
ROSEBUD total		3,400
Grand total (MST)		45,000*

* Of this total, approximately 3,500 MST are estimated to be present within Custer National Forest

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Table PD-4. Computations of confidence intervals within reliability categories for estimated total coal resources in the Anderson-Canyon coal zone in the Decker coalfield, Montana. Volume refers to the calculated resource in millions of short tons (MST). NA, not applicable

Parameter	Reliability Category				Entire Area
	Measured	Indicated	Inferred	Hypothetical	
Area (in square meters)	133,426,743	704,761,677	1,340,332,461	42,411,593	2,220,932,473
Percent of area	6	32	60	2	100
Acres	32,970	174,150	331,203	10,480	548,804
SD (Standard deviation (in ft) from semivariogram model)	5.712	7.730	13.093	16.089	NA
Acre feet (Acres x SD)	188,333	1,346,167	4,336,582	168,610	NA
Volume standard deviation (MST)	21	192	1,794	298	2,305
Pseudo *n* (Minimum number of points in the area)	262	154	18	1	NA

Table PD-5. Volume and estimates of uncertainty for estimated total coal resources in the Anderson-Canyon coal zone, Decker coalfield, Montana, with measurement error. Resource calculations are in millions of short tons (MST) with four significant figures. Volume refers to the calculated resource in millions of short tons (MST).

Parameter	Reliability Category				Entire Area
	Measured	Indicated	Inferred	Hypothetical	
Volume (MST)	2,621	14,400	27,030	675	44,730
Lower 90% confidence bound (MST)	2,587	14,090	24,080	184	40,940
Upper 90% confidence bound (MST)	2,655	14,720	29,980	1,166	48,520