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The Coalbed Methane Potential in the Upper Cretaceous to Early Tertiary Laramie and Denver Formations, Denver Basin, Colorado

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CONTENTS

FIGURES

TABLES

PLATES [appended to end of report]

ABSTRACT

Coals in the Late Cretaceous Laramie Formation and early Tertiary Denver Formation hold some intrigue for coalbed methane potential by virtue of their measured heating values, shallow depths, reasonable thickness and continuity, and the documented occurrences of gas accumulations and explosions in coal mines.

Over the past 140 years, more than 300 historic mines were developed in the Denver Basin. The vast majority of them were underground mines in the Laramie Formation coals from which approximately 130 million tons of subbituminous coal was mined. Now that newly developed completion technologies are allowing commercial methane production from shallow, low rank coals, even the Denver Formation lignitic coals may be prospective.

The great diversity in coalbed methane plays proves that there are various reservoir characteristics critical to successful methane production from low rank coals. Preliminary analyses of coal data collected by mining companies, combined with data collected from gas, oil, and water wells drilled in the Denver Basin, strongly suggest that further research and testing is required to demonstrate the economic feasibility of a coalbed methane play in the basin. In the meantime, the Colorado Geological Survey has compiled a Geographic Information Systems coalbed methane database that captures the data contained in numerous hardcopy publications released over the past twenty years. The GIS ArcView ™ format allows easy manipulation of important data such as isopach and structure maps, log cross sections, desorption and heating value data, locations of historic mines, coal analyses from those mines, and calculated gas content values.

In addition to evaluating the resource potential, careful consideration must be paid to the shallow aquifers which surround and include these coals and into which thousands of water wells have been drilled. Regulatory and environmental factors will play vital roles in determining the producing potential for coalbed methane wells.

INTRODUCTION

The Denver Basin is an asymmetric Laramide foreland basin with a gentle east flank and a faulted, folded, and steeply dipping west flank (Figure 1). The basin is bounded on the west by the Front Range uplift, on the southwest by the Apishapa uplift, on the southeast by the Las Animas Arch, on the northeast by the Chadron Arch, and on the northwest by the Hartville Uplift.

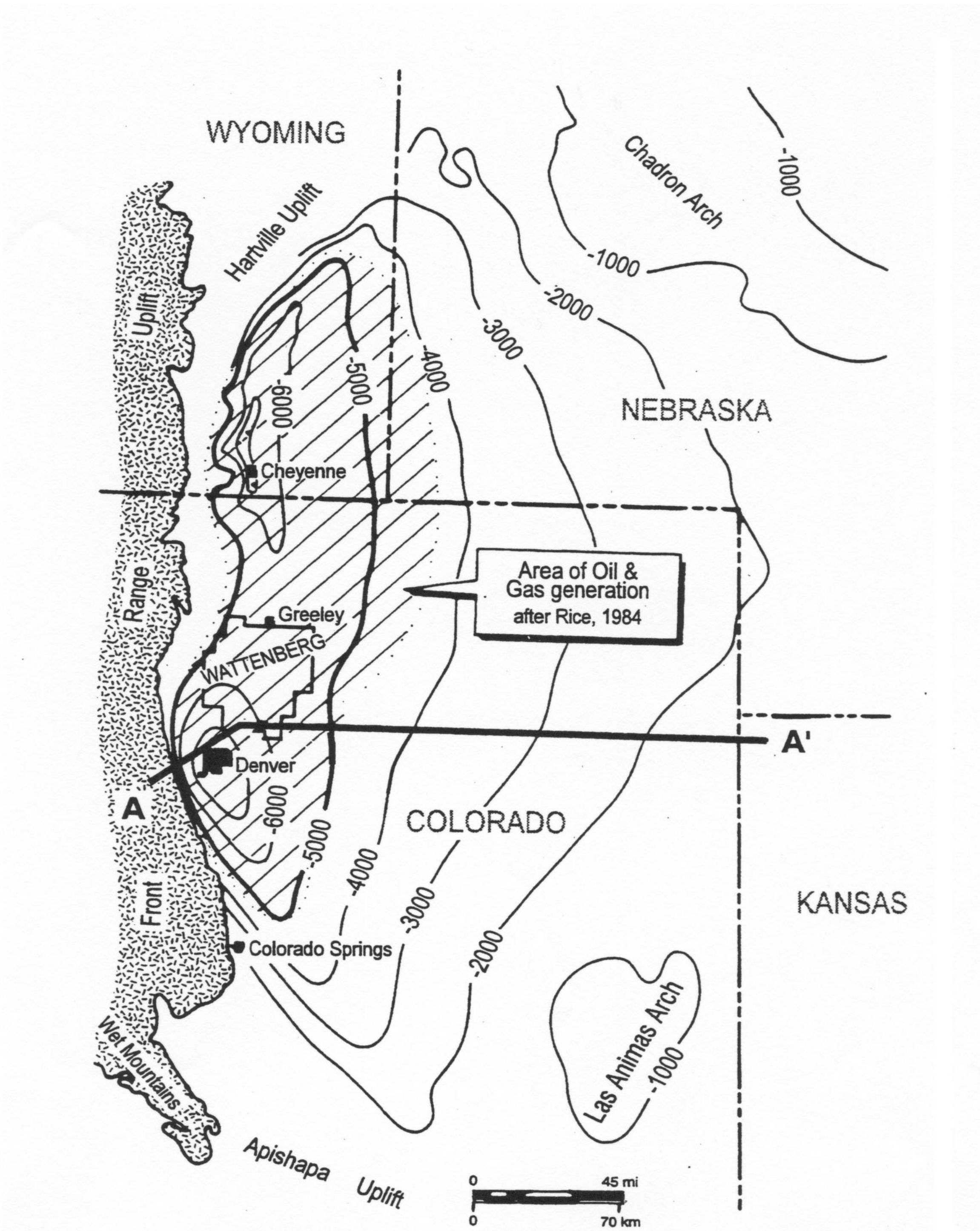

Figure 1. Area of oil and gas generation in the Denver Basin (Rice, 1984) superimposed on structure contour map (Weimer, 1996, Fig. 23). Contour interval = 1000 ft (305 m).

The structural center of the basin is southeast of Cherry Creek Reservoir, approximately fifteen miles southeast of the city of Denver. The basin fill is composed of approximately 13,000 feet (3,900 meters) of sediments of which 9,500 feet (2,850 meters) are Cretaceous and lower Tertiary sediments. Below this entire sedimentary sequence, which includes older Mesozoic and Paleozoic sediments, is the Precambrian age basement composed of igneous and metamorphic rocks older than 1.6 billion years (Weimer, 1996, p. 34). Figure 2 is a generalized composite section of the Denver Basin that shows the stratigraphic relationship of the coal-bearing Laramie and Denver Formations to the overlying and underlying sediments (Romero, 1976).

Era	System or Period	Series	Geologic Unit	
Cenozoic	Quaternary	Recent and Pleistocene	Quaternary surficial deposits	Stream channel, flood-plain and terrace deposits; eolian sand, etc.
	Tertiary	Oligocene	Castle Rock Conglomerate	
			Tertiary intrusive and extrusive rocks	
Cenozoic and Mesozoic	Tertiary and Cretaceous	Paleocene ---?---- Upper Cretaceous	Dawson Group	Dawson Arkose
				Denver Formation
				Arapahoe Formation
Mesozoic	Cretaceous		Laramie Formation	Upper part
				B sandstone
				A sandstone
			Fox Hills Sandstone	Milliken Sandstone
				lower part
			Pierre Formation	
			Niobrara Formation	Smoky Hill Shale
				Fort Hayes Limestone
			Benton Formation	Carlile Shale
				Greenhorn Limestone
				Graneros Shale
		Lower Cretaceous	Dakota Group	South Plate Formation
				Lytle Formation
	Jurassic	Upper Jurassic	Morrison Formation	
			Ralston Creek Formation	
Palezoic	Triassic ? and Permian		Lykins Formation	Strain Shale
				Glennon Limestone
				Bergan Shale
				Falcon Limestone
				Harriman Shale
	Permian		Lyons Sandstone	
	Pennsyl-vanian		Fountain Formation	
			Glen Eyrie Formation	
	Mississi-pian		Madison Limestone	
			Williams Canyon Limestone	
	Ordovician and Cambrian		Manitou Dolomite	
	Cambrian		Sawatch Sandstone	
Precambrian			crystalline rocks	

Figure 2. A generalized stratigraphic chart for the Denver Basin, Colorado (Romero, 1976, p. 11)

The basin axis trends north-south and is separated internally by a structural high known as the Greeley Arch which divides the Upper Cretaceous and Tertiary sediments into two distinct sub-basins, the Denver and Cheyenne Basins. Both basins are doubly plunging synclines in which the Upper Cretaceous and early Tertiary sediments are conformable over the structurally deformed basin fill sediments. Only the Denver sub-basin, however, contains coals from both the Denver and Laramie Formations (Figures 3 and 4).

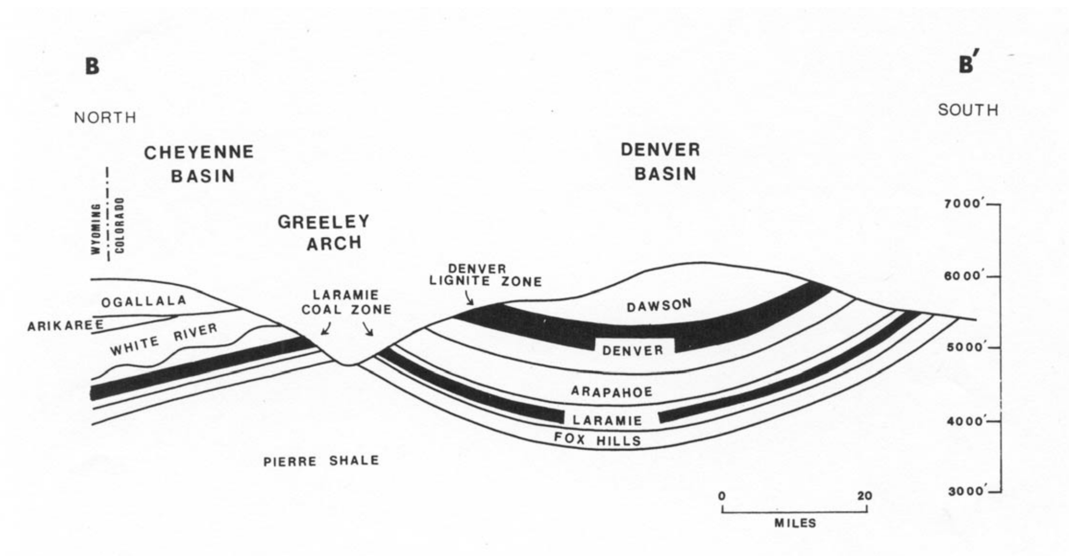

Figure 3. Generalized north-south cross section through the Denver Basin and the south flank of the Cheyenne Basin. Note the configuration of the Greeley Arch that separates the two sub-basins (Kirkham and Ladwig, 1979, p. 14).

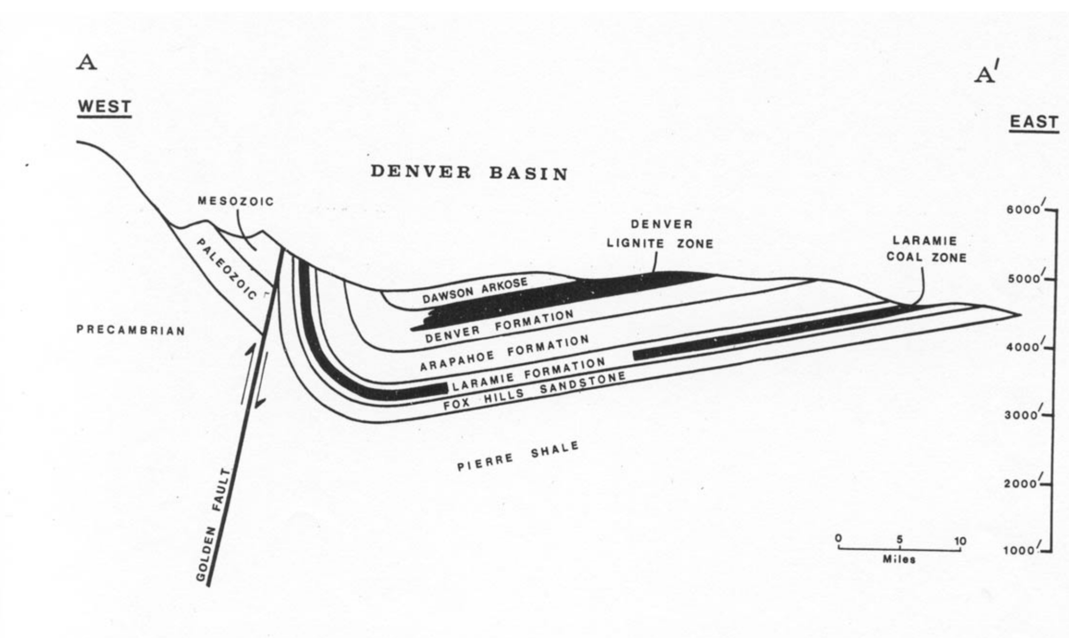

Figure 4. Generalized east-west cross section through the Denver Basin. See Figure 1 for location of cross section (Kirkham and Ladwig, 1979, p. 15).

The Denver sub-basin, which will be henceforth referred to simply as the Denver Basin in this report, is the subject of study for coalbed methane potential. This basin covers approximately 7,500 square miles (19,400 square kilometers) in all or parts of Adams, Arapahoe, Boulder, Douglas, Elbert, El Paso, Jefferson, Morgan, and Weld Counties in eastern Colorado (Plate 1). This area conforms to the aerial extent of Upper Cretaceous and early Tertiary coal-bearing rocks in the basin and is consistent with research and publications by the Colorado Geological Survey from which much of the data in this report were derived.

Like so many other Laramide basins in Colorado, the Denver Basin is rich in both hydrocarbon and coal resources. It is the coalbed methane potential of the Upper Cretaceous and early Tertiary Laramie and Denver Formation coals with which this report is concerned. Thus, the purposes of this report are as follows:

- to compile and document coal data from numerous published reports, accumulated information, and assembled databases produced and stored by the Colorado Geological Survey,
- to present these data, which assemble coal quality and availability data, in displays that specifically address the coalbed methane potential of these coals,
- to utilize ArcView ™ and ArcInfo™ formats for manipulating the various layers of data to be viewed together, and
- to suggest possible concerns relating to the feasibility of coalbed methane production that deal with aquifers, land use issues, and environmental questions.

ACKNOWLEDGEMENTS

In planning a one-day workshop sponsored by the Petroleum Technology Transfer Council (PTTC) and the Colorado Geological Survey (CGS) in September, 2001, we have greatly benefited from planning discussions with all of the speakers and some of the participants. We wish to acknowledge our gratitude to all of those people who submitted abstracts for their workshop presentations. Those abstracts are contained in this report in Appendix C.

Within the CGS, we appreciate the technical guidance and assistance supplied by James Cappa, Chris Carroll, Randy Phillips, Jason Wilson, and Cheryl Brchan.

PREVIOUS WORK

The Denver Basin (Plate 1) has been studied in great detail from all geologic, geophysical, and engineering aspects over the past few decades. For a broad geological background, as well as for references dealing specifically with the Upper Cretaceous and early Tertiary coals in the Denver Basin, please refer to the cited bibliographies contained within this report.

MINING HISTORY

Historically, over 300 underground and surface coal mines were operated in the Upper Cretaceous and early Tertiary Laramie and Denver Formation coals around the periphery of the Denver Basin (Plate 2). Total historic coal production from these two formations is approximately 130 million tons since 1883. Of that volume mined, 99.97 percent was reported from the Laramie Formation coals with 99.8 percent of total coal production mined from underground mines. Coal production (in millions of tons) was recorded for the following Denver Basin counties: Weld (66), Boulder (41), El Paso (16), Jefferson (6), and five others (less than 1). This total represents 12.74 percent of the total coal produced in Colorado since the late 1800s, a relatively significant number.

Despite the historic volumes of coal mined in the Denver Basin, it was the quality of the Upper Cretaceous and early Tertiary coals that failed to provide economic incentives for continued mining in the mid-twentieth century. These Denver Basin subbituminous and lignitic coals could not compete with abundant and higher quality coals in neighboring Wyoming and Utah, and thus the mining activity tapered off. Today, there are no active mines in the Denver Basin.

Nonetheless, coal resources are still abundant in the basin. Though the likelihood of renewed underground or surface mining is small, the potential for extracting methane from the coals provides considerable intrigue for the petroleum industry. The CGS has access to most of the historic coal quality data that provides the foundation for evaluating the coalbed methane potential.

REGIONAL STRATIGRAPHY FOR DENVER BASIN COAL SEQUENCES

The coals of interest in this study are distributed throughout the Upper Cretaceous Laramie Formation and Upper Cretaceous-early Tertiary Denver Formation (Fig. 5a).

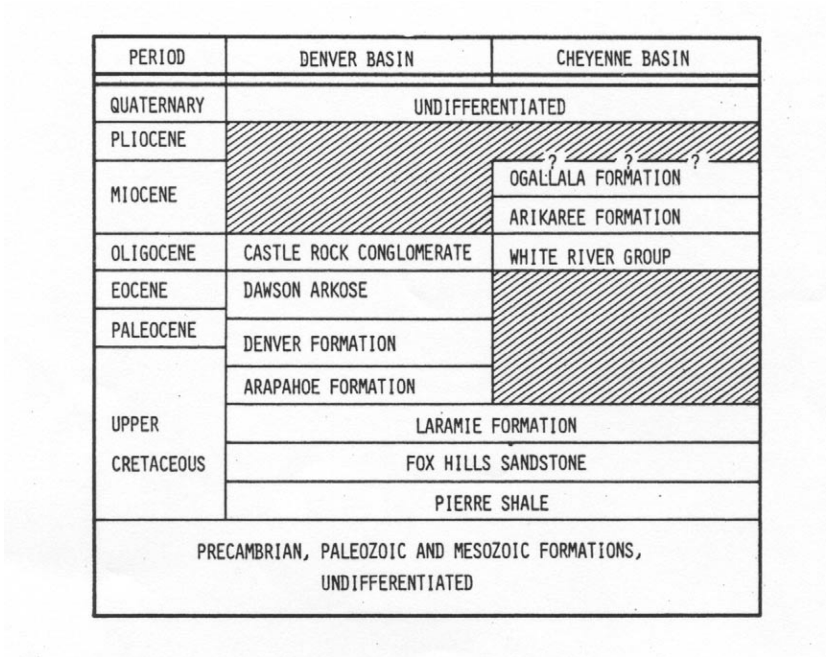

Figure 5a. Generalized stratigraphy of the Denver and Cheyenne Basins, Colorado. Note that the Denver Formation and its lignitic coals are absent in the Cheyenne Basin (Kirkham and Ladwig, 1979, p. 25).

A more detailed stratigraphic chart is presented in Figure 5b. Though this is only a generalized section, it is an excellent representation of the distribution, thickness, and correlative bed names for the coals in the Laramie and Denver Formations.

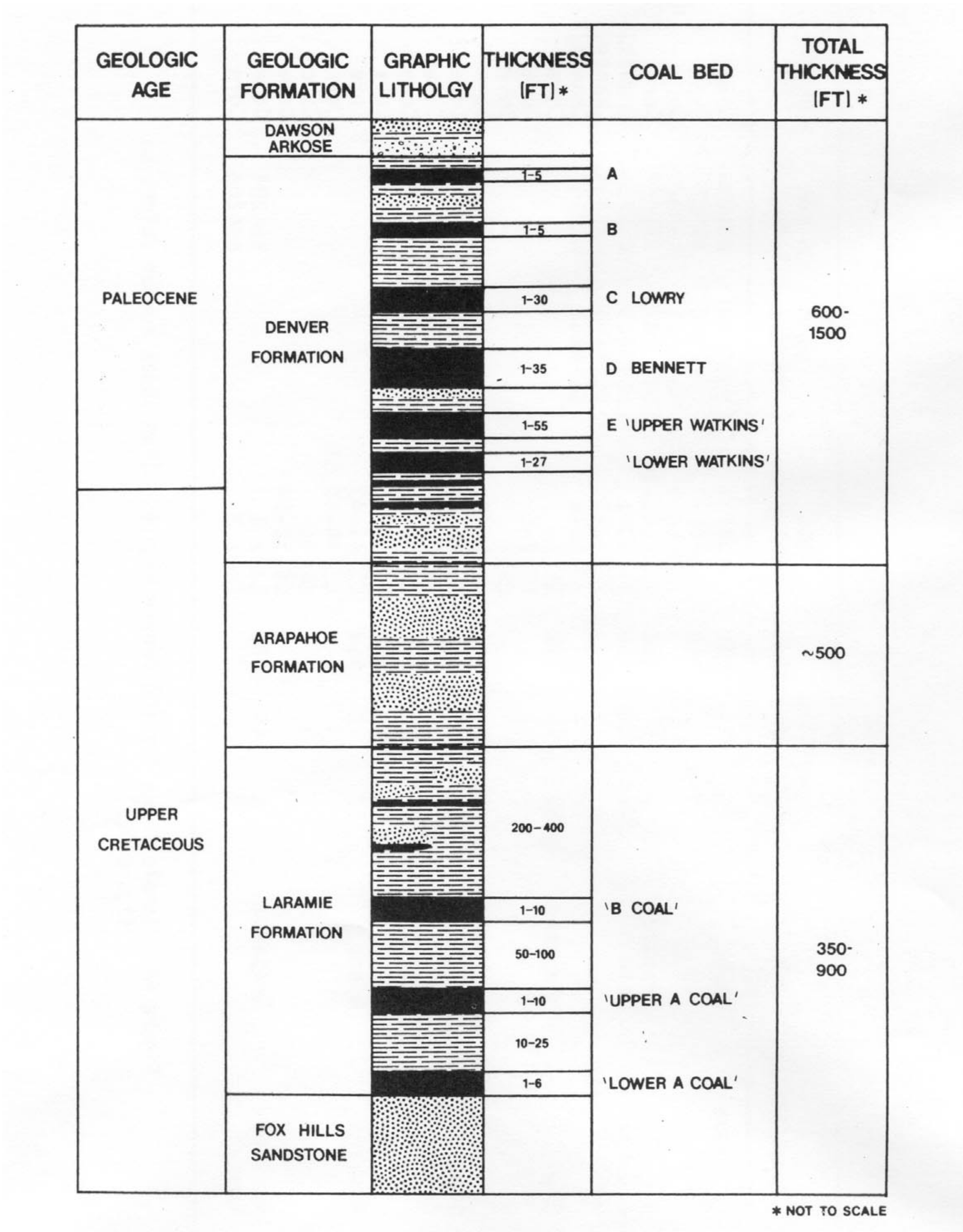

Figure 5b. Generalized stratigraphic column for the Laramie and Denver Formation coal intervals (Brand, 1980).

The strata containing the major groundwater supplies in the Denver Basin surround and include sands within the Denver and Laramie Formations, as shown above in Figures 5a and 5b. The four significant aquifers contained within the Upper Cretaceous Laramie-Fox Hills Formations, the Arapahoe Formation, the Upper Cretaceous-early Tertiary Denver Formation, and the early Tertiary Dawson Arkose, will be discussed in a later section entitled "Groundwater Resources of the Denver Basin Aquifers"(p. 26).

The Laramie Formation coal zone is a 50- to 275-foot (15.0- to 82.5-meter) thick sequence of interbedded coal, shale, siltstone, claystone, and sandstone within the maximum 1,000 feet of total Laramie Formation thickness. Approximately 75 to 85 percent of the outlined coal-bearing Denver Basin region, seen in Plate 1, or about 5,600 to 6,400 square miles (14,500 to 16,500 square kilometers), is underlain by Laramie Formation coal which outcrops along the western margin of the basin. The stratigraphy of the Laramie coals vary dramatically from the northwest part of the basin in the Boulder-Weld field area, located in southwestern Weld County, to the eastern part of the basin in the Buick-Matheson area, located in eastern Elbert County (see Figures 6 and 7).

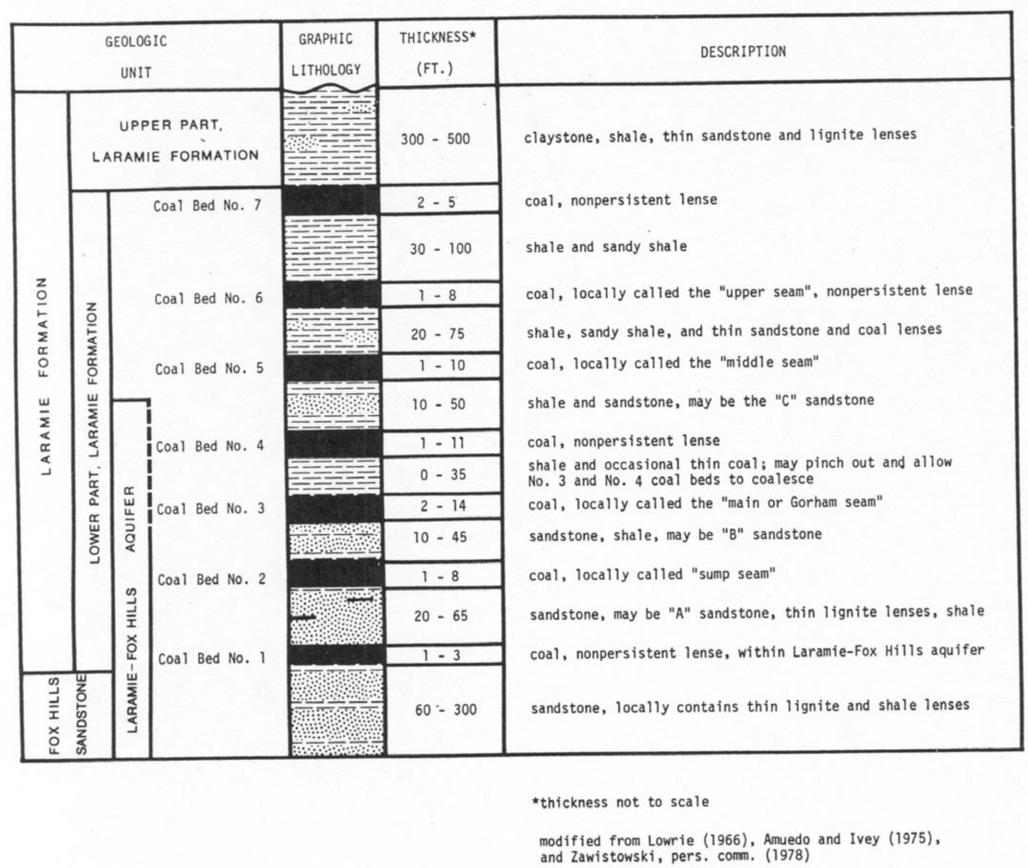

Figure 6. Generalized stratigraphy of the Laramie Formation coal interval, Boulder-Weld field, located in the southwestern portion of Weld County, Colorado (Kirkham and Ladwig, 1979, p. 42).

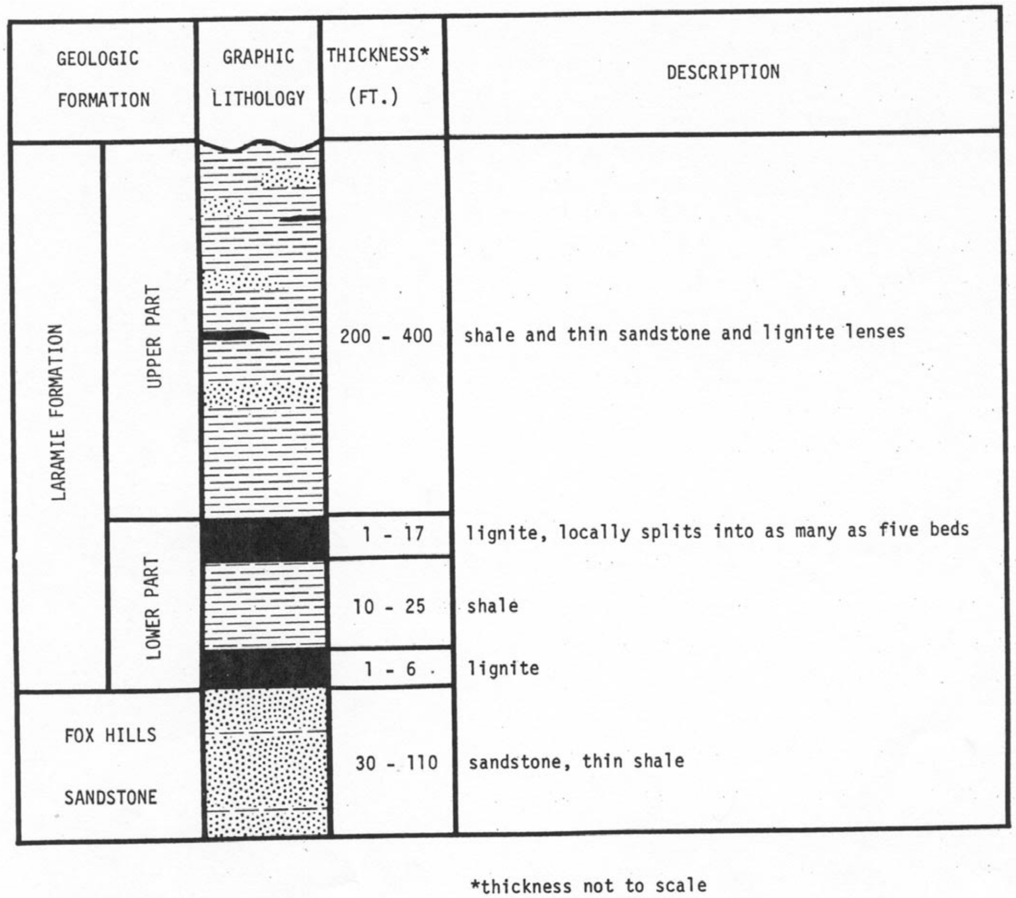

Figure 7. Generalized stratigraphy of the Laramie Formation coal zone, Buick-Matheson area, located in eastern Elbert County, Colorado (Kirkham and Ladwig, 1979, p. 46).

A more detailed discussion of the regional extent of the Laramie coals can be found in Kirkham and Ladwig (1979).

The stratigraphy and nomenclature for the coals within the Laramie Formation are complex and somewhat difficult to summarize. Suffice it to say that the stratigraphy and coal distribution, which depend so heavily upon the facies development and environments of deposition affecting the coals in Late Cretaceous times, vary so much regionally that it is imperative to examine these relationships on a localized basis. Kirkham and Ladwig (1979) present some detailed descriptions of these localized coal relationships.

Deposition of the Laramie Formation probably occurred in a delta plain environment in which a complex arrangement of facies developed that included thriving coal swamps, abandoned distributary channels, levees, splays, and poorly drained swamps in overbank areas adjacent to channel-margins (Weimer, 1973). Superimposed upon these lateral facies developed at any time was the vertical stacking of facies created by eastward progradation. These relationships are nicely summarized in Weimer (1977) by two diagrams shown in Figures 8 and 9.

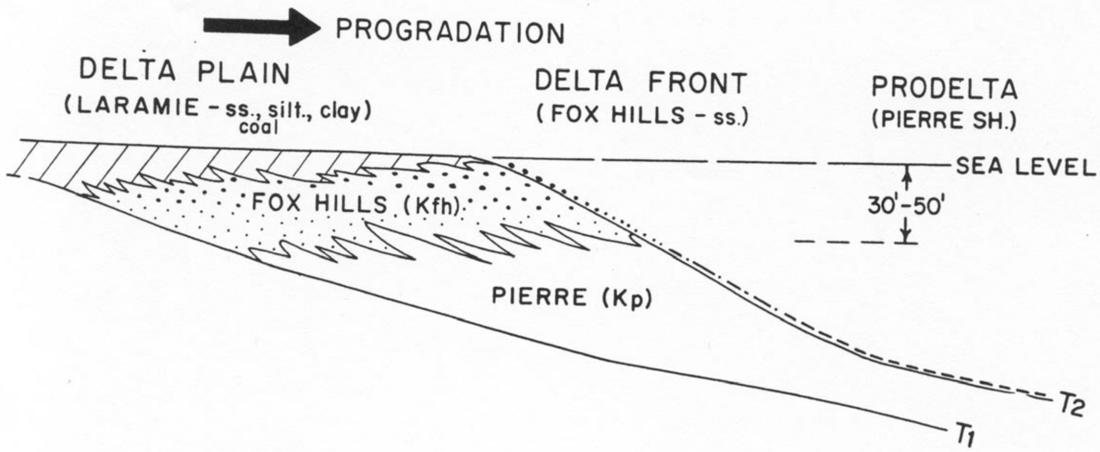

Figure 8. Deltaic sedimentation model showing the relationship between formations and the facies and the depositional environment in which they formed. T1 and T2 are time surfaces (Weimer, 1977, p. 22).

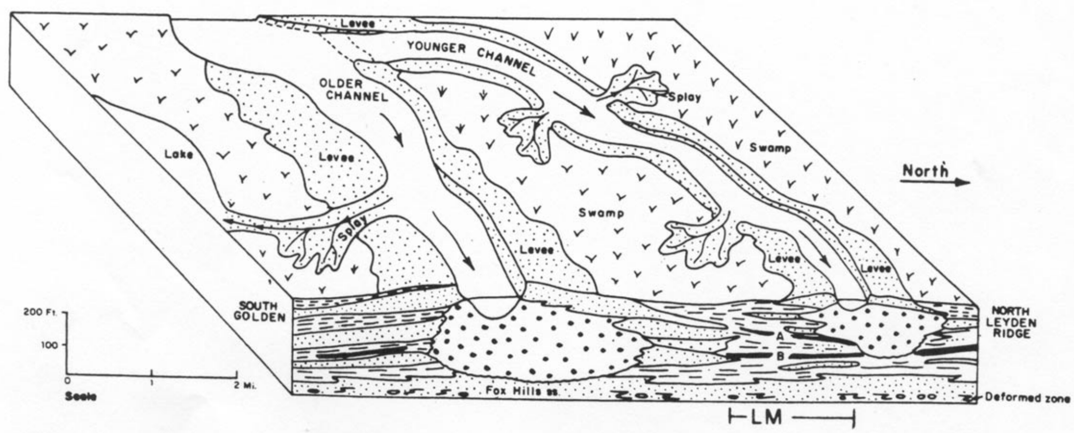

Figure 9. Block diagram showing the interpreted relationships in the lower Laramie Formation from the Leyden Mine area to Golden, Colorado. L.M. = Leyden Mine area (Weimer, 1977, p. 22).

The Denver Formation coal zone contains lignites that occur in the upper 300 to 500 feet (90 to 150 meters) of the Upper Cretaceous-early Tertiary Denver Formation. These lignites lie some 800 to 1,500 feet (240 to 450 meters) above the top of the Laramie coal zone and exist in an area of approximately 1,700 square miles (4,400 square kilometers), outcropping along the eastern margin of the basin. Most lignite beds contain non-coal partings that range from less than 0.1 inch (0.25 centimeters) to over 2 feet (0.6 meters), necessitating the distinction between gross and net lignite thickness for any economic analyses. The partings are composed of kaolinite, likely derived from the alteration of volcanic ash layers, which could represent an economic source of alumina and other mineral constituents. In some areas, the partings can be continuous, possibly up to three miles in length, as traced in drill holes in the Strasburg NW quadrangle (Soister, 1978a). In general, the net lignite thickness is 70 to 95 percent of the gross lignite thickness throughout the basin (Kirkham and Ladwig, 1979).

The Denver Formation lignite zone stratigraphy varies from north to south in the basin. The northern lignites range from 10 to 30 feet with a maximum thickness of 54.5 feet, while the southern ones vary generally between 5 and 10 feet, with a maximum of 30 feet. Figure 10 presents a generalized summary of the lignite distribution in both areas. For more extensive discussions of these individual lignite beds and the manner in which they can be correlated, refer to Kirkham and Ladwig (1979, p. 52-59) and Eakins and Ellis, (1987).

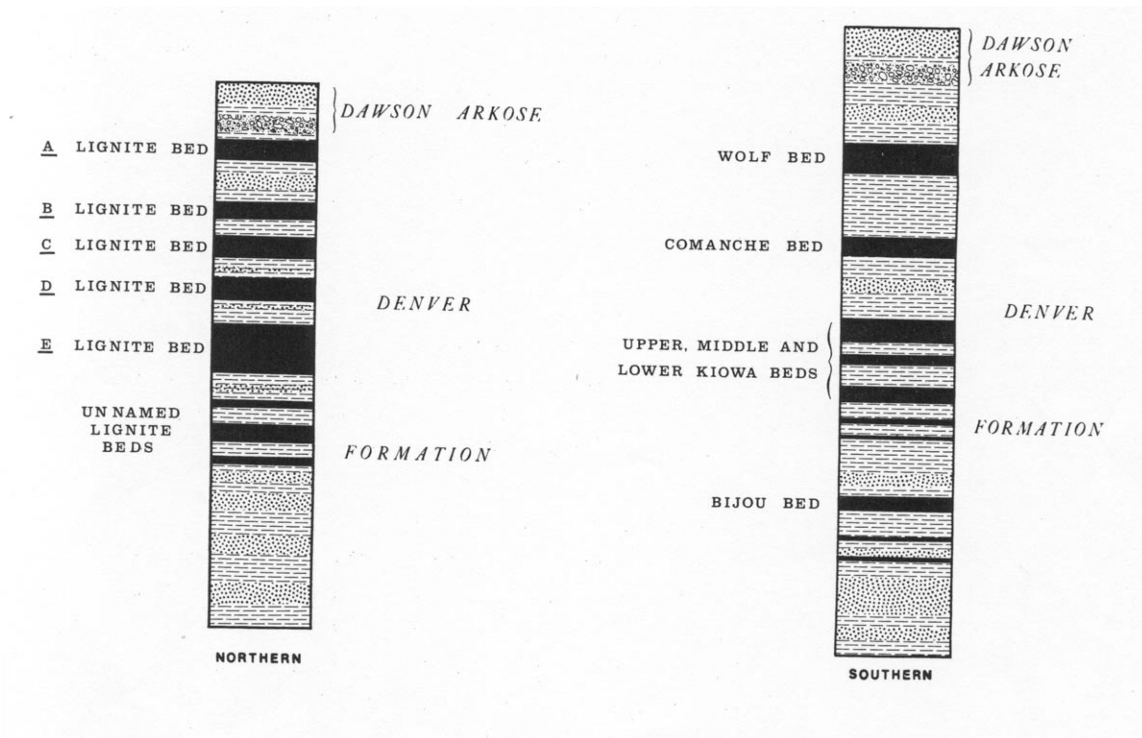

Figure 10. A comparison of the generalized stratigraphy of the Denver Formation in the northern and southern portions of the Denver Basin. (Bed thickness is not to scale) (Kirkham and Ladwig, 1979, p. 53).

The depositional model for Denver Formation lignites, as proposed by Kirkham and Ladwig (1979), explains the stratigraphic variability that exists between the northern and southern part of the basin (Figure 11). Depositional patterns resulting from episodic sedimentation, related to the uplift of the Front Range to the west, and the gradual subsidence of the Denver Basin, are shown in Figure 11.

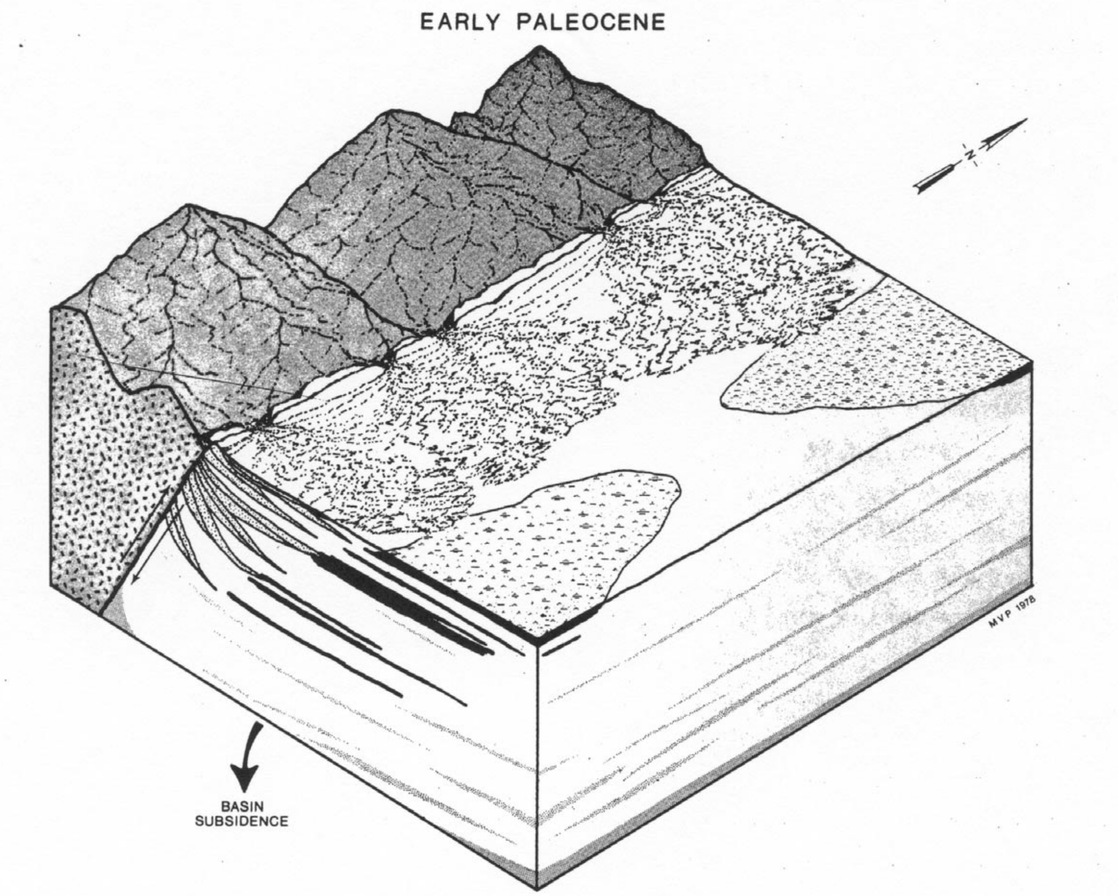

Figure 11. Block diagram depicting the depositional environment of the Denver Formation lignite beds (not to scale). Note the inferred depositional separation between the two coal sub-basins, the Denver and Cheyenne Basins (Kirkham and Ladwig, 1979, p. 56).

The distribution and extent of the lignites and correlative clastic sediments suggest that uplift was slow and that there was not a substantial elevation difference between the uplifted area and the lignite swamps. As with the Laramie Formation coals, the Denver Formation lignites prograded eastward, although post-depositional erosion has removed any record of the correlative sediments east of the basin. The lignites themselves were developed in poorly drained swamps through which prograding braided streams migrated, accounting for the complex horizontal and vertical stratigraphy.

Currently, the Museum of Nature and Science in Denver is conducting detailed sedimentological and stratigraphic research on the Denver Formation lignites. Relying heavily upon outcrop observations, coupled with subsurface well logs and two available cores within the Denver Basin, the stratigraphy is being redefined. Paleosols, unconformities, conglomeratic units, and regional isopach maps for distinguishing sequences within the Denver Formation, are being studied in the context of sedimentation patterns (Bob Raynolds, 2001, pers. communication). One of the abstracts in Appendix C, authored by Bob Raynolds, summarizes some of that research.

REGIONAL STRUCTURE FOR DENVER BASIN COAL SEQUENCES

As mentioned before, the Laramide deformation affected both the Denver and Laramie Formations as well as the sediments above and below them. On the eastern side of the Denver Basin, the gentle dips and lack of significant faulting and folding attest to the relative tectonic quiescence that took place in that area. On the western margin of the basin, however, the tectonic influences were more dramatic. The large-scale "Basin Margin" fault, responsible for folding the Laramie, Fox Hills and Pierre Formations to their near-vertical positions, is represented in Figure 12.

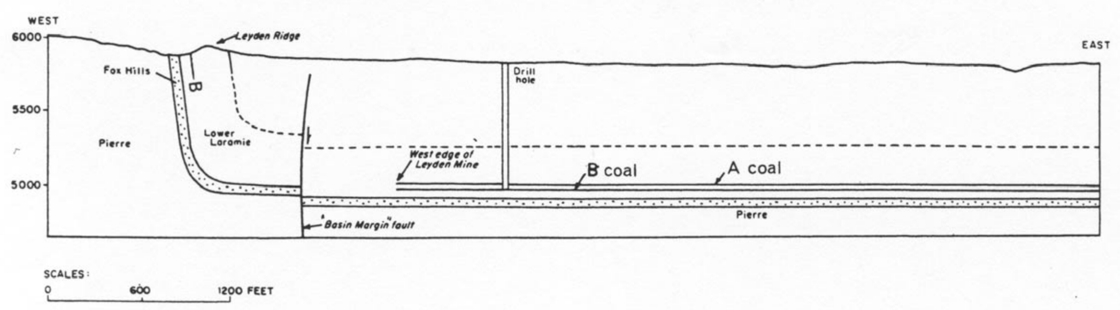

Figure 12. Simplified east-west structural cross section showing the relationship of the Laramie coals on either side of the Basin Margin Fault (Weimer, 1977, p. 23).

The "Basin Margin" fault, seen above in Figure 12, as well as the major fault that juxtaposes the Precambrian metamorphic rocks against the Pennsylvanian Fountain Formation (not shown in Figure 12), contribute to the basement faulting and overlying folds developed in the sediments.

Five interpreted right-lateral wrench faults, seen on Figure 13a, also involve basement rocks and extend up through the early Tertiary sediments, further complicating the patterns of folding and faulting (Higley and Cox, 2001).

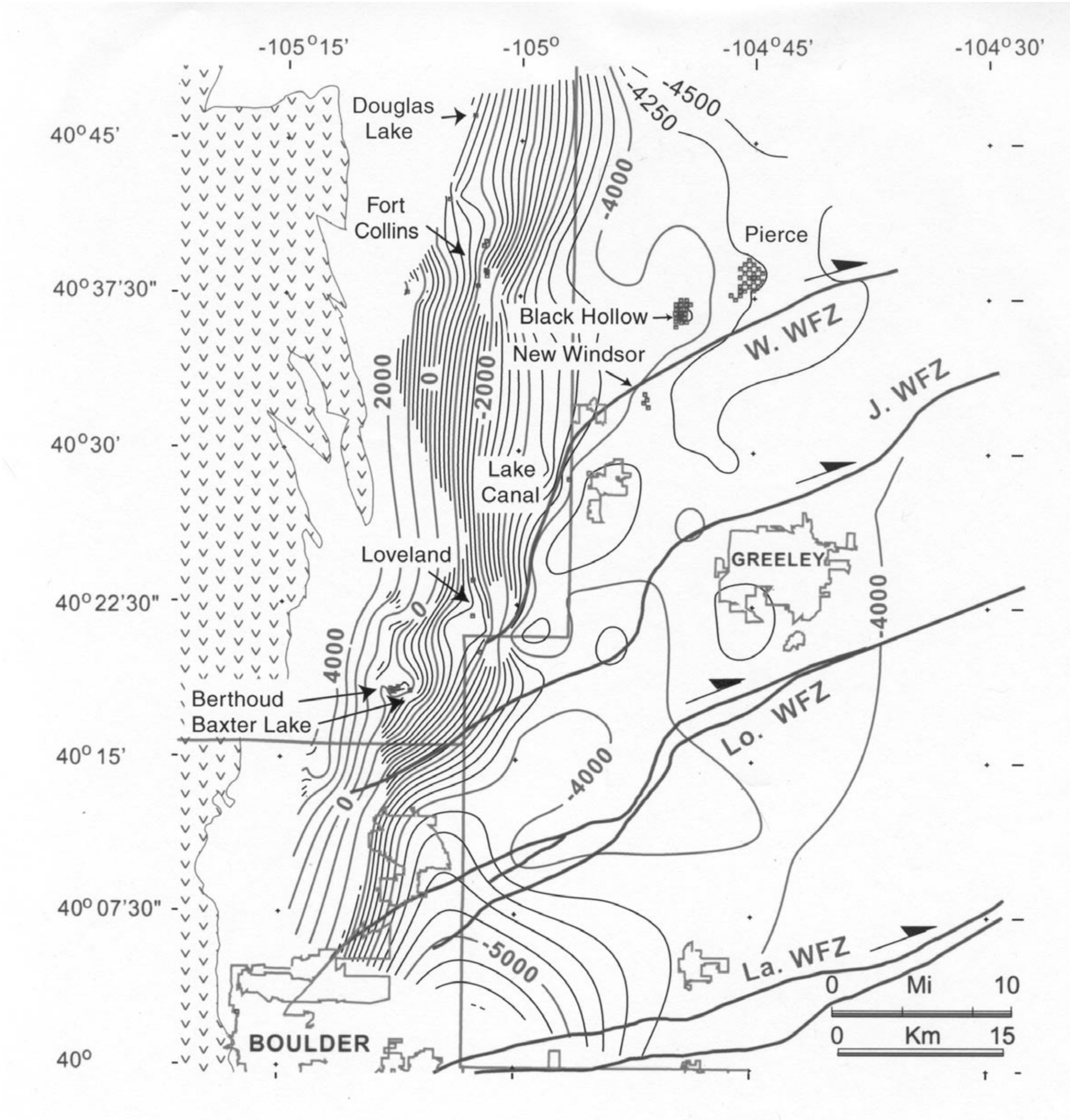

Figure 13a. Prominent northeast-southwest-trending right lateral wrench faults are shown in the northwestern portion of the Denver Basin. These are superimposed upon the structural elevations on top of the Permian Lyons Formation shown in feet. Contour interval is 250 feet. The wrench faults include Windsor (W.WFZ), Johnstown (J.WFZ), Longmont (Lo.WFZ), and Lafayette (La.WFZ) (Higley and Cox, 2001, in press).

Growth faults appeared to be synchronous with Laramie coal formation in the western part of the basin as supported by thicker coals within graben blocks than in adjacent horst blocks. Historically, the locations of underground mines, particularly in the Boulder-Weld field in the northwest part of the basin, were confined to thicker coal accumulations within the graben (Weimer, 1977)

There is some recent published data that suggests that some of these mountain-front faults, particularly in the northwest portion of the Denver Basin, are sub-parallel, high-angle listric reverse faults (Kittleson, 1992). Based upon log data, these faults are interpreted to cut up through the Laramie Formation coals with offsets of up to 600 feet (Figure 13b). A detailed discussion of the structural configuration of these faults, and whether they are have a predominantly strike-slip or reverse movement to them, is beyond the scope of this study. However, the nature and timing of, as well as the offset along, these faults is important to any future coalbed methane development. This subject is discussed in the abstract by Bob Weimer (Appendix C).

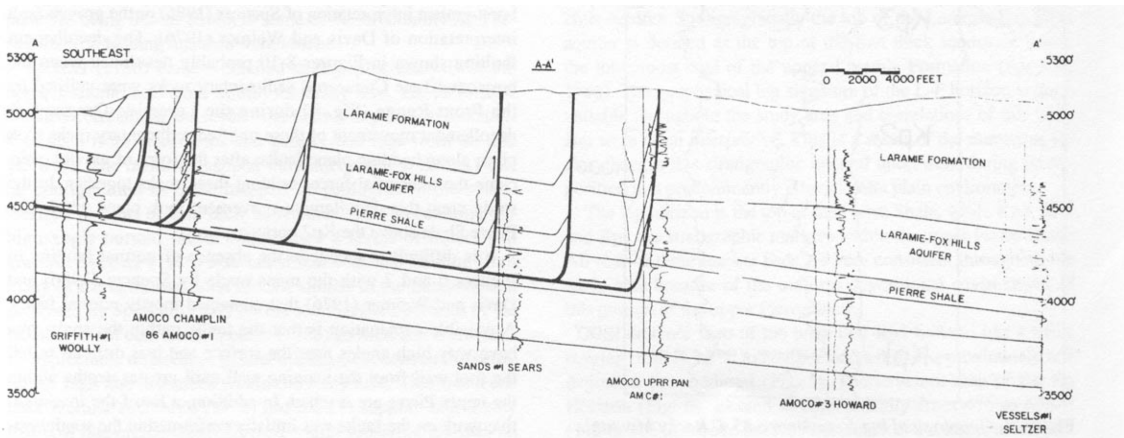

Figure 13b. Northwest to southeast structural cross section through the Boulder-Weld coal field, Townships 1 and 2 North, Ranges 67 and 68 West. Vertical to horizontal exaggeration is 10:1 (Kittleson, 1992, Figure 8).

DATA COLLECTION

The CGS, in collaboration with the Division of Minerals and Geology (DMG), has compiled and documented much of the historic mine and coal quality data. In the early 1980s, the CGS conducted a number of studies focused on the nature and distribution of the subsurface coal resources to supplement data that was so prevalent near the basin edges from coal mining records.

A comprehensive report listing historic coal mines and coal analyses from those Denver and Cheyenne Basin mines was published by Kirkham (1978). The report includes the coal-producing formation, type of mine, known years of production, seam thickness and name, production amounts, and coal seam depth. It also mentions other names for individual mines. A specific coal mine bibliographic reference is listed for each mine. Additionally, there are analyses for samples taken from mines or other locations. The data listed describe sample type (corehole, face channel, delivered sample, or tipple sample), the specific formation from which the sample was taken, the basis or type of analysis for heating values of the coals (as-received, moisture-free, or mineral- and moisture-free), and a bibliographic source for these analyses only.

From the data listed above, we have chosen to display the locations of all the mines included in that report (Plate 2). In addition, the analytical data for heating values were digitized by the CGS and the data have been incorporated in map format (Plates 4-9).

A simplified summary of as-received Laramie Formation coal analyses, with accompanying heating values, is shown in Table 1. These values are representative of various coal samples taken from mining areas within the two sub-basins.

Table 1. Average as-received heating values for the Laramie Formation coals from various mining areas in the Denver and Cheyenne sub-basins (Kirkham and Ladwig, 1979, p. 48).

Location	Moisture (%)	Ash (%)	Heat Value (Btu/lb)	Sulfur (%)
SW Boulder-Weld	21.0	7.0	9,700	0.4
NE Boulder-Weld	30.0	6.0	8,200	0.4
Foothills	26.0	7.0	8,500	0.6
Colorado Springs	23.0	7.0	8,500	0.5
Buick-Matheson	34.0	9.0	6,500	0.4
Wellington	32.0	8.0	7,500	1.7
Briggsdale	33.0	8.0	7,200	0.4

Figure 14 shows these and other averaged as-received heating values for the Laramie Formation coals in the Denver and Cheyenne sub-basins. Within the Denver Basin, there is a gradual increase in heating values from east to west as seen on this simplified map. In examining a more detailed distribution of measured heating values, such as those seen in Plates 4-9, the trend is not as linear as the simplified map suggests. It is true that the highest values exist within the Boulder-Weld Field area of southwestern Weld County and eastern Boulder County. These coals are also higher in rank, suggesting that the coalification process for the Laramie Formation coals was enhanced by either deeper burial along the Front Range and/or proximity to higher heat flows along the right-lateral wrench and/or shallow listric thrust faults.

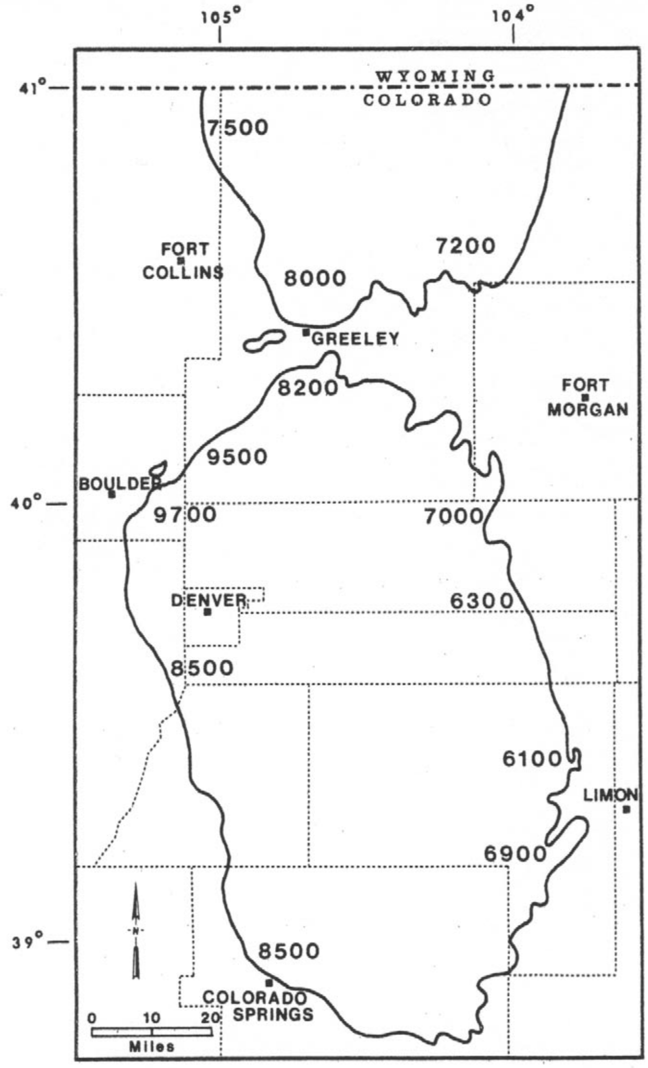

Figure 14. Average as-received heating values for the Laramie Formation coals in the Denver and Cheyenne sub-basins (Kirkham and Ladwig, 1979, p. 48).

A comprehensive report (Kirkham and Ladwig, 1979) set the stage for additional research work by the CGS. An excellent summary of geology, coal mining history, coal resources, and bibliography is presented in this 1979 publication. One of the most intriguing lists of data, from a coalbed methane standpoint, is the summary of gas occurrences in mines in the Denver Basin from 1939 to 1946. These occurrences can be seen in Map B on Plates 4-9, as well as in Table 2.

Table 2. Gas occurrences in mines of the Denver and Cheyenne sub-basins (Fender and Murray, 1978).

Mine	Location (county-section-township-range)	Type and Year of Gas Occurrence	Year
Highway	Boulder-28-1S-69W	gas explosion and mine fire(?)	1939
Monarch No. 2	Boulder-28-1S-69W	gas explosion	1936
Nonpariel	Boulder-16-1S-69W	gas explosion	1908
Simpson	Boulder- 2-1S-69W	gas explosion	1912
Standard	Boulder- 1-1S-69W	gas explosion	1908
Sunnyside	Boulder-28-1S-69W	gas explosion	1902
City No. 2	El Paso-33-13S-66W	gas suffocation(?)	-
Pikeview	El Paso-18-13S-66W	gas explosion	1956
Leyden No. 3	Jefferson-27-2S-70W	gassy mine	-
Leyden	Jefferson-26-2S-70W	mine fire	1910
Old Boulder Valley	Weld-18-1N-68W	gassy mine	-
New Boulder Valley	Weld-20-1N-68W	gassy mine	-
Boulder Valley No. 3	Weld- 1-1N-68W	gassy mine	-
Eagle	Weld-15-1N-68W	gassy mine[1]	-
Imperial	Weld-10-1N-68W	gassy mine	-
Lincoln	Weld-24-1N-68W	gassy mine	-
Parkdale	Weld- 6-1S-68W	gas suffocation	1915
Russell	Weld-20-2N-67W	mine fire	1947
Sterling	Weld- 6-1N-67W	gassy mine	-
Washington	Weld-23-1N-68W	gas explosion	1946

[1]The Eagle mine, Weld County caught fire in October, 1978 and was abandoned.

Forty-one CGS wells were drilled and logged in the basin to collect additional stratigraphic and coal quality data to supplement the generalized information presented in Kirkham and Ladwig (1979). Some of these wells were cored and the coals were desorbed for gas content information (Appendix A, Tables 1-5). All of the wells were logged lithologically and geophysically, and the resulting coal thickness and subsurface elevations were added to a growing database for the Laramie and Denver Formation coals. These logs and coal analyses can be found in Brand (1980); Brand and Caine (1980); and Eakins and Ballenski (1983). Thirty additional geophysical logs from a 1981 water well logging program in the Castle Rock quadrangle are presented in Eakins (1981), but this series of logs does not include lithologic descriptions. From this set of logs, however, a publication describing the coal resources of that quadrangle was published (Eakins and Ellis, 1987) in conjunction with the U.S. Geological Survey.

Coal analyses were conducted for samples taken in the Denver, Raton, San Juan, Piceance, and Sand Wash Basins under the guidance of CGS (Tremain and Toomey, 1983). Only five samples from the Denver Basin were analyzed for methane content, proximate and ultimate analyses. Three of these samples were examined petrographically. The detailed data sheets for these five samples are included in Appendix A, Tables 1-5. The analyses are organized accordingly:

Table 1: Laramie Formation coal analyses in CGS Well 161, Section 34, Township 2 South, Range 60 West

Table 2: Laramie Formation coal analyses in CGS Well 162, Section 4, Township 3 South, Range 61 West

Table 3: Laramie Formation coal analyses in CGS Well 163, Section 4, Township 3 South, Range 61 West
Table 4: Denver Formation coal analyses in CGS Well 164, Section 8, Township 5 South, Range 65 West
Table 5: Denver Formation coal analyses in CGS Well 165, Section 8, Township 5 South, Range 65 West

Following this study, several other open file reports (Kelso and others, 1980; Tremain, 1980; Boreck and others, 1981; Tremain, 1983; and Tremain, 1984a) incorporated the qualitative data from the core analyses to identify the most prospective areas in Colorado's coal basins for methane content. The actual qualitative data was compiled in the form of tables, histograms, graphs, and various plots (Tremain, 1984b) and combined with descriptive statistics and gas prediction equations. No attempt to interpret these analyses was made at the time of publication, but the equations themselves related the methane content to coal composition and may be used to predict gas content from coals for which only proximate, ultimate, or petrographic data is available.
In the case of the methane potential of the Denver Basin, Appendix D contains an estimation of original gas in place for Denver Basin coals by John Seidle, Sproule Associates, Inc. in Denver.

Khalsa and Ladwig (1981) present Colorado coal analyses of samples collected from 1976 to 1979. The CGS and the U.S. Geological Survey conducted this cooperative investigation. The project entailed sampling active and inactive mines, as well as cores from drilling projects, throughout the state. The location of the 21 Denver Basin samples is presented in Figure 15.

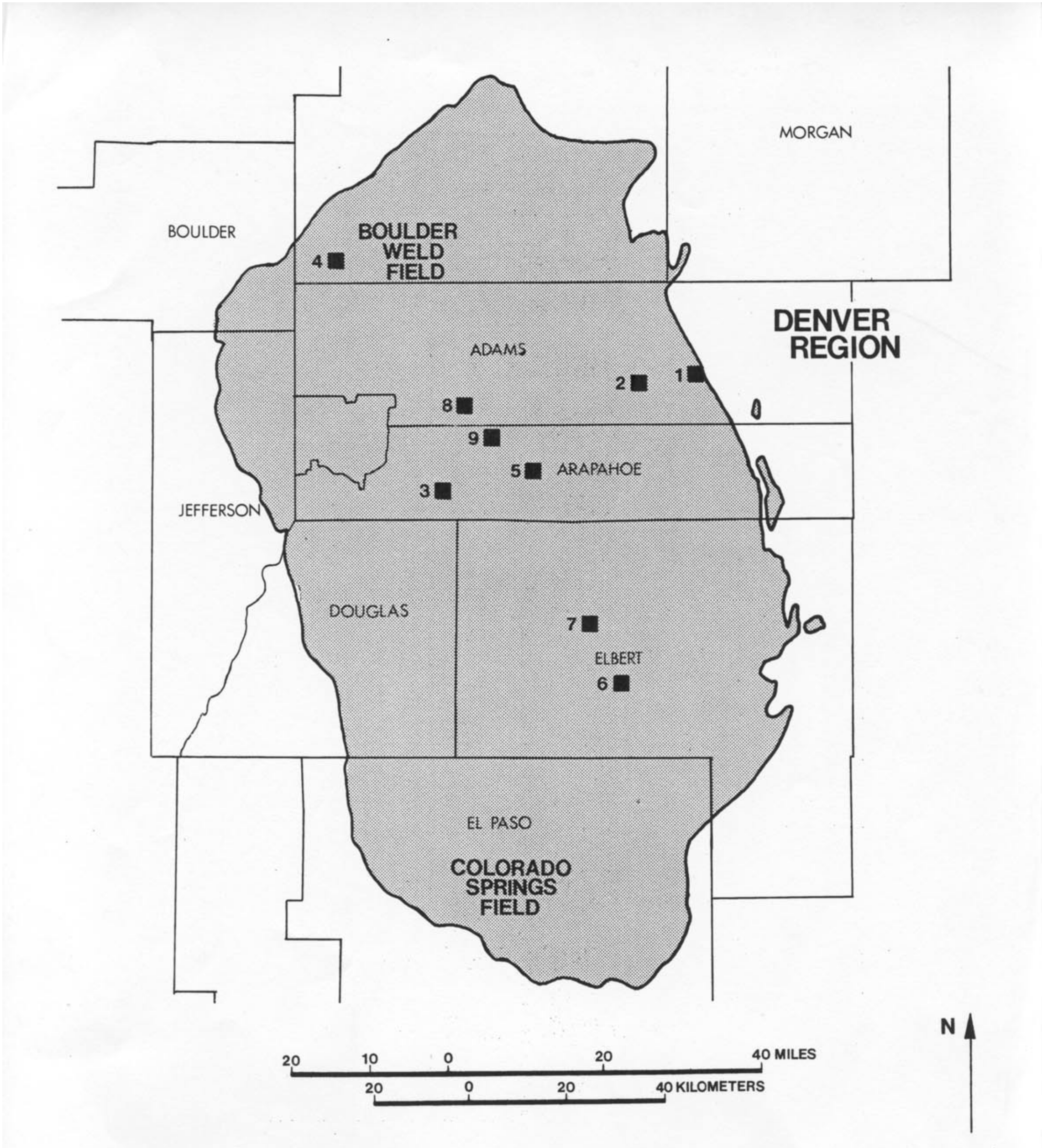

Figure 15. Location of coal samples containing proximate and ultimate analyses within the Denver Basin (Khalsa and Ladwig, 1981, p. 35).

Within the report by Khalsa and Ladwig (1981), is a comparison of arithmetic means and ranges for the proximate and ultimate analyses for all the sampled basins. Compared to other coal basins in Colorado, the Denver Basin samples vary most notably in their high content of moisture, hydrogen, and oxygen. All the other elements analyzed for the Denver Basin samples fall within the range of analyses in the other coal basins. (Khalsa and Ladwig, 1981, p. 13-17)

DATA COMPILATION AND PRESENTATION

Boreck and Murray (1979) compiled data from 1,667 recorded historic coal mines in Colorado including the Denver Basin. In the fall of 2000, mine data from this publication were entered into a database that has been continually updated by Chris Carroll of the CGS. These data will be published in the fall of 2001.

In 2000, the CGS began compiling coal mine and coal analysis data into a Geographic Information System (GIS) using ArcView™. Locations of coal mines and core holes in the Denver Basin were digitized from Kirkham (1978c). These locations are included in Boreck and Murray's (1979) database and include mine number, mine name, mine formation, coal rank, reported methane, and three heating values (as received, moisture free, and mineral and moisture free). Locations of historic mines, reported methane occurrences, and the heating values are compiled in Plates 2 and 4-9. The CGS also compiled coal resource maps within the Denver and Cheyenne Basins (Kirkham and Ladwig, 1979), the Denver East ½° x 1° Quadrangle (Brand and Eakins, 1980), the Castle Rock ½° x 1° Quadrangle (Eakins and Ellis, 1986), and the Colorado Springs ½° x 1° Quadrangle (Eakins, 1986). These 22 maps were digitized and added to the ArcView™ Denver Basin Project and include well data and isopach, isolith, and structure contour maps for individual and total Laramie and Denver Formation coals.

Other information added into the GIS include the approximate locations of the CGS wells used to create the cross sections in this report along with the location of each cross section (Plate 3). All of these data are available as ArcView™ shapefiles with this CD-ROM publication (see Appendix B for a list of shapefiles and their description).

DESCRIPTION OF PLATES

Six plates were generated using the ArcView ™ Denver Basin Project described above. These plates show the relationship of total coal thickness and structure with heat values, coal rank, and gas content in the Laramie and Denver Formations. Each plate has two maps of the Denver Basin : Map A displays three heat values (as received, moisture free, and mineral and moisture free), and Map B displays the rank and any reported gas. On top of these data are contours for either the total thickness or structure. The plates are projected into the Universal Transverse Mercator projection, Zone 13 and are in a scale of 1:500000.

Locations

Plate 1: Overview and location map of the Denver Basin, Colorado

Plate 2: Locations of historic mines in the Denver Basin, Colorado

Plate 3: Locations of CGS coal test wells with cross sections in the Denver Basin, Colorado

Denver Formation Coals

Plate 4: Total thickness of all known Denver Formation coals in the Denver Basin (contour interval = 5') (a) Heat Values and (b) Coal Rank and Reported Gas.

Plate 5: Total thickness of all known Denver Formation coals in the Denver East ½° x 1° Quadrangle (contour interval = 10') and for the Castle Rock ½° x 1° Quadrangle (contour interval = 2.5') (a) Heat Values and (b) Coal Rank and Reported Gas.

Plate 6: Structure contour map on top of the Denver Formation coal zone in the Denver East ½° x 1° Quadrangle (contour interval = 100') and for the Castle Rock ½° x 1° Quadrangle (contour interval = 100') (a) Heat Values and (b) Coal Rank and Reported Gas.

Laramie Formation Coals

Plate 7: Structure contour map on top of the Laramie Formation in the Denver Basin, (contour interval = 100') with (a) Heat Values and (b) Coal Rank and Reported Gas.

Plate 8: Structure contour map on top of the Laramie Formation coal zone in the Denver East ½° x 1° Quadrangle (contour interval = 100') and for the Castle Rock ½° x 1° Quadrangle (contour interval = 100') with (a) Heat Values and (b) Coal Rank and Reported Gas.

Plate 9: Total thickness of all known Laramie Formation coals in the Denver East ½° x 1° Quadrangle (contour interval = 100') and for the Castle Rock ½° x 1° Quadrangle (contour interval = 100') with (a) Heat Values and (b) Coal Rank and Reported Gas.

DESCRIPTION OF CROSS SECTIONS

Regional cross sections showing the stratigraphic and structural correlations for coals in both the Denver and Laramie Formations are published in Kirkham and Ladwig (1979) and Eakins and Ellis (1986). These stick cross sections focus primarily upon the coal intervals and their correlative relationships. In some cases, the sediments between the coals are identified with standard lithologic symbols for sandstone, shale, and siltstone. The degree of coal bed continuity for coals in both the Denver and Laramie Formations varies depending upon the geographic position within the Denver Basin.

In the early 1980s, the CGS obtained funding to drill and geophysically log 41 wells to collect stratigraphic and coal quality information. Some of these wells were cored, desorbed, and analyzed with both proximate and ultimate analytical tests. The geophysical logs include gamma ray, bulk density, resistivity, and caliper curves. Both the analyses as well as copies of the individual logs are published in Brand (1980), Brand and Caine (1980), and Eakins and Ballenski (1983).

To our knowledge, the actual CGS electric log curves have never been published in cross sections. Rather, coal thicknesses were calculated from these logs and then incorporated into the previously referenced stick cross sections. We chose to display actual log cross sections on Plate 10 (Cross section D-D' for Denver Formation coals) and Plate 11 (Cross section for Laramie Formation coals). The locations of the lines of cross section are shown on Plate 3.

Whereas the logs themselves display much more stratigraphic detail and while the character of both the gamma ray and bulk density curves can help delineate correlative coals, the fact that the wells themselves are so far apart in some cases makes the correlations quite difficult. In addition, the top of the Fox Hills sandstone, used for a datum on the cross sections and identified by lithologic descriptions of cuttings in most cases, is variable in nature. Most of these wells were not drilled and logged deep enough to examine the stratigraphic nature of the sandstone beneath the datum. A complex facies relationship has been documented in the Fox Hills sandstone and these cross sections may not provide enough data to provide an accurate correlation (Weimer, 2001 pers. communication). What these cross sections do show, however, is the stratigraphic complexity above the datum arising from the fact that the vertical and horizontal depositional facies themselves were not continuous in Late Cretaceous to early Tertiary times. A second look at Figure 9 reinforces this observation.

METHANE CONTENT, HEATING VALUE

The Denver Basin contains one of the largest basin-centered gas accumulations in this country. Therefore, it is no surprise that gas can be trapped in reservoir rocks within the entire stratigraphic fill sequence, namely Mississippian through Tertiary sediments. The Denver and Laramie Formation coals are no exceptions, though clearly the methane potential from historic evidence appears more significant within the Laramie coals. This may indeed be a function of the fact that the Laramie coals have been much more extensively mined and studied.

There are numerous accounts documented in the literature of gas occurrences in the Laramie Formation coal beds, a summary of which can be found in Kirkham and Lagwig (1979, p. 60-61). Table 2 presents a list of gas occurrences documented in coal mines that demonstrates the geographic diversity of the methane hazards in the Denver Basin. This list supplements the reports of additional mine explosions or gas occurrences shown in Map B in Plates 4-9. State agencies including the Colorado Oil and Gas Conservation Commission (COGCC) and the Colorado Division of Water Resources (State Engineer's Office) have records on file describing complaints related to methane contamination of water wells or even water wells that have caught fire. Many of these gas occurrences may be related to methane desorption from the Laramie Formation coals and possibly even from the Denver Formation lignites on a limited basis. Clearly, more detailed work is needed to quantify coal reservoir parameters such as permeability, gas content, hydrodynamics, reservoir pressure, water saturation, gas and water quality, and lateral extent of the coals.

Map A in Plates 4-9 contain measured heating values (in Btu/pound) for both Denver and Laramie Formation coals. A simplified compilation for as-received heating values for just the Laramie Formation coal samples, coupled with some average as-received coal analyses, is presented in Table 1 and Figure 14. As expected, the lower rank Denver Formation lignites have lower heating values than the sub-bituminous Laramie Formation coals (Table 3).

Table 3 contains some analytical data from some Denver Formation lignites near Watkins, Colorado that were collected in 1996. Public Service Company (PSC) funded a coring program that was supervised and directed by R.V. Bailey (Bailey, 2001, pers. communication). For these analyses, the lignite fraction of the cored intervals were separated by hand by Bailey and Bill Landers of PSC, and subsequently analyzed. The kaolin-rich partings, so common in the Denver Formation coals (Kirkham and Ladwig, 1979), were not included in the Table 3 measurements. By removing the non-coal partings, the low heating values characteristic of high refractory kaolin and other associated mineral constituents in the partings do not lower the recorded heat values that might be representative of a non-sorted lignite sample.

Table 3. Denver Formation coal analyses for three coal cores near Watkins, Colorado. In all three cases, the kaolinitic partings within these coals were removed so that these analyses are representative of just of coal fractions (Bailey, pers. Comm.).

PUBLIC SERVICE CORE HOLES DRILLED IN THE WATKINS AREA, DENVER BASIN

Courtesy of R. V. Bailey, Aspen Exploration, Castle Rock, CO

CORE HOLE DX-503C (2 samples). Sampled bed thickness = 26.4 feet.

Interval of Denver Fm coal	121.6 - 135.8 feet	135.5 - 148.0 feet
Moisture	28.79	30.56
Volatile	29.45	27.48
Fixed Carbon	24.02	22.38
Ash	17.74	19.58
Sulfur	0.39	0.4
Btu	**6585**	**5999**
Btu (dry)	**9247**	**8639**

CORE HOLE DX-516C (3 samples). Sampled bed thickness = 28.58 feet

Interval of Denver Fm coal	46.21 - 55.-0 feet	55.0 - 64.4 feet	64.4 - 74.8 feet
Moisture	25.75	30.03	28.65
Volatile	33.31	30.93	29.29
Fixed Carbon	29.21	27.52	24.1
Ash	10.73	11.52	17.96
Sulfur	0.41	0.36	0.42
Btu	**7687**	**7153**	**6603**
Btu (dry)	**10494**	**10225**	**9254**

CORE HOLE DX-521C (3 samples). Sampled bed thickness = 45.65 feet.

Interval of Denver Fm coal	74.75 - 90.6 feet	90.6 - 106.0 feet	106.0 - 120.6 feet
Moisture	26.28	25.29	22.48
Volatile	32.2	32.23	30.1
Fixed Carbon	23.72	24.95	23.46
Ash	17.8	17.81	23.96
Sulfur	0.41	0.43	0.43
Btu	**6729**	**7000**	**6428**
Btu (dry)	**9123**	**9340**	**8292**

The mineral- and moisture-matter free measurements for the Denver Formation coals in the CGS database are quite similar to those values reported in Table 3, suggesting that the non-lignite fraction was separated out before these analyses were run. By comparing Tables 1, 2, and 3, it is evident that the Denver Formation coals, by virtue of their lower rank, have lower heating values and higher ash contents than the Laramie Formation coals.

RESOURCE POTENTIAL

As with other coals in Colorado, the Denver and Laramie Formation coals are a multiple resource. There exists a wealth of publications, some publicly available, regarding the potential for mineable coal in several areas within the Denver Basin. Surface mining of Denver Formation lignites is technically feasible along most of the eastern margin of the basin. Surface mining of Laramie Formation coals is also technically feasible along the northern, eastern, and southern flanks of the basin. Surface and in situ gasification of the methane in both sets of coals has been explored. (Hand, 1978; Rocky Mountain Energy, 1983)

The question of whether a coalbed methane play exists in either Denver or Laramie Formation coals cannot be answered with certainty at this time. Clearly, a resource does exist as demonstrated by measured gas contents (Tremain and Toomey, 1983), crude as they are due to the inferior desorption technologies of the early 1980s, heating values, and recorded gas explosions, and by the estimations of original gas in place in Appendix D. Further work is required to quantify whether methane extraction is economically feasible. Parameters such as state-of-the-art gas content measurements, permeability, water saturation, reservoir pressure, hydrodynamics, and production tests could better evaluate the potential of a play. What looms as the potential roadblocks to a play at this time, however, has to do with issues of water quality and rights, as well as the protection of groundwater resources which will be discussed in the next section.

GROUNDWATER RESOURCES OF DENVER BASIN AQUIFERS

There are four principal bedrock aquifers above the Pierre Shale in the Denver Basin. In ascending stratigraphic order, they include: the Laramie-Fox Hills, Arapahoe Formation, Denver Formation, and Dawson Arkose aquifers. In some parts of the Denver Basin, the Arapahoe and Dawson aquifers are further divided into an upper and lower hydrogeologic unit (Graham, 2001, pers. communication). The geographic distribution of these aquifers is shown in Figure 16 (Robson and Banta, 1993, p.4).

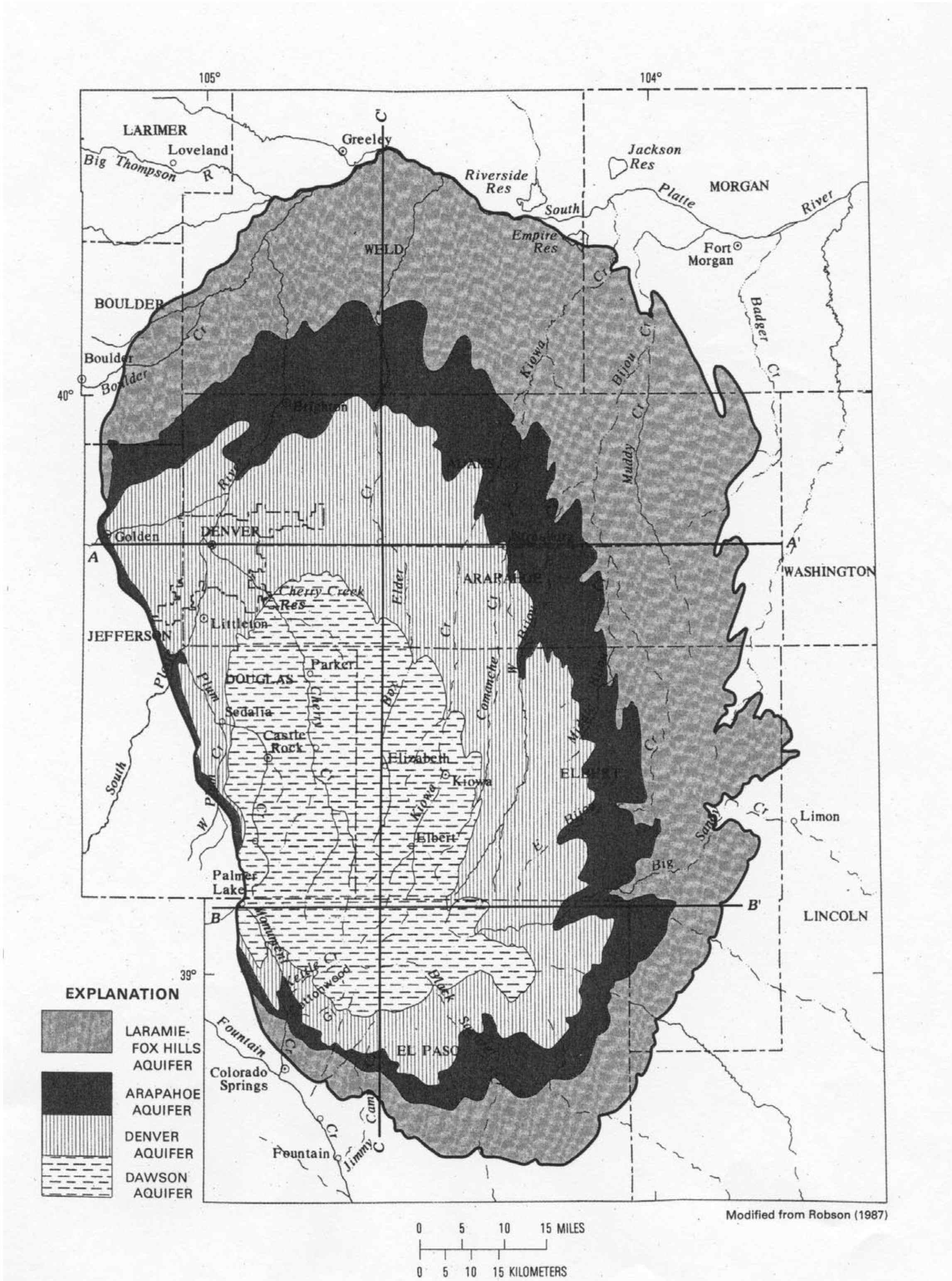

Figure 16. Principal aquifers in the Denver Basin (Robson and Banta, 1993, p. 4).

Three representative cross sections are reproduced in Figure 17 (Robson and Banta, 1993, p. 5). These aquifers will be discussed in more detail in the following sections.

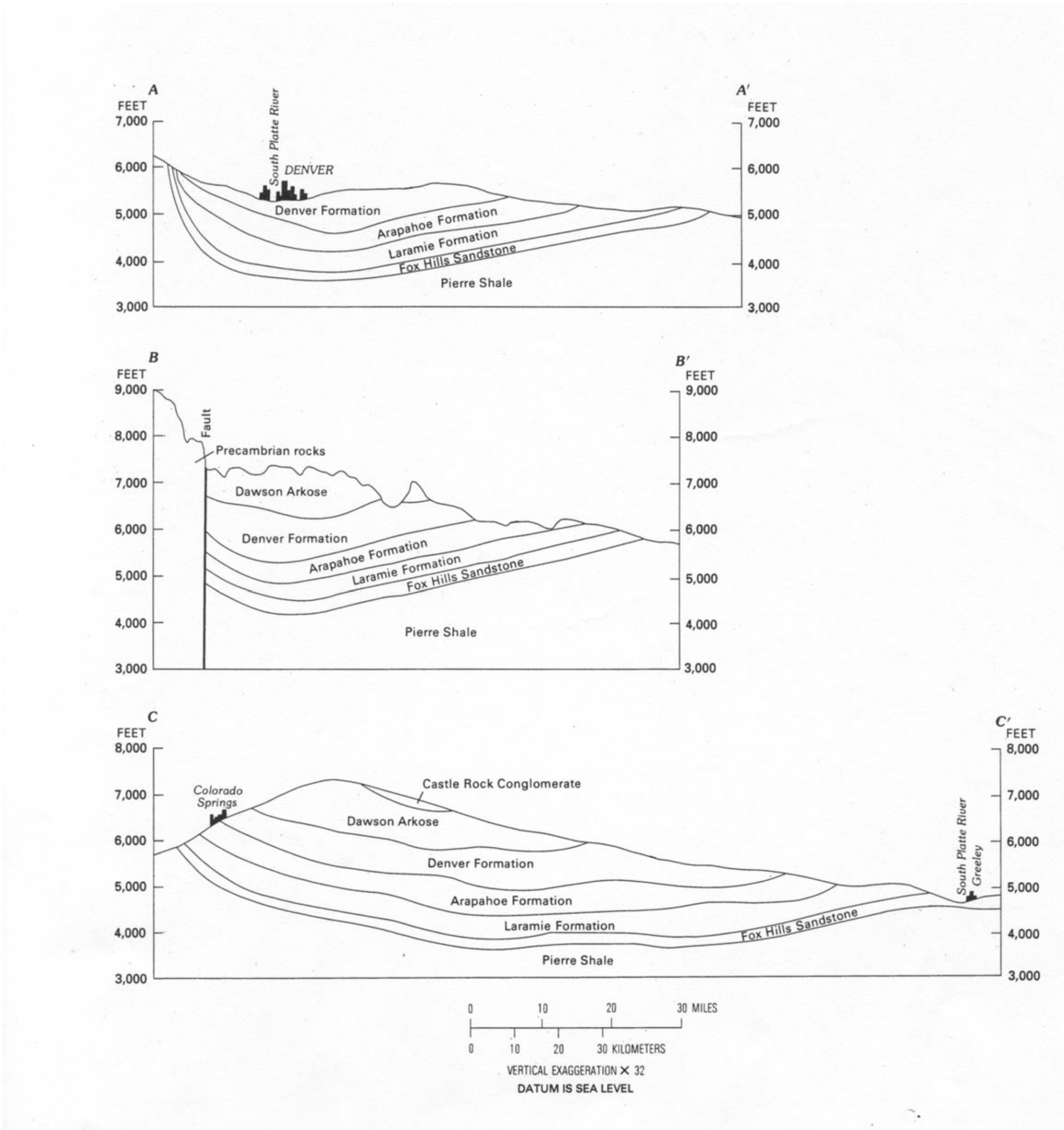

Figure 17. Generalized geologic cross sections through the Denver Basin. Locations for each of these sections is shown on Figure 16 (Robson and Banta, 1993, p. 5).

LARAMIE-FOX HILLS

The deepest and most regionally extensive aquifer, the Laramie-Fox Hills, is composed of fine-to medium-grained sandstones within the lower part of the total 1,700 – foot section. The part of the aquifer within the Fox Hills is usually 150-200 feet thick with an upper bed of very fine-grained silty sandstone, ranging from 40 to 50 feet thick, underlain by 100-150 feet of shaly siltstone and interbedded shale (Robson, 1987). The part of the aquifer within the Laramie Formation is between 50 and 100 feet thick and composed of fine- to medium-grained sandstone with interstitial silt and clay. Between 5 and 20 feet of shale separates the Laramie part from the Fox Hills part of the aquifer. The overlying 400 to 500 feet of Laramie Formation is considered the confining layer that contains shale, coals, siltstones, and sandstones. It is these coals that have been mined extensively in the Denver Basin.

Water from this aquifer is predominantly soft, slightly to moderately mineralized, with locally high levels of fluoride, iron, sodium, and bicarbonate. In the northern part of the basin, high temperatures and contamination by hydrogen sulfide and methane measured in this aquifer may be emplaced along deep-seated faults. In refute of that theory is the fact that northeast-trending wrench faults offset some aquifers, yielding different water-level altitudes in wells. In this latter case, the faults act as seals and not conduits. Regardless, the water has a fair to good quality for both domestic and public use. (Romero, 1976, 2nd printing)

For additional information on the physical and hydrologic characteristics of this aquifer, see Robson and Banta (1993, p. 8).

ARAPAHOE FORMATION

The aquifers in the Arapahoe Formation consist of 400 to 700 feet of interbedded conglomerates, sandstones, siltstones, and shale. The water is predominantly soft with only slight mineralization, requiring chlorination only to meet public water supply quality standards (Robson, 1976, 2nd printing) More detailed descriptions of the physical and hydrologic characteristics of this aquifer can be found in Robson and Banta (1993, p. 7).

DENVER FORMATION

Within the Denver Formation, the aquifers consist of 600 to 1,000 feet of sandstones and interbedded siltstones, shale, claystones, and lignites. This water is predominantly soft and is deemed only fair quality for public and domestic use because of the locally high levels for calcium, fluoride, hydrogen sulfide, iron, sodium, sulfate, and bicarbonate (Romero, 1976, 2nd printing). Additional information on the physical and hydrologic characteristics of this aquifer can be found in Robson and Banta (1993, p. 7).

DAWSON ARKOSE

The Dawson Arkose aquifers have the greatest range in depth within the Denver Basin, attaining maximum depths of 2,500 feet in the south-central part of the basin. Most groundwater utilization within the basin has occurred within this aquifer which is composed of coarse-grained and poorly to moderately consolidated conglomerates, sandstones, and shale (Romero, 1976, 2nd printing). Robson (1976) reported that the water in this aquifer often met the recommended drinking water standards but that may no longer be true. More detailed descriptions of the physical and hydrologic characteristics of this aquifer can be found in Robson and Banta (1993, p. 7).

SUMMARY

COALBED METHANE POTENTIAL

Published data described in this report documents the presence of methane in both the Denver and Laramie Formation coals. Since the CGS does not have access to gas and isotopic analyses, it is impossible to verify whether the methane is of biogenic or thermogenic origin or some mixture thereof. Biogenic gas, generated by anaerobic microorganisms that are carried in groundwater and introduced after the coalification process, is enriched in the light carbon 12 isotope. This secondary biogenic gas requires a low temperature, anoxic environment for generation such as can be found in regional coal aquifers. By comparison, the heavier carbon 13 isotope is prevalent in thermogenic gas, derived from the conversion of humic organic material in coal from the heat and pressure associated with deeper burial. Given the fact that the Denver Basin source rocks are all stratigraphically lower than these coal sequences, and are separated from the coals by thousands of feet of impermeable shales, it is probable that the coals themselves were never buried deeply enough to generate significant quantities of thermogenic gas. The fact that chalks rich in organic material in the Upper Cretaceous Niobrara Formation, which lie stratigraphically below these coals, produce biogenic gas in the northeastern part of the Denver Basin (Longman and others, 1998) lends support to the theory that the coals also contain biogenic gas. One exception may be in the Boulder-Weld Field area of southwestern Weld County where vitrinite reflectance data for the Cretaceous Graneros, Huntsman, Mowry, and Skull Creek Shale source rocks exceeds 1.1 percent vitrinite reflectance (Ro) (Higley and Cox, 2001, in press). The influence of high heat flows associated with the wrench faults and other associated faults trending northeast from the Colorado Mineral Belt may be responsible for the higher Ro values as well as for the higher coal ranks in this area.

In compiling the various data that reside in hardcopy format into a GIS ArcView™ database, we utilized a method to view multiple layers of data, thereby identifying possible relationships between heating values and reports of methane and/or gas explosions with isopach thickness, structural elevation, and/or coal rank. What emerged was a collection of non-relationships instead which are listed below.

Plates 4 and 5 contain some of the same data published by different authors. There is some overlap of areas mapped for the total coal thickness in the Denver Formation, but individual maps contain unique contouring interpretations. Both maps display up to three sets of heating values (in Btu/lb) that were measured for mine and corehole locations. Both Plates 4 and 5 fail to reveal a clear relationship between thickness of total coals and heating value. Similarly, there does not appear to be any significant variations in regional heating value between Denver Formation coals at or near the outcrop versus those deeper in the basin. In fact, some of the highest measured heating values are close to the outcrop, suggesting a biogenic origin of the gas from anaerobic bacteria carried in surface recharge waters.

Plate 6 compares heating value against structural elevation for the top of the Denver Formation. Again, there seems to be no observable relationship to indicate the effects on heating value from depth of burial of the coals. The structural data for the Boulder-Weld field in the northwest part of the basin are not available in any CGS publications, but a poster presentation for the Laramie Formation coals has been compiled (Roberts, 2000) and an abstract is contained in Appendix C. Vertical and lateral movement along faults interpreted to be right-lateral wrench faults may create reservoir compartments that affect the Laramie Formation coals (Higley and Cox, 2001). Interpreted growth faults that appear to be synchronous with Laramie Formation coal formation in this area form graben and horst blocks, thus affecting coal depositional thickness (Weimer, 1977). Figure 13b, proposing listric high-angle reverse faults, displays the structural complexity as being within and above the Laramie Formation coals (Kittleson, 1992). Regardless of the structural interpretation, the Laramie Formation coals in the Boulder-Weld field are compartmentalized in some fashion.

Maps A and B in Plate 7 compare Laramie Formation structure with heating values (in Btu/lb) and structure with presence of gas and coal rank respectively. As noted before, the highest heating values and coal rank, combined with documentation of gas in the mines, exist in the northwest portion of the basin. There is no correlation, however, with any of these values and the structural elevation on top of the Laramie Formation. We had postulated that a structural high might have elevated heating values, but that is clearly not the case as seen in Map 7A.

Plate 8 is another version of Plate 7A that shows the individual structure contours published in two separate papers (Eakins and Ellis, 1983 and Brand and Eakins, 1980). This map is included to show the areas examined in each of the two reports.

Plate 9 shows the heating values plotted against the total coal thickness in the Laramie Formation. No consistent trend is apparent that relates total coal thickness with heating value. Once again, there is an overall increase in heating value from southeast to northwest with the highest values in the Boulder-Weld field area. The CGS has no total Laramie Formation coal isopach data in the northwest part of the Denver Basin; therefore, there is no available information on Plates 4-9 with which to compare isopach thickness trends with heating value trends. One can make the comparisons, however, by examining Plate 9 with the individual Laramie Formation coal isopach maps compiled by Spencer (1986).

PROTECTION OF GROUNDWATER SUPPLIES

The protection of groundwater supplies and of existing senior rights to surface waters is of utmost importance to surface and mineral owners as well as to regulatory agencies. The current regulatory framework, created in 1985 by

Senate Bill 5, pertains to the Denver Basin Bedrock Aquifers. The resulting administrative process does not address the issue of whether good quality waters in these aquifers may be produced as a byproduct of coalbed methane production and be used for some beneficial purpose (Glenn Graham, 2001, pers. communication). Clearly, any coalbed methane production plan must address the administration and development of any waters contained within the coals (see abstract by Graham in Appendix C).

Groundwater can move between aquifers by: 1) communication through poorly completed wells; 2) movement along faults, particularly those along the northwest part of the basin; 3) communication of bedrock and alluvial ground waters at channel/bedrock contacts; 4) failure of or improperly designed seals within water wells; and 5) the improper location of perforations within the wells (Romero, 1976, 2nd printing).

REGULATORY OVERSIGHT

The Colorado Oil and Gas Conservation Commission (COGCC) is charged with protecting groundwater and surface water supplies during petroleum operations. From the 1990s until today, the COGCC has had to promulgate regulations that address the environmentally sound handling of produced waters including those from coalbed methane operations. Any plan to conduct coalbed methane development in the Denver Basin that requires a drilling permit will have to address all such regulations.

FUTURE WORK

Despite the volume of historical data that is available on the Denver and Laramie Formation coals, there is still a lack of accurate reservoir data available. To date, at least three stratigraphic tests have been conducted in the basin but no reports are available. All three wells were apparently cored in the coals (probably in the Laramie Formation). Core data, analyses, and production tests are all needed to access the viability of an economic play.

Detailed stratigraphic cross sections, utilizing both electric and lithologic logs available from the myriad sources described in previous publications, will have to be constructed over any potential development area. The discontinuities of the individual coal beds require this careful scrutiny to insure the adequate reservoir extent of the coals.

CONCLUSIONS

1. There is abundant evidence, as presented in this report, that both the Denver and Laramie Formation coals contain methane. Whether that methane is biogenic, thermogenic, or some mixture of both, remains to be determined. The estimations of original gas in place for both the Denver and Laramie Formations, contained in Appendix D, document the presence of a coalbed methane resource.
2. Isopach maps and cross sections, both in this report and contained within cited references, demonstrate that coal thickness and continuity are sufficient to warrant further evaluation of coalbed methane reservoirs.
3. The presence of major aquifers within, below, and above the Denver and Laramie Formations, requires careful examination of the groundwater resources and their protection in the event of a coalbed methane development program.
4. The question of produced water and water disposal from coalbed methane production in the Denver Basin needs to be addressed.
5. Further scientific data, is required to determine the economic feasibility of a coalbed methane play in the Denver Basin. Critical information that needs to be gathered includes state-of-the-art desorption data, derived gas content data, production tests, coal permeability, hydrodynamics, water analyses, gas analyses, completion techniques, and suitable methods for water disposal.

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APPENDIX A – COAL ANALYSES

Table 1. Detailed coal analyses for CGS Well Number 161, Section 34, Township 2 South, Range 60 West.

CGS No. 161

LOCATION

County: Adams
Location: Sec 34 Twp 2S Rge 60W
Surface Elev (ft) 4975
Coordinates SW corner

GENERAL

CGS Sample No. 161
Sampled By C. Tremain
Operator Colorado Geological Survey
Hole No. 4C
Date 11-15-79
Sample Type core

DRILLING DATA

Drilling Co. Teton Exploration
Address Casper, Wyoming
Core Size 2 7/8"
Barrel Length 10'
Type of core retrieval conventional split barrel
Drilling media mud
Air Temperature 50°
TD Hole 130' * Logs gamma, density, caliper, resistance

GEOLOGY

Geologic Unit Laramie Fm
Age Upper Cretaceous
Coal zone/bed unnamed
Bed Thickness 5'
Depth to top of coal 109' (Driller) same (Log)
Depth to bottom of coal 114' (Driller) same (Log)
Cored interval 108-117' (Driller)
Roof description carb. clay, brown-dark brown
Coal description black, conchoidal fractures, woody texture, resin in cleats
Floor description silty claystone, dark gray

DESORPTION DATA

Sampled interval (ft) 109-114 (Driller) same (Log)
Condition of sample slightly muddy, wet, medium chunks, 1/2 split
Sampled Weight (g) 1147
Lost gas time (min) 13
Lost gas cc 60
Desorbed gas cc 75
Residual gas cc/g 0.0
Total gas content cc/g .12
Total gas content cf/t 4

Miscellaneous Reference: CGS Open File Report No. 80-1, 1980 by Karl E. Brand - Geophysical and Lithological Logs from the 1979 Coal Drilling and Coring Program, Denver East 1/2° x 1° Quadrangle.

* T.D. for Pilot Hole is 200'

CGS No. 161

COAL ANALYSES

Analyses	As Received	Moisture Free	Moisture and Ash Free
Proximate Analyses (%)			
Moisture	25.0	N/A	N/A
Volatile Matter	29.4	39.2	48.9
Fixed Carbon	30.8	41.0	51.1
Ash	14.8	19.8	N/A
Ultimate Analyses (%)			
Hydrogen	4.8	2.7	3.4
Carbon	44.2	59.0	73.6
Nitrogen	1.1	1.5	1.9
Sulfur	.4	.5	.7
Oxygen	34.6	16.5	20.5
Ash	14.8	19.8	N/A
Heating value (BTU/lb)	7417	9893	12334
Sulfur Forms (%)			
Sulfate	not run		
Pyritic	not run		
Organic	not run		

Ash

Initial deformation (°F) 2320
Softening temperature (°F) 2440
Fluid temperature (°F) 2530

Free Swelling Index not run
Fixed Carbon DMMF 52.28
Heating Value BTU/lb MMMF 8827
Apparent Rank subbituminous C

Date of Analysis: 3-3-80
Laboratory: U.S. Dept. of Energy Lab No. K99783
Comments:

GAS ANALYSES - not run

ADSORPTION ISOTHERM DATA - not run

CGS No. 161

PETROGRAPHIC ANALYSES

Lab. Commercial Testing & Engineering Company

Lab No. CGS #161 (Denver Basin)

MACERAL ANALYSIS *
(Volume Percent)
(Mineral-Matter Free Basis)

MACERAL		MACERAL GROUP	
Vitrinite	77.6	Vitrinite	78.3
Pseudovitrinite	0.7		
Sporinite	1.7		
Cutinite	0.2		
Resinite	3.2		
Alginite	---	Exinite	
Bituminite	1.3	(Liptinite)	6.5
Fluorinite	---		
Exudatinite	0.1		
Semi-Fusinite	2.5		
Semi-Macrinite	0.3		
Fusinite	6.6	Inertinite	15.2
Macrinite	0.6		
Micrinite	5.2		
Sclerotinite	---		
TOTAL	100 %		100 %

* COMBINED RESULTS OF ANALYSES IN WHITE AND BLUE LIGHT

REFLECTANCE ANALYSIS

Mean-Maximum Vitrinite Ro- 0.37

V-Type Table for Vitrinites (=100%)

V-2	V-3	V-4	V-
2	77	21	

CGS No. 161

PETROGRAPHIC ANALYSES

Lab. S.I.U. Coal Characterization Lab   Petrographer John C. Crelling
Lab No. S.I.U. #853   Date of Analysis 10/80

Maceral Analysis (white light)		Reflectance Analysis*	
Vitrinite	78.7	Vitrinite Ro	
Pseudovitrinite	1.9		
Semifusinite	3.9	pVit Ro	
Semimacrinite	2.7		
Fusinite	1.0	Combined Ro	
Macrinite	0.5		
Micrinite	3.1	pVit Ro - Vit Ro	
Exinite	6.9		
Resinite	1.3		
Total	100%		

Combined V-Type Table

V-Type	2	3	4	5	6	7	8	9	10	11
%		12.9	84.1	3.0						

V-Type	12	13	14	15	16	17	18	19	20	21
%										

Comments: Apparent rank - Subbituminous C
*The reflectance analysis was undifferentiated due to the low amount of pVit. 0.43 = mean max. reflectance.

Table 2. Detailed coal analyses for CGS Well Number 162, Section 4, Township 3 South, Range 61 West

CGS No. 162

LOCATION

County: Adams
Location: Sec 4 Twp 3S Rge 61W

Surface Elev (ft) 5027'
Coordinates NE corner of NE/4 NE/4

GENERAL

CGS Sample No. 162
Sampled By C. Tremain
Operator Colorado Geological Survey
Hole No. 5C

Date 11-16-79
Sample Type Core

DRILLING DATA

Drilling Co. Teton Exploration Address Casper, Wyoming
Core Size 2 7/8" Barrel Length 10'
Type of core retrieval conventional split barrel
Drilling media mud Air Temperature 60°F
TD Hole 390' Logs Gamma, Density, Caliper, Resistance

GEOLOGY

Geologic Unit Laramie Formation Age Upper Cretaceous
Coal zone/bed unnamed Bed Thickness 6.7'
Depth to top of coal 306.3' (Driller) same (Log)
Depth to bottom of coal 313' (riller) same (Log)
Cored interval 304-314' (Driller)
Roof description carbonaceous shale, fissile, brown-black
Coal description black, hard, resin particles in cleats, woody structure, parting at 311-312'
Floor description dark gray claystone, occassionally thin sandstone lenses

DESORPTION DATA

Sampled interval (ft) 306.3 - 308' (Driller) same (Log)
Condition of sample wet, small pieces
Sampled Weight (g) 459
Lost gas time (min) 18.5 Lost gas cc 230
Desorbed gas cc 112 Residual gas cc/g 0.0
Total gas content cc/g .75 Total gas content cf/t 24

Miscellaneous Reference: CGS Open File Report No. 80-1, 1980, by Karl E. Brand, Geophysical and Lithological Logs from the 1979 Coal Drilling and Coring Program, Denver East 1/2° x 1° Quadrangle

CGS No. 162

COAL ANALYSES

Analyses	As Received	Moisture Free	Moisture and Ash Free
Proximate Analyses (%)			
Moisture	19.0	N/A	N/A
Volatile Matter	30.4	37.5	47.2
Fixed Carbon	34.0	42.0	52.8
Ash	16.6	20.5	N/A
Ultimate Analyses (%)			
Hydrogen	4.8	3.3	4.2
Carbon	46.6	57.6	72.4
Nitrogen	1.2	1.5	1.9
Sulfur	.5	.6	.7
Oxygen	30.3	16.6	20.8
Ash	16.6	20.5	N/A
Heating value (BTU/lb)	7971	9841	12382
Sulfur Forms (%)			
Sulfate	not run		
Pyritic	not run		
Organic	not run		

Ash

Initial deformation (°F) 2310
Softening temperature (°F) 2400
Fluid temperature (°F) 2480

Free Swelling Index not run
Fixed Carbon
DMMF 54.02
Heating Value
BTU/lb MMMF 9714.29
Apparent Rank subbituminous B

Date of Analysis: 3-3-80
Laboratory: U.S. Dept. of Energy Lab No. K99784
Comments:

GAS ANALYSES - not run

ADSORPTION ISOTHERM DATA - not run

PETROGRAPHIC ANALYSES - not run

Table 3. Detailed coal analyses for CGS Well Number 163, Section 4, Township 3 South, Range 61 West.

CGS No. 163

LOCATION

County: Adams
Location: Sec 4 Twp 3S Rge 61W

Surface Elev (ft) 5027
Coordinates NE corner of NE/4 NE/4

GENERAL

CGS Sample No. 163
Sampled By C. Tremain
Operator Colorado Geological Survey
Hole No. 5C

Date 11-16-79
Sample Type conv. core

DRILLING DATA

Drilling Co. Teton Exploration
Address Casper, Wyoming
Core Size 2 7/8"
Barrel Length 10'
Type of core retrieval conventional split barrel
Drilling media mud
Air Temperature 30°
TD Hole 390 Logs gamma, density, caliper, resistance

GEOLOGY

Geologic Unit Laramie Fm
Age Upper Cretaceous
Coal zone/bed unnamed
Bed Thickness 8.0'
Depth to top of coal 362.5' (Driller) same (Log)
Depth to bottom of coal 370.5' (Driller) same (Log)
Cored interval 362.2 - 371.0 (Driller)
Roof description gray siltstone
Coal description black, fractured slightly, with pyrite, woody texture, resin in cleats
Floor description claystone, gray

DESORPTION DATA

Sampled interval (ft) 362.5 - 371.0 (Driller) same (Log)
Condition of sample wet, medium fragments
Sampled Weight (g) 910
Lost gas time (min) --
Lost gas cc 0
Desorbed gas cc 0
Residual gas cc/g 0
Total gas content cc/g 0
Total gas content cf/t 0

Miscellaneous Reference: CGS Open File Report No. 80-1, 1980, by Karl E. Brand - Geophysical and Lithological Logs from the 1979 Coal Drilling and Coring Program, Denver East 1/2° x 1° Quadrangle.

CGS No. 163

COAL ANALYSES

Analyses	As Received	Moisture Free	Moisture and Ash Free
Proximate Analyses (%)			
Moisture	24.7	N/A	N/A
Volatile Matter	31.6	42.0	47.1
Fixed Carbon	35.5	47.2	52.9
Ash	8.2	10.8	N/A
Ultimate Analyses (%)			
Hydrogen	5.0	3.0	3.4
Carbon	49.2	65.4	73.3
Nitrogen	1.3	1.7	1.9
Sulfur	.3	.4	.5
Oxygen	36.0	18.6	20.9
Ash	8.2	10.8	N/A
Heating value (BTU/lb)	8377	11131	12484

Sulfur Forms (%)

Sulfate	not run
Pyritic	not run
Organic	not run

Ash

Initial deformation (°F)	1980
Softening temperature (°F)	2060
Fluid temperature (°F)	2150

Free Swelling Index not run

Fixed Carbon
DMMF 53.49

Heating Value
BTU/lb MMMF 9191.13

Apparent Rank Subbituminous C

Date of Analysis: 3-3-80

Laboratory: U.S. Dept. of Energy Lab No. K99785

Comments:

GAS ANALYSES - not run

ADSORPTION ISOTHERM DATA - not run

PETROGRAPHIC ANALYSES - not run

Table 4. Detailed coal analyses for CGS Well Number 164, Section 8, Township 5 South, Range 65 West.

CGS No. 164

LOCATION

County: Arapahoe

Location: Sec 8 Twp 5S Rge 65W

Surface Elev (ft) 5857'

Coordinates 1150'FNL, 1600'FEL, NW, NE

GENERAL

CGS Sample No. 164

Date 12-2-79

Sampled By Brand/Boreck

Sample Type Core

Operator Colorado Geological Survey

Hole No. 10C

DRILLING DATA

Drilling Co. Teton Exploration

Address Casper, Wyoming

Core Size 2 7/8"

Barrel Length 10'

Type of core retrieval split rod, conventional

Drilling media foam

Air Temperature 40°F

TD Hole 620'

Logs Gamma, Density, Caliper, Resistance

GEOLOGY

Geologic Unit Denver Formation

Age Upper Cretaceous

Coal zone/bed unnamed

Bed Thickness 19.4'

Depth to top of coal 434.3' (Driller) same (Log)

Depth to bottom of coal 453.7'(Driller) same (Log)

Cored interval 425-435' (part of cored interval from 384-511.3') (Driller)

Roof description claystone, gray, blocky

Coal description lignite with sandstone partings, some pyrite or marcasite nodules, also kaolinite splits

Floor description very fine grained-silty, gray sandstone

DESORPTION DATA

Sampled interval (ft) 434.3-434.9 (Driller) same (Log)

Condition of sample ?

Sampled Weight (g) 1217

Lost gas time (min) --

Lost gas cc 0

Desorbed gas cc 0

Residual gas cc/g 0

Total gas content cc/g 0

Total gas content cf/t 0

Miscellaneous Reference: CGS Open File Report No. 80-1, 1980, by Karl E. Brand, Geophysical and Lithologic Logs from the 1979 Coal Drilling and Coring Program, Denver East 1/2° x 1° Quadrangle

CGS No. 164

COAL ANALYSES

Analyses	As Received	Moisture Free	Moisture and Ash Free
Proximate Analyses (%)			
Moisture	29.3	N/A	N/A
Volatile Matter	29.1	41.2	49.5
Fixed Carbon	29.8	42.1	50.5
Ash	11.8	16.7	N/A
Ultimate Analyses (%)			
Hydrogen	5.2	2.7	3.3
Carbon	42.7	60.4	72.5
Nitrogen	1.0	1.5	1.7
Sulfur	0.4	.5	.6
Oxygen	39.0	18.3	21.9
Ash	11.8	16.7	N/A
Heating value (BTU/lb)	7316	10356	12429
Sulfur Forms (%)			
Sulfate	not run		
Pyritic	not run		
Organic	not run		

Ash

Initial deformation (°F) not run
Softening temperature (°F) not run
Fluid temperature (°F) not run

Free Swelling Index 0
Fixed Carbon DMMF 51.51
Heating Value BTU/lb MMMF 8382.73
Apparent Rank subbituminous C

Date of Analysis: 3-3-80
Laboratory: U.S. Dept. of Energy Lab No. K99786
Comments:

GAS ANALYSES - not run

ADSORPTION ISOTHERM DATA - not run

CGS No. 164

PETROGRAPHIC ANALYSES

Lab. S.I.U. Coal Characterization Lab Petrographer John C. Crelling
Lab No. SIU #855 Date of Analysis ?

Macaral Analysis		Reflectance Analysis	
Vitrinite	88.1	Vitrinite Ro	The reflectance analysis was undifferentiated due to the low amount of Pvit. *0.35 = mean-maximum reflectance
Pseudovitrinite	0.6		
Semifusinite	0.7	pVit Ro	
Semimacrinite	1.1		
Fusinite	0.0	Combined Ro	
Macrinite	0.1		
Micrinite	3.8	pVit Ro - Vit Ro	
Exinite	5.0		
Resinite	0.6		
Total	100%		

Combined V-Type Table

V-Type	2	3	4	5	6	7	8	9	10	11
%	3.0	88.0	9.0							

V-Type	12	13	14	15	16	17	18	19	20	21
%										

Comments: Apparent rank = Subbituminous C (abundant lumps of cutinite)

Table 5. Detailed coal analyses for CGS Well Number 165, Section 8, Township 5 South, Range 65 West.

CGS No. 165

LOCATION

County: Arapahoe

Location: Sec 8 Twp 5S Rge 65W

Surface Elev (ft) 5857'

Coordinates 1150' FNL, 1600' FEL, NW/4, NE/4

GENERAL

CGS Sample No. 165

Sampled By D. Boreck

Operator Colorado Geological Survey

Hole No. 10C

Date 12-2-79

Sample Type Core

DRILLING DATA

Drilling Co. Teton Exploration

Address Casper, Wyoming

Core Size 2 7/8"

Barrel Length 10'

Type of core retrieval conventional split barrel

Drilling media foam

Air Temperature 40°

TD Hole 620'

Logs Gamma, Density, Caliper, Resistance

GEOLOGY

Geologic Unit Denver Formation

Age Upper Cretaceous

Coal zone/bed unnamed

Bed Thickness 19.4'

Depth to top of coal 434.3' (Driller) same (Log)

Depth to bottom of coal 453.7'(Driller) same (Log)

Cored interval 435-445' (part of cored interval 384-511.3') (Driller)

Roof description claystone, gray, blocky

Coal description lignite, brown/black, w/carb. clay, some attrital, vitrain

Floor description very fine grained-silty, gray sandstone

DESORPTION DATA

Sampled interval (ft) 435-445' (Driller) same (Log)

Condition of sample wet, pieces all sizes, representative sample

Sampled Weight (g) 839

Lost gas time (min) --

Lost gas cc 0

Desorbed gas cc 0

Residual gas cc/g 0

Total gas content cc/g 0

Total gas content cf/t 0

Miscellaneous Reference: CGS Open File Report No. 80-1, 1980, Geophysical and Lithological Logs from 1979 Coal Drilling and Coring Program, Denver East 1/2° x 1° Quadrangle

CGS No. 165

COAL ANALYSES

Analyses	As Received	Moisture Free	Moisture and Ash Free
Proximate Analyses (%)			
Moisture	22.3	N/A	N/A
Volatile Matter	31.6	40.7	53.1
Fixed Carbon	28.0	36.0	46.9
Ash	18.1	23.3	N/A
Ultimate Analyses (%)			
Hydrogen	4.5	2.6	3.4
Carbon	43.0	55.4	72.2
Nitrogen	1.0	1.3	1.6
Sulfur	.4	.5	.7
Oxygen	33.0	16.9	22.1
Ash	18.1	23.3	N/A
Heating value (BTU/lb)	7441	9581	12495
Sulfur Forms (%)			
Sulfate	not run		
Pyritic	not run		
Organic	not run		

Ash

Initial deformation (°F) 2580
Softening temperature (°F) 2650
Fluid temperature (°F) 2730

Free Swelling Index not run
Fixed Carbon
DMMF 48.22
Heating Value
BTU/lb MMMF 9249.42
Apparent Rank subbituminous C

Date of Analysis: 3-3-80
Laboratory: U.S. Dept. of Energy Lab No. K99787
Comments:

GAS ANALYSES - not run

ADSORPTION ISOTHERM DATA - not run

CGS No. 165

PETROGRAPHIC ANALYSES

Lab. S.I.U. Coal Characterization Lab   Petrographer John C. Crelling
Lab No. SIU #856   Date of Analysis ?

Macaral Analysis		Reflectance Analysis	
Vitrinite	88.3	Vitrinite Ro	The reflectance
Pseudovitrinite	2.2		analysis was un-
Semifusinite	1.0	pVit Ro	differentiated due
Semimacrinite	1.1		to the low amount
Fusinite	0.2	Combined Ro	of Pvit.
Macrinite	0.2		*0.42 = mean-
Micrinite	3.4	pVit Ro - Vit Ro	maximum
Exinite	3.2		reflectance
Resinite	0.4		
Total	100%		

Combined V-Type Table

V-Type	2	3	4	5	6	7	8	9	10	11
%		18.0	82.0							

V-Type	12	13	14	15	16	17	18	19	20	21
%										

Comments: Apparent rank = Subbituminous C

APPENDIX B — LIST OF SHAPE FILES

LARAMIE FORMATION

Resource Series 5 - Denver and Cheyenne Basins

Plate	Shapefile	Type	Description	Scale
1-1&2	wells5_1.shp	point	Wells in the Denver and Cheyenne Basins, Colorado	1:500000
1-1&2	strippable5_1.shp	poly	Areas of strippable Laramie FM coal, Denver and Cheyenne Basins, Colorado	1:500000
1-1&2	geology5_1.shp	poly	Area of complex geology and extensive mining, Denver and Cheyenne Basins, Colorado	1:500000
1-1	lar-struct5_1.shp	line	Structure map of the Laramie FM coal, Denver and Cheyenne Basins, Colorado	1:500000
1-1	lar-extent5_1.shp	line	Outcrop/subcrop of Laramie FM coal, Denver and Cheyenne Basins, Colorado	1:500000
1-2	laramie5_1.shp	poly	Areas known to be underlain by Laramie coal beds, Denver and Cheyenne Basins, Colorado	1:500000

Resource Series 13 - Denver East Quadrangle

Total Laramie Formation

Plate	Shapefile	Type	Description	Scale
4	larthick13_4.shp	line	Total coal thickness map of the Laramie Formation Coal Zone	1:100000
5	larstruct13_5.shp	line	Structure map of the Laramie Formation Coal Zone	1:100000

Upper A Coal

Plate	Shapefile	Type	Description	Scale
6&7	lar-wells13.shp	point	Wells in the Antelope Flats-Deer Trail Area	1:50000
6&7	lar-extent13.shp	line	Outcrop/subcrop of the Laramie FM, Antelope Flats-Deer Trail Area	1:50000
6	a-isopach13_6.shp	line	Isopach map of the Upper "A" coal bed, Laramie FM, Antelope Flats-Deer Trail Area	1:50000
7	a-struct13_7.shp	line	Structure map of the Upper "A" coal bed, Laramie FM, Antelope Flats-Deer Trail Area	1:50000

B Coal

Plate	Shapefile	Type	Description	Scale
8&9	lar-wells13.shp	point	Wells in the Antelope Flats-Deer Trail Area	1:50000
8&9	lar-extent13.shp	line	Outcrop/subcrop of the Laramie FM, Antelope Flats-Deer Trail Area	1:50000
8	b-isopach13_8.shp	line	Isopach map of the "B" coal bed, Laramie FM, Antelope Flats-Deer Trail Area	1:50000
9	b-struct13_9.shp	line	Structure map of the "B" coal bed, Laramie FM, Antelope Flats-Deer Trail Area	1:50000

Resource Series 25 - Castle Rock Quadrangle

Total Laramie Formation

Plate	Shapefile	Type	Description	Scale
1	wells-thick25_1.shp	point	Wells west of the Buick-Matheson area	1:100000
1	lar-thick25_1.shp	line	Isopach map of the Laramie FM, west of the Buick-Matheson area	1:100000
2	wells-elev25_2.shp	point	Wells west of the Buick-Matheson area	1:100000
2	lar-struct25_2.shp	line	Structure map of the Laramie FM, west of the Buick-Matheson area)	1:100000
2	lar-over25_2.shp	line	Overburden thickness of the Laramie FM, west of the Buick-Matheson area	1:100000

A Coal

Plate	Shapefile	Type	Description	Scale
3a	point-elev25_3.shp	point	Wells and mines in the Buick-Matheson area	1:100000
3a	a-struct25_3.shp	line	Structure map of the A coal bed, Laramie FM, Buick-Matheson area	1:100000
3b	point-thick25_3.shp	point	Wells and mines in the Buick-Matheson area	1:100000
3b	a-isopach25_3.shp	line	Isopach map of the A coal bed, Buick-Matheson area	1:100000

Resource Series 27 - Colorado Springs Quadrangle

Plate	Shapefile	Type	Description	Scale
8&9	burned-coal.shp	poly	Area of burned coal in the A coal bed, Colorado Springs 1/2x1-degree Quadrangle	1:100000
8	point-thick27_8.shp	point	Wells and mines in the Colorado Springs 1/2x1-degree Quadrangle	1:100000
8	a-isopach27_8.shp	line	Isopach map of the A coal bed, Colorado Springs 1/2x1-degree Quadrangle	1:100000
9	point-elev27_9.shp	point	Wells and mines in the Colorado Springs 1/2x1-degree Quadrangle	1:100000
9	a-struct27_9.shp	line	Structure map of the A coal bed, Colorado Springs 1/2x1-degree Quadrangle	1:100000

DENVER FORMATION

Resource Series 5 - Denver and Cheyenne Basins

Total Denver Formation

Plate	Shapefile	Type	Description	Scale
2-1	max-lignite5_2.shp	line	Maximum individual lignite bed thickness, Denver Basin, Colorado	1:250000
2-1	wells5_2.shp	point	Wells in the Denver Basin, Colorado	1:250000
2-2	den-thick5_2.shp	line	Total thickness of all known lignite beds, Denver FM, Denver Basin, Colorado	1:250000

Station Creek Area

Plate	Shapefile	Type	Description	Scale
4-1	wells5_4.shp	point	Wells in the Station Creek area, Elbert County, Colorado	1:50000
4-1	com-isopach5_4.shp	line	Isopach map of the Comanche coal bed, Denver FM, Station Creek Area	1:50000
4-2	com-overthick5_4.shp	line	Overburden thickness of the Comanche coal bed, Denver FM, Station Creek Area	1:50000
4-2	alluvial5_4.shp	poly	Limits of the alluvial valley floor defined by Public Law 95-87	1:50000
4-3	com-isolith5_4.shp	line	Isolith map of the Comanche coal bed, Denver FM, Station Creek Area	1:50000

Resource Series 13 - Denver East Quadrangle

Total Denver Formation

Plate	Shapefile	Type	Description	Scale
14	den-thick13_14.shp	line	Total coal thickness map of the Denver Formation Coal Zone	1:100000
15	den-struct13_15.shp	line	Structure map of the Denver Formation Coal Zone	1:100000

Lower Watkins Coal

Plate	Shapefile	Type	Description	Scale
16a	den-wells13.shp	point	Wells in the Watkins-Lowry Area	1:50000
16a	lw-struct13_16.shp	line	Structure map of the Lower Watkins coal bed, Denver FM, Watkins-Lowry Area	1:50000
16b	lw-isopach13_16.shp	line	Isopach map of the Lower Watkins coal bed, Denver FM, Watkins-Lowry Area	1:50000

Upper Watkins Coal

Plate	Shapefile	Type	Description	Scale
17a	den-wells13.shp	point	Wells in the Watkins-Lowry Area	1:50000
17a	uw-struct13_17.shp	line	Structure map of the Upper Watkins coal bed, Denver FM, Watkins-Lowry Area	1:50000
17b	uw-isopach13_17.shp	line	Isopach map of the Upper Watkins coal bed, Denver FM, Watkins-Lowry Area	1:50000

Bennett Coal

Plate	Shapefile	Type	Description	Scale
18a	den-wells13.shp	point	Wells in the Watkins-Lowry Area	1:50000
18a	ben-struct13_18.shp	line	Structure map of the Bennett coal bed, Denver FM, Watkins-Lowry Area	1:50000
18b	ben-isopach13_18.shp	line	Isopach map of the Bennett coal bed, Denver FM, Watkins-Lowry Area	1:50000

Lowry Coal

Plate	Shapefile	Type	Description	Scale
19a	den-wells13.shp	point	Wells in the Watkins-Lowry Area	1:50000
19a	low-struct13_19.shp	line	Structure map of the Lowry coal bed, Denver FM, Watkins-Lowry Area	1:50000
19b	low-isopach13_19.shp	line	Isopach map of the Lowry coal bed, Denver FM, Watkins-Lowry Area	1:50000

Resource Series 25 - Castle Rock Quadrangle

Plate	Shapefile	Type	Description	Scale
9	den-thick25_9.shp	line	Isopach map of the total coal in the Denver FM, west of the Ramah-Fondis area	1:100000
9	wells-thick25_9.shp	point	Wells west of the Ramah-Fondis area	1:100000
10	wells-elev25_10.shp	point	Wells west of the Ramah-Fondis area	1:100000
10	den-struct25_10.shp	line	Structure map of the Denver FM coals, west of the Ramah-Fondis area	1:100000
10	denover25_10.shp	line	Overburden thickness of the Denver FM coals, west of the Ramah-Fondis area	1:100000

OTHER SHAPEFILES INCLUDED

Shapefile	Type	Description
dj_basin.shp	poly	Outline of Denver Basin
dj_mines.shp	point	Location of mines digitized from OF78-08 (Kirkham, 1978)
corehole.shp	point	Approximate locations of coreholes from OF78-09 (Kirkham, 1978)
cgs_wells.shp	point	Approximate locations of CGS wells
db_xsections.shp	line	Locations of cross sections used in this report

APPENDIX C — ABSTRACTS AND AGENDA FROM THE WORKSHOP ON THE COALBED METHANE POTENTIAL IN THE DENVER BASIN, COLORADO

September 28, 2001
Denver Athletic Club
Denver, Colorado

AGENDA

8:00	Registration	
8:30	Welcome	Sandra Mark, Vicki Cowart, and Laura Wray
8:40	The Coalbed Methane Potential in the Denver Basin, Colorado	Laura Wray and Nicole Koenig
9:00	Stratigraphy, Tectonic, and Environments of Deposition of Denver Basin Cretaceous Coals	Bob Weimer
9:30	Coal Exploration and Definition in the Denver Basin	R.V. Bailey
9:45	The Museum of Nature and Science's Denver Basin Project	Bob Raynolds
10:15	Break and Poster Sessions	
11:00	Characteristics of Coalbed Methane Reservoirs	Bob Lamarre
11:20	Reservoir Property Analysis Methods for Low Gas Content, Subbituminous Coals	Charles Nelson
12:00	LUNCH	
1:00	Logging Programs for Low-rank Coals	Ned Clayton
1:30	LESA Coalbed Methane Log Analysis	Michael Holmes
2:00	Estimation of Original Gas in Place in Denver Basin Coals	John Seidle
2:15	Regulatory Framework and Administration of the Denver Basin Aquifers	Glenn Graham
2:45	Break and Poster Session	
3:30	Coalbed Methane Development from the Perspective of the Colorado Oil and Gas Conservation Commission	Morris Bell
4:00	Questions and Answers	

ABSTRACTS (in alphabetical order by senior author)

COAL EXPLORATION AND DEFINITION IN THE DENVER BASIN

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In the late 1960s a coal exploration program was undertaken in the Denver Basin in a search funded by Public Service Company of Colorado. The objective was to determine if coal beds existed which could economically be mined and used to fire existing power plants. This paper will describe the program, the results of the program and efforts to develop the deposits found. Included will be a description of how 100% recovery was obtained from coring operations.

The coal beds in the Denver formation are unusual in that, for the most part, they contain local partings of crystalline kaolin, which apparently developed from chemical reactions when volcanic ash fell in the developing coal swamps. Such minor interbeds decrease the overall Btu value of the coal for conventional combustion purposes, but are not expected to interfere with the generation of coalbed methane from these deposits. Therefore analyses of the coal without the partings is the best indication of coal quality in this situation.

COALBED METHANE DEVELOPMENT FROM THE PERSPECTIVE OF THE COLORADO OIL AND GAS CONSERVATION COMMISSION

Morris Bell
Operations Manager
Colorado Oil and Gas Conservation Commission
Denver, Colorado

The Colorado Oil & Gas Conservation Commission (COGCC) has been involved in the development of coalbed methane in the San Juan Basin since the 1980s and more recently, involved with the development of the coalbed methane resources in the Raton Basin. The COGCC has attempted to resolve concerns of operators, surface owners, local governments, federal agencies, and other state agencies concerned with the development of coalbed methane resources in the state. The COGCC has adopted specific rules concerning spacing, well bore construction, gas well testing, and water well testing for coalbed methane wells to address these concerns. The COGCC has also funded several studies to address environmental concerns. This presentation will discus the concerns that the COGCC has addressed in the San Juan and Raton Basins and how they may affect coalbed methane development in the DJ Basin.

COAL BED METHANE EVALUATION USING ADVANCED BOREHOLE GEOPHYSICAL LOGS

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Geochemical wireline logging provides a real-time, quantitative characterization of coal bed lithology and mineralogy that can estimate total gas volume and degree of cleating in coal beds. Unlike conventional logging methods, a geochemical log directly measures coal and ash mineralogy based on their chemical makeup and these measurements are relatively unaffected by borehole conditions, obtainable in fluid- or air-filled, open or cased boreholes—providing a more accurate and reliable estimate of coal gas volume and cleating. Thus, important information about CBM resources and producibility are derived in-situ—at discrete depths or averaged over one or many coal beds.

The ECS* Elemental Capture Spectrometer sonde and RST* Reservoir Saturation Tool are routinely employed for quantitative geochemical and lithologic characterization in conventional oil and gas reservoirs. These tools use prompt gamma ray neutron activation spectroscopy to analyze for Ca, S, Si, Fe, Ti, and Gd. The processing has been modified to include coal, based on a spectral H measurement that is highly sensitive to coal content. The result is a continuous log of coal plus carbonate, pyrite, clay and sand weight% that characterize the depth, thickness, net footage, and mineral content of coal seams, as well as the lithology throughout the rest of the logged borehole.

No logging tool can directly measure the gas adsorbed to coal. Instead, gas content is derived by correlating coal properties measured with logs to gas content, based on representative core analyses. In-situ gas content in coals is estimated from log measurements by the following empirical steps:

1. Proximate analysis components of coal (fixed carbon, volatiles, and moisture) are determined from the geochemical log of total mineral content weight%, using a relationship derived from proximate analyses performed on core. (This step can be eliminated if density and neutron porosity measurements are available, enabling direct delineation of fixed carbon and volatiles from logs.) While ash, fixed carbon, and volatile volume% can be derived from density and Pe (or neutron porosity) logs alone, this requires assumptions on the bulk density and Pe (or neutron porosity) of each component—particularly difficult for ash. With the addition of geochemical logs, these assumptions are significantly reduced, because the total coal and each mineral constituent are accurately measured.

2. The total gas content and gas adsorption isotherm are determined at discrete depths from the coal rank (fixed carbon versus volatiles) and ash weight%, using an empirical relationship derived from proximate analysis and gas desorption/adsorption tests performed on core. The relationship is derived based on a physical gas adsorption model, such as the Langmuir equation. Also required for the gas adsorption model are estimates of in-situ pore pressure and, secondarily, temperature. Gas content is directly proportional to coal weight%, because gas does not adsorb to the ash minerals. Because geochemical logs provide a more accurate and robust measurement of coal weight% than density logs alone, the resulting estimate of gas content is more reliable.

While general models for the above empirical relationships have been developed using large core data sets from various coal basins, the relationships produce the most accurate results where they are calibrated to local coal, using core analysis results from wells in the area. This calibration is typically only required once for a specific area, after which gas content can be estimated solely from the logs.

An indication of the degree of cleating at discrete depths in coal beds is provided by the geochemical log mineral ash measurements (carbonate, pyrite, clay and sand). Core and log data observations and well performance data have empirically shown that a higher volume of clastic minerals (e.g. quartz and clay) is detrimental to cleat development in coal, by holding the coal together. Conversely, small volumes of secondary minerals (e.g. calcite and pyrite) are good indicators of well-developed cleating, resulting from mineral deposition from water flowing through the coal. Based on these observations, relationships using cutoffs on the mineral ash volume measurements have been developed to determine whether coal beds are poorly, partly, or well cleated. These relationships can be refined for local basins, if similar core and well performance data are available. In a recent Indian study, quantitative estimates of cleat porosity were also made from geochemical logs by deriving an empirical relationship between mineral concentrations and an independent measurement of cleat porosity. In turn, the inferred degree of cleating or cleat porosity provides an indication of gas producibility of the coal at that depth.

Compared to the conventional approach for coal bed methane evaluation, where density is typically the primary logging measurement, geochemical logging provides:

- a more accurate, reliable measurement of coal content and, thus, total gas content;
- a precise measurement of coal bed mineralogy, enabling an estimate of cleating—an important indicator of gas producibility; and
- the option for cased hole evaluation.

In turn, this evaluation enables the optimized well completion, stimulation, and production of coal bed methane. The measurements can be enhanced by running the geochemical probe in combination with a density-Pe probe (or high resolution neutron porosity probe in cased holes), improving the vertical resolution of the geochemical measurements in coal beds from 20 to 8 inches or less and providing a direct measurement of coal rank.

REGULATORY FRAMEWORK AND ADMINISTRATION OF THE DENVER BASIN AQUIFERS

Glenn Graham
Colorado Division of Water Resources
Department of Natural Resources

The recent focus on the evaluation and development of coal bed methane in parts of Colorado has spread to the Denver Basin, and brought to light some regulatory issues that may affect the fate of ground water produced in association with CBM production. If the amount and concentration of CBM is sufficient to warrant commercial production of the resource, both industry and regulatory agencies will be faced with new challenges.

Development of Colorado's ground water was essentially unregulated until 1957, and administration of individual residential well use was not implemented until the early 1970s. Evolution of ground water law in the state was driven by the need to protect existing senior rights to surface waters. In 1985, the Colorado General Assembly passed Senate Bill 5, which created the current regulatory framework for the Denver Basin Bedrock Aquifers. The present administrative process has not anticipated the potential that good quality water contained in the Denver Basin Aquifers may be produced as a byproduct of CBM production. Recent experience in the Raton Basin has shown that when produced water is of good enough quality for even some limited beneficial use, administration and development of that water can become a very complex and contentious issue.

LESA COALBED METHANE LOG ANALYSIS

Michael Holmes
Digital Formation
Denver, Colorado

LESA Coalbed Methane Log Analysis

The attached extract from the equation and methodology documentation for ***LESA*** describes the techniques used to analyze coalbed methane using wireline logs.

One example is shown, from Fruitland Coal Field, Rio Arriba County, New Mexico (Northeast Blanco Unit).

- Raw data
- Interpretations involving the various analytic techniques showing:
  - ash content
  - moisture content
  - volatile matter
  - fixed carbon
  - productivity – MCFD
  - gas content – cubic feet per ton
  - gas in place – MMCF

Included in the interpretive depth plot are regular deterministic outputs of ***LESA*** (porosity, shale, water saturation profile of the non-coal sections) using the in-depth module.

Procedures to follow using the ***LESA*** program are:

a) Edit the file for standard in-depth analysis. Choose petrophysical input for the non-coal intervals.

b) Run the **Coalbed Methane** module, with suitable edits for:

	Default Value
Maximum Rhob for coal	2.0
Minimum neutron for coal	35
Minimum sonic delta t for coal	95
Minimum resistivity for coal	10
Tons per acre	1800
Well spacing, acres	160

Digital LAS files, including interpretations, are included.

Coalbed Methane

A. The program first checks for "generic" coal:

- $R > 10\Omega M$
- $\rho_B < 2.0$
- $\Delta_t > 95$
- $\Phi_N > 35\%$

If more than one log exists, go to density log preferentially. If $\rho_B > 2$, cannot be coal, no matter what. The interpreter can define the inequalities.

B. Then, if more than one porosity log is available, determines different types of coal.

Coal Matrix properties are as follows:

	ρ_B	Φ_N	Δ_t	Δ_{tma}	Pe
Anthracite	1.47	38	105	48	0.16
Bituminous	1.24	60	120	44	0.17
Lignite	1.19	52	160	50	0.20

From Density Neutron

Anthracite	ρ_B Φ_N	1.3 to 1.9 35 - 45
Lignite	ρ_B Φ_N	1.0 to 1.22 45 – 55
Sub-bituminous	ρ_B Φ_N	1.22 to 2.0 55 – 60
Bituminous	ρ_B Φ_N	1.22 to 2.0 > 60

From Neutron Sonic

Anthracite		Can not distinguish
Lignite	Δ_t Φ_N	140 – 170 45 – 55
Sub-bituminous	Δ_t Φ_N	110 – 140 55 – 60
Bituminous	Δ_t Φ_N	95 – 110 > 60

From Sonic / Density

Anthracite	Δ_t ρ_B	80 – 95 1.3 – 2.0
Lignite	Δ_t ρ_B	140 – 170 1.0 – 1.22
Sub-bituminous	Δ_t ρ_B	110 – 140 1.22 – 2.0
Bituminous	Δ_t ρ_B	95 – 110 1.22 – 2.0

C. The program then determines a series of calculations relative to coal components.

- Ash Content $V_A = 64.94 \times \rho_B - 66.27$

- Fixed Carbon $V_{FC} = -0.517V_{ASH} + 51.2$
- Moisture $V_M = -0.10V_{ASH} + 4.61$
- Volatile Matter $V_{VM} = 100 - V_A - V_{FC} - V_M$

D. Using the data calculated in item (C), the program then calculates gas volumes according to several published equations. Basic references used are:

- Olszewski and Schranfnagel, "Development of Formation Evaluation Technology for Coalbed Methane Development," Methane from Coal Series, October, 1992.
- Mavor, Close and McBane, "Formation Evaluation of Exploration Coalbed Methane Wells," paper SPE 90-101, Calgary, 1990.
- Mullen, "Log Evaluation in Wells Drilled for Coal-bed Methane," RMAG, 1988.

Original Kim Equation

$$g = \frac{(1 - w - a) \times V_w}{V_d \times (k_0 p^{n_0} - bT)}$$

where,

g = adsorbed gas volume, cc/g

a = ash content, weight fraction = V_A

b = constant = 0.14

$$k_0 = 0.8 \times \left(V_{FC} / V_M \right) + 5.6$$

$$n_0 = 0.39 - 0.1 \times \left(V_{FC} / V_M \right)$$

p = pressure, atmospheres

T = temperature, °C

V_d = gas volume, dry coal

V_w = gas volume, moist coal

w = moisture content, weight fraction = V_M

$V_w/V_d = 0.75$

Modified Kim Equation

$$V = (1 - V_M - V_A) \times 0.75 \times \left\{ k_0 \times 0.96h^{n_0} - 0.14\left(\frac{1.8h}{100}\right) + 11 \right\}$$

V = Gas content Ft^3 gas / ton

h = Depth in meters

All other terms defined under "Kim Equation".

Langmuir

$$\log G_L = k_1 \log \left(V_{FC} / V_{VM} \right) + k_2$$

$$\log P_L = k_3 \log \left(V_{FC} / V_{VM} \right) + k_4$$

T = temperature, °C

$K_2 = -0.00268T + 2.82873$

$K_3 = 0.00259T + 0.50899$

$K_4 = 0.00402T + 2.20342$

G_L = gas volume (Langmuir) SCF/T (infinite pressure)

P_L = Langmuir pressure, at which sample's gas content is ½ G_L

Mullen

Average Gas Content = $-542\rho_B + 1053$ ft^3 per ton

Mavor, Close, McBane

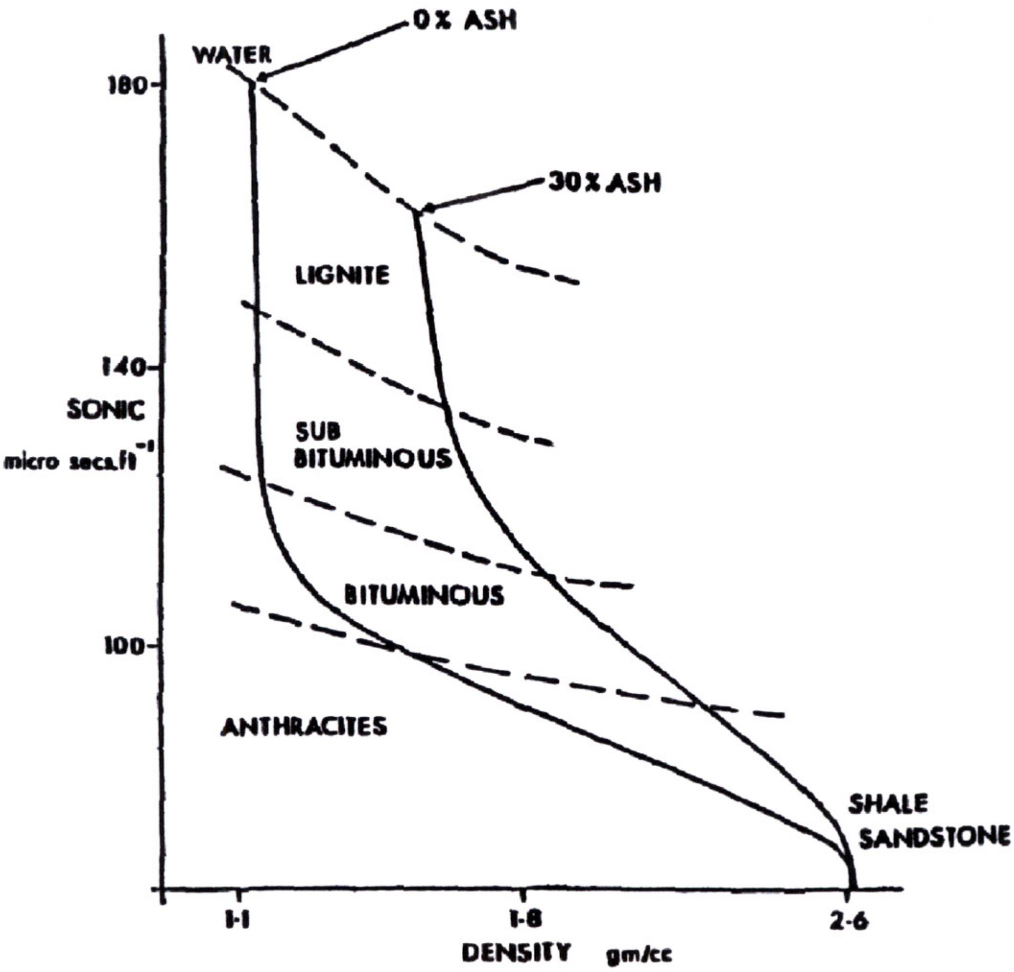
$g = 601.4 - 751.8a_d$

$$a_d = \frac{a}{(1-w)} = \frac{V_A}{(1-V_M)}$$

g = gas content, SCF per ton

Prensky

By comparisons between sonic and density logs, coal rank and ash content is available. A look-up table is a numeric solution to the following graph (Prensky):



Graph showing the relationship between acoustic log travel-time, bulk density, and coal rank 9from BPB, 1981, by permission).

A. Gas in Place is calculated using the equation:

Gas in place MCF = $g \times h \times c \times area$

g = gas content, ft^3 per ton

h = coal be thickness, ft.

c = tons of coal per acre foot of coal (average 1800)

(Area in acres)

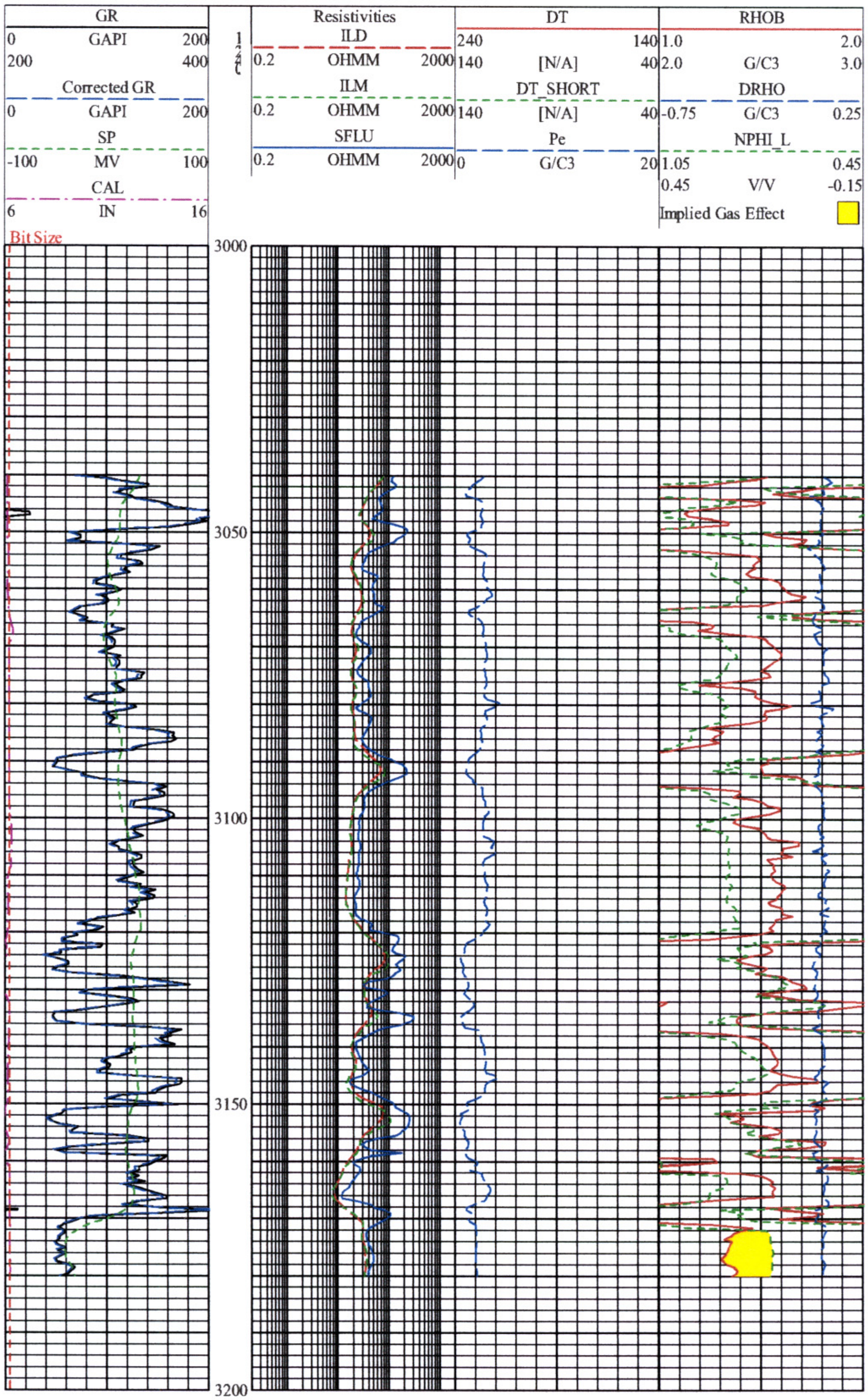
B. Deliverability

Using Mullen's correlation between SP development and deliverability:

Productivity (MMCFD) = $4.3 \times 10^{-3} \times SPM$

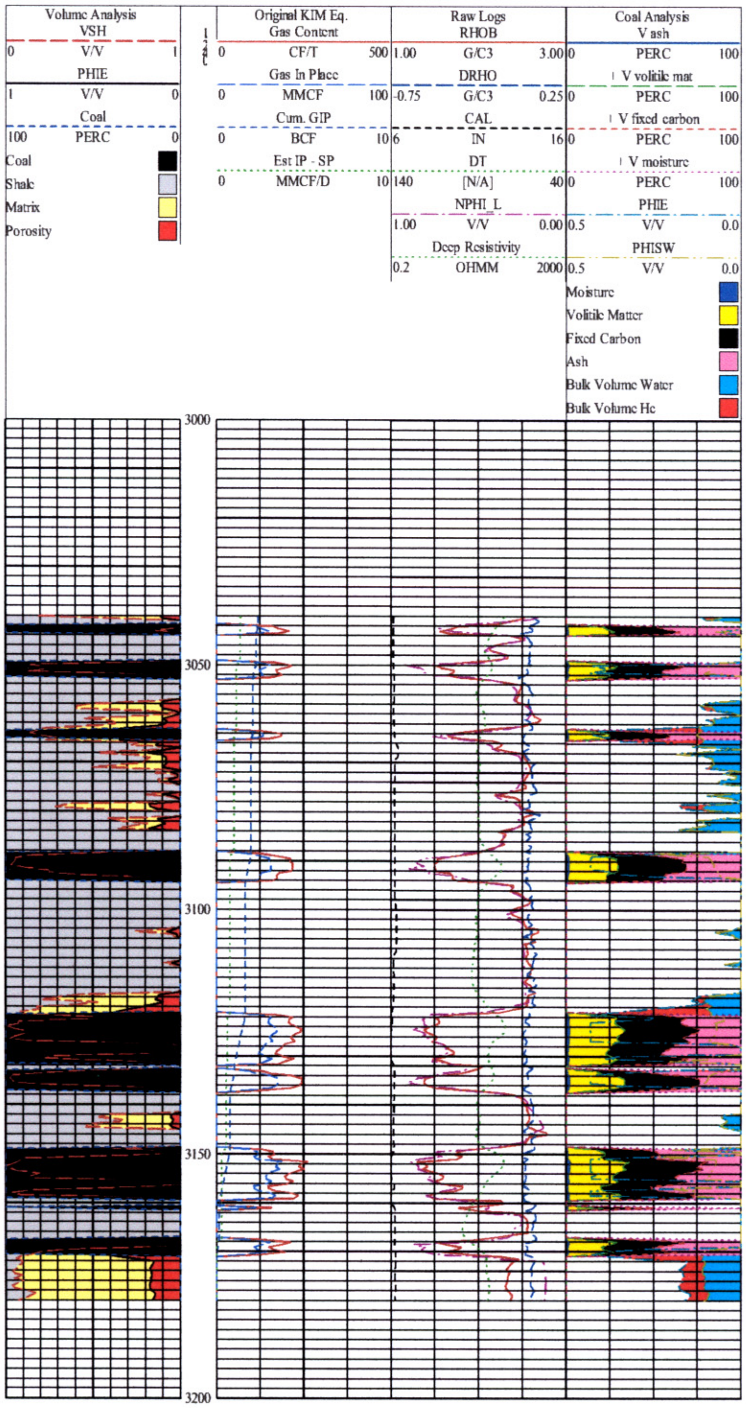
SPM = Maximum SP deflection in coal (MV) $\times$ Coal thickness (ft.)

LESA 2.2, © 1992-2000 Digital Formation, Inc.
File: Nbu495.las
Well Name: Northeast Blanco Unit #495
Plot: L-RAW-U.PLT
Plot Name: Raw Data Log (US and Canada)
Gross Interval: 3040 to 3180 by 0.5 F
Ranges: 3040-3180
Time: 02:57 PM
Date: Tue, Jul 25, 2000



LESA 2.2, © 1992-2000 Digital Formation, Inc.

File: Nbu495.las	Well Name: Northeast Blanco Unit #495
Plot: L-CBM-S.PLT	Plot Name: Coal Bed Methane (Schlumberger)
Gross Interval: 3040	to 3180 by 0.5 F
Ranges: 3040-3180	
Time: 03:12 PM	Date: Tue, Jul 25, 2000



Coal Bed Methane Analysis Parameters

Gross Range: [3040] - [3180]

Interval Analyzed: [3040] - [3180]

Num Beds:	9		Mullen Ave. Gc:	175.399	CF/T
Thickness:	43	ft	Mullen Cum. GIP:	2.172	BCF
Tons/Acre-ft:	1800		Mavor et al. Ave. Gc:	261.59	CF/T
Acres:	160		Mavor et al. Cum. GIP:	3.24	BCF
Density Max.:	2	gm/cc	Original KIM Ave. Gc:	192.678	CF/T
Neutron Min.:	0.35	fractions	Original KIM Cum. GIP:	2.386	BCF
Sonic Min.:	95	us/ft	Modified KIM Ave. Gc:	295.222	CF/T
Resistivity Min.:	10	ohm-m	Modified KIM Cum. GIP:	3.656	BCF
SP PP:	-603.374	mV-ft	Langmuir Ave. Gc:	274.818	CF/T
SP IP:	1.397	MMCF/Day	Langmuir Cum. GIP:	3.403	BCF

Pressures:

[3040] - [3180] FRUITLAND COALS1000 psi

CHARACTERISTICS OF COALBED METHANE RESERVOIRS: WHY ARE THEY SUCH PROLIFIC PRODUCERS?

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Coalbed methane (CBM) reservoirs produced 1.25 Tcf of gas in 1999, comprising 7% of the total U.S. natural gas production. Cumulative CBM production is more than 8 Tcf and proven reserves exceed 13 Tcf. The total in-place CBM resource in the U.S. is estimated to exceed 700 Tcf, with about 100 Tcf being recoverable with current technology.

Methane gas is generated in coals by two distinct processes. Thermogenic gas is a natural by-product of the coalification process that converts humic organic matter into coal. This gas includes methane, carbon dioxide and occasionally, ethane and propane. Secondary biogenic gas is produced in recent geologic time by anaerobic microorganisms carried in an active groundwater system after the coalification process is complete. Secondary biogenic gas can be generated in coals of any rank if an anoxic, low temperature environment exists, such as in regional coal aquifers.

Both thermogenic and secondary biogenic methane are physically adsorbed as a monomolecular layer on the surface of the micropores within the coal matrix. The methane is held in place by the hydrostatic pressure of the water within the coals. Natural fractures (cleats) within the coal contain water and provide permeability. In a coalbed methane well, water is usually produced first, which results in a reduction of the reservoir pressure. This is the de-watering phase of a CBM well's life. As the pressure declines, methane desorbs from the coal matrix by diffusion, and flows through interconnected cleats by Darcy flow. Consequently, most CBM wells show a negative decline curve for gas with the gas rate increasing with time and the water rate decreasing. Productive life may exceed 40 years. Coals are unique reservoirs because they are the source rock, reservoir and seal (trap) all in one.

Coals make excellent reservoirs because their internal surface area can exceed one billion square feet per ton of coal. A ton of high volatile bituminous coal is a cube approximately three feet on a side. In-place gas contents within these coals can range from 200 to 500 standard cubic feet per ton of coal. Reserves can range from one to five Bcf per 160-acre drill block. At reservoir pressures below 1600 psi, coals can hold almost three times as much gas as conventional sandstone reservoirs with 20% porosity and 30% water saturation.

Successful coalbed methane exploration programs must evaluate the following parameters: coal thickness and rank, gas content, permeability, hydrodynamics, gas quality, water quality and water disposal options, depth and potential completion techniques.

RESERVOIR PROPERTY ANALYSIS METHODS FOR LOW GAS CONTENT, SUBBITUMINOUS COALS

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Coalbed natural gas is currently experiencing a second wave of large-scale commercial development in the U.S. Rocky Mountain region. A decade ago, the Fruitland Formation coal in the San Juan Basin was the only significant commercial coalbed natural gas play in this region. One key factor that initially discouraged exploitation of coalbed natural gas resources elsewhere in this region was the general gas industry perception that the large coal deposits in other Rocky Mountain basins simply did not possess the reservoir property characteristics needed for a commercially viable coalbed natural gas play. Today, new coalbed natural gas plays in the Rocky Mountain region's Raton, Uinta and Powder River basins are undergoing large-scale commercial development. The gas industry's success in unlocking these three new coalbed natural gas play areas required exploration persistence as well as the development and use of innovative, low-cost drilling, completion and production solutions tailored to the unique site-specific reservoir properties of each play area.

The geologic setting and reservoir properties of the commercial coalbed gas play in the Fort Union Formation of the Powder River Basin are particularly noteworthy since they completely defy conventional gas industry wisdom, based on experiences in the Fruitland Formation coal of San Juan Basin, regarding the type of geologic setting and reservoir properties required for a commercial coalbed natural gas play. In the Powder River Basin, the commercially productive reservoirs are shallow beds of low gas content, subbituminous rank coal. In 2000, natural gas production from these low gas content, subbituminous coalbed reservoirs totaled 147 Bcf from 4,200 wells.

The enormous commercial potential of the low gas content, subbituminous coalbed reservoirs in the Powder River Basin Fort Union Formation was simply not recognized by the early reservoir property evaluations conducted by industry in the late 1980s and early 1990s. An important implication of this is that the production potential of subbituminous coal deposits in other Rocky Mountain region basins also may have been significantly underestimated during prior industry evaluation processes. An example is the subbituminous coal in the Laramie Formation of the Denver Basin. Gas content data measured during the late 1970s and early 1980s indicated that the Laramie Formation subbituminous coal contains only trace amounts of natural gas. These low gas content values helped discouraged industry interest in the Denver Basin as a coalbed natural gas play prospect. By contrast, during the early 1900s numerous Laramie Formation underground coal mines in the Denver Basin reported gas explosions, a clear indication that the Laramie Formation subbituminous coal may contain a significant amount of natural gas.

One of the important lessons that the gas industry learned from its experiences in the Powder River Basin is that reliably assessing the natural gas resource, production and producible reserve potential of low gas content, subbituminous coalbed reservoirs requires the use of reservoir property analysis methods custom tailored to the unique properties of subbituminous coal. Custom tailored analysis methods are essential because the bulk organic matter comprising subbituminous coal is both chemically reactive and physically unstable. It readily undergoes very rapid aerial oxidation and desiccation, which can result in significant underestimation errors in such key reservoir properties as the in-situ gas content, moisture holding capacity, sorbed phase gas composition, and percent gas saturation. Results from case studies illustrating effective methods for avoiding or minimizing subbituminous coalbed reservoir property analysis errors due to aerial oxidation and desiccation are described in this paper.

THE DENVER MUSEUM OF NATURE AND SCIENCE'S DENVER BASIN PROJECT

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In 1998 the Denver Museum of Nature and Science assembled a multi-disciplinary team to examine the Laramide synorogenic sediments in the Denver Basin. Major funding was obtained from the National Science Foundation and the Colorado Water Conservation Board. One of the principal goals of the Denver Basin Project is to build a rigorous time-framework for the fossiliferous strata in the basin providing a context to better understand the uplift and denudation of the Front Range. A continuous 2256 foot core was obtained in 1999 at Kiowa in Elbert County. The 2.5 inch diameter core recovered 93% of the drilled strata and serves as a primary calibration point for our stratigraphic studies of the Basin. The core is archived at the U.S. Geological Survey's core research facility in Lakewood, CO. Two synorogenic sequences were completely sampled as were the Laramie and Fox Hills Formations. The core hole reached TD in the upper Pierre Shale.

A chronological framework for fluvial strata preserved during the latest Cretaceous and early Paleogene in the Denver Basin has been established using radiometric dating, paleontology and magnetostratigraphy. In the Denver Basin, Laramide style synorogenic sedimentation spans the K/T boundary and extends into the Eocene. The synorogenic strata occur in two unconformity-bounded sequences which are interpreted to reflect two episodes of uplift and deformation in the adjacent Front Range. The first, termed the D1 sequence, accumulated during the first phase of uplift of the Front Range. This sequence started to accumulate about 68 MY, spans the end of the Cretaceous and extends up to about 64 MY. Rates of accumulation in the central part of the Basin are on the order of 100 m/million years with rates of up to 150 m/million years on the active western margin. The synorogenic strata are comprised of alternating fluvial channel sandstone and overbank mudstone beds. Coal and lignite beds occur in the central and eastern portion of the Basin suggesting low gradients and under-filled basin conditions. Sandstone compositions vary as a function of the unroofing of the Front Range and the eruption and subsequent erosion of an andesitic volcanic terrain. Compositions range from andesite-rich litharenites to arkoses, these changes reflect the evolution of the catchments feeding the rivers draining the uplifting Front Range. Fossil plants are common, and vertebrates are locally abundant. Moist, warm and generally well-drained to swampy conditions are indicated. Near the end of this period of accumulation, sedimentation became fine-grained, then ceased for a period of approximately 9 MY during which time little sedimentary record is preserved other than a thin aggradational paleosol.

Sedimentation resumed approximately 54 MY ago and spanned a poorly-defined interval during the early Eocene, comprising the unconformity-bounded D2 sequence. During this interval, arkosic fluvial strata record the erosion of a granite-rich source terrain much like we see today in the modern Front Range. Fossil plants are less common and vertebrate remains are rare in this sequence. Paleocurrent indicators together with isopach and composition patterns suggest derivation from the Pike's Peak area during a second pulse of Laramide deformation. Long after these strata accumulated, the region underwent asymmetric epeirogenic uplift and headward incision of the Arkansas and South Platte river systems sculpted the landscapes we see today in the Denver Basin area.

Colleagues working on the Denver Basin Project have examined the faunal and floral records and efforts are underway to tie the Denver Basin paleontological record to data sets developed elsewhere in the Rocky Mountain West. Significant megafloral heterogeneity may result from orographic effects. Pollen and vertebrate remains are being correlated to more extensive records in Wyoming to extend and refine previously established biozonation patterns. Groundwater resources, sandstone mineralogy, fission track analysis, and present-day temperature profiling have also been conducted under the aegis of this project.

As one of the synthesis products of the research, a series of detailed paleo-landscapes have been reconstructed and painted. These will be used to illustrate the results of the research to the general public.

COALBED METHANE POTENTIAL IN THE LARAMIE FORMATION, GREATER WATTENBERG AREA, DENVER BASIN, COLORADO – POSTER PRESENTATION

Stephen B. Roberts and Neil S. Fishman
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The successful development of shallow coalbed methane resources from low rank coal in the Powder River Basin in Wyoming and Montana has helped to stimulate (or renew) interest in the potential for coalbed methane development in the Denver Basin. The Denver Basin contains an estimated 30-35 billion tons of subbituminous coal and lignite in the Laramie and Denver Formations at depths of less than 3,000 ft, and although there is currently no coalbed methane production in the basin, the Gas Research Institute (GRI) estimates as much as 2 trillion cubic feet (Tcf) of coalbed methane (in-place) within these two formations. Of this total, GRI (1999) suggests that some 0.3 Tcf of methane may be recoverable. In order to better evaluate the coalbed methane potential in the Denver Basin, the USGS Front Range Infrastructure Resources Project initiated a study in the greater Wattenberg area (GWA) in order to gain some perspective on the coal-bed methane potential in the Upper Cretaceous Laramie Formation. The GWA incorporates about 2,900 mi^2 in parts of Adams, Boulder, Denver, Jefferson, Larimer, Morgan, and Weld counties, and extends from T. 2 S. to T. 7 N., and from R. 61 W. to R. 69 W. The area includes most of the Boulder-Weld coal field, and additional areas where Laramie Formation coal was mined in the past. In the GWA, commingled gas production from all Cretaceous units is allowed, and recently relaxed drill-spacing requirements (spacing < 40 acres) might encourage re-completion efforts in existing wells to tap into additional pay zones. Potential coal-bed methane resources in the Laramie Formation overlie targets of current gas production in deeper, older Cretaceous strata, and may constitute a shallow, "behind-pipe" resource in existing gas wells.

The main coal-bearing zone in the Laramie Formation is present within the lower 300 ft of the formation. The maximum thickness of the coal zone in the GWA is about 290 ft and the minimum thickness is on the order of 75-80 ft. Total (cumulative) coal thickness within the coal zone ranges from a few feet or less (traces of coal) to as much as 35 ft. Maximum depth to the top of the zone exceeds 1,300 ft, although in most of the GWA the depth to the top of the coal zone is less than 1,000 ft. The thickest total coal accumulations are at depths of less than 500 ft, in and near the Boulder-Weld coal field. Individual coal-bed thickness can vary from less than 1 ft to as much as 9 ft, and the number of coal beds within the coal zone varies from 2 to 12. Average (arithmetic mean) as-received heat-of-combustion (Btu/lb) values for Laramie coal beds, based on analyses of coal mine and coal core samples, range from 7,200 to more than 9,900 Btu/lb. Heat-of-combustion values for coal in the Boulder-Weld coal field are typically 1,000 to 1,500 Btu/lb higher than for Laramie coal in other areas in the Denver Basin. Total coal gas contents, determined from the desorption of Laramie Formation coal core samples in three drill holes in or adjacent to the GWA, ranged from 0 to as much as 24 cubic ft/ton. At least eight mines in the Boulder-Weld coal field experienced mine fires or explosions during their production history, and an additional eight coal mines reported the presence of gas. Perhaps some of the most compelling evidence for the gassy nature of Laramie

Formation coal was recorded in the Eagle Mine in the northeastern part of the Boulder-Weld coal field, where more than 7,000 cubic ft of gas per day (28 cubic ft of gas per ton of mined coal) was emitted during the first quarter of 1976.

Favorable coal geologic factors for a potential coalbed methane resource in the Laramie Formation in the GWA include the documented presence of coalbed gas, the relatively continuous distribution of Laramie coal beds in subsurface throughout the area, cumulative (total) coal-bed thickness exceeding 30 ft, and individual coal-bed thickness of as much as 12 ft locally. Certain other coal geologic factors, however, could restrict or even negate the prospective development of this resource. For example, in places where total coal accumulations exceed 20 ft, the lower Laramie coal zone is generally shallow (less than 500 ft), and coal beds are near faulted and undermined areas in the Boulder-Weld coal field. The shallow depth and proximity to faults and abandoned underground mines could result in gas leakage into mined-out cavities, or leakage to the surface via faults or up-dip migration to nearby outcrops. In certain areas of the GWA, where greater coal zone depths might enhance methane retention, reported total coal accumulations are typically less than 20 ft, and commonly less than 10 ft. The limited volume of coal in these areas could severely diminish the coalbed methane resource potential. Another factor that could constrain Laramie Formation coalbed methane development is the close association of coal beds with the Laramie-Fox Hills aquifer. This aquifer, which is one of the primary sources of fresh water for residential, agricultural, and commercial use, includes sandstone beds in the lower, coal-bearing part of the Laramie Formation, as well as sandstone in the underlying Fox Hills Sandstone and uppermost Pierre Shale. Dewatering of the coal, which may be required to develop the methane resource, could result in the lowering of subsurface water levels through time. Thus, careful consideration in regard to the development of Laramie Formation coalbed methane resources will be required to ensure that associated water production will not compromise the integrity of this important Front Range water supply.

ESTIMATION OF ORIGINAL GAS IN PLACE IN DENVER BASIN COALS

John Seidle
Sproule Associates, Inc.
Denver, Colorado

Coalbed methane potential of the Denver Basin has long been neglected because the coals were judged to be too thin, too shallow, and too immature to support commercial gas production. With the success of the Powder River Basin coalbed methane play, which has coals of similar rank and depth, this study was undertaken to quantify the gas held by Denver Basin coals by volumetric means. Powder River Basin coals were used as an analog because coals in both basins are generally shallow, Cretaceous to Paleocene in age, subbituminous in rank, and roughly the same temperature.

Coals of the Powder River Basin contain both sorbed and free gas. The sorbed gas contribution is calculated with a sorption isotherm and reservoir pressure, while the free gas component is calculated from conventional gas reservoir engineering principles. This study considered both sorbed and free gas contributions.

The average Bureau of Land Management (BLM) isotherm for Powder River coals published by Crockett and Meier (ref 2) was used to estimate gas content. Analogous to Powder River coals, coalbed density was assumed to be 1.35 grams/cubic centimeters (gm/cc). Sorbed gas was calculated as the product of area, coal thickness, coal density, and gas content. Coal porosity was assumed to be 10 percent and gas formation volume factors were calculated assuming the gas to be pure methane.

This study determined that coals of the Denver Formation hold 704 billion cubic feet of gas (bcf) and those of the Laramie Formation contain 1539 bcf, for a total of 2243 bcf. The total Denver Basin coalbed methane resource is therefore estimated to be 2.24 trillion cubic feet of gas (tcf) with approximately two-thirds of the gas held in the Laramie formation coals and one-third in the Denver formation coals.

STRATIGRAPHY, TECTONIC, AND ENVIRONMENTS OF DEPOSITION OF DENVER BASIN CRETACEOUS COALS

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The Cretaceous Laramie Formation of the Denver Basin contains coal deposits that accumulated in coastal plain and alluvial environments. The coals are generally found in the lower 200 feet of the Laramie (800 to 1000 feet thick), which overlies the shoreline and shallow marine regressive sandstones of the Fox Hills Sandstone (60 to 350 feet thick).

The common swamp environments of the coal are channel margin, coastal, and abandoned channel-fill. Channel margin coal environments are of two general types: 1) restricted back-levee swamps that parallel channel trends, and also are the site of deposition of light-colored leached kaolinitic claystone; and, 2) more extensive flood basin swamps which are commonly associated with lacustrine deposits. Both types are interbedded with fresh water claystones, siltstones and sandstones.

Coastal swamps form landward from barrier islands and parallel shoreline trends. Thickest coal occurs during rising sea level because of greater accommodation space than during sea level fall. The coals may be associated with shales, siltstones and sandstones containing brackish to marine trace fossils.

Coals of the fresh water channel-fill environment are thin and aerially restricted. Other thin lenticular coals, derived from accumulation of transported organic material, may be found in both non-marine and shallow marine environments.

The critical environmental factors necessary for the formation of commercial thickness of coal are: 1) fresh clear water; 2) accumulation of land organics only; 3) balance between ground water table and depositional interface of swamp; 4) climates; and 5) persistence of conditions through time during subsidence to give accommodation space. These conditions are most commonly found in ancient alluvial, deltaic plain and other coastal plain settings.

Penecontemporaneous (growth) faults may occur in the swamps and control locally increased thickness of coal. In the Upper Cretaceous deltaic sequence involving the Laramide and Fox Hills Formations along the west margin of the Denver Basin, two types of growth faults are observed: 1) deep-seated to the basement; and 2) normal or reverse faults that die out at shallow depths. The first type is observed in the Golden – Leyden coal area and is related to early mountain flank deformation.

In the important Boulder-Weld County coal field, a target for coalbed methane, the second type of faulting with horst-graben patterns was a primary control on the number and rates of accumulation of coals. Coal beds with commercial thickness formed in the graben blocks where as many as 7 separate coal beds throughout the field were identified for mining. Individual coals range in thickness from a wedge edge to 14 feet. Usually only 2 to 4 coals are present at any one locality where an aggregate thickness may exceed 25 feet. Both the faulting and the unusual coal occurrence are unique to the Boulder-

Weld County field in comparison with other parts of the Denver Basin, where coals are less abundant and thinner.

The origin of the fault system in this area is controversial with ideas ranging from all faults extending to the basement to shallow detached slide blocks with listric fault planes. The shallow faulting is believed by the author to be related to recurrent movement on the Ralston-Lafayette wrench fault system, and compares favorable with the divergent wrench fault style after Harding but with some modification along the fault zone trend.

The lateral continuity of the Laramie Formation containing the coal and the Fox Hills Sandstone is interrupted by as much as 300 feet of recurrent movement on some faults during the main phase of the Laramide Orogeny. This faulting in the Boulder-Weld County field could possibly have a negative impact on coalbed methane development.

THE COALBED METHANE POTENTIAL IN THE UPPER CRETACEOUS TO EARLY TERTIARY LARAMIE AND DENVER FORMATIONS, DENVER BASIN, COLORADO

Laura Wray and Nicole Koenig
Colorado Geological Survey
Denver, Colorado

Coals in the Late Cretaceous Laramie Formation and Early Tertiary Denver Formation hold some intrigue for coalbed methane potential by virtue of their measured gas contents and heating values, shallow depths, and areas of reasonable thickness and continuity.

Over the past 140 years, more than 300 historic mines were developed in the Denver Basin. The vast majority of them were underground mines in the Laramie Formation coals from which approximately 130 million tons of subbituminous coal was mined. Now that newly developed completion technologies are allowing commercial production from shallow, low rank coals, even the Denver Formation lignitic coals may be prospective.

The great diversity in coalbed methane plays proves that there are various reservoir characteristics critical to the successful methane production from low rank coals. Preliminary analyses of coal data collected by mining companies, combined with data collected from gas, oil, and water wells drilled in the Denver Basin, strongly suggests that further research and testing is required to demonstrate the economic feasibility of a coalbed methane play in the basin. In the meantime, the Colorado Geological Survey has compiled a GIS coalbed methane database that captures the data contained in numerous hardcopy publications released over the past twenty years. The GIS ArcView ™ format allows easy manipulation of important data such as isopach and structure maps, log cross sections, desorbtion and heating value data, locations of historic mines, coal analyses from those mines, and calculated gas content values.

Careful consideration must be paid to the shallow aquifers which surround these coals and into which thousands of water wells have been drilled. Regulatory and environmental factors will play vital roles in determining the producing potential for coalbed methane wells.

APPENDIX D — ESTIMATION OF ORIGINAL GAS IN PLACE IN DENVER BASIN COALS

John Seidle
Sproule Associates, Inc.

Abstract

Coalbed methane potential of the Denver Basin has long been neglected because the coals were judged to be too thin, too shallow, and too immature to support commercial gas production. With the success of the Powder River Basin coalbed methane play, which has coals of similar rank and depth, this study was undertaken to quantify the gas held by Denver Basin coals by volumetric means. Powder River Basin coals were used as an analog because coals in both basins are generally shallow, Cretaceous to Paleocene in age, subbituminous in rank, and roughly the same temperature.

Coals of the Powder River Basin contain both sorbed and free gas. The sorbed gas contribution is calculated with a sorption isotherm and reservoir pressure, while the free gas component is calculated from conventional gas reservoir engineering principles. This study considered both sorbed and free gas contributions.

The average Bureau of Land Management (BLM) isotherm for Powder River coals published by Crockett and Meier (ref 2) was used to estimate gas content. Analogous to Powder River coals, coalbed density was assumed to be 1.35 grams/cubic centimeters (gm/cc). Sorbed gas was calculated as the product of area, coal thickness, coal density, and gas content. Coal porosity was assumed to be 10 percent and gas formation volume factors were calculated assuming the gas to be pure methane.

This study determined that coals of the Denver Formation hold 704 billion cubic feet of gas (bcf) and those of the Laramie Formation contain 1539 bcf, for a total of 2243 bcf. The total Denver Basin coalbed methane resource is therefore estimated to be 2.24 trillion cubic feet of gas (tcf) with approximately two-thirds of the gas held in the Laramie formation coals and one-third in the Denver formation coals.

Introduction

Coalbed methane potential of the Denver Basin has long been neglected because the coals were judged to be too thin, too shallow, and too immature to support commercial gas production. However, with the success of the Powder River Basin coalbed methane play, which has coals of similar rank and depth, this study was undertaken to quantify the gas held by Denver Basin coals by volumetric means. Because of the coarse nature of the data, this study focussed on gas held in the coals of Denver and Laramie Formations, not specific seams, and calculated gas volumes on a township by township basis. Powder River Basin coals were used as an analog because coals in both basins are generally shallow, Cretaceous to Paleocene in age, subbituminous in rank, and roughly the same temperature. Coals of the Powder River Basin contain both sorbed and free gas. The sorbed gas contribution is calculated with a sorption isotherm and reservoir pressure while the free gas component is calculated from conventional gas reservoir engineering principles. This study considered both sorbed and free gas contributions.

Sorbed Gas

Very few gas contents have been reported for coals of the Denver Basin. The ten desorption tests from this basin reported by Tremain and Toomey (ref 1) are collected in Table 1. The majority of the tests suffered from extremely large percentages of lost gas and note that all gas contents are reported in uncorrected cubic feet per ton rather

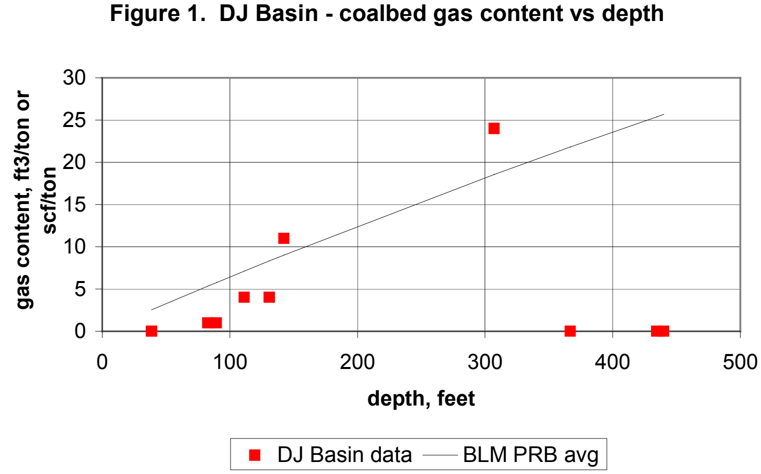
Table 1: Reported Denver Basin coalbed gas contents (Tremain and Toomey)

sample id	well name	sample depth top, feet	bottom, feet	midpay, feet	gas content, ft3/ton	btu/lb ar	btu/lb daf	%Ro	gas content, scf/ton
196	Marshal # 2	37.5	40	39	0	na	na	na	2.5
197	Marshal # 2	81.4	84.4	83	1	na	na	0.42	5.3
198	Marshal # 2	88	91	90	1	na	na	0.42	5.8
161	4C	109	114	112	4	7417	12321	0.37	7.1
121	Biosphere #1	127	135	131	4	5636	11621	na	8.3
122	Biosphere #1	140.25	144.6	142	11	5102	11865	na	9.0
162	5C	306.3	308	307	24	7971	12377	na	18.6
163	5C	362.5	371	367	0	8377	12484	na	21.8
164	10C	434.3	434.9	435	0	7316	12421	0.35	25.4
165	10C	435	445	440	0	7441	12485	0.42	25.7

than standard cubic feet/ton (scf/ton). Three of the tests reported no gas at all. Insufficient details were recorded to determine whether these coals were actually devoid of gas or experimental problems precluded measurement of desorbed gas.

The Powder River Basin coals were used as an analog for this study of Denver Basin coals. Coals in both basins are generally shallow, Cretaceous to Paleocene in age, subbituminous in rank, and roughly the same temperature. Gas content was estimated using the average BLM isotherm for Powder River coals published by Crockett and Meier (ref 2). Figure 1 contains both the Powder River isotherm of Crockett and Meier and the desorption data of Tremain and Toomey. Although the isotherm gas contents are in scf/ton and those of the desorption data are in uncorrected cubic feet per ton, agreement between the two was sufficient to use the BLM isotherm for this study. This study assumed the Denver Basin was slightly underpressured with a gradient of 0.4 psi/ft. Reservoir pressure was calculated from overburden depth (ref 3-6).

Figure 1. DJ Basin - coalbed gas content vs depth



Coal thicknesses in the Denver and Laramie Formations was taken from recent maps by Wray and Koenig (ref 7). Analogous to Powder River coals, coalbed density was assumed to be 1.35 gm/cc.

Sorbed gas was calculated as the product of area, coal thickness, coal density, and gas content.

Free gas

The open structure of subbituminous coals allows the pores and cleats to hold substantial free gas. Porosities of Powder River coals reported by Bustin (ref 8) range from 10 to 15 percent. For this study, coal porosity was assumed to be 10 percent. No gas saturations of Powder River coals have been reported, but rough calculations based on initial well production data indicate gas saturations of 10 percent are not unreasonable. Gas formation volume factors were calculated assuming the gas to be pure methane. Free gas is the product of area, thickness, porosity, and gas saturation divided by formation volume factor.

Original-Gas-In-Place

Gas volumes held by coals of the Denver and Laramie Formations of Denver Basin coals were estimated on a township by township basis. Maximum gas volumes for the Denver formation coals occurred in T6S R64W, T7S R64-66W, and T10S R64W. Original-Gas-In-Place (OGIP) volumes for Denver Formation coals are mapped in Figure 2. Maximum gas volumes for the Laramie Formation coals occurred in T8-10S R66W and T11-12S R64W. OGIP of the Laramie coals is mapped in Figure 3. Maximum total gas volumes are located in T7S R64-65W, T8S R65-66W, and T10S R64W. Denver and Laramie OGIP's were summed for the total OGIP map presented in Figure 4.

Based on this study, coals of the Denver Formation hold 704 bcf and those of the Laramie Formation contain 1539 bcf, for a total of 2243 bcf. Note that the deeper, thicker coals of the Laramie formation hold roughly two-thirds of the DENVER coalbed methane resource.

Summary and Conclusions

Coalbed methane resource potential of the Denver Basin coals was estimated using publicly available overburden and isopach data coupled with isotherms and porosities of Powder River Basin coals. Original-Gas-In-Place (OGIP) was calculated on a township by township basis for both the Denver and Laramie formation coals.

The Denver Basin coalbed methane resource was estimated to be 2.24 tcf with approximately two-thirds of the gas held in the Laramie formation coals and one-third in the Denver Formation coals.

Future Work

- Additional Denver Basin coalbed gas contents should be measured. Drill cuttings and/or sidewall cores could be collected and desorbed from wells drilling to deeper targets. Whole cores could be taken from dedicated coreholes and coal wells. All samples should be desorbed at reservoir temperature and data analyzed with current protocols.
- Updated overburden and coal isopach maps should be constructed incorporating new data.
- Porosities of Denver Basin coals should be measured in the laboratory.

- This study estimated the gas resource held by coals of the Denver and Laramie Formations in the Denver Basin. Commercial exploitation of this resource requires knowledge of coal permeability. Laboratory determination of coal permeability is problematic. Future coal evaluation efforts in this basin should include permeability tests such as diagnostic pump-ins, injection/falloff tests, or drawdown/buildups.

Acknowledgements

The assistance and encouragement of Laura Wray and Nicole Koenig throughout this project is gratefully acknowledged.

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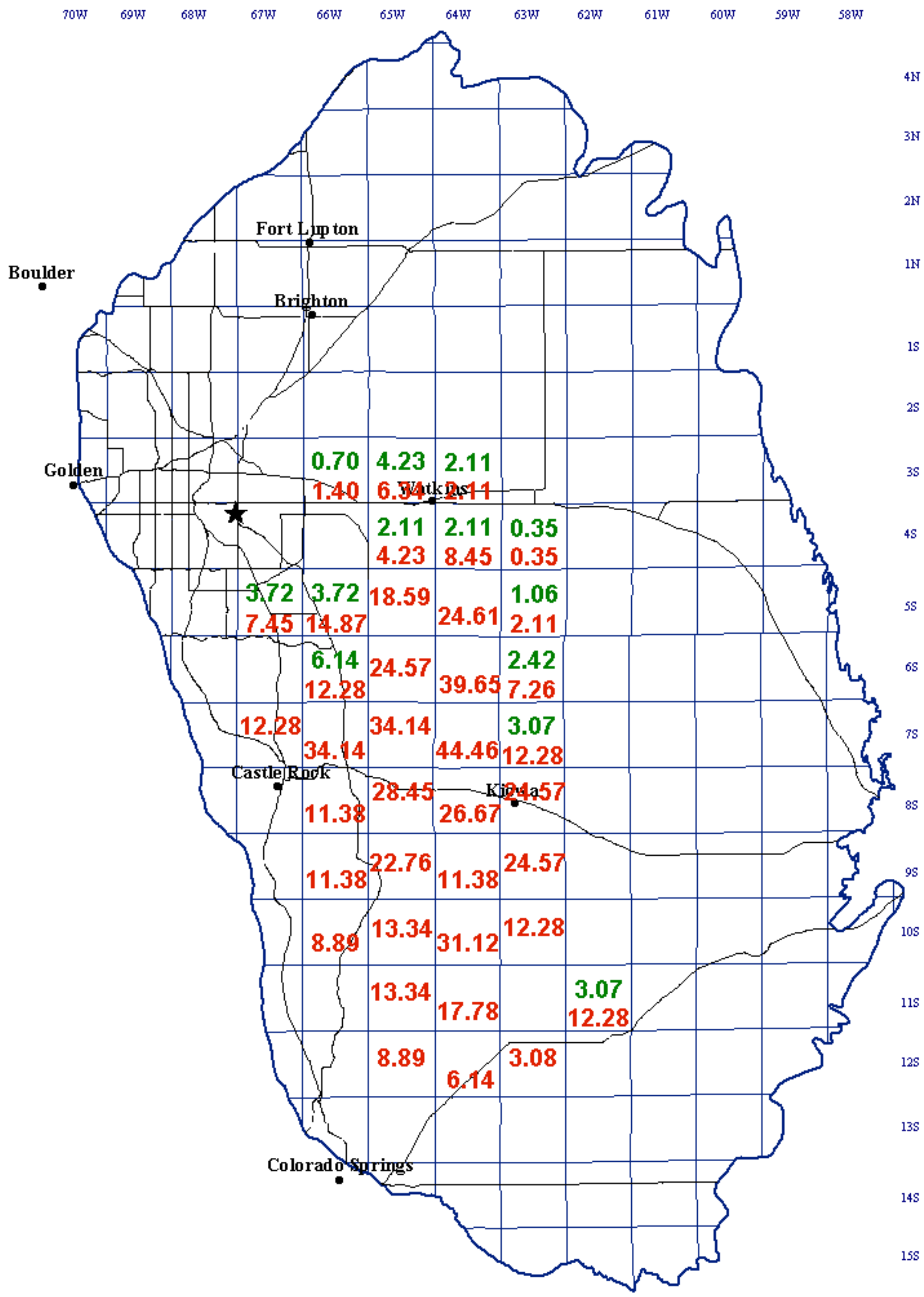


Figure 2: Original-Gas-In-Place (OGIP) for Denver Formation coals in the Denver Basin, Colorado. Green values are from a map with a high value of 50 feet for total Denver Formation cal thickness. Red values are from a map with a high value of 60 feet for total Denver Formation coal thickness.

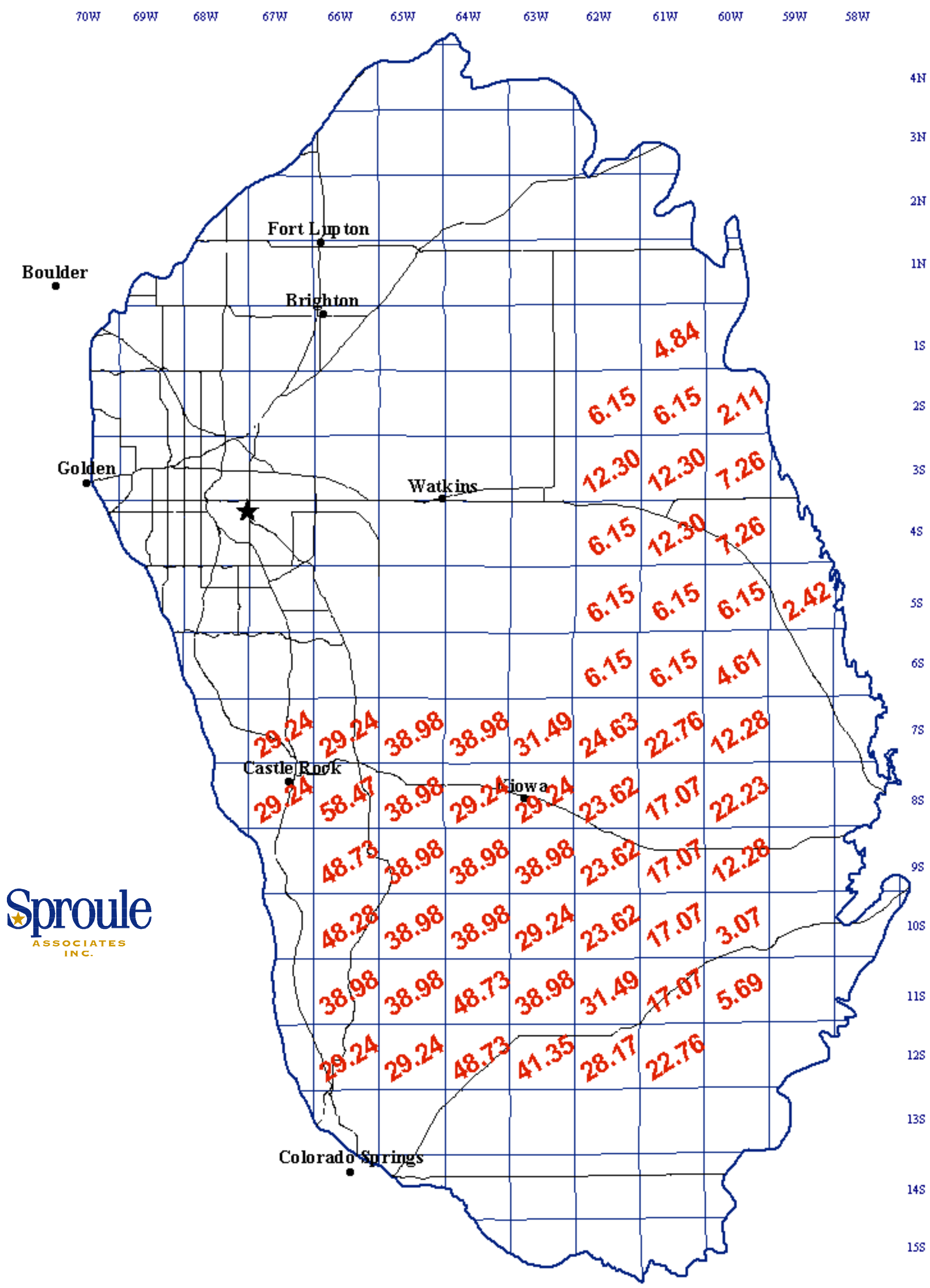


Figure 3: Original-Gas-In-Place (OGIP) for Laramie Formation coals in the Denver Basin, Colorado.

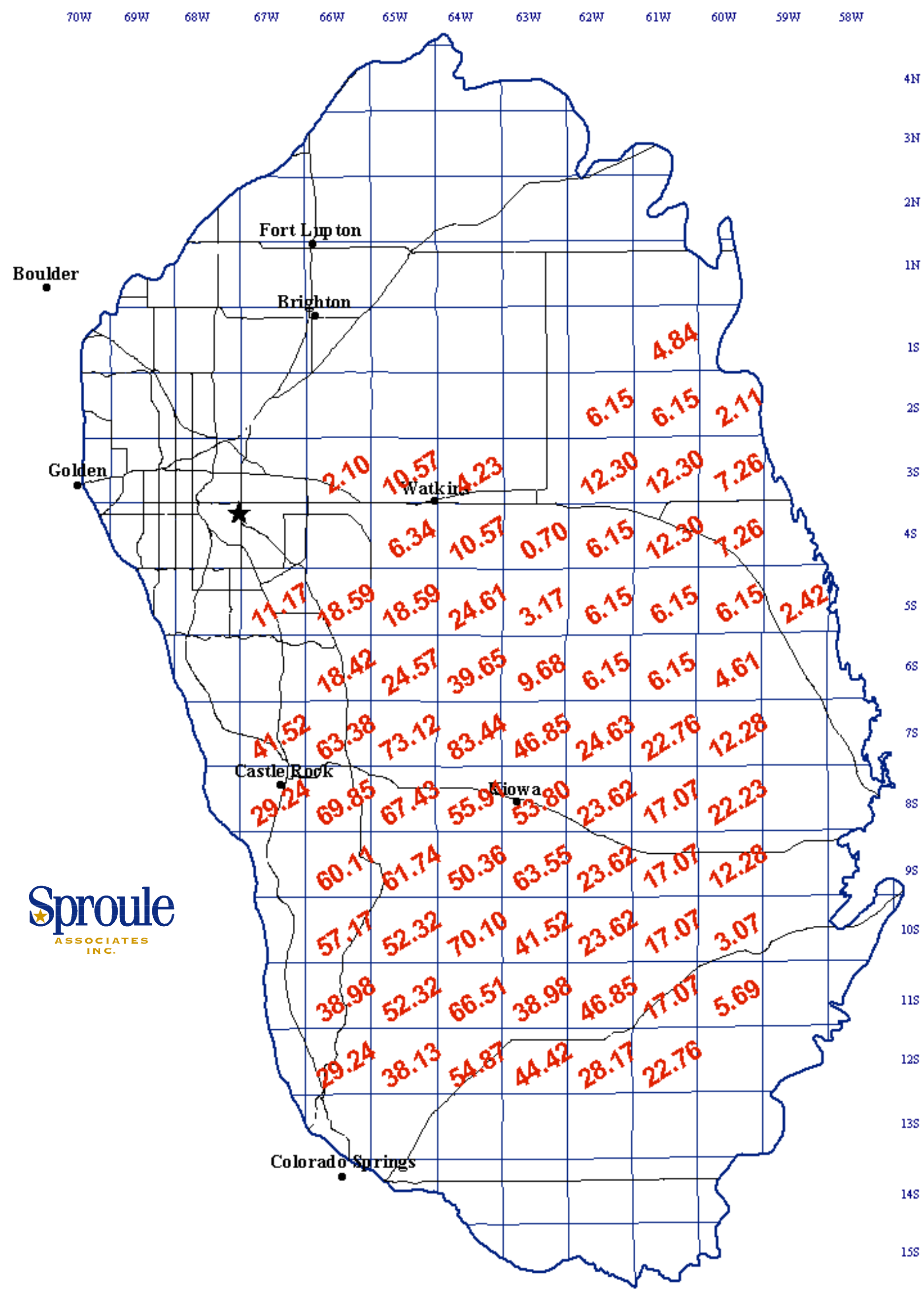
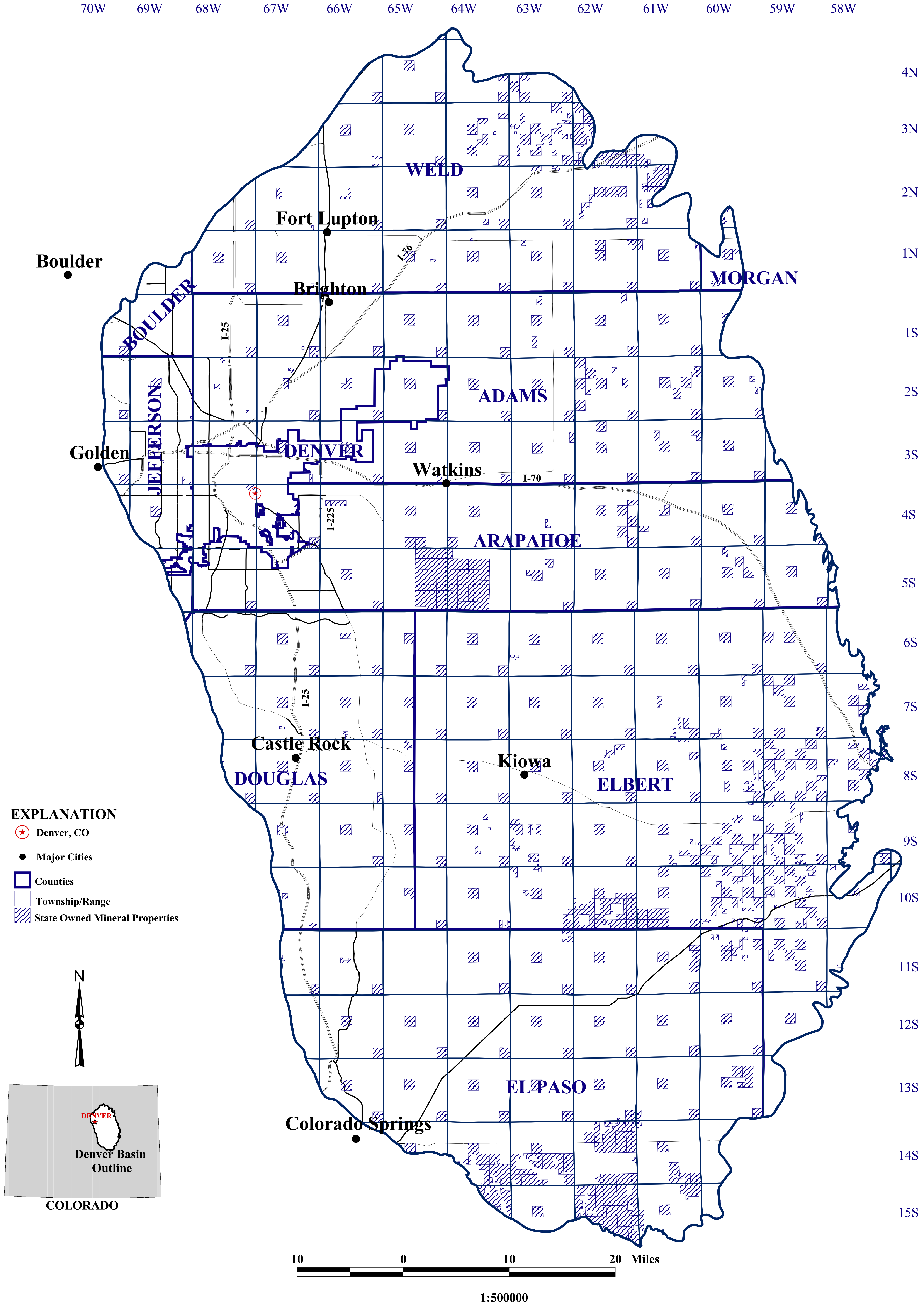


Figure 4: Total Original-Gas-In-Place (OGIP) for Denver Formation and Laramie coals in the Denver Basin, Colorado.

Location map for the Denver Basin, Colorado

Compiled by Nicole V. Koenig



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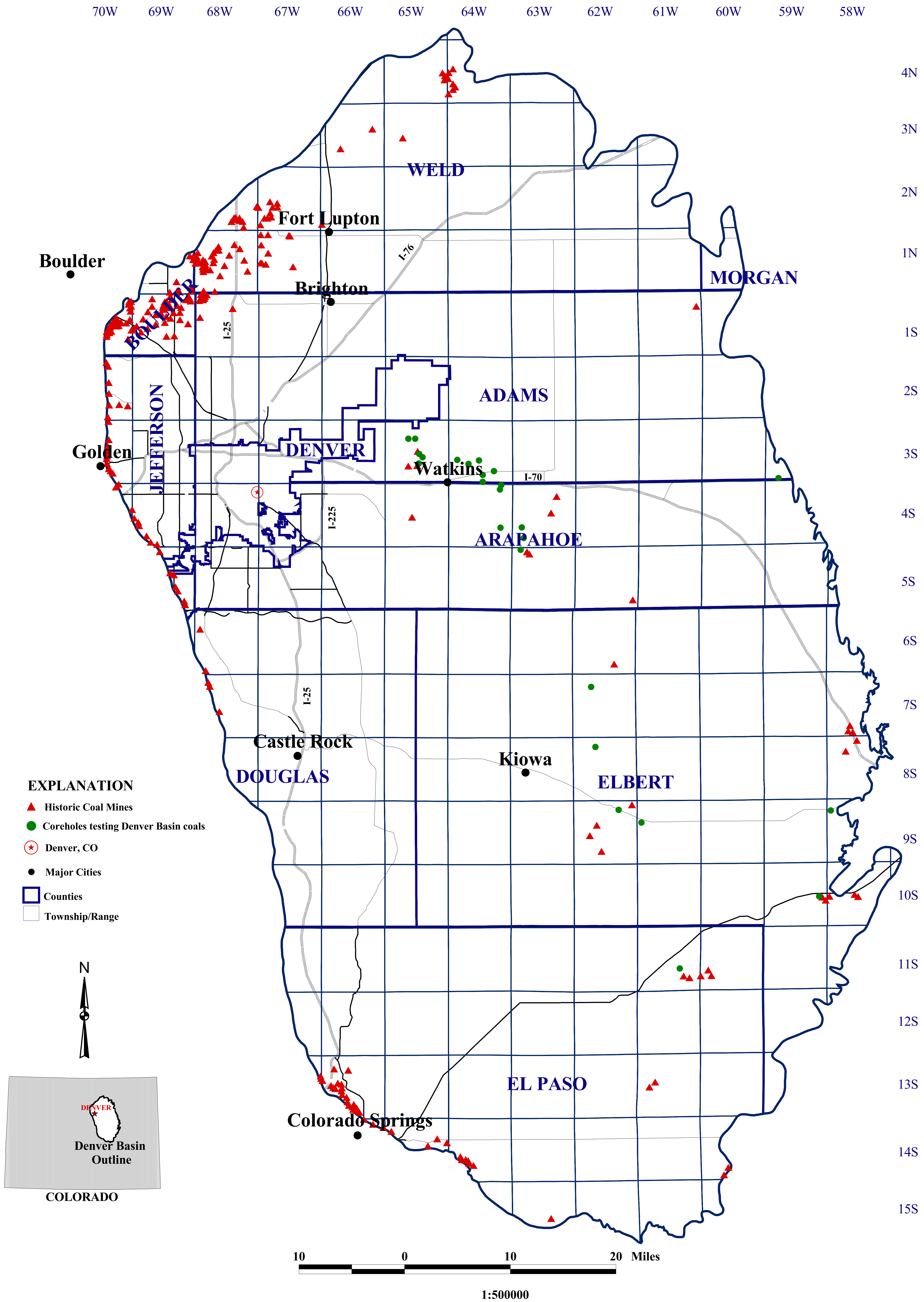
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 2
2001

Locations of Historic Coal Mines and Coreholes in the Denver Basin, Colorado

Compiled by Nicole V. Koenig



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OPEN-FILE REPORT 01-17
PLATE 3
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CGS wells drilled in the Denver Basin with the locations of cross section D-D' and L-L'

Compiled by Nicole V. Koenig

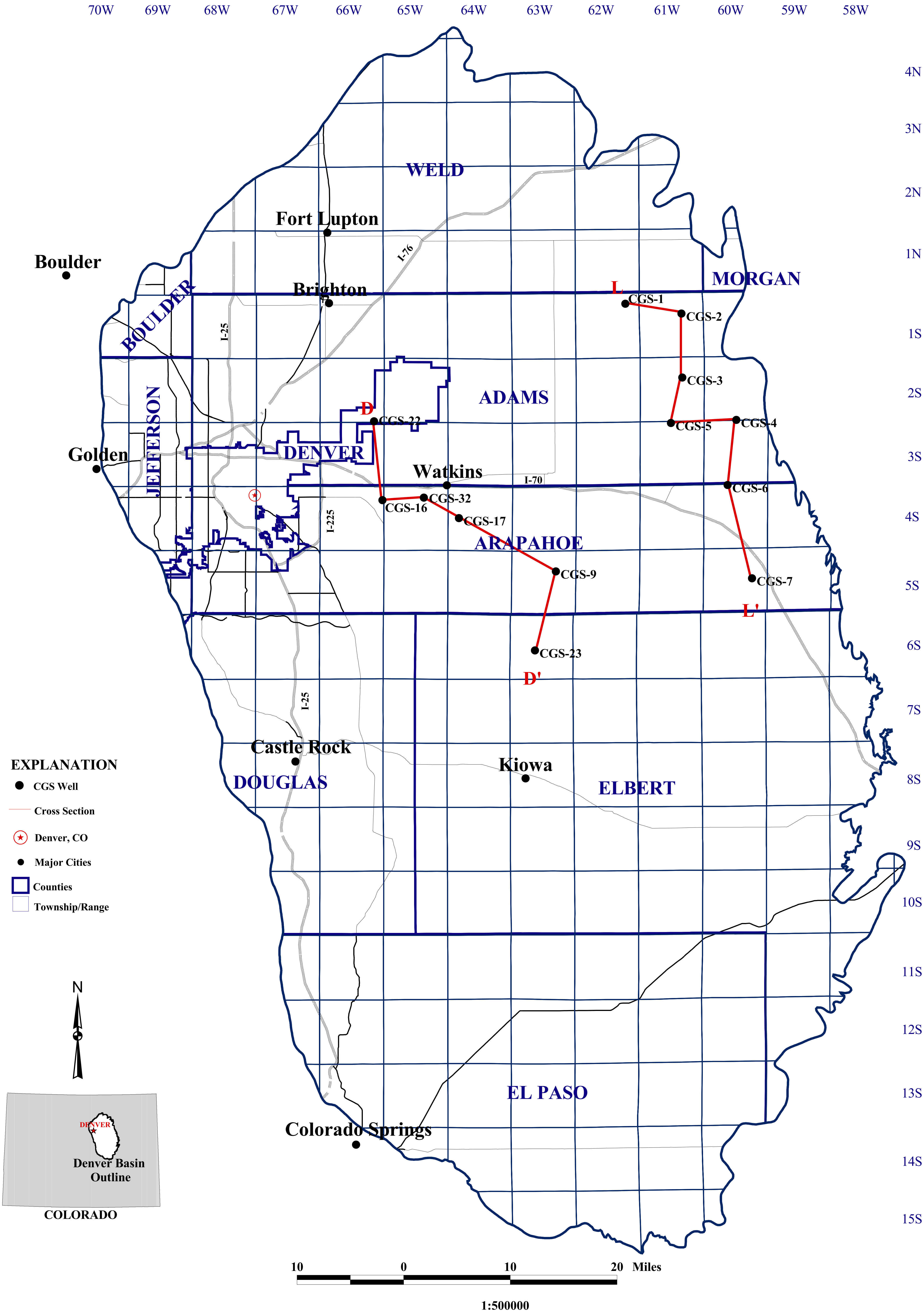

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PLATE 4
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Total thickness of all known Denver Formation coals

Compiled by Nicole V. Koenig

CORE DATA

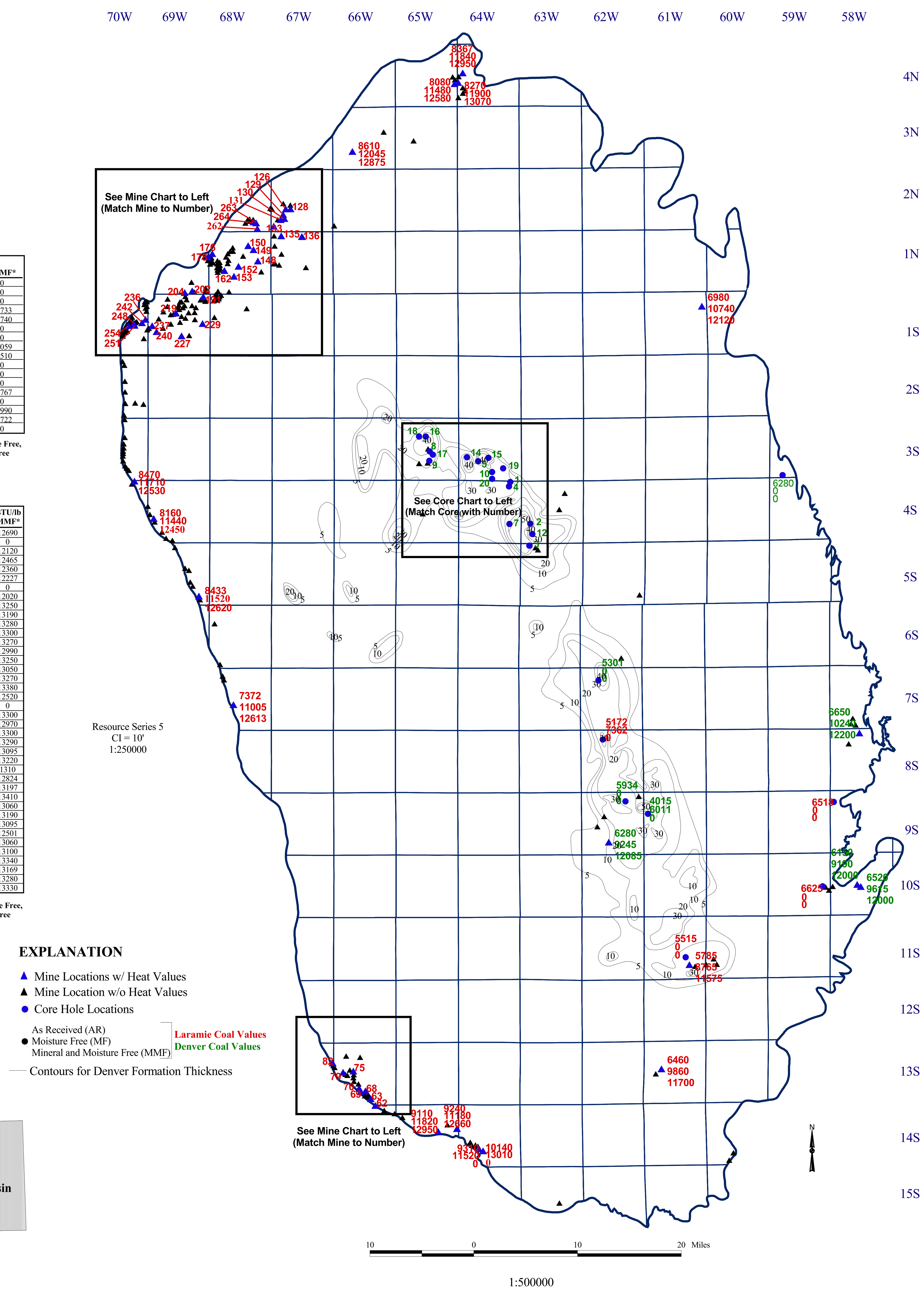
Core Number	AR*	BTU/lb MF*	MMF*
1	4680	6521	0
2	5967	7912	0
3	4802	0	0
4	5748	8317	12733
5	7694	8943	12740
7	4555	0	0
8	7148	9990	0
9	5914	0	12059
10	6375	0	12510
12	6217	0	0
14	5720	11917	0
15	6617	8920	0
16	6931	0	12767
17	5038	7296	0
18	6820	0	12990
19	6590	0	12722
20	4821	0	0

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free

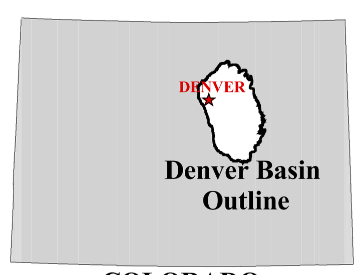
MINE DATA

Mine	Mine Number	BTU/lb AR*	BTU/lb MF*	BTU/lb MMF*
62	172	8730	11740	12690
63	192	8640	10790	0
68	159	8910	11270	12120
69	149	8658	11130	12465
70	145	8535	11480	12360
75	188	8419	11330	12227
79	182	8500	10930	0
82	179	8740	10950	12020
126	279	9235	12470	13250
128	305	9147	12350	13190
129	274	9745	12350	13280
130	312	9180	13240	13300
131	272	9500	12570	13270
133	253	9265	12300	12990
135	308	9276	12450	13250
136	316	8919	12010	13050
148	265	9670	12505	13270
149	282	9678	12620	13380
150	291	9231	11432	12520
152	293	9785	0	0
153	261	9820	12580	13300
162	285	9550	12390	12970
176	14	9483	12460	13300
178	112	9823	12410	13290
191	103	10037	12560	13095
202	21	9788	12470	13220
204	93	9790	12310	1310
219	11	9589	12033	12824
227	76	10106	12397	13197
229	50	10004	13160	13410
236	34	10123	12400	13060
234	98	10010	12430	13190
240	52	9967	12295	13095
242	75	9857	11998	12501
248	100	9913	12220	13060
251	46	9968	12420	13100
254	54	10243	12560	13340
262	303	9547	12525	13169
263	306	9390	12470	13280
264	292	9740	12660	13330

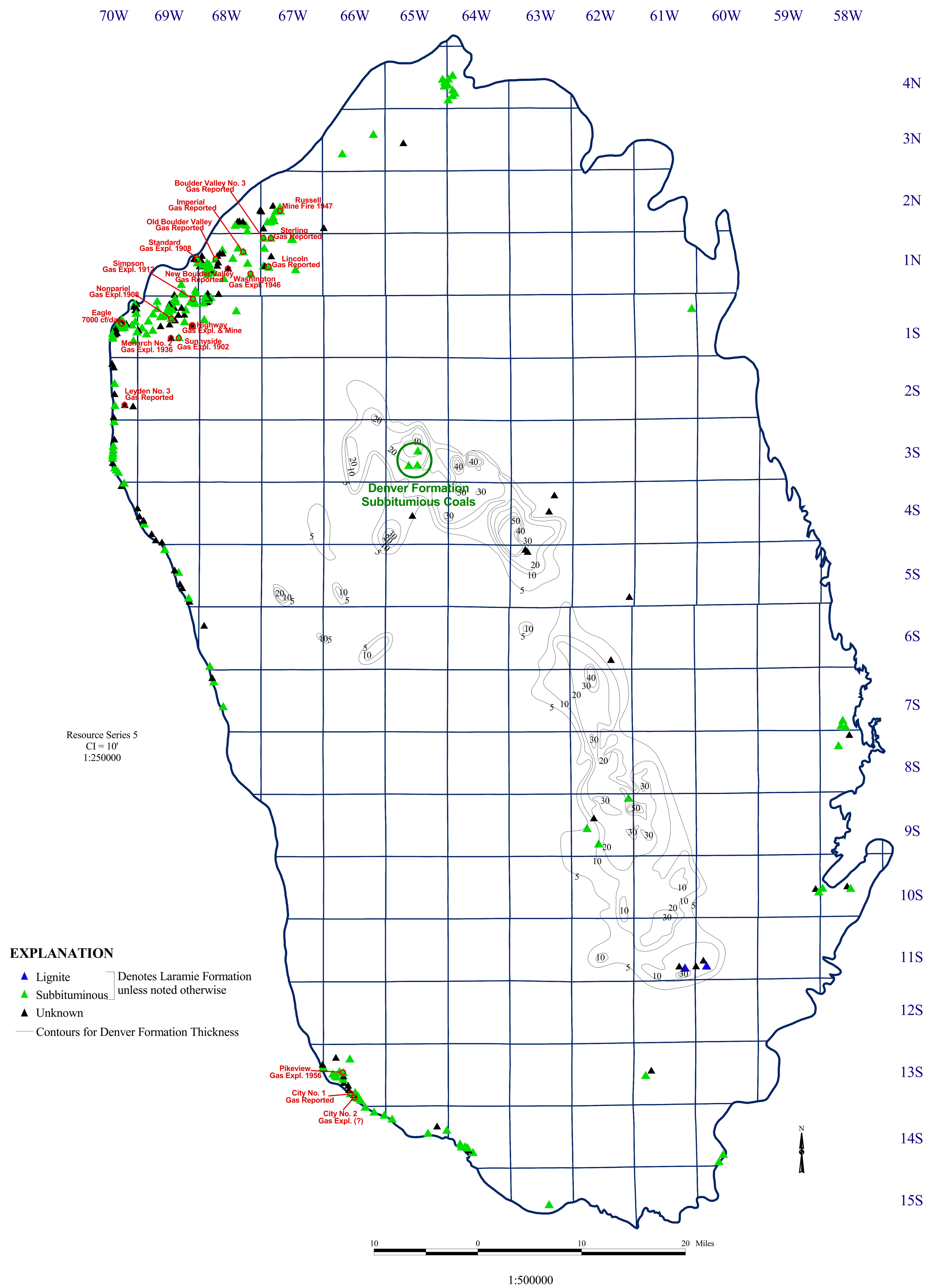
*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free



MAP A: Heat Values



COLORADO



MAP B: Coal Rank and Gas Reported

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 5
2001

Total thickness of all known Denver Formation coals

Compiled by Nicole V. Koenig

CORE DATA

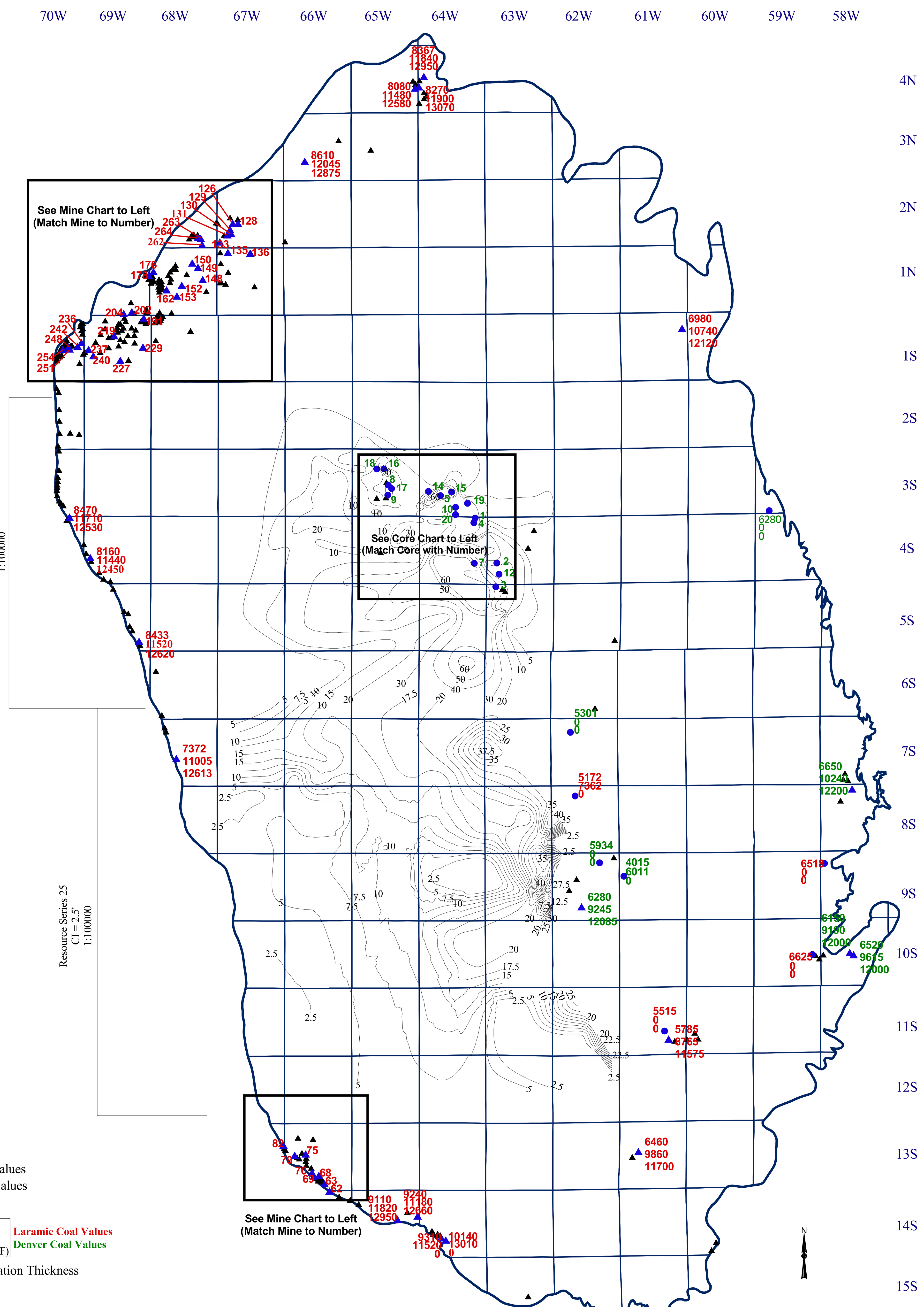
Core Number	AR*	BTU/lb MF*	MMF*
1	4680	6521	0
2	5967	7912	0
3	4802	0	0
4	5748	8317	12733
5	7694	8943	12740
7	4555	0	0
8	7148	9990	0
9	5914	0	12059
10	6375	0	12510
12	6217	0	0
14	5720	11917	0
15	6617	8920	0
16	6931	0	12767
17	5038	7296	0
18	6820	0	12990
19	6590	0	12722
20	4821	0	0

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free

MINE DATA

Mine	Mine Number	BTU/lb AR*	BTU/lb MF*	BTU/lb MMF*
62	172	8730	11740	12690
63	192	8640	10790	0
68	159	8910	11270	12120
69	149	8658	11130	12465
70	145	8535	11480	12360
75	188	8419	11330	12227
79	182	8500	10930	0
82	179	8740	10950	12020
126	279	9235	12470	13250
128	305	9147	12350	13190
129	274	9745	12350	13280
130	312	9180	13240	13300
131	272	9500	12570	13270
133	253	9265	12300	12990
135	308	9276	12450	13250
136	316	8919	12010	13050
148	265	9670	12505	13270
149	282	9678	12620	13380
150	291	9231	11432	12520
152	293	9785	0	0
153	261	9820	12580	13300
162	285	9550	12390	12970
176	14	9483	12460	13300
178	112	9823	12410	13290
191	103	10037	12560	13095
202	21	9788	12470	13220
204	93	9790	12310	1310
219	11	9589	12033	12824
227	76	10106	12397	13197
229	50	10004	13160	13410
236	34	10123	12400	13060
234	98	10010	12430	13190
240	52	9967	12295	13095
242	75	9857	11998	12501
248	100	9913	12220	13060
251	46	9968	12420	13100
254	54	10243	12560	13340
262	303	9547	12525	13169
263	306	9390	12470	13280
264	292	9740	12660	13330

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free



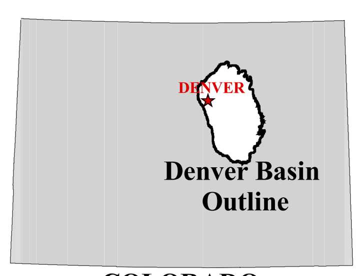
EXPLANATION

- Mine Locations w/ Heat Values
- Mine Location w/o Heat Values
- Core Hole Locations

As Received (AR)
Moisture Free (MF)
Mineral and Moisture Free (MMF)

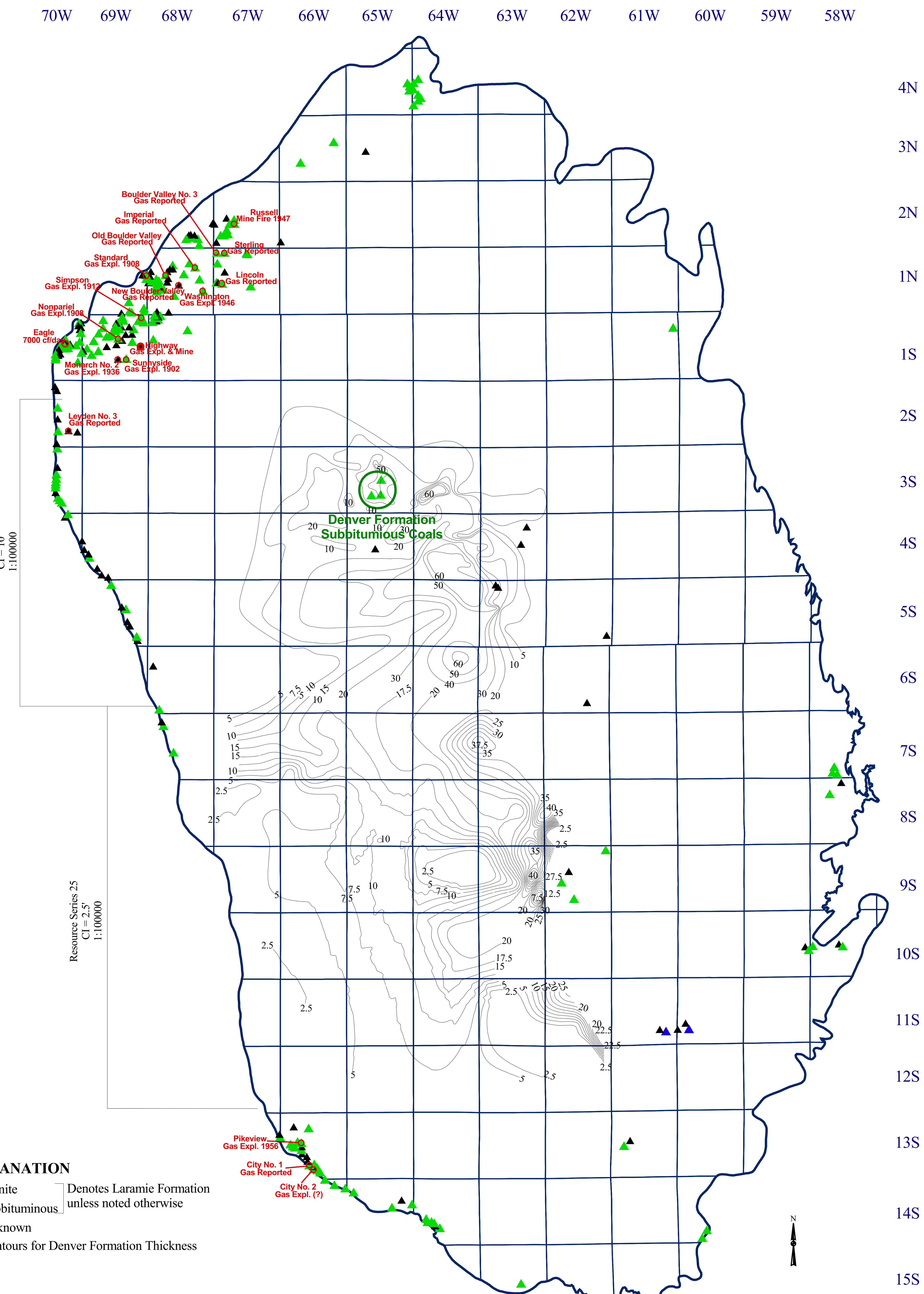
Laramie Coal Values
Denver Coal Values

Contours for Denver Formation Thickness



COLORADO

MAP A: Heat Values



EXPLANATION

- Lignite
- Subbituminous
- Unknown

Denotes Laramie Formation unless noted otherwise

Contours for Denver Formation Thickness

MAP B: Coal Rank and Gas Reported

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 6
2001

Structure on top of the Denver Formation

Compiled by Nicole V. Koenig

CORE DATA

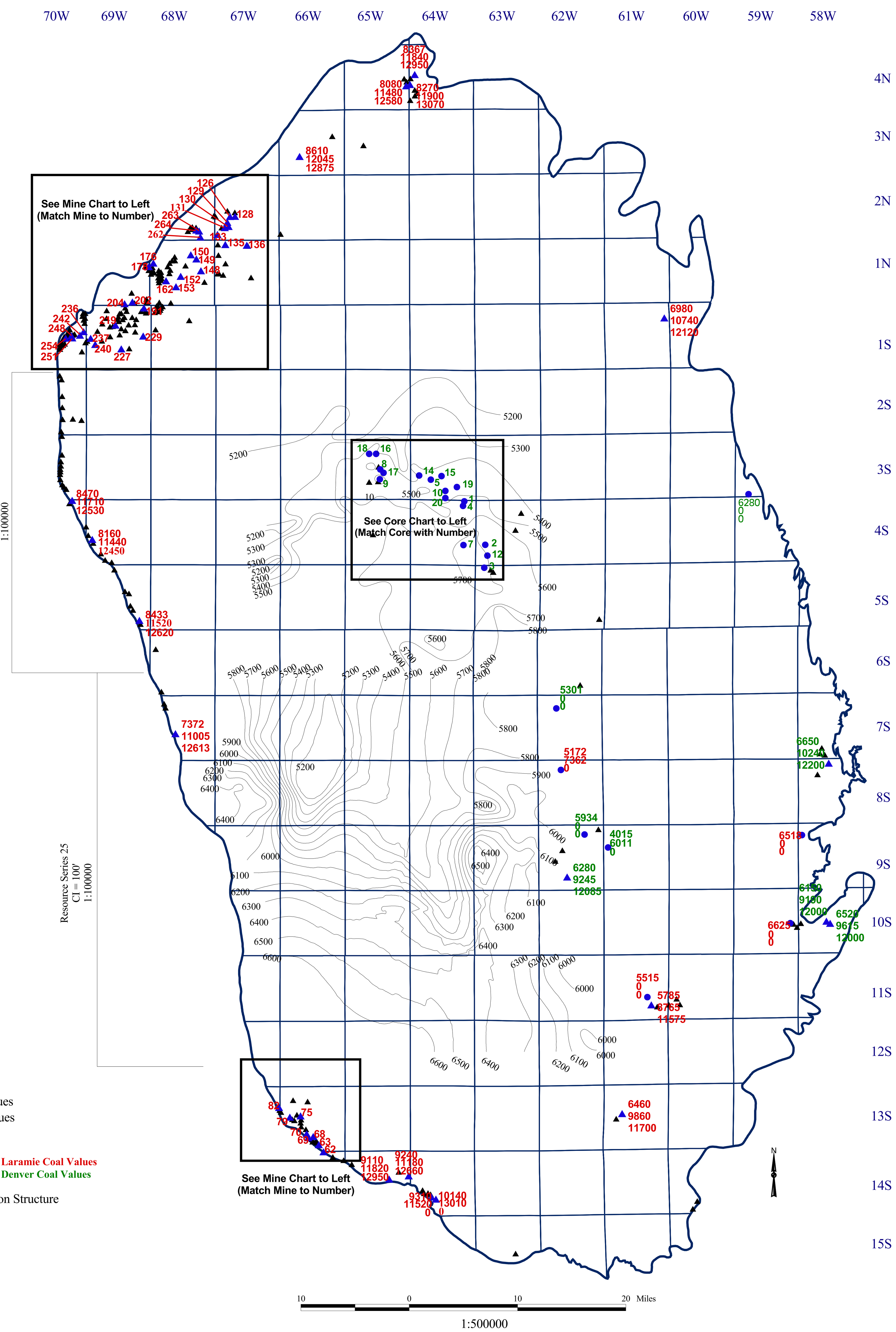
Core Number	AR*	BTU/lb MF*	MMF*
1	4680	6521	0
2	5967	7912	0
3	4802	0	0
4	5748	8317	12733
5	7694	8943	12740
7	4555	0	0
8	7148	9990	0
9	5914	0	12059
10	6375	0	12510
12	6217	0	0
14	5720	11917	0
15	6617	8920	0
16	6931	0	12767
17	5038	7296	0
18	6820	0	12990
19	6590	0	12722
20	4821	0	0

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free

MINE DATA

Mine	Mine Number	BTU/lb AR*	BTU/lb MF*	BTU/lb MMF*
62	172	8730	11740	12690
63	192	8640	10790	0
68	159	8910	11270	12120
69	149	8658	11130	12465
70	145	8535	11480	12360
75	188	8419	11330	12227
79	182	8500	10930	0
82	179	8740	10950	12020
126	279	9235	12470	13250
128	305	9147	12350	13190
129	274	9745	12350	13280
130	312	9180	13240	13300
131	272	9500	12570	13270
133	253	9265	12300	12990
135	308	9276	12450	13250
136	316	8919	12010	13050
148	265	9670	12505	13270
149	282	9678	12620	13380
150	291	9231	11432	12520
152	293	9785	0	0
153	261	9820	12580	13300
162	285	9550	12390	12970
176	14	9483	12460	13300
178	112	9823	12410	13290
191	103	10037	12560	13095
202	21	9788	12470	13220
204	93	9790	12310	1310
219	11	9589	12033	12824
227	76	10106	12397	13197
229	50	10004	13160	13410
236	34	10123	12400	13060
234	98	10010	12430	13190
240	52	9967	12295	13095
242	75	9857	11998	12501
248	100	9913	12220	13060
251	46	9968	12420	13100
254	54	10243	12560	13340
262	303	9547	12525	13169
263	306	9390	12470	13280
264	292	9740	12660	13330

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free



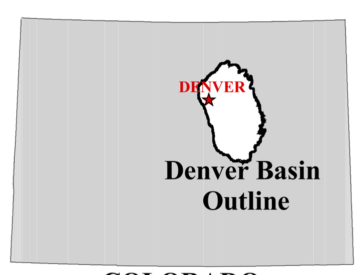
MAP A: Heat Values

EXPLANATION

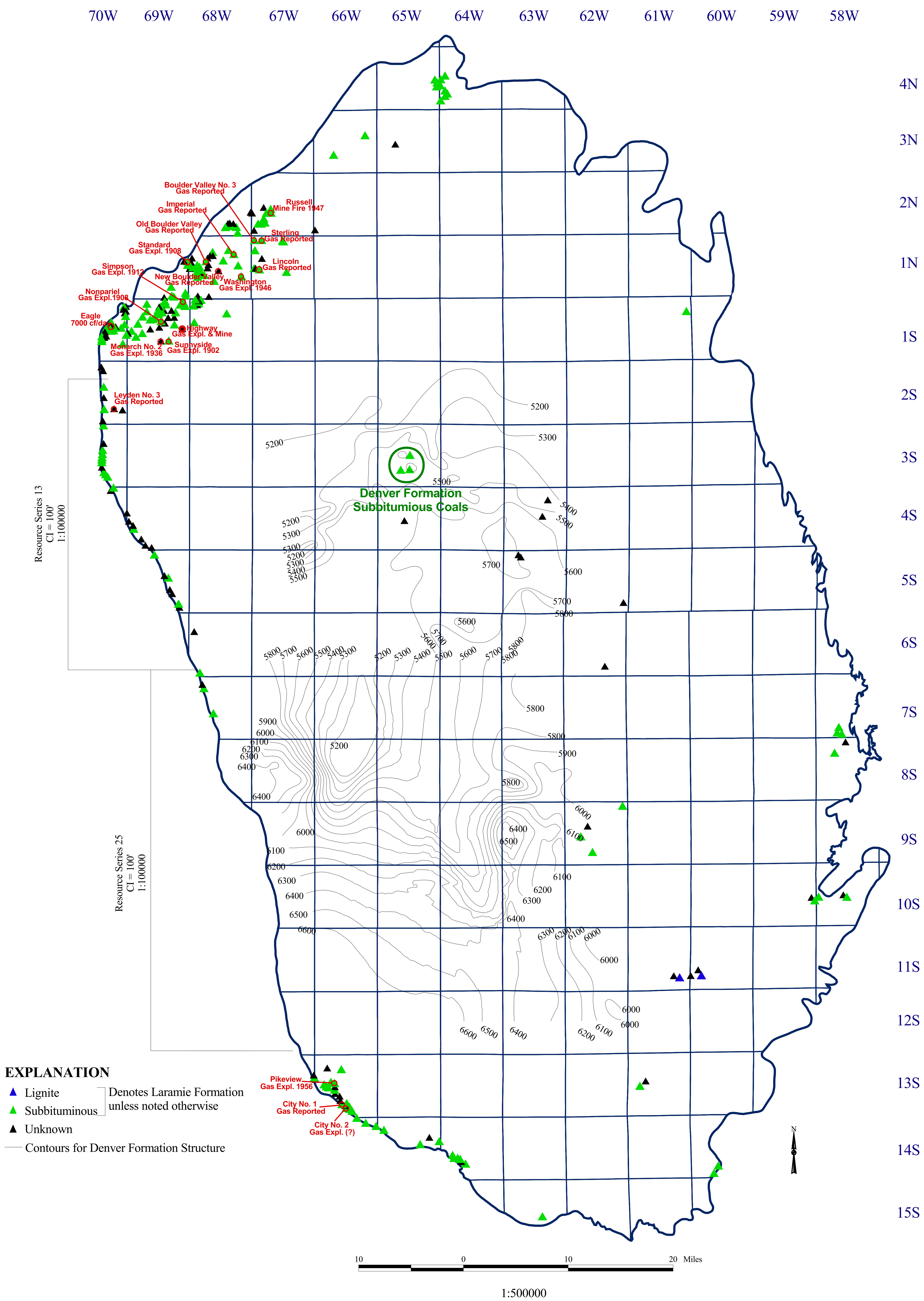
- Mine Locations w/ Heat Values
- Mine Location w/o Heat Values
- Core Hole Locations

As Received (AR)
Moisture Free (MF)
Mineral and Moisture Free (MMF)
Laramie Coal Values
Denver Coal Values

Contours for Denver Formation Structure



COLORADO



EXPLANATION

- Lignite
- Subbituminous
- Unknown

Denotes Laramie Formation unless noted otherwise

Contours for Denver Formation Structure

MAP B: Coal Rank and Gas Reported

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 7
2001

Structure contours on top of the Laramie Formation

Compiled by Nicole V. Koenig

CORE DATA

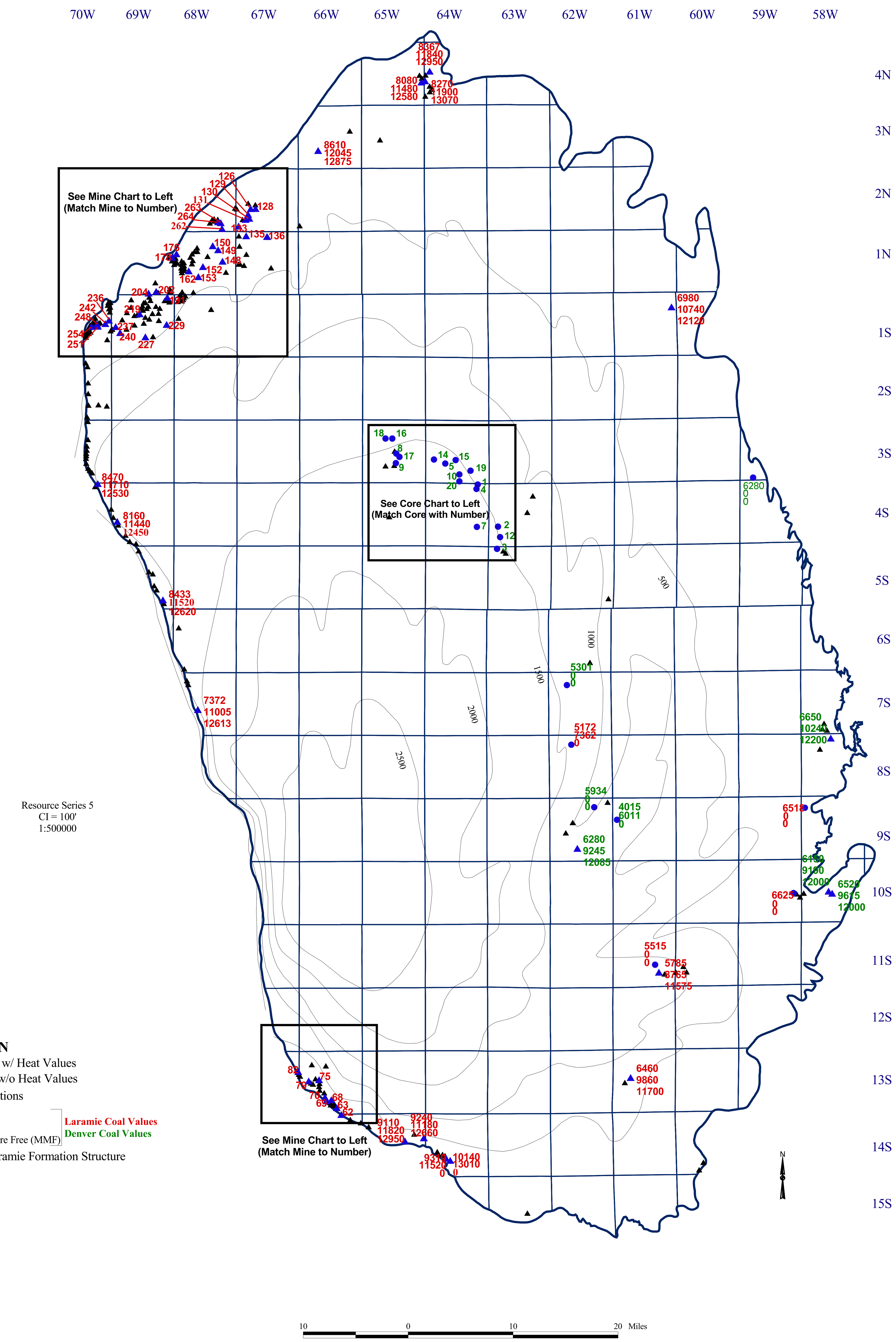
Core Number	AR*	BTU/lb MF*	MMF*
1	4680	6521	0
2	5967	7912	0
3	4802	0	0
4	5748	8317	12733
5	7694	8943	12740
7	4555	0	0
8	7148	9990	0
9	5914	0	12059
10	6375	0	12510
12	6217	0	0
14	5720	11917	0
15	6617	8920	0
16	6931	0	12767
17	5038	7296	0
18	6820	0	12990
19	6590	0	12722
20	4821	0	0

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free

MINE DATA

Mine	Mine Number	BTU/lb AR*	BTU/lb MF*	BTU/lb MMF*
62	172	8730	11740	12690
63	192	8640	10790	0
68	159	8910	11270	12120
69	149	8658	11130	12465
70	145	8535	11480	12360
75	188	8419	11330	12227
79	182	8500	10930	0
82	179	8740	10950	12020
126	279	9235	12470	13250
128	305	9147	12350	13190
129	274	9745	12350	13280
130	312	9180	13240	13300
131	272	9500	12570	13270
133	253	9265	12300	12990
135	308	9276	12450	13250
136	316	8919	12010	13050
148	265	9670	12505	13270
149	282	9678	12620	13380
150	291	9231	11432	12520
152	293	9785	0	0
153	261	9820	12580	13300
162	285	9550	12390	12970
176	14	9483	12460	13300
178	112	9823	12410	13290
191	103	10037	12560	13095
202	21	9788	12470	13220
204	93	9790	12310	1310
219	11	9589	12033	12824
227	76	10106	12397	13197
229	50	10004	13160	13410
236	34	10123	12400	13060
234	98	10010	12430	13190
240	52	9967	12295	13095
242	75	9857	11998	12501
248	100	9913	12220	13060
251	46	9968	12420	13100
254	54	10243	12560	13340
262	303	9547	12525	13169
263	306	9390	12470	13280
264	292	9740	12660	13330

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free



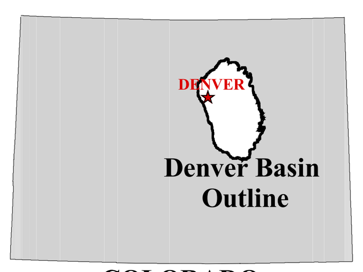
EXPLANATION

- Mine Locations w/ Heat Values
- Mine Location w/o Heat Values
- Core Hole Locations

As Received (AR)
Moisture Free (MF)
Mineral and Moisture Free (MMF)

Laramie Coal Values
Denver Coal Values

Contours for Laramie Formation Structure



COLORADO

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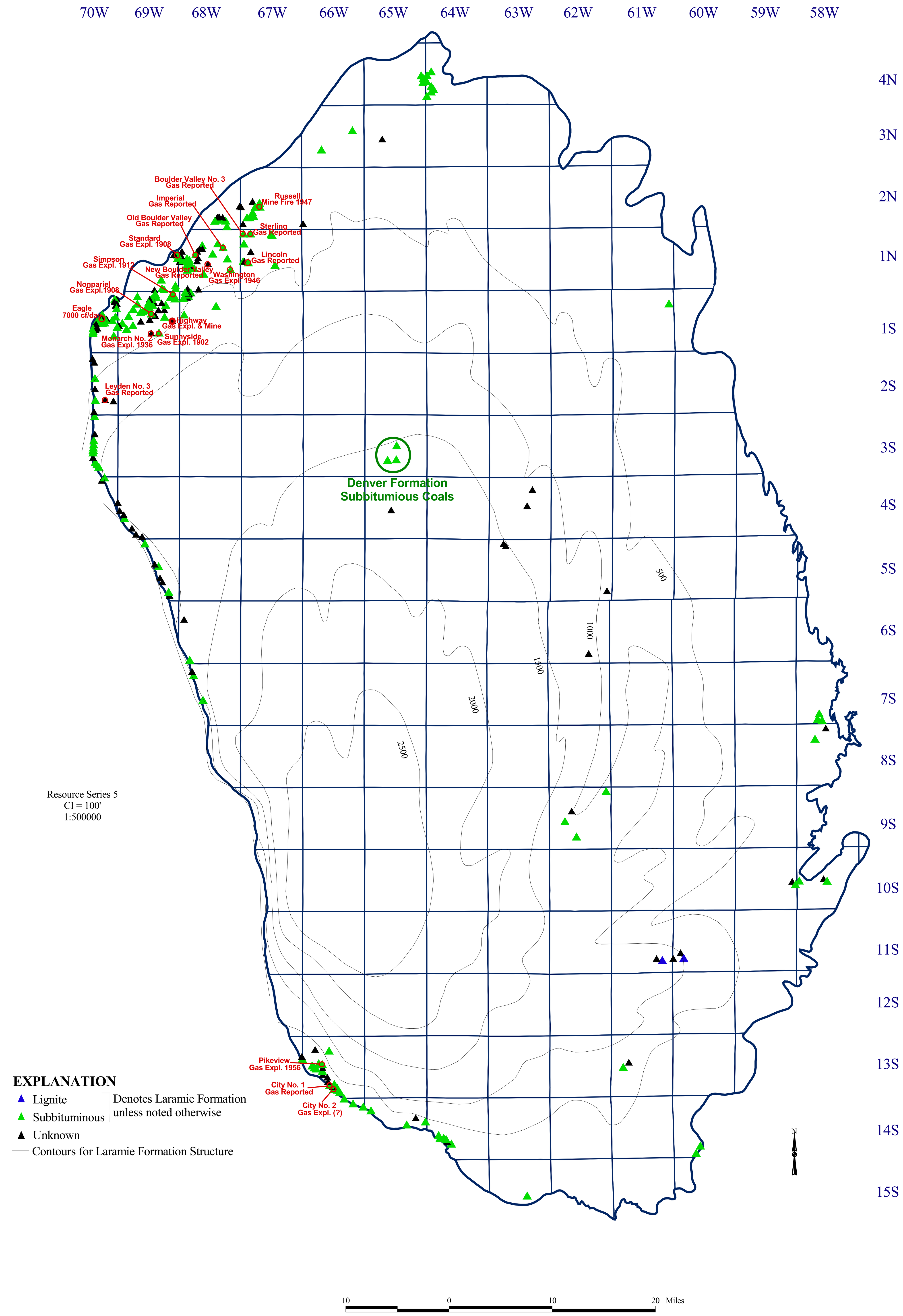
MAP A: Heat Values



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MAP B: Coal Rank and Gas Reported

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 8
2001

Structure contours on top of the Laramie Formation coals

Compiled by Nicole V. Koenig

CORE DATA

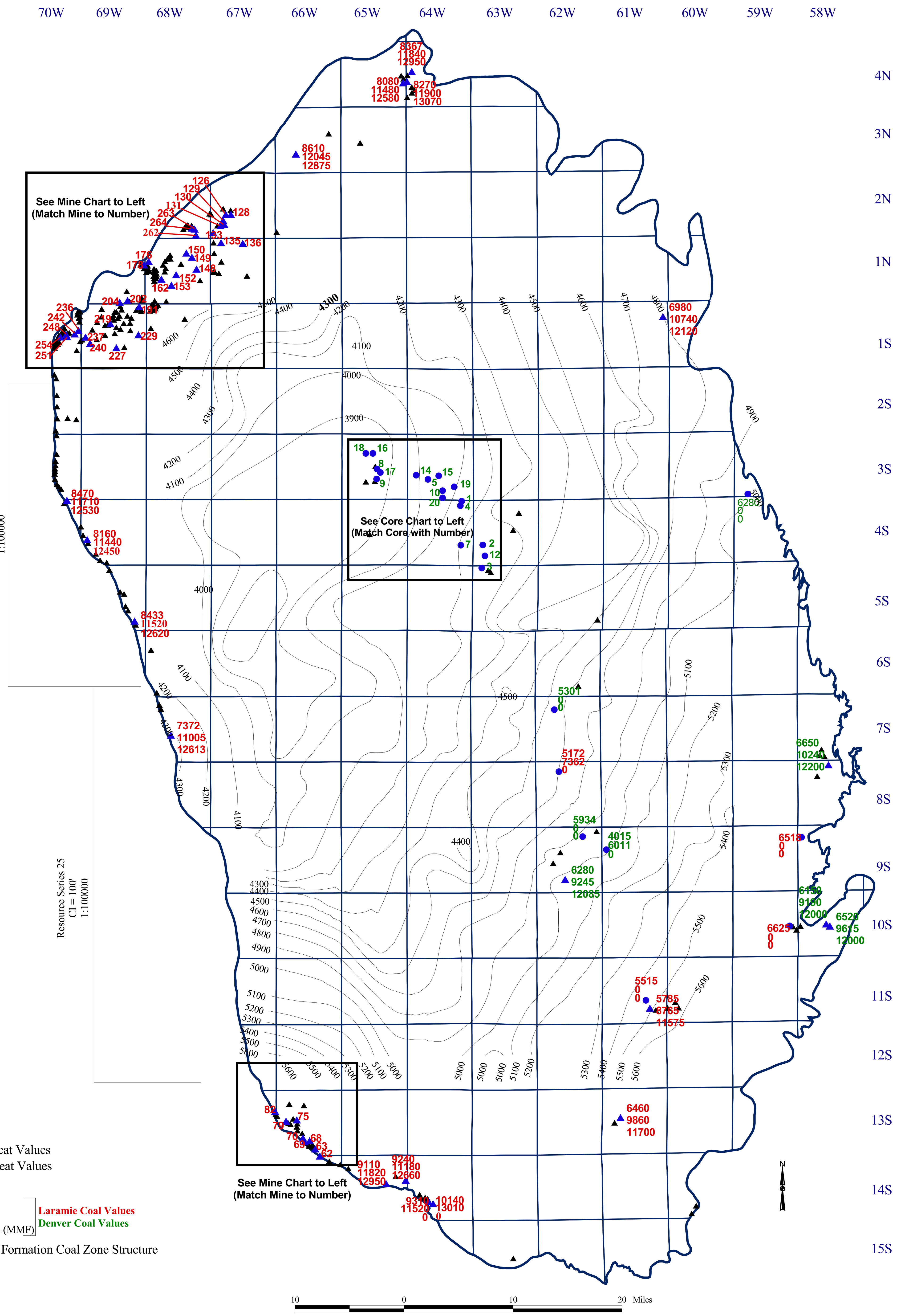
Core Number	AR*	BTU/lb MF*	MMF*
1	4680	6521	0
2	5967	7912	0
3	4802	0	0
4	5748	8317	12733
5	7694	8943	12740
7	4555	0	0
8	7148	9990	0
9	5914	0	12059
10	6375	0	12510
12	6217	0	0
14	5720	11917	0
15	6617	8920	0
16	6931	0	12767
17	5038	7296	0
18	6820	0	12990
19	6590	0	12722
20	4821	0	0

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free

MINE DATA

Mine	Mine Number	BTU/lb AR*	BTU/lb MF*	BTU/lb MMF*
62	172	8730	11740	12690
63	192	8640	10790	0
68	159	8910	11270	12120
69	149	8658	11130	12465
70	145	8535	11480	12360
75	188	8419	11330	12227
79	182	8500	10930	0
82	179	8740	10950	12020
126	279	9235	12470	13250
128	305	9147	12350	13190
129	274	9745	12350	13280
130	312	9180	13240	13300
131	272	9500	12570	13270
133	253	9265	12300	12990
135	308	9276	12450	13250
136	316	8919	12010	13050
148	265	9670	12505	13270
149	282	9678	12620	13380
150	291	9231	11432	12520
152	293	9785	0	0
153	261	9820	12580	13300
162	285	9550	12390	12970
176	14	9483	12460	13300
178	112	9823	12410	13290
191	103	10037	12560	13095
202	21	9788	12470	13220
204	93	9790	12310	1310
219	11	9589	12033	12824
227	76	10106	12397	13197
229	50	10004	13160	13410
236	34	10123	12400	13060
234	98	10010	12430	13190
240	52	9967	12295	13095
242	75	9857	11998	12501
248	100	9913	12220	13060
251	46	9968	12420	13100
254	54	10243	12560	13340
262	303	9547	12525	13169
263	306	9390	12470	13280
264	292	9740	12660	13330

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free



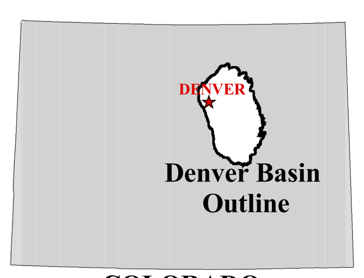
EXPLANATION

- Mine Locations w/ Heat Values
- Mine Location w/o Heat Values
- Core Hole Locations

As Received (AR)
Moisture Free (MF)
Mineral and Moisture Free (MMF)

Laramie Coal Values
Denver Coal Values

Contours for Laramie Formation Coal Zone Structure



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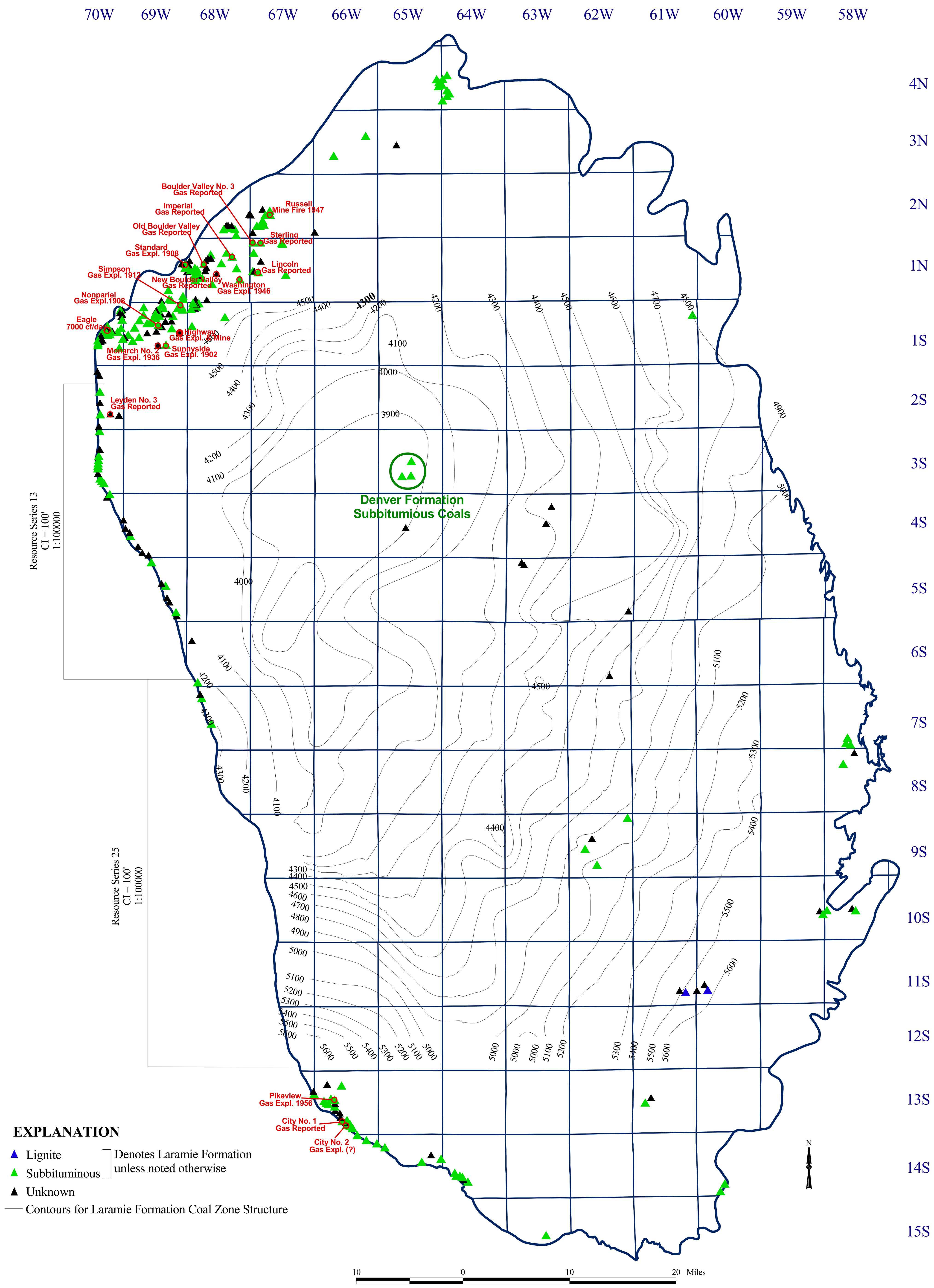
MAP A: Heat Values



EXPLANATION

- Lignite
- Subbituminous
- Unknown

Denotes Laramie Formation unless noted otherwise

Contours for Laramie Formation Coal Zone Structure

MAP B: Coal Rank and Gas Reported

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 9
2001

Total thickness of all known Laramie Formation coals

Compiled by Nicole V. Koenig

CORE DATA

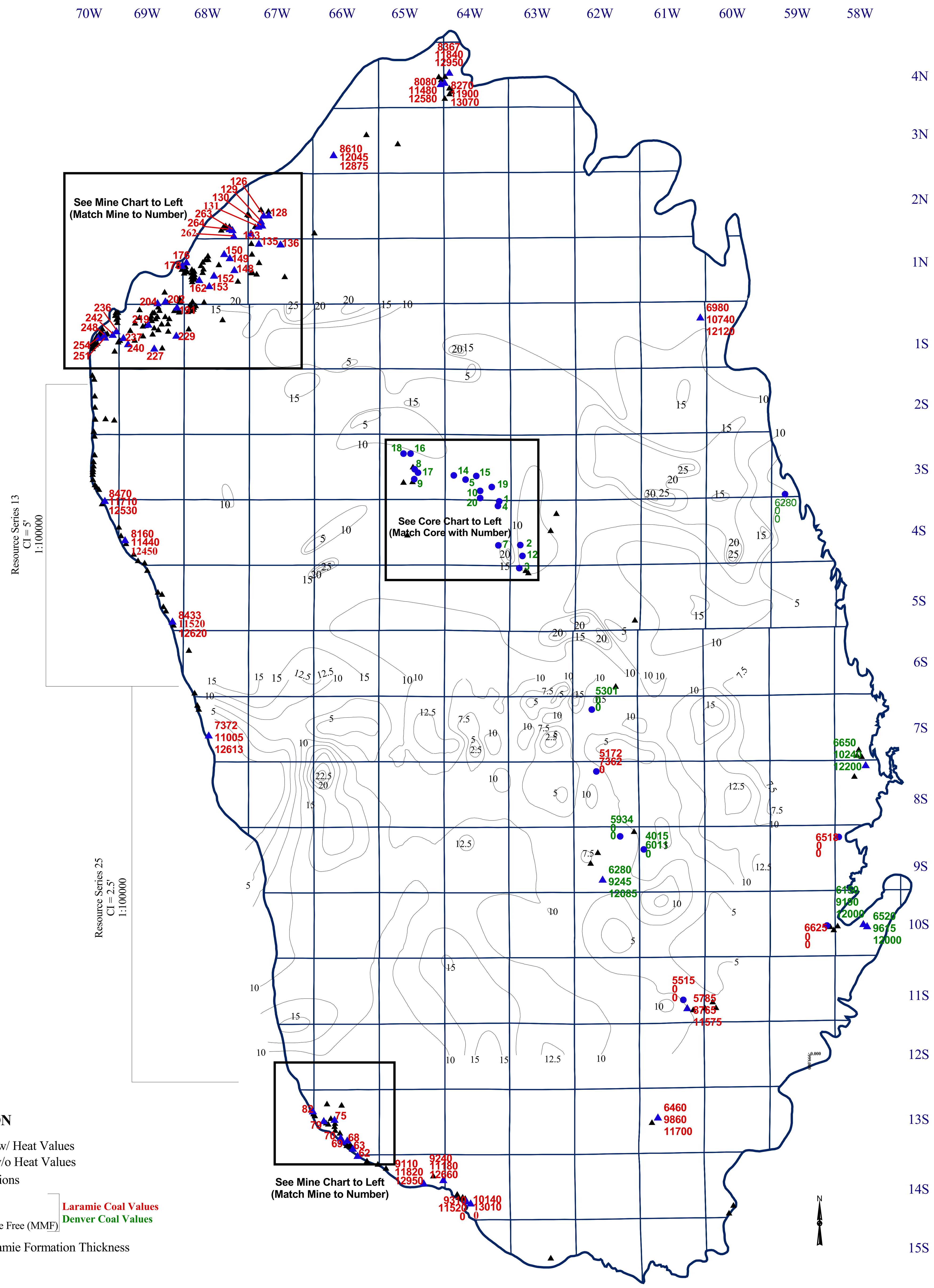
Core Number	AR*	BTU/lb MF*	MMF*
1	4680	6521	0
2	5967	7912	0
3	4802	0	0
4	5748	8317	12733
5	7694	8943	12740
7	4555	0	0
8	7148	9990	0
9	5914	0	12059
10	6375	0	12510
12	6217	0	0
14	5720	11917	0
15	6617	8920	0
16	6931	0	12767
17	5038	7296	0
18	6820	0	12990
19	6590	0	12722
20	4821	0	0

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free

MINE DATA

Mine	Mine Number	BTU/lb AR*	BTU/lb MF*	BTU/lb MMF*
62	172	8730	11740	12690
63	192	8640	10790	0
68	159	8910	11270	12120
69	149	8658	11130	12465
70	145	8535	11480	12360
75	188	8419	11330	12227
79	182	8500	10930	0
82	179	8740	10950	12020
126	279	9235	12470	13250
128	305	9147	12350	13190
129	274	9745	12350	13280
130	312	9180	13240	13300
131	272	9500	12570	13270
133	253	9265	12300	12990
135	308	9276	12450	13250
136	316	8919	12010	13050
148	265	9670	12505	13270
149	282	9678	12620	13380
150	291	9231	11432	12520
152	293	9785	0	0
153	261	9820	12580	13300
162	285	9550	12390	12970
176	14	9483	12460	13300
178	112	9823	12410	13290
191	103	10037	12560	13095
202	21	9788	12470	13220
204	93	9790	12310	1310
219	11	9589	12033	12824
227	76	10106	12397	13197
229	50	10004	13160	13410
236	34	10123	12400	13060
234	98	10010	12430	13190
240	52	9967	12295	13095
242	75	9857	11998	12501
248	100	9913	12220	13060
251	46	9968	12420	13100
254	54	10243	12560	13340
262	303	9547	12525	13169
263	306	9390	12470	13280
264	292	9740	12660	13330

*AR = As received, MF = Moisture Free, MMF = Mineral & Moisture Free



EXPLANATION

- Mine Locations w/ Heat Values
- Mine Location w/o Heat Values
- Core Hole Locations

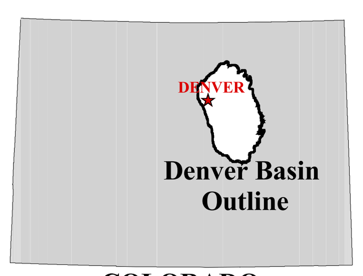
As Received (AR)
Moisture Free (MF)
Mineral and Moisture Free (MMF)
Laramie Coal Values
Denver Coal Values

Contours for Laramie Formation Thickness

10 0 10 20 Miles

1:500000

MAP A: Heat Values



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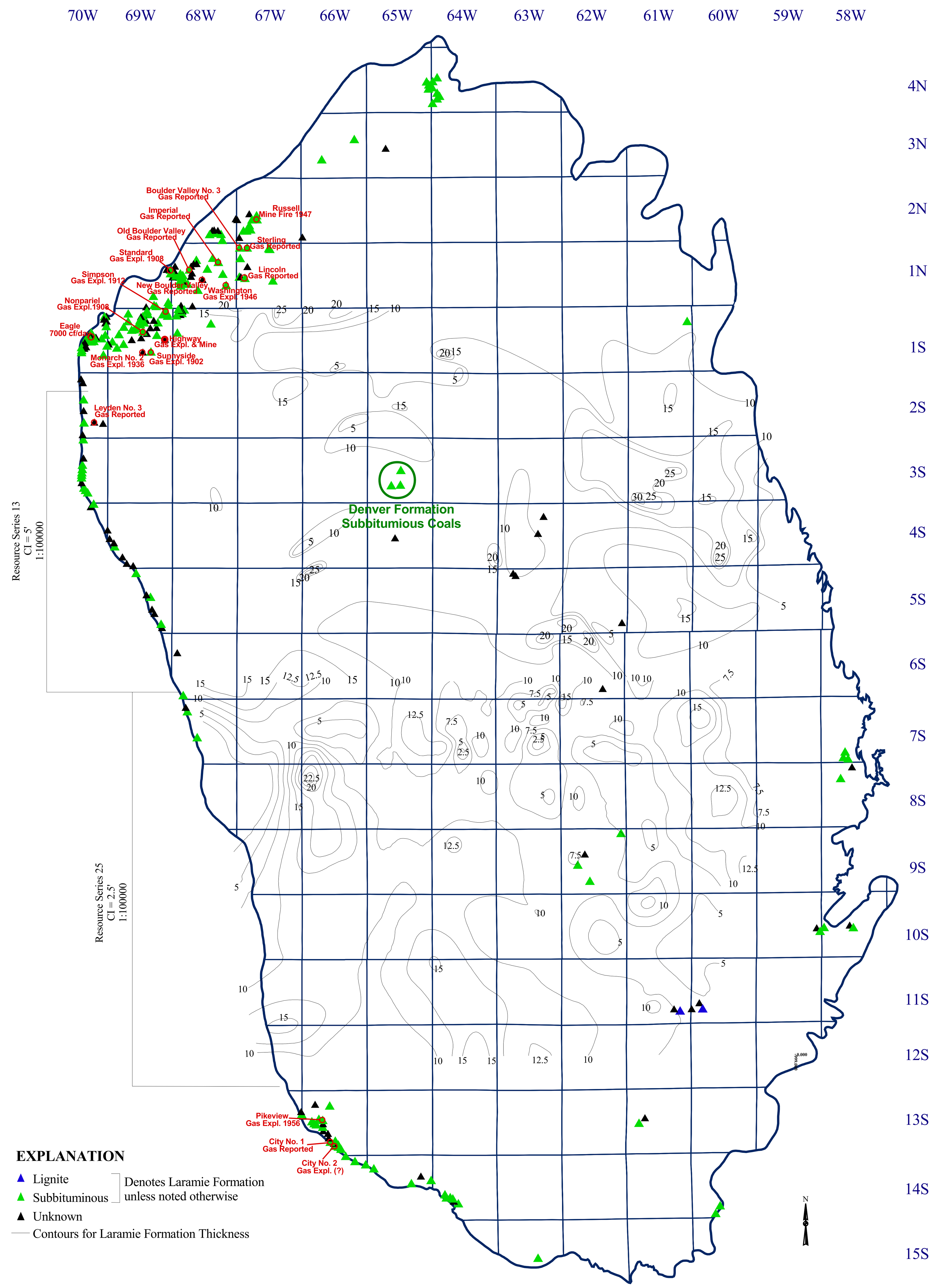

EXPLANATION

- Lignite
- Subbituminous
- Unknown

Denotes Laramie Formation unless noted otherwise

Contours for Laramie Formation Thickness

10 0 10 20 Miles

1:500000

MAP B: Coal Rank and Gas Reported

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

OPEN-FILE REPORT 01-17
PLATE 10
2001

STRATIGRAPHIC CROSS SECTION D-D' - DENVER FORMATION COALS

COLORADO GEOLOGICAL SURVEY
DIVISION OF MINERALS AND GEOLOGY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

STRATIGRAPHIC CROSS SECTION L - L' - LARAMIE FORMATION COALS

OPEN-FILE REPORT 01-17
PLATE 11
2001