Resource Assessment of Deep Coals in Eastern Montana: Potential Targets for Commercialization by *In Situ* Gasification

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PROJECT SUMMARY

Underground coal gasification (UCG) is a method of gasifying deep unmineable coal seams, and producing a synthetic gas (syngas) to the surface for use in power generation or as feedstock for coal-to-liquids. The UCG process has undergone pilot-plant testing at various sites in several countries, proving that the concept works, but in the United States there has been no long-term commercialization of the process.

International developers in search of potential UCG sites for pilot-scale tests, demonstration plants, and commercial operations require very specific information that enable them to make informed decisions when comparing competing sites. Montana's "deep" (500-3000 ft) coal resources have not been adequately described in terms of location, thickness, or lateral extent. The objective of this project was to carry out a regional assessment of the resource potential of deep coal seams in eastern Montana and categorize their suitability for the UCG process.

We studied geophysical logs from over 6,000 oil and gas wells to identify coal beds in the subsurface. These data were used to construct geologic maps and cross sections depicting those areas likely to be most favorable for *in situ* gasification. The Fort Union Formation has enormous potential for UCG, with numerous coal beds that have the appropriate depths and thicknesses, occurring over thousands of square miles in the Powder River Basin and Williston Basin of Eastern Montana. The results of this project clearly demonstrate, based on a first-pass screening of the data, that Montana has considerable deep coal resources that could be exploited by *in situ* gasification or any other technology that may be developed in the future.

The information and data provided by this study are critical for developers and investors so they can identify and evaluate potential UCG sites for future development. Whether or not this leads to commercialization remains to be seen, but several domestic and international companies have shown keen interest in Montana's deep coal and in the progress of this study during the past two years. The number of UCG developers is small, but if just one UCG project were pursued in Montana, the investment in the State would be huge – perhaps on the order of 100's of millions of dollars.

INTRODUCTION

Coal is the most abundant domestic fossil fuel source for the United States. Approximately one-half of all of the electrical power consumed by the U.S. comes from coal. This is not likely to change in the foreseeable future. The Energy Information Administration estimates that total U.S. coal consumption will increase by nearly 30 percent by the year 2035 (EIA, 2010). If the increase in coal consumption is to be met through domestic sources, new and improved methods for extracting the energy content of coal will be necessary to meet future energy demands of the U.S.

Emerging technologies such as Underground Coal Gasification (UCG) provide access to deep coal resources that are otherwise unusable. Researchers at Lawrence Livermore National Laboratory estimate that commercialization of UCG technology could increase the recoverable reserves in the United States by up to 3 or 4 times current estimates (Burton and others, 2006). Thus, UCG holds a great deal of promise as a viable alternative to conventional coal mining and coal-fired power generation.

In situ or Underground Coal Gasification (UCG) is a method of gasifying deep, unmineable coal seams into useable product gases, which are then processed at the surface and fed into pipelines or converted to liquids. It is a "clean coal" process, capable of extracting the energy content of deep, unmineable coal resources while minimizing environmental impacts. The UCG process utilizes injection and production wells drilled from the surface and linked in the coal seam below the water table. Air and/or oxygen are injected and the coal is ignited in a controlled manner. As the coal is gasified through partial oxidation, combustible product gases (called "syngas") are produced to the surface. Syngas is a low-Btu gas (125-350 Btu/scf) composed primarily of a mixture of CO, H_2, CO_2, and CH_4, with relative product concentrations dependent upon subsurface pressure-temperature conditions and the composition of the injected gas. At the surface, syngas is cooled and cleaned for use in power generation or manufacturing synthetic natural gas, liquid hydrocarbons, or petrochemicals.

The process holds many advantages over conventional coal-fired power plants and surface gasification:

- Provides a mechanism to exploit coal which is otherwise "locked up", too deep for conventional mining.
- Product gases offer a great deal of flexibility for final value-added products including:
    - fuel for turbines to produce power directly
    - low-cost coal-to-pipeline quality synthetic natural gas
    - low-cost coal-to-liquids
    - petrochemicals
- Economically more favorable than mining followed by surface gasification.
- Smaller environmental footprint than surface mines and surface gasification.
- CO_2 is captured with product gases and can be removed and contained.
- Avoids the hazards and some of the costs inherent in underground mining.

PURPOSE

With approximately 120 billion tons of demonstrated coal reserves (Averitt, 1974), Montana has considerable energy resources that could have potential for UCG. As much as 60 percent of the State's coal reserves lie at depths greater than 500 ft below the surface and are too deep for surface mining (Matson and White, 1975). Because they were regarded as having little, if any, potential for development, these deeply buried coals have not been adequately characterized in terms of thickness, lateral extent, or quality. Technological advances in underground gasification have made deep coal resources commercially viable and developers need information that enable them to make informed decisions when comparing competing sites.

The objective of this project is to carry out a regional assessment of the resource potential of "deep" (500-3000 ft) coal seams in eastern Montana by interpreting existing data to identify coal beds in the subsurface. The assessment provides new information in the form of specific locations, depths, and thicknesses of deep coal beds that have not been previously identified. The data and maps generated from this study provide a set of tangible results that developers can use as a basis from which they can do more detailed studies. It is intended to lay the foundation for serious investigations that must precede pilot-scale testing and full-scale investment in the State.

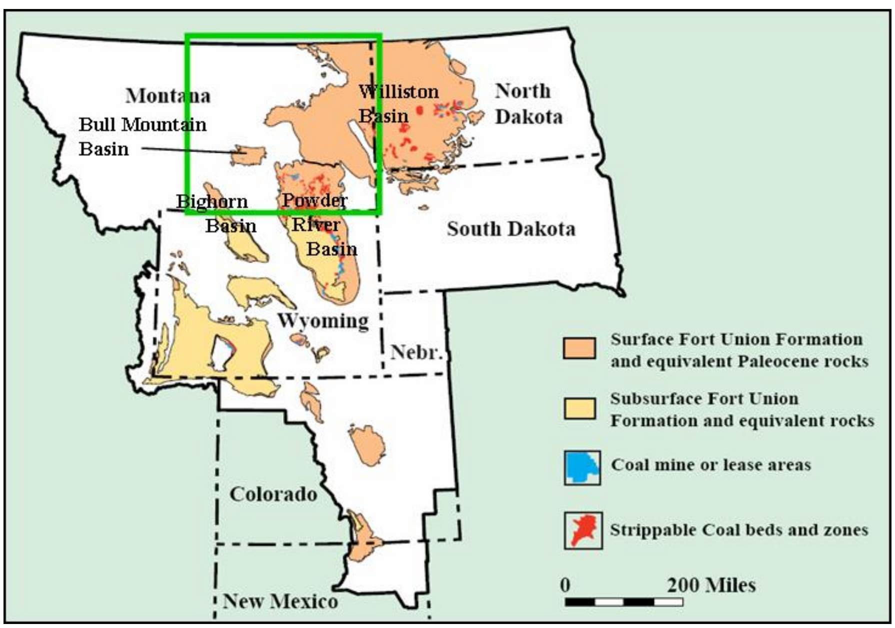

Figure 1. Map showing the extent of the Fort Union Formation in the western United States (from Flores and Nichols, 1999). The study area is outlined in green.

STUDY AREA

The Early Tertiary (Paleocene) Fort Union Formation is one of the richest coal-bearing geologic sequences in the United States and covers extensive areas of North Dakota, Montana, Wyoming, and Colorado. The study area for this project includes some 30,000 mi^2 of eastern Montana where the Fort Union Formation is present in the subsurface (Fig. 1). This sedimentary package contains Montana's most prolific coal deposits, accounting for 90 percent of Montana's coal reserves, and all of its coal production. It is likely to present the best opportunities for UCG.

The Fort Union Formation is comprised of three geologic units. From oldest to youngest these are the: Tullock Member, Lebo Member (informally referred to as the Lebo Shale), and Tongue River Member (Fig. 2). Together, these units form a thick sequence of inter-bedded and laterally discontinuous sands, gravels, silts, and shales. The majority of coal seams occur in the Tongue River Member. In the Powder River Basin (PRB) for example, as many as 20-25 persistent coal beds occur within the Tongue River Member – some with thicknesses up to 40 or 50 ft. Although coals can generally be correlated within basins, they cannot be correlated between the major basins shown in figure 1. Coal rank, a measure of heating value, generally decreases from bituminous to lignite coals going west to east.

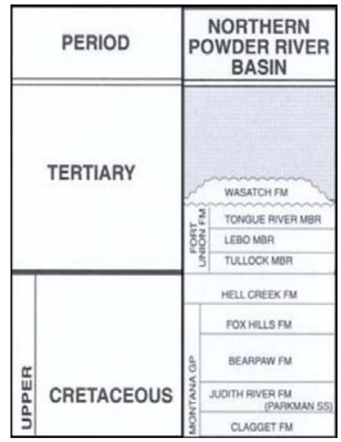

Figure 2. Stratigraphic column for Late Cretaceous – Tertiary of Montana.

METHODS

The project was subdivided into five primary tasks:

1) Acquire geophysical logs and formation tops for all oil and gas wells penetrating the Fort Union Formation in eastern Montana. Add available shallow coal exploration drill-hole information held in the MBMG coal database.

2) Interpret geophysical logs to identify coal beds in the subsurface (0-3000 ft).

3) Where possible, regionally correlate coal seams using geologic cross sections and seismic control if possible.

4) Evaluate the UCG potential of Fort Union coals according to key criteria (criteria identified as part of the project).

5) Generate final products consisting of maps, cross sections, and a database to summarize information on deep coal resources and illustrate the primary areas having UCG potential.

1) Available data

Most exploratory coal drill-hole data for Montana are fairly shallow – typically 100's of feet deep – because coal exploration companies in the State have specifically targeted strippable deposits that lie near the surface. The goal of this project is to identify deep coals (500-3000 ft) that could be suited to UCG, so we need to have information from alternative sources. Wells drilled in the course of petroleum exploration are typically 1000's of feet deep and provide subsurface data in the form of geophysical logs that were acquired during, or immediately following drilling. Geophysical logs provide continuous recordings of physical rock properties measured in the wellbore and are used by geologists and log analysts to evaluate specific characteristics of the subsurface formations. They provide the critical data necessary to identify deep coal seams that might be suitable for UCG.

O&G logs

More than 6,000 oil and gas (O&G) wells penetrate the coal-bearing Fort Union Formation in Eastern Montana and have geophysical log data that are publicly available. For the purposes of this report, the term "wells" refers to any petroleum exploration well regardless of fluids encountered (i.e. not limited to oil- and gas-producing wells, but also dry holes, injection wells, shut-in wells, etc.). Because this study is focused only on coals within the Fort Union Formation, wells that did not penetrate this geologic unit were excluded. Figure 3 is a map showing the oil and gas wells used in this study – note the non-uniform distribution of data. Most of the high-density data is concentrated in areas where resource plays have been developed recently. For example, the Elm Coulee (Bakken oil) field in Richland County and the southern portion of the Montana PRB where coalbed methane (CBM) drilling has been active for the past decade.

Basic well header information (latitude, longitude, elevation, etc) and formation tops were collected from the Montana Board of Oil and Gas (MBOG) website (http://bogc.dnrc.state.mt.us/). Raster images of geophysical logs for all wells available as of February, 2010 were obtained from MJ Systems of Calgary, AB Canada.   Digital data for geophysical logs are generally not available.

Data for an additional 3,000 wells from North Dakota and Wyoming that lie near Montana's borders were used to provide continuity for mapping and correlation across State lines.

Mudlogs

Mudlogs and/or lithologic logs were used to help substantiate coal picks and to identify coal in wells where geophysical logs were either not available or not usable because of poor quality.   However, they were mostly used qualitatively because cutting descriptions from the Fort Union Formation rarely provide the level of detail needed to accurately describe coal bed depths and thicknesses. Mudlogs for most wells are available in hardcopy from the MBOG. Some are also available digitally from the Northwestern Geological Society.

Coal drill holes

Geophysical logs are not always run to surface, often leaving "data gaps" between the surface and several hundred feet of depth. Lithologic data from approximately 7,000 coal exploration holes were included to help delineate coal beds at shallow and intermediate

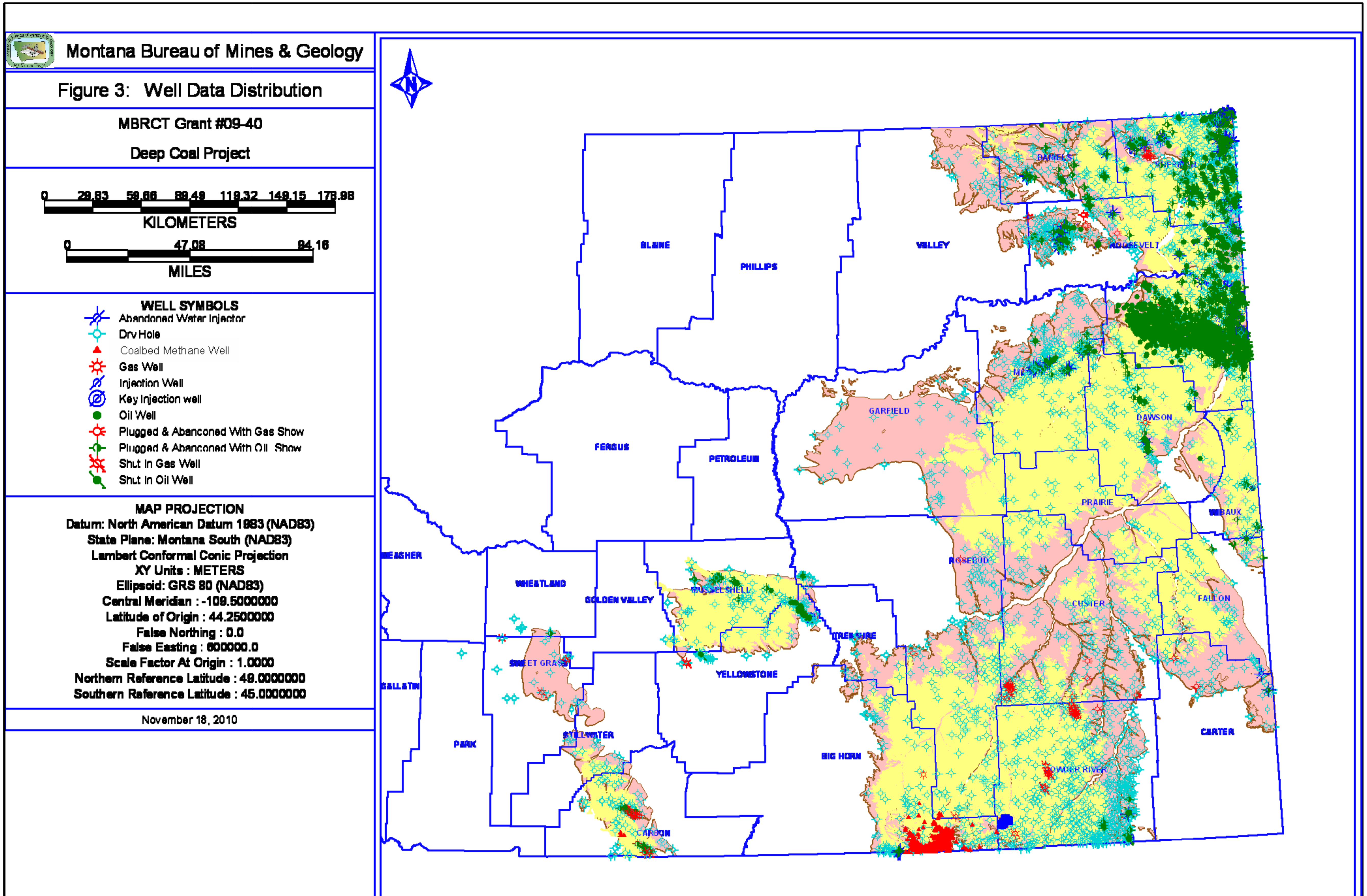

Figure 3. Map of eastern Montana showing distribution of oil and gas well data used in this study.

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depths where geophysical logs were either not present or incomplete. Coal drill holes were obtained from a coal database maintained by the Montana Bureau of Mines and Geology (MBMG), and accessible via their website (www.mbmg.mtech.edu). Holes having total depths greater than 100 ft and located within the study area were important for tracing major coal seams into the subsurface away from known strippable deposits. They are generally not useful for constructing maps that depict total coal or maximum coal thicknesses because their vertical extent is limited.

All well header data, raster images, and lithologic data were imported into IHS's PETRA® software for interpretation and analysis.

2) Geophysical Log Interpretation

Coal has several distinctive petrophysical properties and, when measured with common geophysical logs, can be readily identified in the subsurface ***provided*** the logging suite (i.e. combination of logging tools run) is reasonably complete and the data quality is good. Under these conditions, coal beds can be identified from logs on the basis of one or more of the following measurements: low photo-electric factor (PEF), low density (RHOB), high neutron porosity (NPHI), low gamma ray (GR), low velocity (i.e. high sonic travel time(DT)), and high resistivity. Wood and others (1983) provide a comprehensive review of coal bed interpretation from geophysical logs. Modern-day logs from a coal-bed methane (CBM) well in south-central Montana illustrate typical responses to coal (Fig. 4).

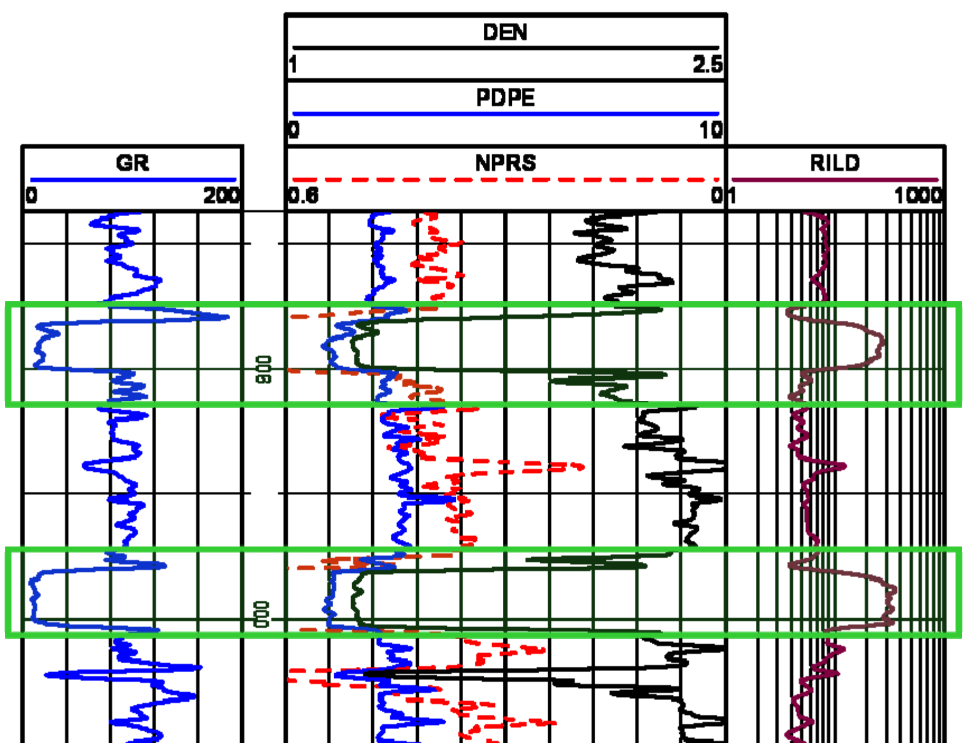

Figure 4. Modern-day logs from a coal-bed methane well showing the log response to coal beds (green). Note low gamma-ray (GR), photoelectric factor (PDPE), and density (DEN) readings in particular.

Geophysical log data used in this study were grouped into five categories based on the type of logs available for interpretation. Each well was assigned a "log quality" value from one to five (one being the best) based on the quality of log data available and therefore, the level of confidence we have in our coal picks for that well. In order of decreasing "log quality" for coal identification, these are:

1) *CBM well with reasonably complete log suites*
   CBM wells usually have reasonably complete log suites and good-quality data for coal identification because the drilling targets *are* coal beds and because these data were acquired during the past 10-15 years using the newer generation logging tools. For these, coal identification is reasonably straight-forward and based on a combination of log responses discussed above. A low GR reading in conjunction with low density is particularly diagnostic for coal identification. CBM wells exist only in the southern PRB.

2) *Conventional open-hole and cased-hole GR logs; sometimes with density, sonic, and/or resistivity.*
   For most wells, only one or two log measurements were acquired in the shallow section (i.e. over the Fort Union Formation) to reduce costs. Limited log suites usually include at least a GR log, but may or may not include any other logs. GR is a robust measurement that can be run either open-hole or through casing, and is minimally affected by borehole conditions. Fortunately, GR alone can be used to identify coal beds because coals tend to have lower natural radioactivity than sands, silts, and shales of the Fort Union Formation (Fig. 4). This strategy has been used routinely by previous workers (Wood and others, 1983; Sholes, 1992). Where density and/or sonic were available, coal beds were identified based on a combination of low GR **and** low density or low velocity.

3) *Cement bond logs*
   Cement bond logs also have a GR, but often with distinctly lower resolution and more "noise" in the signal than either open-hole or cased-hole logs run with conventional logging suites. Cement bond logs are common in the Elm Coulee field of the Williston Basin. Correlation with nearby wells increases our confidence in coal picks for these wells.

4) *Gamma-Neutron logs*
   Gamma-neutron logs were acquired with some of the earliest generation nuclear tools and are difficult to interpret. They generally have poor resolution leading to unreliable coal picks, so they should be used with caution. We chose to exclude Gamma-neutron logs from our final analysis unless coal picks could be supported by mudlog information or nearby wells with good quality data.

5) *Elogs*
   "Elogs" refer to an older generation of logs (circa 1950's and 1960's) having SP and resistivity measurements designed primarily to discriminate between sands and shale – or more accurately, permeable versus non-permeable beds. Out of

necessity, Elogs have been used by several previous workers in the PRB for identifying coals on the basis of high resistivity (i.e. low conductivity). This can be problematic because a high resistivity response is non-unique; other rock types such as low porosity, partially cemented sandstones and calcareous beds of the Fort Union Formation can give similar high resistivity readings on logs (Fig. 5). Therefore, coal beds picked from Elogs were not generally used unless supported by additional information such as mudlogs, correlation with nearby good-quality data, or prior publication.

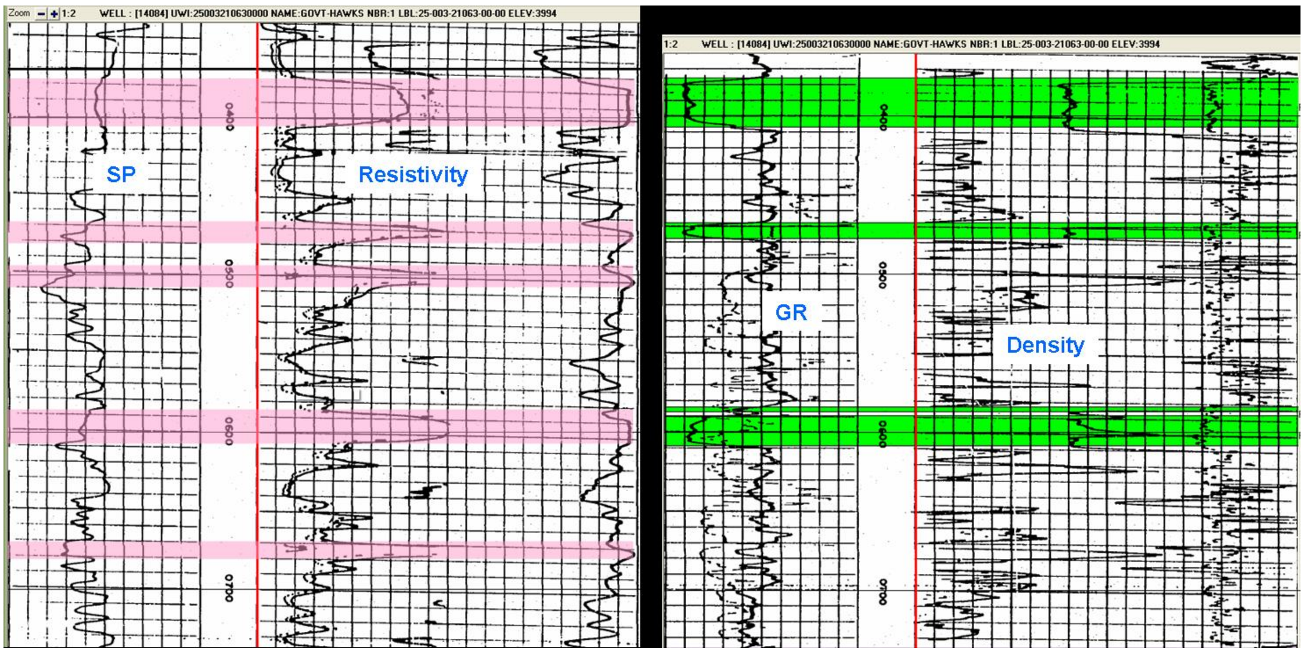

Figure 5. Using high resistivity to identify coals from Elogs is not conclusive (coal picks shaded pink on left-hand display). Comparison with GR and sonic (DT) logs for this well (coals shaded green on right-hand display) indicates that the Elog picks at 500' and 680' are not coals.

For each O&G well, geophysical logs were reviewed and interpreted to identify all coal seams occurring between the top of the log data and the base of the Fox Hills Formation (top Bearpaw Shale). The Bearpaw Shale provides a convenient lower limit because it is regionally pervasive and easily identified on logs.

The top and base of coals were picked from log deflections occurring at bed boundaries. We allowed thin shale layers, or partings, up to 2 ft thick within individual coals to avoid splitting thick coal packages into several thinner seams. Partings are not necessarily laterally continuous and we do not want to exclude potentially thick coal beds on the basis of thin partings. The USGS indicates that partings as thin as 6 inches can give a 2-foot response on logs simply due to the physical limitations on vertical resolution of logging tools (Wood and others., 1983). Thus, we believe 2 ft to be a reasonable limit for acceptance of shale partings within coal seams.

A second quality indicator for each well was necessary to describe its *vertical* coverage through the Fort Union Formation. Many wells are missing 100's or even 1000's of feet of log data in the upper portion of drill-holes and provide only limited vertical data coverage through the Fort Union Formation. Furthermore, log data from CBM wells are frequently missing the lower portion of the Fort Union because drilling usually terminates in the target coal beds somewhere within the unit. We cannot use these wells for interpreting and mapping summary statistics such as total coal, which require a full section (Fig. 6). We used the following "log coverage" quality indicators as a method to differentiate wells for interpretation:

0 = no coverage in the Fort Union Formation
1 = partial coverage through Fort Union Formation
2 = full coverage through Fort Union Formation

Table 1 is a summary of all oil and gas wells used in this study showing the distribution of our "log quality" and "log coverage" attributes. These attributes are included in the deep coal database developed from this study.

Table 1. Well Data Summary

	Full Coverage	Partial Coverage	No Coverage
CBM wells	53	424	0
GR +/- others	1788	651	1034
Cement	609	183	45
GR-Neutron	161	17	17
Elogs	715	269	90

3) Regional Coal Correlation

Regional coal correlations were made, where possible, to determine the lateral extent and continuity of coal seams. Coal seam geometries can be very complex because coal seams often merge, split, and pinch-out in the subsurface due to the depositional environments and processes that control their formation. So, correlations *between* wells are important for understanding structural positioning and thickness variations of individual beds. Locally, areas with high density data and where coals are laterally continuous can be correlated with reasonable confidence. For example, in the PRB near the Montana-Wyoming border, hundreds of closely-spaced CBM wells have been drilled and coal beds can be correlated for many miles (Fig. 6). For remaining areas, data are simply too sparse to reliably correlate coal seams – often with many miles or even 10's of miles between data points.

It is not surprising or unexpected that we were unable to fully correlate coals on a regional basis. The PRB is one of the most studied basins in the world and researchers have worked for decades to correlate coals, yet definitive correlations are still lacking across broad areas (e.g. Culbertson, 1987; Derkey, 1986; McLellan, 1991; McLellan and others, 1988, 1990). Having a complete set of coal correlations, although useful, is not critical for the successful outcome of this project. For any site that is seriously considered for

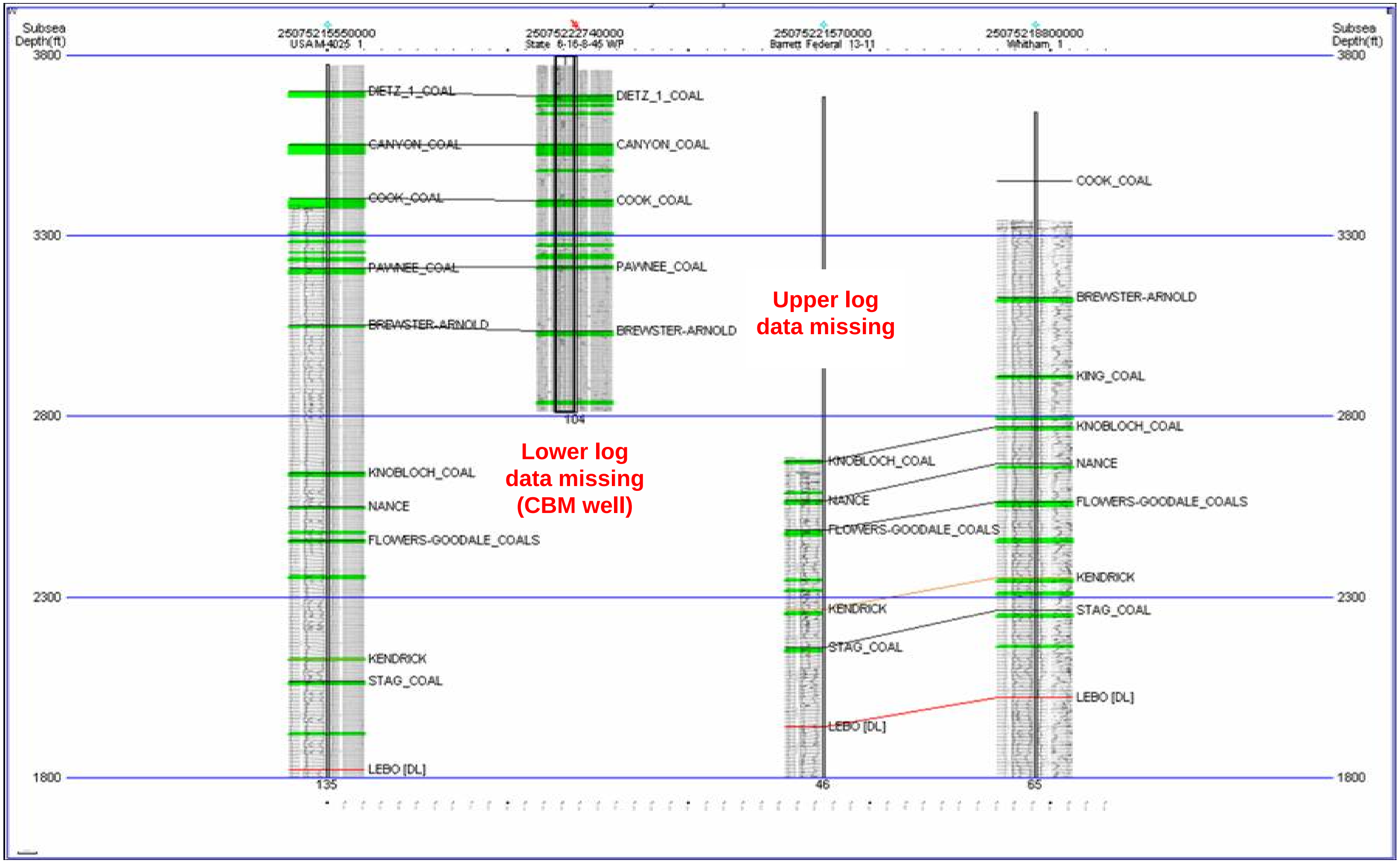

Figure 6. Example cross-section from PRB showing coal correlations (coals are green). These wells illustrate the disparity in vertical data coverage and the difficulty in combining wells for mapping. The two wells in the middle have “partial coverage” and cannot be used for mapping summary statistics such as “total coal”. Numbers below each well are total coal thickness for that well.

UCG, developers will need to drill a number of closely-spaced holes to fully delineate the target coal.

We proposed the use of seismic data to help with the regional correlation of coals because acoustic waves have a very distinctive response to low-impedance coal beds. Discussions with several consultants and industry geophysicists suggested, based on experience, that this would be difficult for a number of reasons:

- attenuation of the seismic signal by high-impedance clinker beds that are prevalent in the PRB.
- General lack of shallow seismic data because acquisition geometries and processing streams are designed to illuminate deeper targets – particularly in the Williston Basin.
- Most coal seams in the Williston Basin are probably too thin to be resolved by seismic reflection data given typical seismic frequencies.

In addition, our review of log data indicates there are not enough good quality sonic and density data in the Fort Union to generate reliable synthetic seismic models for tying seismic data. With the odds seemingly against a successful outcome, the use of seismic data for coal correlation was not considered to be cost or time effective for this initial screening, and omitted.

4) UCG Criteria

The technical and economic viability of any potential UCG site is dependent on a number of geologic and non-geologic factors. Geological factors are related to the burn cavity and/or gasification process below ground and include properties of the coal (thickness, depth, and quality), confining layer geology, structural geology, and hydrogeology. Non-geologic factors include surface topography, proximity to existing infrastructure, land use, surface and mineral ownership, in addition to other aspects of the site that may impact overall project success. Of these, the geologic factors are the least well known, most difficult to determine, and are precisely the kind of information developers need to pursue further evaluation of potential sites.

Several recent publications provide discussions of specific criteria for selecting favorable UCG sites (e.g. Jones and others, 2004; GasTech, 2005; Couch, 2009; Safirovich and others, 2008). Without exception, all agree that “site selection is the key to a successful UCG project” and yet, there is no clear consensus on what the specific criteria for UCG site selection should be. This lack of agreement arises from:

- The results of past UCG trials are varied and not always well documented.
- UCG technology is still evolving and criteria continue to change.
- Developers often have their own set of preferred criteria based upon the gasification technology they intend to employ, project economics, and business strategies.

- Some developers regard their criteria as proprietary information that provides a competitive advantage for identifying and acquiring potential UCG sites.
- Published criteria are sometimes applicable only to the specific coal fields or basins being discussed by the authors.

Burton and others. (2006) and Couch (2009) recently published reports that collate available information and provide some guidelines on site selection. The guidelines are mostly qualitative, but **do** provide a basis for applying some limitations on coal depth, thickness, and quality.

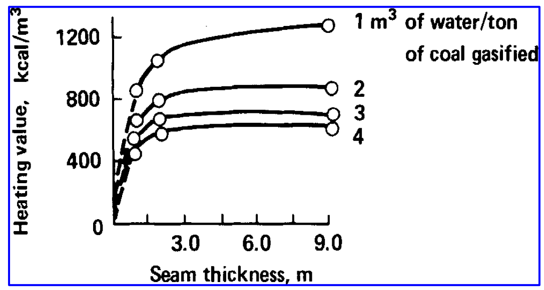

Figure 7. Coal seam thickness versus heating value of product gases from Gregg and Edgar (1978).

The minimum thickness of coal that is technically suitable for gasification is 1.5 - 3.0 ft. However, Gregg and Edgar (1978) demonstrate that the heating value of product gases decrease significantly when coal thickness is less than 6.5 ft (Fig. 7). Diminished heating values are associated with high heat loss to surrounding rocks when the gasified coal seam is thin. Following this rationale, we use 6.5 ft as a more reasonable minimum thickness of coal likely to be economically suitable for gasification. Thicker coals generally improve economics, so we also used thickness cutoffs of 10 ft, 15 ft, and 25 ft for final maps. Some of the leading UCG developers consider 25 ft to be an upper limit for coal thickness because it becomes increasingly difficult to manage the growth and control of the gasification chamber in thick coals. Collapse of large burn cavities can cause significant disturbance of the overlying rock layers and lead to groundwater contamination and/or surface subsidence.

Although Burton and others (2006) indicate that coals as shallow as 40 ft can be gasified successfully, a more practical lower limit for depth is commonly taken to be about 200 ft, the approximate depth limits for surface mining. Coals lying deeper than 500 ft below the surface are preferred to reduce the risk of surface subsidence and groundwater contamination from collapse of the burn cavity. Coals as deep as 4000 ft have been gasified in the U.K., but higher drilling costs offset the reduction in environmental risk, and most developers seem to prefer coal seams no deeper than about 1500 ft. We chose to use 200 ft as the minimum depth and 500 ft as a preferred depth for final maps depicting coals suitable for UCG.

Coals of all ranks have been successfully gasified at the surface, but *in situ* gasification requires coal seam permeability to maintain communication between injection wells, the burn front, and production wells. Because high-rank bituminous coals tend to swell upon heating (Stephens, 1985), lower rank coals are favored for the UCG process. Nearly all coals in the Fort Union of Montana range from lignite to high-volatile sub-bituminous C, and are suitable for UCG.

Given the current state of UCG technology, it seems premature to impose a strict set of criteria that might exclude potential UCG sites. Criteria vary amongst major developers and will undoubtedly change as UCG technology evolves. We chose to apply fewer "limiting" criteria and prefer to provide the data so that developers and other interested parties can do additional analyses based on their own set of criteria. Nevertheless, our basic criteria provide a preliminary screening, used as much to identify obviously unsuitable sites as they are to highlight areas with significant potential.

5) Maps and Cross Sections

Maps and cross sections were generated using IHS PETRA® and ESRI ArcGIS software to summarize deep coal occurrence based on our data interpretations and screening criteria. They are used to illustrate areas having potential for UCG.

Depth maps showing the thickness of the primary coal-bearing sequence were created by subtracting structural grids – either taken from existing literature or generated as part of this study – from the 30m Digital Elevation Models (DEM) published by Montana's Natural Resource Information System (NRIS).

Two types of maps were generated to show UCG potential based on our coal thickness and depth criteria. Given a single set of thickness/depth cutoffs (e.g. 6.5 ft/200 ft), "coal occurrence" maps depict the spatial limits where *at least one coal* meeting the requirements can be found. They are used simply to distinguish between productive and non-productive regions. "Coal attribute" maps highlight those areas that are likely to offer the best potential based on statistical attributes such as total coal thickness or maximum coal thickness.

Coal Occurrence Maps
Given any combination of thickness/depth criteria, each well was assigned a "probability" or "likelihood" that at least one coal meeting the criteria exists at that location (0 = no coal; 1 = has coal). Wells were excluded only if the data quality was too poor to reliably pick coal beds, or if the well contained no coals meeting the criteria *and* the log data was incomplete (partial or no vertical log coverage). Using this method, we are able to utilize many of the wells that have only partial data coverage through the Fort Union if they contain coal. The remaining wells with values of "0" and "1" were gridded using a least squares gridding algorithm to generate a pseudo-probability map. Extracting the 0.5 contour from the resultant grid, we obtained a boundary polygon, within which we can reasonably expect to find at least one coal seam fitting the criteria. Boundary polygons were modified manually in some cases to more accurately fit the data and local geology. This process was repeated for other thickness/depth cutoffs (e.g. 6.5/500, 10/500, 15/500).

Coal Attribute Maps
Total coal thickness and maximum coal thickness maps were generated to identify areas likely to have the greatest UCG potential. As with the "coal occurrence" maps, they are dependent upon our selection of thickness/depth criteria, but can be generated for any set

of cutoffs. Total coal is the sum thickness of all individual coal beds that meet the given criteria. Maximum coal thickness is simply the maximum thickness of any individual coal meeting the criteria. Only wells with full vertical coverage through the Fort Union Formation were used to create these maps. Thus, all coal exploration drill-holes are excluded.

Structural cross sections were constructed to accompany maps and to help illustrate the nature and distribution of some of the primary coal seams that have potential for UCG.

Finally, a database was compiled that includes location, depth, and thickness of all coals that are more than 2 ft thick and lie deeper than 200 ft ± 10 ft below the surface. Data will be delivered in Excel format as part of the final MBMG Open-File Report, and will serve as a database for further interpretation and analysis by interested parties.

RESULTS

The results of this project consist primarily of a set of identified coal picks in the subsurface derived from the interpretation of geophysical logs. Many of these coals have not been previously recognized and constitute valuable resources that could be exploited using *in situ* gasification. These and other coal data were used to develop maps and cross sections that summarize the distribution of deep coals in eastern Montana. The maps are a preliminary screening only – based on coal depth and thickness – but clearly demonstrate that there are vast areas of Montana with potential for UCG. They provide developers with critical information regarding areas that should be investigated further **and** areas that can be ignored.

A more detailed discussion of results is divided into sections for each of the four major regions: Williston Basin (WB), Powder River Basin (PRB), Bull Mountain Basin (BMB), and Bighorn Basin (BB).

Powder River Basin

The Powder River Basin spanning Wyoming and Montana is home to some of the largest coal deposits in the world. The primary coal-bearing unit is the Tongue River Member with up to 25-30 persistent coal beds that can range up to 40-50 ft or more in thickness. The underlying Lebo Shale marks the lower limit of the major coal beds. In the southernmost portion of the PRB study area, the Tongue River Member is over 2500 ft thick.

The PRB contains abundant coals that are suitable for development by *in situ* gasification. Plate 1 shows the approximate aerial limits and the total thickness of coal seams that meet the minimum criteria (thickness>6.5 ft and depth>200 ft) for UCG. Areas with the highest total thickness are likely to provide the best potential and have the widest selection of coals. They lie primarily along the MT-WY border and extend north and northeastward along topographic highs between major river and stream valleys. In general, the number of thick coals that are deep enough for *in situ* gasification decreases to the north.

We also note that, while data density and log quality are excellent in the south where many CBM wells have been drilled, these wells do not normally penetrate the entire Fort Union section. It is likely that total coal thickness is underestimated in this region.

Plate 2 shows the approximate aerial limits where 6.5 ft, 15 ft, and 25 ft thick coal beds can be found below 500 ft – our preferred depth. The maximum thickness of any individual coal seam below 500 ft occurs in T.6-7S, R.39-40E where the Wall coal seam reaches thicknesses of more than 60 ft, and in T.9S, R.39E where the Dietz coals merge into a single seam. Recall that seams more than about 25 ft thick may be less desirable for UCG. However, the cross sections in plates 3 and 4 illustrate that there are also several coals with ideal thicknesses at these locations.

Williston Basin

The Williston Basin (WB) is a broad structural depression centered on a N-S line extending from southern Saskatchewan to the Black Hills of South Dakota. The central axis and deepest part of the Williston Basin lies in western North Dakota. In the MT portion of the WB, the Fort Union Formation covers about 20,000 mi^2 and contains abundant lignite beds that reach thicknesses up to about 25 ft. Unlike the PRB, these coal beds have not been studied in detail because historically, they have been viewed as relatively unimportant for mining.

Most of the oil and gas wells in Montana are concentrated along the western edge of the Williston Basin in a 30-50 mile-wide band that stretches from Richland to Sheridan Counties along the MT-ND border. There are nearly 2,000 wells in Richland County alone because of the recent attention garnered by the Bakken oil shale play. To the southwest, fewer wells have been drilled in the deeper parts of the interior basin in Dawson, McCone, and Prairie Counties (refer to Fig. 3). Shallow drill holes are concentrated near strippable coal deposits exist.

There are extensive areas likely to contain coals suitable for UCG based on our depth and thickness criteria (Plates 5 and 6). Most of the deep coal potential lies in two regions, that correspond to the thickest sections (>1500 ft) of preserved Fort Union sediments. They are located in Dawson County, northwest of the northern terminus of the Cedar Creek Anticline and along Montana's border where beds dip eastward into the central portion of the Williston Basin.

In the region surrounding Richland County, coals occur in two major packages that can be correlated across the border and into North Dakota using data interpreted by Murphy (2006a). The upper coal package is about 600-700 ft thick and typically contains up to five or six distinct coal seams that range in thickness from 8-20 ft or more (Plate 7).

They are laterally continuous over substantial areas and can be reasonably well correlated for 10’s of miles. Approximately 300-400 ft below, a lower package contains mostly thin, discontinuous coals that probably have lower potential for gasification. These cannot be easily correlated more than a mile or two, and appear to merge and split or simply pinch-out between wells.

In the broad structural depression that covers western Dawson and southeastern McCone counties, log data distribution and quality are much poorer. However, our interpretations do suggest some significant deeper coal targets. For example, the “S” seam (or equivalent), which crops out along the western perimeter of the Tongue River unit, appears to reach depths greater than 500 ft in the central portion of the area. Additional unnamed coal seams highlighted in the cross section (Plate 8) may also present viable UCG targets.

Overall potential in the WB is enormous with several 15-25 ft thick coal seams at appropriate depths for *in situ* gasification. In the western half of the region, the risk may be higher because well data are sparse and data quality are lower. However, it constitutes a huge area and additional targets may emerge as more data become available.

Bull Mountain Basin

The Bull Mountain Basin (BMB) covers approximately 1500 mi^2 of Musselshell and Yellowstone Counties in central Montana. The synclinal basin has a dominant structural fabric with NW-SE trending faults and minor folds. Based on the Hell Creek structure map (Noble and others, 1982) and our log interpretation, the depth to the base of the Fort Union Formation (top of Hell Creek) reaches about 1500 ft in the middle of the basin.

Most of the oil and gas drilling occurred along the basin’s perimeter from the 1950’s through the 1980’s. Geophysical log data are generally poor to moderate quality and not particularly well suited to the identification of coal. Shallow coal exploration drill-holes delineate only the Mammoth seam – the largest seam in the basin.

Up to 26 coal beds have been identified within the Fort Union Formation, primarily from outcrop information (Woolsey and others, 1917). Most of these are thin (from 2-5 ft thick) and only the Mammoth seam, which is over 10 ft thick in the southern portion of the basin, is likely to be of interest for UCG. Depths of the Mammoth seam reach about 700 ft beneath Dunn Mountain, which rises roughly 400 ft above the surrounding topography. The mammoth seam outcrop, depth, and thickness were mapped by Connor (1988, 1989). Locally, a few other seams may exceed the 6.5 ft minimum thickness cutoff, but do not maintain that thickness over broader areas. The only other thick seam is the “Big Dirty” which lies about 1000-1200 ft below the Mammoth seam in the Lebo Shale member. It can be up to 17 ft thick, but contains many shale partings – hence its name. It is not known to what extent this will impact *in situ* gasification.

In 2009, Signal Peak Energy renewed operations of Montana's only underground mine and is producing coal from the Mammoth seam. This could pose an obstacle to any implementation of UCG as developers would have to contend with nearby conventional mining.

Overall potential for the Bull Mountain Basin is small compared to the Powder River and Williston Basins. Seams are probably too thin to be seriously considered as leading UCG targets.

Bighorn Basin

The Bighorn Basin occupies an area of just under 1,200 mi^2 and is bounded by the Bighorn and Pryor uplifts to the east and the Beartooth uplift to the west. The Fort Union Formation dips to the southwest and is very thick – up to 8,500 ft nearest the Beartooth Mountains according to Woodruff, 1909. Bituminous coal beds are present in an 825 ft thick middle unit sandwiched between a lower 5700 ft unit and an upper 1975 ft unit which do not contain coal beds (Woodruff, 1909). There are about 8-9 different coal seams that can have thicknesses up to 11-12 ft and numerous partings of carbonaceous shales. Rawlins (1986) estimates that remaining coal reserves in the Red Lodge – Bearcreek fields could exceed 700 million tons.

Although three recent CBM wells were drilled in T.7S, R.20E, there is very little useable geophysical data for documenting deep coals in the Bighorn Basin. Shallow coal beds are only mappable over a relatively small area in T.8S, R.21E near the Bearcreek mining district, and T.7S, R.20E near Red Lodge. Because topography rises and beds dip 4-6 degrees to the southwest, near-surface coal seams at Bearcreek quickly reach depths of 1000-1500' in the CBM wells. Based on this limited information, the area between the Bearcreek mining district and the Beartooth Mountains has potential, but the level of this potential cannot be determined without additional drill-hole data.

It is worth mentioning that several coal beds have been mined on the eastern edge of the Bighorn Basin in Montana. These coal beds occur in the Cretaceous Eagle Formation underlying the Fort Union and, although they could be targets for gasification, they are not considered as part of this study.

PERFORMANCE BENCHMARKS

Performance benchmarks as presented in the original proposal are provided in Table 2. They correspond closely to the major tasks listed and discussed in detail in the "**METHODS**" section of this report.

Table 2: Performance Benchmarks / Target Dates

	Project Year 1												Project Year 2					
	2008				2009												2010	
TASK	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
1. Data Acquisition	<----	------	------	---->														
Geophysical logs	XXX	XXX																
Formation Tops (MBOG)	XXX	XXX																
Other (e.g. seismic, GNP)	XXX	XXX	XXX	XXX														
2. Log Interpretation			XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX								
3. Correlations / Mapping									XXX	XXX	XXX	XXX	XXX					
4. Generate Final Products														XXX	XXX	XXX	XXX	
Review and Publication																	XXX	XXX

A 6-month no-cost extension was requested in December, 2009 and approved by MBRCT, moving the project end date to August 30, 2010. The extension was requested because of key personnel changes within the Bureau and additional demands on the Principal Investigator's time – both of which directly impacted the project schedule. The project goals as stated in the grant agreement did not change and were completed by August 30, 2010.

<u>Benchmark #1: Data Acquisition completed by Dec. 31, 2008</u>
Data acquisition was completed ahead of schedule. All data – other than seismic – were prepared, loaded into databases, and ready for interpretation by Nov., 2008. Data for this project included:

- geophysical log data from over 6,000 existing oil and gas wells
- more than 7,000 coal exploration drill hole data from MBMG's database
- proprietary drill hole data from Great Northern Properties (GNP)
- lithologic data for Wyoming and North Dakota petroleum and coal drill holes obtained from the USGS National Coal Resource Data System and from the Wyoming Geological Survey.

<u>Benchmark #2: Log Interpretation completed by Jul. 1, 2009</u>
Of the 6,000 O&G wells, about 4,000 have log data that are of sufficient quality to be usable for interpretation and provide data that will be published as part of this study.

Initial log interpretations were completed by June 1, 2009 – one month ahead of schedule. However, because much of the data quality is less than ideal, log interpretation and coal correlation required several iterations to improve our confidence in coal picks. A “second-pass” log interpretation to refine coal picks was completed by Sept. 1, 2009 (two months later than the original timeline).

Benchmark #3: Correlations and Mapping completed by Oct. 1, 2009

The second pass of log interpretation caused delays in meeting the correlation/mapping deadline of October 1, 2009. For many areas, correlating coal seams was difficult – and perhaps not even feasible – given the lack of data coverage and data quality. Although important for assessing individual coal picks, having a complete and definitive set of correlations was not critical to the overall success of the project. Again, log interpretation, coal correlation, and mapping were iterative processes that continued throughout the life of the project. This process took more time than originally planned, but was necessary to achieve the best possible results.

Benchmark #4: Final Report and Products – originally due by Feb 28, 2010, but extended to August 31, 2010

Final products in the form of maps and cross sections depicting coal bed distribution and potential UCG targets in Montana are completed and included as part of this project report. A second, more formal scientific report will be published as an MBMG Open-File Report (OFR). The OFR will be more suitable for public consumption by omitting some of the information provided to the MBRCT in this report (e.g. Financial Report and Commercialization Plan), but supplying additional geologic information, data, and discussion that will be important to UCG developers. Final maps, cross sections, and data will also be made available to the public via the MBMG website.

FINANCIAL REPORT

Montana Board of Research and Commercialization Technology

FINAL FINANCIAL REPORT

Grant Agreement: #09-40 Resource Assessment of Deep Coals in Eastern Montana: Potential Targets for Commercialization by In-Situ Gasification
Principal Investigator: Jay A. Gunderson **Date Submitted: November 16, 2010**
Phone #406-657-2702 **E-Mail: jgunderson@mtech.edu**

FINANCIAL STATUS – Please identify the Banner organizational name and number used to compile this data.

Budget Item	Original Amount Budgeted				R&C Funds	Matching Funds	Other Funds	
	R&C Funds	Matching Funds	Other Funds	Total	Expended	Expended	Expended	Total
Salaries	95,695.00	36,412.00		132,107.00	95,998.01	32,801.21		128,799.22
Payroll Benefits	26,927.00	9,244.00		36,171.00	35,099.91	11,975.69		47,075.60
Repair and Maintenance								
Travel	2,200.00	2,200.00		4,400.00	2,016.56	272.48		2,289.04
Communications								
Contracted Services	18,700.00			18,700.00				
Supplies and Materials	3,404.00	721.00		4,125.00	1,084.88	12.00		1,096.88
Rent	2,408.00	1,204.00		3,612.00				
Equipment								
Subcontracts								
Awards								
Participant Support Costs								
Facilities and Administrative Costs								
Total	$149,334.00	$49,781.00		$199,115.00	$ 134,199.36	$ 45,061.38		$179,260.74

Please provide supporting narrative as pertinent.

Project expenditures were in line with the original budget, other than the $18,700 budgeted as “Contracted Services” for the acquisition and processing of seismic data. A preliminary review of feasibility followed by discussions with several industry experts suggested that the use of seismic data to reliably identify and correlate coal seams would have a small chance of success given the quality and availability of seismic data. Therefore, use of seismic data for the project was considered to be neither cost nor time effective for an initial UCG screening. We requested and received MBRCT approval to have $8,150 reclassified for use toward salary and benefits to meet additional obligations given the extended project deadline of August 30, 2010. The unused funds from “Contracted Services” and other categories totals $15,134.64 and this amount will be returned to the MBRCT.

The remaining $4,719.62 in matching funds from Great Northern Properties (GNP) will be used to cover publication costs and the cost of travel to Houston, Texas to deliver the final report and presentation to GNP staff.

COMMERCIALIZATION PLAN

Product Description

Shallow coal beds (less than 300 ft deep) have been reasonably well-defined by studying outcrops and coal-exploration drill holes, but deeper coals have not been similarly characterized. With this study, new information on the extent and distribution of deep coal beds was derived primarily from the study of oil and gas well logs that penetrated and recorded information through the coal-bearing Fort Union section. “Deep” coal data have been compiled into a database and summarized in maps and cross sections to identify areas or sites that appear to be most favorable for development by underground coal gasification – or any other method that can commercially exploit these resources. All summary information, final displays, and data will be published by the MBMG as an Open-File Report that will be available to the public. Therefore, the product itself is **information**, which is needed by anyone interested in developing coal resources at a depth below the range dictated by surface mining.

The summary report will include maps and cross sections depicting the geometry of coal beds based on this preliminary screening. Because these data are digital, maps can be readily updated as more data become available or as UCG screening criteria change. The database to accompany the final report contains location, thickness, and depth of individual coal beds. It is provided so that developers can use these data to apply their own set of UCG criteria and pursue additional interpretations and mapping.

Target Market

The market size in terms of customers is unknown, but will be small. However, if a single customer were to develop a single project, the investment would be enormous---in the magnitude of hundreds of millions of dollars for a single site. During the past year the MBMG has been contacted directly by at least five companies inquiring about sites that would be suitable for UCG. None have wanted their inquiries to become broad public knowledge and several have specified that their inquiry should remain confidential, illustrating the competitive nature of the business. All have expressed a great deal of interest in this study. The information and data supplied by this review are necessary, and help to answer critical questions during the initial stages of exploration for UCG sites.

Marketing Strategy

The marketing in this project is to sell potential investors and developers on the merits of Montana’s deep coal resources. The strategy is to do this by providing the most accurate and complete information possible regarding specific sites that are most favorable for

UCG development. Partners in using these data for marketing will include: coal resource owners — private, State, or Federal; private parties or public officials with interest or responsibility for promoting development of coal resources; and any parties with access to actual development dollars, whether investors or energy companies.

Product Pricing Considerations

Reports generated by the MBMG are publicly available, basically for the nominal cost of reproduction, and even free to the extent that information can be provided via the MBMG website. The payback is eventual development of the deep coal resources.

Business Risk Assessment

The real risk is if we, as a State, are unable to provide developers with basic information that is necessary for them to pursue UCG projects in Montana. Without this study, and perhaps additional investigations, investors and developers will go to states that can provide the necessary information. North Dakota and Wyoming have already completed reports on their deep coal resources (Murphy, 2004; GasTech, 2006), and at least one site in Wyoming is under investigation for a UCG pilot test. This preliminary screening is intended to highlight areas with good potential and to eliminate obviously unsuitable sites – putting the State of Montana in a better position to compete with neighboring states. The potential payback from development of a single site is huge. But, to attract the huge investment required to develop and produce a single UCG site, Montana must be proactive in providing timely and adequate data to those making decisions.

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