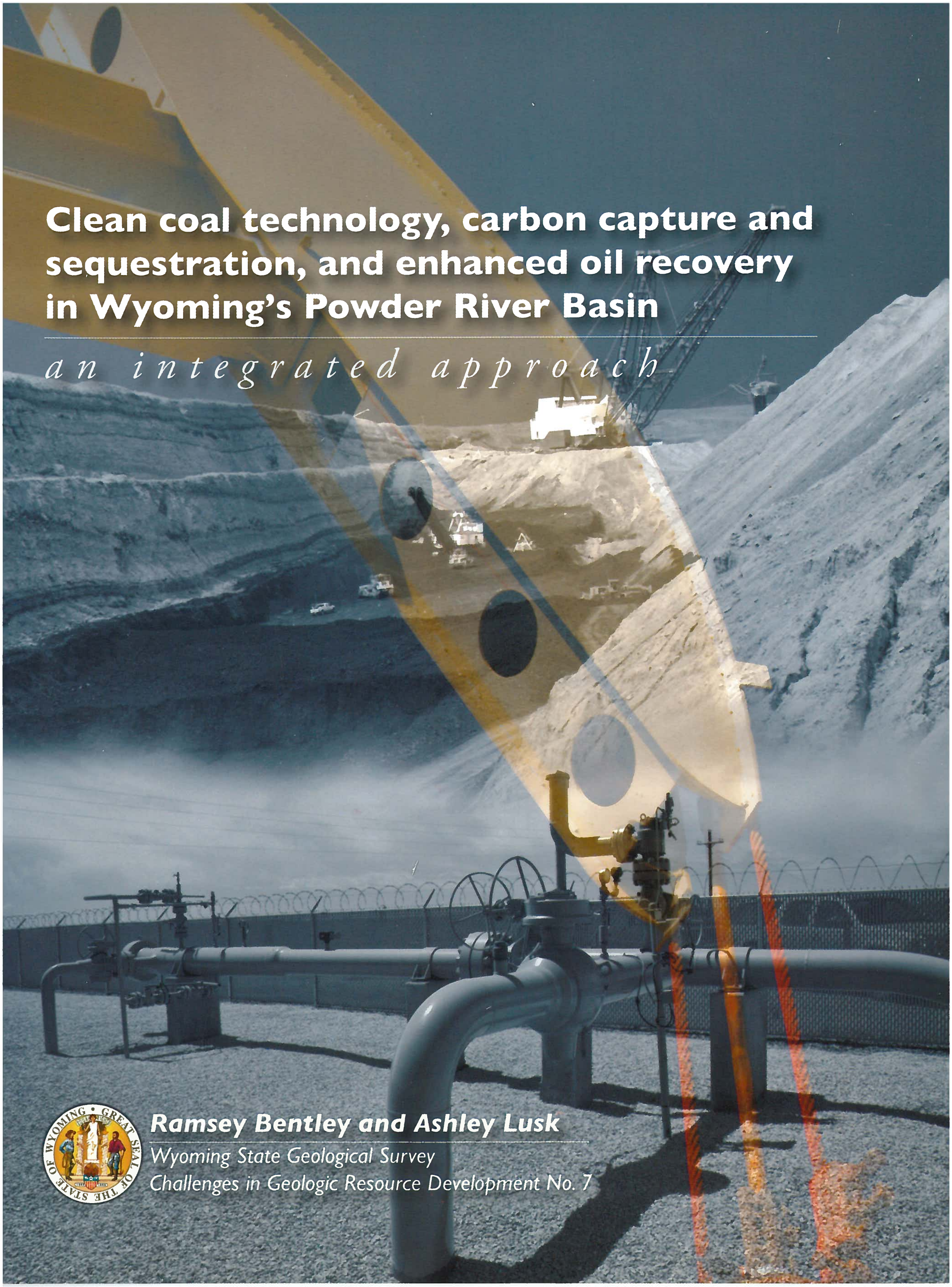

Clean coal technology, carbon capture and sequestration, and enhanced oil recovery in Wyoming's Powder River Basin

an integrated approach

Ramsey Bentley and Ashley Lusk

Wyoming State Geological Survey

Challenges in Geologic Resource Development No. 7

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First printing of 500 copies by Citizen Printing, Fort Collins, Colorado, November 2008.

Clean coal technology, carbon capture and sequestration, and enhanced oil recovery in Wyoming's Powder River Basin, by Ramsey Bentley and Ashley Lusk.
Wyoming State Geological Survey Challenges in Geologic Resource Development No. 7, 2008.
ISBN 1-884589-49-9

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Introduction

In this paper, the Wyoming State Geological Survey (WSGS) outlines a plan to advance clean coal technology, carbon dioxide (CO_2) capture, enhanced oil recovery, and CO_2 sequestration in the Powder River Basin (PRB) of Wyoming. This plan constitutes a new, integrated approach to energy production that reduces the energy expended in the production process, thereby reducing costs while providing for more complete and efficient use of available resources. Implementation would most likely involve industry or an industry/Wyoming state government scientific research collaboration. We explore two strategies for producing clean energy in the PRB: 1) building an integrated gasification combined cycle (IGCC) coal-fueled power plant to produce electricity and/or synfuels, and 2) using underground coal gasification (UCG) in conjunction with an IGCC plant and/or synfuels production. Produced CO_2 would be used for enhanced oil recovery (EOR) in nearby oil fields, then sequestered in the same fields and in other depleted oil and gas fields nearby. The PRB is an ideal location for this type of integrated system because of its abundant coal reserves, industrial infrastructure, and aging oil and gas fields, all very near each other. Shorter pipeline distance requirements, shorter coal supply haul distances, and the ability to use existing well field infrastructure will reduce costs substantially. Use of established power lines and transportation corridors such as roads, highways, and railroads should reduce costs as well. The accompanying map illustrates the proximal locations of the proposed and existing facilities and infrastructure (**Plate 1**).

Nearby Permian-age Minnelusa Formation oil fields will be targeted for EOR, and nearby Cretaceous-age depleted oil and gas fields will be targeted for sequestration. Successful EOR should provide significant return on this integrated process and on the additional investment required to capture and sequester produced CO_2. At present, EOR using CO_2 has helped increase oil production in Wyoming by 10–15 percent. State production increased in 2006 after 21 years of decline, partly due to EOR projects using CO_2 at Salt Creek, Monell, and Wertz-Lost Soldier fields.

Powder River Basin coal resources and fuel source scenarios

With a resource of sub-bituminous coal estimated at 1.18 trillion tons, approximately one quarter of the world's coal, the PRB is a world-class energy reserve. Eight and a half percent of this coal resource is surface mineable, meaning it lies less than 500 feet below ground and is thick enough to make development economically viable. According to WSGS calculations, the surface mineable coal could sustain mining for 200 years at present extraction rates. This high-quality coal is primarily bituminous to subbituminous in rank, low in sulfur, and optimal for coal conversion technologies. Continued development of both surface and deep coal resources, and energy production from both, must proceed in a manner that readily allows for the beneficial use and ultimate sequestration of the tremendous amounts of CO_2 that will be produced. We evaluated this development with the two scenarios outlined below. Each scenario involves an IGCC plant built on state land. The plant sites are located to take advantage of the nearest source of coal and potential geological CO_2 sequestration and EOR sites.

Surface coal source

This approach would involve an IGCC plant, such as the one proposed under the restructured FutureGen initiative announced in early 2008, or a coal to liquids plant. Coal from nearby surface mines would supply the plant. IGCC plants capture CO_2 before combustion occurs, and CO_2 removal costs much less than the flue gas capture required in traditional pulverized coal-fired plants. These IGCC plants reduce other greenhouse gas emissions as well, and are designed to use 20–50 percent less cooling water than conventional plants (Moorstad, 2005). The FutureGen plant DOE calls for in its restructured approach would have a minimum capacity of 300 megawatts, whereas the largest single plant presently operating in the PRB is the 350-megawatt pulverized coal-fired Wyodak plant. In this scenario, we use a plant in the capacity range of 300–335 megawatts. A coal plant of this size emits approximately 2.9 million tons of CO_2 per year [2.6 million metric tonnes/year, 47.3 billion cubic feet (BCF)/year, 130 million cubic feet per day (MMCFD)], or 116 million tons (105.2 million metric tonnes, 1.9 trillion cubic feet (TCF), or 0.105 gigatonnes) over a 40-year plant lifetime. Additionally, CO_2 capture in power plants is energy intensive: power production is effectively reduced by as much as 25 percent. This is the amount of energy required to capture, clean, and pressurize the CO_2.

The proposed IGCC plant site is located on Wyoming state land in sec. 16, T. 48 N., R. 69 W. This site, a highly desirable location with few impediments to surface development, is the same site Wyoming proposed for the FutureGen plant in 2006. The site is central to existing surface mine coal resources, lies within 2.5 miles of Raven Creek, our primary candidate field for EOR, and lies within 29 and 40 miles of proposed final sequestration sites at Kitty and Amos Draw gas fields, respectively.

In-situ coal source

This approach relies on underground coal gasification (UCG), which involves drilling wells into coal seams, injecting air or oxygen and steam, and igniting the coal in-situ. Hot product gases, or "synthetic gases" ("syngas"), are captured in recovery wells and used at the surface to generate power (particularly in IGCC plants), or are converted to liquids to produce ultra-low-sulfur fuels (Montgomery and Morzenti, 2006). Other chemical products include hydrogen for ammonia synthesis or fuel cells, and methanol (Gastech Inc., 2007). Construction of an IGCC plant similar to the one described above is included in this scenario. This UCG-IGCC project would most likely begin at a smaller pre-commercial scale and later expand to commercial operation.

The proposed UCG-IGCC plant site is located on Wyoming state lands in sec. 36, T. 50 N., R. 74 W. Criteria for site selection included a target coal depth of more than 1,000 feet and a coal thickness of more than 100 feet. Surface developments in the section include six producing coal bed natural gas (CBNG) wells, an abandoned wildcat well drilled in 1985, and a gas pipeline running from southeast to northwest. This state section has moderate topographic relief with fairly large, open, level areas suitable for development. Highways and rail lines are located nearby, and target CO_2 sequestration fields lie within 6 to 12 miles. Raven Creek is located 30 miles from the proposed plant site.

Water can be obtained on-site from wells drilled to the Fox Hills-Lance aquifer at either site. Water requirements for the project, 2,500 gallons per minute for more than 40 years, can be adequately met from this aquifer system.

Enhanced oil recovery opportunities

Five Minnelusa oil fields are located within 1.4 and 5.8 miles of the proposed IGCC plant supplied with surface coal: Raven Creek Field (1.4 miles away); Reel Field (3.9 miles away); Dillinger Field (4.3 miles away); Slattery Field (4.6 miles away); and Halverson Ranch Field (5.8 miles away). Production in these fields is declining steeply, and based on geologic criteria outlined by the University of Wyoming's Enhanced Oil Recovery Institute, they are prime candidates for tertiary EOR CO_2 flooding (Xina, 2007).

Raven Creek Field (**Figure 1**) is the oil field nearest the proposed surface-coal-supplied IGCC plant. Discovered in 1960, Raven Creek produces from the Minnelusa "A" sandstone with an average pay zone thickness of 30 feet (pay zone thickness ranges from 13 to 69 feet). Porosity in the pay zone averages 11.6 percent and permeability ranges from 50 to 200 millidarcies (md). The sand is very fine grained, sub-rounded, anhydritic, and dolomitic. The trapping mechanism consists of an updip sand pinchout into a shale barrier with an oil/water contact downdip to the southwest.

Field characteristics of Raven Creek make it a good candidate for a CO_2 miscible flood EOR project. The reservoir depth of 8,300 feet at Raven Creek greatly exceeds the 2,500-foot minimum depth for sufficient reservoir pressure. The oil is 33 degrees API gravity; 27 degrees is the minimum recommended for miscible flood EOR projects (4). A highly successful water flood was initiated in January 1967, and the field has produced approximately 47.0 million standard barrels of oil (MMSTBO) to date. This amounts to 62 percent of the original oil in place (OOIP) of 75.3 MMSTBO. A successful water flood is a good indicator of high potential for a successful CO_2 EOR project (Melzer, 2007).

The relatively low number of wells (63) that penetrate the Raven Creek reservoir reduces the number of potential leakage points for final CO_2 sequestration. Typically, well bores are the most likely leakage points for CO_2 sequestered in oil and gas fields. The reservoir is obviously closed to oil and gas migration by virtue of its existence. The Permian Opeche Shale, a reddish-brown and maroon fine-grained siltstone with demonstrated sealing capacity characteristics, caps the Minnelusa. It ranges from 75 to 160 feet thick. Ninety feet thick at Raven,

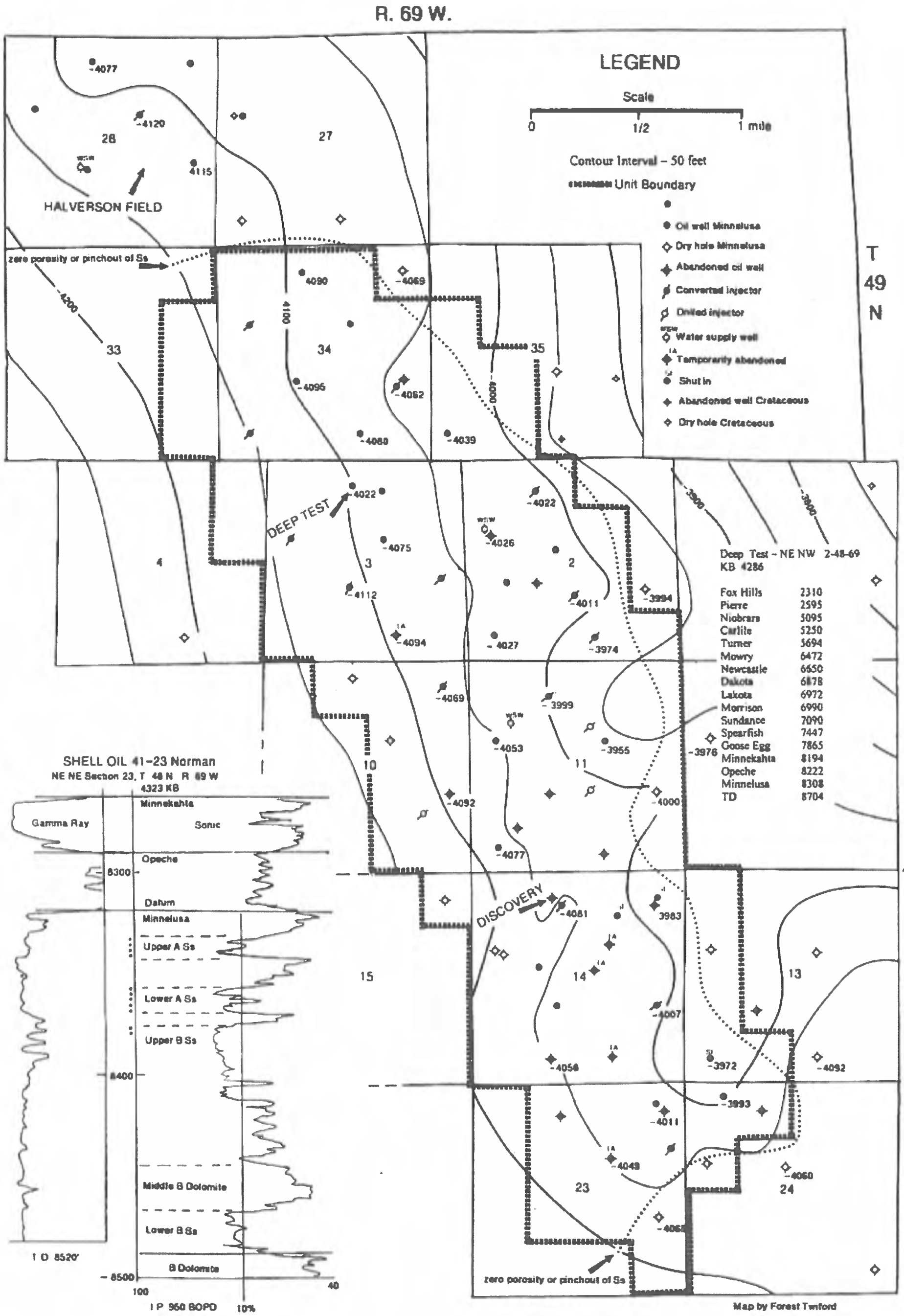

Figure 1. Map showing the approximate boundary of the Raven Creek field, and the locations and types of wells within the field. Contours of the top of the Minnelusa Formation are also shown. Modified from Wyoming Geological Association, 2000, p. 386.

it overlies and encases the many Minnelusa dune sands, which are prolific oil producers in the northeastern Powder River Basin.

Miscible CO_2 flooding is highly desirable in that it is much more efficient than immiscible flooding, and can result in recovery of 10–15 percent of the OOIP (Melzer, 2007). Assuming a recovery factor of 12 percent OOIP, enhanced oil recovery using CO_2 flooding at Raven Creek could produce an additional 9,412,500 barrels of oil. Using the average 2007 price of a barrel of Wyoming crude oil ($58.12), this additional oil would be worth approximately $547 million. For even more optimistic cost returns based on $100/barrel oil pricing, see **Table 1**. To calculate CO_2 usage per unit volume of oil produced, we used a value of eight thousand standard cubic feet per barrel of oil (MSCF/BO) (Wo and Yin, 2007; DOE, 2004). According to our calculations, this EOR project would require approximately 76 BCF (3.94 tonnes) of CO_2. While the EOR process does not use a large amount of CO_2 compared to overall power plant emissions of the gas, the dollar value of the oil produced significantly offsets the cost of CO_2 capture and sequestration.

Table 1. Estimated costs of EOR and sequestration, and revenue from recovered oil, for the proposed fields.

	Raven Creek	**Dillinger, Slattery, Halverson, and Reel Ranch**
12% recovery OOIP (barrels)	9,413,000	21,840,000
CO_2 required (million metric tonnes)	3.94	9.04
Value of oil at $100/barrel	$941 million	$2.184 billion
EOR and sequestration totals		
Barrels recovered		31,253,000
Economic return		$3.125 billion
CO_2 required for EOR		12.98 metric tonnes
CO_2 remaining for sequestration		92 million metric tonnes
Total cost of CCS and EOR		116 million tons (105 million metric tonnes) at $30/ton = **$3.48 billion**

The other four Minnelusa fields exhibit reservoir characteristics similar to those of Raven Creek. Using a 12 percent OOIP EOR recovery factor for these fields, an additional 21,837,500 barrels of oil could be recovered. Again using the average 2007 price of a barrel of Wyoming crude, this oil would be worth approximately $1.3 billion. The EOR process at the four fields would require 174.5 BCF (9.04 million tonnes) of CO_2.

The characteristics that make Raven Creek and the other four Minnelusa fields good candidates for EOR also suit them for CO_2 sequestration (**Table 2**). With total dissolved solids (TDS) levels ranging from 16,000–170,000 milligrams per liter (mg/l), Minnelusa produced water fails to meet the EPA standard of 10,000 mg/l or less for underground sources of drinking water. After EOR, Raven Creek could sequester 6.57 tonnes of CO_2. The other four fields together could sequester 13.9 tonnes of CO_2.

Candidate fields for CO_2 sequestration

Carbon dioxide not used in the EOR process would be sequestered in shallower Cretaceous-age gas fields that produce from the Muddy Sandstone (**Table 2**). Kitty Field and Amos Draw could safely sequester 77.6 tonnes of CO_2. In these fields, the main producing zones within the Muddy Sandstone are compartmented, overpressured units encased by impermeable shale and sand sequences in a complex stratigraphic framework (**Figure 2**). Original overpressuring in the fields indicates an ability to accept and retain large amounts of CO_2 without incurring damage. The Mowry Shale is the primary seal for the Muddy Sandstone

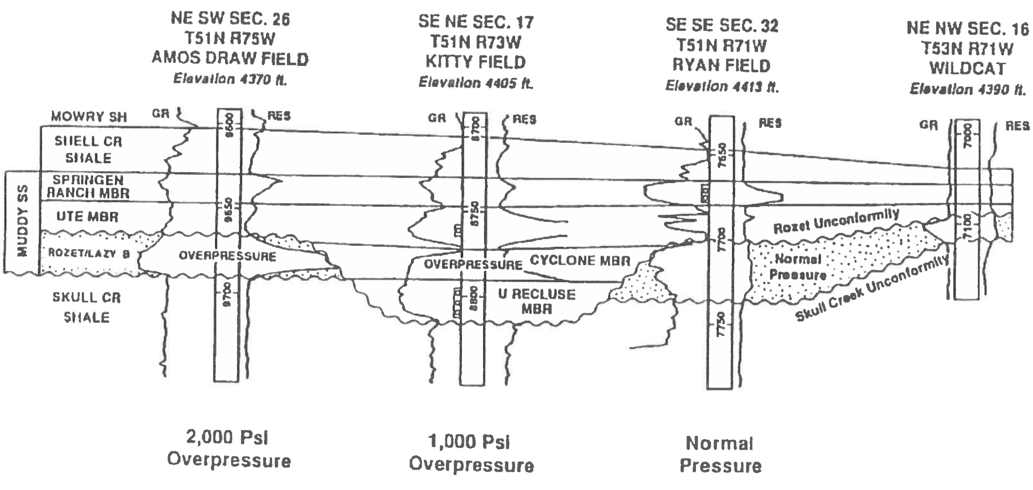

Figure 2. West-east cross section through the Amos Draw and Kitty fields. The cross section displays the pressure regimes within the Muddy Sandstone. The Mowry Shale acts as the primary seal above the Muddy Sandstone, and the Skull Creek Shale seals from below. The Muddy Sandstone is laterally sealed and internally separated into flow compartments by the Rozet unconformity.

Table 2. Capacity and computational parameters for the Minnelusa Formation in selected oil and gas fields in the Powder River Basin, Wyoming.

	Raven Creek	Dillinger Ranch	Slattery	Halverson	Reel
Input parameters					
Formation depth (meters)	2,541	2,798	2,454	2,605	2,593
Formation thickness (meters)	21.6	17.1	24	24.4	16.2
Effective porosity (percent)	11.6	16.3	12.0	13.0	13.6
Temperature (°C)	96.1	110	58	82	86
Dissolved NaCl (molal)	2.05	2.90	1.709	0.265	2.906
Percent of injection (percent)	100	100	100	100	100
Calculated parameters					
Observed formation pressure (Pa)	$2.49 \cdot 10^7$	$2.73 \cdot 10^7$	$2.40 \cdot 10^7$	$2.55 \cdot 10^7$	$2.54 \cdot 10^7$
CO_2 density in reservoir condition (kg/m^3)	$6.03 \cdot 10^2$	$5.81 \cdot 10^2$	$7.85 \cdot 10^2$	$6.83 \cdot 10^2$	$6.63 \cdot 10^2$
CO_2 fugacity coefficient	$5.54 \cdot 10^{-1}$	$5.85 \cdot 10^{-1}$	$4.07 \cdot 10^{-1}$	$4.94 \cdot 10^{-1}$	$5.11 \cdot 10^{-1}$
CO_2 Henry's constant (Pa)	$8.11 \cdot 10^8$	$1.06 \cdot 10^9$	$5.00 \cdot 10^8$	$4.99 \cdot 10^8$	$8.90 \cdot 10^8$
CO_2 aqueous mass fraction (kg/m^3)	$4.15 \cdot 10^{-2}$	$3.70 \cdot 10^{-2}$	$4.79 \cdot 10^{-2}$	$6.17 \cdot 10^{-2}$	$3.57 \cdot 10^{-2}$
Aqueous density (kg/m^3)	$1.05 \cdot 10^3$	$1.07 \cdot 10^3$	$1.06 \cdot 10^3$	$9.92 \cdot 10^2$	$1.09 \cdot 10^3$
Water content (percent)	8.12	11.41	8.40	9.10	9.52
Fixed parameter					
Mass of injected CO_2 (tonnes)	$5.00 \cdot 10^7$	$5.00 \cdot 10^7$	$5.00 \cdot 10^7$	$5.00 \cdot 10^7$	$5.00 \cdot 10^7$
Results					
Formation supercritical CO_2 capacity (kg/m^3)	20.98	28.41	28.27	26.62	27.03
Formation dissolved CO_2 capacity (kg/m^3)	3.54	4.54	4.25	5.57	3.69
CO_2 plume area (km^2)	94.38	88.74	64.06	63.66	100.46
CO_2 plume volume (km^3)	2.04	1.52	1.54	1.55	1.63
Supercritical CO_2 (tonnes)	$4.28 \cdot 10^7$	$4.31 \cdot 10^7$	$4.35 \cdot 10^7$	$4.13 \cdot 10^7$	$4.40 \cdot 10^7$
Dissolved CO_2 (tonnes)	$7.22 \cdot 10^6$	$6.88 \cdot 10^6$	$6.54 \cdot 10^6$	$8.66 \cdot 10^6$	$6.01 \cdot 10^6$
CO_2 (MCF)	$7.63 \cdot 10^5$	$9.26 \cdot 10^5$	$5.96 \cdot 10^5$	$7.88 \cdot 10^5$	$7.14 \cdot 10^5$
CO_2 (square miles)	36.87	34.67	25.02	24.87	39.24
Plume radius (miles)	3.43	3.32	2.82	2.81	3.53
Field extent (square miles)	12.4	5.34	5.18	7.08	2.59
Total CO_2 that could be injected (tonnes)	$6.57 \cdot 10^6$	$3.01 \cdot 10^6$	$4.04 \cdot 10^6$	$5.56 \cdot 10^6$	$1.29 \cdot 10^6$

fields discussed here: it is a thick, persistent regional seal over the Muddy Sandstone. Overlying rock sections of Pierre Shale, Niobrara Shale, and Belle Fourche Shale with a combined thickness of more than 4,000 feet form an additional barrier to vertical migration.

Produced water with salinity ranging from 17,000 to 80,000 mg/l in the Muddy Sandstone precludes these fields from being targeted as possible underground sources of drinking water. In addition, the fields are located in the northeastern Powder River Basin, an area of low seismic potential with an absence of faulting or structural flexure. These factors greatly reduce the potential for leakage of sequestered CO_2. The greatest potential for CO_2 leakage from these fields is along the well bores penetrating the producing/sequestration zone. Completion of producing wells involves cementing the production casing into place. Cement is pumped into the annulus, or void space, between the penetrated formations and the well casing, and provides a seal to prevent formation gases and liquids from entering the annulus space and leaking to other, shallower formations or back to the surface. Cement integrity is important to successful well performance and consequently a good cement job is crucial. Prior to sequestration, well integrity throughout the field areas would be verified.

Amos Draw Complex (includes Andy, Felix, and Alicia field areas)

The Amos Draw Complex (**Figure 3**) produces from a complex stratigraphic unit within the Lower Cretaceous Muddy Sandstone. The sandstone unit is an isolated overpressured compartment found within the basin-wide overpressured shale section in the Powder River Basin. The underlying Skull Creek Shale and the overlying and laterally sealing paleosol of the Rozet unconformity form the compartment at Amos Draw (Surdam et al., 1994; Martinsen, 1994). The producing sands are 20–35 feet thick and cover approximately 28 square miles (47 square kilometers). Drilling began here in 1982, which makes the field fairly young. The complex contains 97 wells which penetrate the producing zone on 160-acre spacing. This is a relatively low number of penetrations, and all locations are obvious. These factors are a plus for CO_2 sequestration. The wells and field infrastructure should be in working order and easily converted for CO_2 sequestration. Amos Draw's CO_2 sequestration capacity is 22.9 million tonnes (**Table 3**).

Kitty Field

Like Amos Draw, Kitty Field (**Figure 4**) produces from a stratigraphically complex group of compartmented sands within the Muddy Sandstone. The sands at Kitty are not as highly overpressured as those at Amos Draw (**Figure 2**). The Rozet unconformity is located lateral to and below the lowermost producing sands, providing compartment seals where the sands are intersected. The sand package at Kitty consists of four discrete units of varying depositional origin, ranging from alluvial to estuarine to tidal channel and barrier island sands. The sands fill the Kitty Valley, one of the larger valley systems that developed during Muddy Sandstone deposition. Net sandstone thickness is just less than 60 feet. Shales lateral to the reservoir sands provide additional seals, and the Mowry Shale caps the entire sequence as a

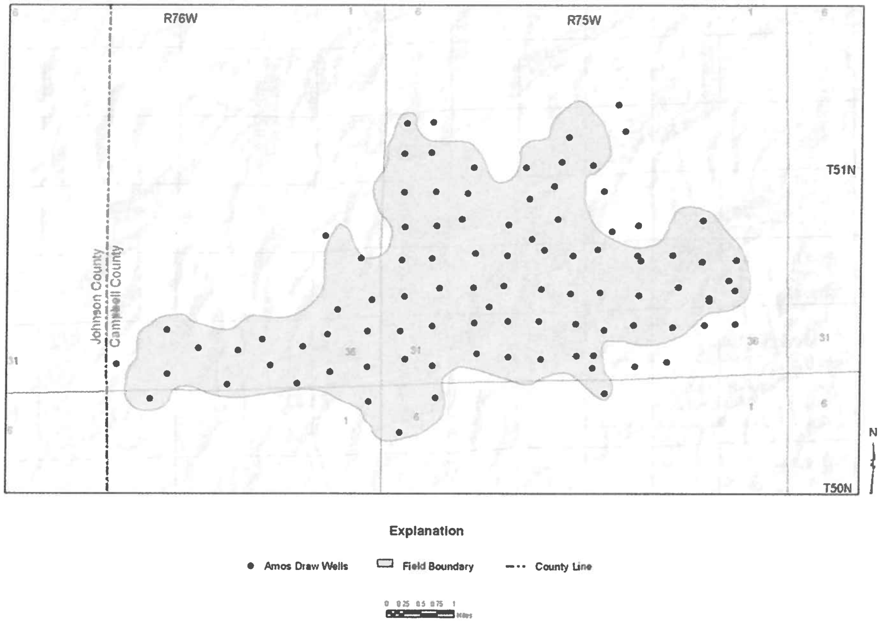

Figure 3. Map showing approximate boundary of the Amos Draw Complex. The Amos Draw Complex comprises the Amos Draw field, the Andy field, the Alicia field, and the Felix field. Well penetrations into the Muddy Sandstone within the field are also shown.

vertical seal (Martinsen, 1994). Since Kitty was discovered in 1965, 338 wells have penetrated the Muddy sequence. Kitty's CO_2 sequestration capacity is 54.7 tonnes (**Table 3**).

Decline curves for the Amos Draw Complex and Kitty Field (**Figure 5** and **Figure 6**) indicate a rapid decline in oil and gas production, and a point of diminishing returns that will probably be reached within the next 5 to 10 years. Use of these fields as sequestration sites should include an economic incentive for field operators. The fields would be prime test sites for the emerging technology of CO_2 sequestration.

Summary, advantages of proposal, and costs

This proposal involves the capture and sequestration of 105 million tonnes of carbon dioxide over a 40-year period. Sequestration at Amos Draw and Kitty would occur concurrently with EOR operations at the Minnelusa Fields. Once EOR was complete at the Minnelusa fields, most likely within 15–20 years, final sequestration would begin there. Amos Draw's capacity of 22.9 million tonnes, and Kitty Field's capacity of 54.7 million tonnes, along with a CO_2 stream to the EOR projects, are more than sufficient to handle plant CO_2 emissions of about 130 MMCFD (**Table 4**).

Table 3. Capacity and computational parameters for the Muddy Sandstone in selected oil and gas fields in the Powder River Basin, Wyoming.

	Kitty Field	Amos Draw Complex
Input parameters		
Formation depth (meters)	2,770	2,913
Formation thickness (meters)	25.6	19.6
Effective porosity (percent)	10	12.5
Temperature (°C)	84.4	126.7
Dissolved NaCl (molal)	0.29	1.37
Percent of injection (percent)	100	100
Calculated parameters		
Observed formation pressure (Pa)	$2.71 \bullet 10^{7}$	$2.85 \bullet 10^{7}$
CO_2 density in reservoir condition (kg/m^3)	$6.91 \bullet 10^{2}$	$5.38 \bullet 10^{2}$
CO_2 fugacity coefficient	$4.92 \bullet 10^{-1}$	$6.30 \bullet 10^{-1}$
CO_2 Henry's constant (Pa)	$5.14 \bullet 10^{8}$	$8.34 \bullet 10^{8}$
CO_2 aqueous mass fraction (kg/m^3)	$6.35 \bullet 10^{-2}$	$5.27 \bullet 10^{-2}$
Aqueous density (kg/m^3)	$9.92 \bullet 10^{2}$	$1.01 \bullet 10^{3}$
Water content (percent)	7.00	8.75
Fixed parameter		
Mass of injected CO_2 (tonnes)	$5.00 \bullet 10^{7}$	$5.00 \bullet 10^{7}$
Results		
Formation supercritical CO_2 capacity (kg/m^3)	20.73	20.19
Formation dissolved CO_2 capacity (kg/m^3)	4.41	4.64
CO_2 plume area (km^2)	77.69	102.71
CO_2 plume volume (km^3)	1.99	2.01
Supercritical CO_2 (tonnes)	$4.12 \bullet 10^{7}$	$4.07 \bullet 10^{7}$
Dissolved CO_2 (tonnes)	$8.77 \bullet 10^{6}$	$9.35 \bullet 10^{6}$
CO_2 (MCF)	$7.79 \bullet 10^{5}$	$9.99 \bullet 10^{5}$
CO_2 (square miles)	30.35	40.12
Plume radius (miles)	3.11	3.57
Field extent (square miles)	85	47
Total CO_2 that could be injected (tonnes)	$5.47 \bullet 10^{7}$	$2.29 \bullet 10^{7}$

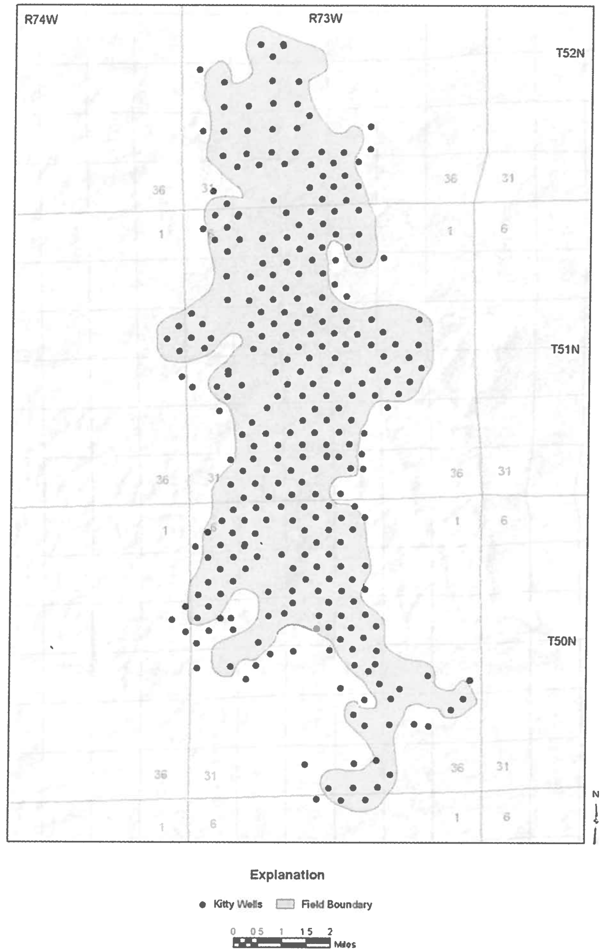

Figure 4. Map showing approximate boundary of Kitty field and well penetrations into the Muddy Sandstone within the field.

One of the greatest strengths of this integrated sequestration/EOR approach is the cost advantage of locating in the Powder River Basin. Depending on oil prices and EOR efficacy, sequestration costs could be substantially reduced or possibly eliminated. Carbon capture and sequestration cost estimates vary, and great uncertainty surrounds possible carbon legislation (CO_2 cap and trade programs and carbon taxation). Regardless of these factors, carbon capture and sequestration will be very expensive, and the amount of CO_2 produced in the burning of fossil fuels, especially coal, is very large. Estimates of capture and sequestration costs vary. At a cost of around $30.00 per ton (available figures are highly variable), this would amount to $87 million per year for the 2.9 million tons needed in the proposed scenario (Melzer, 2007; Guidry, 2008). Over a 40-year period, this would amount to $3.5

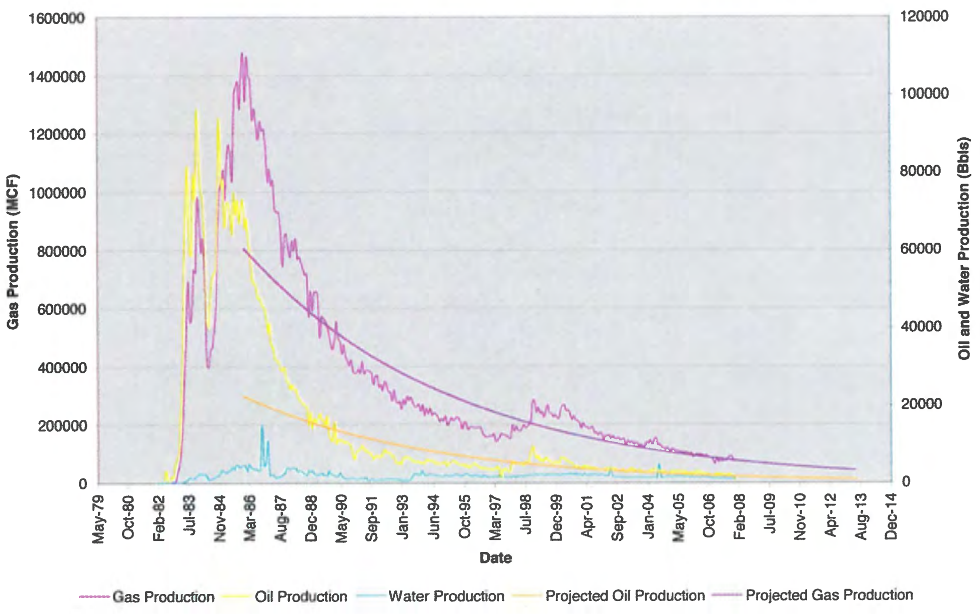

Figure 5. Oil, gas, and water production decline curves for the Amos Draw Complex.

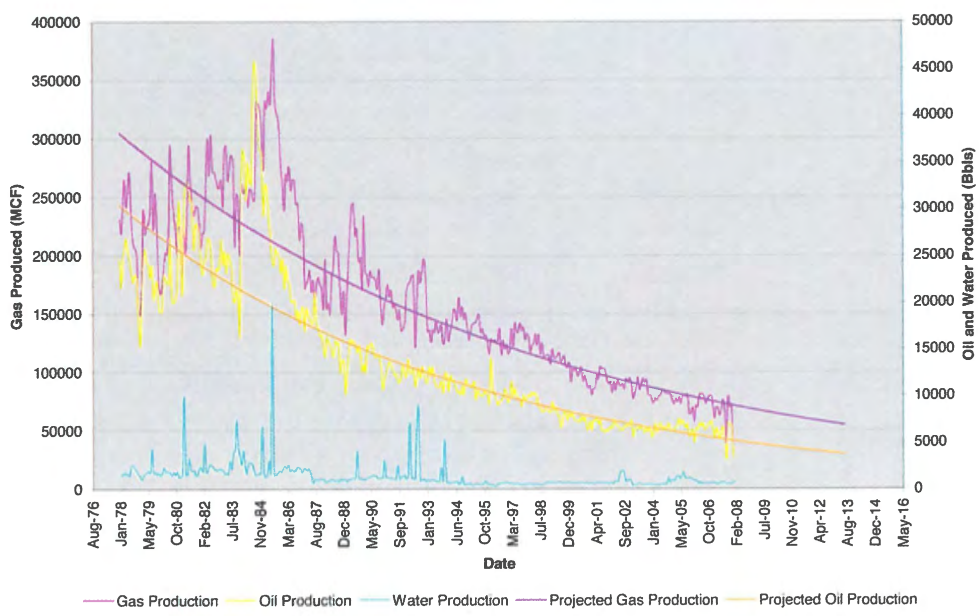

Figure 6. Oil, gas, and water production decline curves for Kitty field.

Table 4. CO_2 capacities of the Minnelusa and Muddy fields.

	Field	**EOR capacity** (millions of tonnes of CO_2)	**Sequestration capacity** (millions of tonnes of CO_2)	**Total CO_2 capacity** (millions of tonnes of CO_2)
Minnelusa	Raven	3.94	6.57	10.51
	Reel/Halverson/ Dillinger/Slattery	9.04	13.90	22.94
Muddy	Amos Draw	–	22.9	22.9
	Kitty	–	54.7	54.7
	Total	**12.98**	**98.07**	**111.05**

billion (note that these are short ton calculations). A summary of estimated costs of sequestration and EOR in the proposed fields, along with revenue from recovered oil, can be found in **Table 1**. Approximately 80 percent of carbon capture costs result from the capture process. Technological advances on this front may reduce this cost (Herzog, 2006).

The approach we describe will minimize costs through the use of new technology and the localization of power and/or fuel production and CO_2 sequestration. IGCC plants provide for easier carbon capture than pulverized coal plants. Reducing the distance CO_2 must be transported should cut costs, as should using existing infrastructure in mature oil and gas fields, and knowing the geologic trapping mechanisms involved (**Table 4**). Most of the technology involved in these scenarios is emerging technology. IGCC plants are just now being developed and tested, and they are very expensive. UCG is a new technology that must be proven. Carbon sequestration is in its infancy. Many questions remain about the effects of CO_2 on existing pipeline infrastructure, well bore integrity, and geologic reservoir rock reactions. The scenarios we propose are fairly small-scale in terms of power generation and CO_2 quantity, but the experimental nature of the project requires this. Success will point to one method capable of dealing with relatively small-scale CO_2 production, and the integrated technology presented here could then be applied on a larger scale in the PRB and other Wyoming basins.

ACKNOWLEDGEMENTS

The authors would like to thank Governor Dave Freudenthal and Energy and Telecommunications advisor Rob Hurless for their encouragement and support. Thanks also to Ron Surdam for creating the integrated concept and strategy described in this report. Dick Jones, Robert Kirkwood, Dave Lucke, and Phyllis Ranz provided invaluable assistance with the map featured in this report. Rod DeBruin's extensive knowledge of Wyoming's oil and gas resources was tremendously helpful, as was the oil and gas map of Wyoming he compiled. Finally, the authors would like to thank Meg Ewald for editorial assistance and graphic design.

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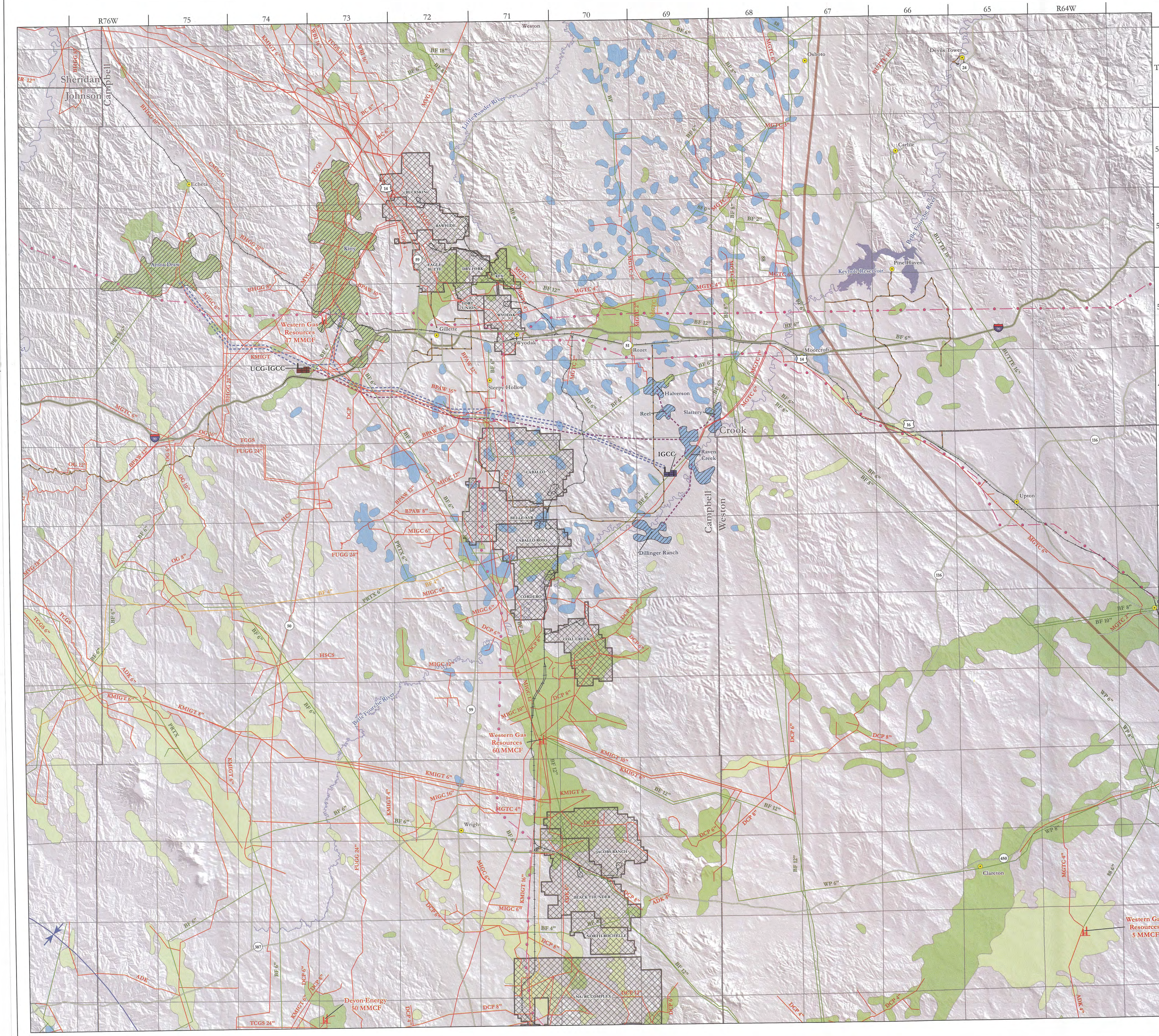


WYOMING STATE GEOLOGICAL SURVEY
Ronald C. Surdam, State Geologist
Laramie, Wyoming

Geology -- Interpreting the past to provide for the future

CHALLENGES IN GEOLOGIC RESOURCE DEVELOPMENT NO. 7, PLATE 1
Clean coal technology, carbon capture and sequestration, and enhanced oil recovery in the Powder River Basin, Wyoming

CLEAN COAL TECHNOLOGY, CARBON CAPTURE AND SEQUESTRATION, AND ENHANCED OIL RECOVERY IN THE POWDER RIVER BASIN, WYOMING

by
Ramsey D. Bentley and Ashley E. Lusk
2008

EXPLANATION

LIST OF ABBREVIATIONS FOR PIPELINE OPERATORS

88	- Eighty Eight
ADK	- Anadarko
BC	- Bitter Creek
BF	- Belle Fourche Pipeline
BHGG	- Big Horn Gas Gathering
BPAW	- Bear Paw
CMSGG	- CMS Gas Gathering
DCP	- DCP Midstream
FUGG	- Fort Union Gas Gathering
HCS	- Hoe Creek System
HSCS	- House Creek System
KMIGT	- Kinder Morgan IGT
MGTC*	- McCulloch Gas Transmission Company
MIGC*	- McCulloch Interstate Gas Company
MVG	- Maverick Gas
OG	- OptiGas
PRTX	- Powder River (Texaco)
RR	- RIM Rock
TCGS	- Thunder Creek Gas Services, LLC.
WBI	- Williston Basin Interstate
WP	- Wyoming Pipeline
WRC	- Wyoming Refining Company

*These pipelines were purchased by Western Gas Resources, but the abbreviations MGTC and MIGC are retained as the designations for these two subsidiaries of Western Gas Resources.

PREDOMINANT AGE OF RESERVOIR ROCKS

(Outlined areas are oil and gas field boundaries)

UPPER CRETACEOUS

LOWER CRETACEOUS

PERMIAN-PENNSYLVANIAN

PIPELINES

BF 16" — Crude oil; operator and diameter in inches

KNGG 6" — Natural gas; operator and diameter in inches

WYCO 10" — Refinery or natural gas processing plant products; operator and diameter in inches

Proposed pipeline from power plant to field for CO_2 sequestration

Proposed pipeline from power plant to field for enhanced oil recovery

OTHER SYMBOLS AND DESIGNATIONS

Possible carbon sequestration or enhanced oil recovery site; current field name shown

Wyodak — Active coal mine permit areas and mine name

Approximate boundary of Powder River Basin

KN ENERGY 96 MMCF — Natural gas processing plant. Notation includes operator and capacity in millions of cubic feet (MMCF) per day. Locations are approximate.

Proposed Integrated Gasification Combined Cycle (IGCC) power plant

Proposed Underground Coal Gasification (UCG)-IGCC power plant

Approximate location of Powder River Basin synclinal axis

230 kilovolt (kV) power lines

Railroad

90 — Interstate highway

14 — Federal highway

59 — State highway

Local road

County boundary

Cities

DATA SOURCES

GEOLOGIC COVERAGES

Basin boundary modified and adapted from Love and Christiansen (1985).

Basin axis: De Bruin (1996).

OIL AND GAS COVERAGES

Field locations and boundaries: De Bruin (2007); Wyoming State Geological Survey (2006) (unpublished), using production data from the Wyoming Oil and Gas Conservation Commission (2007).

Oil, natural gas, and product pipelines; natural gas processing plants; refineries: Wyoming State Geological Survey (2006) (unpublished) and the Wyoming Pipeline Authority (2008).

BASE MAP COVERAGES

City locations: ESRI spatial dataset (2006).

County boundaries: Wyoming Department of Revenue (2003).

Highways and roads: Wyoming State Geological Survey (2002); U.S. Census TIGER files (1997).

Mine permit areas and mine names: Ed Heffern, U.S. Bureau of Land Management State Office, Cheyenne, Wyoming.

Power lines: Wyoming Public Service Commission.

Public Land Survey System (PLSS): U.S. General Land Office and BLM (2004).

Railroads: U.S. Census TIGER files (1995).

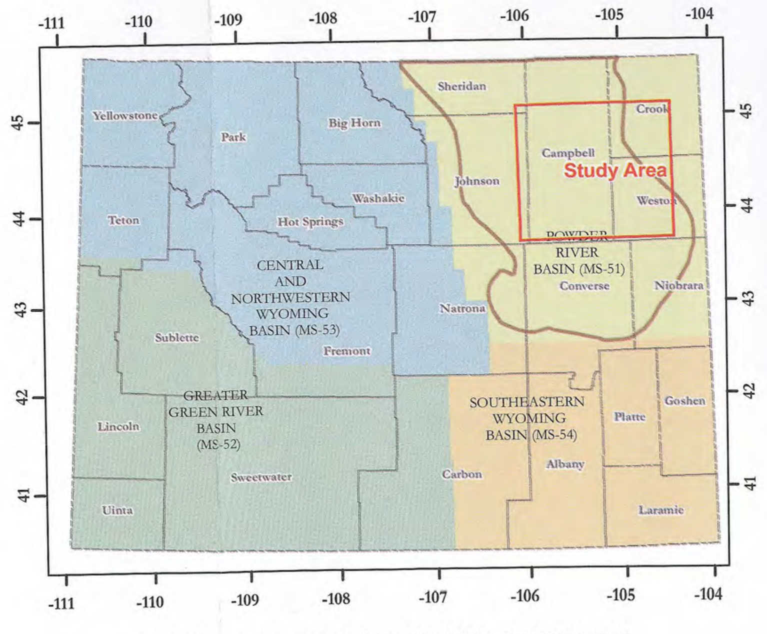
N

SCALE 1:200,000

1 inch equals approximately 3.2 miles

0 5 10 15 Miles

0 5 10 15 20 Kilometers



INDEX TO OIL AND GAS FIELD MAPS OF WYOMING AND LOCATION OF STUDY AREA

[Number indicates Wyoming State Geological Survey Map Series (MS)]

Modified from: De Bruin, R.H., 2007, Oil and gas fields map of the Powder River Basin, Wyoming: Wyoming State Geological Survey Map Series (MS) 51, scale 1:350,000, color.

DISCLAIMERS

ISBN 1-884589-49-9
WSGS-CS7-08