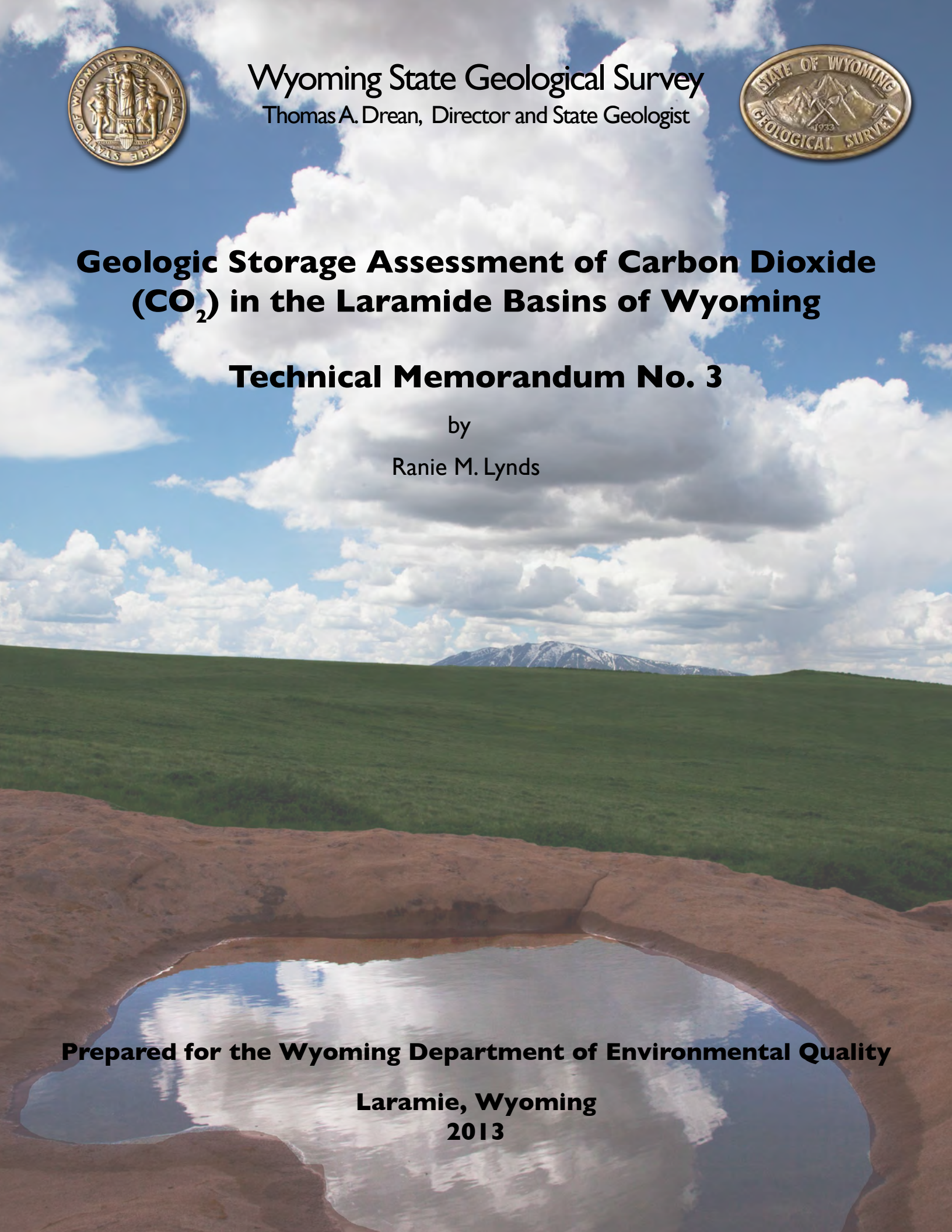

Wyoming State Geological Survey
Thomas A. Drean, Director and State Geologist

Geologic Storage Assessment of Carbon Dioxide (CO_2) in the Laramide Basins of Wyoming

Technical Memorandum No. 3

by

Ranie M. Lynds

Prepared for the Wyoming Department of Environmental Quality

Laramie, Wyoming
2013

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Cover: View of Elk Mountain from Wagon Hound Road, Albany County, Wyoming. *Photo by Robert Kirkwood at WYMAPIT Photography.*

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June 2013

Ranie M. Lynds

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Wyoming State Geological Survey, P.O. Box 1347, Laramie, Wyoming 82073-1347

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Executive Summary

The primary purpose of this technical memorandum is to evaluate and summarize the geologic storage potential of carbon dioxide (CO_2) within the Laramide basins of Wyoming. The Laramide basins were formed during a major geologic event known as the Laramide orogeny, approximately 80–55 million years ago. The Laramide basins assessed for this study include the Greater Green River, Wind River, Bighorn, Powder River, Hanna, and Denver basins.

Carbon dioxide is a greenhouse gas that is released through many natural and anthropogenic processes, including the burning of fossil fuels. In Wyoming, the bulk of electricity-generating plants burn the fossil fuel coal, which is primarily extracted from the Powder River Basin and Greater Green River Basin. Capturing CO_2 emissions from these plants for permanent underground storage in geologic formations offers an environmental as well as potential economic incentive; CO_2 would be prevented from entering the atmosphere and Wyoming would provide low-emissions coal-sourced energy to much of the country.

In fact, Wyoming was the first in the nation to establish regulations for the storage of CO_2. In 2008, the state Legislature passed two laws establishing underground storage rights and a framework for state regulation of carbon storage.

Effective geologic storage of CO_2 requires several site-specific attributes. These attributes include a proper trap (generally structural or stratigraphic), a porous and permeable sequestration zone, an overlying competent seal with very low permeability, under-pressured to normally pressured reservoirs, and the potential to displace significant amounts of saline reservoir fluids. Ideally, subsurface sequestration depths should be greater than 914 m (3,000 feet) to maintain CO_2 in a supercritical state and less than 3,962 m (13,000 feet) to correspond to CO_2-pipeline pressures that would not require significant additional compression at the surface before injection. Within a single basin, there can be several potential storage locations and formations.

This assessment evaluates four distinct methods of CO_2 storage in each Laramide basin. The first method is storage in deep saline aquifers. Saline aquifers, for the purpose of CO_2 storage, are characterized as aquifers with total dissolved solid concentrations greater than 10,000 mg/L, well above the 500 mg/L national standards for safe drinking water. Saline aquifer storage assessment generally focuses on a specific geologic formation, frequently encompassing a large area. This assessment of the Laramide basins follows the guidelines specified in the "CO_2 Atlas III," published by the National Energy Technology Laboratory in 2010. This assessment is limited by the generality of the guidelines, as well as the structure of the Laramide basins. As implied by the term, "basins" have a bowl-shaped geometry, with the deepest part generally near the center. This geometry is not conducive to large-scale and permanent CO_2 storage, as CO_2 will over time migrate up-dip toward the basin margins and potentially escape. The rate of migration varies for each locality, and may be slow enough to consider CO_2 storage a relatively long term proposition (decades to thousands of years), but likely would not be a permanent solution.

The second assessment method is for storage in currently producing oil and gas reservoirs once the reservoirs have reached their economic limit. Hydrocarbon reservoirs have effective traps with proven seals, and thus represent a high potential for effectively storing CO_2 in a more permanent manner. This study determines the largest, or most productive, fields in each of the basins, and assumes these fields have the largest available pore space for storing CO_2. In many cases, the fields are currently and actively producing hydrocarbons. These fields are not depleted, and it is not the intent of this study to imply that CO_2 storage should occur in these fields at this time. Rather, these are potential future reservoirs for CO_2 storage; geologic CO_2 storage will not be a viable option until hydrocarbon recovery in these fields is no longer economically feasible. This method determines the mass of CO_2 that can be stored in these hydrocarbon fields from past production history, and does not account for additional pore space created through future production. This assessment is valid for production reported to the Wyoming Oil and Gas Conservation Commission through 2011, and incorporates assumptions that would need to be independently

verified, on a case-by-case basis, for CO_2 storage in a specific reservoir in a specific field.

The third method of assessment is CO_2 storage as a consequence of enhanced oil recovery, or EOR. Enhanced oil recovery has been an active practice by the petroleum industry in Wyoming since the mid-1980s as a tertiary form of oil recovery. Carbon dioxide is injected into a declining oil reservoir to increase recovery of the oil remaining in the reservoir. Once EOR has been completed and the oil has been removed, the reservoir could become a trap for the CO_2 used in the project. This assessment reviews the CO_2-EOR studies by the Wyoming Enhanced Oil Recovery Institute and summarizes their predicted CO_2 demand in specific reservoirs throughout the state.

The final assessment includes CO_2 storage through enhanced coalbed natural gas (methane) recovery, or CO_2-ECBM. Storage through CO_2-ECBM takes advantage of the preferential adsorbtion of CO_2 to coal at the expense of methane gas; injecting CO_2 into coalbed natural gas reservoirs increases methane production. The significant coalbed natural gas fields in the Greater Green River, Wind River, Powder River, and Hanna basins are potential targets for future CO_2-ECBM, and the theoretical mass of CO_2 that can be stored in coal beds within these basins is summarized in this assessment from work reported in the literature.

Of the assessed methods, CO_2-EOR appears to have the greatest near-term potential to geologically and economically store CO_2 in Wyoming. This is a proven method of storage and in many cases the pipeline infrastructure is already in place. However, the pipeline infrastructure must be expanded before large-scale CO_2-EOR in the highest-priority locations, including the Powder River, Bighorn, and Greater Green River basins, can take place. Only future economics, associated with a long term increase in oil price, will support and drive this development. There are currently six CO_2-EOR projects in Wyoming. Assuming that CO_2 demand is equal to storage, this assessment finds that Wyoming's candidate reservoirs for CO_2-EOR could potentially store 30 years of CO_2 emissions from Wyoming electricity-generating power plants at 2011 emission levels.

Saline aquifers have the potential to store the largest volumes of CO_2 in one location, minimizing the need for extensive pipeline development. The electricity-generating plants with the highest CO_2 emissions reside in the Powder River and Greater Green River basins. This CO_2 storage assessment finds that both basins can theoretically store anthropogenic CO_2 produced from these plants for many years, yet only the Greater Green River Basin has the large geologic traps required for economic longer-term CO_2 storage. These traps include the Rock Springs uplift, Moxa arch, and possibly the Wamsutter and Cherokee Ridge arches. Further evaluation and characterization of these traps is essential to determine the extent of the obstacles associated with CO_2 storage in these locations. Possible and likely obstacles include extreme formation depths, inadequate porosity and permeability, fractured reservoirs, faulted and compartmentalized reservoirs, aquifer salinity less than the required minimum concentration, and significant saline water production at the surface that will require an appropriate disposal solution, to name a few. The Carbon Management Institute at the University of Wyoming is currently evaluating the Rock Springs uplift and Moxa arch, which appear to be the highest potential locations for CO_2 storage in deep saline aquifers in Wyoming.

Carbon dioxide storage in existing hydrocarbon reservoirs has potential, yet this storage method is less attractive because the volume of CO_2 that can be held in each individual field is small. This assessment finds that the largest fields in the Laramide basins can likely store no more than 15 years of CO_2 emissions from Wyoming electricity-generating power plants at 2011 emission levels. Economic and efficient CO_2 storage will require tens of years of storage of CO_2 emissions from power plants.

If CO_2 storage through CO_2-ECBM were to occur in Wyoming, it would probably first occur in the Powder River Basin, which hosts large coalbed natural gas fields with significant CO_2 storage capacity. The CO_2 storage capacity of coalbed natural gas fields of the Greater Green River Basin follows

closely on the heels of the Powder River Basin, and may also be an ideal location for CO_2-ECBM due to its proximity to the natural CO_2 source in western Wyoming. However, CO_2-ECBM is not currently employed anywhere in Wyoming due to a lack of economic viability at current and near-term methane prices. There is potential for this technology and only time will tell if it is economically feasible and utilized. This approach only represents a permanent storage solution if the coal is never mined.

Wyoming is currently in a challenged position regarding long-term geologic CO_2 storage. Technically, CO_2 storage is feasible, by any of the aforementioned methods. The hydrocarbon industry routinely injects and/or stores water, natural gas, and CO_2 in subsurface reservoirs. Although this technology must be slightly modified to accommodate CO_2 storage, the technology is not the limiting factor. Instead, the primary issues are economics and CO_2 source. Estimates for the cost of geologic CO_2 storage vary widely, yet investment, operating, and monitoring costs can be significant and can only be offset by potential economic incentives, such as additional state and federal subsidies, or natural changes in market conditions. Already greenhouse gas emissions from fossil fuel power plants are becoming more regulated, as seen in the proposed U.S. Environmental Protection Agency rule regarding CO_2 emission standards for new power plants (EPA-HQ-OAR-2011-0660, March 27, 2012; delayed April 13, 2013).

Short and long-term sources of CO_2 in Wyoming also remain a significant issue. The only existing utilized source is geologic; CO_2 is produced from subsurface wells, as a byproduct of helium and methane extraction, and distributed via pipelines. This practice, although economic for the purpose of enhancing oil recovery through CO_2-EOR, is in part contradictory to the fundamental goal of geologic CO_2 storage which is to reduce greenhouse gas emissions. Since CO_2 storage is a side effect and not the primary goal of CO_2-EOR (which is economic oil recovery), current CO_2-EOR projects do not use anthropogenic CO_2. The capture and use of CO_2 from power plant emissions would likely be more costly than the current use of CO_2 from underground reservoirs. However, the basic CO_2 delivery pipelines are in place. Adding to or replacing the CO_2 source in these pipelines from geologic to anthropogenic remains a distinct yet potentially economically challenged possibility and would allow for CO_2-EOR to be the first successful storage of anthropogenic CO_2 in Wyoming.

The issues and challenges raised by this study should be addressed in detail before proceeding with long-term geologic CO_2 storage in Wyoming. These issues and challenges are significant, yet so is the potential CO_2 storage resource of Wyoming's basins. If these issues and challenges can be economically alleviated, the future ability to capture and store power plant emissions could place Wyoming at the forefront of sustainable electric power generation.

Chapter 1

Introduction

Wyoming's abundant coal resources provide 7 percent of the energy produced in the United States. Power plants fueled by coal and natural gas are point-sources of the greenhouse gas carbon dioxide (CO_2). As greenhouse gas emissions become more regulated, developing the technology to capture, compress, and store CO_2 emissions in geologic traps could be fundamental to Wyoming's future economy. Research into the feasibility of long-term CO_2 storage in deep saline aquifers, depleted oil and gas reservoirs, oil reservoirs employing enhanced oil recovery with CO_2 (CO_2-EOR), and natural-gas coal seams through enhanced coalbed natural gas (methane) recovery with CO_2 (CO_2-ECBM), is a first step.

This study of geologic CO_2 storage is timely in the wake of the recently proposed U.S. Environmental Protection Agency rule regarding CO_2 emission standards for new power plants (EPA-HQ-OAR-2011-0660, March 27, 2012; delayed April 13, 2013). If implemented, the rule will directly impact Wyoming's economy. In 2011, Wyoming's coal accounted for 40 percent of the coal mined in the United States. Eighty-six percent of the electricity generated within the state was from coal (U.S. Energy Information Administration, 2012). Continuing future electrical generation at 2011 levels will require significant emissions reductions. One approach to reduce emissions is to capture, compress, inject, and ultimately store the emissions (primarily CO_2) underground.

However, the viability of geologic CO_2 storage remains unproven. The complex task of estimating the theoretical CO_2-storage resource in Wyoming is straightforward when compared to the challenges associated with the economic, regulatory, and technical feasibility of the CO_2 storage process. If these challenges can be further investigated and adequately addressed, Wyoming could have the economic benefit of increased oil production through CO_2-EOR, increased gas production through CO_2-ECBM, and place itself at the cutting edge of research into confining systems for long-term, anthropogenic CO_2 storage.

The costs for this project include funding from a Federal Abandoned Mine Lands Grant (CFDA 15.252) provided by the U.S. Department of Interior, Office of Surface Mining, and administered by the Wyoming Department of Environmental Quality. This project was conducted by personnel at the Wyoming State Geological Survey.

Purpose and Scope

The subject of this investigation is the potential for long-term geologic storage of anthropogenic CO_2 within the Laramide basins of Wyoming. Laramide basins are fault-bounded basins that formed between basement-cored mountain ranges during the Late Cretaceous to Early Eocene Laramide orogeny (~80–55 Ma). These basins formed by basement-rooted reverse faults with as much as tens of kilometers of vertical offset. Laramide basins are found from northern Mexico through Canada. The primary Laramide basins in Wyoming are the Greater Green River, Wind River, Bighorn, Powder River, Hanna, Denver, Laramie, and Shirley basins.

This report focuses on the Greater Green River, Wind River, Bighorn, Powder River, Hanna, and Denver basins (Fig. 1-1), and provides geologic maps, cross sections, type logs, and maps of commercially available seismic profiles, as well as descriptions of the storage and confining zones. A general analysis of the mass of CO_2 that could possibly be stored in each basin in deep saline aquifers and in hydrocarbon reservoirs is followed by a discussion of the potential for CO_2 storage via enhanced oil recovery (EOR) and enhanced coalbed natural gas (methane) recovery (ECBM). The aim of this document is to serve as a general reference to generate and support future site-specific research.

Geologic CO_2 storage, otherwise known as CO_2 sequestration, has been proposed as a way to reduce future emissions of greenhouse gases, namely CO_2. The long-term strategy is to collect and store CO_2 that is currently released to the atmosphere from sources such as coal-fired power plants, chemical plants, refineries, natural gas plants and compressor stations. In principle, CO_2 is injected into the subsurface of a basin or reservoir as a supercritical fluid, where it remains in place for an appropriate amount of time (frequently defined as greater than 10,000 years; Lindeberg, 2002). There are

Figure 1-1. Generalized map of Wyoming highlighting the Laramide basins studied in this assessment.

numerous options for where and how to store CO_2 within a basin, including abandoned and unmineable coal seams, depleted or uneconomic petroleum reservoirs, and saline aquifers, defined as aquifers containing groundwater with greater than 10,000 milligrams per liter (mg/L) total dissolved solids, which is significantly above the national standards of 500 mg/L for drinking water. This study focuses on existing oil and gas reservoirs, unmineable coal seams, and saline aquifers.

Several site-specific attributes are necessary for an initial assessment of a deep saline aquifer or a hydrocarbon reservoir for CO_2 storage. These attributes include a proper trap (generally structural or stratigraphic), a porous and permeable sequestration zone, an overlying competent seal with very low permeability, under-pressured to normally pressured reservoirs, and the potential to displace significant amounts of the saline reservoir fluids. Sequestration depths must be greater than 914 m (3,000 feet) to maintain CO_2 in a supercritical state and less than 3,962 m (13,000 feet) to correspond to CO_2-pipeline pressures that would not require additional compression at the surface before injection (Burruss and others, 2009; Brennan and others, 2010). Within a single basin, there can be several potential storage locations and formations.

This study does not consider the technical feasibility or the legal and regulatory framework for CO_2 storage. Rules for geologic sequestration of CO_2, or Class VI underground injection wells, are regulated by the U.S. Environmental Protection Agency (EPA). All wells with the intent of CO_2 storage, which exclude CO_2-EOR wells, must comply with EPA Class VI regulations.

Organization

This Technical Memorandum is organized to allow the reader to quickly reference information for geologic CO_2 storage in all of Wyoming, and in specific basins, as well as the assumptions and background material necessary for an investigation of this scope. The layout is as follows:

Chapter 2: Carbon Dioxide in Wyoming. Chapter 2 summarizes the sources of CO_2 in Wyoming and the infrastructure that has developed to transport CO_2 in pipelines throughout the state. This chapter also discusses the contemporary uses for CO_2, including CO_2-EOR and CO_2-ECBM.

Chapter 3: Storage and Confining Zones. Chapter 3 provides brief descriptions of the formations most likely to become storage and/or confining zones in any future geologic CO_2 storage projects. The presence of a formation in a basin does not imply CO_2 storage or confining potential; instead the formation must be evaluated for each basin.

Chapter 4: Methodologies for CO_2 Storage Resource Calculations. Chapter 4 describes the equations and primary assumptions used to calculate the CO_2 storage capacity in saline aquifers and petroleum reservoirs.

Chapter 5: Greater Green River Basin. Chapter 5 discusses geologic CO_2 storage in the Greater Green River Basin. This discussion includes saline aquifers with their respective storage zones, confining zones, and traps; storage in hydrocarbon reservoirs with field-specific information; CO_2-EOR; and CO_2-ECBM. CO_2 storage resource calculations are reported for saline aquifers and hydrocarbon reservoirs, as well as storage estimates from other workers for CO_2-EOR and CO_2-ECBM.

Chapter 6: Wind River Basin. Chapter 6 discusses geologic CO_2 storage in the Wind River Basin. The discussion includes saline aquifers with their respective storage zones, confining zones, and traps; storage in hydrocarbon reservoirs with field-specific information; CO_2-EOR; and CO_2-ECBM. CO_2 storage resource calculations are reported for saline aquifers and hydrocarbon reservoirs, as well as storage estimates from other workers for CO_2-EOR and CO_2-ECBM.

Chapter 7: Bighorn Basin. Chapter 7 discusses geologic CO_2 storage in the Bighorn Basin. The discussion includes saline aquifers with their respective storage zones, confining zones, and traps; storage in hydrocarbon reservoirs with field-specific information; and CO_2-EOR. CO_2 storage resource calculations are reported for saline aquifers and hydrocarbon reservoirs, as well as storage estimates from other workers for CO_2-EOR.

Chapter 8: Powder River Basin. Chapter 8 discusses geologic CO_2 storage in the Powder River Basin. The discussion includes saline aquifers with their respective storage zones, confining zones, and traps; storage in hydrocarbon reservoirs with field-specific information; CO_2-EOR; and CO_2-ECBM. CO_2 storage resource calculations are reported for saline aquifers and hydrocarbon reservoirs, as well as storage estimates from other workers for CO_2-EOR and CO_2-ECBM.

Chapter 9: Hanna Basin. Chapter 9 discusses geologic CO_2 storage in the Hanna Basin. The discussion includes the reported CO_2 storage estimates from other workers for CO_2-ECBM.

Chapter 10: Denver Basin. Chapter 10 discusses geologic CO_2 storage in the Denver Basin. The discussion includes the reported CO_2 storage estimates from other workers for CO_2-EOR.

Chapter 11: Summary and Implications. Chapter 11 summarizes the storage assessment for each basin and focuses on the implications of geologic CO_2 storage in the Laramide basins of Wyoming.

Basin Boundaries

The basin boundaries and the area they encompass are defined, in this study, to encompass both the structural and energy basin boundaries (Fig. 1.1). For consistency, the topographical basin boundaries were chosen by compiling the lowest-order hydrologic unit boundaries (as defined by the U.S. Geological Survey, 2012) that cover the area of interest. Hydrologic units define drainage basins. Hydrologic units are hierarchically subdivided and numerically coded by region (2 digits), subregion (4 digits), accounting unit (8 digits), and cataloging unit (12 digits) (Seaber and others, 1987). 4-digit unit boundaries were used whenever possible. A combination of 4- and 8-digit unit boundaries are most common for basin boundaries in this study. 12-digit unit boundaries were used for difficult to define boundaries, such as the southern border of the Powder River Basin. Since most of the activity in a basin is confined to the energy basin boundary, such as hydrocarbon production and potential CO_2 storage zones, this approach to defining basin boundaries by hydrologic units successfully captures the larger area of interest and allows the reviewer to evaluate the comprehensive study area.

Previous Investigations

Storing the emissions from fossil fuel power plants underground is an idea that has seen active research for almost 20 years. There are numerous deep saline aquifer test projects around the world in various stages of development. The most well-known include the Sleipner and Snøhvit projects in Norway, and In Salah in Algeria. The United States hosts seven regional partnerships organized to study geologic CO_2 storage. A handful of these partnerships are approaching or actively involved in the demonstration phases of CO_2 storage. These pilot projects are small and generally inject less than 1 million metric tons of CO_2.

In Wyoming, CO_2 sequestration tests are currently under way in the Greater Green River Basin. A collaborative working group that includes the University of Wyoming and several industry partners, with funding by the U.S. Department of Energy, is actively analyzing the northeastern flank of the Rock Springs uplift for CO_2 potential (e.g., Surdam and Jiao, 2007; Surdam and others, 2009; Campbell-Stone and others, 2010; Surdam, 2011; Surdam and others, 2012). As of the writing of this report, the project is nearing completion of Phase I (characterization). Phase II (test injection) will commence pending funding. Tests and results from this pilot study may guide future CO_2 sequestration policy and practice throughout Wyoming.

Laramide Basins: Geologic and Tectonic History

The rocks exposed throughout much of Wyoming record a long and complex geologic history. The Wyoming Craton, one of the oldest cratons in the world, is purportedly older than 3.3 billion years (Chamberlain and Mueller, 2007). Most Precambrian crystalline rocks in Wyoming are exposed in the cores of the Laramide uplifts (Fig. 1-1). Phanerozoic deposition (sedimentation) began approximately 541 million years ago. It is this Phanerozoic sedimentary sequence that is of interest for geologic CO_2 storage (Plate 1).

Paleozoic Era

The Paleozoic strata in Wyoming preserve multiple transgressive and regressive cycles of sedimentation on a stable shelf, with continental-derived rocks to the east and the marine depositional basin to the west. Numerous unconformities within these strata indicate either non-deposition, or periods of large-scale erosion. Paleozoic-age rocks in Wyoming include those from the Cambrian, Ordovician, Devonian, Mississippian, Pennsylvanian, and Permian (Plate 1). No Silurian rocks are present within the state (with the exception of the Laketown Dolomite in the overthrust belt in western Wyoming), but ordovician and silurian rocks preserved in kimberlitic diatremes along the southern border indicate marine rocks were deposited during the Silurian and were subsequently removed by erosion.

The Middle Cambrian Flathead Sandstone is the first recorder of Phanerozoic deposition in Wyoming. The coarse-grained siliciclastic sands and gravels of the Flathead Sandstone are overlain by interbedded siltstones and limestones of the Gros Ventre Formation and Gallatin Limestone, or the Deadwood Formation in the eastern Powder River Basin. These Cambrian sediments thin to near zero in southeastern Wyoming, reflecting uplift and erosion by the Transcontinental arch (Law, 1988). The overlying Ordovician Bighorn Dolomite (Winnipeg Formation and Whitewood Dolomite in the eastern Powder River Basin) is also not present in southeastern Wyoming. Devonian regression resulted in deposition of the Devonian Beartooth Butte Formation in the northeast, and the interbedded siltstone and carbonate strata of the Jefferson and Three Forks formations (or "Darby" Formation) throughout all but southeastern Wyoming.

A major Mississippian transgression deposited the thick heavily dolomitized Madison Limestone (Pahasapa and Englewood limestones in the Black Hills). Late Mississippian uplift resulted in a regional karst surface at the top of the Madison, which is commonly in-filled by shale from the Pennsylvanian Amsden Formation or Round Valley Limestone (southeast Green River Basin and Rock Springs uplift nomenclature). Overlying the Amsden is the dominantly eolian and marginal marine Pennsylvanian and Permian Tensleep and Weber sandstones. Marine conditions were more consistent in eastern Wyoming resulting in the sandstone and limestone deposits of the Minnelusa Formation, and the interbedded siliciclastics and carbonates of the Casper and Hartville formations in extreme southeastern Wyoming. The Pennsylvanian and Permian sequence is capped by the shallow-water chert and phosphate deposits of the Permian Phosphoria and Park City formations, which is laterally-equivalent to the redbeds, carbonates, and evaporites of the rich Goose Egg Formation in central Wyoming, and the Spearfish Formation in the eastern Powder River Basin.

Mesozoic Era

The Mesozoic Era began with continued sedimentation throughout much of the state and relatively little change in environment from the Permian Period. The Goose Egg and Spearfish formations spanned Permian and Lower Triassic time, while the shallow-water siltstones of the Dinwoody Formation were deposited in much of central and western Wyoming. As the stable cratonic shelf that existed throughout all of the Paleozoic Era began to narrow, sedimentation during the Mesozoic became more variable, depositing the characteristic red beds of the Chugwater Formation or Group, with sedimentation continuing into the Triassic with the Spearfish Formation. The Chugwater Formation/Group is interbedded marine and non-marine sandstones, siltstones, and limestones. In central and western Wyoming, the Chugwater Group is overlain by the eolian Jurassic (Triassic?) Nugget Sandstone, Jurassic marine Twin Creek Limestone (only in the overthrust belt), and the marine to marginal marine Gypsum Spring Formation that pinches out to the east. These Lower Jurassic sediments preserve the first significant change in source provenance with a major reorganization of what is now the western United States: previous sources were primarily derived from the east; these rocks suggest a western source region (Law, 1988). Middle Jurassic transgressions and regressions deposited the Sundance Formation, which recorded deep water, off-shore, near-shore, and coastal plan environments. The Jurassic system is capped by the fluvial and lacustrine Morrison Formation.

In Wyoming, the Cretaceous is associated with the initiation of the Western Interior Seaway, a foreland basin associated with the Sevier overthrust belt in western Wyoming. Rocks were deposited during this time from marine cycles of transgression and regression. The Lower Cretaceous fluvial sandstones and conglomerates of the Cloverly Formation and Inyan Kara Formation are overlain by the Thermopolis and Skull Creek shales deposited as the result of a marine transgression. Continuing transgressive and regressive cycles deposited the Lower Cretaceous shallow marine Muddy Sandstone (Newcastle Sandstone in the eastern Powder River Basin), followed by Upper Cretaceous marine shales (Mowry, Belle Fourche, Carlile, Cody, Niobrara, and Baxter). Deposition of these marine shales was punctuated by periods of coarser-grained siliciclastics, responding to flexure beneath the evolving Sevier overthrust belt. The siliciclastics include the marginal-marine Frontier Formation and non-marine Mesaverde Formation or Mesaverde Group. The Lewis Shale represents the last marine transgression in western Wyoming, which reached as far west as the west flank of the Rock Springs uplift (Law, 1988). The Fox Hills Sandstone (regressive shoreline deposit) and Lance Formation (fluvial) conclude sedimentation during the Late Cretaceous.

Cenozoic Era

The Laramide orogeny refers to a change in the style of foreland deformation associated with subduction along the western margin of North America. Beginning in the Late Cretaceous (Conacian) and extending into the Early Eocene, basement-involved deformation propagated well into the continental interior, over 1,000 km (621 mi) from the trench, which contrasts markedly from the thin-skinned Sevier overthrust belt that had been accommodating most of the strain to that time. Most of these basement-involved structures formed during the Paleocene and Eocene, generating a tremendous amount of structural and topographic relief and dissecting the Cretaceous foreland basin into a series of uplifts and basins with varying degrees of isolation (Plate 2). Structural offset of Precambrian basement rocks from Laramide reverse faults is as great as 13,411 m (44,000 feet) on the southwestern flank of the Wind River Mountains (Clarey and others, 2010). The Laramide antiforms and uplifts (e.g., Wind River Mountains, Bighorn Mountains, Laramie Mountains, Moxa arch, Rock Springs uplift, Cherokee Ridge arch, Wamsutter arch) isolated the individual basins (e.g., Wind River, Bighorn, Green River, Great Divide, Washakie, Powder River, Hanna), which promoted discontinuous sedimentation and variable accommodation throughout the region. Shallow marine and non-marine (fluvial and lacustrine) siliclastic sediment and coals of the Paleocene Fort Union Formation (Ferris and Hanna formations, Hanna Basin) are overlain by the intertonguing fluvial Wasatch Formation and lacustrine Green River Formation in the Greater Green River Basin, solely the Wasatch Formation in the Powder River Basin, the Willwood Formation in the Bighorn Basin, and the Wind River Formation in the Wind River and Hanna basins. The Green River Formation hosts the extensive trona deposits mined in Sweetwater County. The Denver Basin does not record Paleocene or Eocene deposition. Upper Eocene, Oligocene, Miocene, and Pliocene sedimentation is exclusively terrestrial yet varies in each basin. Geologic CO_2 storage is unlikely in post-Eocene formations.

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Chapter 2

Carbon Dioxide in Wyoming

The primary goal of geologic CO_2 storage is to sequester CO_2 emissions that would otherwise be released into the atmosphere. These CO_2 emissions are often from anthropogenic point-sources such as fossil-fuel–fired power plants. Currently the CO_2 that is in use for the various projects throughout Wyoming and in much of the Rocky Mountain region is not anthropogenic but instead sourced from a natural CO_2 accumulations in western Wyoming.

Sources of CO_2 and Existing Infrastructure

There are several subsurface accumulations of CO_2 in western Wyoming (see list in Becker and Lynds, 2012, and Plate 3); yet, the Greater Green River Basin currently produces all of the commercial-grade CO_2 used for enhanced oil recovery projects throughout the region. ExxonMobil's Shute Creek facility on the Moxa arch is the only developed source of CO_2 in Wyoming, and CO_2 is a byproduct produced with the extraction of helium. The Shute Creek facility underwent a significant expansion in 2010, and can now capture 365 million cubic feet of CO_2 per day. The pipeline from the Shute Creek facility is divided into five major sections. ExxonMobil owns the section from Shute Creek to near Baroil; Chevron owns a section from Rock Springs to Rangely, Colorado; Anadarko owns the pipeline from near Bairoil to Salt Creek; Devon owns the section from near Baroil to Beaver Creek; and Merit owns the short spur from near Bairoil to Bairoil (Lost Soldier and Wertz fields) (Figure 2-1 and Plate 3) (Wyoming Pipeline Authority, 2006; Murrell, 2011).

As the price of CO_2 has increased due to the increasing price of oil and the success of CO_2-EOR, additional plants and pipelines are in various stages of evaluation and implementation. Denbury Resources recently completed a 373-km (232-mile) pipeline to transport CO_2 from the Lost Cabin gas plant to the Bell Creek Field in Montana (Plate 3). This 51-cm (20-inch) diameter pipeline is now transporting 50 million cubic feet per day of CO_2 and will increase to a maximum of 725 million cubic feet per day (Denbury Resources, Inc., 2012). To supply CO_2 to this pipeline, Denbury purchased Cimarex Energy's Riley Ridge Unit, which is adjacent to ExxonMobil's Labarge field, and has purchased the rights to the CO_2 produced from DKRW Advanced Fuels' proposed coal-to-transport fuels plant near Medicine Bow, Wyoming.

Economics will dictate the viability of other potential sources of CO_2 throughout Wyoming. Currently the cost to capture, purify, and compress the gas stream is prohibitive, except on the LaBarge platform where CO_2 is a byproduct of lucrative methane and helium production. In 2006, the Wyoming Pipeline Authority estimated the cost of capturing and delivering CO_2 from Conoco/Burlington's Madden facility at $1.35 to $2.00 per thousand cubic feet of CO_2 delivered (Wyoming Pipeline Authority, 2006). Cost estimates are dependent on ownership of the CO_2—estimates are cheapest for companies that own the CO_2 versus those that must purchase it from a third party—and are related directly to the price of oil. In the Rocky Mountain region, the most current delivery estimates are $0.50 per thousand cubic feet of CO_2 plus 1.3 percent (U.S. Department of Energy, 2006) to 2.5 percent (van 't Veld and Phillips, 2019) of the contemporaneous price of oil. The near-term projected price of oil will likely continue to motivate interest in EOR projects; availability of a reliable supply of CO_2 is currently the biggest obstacle.

Fossil-fuel–fired power plants throughout Wyoming generate a significant volume of CO_2 (Figure 2-1). Wyoming currently has nine major power plants. These nine facilities, with a total capacity of more than 6,000 megawatts, generate CO_2 emissions of 43.4 million metric tons per year (Table 2-1). Current economics and technology make capture and compression of CO_2 emissions from these plants cost prohibitive, yet future improvements may help the feasibility of coal-fired power plants as a source of CO_2.

Uses for CO_2

Currently, the primary use for CO_2 is enhanced oil recovery with CO_2. At the present time there are no commercial-scale CO_2 enhanced coalbed natural gas projects in Wyoming.

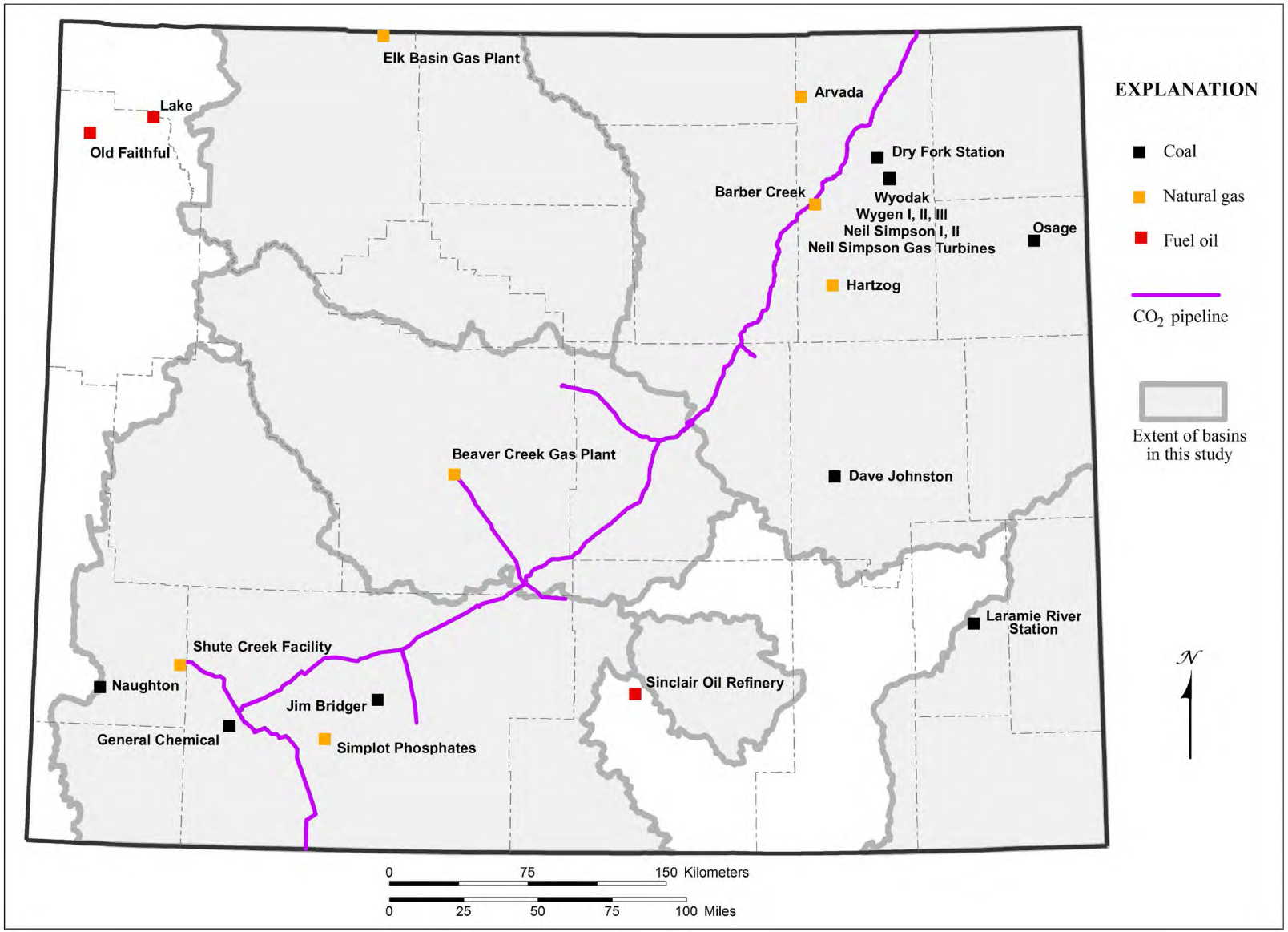


Figure 2-1. Map of electricity generating power plants fueled by hydrocarbons and Wyoming's CO_2 pipeline infrastructure (from the Wyoming Pipeline Authority, 2012).

Table 2-1. 2011 emissions for Wyoming electricity-generating plants. Data retrieved from the U.S. Environmental Protection Agency (2012).

Facility	County	CO_2 (million short tons)	CO_2 (million metric tons)
Dave Johnston	Converse	6.2	5.6
Dry Fork Station	Campbell	1.3	1.2
Jim Bridger	Sweetwater	14.0	12.7
Laramie River	Platte	14.9	13.5
Naughton	Lincoln	5.6	5.1
Neil Simpson II	Campbell	0.87	0.79
Neil Simpson II (CT2)	Campbell	0.004	0.004
Wygen I	Campbell	0.009	0.85
Wygen II	Campbell	0.009	0.83
Wygen III	Campbell	0.010	0.87
Wyodak	Campbell	2.4	2.1
Total		**48.2**	**43.7**

Enhanced Oil Recovery

Enhanced oil recovery (EOR) may have the greatest potential to geologically and economically store CO_2 in the near future. Unlike storing CO_2 in deep saline aquifers, which is an emerging practice, the use and storage of CO_2 during enhanced oil recovery operations has been an active practice by the petroleum industry in Wyoming since the mid-1980s. Oil is first produced from reservoirs under primary recovery (due to in situ reservoir pressure aided by pumps) and followed by secondary recovery. Secondary recovery generally occurs by a waterflood, where water is injected into the reservoir to physically displace the residual oil, which is subsequently recovered by adjacent production wells. The success of waterfloods depends on the permeability of the reservoir and the properties of the oil.

Waterfloods can be followed by tertiary recovery techniques, referred to as enhanced oil recovery, or EOR. Primarily used in declining oil fields, EOR can occur as thermal recovery where heat injection reduces oil viscosity, chemical recovery to lower the surface tension and enhance reservoir flow, or gas injection that displaces and mixes with oil. Gas injection of CO_2 has become the most significant technique, commonly referred to as CO_2-EOR, and is often used interchangeably with EOR.

In Wyoming, CO_2 is produced from gas fields high in CO_2 (LaBarge platform) (Plate 3), processed to remove additional gases, purchased by operators of declining oil fields, and transported via pipelines to specific EOR locations. There, the CO_2 is used to increase recovery of the oil remaining in the reservoir. A portion of the injected CO_2 is recovered with the oil, separated, and reinjected into the reservoir. Some CO_2 is stored during EOR because not all CO_2 is recovered with the oil. Once EOR has been completed and the oil has been removed, the reservoir becomes a trap for the CO_2 used in the project.

CO_2-EOR has been successful in a handful of fields around Wyoming, including Lost Soldier and Wertz fields and the Monell unit in the Patrick Draw field of the Greater Green River Basin, Salt Creek field in the Powder River Basin, and Beaver Creek field in the Wind River Basin. Grieve field, in the Wind River Basin, began CO_2-EOR operations in early 2013. These fields are among the first in Wyoming to employ EOR technologies. Infrastructure has developed to support these CO_2-flood programs. Pipelines transport CO_2 from ExxonMobil's Shute Creek plant in the southwestern Green River Basin to each of these locations (Plate 3). Minimum estimates by Wo and others (2009) suggest 1.2 to 1.8 billion barrels of additional oil can be recovered by CO_2 flooding in Wyoming's basins.

In 2009, an additional 6 million barrels of oil were recovered through CO_2-EOR, accounting for 12 percent of oil production in Wyoming (Whitman, 2011). Carbon dioxide flooding can occur with either miscible or immiscible CO_2. Miscible CO_2 mixes completely with lower viscosity reservoir oils and high reservoir pressures (oil gravity greater than 22° API, reservoir depth greater than 762 m; 2,500 feet). Immiscible CO_2 flooding is less efficient, but can still be economical, and generally occurs at shallower reservoir depths (549–762 m; 1,800–2,500 feet) with more viscous oil (13–22° API gravity).

Using CO_2 to recover oil in residual oil zones (ROZs) is an emerging technology that may play a significant role in future development of Wyoming's oil fields. ROZs are zones beneath the oil water contact that contain large amounts of residual oil. Depending on the amount of oil (versus water) saturation within these zones, CO_2-EOR can potentially recover oil from these untapped reservoirs. Recovery and storage in ROZs is noted when applicable.

Lost Soldier Field, Greater Green River Basin

The Lost Soldier field is part of a small Laramide-style structure on the northeast flank of the Great Divide Basin (Plate 3). Initial discovery of the field was made by Bair Oil Company in 1916. Production was first from the Upper Cretaceous Frontier Formation. The Tensleep Sandstone reservoir was discovered in 1930 and the Darwin Sandstone and Madison Limestone reservoirs in 1947. The Cambrian Flathead Sandstone reservoir discovery occurred in 1948 (Watson, 2010). The Lost Soldier field has more than 500 million barrels of original oil in place (Nevarez, 2009).

Secondary recovery via water floods in the Lost Solider field began in the 1970s, followed by tertiary recovery by CO_2 floods in 1989 (Tensleep and Madison reservoirs) (Fig. 2-2). Four reservoirs (Tensleep, Darwin, Madison, and Flathead) are currently under CO_2 flood within this field. Oil produced from these reservoirs is from depths ranging 1,524–2,134 m (5,000–7,000 feet), with oil gravities at 35° API. Porosities and permeabilities are variable: Tensleep Sandstone: 9.9 percent porosity, 31 millidarcies permeability; Darwin Sandstone: 13 percent porosity, 36 millidarcies permeability; Madison Limestone: 9 percent porosity, 2.5 millidarcies permeability; and Flathead Sandstone: 10.5 percent porosity, 30 millidarcies permeability (Watson, 2010).

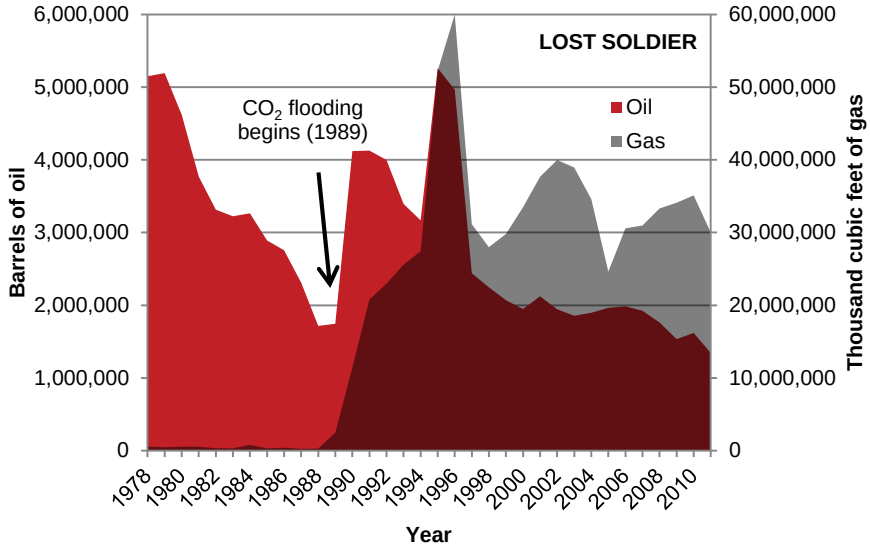


Figure 2-2. Oil and natural gas production for the Lost Soldier field, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

Wertz Field, Greater Green River Basin

The Wertz field is adjacent to the Lost Soldier field on the northeast flank of the Great Divide Basin (Plate 3). These two fields are frequently referred to together as the Bairoil fields because of their proximity, both are faulted anticlines on the same overall structure, they have shared production and recovery histories, and they are owned by a single producer. Merit Energy Company purchased both fields in 1999. Estimates indicate approximately 250 million barrels

of original oil in place in the Wertz field.

Bair Oil Company made the initial discovery of the Wertz field in 1920, with initial production from the Frontier Formation. The Pennsylvanian and Permian Tensleep Sandstone reservoir was discovered in 1937, followed by the discovery of the Darwin Sandstone and Madison Limestone reservoirs in 1948. The final discovery of oil in the Cambrian Flathead Sandstone was made in 1979. The Wertz field was unitized in 1937.

Similar to the history of the Lost Soldier field, water floods began in the Wertz field in the 1970s, followed by CO_2 floods in 1986 in the Tensleep reservoir (Fig. 2-3). The Tensleep, Darwin, and Madison are currently under CO_2 floods in the Wertz field. These formations are from 1,890 to 2,042 m (6,200 to 6,700 feet) below the surface. Average porosities and permeabilities are as high as 13.1 percent and 36 millidarcies in the Darwin Sandstone and as low as 8.7 percent and 2.5 millidarcies in the Madison Limestone. Oil gravities from all reservoirs are 35° API (Nevarez, 2009).

Data for production and storage volumes in the Wertz field are limited. The Wyoming Oil and Gas Conservation Commission (2012) reports that oil production averaged 6,089 barrels per day for both the Lost Soldier and Wertz fields in 2011. These two fields recycle 150 million cubic feet of gas per day (plant capacity), with an additional "makeup" CO_2 volume of 14 million cubic feet per day.

Monell Unit (Patrick Draw Field), Greater Green River Basin

The Patrick Draw field, discovered in 1959, is located approximately 56 km (35 miles) east of Rock Springs, Wyoming (Plate 3). This field consists of two units: the northern Arch unit and the southern Monell unit. The Monell unit produces from the Almond Formation of the Mesaverde Group (Upper Cretaceous). The Monell unit has ideal reservoir properties for CO_2-EOR: average 20 percent porosity, 30 millidarcy permeability, 9 m (30 feet) net pay, 43° API gravity oil, and 49° C (120° F) reservoir temperatures (Lim and Ramsey, 2006). Original oil in place is estimated at 112 million barrels. EOR through CO_2 injection began in 2003 (Fig. 2-4) and the Monell unit is expected to recover an additional 28 million barrels of oil and store 150 billion cubic feet of CO_2.

Beaver Creek Field, Wind River Basin

The Beaver Creek field is the only field in the Wind River Basin that is actively under CO_2 flood. Currently owned by Devon Energy Corporation, the Beaver Creek field was discovered in 1938 in the central Wind River Basin (Plate 3). This asymmetrical anticline has approximately 30 m (100 feet) of closure and produces from several Cretaceous-age reservoirs, in addition to the Phosphoria Formation, Tensleep Sandstone, and Madison Limestone (Specht, 1989). Carbon dioxide-EOR is presently occurring in the Madison reservoir.

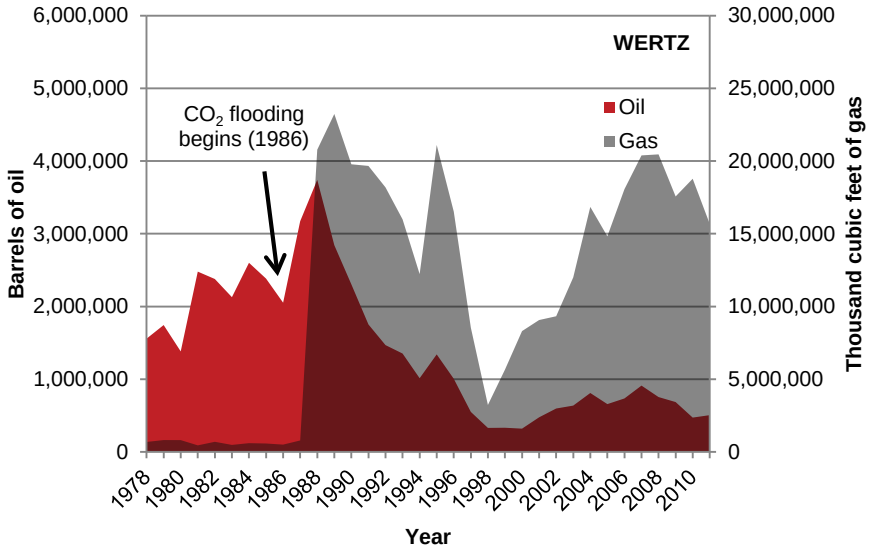


Figure 2-3. Oil and natural gas production for the Wertz field, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

The Madison Limestone in Beaver Creek field was

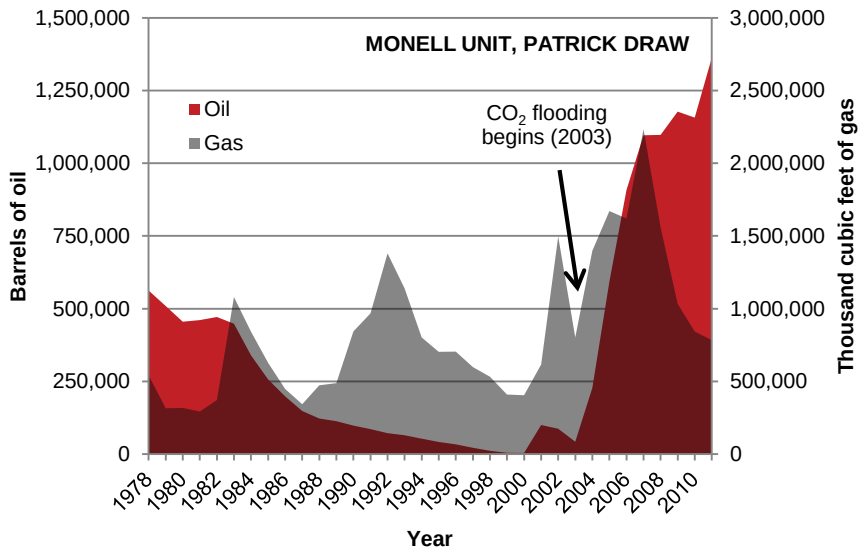


Figure 2-4. Oil and natural gas production for the Monell unit in the Patrick Draw field, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

discovered in 1954, with an average 9–10 percent log porosity and 9 millidarcy core permeability (Specht, 1989). The reservoir zone is 65 m (212 feet) thick and greater than 3,383 m (11,100 feet) below the surface (Peterson, 2009). Oil gravities average 39.5° API. Waterflood was initiated in the Madison reservoir in 1959 (Peterson, 2009), followed by CO_2 flooding in 2008 (Fig. 2-5). Production in Beaver Creek field was more than 62.5 million barrels of oil and 784.8 billion cubic feet of gas through 2011.

Grieve Field, Wind River Basin

Grieve field was discovered in 1954 by Forest Oil Corporation. The field is located 80 km (50 miles) west of Casper in the southeast flank of the Wind River Basin. Production is primarily from the Muddy Sandstone ("Grieve Sand") in a stratigraphic trap. Core porosities from the 14-m (45-foot) thick pay zone average 20.4 percent (Lawson, 1989), with a permeability of 220 millidarcies. Oil gravity from this field is 37° API. Total oil production from Grieve field through 2011 was nearly 30.2 million barrels of oil (29.5 million barrels were produced prior to 1978) and 109 billion cubic feet of gas (Fig. 2-6).

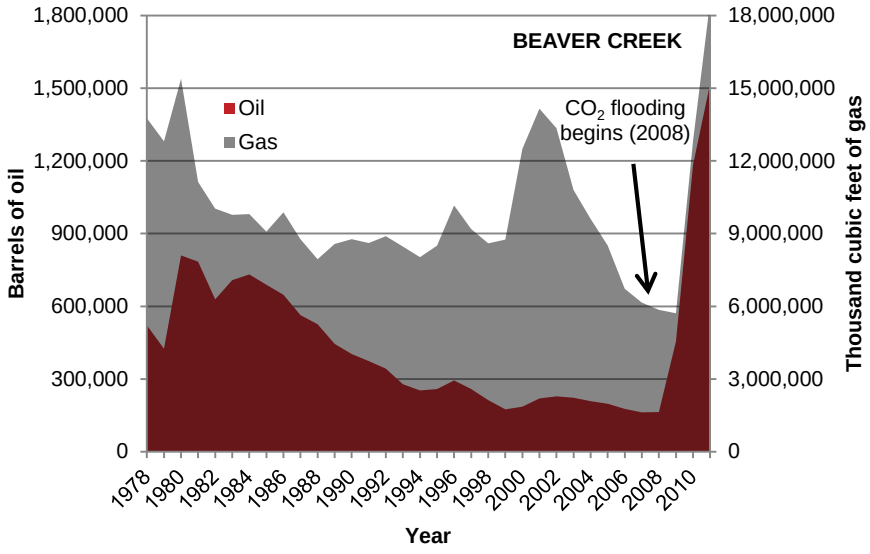


Figure 2-5. Oil and natural gas production for the Beaver Creek field, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

Elk Petroleum purchased Grieve field from World Oil Corporation in 2005. In 2011, Elk Petroleum sold 65 percent working interest in the field to Denbury Resources, the current field operator. Oil reserves, producible by CO_2 miscible flooding, are estimated at 18.6 million barrels (Schulte and Black, 2011). CO_2-EOR operations commenced in early 2013.

Salt Creek Field, Powder River Basin

The Salt Creek field is one of the oldest oil fields

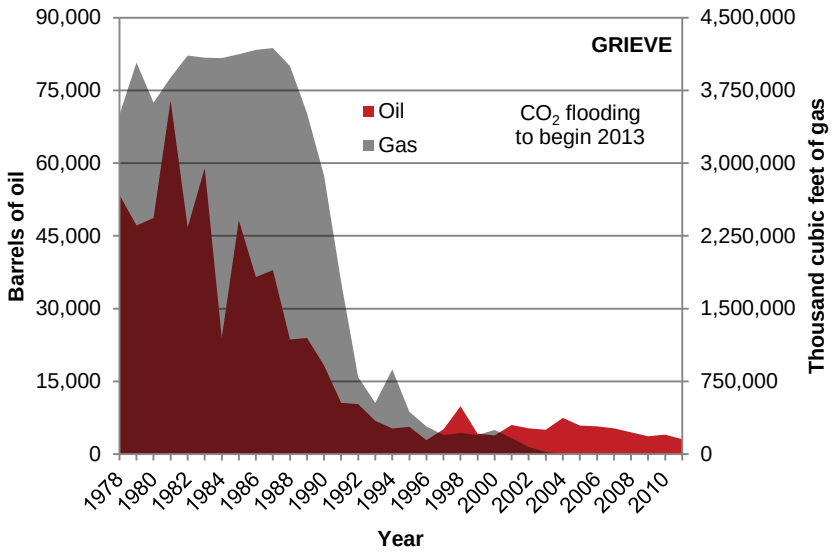


Figure 2-6. Oil and natural gas production for the Grieve field, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

in Wyoming. Located in and around the town of Midwest in the southeastern Powder River Basin area (Plate 3), the Salt Creek field is an asymmetrical anticline with some stratigraphic trapping (Obert and Mather, 2000). The discovery well was drilled in 1889 into the Shannon Sandstone (Wegemann, 1918). Original oil in place is estimated at roughly 1.7 billion barrels (Roux and Andersen, 2010). Oil production through 2011 totaled nearly 693 million barrels.

Anadarko Petroleum purchased the field from Howell Petroleum Corporation in 2002, and began CO_2-EOR in 2004 (previously the field was under waterflood) (Fig. 2-7). Of the 11 productive intervals, the 2nd Wall Creek Sandstone (Frontier Formation) has been the most productive and is currently under CO_2 flood. The 2nd Wall Creek Sandstone is 457–914 m (1,500–3,000 feet) below the surface, approximately 26 m (85 feet) thick, and has a porosity of 19 percent and permeability of 52 millidarcies (Roux and Andersen, 2010). Oil gravity is 39° API. In 2010, Anadarko produced 10,800 barrels of oil per day from CO_2-EOR and injected 420,000 cubic feet of CO_2 per day (Roux and Andersen, 2010). Anadarko intends to sequester 1.65 trillion cubic feet of CO_2 in the Salt Creek field. In April, 2012, Anadarko sold 23 percent interest in the Salt Creek field to LINN Energy, LLC.

Enhanced Coalbed Natural Gas Recovery

Carbon dioxide-enhanced coalbed natural gas (methane) recovery (CO_2-ECBM) is a relatively new approach in the quest to improve production in declining or sub-par coalbed natural gas fields. In the subsurface, injected CO_2 will preferentially adsorb to coal at the expense of methane, resulting in an increase in methane production. In the early 1990s, BP Amoco conducted the first CO_2-ECBM pilot project in the San Juan Basin of southern Colorado. Commercial CO_2-ECBM followed in 1996 with Burlington Resources' successful project in the Allison production unit in the San Juan Basin of northern New Mexico (Gale and Freund, 2001).

Carbon dioxide-ECBM works because of the unique properties of coal. Methane (CH_4) is generated during the maturation of terrestrial organic matter to form coal and either adsorbs onto the surface of the coal or accumulates in its pores. The volume of methane within a coal seam depends upon coal rank and burial depth. If CO_2 is introduced into the system, it is preferentially adsorbed at the expense of CH_4. Laboratory work by Stanton and others (2001) on 13 samples of dry low rank (subbituminous and lignite) coal yielded a CO_2:CH_4 adsorption ratio as high as 10:1. This ratio implies that for every 10 parts carbon dioxide added to the system, 1 part methane is expelled from the coal. Arri and others (1992) suggest this ratio is closer to 2:1. Regardless, adding more CO_2 causes preferential desorption of CH_4 (enhancing methane recovery) and adsorption of CO_2 (increasing storage efficiency) in a ratio that is economically favorable.

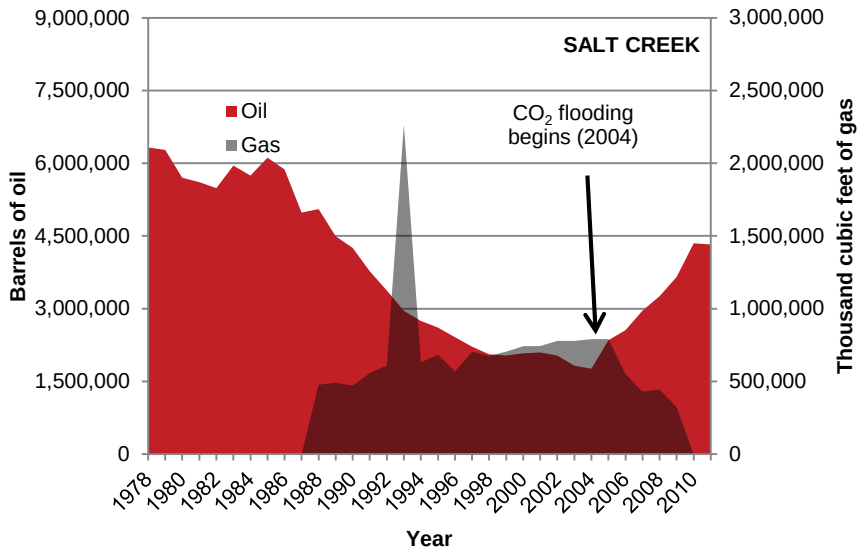


Figure 2-7. Oil and natural gas production for the Salt Creek field, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

Basic screening criteria must be met before pursuing the economic feasibility of CO_2-ECBM in a candidate coal-seam reservoir. Seven criteria are proposed, the first five are from Gale and Freund (2001): (1) the coal-seam reservoir must be homogeneous, laterally continuous, thick, and isolated from over- and under-lying reservoirs; (2) the reservoir must not be structurally complex (i.e., minimal faulting or folding); (3) the coal-seam reservoir needs an adequate permeability, defined as 1 to 5 millidarcies; (4) the reservoir must be between 305 and 1,524 m (1,000 and 5,000 feet) below the surface (some studies, such as Reeves 2003, use 1,829 m; 6,000 feet as the maximum depth); (5) coal-seam reservoirs saturated with respect to methane are most economical; undersaturated reservoirs are acceptable if the primary goal is CO_2 storage; (6) the reservoir must be proximal to a source of CO_2 in the form of a pipeline, in situ source, or anthropogenic point source (e.g., coal-fired power plant), and (7) aquifer TDS concentrations must be more than 10,000 mg/L.

This last requirement may severely limit CO_2 storage through ECBM, because aquifers in coal seams can have TDS concentrations much less than 10,000 mg/L (often approaching acceptable drinking water standards).

Carbon dioxide-ECBM is not currently employed in Wyoming. The significant coalbed natural gas fields in the Greater Green River, Wind River, Powder River, and Hanna basins are potential targets for future CO_2-ECBM.

Chapter 3

Storage and Confining Zones

Storing CO_2 in the subsurface requires a trap, an appropriate injection zone, and an adequate confining zone. Traps can either be stratigraphic or structural, and must be large enough to accommodate the proposed volume of CO_2. Historically, stratigraphic hydrocarbon traps are less common throughout Wyoming, and are less likely candidates for CO_2 storage. Structural traps can be created by a number of different processes, but in Wyoming most suitable structural traps are basement-involved anticlinal structures and are "Laramide" in their style and timing of creation. The Greater Green River Basin hosts the bulk of these potential structural traps which are discussed in the following chapters for each basin.

A storage zone is defined as appropriate if it is: (1) underpressured or normally pressured (with a plan to remove reservoir fluids); (2) has porosity and permeability values high enough to support the planned CO_2 injection stream; (3) is at depths less than 3,962 m (13,000 feet) (following guidelines from the U.S. Geological Survey) (Burruss and others, 2009; Brennan and others, 2010); and (4) has in situ reservoir fluids with TDS concentrations greater than 10,000 mg/L. A confining zone is adequate if it has very low porosities and permeabilities, has low capillary injection pressures, and is continuous over the area of interest (Becker and Lynds, 2012).

Confining zones, or seals, must be of sufficient aerial extent to reach to the limits of a potential trap intended to contain a CO_2 plume. A confining zone must also possess attributes conducive to holding a large buoyant column of gas for a geologically significant period of time (i.e., greater than 10,000 years). These attributes, defined as the sealing capacity (Downey, 1984), include a high capillary injection pressure and an extrinsic stress state able to resist the formation of opening-mode fractures (summarized in Becker and Lynds, 2012). Simply put, it should be difficult to force or inject CO_2 into the potential confining zone, and the zone should not easily fracture. There are several formations in Wyoming that are either proven seals or are likely future research targets to determine sealing capacity. These formations include the Jurassic Gypsum Spring Formation, strata from the Triassic Period, and the Upper Devonian Jefferson Formation.

The following sections include short descriptions of the formations potentially capable of storing CO_2 in saline aquifers, or confining the CO_2 to a specific storage zone. The prospective formations vary from basin to basin (Table 3-1). These sum-

Table 3-1. Storage and confining zones evaluated in this study.

Zone	Greater Green River	Wind River	Bighorn	Powder River	Hanna	Denver
Confining						
Gypsum Spring/Opeche Shale	X	—	X	X	—	—
Triassic Formations	X	X	X	—	—	—
Amsden	X	X	X	—	—	—
Jefferson (Darby)	X	—	—	—	—	—
Storage						
Nugget	X	—	—	—	—	—
Crow Mountain	—	X	X	—	—	—
Phosphoria	—	—	X	—	—	—
Tensleep/Weber/Minnelusa	X	X	X	X	—	—
Madison	X	—	X	X	—	—

maries are statewide; facts related to specific basins are discussed in the individual basin chapters. The formations of interest are summarized in stratigraphic order, from youngest to oldest, with a note to their "storage" or "confining" potential.

Mesozoic System

Gypsum Spring Member/Formation: Confining

The Gypsum Spring Member is found throughout the overthrust belt and west into Idaho. Suggested by Imlay (1950) and formally defined by Oriel (1963), the Gypsum Spring Member is the basal member of the Middle Jurassic Twin Creek Limestone. East of the overthrust belt, the Gypsum Spring is named as a separate formation, unconformably overlain by the Sundance Formation (Love and others, 1993). The Gypsum Spring Formation pinches out to the east and is nonexistent in the eastern Greater Green River Basin, Hanna, and Denver basins. The Gypsum Spring Formation unconformably overlies the Nugget Sandstone, except in the Powder River Basin where the Gypsum Spring Formation overlies the Chugwater and Spearfish formations. The Gypsum Spring Member thickens south and west from 23 m (75 feet) in western Wyoming to 122 m (400 feet) in Idaho (Imlay, 1967). Gypsum beds within the Gypsum Spring Formation in Park County, Wyoming are known to be as thick as 21 m (70 feet) (Bullock and Wilson, 1969). Gypsum is interbedded with brownish red to yellow siltstone and claystone, with notable interbeds of brecciated limestone (Imlay, 1967).

Nugget Sandstone: Storage

The Nugget Sandstone is a Lower to Middle(?) Jurassic (possibly Triassic?) sandstone found throughout central and western Wyoming (Picard, 1993). The Nugget Sandstone also crops out in Utah on the northern flank of the Uinta Mountains, and is frequently correlated (at least lithologically) to the Navajo Sandstone of the Colorado Plateau. The Nugget Sandstone is bounded above and below by unconformities (Picard, 1993). It is underlain by the Ankareh Formation and overlain by the Gypsum Spring Formation in western Wyoming, and underlain by the Popo Agie Formation of the Chugwater Group and capped by the Sundance Formation in central Wyoming (Plate 1).

The Nugget Sandstone has been informally subdivided into two units. The basal unit is a thinly bedded, intercalated series of clayey siltstone, siltstone, mudstone, silty claystone, sandstone, limestone, and dolomite (Picard, 1993). The depositional environment for this finer-grained basal unit was most likely interdune lakes, terrestrial sabkas, and small rivers. The upper unit consists of well-sorted, cross-stratified siltstones and sandstones (Picard, 1977) deposited in a desert-eolian setting.

Crow Mountain Sandstone: Storage

The Crow Mountain Sandstone is a Middle Triassic tidal flat and beach sandstone that accumulated during westward regression of the sea. It is included in the Chugwater Group of redbeds, and is bounded below by the Alcova Limestone and above by the Popo Agie Formation (all formations of the Chugwater Group). Picard (1993) describes the Crow Mountain Sandstone as the best reservoir rock and most important petroleum-producing interval of the Triassic in Wyoming.

The Crow Mountain Sandstone is present in the eastern Greater Green River, Bighorn, and Wind River basins. In the Bighorn Basin, the basal Crow Mountain is the best reservoir rock and is a cross-stratified red, reddish-brown, yellowish red, and brown calcareous sandstone with well-sorted, sub-rounded, very fine grains. Deposition was in a shallow sea with predominant wave and tidal current action.

Triassic Formations: Confining

The Triassic strata are proven seals in the Greater Green River Basin (LaBarge platform and Rock Springs uplift) (Campbell-Stone and others, 2010; Becker and Lynds, 2012). These strata include, from oldest to youngest, the Dinwoody Formation, Woodside Shale, Thaynes Limestone, and Ankareh Formation on the LaBarge platform, and the Dinwoody Formation and Chugwater Group elsewhere throughout the state. The oldest (hence lowest) formation at both locations is the Dinwoody Formation. The Dinwoody Formation is the first clear barrier to upward migration of hydrocarbons and the most likely confining zone for CO_2 storage in the saline Paleozoic aquifers elsewhere in the state.

Dinwoody Formation lithologies resulted from marine deposition and include dolomitized quartz siltstones and very fine grained sandstones, claystones, interbedded carbonates, and rare evaporites. Most samples are highly micaceous. At the surface, the Dinwoody crops out as light green hills with rare rock exposures. Cuttings and one core (RSU #1, API 49-037-07154) reveal the Dinwoody is a red siltstone in the subsurface, in contrast to the green hue observed on surface outcrops. The Dinwoody Formation grades laterally eastward into the upper parts of the Goose Egg Formation. The Dinwoody Formation has not been extensively studied due to its poor surface exposure and rare subsurface data, and it is not clear why this formation is such a successful seal. Johnson (2005) suggests that early lithification of the Dinwoody Formation formed an impermeable seal that trapped the hydrocarbons from the Phosphoria Formation until the start of the Laramide orogeny. Work is currently in progress at the University of Wyoming to constrain and understand the sealing characteristics of the Dinwoody Formation (e.g., Spaeth, 2011; Spaeth and others, 2011).

The overlying Woodside Shale is equivalent to the Red Peak Formation of the Chugwater Group. These two formations are "red beds," and consist of interbedded sandstones, siltstones, and mudstones that intertongue with the upper Dinwoody Formation (Paull and others, 1989). The Thaynes Limestone is comprised of limestone, sandstone, and siltstone. Wireline logs from wells drilled on the LaBarge platform show tens of meters of anhydrite and halite in these formations, which may be additional impermeable seals resisting upward migration of hydrocarbons.

Paleozoic System

Phosphoria Formation: Storage and Confining

The Phosphoria Formation is also known as the Park City Formation, though this name is not widely used by industry geologists. These two formations interfinger and are difficult to differentiate on well logs in the western portions of the state. In the Bighorn Basin, the Phosphoria refers to the interval of carbonate rock, chert, dark shale, and minor sandstone lying above the Tensleep Sandstone and below the Triassic Dinwoody Formation (formerly the Embar Formation of Darton, 1906). Richards and Mansfield (1911) describe the Phosphoria Formation as the sequence of dark-gray to black phosphatic shale, phosphorite, chert, and some carbonate rock that crops out at Phosphoria Gulch north of Montpelier, Idaho. From west to east, the Permian rocks of Wyoming transition from the thick black shale, bioclastic-pelletal-phosphatic limestone, chert, and dolomites of the Phosphoria Formation to the redbeds, evaporites, and thin carbonates of the Goose Egg Formation. In general, the Goose Egg Formation represents deposition on, and marginal to, the relatively stable craton; the Phosphoria carbonates were deposited on the broad and eastward shoaling shelf. The intertonguing and transitional relationship between the Permian and Triassic formations is illustrated in a generalized stratigraphic nomenclature chart (Plate 1).

The Meade Peak and Retort members of the Phosphoria Formation, composed of organic-rich dark shale, reach maximum thickness in southeastern Idaho and western Wyoming and are considered petroleum source rocks (Herrod, 1980). Thickness of post-Permian strata in western Wyoming and eastern Idaho indicate that burial depths were sufficient for petroleum generation to begin as early as Jurassic time. The units also had an eastward migration gradient existing across west-central Wyoming, possibly as far as the Bighorn Basin and Casper arch. In the late Mesozoic, generation and migration most likely began from source rocks, with a migration gradient into local reservoir belts (Peterson, 1984). Reservoir porosity distribution within the Phosphoria carbonate facies resulted from the depositional environment and superimposed diagenetic changes, the most important of which is dolomitization of the limestones (Stone, 1967).

Tensleep Sandstone, Weber Sandstone, and Minnelusa Formation: Storage

The Pennsylvanian and Permian Tensleep and Weber sandstones have a complicated history of stratigraphic nomenclature and correlation. Correlated to the Quadrant Sandstone in Montana and the Wells Formation in Idaho, the Weber Sandstone is a Utah term that is used in the southern

and eastern Green River Basin and on the Rock Springs uplift, while the Tensleep Sandstone is defined throughout the Wind River and Bighorn basins (Plate 1). The Minnelusa Formation is exclusively located in the Powder River Basin and Black Hills (Plate 1). This complex stratigraphic nomenclature is complicated by the correlation of the Weber Sandstone with only the upper Tensleep Sandstone (Love and others, 1993), and the Lower through Upper Pennsylvanian age of the Minnelusa Formation.

The contacts of the Tensleep with the underlying Amsden Formation and the Weber with the underlying Morgan Formation range from gradational, to unconformable, to unknown (Love and others, 1993). The base of the Tensleep and Weber sandstones is difficult to identify on wireline logs. Everywhere in Wyoming the Weber and Tensleep sandstones are unconformably overlain by the Permian Phosphoria or Goose Egg formations, except in the Powder River Basin where the Opeche Shale unconformably overlies the Minnelusa Formation. For simplicity and solely for the purpose of CO_2 storage in the Laramide basins of Wyoming, this document refers to these sandstones as the Tensleep Sandstone in the Wind River and Bighorn basins, the Tensleep/Weber Sandstone in the Greater Green River Basin, and the Minnelusa Formation in the Powder River Basin. This naming convention implies a similar lithology and depositional environment but does not suggest coeval timing of deposition.

The Tensleep and Weber Sandstones have a lower, thinly bedded unit overlain by a large-scale cross-stratified unit. Dolostone and limestone are common in the lower unit. These carbonates are interbedded with sandstone, siltstone, clayey siltstone, claystone, and anhydrite. Pyrite is common in the subsurface. The upper unit is a very fine to fine-grained subarkose to arkose with up to 25 percent feldspar (Odom and others, 1976). Interpretations of the environment of deposition range from marine to terrestrial, and likely varied across western Wyoming and throughout the section. Westward regression of the Paleozoic seaway was accompanied by the westward progradation of terrestrial facies. Shallow-water carbonates and sandstones are overlain by marginal marine facies and coastal sand dunes and capped by a desert-like erg sequence. In eastern Wyoming, during Tensleep/Weber deposition, marine conditions were more prevalent and resulted in alternating deposition of the limestones and sandstones of the Minnelusa, Hartville, and Casper formations (Boyd, 1993).

The Tensleep Sandstone is the most prolific hydrocarbon producer within Wyoming. Much of the Tensleep production comes from large anticlines in the Bighorn and Wind River basins and is likely related to faulting and fracturing. Post-depositional diagenesis is directly responsible for porosity and permeability within Tensleep/Weber reservoirs. On the Moxa arch, calcite or anhydrite cementation and later silica cementation occurred during the earliest phases of diagenesis, followed by a later dolomite cementation event (Edman and Surdam, 1984). The dolomite cementation occurred after migration of hydrocarbons into the reservoir, at least in the Tip Top field, LaBarge platform. On the LaBarge platform, and throughout much of the Moxa arch, late-stage dolomite cement and solidified bitumen produced a very tight Tensleep Sandstone (Edman and Surdam, 1984).

Amsden Formation: Confining

The Amsden Formation consists of the basal Darwin Sandstone, Horseshoe Shale, and uppermost Ranchester Limestone. The age of the Amsden Formation is arguable; the Mississippian(?) Darwin Sandstone may be separated by an unconformity (see Boyd, 1993, for full explanation). Regardless, the Pennsylvanian Horseshoe Shale is the likely confining zone. The Horseshoe Shale is a series of interbedded red sandstones and clastic shales, dolostones, limestones, and anhydrite, overlain by the increasingly pure Ranchester Limestone (Boyd, 1993). The Amsden Formation is a proven hydrocarbon seal on the LaBarge platform where it isolates the large subsurface CO_2 accumulation in the underlying Madison Limestone from the overlying Tensleep Sandstone (Campbell-Stone and others, 2010). The Amsden Formation is also the likely seal for the hydrocarbons trapped within Madison reservoirs throughout Wyoming.

Madison Limestone: Storage

The Madison Limestone may be the formation with the highest potential for deep saline aquifer CO_2-storage in Wyoming. Peale (1893) named the Madison Limestone based on carbonate beds found in the Madison Range of southern Montana. The Madison was deposited in the shallow warm waters on the flanks of a foreland basin formed by the early Mississippian Antler orogeny. This foreland basin was tied to an extensive marine ramp that was about 402 km (250 miles) wide and extended 1,609 km (1,000 miles) from New Mexico to Canada (Sando, 1976; Gutschick and Sandberg, 1983), and was within 5 degrees north of the early Mississippian paleoequator (Maughan, 1983). The Madison is in unconformable contact with the underlying Devonian strata (Jefferson and Three Forks formations, or "Darby" Formation; terminology explained in the next section). The upper contact with the overlying Amsden Formation (throughout most of Wyoming) or the Round Valley Limestone (Rock Springs uplift region of the Greater Green River Basin) is disconformable and karstic. The Madison Group (Montana terminology) has been subdivided into two formations in Montana: the lower Lodgepole Limestone and upper Mission Canyon Limestone. This terminology has been used in Wyoming. More recent work (e.g., Sonnenfeld, 1996; Smith and others, 2004; and Westphal and others, 2004, among others) subdivided Wyoming's Madison Limestone into a sequence stratigraphic framework of six third-order sequences within a second-order transgressive-regressive sequence.

The Madison Limestone is a series of marine carbonate mudstones, wackestones, and ooid and skeletal packstones and grainstones. Surficial karst and evaporite-solution collapse breccias are common, as well as less significant and more isolated tectonic penetrative karst breccias (Smith and others, 2004). The diagenetic history of the Madison Limestone is complicated by a succession of dolomitization and dedolomitization events. Dolomitization and dedolomitization caused significant lateral and vertical heterogeneity in reservoir properties (e.g., Pranter and others, 2006; Thyne and others, 2010). Although fracturing is pervasive throughout Madison reservoirs, the effect of fractures on reservoir quality is thought to be subordinate to primary and secondary lithology, textures, and fabrics (Becker and Lynds, 2012).

Jefferson Formation: Confining

Throughout much of Wyoming, Montana, and Idaho, Upper Devonian strata are subdivided into the Frasnian Jefferson Formation and the Famennian Three Forks Formation. In the subsurface of western Wyoming, strata of equivalent age are frequently referred to as the "Darby" Formation, a term coined by Blackwelder (1918). Subsequent work by Benson (1966) proposed using the name Darby Formation when the upper member of the Jefferson Formation and the complete Three Forks Formation are absent. Lynds and others (2010) followed Benson's (1966) suggestion and picked the Jefferson and Three Forks formations on wireline logs on the Moxa arch. Although the Jefferson and Three Forks formations are distinguishable and correlatable on wireline logs, the "Darby" Formation will likely remain in use to refer to Upper Devonian strata in southwestern Wyoming. Thus the Darby Formation can either refer exclusively to the lower member of the Jefferson Formation, or both the Jefferson and Three Forks formations.

The Devonian interval is a proven seal for CO_2 reservoirs on the LaBarge platform, sealing the underlying Bighorn Dolomite from the overlying Madison Limestone (Becker and Lynds, 2012). Lynds and others (2010) suggest that thin anhydrite beds (0.3–1.2 m; 1–4 feet) in the Lower Jefferson Member are the requisite sealing lithology. Other rock types within the Lower Jefferson Member include sucrosic-textured, thin-bedded (0.3–3 m thick; 1–10 feet) dolostone, brecciated dolostone and limestone, and thin (less than 0.3-m, 1-foot, thick) beds of siliciclastic sandstone, siltstone, and claystone (Lynds and others, 2010). The siliciclastic beds are composed of well-rounded and well-sorted, very fine to fine, frosted quartz grains, common to Upper Devonian strata throughout the region.

The Devonian formations are hydrocarbon producer in parts of the overthrust belt. Only one well (Tip Top 22-19G, API 49-035-05746) on the Moxa arch tested the Birdbear Member of the Jefferson Formation for gas production (Wyoming Oil and Gas Conservation Commission, 2012). Maximum production rates were 2.4 million cubic feet of gas per day, believed to be the result of fracture permeability (Stilwell, 1989).

Bighorn Dolomite: Storage

Like the Madison Limestone, the Upper Ordovician Bighorn Dolomite is a proven CO_2 reservoir on the crest of the Moxa arch (LaBarge platform). As the name implies, the Bighorn Dolomite is primarily a dolostone. The Steamboat Point Member contains the primary reservoir facies and consists of massive burrowed dolostone. Originally deposited as a limestone on a shallow carbonate ramp, the burrow fills of the Steamboat Point Member were selectively dolomitized, initially over fossil fragments, resulting in coarse-grained dolomite burrows encased in a dolomitic wackestone matrix (Zenger, 1996). Later stages of dolomitization and dedolomitization created a mottled dolostone pattern with variable porosity.

For several reasons the Bighorn Dolomite may not be the best potential reservoir for CO_2 storage. Due to eastward thinning (truncation) and the south- and eastward absence of the sealing anhydrite in the Lower Member of the Jefferson Formation, the Moxa arch in the western Greater Green River Basin is the only location potentially suitable for long-term CO_2 storage in the Bighorn Dolomite. On the LaBarge platform, this proven reservoir stores CO_2 at depths greater than 4,633 m (15,200 feet), which would require additional compression of CO_2 at the surface before injection. Also, there is some suggestion that the Bighorn CO_2-reservoir is filled to capacity (Becker and Lynds, 2012). If this is the case, storing CO_2 in this reservoir would require coeval production of the CO_2-reservoir gas (consisting of less than 10 percent methane and other gases with potential commercial value, like He), a likely uneconomic and highly redundant endeavor. However, the possibility remains that further detailed work aimed at defining the hydrostatic pressure gradient in the Bighorn Dolomite on the Moxa arch may reveal an under-filled reservoir with some capacity for additional CO_2 storage.

Cambrian Formations: Storage

Research into CO_2 storage in the deep saline aquifers of Wyoming has been a topic of interest for many different organizations, yet none have focused on the Cambrian formations. This is in part due to the great depths at which these formations are generally found, and also due to the paucity of wells drilled through these formations. From oldest to youngest, the Cambrian formations include the Middle Cambrian Flathead Sandstone, Middle to Upper Cambrian Gros Ventre Formation, and the Upper Cambrian Gallatin Limestone (the Powder River Basin hosts solely the Upper Cambrian Deadwood Formation). The Flathead Sandstone is a siliciclastic sandstone and conglomerate that is commonly heavily cemented. The Gros Ventre Formation overlies the Flathead Sandstone and consists of a basal shale, middle limestone, and upper shale (Boyd, 1993). The capping Gallatin Limestone is predominately a carbonate.

Other than the Lost Soldier and Wertz CO_2-EOR fields, which produce from the Cambrian Flathead Sandstone, only a handful of wells penetrate Cambrian strata in all of Wyoming. The Cambrian section is too deep for feasible CO_2 storage in most of Wyoming. On the crest of the Rock Springs uplift, the Cambrian formations were cored in the UPRR-11-19-104 4 (API 49-037-05655) from depths ranging from 2,438 to almost 2,835 m (8,000–9,300 feet). This core is beautifully preserved and available for viewing at the U.S. Geological Survey Core Research Center in Lakewood, Colorado, although no reservoir property data are available. The reservoir properties of the Gallatin and Gros Ventre carbonates should be further explored for CO_2-storage feasibility, as they may be viable storage zones on the crest of the Rock Springs uplift in the Greater Green River Basin.

Chapter 4

Methodologies for CO_2 Storage Resource Calculations

Quantifying the capacity (mass or volume) of CO_2 that can potentially be stored underground in geologic formations (defined as the CO_2 storage resource) is not a straightforward task. Geologic storage of CO_2 is an emergent technology that has not been tested on an industrial scale in the United States. There are no studies that compare predicted storage to actual storage, thus current predictions carry a high range of uncertainty. Nevertheless, because Wyoming's Laramide basins have many of the necessary components for safely storing CO_2, several organizations with very different goals have endeavored to quantify this resource.

Wo and others (2009) calculated the volume of CO_2 that could be stored in oil reservoirs depleted through the CO_2-EOR process. The U.S. Geological Survey (USGS) was directed by the 2007 Energy Independence and Security Act (Public Law 110-140) to lead a national study of geologic CO_2 storage resources. A methodology to accomplish this task was proposed by Burruss and others (2009) and refined by Brennan and others (2010). The USGS study began with the basins in Wyoming. The Bighorn Basin was their first investigation and Covault and others (2012) published an initial report detailing the area and summarizing reservoir characteristics of the potential storage zones. Storage calculations are not currently available.

The analyses presented in the following chapters are not intended to rival work by the Wyoming Enhanced Oil Recovery Institute or the USGS. Instead, these analyses synthesize existing research and streamline the various methods of CO_2 storage resource calculations for the purpose of generalized estimation. Field data were used when possible, and assumptions were made when necessary. Storage estimates should be refined with the future increased availability of subsurface data.

The CO_2 storage capacity in Wyoming basins is assessed as four distinct categories. The first category is a generalized estimation of the mass of CO_2 that can theoretically be held in laterally persistent, deep saline aquifers within the Laramide basins. This assessment follows the methods outline by the National Energy Technology Laboratory (U.S. Department of Energy, 2010). The second category is depleted (or declining or sub-economic) oil and gas reservoirs. This category includes discrete reservoirs within defined fields and generally follows the guidelines of Brennan and others (2010). The third category is storage through CO_2-EOR, summarized from work by Wo and others (2009) and Wyoming's Enhanced Oil Recovery Institute (2011). The final category is storage in coalbed natural gas reservoirs, through CO_2-ECBM, and is summarized from work by Reeves (2003).

The results for all four categories are reported in the chapter corresponding to the specific basin. This chapter describes the procedure for calculating the CO_2 storage resource in deep saline aquifers and petroleum reservoirs.

This study does not consider the technical feasibility or the legal and regulatory framework for CO_2 storage. Estimates of the CO_2 storage capacity in Wyoming assume storage is technically feasible and complies with all federal and state regulations. These assumptions are employed for practical considerations, yet may not be valid in all cases. Specifically, Class VI well regulations require CO_2 storage below the lowest Underground Source of Drinking Water (USDW), defined as an aquifer with less than 10,000 mg/L total dissolved solids that supplies or contains a sufficiently large quantity of water to supply a public water system. Exceptions can be made to this rule on a case-by-case basis. Some of the deep saline aquifers in the Laramide basins have total dissolved solids of less than 10,000 mg/L, but are clearly not USDWs. Issues such as these will have to be resolved if geologic CO_2 storage is to proceed in Wyoming.

Storage in Saline Aquifers

The method used to obtain a simplified storage capacity (mass) of CO_2 in saline aquifers in the basins of Wyoming was published by the National Energy Technology Laboratory in the "CO_2 Atlas III" (U.S. Department of Energy, 2010). The storage calculations in the "CO_2 Atlas III" were designed for regional and national assessments of CO_2 storage estimates. This method was chosen for Wyoming's basin assessments because it is simplified,

fast, and produces generalized, yet robust results. Potential receiving formations are limited by depth (914–3,962 m; 3,000–13,000 feet). Specific structural traps are considered in this evaluation with the assumption of viable overlying confining zones. The results are not intended to be used as absolute estimates. Instead, they should be used for orders of magnitude in ideal conditions, and for comparison between basins. This study is meant to be an initial assessment to be refined in future studies on a case-by-case basis.

The theoretical storage resource (mass) of CO_2 in deep saline aquifers (S_{basin}) follows the general equation:

$$S_{basin} = A_t h_g \phi_{tot} \rho_{CO2} E_{basin} , \qquad (4\text{-}1)$$

where A_t is the total area of the formation, h_g is the gross formation thickness, ϕ_{tot} is the total porosity, ρ_{CO2} is the density of CO_2 at reservoir conditions, and E_{basin} is the CO_2 storage efficiency factor that reflects the proportion of CO_2 that can be stored in the available pore space.

The total area of each chosen formations is calculated differently for each basin, depending on the available data. Structure contour maps are generated and filtered in ArcGIS (when possible) to retain only depths between 914 and 3,962 m (3,000 and 13,000 feet) and clipped to the boundary of the basin, or the boundary of the structure under evaluation (as in the case of the Greater Green River Basin).

CO_2 density at reservoir conditions is dependent upon pressure and temperature. ρ_{CO2} is therefore directly related to the depth of the receiving formation, which can be simplified to the midpoint of the target depth range for CO_2 storage (914–3,962 m; 3,000–13,000 feet), or 2,438 m (8,000 feet). Following Burke (2012), a standard normally pressured saline aquifer has a hydrostatic pressure gradient of 10.516 kPa/m (0.465 psi/ft) (Schlumberger, 2012), a generalized geothermal gradient of 0.0301 °C/m (0.0165 °F/ft) (Sheriff, 1991), and an average surface temperature of 20 °C (68 °F). A depth of 2,438 m (8,000 feet) corresponds to 25.5 MPa (3,698.5 psi) and 93 °C (200 °F). ρ_{CO2} at these conditions is 628 kg/m^3 (39 lb/ft^3) and is used in this assessment to account for the wide range of depths evaluated by one equation.

E_{basin} can be calculated mathematically with extensive knowledge of a basin, or can be estimated by formation lithology (U.S. Department of Energy, 2010). This study estimates E_{basin} by formation lithology. Probabilistic values for E_{basin} were calculated by Monte Carlo sampling to determine the 10th, 50th, and 90th percentile probabilities for dolomite, limestone, and clastics (U.S. Department of Energy, 2010) and are summarized in Table 4-1.

Any additional assumptions are described in the individual basin chapters. The resultant calculations are reported in the subsequent basin chapters (Chapters 5–10). The results are estimates that require significant assumptions and should not be used without acknowledging and incorporating the associated assumptions.

Table 4-1. Values of E_{basin} used in the estimation of CO_2 storage capacity of saline aquifers (from U.S. Department of Energy, 2010).

Lithology	10th percentile (%)	50th percentile (%)	90th percentile (%)
Dolomite	0.64	2.2	5.5
Limestone	0.40	1.5	4.0
Clastics	0.51	2.0	5.4

Storage in Petroleum Reservoirs

Petroleum reservoirs have a high potential for safely storing CO_2. They are effective traps with proven seals. The method used to calculate the CO_2 storage resource (mass) for existing hydrocarbon reservoirs relies heavily on Brennan and others (2010), with some modifications that reflect intentionally conservative estimations as well as specific reservoir conditions. This approach assumes the mass

of CO_2 that can be stored in an existing reservoir (S_{res}) is equal to the product of the net volume of hydrocarbons and water produced from that reservoir (known recovery) at reservoir conditions (V_{prod}), a CO_2 storage efficiency factor that reflects the proportion of CO_2 that can fill the available pore space (E_{res}), and the density of CO_2 at reservoir conditions (ρ_{CO2}), or

$$S_{res} = V_{prod}\rho_{CO2}E_{res}\,. \qquad (4\text{-}2)$$

V_{prod} is the sum of the volume of the net surface production of oil (V_o), gas (V_g), and water (V_w) corrected to subsurface pressure and temperature conditions by a formation volume factor:

$$V_{prod} = V_oB_o + V_gB_g + 0.2V_wB_w\,, \qquad (4\text{-}3)$$

where B_o is the formation volume factor for oil (assuming no natural gas liquids), B_g is the formation volume factor for gas, and B_W is the formation volume factor for water. A conservative 20 percent of the initial water pore volume can presumably be replaced by CO_2. Initial water pore volume is assumed equal to the volume of produced water. Natural water recharge into the reservoir is not considered.

Hydrocarbon and water production volumes were obtained through 2011 from the Wyoming Oil and Gas Conservation Commission (2012). The agency reports yearly production, by reservoir, for oil, gas, and water, since 1978. Pre-1978 production is reported as a single value for all reservoirs from the field, and not all reservoirs are of interest. Pre-1978 oil production ($V_{o,\,pre1978}$), by reservoir, was thus calculated using the assumption that the proportion of reservoir production to total field production in 1978 is equal to the proportion of pre-1978 reservoir production to the pre-1978 total field production, or

$$V_{o,pre1978} = \left(V_{o,\,field,pre1978}\right)\left(V_{o,1978} / V_{o,\,field,1978}\right). \qquad (4\text{-}4)$$

$V_{o,\,field,\,pre1978}$ represents the volume of produced oil reported for the field before 1978. $V_{o,1978}$ is the volume of oil produced in 1978 for the specific reservoir within the field. $V_{o,\,field,1978}$ is the volume of produced oil for the field in 1978. The net surface production of oil is thus

$$V_o = V_{o,pre1978} + V_{o,1978-2011}\,, \qquad (4\text{-}5)$$

where $V_{o,1978\text{-}2011}$ is the 1978 through 2011 production volumes reported to the Wyoming Oil and Gas Conservation Commission.

For hydrocarbon reservoirs that are primarily gas and condensate (not oil) reservoirs with significant gas caps, gas production reported to the Wyoming Oil and Gas Conservation Commission (2012) is not primarily solution gas. Gas production is thus accounted for separately and similar to oil production, where

$$V_{g,pre1978} = \left(V_{g,\,field,pre1978}\right)\left(V_{g,1978} / V_{g,\,field,1978}\right), \qquad (4\text{-}6)$$

and

$$V_g = V_{g,pre1978} + V_{g,1978-2011} - V_{g,i}\,. \qquad (4\text{-}7)$$

$V_{g,\,field,\,pre1978}$ represents the volume of produced gas reported for the field before 1978. $V_{g,1978}$ is the volume of gas produced in 1978 for the specific reservoir within the field. $V_{g,\,field,1978}$ is the volume of produced gas for the field in 1978. $V_{g,1978\text{-}2011}$ is the 1978 through 2011 gas production volumes reported to the Wyoming Oil and Gas Commission, and $V_{g,i}$ is the volume of gas re-injected into the reservoir (only reported since 1978).

Reservoirs without gas caps imply that gas production reported to the Wyoming Oil and Gas Conservation Commission is solution gas and is accounted for by B_o. For many of these aging oil fields peak production was prior to 1978. Presumably the majority of the gas in these fields was produced and burned off prior to 1978. For these reasons, and in the appropriate basins (e.g., the Bighorn Basin), the volume of produced gas is considered negligible.

Water production and injection was not recorded by the Wyoming Oil and Gas Conservation Commission before 1978 and is unknown. V_w is equal to the surface volume of produced water from 1978 through 2011 ($V_{w,1978\text{-}2011}$) minus the injected volume ($V_{w,i}$), or

$$V_w = V_{w,1978-2011} - V_{w,i}\,. \qquad (4\text{-}8)$$

$V_{w,i}$ was also not reported prior to 1978.

CO_2 density at reservoir conditions is dependent upon pressure and temperature, therefore an average value for ρ_{CO2} is calculated for each basin, depending on the average reservoir depth.

E_{res} can vary widely and is difficult to constrain. A value of E_{res} equal to one assumes all the hydrocarbons produced from the reservoir can be replaced by CO_2. This scenario was proven unrealistic by laboratory experiments that instead relate E_{res} to relative permeability curves (e.g., Bennion and Bachu, 2005, 2008; Burton and others, 2008). It is difficult to extrapolate an experimentally derived E_{res} to a specific reservoir in a field. Following the guide of Brennan and others (2010), this study uses the range 0.1, 0.3, and 0.6 for the minimum, mode, and maximum values of E_{res}, respectively. Deviations in E_{res} can significantly change the calculated storage resource. It is therefore necessary to refine these storage calculations in the future with CO_2 storage efficiency values for specific reservoirs. B_o and B_g vary widely based on hydrocarbon properties. Averaged values of B_o and B_g are used for each basin.

For all reservoirs within all fields, the following additional assumptions are made:

1. The reservoir must be between 914 and 3,962 m (3,000 and 13,000 feet) below the surface. Reservoirs outside this range are not considered. Average reservoir depths were retrieved from the Wyoming Enhanced Oil Recovery Institute (2012).
2. Remaining reserves are assumed to be negligible and no future production is taken into account. All volumes are calculated through 2011, as reported to the Wyoming Oil and Gas Conservation Commission (2012).
3. Production and injection volumes were retrieved solely for Wyoming; the CO_2 storage resource reflects storage only in the Wyoming portion of fields that straddle the state boundary.
4. For reservoirs under waterflood, where $V_{w,\,1978\text{-}2011} > V_w$, V_w was not incorporated into the calculation and Equation 4-3 reduces to $V_{prod} = V_o B_o + V_g B_g$.

This investigation assumes the most productive hydrocarbon fields within Wyoming have the largest available pore space for storing CO_2, and completes calculations within these fields. These chosen fields are not presumed depleted and the method does not account for additional pore space created through future production. Geologic CO_2 storage (excluding CO_2-EOR) will not be a viable option until hydrocarbon recovery in these fields is no longer economic.

As previously noted, the estimates of the CO_2 storage resource for existing petroleum reservoirs are purposefully generalized and intentionally conservative. Each reservoir and field has different properties that are presumed similar and constant for these calculations. This method assumes no mineralization and does not specifically consider engineering aspects such as injectivity. The calculated storage resource would significantly increase by using original oil or gas in-place estimates instead of oil and gas production, or by considering a higher replacement percentage of produced water. These results are intended to provide the user with order-of-magnitude values that should be further refined on a reservoir-by-reservoir basis.

The results are summarized in the basin chapters (Chapters 5–10).

Chapter 5

Greater Green River Basin

The Greater Green River Basin contains the state's largest accumulation of naturally occurring CO_2 (LaBarge platform). Two of the largest doubly plunging anticlines within the basin, the Moxa arch and Rock Springs uplift, are the likeliest targets in Wyoming for long-term and high-volume storage of CO_2 in deep saline aquifers. The Greater Green River Basin is thus a unique laboratory to study natural CO_2 trapping and storage, with nearby opportunities for injection and storage of anthropogenic carbon dioxide.

Background

The Greater Green River Basin encompasses the southwest portion of Wyoming and extends south into northeastern Utah and northwestern Colorado. For the purpose of this assessment, the basin boundary is defined by the Wyoming portion of the Upper Colorado River 2-digit hydrologic unit (Fig. 5-1). The basin is an amalgamation of several sub-basins, including the Green River Basin, Great Divide Basin, Washakie Basin, and Sand Wash Basin (Plates 2, 4, and 5, Figs. 5-1 and 5-2). These sub-basins were formed during the Late Cretaceous to Early Eocene Laramide orogeny, with the uplift of the Moxa arch, Rock Springs uplift, Cherokee Ridge arch, and Wamsutter arch. The Greater Green River Basin is bounded on the west by the Sevier overthrust belt, on the north by the Wind River Mountains, to the east by the Rawlins uplift and Sierra Madre Mountains, and to the south by the Uinta Mountains. The footprint of the basin covers 54,269 km^2 (20,953 square miles) in Wyoming. An intermittent record of sedimentation from the Cambrian through present is preserved in the basin, with total compacted sediment fill that can be greater than 9,144 m (30,000 feet) thick.

Coverage of the Greater Green River Basin by two-dimensional (2-D) seismic surveys is extensive (Fig. 5-3). Surveys of various vintages can be purchased through third-party vendors. Two publicly available seismic surveys in the Greater Green River Basin are available for download from the USGS at http://walrus.wr.usgs.gov/NAMSS/. Green River Basin Phase 2 (W-2-91-WY) is a series of six 2-D lines and Green River Basin Phase 3 (W-3-91-WY) consists of eight 2-D lines. Both surveys were taken north of the town of Green River. No other publicly available seismic datasets are known.

An important side note must be made regarding trona. Trona is a mineral that is extensively mined in the subsurface (244–488 m; 800–1,600 feet; below the surface) of Sweetwater County, in the heart of the Greater Green River Basin. Production from the Eocene Green River Formation comprises 30 percent of total global production of trona. The estimated total extent of trona and the known sodium leasing area are shown on Figure 5-4. Carbon dioxide storage, EOR, and ECBM cannot interfere with trona mining (or any other mineral leases) and are therefore not viable within the known sodium leasing area.

Storage in Saline Aquifers

The stratigraphy in the Greater Green River Basin is complex (Plate 1). Only Upper Cretaceous and Cenozoic sediments are exposed at the surface within the basin proper. Mesozoic and Paleozoic sedimentary units crop out in isolated locations on the flanks of the mountain ranges that border the basin. Since the Greater Green River Basin covers such a large area, correlation between distant outcrops is difficult. This issue is mitigated by hydrocarbon exploration wells that penetrate older and deeper formations within the basin, although correlating the wireline log signatures in the subsurface to the surface outcrops is challenging. As a result, many formations change names in the middle of the Greater Green River Basin (e.g., Plates 1, 6a, and 6b). Stratigraphic units in the southern and eastern regions of the basin carry formation names common to Utah and Colorado, while the western and northern parts of the basin use nomenclature found throughout Wyoming (Plate 1). Stratigraphic terminology in the Sevier overthrust belt is a mixture of formation names originating from Wyoming and Idaho.

In the Greater Green River Basin, potential storage zones can be identified by geochemical analyses of reservoir fluids. Smith and others (2010) report that formations younger than and including the Jurassic (Triassic?) Nugget Sandstone have potential total dissolved solids concentrations less than 10,000 mg/L in the vicinity of the Rock Springs uplift. On the Moxa arch, the Nugget Sandstone

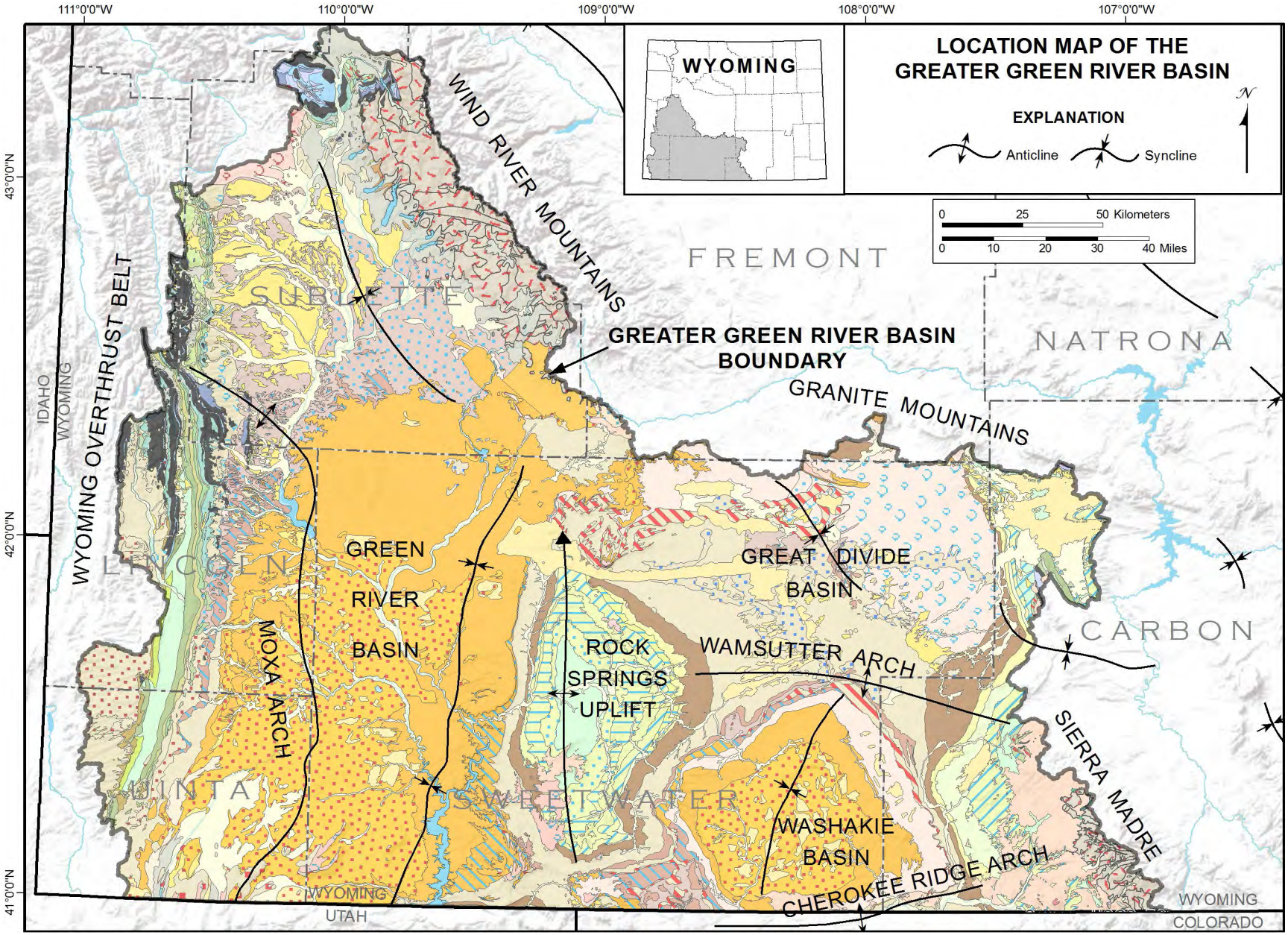


Figure 5-1. Location map of the Greater Green River Basin. The Greater Green River Basin is defined by the Upper Colorado River 2-digit hydrologic unit and includes the Green River, Great Divide, Washake, and Sand Wash (Colorado) basins, separated by the Rock Springs uplift, Wamsutter arch, and Cherokee Ridge arch.

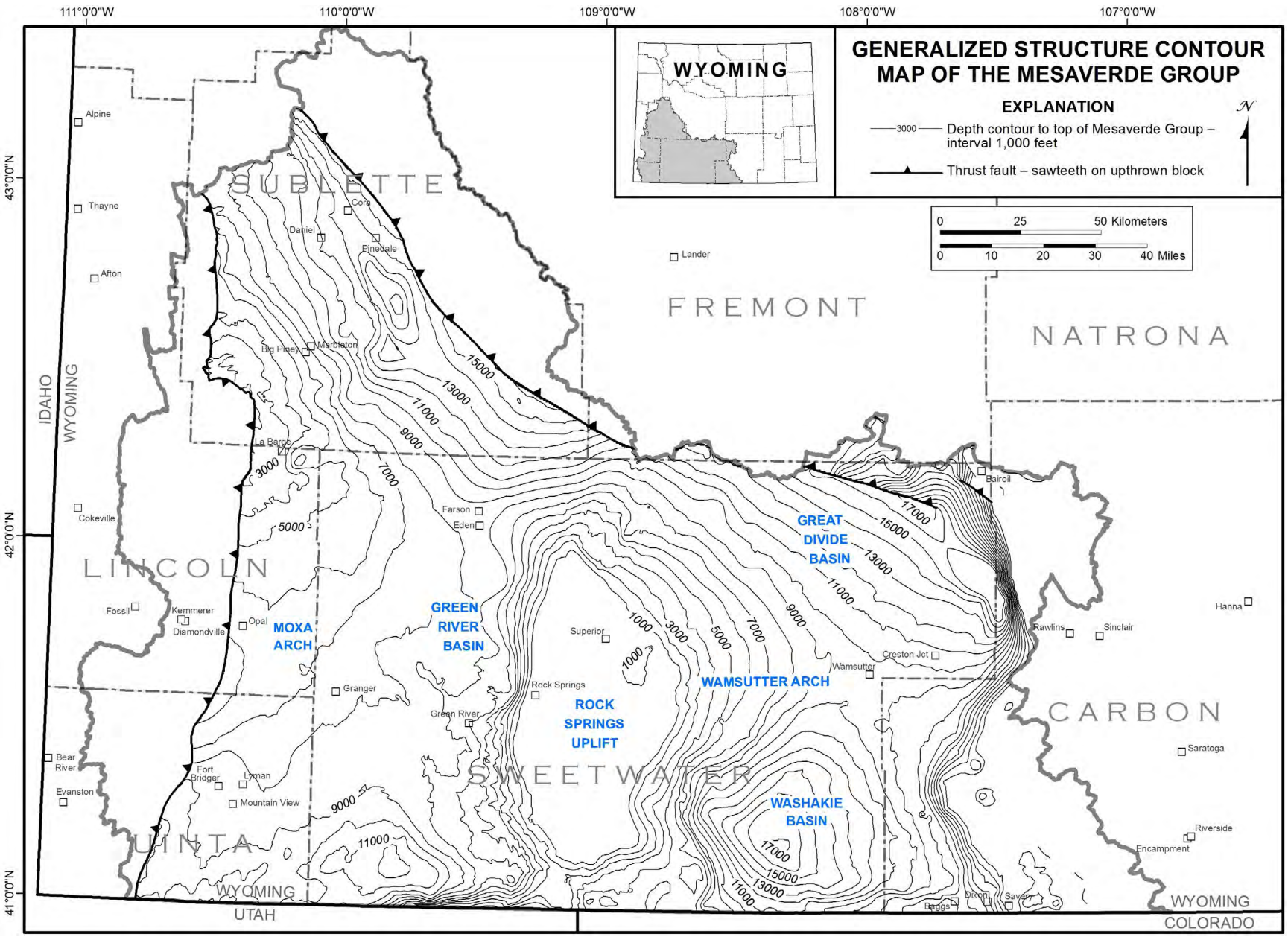


Figure 5-2. Depth-contour map on the top of the Mesaverde Group. Contours highlight the sub-basins that comprise the Greater Green River Basin. Contours modified from Finn and others (2005).

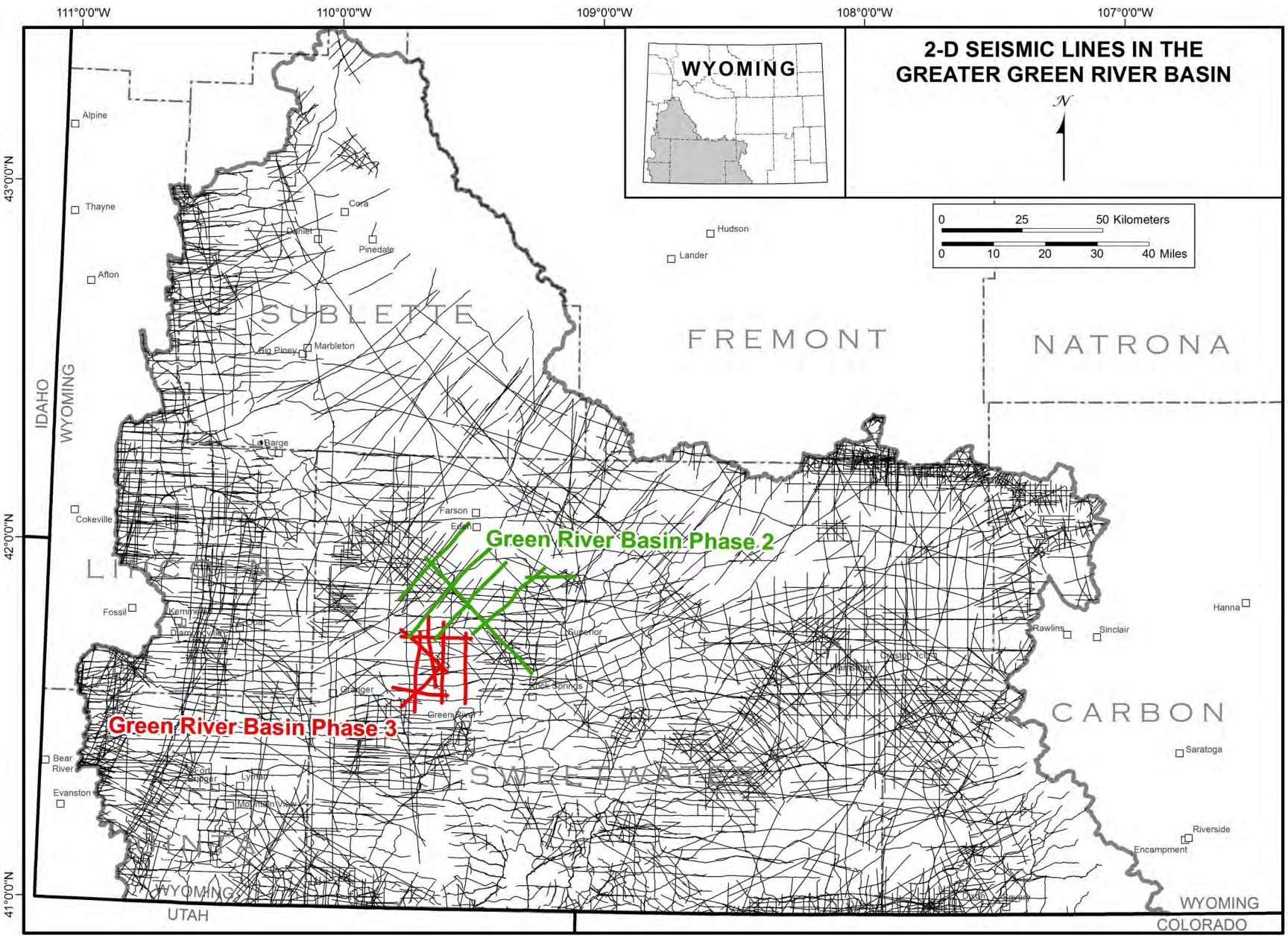


Figure 5-3. Map showing the location of 2-D seismic lines in the Greater Green River Basin. The line locations were provided by and are available for purchase from Seismic Exchange, Inc. (2011). Green River Basin Phase 2 (W-2-91-WY) and Green River Basin Phase 3 (W-3-91-WY) seismic lines can be downloaded from the U.S. Geological survey at http://walrus.wr.usgs.gov/NAMSS/.

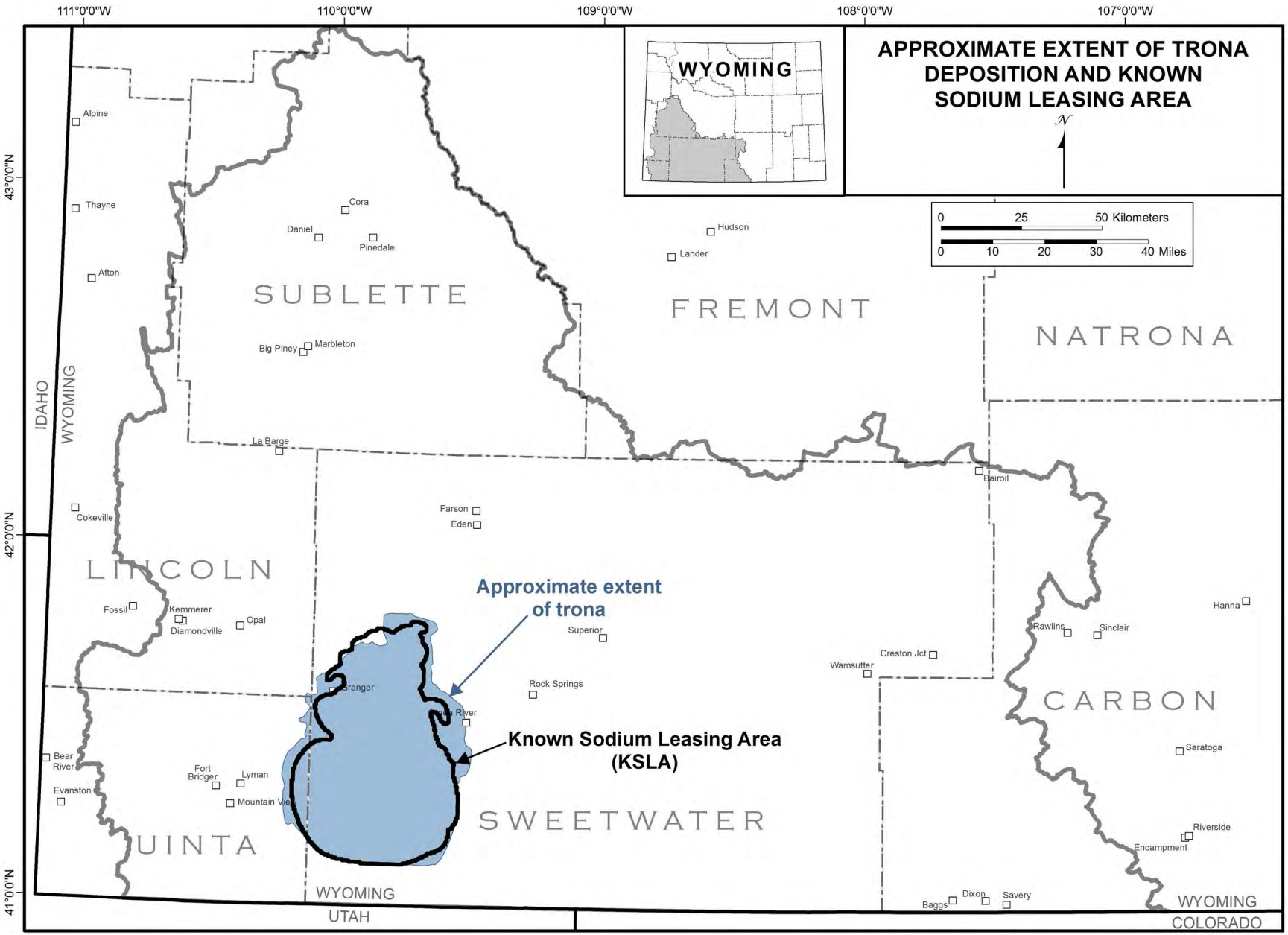


Figure 5-4. Map showing the approximate extent of trona deposition and the Known Sodium Leasing Area (KSLA) in the Greater Green River Basin. Trona extent and KSLA from S. Wiig, Bureau of Land Management, Rock Springs Field Office, 2012.

water quality samples have total dissolved solids concentrations greater than 10,000 mg/L (Smith and others, 2010). With the added consideration of adequate porosity and permeability, the potential storage zones in the Greater Green River Basin include the Nugget Sandstone (on the Moxa arch exclusively), the Weber Sandstone, Madison Limestone, Bighorn Dolomite, and possibly the Cambrian formations. The largest and most appropriate structural traps include the Moxa arch, Rock Springs uplift, Wamsutter arch, and Cherokee Ridge arch (Fig. 5-1, Plate 4).

Traps

Moxa Arch

The Moxa arch is an elongate, doubly plunging anticline that extends north approximately 193 km (120 miles) from the flank of the Uinta Mountains at the Wyoming–Utah border to its culmination at the LaBarge platform (Fig. 5-1, Plate 4). North of the LaBarge platform, the trend of the arch becomes northwest and is lost beneath the thrust sheets associated with the Sevier overthrust belt. The Moxa arch is a gentle structure with approximately 3,305 m (11,500 feet) of structural relief (Royse, 1993; Becker and others, 2010) (Plate 5) with limbs dipping a maximum of 5 degrees on the steeper east flank (Campbell-Stone and others, 2010). Based on low-angle unconformities within the Campanian (Late Cretaceous, ~75 Ma) Ericson Formation that place the Canyon Creek Member directly on strata as old as Santonian Baxter/Hilliard/Cody Shale, the Moxa arch grew during the deposition of the Ericson (Wach, 1977; Devlin and others, 1993; Finn and Johnson, 2005).

Along much of the length of the Moxa arch, the folded strata are apparently not displaced by an emergent basement fault, which supports the interpretation that the arch is a low-amplitude, basement-involved structure. An exception to the non-displaced strata exists on the southwest edge of the LaBarge platform, where an Eocene phase of shortening accentuated a portion of the Moxa arch and some Paleozoic strata are duplicated by west-vergent, basement-involved reverse faults (Kraig and others, 1987; Royse, 1993; Becker and Lynds, 2012). Consequently, the LaBarge platform is the current culmination of the Moxa arch. The timing for emplacement of the easternmost major thrust sheet of the Sevier overthrust belt, the Hogsback thrust, has been bracketed between the Paleocene and the Early Eocene, based on growth strata and unconformities exposed near LaBarge Creek. The LaBarge platform (a structural feature) folds and exhumes the Hogsback thrust, revealing that the latest phase of Moxa growth is likely Early Eocene in age (Royse, 1993; Becker and others, 2010; Becker and Lynds, 2012). A portion of the Eocene Wasatch Formation and overlying Green River Formation onlaps the LaBarge platform, which supports an interpretation of Early Eocene deformation (Royse, 1993).

The Moxa arch hosts numerous hydrocarbon accumulations within several different reservoir intervals (Plate 6a) (Wach, 1977; Doyle and others, 1987). Production is primarily sweet gas (does not contain significant amounts of hydrogen sulfide) and oil from the Upper Cretaceous formations (e.g., Muddy Sandstone, Frontier Formation, Baxter Formation, Mesaverde Group) (Plate 6a), yet the largest hydrocarbon accumulation is sour gas hosted within the Paleozoic strata on the LaBarge platform. In fact, this is the largest conventional accumulation of gas and hydrocarbons within Wyoming. The gas trapped in the Mississippian Madison Limestone and Ordovician Bighorn Dolomite is dominantly CO_2, with methane (CH_4), hydrogen sulfide (H_2S), and other trace gases making up the remainder. Helium (He) is also in commercially viable concentrations and the Labarge field (operated by ExxonMobil) produces roughly 25 percent of the nation's helium. The CO_2 produced in and on the flanks of the LaBarge platform is the byproduct from helium and methane production, and the primary CO_2 source used for EOR throughout Wyoming.

Although little data are publicly available, drill stem tests indicate increasing CO_2 saturation with depth within the Paleozoic formations. The Tip Top 22-19G well (API 49-035-05746), on the crest of the LaBarge platform, tested 9 percent CO_2 in the Phosphoria Formation, 64.2 percent in the Tensleep Sandstone, 64.9 percent in the Madison Limestone, and 84.7 percent in the Bighorn Dolomite (Stilwell, 1989). Approximately 44 km (27 miles) south, near the gas-water contact (FU 22-

35, API 49-023-20483), these values increase to 89.8 percent in the Madison Limestone and 95.8 percent in the Bighorn Dolomite (Stilwell, 1989). The origin of the CO_2 on the Moxa arch is not well understood and may be the product of several sources (Stilwell, 1989; De Bruin, 2001; Becker and Lynds, 2012). However, for the purpose of carbon dioxide storage, it is important to note that naturally occurring CO_2 has been successfully stored in the Moxa arch for a significant (geologic) amount of time; this proven trap is a strong candidate for future anthropogenic CO_2 storage (Becker and Lynds, 2012). Of the roughly 1 trillion cubic feet of raw gas produced from the Mississippian Madison Limestone since 1987, only a very small percentage has been reinjected into the Madison reservoir (most has been vented), leaving substantial pore space that could be potentially utilized for future anthropogenic CO_2 storage.

Rock Springs Uplift

Similar to the Moxa arch, the Rock Springs uplift resulted from Late Cretaceous through Early Eocene (Laramide orogeny) displacement of a west-vergent, basement-rooted thrust fault. The Rock Springs uplift is an asymmetrical, doubly plunging, north–south-trending anticline, 121 km (75 miles) long, with dips of 3 to 8 degrees on the east limb and 5 to 35 degrees on the west limb (Plate 5). The anticline-forming thrust fault is nearly exposed at the surface west of the fold axis. The complete structure is overprinted by normal faults that trend northeast–southwest and east–west (Plate 4) (Roehler, 1992).

Primary production on the Rock Springs uplift is from the Dakota Sandstone, Frontier Formation, and various formations within the Mesaverde Group (Plate 6b). Production also occurs from the Paleozoic formations in deeper fields on the flanks of the Rock Springs uplift, like Brady and Table Rock (Plate 3). Analysis from cuttings on a well near the crest of the anticline (Amoco-Texas #1, API 49-037-21201) show hydrocarbons were present in the Paleozoic section near the crest of the uplift for some undetermined interval in the past (Campbell-Stone and others, 2010). Although data are sparse, there is no known current Paleozoic hydrocarbon accumulation on the crest of the uplift. The lack of a modern reservoir implies hydrocarbons moved through the Paleozoic rocks prior to folding, or the Rock Springs uplift is a breached trap.

As mentioned, work is currently under way on a project to evaluate the feasibility of storing CO_2 in the Rock Springs uplift (e.g., Surdam and Jiao, 2007; Surdam and others, 2009; Campbell-Stone and others, 2010; Surdam, 2011; Surdam and others, 2012). The project is a joint project between the University of Wyoming and several industry partners. Complete results from this project should become available in 2013.

Wamsutter Arch

The Wamsutter arch is a northwest–southeast-trending broad structural high that divides the Great Divide Basin to the north from the Washakie Basin to the south (Fig. 5-1). The arch plunges from the Rock Springs uplift down to the east toward the Rawlins uplift. The south and southeastern flanks of the arch dip 1–5 degrees south (Ritzma, 1963). The timing of the formation of the Wamsutter arch is not well constrained. It seems that uplift on the Table Rock platform (a northeastern extension of the Rock Springs uplift, correlated to the western Wamsutter arch) began during the latest Cretaceous and continued with folding of the arch during the Late Eocene through Oligocene (Ritzma, 1968). The nearly continuous slope from the Wamsutter arch to the Rock Springs uplift (Fig. 5-1) suggests that the arch is an improbable structure for isolated CO_2 storage, as CO_2 would migrate up dip to the Rock Springs uplift. However, seismic data could help define possible closure and storage space on the Wamsutter arch.

Cherokee Ridge Arch

The Cherokee Ridge arch divides the Sand Wash Basin in northwestern Colorado from the Washakie Basin southeast of the Rock Springs uplift (Fig. 5-1). The Cherokee Ridge arch is an east–west-trending anticline that straddles the Colorado–Wyoming border. The arch plunges down to the west and can be seen on the surface as a distinct east–west-trending lineament (Bader, 2008). The eastward climb of the subsurface strata may make the Cherokee Ridge arch an indeterminate struc-

tural trap for CO_2 storage, yet this structure should not be ruled out without further investigation using seismic data.

Storage Zones

Nugget Sandstone

The Nugget Sandstone only crops out on the flanks of the Greater Green River Basin (Plate 4) and is not exposed on the Moxa arch. Cores from the Moxa arch reveal the Nugget is an eolian subarkose or quartzarenite, fine-grained sandstone, interbedded with interdune siltstones, mudstones, and limestones (Edman and Cook, 1992). Although the Nugget Sandstone is an important hydrocarbon reservoir in the overthrust belt west of the Greater Green River Basin, it is not a significant producer on the Moxa arch. The Tip Top (discovered 1951), Hogsback (discovered 1960), and Dry Piney (discovered 1970) fields (Plate 3) are the primary Nugget producers on the LaBarge platform and have recovered approximately 15 thousand barrels of oil cumulatively. Porosity in these fields ranges 2–17 percent with permeabilities 8–200 millidarcies (Webel, 1977). These deep fields (3,048–3,505 m; 10,000–11,500 feet; below the surface) have a nonuniform porosity distribution within the reservoirs. Net pay zones are 15–29 m (48–95 feet) thick, and oil produced from these fields has a gravity of 52–59° API (Webel, 1977). The Nugget Sandstone thins from a maximum of 235 m (772 feet) in the Church Buttes field on the Moxa arch, to 135 m (442 feet) in the Table Rock field east of the Rock Springs uplift (Fig. 5-5a). The formation pinches out east of Rawlins.

Investigations are ongoing by several organizations into the feasibility of storing CO_2 in the Nugget Sandstone on the Moxa arch. Li and others (2011) have constructed elaborate subsurface models to predict CO_2 migration and storage potential with an injection location at ExxonMobil's Shute Creek facility on the central Moxa arch. The Big Sky Carbon Sequestration Partnership began a preliminary analysis of the Nugget Sandstone for a Phase III large-scale injection project. This project did not progress beyond the preliminary stages, yet all findings are summarized in the carbon atlas at http://www.bigskyco2.org/atlas. Most studies have shown that there is likely to be some storage space within the Nugget Sandstone, but the space is limited by the proximity of the LaBarge platform to the leading thrust of the Wyoming overthrust belt, a distinct leakage pathway.

Tensleep/Weber Sandstone

The Tensleep Sandstone has a maximum thickness of 162 m (530 feet) in the Church Buttes field on the Moxa arch and the Weber Sandstone has a maximum thickness of 223 m (730 feet) on the southeastern flank of the Rock Springs uplift (Fig. 5-5c). The top of the Tensleep Sandstone is 3,962–5,182 m (13,000–17,000 feet) below the surface on the Moxa arch. On the Rock Springs uplift, the Weber lies at depths between 1,829 m (6,000 feet) near the crest to over 5,182 m (17,000 feet) on the flanks.

The Weber Sandstone is a producing reservoir on the Rock Springs uplift. The Brady field on the southeastern flank of the uplift produces from seven different intervals on two different structures (Montgomery, 1996). Production is primarily from dune fields (Brock and Nicolaysen, 1975; Robinson, 1992a, b) and pay thickness ranges from 51 to 53 m (167 to 188 feet) (Miller and others, 1992). Log-derived porosity measurements are as high as 19 percent with permeabilities up to 246 millidarcies in the South Brady field. Much of the porosity and permeability may be in part due to micro fracturing. Oil produced from these reservoirs has a near-condensate gravity of 52–54.7° API (Miller and others, 1992).

Publicly available wireline logs from the recently drilled University of Wyoming well on the Rock Springs uplift (RSU #1, API 49-037-07154) suggest a low-permeability sandstone with porosity values less than 10 percent. The Tensleep/Weber Sandstone is either a high-porosity (fractured) prolific hydrocarbon producer or heavily dolomitized low-porosity sandstone. Carbon dioxide storage locations within the Tensleep/Weber Sandstone of the Greater Green River Basin will have to be chosen carefully to correspond to regions of enhanced porosity and permeability.

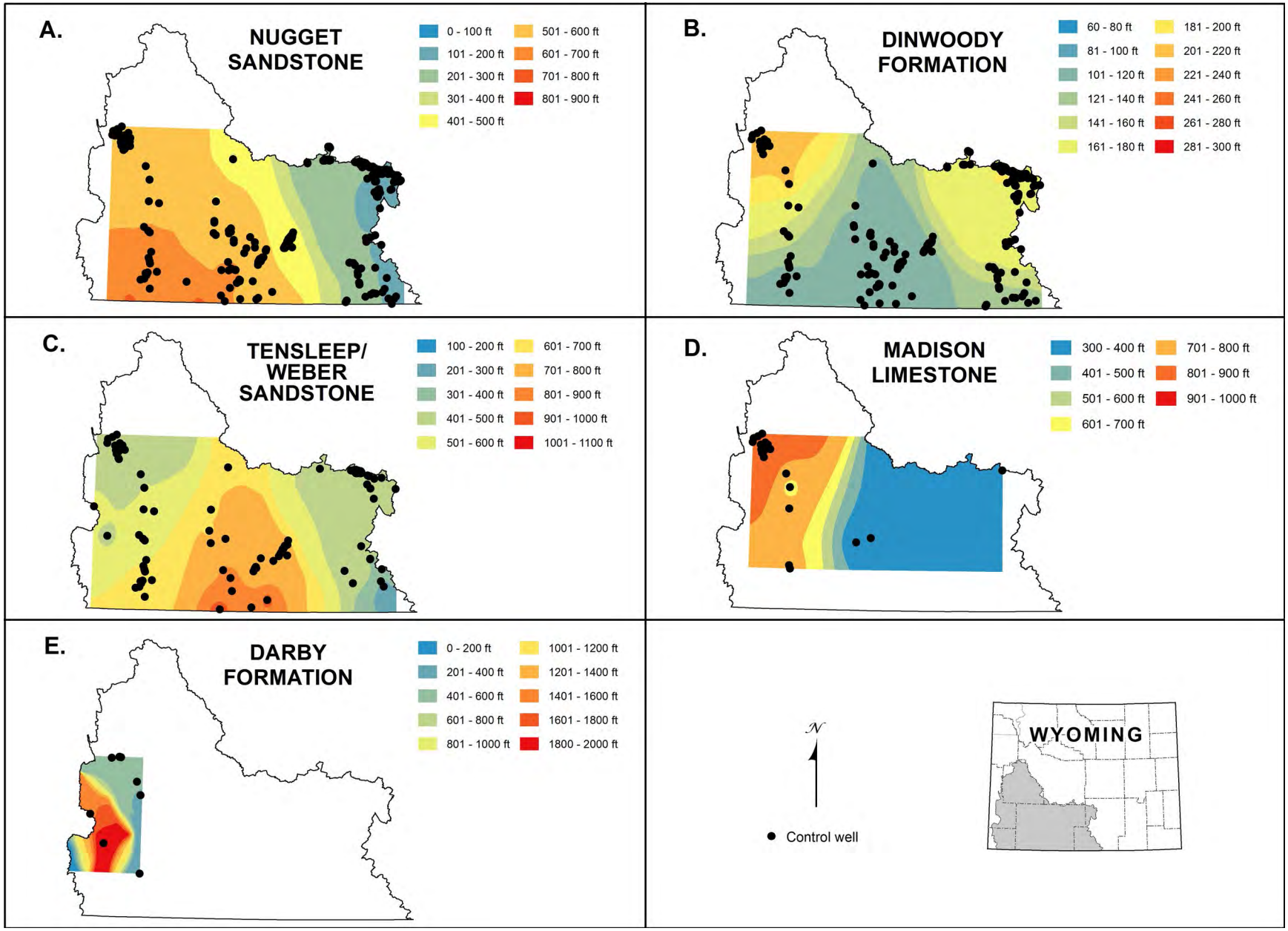


Figure 5-5. Isopach maps of several formations in the Greater Green River Basin. Isopachs were constructed using subsurface data obtained from IHS Energy Group (2011), and were contoured using smoothed inverse distance weighting. **A.** Isopach of the Nugget Sandstone. **B.** Isopach of the Dinwoody Formation. **C.** Isopach of the Tensleep/Weber Sandstone. **D.** Isopach of the Madison Limestone. **E.** Isopach of the "Darby" Formation. The construction of isopach maps for the Bighorn Dolomite and Cambrian formations was limited by the paucity of subsurface data.

Madison Limestone
On the Moxa arch, the Madison thins from a maximum of 250 m (820 feet) on the LaBarge platform to 211 m (693 feet) south in the Church Buttes field. On the northeast flank of the Rock Springs uplift, the Madison Limestone is 130 m (426 feet) thick and thins to 104 m (341 feet) in the Table Rock field (Fig. 5-5d). Reservoir depths range from over 5,486 m (18,000 feet) on the flanks of the Rock Springs uplift to 2,256 m (7,400 feet) at the crest. The fields on the LaBarge platform are greater than 4,191 m (13,750 feet) below the surface, and 5,532 m (18,150 feet) in the Church Buttes field. These great depths may limit the potential to store CO_2 in the Madison at the crest of the Moxa arch (depths greater than 3,962 m; 13,000 feet; require additional surface compression of CO_2 beyond pipeline pressures). Injection near a compression station, such as the Shute Creek facility, could mediate this concern.

The highest porosities and permeabilities in the subsurface of the Madison Limestone are found in the dolostones (Thyne and others, 2010), including sucrosic dolomite zones and zones of moldic porosity (Westphal and others, 2004). The Table Rock field on the southeast flank of the Rock Springs uplift (Plate 3) has an average porosity of 13 percent with a pay zone of 498 m (160 feet) (Miller and others, 1992). On the LaBarge platform, porosities range from 4 to 26 percent, but are commonly 12 to 14 percent in the 91–183 m-thick (300–600 feet-thick) pay zone. Rare permeability data range from 0.2 to 200 millidarcies with outliers of 1 to 2 darcies (Miller and others, 1992), that are likely fracture zones. Production from the Madison Limestone throughout the Greater Green River Basin is primarily gas in the form of CO_2 (65 percent), CH_4 (22 percent), H_2S (5 percent), and He (less than 1 percent).

Other Potential Storage Zones
The Bighorn Dolomite and Cambrian formations are potential storage zones in the Greater Green River Basin that are not assessed in this study. The Bighorn Dolomite thins from 120 m (394 feet) on the LaBarge platform to 67 m (220 feet) near the Wyoming–Utah border, and is completely truncated by subsequent erosion further south in the Uinta uplift (Rowley and others, 1985). The Bighorn Dolomite is approximately 6 m (20 feet) thick on the crest of the Rock Springs uplift and absent further east in the Table Rock field. The Steamboat Point Member (maximum thickness of 104 m; 341 feet) and base of the Leigh Member (0–19 m thick; 0–61 feet) are the only members preserved on the Moxa arch.

Reservoir property data are rare because few wells have been drilled into the Bighorn Dolomite on the Moxa arch. Neutron porosity logs from the Tip Top field (LaBarge platform) show porosities ranging from 0–14 percent (Becker and Lynds, 2012) with an average permeability of 77.7 millidarcies (Stilwell, 1989). Initial measured bottom hole pressures from one well on the LaBarge platform are at or below 47,570 kPa (6,900 psig) (Becker and Lynds, 2012). The FU 22-35 (API 49-023-20483) on the southern flank of the LaBarge platform tested 95.8 percent CO_2 (Stilwell, 1989).

The Bighorn Dolomite is not present east of the Rock Springs uplift and is deeper than 3,962 m (13,000 feet) west of the Rock Springs uplift. The Cambrian formations are present in all areas and are within the required depth range near the crest of the Rock Springs uplift and on the eastern edge of the Great Divide Basin and Wamsutter arch, yet there is a paucity of subsurface data on these formations. For these reasons, neither the Bighorn Dolomite nor the Cambrian formations were assessed for CO_2 storage.

Confining Zones
Gypsum Spring Member
In the Greater Green River Basin, the Gypsum Spring Member/Formation contains gypsum accumulations commonly up to 9 m (30 feet) thick. Plastic-like properties of the gypsum beds are the probable cause for irregular thinning/thickening of the unit. On the LaBarge platform, the Gypsum Spring Formation thins over the crest of local anticlines and thickens in the associated synclines. The Gypsum Spring Formation is not apparent from wireline logs further south in the Church Buttes field (note the absence of the Gypsum Spring from the type log of the Moxa arch, Plate 6a). Due to the thickness of the gypsum in the subsurface

and the plastic-like deformation behavior of gypsum, the Gypsum Spring Formation is a potential confining zone for CO_2 storage in the Nugget Sandstone only in very specific locations. Detailed subsurface work must be carried out to determine the thickness and continuity of the Gypsum Spring over a storage-structure of interest.

Triassic Formations

The Triassic formations, including the Dinwoody Formation, Woodside Shale, Thaynes Limestone, and Ankareh Formation on the LaBarge platform, and the Dinwoody Formation and Chugwater Group on the Rock Springs uplift, are proven hydrocarbon seals to the Paleozoic hydrocarbon system (Campbell-Stone and others, 2010). The section thins from a maximum of 579 m (1,900 feet) on the Moxa arch to 370 m (1,215 feet) on the Rock Springs uplift (Fig. 5-5b).

Amsden Formation

The Amsden Formation thickens from approximately 116 m (380 feet) on the LaBarge platform to 130 m (425 feet) on the crest of the Rock Springs uplift. Very little information is available for the Amsden Formation in the subsurface of the Greater Green River Basin, however fluid inclusion volatile analysis suggests the Amsden Formation has been a viable hydrocarbon seal in the past (Campbell-Stone and others, 2010). Also, the significant CO_2 accumulation within the Madison Limestone on the LaBarge platform proves the competence of the Amsden Formation seal, on the Moxa arch.

Jefferson Formation

The Upper Devonian section thins from a maximum of 143 m (470 feet) on the crest of the Moxa arch (LaBarge platform) south to 86 m (282 feet) in the Church Buttes field. Here the Jefferson Formation is subdivided into the Lower Jefferson Member and the (upper) Birdbear Member (Lynds and others, 2010). Both the Three Forks Formation and Birdbear Member of the Jefferson Formation have been removed by erosion and are not present on the Rock Springs uplift, leaving only the Lower Jefferson Member, which is also not present in the Washakie and Great Divide basins (Fig. 5-5e). If the Bighorn Dolomite is determined to be an adequate storage zone for CO_2, the Jefferson Formation is likely a good seal only near the crest of the Moxa arch, but not further south on the Moxa arch or east on the Rock Springs uplift or the Great Divide and Washakie basins.

Results

Locations corresponding to structural traps with adequate storage and confining zones were assessed for CO_2 storage resource. These locations include the LaBarge platform, Rock Springs uplift, and Wamsutter arch and Great Divide Basin. The formations assessed for each trap include the Nugget Sandstone, Tensleep/Weber Sandstone, and Madison Limestone (Table 5-1). The total areas of the formations were calculated from structure contour maps produced for each formation of interest from interpreted well tops purchased through IHS Energy Group (2011). The resulting maps were filtered in ArcGIS to retain only depths between

Table 5-1. Input values used in the estimation of CO_2 storage capacity of saline aquifers. RSU is Rock Springs uplift, LB is the LaBarge platform, and W/GD is the Wamsutter arch and Great Divide Basin.

Formation	A_t (km²)	h_g min (m)	h_g max (m)	ϕ_{tot} min (%)	ϕ_{tot} max (%)
Nugget RSU	3,538	12	36	11	18
Nugget LB	1,366	12	36	11	18
Nugget W/GD	9,164	12	36	11	18
Tensleep/Weber RSU	2,754	21	64	3	12
Tensleep/Weber W/GD	7,413	21	64	3	12
Madison RSU	1,457	49	62	10	13
Madison W/GD	6,237	49	62	10	13

914 and 3,962 m (3,000 and 13,000 feet), clipped to the boundary of the Greater Green River Basin, and clipped to the sub-basin boundaries (Fig. 5-6). Maximum and minimum formation thickness and porosity for the assessed formations were obtained from Johnson (2005). The Tensleep and Weber sandstones were combined into one unit. The total area, maximum and minimum total porosity, and maximum and minimum gross formation thickness are summarized in Table 5-1. The mean value for each parameter is calculated from the minimum and maximum values.

Theoretical maximum and minimum estimates of the CO_2 storage resource (mass) for saline aquifers, by formation, were calculated using the parameters in Table 5-1, for the aforementioned assumptions and method summarized in Chapter 4. Similar to the maximum and minimum variable estimates, the average estimates for each variables are used to calculate an average (S_{basin} is not averaged, instead the input variable are averaged). The results are summarized in Table 5-2. These calculations suggest the potential for an average of 1.9 billion metric tons (2.1 billion short tons) of CO_2 storage in the saline aquifers of the Greater Green River Basin. The results are estimates that require significant assumptions and should not be used without acknowledging and incorporating the associated assumptions and method summarized in Chapter 4.

Storage in Hydrocarbon Reservoirs

Hydrocarbon Exploration and Production

The Greater Green River Basin is a mature hydrocarbon province that has been under production since the early 20th century. Since that time, the Greater Green River Basin has produced over 914.1 million barrels of oil and 23.2 trillion cubic feet of gas. There are 283 producing fields in the basin, as defined by the Wyoming Oil and Gas Conservation Commission (2012), 252 of which have produced oil and 267 have produced gas. The basin is home to an accumulation of CO_2 greater than 100 trillion cubic feet on the crest of the Moxa arch (Plate 3), as well as the nation's primary helium reserve. Twelve of the top 100 highest-producing oil fields in Wyoming are in the Greater Green River Basin. More than half of the most productive gas fields in the state (58 of the top 100) are also in the Greater Green River Basin. In 2009, the Greater Green River Basin produced 2.6 percent of the nation's oil and 10.8 percent of the nation's gas (U.S. Energy Information Administration, 2012a).

The principal oil and gas fields in the Greater Green River Basin occur in anticlinal traps (Law, 1988). These anticlinal traps are secondary folds on the larger-scale Laramide uplifts. Stratigraphic traps are rare in the basin, with the exception of the Cretaceous formations, such as Patrick Draw field, where an up-dip pinch-out of the Almond Formation traps a significant accumulation of oil (Weimer and Sonnenberg, 1965, 1966).

Table 5-2. Mass of CO_2 that can theoretically be stored in saline aquifers in the Greater Green River Basin. Calculations follow Equation 4-1. Lithologies were used to determine E_{basin}; ss represents sandstone and dol represents dolomite. RSU is Rock Springs uplift, LB is the LaBarge platform, and W/GD is the Wamsutter arch and Great Divide Basin.

	S_{basin} (million metric tons)		
Reservoir	minimum	average	maximum
Nugget RSU (ss)	17	176	880
Nugget LB (ss)	6.6	68	339
Nugget W/GD (ss)	45	455	2,278
Tensleep/Weber RSU (ss)	6.2	124	813
Tensleep/Weber W/GD (ss)	17	335	2,186
Madison RSU (dol)	32	146	463
Madison W/GD (dol)	138	624	1,981
Total	**262**	**1,928**	**8,940**

Primary oil production is from the Upper Cretaceous Frontier Formation and Mesaverde Group, followed by the Lower Cretaceous Dakota Sandstone ("Dakota Sandstone" is a formation name borrowed from neighboring states and frequently used in the hydrocarbon industry, but is unofficially recognized in Wyoming; Cloverly Formation is the preferred terminology). Carbon dioxide and helium production on the LaBarge platform is from the Mississippian Madison Limestone. Hydrocarbons are also commonly produced from the Pennsylvanian and Permian

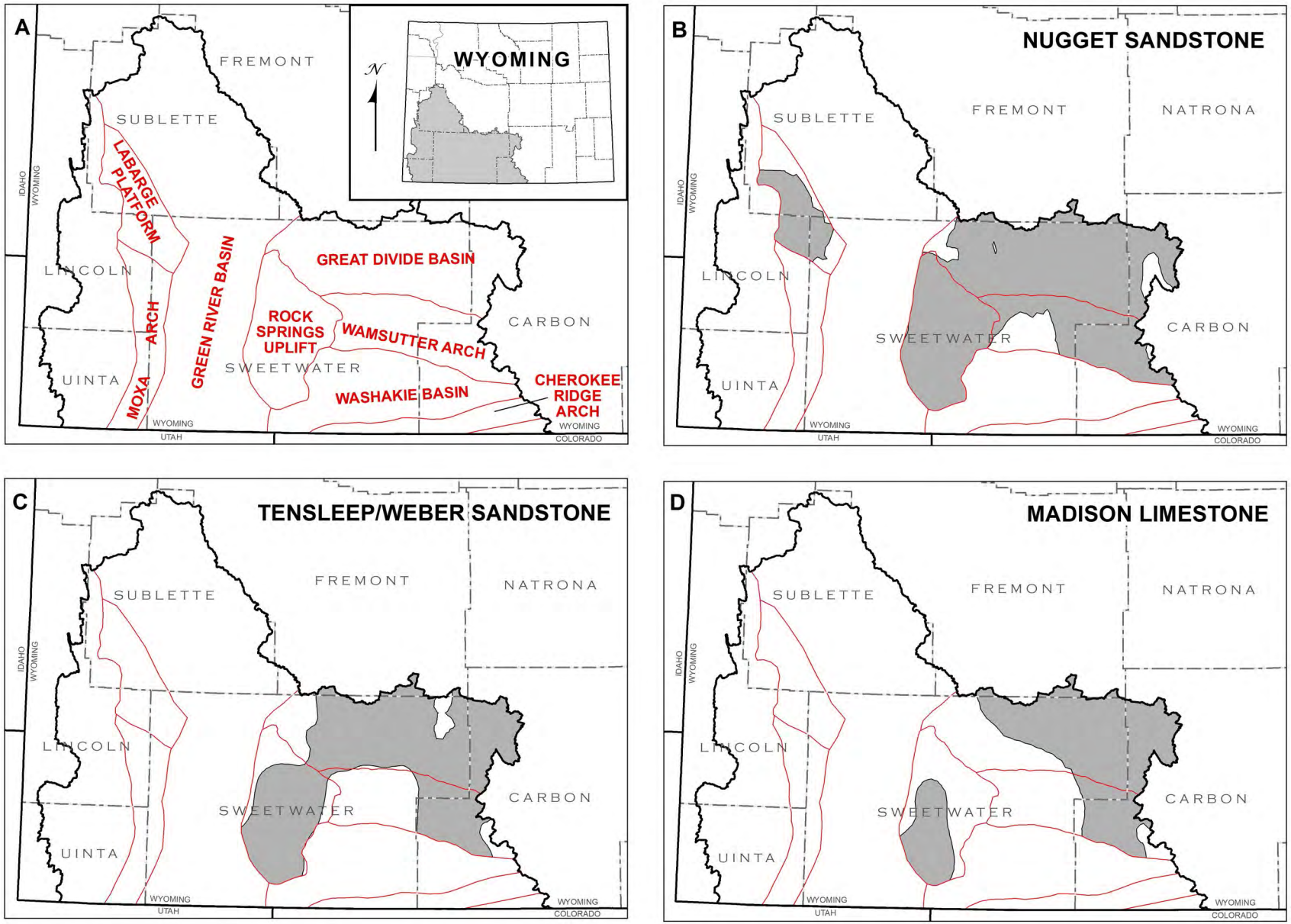


Figure 5-6. Total formation area (A_t) for the three primary storage formations in the Greater Green River Basin, summarized in Table 5-1. **A.** Sub-basin boundaries. The overlap of the sub-basins with the storage formations is shown for **B.** the Nugget Sandstone, **C.** the Tensleep/Weber Sandstone, and **D.** the Madison Limestone.

Tensleep/Weber Sandstone. Nearly all formations are known to contain hydrocarbons at one location or another within the Greater Green River Basin.

Hydrocarbon source rocks vary by location within the section and within the basin. The U.S. Geological Survey (USGS Southwestern Wyoming Province Assessment Team, 2005) determined nine regional total petroleum systems in the southwestern Wyoming province (the bulk of which includes the Greater Green River Basin of Wyoming). These nine systems imply source rocks in the Phosphoria Formation, Mowry/Aspen Shale, Hilliard/Baxter Shale, Niobrara Formation, Mesaverde Group, Lewis Shale, Lance and Fort Union formations, and the Wasatch and Green River formations. Excluding the Phosphoria (Permian), Wasatch and Green River formations (Eocene), and Fort Union Formation (Paleocene), all other source rocks are Cretaceous—primarily Upper Cretaceous.

The source rock facies within the Phosphoria Formation are contained within the Meade Peak and Retort members. The Phosphoria was deposited in a sediment-starved, restricted basin on the western edge of the Wyoming shelf (Piper and Link, 2002). Within this complex, the Meade Peak and Retort members were formed in areas that were favorable for upwelling, high organic productivity, and preservation of organic matter (e.g., Piper and Link, 2002). Total organic content values are as high as 30 weight percent in this organic-rich source rock. High amounts of sulfur suggest original oil composition within the Phosphoria was Type-IIS kerogen, with oil generation beginning during the Late Cretaceous (Johnson, 2005).

The Cretaceous source rocks resulted from relative transgressions and regressions within a foreland basin that was progressively subsiding from the advancing Sevier orogen. These source rocks are all marine shales, some of which were deposited under anoxic conditions that preserved an unusual amount of carbonaceous matter. Of the Cretaceous shales, the Mowry/Aspen Shale has the highest total organic content (Burtner and Warner, 1984) and is primarily responsible for charging the Dakota Sandstone and Frontier Formation reservoirs throughout the Rocky Mountain region (Warner, 1982; Burtner and Warner, 1984), with additional gas locally sourced from the Frontier coals.

Eocene Wasatch and Green River source rocks are lacustrine organic-rich shales and marginal marine and terrestrial coal and carbonaceous mudstones (Roberts, 2005b). Lacustrine source rocks contain Type-I and mixed Type-I and Type-III kerogen, while the coal and carbonaceous units contain Type-III kerogen (Grabowski and Bohacs, 1996; Carroll and Bohacs, 2001). These source rocks are responsible for significant oil shale deposits in the Green River Formation and biogenic gas accumulations (i.e., coalbed natural gas) in both the Wasatch and Green River formations.

The production of oil and gas in the Greater Green River Basin has not declined like it has in other Laramide basins throughout Wyoming (Fig. 5-7),

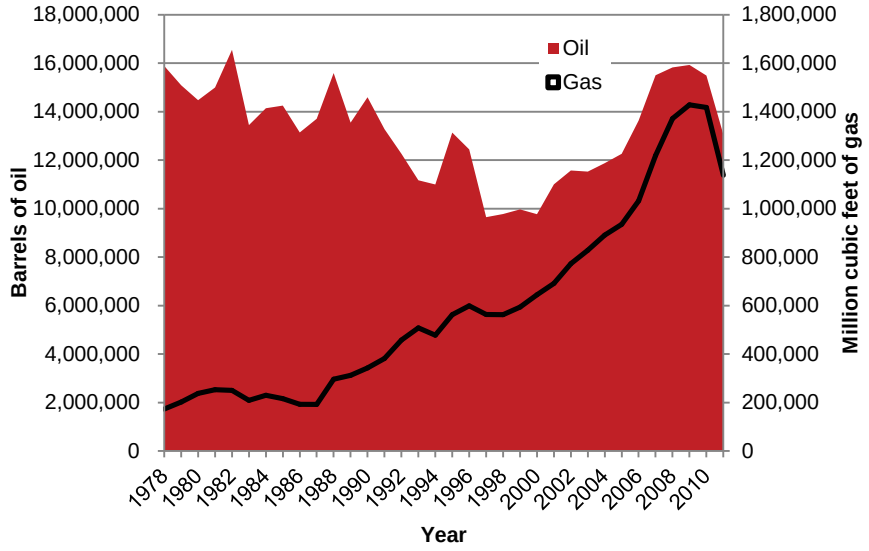


Figure 5-7. Oil and natural gas production for all fields in the Greater Green River Basin, from 1978 through 2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

in part due to the discovery of the giant Jonah gas field, and also due to the success of CO_2-EOR projects in the Lost Soldier and Wertz fields, and the Monell unit in the Patrick Draw field. Since 1980, oil production throughout the basin has remained relatively steady, fluctuating from below 10 million barrels per year to over 16 million barrels per year. In 2011, production was just less than 16 million barrels of oil (Wyoming Oil and Gas Conservation Commission, 2012). Gas production, in fact, has steadily increased since 1978, with a minimum of 173 billion cubic feet in 1978 to 1.4 trillion cubic feet in 2011 (Wyoming Oil and Gas Conservation Commission, 2012). Increased gas production with time is mainly due to the discovery and development of the Jonah and Pinedale anticline fields. Hydrocarbon exploration and production is alive and well in the Greater Green River Basin.

Hydrocarbon Fields with CO_2 Storage Potential

The Greater Green River Basin hosts numerous hydrocarbon fields that produce oil, gas, and gas condensate. Of these fields, as a first cut, those with the largest production volumes hold the most potential for carbon dioxide storage, presuming they meet specific depth, pressure, and seal criteria. In the Greater Green River Basin, the fields with the most production (by volume) are primarily gas and condensate reservoirs. Oil and gas production statistics for six fields identified as the most productive (corrected to subsurface volumes) and meeting the necessary criteria for depth for CO_2 storage (914–3,962 m; 3,000–13,000 feet), are reported in Appendix A.

The following pages summarize field statistics for these six fields. Production data for all six fields were retrieved from the Wyoming Oil and Gas Conservation Commission (2012); all other field data were retrieved from the Wyoming Geological Association symposium on the Greater Green River Basin (Cardinal and Stewart, 1979; Miller and others, 1992). The available data were not determined consistently (e.g., porosity values were determined from core or log data; pressures were reported in a variety of ways such as drill stem tests, rock pressures, shut-in tubing pressures, etc.). Whenever possible, the data type or acquisition method is denoted by a superscript listed as the following:

BHP = bottom hole pressure
DST = drill stem test
SIP = shut-in pressure
SITP = shut-in tubing pressure
SIBHB = shut-in bottom hole pressure
SDST = shut-in pressure, drill stem test
FTP = flowing tubing pressure
l = calculated from log
c = measured from core

Rock type abbreviations are as follows:

md = mudstone
ss = sandstone
ls = limestone
dol = dolostone

Rw represents water resistivity and an em dash (—) is used to denote unavailable data.

Jonah Field

Jonah field is a giant gas field located in Sublette County, west of the Wind River Mountains and south of the town of Pinedale (Plate 3). This unusual field is a wedge-shaped structural block bounded by two sub-vertical shear fault zones (Fig. 5-9) (DuBois and others, 2004). The discovery well for the field was completed in 1987 (Robinson and Shanley, 2004), but the full potential of the field was not realized until the late 1990s, when production increased to several hundred billion cubic feet of gas per year (Fig. 5-8). Production is primarily from the Upper Cretaceous Lance Formation, in addition to the underlying Cretaceous Mesaverde Group (Table 5-3). Through 2011, oil production in the Jonah field was greater than 33.7 million barrels, and gas production exceeded 3.5 trillion cubic feet (Fig. 5-8).

Table 5-3. Jonah field statistics, from Robinson and Shanley (2004).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Lance	ss, md	4–12[c]	0.01–1.0[c]	150–600	6,133[BHP]	5.05–8	65
Upper Mesaverde	ss, md	4–10[l]	—	100–500	6,133[BHP]	5.05–8	65

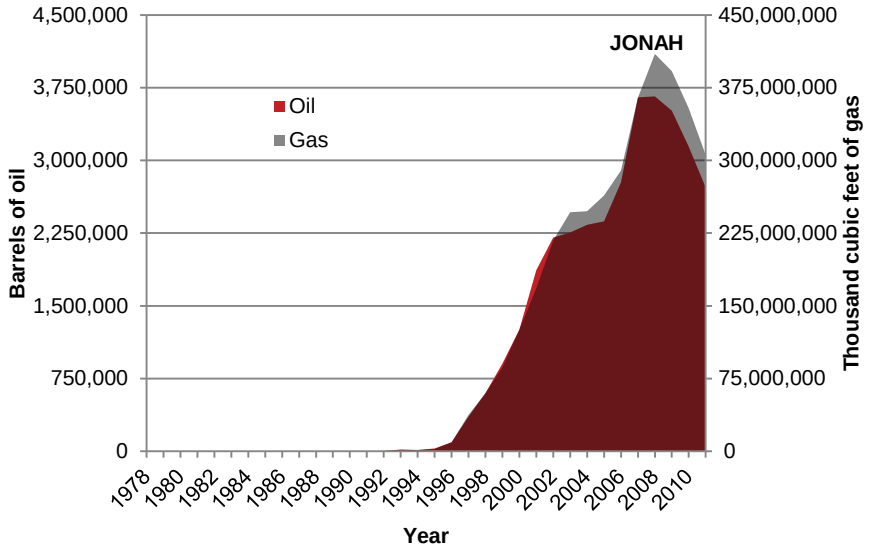


Figure 5-8. Jonah field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix A.

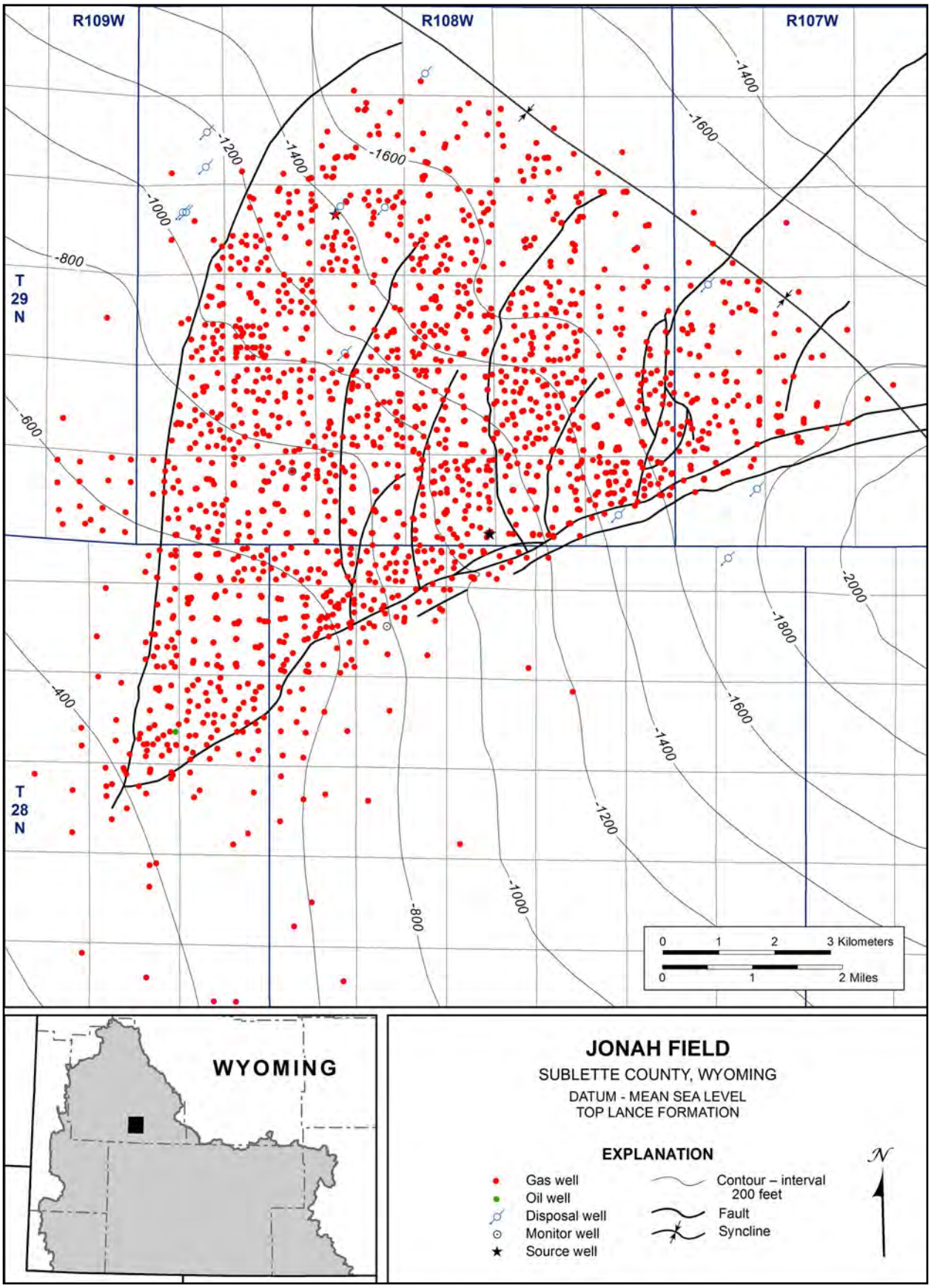


Figure 5-9. Jonah field structure-contour map, modified from DuBois and others (2004). Well locations and well types downloaded from the Wyoming Oil and Gas Conservation Commission (2012).

Bruff Field

Bruff field is located in northern Uinta County, in the southern Moxa arch (Plate 3). This gas reservoir, discovered in 1961, saw initial production from the Upper Cretaceous Frontier Formation in a mixed stratigraphic and structural trap (Fig. 5-11) (Borgerding, 1992). Production is also from the Dakota Sandstone and Morgan Formation (Table 5-4). Together these reservoirs have produced more than 986 billion cubic feet of gas and 5.5 million barrels of oil (Fig. 5-10).

Table 5-4. Bruff field statistics, from Borgerding (1992).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	11.3	0.01	27	6,540	—	—
Dakota	ss	12	2.5	18	—	—	—
Morgan	dol, ls	8.6	—	30	11,288[SIBHP]	0.185	66

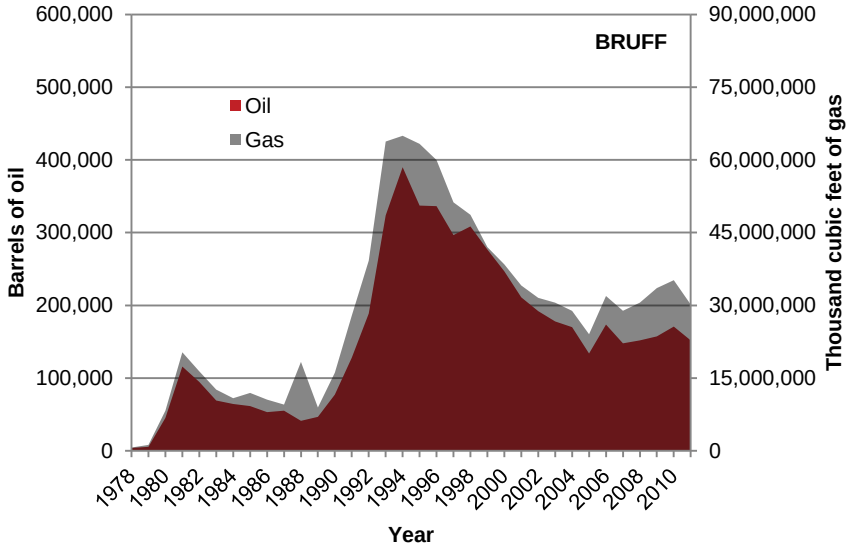


Figure 5-10. Bruff field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix A.

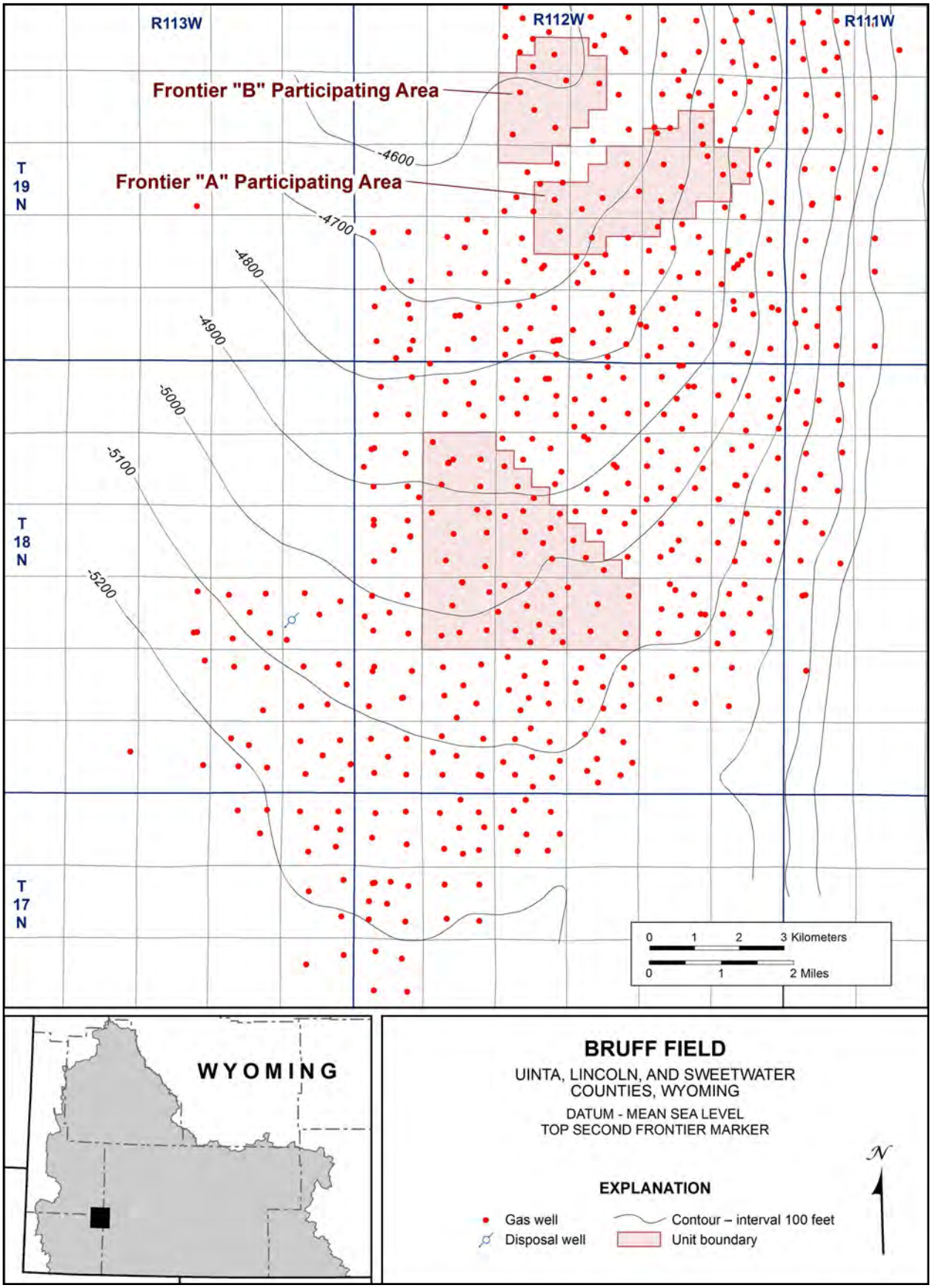


Figure 5-11. Bruff field structure-contour map, modified from Borgerding (1992). Well locations, well types, and unit boundaries downloaded from the Wyoming Oil and Gas Conservation Commission (2012).

Brady Field

The Brady field is located in Sweetwater County, approximately 32 km (20 miles) south of Point of Rocks (Plate 3). This northeast–southwest-trending anticlinal structure consists of the North and South Brady fields (Fig. 5-13) that were discovered in 1975 and 1973, respectively (Robinson, 1992a, 1992b). The Dakota, Entrada, Nugget, and Weber formations are the main producers, with other shows observed in the Mesaverde and Phosphoria formations (Table 5-5). Total oil production for the Brady field was more than 71 million barrels of oil through 2011, with an additional 636.7 billion cubic feet of gas (Fig. 5-12).

Table 5-5. Brady field statistics, from Robinson (1992a, 1992b).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
North							
Dakota	ss	9.5–23[l]	—	76	4500	0.029	—
Entrada	ss	11	1.4–70	40	5,061[SIP]	0.16	50.4
Nugget	ss	11[l]	20	72	5,080[BHP]	0.12	49.3
Weber	ss	1-15	0.01-74	188	6,045[SDST]	0.02	54.7
South							
Mesaverde	ss	10	<0.1	64	2,565[SDST]	0.35	—
Frontier	ss	11	0.1	20	3,900	0.04	—
Dakota	ss	11	10	25	4,850	0.09	—
Nugget	ss	14[l]	23.2[c]	118	4,938[BHP]	0.17	50.5
Phosphoria	dol, md	17[c]	5.5[c]	4–8	5,997[BHP]	—	47.2
Weber	ss	8.6	3	167	6,041[DST]	0.17	52

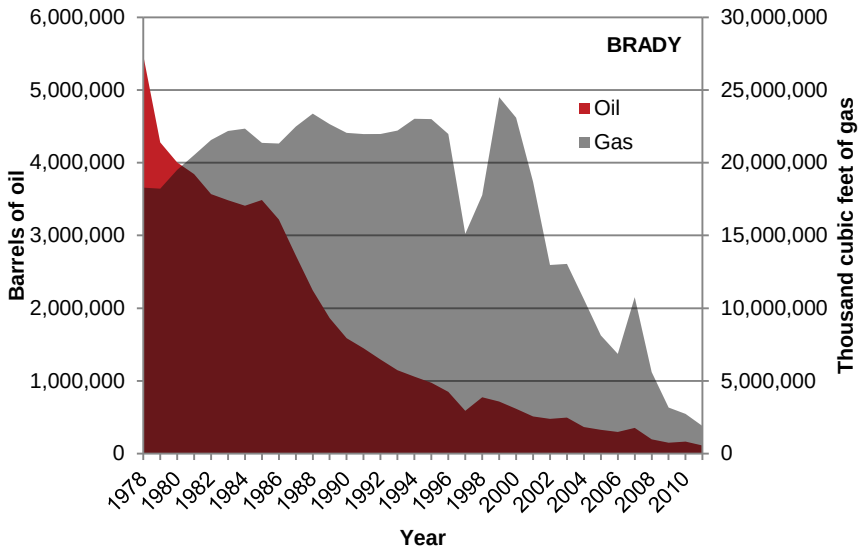


Figure. 5-12. Brady field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix A.

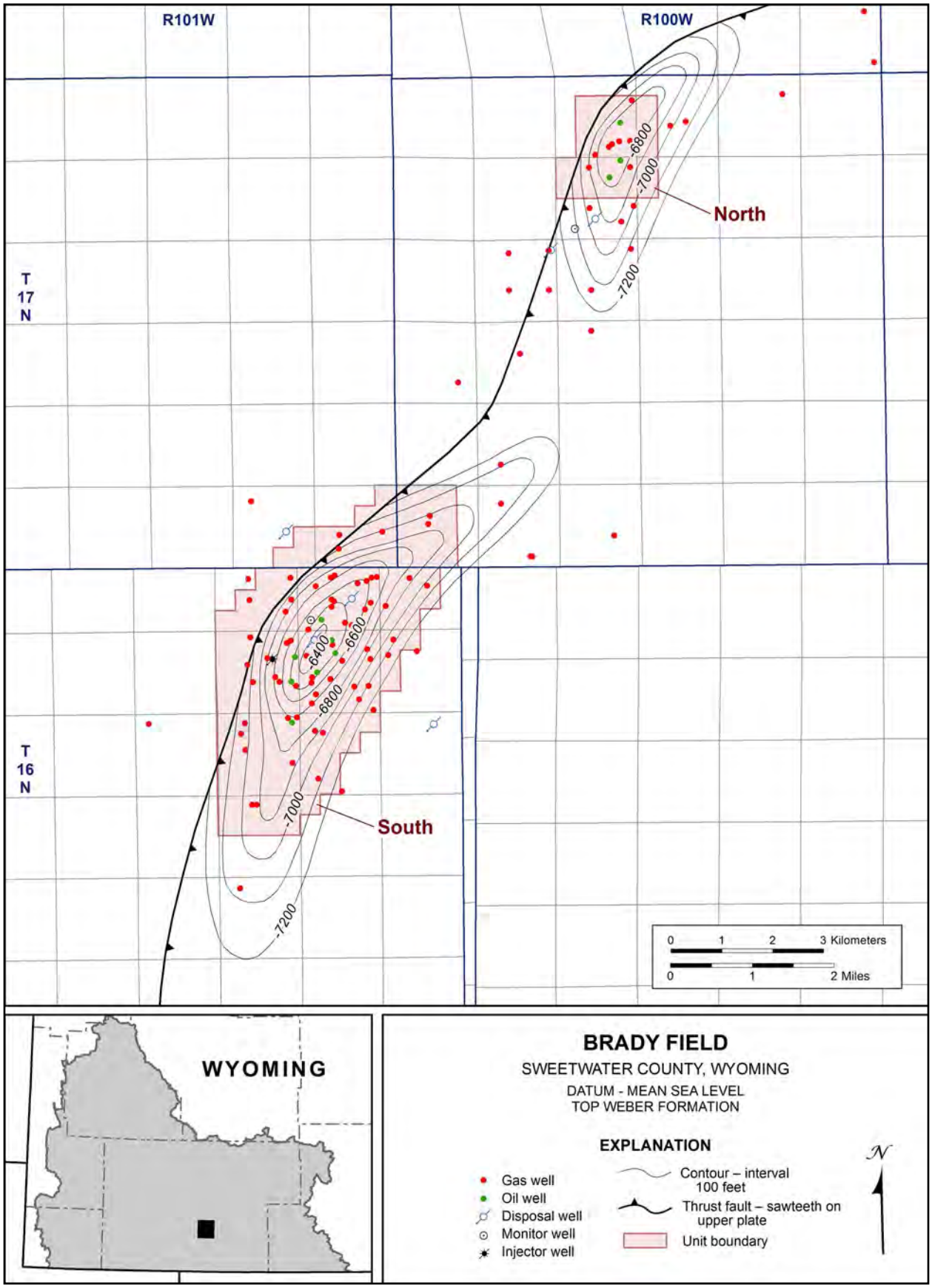


Figure 5-13. Brady field structure-contour map, modified from Robinson (1992a, 1992b). Wells downloaded from the Wyoming Oil and Gas Conservation Commission (2012).

Church Buttes Field

Church Buttes field straddles Sweetwater and Uinta counties on the southern Moxa arch, south of Bruff field (Plate 3). This north–south-trending anticlinal trap has a larger southern dome and a smaller northern dome (Fig. 5-15). Discovered in 1946, Church Buttes field produces from the Frontier Formation, Dakota Sandstone, and Morgan Formation (Table 5-6). Tests from the Madison Limestone have significant gas shows (Curry, 1992). Over 633.5 million cubic feet of gas and 1.6 million barrels of oil were produced from the Church Buttes field through 2011 (Fig. 5-14).

Table 5-6. Church Buttes field statistics, from Curry (1992).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	12[c]	0.5[c]	18	6,463[DST]	0.9	—
Dakota	ss	8–21	14–750	56	7,040[BHP]	0.4	48.8
Morgan	dol, ls	12	—	150	8,021[SIP DST]	—	50

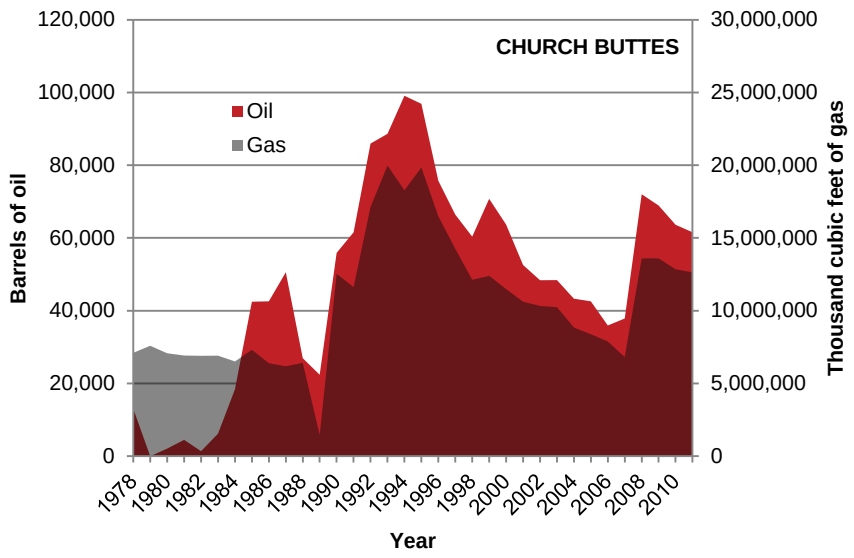


Figure 5-14. Church Buttes field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix A.

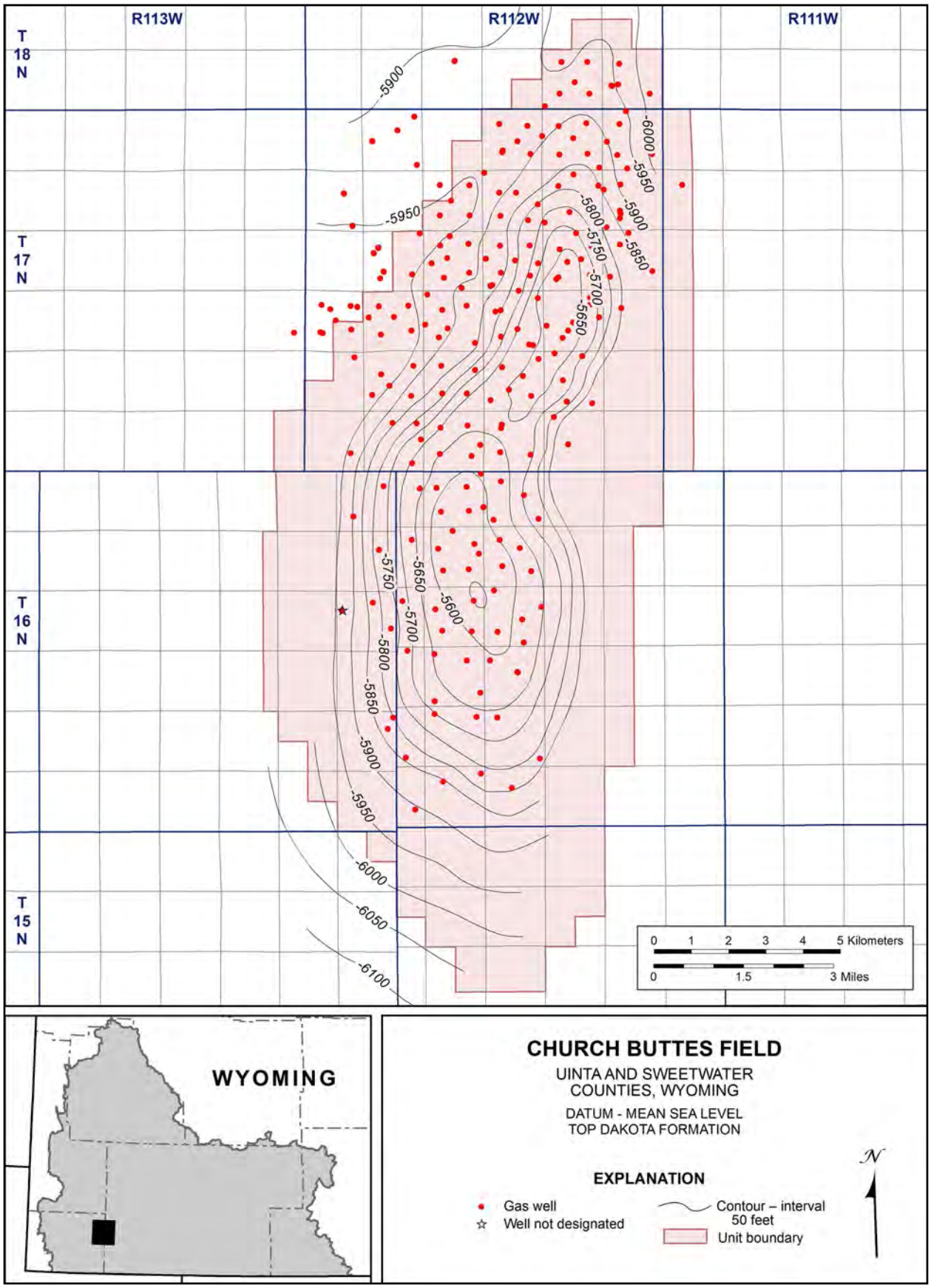


Figure 5-15. Church Buttes field structure-contour map, modified from Curry (1992). Well locations, well types, and unit boundary downloaded from the Wyoming Oil and Gas Conservation Commission (2012).

Echo Springs–Standard Draw Field

The Echo Springs–Standard Draw field is a large gas field located in the northern Washakie Basin, on the southern flank of the Wamsutter arch, approximately 13 km (8 miles) southeast of Wamsutter (Plate 3). The Echo Springs–Standard Draw field area is a compilation of four regulatory defined fields, including Echo Springs, Standard Draw, Wild Rose, and Coal Gulch (Fig. 5-17). Production from these four fields is reported separately by the Wyoming Oil and Gas Conservation Commission, yet there is precedence and geologic evidence to combine the fields into one larger field for the purpose of this study (Table 5-7) (i.e., Horn and Schrooten, 2001). Production is primarily from the Late Cretaceous Almond Formation, specifically the Echo Springs ("sweetspot") sandstone interval (Horn and Schrooten, 2001). Since the completion of the first well in the Wild Rose field in 1974, these four fields have produced a combined total of 34.3 million barrels of oil and nearly 2 trillion cubic feet of gas through 2011 (Fig. 5-16).

Table 5-7. Echo Springs–Standard Draw field statistics (including Coal Gulch and Wild Rose fields), from Coalson (1979a, 1979b) and Henry and Logan (1992).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Almond ("sweetspot")	ss	10–18	—	12–35	4,985–4,993[DST]	0.64	53–59
other Mesaverde	ss	9[c]	0.07	variable	5,300	0.64	50

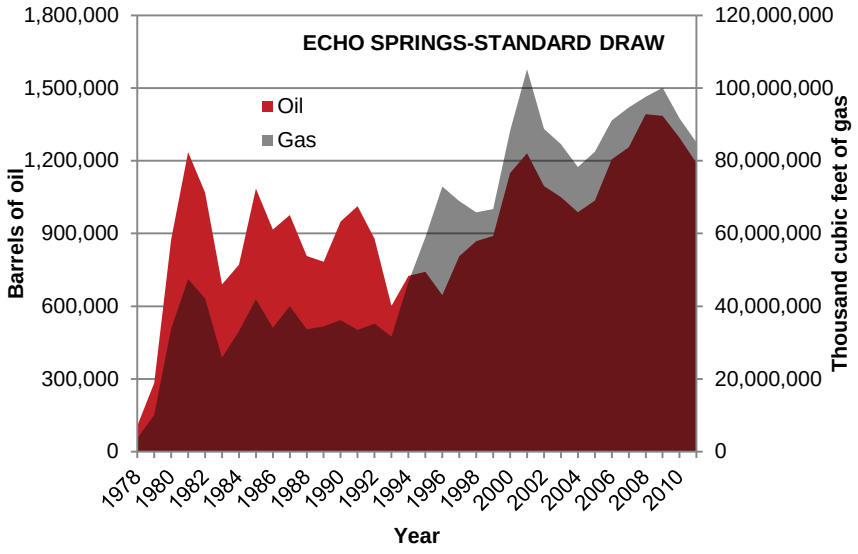


Figure 5-16. Echo Springs–Standard Draw field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix A.

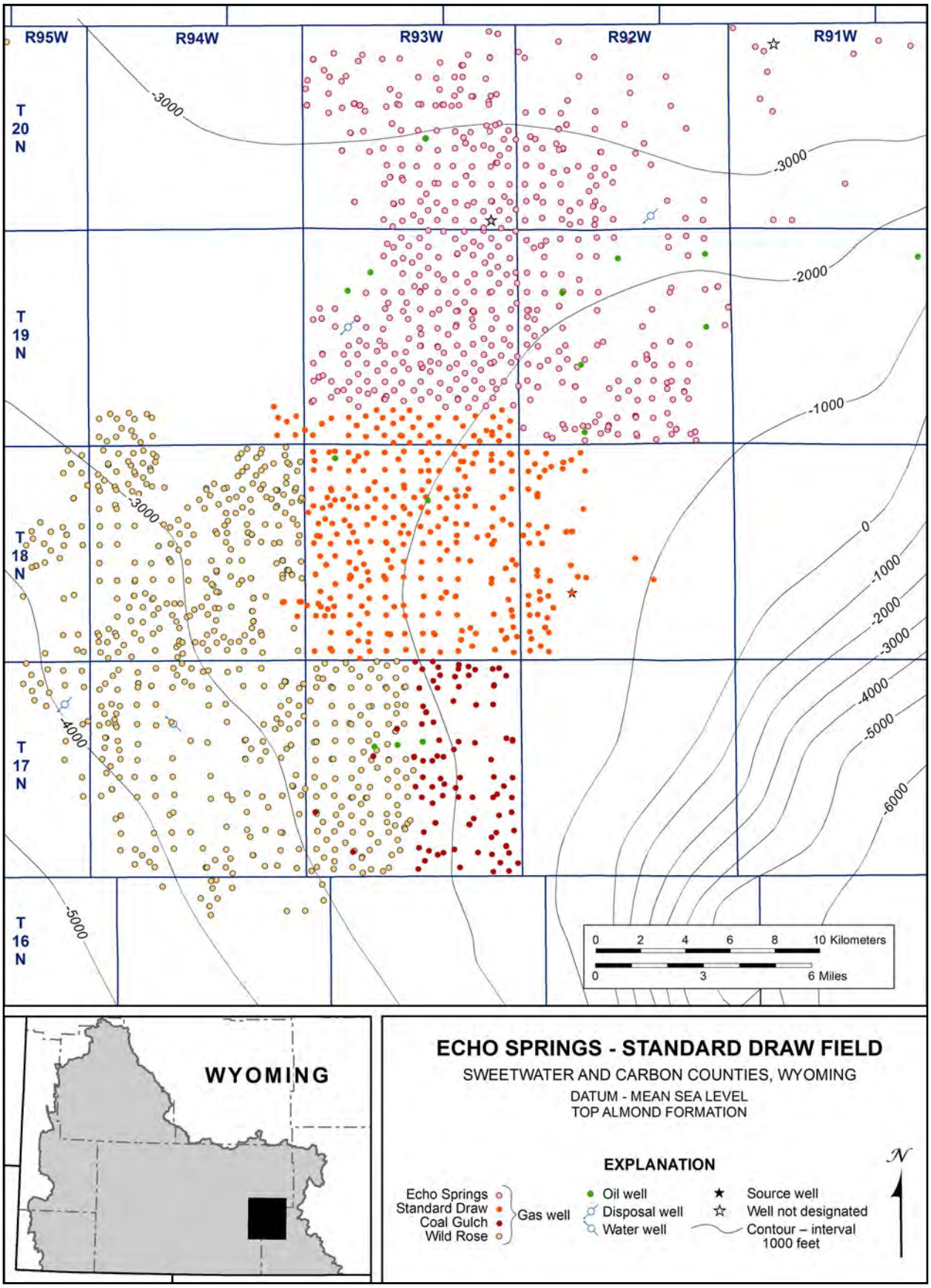


Figure 5-17. Echo Springs–Standard Draw field structure-contour map, including Echo Springs, Standard Draw, Wild Rose, and Coal Gulch fields, modified from Coalson (1979b). Well locations and well types downloaded from the Wyoming Oil and Gas Conservation Commission (2012).

Labarge Field

The Labarge field is located just west of the town of La Barge and abuts the Green River Bend and Birch Creek fields to the east (Plate 3). The Labarge field is one of many fields on the LaBarge platform and this field has been subdivided by Cardinal and Stewart (1979) into the Labarge, Labarge North (Shallow), and Labarge East fields, which are distinct from the Labarge Anticline composed of several different fields (Stewart and Street, 1992). The Wyoming Oil and Gas Commission reports only the Labarge field (Fig. 5-19). Portions of the field extend south into Lincoln County, but the majority of the field is in Sublette County. Production is from the Fort Union Formation, Hilliard Shale, Frontier Formation (overthrust and subthrust), and Bear River Formation (Table 5-8). Since its discovery in 1929, the Labarge field produced 29.1 million barrels of oil and 522.4 million cubic feet of gas (Fig. 5-18).

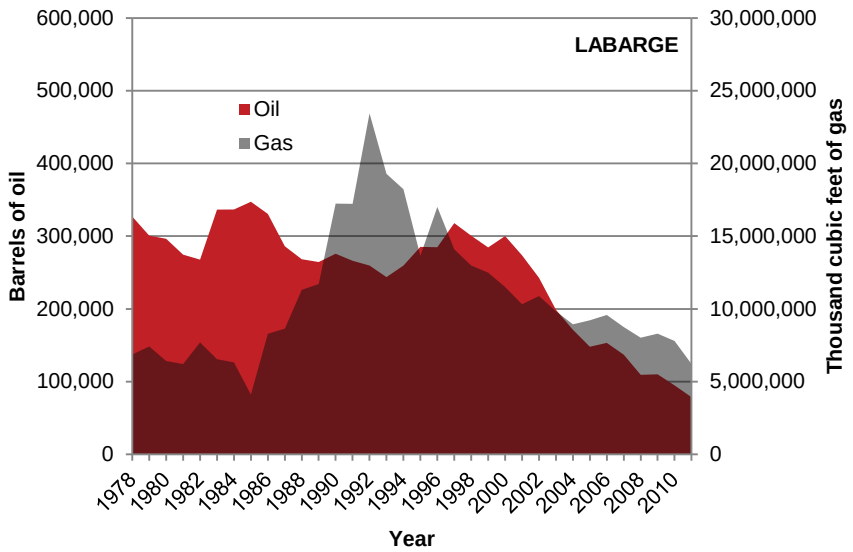


Figure 5-18. Labarge field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix A.

Table 5-8. Labarge field statistics, from Lehman (1979).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Labarge							
Almy	ss	26	230–450	15	385	0.33@70°F	17–42
Hilliard	ss	10–12	—	18	930[SITP]	0.9	44.7
Frontier (Overthrust)	ss	12–14	0.1–0.25	40	2,978[SDST]	0.3	—
Frontier (Subthrust)	ss	12–14	0.1–0.25	120	3,018[DST]	0.28	—
Bear River	ss	10–12	<0.1	30	—	0.17	—
East							
Almy	ss	28	—	12	1400	1.0	43
Mesaverde	ss	20	—	14	300[FTP]	0.75	—
Frontier (2nd)	ss	14[c]	—	27	3,485[SITP]	0.14	51.8–53
North (Shallow)							
Almy/Mesaverde	ss	21–24	variable	variable	—	0.73	45
Frontier	ss	13	0.1–1.0	50–125	3,880	0.26	—

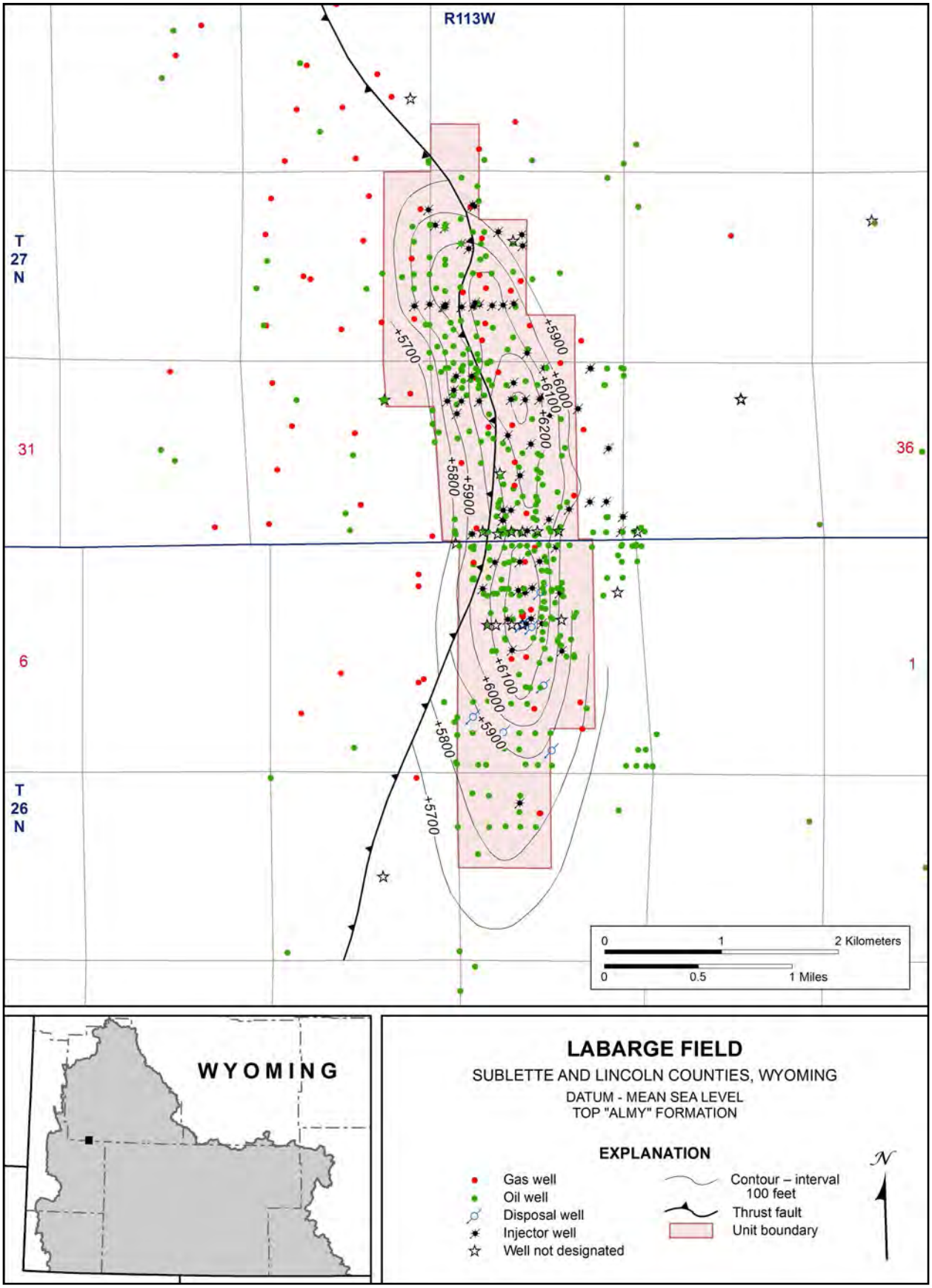


Figure 5-19. Labarge field structure-contour map, modified from Lehman (1979). Well locations, well types, and unit boundary downloaded from the Wyoming Oil and Gas Conservation Commission (2012).

Results

All reservoirs in this evaluation are 2,743–3,962 m (9,000–13,000 feet) below the surface, and average 3,353 m (11,000 feet). A standard normally pressured saline aquifer has a hydrostatic pressure gradient of 10.516 kPa/m (0.465 psi/ft) (Schlumberger, 2012), a generalized geothermal gradient of 0.0301 °C/m (0.0165 °F/ft) (Sheriff, 1991), and an average surface temperature of 20 °C (68 °F). 3,353 m (11,000 feet) depth corresponds to 35.3 MPa (5,115 psi) and 120.8 °C (249.5 °F). ρ_{CO2} at these conditions is 646 kg/m^3 (40.3 lb/ft^3) and is used in this assessment to account for the wide range of depths evaluated by one equation.

A conservative value for B_o of 1.02 is used for all fields in this study. B_g is 0.00365 in the Brady field (Scientific Software of Canada, LTD, 1975) and approximately 0.00308 in the Jonah field (calculated from data in Robinson and Shanley, 2004). An average value for B_g of 0.0034 is assumed for the Greater Green River Basin. B_w equals one.

Table 5-9 summarizes the theoretical storage resource for the producing reservoirs that meet the above criteria, from the most-productive fields in the Greater Green River Basin, including the combined Echo Springs–Standard Draw field (Echo Springs, Standard Draw, Wild Rose, and Coal Gulch). These six fields can theoretically store 49–295 million metric tons (54–325 million short tons) of CO_2. As with storage estimates from saline aquifers, the results presented in Table 5-9 are estimates that require significant assumptions and should not be used without acknowledging and incorporating the associated assumptions.

Table 5-9. Mass of CO_2 that can theoretically be stored in six hydrocarbon fields in the Greater Green River Basin, for a range of E_{res}. Calculations follow Equations 4-2 through 4-8.

		S_{res} (million metric tons)		
Field	Reservoir	minimum E_{res} = 0.1	mode E_{res} = 0.3	maximum E_{res} = 0.6
Jonah	*Lance*	20	60	121
	Mesaverde	0.20	0.60	1.2
	Total	**20**	**61**	**122**
Bruff	*Frontier*	3.5	11	21
	Muddy	0.05	0.16	0.32
	Dakota	1.9	5.6	11
	Total	**5.5**	**16**	**33**
Brady	*Nugget*	0.80	2.4	4.9
	Weber[1]	2.7	8.1	16
	Total	**3.5**	**11**	**21**
Church Buttes	*Frontier*	1.4	4.3	8.6
	Dakota	2.6	7.8	16
	Total	**4.0**	**12**	**24**
Echo Springs - Standard Draw	*Almond/Mesaverde*	12	37	75
	Total	**12**	**37**	**75**
Labarge	*Frontier*	3.2	9.5	19
	Muddy/Bear River	0.17	0.52	1.0
	Total	**3.3**	**10**	**20**
Total		**49**	**147**	**295**

[1]Reservoir is deeper than 3,962 m (13,000 feet).

Storage through Enhanced Oil Recovery

Wo and others (2009) rank candidate reservoirs for EOR in fields across Wyoming for both miscible and immiscible CO_2 flooding based on technical feasibility. Their study identifies 40 reservoirs in the Greater Green River Basin for miscible CO_2 flooding and nine reservoirs for immiscible CO_2 flooding. Of the top 100 candidate EOR fields for miscible CO_2 flooding in Wyoming, eight are in the Greater Green River Basin, along with two of the top 20 candidate fields for immiscible CO_2 floods. Minimum and maximum estimated total volumes of CO_2 for these miscible and immiscible CO_2 floods (from Wo and others, 2009) are summarized in Table 5-10. These estimates do not include oil recovery within the residual oil zone. There are no estimates for the amount of additional oil recoverable from ROZs in the Greater Green River Basin, yet estimates from the Tensleep reservoirs in the Bighorn Basin (e.g., Yin and others, 2011) suggest recovery from ROZs will contribute a substantial amount to the potentially recoverable oil.

Because oil is found throughout the stratigraphic section in the Greater Green River Basin, it is not clear if some formations are more likely to respond better to CO_2-EOR than others. Wo and others (2009) rank the Almond Formation in the Arch unit of the Patrick Draw field as the highest priority, closely followed by the Weber and Nugget sandstones in the Brady field (Table 5-10). The Paleozoic formations on the Moxa arch are not viable potential EOR reservoirs because they are gas fields.

Wo and others (2009) estimate between 1 and 1.4 trillion cubic feet (~52–72 million metric tons; 57–79 million short tons) of CO_2 could be required for CO_2-EOR operations in the Greater Green River Basin (historically produced reservoirs, not including ROZs). These estimates do not include the three fields currently under CO_2 floods. Fields within the Greater Green River Basin have proven successful for CO_2-EOR in the past, and it is likely that additional oil reservoirs that are in decline will come under tertiary recovery with CO_2 due to the proximity to a reliable source of CO_2.

Storage through Enhanced Coalbed Natural Gas Recovery

The Greater Green River Basin hosts several mineable coal fields, including the fields near Kemmerer and Rock Springs (Fig. 5-20). The Hams Fork coal

Table 5-10. Estimated CO_2 demand, in billion cubic feet (BCF), for the top ranked reservoirs within the Greater Green River Basin for miscible and immiscible CO_2 flooding, from Wo and others (2009).

Rank[1]	Field name	Reservoir	Minimum total CO_2 (BCF)	Maximum total CO_2 (BCF)
miscible CO_2 flooding				
12	Arch (Patrick Draw)	*Almond*	168	252
14	Brady	*Weber*	155	232
19	Brady	*Nugget*	122	183
50	Birch Creek	*Bear River*	44	67
55	Luckey Ditch	*Dakota*	41	61
76	Patrick Draw	*Almond*	27	41
77	Standard Draw	*Mesaverde*	27	40
91	Henry	*Dakota*	22	34
immiscible CO_2 flooding				
11	Birch Creek	*Mesaverde*	46	69
20	Labarge	*Mesaverde*	18	27
	Total		**670**	**1,006**

[1]Rank within the top 100 Wyoming fields for miscible CO_2 flooding and top 20 for immiscible CO_2 flooding.

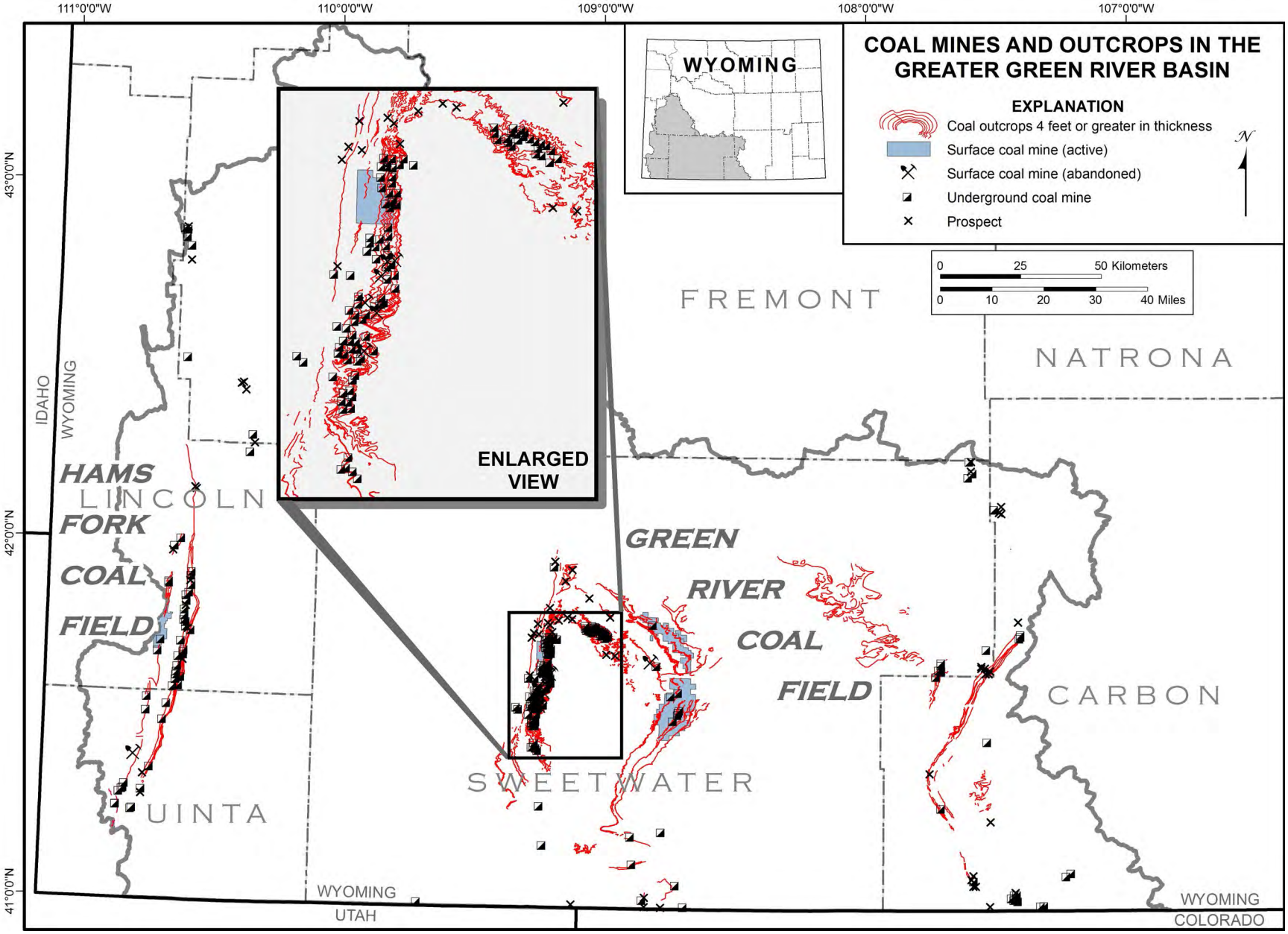


Figure 5-20. Map showing the location of coal outcrops and surface and underground coal mines in the Greater Green River Basin. Modified from Jones and others (2009).

field is in the overthrust belt west of the Green River Basin. Commercial coal mining began in 1868 in Sweetwater County (Root and others, 1973).

The primary focus of this field summary is the Green River coal field (often termed the Rock Springs coal field) because the areas beneath and adjacent to this field (unmineable seams) have the highest potential for CO_2-ECBM based on coal quality and depth, and because more data are available for this region.

The Green River coal field covers an approximate 7,770-km^2 (3,000-square-mile) area in central Sweetwater County (Robinson and Roehler, 1979) (Fig. 5-20). Coal is produced from several formations within the Green River coal field, with the primary production from the Rock Springs and Almond formations of the Mesaverde Group, and the Lance, Fort Union, and Wasatch/Green River formations (Robinson and Roehler, 1979). The six criteria for screening coal-seam reservoir feasibility for CO_2-ECBM (described in Chapter 2) do not include the implied presence of a trap. As with any CO_2-injection plan, it is necessary to have a structural or stratigraphic trap to hold the CO_2 in place once the methane has been recovered from the coal seam.

Coalbed Natural Gas Formations with CO_2 Storage Potential

Wasatch and Green River Formations

The Eocene Wasatch and Green River formations are intertonguing lacustrine and fluvial sediments found throughout the Greater Green River Basin. These two formations are grouped together by the USGS and evaluated as a single coalbed gas assessment unit (Roberts, 2005b). The USGS assessment includes coals from the main body, Red Desert, and Niland tongues of the Wasatch Formation, as well as the Luman Tongue of the Green River Formation. Potential coalbed natural gas fields are south of the Rock Springs uplift and in the northeast corner of the Great Divide Basin. Coals are locally up to 13 m (42 feet) thick (Masursky, 1962), yet are more commonly less than 3 m (10 feet) thick. The thickest coals are lenticular and discontinuous (Roberts, 2005b). Roberts (2005b) suggests that coalbed gas production from the Wasatch and Green River formations has limited potential due to economic uncertainty associated with the discontinuous nature of the coal seams.

Fort Union Formation

The Paleocene Fort Union Formation may have the highest priority for ECBM based on coal thickness and continuity. The USGS evaluated the Fort Union Formation as a hypothetical coalbed gas assessment unit because there are no actively producing coalbed natural gas wells in this formation (Roberts, 2005a). The Fort Union Formation crops out on the flanks of the Rock Springs uplift, in the northern Great Divide Basin, and along the eastern flank of the Great Divide, Washakie, and Sand Wash basins. Coals within the lower Fort Union Formation are continuous with a cumulative thickness of greater than 24 m (80 feet) (Tyler and McMurry, 1993; Roberts, 2005a) and individual beds up to 12 m (40 feet) (Tyler and others, 1995). Coals in the upper Fort Union Formation are lenticular and less continuous (Hettinger and others, 1991; Tyler and McMurry, 1993; Roberts, 2005a).

Reflection seismic data can be used to estimate subsurface depth and extent of buried coals. Figure 5-21 is a seismic line from the western flank of the Rock Springs uplift (seismic data freely available at http://walrus.wr.usgs.gov/NAMSS/), and correlated to two deep wells (Sandy Bend 1, API 49-037-20650 and Stratos 1, API 49-037-23539). The coal reflections highlighted in Figure 5-21 are continuous in the subsurface for over 48 km (30 miles).

Lance Formation

The Upper Cretaceous Lance Formation was assessed as a hypothetical coalbed assessment unit by the USGS due to the lack of recorded coalbed gas production from the formation (Roberts, 2005a). Subsurface locations shallower than 1,524 m (5,000 feet) include the region surrounding the Rock Springs uplift, on the eastern flank of the Washakie Basin, and in the northeastern corner of the Great Divide Basin. Individual coal beds range from 0.3–4 m (1–13 feet) thick (Law, 1996), with cumulative coal thickness averaging 9–12 m (30–40 feet) (Roberts, 2005a).

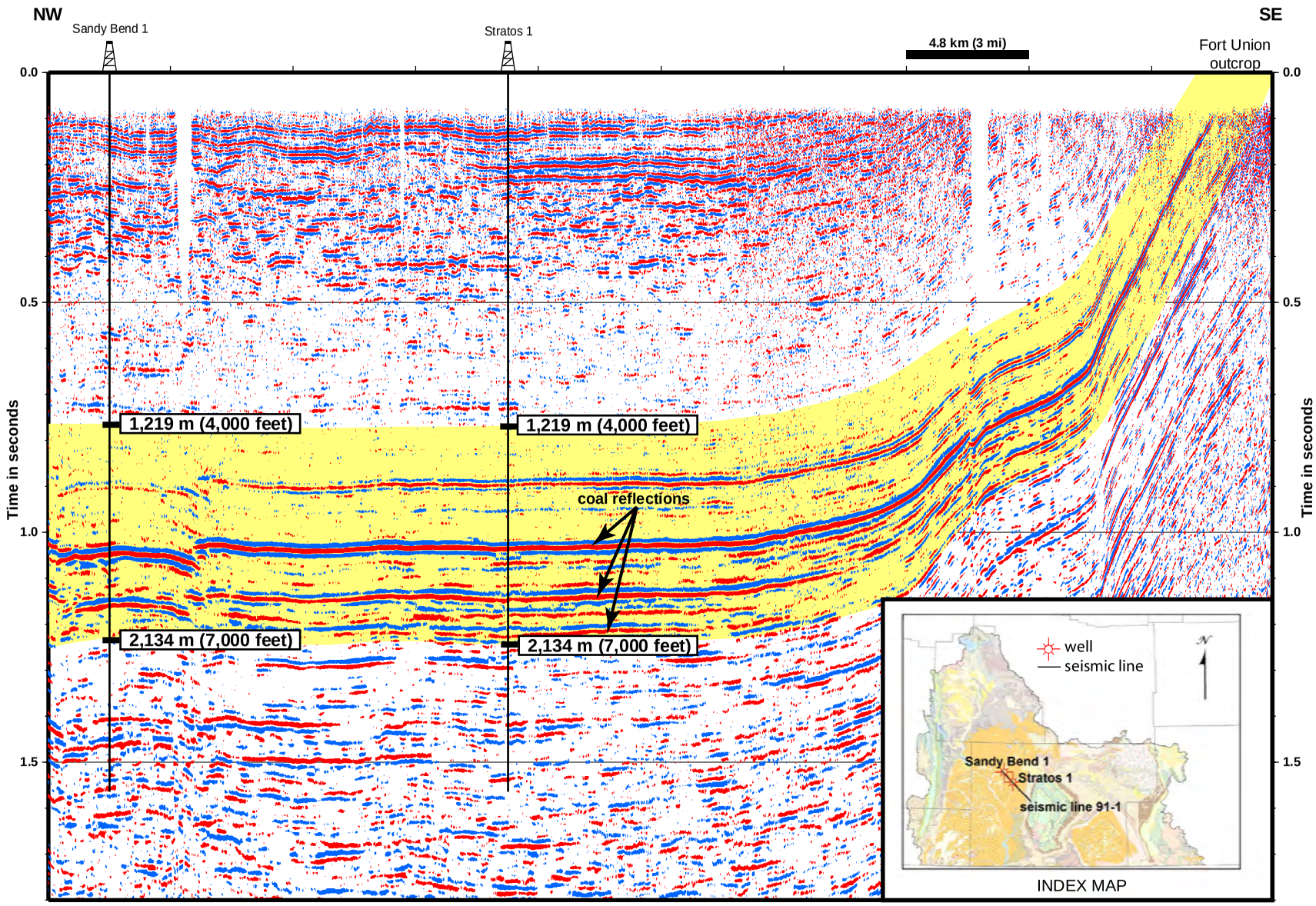


Figure 5-21. Interpreted seismic reflectivity section 91-1 from the Green River Basin Phase 2 (W-2-91-WY) survey, retrieved from the U.S. Geological Survey at http://walrus.wr.usgs.gov/NAMSS/. Negative seismic deflections are shown in red, positive in blue. Reflections corresponding to the Fort Union Formation are highlighted in yellow. Black vertical lines indicate logged wells that were used to calibrate seismic reflections. Vertical exaggeration is approximately 10x. Figure by Y. Ganshin.

Mesaverde Group

Coals within the Upper Cretaceous Mesaverde Group include those within the Almond Formation and the thicker and higher grade coals of the Rock Springs Formation. Coals within these formations are typically less than 3 m (10 feet) thick (Roehler, 1990). The subsurface extent of the top of the Almond Formation, at depths less than 1,525 m (5,000 feet), occurs on the flanks of the Rock Springs uplift, along the eastern Washakie Basin, and on the eastern and southern Sand Wash Basin (Johnson and others, 2005). Coals from the Almond and Rock Springs formations have sufficient thickness and lateral extent to be considered for future CO_2-ECBM recovery projects.

Results

Reeves (2003) considered the CO_2 storage resource of commercial and non-commercial coalbeds in the United States. In his study, the Greater Green River Basin is second only to Alaska with an estimated in-place resource of 314 trillion cubic feet of natural gas, from the Mesaverde Group and Fort Union Formation. Of this assessed in-place resource, it is estimated that 11 trillion cubic feet are recoverable, a recovery factor of 3.5 percent. Due to the large area represented by the Greater Green River Basin and the total resource at depths greater than 1,829 m (6,000 feet), Reeves (2003) applied an adjustment factor of 0.25 to the accessible portion of the non-commercial area for CO_2-ECBM and sequestration. These adjustments result in an incremental recovery potential of 18.5 trillion cubic feet of gas in the Greater Green River Basin, with a total CO_2 storage potential of 7.9 billion metric tons (8.7 billion short tons), or 9 percent of the U.S. coalbed total.

Chapter 6

Wind River Basin

The Wind River Basin is interesting from a geologic as well as historic perspective. Oil production began as early as 1884. The basin contains the first drilled oil well in Wyoming, the first logged well in Wyoming, and the deepest completed well in the Rocky Mountain region. Much of the basin is tribal land, shared by the Northern Arapaho and Eastern Shoshoni tribes. Coal production was, but is no longer, common in the basin, although production volumes were trivial compared to those of the larger Greater Green River Basin and Powder River Basin coal fields.

The Wind River Mountains that border the southwestern edge of the basin contain the highest peaks in Wyoming. Flanking the Wind River Mountains are gentle dip slopes that continue tens of kilometers to the basin axis. There are no major structures in the basin center appropriate for CO_2 storage, only relatively minor structures on the margins where most of the Wind River Basin's hydrocarbon fields are located. However, CO_2-EOR is currently employed in two oil fields; Beaver Creek and Grieve. Given the lack of suitable storage structure, it is likely that CO_2-EOR may constitute the sole form of CO_2 storage in the Wind River Basin for the foreseeable future.

Background

The Wind River Basin, in central Wyoming, is an east-west elongate structural basin of typical Laramide style, 115 km (71 miles) wide by 300 km (186 mi) long. The primary basin axis trends northwest-southeast, and is asymmetrically located near the northern basin margin (Plate 7). The basin is bounded by the Wind River Mountains on the west, the Owl Creek Mountains on the north, the Casper arch to the east, and the Granite Mountains to the south (Fig. 6-1). For the purpose of this study, the basin boundary is defined by the 12-digit hydrologic unit to the east, the 4-digit hydrologic unit to the north, and the 8-digit hydrologic unit to the south and west.

The general structural configuration and thickness of sediments younger than and including the Permian Phosphoria Formation are well-defined by extensive studies from Keefer (1969) and Kirschbaum and others (2007). Significant deformation occurred during the Laramide orogeny that resulted in a basin center greater than 7,620 m (25,000 feet) deep (Plate 2), beds dipping 10–20 degrees toward the basin center on the south and western margins, and near-vertical to overturned strata on the north and eastern margins (Plate 8) (Keefer, 1969). A thick succession of undeformed post-Laramide basin-fill strata was deposited unconformably on the pre-Laramide (pre-Eocene) rocks (Plates 8 and 9).

Seismic data show this unconformable relationship, as well as the basin-margin structures. Although two-dimensional seismic surveys are available for purchase for most regions in the Wind River Basin (Fig. 6-2), publicly available seismic data are rare. In 1976, the Consortium for Continental Reflection Profiling (COCORP) program conducted two-dimensional seismic imaging of the Wind River Mountains, the northern margin of the Greater Green River Basin, and the southern Wind River Basin. These seismic lines can be downloaded at http://www.geo.cornell.edu/geology/cocorp/COCORP.html. No other publicly available seismic datasets are known.

Storage in Saline Aquifers

Carbon dioxide storage in the deep saline aquifers of the Wind River Basin has not been extensively investigated because other basins in Wyoming are better suited to CO_2 storage. Long-term CO_2 storage in saline aquifers requires an adequate storage reservoir in the requisite depth range of 914–3,962 m (3,000–13,000 feet), as well as the presence of proper geologic traps such as anticlines or domes. There are no large traps in the Wind River Basin that could potentially store significant volumes of CO_2 (Fig. 6-3). Furthermore, the deep basin center and synformal geometry are not ideal for CO_2 storage. A few potential storage reservoirs at the requisite depths do occur along a linear trend southwest of the basin axis. The formations represented in this linear trend dip to the northeast. The potential for up-dip CO_2 migration to the southwest could make injection and storage in these reservoirs technically difficult. Unless up-dip CO_2 migration from the basin center to the margins is slowed by stratigraphy, lithology, or structure to a rate lower than that required for long-term storage, and CO_2

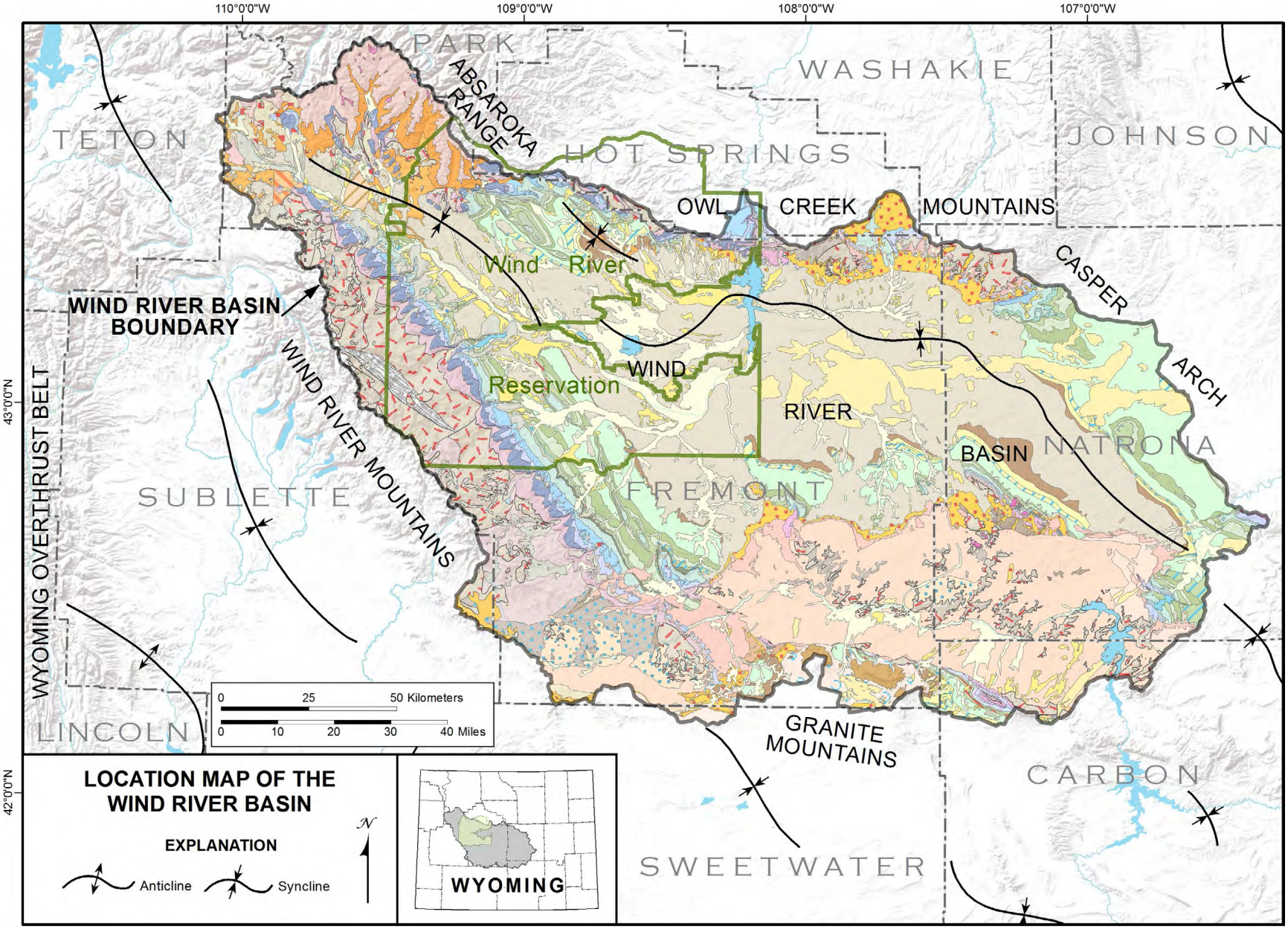


Figure 6-1. Location map of the Wind River Basin. The Wind River Basin is defined by the 12-digit hydrologic unit to the east, the 4-digit hydrologic unit to the north, and the 8-digit hydrologic unit to the south and west.

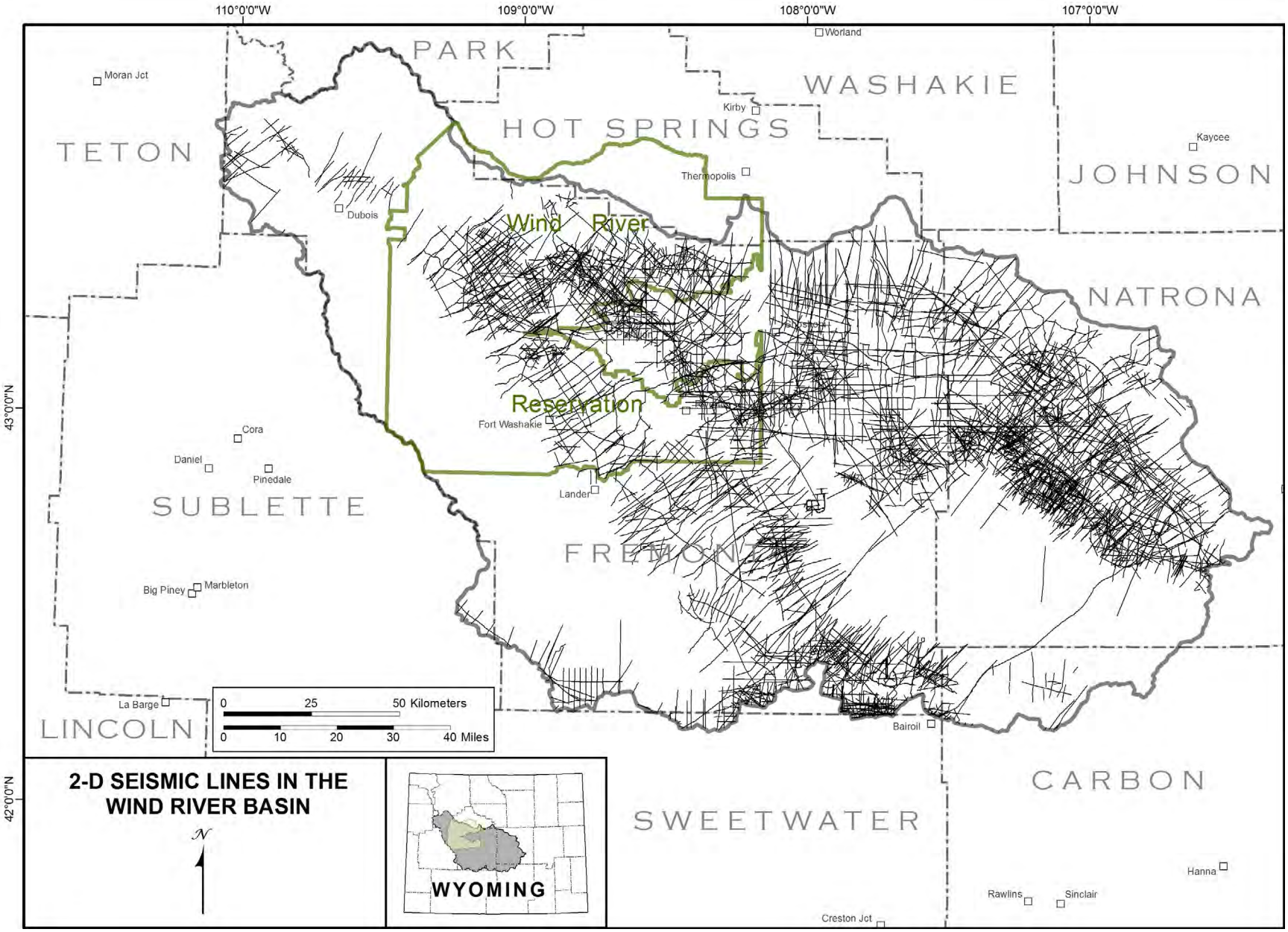


Figure 6-2. Map showing the location of 2-D seismic lines in the Wind River Basin. The line locations were provided by and are available for purchase from Seismic Exchange, Inc. (2011)

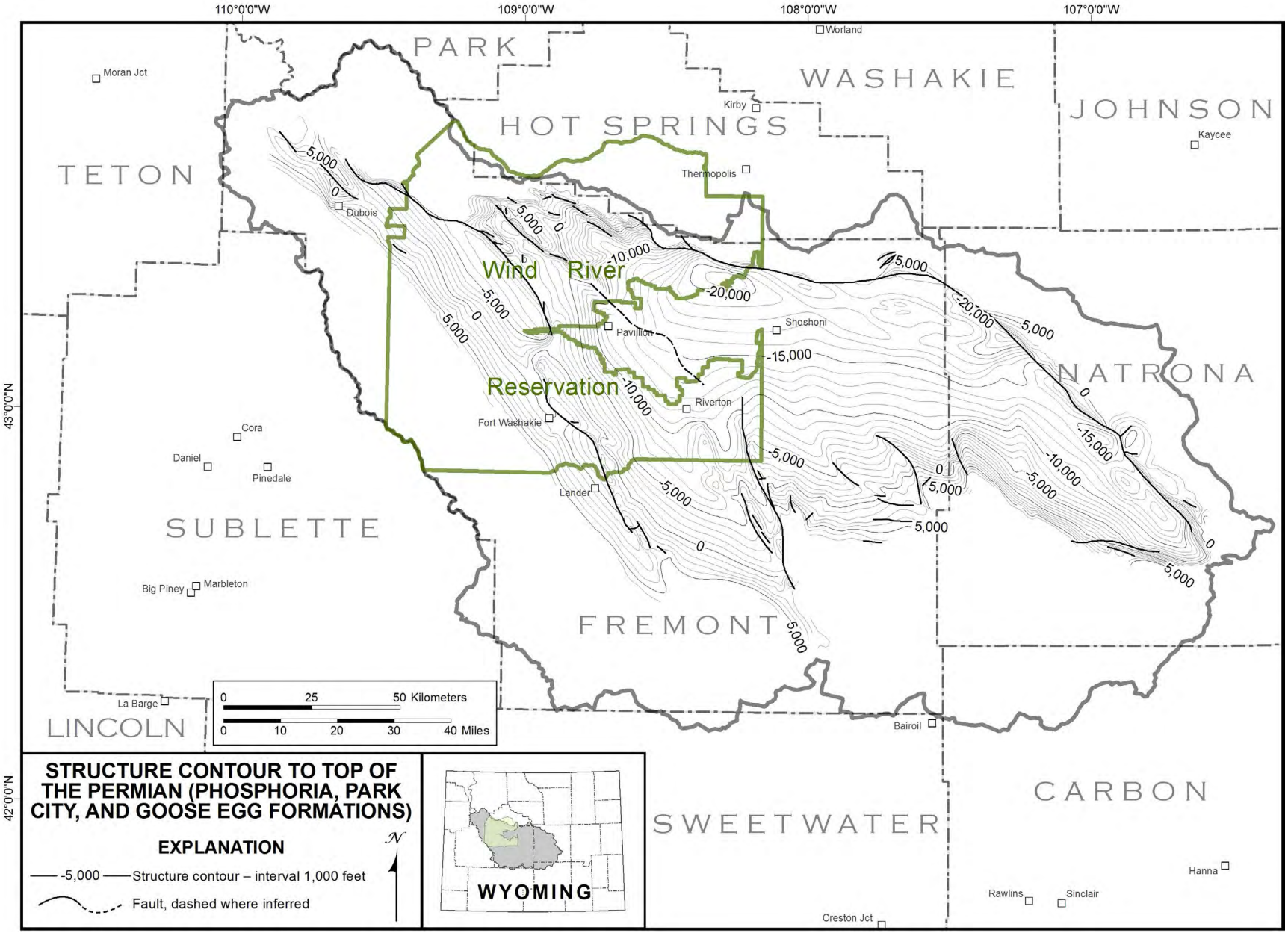


Figure 6-3. Structure-contour map to the top of the Phosphoria and Park City formations in the Wind River Basin. Datum is sea level. Modified from Kirschbaum and others (2007).

storage can be economically developed at depths greater than 3,962 m (13,000 feet), storage in the saline aquifers of the Wind River Basin remains an unlikely option. Still, to provide a complete review, the mass of CO_2 that can potentially be stored in the Paleozoic saline aquifers has been calculated in this chapter.

In the Wind River Basin, the formations with the highest potential to store CO_2 in deep saline aquifers are the Phosphoria and Park City formations, the Tensleep Sandstone, and the Madison Limestone (Plates 1 and 9). The Crow Mountain Sandstone is not evaluated here because it is discontinuous with significant lateral stratigraphic heterogeneity and may have the potential to store only minor amounts of CO_2 in specific locations. The primary seal for these Paleozoic formations is the Goose Egg Formation in the western Wind River Basin, and the Dinwoody Formation and Chugwater Group in the eastern Wind River Basin.

Traps

Traps for large-scale geologic CO_2 storage in saline aquifers are not present in the Wind River Basin. Minor traps that occur on the basin margins (Plate 8) frequently contain hydrocarbons yet are not large enough for large-scale CO_2 storage in deep saline aquifers.

Storage Zones

Phosphoria, Park City, and Goose Egg Formations

The Permian Phosphoria and Park City formations and the Permian and Lower Triassic Goose Egg Formation are predominantly time-synchronous formations deposited in adjacent marine to marginal-marine depositional settings. During Permian time, there was deposition of the deeper water chert, cherty shale, and phosphatic shale of the Phosphoria Formation, the shallower-water carbonates and shales of the Park City Formation, and red beds and evaporites of the Goose Egg Formation (Kirschbaum and others, 2007). All three formations/facies are preserved in the Wind River Basin. These Permian strata are everywhere unconformably underlain by the Permian Tensleep Sandstone and overlain by the Triassic Dinwoody Formation to the west and the Triassic portion of the Goose Egg Formation to the east.

The Phosphoria Formation has been extensively studied because of its commercial phosphate deposits and because it is commonly the source rock for the Paleozoic hydrocarbon fields throughout Wyoming. The Meade Peak and Retort phosphatic shale members of the Phosphoria Formation comprise the primary source of hydrocarbons, with total organic carbon levels measured at 0.1–2.9 percent from outcrop samples (Maughan, 1976; Claypool and others, 1978; Kirschbaum and others, 2007). Due to the temporal synchronicity of deposition and frequent intertonguing, the Phosphoria and Park City formations are often used interchangeably, especially in the subsurface. However, the Park City Formation is most commonly the hydrocarbon host rock for the Permian interval.

The Park City Formation consists of three members. The uppermost member, the Ervay Member, is the primary reservoir rock in the Permian strata in the Wind River Basin (Kirschbaum and others, 2007). In outcrop, the Park City Formation forms distinct grass-covered dip slopes capping the Tensleep Sandstone, and ranges in thickness from 46–79 m (150–260 feet) in the west to 55–99 m (180–325 feet) in the south (Keefer and Van Lieu, 1966). The Ervay Member pay-zone is generally 6–21 m (20–70 feet) thick, porosities can be as high as 26 percent, and permeabilities are less than 10 millidarcies (Cardinal and others, 1989). Oil gravity ranges 22–68° API (Wyoming Enhanced Oil Recovery Institute, 2012).The Park City Formation grades laterally into the Goose Egg Formation east of the Rattlesnake Hills. The evaporites of the Goose Egg Formation form the primary seal for the Park City Formation reservoirs and are described in further detail below.

Water quality in the Phosphoria-Park City aquifer system varies from fresh to moderately saline. TDS concentrations sampled from seven wells and seven springs in the basin range from 215 to 4,030 mg/L, with a median concentration of 812 mg/L (Bartos and others, 2012). TDS concentrations for all samples were much lower than the minimum 10,000 mg/L concentration required for CO_2 storage. Additional sampling will be needed to determine local water quality within potential Phosphoria and Park City CO_2 storage zones in the basin.

Tensleep Sandstone

The Pennsylvanian Tensleep Sandstone is the most prolific oil-producing formation of the Paleozoic strata in the Wind River Basin. Significant hydrocarbon storage and production suggests that the Tensleep holds the greatest potential to store CO_2. In the Wind River Basin, the Tensleep Sandstone is 76–122 m (250–400 feet) thick, and is primarily eolian cross-bedded sandstone, with interbedded dolostone and dolomitic sandstone (Kirschbaum and others, 2007). The various eolian sandstone zones, which are either quartz and/or carbonate cemented, constitute the chief reservoirs. Unfractured interbedded dolostones and dolomitic sandstones act as impermeable barriers to vertical fluid migration (Carr-Crabaugh and Dunn, 1996).

The Tensleep Sandstone is apparent on gamma logs as a clean sandstone (Plate 9). Porosity ranges from 5 to 22 percent and permeability from 0.1 to 100 millidarcies (Fox and others, 1975; Kirschbaum and others, 2007). Porosity decreases with depth, and is less than 8 percent below 3,048 m (10,000 feet) (Fox and others, 1975; Kirschbaum and others, 2007). The decrease in porosity with depth is likely due to an increase in secondary cementation, common to the Tensleep Sandstone throughout Wyoming (Bredehoeft, 1964). The Wyoming Enhanced Oil Recovery Institute (2012) database reports suitable Tensleep fields for EOR occur at average depths of 1,471 m (4,827 feet), with no fields deeper than 2,560 m (8,400 feet). Pay zone thicknesses range up to 61 m (200 feet) (Cardinal and others, 1989), and oil gravity ranges from 20–28° API (Wyoming Enhanced Oil Recovery Institute, 2012). TDS concentrations measured from 14 wells in the basin have a median value of 208 mg/L and a range of 146 to 1,060 mg/L (Bartos and others, 2012). Tensleep production accounts for approximately 48 percent of total oil production in the Wind River Basin (Kirschbaum and others, 2007).

Madison Limestone

The Mississippian Madison Limestone is the characteristic mix of limestone and dolostone found through the basins and uplifts of Wyoming. The Madison Limestone is commonly subdivided into the lower Lodgepole Member and the upper Mission Canyon Member (Sando and Bamber, 1985), although more recent work by Sonnenfeld (1996), Smith and others (2004), and Westphal and others (2004) have defined the Madison Limestone with a series of six third-order sequences. In the western Wind River Basin, the Lodgepole Member is 152–183 m (500–600 feet) thick and the Mission Canyon Member is 30 m (100 feet) thick (Keefer and Van Lieu, 1996). The Madison Limestone thins to 91 m (300 feet) in the eastern Wind River Basin (Kirschbaum and others, 2007).

The primary Madison reservoir in the Wind River Basin is found in the Madden gas field located in the northeastern part of the basin. Interestingly, the dry gas produced from this field is believed to be sourced from the Cretaceous-Lower Tertiary petroleum system, not the Phosphoria Formation (Kirschbaum and others, 2007). This deep field, 7,193–7,437 m (23,600–24,400 feet) below the surface, has an average porosity of 7 percent and an average permeability of 1.2 millidarcies (Brown and Shannon, 1989). Limited data from this field suggests a 44-m (145-foot) thick pay zone that is likely continuous over the anticline (Brown and Shannon, 1989). Phosphoria-sourced Madison Limestone reservoirs are generally much shallower, thinner (e.g., the Madison pay zone in the Sage Creek field is 6 m, 20 feet, thick; O'Keefe, 1989), and contribute only nine percent of total oil production in the Wind River Basin (Kirschbaum and others, 2007).

As with similar reservoirs throughout Wyoming, the Madison reservoir is heterogeneous, with complex lateral and vertical variations in porosity and permeability, due to secondary fracturing and dolomitization/dedolomitization. Nine water samples from the basin have TDS concentrations ranging 181–920 mg/L, with a median of 216 mg/L (Bartos and others, 2012). At a 2013 hearing before the Wyoming Oil and Gas Commission, Encana reported TDS concentrations of approximately 1,100 mg/L from a well recently drilled into the Madison aquifer in the central Wind River Basin (Marlin 29-21WDW, API 49-013-23374). Water samples were taken from more than 4,572 (15,000 ft) below the surface. These low TDS concentrations may disqualify the Madison Limestone

as a candidate storage reservoir in the Wind River Basin.

Confining Zones

The Paleozoic hydrocarbon system (or the Phosphoria Total Petroleum System, as defined by Kirschbaum and others, 2007, is well-sealed in all but the eastern basin by the Jurassic Gypsum Spring Formation. The Permian Goose Egg Formation is a lateral seal to the Park City Formation. Other potential minor sealing formations include the Chugwater, Dinwoody, Park City, and Madison formations (Coalson and others, 1994; Westphal and others, 2004; Kirschbaum and others, 2007).

Gypsum Spring Formation

The Gypsum Spring Formation is only present in the central, western, and northwestern Wind River Basin, where it attains a maximum thickness of 76 m (250 feet) (Love, 1948). The formation is unconformably overlain by the Jurassic Sundance Formation. Erosion of the Gypsum Spring by the Sundance Sea caused eastward thinning until it was entirely removed in eastern Fremont County (Peterson, 1957). The Gypsum Spring Formation consists of a lower unit of primarily gypsum with minor red shale and siltstone, a middle limestone, dolostone, and shale unit with minor gypsum, and an upper red shale unit again with minor local gypsum (Love, 1948; Peterson, 1957). The gypsum in the basal unit (Plate 9) is 15–38 m (50–125 feet) thick (Love, 1948), and is most likely the sealing lithology for the Paleozoic hydrocarbon system as well as for future CO_2 storage in the Paleozoic saline reservoirs.

Results

This CO_2 storage resource assessment for deep saline reservoirs in the Wind River Basin considers potential storage in the Phosphoria and Park City formations, the Tensleep Sandstone, and the Madison Limestone (Table 6-1). The approximate total formation area (A_t), determined for the Phosphoria and Park City formations, considers only those extents where the formations are buried at depths between 914 and 3,962 m (3,000 and 13,000 feet) below the surface using the structure contour map of Kirschbaum and others (2007; their Figure 14). The total formation area for the Tensleep Sandstone was assumed to be equivalent to that measured for the Phosphoria and Park City formations. Total formation area of the Madison Limestone was determined by the extent of the next full contour (305 m; 1,000 feet) underlying the Phosphoria and Park City formations. Total formation areas for each unit are summarized in Table 6-1 and presented graphically in Figure 6-4.

Maximum and minimum gross formation thickness and porosity (Table 6-1) were obtained from a number of sources, as described in the preceding paragraphs. Because little formation porosity data is available for the Madison Limestone in the Wind River Basin, this study extends the mean porosity value of seven percent reported for the Madden Field by Kirschbaum and others (2007) to the entirety of the formation; lacking further data, the 7 percent mean value is used to make conservative estimates of the minimum and maximum porosity values provided in Table 6-1. For all other formations, average values for each parameter are calculated as the arithmetic mean of the given minimum and maximum values.

Theoretical maximum, average, and minimum estimates of the CO_2 storage resource (mass) for saline aquifers, by formation (Table 6-2), are calculated using the parameters shown in Table 6-1. These calculations indicate that the saline aquifers of the Wind River Basin could store from 194 million to 16.6 billion metric tons (214 million to 18.3 billion short tons) of CO_2 with an average of 2.9 billion metric tons (3.2 billion short tons). These results include storage in the Madison Limestone, which may not be a legitimate storage zone due to low TDS concentra-

Table 6-1. Input values used in the estimation of CO_2 storage capacity of saline aquifers.

Formation	A_t (km^2)	h_g min (m)	h_g max (m)	ϕ_{tot} min (%)	ϕ_{tot} max (%)
Phosphoria/Park City	6,805	46	99	5	26
Tensleep	6,805	76	122	5	22
Madison	5,501	91	213	3	11

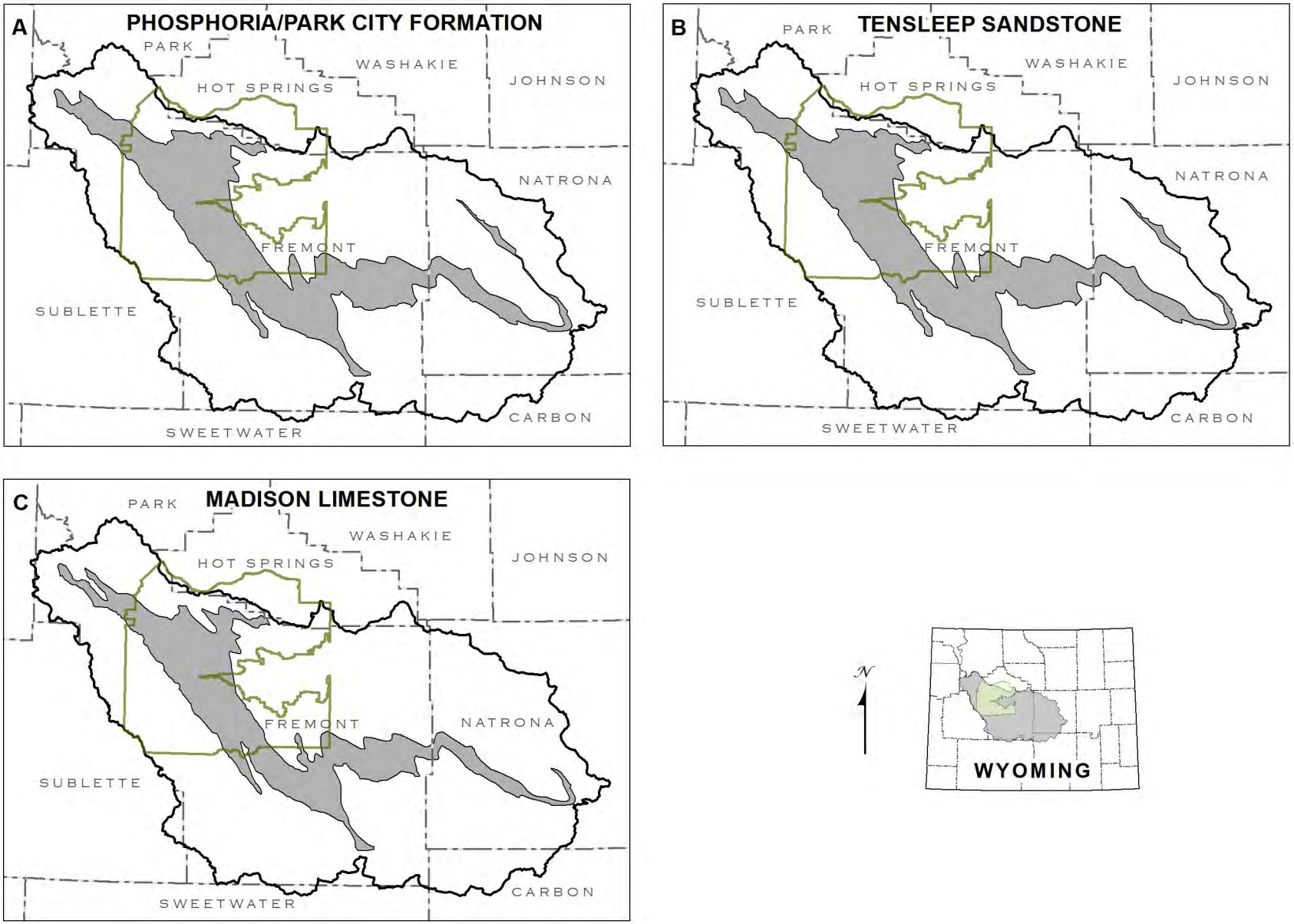


Figure 6-4. Total formation area (A_t) of the Phosphoria and Park City formations, the Tensleep Sandstone, and the Madison Limestone, summarized in Table 6-1. A_t is limited by depth from data modified from Kirschbaum and others (2012, Fig. 14).

Table 6-2. Mass of CO_2 that can theoretically be stored in saline aquifers in the Wind River Basin. Calculations follow Equation 4-1. Lithologies were used to determine E_{basin}; ss represents sandstone and dol represents dolomite.

Reservoir	S_{basin} (million metric tons)		
	minimum	average	maximum
Phosphoria/Park City (ss)	50	959	5,943
Weber (ss)	83	1,143	6,190
Madison (dol)	61	811	4,460
Total	**194**	**2,913**	**16,593**

tions. Note that the results shown are estimates and should not be used without incorporating the significant assumptions used in their formulation.

Storage in Hydrocarbon Reservoirs

Hydrocarbon Exploration and Production

Oil production in the Wind River Basin, and Wyoming, began with the completion of the Mike Murphy #1 well in 1884, just five years after America's first commercial oil well, the Drake well, was drilled. Mike Murphy #1 (Barber 1), completed in the Chugwater Group to a depth of 91 m (300 feet) (Mullen, 1989; De Bruin, 2012), was the discovery well for the Dallas (or Dallas Dome) field in the southwestern Wind River Basin (Plate 3). Since then, 110 fields in the Wind River Basin have recorded gas and/or oil production.

Of the 110 producing fields reported in 2012 to the Wyoming Oil and Gas Conservation Commission, 98 produce, or have produced, oil and 101 record gas production. Additionally, a handful of these reservoirs produce condensate liquids which are reported as oil by the Wyoming Oil and Gas Conservation Commission. Cumulative production from these fields through 2011 was 562.5 million barrels of oil and 5.2 trillion cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 2012). Oil production in the Wind River Basin declined from 1978 through 1995, and has since held steady near 4 million barrels per year (Fig. 6-5). Gas production in the basin generally increased through 2005, and has since remained at just under 200 million cubic feet per year (Fig. 6-5). In 2011, the Wind River Basin produced 8.3 percent of Wyoming's oil and 7.9 percent of Wyoming's gas. Reservoirs range from Mississippian to Eocene in age.

In the Wind River Basin, hydrocarbon traps typically consist of structural features such as domes, anticlines, or faulted anticlines (Keefer, 1969) situated on the basin margins, in rocks deposited previous to or coincident with Laramide-age faulting. Other types of structural traps include anticlines or domes near the basin axis, generally in the north and northeast, as well as traps beneath the basin-bounding thrust faults, or sub-thrust plays (Fox and Dolton, 1996b).

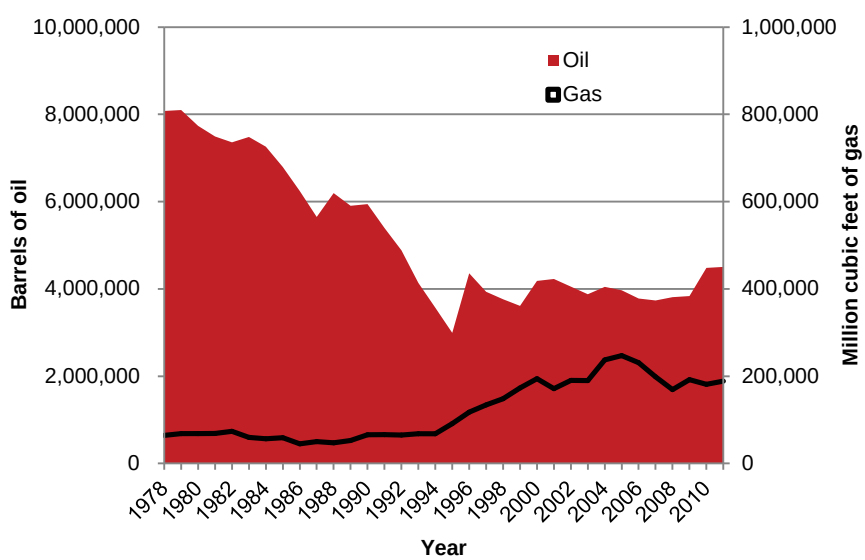


Figure 6-5. Oil and gas production for all fields in the Wind River Basin from 1978 through 2010. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

Some purely stratigraphic traps are also found in the Wind River Basin. The most commonly occurring consist of lateral up-dip (to the east) facies changes in the Phosphoria, Park City, and Goose Egg formations (Plate 1). Others include sandstone pinchouts in the primary sandstone reservoirs such as the Frontier Formation, Mesaverde Group, and Muddy Sandstone, as well as vertical and lateral cementation variations in Tensleep reservoirs. In some cases, structural traps are enhanced by the effects of stratigraphic-trapping. For example, hydrocarbons in Morrison Formation sands are held by a combination structural-stratigraphic trap on the nose of a domal structure in the Poison Spider West field (Plate 3) (Gouger, 1989).

The Tensleep Sandstone and Phosphoria and Park City formations comprise the primary reservoir rocks in the basin. The bulk of the hydrocarbons in these formations were sourced from the black shales of the Mead Peak and Retort members of the Phosphoria Formation in western Wyoming and eastern Idaho (Sheldon, 1967; Stone, 1967; Kirschbaum and others, 2007). Migration began soon after generation, and may have been associated with Sevier orogenesis. Hydrocarbons moved up-dip, likely via the porous and permeable Tensleep Sandstone, into the area that is now the Wind River Basin and were trapped by the overlying impermeable Goose Egg Formation (Stone, 1967; Kirschbaum and others, 2007). Laramide faulting and folding was responsible for the subsequent rearrangement of the hydrocarbons into their present day structural and stratigraphic traps. Phosphoria-sourced hydrocarbons are commonly high in sulfur, exhibit high API gravities, and are Type-IIS kerogen (Kirschbaum and others, 2007).

The Cretaceous and Tertiary petroleum system includes sources of the Fort Union, Meeteetse, and Mesaverde formation coals and carbonaceous shales, as well as the organic-rich marine shales of the Cody Shale, Belle Fourche Member of the Frontier Formation, Mowry Shale, and Thermopolis Shale (Johnson and others, 2007).

The decline in oil production in the Wind River Basin has been offset recently with the use of efficient secondary and tertiary production techniques like those employed at the current CO_2-EOR project at Beaver Creek field. Although it is possible that small undiscovered petroleum accumulations may exist in the basin (Fox and Dolton, 1996b), as with most hydrocarbon fields throughout Wyoming, it is more likely that any future increases in production will be the result of improved recovery methods.

Hydrocarbon Fields with CO_2 Storage Potential

Most hydrocarbon fields in the Wind River Basin produce some combination of oil, condensate, and gas; the proportion of which depends on the field. Because condensate is reported as oil production to the Wyoming Oil and Gas Conservation Commission, it is not possible to determine from public records the volume of produced condensate. For this study, only the four fields (Big Sand Draw, Riverton Dome, Steamboat Butte and Poison Spider West) with the greatest levels of historical oil and gas production are considered for CO_2 storage (Appendix B). The chosen fields meet specific depth, pressure, and seal criteria, and presumably have available pore space that can store CO_2. Existing geologic features or current production projects excluded several other large fields from consideration for this summary. Specifically, the Madden field is too deep for CO_2 storage. Beaver Creek is currently being produced with CO_2-EOR and Grieve will be under CO_2-EOR production in the near future (see Chapter 2). Waltman field is too deep, and contains a complexly-faulted stratigraphic trap that may not be suitable for CO_2 storage. Finally, numerous shallow fields located on the flanks of the Wind River Basin were not considered for this assessment because they are not completed to minimum requisite depths.

The following pages summarize field statistics for the four fields. Field production data were retrieved from the Wyoming Oil and Gas Conservation Commission (2012); all other field data were obtained from the Wyoming Geological Association symposium on the Bighorn and Wind River basins (Cardinal and others, 1989). The sources from which the available data were acquired did not use consistent methods (e.g., porosity values were determined from both core and log data; pressures were reported in a variety of ways such as drill stem

tests and shut-in tubing pressures). When known, data type/acquisition methods are denoted by superscripts, listed below:

DST = drill stem test
SIP = shut-in pressure
SITP = shut-in tubing pressure
l = calculated from log
c = measured from core

Rock type abbreviations are as follows:

ss = sandstone
sh = shale
ls = limestone
dol = dolostone

Rw represents water resistivity and an em dash (—) is used to denote unavailable data.

Big Sand Draw Area

The Big Sand Draw area is located in the southeastern part of the Wind River Basin in Fremont County, 35 km (22 miles) southeast of Riverton (Plate 3). Gas was first discovered in the Frontier Formation in this faulted anticline (Fig. 6-7) in 1918. The Frontier Formation contains numerous sandstones, all of which are apparently connected as a result of past petroleum development practices such as fracturing and poor or no cementing of production casing (Wold and Wellborn, 1989). Current production is from seven formations (Table 6-3). Carbon dioxide levels range 0.2–0.4 percent in gas from these reservoirs (Wold and Wellborn, 1989). Gas production has steadily declined in the Big Sand Draw field since 1995; oil production reached a maximum in 2009 (Fig. 6-6). Production through 2011 totaled 58.6 million barrels of oil and 171 billion cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 2012).

Table 6-3. Big Sand Draw area statistics, from Wold and Wellborn (1989).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	22[l]	—	10–60	1,350	2.8–2.11	—
Cloverly (Lakota)	ss	17[l]	—	30	1,710[SITP]	—	gas
Morrison	ss	17[l]	—	14	1,590	2.2	gas
Chugwater	ss,ls	11[l]	0.2[c]	46	2,415	0.77	34
Phosphoria (upper)	dol,ss	15–16.5	1.5	20–28	3,100	0.94–1.95	62.1
Phosphoria (basal)	dol,ss	11	1.2	20	3,145	2.7	33
Tensleep	ss	12.6	50	278	3,303	2.4	33.6

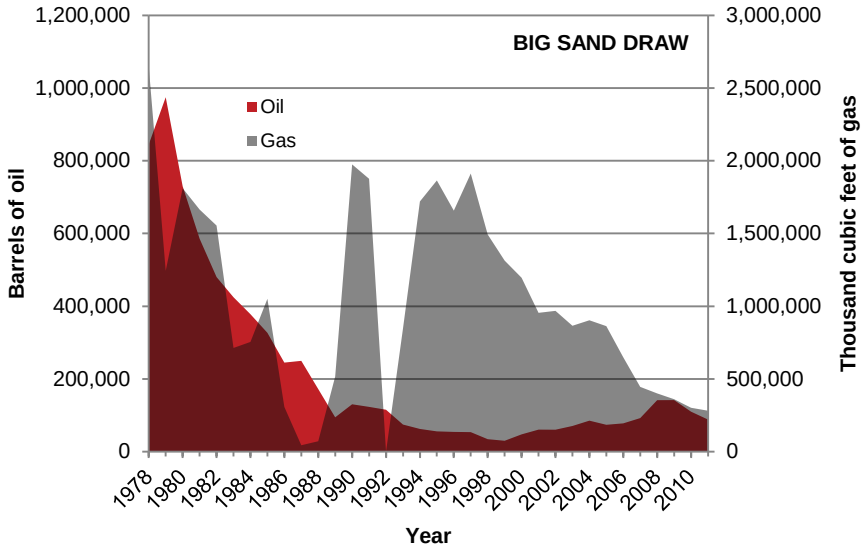


Figure 6-6. Big Sand Draw area oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix B.

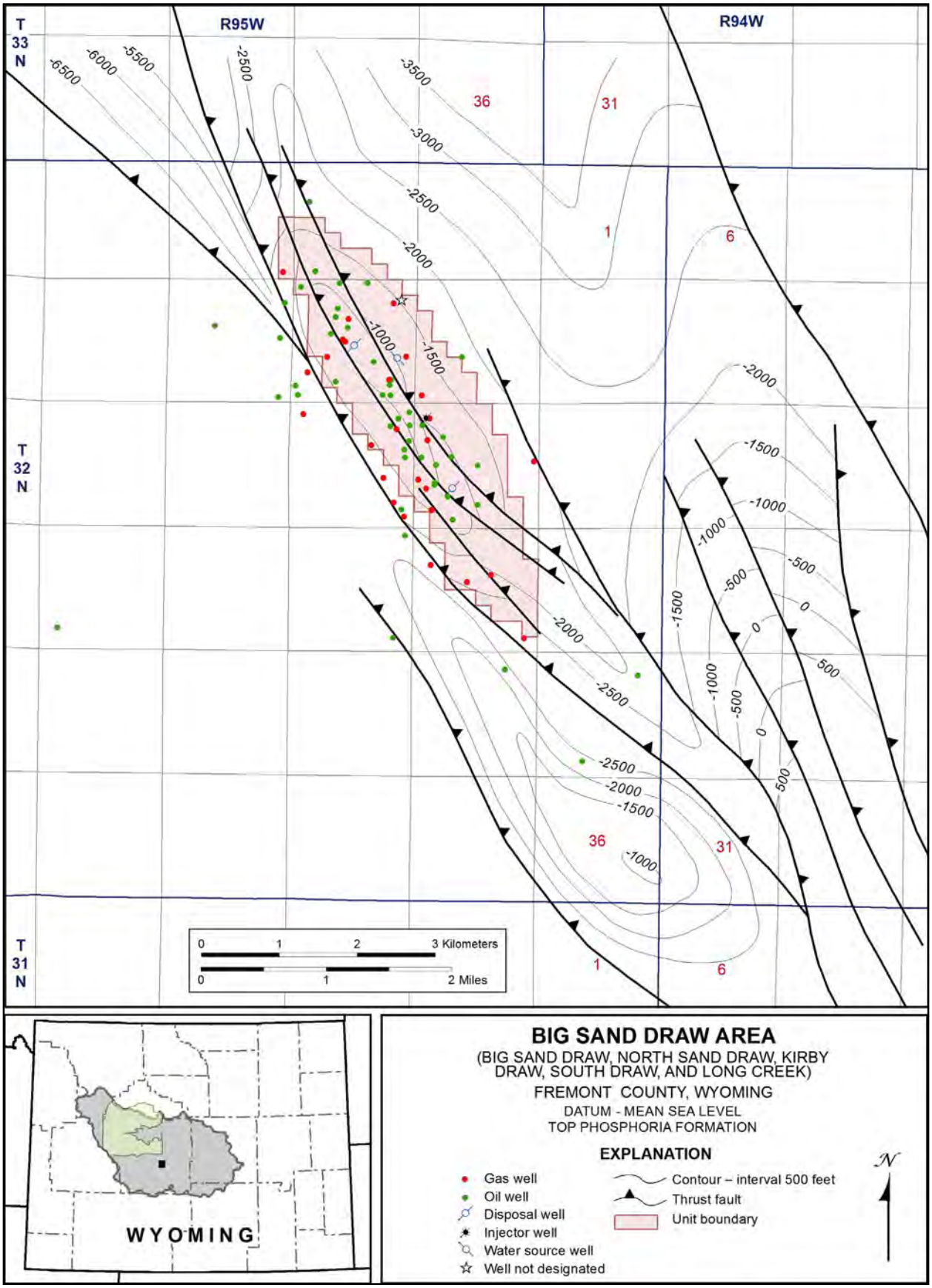


Figure 6-7. Big Sand Draw area structure-contour map, modified from Wold and Wellborn (1989). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Riverton Dome Field

The Riverton Dome field is located in central Fremont County, 10 km (6 miles) southeast of Riverton, within the Wind River Reservation (Plate 3). Riverton Dome was discovered in 1949 as a Tensleep oil-producing field. During the 1950s and 1960s, eight additional reservoirs were discovered in the Fort Union, Mesaverde, Cody (Shannon Sandstone Member), Frontier, Muddy, Cloverly, and Phosphoria formations (Table 6-4) (Borgerding, 1989). All reservoirs consist primarily of sandstones except the Phosphoria which is a dolomite. Many of these formations have been shut-in, and only the Shannon, Frontier, Cloverly ("Dakota"), and Muddy are currently produced, with additional significant gas production reported from Mesaverde coals. This anticlinal trap (Fig. 6-9) has produced over 208.7 billion cubic feet of gas and 4.6 million barrels of oil through 2011 (Fig. 6-8) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 6-4. Riverton Dome field statistics, from Borgerding (1989).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Fort Union	ss	20.7[l]	—	35	1,150	0.7	45.2
Mesaverde	ss	19.5	—	37	1,380	0.97	45.9
Cody	ss	15.3	—	48	2,025	—	46
Frontier	ss	11.1[l]	—	60	3,680	4.29	45.9
Muddy	ss	12	—	15	4,280	—	45.9
Cloverly (Dakota)	ss	10[l]	—	16	4,350	—	45.9
Cloverly (Lakota)	ss	8[l]	—	50	4,420	—	45.9
Phosphoria	dol	8.5[l]	—	72	5,245	0.58	55.9
Tensleep	ss	4.7[c]	6.9[c]	193	5,380	1.15	40.8

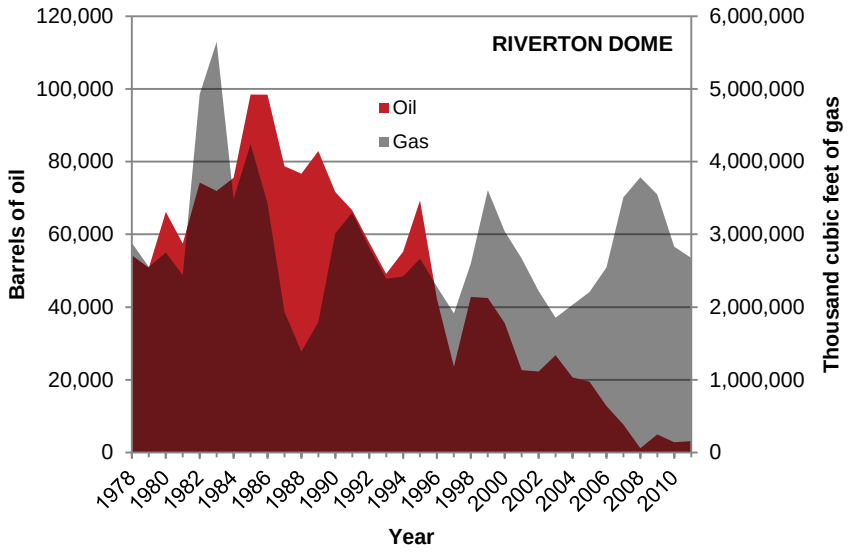


Figure 6-8. Riverton Dome field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix B.

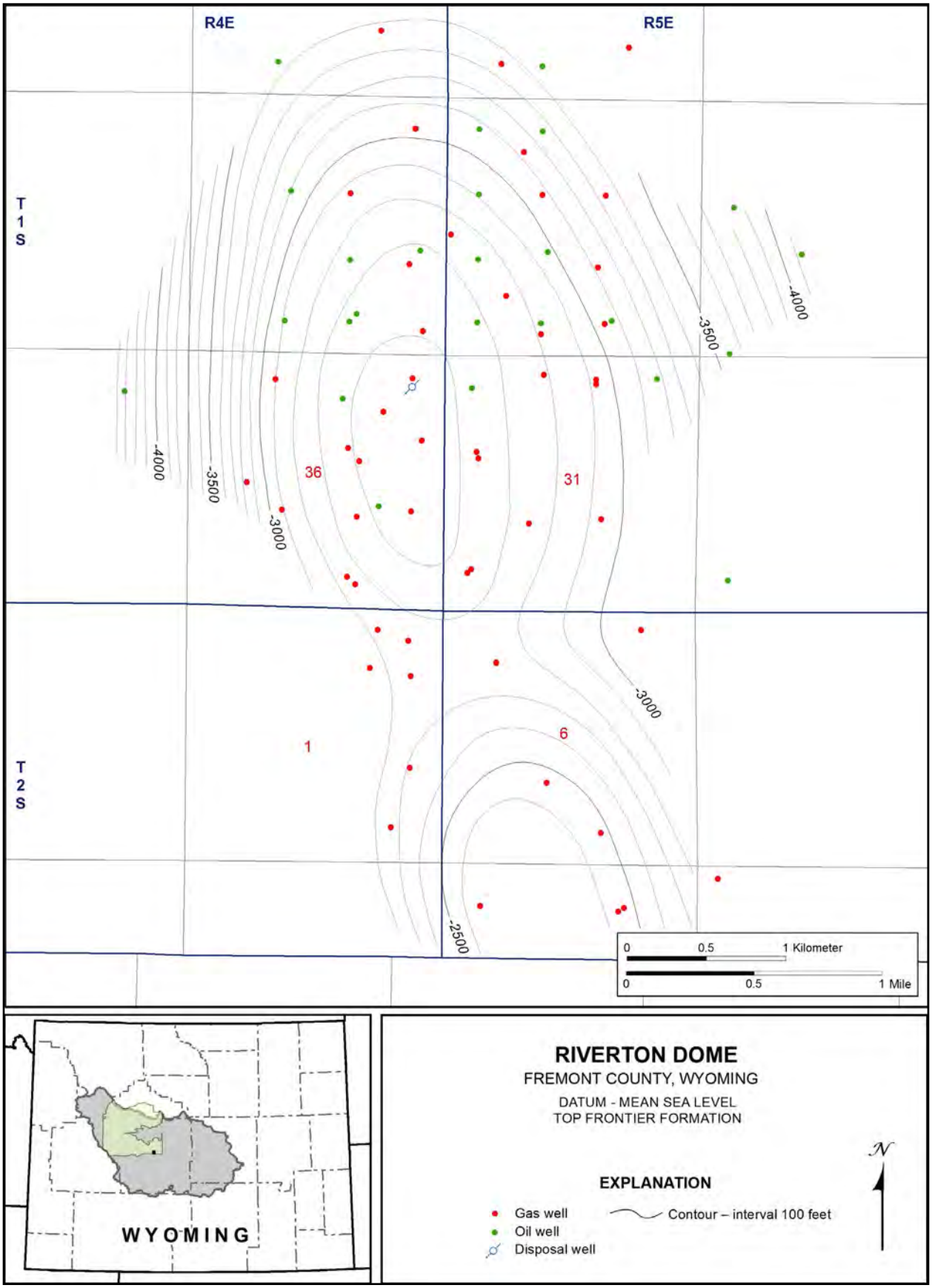


Figure 6-9. Riverton Dome field structure-contour map, modified from Borgerding (1989). Well locations and well types from the Wyoming Oil and Gas Conservation Commission (2012), no unit boundary was available.

Steamboat Butte Field

The Steamboat Butte field is located in the northwest portion of the Wind River Basin, 48 km (30 miles) northwest of Riverton, on the Wind River Reservation (Plate 3). This northwest-trending faulted anticline (Fig. 6-11) was discovered with a well drilled in 1943 that was initially completed as a Nugget well (Miller, 1989). Since the initial discovery, eight additional reservoirs have been produced (Table 6-5), including the Frontier, Muddy, Cloverly ("Dakota" and "Lakota"), Crow Mountain ("Curtis"), Dinwoody, Phosphoria, and Tensleep formations (Miller, 1989). In 2011, gas production was reported from the Frontier, and gas and oil from the Muddy, Nugget, Tensleep, and combined Nugget/Dinwoody/Phosphoria/Tensleep reservoirs. Oil production in the Steamboat Butte field has steadily declined since the early 2000s, while gas production has fluctuated with time (Fig. 6-10). Cumulative production through 2011 was 99.7 million barrels of oil and 13.7 billion cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 2012).

Table 6-5. Steamboat Butte field statistics, from Miller (1989).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	—	—	34	1,130[SIP DST]	1.5	gas
Muddy	ss	6[l]	—	23	—	—	gas
Clovery (Dakota)	ss	—	—	4–32	—	—	43.5
Clovery (Lakota)	ss	—	—	29	1,820[SIP DST]	1.7	37
Crow Mountain	ss	11.8–13.7[c]	24[c]	20	1,900	—	29.3
Nugget	ss	15.6	147.5	100	2,082[SIP DST]	0.2	23.1–38.5
Dinwoody	dol	16.2[c]	—	5	—	—	—
Phosphoria	ls,dol	16.5[c]	6.11[c]	26	2,800	1.4	29–34
Tensleep	ss	12[c]	41[c]	200	2,954[SIP DST]	2.6	28.2

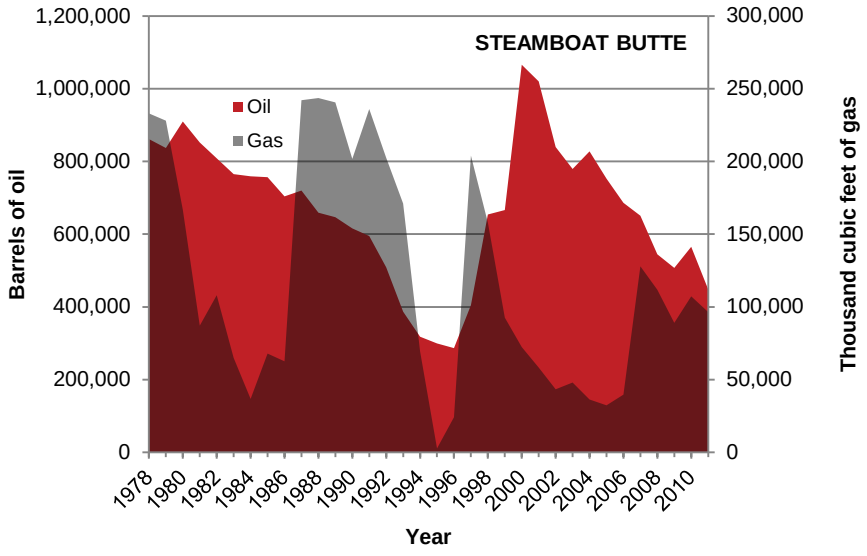


Figure 6-10. Steamboat Butte field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix B.

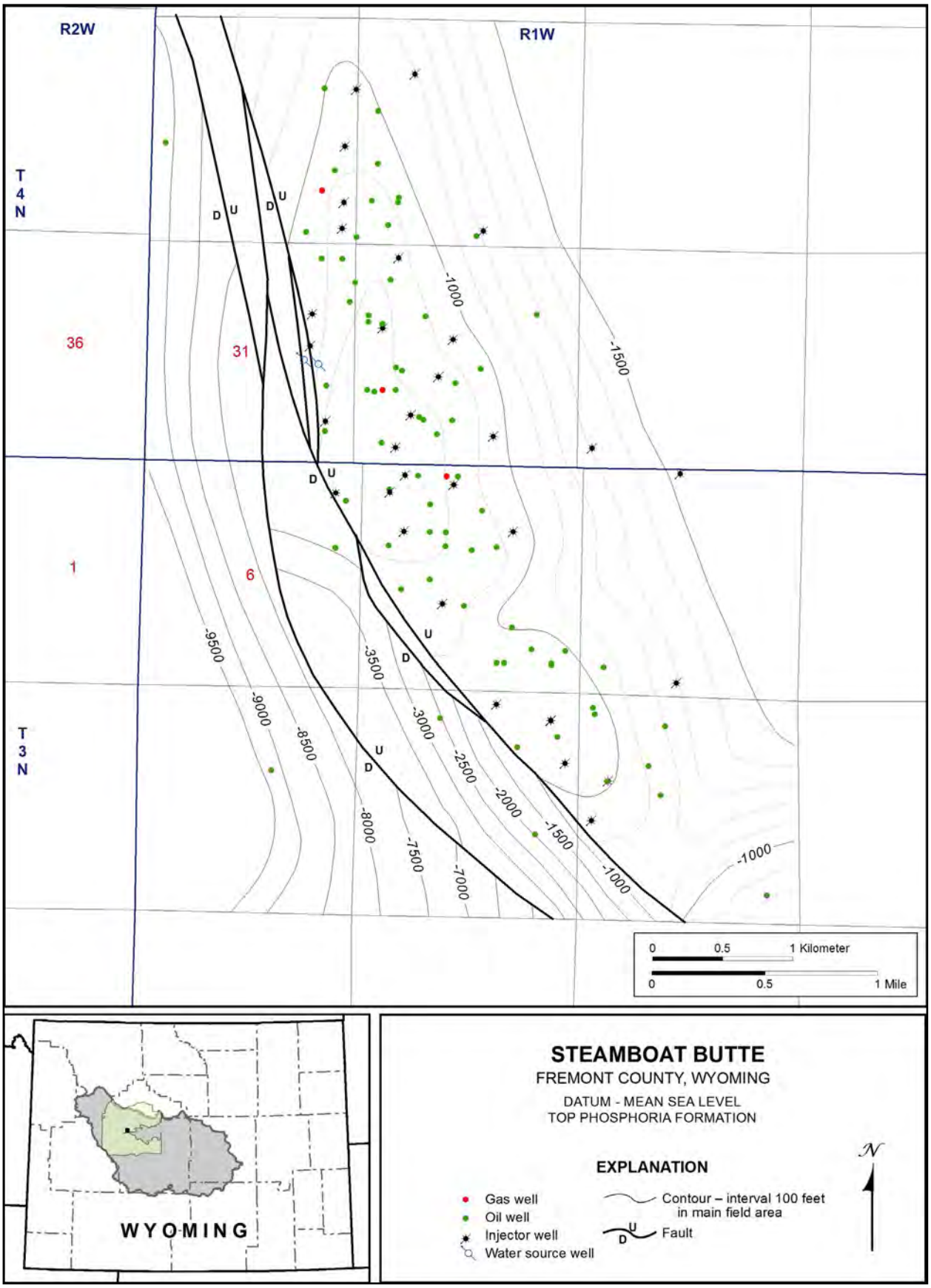


Figure 6-11. Steamboat Butte field structure-contour map, modified from Miller (1989). Well locations and well types from the Wyoming Oil and Gas Conservation Commission (2012), no unit boundary was available.

Poison Spider West Field

Poison Spider West field is located in the far eastern Wind River Basin, 45 km (30 mi) east of Casper (Plate 3). The Poison Spider West field is a north–west-trending faulted asymmetrical anticline (Fig. 6-13) (Gouger, 1989). The field was originally a Frontier discovery, with the first completion in the spring of 1948. Five additional reservoirs were discovered over the following decades (Table 6-6), with the most recent 1983 discovery of the Niobrara oil reservoir (presumably comingled with the Frontier) (Gouger, 1989). Oil and gas production have steadily declined over recent years, yet through 2011, the Poison Spider West field has produced over 12.3 million barrels of oil and nearly 57.1 billion cubic feet of gas (Fig. 6-12) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 6-6. Poison Spider West field statistics, from Gouger (1989).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	7.3[c]	0.1–7.5[c]	40	6,200	0.4	43.8
Teapot	ss	12[c]	17.7[c]	45	4,010	4.61	42.8
Parkman	ss	13.7[c]	0.46[c]	43	4,173[DST]	1.1	43.5
Cody	ss	11.9[c]	1.4[c]	25	4,470	0.52	45
Niobrara	sh	fracture	—	20	919	—	40.5
Morrison	ss	11.2[c]	0.89[c]	95	6,886	0.2	47.9

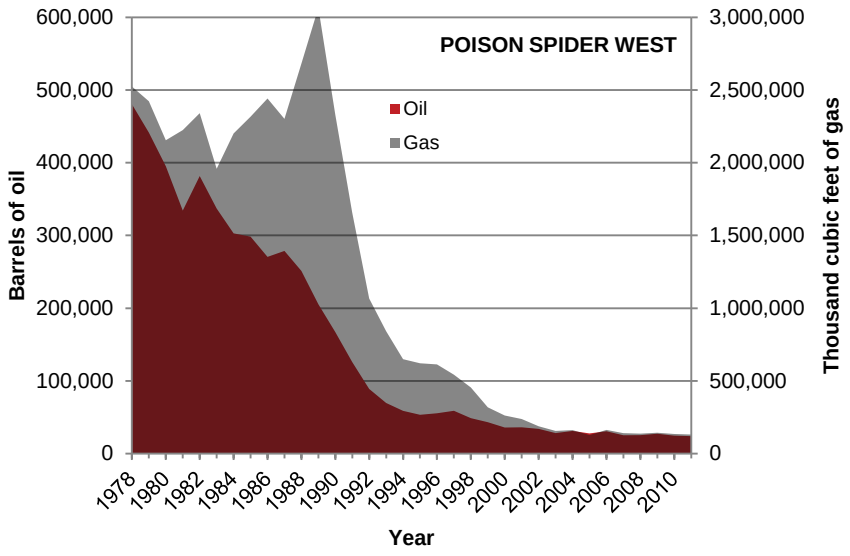


Figure 6-12. Poison Spider West field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix B.

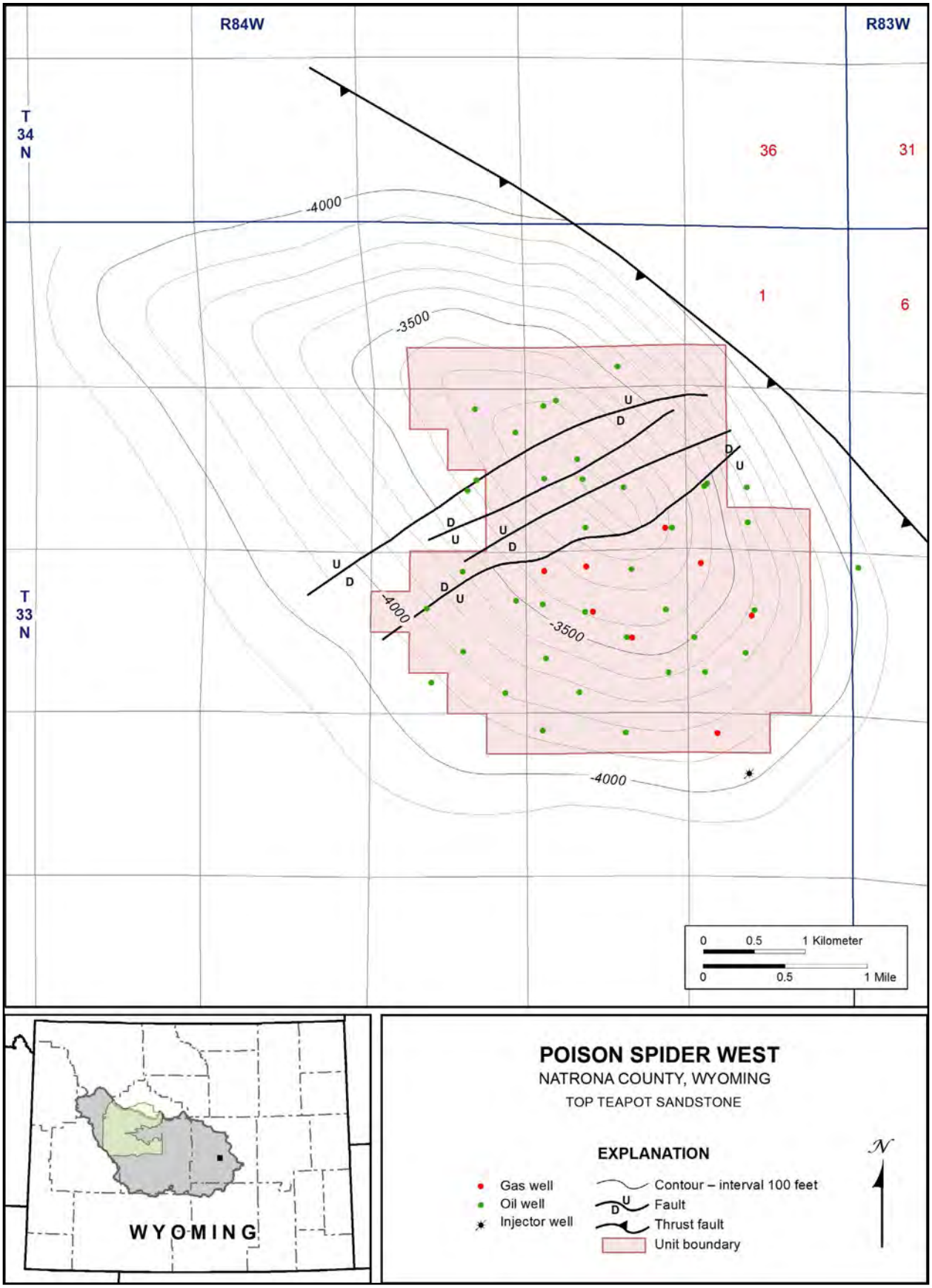


Figure 6-13. Poison Spider West field structure-contour map, modified from Gouger (1989). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Results

The calculation of the CO_2 storage resource of hydrocarbon reservoirs in the Wind River Basin is hampered by many unknowns and a general lack of data. The Wind River Basin hydrocarbons fields are old; most have been producing for over 70 years. These old oil fields frequently flared their gas, which was not recorded as production. Historic production volumes from these fields are circumspect at best, and recorded volumes are likely to be significantly lower than those actually produced. The problem is further complicated by poor, incomplete, or non-existent cementing of production casing, as well as the presence of undocumented (and presumably unplugged) wells. Thus, it should be noted that the results presented here are based on certain judgments and estimates necessary to account for the paucity of information.

All reservoirs in this evaluation are 914–3,658 m (3,000–12,000 feet) below the surface, and average 2,286 m (7,500 feet) in depth. A standard normally pressured saline aquifer has a hydrostatic pressure gradient of 10.516 kPa/m (0.465 psi/ft) (Schlumberger, 2012), a generalized geothermal gradient of 0.0301 °C/m (0.0165 °F/ft) (Sheriff, 1991), and an average surface temperature of 20 °C (68 °F). 2,286 m (7,500 feet) depth corresponds to 24.0 MPa (3,481 psi) and 88.8 °C (191.8 °F). Under these conditions, the expected CO_2 is 625 kg/m^3 (39 lb/ft^3). That value is used in this assessment to account for the wide range of depths evaluated by one equation.

Formation volume factors were estimated using data reported in Cardinal and others (1989), however, they cannot be independently verified. Values for B_o and B_g exhibit significant variability among fields. Calculated average values for B_o (1.07) and B_g (0.006) were assigned to the oil reservoirs at the Big Sand Draw and Steamboat Butte fields. Higher values for B_o (1.6) and B_g (0.004) were estimated for Riverton Dome and Poison Spider West fields. Finally, a B_w value of 1.0 was assumed for all fields.

The calculated CO_2 storage resource for the Big Sand Draw, Riverton Dome, Steamboat Butte, and Poison Spider West fields is summarized in Table 6-7. Reservoirs were combined in cases where combined production numbers were reported to the Wyoming Oil and Gas Conservation Commission (2012). This estimate suggests the potential to store 7.3–44 million metric tons (8.0–49 million short tons) of CO_2 in these four fields. These fields are not depleted, and future production will create additional pore space. As with storage estimates from saline aquifers, the results presented in Table 6-7 are only estimates and should not be used without incorporating the significant assumptions used in their formulation.

Storage through Enhanced Oil Recovery

Based on technical feasibility, Wo and others (2009) ranked the top candidate reservoirs for CO_2-EOR in fields across Wyoming for both miscible and immiscible CO_2 flooding. Their study ranked 37 reservoirs in the Wind River Basin for miscible CO_2 flooding and 8 reservoirs for immiscible CO_2 flooding. Of the top 100 candidate EOR fields for miscible CO_2 flooding in Wyoming (by CO_2 volume), 13 are in the Wind River Basin; none are in the top 20 candidate fields for immiscible CO_2 floods. Minimum and maximum estimated total volumes of CO_2 for these miscible CO_2 floods (from Wo and others, 2009) are summarized in Table 6-8. These estimates do not include oil recovery within the residual oil zone. There are no estimates for the amount of additional oil recoverable from ROZs in the Wind River Basin, yet estimates from the Tensleep reservoirs in the Bighorn Basin (e.g., Yin and others, 2011) suggest recovery from ROZs will contribute a substantial amount to the potentially recoverable oil.

The Tensleep and Phosphoria reservoirs are the highest priority targets for miscible CO_2-EOR. Oil viscosities from these formations within the best candidate fields range 22.5–62.1° API (average 35.7° API), within the required range for miscible and immiscible CO_2 flooding.

Wo and others (2009) estimate 1.2–1.8 trillion cubic feet (~62–94 million metric tons; 68–103 million short tons) of carbon dioxide could be required for CO_2-EOR in the Wind River Basin (historically produced reservoirs, not including

Table 6-7. Mass of CO_2 that can theoretically be stored in four hydrocarbon fields in the Wind River Basin, for a range of E_{res}. Calculations follow Equations 4-2 through 4-8.

Field	Reservoir	S_{res} (million metric tons) minimum E_{res} = 0.1	mode E_{res} = 0.3	maximum E_{res} = 0.6
Big Sand Draw	*Frontier*[1]	1.1	3.4	6.7
	Phosphoria/Park City	0.52	1.6	3.1
	Tensleep	2.1	6.2	12.4
	Total	**3.7**	**11**	**22**
Riverton Dome	*Cody*	0.060	0.19	0.37
	Frontier/Muddy/ Dakota/Lakota	1.0	3.1	6.1
	Phosphoria	0.24	0.72	1.4
	Tensleep	0.090	0.26	0.52
	Total	**1.4**	**4.2**	**8.5**
Steamboat Butte	*Frontier*	0.13	0.4	0.8
	Nugget/Dinwoody/ Phosphoria/Tensleep	0.51	1.5	3.0
	Nugget[1]	0.15	0.46	0.93
	Phosphoria[1]	0.16	0.49	1.0
	Tensleep[1]	0.62	1.9	3.8
	Total	**1.6**	**4.7**	**9.5**
Poison Spider West	*Mesaverde*[1]	0.32	1.0	1.9
	Cody[1]	0.25	0.75	1.5
	Total	**0.57**	**1.7**	**3.4**
Total		**7.3**	**22**	**44**

[1]Denotes reservoirs where water production was not considered. Post-1978 water injection exceeds water production reported to the Wyoming Oil and Gas Conservation Commission (2012).

ROZs). These estimates include the noteworthy demand for CO_2 in the Beaver Creek field, which is currently under CO_2 flood, and the Grieve field, which will soon have additional oil recovery through CO_2-EOR.

CO_2-EOR has proven successful for fields within the Wind River Basin in the past, and it is likely that additional tertiary recovery projects will be undertaken at oil reservoirs in decline in the eastern part of the basin first, because of the existing CO_2 pipeline in that region. CO_2-EOR in the northern and western Wind River Basin will likely require a CO_2-pipeline extension.

Enhanced Coalbed Natural Gas Recovery

Mining in the Wind River Basin coal field began as early as 1870 with the opening of the Wyoming Central underground mine, located south of Hudson (Glass and Roberts, 1978). Since then, at least 58 coal mines have been in operation, although production levels from most of the mines were minimal. Production steadily increased to a maximum of 263,532 metric tons (290,495 short tons) of coal in 1920. The steady decline in Wind River coal production that began in the 1920s ended in 1973 with the closure of the last coal mine (Glass and Roberts, 1978). No coal mines are in operation today in the Wind River Basin.

Coalbed natural gas exploration in the Wind River Basin has not been extensive. Johnson and Rice (in Fox and Dolton, 1996b) report only one CBNG well in the basin, as of 1996. This well was drilled in 1990 in the Riverton Dome field, and has subsequently been plugged and abandoned. Wyoming Oil and Gas Conservation Commission (2012) records show 18 additional wells with CBNG production from coals within the Mesaverde Formation in the Riverton Dome field, with production records beginning in 2005. These are the only CBNG wells in the Wind River Basin. In 2009, Devon Energy proposed 208 CBNG wells in the Beaver Creek area. This project is pending with a draft environmental impact statement (EIS).

Table 6-8. Estimated CO_2 demand, in billion cubic feet (BCF), for the top ranked reservoirs within the Wind River Basin for miscible CO_2 flooding, from Wo and others (2009).

Rank[1]	Field name	Reservoir	Minimum total CO_2 (BCF)	Maximum total CO_2 (BCF)
miscible CO_2 flooding				
9	Steamboat Butte	*Tensleep*	219	329
21	Beaver Creek	*Madison*	117	176
22	Big Sand Draw	*Tensleep*	116	174
25	Steamboat Butte	*Phosphoria-Tensleep*	91	136
26	Winkleman	*Tensleep*	83	124
29	Grieve	*Muddy*	77	116
30	Winkelman	*Phosphoria*	74	111
37	Steamboat Butte	*Nugget*	61	92
39	Beaver Creek	*Tensleep*	59	89
46	Steamboat Butte	*Phosphoria*	48	72
80	Notches	*Tensleep*	26	39
88	Poison Spider West	*Cody*	24	36
94	Big Sand Draw	*Phosphoria*	22	33

[1]Rank within the top 100 Wyoming fields for miscible CO_2 flooding.

Coal deposits are known to occur in Upper Cretaceous and Tertiary age rocks within the Wind River Basin. Formations with coal deposits of resource thickness (greater than 76 cm; 30 inches) include the Frontier Formation, Mesaverde Formation, and Meeteetse Formation (Hickling and others, 1989). Although the CO_2-storage potential through CO_2-ECBM is not significant in Wind River Basin CBNG fields, storage potential does exist. Carbon dioxide storage in CBNG fields would most likely occur in the coals of the Mesaverde Formation.

Coalbed Natural Gas Formations with CO_2 Storage Potential

Mesaverde Formation

The stratigraphy of the Upper Cretaceous Mesaverde Formation in the Wind River Basin records the eastward migration of the Western Interior Seaway shoreline (Johnson and others, 2007). The rocks deposited by this migration represent fluvial and coastal plain depositional environments, and thin from 671 m (2,200 feet) in the west to less than 152 m (500 feet) in the east (Johnson and others, 2007). Sandstones are thus the predominant rock type of the Mesaverde Formation, but peat also accumulated in bogs in this marginal marine environment. The peat bogs formed bituminous and subbituminous coal beds up to 6 m (20 feet) thick (Hickling and others, 1989). Current CBNG production in the Riverton Dome field is from coalbeds in the Mesaverde Formation.

Results

Reeves (2003) assessed Wind River Basin coal seams for CO_2 storage through CO_2-ECBM on sparse data prior to the 2005 CBNG production at Riverton Dome. Reeves' (2003) assessment considered the CO_2 storage resource of commercial and non-commercial coalbeds in the United States. In his study, the Wind River Basin has an estimated in-place resource of 6 trillion cubic feet of natural gas. Of this assessed in-place resource, it is estimated that nearly 2.5 trillion cubic feet are recoverable, a recovery factor of 41 percent. Reeves (2003) assumed 50 percent of the coal is subbituminous and 50 percent is highly volatile. Accounting for a standard voidage replacement and ECBM efficiency in commercial areas of 75 percent, as well as a 50 percent accessible portion of the non-commercial area for CO_2-ECBM, resulted in an incremental recovery potential of 1.5 trillion cubic feet of gas in the Wind River Basin, with a total CO_2 storage potential of 1.4 billion metric tons (1.5 billion short tons), or 2 percent of the U.S. total.

Chapter 7

Bighorn Basin

The Bighorn Basin highlights the dynamic relationship between CO_2-EOR and long-term CO_2 storage. The overlap between EOR and CO_2 storage is significant, and it can be difficult to separate one from the other. EOR is beneficial from an economic standpoint because it is a viable technique for producing oil bypassed by conventional retrieval methods. It also represents an opportunity to sequester CO_2, though its usefulness in reducing greenhouse gas emissions depends on the source of CO_2 and the reservoir storage volumes. In the heavily and historically explored oil-producing Bighorn Basin, CO_2-EOR may be more lucrative for long-term CO_2 storage than saline aquifers.

Few locations within the Bighorn Basin are suitable solely for CO_2 storage without EOR. The generally saline Paleozoic section that is found in most other basins in Wyoming is too deep (greater than 6,096 m; 20,000 feet) for storage in the center of the Bighorn Basin, but may be usable for storage in basin-margin structural traps. Furthermore, most of the traps that are suitable for CO_2 storage are not saline reservoirs but contain producing or depleted oil-producing reservoirs, or conventionally non-commercial quantities of oil, such as residual oil zones. The complex interplay between deep saline aquifers, depleted oil and gas reservoirs, and CO_2-EOR as storage options will likely drive future decisions and policy for long-term geologic storage of carbon dioxide.

Background

Wyoming's Bighorn Basin is an elongate, northwest-trending structural basin approximately 193 km (120 miles) long and a maximum of 145 km (90 miles) wide (Plate 10). For the purpose of this assessment, the basin boundary is defined by the Big Horn River 4-digit hydrologic unit (Fig. 1-1, Plate 10, Fig. 7-1). The basin is bounded on the north and east by the Pryor and Bighorn mountains, and on the south and west by the Owl Creek, Absaroka, and Beartooth mountains. The present structural configuration of the basin resulted from the Late Cretaceous through Early Eocene Laramide orogeny (Blackstone, 1963), during which the peripheral mountain uplifts experienced their major growth (Plate 2). The folding and faulting that formed the present oil-producing anticlines in the Bighorn Basin (Plate 11) occurred during pulses of compressional stress, mainly oriented northeast–southwest.

In the axis of the Bighorn Basin, Paleozoic, Mesozoic, and Cenozoic rocks are present with a total thickness that exceeds 7,620 m (25,000 feet) (Plates 1 and 12). The structure of the Bighorn Basin is best defined through seismic survey data. Two-dimensional seismic surveys related to historic and more recent hydrocarbon exploration within the Bighorn Basin (Fig. 7-2) are available for purchase through third-party vendors. No publicly available seismic data have been located.

Storage in Saline Aquifers

The potential for CO_2 storage within the Bighorn Basin, not considering enhanced oil recovery, has not been extensively investigated. The Paleozoic injection zones of interest are at depths greater than 3,962 m (13,000 feet) in many of the most probable structural traps. Depths more than 3,962 m (13,000 feet) are considered too deep for CO_2 storage, requiring additional compression at the surface above pipeline pressures (Burruss and others, 2009; Brennan and others, 2010). There are a few possible structures, including the Worland thrust and Marshall thrust (Plate 11), that have anticlinal-trap geometries conducive to CO_2 storage. The Golden Eagle and Waugh thrusts may possess potential Paleozoic injection zones, as well as numerous other basin-margin thrusts (Plate 11). These structures generally are at depths greater than 3,048 m (10,000 feet) and are fault-bounded anticlines. The depth limitation and geometry of these anticlines, as well as constraints on porosity and permeability of the potential receiving formations, will limit the feasibility and volume of CO_2 that can be safely stored within these traps.

Traps

Traps for large-scale geologic CO_2 storage in saline aquifers are non-existent in the Bighorn Basin. The Bighorn Basin has a bowl-shaped geometry, where all formations dip toward the basin center. It may be unreasonable to store CO_2 in the basin center; presumably CO_2 will migrate away from the injection point, up dip, toward the basin flanks.

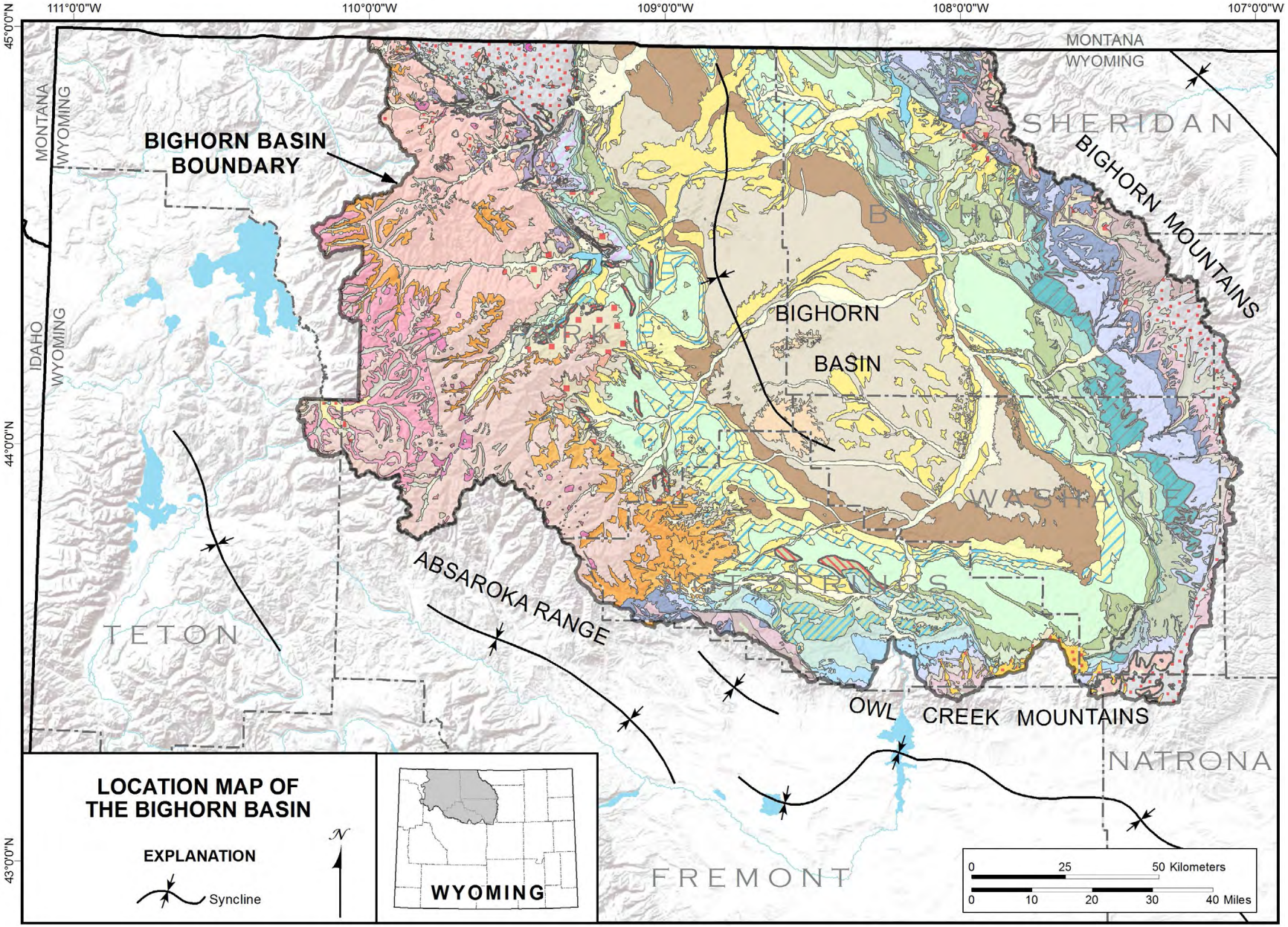


Figure 7-1. Location map of the Bighorn Basin. The Bighorn Basin is defined by the Big Horn River 4-digit hydrologic unit.

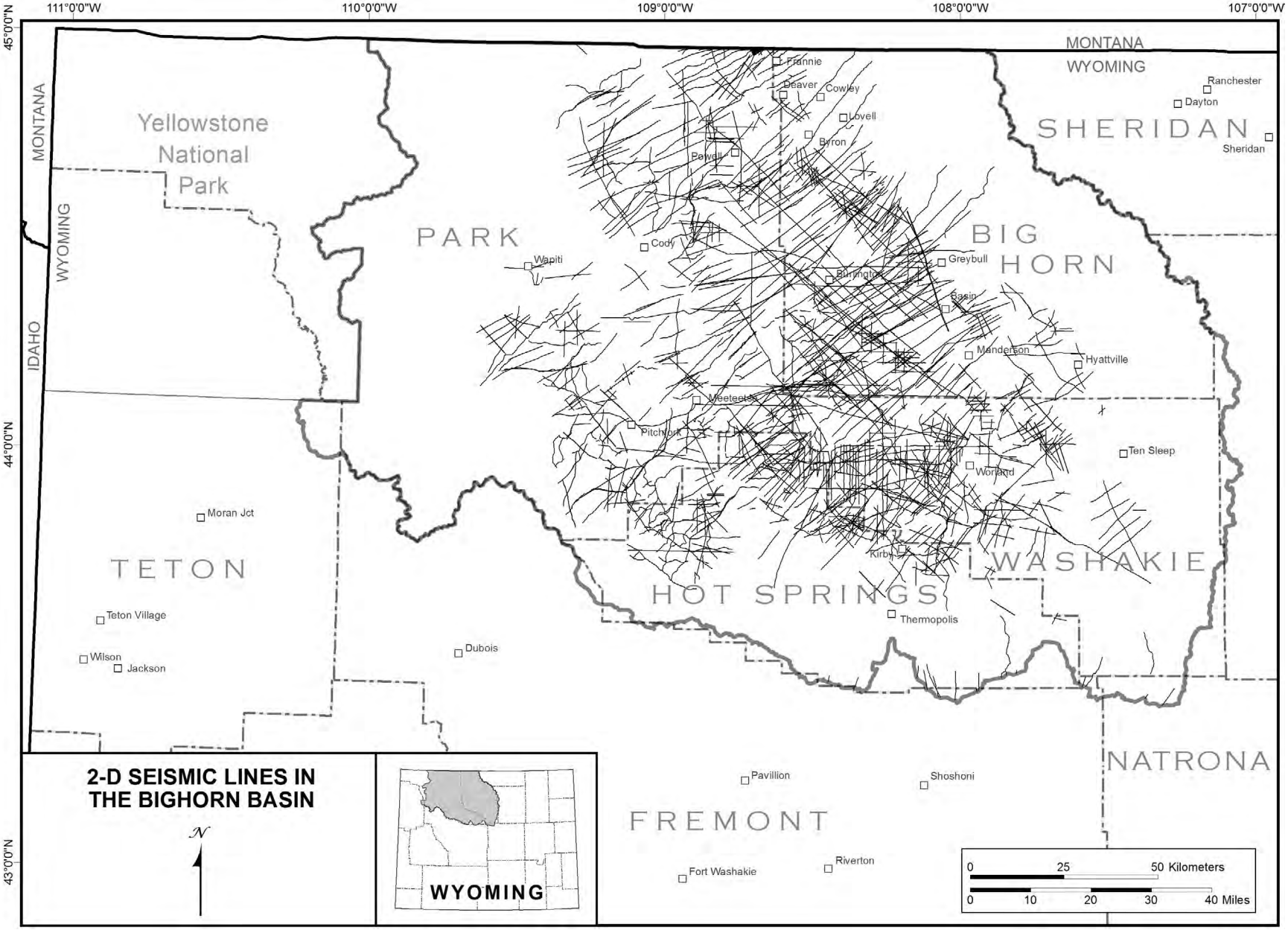


Figure 7-2. Map showing the location of 2-D seismic lines in the Bighorn Basin. The line locations were provided by and are available for purchase from Seismic Exchange, Inc. (2011).

Storage Zones

The three most prolific oil-producing reservoirs in the Bighorn Basin, in decreasing volumes of produced oil, are the Pennsylvanian Tensleep Sandstone, the Permian Phosphoria Formation, and the Mississippian Madison Limestone. Additional producing reservoirs, which range in age from Late Cretaceous to Cambrian, are the Mesaverde, Frontier, Muddy, Cloverly/Dakota/Lakota, Crow Mountain/Chugwater, Dinwoody, Amsden, Jefferson/Darby, Bighorn, and Flathead formations (Plates 1 and 12). The primary producing formations are also the most promising reservoirs for CO_2 storage. Each reservoir is associated with an overlying seal. Although the sealing formation as well as the character of the seal can vary among fields, the primary formations that seal hydrocarbons include the Middle Jurassic Gypsum Spring Formation and the Permian and Triassic Dinwoody Formation.

The following sections summarize the geologic history and reservoir properties of the Crow Mountain Sandstone (included due to high porosity and permeability estimates), Tensleep Sandstone, Phosphoria Formation, and Madison Limestone. These formations have the highest potential for long-term storage of CO_2, as assessed from production history, depth within the basin, and permeability.

Crow Mountain Sandstone

The thickness of the Crow Mountain Sandstone in the Bighorn Basin ranges from 0–53 m (0–175 feet). The basal Crow Mountain is the best reservoir rock, with oil field porosities varying from 14–24 percent and permeabilities from 18–112 millidarcies. Pay thicknesses range 0.6–20 m (2–66 feet), and average 11 m (35 feet).

Production from the Crow Mountain Sandstone occurs in the southern Bighorn Basin in Grass Creek field (Plate 3). The producing zone in the sand is 8 m (25 feet) thick, with a porosity of 17 percent, and a permeability of 120 millidarcies. Initial formation pressure was 1,317 psi (191 kPa), and the sand is continuous over the asymmetric anticlinal structure, which is fault bounded to the southwest. Depth to the Crow Mountain Sandstone in the Grass Creek field ranges from 914–1,069 m (3,000–3,500 feet) (Marathon Oil Company, 1989c).

Water quality in the Crow Mountain Sandstone at Grass Creek field is highly saline. Produced water with a reported resistivity of 0.20 ohm-m at 68° F (20° C) indicates a TDS concentration of around 35,000 ppm. This figure is derived from Schlumberger's chart of resistivity of NaCl solutions (GEN-5H). Other water analyses on record with the Wyoming Oil and Gas Conservation Commission indicate water with a TDS of 14,000 ppm. A sample taken at Cottonwood Creek field near Worland (Plate 3) measured a TDS of 12,000 ppm.

Phosphoria Formation

The Phosphoria Formation is or has been productive in at least 56 fields within the Bighorn Basin. Production from this formation is unique within the Paleozoic section in the basin because it produces from both structural and stratigraphic traps. Stratigraphy influences the trapping mechanisms of at least 16 Phosphoria producing fields (Stone, 1967), the most significant being Cottonwood Creek field (Plate 3).

Only a small portion of the Phosphoria, the Ervay Member at the top, generally has good reservoir characteristics. The Phosphoria pay-zone in the basin ranges from 3–23 m (10–75 feet) thick, averaging about 6 m (20 feet) thick. Porosity values are less than 10 percent and permeability is less than 10 millidarcies. Fractures are important and usually required for commercial production, especially in the lower part of the formation.

Tensleep Sandstone

The Tensleep Sandstone thickens from about 15 m (50 feet) in the northern Bighorn Basin to about 91 m (300 feet) in the southern part of the basin (Fig. 7-3). It is underlain by the Pennsylvanian Amsden Formation and overlain by the Permian Phosphoria Formation in the west. In the eastern part of the basin, the Tensleep is overlain by the nonreservoir Triassic/Permian Goose Egg Formation red shales and evaporites. Todd (1964) describes the Tensleep Sandstone as a "white, weathering dun, hard-friable, massive to cross-bedded, quartz and carbonate-cemented, moderately to well-sorted, fine- to very

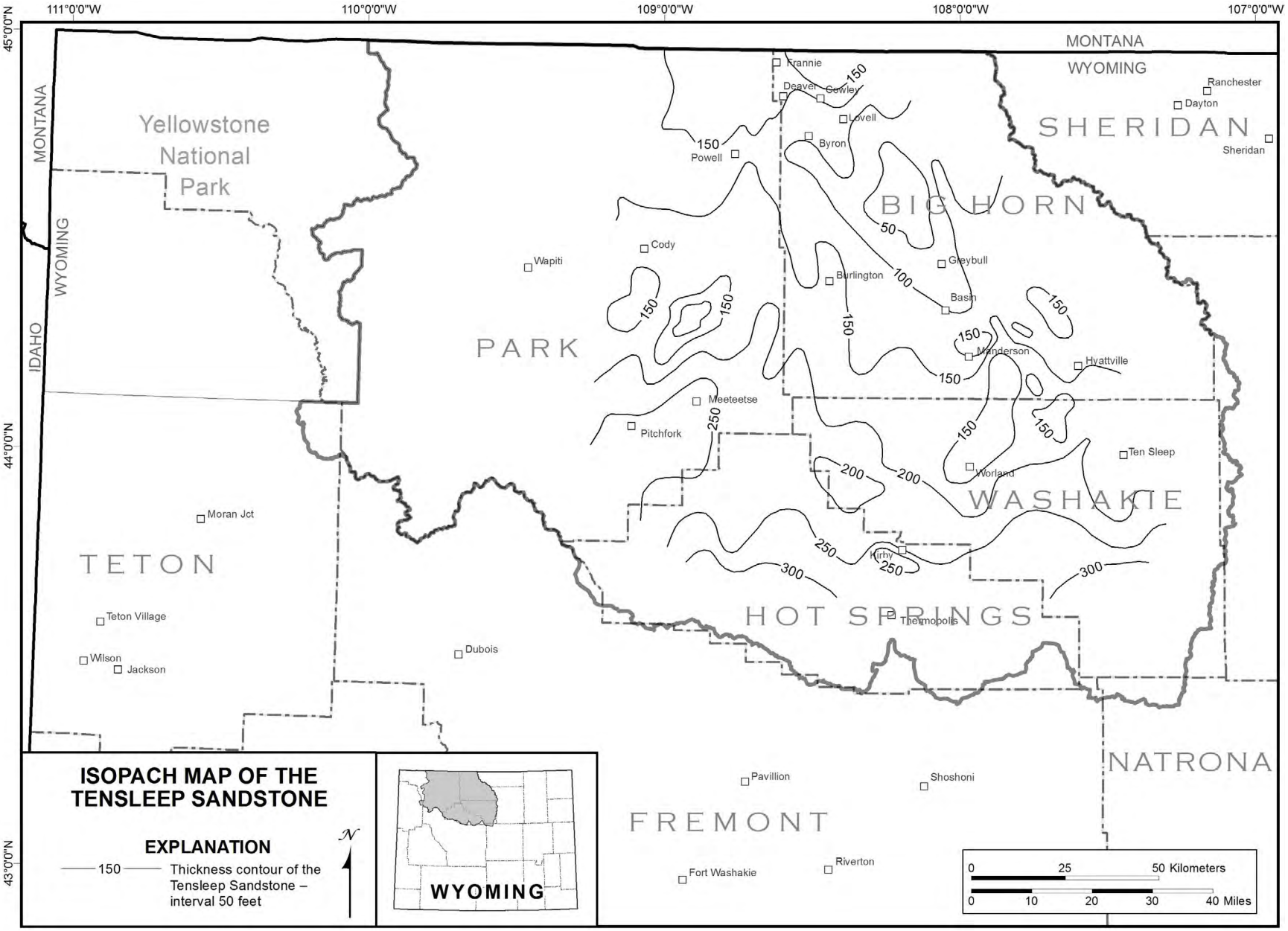


Figure 7-3. Isopach map of the Tensleep Sandstone in the Bighorn Basin. Contour interval is 50 feet (15 m). Modified from Lawson and Smith (1966).

fine-grained orthoquartzite." Interbeds of dolomite and dolomitic sandstone are common, especially in the lower part. Stone (1967) notes the occurrence of pink carbonate lentils below the lower Tensleep, which show up as characteristically higher and variable resistivity values on electric logs, forming a basis for selecting a Tensleep/Amsden contact in the subsurface (Plate 12).

Diagenesis significantly influenced subsequent hydrocarbon accumulation and trapping. Mankiewicz and Steidtmann (1979) postulate that Late Pennsylvanian and Triassic cementing events (dolomitization) serve as lateral controls on the Tensleep reservoirs in several of the major fields. In addition, reservoir compartmentalization exists in many of these major fields due to faulting and fracturing perpendicular to structural axes.

Lawson and Smith (1966) state that Tensleep reservoirs in established producing areas have an average pay thickness of 36 m (118 feet); porosity ranges 5–27 percent, with an average of 13 percent; and permeabilities range from effectively zero to more than 800 millidarcies, with an average of 120 millidarcies. Oil gravity ranges 14–58.5° API, and averages 26.2°. Crude oil produced from Tensleep reservoirs is brownish-green and varies in sulfur content. Porosity data from the major producing fields show an apparent decrease in porosity with increased depth to reservoir. In fields shallower than 2,438 m (8,000 feet), average porosity ranges from 24 percent (Bonanza field) to 9.7 percent (Fourbear field) (Plate 3). Fields with Tensleep reservoirs at depths greater than 2,438 m (8,000 feet) have porosities ranging from a high of 10 percent to as low as 2 percent in producing reservoirs 3,658–4,267 m (12,000–14,000 feet) deep. This decrease in porosity with depth seems to be related to an increase in secondary cementation. However, there are relatively few deep producing wells and the trend is supported by limited data. The Tensleep ranges in elevation from +1,219 m (+4000 feet) above sea level to -3,810 m (-12,500 feet) below sea level in the basin center (Plate 11).

Madison Limestone

The Madison Limestone, predominantly dolomite with characteristic limestone interbeds, thins from more than 274 m (900 feet) at Elk Basin field and 244 m (800 feet) near Sage Creek field (Plate 3) in the northern Bighorn Basin, to less than 152 m (500 feet) in the southern Bighorn Basin (Mills, 1956). The thinning results from onlap at the base and erosion at the top (Stone, 1967). Sando and Bamber (1985) divide the Madison Limestone into an upper and lower sequence, referred to as the Mission Canyon Member and the Lodgepole Member in the Bighorn Basin, respectively.

The Madison carbonates are usually massive and can be highly porous. The Madison is gray to buff or brown, finely crystalline or saccharoidal, and often contains chert. A thin-bedded limestone and dolomite unit with interbedded tight sandstone and variegated shale occurs near the top of the section (Stone, 1967). Sixteen of the larger fields in the Bighorn Basin produce from the Madison Limestone.

McCaleb and Wayhan (1969) note that the Madison reservoir in Elk Basin field (Plate 3) has been greatly affected by groundwater action, which produced the karst topography and cavernous zones, subsequent brecciation in Late Mississippian and Early Pennsylvanian time, and dolomitization by recrystallization of calcite to dolomite. Groundwater action removed the more-soluble limestone but left the less-soluble dolomite, forming good secondary porosity in the Madison reservoir. These secondary porosity zones can be correlated and subdivided into readily recognizable, distinct zones. Porosity within the various producing zones in the Madison reservoir in Elk Basin field ranges from 10 percent in a lower producing zone to 13.6 percent in the uppermost zone. Permeability ranges from a low of 3 millidarcies in two of the lower zones to 368 millidarcies in one of the upper zones (McCaleb and Wayhan, 1969). Generally, the upper zones are medium-grained dolomites exhibiting better porosity and permeability than the lower zones, which are fine to microcrystalline dolomite. Average pay thickness within the Madison Limestone is 15–62 m (50–205 feet), and oil gravity ranges 14–28° API throughout the Bighorn Basin.

Electric log and core evaluation of other fields in the basin producing from the Madison reservoir

indicate reservoirs similar to that noted for Elk Basin field. However, most of the other fields do not show the same degree of porosity development. As noted for the upper Tensleep reservoir, the Madison reservoir proves to be quite heterogeneous with complex lateral and vertical variations.

Confining Zones

There are two formations in the Bighorn Basin that are proven seals for hydrocarbon systems: the Jurassic Gypsum Spring Formation, and the Permian and Triassic Dinwoody Formation.

Gypsum Spring Formation

In the Bighorn Basin, the Gypsum Spring Formation consists of a lower, middle, and upper unit (Bullock and Wilson, 1969). The lower unit contains gypsum and red shale and ranges in thickness 5–30 m (15–100 feet). The middle unit is 24 m (80 feet) of intercalated shale, limestone, and minor gypsum, overlain by a 21-m (70-foot) thick upper unit consisting primarily of gypsum (Bullock and Wilson, 1969). The gypsum beds within the Gypsum Spring Formation are the likely sealing lithology.

Dinwoody Formation

In the Bighorn Basin, the basal contact of the Dinwoody Formation is an unconformity with the Permian Phosphoria Formation; the upper contact is conformable with the overlying Chugwater Group. The Dinwoody Formation grades laterally eastward into the upper parts of the Goose Egg Formation. The Dinwoody Formation is thin; 0–3 m (0–10 feet) are reported from outcrops (Partridge, 1949) and less than 15 m (50 feet) is interpreted in the subsurface (Plate 12).

Results

This assessment takes advantage of the U.S. Geological Survey's recently published study of CO_2 storage formations in the Bighorn Basin (Covault and others, 2012). Covault and others (2012) identify the map extent of potential storage formations between the depths of 914 and 3,962 m (3,000 and 13,000 feet). Depths greater than 3,962 m (13,000 feet) were also assessed by Covault and others (2012) but are not considered for this study. Carbon dioxide storage assessment units C50340101 (Tensleep Sandstone), C50340103 (Ervay Member of the Phosphoria Formation), and C50340105 (Crow Mountain Sandstone), defined by Covault and others (2012), were clipped to the hydrologic boundary of the Bighorn Basin and the boundary of the State of Wyoming in ArcGIS (Fig. 7-4). A_t was determined from the resulting storage assessment unit boundary. This study also includes the Madison Limestone, which was not assessed by Covault and others (2012), likely due to the prevalence of reservoir fractures. For this study fractures in the Madison Limestone were disregarded because they are not well constrained. The map extent and area of the Madison Limestone are similar to the Tensleep Sandstone and the same value is used for both formations. Maximum and minimum formation thickness and porosity for the Tensleep, Phosphoria, and Crow Mountain were obtained from Covault and others (2012). Thickness and porosity for the Madison Limestone was determined from Mills (1956) and Cardinal and others (1989), respectively. The total area, maximum and minimum total porosity, and maximum and minimum gross formation thickness are summarized in Table 7-1. The mean value for each parameter is calculated from the minimum and maximum values.

Theoretical maximum and minimum estimates of the CO_2 storage resource (mass) for saline aquifers, by formation, were calculated using the parameters in Table 7-1, for the aforementioned assumptions. Similar to the maximum and minimum variable estimates, the average estimates for each variable are used to calculate an average S_{basin} (is not aver-

Table 7-1. Input values used in the estimation of CO_2 storage capacity of saline aquifers.

Formation	A_t (km^2)	h_g min (m)	h_g max (m)	ϕ_{tot} min (%)	ϕ_{tot} max (%)
Crow Mountain	9,007	3	53	5	22
Phosphoria	9,403	6	85	2	24
Tensleep	10,870	30	91	4	15
Madison	10,870	152	274	9	18

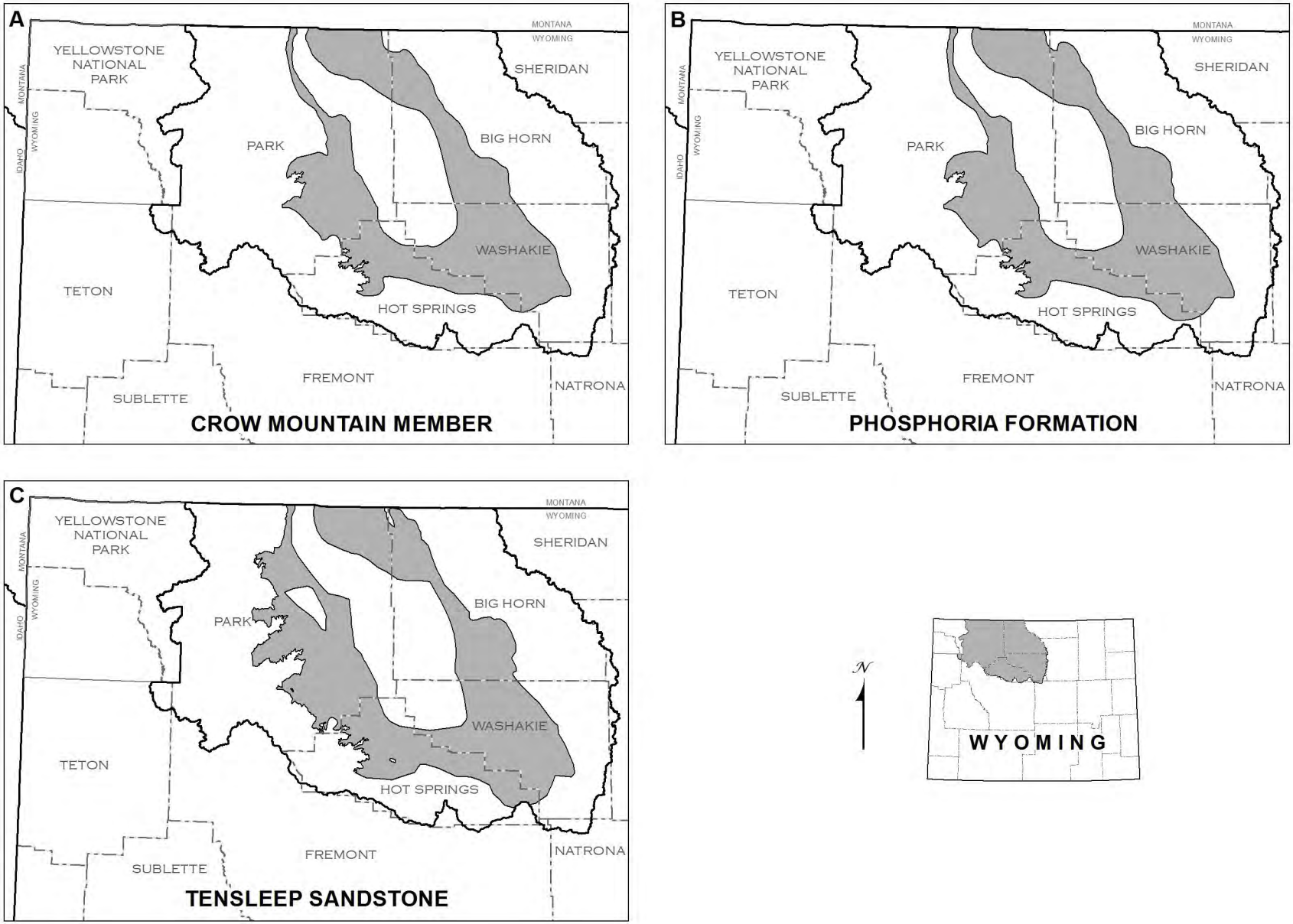


Figure 7-4. Total formation area (A_t) of the **A.** Crow Mountain Member of the Chugwater Formation (Curtis), **B.** the Phosphoria Formation, and **C.** the Tensleep Sandstone, summarized in Table 7-1. Data modified from the carbon dioxide storage assessment units defined by Covault and others (2012).

aged, instead the input variables are averaged). The results are summarized in Table 7-2. These calculations suggest the potential for an average of nearly 6.3 billion metric tons (6.9 billion short tons) of CO_2 storage in the saline aquifers of the Bighorn Basin. These results are estimates that require significant assumptions and should not be used without acknowledging and incorporating the associated assumptions.

Table 7-2. Mass of CO_2 that can theoretically be stored in saline aquifers in the Bighorn Basin. Calculations follow Equation 4-1. Lithologies were used to determine E_{basin}; ss represents sandstone and dol represents dolomite.

	S_{basin} (million metric tons)		
Reservoir	minimum	average	maximum
Crow Mountain (ss)	4.4	431	3,584
Phosphoria (dol)	4.6	772	6,652
Tensleep (ss)	42	791	5,056
Madison (dol)	599	4,278	18,230
Total	**651**	**6,271**	**33,523**

Storage in Petroleum Reservoirs

Hydrocarbon Exploration and Production

Oil was discovered as a spring on the Bonanza anticline in the Bighorn Basin in 1904 (Hares, 1947). In 1905, the first producing oil well in the basin was drilled into the Tensleep Sandstone in the Bonanza field (Plate 3). Since these initial discoveries, cumulative production in the Bighorn Basin, from initial discovery through 2011, amounts to more than 3.7 billion barrels of oil (Wyoming Oil and Gas Conservation Commission, 2012).

The Bighorn Basin is primarily an oil-producing basin, and contains 134 fields that produce (or have produced) from 60 reservoirs and/or co-mingled reservoirs (Plate 3) ranging in age from Cambrian to Paleocene. Over 75 percent of produced oil in the basin is from the eight largest fields (Appendix C). In terms of cumulative production, nine fields within the Bighorn Basin are in the top 25 producing fields in Wyoming. Seven of these rank in the top 10 (Wyoming Enhanced Oil Recovery Institute, 2011). In 2011, the Bighorn Basin produced 22 percent of Wyoming's oil (Wyoming Oil and Gas Conservation Commission, 2012), yet oil production in the Bighorn Basin has steadily declined over the past 35 years (Fig. 7-5).

Fox and Dolton (1996a) defined the types of plays prevalent in the Bighorn Basin and suggested some potential plays for future development as part of a resource assessment of the basin. Both structural and stratigraphic traps occur in Paleozoic and Cretaceous source-rock/reservoir systems in the basin. Structural plays include basin margin subthrusts, basin margin anticlines, deep basin structures, and sub-Absaroka volcanic plays. Principal stratigraphic plays include Phosphoria pinch-out (up-dip facies change) and Tensleep paleogeography (dune fields versus interdune regions) (Fox and Dolton, 1996a).

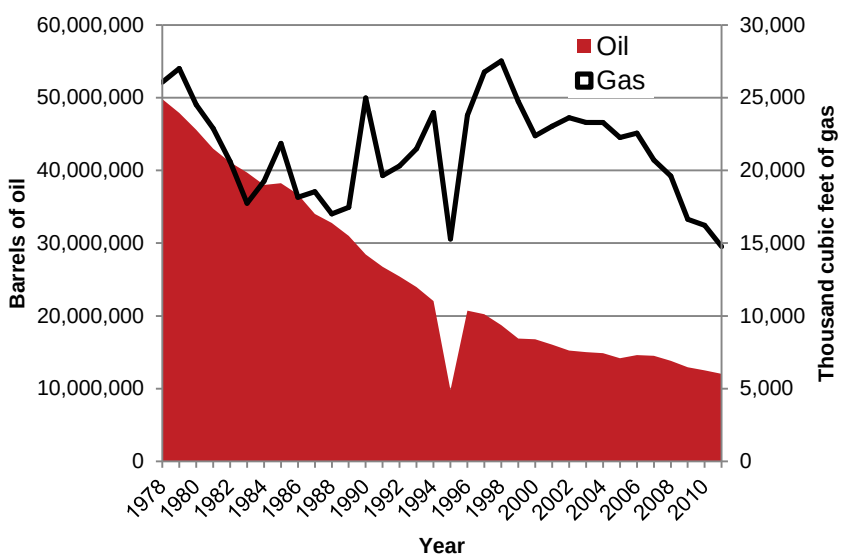


Figure 7-5. Oil and gas production for all fields in the Bighorn Basin, from 1978 through 2010. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

Significant potential plays include basin center/deep gas and coalbed natural gas.

Although most of the basin's production comes from anticlinal or other structural traps, Lawson and Smith (1966) suggest that many of the structurally controlled traps are influenced by stratigraphic effects, including intraformational variations in permeability and, as in the Bonanza-Nowood field, incised channels in the Tensleep surface that were later filled with impervious Goose Egg sediments. Later Laramide folding may have been superimposed on or near these primary traps. Pure stratigraphic traps are also productive within the Bighorn Basin. The largest of these is the Cottonwood Creek field in the southeast corner of the basin (Plate 3), a trap resulting from an eastward, up-dip facies change from Phosphoria carbonate to the impermeable red shale and anhydrite facies of the Goose Egg Formation (Plate 1).

The source of essentially all the oil and gas found in Paleozoic reservoirs in the basin is the dark, phosphatic, fine-grained, marine facies of the Phosphoria Formation (Stone, 1967). Primary migration began immediately after deposition of Triassic sediments and was completed by Early Jurassic time. Hydrocarbons accumulated in regional stratigraphic traps created by up-dip facies change, pinch-out, truncation of the reservoir rocks in the Phosphoria, and irregular truncation of thick Tensleep Sandstone beds prior to the deposition of the impervious Phosphoria/Goose Egg Formation. This situation is especially prevalent east of the area covered by marine carbonate facies of the Phosphoria Formation (Stone, 1967). Oil and gas in some of these stratigraphic traps were later released by fracturing and faulting associated with Laramide folding. During the Laramide orogeny, these hydrocarbons moved into older Paleozoic reservoir rocks and older structures where they were trapped in common pools. The occurrence of a common oil-water contact, in many cases, is attributed to fractures joining the reservoirs. Also, the oil-water contact is commonly tilted as a result of hydrodynamic flow (Stone, 1967).

Mesozoic rocks produce a much lower percentage of the basin's oil and gas. The Upper Cretaceous Frontier Formation (Plate 1) accounts for most of the production from Mesozoic rocks. Source rocks in the Mesozoic include the Cody, Frontier, Mowry, and Thermopolis black shale units (Stone, 1967).

As mentioned, oil and gas production in the Bighorn Basin has steadily declined over the last 35 years (Fig. 7-5). Most fields still hold a significant quantity of recoverable oil. In response, energy extraction companies are utilizing new and traditional secondary and tertiary recovery techniques to revitalize old fields and to activate fields that were not economically feasible in years past. Future oil production in the Bighorn Basin will heavily rely on these recovery techniques.

Hydrocarbon Fields with CO_2 Storage Potential

The Bighorn Basin hosts numerous hydrocarbon fields of various sizes. The largest producing fields hold the most potential for CO_2 storage, presuming they meet specific depth, pressure, and seal criteria. Production for the eight largest oil-producing fields within the Bighorn Basin is summarized in Appendix C. All eight fields have cumulative oil production greater than 100 million barrels. Secondary production through water flooding is standard in these fields. The following pages summarize field statistics for the eight fields, in order of decreasing production volumes. Production data for the fields were retrieved from the Wyoming Oil and Gas Conservation Commission (2012); all other field data were retrieved from the Wyoming Geological Association symposium on the Bighorn and Wind River basins (Cardinal and others, 1989). The available data were not determined consistently (e.g., porosity values were determined from core and log data; pressures were reported in a variety of ways such as drill stem tests, rock pressures, shut-in tubing pressures, etc.). Whenever possible, the data type/acquisition method is denoted by a superscript listed below:

w = wellhead pressure
R = rock pressure
DST = drill stem test
SIP = shut-in pressure
SITP = shut-in tubing pressure
SDST = shut-in pressure, drill stem test
FSIP = formation shut in pressure

l = calculated from log
c = measured from core

Rock type abbreviations are as follows:

ss = sandstone
ls = limestone
dol = dolostone

Rw represents water resistivity and an em dash (—) is used to denote unavailable data.

Oregon Basin Field

The Oregon Basin field (North Dome and South Dome) is located on the western edge of the Bighorn Basin just southeast of Cody (Plate 3). These north–south-trending anticlinal traps (Fig. 7-7) produce from a number of formations, which are, from youngest to oldest, the Frontier, Cloverly, Chugwater, Phosphoria, Tensleep, Madison, Gros Ventre, and Flathead (Marathon Oil Company, 1989d) (Table 7-3). Initial production in the Oregon Basin field was from the Cloverly, discovered in 1912. Total production from the Oregon Basin field through 2011 was nearly 480 million barrels of oil (Fig. 7-6).

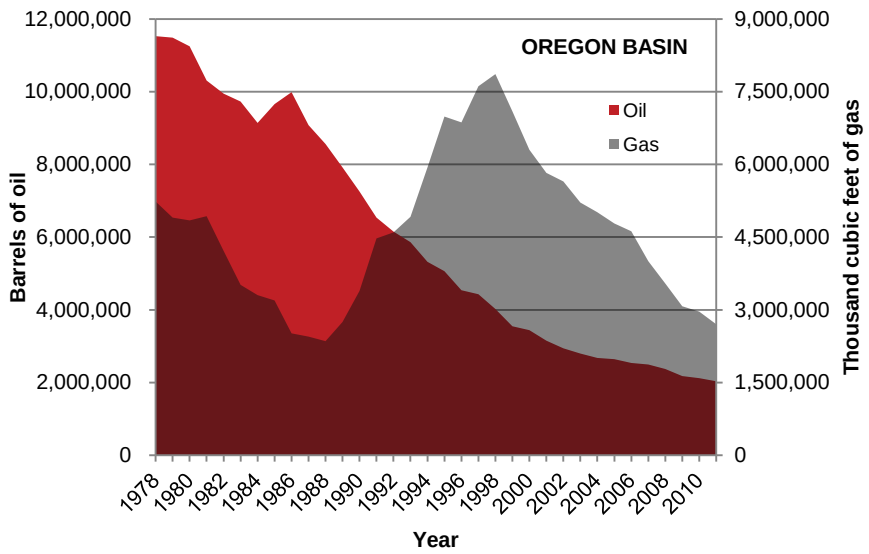


Figure 7-6. Oregon Basin field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

Table 7-3. Oregon Basin field statistics, from Marathon Oil Company (1989d).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
North Dome							
Frontier	ss	24[l]	—	10	520[R]	2.5	gas
Cloverly	ss	23[l]	—	15	680[w]	2.2	gas
Chugwater	ss	13[c]	5[c]	25	1,850[w]	—	gas
Phosphoria	dol	20.2[c]	68[c]	38	1,430	1.23	23.2
Tensleep	ss	14.7[c]	193[c]	83	1,471	1.45	23
Madison	ls, dol	13[c]	6.3[c]	50	1,650	2.2	22
Gros Ventre	ss	3[l]	—	55	—	—	—
Flathead	ss	12.5[c]	20[c]	61	1,770[w], 2,510[SDST]	1.7	—
South Dome							
Frontier	ss	24[l]	—	10	520[R]	2.5	gas
Cloverly	ss	23[l]	—	15	500[R]	2.2	gas
Chugwater	ss	13[c]	5	20	949[SIP]	0.18	—
Phosphoria	dol	16[c]	45[c]	30	1,524	1.03	20.8
Tensleep	ss	14[c]	90[c]	60	1,560	1.04	21
Madison	ls, dol	13[c]	6[c]	120	1,650	2.36	18.6
Gros Ventre	ss	15[l]	—	20	1,825[SITP], 2,790[SDST]	1.2	67
Flathead	ss	12.5[c]	20[c]	50	2,405[SDST]	0.38	67

[1]This is the initial pressure value as reported by Marathon Oil Company (1989d). Attempts to verify this value with the Wyoming Oil and Gas Conservation Commission (2012) were unsuccessful.

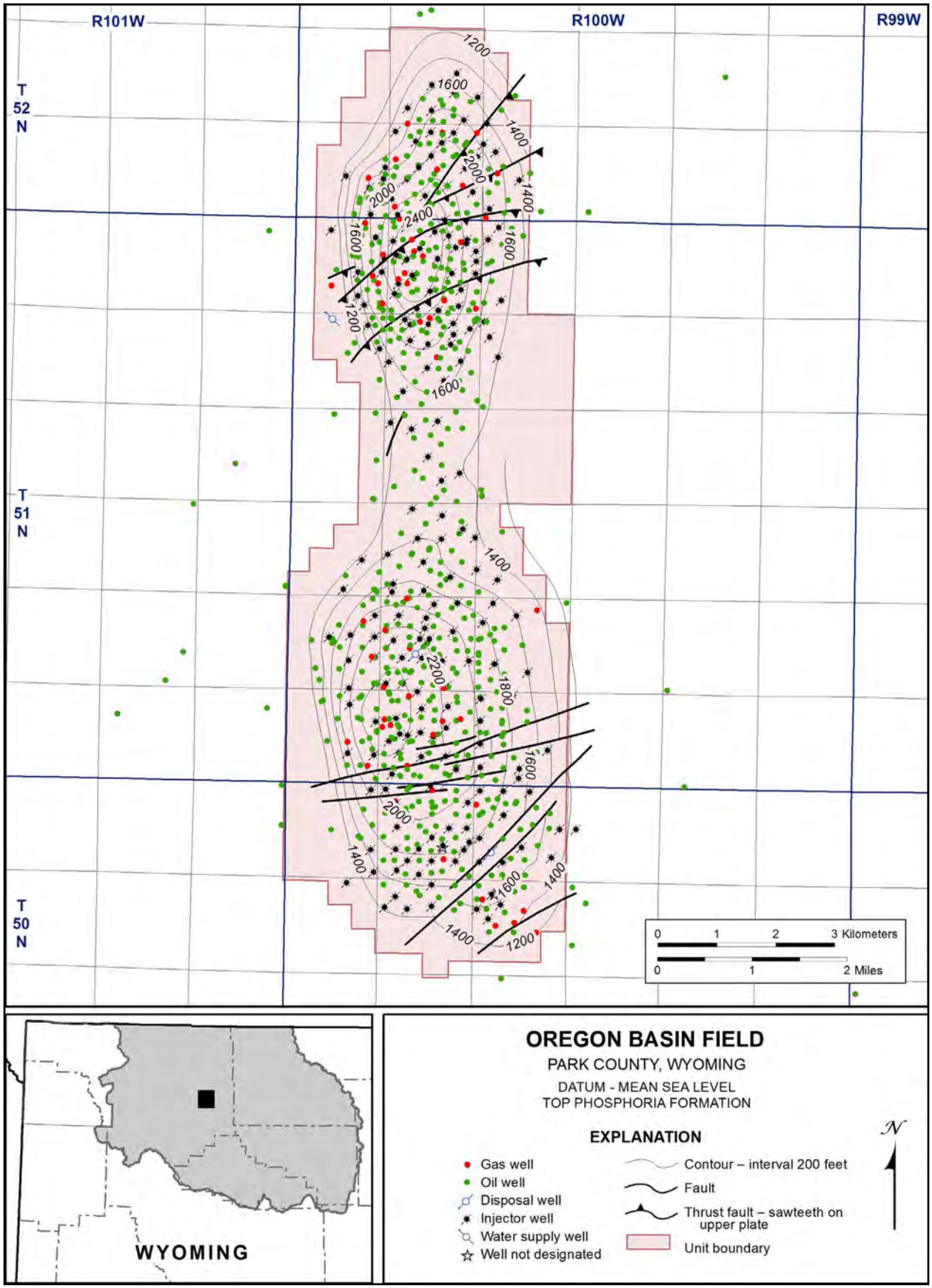


Figure 7-7. Oregon Basin field structure-contour map, modified from Marathon Oil Company (1989d). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Elk Basin Field

The Elk Basin field is located on the Wyoming–Montana border, just west of the axis of the Bighorn Basin (Plate 3). Oil from this northwest–southeast-trending asymmetrical anticline (Fig. 7-9) was discovered in 1915 in the Frontier Formation (Wehrle, 1989a). Elk Basin's most productive reservoir is the commingled Phosphoria and Tensleep. Reservoirs in several other formations also produce in the Elk Basin field, including the Frontier, Cloverly, Darwin, Madison, Jefferson, and Bighorn (Table 7-4). Cumulative production through 2011 was greater than 472 million barrels of oil (Fig. 7-8).

Table 7-4. Elk Basin field statistics, from Wehrle (1989a).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	23[c]	118[c]	60	500–600	0.78	43
Cloverly	ss	20[l]	—	45	1,249	0.9	gas
Phosphoria	ss, ls	9[c]	60[c]	166	2,234	0.95	29–30
Darwin/Madison	ss, ls	9[c]	7[c]	205	1,054	2	28
Jefferson/Bighorn	dol	9[c]	4[c]	100	2,160	3	28

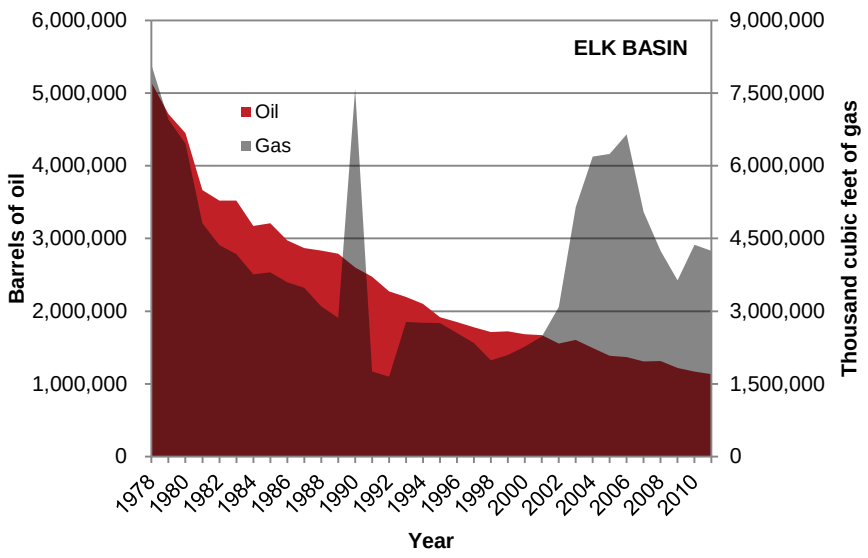


Figure 7-8. Elk Basin field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

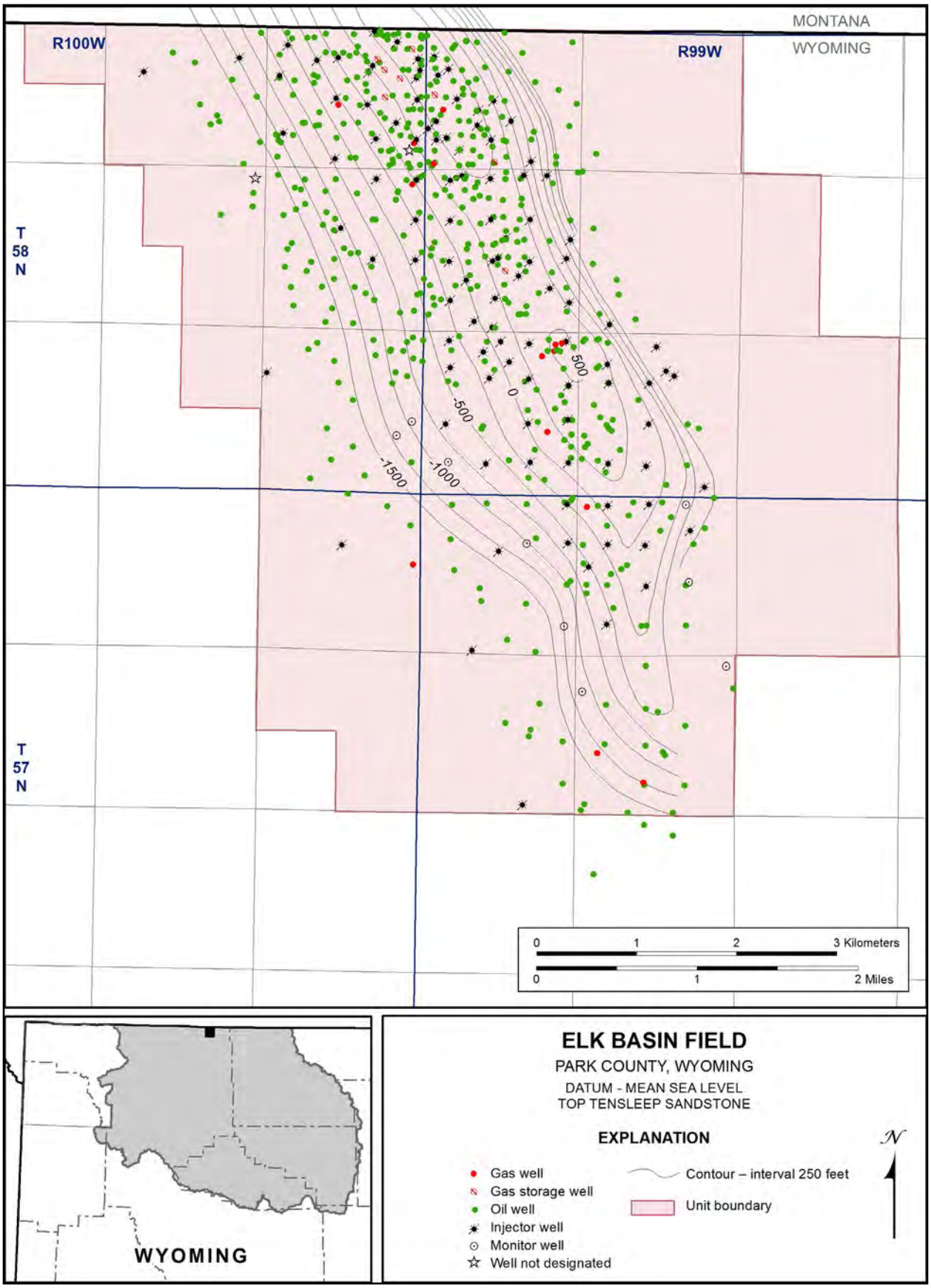


Figure 7-9. Elk Basin field structure-contour map, modified from Wehrle (1989a). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Hamilton Dome Field

The Hamilton Dome field is a faulted, northwest–southeast-trending anticlinal trap located in the south-central Bighorn Basin (Frerichs, 1982; Chapman, 1989) (Plate 3; Fig. 7-11). Oil production began in 1918 with the discovery of oil in the Crow Mountain ("Curtis") Sandstone (Chapman, 1989). Current and historic production is from the Crow Mountain, Muddy, Phosphoria, Tensleep, Amsden, Madison, and Bighorn formations (Table 7-5), with total production through 2011 at more than 268 million barrels of oil (Fig. 7-10).

Table 7-5. Hamilton Dome field statistics, from Chapman (1989).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Crow Mountain	ss	15	40	15	500	0.25–0.4	20.2–22.7
Muddy	ss	—	—	9	30[R]	0.78–1.1	gas
Phosphoria	ls	15	85	31	500	2.2	18.8–26
Tensleep	ss, dol	15	60	184	750	2.2	20.5–22.6
Amsden	ss	13.9	25.9	50	675	1.2	20.1
Madison	ls	16	25	160	980	2.7	14.7
Bighorn	dol	18	50	44	1,020	3.5	14.5

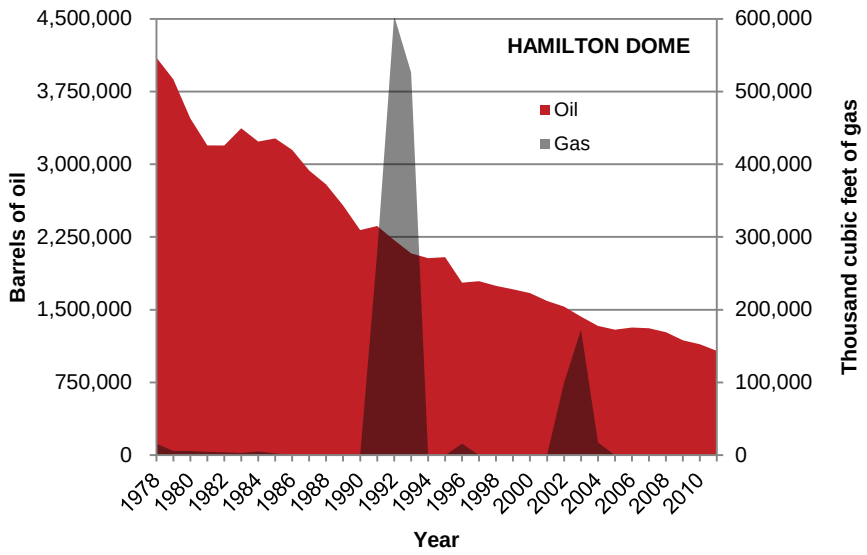


Figure 7-10. Hamilton Dome field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

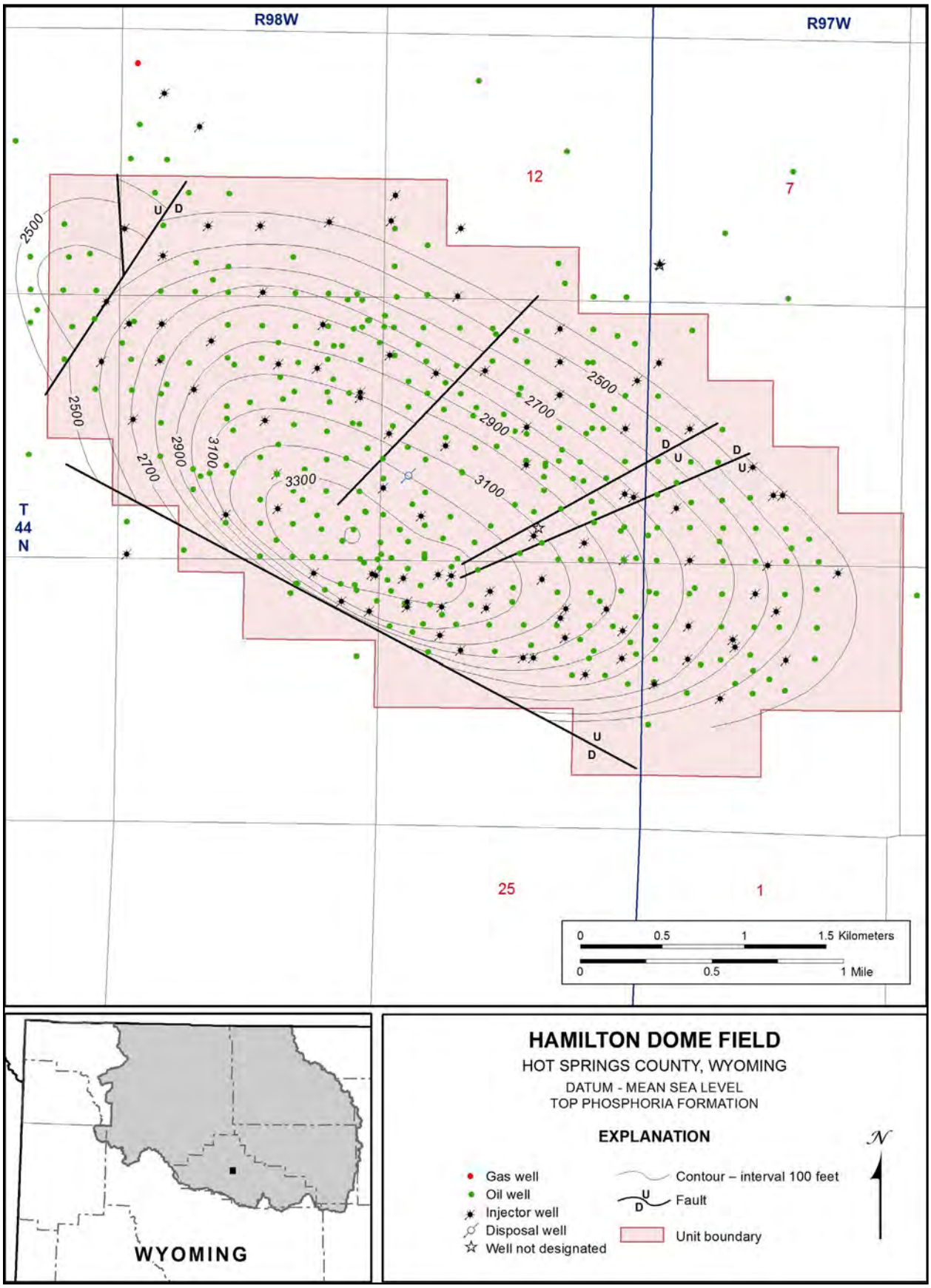


Figure 7-11. Hamilton Dome field structure-contour map, modified from Chapman (1989). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Grass Creek Field

The Grass Creek field is located in the southwestern Bighorn Basin, north of Hamilton Dome (Plate 3). Grass Creek is a fault-bounded, asymmetric, northwest–southeast-trending anticline (Fig. 7-13). The discovery well was completed in the Frontier Formation in 1914 (Marathon Oil Company, 1989c). Production is primarily from the Frontier and Crow Mountain ("Curtis"), with additional production from the Phosphoria and Tensleep (Table 7-6). 2011 cumulative production for the Grass Creek field totaled 215.6 million barrels of oil (Fig. 7-12).

Table 7-6. Grass Creek field statistics, from Marathon Oil Company (1989c).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	21	35	77	400	2.31	44.5
Crow Mountain/ Curtis	ss	17	120	25	1,317	0.2	24.2
Phosphoria	ls	22	20	35	1,300	0.82	24.5
Tensleep	ss	13	112	124	1,300	1.38	24.5

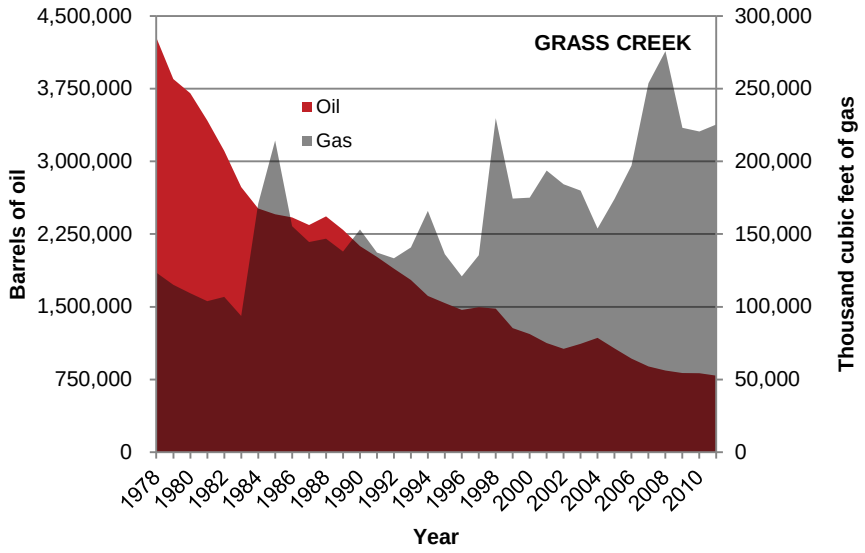


Figure 7-12. Grass Creek field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

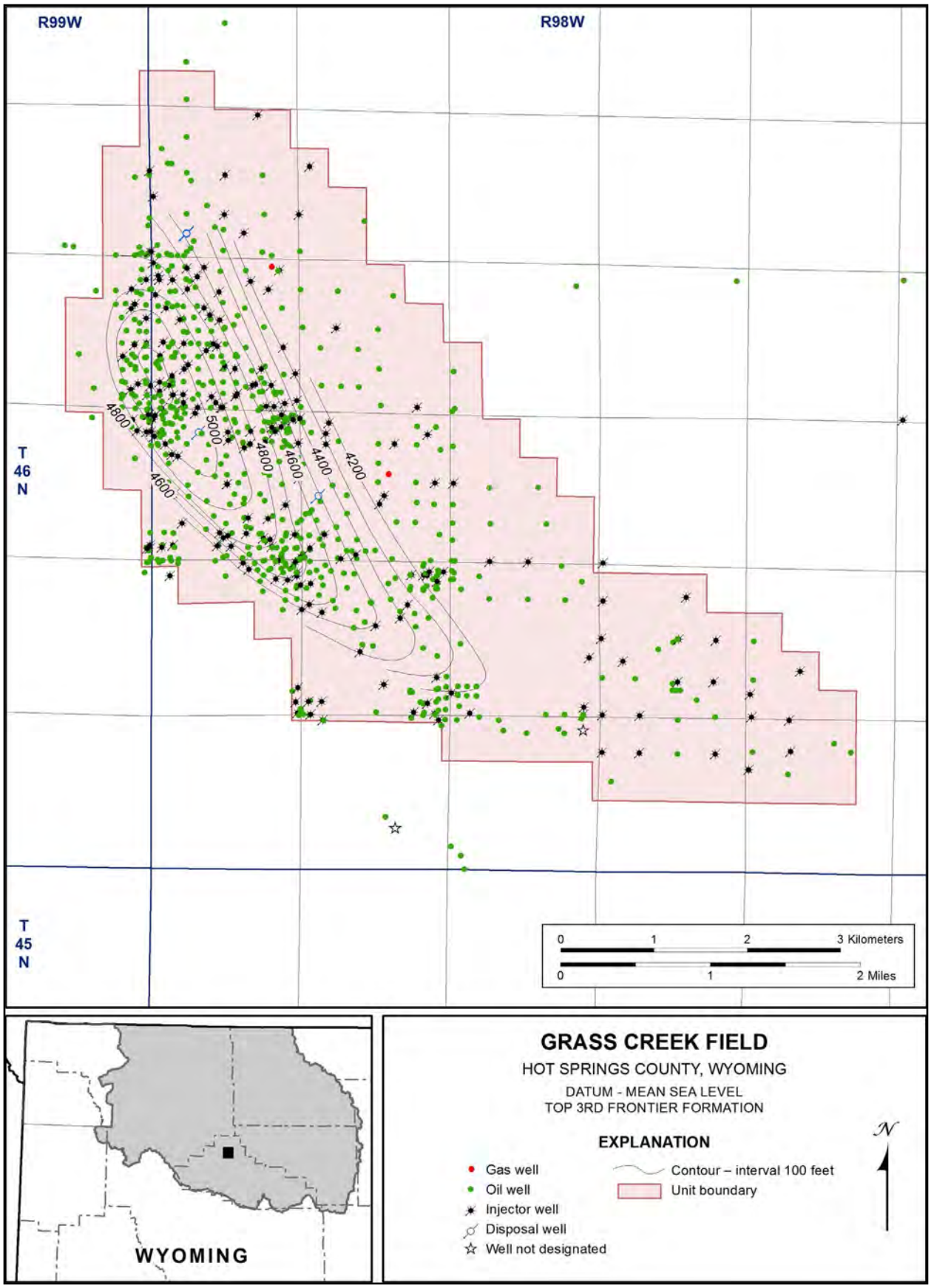


Figure 7-13. Grass Creek field structure-contour map, modified from Marathon Oil Company (1989c). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Garland Field

The Garland field is in the northern Bighorn Basin just northeast of Powell and south of the Montana border (Plate 3). The field is a northwest–southeast-trending asymmetrical anticline with several hinge-perpendicular tear faults (Marathon Oil Company, 1989b) (Fig. 7-15). The Garland field discovery well was completed in 1906. The Madison is the most productive formation in the Garland field. There are, however, a number of other producing formations within the field, including the Frontier, Cloverly, Morrison, Sundance, Chugwater, Phosphoria, Tensleep, Amsden, Darwin, and Jefferson (Table 7-7). Oil production through 2011 was nearly 201 million barrels (Fig. 7-14), and original oil in place is estimated at over 350 million barrels (Koperna and Kuuskraa, 2006). Acid gas disposal into the Madison Limestone is ongoing in the Garland field.

Table 7-7. Garland field statistics, from Marathon Oil Company (1989b).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	22[l]	—	15	—	1.1–1.4	49.2
Cloverly	ss	18.6[c]	25.6[c]	32	—	1.45	52
Morrison	ss	17[c]	268[c]	12	1,373	2.2	31
Sundance	ss	13[c]	20[c]	75	1,479	2.6	30
Chugwater	ss	18	—	5	756[DST]	—	—
Phosphoria	dol	20.1	14	23.5	1,735	2.1	20–24.3
Tensleep	ss	13.3	150, 53	60	1,735	2.69	23
Amsden	dol	10	—	15	—	1.3–3.2	18–22
Darwin	ss	12	—	16	—	1.3–3.2	18–22
Madison	ls, dol	17.7	16.2	84	1,635	2.52	19.8
Jefferson	dol	11.4	—	30	—	0.8–3.2	13–19

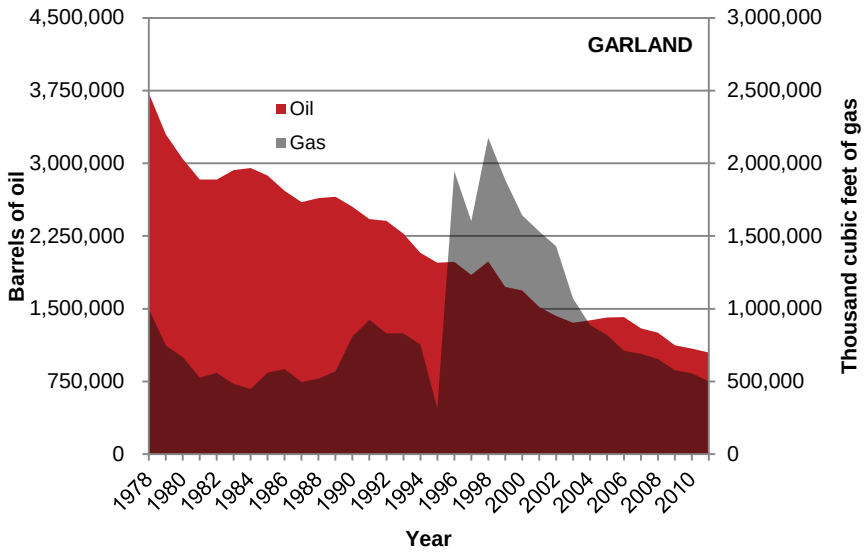


Figure 7-14. Garland field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

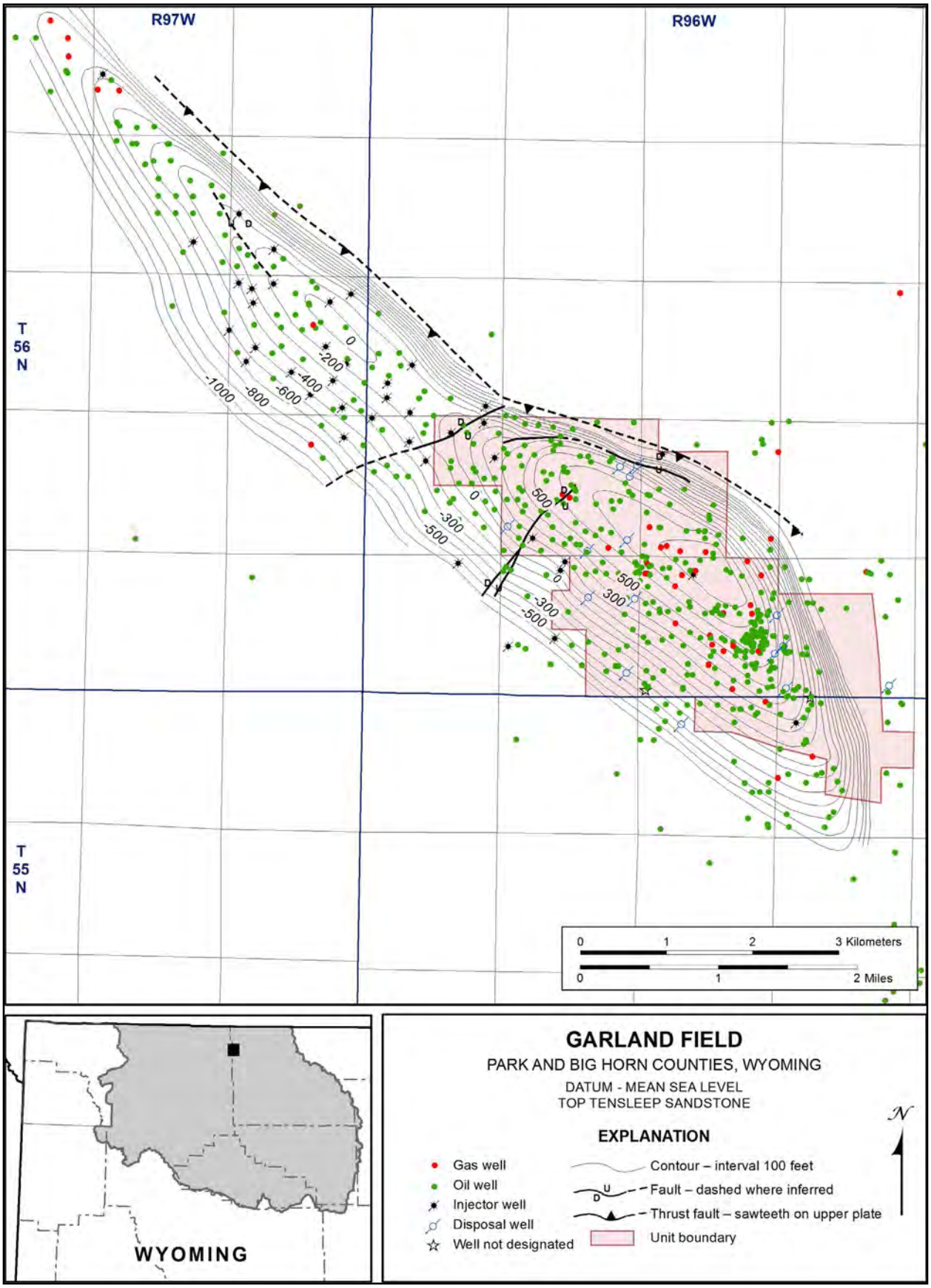


Figure 7-15. Garland field structure-contour map, modified from Marathon Oil Company (1989b). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Little Buffalo Basin Field

Little Buffalo Basin field, in the western Bighorn Basin (Plate 3), is a two-dome anticlinal trap. Each dome trends north–south, and both are cross-cut by axis-oblique reverse faults (Fig. 7-17). Little Buffalo Basin field was discovered in 1914 with initial production from the Frontier Formation (Wehrle, 1989b). The Phosphoria and Tensleep are the primary producers, followed by the Frontier, Muddy, Cloverly, and Darwin formations (Table 7-8). Cumulative production through 2011 was over 139 million barrels of oil (Fig. 7-16).

Table 7-8. Little Buffalo Basin field statistics, from Wehrle (1989b).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	20[c]	47[c]	32	900	1.5–3.9	gas
Muddy	ss	16[c]	8[c]	32	734[SDST]	—	gas
Cloverly	ss	17[c]	—	31	1,200[SDST]	—	gas
Phosphoria	dol	13[c]	9[c]	39	1,560	—	16.1–20.3
Tensleep	ss	13[c]	75[c]	158	1,674	—	16.1–19.6
Darwin	ss	12[c]	3[c]	35	1,617	—	18.7

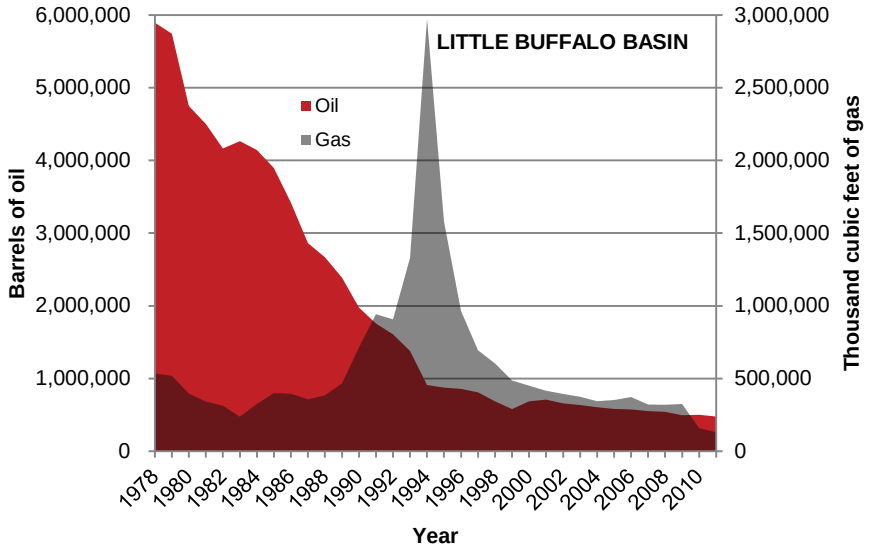


Figure 7-16. Little Buffalo Basin field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

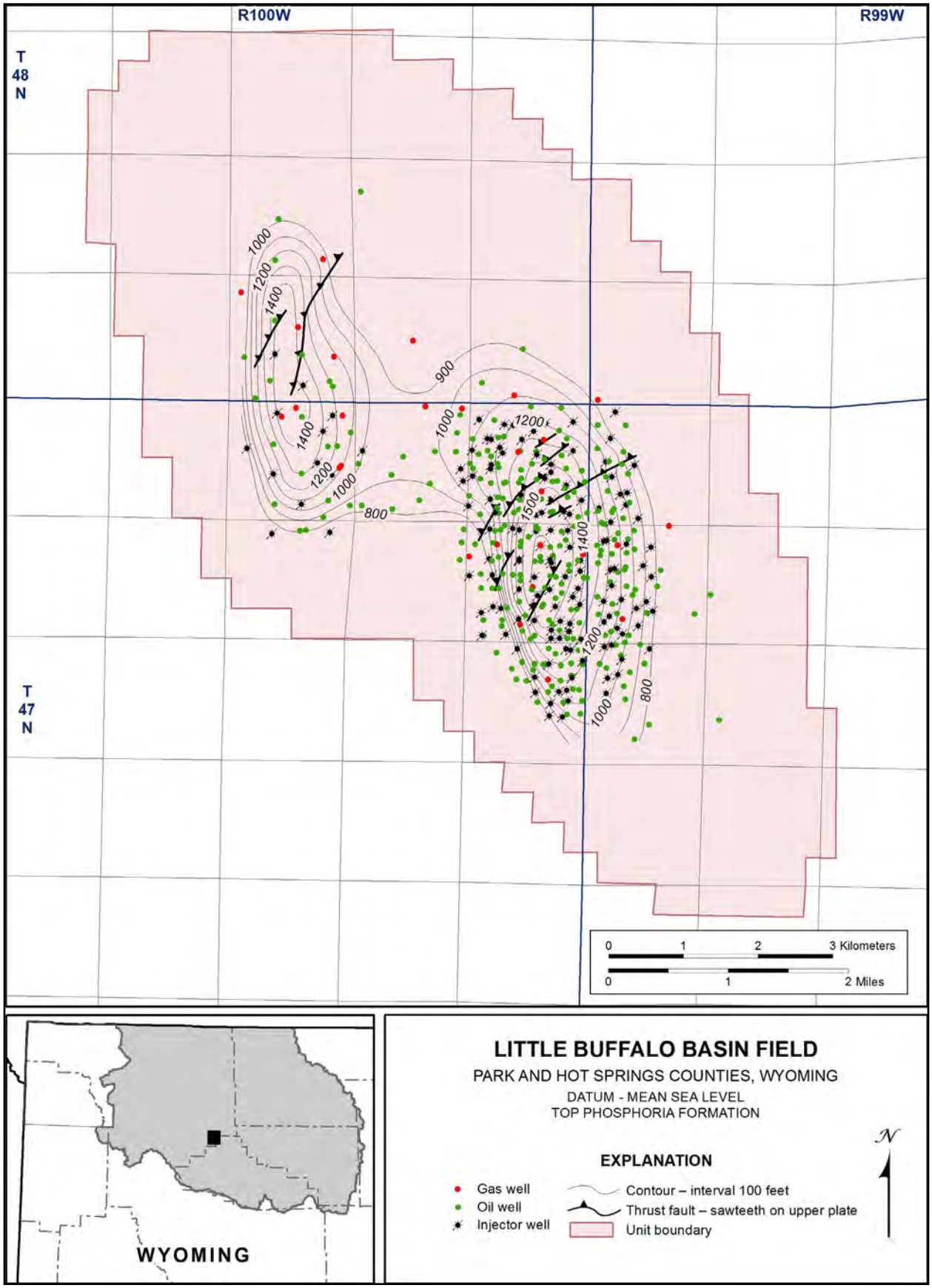


Figure 7-17. Little Buffalo Basin field structure-contour map, modified from Wehrle (1989b). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Byron Field

The Byron field is located in the northeast Bighorn Basin, just west of Lovell and due east of the Garland field (Plate 3). The field is an asymmetrical faulted anticline, trending northwest–southeast (Fig. 7-19). Byron field was discovered in 1918 with initial production from the Frontier Formation ("Torchlight;" Marathon Oil Company, 1989a). Current production is primarily from the Phosphoria-Tensleep, but also from the Frontier, Sundance, and Amsden formations (Table 7-9). Total production through 2011 was more than 134 million barrels of oil (Fig. 7-18).

Table 7-9. Byron field statistics, from Marathon Oil Company (1989a).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	22[1]	—	22, 25	1,000	0.642, 3.6	50.4
Sundance	ss	14[1]	—	30	—	0.66	31.4
Phosphoria/ Tensleep	dol, ss	13.9	78	97	2,085	2.5	24.3
Amsden	dol	6.3	—	12	1,953	—	21.3

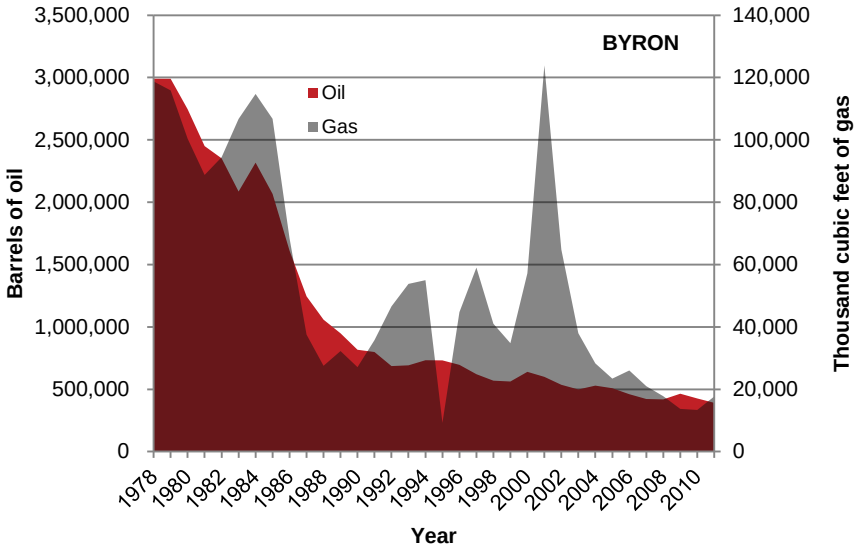


Figure 7-18. Byron field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

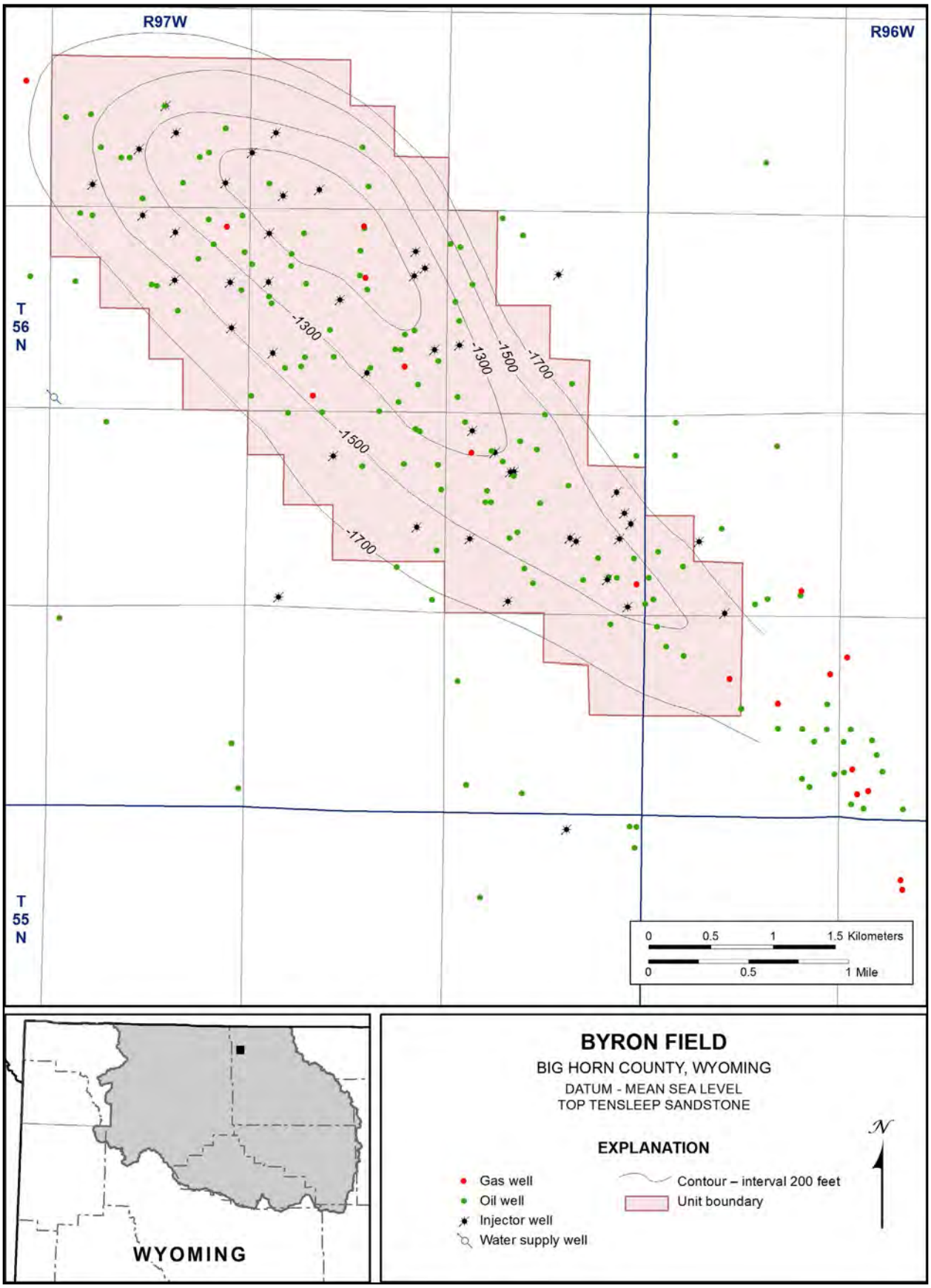


Figure 7-19. Byron field structure-contour map, modified from Marathon Oil Company (1989a). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Frannie Field

The Frannie field is located in the northern Bighorn Basin, along the Montana border (Plate 3). Frannie field is on a northwest–southeast-trending anticline with 13° dips to the southwest and 40° to the northeast (Continental Oil Company, 1968) (Fig. 7-21). Oil production began in 1928 with discovery in the Tensleep Sandstone (frequently termed the Phosphoria-Tensleep reservoir), followed by the 1929 discovery of oil in the Madison Limestone. Since discovery, production has been primarily from the Tensleep Sandstone, with only minor historical production from the Madison Limestone (Vernon, 1989) (Table 7-10). Cumulative oil production through 2011 for the Frannie field (primarily Phosphoria-Tensleep production) was greater than 119 million barrels (Fig. 7-20).

Table 7-10. Frannie field statistics, from Vernon (1989).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Tensleep	ss	17[c]	75[c]	100	1350[SDST]	1.0–2.3	25.6–28.3
Madison	dol, ls	7–13[c]	—	<100	1,875-1,300[FSIP]	—	14–20

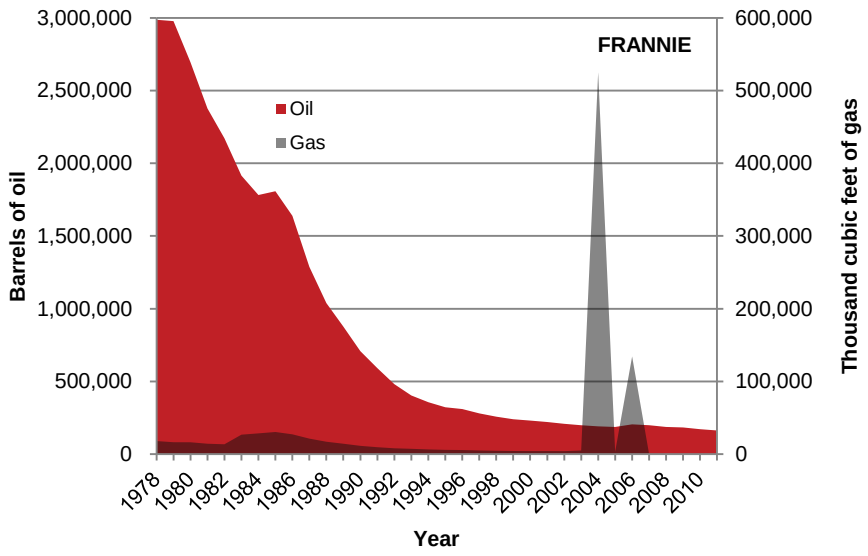


Figure 7-20. Frannie field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix C.

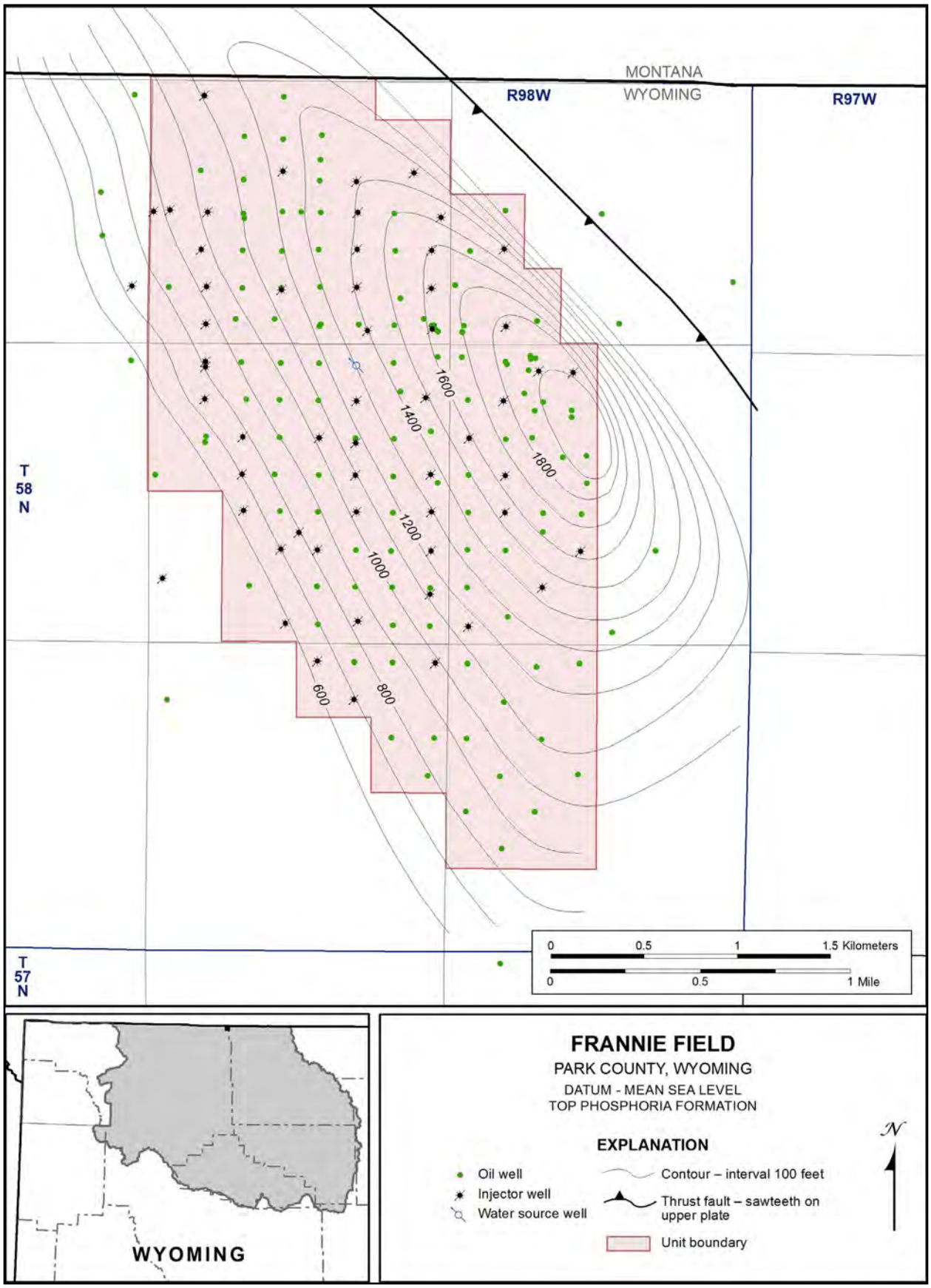


Figure 7-21. Frannie structure-contour map, modified from Vernon (1989). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Results

The hydrocarbon reservoirs in the Bighorn Basin are unique because they are primarily oil reservoirs without gas caps. Gas production reported to the Wyoming Oil and Gas Conservation Commission (2012) is solution gas and is accounted for by B_o. Also, most of the oil fields in the Bighorn Basin are old and peak production was prior to 1978. Presumably the majority of the gas in these fields was produced and burned off prior to 1978. For these reasons, the volume of produced gas is considered negligible. A constant value of 700 kg/m^3 is used for ρ_{CO2}, the density of CO_2 at reservoir conditions (generally 100–120 °F, 38–49 °C; 1,700–2,200 psia, 11,721–15,168 kPa).

This investigation assumes the eight most productive oil fields within the Bighorn Basin have the largest available pore space for storing CO_2, and completes calculations within these eight fields. These chosen fields are not presumed depleted and the method does not account for additional pore space created through future production. Geologic CO_2 storage (excluding CO_2-EOR) will never be a viable option until hydrocarbon recovery in these fields is no longer economic. In fact, the eight fields are all candidates for CO_2-EOR (Wo and others, 2009) and are likely not practical candidate storage reservoirs at current economic conditions.

Table 7-11 summarizes the theoretical storage resource for the producing reservoirs that meet the aforementioned criteria, from the eight largest oil-producing fields in the Bighorn Basin. These eight fields can theoretically store 34–204 million metric tons (37–225 million short tons) of CO_2.

Storage through Enhanced Oil Recovery

Wo and others (2009) rank the top 100 candidate reservoirs for CO_2-EOR in fields across Wyoming for both miscible and immiscible CO_2 flooding, based on technical feasibility. Their study ranks 63 reservoirs in the Bighorn Basin for miscible CO_2 flooding and 42 reservoirs for immiscible CO_2 flooding. The Wyoming Enhanced Oil Recovery Institute (2011) assumes an average recovery factor of 12 percent original oil in place for miscible floods and 6.5 percent for immiscible CO_2 floods, and estimates that 500–800 million barrels of additional oil could be recovered from existing reservoirs within the Bighorn Basin through CO_2 flooding. Minimum and maximum estimated total volumes of CO_2 for miscible and immiscible flooding are summarized in Table 7-12. Table 7-12 ranks the Bighorn Basin reservoirs relative to the top 100 reservoirs (by CO_2 volume) in Wyoming for miscible CO_2 flooding and relative to the top 20 reservoirs (by CO_2 volume) in Wyoming for immiscible CO_2 flooding. These estimates do not include oil recovery within the residual oil zone. Preliminary work by the Wyoming Enhanced Oil Recovery Institute (2011) suggests greater oil reserves in these ROZs (specifically in the Tensleep Sandstone) than in the historically produced zones, with potential additional oil estimates of 800–1,200 million barrels.

The Tensleep Sandstone is the highest priority target for any type of EOR, followed by the Phosphoria Formation. Oil viscosities from these formations within the best candidate fields range 8–31° API, well within the required range for miscible and immiscible CO_2 flooding. The Madison Limestone is not considered a good candidate for CO_2 floods because reservoirs within this formation are commonly highly fractured, have vuggy porosity and low permeability, and usually have a strong water drive that inhibits tertiary oil recovery. However, successful miscible CO_2 flooding of the Madison is currently taking place in the Beaver Creek field in the Wind River Basin.

Several of the potential candidate fields on the east flank of the basin (Elk Basin, Oregon Basin, Grass Creek, Garland, Byron, and Frannie) have been subjected to hydrodynamic flow through the Tensleep Sandstone, with the water originating from recharge at surface outcrops several miles to the east on the flank of the Bighorn Mountains. Hydrodynamic flow into the basin has flushed the oil in these traps down-dip to the west and created tilted oil-water contacts (Hubbert, 1953). These tilted oil-water contacts will need to be addressed in any plan for CO_2 flooding.

Assuming stored CO_2 is equal to CO_2 capacity, between 12 and 18 trillion cubic feet (~620–930 mil-

Table 7-11. Mass of CO_2 that can theoretically be stored in eight hydrocarbon fields in the Bighorn Basin, for a range of E_{res}. Calculations follow Equations 4-2 through 4-8.

Field	Reservoir	S_{res} (million metric tons) minimum E_{res} = 0.1	mode E_{res} = 0.3	maximum E_{res} = 0.6
Oregon Basin	*Embar*[1]	2.0	6.1	12
	Tensleep[2]	2.4	7.3	15
	Madison	2.9	8.8	18
	Total	**7.4**	**22**	**44**
Elk Basin	*Embar*[1]*-Tensleep*	2.2	6.6	13
	Madison[2]	1.7	5.0	10
	Bighorn	0.43	1.3	2.6
	Total	**4.3**	**13**	**26**
Hamilton Dome	*Phosphoria*[2]	0.49	1.5	2.9
	Tensleep	7.4	22	44
	Madison	0.34	1.0	2.0
	Total	**8.2**	**25**	**49**
Grass Creek	*Curtis*[2]	0.42	1.3	2.5
	Embar[1,2]	0.031	0.093	0.19
	Embar[1]*-Tensleep*	0.20	0.60	1.2
	Phosphoria[2]	0.17	0.50	1.0
	Phosphoria-Tensleep	1.5	4.5	9.0
	Tensleep[2]	0.012	0.035	0.070
	Darwin	0.081	0.24	0.49
	Total	**2.4**	**7.2**	**14**
Garland	*Embar*[1,2]	0.025	0.075	0.15
	Phosphoria[2]	0.11	0.33	0.66
	Phosphoria-Tensleep	0.17	0.5	1.0
	Tensleep	0.95	2.9	5.7
	Amsden	0.15	0.46	0.91
	Madison	5.2	16	31
	Total	**6.6**	**20**	**40**
Little Buffalo Basin	*Embar*[1]	0.95	2.8	5.7
	Embar[1]*-Tensleep*	0.062	0.19	0.37
	Tensleep	1.3	3.9	7.9
	Total	**2.3**	**7.0**	**14**
Byron	*Embar*[1]	0.061	0.18	0.37
	Embar[1]*-Tensleep*	0.55	1.7	3.3
	Tensleep[2]	0.83	2.5	5.0
	Total	**1.4**	**4.3**	**8.7**
Frannie	*Phosphoria-Tensleep*	1.3	3.8	7.5
	Tensleep[2]	0.029	0.086	0.17
	Total	**1.3**	**3.8**	**7.5**
Total		**34**	**102**	**204**

[1]"Embar" is outdated terminology for the undifferentiated Dinwoody and Park City formations.

[2]Denotes reservoirs where water production was not considered. Post-1978 water injection exceeds water production reported to the Wyoming Oil and Gas Conservation Commission (2012).

Table 7-12. Estimated CO_2 demand, in billion cubic feet (BCF), for the top ranked reservoirs within the Bighorn Basin for miscible and immiscible CO_2 flooding, from Wo and others (2009).

Rank[1]	Field name	Reservoir	Minimum total CO_2 (BCF)	Maximum total CO_2 (BCF)
miscible CO_2 flooding				
2	Elk Basin	*Madison*	520	780
3	Elk Basin	*Embar-Tensleep*	403	605
6	Byron	*Tensleep*	244	366
7	Hamilton Dome	*Tensleep*	233	350
10	Frannie	*Phosphoria-Tensleep*	209	314
11	Grass Creek	*Phosphoria-Tensleep*	192	288
13	Oregon Basin	*Tensleep*	159	238
15	Cottonwood Creek	*Phosphoria*	152	228
28	Byron	*Embar-Tensleep*	79	119
33	Grass Creek	*Phosphoria*	68	102
35	Grass Creek	*Curtis*	66	100
42	Garland	*Tensleep*	54	81
57	Black Mountain	*Tensleep*	39	59
66	Gebo	*Embar-Tensleep*	34	51
68	Elk Basin South	*Embar-Tensleep*	33	50
69	Garland	*Phosphoria*	33	49
75	Worland	*Tensleep*	28	43
76	Elk Basin	*Bighorn*	28	42
81	Garland	*Embar*	26	39
84	Golden Eagle	*Phosphoria*	25	38
99	Gooseberry	*Phosphoria-Tensleep*	22	33
immiscible CO_2 flooding				
2	Oregon Basin	*Embar*	677	1,016
3	Garland	*Madison*	230	345
4	Little Buffalo Basin	*Tensleep*	137	206
5	Little Buffalo Basin	*Embar*	99	149
6	Oregon Basin	*Madison*	93	140
7	Hamilton Dome	*Phosphoria*	82	123
8	Byron	*Embar*	64	96
9	Pitchfork	*Tensleep*	57	86
13	Torchlight	*Madison*	28	42
14	Spring Creek South	*Tensleep*	27	40
15	Little Buffalo Basin	*Embar-Tensleep*	26	39
17	Fourbear	*Dinwoody-Phosphoria-Tensleep-Darwin-Madison*	24	37
	Total		**4,191**	**6,294**

[1]Rank within the top 100 Wyoming fields for miscible CO_2 flooding and top 20 for immiscible CO_2 flooding.

lion metric tons; 683–1.03 million short tons) of CO_2 can potentially be sequestered within existing reservoirs (historically produced and ROZs) of the Bighorn Basin through CO_2-EOR, with additional oil recovery of 1.3–2 billion barrels (Wyoming Enhanced Oil Recovery Institute, 2011). These very large numbers suggest significant economic potential as well as a noteworthy storage potential for CO_2 through EOR in the Bighorn Basin.

Storage through Enhanced Coalbed Natural Gas Recovery

Coal mining began in the Bighorn Basin in the late 1800s, and was commercially developed by the early 1900s. Eleven coal fields have been designated in the basin; eight are in Wyoming. These eight fields include Silvertip, Garland, Basin, Southeastern, Gebo, Grass Creek, Meeteetse, and Oregon Basin (Cody) coal fields (Glass and others, 1975). The fields lie on the margins of the Bighorn Basin, adjacent to the hydrocarbon fields bearing the same names (Plate 3). Thin and generally unmineable coal has been reported from the Cloverly, Frontier, Lance, Willwood, and Tatman formations. Thicker and more continuous coals are found in the Mesaverde, Meeteetse, and Fort Union (Polecat Bench) Formation (Glass and other, 1975).

The Upper Cretaceous Mesaverde Formation coals have a maximum thickness of 3.7 m (12 feet) in the south and southwestern portion of the basin, and thin to less than 0.4 m (1.2 feet) in the southeast (Glass and others, 1975). The Upper Cretaceous Meeteetse Formation has coal beds commonly 1.2–1.8 m (4–6 feet) thick, with a maximum thickness of 3.6 m (11 feet). The Paleocene Fort Union Formation was termed the Polecat Bench Formation by Jepsen (1940), and is referred to as such in Glass and others (1975). The Fort Union coals are as thick as 38 m (11.6 feet) in the Grass Creek coal field (Glass and others, 1975). These are the thickest and most mineable coals in the Bighorn Basin.

Roberts and Rossi (1999) evaluated the Fort Union coals in the Bighorn Basin as part of the U.S. Geological Survey's National Coal Resources Assessment project. Their study designated these coals "low priority" as viable production targets in the near future. In the mid-2000s, a handful of wells were drilled into the Upper Cretaceous and Paleocene coals for coalbed natural gas. The wells were subsequently plugged and abandoned, generally producing only water.

Results

Coal mining has occurred in the Bighorn Basin, but on a much smaller scale than in most of the other Laramide basins in Wyoming. Coalbed natural gas is also not a significant resource in the Bighorn Basin. Carbon dioxide storage through CO_2-ECBM or in unmineable coal seams is not feasible in the Bighorn Basin.

Chapter 8

Powder River Basin

The Powder River Basin, in northeast Wyoming, has had a long history of hydrocarbon extraction. Oil production began in the late nineteenth century, and continues today. Over 100 years later, the Powder River Basin is now Wyoming's primary coal producing basin. Of the 401.4 million metric tons (442.5 million short tons) of coal produced in Wyoming in 2010, 356.1 million metric tons (392.5 million short tons), or 89 percent, were from the Powder River basin (U.S. Energy Information Administration, 2012b). Powder River Basin coal accounted for 36 percent of coal mined in underground and surface mines in the United States in 2010 (U.S. Energy Information Administration, 2012b). Natural gas is also actively produced from coal seams in the Powder River Basin. In 2011, Powder River Basin coal produced 478.5 billion cubic feet of natural gas, or 95 percent of the coalbed natural gas produced in Wyoming (Wyoming Oil and Gas Conservation Commission, 2012). This significant coal and coalbed natural gas resource suggests a high potential for CO_2 storage in unmineable coal seams and through enhanced coalbed natural gas recovery in the Powder River Basin.

Background

The Powder River Basin area encompasses the Powder River structural basin and Powder River energy basin. The structural basin is in southeastern Montana and northeastern Wyoming, bounded to the south by the Casper arch, Laramie Mountains, and Hartville uplift; to the west by the Bighorn Mountains; to the north by the Miles City arch in Montana; and to the east by the Black Hills. The structural basin is an asymmetric trough that trends north–south for approximately 401 km (250 miles) and is 161 km (100 miles) wide (Ver Ploeg and others, 2008) (Plates 13 and 14, Figure 8-1). The Powder River energy basin is loosely defined by the Cretaceous–Tertiary boundary observed in outcrops. For the purpose of this study, the Powder River Basin area is defined on the west by the Big Horn River 4-digit hydrologic unit, to the north and east by the Montana and South Dakota borders, respectively, and to the south by a connection of several 12-digit hydrologic unit boundaries.

Most regions of the Powder River Basin are covered by two-dimensional seismic surveys (Fig. 8-2). Surveys of various vintages can be purchased through third-party vendors. In addition, the U.S. Geological Survey recorded four 2-D seismic surveys in the Powder River structural basin as part of their "Madison Project" (Cushing, 1977). The data were collected from 1975 through 1978. Two of these lines are entirely in Montana, one spans the Wyoming-Montana border, and the fourth is solely in Wyoming. The locations of the Wyoming data are displayed on Figure 8-2, and available from Miller and others (1996).

The Powder River Basin differs from the other Laramide basins in Wyoming because it has been extensively investigated for CO_2 storage by a variety of organizations ranging from private companies, to government entities, to universities and private/public consortia. In many cases, these studies are specific to a field, reservoir, location, or formation. This chapter does not delve into the details of each analysis, but instead reviews the results only when the topic of a previous investigation aligns with the goals of this study.

Storage in Saline Aquifers

The stratigraphy in the Powder River Basin region is complicated by nomenclature. Formations in the western Powder River Basin follow common Wyoming stratigraphic terminology; formations in the eastern Powder River Basin follow Black Hills (South Dakota) stratigraphic terminology (Plates 1 and 15). In some cases, a formation name is used in both the eastern and western Powder River Basin. When this is not the case, both terms are used when referring to basinwide formations, and individual terms are chosen to refer to specific sides of the basin. Plates 1 and 15 show a detailed breakdown of the Powder River Basin stratigraphic terminology.

Traps

Most known Minnelusa Formation hydrocarbon traps are stratigraphic, formed by lateral facies or porosity variations. Structural traps do occur, but they are generally small (Minnelusa oil fields aver-

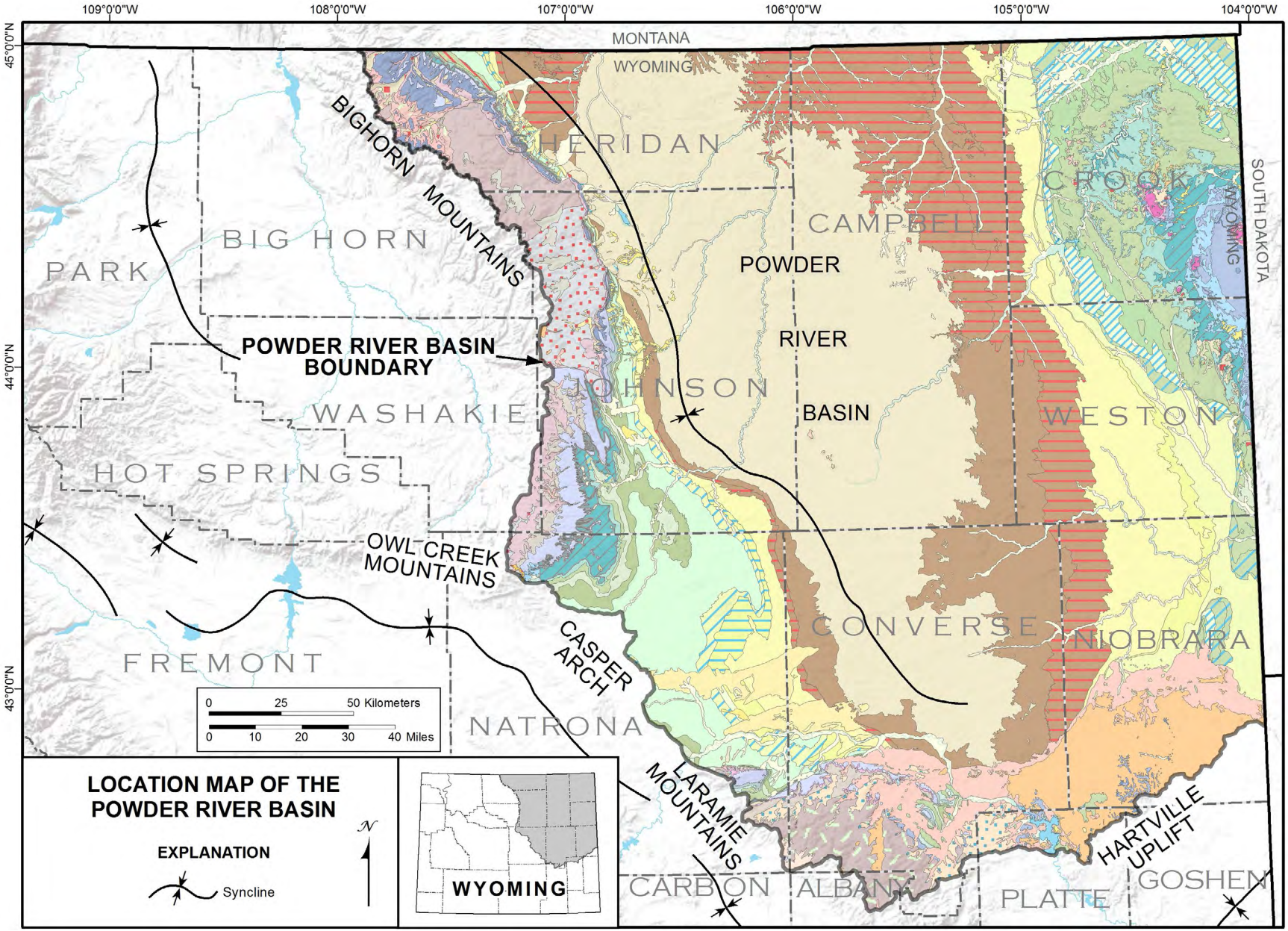


Figure 8-1. Location map of the Powder River Basin. The Powder River Basin is defined on the west by the Big Horn River 4-digit hydrologic unit, to the north and east by the Montana and South Dakota state boundaries, respectively, and to the south by a connection of 12-digit hydrologic unit boundaries.

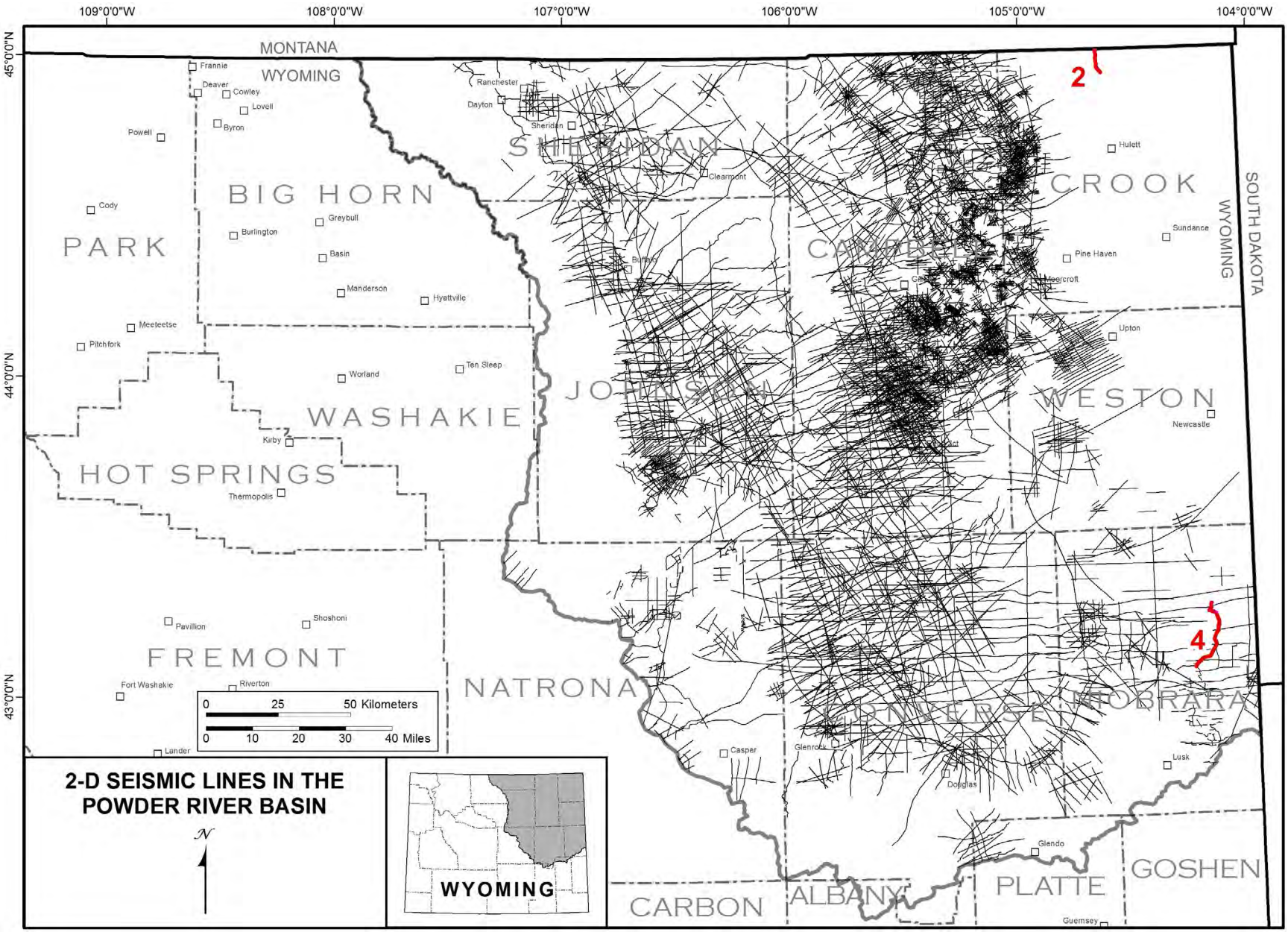


Figure 8-2. Map showing the location of 2-D seismic lines in the Powder River Basin. The line locations were provided by and are available for purchase from Seismic Exchange, Inc. (2011). The lines in red are from the U.S. Geological Survey "Madison Project," study areas 2 and 4, and are available from Miller and others (1996).

age four wells per field) (Anna, 2010). Traps for large-scale geologic CO_2 storage in saline aquifers are non-existent in the Powder River Basin, as in most of the other Laramide basins. The Powder River Basin has a synclinal geometry, where all formations dip toward the basin center. This geometry may prove problematic for CO_2 storage in deep saline reservoirs.

Storage Zones

The Powder River Basin hosts numerous Cretaceous age sandstones with CO_2 storage potential, including the Muddy Sandstone, Frontier Formation, Sussex and Shannon sandstones (members of the Cody Shale), and Parkman Sandstone (member of the Mesaverde Formation). These sandstones are significant hydrocarbon producers in the basin. Their deposition was related to regression and transgression of the Cretaceous Western Interior Seaway. As a result, the sandstones are often laterally continuous over tens of kilometers, but not throughout the basin, and are interbedded with less permeable mudstones and siltstones. These Cretaceous sandstones may not be appropriate for the purpose of large-scale CO_2 storage in deep saline aquifers, but may make suitable storage zones in depleted hydrocarbon reservoirs. As in the other Laramide basins throughout Wyoming, the Tensleep/Minnelusa formations and Madison/Pahasapa/Englewood limestones are the most likely large-scale storage formations. The Nugget Sandstone is not present in the Powder River Basin area.

Tensleep Sandstone and Minnelusa Formation

The Minnelusa Formation is the primary oil producer in the Powder River Basin. In 2011, 5.7 million barrels of oil were produced from the Minnelusa alone, 28 percent of total oil production in the Powder River Basin (Wyoming Oil and Gas Conservation Commission, 2012). The Minnelusa Formation, deposited in a sabkha, coastal dune, and shallow evaporitic sea environment, has been informally divided into the Pennsylvanian lower and middle members, and the Permian upper member (Anna, 2010). In the western Powder River Basin, the lower member of the Minnelusa is correlative to the Amsden Formation. The middle member and part of the upper member is correlative to the Tensleep Sandstone. The lower member is almost always low porosity shales and carbonates.

In the southern Powder River Basin, the middle member of the Minnelusa Formation is equivalent to the oil-producing Leo Sandstone, which produced 120,433 barrels of oil in 2011 (Wyoming Oil and Gas Conservation Commission, 2012). The Leo Sandstone has six sandstone reservoirs, ranging in thickness from approximately 1 m (3 feet) to 9 m (30 feet) with highly variable vertical and lateral porosities from less than five to more than 20 percent (Anna, 2010). Production is primarily from southeastern and southern basin margin anticlines.

In the northern Powder River Basin, both the lower and middle members are low-porosity shales and carbonates. The upper Permian member is the primary oil producer. Hydrocarbon exploration companies have subdivided the upper member into 5 zones, of which the middle, zone C, is the most laterally continuous throughout the basin (Anna, 2010). The Tensleep Sandstone in the western Powder River Basin is equivalent to the lower C, D, and E zones.

Tensleep reservoirs are generally anticlinal traps, with the notable examples of Teapot Dome and Salt Creek fields (Anna, 2010). Tensleep and Minnelusa reservoirs are primarily sandstone, but fractured dolostone is not uncommon. Nearly all upper Minnelusa oil reservoirs are small due to differential cementation and complex stratigraphic interfingering, suggesting Minnelusa reservoirs may prove too discontinuous and require too high of injection pressures for CO_2 storage. Minnelusa reservoirs range 6–25 percent porosity with TDS concentrations 600–3,000 mg/L on the basin margins and more than 10,000 mg/L in the basin center (Clarey and Stafford, 2008).

Madison, Pahasapa, and Englewood Limestones

The Mississippian Madison, Pahasapa, and Englewood limestones produce very little oil in the Powder River Basin area. The Wyoming Oil and Gas Conservation Commission (2012) reports only 95 barrels of oil from the Tensleep-Madison reservoir

(the Madison is not reported separately), and none from the Pahasapa or Englewood limestones.

The Madison Limestone thins from approximately 335 m (1,100 feet) in the northwestern Powder River Basin (Feathers and others, 1981) to only 16 m (53 feet) near the Hartville uplift (Fig. 8-3) (Sando and Sandberg, 1987). The Madison Limestone is frequently divided into the upper Mission Canyon Limestone and lower Lodgepole Limestone. The Pahasapa Limestone in the eastern Powder River Basin is approximately equivalent to the Mission Canyon Limestone; the Englewood Formation is approximately equivalent to the Lodgepole Limestone.

As is common to the Madison Limestone throughout Wyoming, porosity and permeability are highly variable due to karsting and dolomitization/dedolomitization. In general, porosity in the Madison Limestone in the Powder River Basin can range as high as 10–30 percent (Clarey and Stafford, 2008). TDS concentrations are less than 600 mg/L near outcrops on the basin margins, and 3,000–5,000 mg/L in the basin center. The Englewood Formation has estimated TDS concentrations greater than 10,000 mg/L in the basin center (Clarey and Stafford, 2008). The Madison Limestone is a significant drinking water aquifer on the basin margins. Wells in these areas are generally less than 914 m (3,000 feet) deep. Recharge to these wells is from surface outcrops. Carbon dioxide storage in the Madison saline aquifer should not be allowed to impact the freshwater aquifer, limiting potential storage to the deepest and most saline parts of the basin.

Confining Zones

Opeche Shale/Goose Egg Formation

The Opeche Shale/Goose Egg Formation is a regional seal for many of the Minnelusa oil fields in the eastern Powder River Basin. The Permian Opeche Shale is equivalent to the basal Goose Egg Formation in the western Powder River Basin. The Opeche Shale and Goose Egg Formation were formed by a shallow evaporitic sea that deposited mudstone, siltstone, and minor sandy layers, as well as bedded anhydrite and halite (Benison and Goldstein, 2000). The Opeche Shale/Goose Egg Formation unconformably overlies the Minnelusa Formation in the eastern Powder River Basin or the Tensleep Sandstone in the western Powder River Basin. The Opeche Shale is 7–30 m (25–100 feet) thick in the southern Powder River Basin, 21–37 m (70–120 feet) thick in the Black Hills region, and 18–27 m (60–90 feet) thick in the northeastern basin (Hodson and others, 1973; Feathers and others, 1981). The Wyoming Framework Water Plan classifies the Opeche Shale/Goose Egg Formation as a major regional confining unit with low permeability (Clarey and Stafford, 2008).

Results

This assessment considers the volumetric storage resource of the Leo Sandstone (Minnelusa Formation), the upper Minnelusa Formation and Tensleep Sandstone, and the Madison Limestone (Table 8-1). The total formation area A_t, between 914 and 3,962 m (3,000 and 13,000 feet) depth was determined from published isopach and structure contour maps (Fig. 8-4) (Balch, 1988; Fox and Higley, 1996a, 1996b). The total formation area of the Leo Sandstone and the upper Minnelusa/Tensleep is presumed to be the same. Porosity and thickness values were obtained from Anna (2010) for the Leo Sandstone; from Melick and others (2009) for the upper Minnelusa/Tensleep; and from Feathers and others (1981), Sando and Sandberg (1987), and Clarey and Stafford (2008) for the Madison Limestone. The total area, maximum and minimum total porosity, and maximum and minimum gross formation thickness are

Table 8-1. Input values used in the estimation of CO_2 storage capacity of saline aquifers.

Formation	A_t (km^2)	h_g min (m)	h_g max (m)	ϕ_{tot} min (%)	ϕ_{tot} max (%)
Leo (Minnelusa)	29,378	2	183	6	25
Upper Minnelusa/Tensleep	29,378	1	9	5	20
Madison	19,151	16	335	10	30

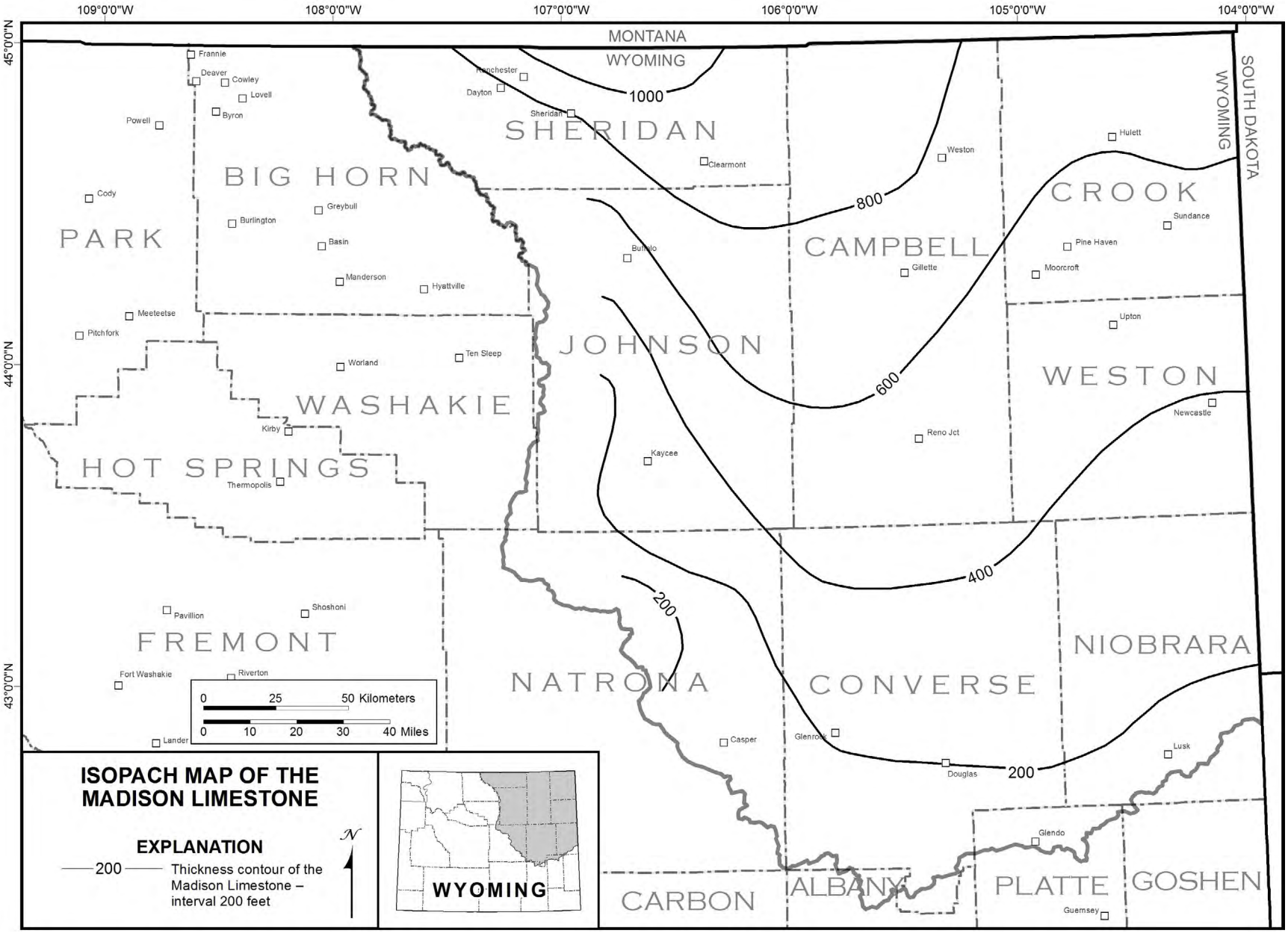


Figure 8-3. Isopach map of the Madison Limestone in the Powder River Basin area, modified from Balch (1988).

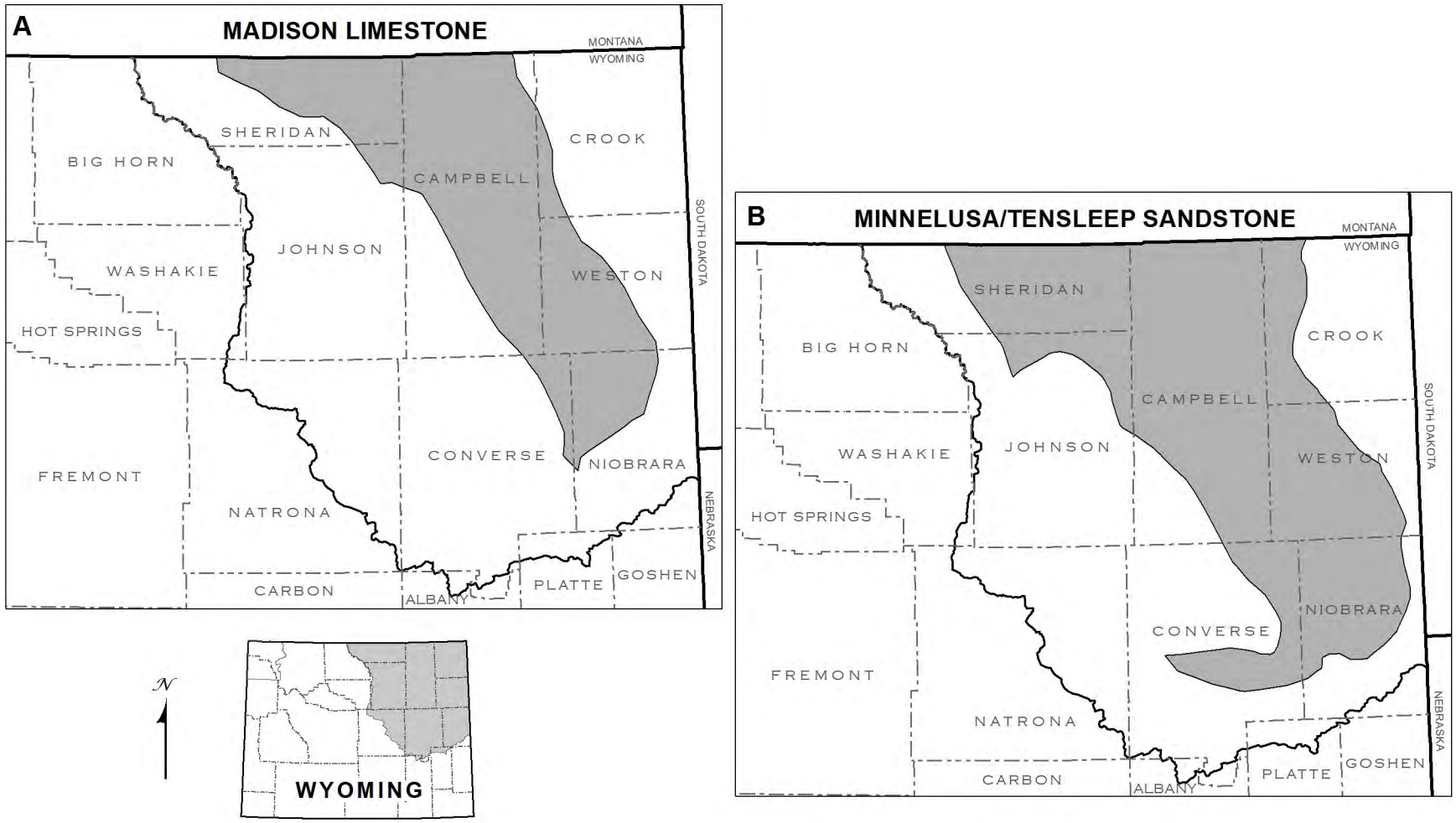


Figure 8-4. Total formation area (A_t) of the Minnelusa/Tensleep Formation and the Madison Limestone, summarized in Table 8-1. A_t is limited by depth from data modified from Balch (1988) and Fox and Higley (1996a, 1996b).

summarized in Table 8-1. The mean value for each parameter is calculated from the minimum and maximum values.

Theoretical maximum and minimum estimates of the CO_2 storage resource (mass) for saline aquifers, by formation, were calculated using the parameters in Table 8-1, for the aforementioned assumptions. Similar to the maximum and minimum variable estimates, the average estimates for each variable are used to calculate an average (S_{basin} is not averaged, instead the input variables are averaged). The results are summarized in Table 8-2. These calculations suggest the potential for an average of 14.8 billion metric tons (16.3 billion short tons), ranging 137 million to 113.9 billion metric tons (151 million to 125.6 billion short tons), of CO_2 storage in the saline aquifers of the Powder River Basin. The results are estimates that require significant assumptions and should not be used without acknowledging and incorporating the associated assumptions.

Table 8-2. Mass of CO_2 that can theoretically be stored in saline aquifers in the Powder River Basin. Calculations follow Equation 4-1. Lithologies were used to determine E_{basin} ; ss represents sandstone and dol represents dolomite.

	S_{basin} (million metric tons)		
Reservoir	minimum	average	maximum
Leo (Minnelusa) (ss)	8.6	5,273	45,550
Upper Minnelusa/Tensleep (ss)	4.3	232	1,822
Madison (dol)	124	9,299	66,535
Total	**137**	**14,801**	**113,907**

Storage in Petroleum Reservoirs

Hydrocarbon Exploration and Production

Development of the Powder River Basin as a hydrocarbon-producing basin followed slowly behind development in the other Laramide basins. The first producing oil well in the basin was drilled in 1889 north of Salt Creek field (Plate 3). The discovery well for the Salt Creek field, the most productive oil field in Wyoming, was drilled in 1908. Numerous fields were discovered over the following 30 years, but development was not steady until crude prices and transportation stabilized (Hughes, 1983).

The Powder River Basin was historically an oil-producing basin. Gas occurrences were rare and were usually as gas caps associated with oil reservoirs. Coalbed natural gas development in the late 1990s and 2000s changed the Powder River Basin into a significant natural gas producing region. In 1990, the Powder River Basin fields produced over 58 million cubic feet of natural gas and 47.4 million barrels of oil. In 2011, gas production was up to 509.7 million cubic feet while oil was only 20.3 million barrels. The Wyoming Oil and Gas Conservation Commission (2012) reports production from 688 total fields (505 reported gas; 529 reported oil) in 2011.

Hydrocarbon fields within the Powder River Basin generally occur as stratigraphic traps or in basin-bounding anticlinal structures. The Tensleep Sandstone and Minnelusa Formation are the major Paleozoic oil producers. According to Dolton and others (1990), the Tensleep primarily produces from structural (anticlinal) traps and the Minnelusa produces from both structural and stratigraphic traps. Sandstones deposited during the Cretaceous represent the other major hydrocarbon reservoirs, and include the Muddy Sandstone (eastern equivalent of the Newcastle Sandstone), 2nd Wall Creek Sandstone Member of the Frontier Formation, and the Turner Sandstone Member of the Carlile Shale. Less productive Cretaceous-age reservoirs include the Lakota Formation, Fall River (Dakota) Sandstone, Mowry Shale, Teapot and Parkman sandstone members of the Mesaverde Formation, and the Tecla Sandstone Member of the Lewis Shale, among others (Dolton and others, 1990).

The hydrocarbon source rocks that likely charged the Tensleep and Minnelusa reservoirs were Permian shales in western Wyoming. Dolton and others (1990) argue that the hydrocarbons were generated by Jurassic time, migrated east and were trapped until the Laramide orogeny. Subsequent uplift allowed some hydrocarbons to escape, while some remained in the Tensleep and Minnelusa reservoirs.

In the eastern parts of the basin, lower Minnelusa reservoirs may have been locally sourced from interbedded black shales (Clayton and Ryder, 1984).

The source rock for the bulk of the Upper Cretaceous-age hydrocarbon reservoirs is the Mowry Shale, with significant contributions from the Niobrara Formation and Carlile Shale (Momper and Williams, 1984; Dolton and others, 1990). Hydrocarbons were generated in the deeper western part of the basin and migrated up-dip toward the east into the Cretaceous reservoirs. Estimates suggest nearly 12 billion barrels of oil were generated in the Mowry Shale (Momper and Williams, 1984).

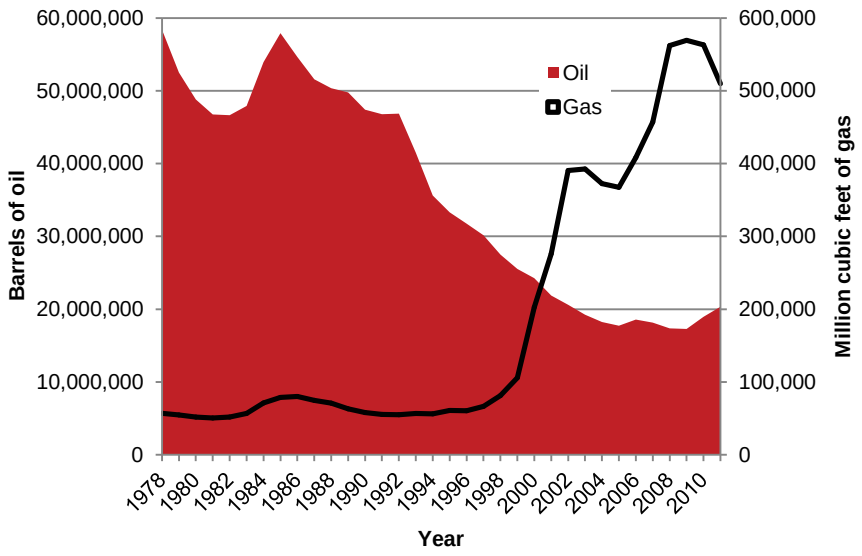


Figure 8-5. Oil and gas production for all fields in the Powder River Basin, from 1978 through 2010. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

In 2010, the Powder River Basin produced 35.6 percent of Wyoming's and 0.95 percent of the nation's oil, as well as 24.4 percent of Wyoming's and 2.5 percent of the nation's natural gas (U.S. Energy Information Administration, 2012a; Wyoming Oil and Gas Conservation Commission, 2012). Since 1978, oil production in the basin has fluctuated; gas production increased since 1998, slowed in 2008, and declined in 2010 and 2011 (Fig. 8-5). In total, the Powder River Basin has produced greater than 8 trillion cubic feet of gas and 2.9 billion barrels of oil.

Hydrocarbon Fields with CO_2 Storage Potential

The Powder River Basin area hosts numerous hydrocarbon fields of that produce both oil and gas. Oil and gas production statistics for eight fields identified as highest potential for CO_2 storage are summarized in Appendix D. These fields were chosen because the productive reservoirs are within the required depth limits (914–3,962 m; 3,000–13,000 feet) and they have produced significant volumes of hydrocarbons, suggesting notable creation of void space and future CO_2 storage potential. The following pages summarize field statistics for these eight fields. Production data for all fields were retrieved from the Wyoming Oil and Gas Conservation Commission (2012); all other field data were retrieved from the Wyoming Geological Association symposium on the Powder River Basin (Finley and others, 2000). The available data were not determined consistently (e.g., porosity values were determined from core or log data; pressures were reported in a variety of ways such as drill stem tests, rock pressures, shut-in tubing pressures, etc.). Whenever possible, the data type/acquisition method is denoted by a superscript listed as:

BHP = bottom hole pressure
DST = drill stem test
SIP = shut-in pressure
FTP = flowing tubing pressure
FSIP = formation shut-in pressure
l = calculated from log
c = measured from core

Rock type abbreviations are as follows:

sh = shale
ss = sandstone

Rw represents water resistivity and an em dash (—) is used to denote unavailable data.

Amos Draw Complex

The Amos Draw complex is located in the northern part of the Powder River Basin in Campbell County, 32 km (20 miles) west of Gillette (Plate 3). The complex is comprised of the Amos Draw, Alicia, Andy, and Felix fields. Discovered in 1981, this complex produces from the Cretaceous Muddy Sandstone that is generally overpressured and capped by shale (von Drehle, 1985). Sandstones in this stratigraphic hydrocarbon trap (Fig. 8-7) average 9.6 percent porosity and 12 millidarcies permeability (Table 8-3). The average pay thickness is from 3.7–4.3 m (12–14 feet) (von Drehle, 1985). Production from the Amos Draw complex began in 1982 and through 2011 totaled 4.9 million barrels of oil and 119.9 million cubic feet of gas (Fig. 8-6) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 8-3. Amos Draw complex statistics, including Amos Draw, Alicia, Andy, and Felix fields, from von Drehle (1985) and Odland and others (1988).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Muddy	ss	4–18	1–2	20–35	5,560	—	52–56

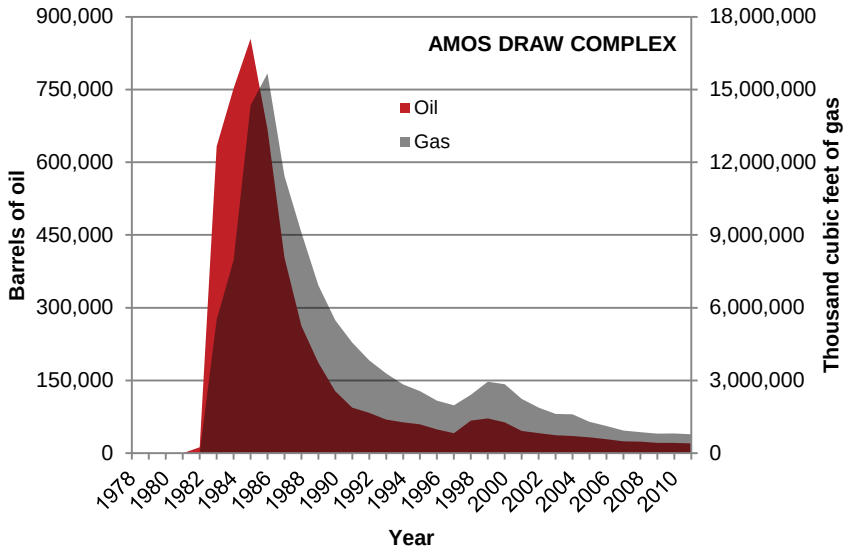


Figure 8-6. Amos Draw complex oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

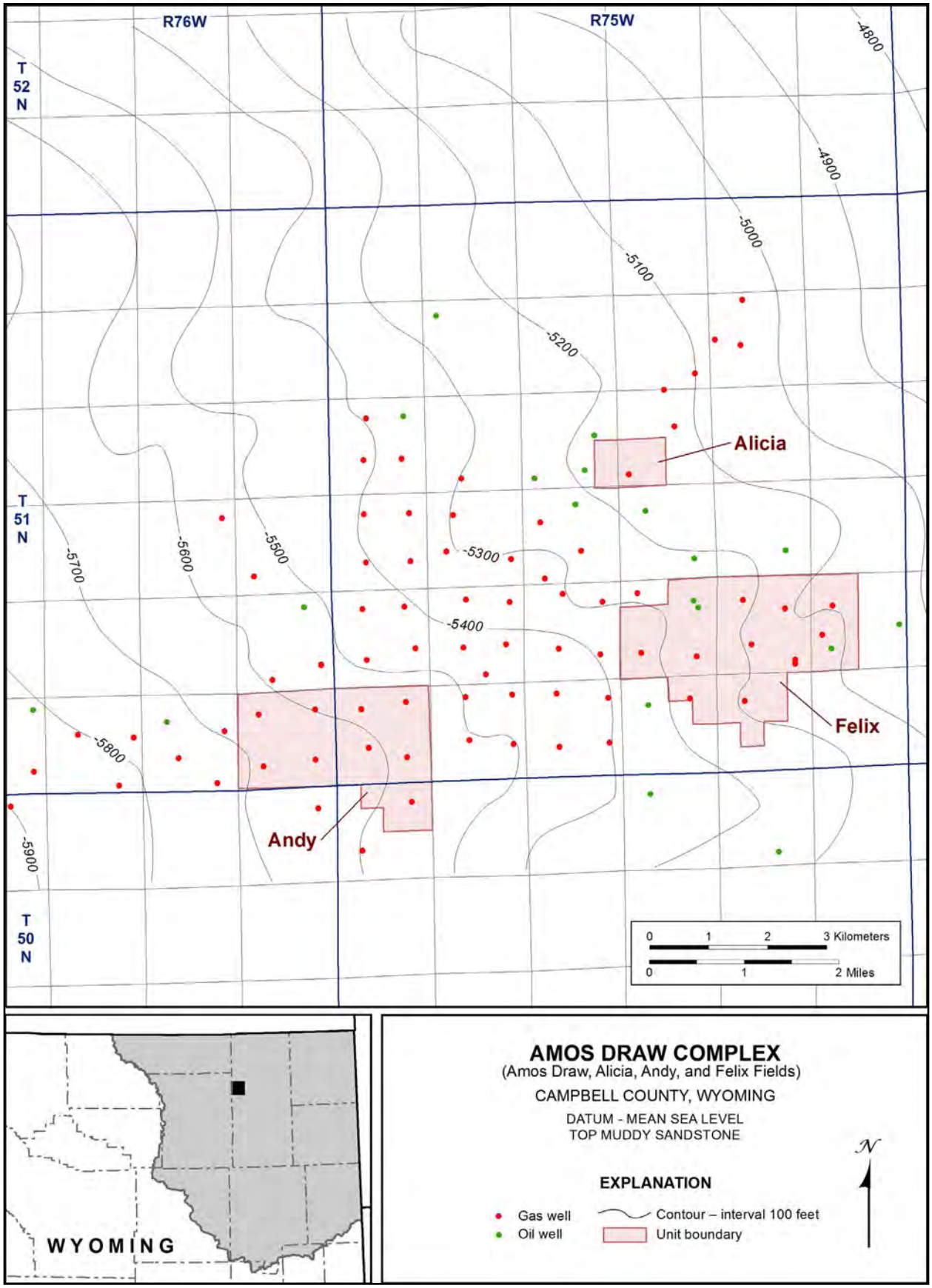


Figure 8-7. Amos Draw complex structure-contour map, modified from von Drehle (1985). The Amos Draw complex includes Amos Draw (unit boundary not provided by the Wyoming Oil and Gas Conservation Commission, 2012), Alicia, Andy, and Felix fields. Well locations, well types, and unit boundaries from the Wyoming Oil and Gas Conservation Commission (2012).

Hartzog Draw Field

The Hartzog Draw field is located in southwest Campbell County, approximately 60 km (39 miles) southwest of Gillette (Plate 3). The Hartzog Draw field covers an area of roughly 109 square kilometers (42 square miles). The Hartzog Draw field is an elongate stratigraphic trap (Fig. 8-9) that produces from the Shannon Sandstone Member of the Upper Cretaceous Cody Shale. The Shannon Sandstone is an argillaceous sandstone with an average porosity of 12 percent and permeability of 8 millidarcies (Table 8-4). The average pay thickness is 6.7 m (22 feet) (Foster, 2000). There are 671 wells within the field; 208 are oil wells and the bulk of the remainder are coalbed natural gas wells (not shown in Figure 8-9). Cumulative production through 2011 was 116 million barrels of oil and 41 billion cubic feet of gas (Fig. 8-8) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 8-4. Hartzog Draw field statistics, from Foster (2000).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Shannon	ss	12	8	22	5,000	0.17	36

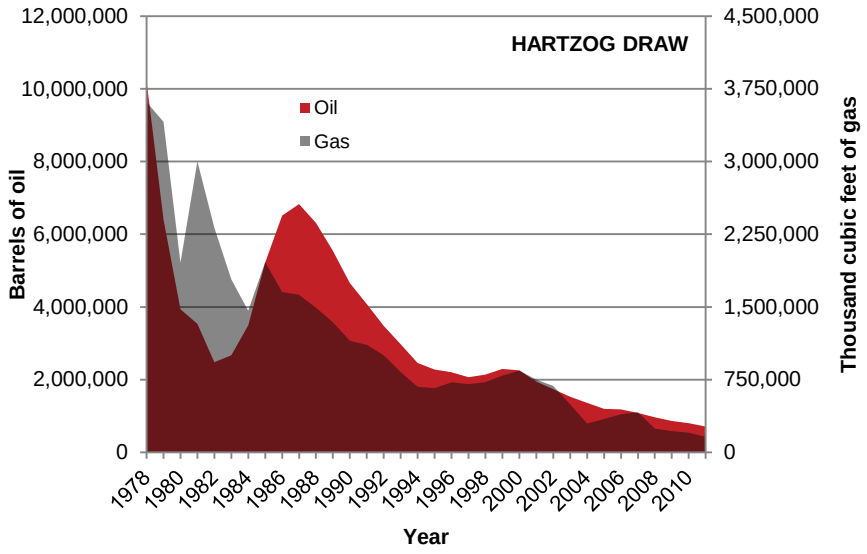


Figure 8-8. Hartzog Draw field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

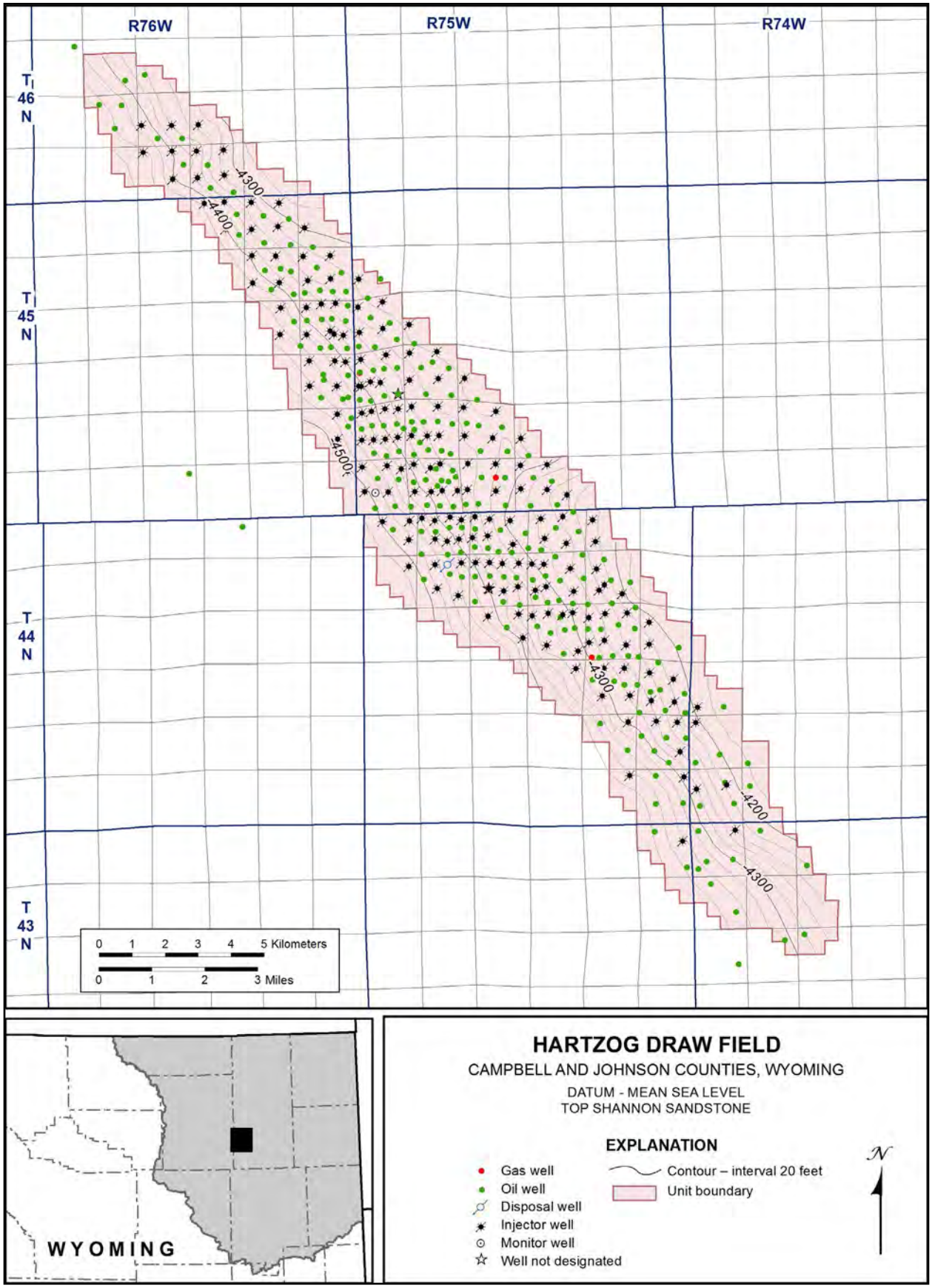


Figure 8-9. Hartzog Draw field structure-contour map, modified from Foster (2000). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Hilight Field

Hilight field was discovered in 1969 in the central Powder River Basin, 14 km (9 miles) east of the town of Wright (Plate 3). The Highlight area (field) is a combination of the Central Highlight, Grady, and Jayson units (Fig. 8-11). Hilight field produces from the Muddy Sandstone, Niobrara Formation, and Minnelusa Formation. Production is primarily from the Muddy Sandstone—a fine-grained quartz-rich sandstone with an average pay thickness of 3 m (10 feet). The Muddy Sandstone averages 15 percent porosity, 110 millidarcies permeability (Table 8-5), and is a stratigraphic trap with multiple up-dip sandstone reservoir pinchouts (Lange, 2000). Cumulative production through 2011 was nearly 80 million barrels of oil and 316.7 billion cubic feet of gas (Fig. 8-10) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 8-5. Hilight field statistics, from Lange (2000).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Muddy	ss	15	110	10	4,010	0.2[1]	41
Niobrara	ss	9.5[1]	—	—	—	—	35–40
Minnelusa	ss	—	—	6	4,311[DST]	—	41

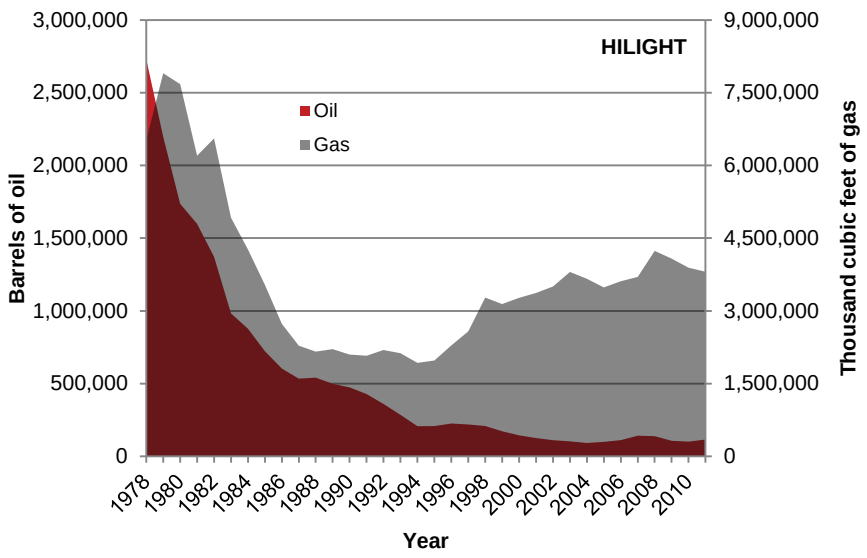


Figure 8-10. Hilight field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

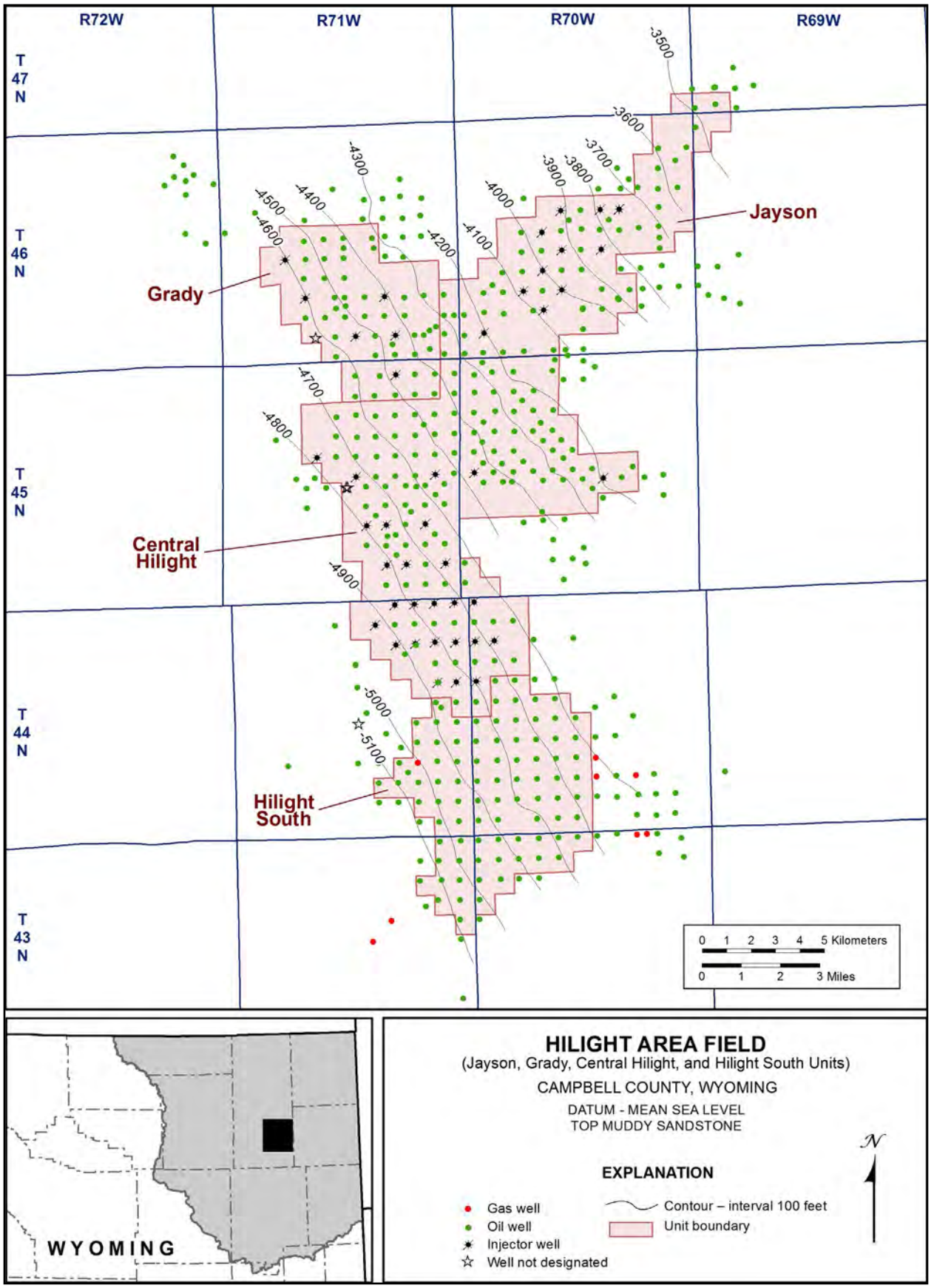


Figure 8-11. Hilight area field structure-contour map, modified from Lange (2000). Hilight area field includes Highlight South, Central Highlight, Grady, and Jayson units. Well locations, well types, and unit boundaries from the Wyoming Oil and Gas Conservation Commission (2012).

House Creek Field

The House Creek field is on the eastern flank of the Powder River Basin, in south-central Campbell County (Plate 3). The House Creek field was discovered in 1968 and stretches 27 km (17 miles) northwest to southeast (Fig. 8-13). The field produces stratigraphically trapped hydrocarbons from the Sussex Sandstone Member of the Upper Cretaceous Cody Shale, as well as from the Parkman Sandstone Member of the Upper Cretaceous Mesaverde Formation (Table 8-6). The Sussex Sandstone averages 12 percent porosity with an average pay thickness of 1.5 m (5 feet) (Stirling, 2000). Cumulative production through 2011 was 43.9 million barrels of oil and 22.7 billion cubic feet of gas (Fig. 8-12) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 8-6. House Creek field statistics, from Stirling (2000).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Parkman	ss	16	—	8	2,928[SIP]	0.66	35–37
Sussex	ss	12	—	5	2,232[DST]	0.24	37

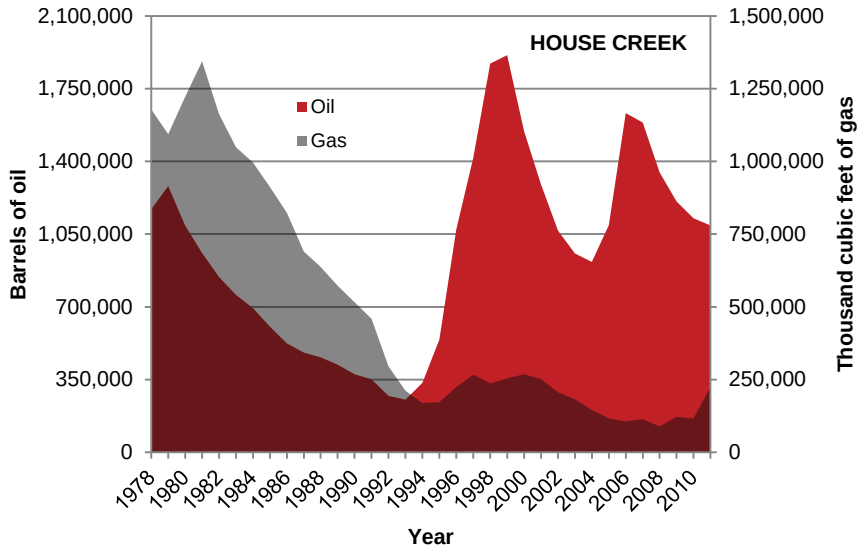


Figure 8-12. House Creek field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

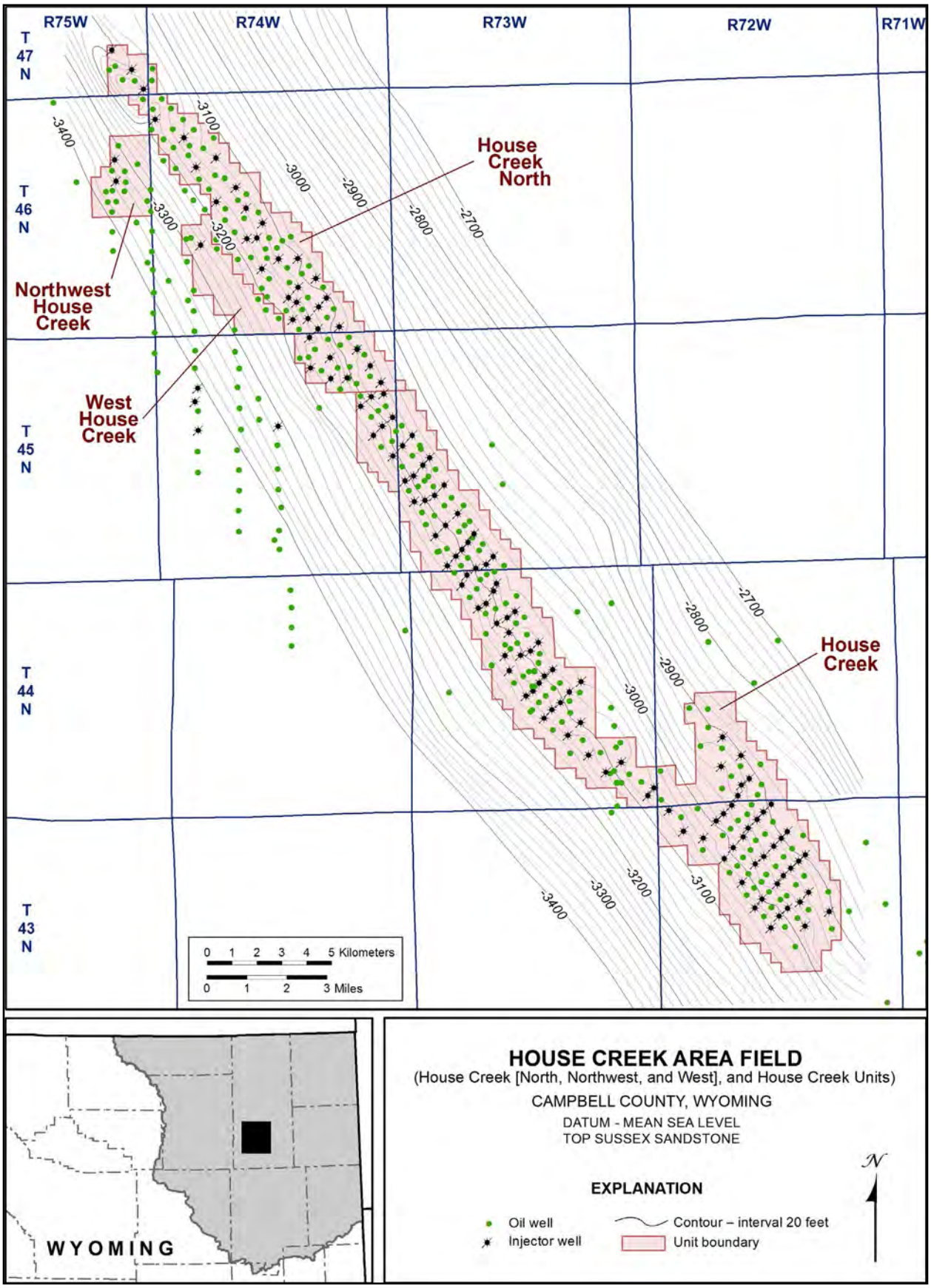


Figure 8-13. House Creek field structure-contour map, modified from Stirling (2000). Well locations, well types, and unit boundaries from the Wyoming Oil and Gas Conservation Commission (2012).

Kitty Field

The Kitty field is a large field located in central Campbell County, 1.5 km (5 miles) west of Gillette (Plate 3). The field encompasses over 104 square kilometers (40 square miles) and is a north–south-trending stratigraphic trap (Fig. 8-15). The field contains a total of 812 wells, the majority of which produce coalbed natural gas (not shown in Fig. 8-5). The Muddy Sandstone is the primary producing formation (Table 8-7). It has an average porosity of 10 percent, an average permeability of 10 millidarcies, and an average pay thickness of 4.6 m (15 feet) (Goolsby and Finley, 2000). Over 22.6 million barrels of oil and 126.9 billion cubic feet of gas were produced from the Kitty field through 2011 (Fig. 8-14) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 8-7. Kitty field statistics, from Goolsby and Finley (2000).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Muddy	ss	10	10[l,c]	15	4,397[SIP]	0.05	42

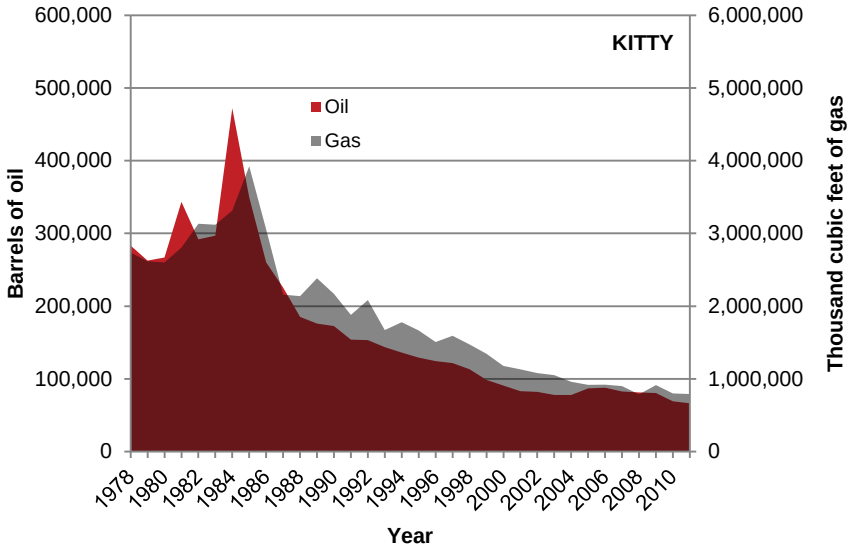


Figure 8-14. Kitty field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

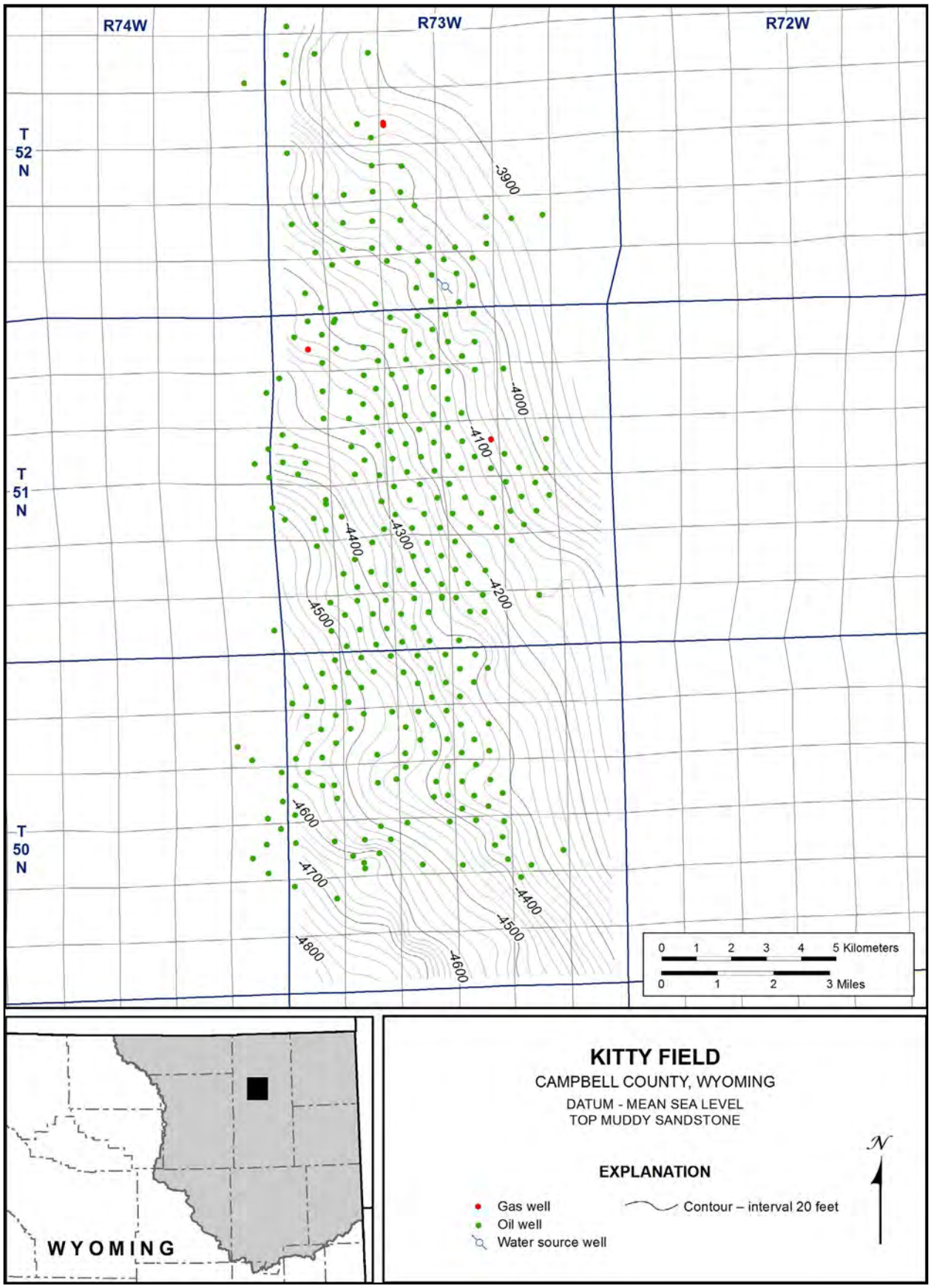


Figure 8-15. Kitty field structure-contour map, modified from Goolsby and Finley (2000). Well locations and well types from the Wyoming Oil and Gas Commission (2012), no unit boundary was available.

Powell Field

The Powell field was discovered in 1975 with initial production from the First Bench of the First Frontier Sandstone. The Powell field is located in the southwest Powder River Basin, northwest Converse County (Plate 3). The Powell field produces from the Frontier Formation, the Sussex Sandstone Member of the Cody Shale, the Muddy Sandstone, and the Dakota (Fall River) Formation. Production is primarily from a stratigraphic trap in the Frontier Sandstone (Fig. 8-17) that has an average pay zone thickness of 1.5 m (5 feet), an average porosity of 14.5 percent, and an average permeability of 100 millidarcies, at approximately 3,566 m (11,700 feet) depth (Table 8-8) (Graham, 2000a). Through 2011, the Powell field produced over 28.6 million barrels of oil and nearly 317.5 billion cubic feet of gas (Fig. 8-16) (Wyoming Oil and Gas Conservation Commission, 2012). Graham (2000a) notes that reported production is approximate because production from the Sussex Sandstone in the Spearhead Ranch field overlaps the area spaced for Frontier production in the Powell field, and Frontier production in the Powell field overlaps Dakota (Fall River) production in the Buck Draw North field.

Table 8-8. Powell field statistics, from Graham (2000a).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	14.5	100[c]	5	8,037[BHP]	—	48.2
Sussex	ss	—	—	—	—	—	—
Muddy	ss	17	—	3	1,955[FTP]	0.3	43.8
Dakota	ss	10.5	1.25	8.5	1,550[FTP]	—	47

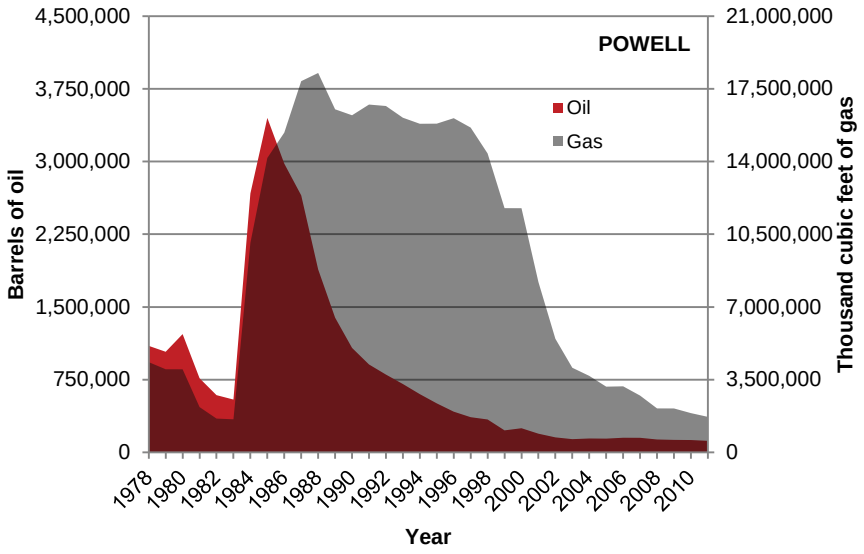


Figure 8-16. Powell field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

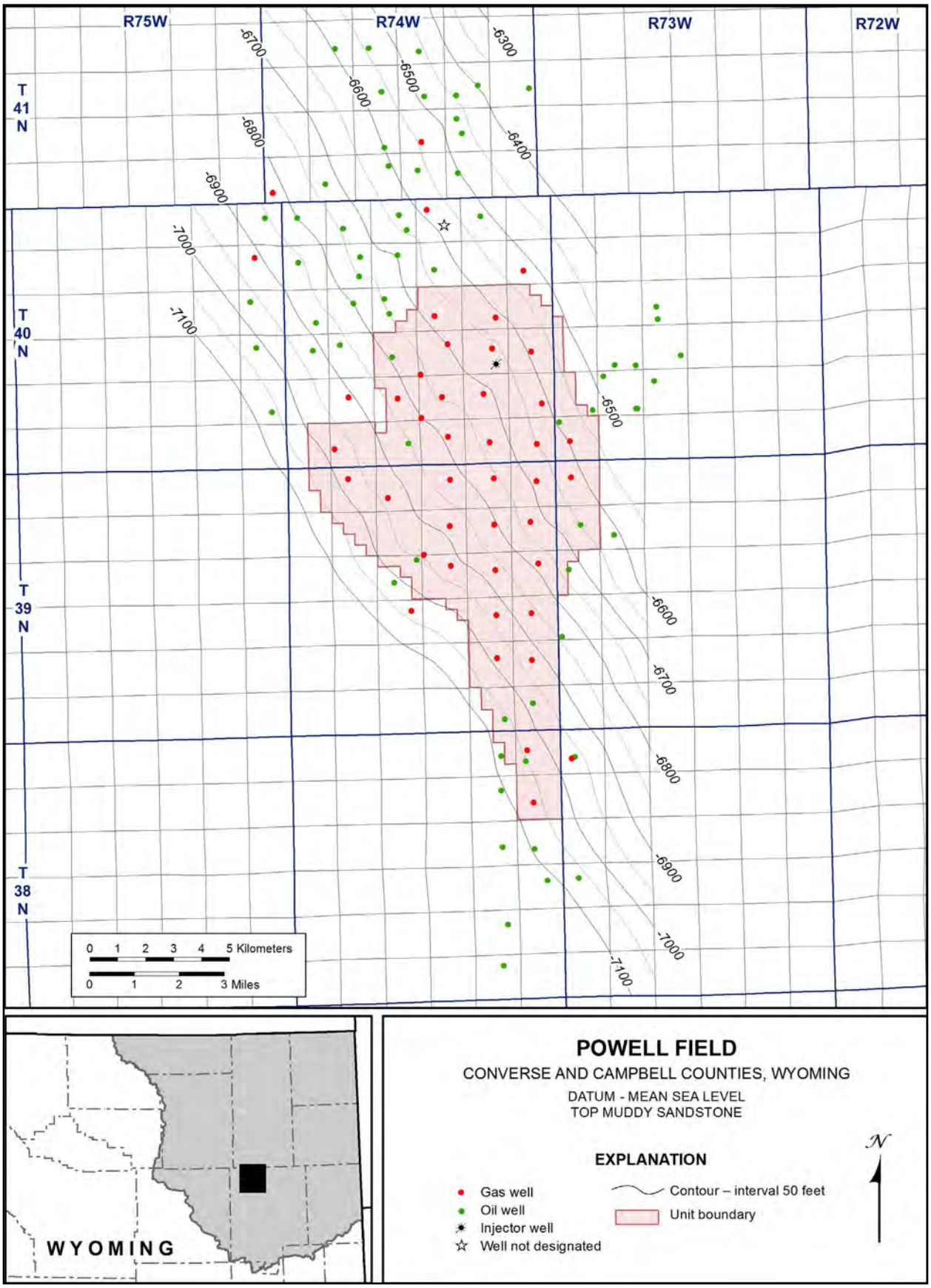


Figure 8-17. Powell field structure-contour map, modified from Graham (2000a). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Scott Field

The Scott field is located in central Converse County along the southern edge of the Powder River Basin (Plate 3). The Scott field produces from the Teapot and Parkman sandstone members of the Mesaverde Formation, as well as the Sussex Sandstone Member of the Cody Shale (Table 8-9). Production is primarily from lateral stratigraphic facies changes in the Parkman Sandstone (Fig. 8-19). The Parkman Sandstone is a fine to very fine grained sandstone with a salt and pepper appearance that often contains abundant clay in the pore space. Commonly divided into two sub-members, the upper Parkman pay zone averages 9 m (30 feet) thick, the lower Parkman averages 8 m (25 feet) (Wellborn, 2000). Parkman Sandstone porosity averages 12 percent with a permeability of 0.1–3.0 millidarcies. The Teapot Sandstone, similar to the Parkman Sandstone, is a fine grained sandstone with a salt and pepper appearance and abundant clay. The porosity of the Teapot Sandstone averages 15 percent with an average 8 millidarcy permeability and average pay thickness of 12 m (40 feet) (Wellborn, 2000). The Sussex Sandstone has an average porosity of 12 percent and an average pay thickness of 11 m (35 feet) (Wellborn, 2000). Cumulative production through 2011 was 20.9 million barrels of oil and 31.4 billion cubic feet of gas (Fig. 8-18) (Wyoming Oil and Gas Conservation Commission, 2012).

Table 8-9. Scott field statistics, from Wellborn (2000).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Parkman	ss	12	0.1–3[c]	30	3,051[FSIP]	4.13	37–42
Teapot	ss	15	8	40	2,811[FSIP]	1.97	36.8
Sussex	ss	12[l]	—	35	4,709[FSIP]	—	34

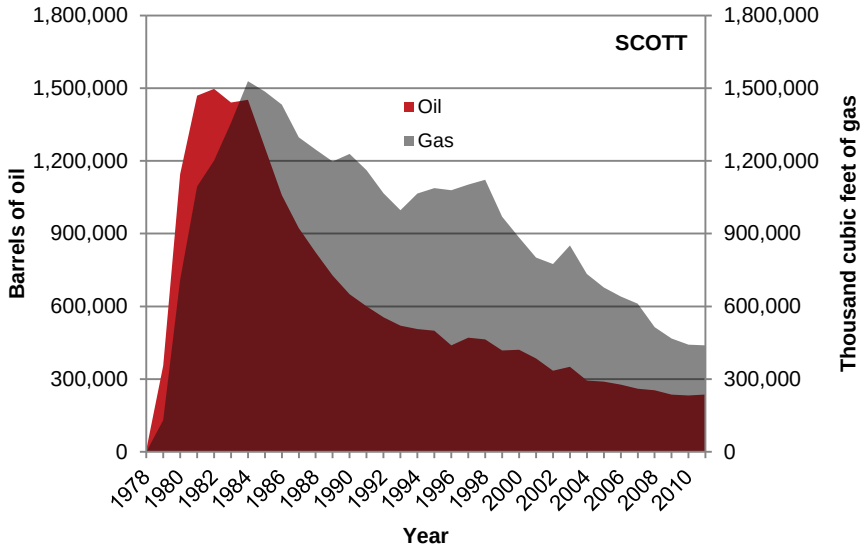


Figure 8-18. Scott field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

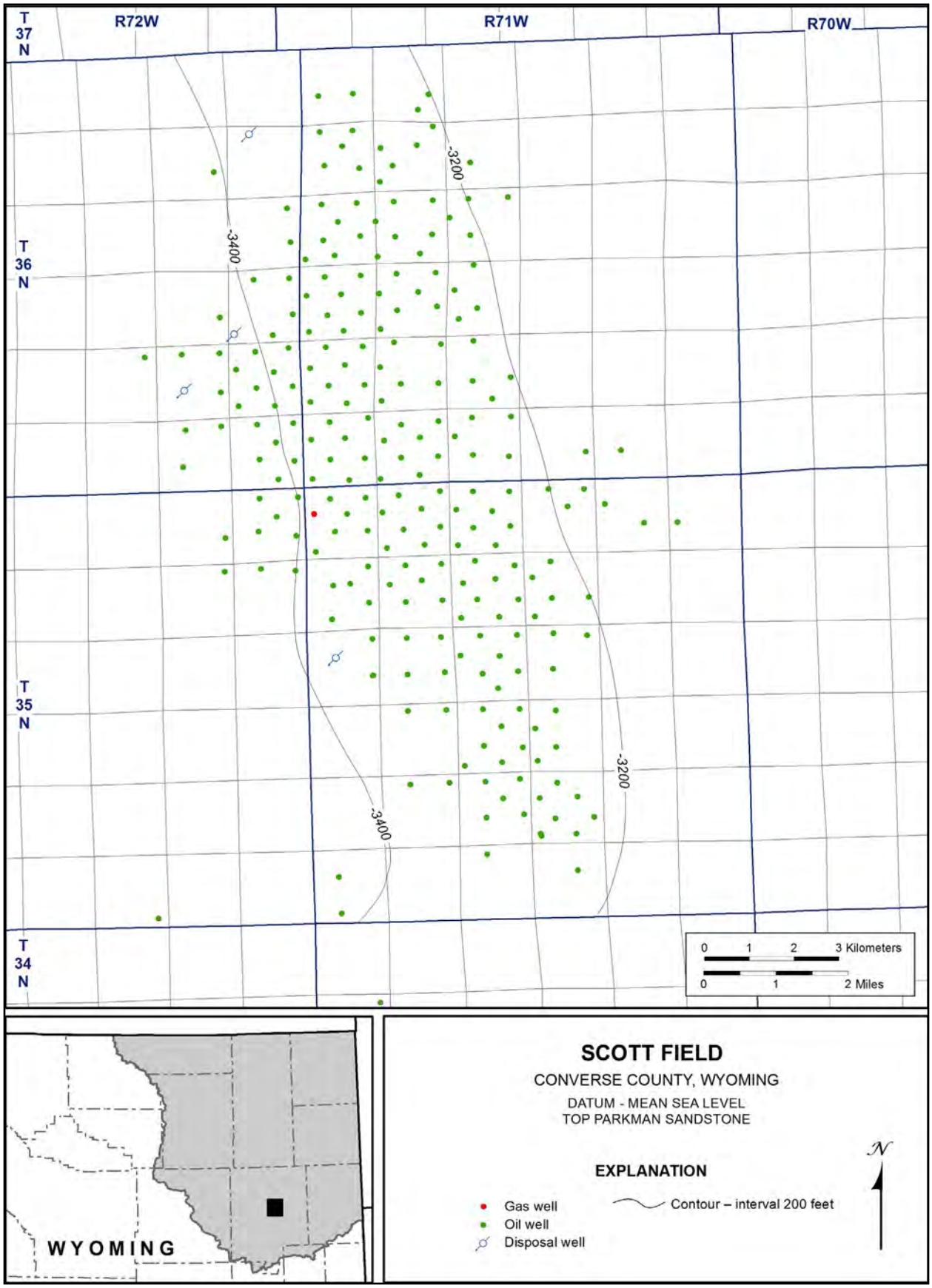


Figure 8-19. Scott field structure-contour map, modified from Wellborn (2000). Well locations and well types from the Wyoming Oil and Gas Commission (2012), no unit boundary was available.

Spearhead Ranch Field

The Spearhead Ranch field is located in northwestern Converse County, just east of the axis of the Powder River Basin (Plate 3). The field produces from stratigraphic traps in the Frontier Formation and the Sussex Sandstone Member of the Cody Shale (Fig. 8-21; Table 8-10). The Frontier has an average porosity of 22 percent, an average permeability of 60 millidarcies, and an average pay thickness of 1.5 m (5 feet) (Graham, 2000b). The Sussex has an average porosity of 10 percent, an average permeability of 2 millidarcies, and an average pay thickness of 3 m (10 feet) (Graham, 2000b). As previously noted, Frontier production in the Powell field overlaps Sussex production in the Spearhead Ranch field (Graham, 2000), resulting in an estimated value for total production. As reported to the Wyoming Oil and Gas Conservation Commission (2012), cumulative production through 2011 in the Spearhead Ranch field was more than 8.2 million barrels of oil and 55.4 billion cubic feet of gas (Fig. 8-20).

Table 8-10. Spearhead Ranch field statistics, from Graham (2000b).

Reservoir	Rock type	Average porosity (%)	Average permeability (millidarcy)	Average pay thickness (feet)	Initial pressure (psi)	Rw @ 68°F (ohm-m)	Average oil gravity (° API)
Frontier	ss	22	60	5	7,000	0.22	41.6
Sussex	ss	10	2	10	4,660[FSIP]	0.17	40.8

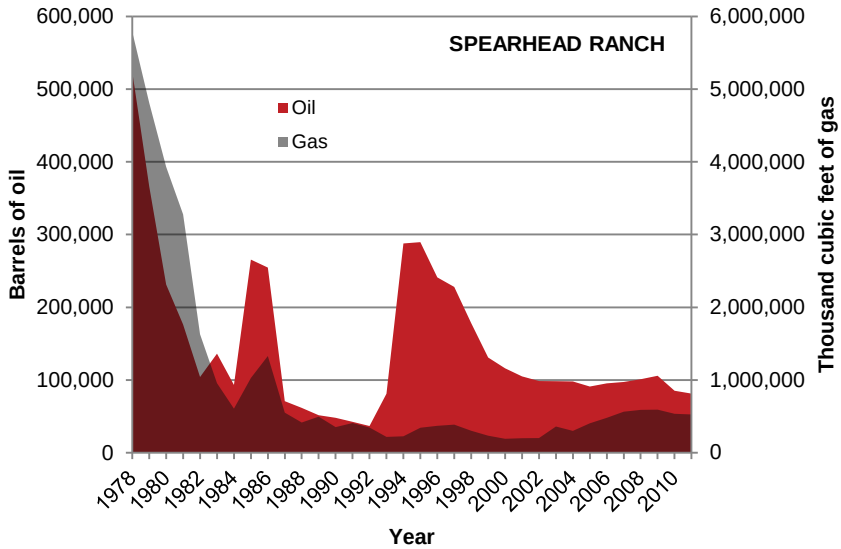


Figure 8-20. Spearhead Ranch field oil and gas production, by year, 1978–2011. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012) and available in Appendix D.

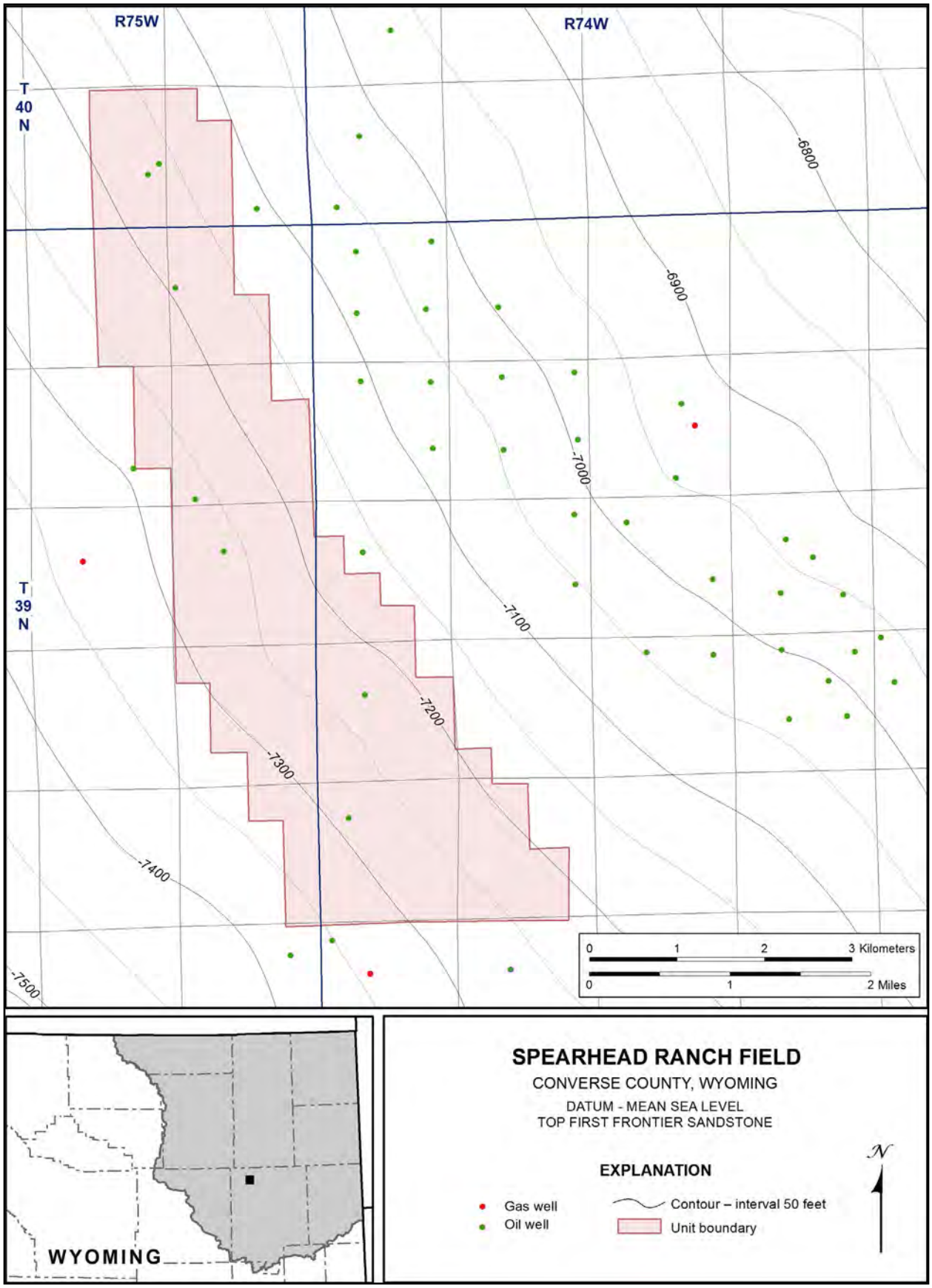


Figure 8-21. Spearhead Ranch field structure-contour map, modified from Graham (2006). Well locations, well types, and unit boundary from the Wyoming Oil and Gas Conservation Commission (2012).

Results

All reservoirs in this evaluation are 2,438–3,962 m (8,000–13,000 feet) below the surface, and average 3,200 m (10,500 feet). A standard normally pressured saline aquifer has a hydrostatic pressure gradient of 10.516 kPa/m (0.465 psi/ft) (Schlumberger, 2012), a generalized geothermal gradient of 0.0301 °C/m (0.0165 °F/ft) (Sheriff, 1991), and an average surface temperature of 20 °C (68 °F). 3,200 m (10,500 feet) depth corresponds to 33.7 MPa (4,888 psi) and 116.3 °C (241.3 °F). ρ_{CO2} at these conditions is 644 kg/m^3 (40.2 lb/ft^3) and is used in this assessment to account for the wide range of depths evaluated by one equation.

A conservative value of 1.25 is assumed for B_o for all fields in the Powder River Basin. This minimum value was derived by calculating B_o for numerous reservoirs in the Powder River Basin from reported reservoir temperatures, pressures, and oil-to-gas ratios. B_o is also reported in a handful of Powder River Basin field unitization reports posted by the Wyoming Oil and Gas Conservation Commission (2012). Calculated and reported values of B_o are as high as 1.9. B_g was calculated for the fields used in this study and averages 0.004. B_w equals one.

Table 8-11 summarizes the theoretical storage resource for the producing reservoirs that meet the above criteria, from the most-promising fields for CO_2 storage in the Powder River Basin. These eight fields can theoretically store 10–61 million metric tons (11–67 million short tons) of CO_2. As with storage estimates from saline aquifers, the results presented in Table 8-11 are estimates that require significant assumptions and should not be used without acknowledging and incorporating the associated assumptions.

Storage through Enhanced Oil Recovery

Wo and others (2009) rank candidate reservoirs for CO_2-EOR in fields across Wyoming for both miscible and immiscible CO_2 flooding, based on technical feasibility. Their study finds 213 and 76 candidate reservoirs for miscible and immiscible flooding, respectively. Of the top 100 candidate EOR fields for miscible CO_2 flooding in Wyoming (by CO_2 volume), 50 are in the Powder River Basin, along with six of the top 20 candidate fields for immiscible CO_2 floods. Minimum and maximum estimated total volumes of CO_2 for these miscible and immiscible CO_2 floods (from Wo and others, 2009) are summarized in Table 8-12. These estimates do not include oil recovery within the residual oil zone. There are no estimates for the amount of additional oil recoverable from ROZs in the Powder River Basin, yet estimates from the Tensleep reservoirs in the Bighorn Basin (e.g., Yin and others, 2011) suggest recovery from ROZs will contribute a substantial amount to the potentially recoverable oil.

The Minnelusa and Tensleep reservoirs are the highest priority targets for CO_2-EOR, followed by the Muddy Sandstone and the sandstone members of the Cody Shale and Mesaverde Formation. Oil viscosities for these candidate reservoirs range 16.8–48.8° API, well within the range for miscible and immiscible CO_2 flooding.

Wo and others (2009) estimate 6.1–9.2 trillion cubic feet (~317–478 million metric tons; 347–524 million short tons) of CO_2 could be required for CO_2-EOR in the Powder River Basin (historically produced reservoirs, not including ROZs). These estimates include the substantial demand for CO_2 in the Salt Creek field, which has been under CO_2 flood since 2004. The CO_2 demand in the Powder River Basin would be significant if CO_2-EOR becomes an economical method of tertiary oil recovery. The resultant CO_2 storage potential from EOR in the Powder River Basin will depend on the optimization of the candidate reservoirs for CO_2 storage.

Storage through Enhanced Coalbed Natural Gas Recovery

While oil and gas production are significant in the Powder River Basin, coal is the chief export from the region. In 2011, the ten largest coal mines in the U.S. were in the Powder River Basin, nine of these mines are in Wyoming and one is in Montana (U.S. Energy Information Administration, 2012b). Production from 16 mines in the Powder River Basin was 419.3 million metric tons (462.6 million short tons) of sub-bituminous coal, over

Table 8-11. Mass of CO_2 that can theoretically be stored in ten hydrocarbon fields in the Powder River Basin, for a range of E_{res}. Calculations follow Equations 4-2 through 4-8.

Field	Reservoir	S_{res} (million metric tons) minimum E_{res} = 0.1	mode E_{res} = 0.3	maximum E_{res} = 0.6
Amos Draw Complex	*Muddy*	0.94	2.8	5.6
	Total	**0.94**	**2.8**	**5.6**
Hartzog Draw	*Shannon*[1]	1.3	4.0	7.9
	Total	**1.3**	**4.0**	**7.9**
Hilight	*Niobrara*	0.024	0.071	0.14
	Muddy	3.4	10	20
	Total	**3.4**	**10**	**20**
House Creek	*Parkman*	0.040	0.12	0.24
	Sussex[1]	0.57	1.7	3.4
	Total	**0.6**	**1.8**	**3.6**
Kitty	*Muddy*	1.2	3.6	7.3
	Total	**1.2**	**3.6**	**7.3**
Powell	*Frontier*[1]	1.2	3.7	7.4
	Frontier-Dakota	0.011	0.033	0.066
	Dakota	0.40	1.2	2.4
	Dakota-Lakota	0.012	0.035	0.071
	Total	**1.6**	**5.0**	**10**
Scott	*Teapot-Parkman*	0.027	0.080	0.16
	Parkman	0.44	1.3	2.7
	Sussex-Parkman	0.015	0.045	0.090
	Sussex	0.019	0.056	0.011
	Total	**0.50**	**1.5**	**3.0**
Spearhead Ranch	*Sussex*	0.039	0.12	0.23
	Frontier	0.46	1.4	2.8
	Total	**0.50**	**1.5**	**3.0**
Total		**10**	**30**	**61**

[1]Denotes reservoirs where water production was not considered. Post-1978 water injection exceeds water production reported to the Wyoming Oil and Gas Conservation Commission (2012).

42 percent of national production for 2011 (U.S. Energy Information Administration, 2012b). All coal production in the Powder River Basin is from surface mines.

Coalbed natural gas production follows closely on the heels of coal production. Coalbed natural gas was first produced in Wyoming in the mid-1990s and peaked in 2009 with production of more than 580 billion cubic feet of gas. In 2011, production was 503 billion cubic feet (Wyoming Oil and Gas Conservation Commission, 2012). Powder River Basin CBNG production for 2011 was nearly 478.5 billion cubic feet, 95 percent of Wyoming's CBNG production (Wyoming Oil and Gas Conservation Commission, 2012). As of the end of 2012, there were over 23,000 completed

Table 8-12. Estimated CO_2 demand, in billion cubic feet (BCF), for the top ranked reservoirs within the Powder River Basin for miscible and immiscible CO_2 flooding, from Wo and others (2009).

Rank[1]	Field name	Reservoir	Minimum total CO_2 (BCF)	Maximum total CO_2 (BCF)
miscible CO_2 flooding				
1	Hartzog Draw	*Shannon*	564	846
5	Hilight	*Muddy*	248	373
8	Lance Creek	*Leo*	226	339
17	Glenrock South	*Dakota*	136	204
18	House Creek	*Sussex*	123	185
20	Sussex	*Tensleep-Amsden*	120	181
23	Salt Creek	*Tensleep*	100	150
24	Well Draw	*Teapot*	91	137
27	Powell	*Frontier*	79	119
31	Gas Draw	*Muddy*	71	107
32	Big Muddy	*Dakota*	70	106
34	Kitty	*Muddy*	68	102
36	Sand Dunes	*Muddy*	65	97
41	Coyote Creek	*Dakota*	55	83
44	Rozet	*Minnelusa*	50	75
45	Salt Creek	*Sundance-3*	49	73
47	Reno	*Minnelusa*	48	72
48	Timber Creek	*Minnelusa*	47	71
49	Meadow Creek	*Tensleep*	46	70
51	Scott	*Parkman*	44	66
52	Lance Creek	*Converse*	42	64
53	Dillinger Ranch	*Minnelusa*	42	63
54	Sussex West	*Shannon*	41	61
57	Raven Creek	*Minnelusa*	39	58
58	Big Muddy	*Wall Creek*	39	58
59	Cole Creek	*Dakota*	37	56
60	Mikes Draw	*Teapot*	37	56
62	Halverson	*Minnelusa*	35	53
63	Finn-Shurley	*Turner*	35	52
64	Recluse	*Muddy*	35	52
65	Stewart	*Minnelusa*	34	52
67	Sage Spring Creek	*Dakota*	34	51
70	Cole Creek South	*Dakota*	32	49
71	Pine Tree	*Shannon*	31	47

Table 8-12. Continued.

Rank[1]	Field name	Reservoir	Minimum total CO_2 (BCF)	Maximum total CO_2 (BCF)
72	Slattery	*Minnelusa*	30	45
73	Springen Ranch	*Muddy*	29	43
78	Sandbar East	*Minnelusa*	26	40
79	Reel	*Minnelusa*	26	40
83	Powell	*Dakota*	25	38
85	Skull Creek	*Newcastle*	25	37
86	Pownall Ranch	*Minnelusa*	24	37
89	Little Mitchell Creek	*Minnelusa*	24	36
90	Ute	*Muddy*	23	35
92	Bone Pile	*Minnelusa*	22	34
93	Rozet	*Muddy*	22	33
95	Donkey Creek	*Minnelusa*	22	33
96	Kaye	*Teapot*	22	33
97	Sussex	*Tensleep*	22	33
98	Glenrock South	*Muddy*	22	33
100	Heldt Draw	*Shannon*	22	33
immiscible CO_2 flooding				
1	Salt Creek	*Wall Creek-2*	852	1,278
10	North Fork	*Tensleep*	48	72
12	Salt Creek	*Wall Creek 1-2*	29	44
16	Rocky Point	*Minnelusa*	25	38
18	Kummerfeld	*Minnelusa*	22	33
19	Rozet West	*Minnelusa*	20	30
	Total		**4,195**	**6,306**

[1]Rank within the top 100 Wyoming fields for miscible CO_2 flooding and top 20 for immiscible CO_2 flooding.

CBNG wells in the Wyoming Powder River Basin (Wyoming Oil and Gas Conservation Commission, 2012).

There is significant potential for CO_2 storage through CO_2-ECBM, or as these CBNG fields are depleted and become available for storage. Traps are either stratigraphic, structural, or can be the result of differential compaction of coal beds (Flores, 2004). Production and storage potential are generally within the Paleocene Fort Union and Eocene Wasatch formations.

Coalbed Natural Gas Formations with CO_2 Storage Potential

Wasatch Formation

The Eocene Wasatch Formation is a thick amalgamation of siliciclastic sedimentary units that is unconformably overlain by the Oligocene White River Formation and conformably underlain by the Paleocene Fort Union Formation in the basin center. The contact with the Fort Union Formation becomes unconformable along the basin margins. The Wasatch Formation is as thick as 427 m (1,400 feet) in the basin center (Flores, 2004), and was deposited in alternating fluvial, lacustrine, and bog-like environments. Lithologies include lenticular sandstones, variegated mudstones, and intercalated sand-, silt-, and mudstones. Sub-bituminous coal can be found throughout the formation generally as thin coal beds but in rare cases can be up to 61 m (200 feet) thick.

Fort Union Formation

The Paleocene Fort Union Formation is unconformably underlain by the Upper Cretaceous Lance Formation. The Fort Union Formation was deposited in a setting similar to the Wasatch Formation, and includes fluvial lenticular sandstones, floodplain siltstones and claystones, lacustrine mudstones, and coals derived from organic-rich swamp deposits. The formation ranges 305–762 m (1,000–2,500 feet) in thickness (Feathers and others, 1981) and consists of three members. The basal Tullock Member is a brown sandstone with interbedded shales, siltstones, and coal; the middle Lebo Shale Member contains lacustrine-derived gray siltstones, claystones, and sandstones; the capping Tongue River Member contains multiple lithologies, including sandstone, mudstone, carbonaceous shale, and coal (Zelt and others, 1999). Coalbed natural gas production in the Powder River Basin is primarily from the thick coals (up to 43 m; 140 feet) in the Tongue River Member of the Fort Union Formation (Flores, 2004).

Results

A number of studies have evaluated the feasibility, economic potential, and resource estimate of CO_2 storage in coal seams in the Powder River Basin (e.g., Stevens and Spector, 1998; Reeves, 2003; Nelson and others, 2005; Bentley and Lusk, 2008; Robertson, 2009, 2010). Specifically, Stevens and Spector (1998) report a CO_2 storage potential of 3.2 billion metric tons (3.5 billion short tons) with a natural gas recovery potential of 30 trillion cubic feet in the Powder River Basin. Nelson and others (2005) report 6.2 billion metric tons (6.8 billion short tons) of CO_2 can be stored in the Wyodak–Anderson coal zone alone (one of the largest zones in the Powder River Basin).

Reeves (2003) considered the CO_2 storage resource of commercial and non-commercial coalbeds in the United States. In his study, the Powder River Basin has an estimated in-place resource of 61 trillion cubic feet of natural gas. Of this assessed in-place resource, it is estimated that 11.1 trillion cubic feet are recoverable, a recovery factor of 18 percent. Because the shallow coals in the Powder River Basin may require a reduction in storage pressure from original pressure, Reeves (2003) applied an adjustment factor of 0.75 to his voidage replacement and ECBM efficiency in commercial area assumption. This adjustment resulted in an incremental recovery potential of 19.6 trillion cubic feet of gas in the Powder River Basin, with a total CO_2 storage potential of 13.6 billion metric tons (15 billion short tons), or 15 percent of the U.S. total.

Chapter 9

Hanna Basin

The Hanna Basin is a small yet very deep intermontane basin. The potential to store CO_2 in the Hanna Basin is low, for three reasons. First, the basin structure and stratigraphy is not suited for CO_2 storage in saline aquifers. Second, CO_2-EOR is unlikely because there are only a handful of oil fields in the basin, all of which are relatively small. Third, although there is a chance that at some future date CBNG fields could be established—there is documented gas production in the Upper Cretaceous and Paleocene formations in the basin—even in this ideal case, the Hanna Basin will not be able to store CO_2 until CBNG fields and the supporting infrastructure are well established. There are no known current plans for future development in the Hanna Basin at the requisite scale.

Background

The Hanna Basin is a small Laramide-style basin, approximately 64 km (40 miles) east-west and 40 km (25 miles) north-south. The basin is bounded to the north by the Shirley and Seminoe mountains, to the east by Simpson Ridge, to the south by the Medicine Bow Mountains and Park Range, and to the west by the Rawlins uplift (Fig. 9-1) (Wilson and others, 2001). For the purpose of this study, the basin boundary is defined by the 12-digit hydrologic unit to the north, east, and south, and the 4-digit hydrologic unit to the west.

The structural development of the Hanna Basin occurred in multiple stages. The Hanna Basin was first isolated from the Greater Green River Basin by the uplift of the Shirley and Granite mountains during the early Paleocene, followed by middle-Paleocene growth of the Sweetwater uplift of the Medicine Bow Mountains and Rawlins uplift occurred during the late Paleocene (Perry and Flores, 1997), resulting in an anomalously deep intermontane basin of more than 9,144 m (30,000 feet) with an axis that trends west—northwest (Plate 2). The Cambrian through Jurassic age sedimentary strata that accumulated before the structural development of the Hanna Basin are less than 762 m (2,500 feet) thick (Plates 16 and 17) (Wilson and others, 2001).

During the Laramide orogeny, the Hanna Basin was isolated from the surrounding basins and became a closed drainage. This structural configuration resulted in a thick succession of Upper Cretaceous to Lower Tertiary fluvial and lacustrine sedimentary deposits. These fluvial and lacustrine sediments account for the bulk of the strata in the basin center, and can be up to 5,791 m (19,000 feet) thick (Plate 18) (Hansen, 1986). Numerous 2-D seismic lines (Fig. 9-2) show the basin fill and are available for purchase from Seismic Exchange, Inc.

Storage in Saline Aquifers

The Hanna Basin is not ideal for CO_2 storage in saline aquifers for a number of reasons. The extraordinary depth of the basin limits the areal extent of CO_2 storage at the requisite depths of 914 m to 3,962 m (3,000 to 13,000 feet); the areal extent is thus extremely small. The steeply-dipping basin geometry promotes lateral up-dip migration of CO_2 out of the basin. Finally, the sedimentary strata are not conducive to CO_2 storage: lacustrine and fluvial sediments are not laterally and regionally continuous.

Merrill and others (2012) assessed the geologic framework for the CO_2 storage resource of the Hanna, Laramie, and Shirley basins. Their study defines deep storage assessment units in the Upper Cretaceous sandstones of the Hanna Basin. These deep units are greater than 944 m (13,000 feet) below the surface. Due to the aforementioned factors of geometry and stratigraphy, these deep storage assessment units are not considered viable at this point in time.

Storage in Hydrocarbon Reservoirs

Petroleum exploration has occurred in the Hanna Basin throughout the 20th century. Prior to 1978, production from 10 fields was reported to the Wyoming Oil and Gas Conservation (2012). Since 1978, an additional five fields have reported production, as well as a handful of wildcat wells. These fields are primarily on the flanks of the basin. Of these 15 fields, 11 reported oil production and 10 reported gas production, for a total through 2011 of 9.7 million barrels of oil and 10.0 billion cubic feet of gas (Fig. 9-3) (Wyoming Oil and Gas Conservation Commission, 2012).

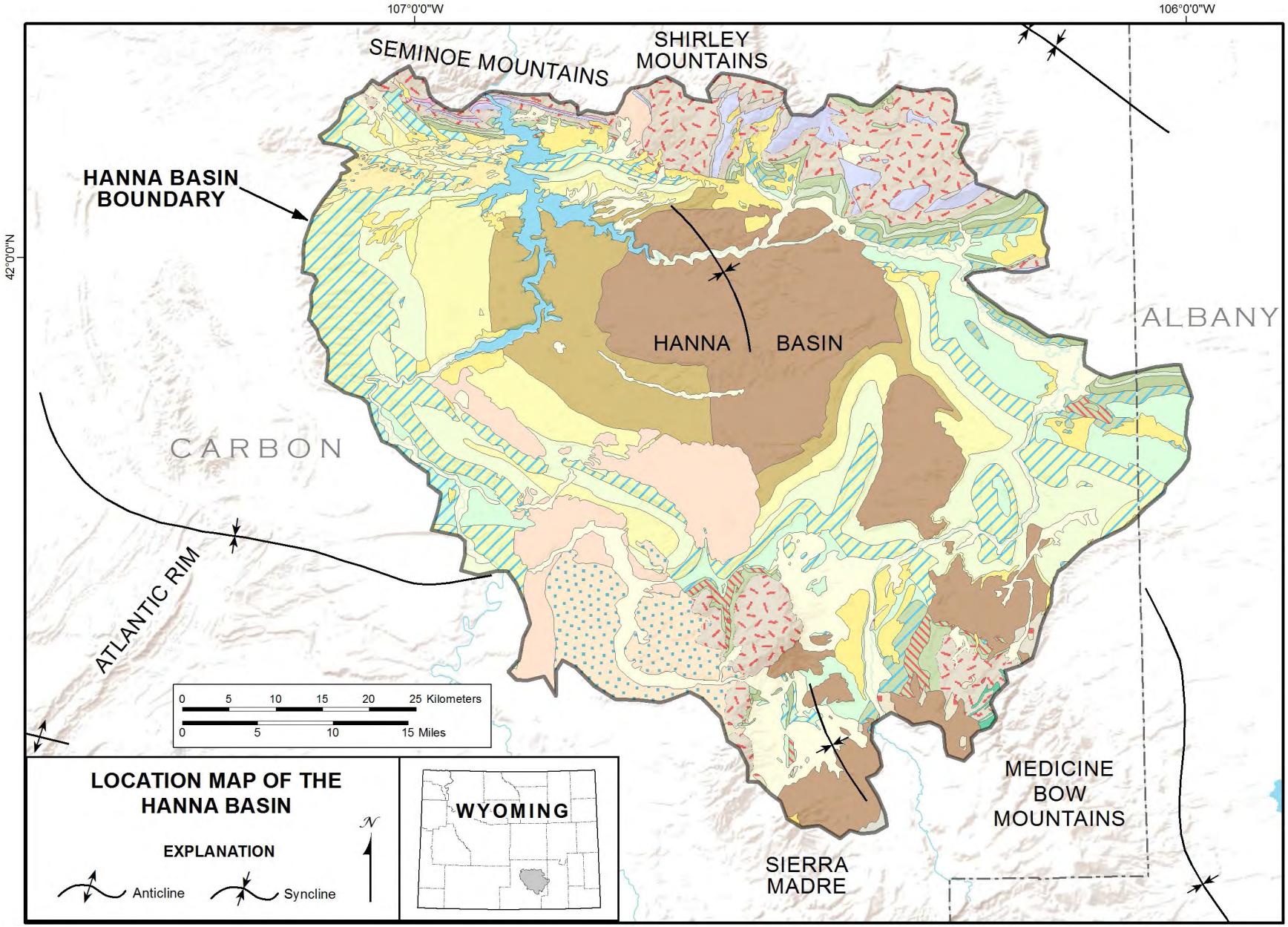


Figure 9-1. Location map of the Hanna Basin. The Hanna Basin is defined by the 12-digit hydrologic unit to the north, east, and south, and the 4-digit hydrologic unit to the west.

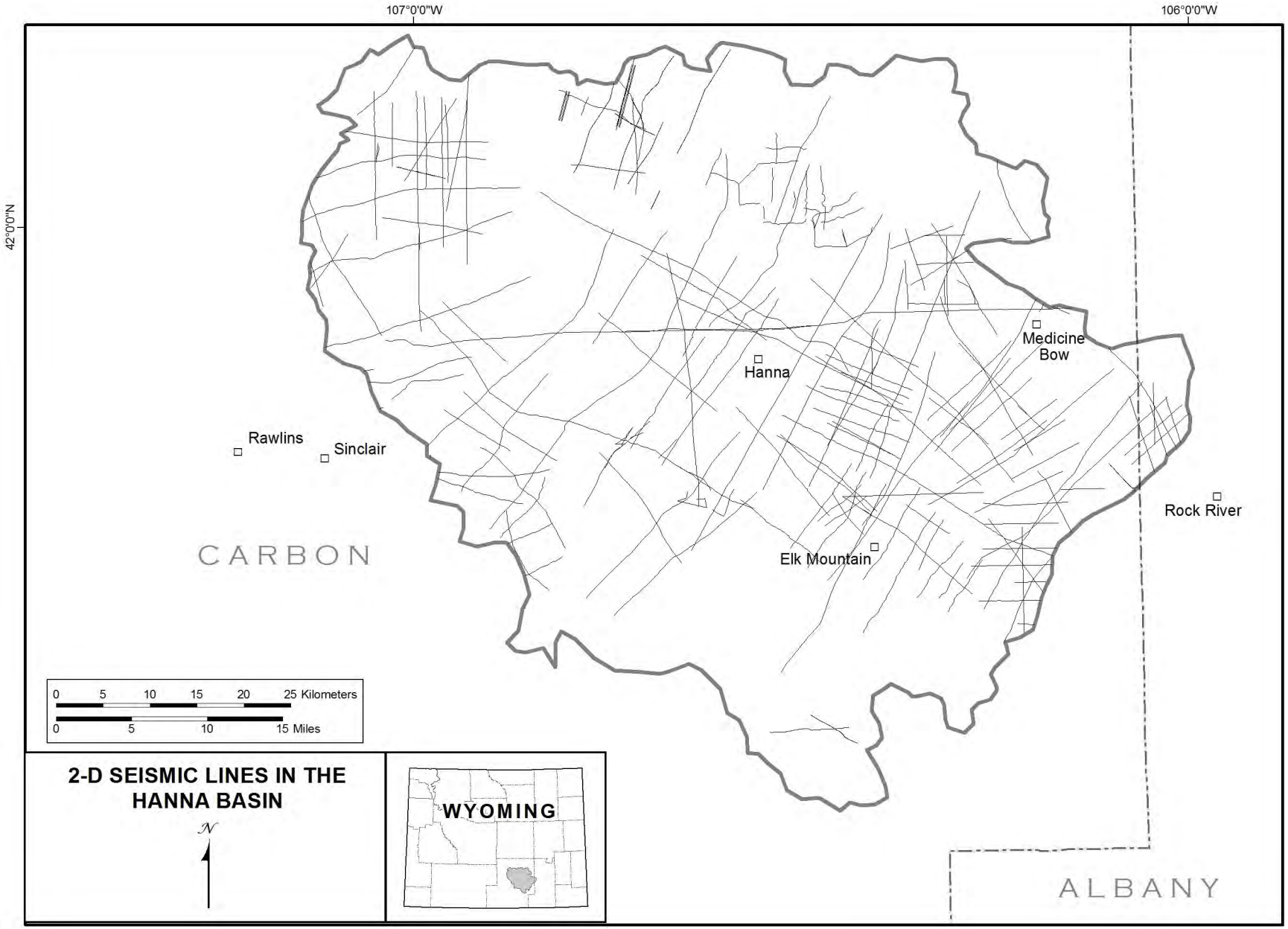


Figure 9-2. Map showing the location of 2-D seismic lines in the Hanna Basin. The line locations were provided by and are available for purchase from Seismic Exchange, Inc. (2011).

The most productive oil field, Big Medicine Bow field, produces from the Cloverly (Dakota), Sundance, and Tensleep. The most productive gas field, Separation Flats field, produces from the Muddy Sandstone. The Hanna Basin has not been extensively explored for undiscovered petroleum accumulations, and there are potential conventional and unconventional undiscovered accumulations (Dyman and Condon, 2007).

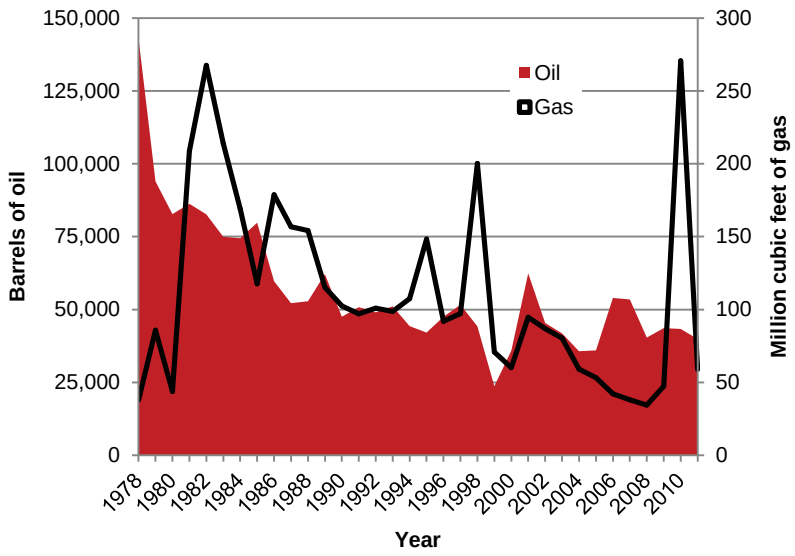


Figure 9-3. Oil and gas production for all fields in the Hanna Basin, from 1978 through 2010. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

However, production from these fields is small. The Big Medicine Bow field produced 6.4 million barrels of oil and 2.1 billion cubic feet of gas through 2011. These production volumes are extremely small relative to other hydrocarbon fields in Wyoming, indicating that not enough pore space was created through hydrocarbon production for efficient and economic CO_2 storage.

Storage through Enhanced Oil Recovery

Based on technical feasibility, Wo and others (2009) ranked the top candidate reservoirs for CO_2-EOR in fields across Wyoming for both miscible and immiscible CO_2 flooding. None of the fields in the Hanna Basin are considered CO_2-EOR candidate fields.

Storage through Enhanced Coalbed Natural Gas Recovery

Coal mining began in the Hanna Basin in 1868, at the town site of Carbon, Wyoming (Flores and others, 1999). These mines operated until 1900, when mining operations moved to the town of Hanna after the railroad was rerouted. Most of the coal extraction in the Hanna as well as Carbon basins (which is separated from the Hanna Basin by the northeast–southwest trending Saddleback Hills anticline), has been from the Hanna coal field (Pierce, 1996). Coal is primarily mined from the Upper Cretaceous and Paleocene Ferris Formation, as well as the Paleocene Hanna Formation.

Dyman and Condon (2007) define the Hanna-Mesaverde coalbed gas total petroleum system, in the Hanna Basin, as parts of the Mesaverde (Almond), Medicine Bow, Ferris, and Hanna formations. Very little gas has been produced from this system, and as of 2005, there were two CBNG pilot projects in the basin. The Seminoe Road CBNG pilot project contained 16 wells that produced 1,400 cubic feet of gas per day; the Hanna Draw CBNG pilot project has nine wells that averaged less than 1,000 cubic feet of gas per day (Dyman and Condon, 2007). No current production has been reported to the Wyoming Oil and Gas Conservation Commission (2012) from these fields.

CO_2-ECBM in the Hanna Basin is not expected to occur anytime in the near future, due to the lack of established CBNG fields. Future CO_2-ECBM will only occur if there are forthcoming discoveries of viable CBNG fields.

Coalbed Natural Gas Formations with CO_2 Storage Potential

Ferris and Hanna Formations

The Upper Cretaceous and Paleocene Ferris Formation and Paleocene Hanna Formation are the primary hosts for coalbed natural gas, in addition to the Mesaverde and Medicine Bow formations. The Ferris and Hanna formations are stratigraphically equivalent to the Fort Union Formation in other basins of Wyoming. Both formations were deposited exclusively within the Hanna and Carbon basins, and are thick accumulations of fluvial sandstones with extensive freshwater overbank mudstones, siltstones, and coals. Coals in the Ferris Formation are 38 to 93 m (125 to 305 feet) thick, and coals in the Hanna Formation are 9 to 114 m (30 to 375 feet) thick (Dyman and Condon, 2007). Coal quality is bituminous to subbituminous.

Results

Reeves (2003) assessed Hanna Basin coal seams for CO_2 storage through CO_2-ECBM with very little data. Reeves' (2003) assessment considered the CO_2 storage resource of commercial and non-commercial coalbeds in the United States. In his study, the Hanna Basin has an estimated in-place resource of 15 trillion cubic feet of natural gas. Of this assessed in-place resource, it is estimated that nearly 4.4 trillion cubic feet are recoverable, a recovery factor of 29 percent. Reeves (2003) assumed 50 percent of the coal is subbituminous and 50 percent is highly volatile. Accounting for a standard voidage replacement and ECBM efficiency in commercial areas of 75 percent, as well as a 50 percent accessible portion of the non-commercial area for CO_2-ECBM, resulted in an incremental recovery potential of 3.9 trillion cubic feet of gas in the Hanna Basin, with a total CO_2 storage potential of 3.0 billion metric tons (3.3 billion short tons), or 3 percent of the U.S. total.

Chapter 10

Denver Basin

The Denver Basin of Wyoming is a foreland-style, asymmetrical basin in the southeastern corner of the state. This assessment considers possible CO_2 storage in deep saline aquifers, depleted hydrocarbon reservoirs, through EOR, and through CO_2-ECBM, and has determined there are currently no feasible storage locations for CO_2 in the Denver Basin of Wyoming.

Background

The Denver Basin is a Laramide-age basin that covers more than 180,000 square kilometers (70,000 square miles) (Higley and Cox, 2007) in parts of Colorado, Wyoming, South Dakota, Kansas, and Nebraska. The basin is often termed the Denver-Julesburg Basin, or the Denver-Julesburg-Wattenburg Basin. The bulk of the basin is in Colorado. In Wyoming, the Denver Basin is bounded on the west by the Laramie Range and on the north by the Hartville uplift (Fig. 10-1). For the purpose of this study, the basin boundary is defined by the 8-digit hydrologic unit to the west, the 12-digit hydrologic unit to the north, and the state boundary to the south and east.

The Denver Basin has typical foreland basin-style geometry (Plate 19). The basin axis trends north-south, and the strata on the western side of the basin dip steeply toward the east, or the basin axis. The strata in the eastern Denver Basin gently slope to the west. The basin is more than 3,962 m (13,000 feet) deep (Higley and Cox, 2007), as defined by the Precambrian basement dated as 1.6 billion years old (Plate 2) (Weimer and Sonnenberg, 1996). The bulk of the strata preserved in the Denver Basin were deposited during and after Laramide deformation, and are thus Cretaceous age and younger (Plates 1 and 20). Surface outcrops in the Denver Basin are generally Tertiary in age.

There are a handful of primarily north–south and east–west two-dimensional seismic lines that can be purchased from third party vendors (Fig. 10-2). Most of the seismic lines were optimized for imaging Upper Cretaceous reservoirs, as well as lineaments mapable with Landsat imagery and thought to control the location of oil trapping in the Niobrara Formation (i.e. Merin and Moore, 1986).

Storage in Saline Aquifers

The saline aquifers of the Denver Basin are not viable storage aquifers for CO_2. The steeply dipping strata of the western basin most likely cannot store CO_2 because they lack adequate traps and the existing traps are small. The shallowly dipping strata of the eastern basin allow for eastern migration of CO_2 to the surface and also do not have adequate traps.

Storage in Hydrocarbon Reservoirs

The Denver Basin is a noteworthy hydrocarbon-producing basin. Oil and gas was first discovered in the basin in 1901, which now houses approximately 1,500 hydrocarbon fields, spanning several states (Higley and Cox, 2007). The Denver Basin of Wyoming has 28 of these fields, two of which have produced less than 100 total barrels of oil (Wyoming Oil and Gas Conservation Commission, 2012). In 2011, there were 12 active oil and gas fields, and a sizeable wildcat well production of over 416.8 thousand barrels of oil and 315.2 million cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 2012).

The combined production in the Denver Basin of Wyoming, through 2011, was over 3 million barrels of oil and nearly 12.7 billion cubic feet of gas (Wyoming Oil and Gas Conservation Commission, 2012). However, production has fluctuated through the years. Oil production peaked in 1994, with 2.2 million barrels, while gas production peaked in 1995 with 1.6 billion cubic feet (Fig. 10-3).

The Silo field, discovered in 1983, is the largest field in the basin. Silo field is also the largest horizontally-drilled field in Wyoming (De Bruin, 2012), and has produced more than 10.4 million barrels of oil and 9.2 billion cubic feet of gas, or 30 percent of the basin's produced oil and nearly 73 percent of the produced gas (Wyoming Oil and Gas Conservation Commission, 2012).

Production in the Silo field is primarily from the Cretaceous Niobrara Formation, which is predominantly fractured chalk (reservoir) encased in tight shales and mudstones (seal). This unconventional

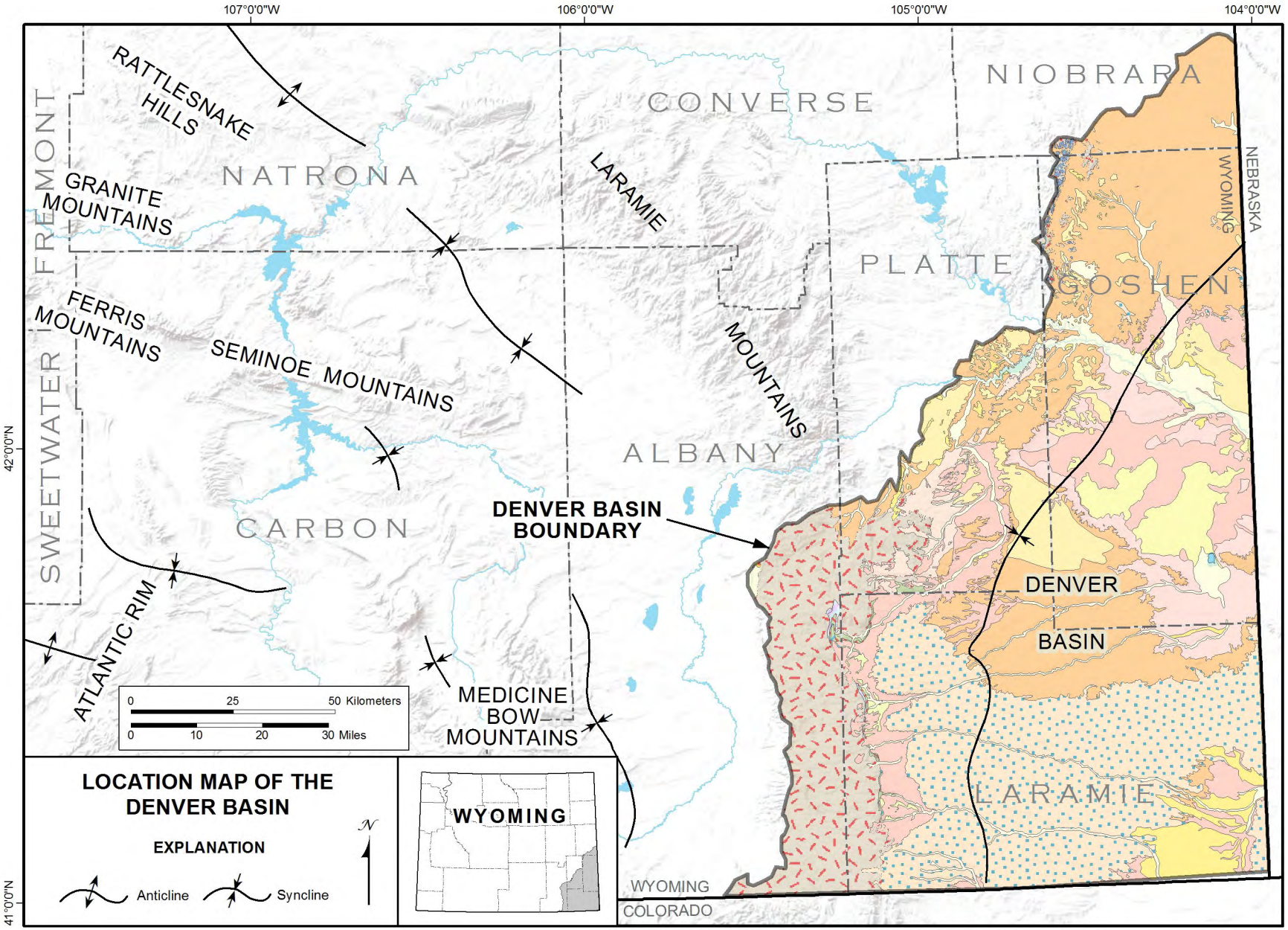


Figure 10-1. Location map of the Denver Basin. The Denver Basin is defined by the 8-digit hydrologic unit to the west, the 12-digit hydrologic unit to the north, and the state boundary to the south and east.

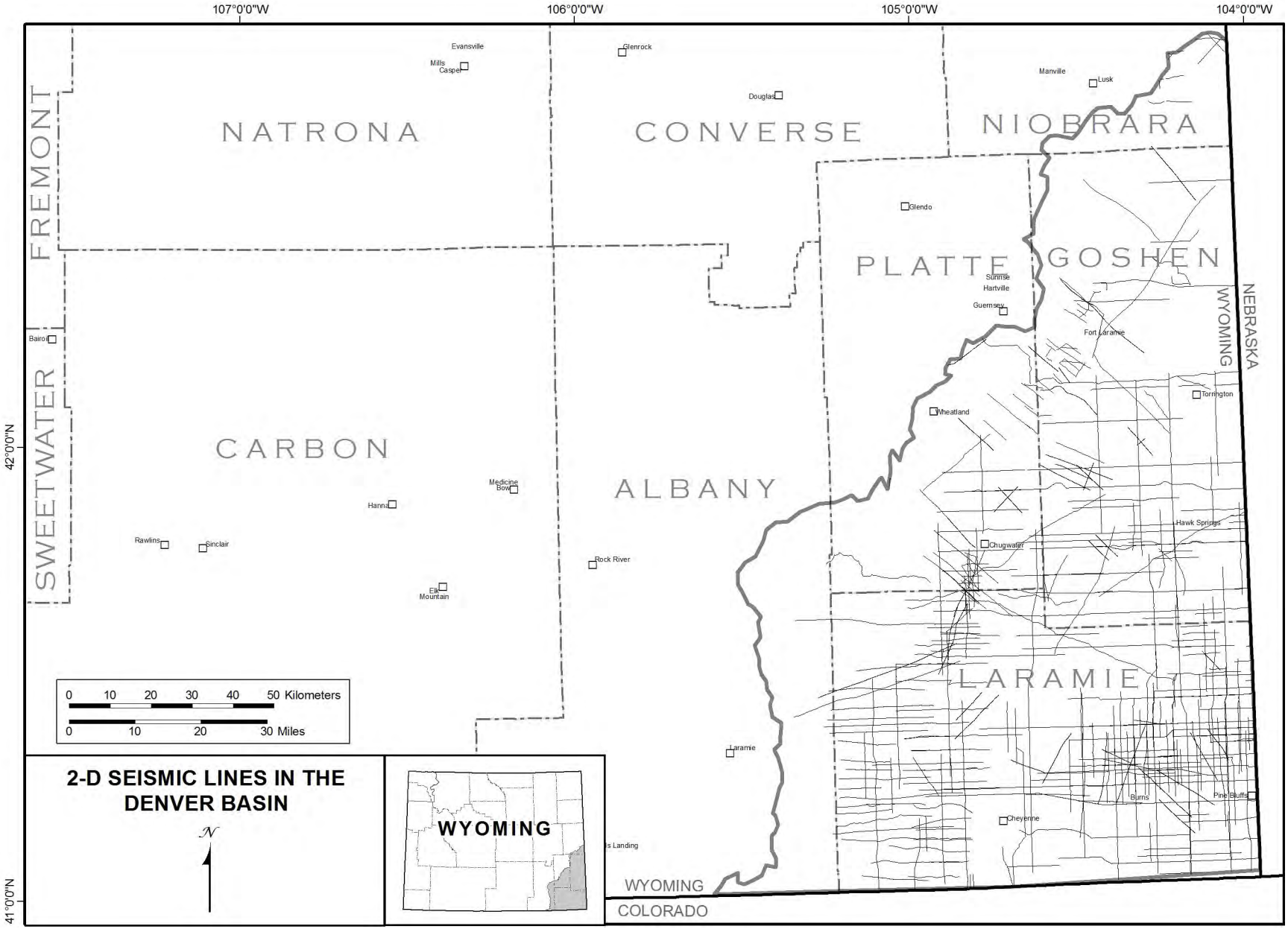


Figure 10-2. Map showing the location of 2-D seismic lines in the Denver Basin. The line locations were provided by and are available for purchase from Seismic Exchange, Inc. (2011).

reservoir is conducive to horizontal drilling that significantly enhances production, yet CO_2 storage in this type of reservoir is not efficient. Fractured reservoirs do not make ideal CO_2 storage zones. However, Silo field in particular may make an appropriate field for CO_2-EOR.

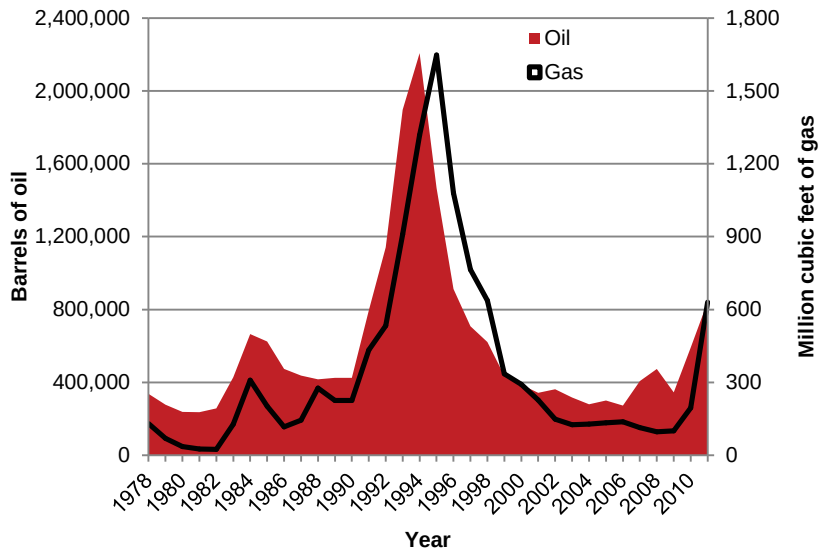


Figure 10-3. Oil and gas production for all fields in the Denver Basin, from 1978 through 2010. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

Storage through Enhanced Oil Recovery

Wo and others (2009) rank candidate reservoirs for CO_2-EOR in fields across Wyoming for both miscible and immiscible CO_2 flooding, based on technical feasibility. Their study finds six candidate reservoirs for miscible flooding, and none for immiscible flooding in the Denver Basin of Wyoming. Of the top 100 candidate EOR fields for miscible CO_2 flooding in Wyoming (by CO_2 volume), one is in the Denver Basin: Silo field. Minimum and maximum estimated total CO_2 demand for a miscible CO_2 flood in the Upper Cretaceous Niobrara Formation of Silo field (from Wo and others, 2009) is 26–39 billion cubic feet, respectively. Oil viscosity in this field is 35° API.

Wo and others (2009) estimate 0.08–0.12 trillion cubic feet (~4.2–6.2 million metric tons; 4.6–6.8 million short tons) of CO_2 could be required for CO_2-EOR in the Denver Basin (historically produced reservoirs, not including ROZs). These estimates are primarily from potential storage in the Silo field, but also include CO_2-EOR in five other fields.

The maximum CO_2 requirement suggested by Wo and others (2009) for the Denver Basin is approximately 6.2 million metric tons (6.8 million short tons). This volume is less than half the yearly CO_2 emissions for the largest Wyoming electricity-generating plants, including the Laramie River and Jim Bridger plants, and only 14 percent of the total 2011 CO_2 emissions from all Wyoming electricity-generating plants (Table 2-1 summarizes the 2011 CO_2 emissions for electricity-generating plants throughout Wyoming). The investment in infrastructure required to support a major CO_2-EOR operation with very little return on storage capacity is expensive. Consideration of the most optimistic storage scenario suggests there is not enough storage capacity to efficiently store CO_2 through CO_2-EOR in the Denver Basin of Wyoming.

Storage through Enhanced Coalbed Natural Gas Recovery

Although coal mining has occurred in a handful of locations in the Denver Basin of Colorado, there has been no coalbed natural gas development (Roberts, 2007). While there is a suggestion of coals in the Upper Cretaceous Lance Formation, the Denver Basin of Wyoming has seen neither coal mining (surface or underground) nor CBNG exploration. Carbon dioxide storage through CO_2-ECBM is unlikely to occur in the Denver Basin in the near future.

Chapter 11

Summary and Implications

Summary

Carbon dioxide is a greenhouse gas that is released to the atmosphere from natural and anthropogenic processes. One of the largest contributors to anthropogenic CO_2 emissions are electricity-generating power plants that burn fossil fuels. In Wyoming, most power plants burn coal. In 2011, Wyoming coal provided 86 percent of the electricity generated in Wyoming and seven percent of the electricity generated in the United States. As greenhouse gas emissions become more regulated, especially in the wake of the recently proposed U.S. Environmental Protection Agency rule regarding CO_2 emission standards for new power plants (EPA-HQ-OAR-2011-0660, March 27, 2012; delayed until April 13, 2013), managing CO_2 emissions will become crucial. The ability to capture, compress, and store CO_2 emissions from coal-fired power plants may become fundamental to Wyoming's future economy.

This study evaluates the geologic CO_2 storage capacity of Wyoming's Laramide basins and the feasibility of storing CO_2 within them. Laramide basins are fault-bounded structures formed during the Late Cretaceous to Early Eocene Laramide orogeny (~80–55 Ma). This assessment focuses on the Greater Green River, Wind River, Bighorn, Powder River, Hanna, and Denver basins. Each basin is assessed for storage in deep saline aquifers (assessment method described in Chapter 4), in hydrocarbon reservoirs (assessment method described in Chapter 4), through CO_2-EOR (reviewed from Wo and others, 2009, and described in Chapter 2), and through CO_2-ECBM (reviewed from Reeves, 2003, and described in Chapter 2). The results are summarized in the subsequent sections.

Greater Green River Basin

The Greater Green River Basin contains a collection of Laramide structural basins grouped within the hydrologic boundary of the Green River drainage area, encompassing the Green River, Great Divide, and Washakie basins in Wyoming, and the Sand Wash Basin in Colorado. These smaller Laramide basins are subdivided by the Rock Springs uplift, Wamsutter arch, Cherokee Ridge arch, and Sandy Bend arch. The Moxa arch divides the western flank of the Greater Green River Basin from the overthrust belt to the west.

The Greater Green River Basin contains extensive hydrocarbon reserves that have produced more than 911 million barrels of oil and 23 trillion cubic feet of gas from 283 fields since the early twentieth century. In addition to these hydrocarbon resources, coal is mined from both surface and subsurface mines, and natural gas is produced from coalbed natural gas wells. Furthermore, the Greater Green River Basin is home to one of the world's largest natural CO_2 accumulations, estimated at more than 100 trillion cubic feet, along the crest of the Moxa arch.

The principal conclusions from this study of the Greater Green River Basin are:

1. The Nugget Sandstone, Tensleep/Weber Sandstone, and Madison Limestone have the highest potential for long-term CO_2 storage.
2. Carbon dioxide storage is limited by the depth of these formations—most are greater than 3,962 m (13,000 feet) deep—requiring additional compression at the surface.
3. The Gypsum Spring, Dinwoody, and Jefferson formations are likely adequate confining zones.
4. Theoretical estimates of the CO_2 storage resource in saline aquifers average 1.9 billion metric tons (2.1 billion short tons).
5. Six of the most productive hydrocarbon fields that meet the depth criteria can theoretically store 49–295 million metric tons (54–325 million short tons) of CO_2, or 147 million metric tons (162 million short tons) using the modal value for CO_2 storage efficiency.
6. An estimated 52–72 million metric tons (57–79 million short tons) of CO_2 can be stored through CO_2-EOR.
7. 7.9 billion metric tons (8.7 billion short tons) of CO_2, or 9 percent of the U.S. total, could possibly be stored through CO_2-ECBM.
8. The Greater Green River Basin has the highest potential for safely storing CO_2 in deep saline aquifers of all the Laramide basins in Wyoming due to the presence of large sub-

surface structures such as the Rock Springs Uplift and the Moxa arch.

The Greater Green River Basin is unusual among Wyoming's Laramide basins because it has one of the world's largest accumulations of natural CO_2 and various anthropogenic point sources of CO_2, candidate (and demonstrated) EOR and ECBM fields, as well as two of the highest priority structures for deep saline aquifer storage. Paleozoic formations on the Rock Springs uplift and Moxa arch, and possibly the Jurassic Nugget Sandstone on the Moxa arch, have the potential to safely store CO_2 for a geologically significant period of time. The saline aquifers associated with the large anticlinal traps in the Greater Green River Basin will likely offer Wyoming's best prospects for economically-feasible large-scale geologic CO_2 storage in the future, although the economic viability of this storage is far from proven.

Wind River Basin

The Wind River Basin is a west–northwest elongate basin located in central Wyoming. The major basin structures are anticlines on the flanks of the basin. Oil and gas production in the Wind River Basin has not been as active as in some of the other Laramide basins of Wyoming, yet through 2011 a respectable 562.5 million barrels of oil and 5.2 trillion cubic feet of gas have been produced in 110 fields throughout the basin.

The principal conclusions from this study of the Wind River Basin are:

1. The most prolific oil-producing reservoirs, the Tensleep Sandstone, Phosphoria Formation, and Madison Limestone, have the highest potential for long-term CO_2 storage.
2. Median TDS concentrations reported for the potential Paleozoic storage aquifers are much less than 10,000 mg/L. Median concentrations of 812, 208, and 216 mg/L are reported for the Phosphoria-Park City, Tensleep, and Madison aquifers, respectively, classifying these aquifers as fresh to moderately saline and presenting substantial obstacles to permitting for Class VI CO_2 storage wells.
3. The Gypsum Spring Formation is likely an adequate confining zone.
4. Theoretical estimates of the CO_2 storage resource in saline aquifers average 2.9 billion metric tons (3.2 billion short tons).
5. The five largest hydrocarbon fields have a theoretical CO_2 storage resource of 7.3–44 million metric tons (8.0–49 million short tons), or 22 million metric tons (24 million short tons) considering only the modal value for CO_2 storage efficiency.
6. Additional CO_2 storage from CO_2-EOR operations are estimated at 62–94 million metric tons (68–103 million short tons).
7. CO_2-ECBM has the potential to store 1.4 billion metric tons (1.5 billion short tons) of CO_2, or 2 percent of the U.S. total.

It is difficult to make confident estimates of CO_2 storage for the Wind River Basin because there are too many unknowns. Requisite data are not available, the deep basin geometry is not well constrained, and existing hydrocarbon fields are old and poorly documented. This study currently provides the best possible assessment with the available data, but will need to be revised as more information is obtained.

From the available information, though, it is clear that there are better storage options in the Powder River, Greater Green River, and Bighorn basins. The basin structure and low TDS concentrations characteristic of the Wind River Basin significantly restrict storage potential in saline aquifers, and there are few hydrocarbon fields with historical production sufficient to consider CO_2 storage.

However, many of the oil fields are suited for CO_2-EOR. Enhanced oil recovery with CO_2 is currently employed in two fields in the Wind River Basin. It is possible that the pipeline infrastructure that supports CO_2-EOR in these fields could be expanded to provide CO_2 to other declining oil fields, yet the associated CO_2 storage resource is nearly negligible.

Bighorn Basin

The Bighorn Basin is a Laramide basin flanked by numerous anticlinal structures. These structures, in addition to a few stratigraphically controlled

reservoirs, have trapped large amounts of oil in 134 fields. Approximately 3.7 billion barrels of oil and 4.3 trillion cubic feet of gas have been produced in this basin through 2011.

The principal conclusions from this study in the Bighorn Basin are:

1. The most prolific oil-producing reservoirs, the Tensleep Sandstone, Phosphoria Formation, and Madison Limestone, have the highest potential for long-term CO_2 storage.
2. Most reservoirs and aquifers in the Bighorn Basin are subject to strong hydrodynamic flow conditions from recharged outcrops located on the periphery of the basin. These flow conditions result in a tilted oil-water contact in existing oil fields and may present a technical difficulty for CO_2 storage.
3. All Paleozoic aquifers in the Bighorn Basin report median TDS concentrations less than 10,000 mg/L, with samples from the Flathead (Cambrian) aquifer as low as 163 mg/L. Again, this presents substantial obstacles for obtaining the requisite permits for Class VI CO_2 storage wells
4. The Gypsum Spring and Dinwoody formations are likely adequate confining zones.
5. Theoretical estimates of the CO_2 storage resource in saline aquifers average nearly 6.3 billion metric tons (6.9 billion short tons).
6. Using only the mode value for CO_2 storage efficiency, it is estimated that the eight largest hydrocarbon fields can store 102 million metric tons (112 million short tons) of CO_2, with a range of 34–201 million metric tons (37–222 million short tons).
7. Estimates of CO_2 storage through CO_2-EOR are 620–930 million metric tons (683–1,025 million short tons).
8. CO_2 storage through CO_2-ECBM does not represent a significant storage resource.

CO_2-EOR is the most likely storage scenario for CO_2 in the Bighorn Basin, yet it faces the challenge of infrastructure. There are no CO_2 pipelines existing or planned for the Bighorn Basin. Furthermore, there is not a large anthropogenic point source of CO_2 conveniently located near the Bighorn Basin. If the infrastructure issue and CO_2 source can be resolved, CO_2-EOR in the Bighorn Basin could economically recover an additional 1.3–2 billion barrels of oil and store a significant volume of CO_2. Without a CO_2-delivery pipeline and an anthropogenic source of CO_2, however, long-term geologic storage of CO_2 in the Bighorn Basin may never be achievable for the purpose of reducing CO_2 emissions to the atmosphere.

Powder River Basin

The Powder River Basin is a large north–south-trending basin in northeast Wyoming and southeast Montana. The Powder River Basin of Wyoming has produced greater than 8 trillion cubic feet of gas and 2.9 billion barrels of oil in 688 fields since 1889.

The principal conclusions from this study of the Powder River Basin are:

1. The most prolific oil-producing reservoirs, the Minnelusa Formation and Madison Limestone, have the highest potential for long-term CO_2 storage.
2. Minnelusa and Madison (and equivalent) reservoirs report TDS concentrations as low as 600 mg/L on the basin margins and more than 10,000 mg/L in the basin center. The Madison Limestone is a significant drinking water aquifer on the basin margins. Carbon dioxide storage in these aquifers cannot impact freshwater resources, limiting potential storage to the deepest and most saline parts of the basin.
3. The Opeche Shale and laterally equivalent Goose Egg Formation are likely adequate confining zones.
4. Theoretical estimates of the CO_2 storage resource in saline aquifers average nearly 14.8 billion metric tons (16.3 billion short tons).
5. The eight largest hydrocarbon fields can theoretically store 10–61 million metric tons (11–67 million short tons) of CO_2, or 30 million metric tons (33 million short tons) using only the modal value for CO_2 storage efficiency.
6. Estimates of CO_2 storage through CO_2-EOR are 317–478 million metric tons (347–524 million short tons).

7. CO_2-ECBM has the potential to store 13.6 billion metric tons (15 billion short tons) of CO_2 in the Powder River Basin, or 15 percent of the U.S. total.

The calculated storage resource for deep saline aquifers in the Powder River Basin is from two to seven times larger than the storage resource of any of the other Laramide basins. Carbon dioxide, stored in this manner, would be injected east of the basin axis with the expectation of eastward migration. Reservoir fluids would need to be managed to maintain injection pressures. This would require thoughtful engineering, as there are no geologic structures to trap CO_2 in the basin. Although technically possible, appropriate economic incentives are lacking for this costly method of CO_2 storage.

It may be more likely that the Powder River Basin will host some of the first CO_2-ECBM projects in Wyoming. The extensive coal seams in the Powder River Basin region are ideally suited for CO_2-ECBM (assuming aquifer TDS concentrations are above 10,000 mg/L), yet low natural gas prices and large reserves recently discovered throughout the country are not encouraging ECBM projects. However, as natural gas supplies decrease and prices increase over the coming decades, CO_2-ECBM may be a viable technique for increasing methane recovery and storing CO_2 in the Powder River Basin.

Hanna Basin

The Hanna Basin is a small deep basin in central Wyoming. Total hydrocarbon production has remained below 10 million barrels of oil and just over 10 billion cubic feet of gas from 15 fields.

The principal conclusions from this study of the Hanna Basin are:

1. Geologic storage of CO_2 in the deep saline aquifers of the Hanna Basin is not feasible because of the structure and stratigraphy of the basin.
2. Existing oil and gas reservoirs are not large enough to support economic CO_2 storage.
3. There are no oil reservoirs in the Hanna Basin suitable for CO_2-EOR.
4. CO_2-ECBM has the potential to store 3.0 billion metric tons (3.3 billion short tons) of CO_2 in the Hanna Basin, or 3 percent of the U.S. total.

Of the possible CO_2 storage methods assessed in this study, only storage through CO_2-ECBM shows some signs of promise. However, there are presently no CBNG fields in the Hanna Basin. These fields must first be developed then produced through traditional recovery methods. Only then can CO_2-ECBM projects proceed.
This assessment finds that geologic CO_2 storage is not feasible, at the present time, in the Hanna Basin.

Denver Basin

The Denver Basin is a foreland-style basin in southeastern Wyoming. The Denver Basin produces hydrocarbons primarily from the Upper Cretaceous Niobrara Formation. The 28 fields of the basin produced 34.1 million barrels of oil and 12.7 billion cubic feet of gas through 2011.

The principal conclusions from this study of the Denver Basin are:

1. Geologic storage of CO_2 in the deep saline aquifers of the Denver Basin is not feasible because adequate geologic traps are absent.
2. Existing oil and gas reservoirs are not large enough to support economic CO_2 storage.
3. Estimates of CO_2 storage through CO_2-EOR are approximately 4.2–6.2 million metric tons (4.6–6.8 million short tons).
4. CO_2-ECBM does not represent a significant CO_2 storage resource in the Denver Basin.

The Denver Basin hosts one major oil and gas field: Silo field. Production in Silo field is from horizontal wells drilled into the Niobrara Formation that are fractured to release the oil and gas stored in the pore space. Although Silo field may benefit from CO_2-EOR, it is not suitable for CO_2 storage because of insignificant pore volume.

This assessment finds that geologic CO_2 storage is not feasible, at the present time, in the Denver Basin of Wyoming.

Implications

The long-term storage of CO_2 deep underground in geologic formations is a concept that has received much attention in the last decade. This concept has been tested in large projects outside the U.S., such as the Sleipner and Snøhvit projects in Norway, and In Salah in Algeria. The success of these projects makes it clear that geologic CO_2 storage can be technically accomplished, under ideal conditions.

In Wyoming, and potentially throughout the world, economics is the fundamental challenge to long-term geologic storage of CO_2. Estimates for the cost of geologic CO_2 storage vary widely and are site-specific (see Benson and Cook, 2005, for storage cost summary). Investment, operating, and monitoring costs can be significant and can only be offset with potential economic incentives, such as additional state and federal subsidies or natural changes in market conditions. Current market conditions in Wyoming as well as the rest of the United States are, in fact, economically prohibitive to CO_2 storage. Geologic CO_2 storage will not take place until it is economically feasible or required by regulations, which in turn could have a substantially negative impact on several key industries.

In addition to economic considerations, there are substantial second-order issues and challenges associated with geologic CO_2 storage that must be addressed before storage can occur in Wyoming. Storage in deep saline aquifers has been the subject of numerous investigations in Wyoming, and much was learned from the detailed study of CO_2 storage in the saline aquifers of the Rock Springs uplift in the Greater Green River Basin (Surdam and Jiao, 2007; Surdam and others, 2009; Campbell-Stone and others, 2010; Surdam and others, 2012). Specifically, these investigations led to the recognition that significant volumes of in situ highly saline water would be displaced by CO_2 injection. In most cases, the bowl-shaped geometry of the Laramide basins promotes lateral up-dip migration of buoyant CO_2. The primary hindrance to up-dip migration is formation fluids, or saline water. In the specific case of the doubly-plunging anticline of the Rock Springs uplift, CO_2 injectivity would need to be maintained by removing the in situ saline waters from the storage reservoir. For both cases, water production wells would need to be incorporated into the design, including a plan for management of the displaced saline waters. Water production and management is therefore essential to the CO_2 storage process in deep saline aquifers throughout Wyoming, and could present a substantial challenge.

Water salinity is also an issue for Class VI—geologic CO_2 sequestration—wells. Class VI well permits require storage beneath the lowest possible drinking water aquifer, in a zone with greater than 10,000 mg/L TDS concentration. The reported TDS concentrations from a handful of samples for the storage formations of interest within the basins are highly variable and frequently less than 10,000 mg/L. The variable and often low TDS concentrations may present regulatory hurdles.

If the issues for CO_2 storage in deep saline aquifers can be properly managed, Wyoming's Laramide basins have significant CO_2 storage potential. Considering the assessment method described in Chapter 4, as well as the assumptions summarized in Chapters 5–8, the sum of the average value of the storage resource of CO_2 in deep saline aquifers (S_{basin}) of the Greater Green River, Wind River, Bighorn, and Powder River basins, is nearly 26 billion metric tons (28.5 billion short tons) (Table 11-1). This mass of CO_2 is equivalent to almost 600 years of storage of CO_2 from Wyoming's power plants (Table 11-2), for 2011 emissions.

These calculations also suggest that the Powder River Basin has the largest potential CO_2 storage capacity for deep saline aquifers, followed by the Bighorn, Wind River, and finally Greater Green River basins. What these calculations do not show is that only the Greater Green River Basin has the geologic traps required for *significant* CO_2 storage, including the Rock Springs uplift, Moxa arch, and potentially the Wamsutter and Cherokee Ridge arches. These large-scale traps appear to be the highest potential storage locations for CO_2 in Wyoming, and if this is the case, calculations suggest 44 years of CO_2 storage from Wyoming's power plants in the Greater Green River Basin (Table 11-2). Further evaluation and characterization of these traps

Table 11-1. Summary of CO_2 storage resource for the Laramide basins of Wyoming.

Basin	S_{basin} [1]	S_{res} [2]	CO_2-EOR[3]	CO_2-ECBM[4]
	(million metric tons)			
Greater Green River	1,928	147	62	7,900
Wind River	2,913	22	78	1,400
Bighorn	6,271	102	775	—
Powder River	14,801	30	398	13,600
Hanna	—	—	5.2	3,000
Denver	—	—	—	—
Total	**25,913**	**301**	**1,318**	**25,900**

[1]Average

[2]Calculated using the modal E_{res} value of 0.03

[3]Demand, not storage, averaged for the range reported in Wo and others (2009)

[4]Summarized from Reeves (2003)

is essential to determine the extent of the obstacles associated with CO_2 storage in these locations. Possible and likely obstacles include extreme formation depths, inadequate porosity and permeability, fractured reservoirs, faulted and compartmentalized reservoirs, aquifer salinity below the required minimum concentration, and significant saline water production at the surface that will require an appropriate disposal solution, to name a few. Many of the issues associated with deep saline aquifers are shared with CO_2 storage in petroleum reservoirs. Class VI well permitting and aquifer TDS concentrations may be problematic, yet the most pressing issue is reservoir size. Although the reservoir storage capacity results presented in this assessment are conservative and based on current (not future) production (as summarized in Chapter 4), the selected fields can potentially store, at a maximum, less than 15 years of CO_2 emissions from fossil fuel power plants in Wyoming. In fact, the sum of the storage resource for the chosen reservoirs (S_{res}), for the modal efficiency factor (E_{res}) of 0.3, yields less than 7 years of CO_2 storage from all electricity-generating power plants in Wyoming (Table 11-2). This storage method may be the least attractive option because economics associated with storage of such small volumes of CO_2 in each individual field are likely prohibitive.

Table 11-2. Years of CO_2 storage for Wyoming power plant emissions, assuming annual emissions equal to the 2011 value of 43.7 million metric tons (48.2 million metric short tons).

Basin	S_{basin}	S_{res}	CO_2-EOR	CO_2-ECBM
	(years)			
Greater Green River	44	3.4	1.4	181
Wind River	67	0.50	1.8	32
Bighorn	144	2.3	18	—
Powder River	339	0.7	9.1	311
Hanna	—	—	0.12	69
Denver	—	—	—	—
Total	**593**	**6.9**	**30**	**593**

There are additional concerns regarding CO_2-EOR. All CO_2-EOR projects in Wyoming use CO_2 produced from the Moxa arch in western Wyoming. Producing CO_2 from a geologic source is in part contradictory to the purpose of CO_2 storage that is to prevent emissions of the greenhouse gas CO_2 to the atmosphere. CO_2 pipelines would need to transport anthropogenic CO_2 for EOR to reduce CO_2 emissions. Furthermore, CO_2-EOR projects use a considerable volume of CO_2, as reported by Wo and others (2009). The reported volumes are for total CO_2 demand and not storage. For the best-case scenario, where CO_2 demand equals CO_2 storage, CO_2-EOR projects in Wyoming could potentially store approximately 30 years of power plant emissions (Table 11-2), or 1.3 billion metric tons (1.4 billion short tons) (Table 11-1).

It is important to note, however, that in some cases CO_2-EOR can be economic. The cost associated with CO_2 transportation and injection can be offset by the additional oil recovered during the process. There are currently five CO_2-EOR projects in Wyoming, with a sixth to begin implementation in the near future. The capture and use of CO_2 from power plant emissions would likely be more costly than the current use of CO_2 from underground reservoirs. However, if the CO_2 emissions from electricity-generating power plants could be economically added to the CO_2 pipeline network throughout the state, EOR projects that use CO_2 would be the first successful anthropogenic CO_2 storage project in Wyoming. This is the most-likely storage scenario for CO_2 in Wyoming over the next decade.

Enhanced coalbed natural gas (methane) recovery using CO_2 has potential in Wyoming in the significant biogenic gas accumulations in the Upper Cretaceous and Tertiary formations of the Powder River Basin, as well as in the notable accumulations in the Greater Green River, Hanna, and Wind River basins. There are very few CO_2-ECBM projects in the U.S.–the most prominent are located in the San Juan Basin of northern New Mexico and southern Colorado–and the technology is still in the final development phases. There are currently no ECBM projects in Wyoming. CO_2-ECBM will likely become a more common approach for recovering additional methane from unmineable coal seams if there is a significant and long-term natural gas price increase. CBNG production in the Powder River Basin was down 11 percent in 2011 from 2010, due to falling gas prices. For now, natural gas reserves in Wyoming are large and it is cheaper to drill new natural gas wells than to enhance recovery in existing coal seams. Also, these coal seams often host freshwater aquifers, with TDS concentrations much below the requisite minimum of 10,000 mg/L. However, if CO_2-ECBM becomes more attractive in the future, and if aquifer considerations are disregarded, CO_2 can potentially be stored in coal beds in four of Wyoming's Laramide basins, holding 593 years of CO_2 emissions from electricity-generating power plants (Table 11-2).

Wyoming is in a complex position regarding long-term geologic CO_2 storage. Storing CO_2 underground is expensive, yet Wyoming could choose to employ this technology as a method to offset emissions from power plants that burn coal. With increased future regulations of greenhouse gas emissions, developing the technology to capture, compress, and store CO_2 emissions in geologic traps may be fundamental to Wyoming's future economy. This study raises significant issues and challenges that should be addressed in detail before proceeding with long-term geologic CO_2 storage in Wyoming. The future ability to capture and store power plant emissions could place Wyoming at the forefront of sustainable and economic electric power generation.

References

Anna, L.O., 2010, Geologic assessment of undiscovered oil and gas in the Powder River Basin Province, Wyoming and Montana, *in* U.S. Geological Survey Powder River Basin Assessment Team, Geologic assessment of undiscovered oil and gas resources in the Powder River Basin Province, Wyoming and Montana: U.S. Geological Survey Digital Data Series DDS-69-U, chap. 1, 97 p.

Arri, L.E., Yee, D., Morgan, W.D., and Jeansonne, M.W., 1992, Modeling coalbed methane production with binary gas sorption: Casper, Wy., Society of Petroleum Engineers, Rocky Mountain Regional Meeting, p. 459–472.

Bader, J.W., 2008, Structural and tectonic evolution of the Cherokee Ridge arch, south-central Wyoming; implications for recurring strike-slip along the Cheyenne belt suture zone: Contributions to Geology, v. 43, no. 1, p. 23–40.

Balch, A.H., 1988, Introduction to seismic-stratigraphic study of the Madison and associated aquifers, *in* Balch, A.H., ed., A seismic-stratigraphic investigation of the Madison and associated aquifers—Application to ground-water exploration, Powder River Basin, Montana–Wyoming: U.S. Geological Survey Professional Paper 1330, chap. 1, 4 p.

Bartos, T.T., Hallberg, L.L., and Clark, M.L., 2012, WBRB hydrogeologic units—Physical and chemical characteristics, *in* Copeland, D., ed., Available groundwater determination, Technical Memorandum, Wind/Bighorn River Basin water plan update, groundwater study, Level I (2008–2011): Prepared for the Wyoming Water Development Commission, by the Wyoming State Geological Survey, Laramie, Wy., chap. 7, [variously paged].

Becker, T.P., and Lynds, R., 2012, A geologic deconstruction of one of the world's largest natural accumulations of CO_2, Moxa arch, southwestern Wyoming: American Association of Petroleum Geologists Bulletin, v. 96, no. 9, p. 1643–1664.

Becker, T.P., McGroder, M.F., Rudolph, K., Hauge, T.A., and Fan, M., 2010, Paleogene influence of the Moxa arch on the architecture of the composite Darby-Hogsback-Prospect (DHP) thrust sheet near La Barge, Wyoming, U.S.A. [abs.]: New Orleans, La., American Association of Petroleum Geologists Annual Convention and Exhibition, v. 19, p. 23.

Benison, K.C., and Goldstein, R.H., 2000, Sedimentology of ancient saline pans—An example from the Permian Opeche Shale, Williston Basin, North Dakota, U.S.A.: Journal of Sedimentary Research, v. 70, no. 1, p. 159–169.

Bennion, B., and Bachu, S., 2005, Relative permeability characteristics for supercritical CO_2 displacing water in a variety of potential sequestration zones in the western Canada sedimentary basin: Dallas, Tx., Society of Petroleum Engineers Annual Technical Conference and Exhibition, Proceedings, SPE 95547, 15 p.

Bennion, D.B., and Bachu, S., 2008, Drainage and imbibition relative permeability relationships for supercritical CO_2/brine and H_2S/brine systems in intergranular sandstone, carbonate, shale, and anhydrite rocks: Society of Petroleum Engineers Reservoir Evaluation and Engineering, v. 11, no. 3, p. 487–496.

Benson, A.L., 1966, Devonian stratigraphy of western Wyoming and adjacent areas: American Association of Petroleum Geologists Bulletin, v. 50, no. 12, p. 2566–2603.

Benson, S., and Cook, P., 2005, Underground geological storage, *in* Metz, B., Davidson, O., de Coninck, H.C., Loos, M., and Meyer, L.A., eds., IPCC special report on carbon dioxide capture and storage: Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York, chap. 5, p. 195–276.

Bentley, R. and Lusk, A., 2008, Clean coal technology, carbon capture and sequestration, and enhanced oil recovery in Wyoming's Powder River Basin: Wyoming State Geological Survey Challenges in Geologic Resource Development 7, 20 p.

Blackstone, D.L., Jr., 1963, Development of geologic structures in central Rocky Mountains, *in* Childs, O.E., and Beebe, B.W., eds., Backbone of the Americas—Tectonic history from pole to pole: Tulsa, Ok., American Association of Petroleum Geologists Memoir, p. 160–179.

Blackwelder, E., 1918, New geological formations in western Wyoming: Journal of the Wash-

ington Academy of Sciences, v. 8, no. 13, p. 417–426.

Borgerding, J.H., 1989, Riverton Dome, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 404–409.

Borgerding, J.H., 1992, Bruff, *in* Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Casper, Wy., Wyoming Geological Association, p. 72–74.

Boyd, D.W., 1993, Paleozoic history of Wyoming, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir 5, p. 164–187.

Bredehoeft, J.D., 1964, Variation of permeability in the Tensleep Sandstone in the Bighorn Basin, Wyoming, as interpreted from core analyses and geophysical logs: U.S. Geological Survey Professional Paper 501-D, p. 166–170.

Brennan, S.T., Burruss, R.C., Merrill, M.D., Freeman, P.A., and Ruppert, L.F., 2010, A probabilistic assessment methodology for the evaluation of geologic carbon dioxide storage: U.S. Geological Survey Open-File Report 2010-1127, 31 p.

Brock, W.G., and Nicolaysen, J.G., 1975, Geology of the Brady unit, Sweetwater County, Wyoming, *in* Bolyard, D.W., ed., Deep drilling frontiers of the central Rocky Mountains: Rocky Mountain Association of Geologists, p. 225–237.

Brown, R.G., and Shannon, L.T., 1989, Madden (Greater)–Long Butte, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 293–295.

Bullock, J.M., and Wilson, W.H., 1969, Gypsum deposits in the Cody area, Park County, Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Preliminary Report 9, 12 p.

Burke, L.A., 2012, Migration rates and formation injectivity to determine containment time scales of sequestered carbon dioxide: U.S. Geological Survey Open-File Report 2012-1062, 23 p.

Burruss, R.C., Brennan, S.T., Freeman, P.A., Merrill, M.D., Ruppert, L.F., Becker, M.F., Herkelrath, W.N., Kharaka, Y.K., Neuzil, C.E., Swanson, S.M., Cook, T.A., Klett, T.R., Nelson, P.H., and Schenk, C.J., 2009, Development of a probabilistic assessment methodology for evaluation of carbon dioxide storage: U.S. Geological Survey Open-File Report 2009-1035, 81 p.

Burtner, R.L., and Warner, M.A., 1984, Hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek shales of the northern Rocky Mountain areas, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Symposium on hydrocarbon source rocks of the greater Rocky Mountain Region: Denver, Co., Rocky Mountain Association of Geologists, p. 449–467.

Burton, M., Kumar, N., and Bryant, S.L., 2008, Time-dependent injectivity during CO_2 storage in aquifers: Tulsa, Ok., Society of Petroleum Engineers, Symposium on Improved Oil Recovery, Proceedings, SPE 113937, 15 p.

Campbell-Stone, E., Lynds, R., Frost, C., Becker, T.P., and Diem, B., 2010, The Wyoming Carbon Underground Storage Project—Geologic characterization of the Moxa arch and Rock Springs uplift: Energy Procedia, v. 4, p. 4656–4663.

Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., 1989, Wyoming oil and gas fields symposium, Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, 558 p.

Cardinal, D.F., and Stewart, W.W., eds., 1979, Wyoming oil and gas fields symposium, Greater Green River Basin: Casper, Wy., Wyoming Geological Association, 428 p.

Carr-Crabaugh, M., and Dunn, T.L., 1996, Reservoir heterogeneity as a function of accumulation and preservation dynamics, Tensleep Sandstone, Bighorn and Wind River basins, Wyoming, *in* Longman, M.W., and Sonnenfeld, M.D., eds., Paleozoic systems of the Rocky Mountain Region: Society for Sedimentary Geology, Rocky Mountain Section, p. 305–320.

Carroll, A.R., and Bohacs, K.M., 2001, Lake-type controls on petroleum source rock potential in nonmarine basins: American Association of Petroleum Geologists Bulletin, v. 85, no. 6, p. 1033–1053.

Chamberlain, K.R., and Mueller, P.A., 2007, Oldest rocks of the Wyoming Craton, *in* Van Kranendonk, M.J., Smithies, R.H., and Bennett, V.C., eds.: Developments in Precambrian Geology, v. 15, p. 775-791.

Chapman, C.M., 1989, Hamilton Dome, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 219–224.

Clarey, K.E., Bartos, T., Copeland, D., Hallberg, L.L., Clark, M.L., Thompson, M.L., and Copeland, D., and Ewald, M., eds., 2010, Available groundwater determination, Technical Memorandum, Green River Basin Water Plan II, groundwater study, Level 1 (2007-2009): Prepared for the Wyoming Water Development Commission, by the Wyoming State Geological Survey, Laramie, Wy., 478 p., 8 pls.

Clarey, K.E., and Stafford, J.E., 2008, Chapter 3—Water production and quality, *in* Copeland, D.A., and Ewald, M.L., eds., Water associated with coal beds in Wyoming's Powder River Basin—Geology, hydrology, and water quality: Wyoming State Geological Survey Exploration Memoir No. 2, p. 111–161.

Claypool, G.E., Love, A.H., and Maughan, E.K., 1978, Organic geochemistry, incipient metamorphism and oil generation in black shale members of the Phosphoria Formation, western interior United States: American Association of Petroleum Geologists Bulletin, v. 62, no. 1, p. 98–120.

Clayton, J.L., and Ryder, R.T., 1984, Organic geochemistry of black shales and oils in the Minnelusa Formation (Permian and Pennsylvanian), Powder River Basin, Wyoming, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Denver, Co., Rocky Mountain Association of Geologists, p. 231–244.

Coalson, E.B., 1979a, Coal Gulch, *in* Cardinal, D.F., and Stewart, W.W., eds., Wyoming oil and gas fields symposium, Greater Green River Basin: Casper, Wy., Wyoming Geological Association, p. 102.

Coalson, E.B., 1979b, Echo Springs, *in* Cardinal, D.F., and Stewart, W.W., eds., Wyoming oil and gas fields symposium, Greater Green River Basin: Casper, Wy., Wyoming Geological Association, p. 102.

Coalson, E.B., Goolsby, S.M., and Franklin, M.H., 1994, Subtle seals and fluid-flow barriers in carbonate rocks, *in* Dolson, J.C., Hendricks, and M.L., Wescott, W.A., eds., Unconformity-related hydrocarbons in sedimentary sequences; guidebook for petroleum exploration and exploitation in clastic and carbonate sediments: Denver, Co., Rocky Mountain Association of Geologists, p. 45–58.

Continental Oil Company, 1968, Frannie Phosphoria-Tensleep engineering and geologic report: Joint Engineering and Geological Study, Frannie field area, Phosphoria-Tensleep Formation, Carbon County, Montana and Park County, Wyoming—Proposed Unitization, 17 p.

Covault, J.A., Buursink, M.L., Craddock, W.H., Merrill, M.D., Blondes, M.S., Gosai, M.A., and Freeman, P.A., 2012, Geologic framework for the national assessment of carbon dioxide storage resources—Bighorn Basin, Wyoming and Montana, *in* Geologic framework for the national assessment of carbon dioxide storage resources: U.S. Geological Survey Open-File Report 2012-1024-A, chap. A, 23 p.

Curry, W.H., III, 1992, Church Buttes, *in* Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Casper, Wy., Wyoming Geological Association, p. 100–102.

Cushing, E.M., 1977, Description of the Madison aquifer study, Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Open-File Report 77-0514, 8 p.

Darton, N.H., 1906, Geology of the Bighorn Mountains: U.S. Geological Survey Professional Paper 51, 129 p.

De Bruin, R.H., 2001, Carbon dioxide in Wyoming: Wyoming State Geological Survey Information Pamphlet 8, 9 p.

De Bruin, R.H., 2012, Oil and gas map of Wyoming: Wyoming State Geological Survey Map Series MS-55, scale 1:500,000.

Denbury Resources, Inc., 2012, Pipeline Projects, at http://www.denbury.com/index.php?id=137, accessed January 27, 2012.

Devlin, W. J., Rudolph, K. W., Shaw, C. A., and Ehman, K. D., 1993, The effect of tectonic and eustatic cycles on accommodation and sequence stratigraphic framework in the Upper Cretaceous foreland basin of southwestern Wyoming, *in* Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P., eds., Sequence stratigraphy and facies associations: Oxford, International Association of Sedimentologists Special Publication, v. 18, p. 501–520.

Dolton, G.L., Fox, J.E., Clayton, J.L., 1990, Petroleum geology of the Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 88-450-P, 64 p.

Downey, M.W., 1984, Evaluating seals for hydrocarbon accumulations: American Association of Petroleum Geologists Bulletin, v. 68, no. 11, p. 1752–1763

Doyle, A.B., de Vries, J.L., and Alban, D.J., 1987, Production statistics for the overthrust belt and Moxa arch: Casper, Wy., Wyoming Geological Association, 38th annual field conference, Guidebook, p. 245–252.

DuBois, D.P., Wynne, P.J., Smagala, T.M., Johnson, J.L., Engler, K.D., and McBride, B.C., 2004, Geology of Jonah field, Sublette County, Wyoming, *in* Robinson, J.W., and Shanley, K.W., eds., Jonah field—Case study of a giant tight-gas fluvial reservoir: Tulsa, Ok., American Association of Petroleum Geologists Studies in Geology 52 and Rocky Mountain Association of Geologists 2004 Guidebook, American Association of Petroleum Geologists, v. 52, p. 37–59.

Dyman, T.S., and Condon, S.M., 2007, 2005 geologic assessment of undiscovered oil and gas resources, Hanna, Laramie, and Shirley basins Province, Wyoming and Colorado, *in* U.S. Geological Survey Hanna, Laramie, and Shirley Basins Province Assessment Team, Petroleum systems and geologic assessment of undiscovered oil and gas, Hanna, Laramie, and Shirley basins Province, Wyoming and Colorado: U.S. Geological Survey Digital Data Series DDS-69-K, chap. 2, 62 p.

Edman, J.D., and Cook, L., 1992, Tip Top field—U.S.A. Wyoming-Utah-Idaho overthrust belt, Wyoming, *in* Foster, N.H., and Beaumont, E.A. comps., Structural Traps VII; AAPG treatise of petroleum geology, atlas of oil and gas fields: Tulsa, Ok., American Association of Petroleum Geologists Special Publication, v. A-25, p. 1–27.

Edman, J.D., and Surdam, R.C., 1984, Diagenetic history of the Phosphoria, Tensleep and Madison formations, Tip Top field, Wyoming, *in* McDonald, D.A., and Surdam, R.C., eds., Clastic diagenesis: Tulsa, Ok., American Association of Petroleum Geologists Memoir, v. 37, p. 317–345.

Feathers, K.R., Libra, R., and Stephenson, T.R., 1981, Occurrence and characteristics of ground water in the Powder River Basin, Wyoming: Water Resources Research Institute Report to U.S. Environmental Protection Agency, Contract Number G-008269-79, University of Wyoming, Laramie, Wy., V. I-A and I-B, 171 p.

Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., 2000, Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 1 and 2, 566 p.

Finn, T.M., and Johnson, R.C., 2005, Subsurface stratigraphic cross sections of Cretaceous and Lower Tertiary rocks in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah, *in* U.S. Geological Survey, Southwestern Wyoming Province Assessment Team, comp., Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, chap. 14, 12 p.

Finn, T.M., Johnson, R.C., and Roberts, S.B., 2005, The Mesaverde-Lance-Fort Union composite Total Petroleum System, Southwestern Wyoming Province, *in* U.S. Geological Survey

Southwestern Wyoming Province Assessment Team, comp., Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, chap. 10, 37 p.

Flores, R.M., 2004, Coalbed methane in the Powder River Basin, Wyoming and Montana—An assessment of the Tertiary-Upper Cretaceous Coalbed Methane Total Petroleum System, *in* U.S. Geological Survey Powder River Basin Province Assessment Team, Total Petroleum System and assessment of coalbed gas in the Powder River Basin Province, Wyoming and Montana: U.S. Geological Survey Digital Data Series DDS-69-C, chap. 2, 56 p.

Flores, R.M., Cavaroc, V.V., Jr., and Bader, L.R., 1999, Ferris and Hanna coal in the Hanna and Carbon basins, Wyoming—A synthesis: U.S. Geological Survey Professional Paper 1625-A, chap. HS, 49 p.

Foster, M.E., 2000, Hartzog Draw, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 1, p. 224–226.

Fox, J.E., and Dolton, G.L., 1996a, Petroleum geology of the Bighorn Basin, north-central Wyoming and south-central Montana, *in* Bowen, C.E., Kirkwood, S.C., and Miller, T.S., eds., Resources of the Bighorn Basin: Casper, Wy., Wyoming Geological Association, 47th annual field conference, Guidebook, p. 19–39.

Fox, J.E., and Dolton, G.L., 1996b, Wind River Basin Province (035), *in* Gautier, D.L., Dolton, G.L., Takashashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS-30, release 2, 21 p.

Fox, J.E., and Higley, D.K., 1996a, Structure-contour maps of the Powder River Basin, Montana and Wyoming: U.S. Geological Survey Oil and Gas Investigation Chart 147-A.

Fox, J.E., and Higley, D.K., 1996b, Isopach maps of the Powder River Basin, Montana and Wyoming: U.S. Geological Survey Oil and Gas Investigation Chart 147-B.

Fox, J.E., Lambert, P.W., Mast, R.F., Nuss, N.W., and Rein, R.D., 1975, Porosity variation in the Tensleep and its equivalent the Weber Sandstone, western Wyoming—A log and petrographic analysis, *in* Boylard, D.W., ed., Symposium on deep drilling frontiers of the central Rocky Mountains: Steamboat Springs, Co., Rocky Mountain Association of Geologists, p. 185–216.

Frerichs, K.J., 1982, Waterflood pilot project, basal Amsden Formation, Hamilton Dome field, Hot Springs County, Wyoming: Denver, Co., ARCO Oil and Gas Company Engineering Report, Rocky Mountain District, 44 p.

Gale, J., and Freund, P., 2001, Coal-bed methane enhancement with CO_2 sequestration worldwide potential: Environmental Geosciences, v. 8, no. 3, p. 210–217.

Glass, G.B., and Roberts, J.T., 1978, Update on the Wind River coal basin, *in* Boyd, R.G., Bogerg, W.W., and Olson, G.M., eds., Resources of the Wind River Basin: Casper, Wy., Wyoming Geological Association, 30th annual field conference, Guidebook, p. 363–377.

Glass, G.B., Westervelt, K., and Oviatt, C.G., 1975, Coal mining in the Bighorn coal basin of Wyoming, *in* Geology and mineral resources of the Bighorn Basin: Casper, Wy., Wyoming Geological Association, 27th annual field conference, Guidebook, p. 221–228.

Goolsby, J.E., and Finley, G.D., 2000, Kitty, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 1, p. 264–266.

Gouger, B.I., 1989, Poison Spider West, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 380–383.

Grabowski, G.J., Jr., and Bohacs, K.M., 1996, Controls on compositions and distributions of lacustrine organic-rich rocks of the Green River Formation, Wyoming [abs.]: San Diego, Ca., American Association of Petroleum Ge-

ologists and Society of Economic Paleontologists and Mineralogists Annual Meeting, v. 5, p.55.

Graham, A.T., Jr., 2000a, Powell, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 1, p. 366–367.

Graham, A.T., Jr., 2000b, Spearhead Ranch, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 2, p. 476–477.

Gutschick, R.C., and Sandberg, C.A., 1983, Mississippian continental margins of the conterminous United States, *in* Stanley, D.J., and Moore, G.T., eds., The shelfbreak—Critical interface on continental margins: Tulsa, Ok., Society of Economic Paleontologists and Mineralogists Special Publication, v. 33, p. 79–96.

Hansen, D.E., 1986, Laramide tectonics and deposition of the Ferris and Hanna formations, south-central Wyoming: Tulsa, Ok., American Association of Petroleum Geologists Memoir 41, p. 481–495.

Hares, C.J., 1947, A history of the oil business in the Bighorn Basin, Wyoming: Wyoming Geological Association, 2nd annual field conference, Guidebook, p. 198–209.

Henry, M., and Logan, A., 1992, Wild Rose, *in* Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Casper, Wy., Wyoming Geological Association, p. 356–358.

Herrod, W.H., 1980, Relationship of Cottonwood Creek field, Washakie County, Wyoming to carbonate facies of Permian Goose Egg Formation, eastern Bighorn Basin: Wyoming Geological Association, 31st annual field conference, Guidebook, p. 67–89.

Hettinger, R.D., Honey, J.G., and Nichols, D.J., 1991, Chart showing correlations of Upper Cretaceous Fox Hills Sandstone and Lance Formation, and Lower Tertiary Fort Union, Wasatch, and Green River formations, from the eastern flank of the Washakie Basin to the southeastern part of the Great Divide Basin, Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-2151.

Hickling, N.L., Warlow, R.C., and Windolph, J.F., Jr., 1989, Geology of the Upper Cretaceous and Tertiary coal-bearing rocks in the western part of the Wind River Basin, Wyoming: U.S. Geological Survey Bulletin 1813, 128 p.

Higley, D.K., and Cox, D.O., 2007, Oil and gas exploration and development along the Front Range in the Denver Basin of Colorado, Nebraska, and Wyoming, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Denver Basin Province, Colorado, Kansas, Nebraska, South Dakota, and Wyoming—USGS Province 39: U.S. Geological Survey Digital Data Series DDS-69-P, chap. 2, 41 p.

Hodson, W.G., Pearl, R.H., and Druse, S.A., 1973, Water resources of the Powder River Basin and adjacent areas, northeastern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-465, 4 sheets, scale 1:250,000.

Horn, B.W., and Schrooten, R.A., 2001, Development of the Echo Springs–Standard Draw field area—Using technology to enhance an infill program, Washakie Basin, Wyoming, *in* Anderson, D.S., Robinson, J.R., Estes-Jackson, J., and Coalson, E.B., eds., Gas in the Rockies: Denver, Co., Rocky Mountain Association of Geologists, chap. 12, p.171–188.

Hubbert, M.K., 1953, Entrapment of petroleum under hydrodynamic conditions: American Association of Petroleum Geologists Bulletin, v. 37, no. 8, p. 1954–2026.

Hughes, L., 1983, Case histories of an electromagnetic method for petroleum exploration: Prepared by Zonge Engineering and Research Organization, Inc., Tucson, Az., 332 p.

IHS Energy Group, 2011 [includes data current as of December, 2011], Interpreted tops/GDS/Green River Basin: Database available from IHS Global, 15 Inverness Way East, Englewood, Co., 80112, U.S.A.

Imlay, R.W., 1950, Jurassic rocks in the mountains along the west side of the Green River Basin: Casper, Wy., Wyoming Geological Association, 5th annual field conference, Guidebook, p. 37–48.

Imlay, R.W., 1967, Twin Creek Limestone (Jurassic) in the western interior of the United States: U.S. Geological Survey Professional Paper 540, 16 pls., 105 p.

Jepsen, G.L., 1940, Paleocene faunas of the Polecat Bench Formation, Park County, Wyoming: Proceedings of the American Philosophical Society, v. 83, no. 2, p. 217–340.

Johnson, R.C., 2005, Geologic assessment of undiscovered oil and gas resources in the Phosphoria Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah, *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, chap. 4, 46 p.

Johnson, R.C., Finn, T.M., Kirschbaum, M.A., Roberts, S.B., Roberts, L.N.R., Cook, T., and Taylor, D.J., 2007, The Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin, Wyoming, *in* U.S. Geological Survey Wind River Basin Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Wind River Basin Province, Wyoming: U.S. Geological Survey Digital Data Series DDS-69-J, chap. 4, 96 p.

Johnson, R.C., Finn, T.M., and Roberts, L.N.R., 2005, The Mesaverde Total Petroleum System, southwestern Wyoming Province, *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, chap. 8, 38 p.

Jones, N., Jones, R., Scott, J., and Lucke, D., 2009, Coal map of Wyoming: Wyoming State Geological Survey Map Series MS-93, scale 1:500,000.

Keefer, W.R., 1969, Geology of petroleum in Wind River Basin, central Wyoming: American Association of Petroleum Geologists Bulletin, v. 53, no. 9, p. 1839–1865.

Keefer, W.R., and Van Lieu, J.A., 1966, Paleozoic formations in the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495-B, 60 p.

Kirschbaum, M.A., Lillis, P.G., and Roberts, L.N.R., 2007, Geologic assessment of undiscovered oil and gas resources in the Phosphoria Total Petroleum System of the Wind River Basin Province, *in* U.S. Geological Survey Wind River Basin Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Wind River Basin Province, Wyoming: U.S. Geological Survey Digital Data Series DDS-69-J, chap. 3, 27 p.

Koperna, G.J., and Kuuskraa, V.A., 2006, Technical oil recovery potential from residual oil zones—Big Horn Basin: Prepared for the U.S. Department of Energy, Office of Fossil Energy, Office of Oil and Natural Gas, by Advanced Resources International, Arlington, Va., 30 p.

Kraig, D.H., Wiltschko, D.V., and Spang, J.H., 1987, Interaction of basement uplifted and thin-skinned thrusting, Moxa arch and the western overthrust belt, Wyoming—A hypothesis: Geological Society of America Bulletin, v. 99, p. 654–662.

Lange, A., 2000, Hilight, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 2, p. 234–235.

Law, B.E., 1988, Geologic framework and hydrocarbon plays in the Southwestern Wyoming Basins Province: U.S. Geological Survey Open-File Report 88-450-F, 29 p.

Law, B.E., 1996, Southwestern Wyoming Province (037), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 national assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS-30, release 2, 34 p.

Lawson, D.E. 1989, Grieve, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 212–213.

Lawson, D.E., and Smith, J.R., 1966, Pennsylvanian and Permian influence on Tensleep oil accumulation, Bighorn Basin, Wyoming:

American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2197–2220.

Lehman, D.D., 1979, LaBarge, *in* Cardinal, D.F., and Stewart, W.W. eds., Wyoming oil and gas fields symposium, Greater Green River Basin: Casper, Wy., Wyoming Geological Association, p. 208–210.

Li, S., Zhang, Y., and Zhang, X., 2011, A study of conceptual model uncertainty in large-scale CO_2 storage simulation: Water Resources Research, v. 47, W05534, doi:10.1029/2010WR009709.

Lim, F.H., and Ramsey, H.N., 2006, The Monell unit of the Patrick Draw field, Wyoming—CO_2 flood in an old field using new technology [abs.]: Billings, Mt., American Association of Petroleum Geologists Rocky Mountain Section Meeting, 1 p.

Lindeberg, E., 2002, The quality of a CO_2 repository—What is the sufficient retention time of CO_2 stored underground?, *in* Gale, J., and Kaya, Y., eds., 6th Greenhouse Gas Control Technologies Conference, Proceedings: Kyoto, Japan, Elsevier, p. 255–260.

Love, J.D., 1948, Mesozoic stratigraphy of the Wind River Basin, central Wyoming: Wyoming Geological Association, 3rd annual field conference, Guidebook, p. 96–111, 1 pl.

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., comps., 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-41.

Lynds, R., Campbell-Stone, E., Becker, T.P., and Frost, C.D., 2010, Stratigraphic evaluation of reservoir and seal in a natural CO_2 field—Lower Paleozoic, Moxa arch, southwest Wyoming: Rocky Mountain Geology, v. 45, no. 2, p. 113–132.

Mankiewicz, D., and Steidtmann, J.R., 1979, Depositional environments and diagenesis of the Tensleep Sandstone, eastern Bighorn Basin, Wyoming: Society of Economic Paleontologists and Mineralogists Special Publication 26, p. 319–336.

Marathon Oil Company, 1989a, Byron, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 76–78.

Marathon Oil Company, 1989b, Garland, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 182–187.

Marathon Oil Company, 1989c, Grass Creek, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 202–205.

Marathon Oil Company, 1989d, Oregon Basin, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 243–248, 2 pls.

Maughan, E.K., 1976, Organic carbon and selected element distribution in the phosphatic shale members of the Permian Phosphoria Formation, eastern Idaho and parts of adjacent states: U.S. Geological Survey Open-File Report 76-577, 92 p.

Maughan, E.K., 1983, Tectonic setting of the Rocky Mountain Region during the Late Paleozoic and the Early Mesozoic, *in* Symposium on the genesis of Rocky Mountain ore deposits—Changes with time and tectonics: Denver, Co., Denver Regional Exploration Geologists Society, Proceedings, p. 39–50.

Masursky, H., 1962, Uranium-bearing coal in the eastern part of the Red Desert area, Wyoming: U.S. Geological Survey Bulletin 1099-B, 152 p.

McCaleb, J.A., and Wayhan, D.A., 1969, Geologic reservoir analysis, Mississippian Madison Formation, Elk Basin field, Wyoming–Montana [Part 1]: American Association of Petroleum Geologists Bulletin, v. 53, no. 10, p. 2094–2113.

Melick, J.J., Gardner, M.H., and Uland, M.J., 2009, Incorporating geologic heterogeneity in 3D basin-scale models for CO_2 sequestration—Examples from the Powder River Basin, NE Wyoming and SE Montana [abs.]: San

Diego, CA, Society of Petroleum Engineers, International Conference on CO_2 Capture, Storage, and Utilization, presentation, SPE 126443.

Merin, I.S., and Moore, W.R., 1986, Application of Landsat imagery to oil exploration in Niobrara Formation, Denver Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 70, no. 4, p. 351–359.

Merrill, M.S., Covault, J.A., Craddock, W.H., Slucher, E.R., Warwick, P.D., Blondes, M.S., Gosai, M.A., Freeman, P.A., Cahan, S.M., and Lohr, C.D., 2012, Geologic framework for the national assessment of carbon dioxide storage resources—Hanna, Laramie, and Shirley basins, Wyoming, *in* Warwick, P.D., and Corum, M.D., eds., Geologic framework for the national assessment of carbon dioxide storage resources: U.S. Geological Survey Open-File Report 2012-1024-C, 24 p.

Miller, J.J., Lee, M.W., Ryder, R.T., and Balch, A.H., 1996, National energy research seismic library—Powder River Basin, Montana–Wyoming—Surface reflection and vertical seismic profile data used in seismic stratigraphic investigations for ground-water aquifers and hydrocarbon traps: U.S. Geological Survey Digital Data Series DDS-32.

Miller, R., 1989, Steamboat Butte, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 484–489.

Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., 1992, Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Casper, Wy., Wyoming Geological Association, 372 p.

Mills, N.K., 1956, Subsurface stratigraphy of the pre-Niobrara formations in the Bighorn Basin, Wyoming, in Wyoming stratigraphy, Part I: Wyoming Geological Association Nomenclature Committee, p. 9–22.

Momper, J.A., and Williams, J.A., 1984, Geochemical exploration in the Powder River Basin, *in* Demaison, G., and Murris, R.J., eds., Petroleum geochemistry and basin evaluation: Tulsa, Ok., American Association of Petroleum Geologists Memoir 35, p. 181–191.

Montgomery, S.L., 1996, Brady unit, Rock Springs uplift, Wyoming—Migration and structural history: American Association of Petroleum Geologists Bulletin, v. 80, no. 10, p. 1535–1546.

Mullen, C., 1989, Dallas, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 114–116.

Murrell, G., 2011, Wyoming CO_2 market status and developments: Casper, Wy., 5th Annual Wyoming CO_2 Conference, at http://www.uwyo.edu/eori/_files/co2conference11/glen - market intell.pdf, accessed October 25, 2011.

Nelson, C.R., Steadman, E.N., and Harju, J.A., 2005, Geologic CO_2 sequestration potential of the Wyodak-Anderson coal zone in the Powder River Basin: Plains CO_2 Reduction (PCOR) Partnership, 23 p.

Nevarez, J.J., 2009, Implementing surveillance tools and processes to improve performance and identify possible opportunities in mature CO_2 floods: Casper, Wy., 3rd Annual Wyoming CO_2 Conference, at http://www.uwyo.edu/eori/_files/co2conference09/juan nevarez wyoming eor conference-final.pdf, accessed October 25, 2011.

Obert, K.R., and Mather, T.T., 2000, Salt Creek, *in* Finley, A.K, Miller, T.S., Cardinal, D.E., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium Powder River Basin: Casper, Wy., Wyoming Geological Association, p. 424–429.

Odland, S.K., Patterson, P.E., and Gustason, E.R., 1988: Casper, Wy., Wyoming Geological Association, 39th annual field conference, Guidebook, p. 147–160.

Odom, I.E., Doe, T.W., and Dott, R.H., Jr., 1976, Nature of feldspar-grain size relations in some quartz-rich sandstones: Journal of Sedimentary Petrology, v. 46, no. 4, p. 862–870.

O'Keefe, M.E., 1989, Sage Creek, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper,

Wy., Wyoming Geological Association, p. 420–422.

Oriel, S.S., 1963, Preliminary geologic map of the Fort Hill quadrangle, Lincoln County, Wyoming: U.S. Geological Survey Oil and Gas Investigations Map OM-212.

Paull, R.K., Paull, R.K., and Kraemer, B.R., 1989, Depositional history of Lower Triassic rocks in southwestern Montana and adjacent parts of Wyoming and Idaho, *in* French, D.E, and Grabb, R.F., eds., Geologic resources of Montana: Montana Geological Society, 1989 field conference, Guidebook, v. 1, p. 69–90.

Peale, A.C., 1893, The Paleozoic section in the vicinity of Three Forks, Montana: U.S. Geological Survey Bulletin B 0110, 56 p.

Partridge, L.R., 1949, The Phosphoria and Dinwoody formations, northern Bighorn Basin, Wyoming and Montana: MS thesis, University of Wyoming, Laramie, 75 p., 5 pls,

Perry, W.J., Jr., and Flores, R.W., 1997, Sequential Laramide deformation and Paleocene depositional patterns in deep gas-prone basins of the Rocky Mountain region, *in* Dyman, T.S., Rice, D.D., and Westcott, P.A., eds., Geologic controls of deep natural resources in the United States: U.S. Geological Survey Bulletin B 2146, p. 49–59.

Peterson, C., 2009, The Beaver Creek field Madison CO_2 project—Spring 2009 update: 3rd Annual Wyoming CO_2 Conference, Casper, Wy., at http://www.uwyo.edu/eori/_files/co2conference09/chuck peterson wyoming eor producers meeting presentation 6-23-09 project update.pdf, accessed August 29, 2012.

Peterson, J.A., 1957, Gypsum Spring and Sundance formations, central Wyoming: Wyoming Geological Association, 12th annual field conference, Guidebook, p. 47–54.

Peterson, J.A., 1984, Permian stratigraphy, sedimentary facies, and petroleum geology, Wyoming and adjacent area: Wyoming Geological Association, 35th annual field conference, Guidebook, v. 35, p. 25–64.

Picard, M.D., 1977, Petrology of the Jurassic nugget sandstone, northeast Utah and southwest Wyoming: Wyoming Geological Association, 29th annual field conference, Guidebook, p. 239–258.

Picard, M.D., 1993, The early Mesozoic history of Wyoming, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M.,eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir 5, v. 1, p. 210–248.

Pierce, B.S., 1996, Quality and petrographic characteristics of Paleocene coals from the Hanna Basin, Wyoming: Jackson, Wy., 12th Annual Meeting of the Society of Organic Petrology, Organic Geochemistry, v. 24, no. 2, p. 181–187.

Piper, D.Z., and Link, P.K., 2002, An upwelling model for the Phosphoria sea—A Permian, ocean-margin sea in the northwest United States: American Association of Petroleum Geologists Bulletin, v. 86, no. 7, p. 1217–1235.

Pranter, M.J., Reza, Z.A., and Budd, D.A., 2006, Reservoir-scale characterization and multiphase fluid-flow modeling of lateral petrophysical heterogeneity within dolomite facies of the Madison Formation, Sheep Canyon and Lysite Mountain, Wyoming, USA: Petroleum Geoscience, v. 12, no. 1, p. 29–40.

Reeves, S.R., 2003, Assessment of CO_2 sequestration and ECBM potential of U.S. coalbeds: U.S. Department of Energy Topical Report DE-FC26-00NT40924, February, 48 p.

Richards, R.W., and Mansfield, G.R., 1911, Phosphates—Preliminary report on a portion of the Idaho phosphate reserve: U.S. Geological Survey Bulletin B 0470-H, p. 371–439.

Ritzma, H.R., 1963, Geology and occurrence of oil and gas, Wamsutter arch, Wyoming, *in* Childs, O.E., and Beebe, B.W., eds., Backbone of the Americas—Tectonic history from pole to pole: Tulsa, Ok., American Association of Petroleum Geologists Memoir, p. 188–195.

Ritzma, H.R., 1968, Geology and occurrence of gas, Wamsutter arch, Sweetwater County, Wyoming, *in* Beebe, B.W., and Curtis, B.F., eds., M9—Natural gases of North America, Volume 1: Tulsa, Ok., American Association of Petroleum Geologists Memoir, p. 817–827.

Roberts, S.B., 2005a, Geologic assessment of undiscovered petroleum resources in the Lance-Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming and Colorado, *in* U.S. Geological

Survey Southwestern Wyoming Province Assessment Team, petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, chap. 11, 40 p.

Roberts, S.B., 2005b, Geologic assessment of undiscovered petroleum resources in the Wasatch-Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah, *in* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D, chap.12, 22 p.

Roberts, S.B., 2007, Coal in the Front Range urban corridor—An overview of coal geology, coal production, and coal-bed methane potential in selected areas of the Denver Basin, Colorado, and the potential effects of historical coal mining on development and land-use planning, *in* Higley, D.K., comp., Petroleum systems and assessment of undiscovered oil and gas in the Denver Basin Province, Colorado, Kansas, Nebraska, South Dakota, and Wyoming—USGS Province 39: U.S. Geological Survey Digital Data Series DDS-69-P, chap. 3, 45 p.

Roberts, S,B., and Rossi, G.S., 1999, A summary of coal in the Fort Union Formation (Tertiary), Bighorn Basin, Wyoming and Montana, *in* Fort Union Coal Assessment Team, 1999 resource assessment of selected Tertiary coal beds and zones in the northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625-A, chap. SB, 33 p.

Robertson, E.P., 2009, Economic analysis of carbon dioxide sequestration in Powder River Basin coal: International Journal of Coal Geology, v. 77, no. 1-2, p. 234–241.

Robertson, E.P., 2010, Enhanced coal bed methane recovery and CO_2 sequestration in the Powder River Basin: Big Sky Carbon Sequestration Partnership—Phase II [Deliverable Gd10], prepared for the U.S. Department of Energy, Contract DE-AC07-05ID14517, 25 p.

Robinson, L., 1992a, Brady North, *in* Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Wyoming Geological Association, p. 57–60.

Robinson, L., 1992b, Brady South, *in* Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Casper, Wy., Wyoming Geological Association, p. 60–62.

Robinson, L., and Roehler, H.W., 1979, Hypothetical coal resources of the Almond Formation in the Rock Springs coal field, Wyoming: U.S. Geological Survey Open-File Report 79-588, 11 p.

Robinson, J.W., and Shanley, K.W., 2004, Jonah field—T28-29N, R107-109W, Sublette County, Wyoming, *in* Robinson, J.W., and Shanley, K.W., eds., Jonah field—Case study of a giant tight-gas fluvial reservoir: Tulsa, Ok., American Association of Petroleum Geologists Studies in Geology 52 and Rocky Mountain Association of Geologists, Guidebook, v. 52, chap. 2, p. 5–8.

Roehler, H.W., 1990, Stratigraphy of the Mesaverde Group in the central and eastern Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Professional Paper P 1508, 52 p.

Roehler, H.W., 1992, Introduction to the Greater Green River Basin geology, physiography, and history of investigations: U.S. Geological Survey Professional Paper P 1506-A, 14 p.

Root, F.K., Glass, G.B., and Lane, D.W., 1973, Sweetwater County, Wyoming, Geologic map atlas and summary of economic mineral resources: Geological Survey of Wyoming [Wyoming State Geological Survey] County Resource Series 2, scale 1:500,000.

Roux, B., and Andersen, J. 2010, Salt Creek and Monell CO_2 projects—Status update and 4D seismic applications: Casper, Wy., 4th Annual Wyoming CO_2 Conference, at http://www.uwyo.edu/eori/_files/co2conference10/andarko 20pdf 20eori 202010 20062510 20pdf.pdf, accessed September 7, 2012.

Rowley, P.D., Hansen, W.R., Tweto, O., and Carrara, P.E., 1985, Geologic map of the Vernal

1°x2° quadrangle, Colorado, Utah, and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series I:1526, scale 1:250,000.

Royse, F., Jr., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir 5, v. 1, p. 272–311.

Sando, W.J., 1976, Mississippian history of the northern Rocky Mountains region: Journal of Research of the U.S. Geological Survey, v. 4, no. 3, p. 317–338.

Sando, W.J., and Bamber, E.W., 1985, Coral zonation of the Mississippian system in the western interior province of North America: U.S. Geological Survey Professional Paper P 1334, p 61.

Sando, W.J., and Sandberg, C.A., 1987, New interpretations of Paleozoic stratigraphy and history in the northern Laramie Range and vicinity, southeast Wyoming: U.S. Geological Survey Professional Paper P 1450, 39 p.

Schulte, R., and Black, B., 2011, Grieve field CO_2 project—2011 status report: Casper, Wy., 5th Annual Wyoming CO_2 Conference, at http://www.uwyo.edu/eori/_files/co2conference11/brian - grievefield_co2update-eori_july2011.pdf, accessed August 27, 2012.

Schlumberger, 2012, Schlumberger oilfield glossary—Normal pressure, at http://www.glossary.oilfield.slb.com/Display.cfm?Term=normal pressure, accessed July 27, 2012.

Scientific Software of Canada, LTD, 1975, Reservoir simulation study II Brady field, south Weber reservoir: Report to Champlin Petroleum Company, 151 p., at http://wogcc.state.wy.us, accessed July 15, 2012.

Seaber, P.R., Kapinos, F.P., and Knapp, G.L., 1987, Hydrologic unit maps: U.S. Geological Survey Water-Supply Paper W 2294, 63 p.

Seismic Exchange, Inc., 2011, at http://www.seismicexchange.com

Sheldon, R.P., 1967, Long-distance migration of oil in Wyoming: Mountain Geologist, v. 4, no. 2, p. 5365.

Sheriff, R.E., 1991, Encyclopedia dictionary of exploration geophysics: Tulsa, Ok., Society of Exploration Geophysicists, 3rd edition, 376 p.

Smith, L.B. Jr., Eberli, G.P., Sonnenfeld, M., 2004, Sequence-stratigraphic and paleogeographic distribution of reservoir-quality dolomite, Madison Formation, Wyoming and Montana, *in* Grammer, G. M., Harris, P. M., and Eberli, G.P., eds., Integration of outcrop and modern analogs in reservoir modeling: Tulsa, Ok., American Association of Petroleum Geologists Memoir, v. 80, p. 67–92.

Smith, M.S., Sharma, S., Wyckoff, T.B., and Frost, C.D., 2010, Baseline geochemical characterization of potential receiving reservoirs for carbon dioxide in the Greater Green River Basin, Wyoming: Rocky Mountain Geology, v. 45. no. 2, p. 93–111.

Sonnenfeld, M.D., 1996, Sequence evolution and hierarchy within the lower Mississippian Madison Limestone of Wyoming, *in* Longman, M.W., and Sonnenfeld, M.D., eds., Paleozoic systems of the Rocky Mountain region: Society for Sedimentary Geology, Rocky Mountain Section, p. 165–192.

Spaeth, L.J., 2011, Triassic confining units for carbon dioxide sequestration in Wyoming [abs.]: American Association of Petroleum Geologists Bulletin 90132, 1 p.

Spaeth, L.J., Frost, C.D., Campbell-Stone, E.A., and Lynds, R., 2011, Analysis of Permo-Triassic formations as potential confining systems for CO_2 sequestration in Wyoming [abs.]: Cheyenne, Wy., American Association of Petroleum Geologists Abstracts with Programs, Rocky Mountain Section, p. 47.

Specht, R.G., 1989, Beaver Creek, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 48–53.

Stanton, R., Flores, R.M., Warwick, P.D., Gluskoter, H.J., and Stricker, G.D., 2001, Coal bed sequestration of carbon dioxide, *in* First National Conference on Carbon Sequestration, Washington, D.C., 2001, Proceedings: Washington, D.C., U.S. Geological Survey,12 p.

Stevens, S.H., and Spector, D., 1998, Enhanced coalbed methane recovery—Worldwide application and CO_2 sequestration potential:

prepared for the IEA Greenhouse Gas R&D Programme, Final Report IEA/CONS/97/27.

Stewart, W.W., and Street, B.A., 1992, LaBarge Anticline, *in* Miller, T.S., Crockett, F.J., and Hollis, S.H., eds., Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Casper, Wy., Wyoming Geological Association, p. 200–202.

Stilwell, D.P., 1989, CO_2 resources of the Moxa arch and the Madison reservoir: Casper, Wy., Wyoming Geological Association, 40th field conference, Guidebook, p. 105–115.

Stirling, A., 2000, House Creek, House Creek North, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Casper, Wy., Wyoming Geological Association, v. 2, p. 240–241.

Stone, D.S, 1967, Theory of Paleozoic oil and gas accumulation in Bighorn Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 51, no. 10, p. 2056–2114.

Surdam, R.C., 2011, Site characterization of the highest-priority geologic formations for CO_2 storage in Wyoming; eighth quarterly report, October through December 201, and second annual report, January through December 2011: U.S. Department of Energy Report DE-FE0002142, 16 p.

Surdam, R.C., and Jiao, Z., 2007, The Rock Springs uplift—An outstanding geological CO_2 sequestration site in southwest Wyoming: Wyoming State Geological Survey Challenges in Resource Development 2, 31 p., 1 pl.

Surdam, R.C., Jiao, Z., Dahl, S.C., Bentley, R., Garcia-Gonzalez, M., and Hurless, R., 2012, The WY-CUSP Program—Working to deliver a certified commercial storage site to Wyoming: Orlando, Fl., poster presented at Society of Petroleum Engineers Carbon Management Technology Conference, February 7–9, 2012.

Surdam, R.C., Jiao, Z., Stauffer, P., and Miller, T., 2009, An integrated strategy for carbon management combining geological CO_2 sequestration, displaced fluid production, and water treatment: Wyoming State Geological Survey Challenges in Resource Development 8, 25 p.

Thyne, G.D., Tomasso, M., Bywater-Reyes, S.V., Budd, D.A., and Reyes, B.M., 2010, Characterization of porosity and permeability for CO_2 sequestration models in the Mississippian Madison Group, Moxa arch—LaBarge platform, southwestern Wyoming: Rocky Mountain Geology, v. 45, no. 2, p. 133–150.

Todd, T.W., 1964, Petrology of Pennsylvanian rocks, Bighorn Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 48, no. 7, p. 1063–1090.

Tyler, R., and McMurry, R.G., 1993, Stratigraphy and coal occurrences of the Paleocene Fort Union Formation, Sand Wash Basin, *in* Kaiser, W.R., Scott, A.R., Hamilton, D.S., Tyler, R., McMurry, R.G., Zhou, N., and Tremain, C.M. (contributors), Geologic and hydrologic controls on coalbed methane—Sand Wash Basin, Colorado and Wyoming: Gas Research Institute, Report of Investigations Topical Report GR-92/0420, p. 79–106.

Tyler, R., Kaiser, W.R., Scott, A.R., Hamilton, D.S., and Ambrose, W.A., 1995, Geologic and hydrologic assessment of natural gas from coal—Greater Green River, Piceance, Powder River, and Raton basins, western United States: [Texas University] Bureau of Economic Geology and Gas Research Institute, Report of Investigations 228, 219 p.

U.S. Department of Energy, 2006, National strategic unconventional resource model—A decision support system: developed by the U.S. Department of Energy, Office of Petroleum Reserves, Office of the Naval Petroleum and Oil Shale Reserves, 48 p.

U.S. Department of Energy, 2010, 2010 carbon sequestration atlas of the United States and Canada: National Energy Technology Laboratory, 162 p.

U.S. Energy Information Administration, 2012a, at http://www.eia.gov

U.S. Energy Information Administration, 2012b, Annual Coal Report 2011, 58 p.

U.S. Environmental Protection Agency, 2012, at http://ampd.epa.gov/ampd/, accessed June 26, 2012.

U.S. Geological Survey, 2012, at http://water.usgs.gov/GIS/huc.html, accessed December 10, 2012.

USGS Southwestern Wyoming Province Assessment Team, 2005, Petroleum systems and

geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS-69-D.

van 't Veld, K., and Phillips, O.W., 2009, Pegging input prices to output prices in long-term contracts: CO_2 purchase agreements in enhanced oil recovery: Laramie, Wy., Department of Economics and Finance, Enhanced Oil Recovery Institute, University of Wyoming, 34 p.

Ver Ploeg, A.J., De Bruin, R.H., and Jones, R.W., 2008, Chapter 1—Geography and geology, *in* Copeland, D.A., and Ewald, M.L., eds., Water associated with coal beds in Wyoming's Powder River Basin—Geology, hydrology, and water quality: Wyoming State Geological Survey Exploration Memoir 2, p. 13–42.

Vernon, F., 1989, Frannie, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium, Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 172–173.

von Drehle, W.F., 1985, Amos Draw field, Campbell County, Wyoming: Casper, Wy., Wyoming Geological Association Guidebook, 36th annual field conference, Guidebook, p. 11–31.

Wach, P.H., 1977, The Moxa arch, an overthrust model?, *in* Heisey, E.L., Lawson, D.E., Norwood, E.R., and Wach, P.H., and Hale, L.A.,eds., Rocky Mountain thrust belt geology and resources: Grand Teton, Wy., Wyoming Geological Association, 29th annual field conference, Guidebook, in conjunction with Montana Geological Society and Utah Geological Society, p. 651–664.

Warner, M.A., 1982, Source and time of generation of hydrocarbons in the fossil basin, western Wyoming thrust belt, *in* Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, p. 805–815.

Watson, M., 2010, Development and performance update of the Cambrian reservoir in Bairoil: 4th Annual Wyoming CO_2 Conference, Casper, Wy., at http://www.uwyo.edu/eori/_files/co2conference10/matt watson - merit - Wyoming 2010 eor conference-final.pdf, accessed January 30, 2012.

Webel, S., 1977, Some new perspectives on the old Nugget oil fields of the LaBarge platform: Grand Teton, Wy., Wyoming Geological Association, 29th annual field conference, Guidebook, p. 665–671.

Wegemann, C.H., 1918, The Salt Creek oil field Wyoming: U.S. Geological Survey Bulletin B 670, 52 p.

Wehrle, F.P., 1989a, Elk Basin, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 132–135.

Wehrle, F.P., 1989b, Little Buffalo Basin, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Casper, Wy., Wyoming Geological Association, p. 274–277.

Weimer, R.J., 1965, Stratigraphy and petroleum occurrences, Almond and Lewis formations (Upper Cretaceous), Wamsutter arch, Wyoming: Casper, Wy., Wyoming Geological Association, 19th annual field conference, Guidebook, p. 65–81.

Weimer, R.J., 1966, Time-stratigraphic analysis and petroleum accumulations, Patrick Draw field, Sweetwater County, Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2150–2175.

Weimer, R.J., and Sonnenberg, S.A.,1996, Guide to the petroleum geology and Laramide orogeny, Denver Basin and Front Range, Colorado: Colorado Geological Survey Bulletin 51, 127 p.

Wellborn, B., 2000, Scott, *in* Finley, A.K., Miller, T.S., Cardinal, D.F., Stewart, W.W., and Stilwell, D., eds., Wyoming oil and gas fields symposium, Powder River Basin: Wyoming Geological Association, v. 2, p. 448–450.

Westphal, H., Eberli, G.P., Smith, L.B., Grammer, G.M., and Kislak, J., 2004, Reservoir characterization of the Mississippian Madison Formation, Wind River basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 88, no. 4, p. 405–432.

Whitman, L., 2011, CO_2 and EOR in Wyoming: Denver, Co., EORC/TAB meeting, January 18, 2011, at http://www.uwyo.edu/eori/_files/

eortab_jan11/lon_co2 status updates.pdf, accessed January 30, 2012.

Wilson, M.S., Dyman, T.S., and Nuccio, V.F., 2001, Potential for deep basin-centered gas accumulation in Hanna Basin, Wyoming, *in* Nuccio, V.F., and Dyman, T.S., eds., Geologic studies of basin-centered gas systems: U.S. Geological Survey Bulletin B 2184-A, 12 p.

Wo, S., Whitman, L.D., and Steidtmann, J.R., 2009, Estimates of potential CO_2 demand for CO_2 EOR in Wyoming basins: Denver, Co., 2009 SPE Rocky Mountain Petroleum Technology Conference, Society of Petroleum Engineers 122921, 12 p.

Wold, J., and Wellborn, B., 1989, Big Sand Draw, *in* Cardinal, D.F., Miller, T., Stewart, W.W., and Trotter, J.F., eds., Wyoming oil and gas fields symposium Bighorn and Wind River basins: Wyoming Geological Association, p. 57–61.

Wyoming Enhanced Oil Recovery Institute, 2011, Facts regarding future development of enhanced oil recovery in the Bighorn Basin: Memorandum to the Wyoming Enhanced Oil Recovery Commission, 7 p., at http://eorc.wy.gov, accessed October 2011.

Wyoming Enhanced Oil Recovery Institute, 2012, Wyoming EOR database: University of Wyoming, at http://www.uwyo.edu/eori/areas_of_focus/data_generation.html, accessed May 15, 2012.

Wyoming Oil and Gas Conservation Commission, 2012, at http://wogcc.state.wy.us

Wyoming Pipeline Authority, 2006, Carbon dioxide white paper: Casper, Wy., prepared for the Wyoming Joint Minerals, Business and economic development interim committee, 10 p.

Wyoming Pipeline Authority, 2012, written communication, at http://www.wyopipeline.com/.

Yin, P., Wo, S., and Mohrbacher, D., 2011, Preliminary mapping for potential EOR development of transition and residual oil zones in the Bighorn Basin, Wyoming: Laramie, Wy., Wyoming Enhanced Oil Recovery Institute Memo, August 1, 2011, 6 p.

Zelt, R.B., Boughton, G.K., Miller, K.A., Mason, J.P., and Gianakos, L.M., 1999, Environmental setting of the Yellowstone River Basin, Montana, North Dakota, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report WRI 98-4269, 112 p.

Zenger, D.H., 1996, Dolomitization patterns in widespread "Bighorn facies" (Upper Ordovician), western craton, USA: Carbonates and Evaporites, v. 11, no. 2, p. 219–225.

Appendices

Appendix A. Greater Green River Basin

Part 1. Oil production by year for six large fields in the Greater Green River Basin with potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (barrels) by field					
Year(s)	Jonah	Bruff	Brady	Church Buttes	Echo Spgs-Standard Draw	Labarge
Prior to 1978	—	93,438	14,921,556	8,852	19,720	20,651,950
1978	—	4,053	5,474,480	13,025	106,757	326,940
1979	—	5,576	4,279,835	—	283,646	300,805
1980	—	45,297	4,003,663	2,095	875,941	296,424
1981	—	115,921	3,843,213	4,498	1,235,676	274,611
1982	—	94,829	3,568,639	1,387	1,069,069	267,804
1983	—	69,252	3,484,315	6,197	690,019	336,538
1984	—	64,493	3,408,996	18,417	771,181	336,705
1985	283	61,594	3,487,542	42,480	1,085,273	347,332
1986	—	53,293	3,219,469	42,583	916,359	330,619
1987	—	55,280	2,725,373	50,574	976,313	286,176
1988	88	41,338	2,245,287	26,949	807,461	268,320
1989	—	46,800	1,863,767	22,402	783,475	264,468
1990	—	77,389	1,588,166	55,906	949,436	275,880
1991	—	128,169	1,449,027	61,564	1,012,826	266,187
1992	5,292	188,811	1,294,697	85,958	878,421	259,665
1993	18,456	323,746	1,147,930	88,627	601,459	243,788
1994	13,744	389,946	1,059,602	99,097	725,262	259,597
1995	29,899	337,216	975,661	96,878	742,114	285,306
1996	93,455	336,428	850,409	75,731	645,850	284,828
1997	357,222	296,671	589,786	66,423	806,347	317,976
1998	599,867	308,560	776,032	60,369	868,410	300,655
1999	904,640	276,793	717,318	70,769	890,030	284,541
2000	1,254,592	246,858	617,735	63,685	1,149,327	300,170
2001	1,867,986	211,082	512,422	52,580	1,231,053	273,661
2002	2,204,434	192,122	479,230	48,385	1,095,736	242,761
2003	2,256,643	177,950	496,938	48,417	1,050,022	198,805
2004	2,335,923	170,090	366,753	43,314	987,973	171,395
2005	2,372,161	133,874	328,478	42,584	1,035,627	148,041
2006	2,774,971	173,669	299,463	35,948	1,206,068	153,338
2007	3,650,307	147,862	355,134	37,865	1,255,528	137,146
2008	3,660,074	151,920	197,755	72,021	1,392,072	109,449
2009	3,512,766	157,407	151,285	68,927	1,385,039	110,121
2010	3,140,655	170,892	166,706	63,627	1,294,645	94,914
2011	2,720,297	151,880	112,814	61,569	1,190,458	78,695
Total	**33,773,755**	**5,500,499**	**71,059,476**	**1,639,703**	**32,014,593**	**29,085,611**

Appendix A. cont.

Part 2. Gas production by year for six large fields in the Greater Green River Basin with potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (cubic feet) by field					
Year(s)	Jonah	Bruff	Brady	Church Buttes	Echo Spgs-Standard Draw	Labarge
Prior to 1978	—	1,165,944	51,751,644	274,837,955	652,158	155,754,283
1978	—	695,158	18,288,934	7,107,834	3,662,458	6,870,093
1979	—	1,234,238	18,217,343	7,591,798	10,144,384	7,418,772
1980	—	8,287,695	19,510,435	7,076,304	33,847,793	6,422,605
1981	—	20,334,400	20,526,252	6,921,489	47,454,890	6,208,614
1982	—	16,405,965	21,563,820	6,902,164	42,130,219	7,698,774
1983	—	12,638,551	22,182,729	6,912,067	25,893,666	6,545,164
1984	—	10,865,002	22,344,195	6,513,993	33,167,988	6,325,035
1985	20,991	11,957,499	21,365,108	7,311,237	41,916,338	4,111,958
1986	—	10,574,135	21,320,867	6,391,255	34,094,988	8,290,743
1987	—	9,551,586	22,485,548	6,184,349	40,036,742	8,643,079
1988	—	18,354,796	23,374,335	6,414,438	33,655,734	11,310,838
1989	—	8,953,495	22,651,160	1,456,921	34,468,830	11,709,922
1990	—	16,129,959	22,053,363	12,537,104	36,193,648	17,239,510
1991	—	27,910,691	21,970,284	11,623,399	33,502,207	17,223,438
1992	175,222	39,228,525	21,975,962	17,125,071	35,214,869	23,442,464
1993	1,635,654	63,791,532	22,210,848	19,976,222	31,679,635	19,286,891
1994	1,440,360	64,973,997	23,021,215	18,281,967	46,657,257	18,229,094
1995	2,310,259	63,308,468	22,999,315	19,845,878	58,975,137	13,651,105
1996	9,352,192	59,970,049	21,974,717	16,488,525	72,911,534	17,011,327
1997	37,541,529	51,250,809	15,113,346	14,258,017	68,917,513	14,095,229
1998	60,039,767	48,681,484	17,774,845	12,125,774	65,833,024	12,982,346
1999	86,337,531	42,019,717	24,507,439	12,395,258	66,709,821	12,491,657
2000	125,421,509	38,461,100	23,096,602	11,486,897	88,243,704	11,508,769
2001	168,106,862	34,109,252	18,692,357	10,619,175	105,176,352	10,323,097
2002	217,498,362	31,559,844	12,972,260	10,330,581	88,769,633	10,884,519
2003	246,527,155	30,565,909	13,046,408	10,243,597	84,565,092	9,843,307
2004	247,602,878	28,872,827	10,613,372	8,847,429	78,284,574	8,943,113
2005	263,858,179	24,055,980	8,134,206	8,381,406	82,477,862	9,219,702
2006	289,653,151	31,940,401	6,863,362	7,890,176	91,099,732	9,587,038
2007	364,733,827	28,893,992	10,759,851	6,818,085	94,652,362	8,755,896
2008	409,826,839	30,576,492	5,610,048	13,594,899	97,590,555	8,023,347
2009	392,092,810	33,573,162	3,174,494	13,596,815	100,070,531	8,300,792
2010	353,682,899	35,201,671	2,736,386	12,848,377	91,652,453	7,797,149
2011	305,572,595	30,180,966	1,902,732	12,633,814	85,017,142	6,218,225
Total	**3,583,430,571**	**986,275,291**	**636,785,782**	**633,570,270**	**1,985,320,825**	**522,367,895**

Appendix B. Wind River Basin

Part 1. Oil production by year for four large fields in the Wind River Basin with potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (barrels) by field			
Year(s)	Big Sand Draw	Riverton Dome	Steamboat Butte	Poison Spider West
Prior to 1978	51,333,135	3,055,148	76,998,037	7,231,493
1978	845,142	54,243	861,468	480,383
1979	974,686	50,832	836,958	441,411
1980	729,874	66,176	909,743	395,189
1981	585,771	57,493	852,065	334,254
1982	480,265	74,240	808,581	381,689
1983	424,814	71,938	765,092	337,051
1984	378,144	75,562	759,139	302,885
1985	327,023	98,440	756,732	298,423
1986	245,146	98,414	703,926	270,585
1987	249,987	78,752	720,001	278,770
1988	172,376	76,690	659,106	251,276
1989	94,692	82,889	646,711	205,507
1990	130,544	71,651	615,914	167,219
1991	123,394	66,627	594,988	125,989
1992	115,520	57,783	508,944	89,045
1993	74,820	49,148	387,056	69,774
1994	62,732	55,218	318,157	58,936
1995	56,042	69,359	299,653	53,521
1996	54,591	42,174	286,793	55,609
1997	53,972	23,617	404,880	59,005
1998	34,584	42,807	654,177	48,889
1999	30,222	42,524	666,346	43,336
2000	47,823	35,597	1,065,834	36,019
2001	60,887	22,670	1,020,010	36,314
2002	60,665	22,309	839,651	34,165
2003	70,896	26,786	779,312	28,365
2004	85,517	20,682	827,660	31,317
2005	74,170	19,509	752,741	27,919
2006	78,077	12,829	686,255	30,886
2007	92,589	7,720	650,769	25,377
2008	141,831	1,214	544,696	25,545
2009	142,028	5,006	507,302	27,476
2010	110,190	2,856	565,322	24,847
2011	88,514	3,167	448,373	24,187
Total	**58,630,663**	**4,642,070**	**99,702,392**	**12,332,656**

Appendix B. cont.

Part 2. Gas production by year for four large fields in the Wind River Basin with potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (cubic feet) by field			
Year(s)	Big Sand Draw	Riverton Dome	Steamboat Butte	Poison Spider West
Prior to 1978	135,712,695	111,343,402	9,677,173	17,344,452
1978	2,647,111	2,880,591	233,018	2,523,710
1979	1,243,875	2,552,410	228,023	2,422,464
1980	1,811,147	2,751,041	166,766	2,154,570
1981	1,664,785	2,438,041	87,150	2,224,344
1982	1,554,765	4,929,637	108,058	2,340,674
1983	713,554	5,647,560	64,965	1,958,455
1984	754,896	3,486,671	36,793	2,201,275
1985	1,051,333	4,241,922	67,945	2,316,608
1986	308,219	3,426,475	62,629	2,441,429
1987	44,744	1,935,805	242,093	2,301,650
1988	72,352	1,390,614	243,582	2,681,342
1989	517,042	1,793,394	240,581	3,065,230
1990	1,974,934	3,014,843	201,752	2,330,309
1991	1,876,257	3,297,018	236,025	1,656,476
1992	0	2,821,505	202,531	1,066,866
1993	846209	2,390,269	171,066	842,180
1994	1,720,383	2,420,988	69,451	649,778
1995	1,864,758	2,668,303	2,760	621,727
1996	1,657,517	2,279,686	24,205	613,934
1997	1,912,174	1,914,905	204,034	543,197
1998	1,493,386	2,601,811	158,000	455,262
1999	1,313,786	3,608,315	92,652	318,958
2000	1,195,934	3,040,522	72,415	262,678
2001	954,909	2,667,804	58,338	238,537
2002	968,484	2,221,238	43,402	188,762
2003	866,050	1,854,321	48,048	156,765
2004	903,773	2,031,759	36,377	162,567
2005	863,421	2,208,041	32,381	128,456
2006	649,173	2,545,250	39,730	163,737
2007	445,939	3,509,186	127,917	141,467
2008	401,084	3,785,307	111,789	138,137
2009	361,243	3,548,063	89,066	144,251
2010	302,406	2,831,319	107,284	135,718
2011	282,125	2,676,625	96,500	131,931
Total	**170,950,463**	**208,754,641**	**13,684,499**	**57,067,896**

Appendix C. Bighorn Basin

Part 1. Oil production by year for eight large fields in the Bighorn Basin with the potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (barrels) by field							
Year(s)	Oregon Basin	Elk Basin	Hamilton Dome	Grass Creek	Garland	Little Buffalo Basin	Byron	Frannie
Prior to 1978	277,281,486	391,690,339	193,228,287	151,559,113	128,694,123	71,953,364	96,630,321	89,531,227
1978	11,526,246	5,144,630	4,101,457	4,275,445	3,723,609	5,893,493	2,990,482	2,986,530
1979	11,485,735	4,710,945	3,875,978	3,848,774	3,298,624	5,742,142	2,990,124	2,977,314
1980	11,247,228	4,449,315	3,473,789	3,702,341	3,044,850	4,747,486	2,745,859	2,694,471
1981	10,306,163	3,665,541	3,194,738	3,421,963	2,833,322	4,500,380	2,450,273	2,376,982
1982	9,945,959	3,521,102	3,193,613	3,108,233	2,832,831	4,163,829	2,352,020	2,171,670
1983	9,728,183	3,521,485	3,371,101	2,735,014	2,930,165	4,264,677	2,085,887	1,915,217
1984	9,140,847	3,172,638	3,233,946	2,514,260	2,951,596	4,142,797	2,317,513	1,781,946
1985	9,658,659	3,209,906	3,266,556	2,454,549	2,873,768	3,894,253	2,066,748	1,807,888
1986	9,986,182	2,974,391	3,147,906	2,422,191	2,716,167	3,418,312	1,611,089	1,638,821
1987	9,079,443	2,868,657	2,935,513	2,343,685	2,599,901	2,862,738	1,245,342	1,287,598
1988	8,561,076	2,833,930	2,791,470	2,432,780	2,641,306	2,667,937	1,058,235	1,038,995
1989	7,917,182	2,791,281	2,574,123	2,293,755	2,655,255	2,388,915	948,828	877,250
1990	7,254,701	2,602,101	2,321,103	2,126,256	2,551,338	1,976,872	816,711	708,645
1991	6,537,578	2,474,718	2,363,533	2,015,066	2,424,955	1,757,232	798,680	591,854
1992	6,153,215	2,273,375	2,218,119	1,893,730	2,407,000	1,609,014	685,949	481,792
1993	5,862,323	2,196,637	2,081,742	1,776,915	2,274,854	1,381,002	691,880	403,980
1994	5,321,503	2,100,883	2,031,668	1,612,373	2,076,947	912,152	732,748	357,672
1995	5,063,379	1,917,871	2,042,466	1,538,957	1,975,204	876,373	731,518	322,870
1996	4,540,174	1,851,341	1,779,409	1,468,306	1,983,656	858,617	695,703	310,606
1997	4,430,211	1,779,346	1,794,304	1,496,088	1,850,027	811,173	620,711	280,821
1998	4,023,544	1,713,876	1,746,205	1,481,528	1,988,087	687,011	568,774	258,190
1999	3,549,138	1,724,068	1,710,641	1,280,494	1,725,879	581,414	562,165	240,463
2000	3,442,149	1,683,800	1,671,629	1,219,416	1,688,817	688,068	639,682	231,348
2001	3,153,252	1,671,812	1,590,677	1,126,604	1,518,998	711,164	599,426	221,469
2002	2,943,046	1,555,981	1,532,638	1,067,051	1,426,148	659,776	535,710	209,141
2003	2,799,369	1,605,826	1,429,096	1,118,625	1,356,188	636,610	498,338	199,274
2004	2,678,540	1,494,766	1,333,317	1,180,148	1,381,124	606,618	529,129	191,630
2005	2,644,700	1,387,889	1,294,328	1,070,978	1,410,278	583,154	508,337	187,447
2006	2,540,361	1,369,775	1,316,659	965,979	1,414,487	576,654	460,260	205,434
2007	2,497,933	1,309,995	1,309,204	885,379	1,298,133	553,605	421,855	199,394
2008	2,374,436	1,315,352	1,268,425	843,241	1,253,655	543,386	418,744	187,520
2009	2,179,682	1,220,452	1,184,917	817,445	1,123,754	496,880	464,277	184,045
2010	2,122,387	1,170,370	1,143,858	815,590	1,089,475	502,637	426,227	172,067
2011	2,036,614	1,134,669	1,075,866	790,360	1,048,898	478,485	391,145	163,352
Total	**480,012,624**	**472,109,063**	**268,628,281**	**215,702,632**	**201,063,419**	**139,128,220**	**134,290,690**	**119,394,923**

Appendix C. cont.

Part 2. Gas production by year for eight large fields in the Bighorn Basin with the potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (thousand cubic feet) by field							
Year(s)	Oregon Basin	Elk Basin	Hamilton Dome	Grass Creek	Garland	Little Buffalo Basin	Byron	Frannie
Prior to 1978	145,624,638	246,940,578	70,489	5,827,099	130,523,149	114,632,235	11,941,633	234,885
1978	5,233,787	8,077,411	15,974	123,515	1,000,020	535,621	118,742	18,097
1979	4,902,973	6,952,829	5,851	115,148	747,381	519,002	115,868	16,518
1980	4,845,410	6,458,176	5,846	109,338	667,598	396,675	100,382	16,440
1981	4,932,224	4,813,558	4,684	103,898	527,117	341,946	88,749	14,427
1982	4,216,603	4,362,820	4,041	106,846	559,290	313,280	94,433	13,686
1983	3,515,731	4,178,163	2,990	93,728	483,246	238,235	106,728	26,900
1984	3,304,487	3,760,717	5,144	170,814	448,702	325,713	114,737	28,672
1985	3,194,158	3,802,667	2,428	214,360	560,725	400,354	106,753	30,583
1986	2,515,754	3,596,380	290	155,455	585,784	396,636	68,437	27,354
1987	2,448,593	3,483,658	0	144,549	496,676	357,480	37,535	21,458
1988	2,354,674	3,101,711	0	146,847	519,480	385,043	27,527	17,181
1989	2,750,603	2,863,245	0	138,000	569,940	466,580	32,252	14,433
1990	3,390,607	7,587,331	0	153,160	809,331	714,527	27,095	11,537
1991	4,473,751	1,757,125	277,789	137,324	923,749	942,852	35,767	9,658
1992	4,597,903	1,650,635	604,163	133,382	831,640	907,449	46,593	8,169
1993	4,919,863	2,779,958	526,030	140,848	830,962	1,329,282	53,801	7,450
1994	5,936,474	2,761,714	0	165,948	754,972	2,975,173	54,998	6,611
1995	6,986,950	2,756,547	0	136,205	315,293	1,579,095	9,227	6,011
1996	6,866,616	2,550,815	15,950	120,971	1,945,842	964,960	44,743	5,761
1997	7,612,070	2,343,740	0	135,472	1,602,870	694,612	59,033	5,194
1998	7,862,623	1,987,532	0	229,736	2,176,172	604,228	41,017	4,762
1999	7,095,131	2,098,311	0	174,433	1,887,359	487,026	34,788	4,444
2000	6,302,486	2,271,223	0	175,048	1,643,056	451,418	57,210	4,311
2001	5,825,606	2,478,034	0	193,686	1,531,938	416,539	123,908	4,320
2002	5,648,991	3,086,328	99,615	184,259	1,430,282	394,799	64,806	4,232
2003	5,213,812	5,147,391	172,674	179,905	1,070,161	375,132	37,979	5,115
2004	5,013,672	6,189,636	17,524	153,864	888,769	344,782	28,302	525,095
2005	4,782,523	6,244,173	0	174,219	819,768	352,989	23,413	3,386
2006	4,621,152	6,648,186	0	197,180	711,752	373,358	26,029	134,459
2007	4,004,814	5,048,964	0	253,739	690,519	321,866	20,990	0
2008	3,544,623	4,246,936	229	275,769	654,568	320,270	17,768	180
2009	3,074,725	3,637,368	0	223,070	577,707	325,287	13,700	0
2010	2,964,355	4,371,271	0	220,545	556,341	158,906	13,358	185
2011	2,703,395	4,244,767	0	225,367	501,445	131,146	17,678	0
Total	**303,281,777**	**384,279,898**	**1,831,711**	**11,433,727**	**160,843,604**	**134,474,496**	**13,805,979**	**1,231,514**

Appendix D. Powder River Basin

Part 1. Oil production by year for eight large fields in the Powder River Basin with potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (barrels) by field							
Year(s)	Amos Draw Complex	Hartzog Draw	Hilight	House Creek	Kitty	Powell	Scott	Spearhead Ranch
Prior to 1978		8,479,928	61,390,469	11,367,193	16,881,838	522,960		3,161,158
1978		10,218,311	2,730,730	1,170,312	283,403	1,099,252	7,691	523,770
1979		6,407,390	2,196,786	1,280,949	262,660	1,038,378	355,857	366,299
1980		3,938,510	1,736,454	1,091,284	266,944	1,220,613	1,145,603	231,350
1981		3,536,961	1,598,455	959,176	343,451	765,303	1,469,065	176,352
1982	12,425	2,481,323	1,372,214	843,438	291,866	591,044	1,497,018	104,231
1983	632,874	2,671,990	982,869	757,369	296,993	545,589	1,440,786	136,334
1984	752,343	3,495,071	877,676	694,120	472,041	2,671,048	1,452,058	93,364
1985	854,645	5,221,538	723,428	604,915	349,686	3,449,811	1,255,123	265,598
1986	667,890	6,512,823	604,120	524,454	260,170	2,978,268	1,058,824	254,653
1987	403,563	6,829,163	534,679	480,487	225,599	2,650,758	923,011	71,007
1988	262,641	6,311,431	541,623	456,997	185,286	1,887,190	822,269	61,801
1989	186,690	5,541,132	499,130	422,077	176,089	1,389,949	726,997	51,701
1990	127,859	4,656,943	474,532	375,762	172,664	1,078,214	650,057	48,152
1991	94,064	4,079,026	428,639	351,464	154,019	907,523	600,423	42,608
1992	83,367	3,479,524	360,780	271,840	153,378	803,127	555,166	36,886
1993	69,451	2,974,502	285,648	253,726	143,681	705,744	520,593	81,261
1994	63,787	2,460,198	208,087	334,733	136,229	601,452	506,618	287,812
1995	59,608	2,280,205	208,652	542,683	129,302	506,195	499,800	289,612
1996	49,167	2,206,183	226,362	1,072,916	124,472	420,726	439,374	241,195
1997	41,351	2,068,756	219,658	1,416,946	121,775	363,818	471,013	228,044
1998	67,380	2,141,375	209,148	1,870,418	113,336	340,150	463,975	178,298
1999	71,848	2,297,211	172,985	1,911,111	98,638	227,876	418,303	131,051
2000	63,678	2,257,865	144,829	1,544,899	90,912	249,896	421,223	116,183
2001	46,023	1,948,730	126,487	1,288,929	83,184	193,594	385,402	105,076
2002	41,505	1,741,382	111,755	1,066,946	82,198	155,638	334,843	98,699
2003	37,178	1,532,743	103,583	956,862	77,987	137,410	351,046	98,467
2004	35,552	1,363,882	92,424	916,548	77,946	144,166	294,380	98,107
2005	32,824	1,199,611	100,187	1,093,124	87,012	142,766	289,823	91,142
2006	29,011	1,184,162	112,075	1,632,277	87,962	151,806	277,421	95,500
2007	24,538	1,086,234	142,500	1,587,016	82,748	151,221	260,594	97,403
2008	23,995	967,135	139,473	1,346,709	81,454	133,955	254,142	101,167
2009	21,428	866,153	107,526	1,206,818	80,608	129,797	236,213	105,930
2010	21,354	805,590	101,663	1,126,142	69,209	128,238	232,744	85,337
2011	20,274	712,274	116,131	1,091,836	66,553	119,667	236,669	81,422
Total	**4,898,313**	**115,955,255**	**79,981,757**	**43,912,476**	**22,611,293**	**28,603,142**	**20,854,124**	**8,236,970**

Appendix D. cont.

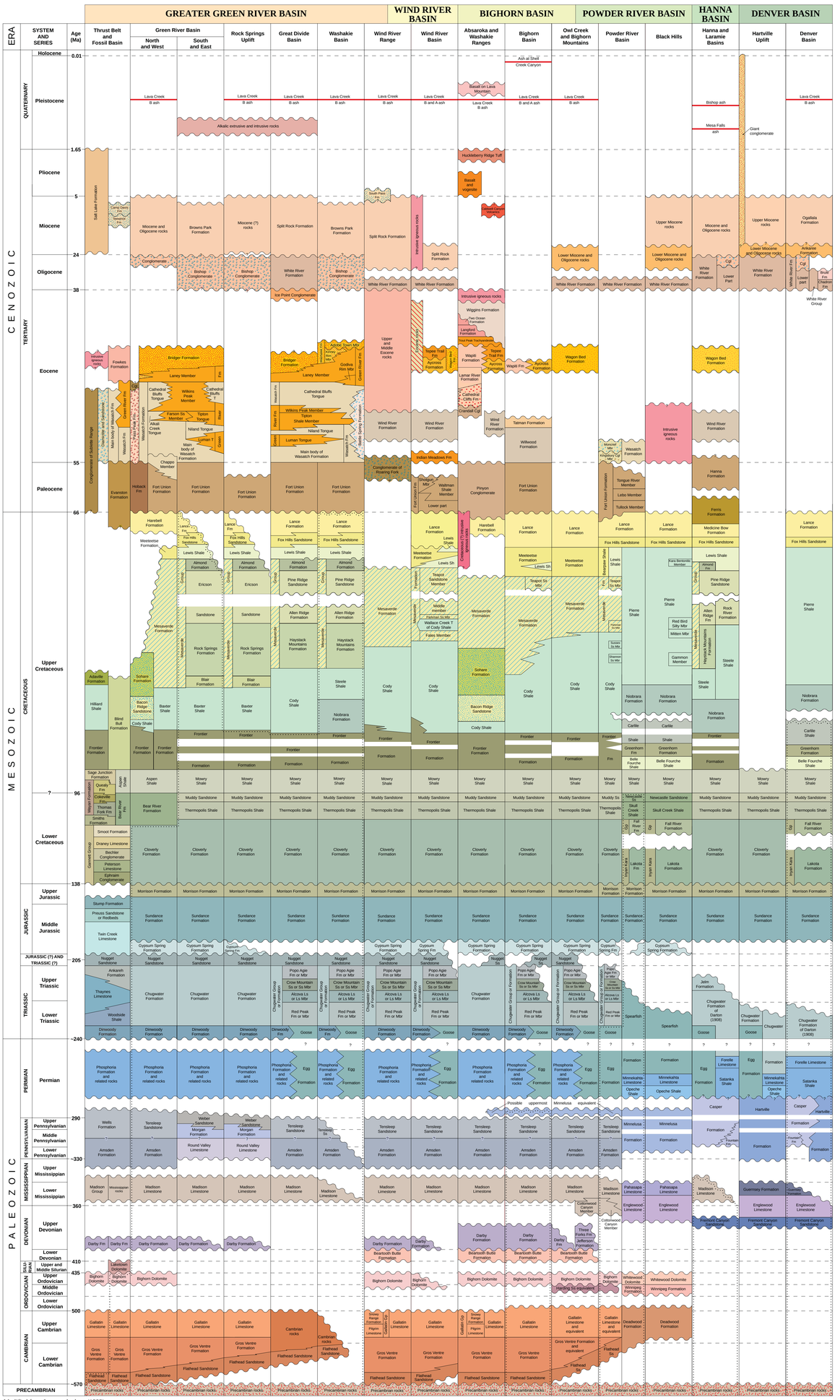
Part 2. Gas production by year for eight large fields in the Powder River Basin with potential for future CO_2 storage. Data retrieved from the Wyoming Oil and Gas Conservation Commission (2012).

	Production (cubic feet) by field							
Year(s)	Amos Draw Complex	Hartzog Draw	Hilight	House Creek	Kitty	Powell	Scott	Spearhead Ranch
Prior to 1978		1,968,768	191651004	6,224,335	64,341,407	2040663		22,432,335
1978		3,613,237	6,518,034	1,178,602	2,736,372	4,346,117	0	5,788,060
1979		3,409,557	7,900,843	1,093,624	2,617,367	4,003,567	130,983	4,812,121
1980		1,957,350	7,676,759	1,222,115	2,600,943	4,002,145	710,173	3,930,726
1981		3,001,886	6,201,633	1,343,888	2,805,072	2,183,255	1,094,633	3,278,038
1982	18,025	2,317,166	6,556,901	1,162,602	3,133,176	1,630,892	1,201,272	1,630,124
1983	5,503,807	1,785,400	4,922,964	1,048,929	3,119,693	1,596,012	1,357,076	957,594
1984	7,968,404	1,461,832	4,267,695	996,343	3,314,166	10,085,146	1,528,794	607,626
1985	14,343,711	1,962,812	3,539,133	912,138	3,923,331	14,173,092	1,486,078	1,028,812
1986	15,668,994	1,654,723	2,734,715	823,720	3,054,756	15,392,054	1,432,137	1,330,625
1987	11,438,381	1,625,813	2,283,779	690,560	2,158,590	17,867,821	1,297,328	552,508
1988	9,101,871	1,492,262	2,161,549	637,123	2,138,273	18,261,309	1,246,570	416,684
1989	6,927,961	1,342,303	2,212,356	572,683	2,384,052	16,513,343	1,197,611	497,138
1990	5,484,902	1,151,184	2,100,612	515,780	2,169,407	16,226,531	1,228,854	353,561
1991	4,563,660	1,109,351	2,076,076	458,986	1,880,740	16,741,475	1,161,659	409,623
1992	3,832,469	1,001,181	2,194,425	295,538	2,084,016	16,671,929	1,066,638	347,777
1993	3,292,386	828,190	2,128,292	211,943	1,672,014	16,108,402	996,686	219,156
1994	2,839,811	676,629	1,929,474	169,562	1,779,753	15,817,073	1,065,553	227,411
1995	2,560,855	663,101	1,978,243	172,418	1,666,188	15,822,922	1,087,815	344,934
1996	2,169,374	723,325	2,288,725	224,759	1,507,571	16,085,741	1,079,117	371,408
1997	1,977,937	704,326	2,578,395	266,717	1,593,352	15,633,627	1,102,326	387,621
1998	2,412,598	724,560	3,275,229	237,006	1,474,287	14,388,596	1,122,276	303,614
1999	2,950,361	792,612	3,142,382	254,305	1,346,100	11,757,014	969,868	235,714
2000	2,847,093	844,056	3,270,493	268,452	1,178,596	11,754,664	884,065	193,223
2001	2,243,158	751,311	3,370,778	251,967	1,132,060	8,199,809	801,431	201,097
2002	1,881,930	686,298	3,503,876	206,578	1,080,654	5,471,491	774,766	203,081
2003	1,622,379	495,495	3,803,812	182,392	1,052,058	4,076,401	851,308	361,905
2004	1,606,168	298,502	3,663,198	145,360	960,769	3,685,230	733,672	301,749
2005	1,295,941	344,586	3,485,372	117,095	918,827	3,167,062	678,156	406,032
2006	1,125,049	394,160	3,612,415	106,095	921,413	3,183,273	640,828	481,226
2007	936,994	415,647	3,701,466	113,864	901,532	2,737,215	611,243	565,481
2008	870,755	245,597	4,238,704	89,313	787,779	2,120,341	514,449	590,521
2009	809,571	220,193	4,079,050	122,032	915,336	2,118,293	467,588	593,577
2010	817,691	203,757	3,891,705	116,747	800,663	1,893,791	442,154	536,721
2011	782,925	160,528	3,808,374	224,851	792,874	1,713,610	439,426	527,573
Total	**119,895,161**	**41,027,698**	**316,748,461**	**22,658,422**	**126,943,187**	**317,469,906**	**31,402,533**	**55,425,396**

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

TECHNICAL MEMORANDUM 3
Plate 1
Stratigraphic Chart

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING



Modified from Love and others (1993)

STRATIGRAPHIC NOMENCLATURE CHART OF THE LARAMIDE BASINS, WYOMING

EXPLANATION

Unconformity (generally of regional extent)

Hiatus

Rocks in subsurface only

Abbreviations used in the columns

Cgl	Conglomerate	Mbr	Member
Fm	Formation		
Gp	Group		
Ls	Limestone	Ss	Sandstone
		T	Tongue

REFERENCE

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., comps.,1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-41.

Layout and design by James R. Rodgers and Robin W. Lyons

Edited by Suzanne C. Luhr

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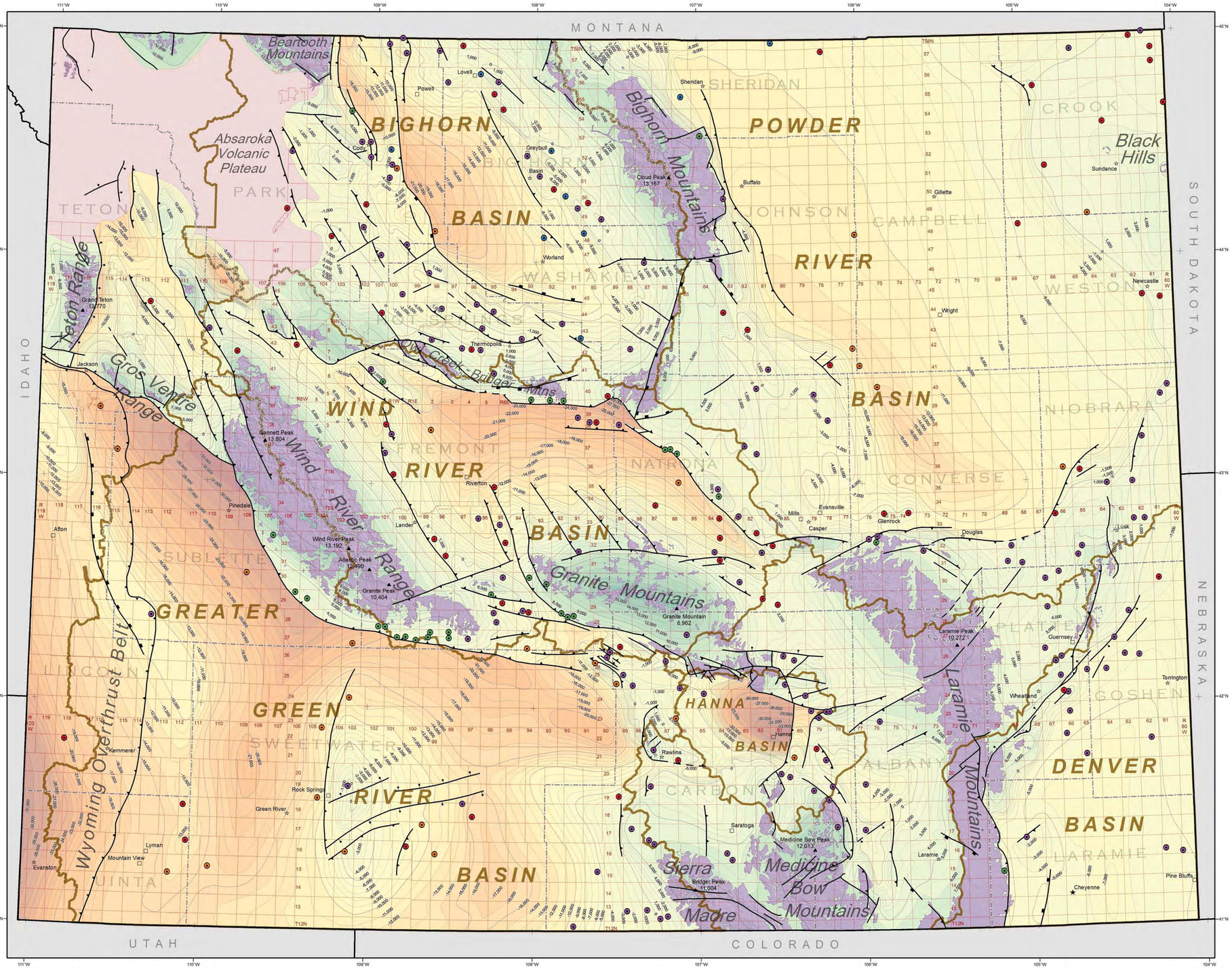
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 2
Modified Precambrian Basement Map of Wyoming



Projection: Lambert Conformal Conic
False Easting: 0.0, False Northing: 0.0
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41.0 degrees North
Standard Parallel 2: 45.0 degrees North
Latitude of Origin: 43.0 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

N
MN

Magnetic Declination = 10° 22' E
at center of map
(Feb. 12, 2013)

Scale 1:1,000,000

0 30 60 90 120 Miles

0 50 100 150 200 Kilometers

Cartography by Tomas Gracias and David W. Lucke
Edited by Suzanne C. Luhr

MODIFIED PRECAMBRIAN BASEMENT MAP OF WYOMING: OUTCROP AND STRUCTURAL CONFIGURATION

EXPLANATION

This map illustrates a general understanding of the Precambrian basement in Wyoming. The map is a revision of the original publication *Precambrian Map of Wyoming: Outcrop and Structural Configuration* by D.L. Blackstone, Jr., 1993. Contour lines revised by Richard W. Jones and Tomas Gracias, 2010.

MAP SYMBOLS

Boundaries

- Precambrian outcrop
- Area not included in revision
- Extent of basins in this study

Base Data

- State capital
- County seat
- City or town
- Mountain peak elevation (in feet)
- County boundary
- State boundary

Faults

- **Fault**—Displacement unknown; dashed where inferred
- **Thrust fault**—Dashed where inferred; sawteeth on upper (tectonically higher) block
- **Reverse fault**—Dashed where inferred; rectangles on upthrown block
- **Normal fault**—Dashed where inferred; ball and bar on downthrown block

Well Control Points

- Well drilled to units younger than Ordovician
- Well drilled to the Ordovician
- Well drilled to the Cambrian
- Well drilled to the Precambrian
- Well drilled into or through the Precambrian

Basement Contours

- Precambrian basement elevation relative to mean sea level. Contour interval 1,000 feet

Precambrian Basement Elevation (above or below mean sea level)

Meters	Feet
4,000	15,000
	10,000
2,000	5,000
Sea Level	Sea Level
-2,000	-5,000
-4,000	-10,000
	-15,000
-6,000	-20,000
-8,000	-25,000
-10,000	-30,000

DATA REFERENCE

Blackstone, D.L. Jr., 1993, Precambrian basement map of Wyoming—Outcrop and structural configuration: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-43, scale 1:1,000,000.

BASE MAP REFERENCES

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/lsis_home/home/index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital Magnetic Declination: National Geophysical Data Center, at http://www.ngdc.noaa.gov/geomagmodels/struts/calcIDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

Wyoming Geographic Information Science Center, 1997, Internet mapping service—Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

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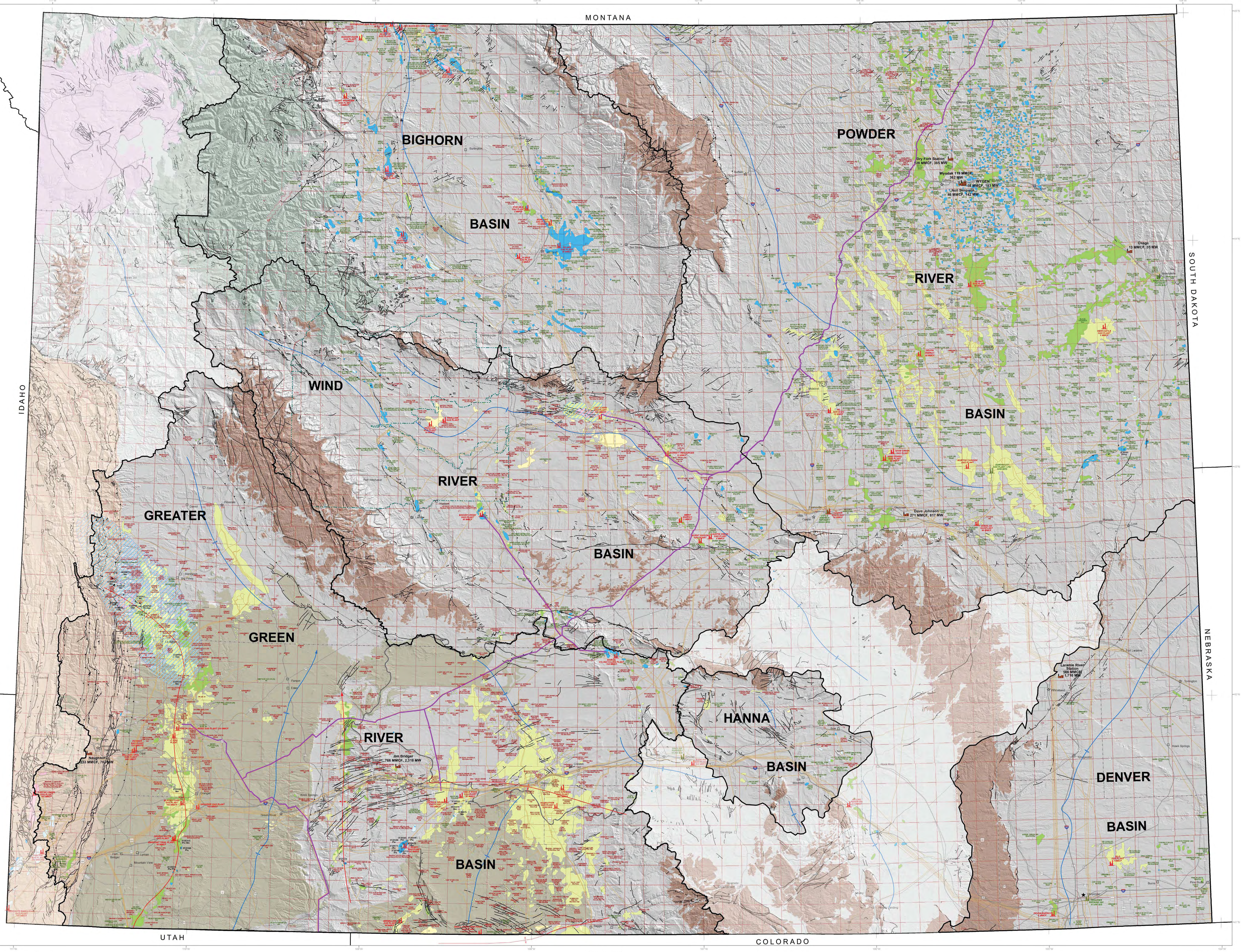
Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 3
Oil, Gas, and CO_2 Map of the
Laramide Basins, Wyoming



Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

Magnetic Declination = 10° 22' E
at center of map
(Feb. 26, 2013)

Scale 1:500,000

Modified from De Bruin (2012b)
Digital cartography and layout by Phyllis A. Ranz
Edited by Suzanne C. Luhr

OIL, GAS, AND CO_2 MAP OF THE LARAMIDE BASINS, WYOMING

EXPLANATION

INFRASTRUCTURE

Osage 3 MMCF, 35 MW — Coal-fired power plant. Notation includes plant name, carbon dioxide (CO_2) production in million cubic feet (MMCF) per day and electrical production in megawatts (MW). Locations approximate

NEWCASTLE REFINERY 14,000 B/D — Oil refinery. Notation includes plant name (or operator if plant name is unknown) and capacity in barrels of oil per day (B/D). Locations approximate

LOST CABIN GAS PLANT 145 MMCF — Natural gas processing plant. Notation includes plant name (or operator if plant name is unknown) and capacity in million cubic feet (MMCF) per day. Locations approximate

3720715 JTrn — Well testing high in CO_2, showing last seven digits of API number and the producing formation

PIPELINES

Pipeline routes are plotted as accurately as possible and are only accurate within the scale of this map or maps of smaller scale.

- Carbon dioxide
- All other pipelines

PREDOMINANT AGE OF RESERVOIR ROCKS

- TERTIARY
- UPPER CRETACEOUS
- LOWER CRETACEOUS
- JURASSIC-TRIASSIC
- PERMIAN-PENNSYLVANIAN
- MISSISSIPPIAN-DEVONIAN-ORDOVICIAN-CAMBRIAN-PRECAMBRIAN

GEOLOGIC DESCRIPTIONS

- Approximate location of major basin axis; end arrow indicates direction of plunge
- Approximate location of major anticlinal axis; end arrow indicates direction of plunge
- Fault, displacement unknown; dotted where concealed
- Normal fault, dotted where concealed; ball and bar on downthrown block
- Thrust fault, dotted where concealed; sawteeth on upper (tectonically higher) plate
- Quaternary volcanic rocks in the Yellowstone National Park area. Includes Pleistocene-age basalt flows and basaltic intrusive igneous rocks; rhyolite flows, tuffs, and rhyolitic intrusive igneous rocks; and alkalic extrusive and intrusive igneous rocks. Modified from Love and Christiansen (1985)
- Tertiary volcanic rocks of the Absaroka Range. Includes Eocene-age rocks of the Absaroka Volcanic Supergroup and related intrusive igneous rocks. Modified from Love and Christiansen (1985)
- Oil shale-bearing strata. The shaded area depicts the oil shale occurrence. Oil shale occurs in the Luman Tongue, Fontenelle Tongue, Tipton Shale Member, and Laney Shale Member of the Green River Formation (Eocene) (Bradley, 1964; Love and Christiansen, 1985); in the Eocene Tatman Formation along the southwestern margin of the Bighorn Basin (J.D. Love, personal communication, 1984); and in the Eocene Wagon Bed Formation in the Lysite Mountain area, Tps. 41-42 N, Rgs. 89-92 W (Bay, 1969)
- Major Wyoming sedimentary basins. Map shows approximate extent of Paleocene and younger rocks
- Overthrust belt
- Undifferentiated Precambrian rocks exposed at the surface. Modified and adapted from Love and Christiansen (1985)

FIELDS

Fields are spotted through March 30, 2012. Field boundaries are approximate.

HARTZOG DRAW (W) Kfh — Names in green denote fields that primarily produce oil. These fields may produce significant associated natural gas along with the oil in the primary reservoir or nonassociated natural gas from secondary reservoirs

FRENCHIE DRAW Tfu Kl — Names in red denote fields that primarily produce natural gas. These fields may produce significant condensate along with the natural gas in the primary reservoir or oil from secondary reservoirs

Carbon dioxide (CO_2) producing fields. Partially modified after Stilwell (1989); from De Bruin (1991)

FIELD DESIGNATIONS

(A)	Abandoned field
(AIR)	Air injection project
(CM)	Coalbed natural gas
(D)	Produced water disposal project
(G)	Gas injection project
(GD)	Gas disposal
(H)	Hydrothermal (steam) injection project
(HD)	Horizontal drilling project
(HO)	Heavy oil–less than 20°API gravity
(HP)	Huff 'n' Puff tertiary project
(HS)	Hydrogen sulfide
(S)	Gas or LPG storage
(SI)	Shut-in field
(T)	Tertiary recovery project
(W)	Waterflood project

Note: These designations appear after the oil or gas field name.

BASE DATA

Cities
- State capital
- County seat
- City or town

Roads
- Interstate highway
- U.S. highway
- State highway
- County or other road
- Railroad

Boundaries
- Continental Divide
- County boundary
- Wind River reservation boundary
- Yellowstone National Park boundary
- State boundary
- Basin boundary

LIST OF OIL AND GAS PRODUCING GROUPS, FORMATIONS, AND MEMBERS

Both abandoned and currently producing formations are shown for each field. On the map, formations from which heavy oil is produced are enclosed in parentheses, e.g., (Kf); formations from which significant hydrogen sulfide is produced are enclosed in brackets, e.g., [Mm].

Tertiary
- Twk Knight Formation*
- Ta Almy Formation*
- Twr White River Formation
- Tw Wasatch Formation
- Twdr Wind River Formation
- Tgr Green River Formation
- Tfu Fort Union Formation
- Th Hanna Formation

Upper Cretaceous
- Kl Lance Formation
- Kfh Fox Hills Sandstone
- Kle Lewis Shale
- Kme Meeteetse Formation
- Kmv Mesaverde Formation (or Group)
- Kad Adaville Formation
- Kmd Teapot Sandstone
- Kmvp Parkman Sandstone
- Kal Almond Formation
- Ke Ericson Sandstone
- Krs Rock Springs Formation
- Kbl Blair Formation
- Kh Hilliard Shale
- Kba Baxter Shale
- Ksx Sussex Sandstone
- Ksh Shannon Sandstone
- Kc Cody Shale
- Ks Steele Shale
- Kn Niobrara Formation
- Ktr Turner Sandstone*
- Kg Greenhorn Formation
- Kbf Belle Fourche Shale
- Kcd Codell Sandstone
- Kf Frontier Formation
- Kmr Mowry Shale
- Ka Aspen Shale

Lower Cretaceous
- Knc Newcastle Sandstone
- Kmd Muddy Sandstone
- Kbr Bear River Formation
- Kcv Cloverly Formation
- Ksc Skull Creek Shale
- Kd Dakota Sandstone*
- Kfr Fall River Formation
- Kla Lakota Formation

Cretaceous and Jurassic
- KJg Gannett Group

Jurassic
- Jm Morrison Formation
- Jtc Twin Creek Limestone
- Js Sundance Formation

Jurassic and Triassic
- JTrn Nugget Sandstone

Triassic
- Tra Ankareh Formation
- Trt Thaynes Limestone
- Trcm Crow Mountain Sandstone (or Sandstone Member)
- Trc Chugwater Formation (or Group)
- Trca Alcova Limestone
- Trcr Red Peak Formation (or Member)
- Trw Woodside Shale
- Trd Dinwoody Formation

Permian
- Pm Minnekahta Limestone
- Pp Phosphoria Formation

Permian and Pennsylvanian
- PPc Casper Formation
- PPml Minnelusa Formation

Pennsylvanian
- Pm Morgan Formation
- Pw Weber Sandstone
- Pt Tensleep Sandstone

Pennsylvanian and Mississippian
- PMa Amsden Formation

Mississippian
- Md Darwin Sandstone
- Mm Madison Limestone

Devonian
- Dj Jefferson Formation
- Dd Darby Formation

Ordovician
- Obh Bighorn Dolomite

Cambrian
- Cgv Gros Ventre Formation
- Cf Flathead Sandstone

Precambrian
- p€ Archean and Proterozoic rocks, undifferentiated

* Formation name extended from neighboring states, not formally recognized in Wyoming, or not commonly used in Wyoming.

KEY TO NUMBERED OIL AND GAS FIELDS IN THE POWDER RIVER BASIN*

1. (52, 70) ADON ROAD NORTH (W) Kmd PPml
2. (50, 71) AG FARM PPml
3. (50, 69) AJAX (SI) PPml
4. (51, 69) ALPHA (T) (D) PPml
5. (52, 68) AMERICAN (T) PPml
6. (52, 68) AMMO (W) Kmd PPml
7. (52, 68) AMMO SOUTH (SI) PPml
8. (53, 69) ARROW (A) PPml
9. (52, 69) ASH (T) PPml
10. (50, 71) BAR U DRAW PPml
11. (47, 70) BASIN (SI) PPml
12. (50, 71) BAUMFALK PPml
13. (46/47, 71) BIGFOOT PPml
14. (47, 70/71) BIG HAND (W) (D) Kmr Kmd Kd PPml
15. (48, 70) BISHOP RANCH (W) (T) PPml
16. (48, 69) BISHOP RANCH EAST (SI) PPml
17. (48, 69) BISHOP RANCH SOUTH (W) PPml
18. (52, 69) BRACKEN (T) Kmd PPml
19. (52, 69) BREAKS (D) (W) PPml
20. (47, 72) BREEN (W) Kmr Kmd PPml
21. (50, 69) BRENNAN (W) PPml
22. (51, 70) BRONCO PPml
23. (53, 69) BULLMARCH PPml
24. (48, 71) BUTTE CREEK (D) PPml
25. (48, 70) CABIN CANYON (A) PPml
26. (52, 67) CABIN CREEK (A) Kmd
27. (53, 68) CAMBRIDGE PPml
28. (51, 69) CARDINAL (D) PPml
29. (49, 70) CHALK HILLS (A) PPml
30. (47/48, 71) CLABAUGH PPml
31. (52, 69) CLEARWATER PPml
32. COALBED NATURAL GAS DEVELOPMENT AREA (CM) Tw Tfu
33. (52, 68) COUNTY LINE PPml
34. (53, 69) DEEP DRAW PPml
35. (53, 70) DEER FLY SOUTH PPml
36. (48, 71/72) DERMOTT DRAW (A) PPml
37. (48, 71/72) DERMOTT DRAW WEST PPml
38. (47, 69) DILLINGER RANCH (W) PPml
39. (50, 71) DITTO LAKE PPml
40. (48, 68) DONKEY CREEK (W) (D) Kmd Kd PPml
41. (51, 70) DOUBLE SHIELD (D) PPml
42. (49, 72) DRY GULCH (W) PPml
43. (48, 69) DUCK NEST CREEK (A) Kmd
44. (47, 71) DUNLAP PPml
45. (51, 70) DUTCH (D) PPml
46. (49, 69) DUVALL RANCH (W) PPml
47. (49, 72) EAST DRAW Kmd
48. (49, 72) EINAR (W) PPml
49. (48, 70) ENYARD DRAW (A) PPml
50. (50, 71) FALCON RIDGE (T) PPml
51. (50, 70/71) FD (W) PPml
52. (49, 72) FISHING LAKE PPml
53. (49, 71/72) GAP (D) PPml
54. (51, 69) GARNER LAKE (W) PPml
55. (51, 69) GARNER LAKE NORTH PPml
56. (52, 69) GIBBS (W) PPml
57. (52, 69) GIBBS NORTH (A) PPml
58. (52, 69) GIBBS SOUTH (D) PPml
59. (50, 69) GLO (T) (W) PPml
60. (50, 69) GLO NORTH (W) (T) PPml
61. (48, 70/71) GOLD MINE DRAW PPml
62. (50, 69) GRAY (A) PPml
63. (50, 69) GRAY SOUTH PPml
64. (51, 68) GUTHERY (W) PPml
65. (47, 71) HAIGHT (W) PPml
66. (48, 69) HAL (SI) PPml
67. (49, 69) HALVERSON (W) Kd PPml
68. (51, 69) HAMM (W) PPml
69. (51, 70) HAWKEYE (W) PPml
70. (52/53, 68) HEATH (D) PPml
71. (53, 69) HELLS DRAW Kmd
72. (48, 70) HIGH ROAD (D) PPml
73. (52, 69) HILDA PPml
74. (52, 69) HIRSCH Kmd
75. (52, 69) HOOVER GULCH (D) PPml
76. (51, 70) INDIAN TREE PPml
77. (50, 70/71) INFINITY (SI) PPml
78. (53, 70) JACKELOPE PPml
79. (53, 68) JB (D) PPml
80. (51, 70) KANE PPml
81. (47, 70) KICKEN DRAW PPml
82. (53, 68) KIEHL WEST (T) (W) (D) PPml
83. (51, 70) KUEHNE RANCH (W) PPml
84. (51, 69) KUEHNE RANCH EAST (W) PPml
85. (51, 69) KUEHNE RANCH NORTHEAST (W) PPml
86. (51, 69) KUEHNE RANCH SOUTHEAST PPml
87. (51, 68) KUMMERFELD (W) (D) Kd Kla PPml
88. (49, 71/72) LANEY (A) PPml
89. (49, 71) LEE DRAW (A) PPml
90. (52, 69) LITTLE MITCHELL CREEK (W) PPml
91. (53, 68) LITTLE MO PPml
92. (51, 69) LITTLE PINE PPml
93. (51, 69) LONE CEDAR (T) (W) PPml
94. (52, 69) MAC (D) PPml
95. (49, 72) MALLARD PPml
96. (48, 71) MALMQUIST PPml
97. (51, 70) MAPES (D) PPml
98. (51, 70) MARNIE (D) PPml
99. (51, 70) MARNIE SOUTH (W) PPml
100. (49, 70) MARY RESERVOIR PPml
101. (49, 69) MAY (A) PPml
102. (47, 71) MAYSDORF (W) PPml
103. (47, 71) MAYSDORF SOUTH (W) PPml
104. (48/49, 72) McCREERY (D) PPml
105. (52, 67) MELLOTT RANCH (W) PPml
106. (51, 68) MILLER CREEK (D) Kmd Kd PPml
107. (49, 71) MINTURN (A) PPml
108. (53, 68) MISSOURI PPml
109. (52, 67) MOORCROFT Kmd PPml
110. (52, 67) MOORCROFT EAST Kmd
111. (51/52, 67) MOORCROFT WEST (W) (T) Kmd Kd PPml
112. (49, 69/70) MORAN (W) PPml
113. (53, 68) MOREL PPml
114. (53, 68) MULE HERDER PPml
115. (51, 70) NETA PPml
116. (52, 69) O'CONNOR Kmd
117. (51, 70) OK (T) (W) PPml
118. (49, 71) OLSEN (D) PPml
119. (53, 68) OSHOTO (D) Kmd PPml
120. (52, 69) OTTIE DRAW (W) (T) Tfu PPml
121. (48, 72) OXBOW (W) PPml
122. (51, 69) PEBBLE BEACH (SI) PPml
123. (48, 69) PICKREL RANCH (D) (A) PPml
124. (48, 70) PIERCE (W) PPml
125. (47, 70) PINEY PPml
126. (51, 69) PLEASANT VALLEY (D) (W) PPml
127. (53, 70) POWNALL RANCH (W) (T) (D) PPml
128. (53, 68) PRAIRIE CREEK SOUTH (W) PPml
129. (51, 68) PRONG CREEK WEST PPml
130. (48, 70) RAILROAD BEND PPml
131. (49, 71) RAINBOW RANCH NORTH (W) (T) Kmd PPml
132. (52, 67) REYNOLDS RANCH (D) PPml
133. (48, 72) RIDGEVIEW PPml
134. (50, 68) RIGHT A WAY (T) (W) PPml
135. (51, 69) ROCKHOPPER PPml
136. (58, 70) ROCKY BUTTE (W) PPml
137. (53, 70) ROEHRS (D) PPml
138. (48, 71) ROURKE GAP PPml
139. (47, 71) ROYAL DRAW (W) PPml
140. (52, 69) RULE (T) (W) PPml
141. (47, 72) SAND ROCK PPml
142. (52, 68) SEMLEK PPml
143. (52, 68) SEMLEK SOUTHWEST (SI) Kmd PPml
144. (52, 68) SEMLEK WEST (W) (D) Kmd Kla PPml
145. (49, 71) SHARP (W) (D) Tfu PPml
146. (49, 71) SHEARING PEN DRAW (A) Kmd
147. (51, 68) SIMPSON NORTH PPml
148. (51, 69) SIMPSON RANCH (W) PPml
149. (50, 69) STEWART (T) (W) (D) PPml
150. (51, 69) STEWART EAST (W) (T) PPml
151. (49, 71) SUMMERFIELD (W) (T) PPml
152. 50, 71) SUPERHORNET PPml
153. (49, 71) T A BUTTES (W) PPml
154. (51, 70) TANNER PPml
155. (51, 69) TERRACE (D) PPml
156. (53, 68) TEXAS TRAIL (D) PPml
157. (49, 70) THOLSON (W) (D) PPml
158. (49, 67) THORSON (D) PPml
159. (49, 70) TIMBER CREEK NORTH (W) Kmd PPml
160. (49, 70) TIMBER CREEK NORTH SHALLOW Kmd
161. (48, 71) TIMBER CREEK NORTHWEST PPml
162. (47, 71) T-T- ROAD PPml
163. (52, 70) TWIN CREEK (SI) PPml
164. (49/71) UNNAMED Kmd
165. (50, 69) UNNAMED PPml
166. (51, 68) UNNAMED PPml
167. (51, 69) UNNAMED PPml
168. (51, 69) UNNAMED Kmd
169. (52, 67) UNNAMED (A) Knc
170. (52, 69) UNNAMED PPml
171. (53, 69) UNNAMED PPml
172. (53, 69) UNNAMED PPml
173. (53, 70) UNNAMED PPml
174. (53, 69) WAGON SPOKE (W) PPml
175. (52, 70) WALLACE NORTH PPml
176. (51, 70) WALLACE SOUTH (W) PPml
177. (50, 70) WARD CREEK (A) Kmd PPml
178. (49, 71) WD (T) (D) PPml
179. (50, 69) WELL CREEK (SI) Kmd PPml
180. (51, 69) WHEAT DRAW (D) PPml
181. (51, 70) WHISLER (W) (D) PPml
182. (53, 68) WILDFIRE (HO) (D) (SI) PPml
183. (50/51, 69) WINDMILL (W) (HO) Kmd (PPml)
184. (49, 70) WINTER DRAW (T) PPml
185. (52, 68) WOLF DRAW (T) PPml
186. (49, 72) WOLFF (D) PPml
187. (48, 72) WORTH (A) PPml
188. (53, 69) YORK (D) PPml
189. (51, 69) ZOE DRAW PPml

* Numbers in parentheses indicate Townships North and Ranges West
Green labels denote oil fields; red labels denote gas fields

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GENERAL MAP REFERENCES

Bay, K.W., 1969, Stratigraphy of Eocene sedimentary rocks in the Lysite Mountain area, Hot Springs, Fremont, and Washakie Counties, Wyoming: Ph.D. dissertation, University of Wyoming, Laramie, 181 p.

Biggs, P., and Espach, R.H., 1960, Petroleum and natural gas fields in Wyoming: U.S. Bureau of Mines Bulletin 582, 538 p.

Blackstone, D.L., Jr., and De Bruin, R.H., 1987, Tectonic map of the overthrust belt, western Wyoming, northeastern Utah, and southeastern Idaho, showing oil and gas fields and exploratory wells in the overthrust belt and adjacent Green River Basin: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-23, scale 1:316,800.

Bradley, W.H., 1964, Geology of the Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey Professional Paper 496-A, 86 p.

De Bruin, R.H., 1996, Oil and gas map of Wyoming: Wyoming State Geological Survey Map Series MS-48, scale 1:500,000.

De Bruin, R.H., 2012a, Carbon dioxide (CO_2) map of Wyoming: Wyoming State Geological Survey Map Series MS-90, scale 1:500,000.

De Bruin, R.H., 2012b, Oil and gas map of Wyoming: Wyoming State Geological Survey Map Series MS-55, scale 1:500,000.

De Bruin, R.H., and Boyd, C.S., 1990, Oil and gas fields map of the Powder River Basin, Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-31, scale 1:316,800.

De Bruin, R.H., and Hostetler, S.D., 1991, Oil and gas fields map of the Wind River Basin, Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-37, scale 1:316,800.

De Bruin, R.H., and Hostetler, S.D., 1993a, Oil and gas fields map of southeastern Wyoming basins: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-42, scale 1:316,800.

De Bruin, R.H., and Hostetler, S.D., 1993b, Oil and gas fields map of the Bighorn Basin, Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-40, scale 1:316,800.

De Bruin, R.H., Lyman, R.M., and Hallberg, L.L., 2001, Coalbed methane activity in the eastern Powder River Basin, Campbell and Converse Counties, Wyoming: Wyoming State Geological Survey Coalbed Methane Map CMM 01-6, scale 1:126,720.

De Bruin, R.H., Lyman, R.M., Hallberg, L.L., and Harrison, M.M., 2001, Coalbed methane activity in the western Powder River Basin, Campbell, Converse, Johnson, Natrona, and Sheridan Counties, Wyoming: Wyoming State Geological Survey Coalbed Methane Map CMM 01-7, scale 1:126,720.

Gregory, R.W., and De Bruin, R.H., 1991, Oil and gas fields map of the Greater Green River Basin and overthrust belt, southwestern Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-36, scale 1:316,800.

Krueger, M.L., 1955, Preliminary geological report, Big Piney gas field, Sublette County, Wyoming: Wyoming Geological Association, Tenth Annual Field Conference Guidebook, p. 142-144.

Krueger, M.L., 1968, Occurrence of natural gas in Green River Basin, Wyoming, *in* Beebe. B.W., and Curtis, B.F., eds., Natural gases of North America: American Association of Petroleum Geologists Memoir 9, v. 1, p. 780-797.

Lawyer, G., Newcomer, J., Eger, C., eds., 1981, Oil and gas fields—Powder River Basin, vols. I and II: Wyoming Geological Association, 472 p.

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, scale 1:500,000.

Oil and Gas Fields Symposium Committee, 1957, Wyoming oil and gas fields symposium: Wyoming Geological Association, 579 p.

Oil and Gas Fields Symposium Committee, 1979, Wyoming oil and gas fields symposium, Green River Basin, vols. I and II: Wyoming Geological Association, 428 p.

Oil and Gas Fields Symposium Committee, 1984, SE Wyoming oil and gas fields symposium, Laramie, Hanna and D-J Basins: Wyoming Geological Association, 133 p.

Oil and Gas Fields Symposium Committee, 1989, Oil and gas fields, Bighorn and Wind River Basins: Wyoming Geological Association, 558 p.

Oil and Gas Fields Symposium Committee, 1992, Wyoming oil and gas fields symposium, Greater Green River Basin and overthrust belt: Wyoming Geological Association, 372 p.

Oil and Gas Fields Symposium Committee, 2000, Wyoming oil and gas fields symposium, Powder River Basin: Wyoming Geological Association, 566 p.

Petroleum Information Corporation, 1987, Structure contour map of the Powder River Basin and Casper arch, Wyoming and Montana: Denver, 2 sheets, scale 1:250,000.

Petroleum Information Corporation/Dwights, 1997-2007 [various], Production reports: Denver.

Stilwell, D.P., 1989, CO_2 resources of the Moxa arch and the Madison reservoir: Wyoming Geological Association, 40th field conference, Guidebook, p. 105-115.

Wyoming Oil and Gas Conservation Commission, 2012, at http://wogcc.state.wy.us/.

Wyoming Pipeline Authority, 2012, written communication, at https://www.wyopipeline.com/.

OIL AND GAS DATA REFERENCES

Field locations and boundaries: De Bruin (1996-2012); Wyoming State Geological Survey (2007-2012) (unpublished), using production data from the Wyoming Oil and Gas Conservation Commission (2012).

Coalbed natural gas fields: De Bruin, Lyman, and Hallberg (2001); De Bruin, Lyman, Hallberg, and Harrison (2001); Wyoming State Geological Survey (2012) (unpublished); and Wyoming Oil and Gas Conservation Commission (2012).

Oil, natural gas, carbon dioxide and product pipelines, natural gas processing plants, and refineries: Wyoming State Geological Survey (2007) (unpublished); Wyoming Pipeline Authority (2012) (unpublished), and Wyoming Oil and Gas Conservation Commission (2012).

BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ lsis_home/home /index.htm.

Huss, J.M., 2002, Railroads for Wyoming at 1:500,000: Wyoming State Geological Survey, at http://piney.wygisc.uwyo.edu/data/transportation/railroads.zip.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc.noaa.gov/geomagmodels/struts/calcDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2006, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

Wyoming Geographic Information Science Center, 1997, Internet mapping service—Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

Wyoming Geographic Information Science Center, 2002, Continental Divide of the United States at 1:2,000,000 (modified), at http://piney.wygisc.uwyo.edu/data/geology/continentaldivide.zip.

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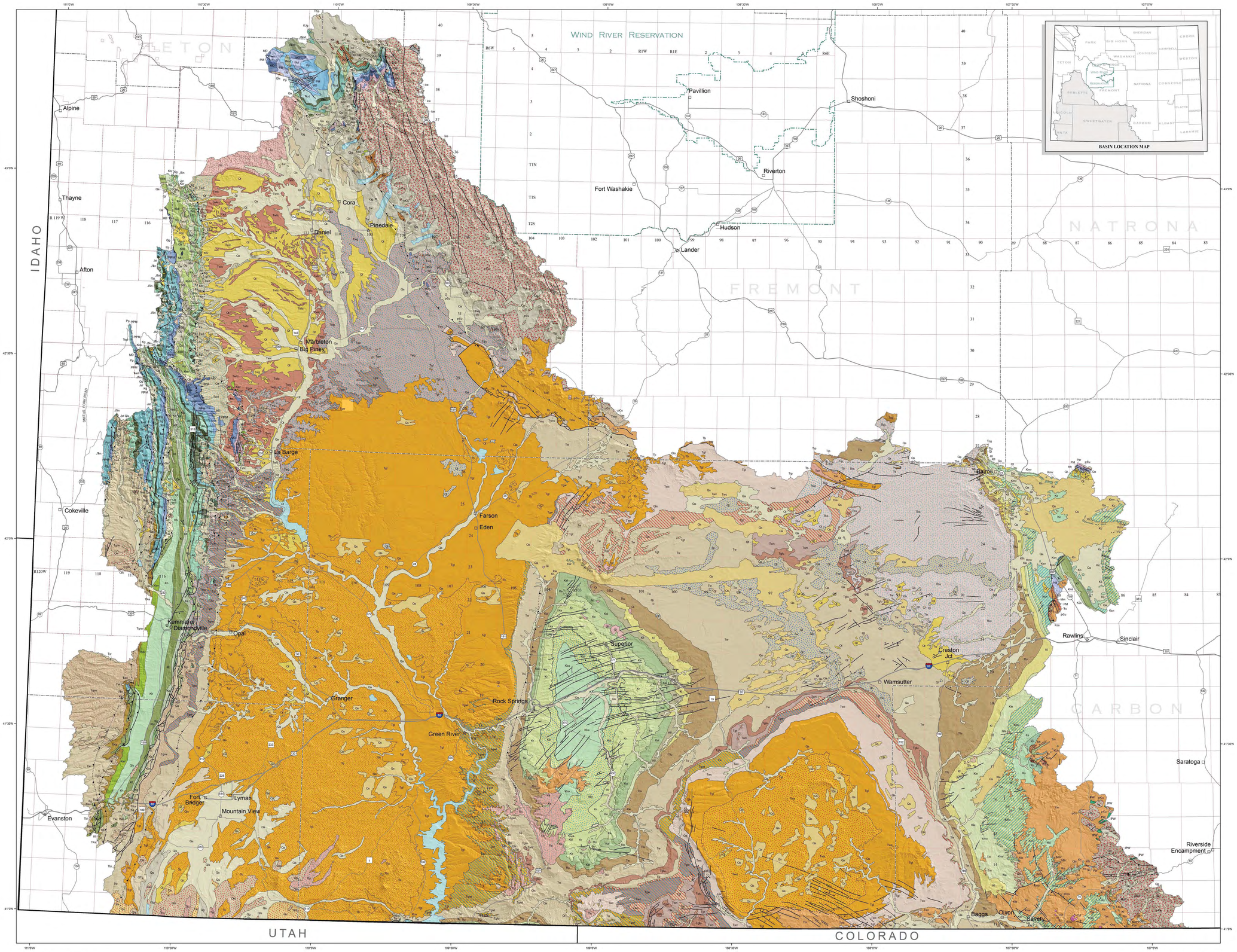
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 4
Geologic Map of the Greater Green River Basin



Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

Magnetic Declination = 10° 55' E
at center of map
(Feb. 12, 2013)

Scale 1:350,000

0 10 20 30 40 50 Miles

0 20 40 60 80 Kilometers

Geology modified from Love and Christiansen (1985)

Digital cartography and layout by
Robin W. Lyons and Phyllis A. Ranz

Edited by Suzanne C. Luhr

GEOLOGIC MAP OF THE GREATER GREEN RIVER BASIN, WYOMING

EXPLANATION

MAP SYMBOLS

Formation contact

Normal fault—Dotted where concealed; bar and ball on downthrown block; no designation on fault trace indicates undetermined motion

Thrust fault—Dotted where concealed; sawteeth on upthrown (tectonically higher) block

Shear zone

County seat
City or town
Lake or reservoir
Interstate highway
U.S. highway
State highway
County or other road
Wind River Reservation boundary
County boundary
State boundary

GEOLOGIC UNITS
(Geology enlarged from 1:500,000 scale to improve readability)

CENOZOIC

Quaternary

- Qa — Alluvium and colluvium
- Qg — Gravel, pediment, and fan deposits
- Qgl — Glacial deposits
- Qls — Landslide deposits
- Qs — Dune sand and loess
- Qp — Playa lake and other lacustrine deposits
- Qsd — Surficial deposits, undifferentiated
- Qi — Alkalic extrusive and intrusive igneous rocks

Quaternary and Tertiary

- QTg — Terrace gravel (Pleistocene and/or Pliocene)

Tertiary

- Ti — Intrusive and extrusive igneous rocks
- Tbf — Basalt flows and intrusive igneous rocks
- Tm — Miocene rocks
- Tmu — Upper Miocene rocks
- Tbc — Bishop Conglomerate
- Twr — White River Formation
- Twru — Upper conglomerate member
- Toe — Oligocene and/or upper and middle Eocene rocks
- Tcp — Ice Point Conglomerate
- Twa — Washakie Formation
- Tb — Bridger Formation
- Tcg — Crooks Gap Conglomerate
- Tgrw — Green River and Wasatch Formations
- Tgu — Granitic conglomerate above or in upper part of Wasatch Formation
- Tgl — Laney Member of Green River Formation
- Twc — Cathedral Bluffs Tongue of Wasatch Formation
- Tgw — Wilkins Peak Member of Green River Formation
- Tgwt — Wilkins Peak Member and Tipton Shale Member or Tongue of Green River Formation
- Tgt — Tipton Shale Member or Tongue of Green River Formation
- Twn — Niland Tongue of Wasatch Formation
- Twg — New Fork Tongue of Wasatch Formation and Fontenelle Tongue or Member of Green River Formation
- Tgla — Luman Tongue of Green River Formation
- Twd — Diamictite and sandstone of Wasatch Formation
- Tw — Main body of Wasatch Formation
- Twlc — La Barge and Chappo Members of Wasatch Formation
- Twts — Transitional unit between Battle Spring and Wasatch Formations
- Tbs — Battle Spring Formation
- Tg — Bass Peak Formation and equivalents
- Tcr — Conglomerate of Roaring Creek
- Th — Hoback Formation
- Tdb — Devils Basin Formation
- Tfu — Fort Union Formation

CENOZOIC AND MESOZOIC

Tertiary and Cretaceous

- TKe — Evanston Formation
- TKp — Pinyon Conglomerate

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Kfh — Fox Hills Sandstone
- Kfl — Fox Hills Sandstone and Lewis Shale
- Kle — Lewis Shale
- Kmv — Mesaverde Group
- Kal — Almond Formation
- Ke — Ericson Sandstone
- Kr — Rock Springs Formation
- Kbl — Blair Formation
- Kav — Adaville Formation
- Kh — Hilliard Shale
- Kbb — Blind Bull Formation
- Ksb — Sohare Formation and Bacon Ridge Sandstone
- Kba — Baxter Shale
- Kc — Cody Shale
- Ks — Steele Shale
- Ksn — Steele Shale and Niobrara Formation
- Kn — Niobrara Formation
- Kf — Frontier Formation
- Kmt — Frontier Formation, and Mowry and Thermopolis Shales
- Ksjs — Sage Junction, Quealy, Cokeville, Thomas Fork, and Smiths Formations
- Ka — Aspen Shale
- Kbr — Bear River Formation
- Kmt — Mowry and Thermopolis Shales
- Kg — Gannett Group

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations
- KJs — Cloverly, Morrison, and Sundance Formations
- KJsg — Cloverly, Morrison, Sundance, and Gypsum Spring Formations

Jurassic

- Jst — Stump Formation, Preuss Sandstone or Redbeds, and Twin Creek Limestone
- Jsg — Sundance and Gypsum Spring Formations

Jurassic and Triassic

- Jn — Nugget Sandstone
- JTRnd — Nugget Sandstone, and Chugwater and Dinwoody Formations

Triassic

- TRad — Ankareh Formation, Thaynes Limestone, Woodside Shale, and Dinwoody Formation
- TRc — Chugwater Formation or Group
- TRcd — Chugwater and Dinwoody Formations

MESOZOIC AND PALEOZOIC

- MzPz — Mesozoic and Paleozoic rocks, undifferentiated

PALEOZOIC

Permian

- Pp — Phosphoria Formation and related rocks

Pennsylvanian

- IPNi — Mafic intrusive rocks

Permian, Pennsylvanian, and Mississippian

- PM — Tensleep Sandstone and Amsden Formation
- PPM — Wells and Amsden Formations

Mississippian

- Mm — Madison Limestone or Group

Mississippian and Devonian

- MD — Madison Limestone and Darby Formation

Mississippian, Devonian, Ordovician, and Cambrian

- Pzr — Madison Limestone, Darby Formation, Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

Ordovician

- OC — Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

Cambrian

- Cu — Gallatin Limestone, Gros Ventre Formation and equivalents, and Flathead Sandstone

PRECAMBRIAN

- p€p — Precambrian rocks, undifferentiated

DATA REFERENCE

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ bis_home/home /index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc.noaa.gov/geomagmodels/struts/calDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

Wyoming Geographic Information Science Center, 1997, Internet mapping service—Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

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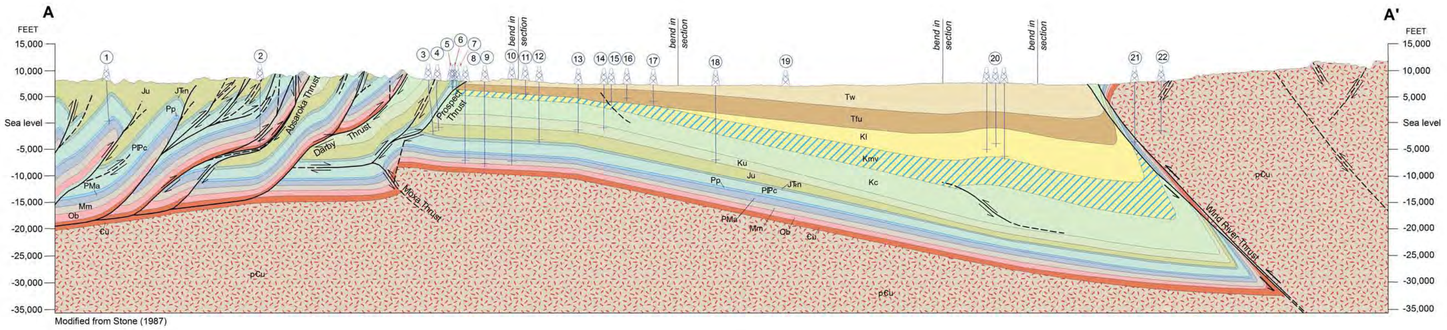
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

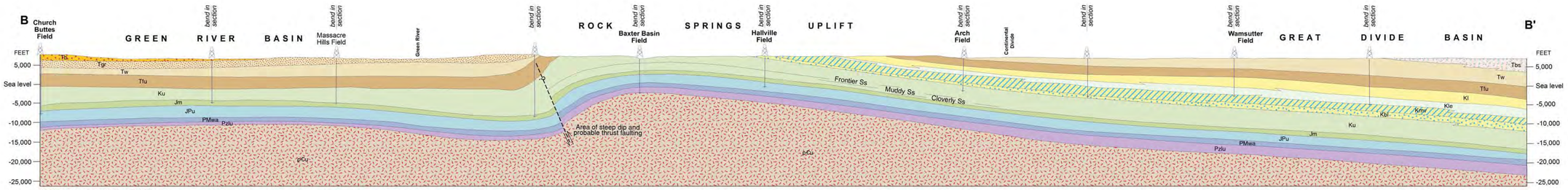
Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 5
Cross Sections
Greater Green River Basin



Modified from Stone (1987)



Modified from Root and others (1973)

EXPLANATION

CROSS SECTION SYMBOLS

Formation contact

Fault – Dashed where inferred; arrows indicate relative movement

Drill hole – Well logs used to construct cross sections

GEOLOGIC UNITS

CENOZOIC

Tertiary

- Tb — Bridger Formation
- Tgr — Green River Formation
- Tbs — Battle Springs Formation
- Tw — Wasatch Formation
- Tfu — Fort Union Formation

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Kle — Lewis Shale
- Kmv — Mesaverde Formation
- Kc — Cody Shale
- Kbl — Blair Formation
- Ku — Cretaceous rocks, undifferentiated

Jurassic

- Jm — Morrison Formation
- Ju — Jurassic rocks, undifferentiated

Jurassic and Triassic

- JTRn — Nugget Sandstone

MESOZOIC AND PALEOZOIC

Jurassic, Triassic, and Permian

- JPu — Jurassic, Triassic, and Permian rocks, undifferentiated

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Permian and Pennsylvanian

- PIPc — Casper Formation

Permian, Pennsylvanian, and Mississippian

- PMa — Phosphoria, Wells, and Amsden Formations
- PMwa — Weber and Tensleep Sandstones, and Amsden Formation
- Pzlu — Lower Paleozoic rocks, undifferentiated

Mississippian

- Mm — Madison Limestone

Devonian and Ordovician

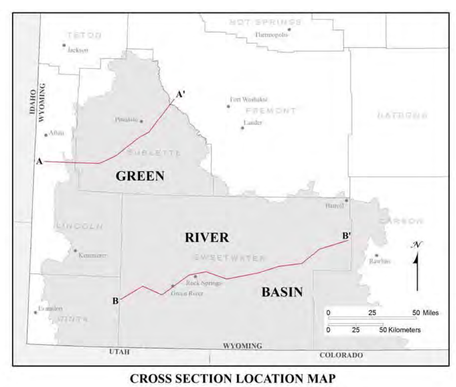
- Ob — Bighorn Dolomite

Cambrian

- Cu — Cambrian rocks, undifferentiated

PRECAMBRIAN

- pCu — Precambrian rocks, undifferentiated



CROSS SECTION LOCATION MAP

WELL CONTROL ALONG CROSS SECTIONS

Well no.	API no.	Operator	Well name	Bottom formation	Surface location sec.	T.	R.	County	Spud year
1	49-023-20474	Champion Ventures Inc.	Federal 34A-9 1	Pennsylvanian	9	30 N	119 W	Lincoln	1981
2	49-023-20466	Atlantic Richfield Company	USA Poker Hollow 1-9	Bear River	9	29 N	117 W	Lincoln	1982
3	49-035-20316	Pacific Enterprises Oil Co. USA	Federal 23-15	Nugget	15	29 N	115 W	Sublette	1974
4	49-035-06083	Chevron USA Inc.	Tierney 1	Twin Creek	15	29 N	115 W	Sublette	1947
5	49-035-06093	Chevron USA Inc.	Bushnell 1	Triassic	11	29 N	115 W	Sublette	1927
6	49-035-06088	Chevron USA Inc.	Govt 1	Triassic	11	29 N	115 W	Sublette	1928
7	49-035-06091	Chevron USA Inc.	Bushnell 2	Cretaceous	11	29 N	115 W	Sublette	1928
8	49-035-20670	Denbury Onshore LLC	Riley Ridge Fed 12-43	Devonian	12	29 N	115 W	Sublette	1981
9	49-035-20537	Denbury Onshore LLC	Riley Ridge 8-24	Bighorn	8	29 N	114 W	Sublette	1979
10	49-035-20603	Denbury Onshore LLC	Riley Ridge Fed 10-14	Darby	10	29 N	114 W	Sublette	1980
11	49-035-20047	Wexpro Company	Govt 1	Cretaceous	11	29 N	114 W	Sublette	1968
12	49-035-20634	Pacific Enterprises Oil Co USA	Federal 1-12	Nugget	12	29 N	114 W	Sublette	1981
13	49-035-20430	EOG Resources Inc.	Thompson 2-8	Cretaceous	8	29 N	113 W	Sublette	1977
14	49-035-06115	EOG Resources Inc.	Unit 3	Frontier	3	29 N	113 W	Sublette	1959
15	49-035-06114	EOG Resources Inc.	Unit 1	Mesaverde	3	29 N	113 W	Sublette	1962
16	49-035-06113	EOG Resources Inc.	Fed E 022769A B48	Fort Union	1	29 N	113 W	Sublette	1959
17	49-035-20066	Shenandoah Energy Inc.	Belco-Govt 1	Tertiary	31	30 N	112 W	Sublette	1968
18	49-035-20528	Woods Petroleum Corporation	Guio 23-1	Morrison	23	30 N	112 W	Sublette	1979
19	49-035-06178	Phillips Petroleum Company	Unit C 2	---------	6	30 N	111 W	Sublette	1958
20	49-035-20620	QEP Energy Company	Mesa Unit 2	Fort Union	16	32 N	109 W	Sublette	1981
21	49-035-20265	Husky Oil Company	Federal 8-2	Nugget	2	29 N	106 W	Sublette	1973
22	---------	---------	Air Force Exploratory A	Precambrian	2	32 N	107 W	Sublette	---------

REFERENCES

Root, F.K., Glass, G.B., and Lane, D.W., 1973, Sweetwater County, Wyoming—Geologic map atlas and summary of economic mineral resources: Geological Survey of Wyoming [Wyoming State Geological Survey], County Resource Series, no. 2.

Stone, D.S., 1987, Rocky Mountain Transect—Wyoming, transect segments SW 7, SW 6, SW 5, SW 4: Littleton, Co., DVD, version 2.0.

ACKNOWLEDGMENT

The Wyoming State Geological Survey thanks D.S. Stone for his permission to modify portions of the Rocky Mountain Transect, as shown in cross section A - A'.

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Layout and design by Robin W. Lyons and Phyllis A. Ranz
Edited by Suzanne C. Luhr

GEOLOGIC CROSS SECTIONS, GREATER GREEN RIVER BASIN, WYOMING

Vertical exaggeration ~ 2x

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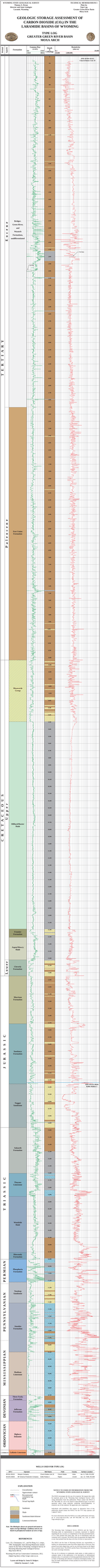
WYOMING STATE GEOLOGICAL SURVEY
Mark A. Jaworowski, Director
Erin Campbell, Director
Laramie, Wyoming

TECHNICAL INFORMATION
Open File
Date 2/2/2010
Greater Green River Basin
Moxa Arch

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
GREATER GREEN RIVER BASIN
MOXA ARCH



WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Twsp	County	Section Location
49-037-20374	Chuck's Butte Unit, LLC	Chuck's Butte Unit 34	16N-109W	Lincoln	sec. 34, T16N, R109W
49-013-20205	BP American Production Company	Moxa Unit 1	17N-113W	Sublette	sec. 13, T17N, R113W

EXPLANATION

Lithostratigraphic
- Approximate contact
- Formation
- Formation and member
- Actual log depth

Gamma
- Shale
- Sandstone/carbonate
- Carbonate/dolomite

Note: The lithologic columns are generated and stored as .png files. Gamma ray curves are stored as .las files based on gamma/depth measurements and scaled to .dlog files.

REFERENCES

Cross, T.A., Christiansen, K.C., and Pitman, J.K., 1986, Geologic time scale for foreland basins, *in* Foreland basin tectonics, Rocky Mountain foreland basins: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Field Trip Guidebook, p. 1-4.

Wyoming Oil and Gas Conservation Commission, 2011, Digital log data, at http://pipeline.wogcc.state.wy.us/

Layout and design by James R. Rodgers
Gamma ray curves by Jason Lenox

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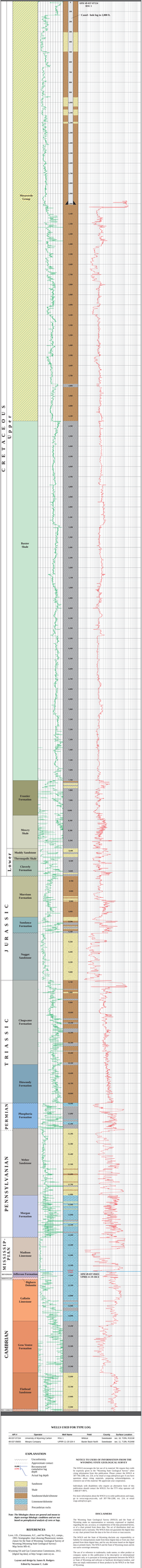
GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
GREATER GREEN RIVER BASIN
ROCK SPRINGS UPLIFT



WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Field	County	Surface Location
49-037-0732A	University of Wyoming Carter	FSU 1	Wildcat	Sweetwater	sec. 16, T20N, R102W
49-037-0903	Mesaro Company	UPHE 15-19-104-1	Bacon Basin North	Sweetwater	sec. 15, T20N, R104W

EXPLANATION

Unconformity
Approximate contact
Approximate cumulative log depth
Actual log depth

Sandstone
Shale
Sandstone/shale/siltstone
Limestone/dolomite
Precambrian rocks

Note: The lithologies shown are general and assume to depict average lithologic conditions and are not based on petrophysical analysis of cores or logs.

REFERENCES

Lunn, J.D., Christiansen, K.J., and Nye Pfeng, K.L., compiers, 2011, Wyoming oil and gas fields symbol book: Wyoming Oil and Gas Conservation Commission, 2011 (digital log data), at http://wogcc.state.wy.us/.

Wyoming Oil and Gas Conservation Commission, 2011, [digital log data], at http://wogcc.state.wy.us/.

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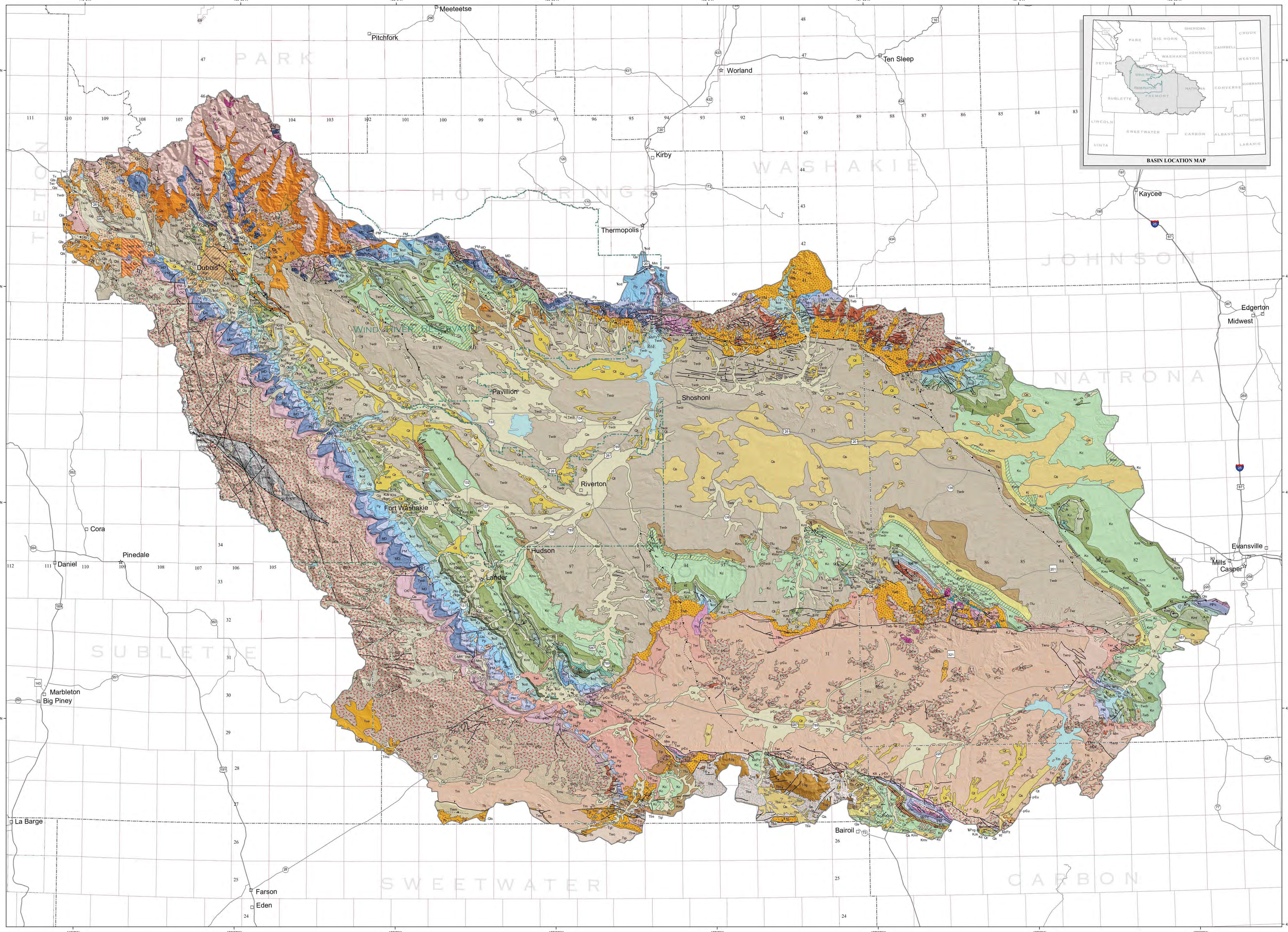
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 7
Geologic Map of the Wind River Basin



EXPLANATION

MAP SYMBOLS

- Formation contact
- **Normal fault**—Dotted where concealed; bar and ball on downthrown block; no designation on fault trace indicates undetermined motion
- **Thrust fault**—Dotted where concealed; sawteeth on upthrown (tectonically higher) block
- **Shear zone**
- **Ice**
- County seat
- City or town
- Lake or reservoir
- Interstate highway
- U.S. highway
- State highway
- County or other road
- Wind River Reservation boundary
- County boundary

GEOLOGIC UNITS
(Geology enlarged from 1:500,000 scale to improve readability)

CENOZOIC

Quaternary

- Qa — Alluvium and colluvium
- Qt — Gravel, pediment, and fan deposits
- Qg — Glacial deposits
- Qls — Landslide deposits
- Qs — Dune sand and loess
- Ql — Playa lake and other lacustrine deposits
- Qb — Basalt flows, tuff, and intrusive igneous rocks

Quaternary and Tertiary

- QTb — Bug Formation (Pleistocene or Pliocene)

Tertiary

- Tcv — Caldwell Canyon volcanics, southern Absaroka Range
- Tm — Miocene rocks
- Tmu — Upper Miocene rocks
- Tml — Lower Miocene rocks–Bighorn Mountains
- Twr — White River Formation
- Twru — Upper conglomerate member of White River Formation
- Toe — Oligocene and/or upper and middle Eocene rocks
- Tip — Ice Point Conglomerate
- Tid — Dacite and quartz latite intrusive and extrusive igneous rocks
- Tai — Alkalic intrusive and extrusive rocks
- Tu — Post-Eocene sandstone and conglomerate
- Ti — Intrusive igneous rocks
- Absaroka Volcanic Supergroup: Thorofare Creek Group
  - Twi — Wiggins Formation
  - Tt — Tepee Trail Formation
  - Ta — Aycross Formation
- Teml — Middle and lower Eocene rocks–equivalent to Aycross and Wind River Formations
- Tv — Volcanic conglomerate–Jackson Hole
- Twdr — Wind River Formation–at base locally includes equivalent of Indian Meadows Formation
- Twim — Wind River and Indian Meadows Formations
- Tim — Indian Meadows Formation
- Twb — Wagon Bed Formation
- Tb — Bridger Formation
- Tcg — Crooks Gap Conglomerate
- Tgl — Laney Member of Green River Formation
- Tgt — Tipton Shale Member or Tongue of Green River Formation
- Twc — Cathedral Bluffs Tongue of Wasatch Formation
- Twm — Main body of Wasatch Formation
- Tbw — Transitional unit between Battle Spring and Wasatch Formations
- Tbs — Battle Spring Formation
- Tfu — Fort Union Formation

CENOZOIC AND MESOZOIC

Tertiary and Cretaceous

- TKu — Sedimentary rocks–northern part of Wind River Basin

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Klm — Lance Formation, Fox Hills Sandstone, Meeteetse Formation, and Bearpaw and Lewis Shales
- Kfl — Fox Hills Sandstone and Lewis Shale
- Kml — Meeteetse Formation and Lewis Shale
- Kle — Lewis Shale
- Kmv — Mesaverde Group
- Kc — Cody Shale
- Ks — Steele Shale
- Kn — Niobrara Formation
- Kf — Frontier Formation
- Kft — Frontier Formation, and Mowry and Thermopolis Shales
- Kmt — Mowry and Thermopolis Shales

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations
- KJs — Cloverly, Morrison, and Sundance Formations
- KJg — Cloverly, Morrison, Sundance and Gypsum Spring Formations

Cretaceous, Jurassic, and Triassic

- KŦ — Cloverly, Morrison, Sundance, and Gypsum Spring Formations and Nugget Sandstone

Jurassic

- Js — Sundance Formation
- Jsg — Sundance and Gypsum Spring Formations

Jurassic and Triassic

- JŦ — Sundance and Gypsum Spring Formations and Chugwater Formation
- JŦgn — Gypsum Spring Formation, Nugget Sandstone and Chugwater Formation
- JŦn — Nugget Sandstone

Triassic

- Ŧc — Chugwater Formation or Group
- Ŧcd — Chugwater and Dinwoody Formations

MESOZOIC AND PALEOZOIC

- ŦPcg — Chugwater and Goose Egg Formations
- ŦPg — Goose Egg Formation
- MzPz — Mesozoic and Paleozoic rocks, undifferentiated

PALEOZOIC

Permian

- Pp — Phosphoria Formation and related rocks

Permian and Pennsylvanian

- PPc — Casper Formation

Permian, Pennsylvanian, and Mississippian

- PM — Tensleep Sandstone and Amsden Formation
- PPM — Wells and Amsden Formations

Mississippian

- Mm — Madison Limestone or Group

Mississippian and Devonian

- MD — Madison Limestone and Darby Formation

Mississippian, Devonian, Ordovician, and Cambrian

- Pzr — Madison Limestone, Darby Formation, Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

Ordovician and Cambrian

- O€ — Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

Cambrian

- €u — Gallatin Limestone, Gros Ventre Formation and equivalents, and Flathead Sandstone

PRECAMBRIAN

- p€u — Precambrian rocks, undifferentiated

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BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ lsis_home/home /index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc.noaa.gov/geomagmodels/struts/calcDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

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Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

Magnetic Declination = 10° 41' E at center of map (Feb. 12, 2013)

Scale 1:350,000
0 10 20 30 40 50 Miles
0 20 40 60 80 Kilometers

Geology modified from Love and Christiansen (1985)
Digital cartography and layout by Phyllis A. Ranz
Edited by Suzanne C. Luhr

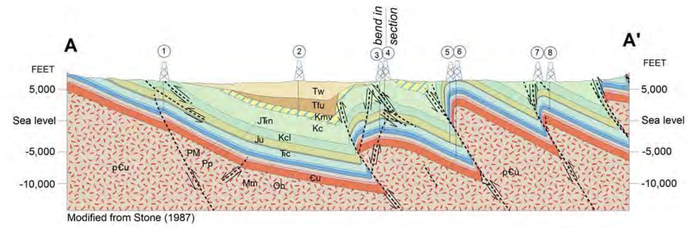
GEOLOGIC MAP OF THE WIND RIVER BASIN, WYOMING

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

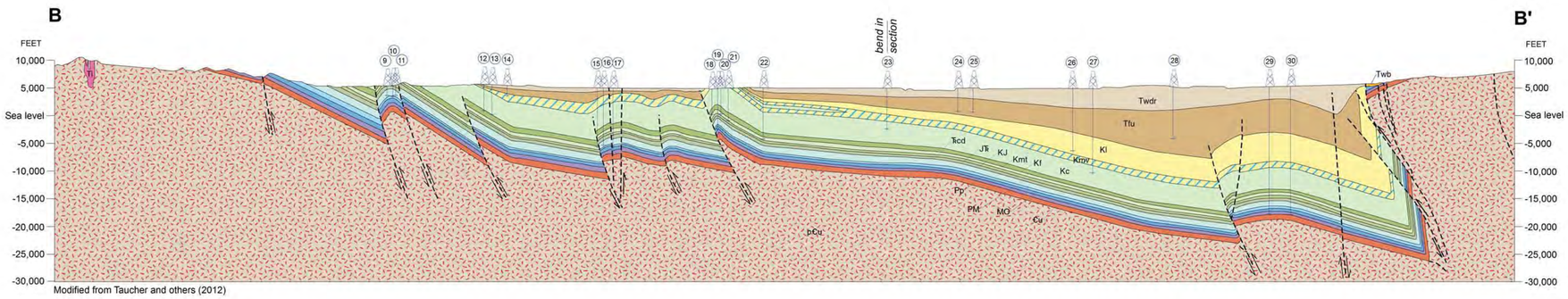
Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 8
Cross Sections
Wind River Basin



Modified from Stone (1987)



Modified from Taucher and others (2012)

EXPLANATION

CROSS SECTION SYMBOLS

Formation contact – Dashed where inferred

Fault – Dashed where inferred; arrows indicate relative movement

Drill hole – Well logs used to construct cross sections

GEOLOGIC UNITS

CENOZOIC

Tertiary

- Ti — Intrusive igneous rocks
- Twb — Wagon Bed Formation
- Twdr — Wind River Formation
- Tw — Wasatch Formation
- Tfu — Fort Union Formation

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Kmv — Mesaverde Formation
- Kc — Cody Shale
- Kf — Frontier Formation
- Kmt — Mowry Shale, Muddy Sandstone, and Thermopolis Shale
- Kcl — Coverly Formation

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations

Jurassic

- Ju — Jurassic rocks, undifferentiated

Jurassic and Triassic

- JTR — Sundance and Gypsum Spring Formations, and Nugget Sandstone
- JTRn — Nugget Sandstone

Triassic

- TRc — Chugwater Formation
- TRcd — Chugwater and Dinwoody Formations

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Permian, Pennsylvanian, and Mississippian

- PM — Tensleep Sandstone and Amsden Formation

Mississippian

- Mm — Madison Limestone

Mississippian, Devonian, and Ordovician

- MO — Mississippian, Devonian, and Ordovician rocks, undifferentiated

Ordovician

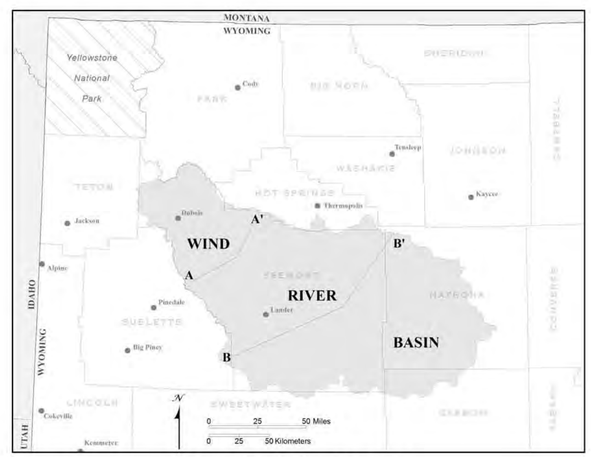
- Ob — Bighorn Dolomite

Cambrian

- Cu — Cambrian rocks, undifferentiated

PRECAMBRIAN

- pCu — Precambrian rocks, undifferentiated



CROSS SECTION LOCATION MAP

WELL CONTROL ALONG CROSS SECTIONS

Well no.	API no.	Operator	Well name	Bottom formation	Surface location sec.	T.	R.	County	Spud year
1	49-013-20303	Stoltz & Co.	Tribal 1-35	Tensleep	35	4N	4W	Fremont	1970
2	49-013-21236	Gulf Energy Corporation	Crowheart Butte I 1-35-1	Cody	35	5N	3W	Fremont	1982
3	49-013-20090	Clinton Oil Company	Tribal Q 1	Madison	8	5N	2W	Fremont	1967
4	49-031-20054	Turner Smith & Associates	Tribal R 8-1	Madison	8	5N	2W	Fremont	1968
5	49-013-21422	American Beryllium Oil Corp.	AQP Tribal 36-33	Chugwater	36	6N	2W	Fremont	1984
6	49-013-21318	American Beryllium Oil Corp.	Tribal 9-24	Tensleep	9	6N	2W	Fremont	1981
7	49-013-06740	British American Oil	Tribal 1	Chugwater	4	6N	2W	Fremont	1954
8	49-013-06751	British American Oil	Arapahoe 2	Tensleep	3	6N	1W	Fremont	1956
9	49-013-21383	Hrubetz Oil Company	Dallas-Federal 1-19	Tensleep	19	32N	98W	Wind River	1983
10	49-013-06936	Sunset International	Govt 29-4B	Tensleep	29	32N	98W	Wind River	1966
11	49-013-05367	Cabeen Exploration	Govt 1	Tensleep	19	32N	98W	Wind River	1957
12	49-013-21915	Sauer Bill Oil & Gas Company LLC	Sauer Ogle 1	Frontier	7	32N	97W	Wind River	1999
13	49-013-05490	Conoco Inc.	Govt 29-4B	Morrison	8	32N	97W	Wind River	1956
14	49-013-22204	Phillips Petroleum Company	Corehole 2	Mesaverde	28	33N	97W	Wind River	2001
15	49-013-05623	Devon Energy Production Company LP	Beaver Creek Unit 10	Phosphoria	16	33N	96W	Wind River	1948
16	49-013-05639	Devon Energy Production Company LP	Beaver Creek Unit 55	Tensleep	16	33N	96W	Wind River	1958
17	49-013-05649	Devon Energy Production Company LP	Beaver Creek Unit 40	Cambrian	10	33N	96W	Wind River	1955
18	49-013-20381	Texaco Exploration & Prod.	Govt-P L Ackerman 1	Skull Creek	27	34N	95W	Wind River	1972
19	49-013-20334	Legacy Reserves Operation LP	Alkali Butte Unit 8	Madison	26	34N	95W	Wind River	1971
20	49-013-20547	Legacy Reserves Operation LP	Federal 1	Thermopolis	23	34N	95W	Wind River	1975
21	49-013-05903	M K M Oil Company	Hagood 1	Thermopolis	23	34N	95W	Wind River	1959
22	49-013-20184	Occidental	Govt-Campbell Ridge 1	Morrison	7	34N	94W	Wind River	1969
23	49-013-05997	SWEPI LP	Conant Creek Unit 22-27	Cody	27	35N	93W	Wind River	1962
24	49-013-21347	ANR Production Company	Conant Creek Unit 1-6	Fort Union	6	35N	92W	Wind River	1982
25	49-013-21454	Amerada Hess Corporation	Federal 30-23	Fort Union	30	36N	92W	Wind River	1984
26	49-013-22427	Encana Oil and Gas USA Inc.	Riverbank Unit 1	Meeteetse	31	37N	91W	Wind River	2004
27	49-013-20845	Dome Petroleum Corporation	Moneta Unit 1-29	Cody	29	37N	91W	Wind River	1978
28	49-013-21820	Noble Energy Inc.	State 44-36	Fort Union	36	38N	91W	Wind River	1997
29	49-013-21510	Burlington Resources Oil & Gas Company L	Bighorn 2-3	Gallatin	3	38N	90W	Wind River	1991
30	49-013-22127	Burlington Resources Oil & Gas Company L	Bighorn 8-35	Madison	35	39N	90W	Wind River	2001

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REFERENCES

Stone, D.S., 1987, Rocky Mountain Transect–Wyoming, transect segments SW 3 and SW 2: Littleton, Co., DVD, version 2.0.

Taucher, P., Bartons, T.T., Clarey, K.E., Quillinan, S.A., Hallberg, L.L., Clark, M.L., Thompson, M., Gribb, N., Worman, B., and Gracias, T., 2012, *in* Copeland, D. ed., Available groundwater determination, Technical Memorandum, Wind/Bighorn River Basin water plan update, groundwater study, Level I (2008–2011): Prepared for the Wyoming Water Development Commission, by the Wyoming State Geological Survey, Laramie, Wy., [variously paged].

ACKNOWLEDGMENT

The Wyoming State Geological Survey thanks D.S. Stone for his permission to modify portions of the Rocky Mountain Transect, as shown in cross section A - A'.

Layout and design by Phyllis A. Ranz and Robert Kirkwood
Edited by Suzanne C. Luhr

GEOLOGIC CROSS SECTIONS, WIND RIVER BASIN, WYOMING

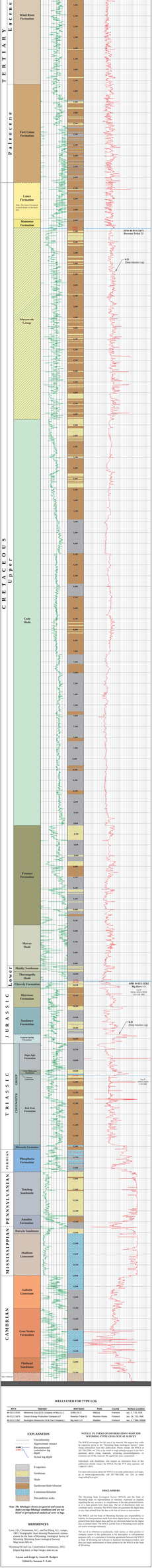
Vertical exaggeration ~ 2x

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

TECHNICAL MEMORANDUM 3
Plate 1
Type Log
Wind River Basin

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
WIND RIVER BASIN



WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Field	County	Surface Location
49-013-22545	Wolverine Gas & Oil Company of Wyo LLC	Griffin 04-2	Wildcat	Fremont	sec. 2, T35, R5E
49-013-21871	Devon Energy Production Company, LP	Hiawatha Velsir 52	Hiawatha Dome	Fremont	sec. 24, T31, R4E
49-013-21963	Burlington Resources Oil & Gas Company L	Big Horn 1-5	Madden	Fremont	sec. 5, T28N, R95W

EXPLANATION

Uncertainty
Representative gamma ray
Resistivity
cumulative log depth
Actual log depth

Evaporites
Sandstone
Shale
Sandstone/shale/siltstone
Limestone/dolomite
Precambrian rocks

Note: The lithologic shown are general and meant to depict average lithologic conditions and are not based on petrophysical analysis of cores or logs.

REFERENCES

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., compiz., 1993, Stratigraphic chart showing Phanerozoic nomenclature for parts of Wyoming and vicinity: Wyoming Geological Survey and U.S. Geological Survey Map Series MS-45.

Wyoming Oil and Gas Conservation Commission, 2012, [digital log data], at http://wogcc.state.wy.us.

Layout and design by James R. Rodgers
Edited by Suzanne C. Lube

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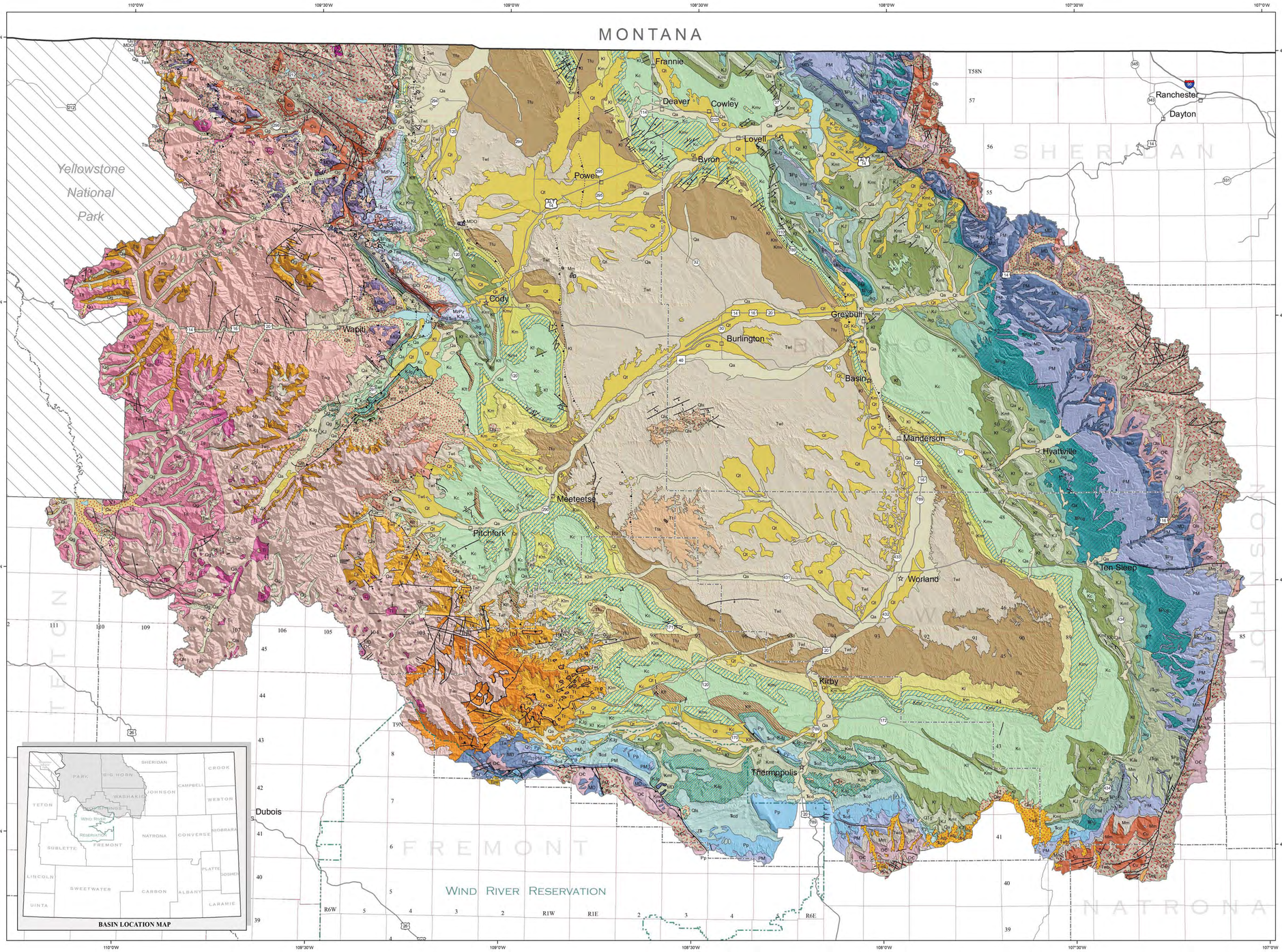
GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 10
Geologic Map of the Bighorn Basin



Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

Magnetic Declination = 11° 1' E
at center of map
(Feb. 12, 2013)

Scale 1:350,000

0 10 20 30 40 50 Miles

0 20 40 60 80 Kilometers

Geology modified from Love and Christiansen (1985)

Digital cartography and layout by Tomas Gracias, Phyllis A. Ranz, and Robin W. Lyons

Edited by Suzanne C. Luhr

GEOLOGIC MAP OF THE BIGHORN BASIN, WYOMING

EXPLANATION

MAP SYMBOLS

Formation contact

Normal fault—Dotted where concealed; ball and bar on downthrown block; no designation on fault trace indicates undetermined motion

Thrust fault—Dotted where concealed; sawteeth on upthrown (tectonically higher) block

County seat
City or town
Lake or reservoir
U.S. highway
State highway
County or other road
Wind River Reservation boundary
County boundary
State boundary

GEOLOGIC UNITS
(Geology enlarged from 1:500,000 scale to improve readability)

CENOZOIC

Quaternary

- Qa — Alluvium and colluvium
- Qt — Gravel, pediment, and fan deposits
- Qg — Glacial deposits
- Landslide deposits
- Surficial deposits, undifferentiated

Quaternary and Tertiary

- QTg — Terrace gravel

Tertiary

- Thv — Huckleberry Ridge Tuff of Yellowstone Group
- Tml — Lower Miocene rocks
- Twr — White River Formation
- Ti — Intrusive igneous rocks

Absaroka Volcanic Supergroup:

- Thorofare Creek Group
  - Twi — Wiggins Formation
  - Ttl — Two Ocean and Langford Formations–in places may include Trout Peak Trachyandesite of Sunlight Group
  - Tt — Tepee Trail Formation
  - Ta — Aycross Formation
  - Thorofare Creek and Sunlight Groups–includes Two Ocean and Langford Formations, Trout Peak Trachyandesite, and Wapiti Formation
- Sunlight Group–includes Trout Peak Trachyandesite, Wapiti Formation, Crescent Hill Basalt, and Mount Wallace Formation
  - Ttp — Trout Peak Trachyandesite
  - Twp — Wapiti Formation
- Washburn Group–includes Sepulcher, Lamar River, and Cathedral Cliffs Formations

- Twb — Wagon Bed Formation
- Tta — Tatman Formation
- Twf — Willwood Formation
- Tim — Indian Meadows Formation
- Tcr — Crandall Conglomerate
- Tfu — Fort Union Formation

MESOZOIC

Cretaceous

- Ki — Intrusive igneous rocks
- Kl — Lance Formation
- Klm — Lance Formation, Fox Hills Sandstone, Meeteetse Formation, and Bearpaw and Lewis Shales
- Km — Meeteetse Formation
- Mesaverde Formation
- Kc — Cody Shale
- Kf — Frontier Formation
- Frontier Formation, Mowry Shale, Muddy Sandstone and Thermopolis Shale
- Kmt — Mowry Shale, Muddy Sandstone, and Thermopolis Shale

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations
- KJs — Cloverly, Morrison, and Sundance Formations
- KJg — Cloverly, Morrison, Sundance and Gypsum Spring Formations

Jurassic

- Js — Sundance Formation
- Jsg — Sundance and Gypsum Spring Formations

Jurassic and Triassic

- JTs — Sundance and Gypsum Spring Formations, and Nugget Sandstone
- JTsgc — Gypsum Spring Formation, Nugget Sandstone, and Chugwater Formation

Triassic

- Tc — Chugwater Formation or Group
- Tcd — Chugwater and Dinwoody Formations

MESOZOIC AND PALEOZOIC

- MPzg — Chugwater and Goose Egg Formations
- MPg — Goose Egg Formation
- MzPz — Mesozoic and Paleozoic rocks, undifferentiated

PALEOZOIC

Permian

- Pp — Phosphoria Formation and related rocks

Permian, Pennsylvanian, and Mississippian

- PM — Tensleep Sandstone and Amsden Formation

Mississippian

- Mm — Madison Limestone or Group

Mississippian and Devonian

- MD — Madison Limestone and Darby Formation

Mississippian, Devonian, and Ordovician

- MDO — Madison Limestone, Darby or Three Forks, Jefferson, and Beartooth Butte Formations, and Bighorn Dolomite

Mississippian and Ordovician

- MO — Madison Limestone and Bighorn Dolomite

Devonian and Ordovician

- DO — Three Forks, Jefferson, and Beartooth Butte Formations and Bighorn Dolomite

Ordovician

- Ob — Bighorn Dolomite

Ordovician and Cambrian

- OC — Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

Cambrian

- Ꞓu — Gallatin Limestone, Gros Ventre Formation and equivalents, and Flathead Sandstone

PRECAMBRIAN

- Precambrian rocks, undifferentiated

DATA REFERENCES

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ lsis_home/home /index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc.noaa.gov/geomagmodels/struts/calcDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

Wyoming Geographic Information Science Center, 1997, Internet mapping service—Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

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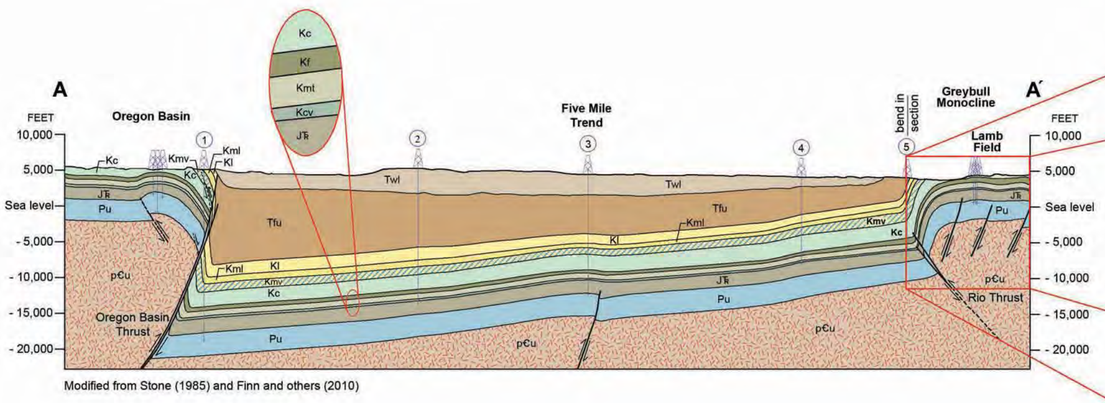
TECHNICAL MEMORANDUM 3
Plate 11
Cross Sections
Bighorn Basin



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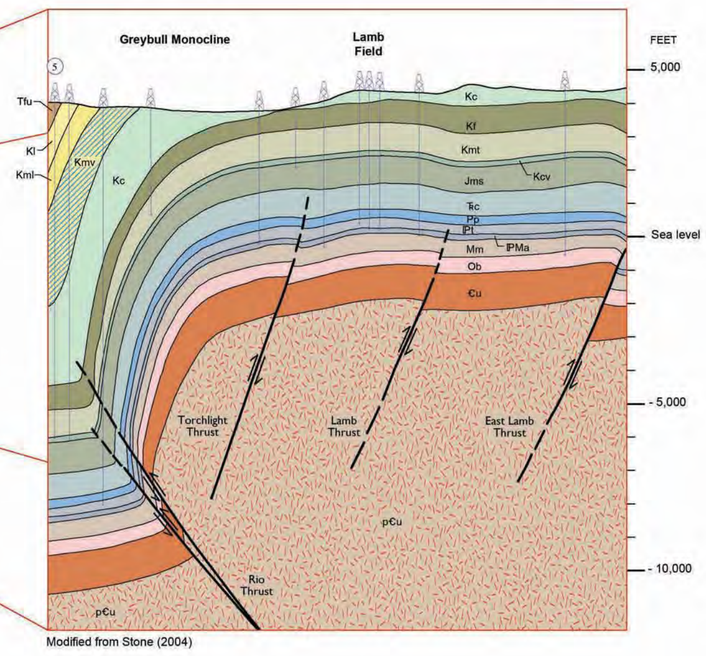

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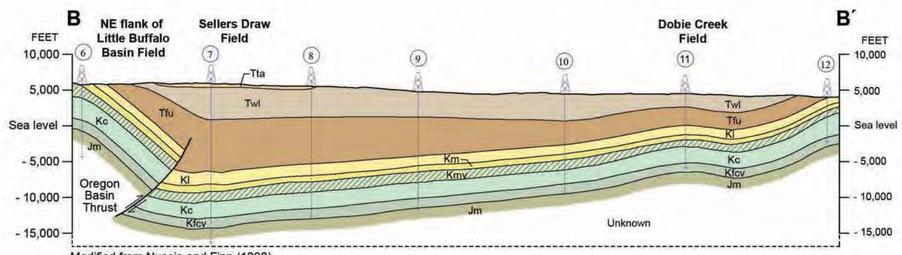

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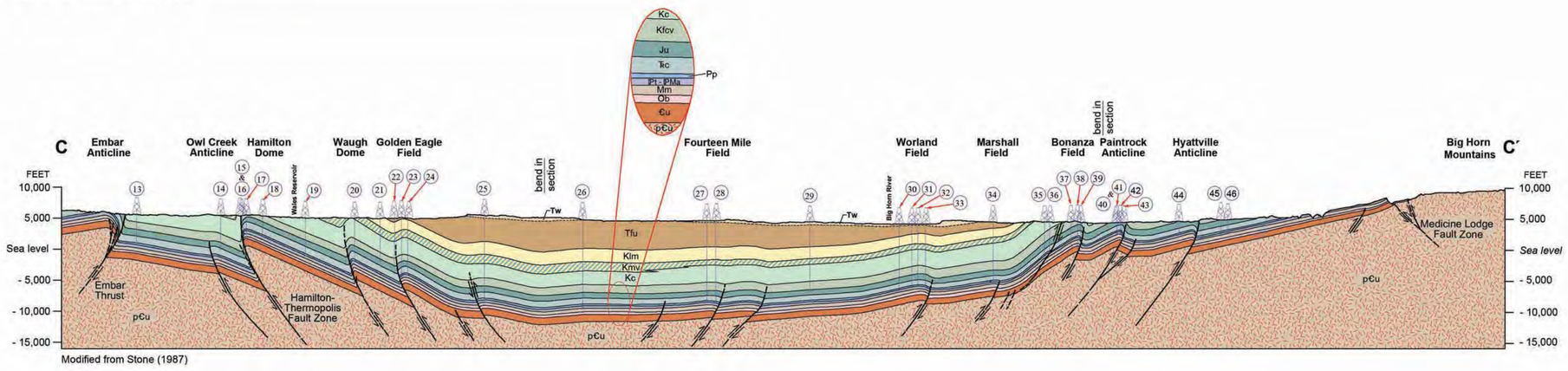

Modified from Stone (1987)

EXPLANATION

CROSS SECTION SYMBOLS

Formation contact

Fault – Dashed where inferred; arrows indicate relative movement

Drill hole – Well logs used to construct cross sections

GEOLOGIC UNITS

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- Tta — Tatman Formation
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MESOZOIC

Cretaceous

- Kl — Lance Formation
- Klm — Lance and Meeteetse Formations
- Km — Meeteetse Formation
- Kml — Meeteetse Formation and Lewis Shale
- Kmv — Mesaverde Formation
- Kc — Cody Shale
- Kfcv — Frontier Formation, Mowry Shale, Muddy Sandstone, Thermopolis Shale, and Cloverly Formation
- Kf — Frontier Formation
- Kmt — Mowry Shale, Muddy Sandstone, and Thermopolis Shale
- Kcv — Cloverly Formation

Jurassic

- Jms — Morrison Formation
- Jm — Morrison, Sundance, and Gypsum Spring Formations
- Ju — Jurrassic rocks, undifferentiated

Jurassic and Triassic

- JTR — Morrison, Sundance, Gypsum Spring, and Chugwater Formations

Triassic

- TRc — Chugwater Formation

PALEOZOIC

Permian

- Pp — Phosphoria Formation
- Pu — Paleozoic rocks, undifferentiated

Pennsylvanian

- IPt — Tensleep Sandstone

Pennsylvanian and Mississippian

- IPMa — Amsden Formation

Mississippian

- Mm — Madison Limestone

Ordovician

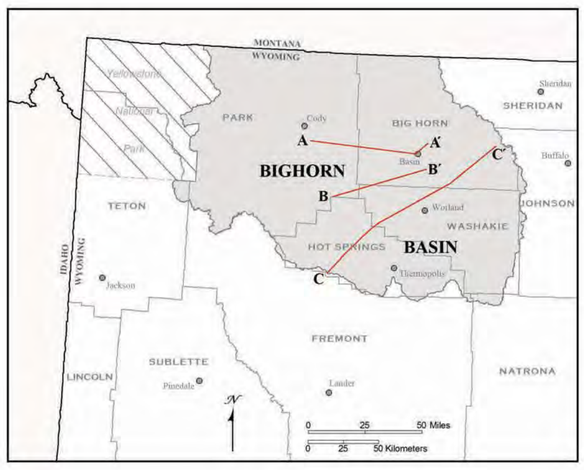
- Ob — Bighorn Dolomite

Cambrian

- Ꞓu — Cambrian rocks, undifferentiated

PRECAMBRIAN

- p€u — Precambrian rocks, undifferentiated



CROSS SECTION LOCATION MAP

WELL CONTROL ALONG CROSS SECTIONS

Well no.	API no.	Operator	Well name	Bottom formation	Surface location sec.	T.	R.	County	Spud year
1	49-029-21009	Hunt Energy Corporation	Loch Katrine Unit 1	Madison	2	51 N	100 W	Park	1982
2	49-029-21064	Gary-Williams Production Company	Emblem Bench 1R	Morrison	2	51 N	98 W	Park	1991
3	49-003-20379	Eastern Minerals Corporation	Michaels Ranch Fee 17-15	Tensleep	17	51 N	96 W	Big Horn	1996
4	49-003-20597	BP America Production Company	Adams 1	Morrison	17	51 N	94 W	Big Horn	1981
5	49-003-20124	True Oil LLC	Rio Unit 33-20	Fuson	20	51 N	93 W	Big Horn	1969
6	49-029-20601	Gulf Energy Corporation	Buffalo Creek-Fed 1	Tensleep	32	48 N	99 W	Park	1976
7	49-029-20489	Bill Barrett Corporation	Sellers Draw Unit II 1	Phosphoria	21	48 N	99 W	Park	1976
8	49-043-20380	American Beryllium Oil Corp.	Ridge Unit 1-21	Dakota	21	48 N	97 W	Washakie	1978
9	49-003-20574	Devon Energy Production Company LP	Tatman Mtn. W-60980 1-20	Morrison	20	49 N	96 W	Big Horn	1981
10	49-003-20469	Southern Mineral Corporation	Schuster Flats 13355 26-1	Dakota	26	49 N	95 W	Big Horn	1978
11	49-003-20466	Devon Energy Production Company LP	Dobie Creek W-14076 1-11	Skull Creek	11	49 N	94 W	Big Horn	1978
12	49-003-05250	Stanolind Oil & Gas Company	Sykes Mobley 1	Muddy	25	50 N	93 W	Big Horn	1955
13	49-017-05354	Wyo. Oil & Minerals Inc.	Daniels 1	Embar	32	9 N	2 E	Hot Springs	1954
14	49-017-06691	Dunoco Inc.	USA 1	Tensleep	26	44 N	98 W	Hot Springs	1966
15	49-017-05582	Merit Energy Company	Kennedy Govt 2	Amsden	23	44 N	98 W	Hot Springs	1963
16	49-017-05582*	Merit Energy Company	Kennedy Govt 2	Amsden	23	44 N	98 W	Hot Springs	1964
17	49-017-05808	Merit Energy Company	Unit C-410400 51	Flathead	14	44 N	98 W	Hot Springs	1953
18	49-017-05812	Merit Energy Company	Placer C-044140 86	Tensleep	13	44 N	98 W	Hot Springs	1959
19	49-017-05929	Husky Oil Company	Cottonwood Land Co 1	Tensleep	26	45 N	98 W	Hot Springs	1954
20	49-017-05924	Ajax Oil Company	Loeb 1	Tensleep	27	45 N	97 W	Hot Springs	1951
21	49-017-20218	Fulton Producing Company	Cottonwood Land Co 31-23	Dakota	23	45 N	97 W	Hot Springs	1975
22	49-017-06631	Husky Oil Company	Cottonwood Land 1	Phosphoria	14	45 N	97 W	Hot Springs	1952
23	49-017-05951	Saga Petroleum LLC of Colorado	Golden Eagle Unit 1	Tensleep	12	45 N	97 W	Hot Springs	1948
24	49-017-05959	Saga Petroleum LLC of Colorado	Golden Eagle Unit 10	Phosphoria	12	45 N	97 W	Hot Springs	1955
25	49-043-05138	Phillips Petroleum Company	Mesa A W-010296 1	Madison	27	46 N	96 W	Washakie	1956
26	49-043-20270	Tenneco Oil Company	Winchester W-0325048 1	Tensleep	22	46 N	95 W	Washakie	1975
27	49-043-20422	Natural Gas Processing Company	Federal 3-35	Phosphoria	35	47 N	94 W	Washakie	1996
28	49-043-05081	Gulf Energy Corporation	Butler 1	Phosphoria	35	47 N	94 W	Washakie	1953
29	49-043-20429	Davis Oil Company	Okaloosa-Federal 1	Morrison	10	47 N	93 W	Washakie	1980
30	49-043-05006	Devon Energy Production Company LP	Unit Patent 27-5	Embar	29	48 N	92 W	Washakie	1950
31	49-043-05428	Devon Energy Production Company LP	Worland Unit 24-F2	Phosphoria	29	48 N	92 W	Washakie	1996
32	49-043-05434	Devon Energy Production Company LP	Unit Franks Patent 7-F3	Embar	21	48 N	92 W	Washakie	1948
33	49-043-05701	Devon Energy Production Company LP	Worland Unit 12-F2	Embar	21	48 N	92 W	Washakie	1948
34	49-043-20371	Altus Exploration Company	North Marshall-Govt 7-1	Phosphoria	7	48 N	92 W	Washakie	1978
35	49-003-05057	Cater Oil Company	Hanover 1X	Phosphoria	34	48 N	91 W	Big Horn	1957
36	49-003-05100	Amerada Hess Corporation	Neal B-0224083 1	Phosphoria	28	49 N	91 W	Big Horn	1963
37	49-003-05083	Gulf Energy Corporation	Mayou B-0368644A 1	Madison	35	49 N	91 W	Big Horn	1951
38	49-003-05085	Conoco Inc.	Federal B-044043 7	Gros Ventre	25	49 N	91 W	Big Horn	1959
39	49-003-05111	General American Oil Co. of Texas	Federal W-03511 6	Tensleep	26	49 N	91 W	Big Horn	1952
40	49-003-05000	Christiana Oil Corp.	Federal 1	Tensleep	18	49 N	90 W	Big Horn	1953
41	49-003-20502	Husky Oil Company	Paintrock #58309 10-12	Granite	12	49 N	91 W	Big Horn	1979
42	49-003-05002	Christmann John J.	Govt. 1	Tensleep	18	49 N	90 W	Big Horn	1963
43	49-003-05165	Christmann John J.	---------	Tensleep	18	49 N	90 W	Big Horn	1963
44	49-003-05235	Mobil Expl. & Producing North America Inc.	Mercer Patented 1	Tensleep	2	49 N	90 W	Big Horn	1953
45	49-003-20683	Data Big Horn Basin	Mineral 23X-25	Madison	25	50 N	90 W	Big Horn	1983
46	49-003-20729	Data Big Horn Basin	Hoya 43X-25	Amsden	25	50 N	90 W	Big Horn	1984

** Sidetrack well*

REFERENCES

Finn, T.M., Kirschbaum, M.A., Roberts, S.B., Condon, S.M., Roberts, L.N.R., and Johnson, R.C., 2010, Cretaceous-Tertiary composite total petroleum system (503402), Bighorn Basin, Wyoming and Montana, *in* U.S. Geological Survey Bighorn Basin Province Assessment Team., comp., Petroleum systems and geologic assessment of oil and gas in the Bighorn Basin Province, Wyoming and Montana: U.S. Geological Survey Digital Data Series DDS-69-V, chap. 3, 156 p.

Nuccio, V.F., and Finn, T.M., 1998, Thermal maturity and petroleum generation history of Cretaceous and Tertiary source rocks, Bighorn Basin, Wyoming and Montana, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Casper, Wy., Wyoming Geological Association, 49th annual field conference, Guidebook, p. 211-231.

Stone, D.S., 1985, Geologic interpretation of seismic profiles, Bighorn Basin, Wyoming, part II—West flank, *in* Gries, R.R., and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain region: Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 175-186.

Stone, D.S., 1987, Rocky Mountain Transect—Wyoming, transect segments SW 2, SW 1, NE 1, NE 2: Littleton, Co., DVD, version 2.0.

Stone, D.S., 2004, Rio thrusting, multi-stage migration, and formation of vertically segregated Paleozoic oil pools at Torchlight Field on the Greybull Platform (eastern Bighorn Basin)—Implications for exploration: The Mountain Geologist, v. 41, no. 3, p. 119-138.

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The Wyoming State Geological Survey thanks D.S. Stone for his permission to modify portions of the Rocky Mountain Transect, as shown in cross section C - C'.

Layout and design by James R. Rodgers and Phyllis A. Ranz
Edited by Suzanne C. Luhr

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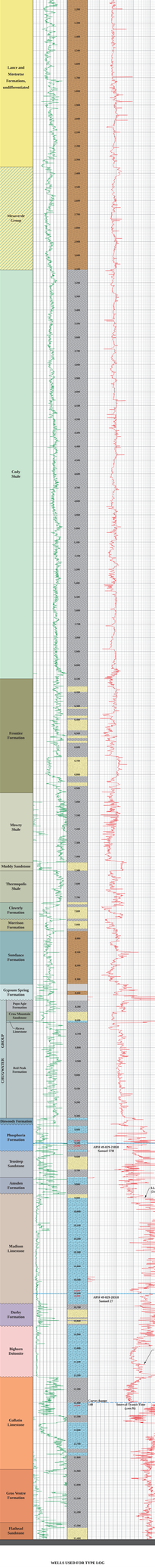
GEOLOGIC CROSS SECTIONS, BIGHORN BASIN, WYOMING

Vertical exaggeration ~ 2x

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
BIGHORN BASIN



WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Field	County	Surface Location
49-045-20715	Continental Resources Inc.	Continental Creek Unit 10-1X	Continental Creek	Hot Springs	sec. 31, T43N, R93W
49-029-21050	Marathon Oil Company	Samuel 57H	Oregon Basin	Park	sec. 32, T52N, R103W
49-029-20510	Marathon Oil Company	Samuel 27	Oregon Basin	Park	sec. 32, T52N, R103W

EXPLANATION

Unconformity
Approximate contact
Reconstructed cumulative log curve
Actual log depth

Evaporites
Sandstone
Shale
Sandstone/shale/siltstone
Limestone/dolostone

Note: *The lithologies shown are general and meant to depict average lithologic conditions and are not based on petrophysical analysis of cores or logs.*

REFERENCES

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., compo., 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming, Map Series 51 (Wyoming State Geological Survey).

Wyoming Oil and Gas Conservation Commission, 2012, [digital log data], at http://wogcc.state.wy.us.

Layout and design by James R. Rodgers
Edited by Rodney H. De Bruin and Suzanne C. Lahr

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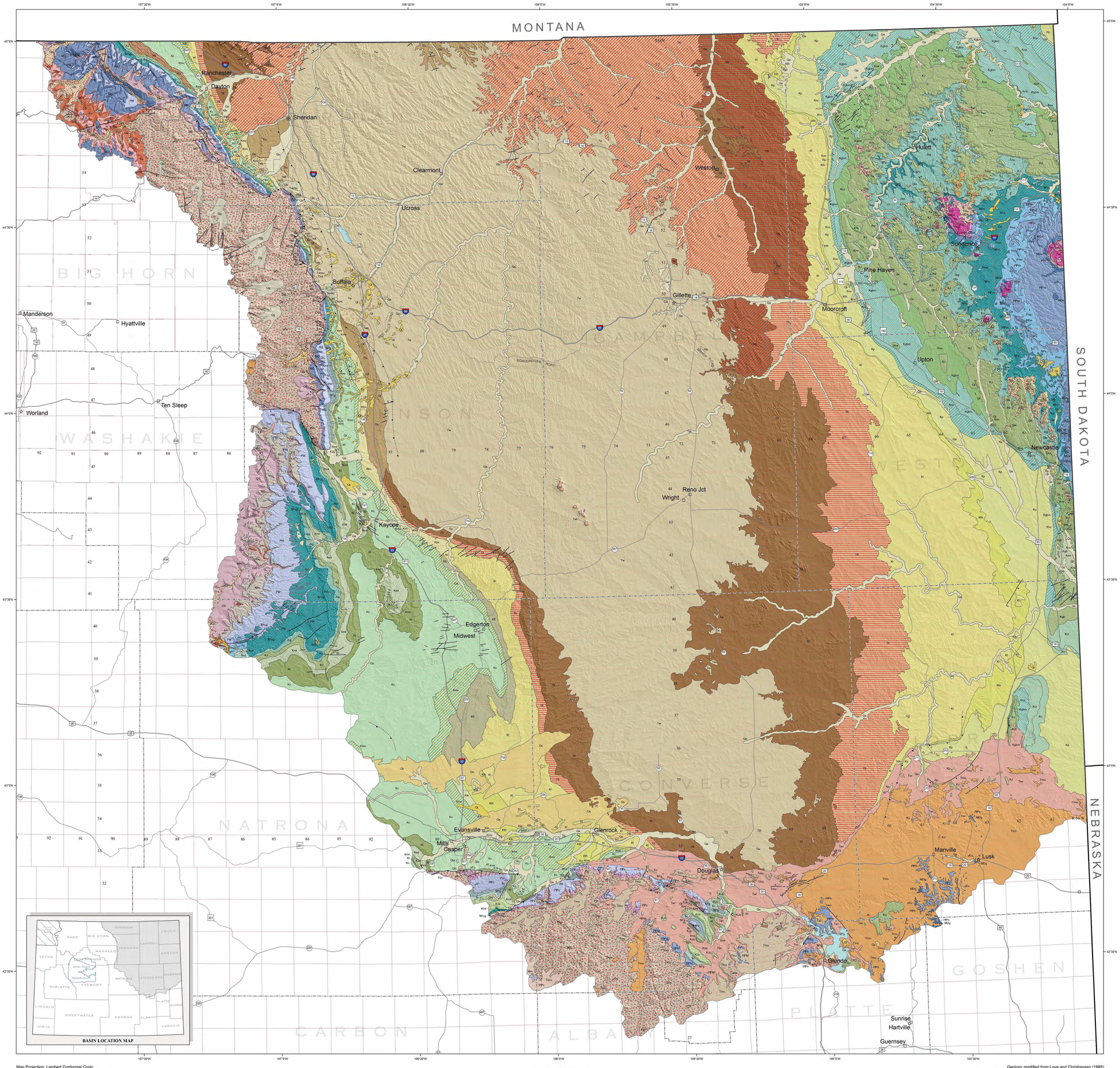
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 13
Geologic Map of the Powder River Basin



EXPLANATION

MAP SYMBOLS

- **Formation contact**
- **Normal fault**—Dotted where concealed; ball and bar on downthrown block; no designation on fault trace indicates undetermined motion
- **Thrust fault**—Dotted where concealed; sawteeth on upthrown (tectonically higher) block
- County seat
- City or town
- Lake or reservoir
- Interstate highway
- U.S. highway
- State highway
- County or other road
- County boundary
- State boundary

GEOLOGIC UNITS
(Geology enlarged from 1:500,000 scale to improve readability)

CENOZOIC

Quaternary

- Qa — Alluvium and colluvium
- Ql — Gravel, pediment, and fan deposits
- Qg — Glacial deposits
- Qls — Landslide deposits
- Qs — Dune sand and loess
- Qs — Surficial deposits, undifferentiated

Quaternary and Tertiary

- QTg — Terrace gravel

Tertiary

- Tmu — Upper Miocene rocks
- Tml — Lower Miocene rocks
- Tmo — Lower Miocene and upper Oligocene rocks or rocks equivalent to upper and lower Miocene rocks and White River Formation
- Twb — Wagon Bed Formation
- Tw — White River Formation
- Twu — Upper conglomerate member
- Tvi — Intrusive and extrusive igneous rocks–incorporates masses of Mississippian through Cambrian formations
- Tw — Wasatch Formation
- Twm — Moncrief Member
- Twk — Kingsbury Conglomerate Member
- Tfu — Fort Union Formation
- Tfr — Tongue River Member
- Tfrl — Tongue River and Lebo Members
- Tfl — Lebo Member
- Tfll — Lebo and Tullock Members
- Tfu — Tullock Member

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Klm — Lance Formation, Fox Hills Sandstone, Meeteetse Formation, and Bearpaw and Lewis Shales
- Kfh — Fox Hills Sandstone
- Kfl — Fox Hills Sandstone and Lewis Shale
- Kfb — Fox Hills Sandstone and Bearpaw Shale
- Kmv — Mesaverde Formation
- Kc — Cody Shale
- Kp — Pierre Shale
- Kn — Niobrara Formation
- Knl — Niobrara Formation and Carlile Shale
- Kcl — Carlile Shale
- Kgb — Greenhorn Formation and Belle Fourche Shale
- Kmb — Greenhorn Formation, and Belle Fourche and Mowry Shales
- Kf — Frontier Formation
- Kmf — Frontier Formation, and Mowry and Thermopolis Shales
- Kmv — Mowry Shale
- Kmt — Mowry and Thermopolis Shales
- Kns — Newcastle Sandstone and Skull Creek Shale
- Kls — Lewis Shale

Cretaceous and Jurassic

- KJ — Cloverly Formation (Hartville Uplift) or Inyan Kara Group (Black Hills) and Morrison Formation
- KJu — Cloverly, Morrison, and Sundance Formations
- KJg — Cloverly, Morrison, Sundance, and Gypsum Spring Formations

Jurassic

- Js — Sundance Formation
- Jsg — Sundance and Gypsum Spring Formations

Triassic

- Tc — Chugwater Formation
- Tcd — Chugwater and Dinwoody Formations

MESOZOIC AND PALEOZOIC

- MPg — Chugwater and Goose Egg Formations
- MPg — Goose Egg Formation
- MPs — Spearfish Formation
- MzPz — Mesozoic and Paleozoic rocks, undifferentiated

PALEOZOIC

Permian

- Pp — Phosphoria Formation and related rocks
- Pmo — Minnekahta Limestone and Opeche Shale

Permian and Pennsylvanian

- PIPc — Casper Formation
- PIPh — Hartville Formation–lowermost unit may be Late Mississippian
- PIPm — Minnelusa Formation

Permian, Pennsylvanian, and Mississippian

- PM — Tensleep Sandstone and Amsden Formation
- PIPM — Casper Formation and Madison Limestone

Mississippian

- Mm — Madison Limestone or Group–includes wedge edge of Bighorn Dolomite in Tps. 43 and 44 N., Rgs. 85 and 86 W

Mississippian and Devonian

- MD — Madison Limestone and Darby Formation
- MDu — Pahasapa and Englewood Limestones
- MDg — Guernsey Formation–locally includes dolomite and sandstone of Devonian and Cambrian(?) age

Mississippian and Ordovician

- MO — Madison Limestone and Bighorn Dolomite–east side of Bighorn Mountains

Mississippian, Devonian, Ordovician, and Cambrian

- Pzr — Minnekahta Limestone, Opeche Shale, Minnelusa Formation; Pahasapa and Englewood Limestones, Whitewood Dolomite, and Winnipeg and Deadwood Formations–various combinations

Ordovician

- Ob — Bighorn Dolomite

Ordovician and Cambrian

- OC — Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

Cambrian

- Ꞓu — Gallatin Limestone, Gros Ventre Formation and equivalents, and Flathead Sandstone

PRECAMBRIAN

- Precambrian rocks, undifferentiated

DATA REFERENCE

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ lsis_home/home /index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc. noaa.gov/geomagmodels/struts/calcDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov/.

Wyoming Geographic Information Science Center, 1997, Internet mapping service—Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

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Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

Magnetic Declination = 9° 38' E
at center of map
(Feb. 12, 2013)

Scale 1:350,000

0 10 20 30 40 50 Miles

0 20 40 60 80 Kilometers

Geology modified from Love and Christiansen (1985)
Digital cartography and layout by Suzanne C. Luhr
Edited by Phyllis A. Ranz and Suzanne C. Luhr

GEOLOGIC MAP OF THE POWDER RIVER BASIN, WYOMING

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
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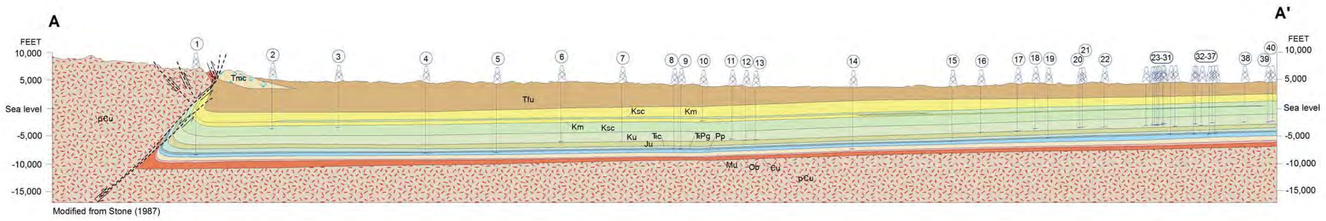
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 14
Cross Sections
Powder River Basin



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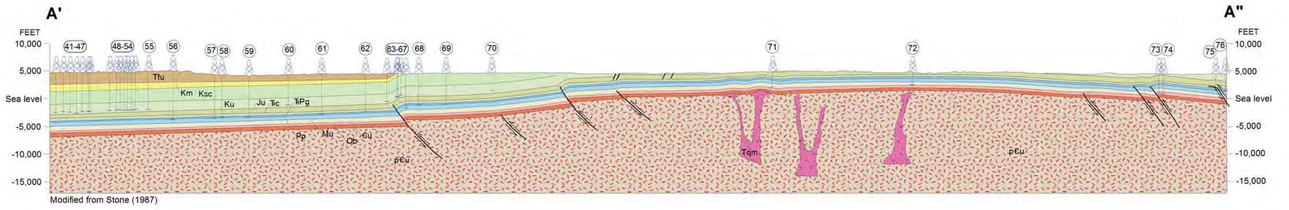
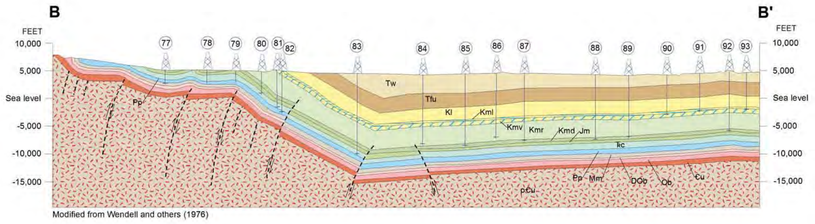


Modified from Stone (1987)



Modified from Wendell and others (1976)

EXPLANATION

CROSS SECTION SYMBOLS

Formation contact – Dashed where inferred

Fault – Dashed where inferred; arrows indicate relative movement

Drill hole – Well logs used to construct cross sections

GEOLOGIC UNITS

CENOZOIC

Tertiary

- Tw — Wasatch Formation
- Tmc — Moncrief and Kingsbury Conglomerate Members of Wasatch Formation
- Tqm — Quartz monzanite intrusion
- Tfu — Fort Union Formation

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Km — Meeteetse Formation
- Kml — Lewis Shale
- Kmv — Mesaverde Formation
- Kmd — Muddy Sandstone
- Kmr — Mowry Shale
- Ksc — Skull Creek Shale
- Ku — Cretaceous rocks, undifferentiated

Jurassic

- Jm — Morrison Formation
- Ju — Jurassic rocks, undifferentiated

Triassic

- Tic — Chugwater Formation

PALEOZOIC

Permian

- Pp — Phosphoria Formation

Triassic and Permian

- TRPg — Goose Egg Formation

Mississippian

- Mm — Madison Limestone
- Mu — Mississippian rocks, undifferentiated

Devonian and Ordovician

- DOb — Devonian rocks and Bighorn Dolomite, undifferentiated

Ordovician

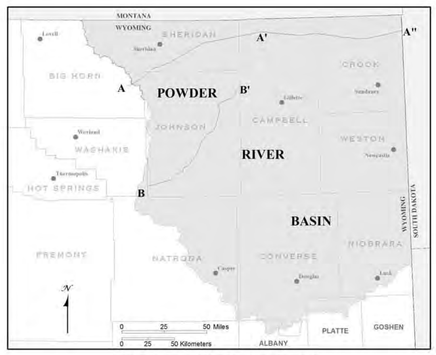
- Ob — Bighorn Dolomite

Cambrian

- Cu — Cambrian rocks, undifferentiated

PRECAMBRIAN

- pCu — Precambrian rocks, undifferentiated



CROSS SECTION LOCATION MAP

REFERENCES

Stone, D.S., 1987, Rocky Mountain Transect—Wyoming, transect segments NE 3, NE 4, NE 5, NE 6, NE 7, NE 8: Littleton, Co., DVD, version 2.0.

Wendell, W.G., Glass, G.B., Breckenridge, R.M., Root, F.K., Lageson, D., and the Remote Sensing Lab at the University of Wyoming, 1976, Johnson County, Wyoming—Geologic map atlas and summary of land, water and mineral resources: Geological Survey of Wyoming [Wyoming State Geological Survey], County Resource Series, no. 4.

ACKNOWLEDGMENT

The Wyoming State Geological Survey thanks D.S. Stone for his permission to modify portions of the Rocky Mountain Transect, as shown in cross section A – A".

Layout and design by Phyllis A. Ranz and Robert Kirkwood
Edited by Suzanne C. Luhr

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WELL CONTROL ALONG CROSS SECTIONS

Well no.	API no.	Operator	Well name	Bottom formation	Surface location sec.	T.	R.	County	Spud year
1	49-033-20176	Gulf Energy Corporation	Granite Ridge Fee 1-9-2D	Amsden	9	53 N	84 W	Sheridan	1983
2	49-033-20086	Anadarko Petroleum Corporation	Demple Swearngin A 1	Shannon	32	54 N	83 W	Sheridan	1973
3	49-033-20128	Florida Gas Exploration Co.	Fordyce Stout Fee 1-16	Shannon	16	54 N	82 W	Sheridan	1980
4	49-033-20133	Union Oil Co. of California	Scales Fee 1-H-10	Minnelusa	10	54 N	81 W	Sheridan	1981
5	49-033-20184	SWEPI LP	State 79-330 33-3	Madison	3	55 N	82 W	Sheridan	1984
6	49-033-20093	Phillips Petroleum Company	Peters-B 1	Skull Creek	12	55 N	81 W	Sheridan	1974
7	49-033-20014	BP America Production Company	Roberts A Patented 1	Morrison	2	55 N	80 W	Sheridan	1968
8	49-033-05021	Amerada Hess Corporation	Boland 1	Minnelusa	19	56 N	79 W	Sheridan	1963
9	49-033-20019	Dugger William L Jr	Petrofina W-0324779 1	Minnelusa	30	56 N	79 W	Sheridan	1968
10	49-033-20002	Dugger William L Jr	Donald H Roberts Pat 1	Parkman	21	56 N	79 W	Sheridan	1967
11	49-033-20018	BP America Production Company	Don H Roberts D Pat 1	Morrison	31	56 N	78 W	Sheridan	1968
12	49-033-20030	BP America Production Company	Don H Roberts E Pat 1	Morrison	15	56 N	79 W	Sheridan	1968
13	49-033-20137	Harper Oil Company	Griffith Roberts Fee 10-14	Morrison	14	56 N	79 W	Sheridan	1980
14	49-033-20170	Hershey Oil Corporation	Buffalo Creek Fee 1-10	Madison	10	56 N	78 W	Sheridan	1983
15	49-033-20177	Amberex Corporation	State 77-674 23-12	Amsden	12	56 N	77 W	Sheridan	1983
16	49-005-20504	Brinkerhoff Drilling Company	Brinkerhoff Patented 2266-1	Morrison	22	56 N	76 W	Campbell	1968
17	49-005-21538	Texaco Exploration & Production	M H Lacoy A W0311410 1	Morrison	11	56 N	76 W	Campbell	1969
18	49-005-23435	Davis Oil Company	Ida Federal 1	Skull Creek	12	56 N	76 W	Campbell	1973
19	49-005-20303	Dow Glenn A	Kirby W-0151480A 1	Minnelusa	18	56 N	75 W	Campbell	1968
20	49-005-22353	Davis Oil Company	Gil W-084345 2	Skull Creek	9	56 N	75 W	Campbell	1970
21	49-005-23084	The Termo Company	Joe Creek Ut Patent 10	Skull Creek	10	56 N	75 W	Campbell	1972
22	49-005-22526	Apache Corporation	U S Plank 1	Skull Creek	11	56 N	75 W	Campbell	1970
23	49-005-20667	Atlantic Richfield Company	Beard W-1885 7	Skull Creek	8	56 N	74 W	Campbell	1968
24	49-005-20790	Powder River Oil	Greenough 9-8	Skull Creek	8	56 N	74 W	Campbell	1968
25	49-005-20331	Adams Don and Associates	Recluse Unit W-1885 458	Dakota	8	56 N	74 W	Campbell	1968
26	49-005-20272	Oilfield Salvage & Service Company	Greenough W-043718 5	Muddy	9	56 N	74 W	Campbell	1968
27	49-005-20288	Adams Don and Associates	Recluse Unit W-1885 457	Skull Creek	9	56 N	74 W	Campbell	1968
28	49-005-20271	Atlantic Richfield Company	Beard W-1885 1	Skull Creek	9	56 N	74 W	Campbell	1968
29	49-005-20177	Oilfield Salvage & Service Company	Greenough W-043718 3	Skull Creek	9	56 N	74 W	Campbell	1968
30	49-005-20275	P&M Petroleum Management LLC	U S Apache A W-2498 7	Minnelusa	9	56 N	74 W	Campbell	1968
31	49-005-24356	Oilfield Salvage & Service Company	Greenough W-43718 7	Skull Creek	10	56 N	74 W	Campbell	1976
32	49-005-28628	Yates Petroleum Corporation	Calamity Spring Unit 6	Minnelusa	11	56 N	74 W	Campbell	1985
33	49-005-22904	Apache Corporation	U S Thomas W-091203 1-11	Skull Creek	11	56 N	74 W	Campbell	1971
34	49-005-20219	McClure Enterprises	Southland W-0311394 1	Morrison	11	56 N	74 W	Campbell	1967
35	49-005-27067	Southland Royalty Company	T R Ranch W-25915 1-12	Minnelusa	12	56 N	74 W	Campbell	1983
36	49-005-21399	Samedan Oil Corporation	Greenough 1	Skull Creek	1	56 N	74 W	Campbell	1969
37	49-005-24777	Coquina Oil Corporation	Lester Fee 1	Minnelusa	7	56 N	73 W	Campbell	1977
38	49-005-20966	Kissinger Petroleum Corporation	Snoddy Patented 1	Skull Creek	9	56 N	73 W	Campbell	1968
39	49-005-22660	Kissinger Petroleum Corporation	Exeter Phillip W3097 6-10	Skull Creek	10	56 N	73 W	Campbell	1971
40	49-005-21667	Oilfield Salvage & Service Company	Chan Muddy Sand Unit 2-10	Skull Creek	10	56 N	73 W	Campbell	1969
41	49-005-22896	Main Energy Inc.	Chan Muddy Sand Unit 6-11	Skull Creek	11	56 N	73 W	Campbell	1972
42	49-005-22898	Oilfield Salvage & Service Company	Chan Muddy Ut W-3097 8-11	Skull Creek	11	56 N	73 W	Campbell	1971
43	49-005-22712	Oilfield Salvage & Service Company	Chan Muddy Ut W-1872 4-12	Skull Creek	12	56 N	73 W	Campbell	1971
44	49-005-27792	Henderson Petroleum Corp.	Chan Muddy Ut W-6522 6-12	Muddy	12	56 N	73 W	Campbell	1984
45	49-005-22303	Petroleum Inc.	Atlantic 2	Skull Creek	7	56 N	72 W	Campbell	1970
46	49-005-24264	Davis Oil Company	Klaenhammer W-39064 1	Skull Creek	7	56 N	72 W	Campbell	1976
47	49-005-21415	Petroleum Inc.	Atlantic 1	Skull Creek	7	56 N	72 W	Campbell	1969
48	49-005-20810	Gibson W R	Emigh A Patented 16-8	Skull Creek	8	56 N	72 W	Campbell	1968
49	49-005-20480	Century Energy	Whitetail W-048897 107	Muddy	9	56 N	72 W	Campbell	1968
50	49-005-20484	Century Energy	Whitetail W-0310894 6	Muddy	9	56 N	72 W	Campbell	1968
51	49-005-20725	Century Energy	Whitetail W-055891 105	Muddy	9	56 N	72 W	Campbell	1968
52	49-005-20477	Century Energy	Whitetail W-055891-A 7	Skull Creek	10	56 N	72 W	Campbell	1968
53	49-005-20724	Century Energy	Whitetail W-048897 5	Skull Creek	10	56 N	72 W	Campbell	1968
54	49-005-20720	Century Energy	Whitetail W-0310894 106	Skull Creek	10	56 N	72 W	Campbell	1968
55	49-005-20876	True Oil LLC	Jones Patented 31-14	Skull Creek	14	56 N	72 W	Campbell	1968
56	49-005-21787	Kissinger Clyde G	Union Texas W0277310 1-7	Skull Creek	7	56 N	71 W	Campbell	1969
57	49-005-06105	Union Oil Co. of California	Swinehart W-030971 1-9	Minnelusa	9	56 N	71 W	Campbell	1962
58	49-005-06113	Gulf Oil Corporation	Govt B W-0271844 1	Minnelusa	3	56 N	71 W	Campbell	1965
59	49-005-06106	Powder River Oil	Allison Patented 1	Minnelusa	12	56 N	71 W	Campbell	1958
60	49-005-21037	Davis Oil Company	Cow Gulch W-054671B 1	Skull Creek	5	56 N	70 W	Campbell	1968
61	49-005-27157	BP America Production Company	Eighty Five Divide 45117 1	Minnelusa	3	56 N	70 W	Campbell	1983
62	49-005-27378	Amberex Corporation	Federal W-56565 33-6	Minnelusa	6	56 N	69 W	Campbell	1983
63	49-005-21382	Love Oil Company	Skyline W-0323663 5-1	Skull Creek	5	56 N	69 W	Campbell	1969
64	49-005-20776	Love Oil Company	Knapp Etal Patented 1	Skull Creek	4	56 N	69 W	Campbell	1968
65	49-005-22299	Webb Resources Inc.	Knapp Patented 4-1A	Skull Creek	4	56 N	69 W	Campbell	1970
66	49-005-21288	Gary-Williams Production Company	Knapp Patented 4-2	Skull Creek	4	56 N	69 W	Campbell	1969
67	49-005-06112	Conoco Inc.	Knapp Patented 1	Madison	4	56 N	69 W	Campbell	1940
68	49-005-06109	Union Texas Petroleum	Gentry W-022667B 1	Minnelusa	3	56 N	69 W	Campbell	1963
69	49-005-22716	Consolidated Oil & Gas Inc.	Federal W-17860 1-1	Minnelusa	1	56 N	69 W	Campbell	1971
70	49-005-06128	Murray Rob	Otis Roberts B040764 1	Skull Creek	4	56 N	68 W	Campbell	1948
71	49-011-06126	Atlantic Richfield Company	Sheridan 1	Bighorn	27	56 N	65 W	Crook	1959
72	49-011-06123	Atlantic Richfield Company	W J Pannell Patent 1	Bighorn	30	56 N	63 W	Crook	1959
73	49-011-06127	Hunt Oil Company	Miller 1	Deadwood	14	56 N	61 W	Crook	1953
74	49-011-20222	McCullough Oil	Bright Patented 1-14	Winnipeg	14	56 N	61 W	Crook	1970
75	49-011-21341	Penrod Geisinger Exploration	Geisinger Fee 1-9	Minnelusa	9	56 N	60 W	Crook	1983
76	49-011-06129	Dunbar O D	Geisinger Patented 1	Minnelusa	4	56 N	60 W	Crook	1958
77	49-019-05854	The Chicago Corporation	C L Harlan 1	Madison	4	42N	83W	Johnson	1953
78	49-019-20178	Husky Oil Company	Husky 7-13	Minnelusa	13	43N	83W	Johnson	1975
79	49-019-05976	Union Oil Co of California	Arndt-Fed 1	Tensleep	9	43N	82W	Johnson	1961
80	49-019-20132	General American Oil Co of Texas	Univ Res-Fed-Kaycee 1	Tensleep	26	44N	82W	Johnson	1974
81	49-019-06249	BP America Production Company	North Fork Unit 13	Tensleep	25	44N	82W	Johnson	1962
82	49-019-06002	The Daube Company	North Fork Unit 13	Madison	19	44N	81W	Johnson	1951
83	49-019-06204	SWEPI LP	Pheasant Unit 22X18	Minnelusa	18	45N	80W	Johnson	1966
84	49-019-20168	Wexpro Company	Boumas Zezas 1-3	Frontier	3	46N	80W	Johnson	1974
85	49-019-20115	Phillips Petroleum Company	Faxla A 1	Morrison	18	47N	79W	Johnson	1974
86	49-019-20101	Davis Oil Company	Curtis Draw Unit 1	Frontier	11	47N	79W	Johnson	1973
87	49-019-20088	Davis Oil Company	Indian Creek Unit 1	Skull Creek	25	48N	79W	Johnson	1973
88	49-019-20107	Davis Oil Company	South Rainbow 1-A	Skull Creek	8	49N	78W	Johnson	1974
89	49-019-20116	Davis Oil Company	North Rainbow-Fed 1	Skull Creek	20	50N	78W	Johnson	1974
90	49-019-06118	Davis Oil Company	Fed-Walker 1	Mesaverde	12	50N	78W	Johnson	1958
91	49-019-06129	SWEPI LP	Govt 41-18	Mesaverde	18	51N	76W	Johnson	1957
92	49-019-20031	Fred Goodstein	Goodstein-MKM 1	Morrison	24	51N	77W	Johnson	1969
93	49-019-06123	SWEPI LP	Govt 11-3	Mesaverde	3	50N	77W	Johnson	1957

GEOLOGIC CROSS SECTIONS, POWDER RIVER BASIN, WYOMING

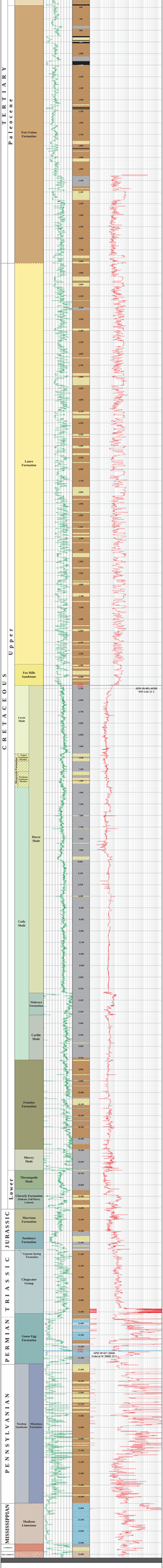
Vertical exaggeration ~ 2x

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drost
Director and State Geologist
Laramie, Wyoming

TECHNICAL MEMORANDUM
Plate 15
Type Log
Powder River Basin

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
POWDER RIVER BASIN



WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Field	County	Surface Location
49-000-61133	Amoco Production Corporation	Geneva #B8	Hilight	Campbell	sec. 5, T43N, R75W
49-005-60589	Marlin Oil Company, LLC	WD Unit 21-3	MD	Campbell	sec. 3, T44N, R75W
49-017-20600	Burlington Resources Oil & Gas Company	Federal W 20602 21-1	Hilliard	Natrona	sec. 1, T27N, R84W

EXPLANATION

- Unconformity
- Approximate contact
- Reconstructed gamma ray profile
- 10,000 — Depth
- Actual log depth
- Coal
- Evaporites
- Sandstone
- Shale
- Sandstone/shale/siltstone
- Limestone/dolomite
- Precambrian rocks

Note: The lithologies shown are general and reason to depict average lithologic conditions and are not based on petrophysical analysis of cores or logs.

REFERENCES

Lines, J.D., Christiansen, A.C., and Nye Pinsg, K.E., comps., 2011, Geologic map of Wyoming: Wyoming State Geological Survey, chasm for the State of Wyoming, Geological Survey of Wyoming (Wyoming State Geological Survey) Map Series 150.

Wyoming Oil and Gas Conservation Commission, 2011, [digital log data], at http://wogcc.state.wy.us.

Layout and design by James D. Rodgers
Edited by Suzanne C. Lake

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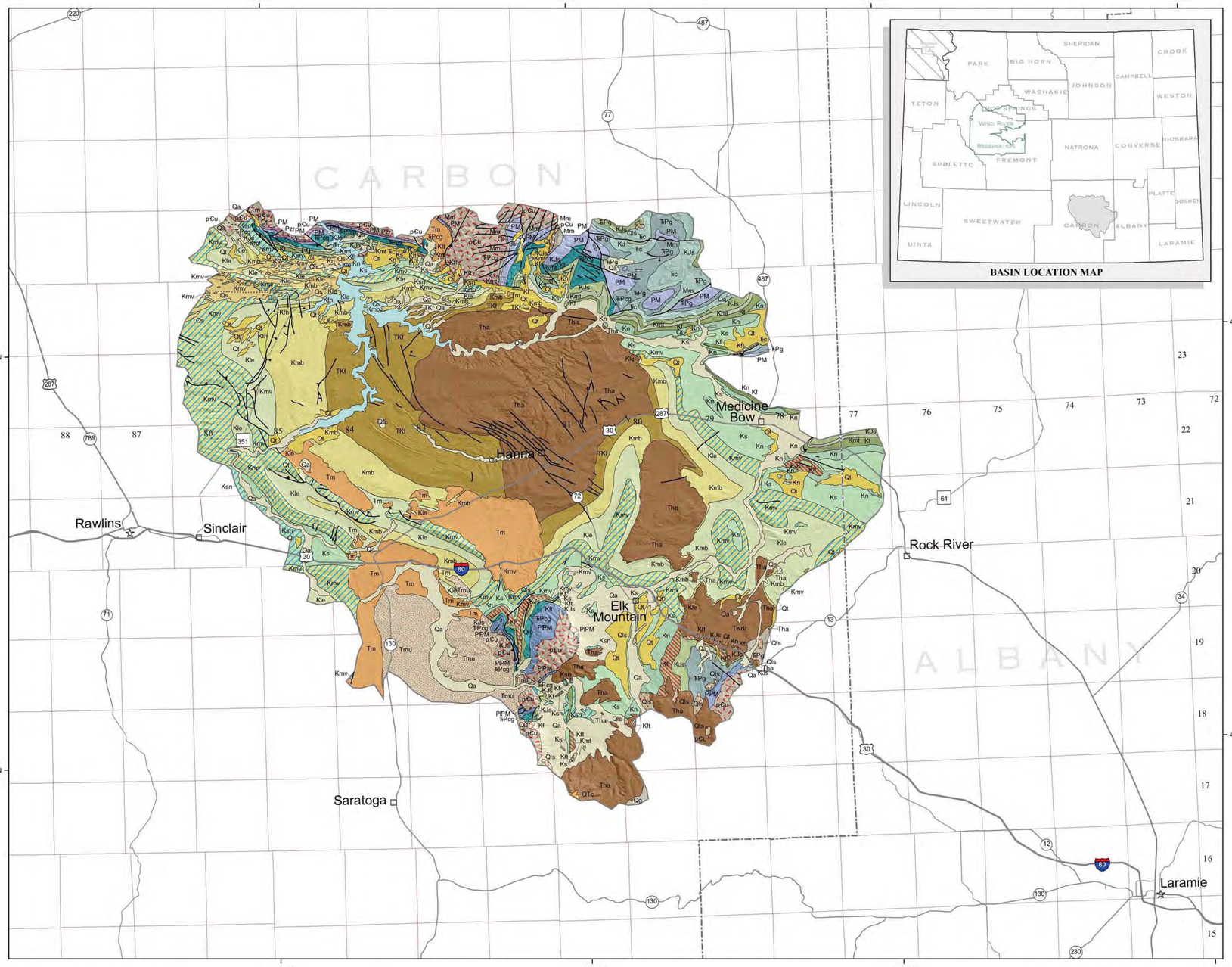
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 16
Geologic Map of the Hanna Basin



Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

N
MN
Magnetic Declination = 9° 40' E
at center of map
(Feb. 12, 2013)

Scale 1:350,000
0 10 20 30 Miles
0 10 20 30 40 50 Kilometers

Geology modified from Love and Christiansen (1985)
Digital cartography and layout by Phyllis A. Ranz
Edited by Suzanne C. Luhr

GEOLOGIC MAP OF THE HANNA BASIN, WYOMING

EXPLANATION

MAP SYMBOLS

Formation contact

Normal fault—Dotted where concealed; bar and ball on downthrown block; no designation on fault trace indicates undetermined motion

Thrust fault—Dotted where concealed; sawteeth on upthrown (tectonically higher) block

County seat
City or town
Lake or reservoir
Interstate highway
U.S. highway
State highway
County or other road
County boundary

GEOLOGIC UNITS

(Geology enlarged from 1:500,000 scale to improve readability)

CENOZOIC

Quaternary

- Qa — Alluvium and colluvium
- Qt — Gravel, pediment, and fan deposits
- Qg — Glacial deposits
- Qls — Landslide deposits
- Qs — Dune sand and loess

Quaternary and Tertiary

- QTc — Conglomerate (Pleistocene to Miocene)

Tertiary

- Tm — Miocene rocks
- Tmu — Upper Miocene rocks
- Twdr — Wind River Formation–at base locally includes equivalent of Indian Meadows Formation
- Tha — Hanna Formation

Tertiary and Cretaceous

- TKf — Ferris Formation

MESOZOIC

Cretaceous

- Kmb — Medicine Bow Formation
- Klh — Fox Hills Sandstone
- Kle — Lewis Shale
- Kmv — Mesaverde Group
- Kc — Cody Shale
- Ks — Steele Shale
- Ksn — Steele Shale and Niobrara Formation
- Kn — Niobrara Formation
- Kf — Frontier Formation
- Kmt — Frontier Formation, and Mowry and Thermopolis Shales
- Kmt — Mowry and Thermopolis Shales

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations
- KJs — Cloverly, Morrison, and Sundance Formations

Jurassic

- Js — Sundance Formation

Triassic

- Ꞧc — Chugwater Formation or Group

PALEOZOIC AND MESOZOIC

Triassic and Permian

- ꞦPcg — Chugwater and Goose Egg Formations
- ꞦPg — Goose Egg Formation

PALEOZOIC

Permian, Pennsylvanian, and Mississippian

- PM — Tensleep Sandstone and Amsden Formation
- PPM — Wells and Amsden Formations

Mississippian

- Mm — Madison Limestone or Group

Mississippian, Devonian, Ordovician, and Cambrian

- Pzr — Madison Limestone, Darby Formation, Bighorn Dolomite, Gallatin Limestone, Gros Ventre Formation, and Flathead Sandstone

PRECAMBRIAN

- pCu — Precambrian rocks, undifferentiated

DATA REFERENCE

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ lsis_home/home /index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc. noaa.gov/geomagmodels/struts/calcDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

Wyoming Geographic Information Science Center, 1997, Internet mapping service—Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

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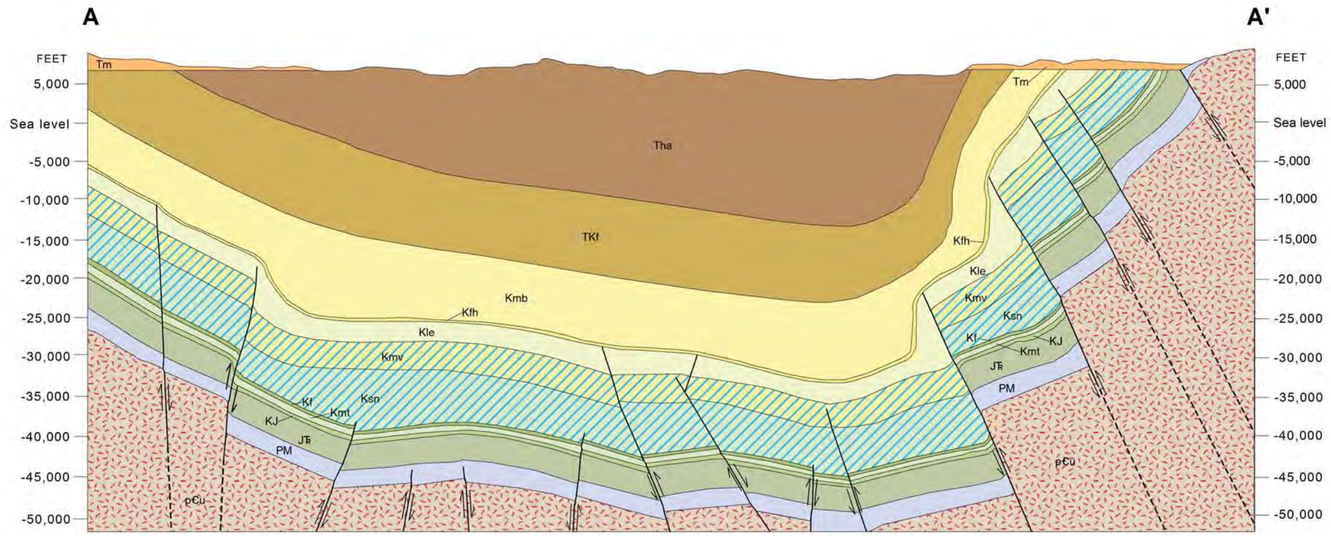
GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 17
Cross Section
Hanna Basin



Modified from Kaplan and Skeen (1985). Depth was determined from time-to-depth conversion of original seismic data and may not be entirely accurate.

EXPLANATION

CROSS SECTION SYMBOLS

Formation contact

Fault – Dashed where inferred; arrows indicate relative movement

GEOLOGIC UNITS

CENOZOIC

Tertiary

- Tm — Browns Park Formation
- Tha — Hanna Formation

CENOZOIC AND MESOZOIC

Paleocene and Cretaceous

- TKf — Ferris Formation

MESOZOIC

Cretaceous

- Kmb — Medicine Bow Formation
- Kfh — Fox Hills Sandstone
- Kle — Lewis Shale
- Kmv — Mesaverde Formation
- Ksn — Steele Shale and Niobrara Formation
- Kf — Frontier Formation
- Kmt — Mowry Shale, Muddy Sandstone, and Thermopolis Shale
- KJ — Cloverly and Morrison Formations, undifferentiated

Jurassic and Triassic

- JTR — Sundance and Gypsum Spring Formations, and Nugget Sandstone

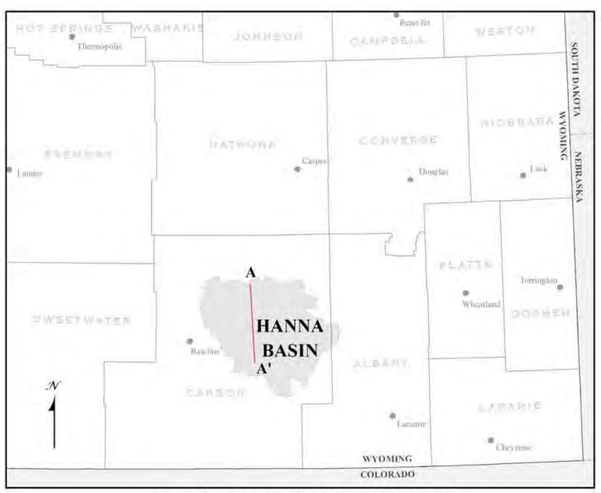
PALEOZOIC

Permian, Pennsylvanian, and Mississippian

- PM — Permian, Pennsylvanian, and Mississippian rocks undifferentiated

PRECAMBRIAN

- pCu — Precambrian rocks, undifferentiated



CROSS SECTION LOCATION MAP

REFERENCE

Kaplan, S.S., and Skeen, R.C., 1985, North-south regional seismic profile of the Hanna Basin, Wyoming, *in* Gries, R.R., and Dyer, R.C., eds., Seismic exploration of the Rocky Mountain region: Denver, Co., Rocky Mountain Association of Geologists, p. 219-224.

Layout and design by Robert Kirkwood and Phyllis A. Ranz
Edited by Suzanne C. Luhr

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GEOLOGIC CROSS SECTION, HANNA BASIN, WYOMING

Vertical exaggeration ~ 2x

WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

TECHNICAL MEMORANDUM 3
Plate 18
Type Log
Hanna Basin

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
HANNA BASIN

WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Field	County	Surface Location
49-007-20667	FMF Oil & Gas Property Inc.	Seminoe W-36958 1-30	Wildcat	Carbon	sec. 30, T24N, R83W
49-007-21907	Dudley & Associates LLC	Dudley UPLRC 3-27-24-85	Wildcat	Carbon	sec. 27, T24N, R85W
49-007-22438	Western Interior Oil & Gas Corp.	Elk Mountain 1-22	Elk Mountain	Carbon	sec. 22, T20N, R80W
49-007-21093	Union Oil Co. of California	UPRR 44G-21 1	Wildcat	Carbon	sec. 21, T22N, R78W

EXPLANATION

- Unconformity
- Approximate contact
- 10,000 / (4,000): Reconstructed cumulative log depth; Actual log depth
- Evaporites
- Sandstone
- Shale
- Sandstone/shale/siltstone
- Limestone/dolomite

***Note:** The lithologies shown are general and meant to depict average lithologic conditions and are not based on petrophysical analysis of cores or logs.*

REFERENCES

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., comps., 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Map Series MS-41.

Wyoming Oil and Gas Conservation Commission, 2012, [digital log data], at http://wogcc.state.wy.us.

Layout and design by James R. Rodgers
Edited by Suzanne C. Luhr

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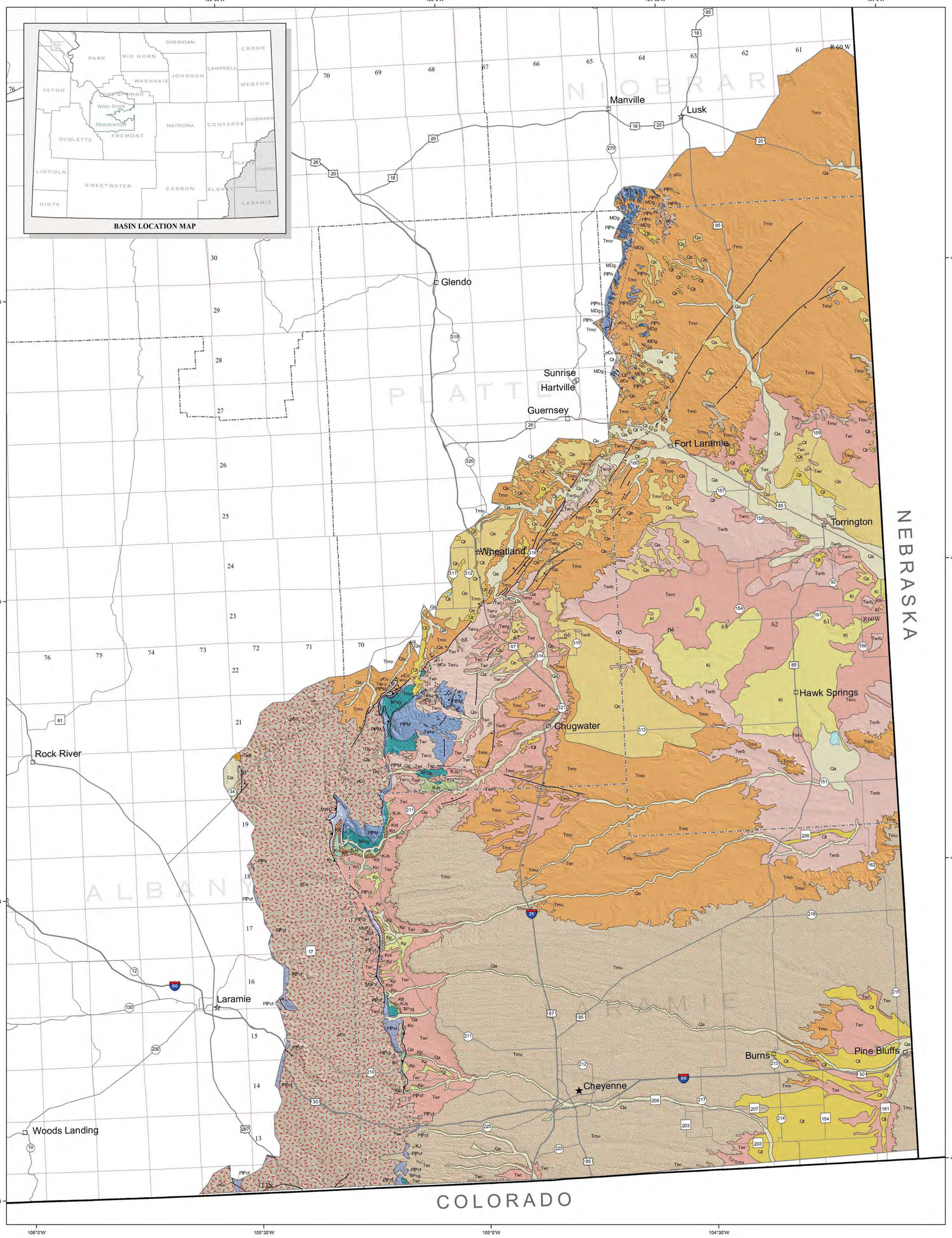
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean
Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - providing for the future

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TECHNICAL MEMORANDUM 3
Plate 19
Geologic Map of the Denver Basin



Map Projection: Lambert Conformal Conic
False Easting: 500000, False Northing: 200000
Central Meridian: -107.5 degrees West
Standard Parallel 1: 41 degrees North
Standard Parallel 2: 45 degrees North
Latitude of Origin: 41 degrees North
Linear Unit: Meter
Horizontal Datum: North American Datum of 1983 (NAD 83)
Ellipsoid: Geodetic Reference System 80

Magnetic Declination = 8° 55' E
at center of map
(Feb. 12, 2013)

Scale 1:350,000
0 10 20 30 Miles
0 10 20 30 40 50 Kilometers

Geology modified from Love and Christiansen (1985)
Digital cartography and layout by Phyllis A. Ranz
Edited by Suzanne C. Luhr

GEOLOGIC MAP OF THE DENVER BASIN, WYOMING

EXPLANATION

MAP SYMBOLS

Formation contact

Normal fault —Dotted where concealed; bar and ball on downthrown block; no designation on fault trace indicates undetermined motion

Thrust fault—Dotted where concealed; sawteeth on upthrown (tectonically higher) block

State capital
County seat
City or town
Lake or reservoir
Interstate highway
U.S. highway
State highway
County or other road
County boundary
State boundary

GEOLOGIC UNITS
(Geology enlarged from 1:500,000 scale to improve readability)

CENOZOIC

Quaternary

- Qa — Alluvium and colluvium
- Qt — Gravel, pediment, and fan deposits
- Qs — Dune sand and loess
- Qe — Playa lake and other lacustrine deposits

Tertiary

- Tmu — Upper Miocene rocks
- Tmo — Lower Miocene and upper Oligocene rocks
- Twr — White River Formation
- Twru — Upper conglomerate member
- Twrb — Brule Member
- Twrc — Chadron Memberr
- Twb — Wagon Bed Formation

MESOZOIC

Cretaceous

- Kl — Lance Formation
- Kfh — Fox Hills Sandstone
- Kp — Pierre Shale
- Kn — Niobrara Formation
- Knf — Niobrara and Frontier Formations, and Mowry and Thermopolis Shales
- Kf — Frontier Formation and Mowry and Thermopolis Shales

Cretaceous and Jurassic

- KJ — Cloverly and Morrison Formations
- KJs — Cloverly, Morrison, and Sundance Formations

MESOZOIC AND PALEOZOIC

- MzPz — Mesozoic and Paleozoic rocks, undifferentiated

Triassic and Permian

- ŦPcg — Chugwater and Goose Egg Formations
- ŦPg — Goose Egg Formation

PALEOZOIC

Permian and Pennsylvanian

- PIPc — Casper Formation
- PIPcf — Casper and Fountain Formations

Permian, Pennsylvanian, and Mississippian

- PIPM — Wells and Amsden Formations
- PIPh — Hartville Formation

Mississippian and Devonian

- MDg — Guernsey Formation–locally includes dolomite and sandstone of Devonian and Cambrian(?) age

PRECAMBRIAN

- pCu — Precambrian rocks, undifferentiated

DATA REFERENCE

Love, J.D., and Christiansen, A.C., comps., 1985, Geologic map of Wyoming: U.S. Geological Survey, 3 sheets, scale 1:500,000.

BASE MAP REFERENCES

Bureau of Indian Affairs, 2005, Boundaries—Indian Lands, Raw Data Release, December, 2005: National Atlas of the United States, at http://nationalatlas.gov/.

Bureau of Land Management, 2011, Cadastral National Spatial Data Infrastructure (CadNSDI) Public Land Survey System (PLSS) for Wyoming, at http://www.geocommunicator.gov/geocomm/ lsis_home/home /index.htm.

National Oceanic and Atmospheric Administration, 1985, Digital magnetic declination: National Geophysical Data Center, at http://www.ngdc. noaa.gov/geomagmodels/struts/calcDeclination.

Stoeser, D.B., Green, G.N., Morath, L.C., Heran, W.D., Wilson, A.B., Moore, D.W., and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States—Central states—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: U.S. Geological Survey Open-File Report 2005-1351, 18 p.

U.S. Census Bureau, 1996, Cities, towns, census designated places of Wyoming at 1:100,000, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

U.S. Census Bureau, 1997, Wyoming roads at 1:100,000, at http://piney.wygisc.uwyo.edu/data/transportation/road100k.zip.

U.S. Geological Survey, 2002, The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing, v. 68, no. 1, at http://ned.usgs.gov.

Wyoming Geographic Information Science Center, 1997, Internet mapping service: Basemap data for Wyoming: Spatial Data and Visualization Center, at http://wygl.wygisc.org/wygeolib/catalog/main/home.page.

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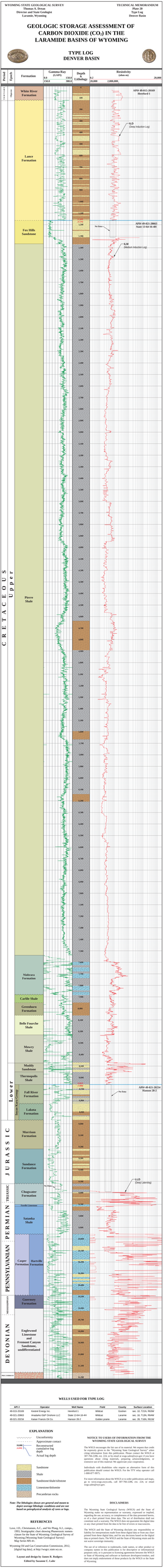
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drexler
Director and State Geologist
Laramie, Wyoming

TECHNICAL MEMORANDUM
Plate 20
Type Log
Denver Basin

GEOLOGIC STORAGE ASSESSMENT OF CARBON DIOXIDE (CO_2) IN THE LARAMIDE BASINS OF WYOMING

TYPE LOG
DENVER BASIN



WELLS USED FOR TYPE LOG

API #	Operator	Well Name	Field	County	Surface Location
49-021-20230	Kastrel Energy Inc.	Hoerdler12	Wildcat	Goshen	sec. 21, T12N, R63W
49-021-20043	Arsenault E&P Onshore LLC	State 13-6-6 16-4H	Wildcat	Laramie	sec. 16, T12N, R64W
49-021-20234	Anter Petrolia Dr Co.	Hansen 28-2	Golden prairie	Laramie	sec. 28, T14N, R61W

EXPLANATION

Unconformity
Approximate contact
SLDD Reconstructed cumulative log curve
SLD Actual log depth

Sandstone
Shale
Sandstone/shale/siltstone
Limestone/dolomite
Precambrian rocks

Note: *The lithologies shown are general and meant to depict average lithologic conditions and are not based on petrophysical analysis of cores or logs.*

REFERENCES

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., compiz., 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming (Wyoming State Geological Survey) Map Series MS-41.

Wyoming Oil and Gas Conservation Commission, 2012, [digital log data], at http://wogcc.state.wy.us.

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