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Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Bighorn Basin, Wyoming and Montana

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U.S. Department of the Interior
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By Jacob A. Covault, Marc L. Buursink, William H. Craddock, Matthew D. Merrill, Madalyn S. Blondes, Mayur A. Gosai, and Philip A. Freeman

Chapter A of
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Edited by Peter D. Warwick and Margo D. Corum

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Editors' Preface

By Peter D. Warwick and Margo D. Corum

The 2007 Energy Independence and Security Act (Public Law 110–140) directs the U.S. Geological Survey (USGS) to conduct a national assessment of potential geologic storage resources for carbon dioxide (CO_2) and to consult with other Federal and State agencies to locate the pertinent geological data needed for the assessment. The geologic sequestration of CO_2 is one possible way to mitigate its effects on climate change.

The methodology that is being used by the USGS for the assessment was described by Brennan and others (2010), who revised the methodology by Burruss and others (2009) according to comments from peer reviewers, members of the public, and experts on an external panel. The assessment methodology is non-economic and is intended to be used at regional to subbasinal scales.

The operational unit of the assessment is a storage assessment unit (SAU), composed of a porous storage formation with fluid flow and an overlying fine-grained sealing unit. Assessments are conducted at the SAU level and are aggregated to basinal and regional results. SAUs have a minimum depth of 3,000 feet (ft), which ensures that the CO_2 is in a supercritical state (and thus occupies less pore space than a gas). Standard SAUs have a maximum depth of 13,000 ft below the surface, a depth accessible with average injection pipeline pressures (Burruss and others, 2009; Brennan and others, 2010). Where geologic conditions favor CO_2 storage below 13,000 ft, an additional deep SAU is assessed.

The assessments are also constrained by the occurrence of relatively fresh formation water; any formation water having a salinity less than 10,000 parts per million (ppm, which is equivalent to milligrams per liter, mg/L) total dissolved solids (TDS), regardless of depth, has the potential to be used as a potable water supply (U.S. Environmental Protection Agency, 2009). The U.S. Environmental Protection Agency (2008) has proposed the limit of 10,000 ppm (mg/L) TDS for injection of CO_2. Therefore, the potential storage resources for CO_2 in formations where formation waters have salinities less than 10,000 ppm (mg/L) TDS are not assessed (Brennan and others, 2010).

This report series contains geologic descriptions of each SAU identified within the assessed basins and focuses on the particular characteristics specified in the methodology that influence the potential CO_2 storage resource. Although assessment results are not contained in these reports, the geologic framework information will be used to calculate a statistical Monte Carlo-based distribution of potential storage space in the various SAUs following Brennan and others (2010). Figures in this report series show SAU boundaries and cell maps of well penetrations through the sealing unit into the top of the storage formation. Wells sharing the same well borehole are treated as a single penetration. Cell maps show the number of penetrating wells within one square mile and are derived from interpretations of incompletely attributed well data (IHS Energy Group, 2011; and other data as available), a digital compilation that is known not to include all drilling. The USGS does not expect to know the location of all wells and cannot guarantee the amount of drilling through specific formations in any given cell shown on cell maps.

References Cited

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., accessed March 22, 2011, at *http://pubs.usgs.gov/of/2010/1127/*.

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., accessed March 22, 2011, at *http://pubs.usgs.gov/of/2009/1035/*.

IHS Energy Group, 2011, ENERDEQ U.S. well data: IHS Energy Group; online database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112, U.S.A., accessed January 20, 2011, at *http://energy.ihs.com/*.

U.S. Environmental Protection Agency, 2008, Federal requirements under the underground injection control (UIC) program for carbon dioxide (CO_2) geologic sequestration (GS) wells: Washington, D.C., U.S. Environmental Protection Agency, proposed rule, accessed March 23, 2011, at *http://www.epa.gov/fedrgstr/EPA-WATER/2008/July/Day-25/w16626.htm*.

U.S. Environmental Protection Agency, 2009, Safe Drinking Water Act (SDWA): Washington, D.C., U.S. Environmental Protection Agency Web site, accessed January 14, 2009, at *http://www.epa.gov/ogwdw/sdwa/index.html*.

Contents

Figures

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square foot (ft^2)	0.00002296	acre
square mile (mi^2)	2.59	square kilometer (km^2)
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
1,000 cubic feet (MCF)	28.32	cubic meter (m^3)
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)

Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Bighorn Basin, Wyoming and Montana

By Jacob A. Covault,[1] Marc L. Buursink, William H. Craddock, Matthew D. Merrill, Madalyn S. Blondes, Mayur A. Gosai, and Philip A. Freeman

Abstract

The 2007 Energy Independence and Security Act (*Public Law 110–140*) directs the U.S. Geological Survey (USGS) to conduct a national assessment of potential geologic storage resources for carbon dioxide (CO_2). The methodology used for the national CO_2 assessment follows that of previous USGS work. The methodology is non-economic and intended to be used at regional to subbasinal scales.

This report identifies and contains geologic descriptions of twelve storage assessment units (SAUs) in six separate packages of sedimentary rocks within the Bighorn Basin of Wyoming and Montana and focuses on the particular characteristics, specified in the methodology, that influence the potential CO_2 storage resource in those SAUs. Specific descriptions of the SAU boundaries as well as their sealing and reservoir units are included. Properties for each SAU such as depth to top, gross thickness, net porous thickness, porosity, permeability, groundwater quality, and structural reservoir traps are provided to illustrate geologic factors critical to the assessment. Although assessment results are not contained in this report, the geologic information included here will be employed, as specified in the methodology of earlier work, to calculate a statistical Monte Carlo-based distribution of potential storage space in the various SAUs. Figures in this report show SAU boundaries and cell maps of well penetrations through the sealing unit into the top of the storage formation. Wells sharing the same well borehole are treated as a single penetration. Cell maps show the number of penetrating wells within one square mile and are derived from interpretations of incompletely attributed well data, a digital compilation that is known not to include all drilling. The USGS does not expect to know the location of all wells and cannot guarantee the amount of drilling through specific formations in any given cell shown on cell maps.

Introduction

The Bighorn Basin of Montana and Wyoming is a large (≈10,400 mi^2) sedimentary basin structurally bounded on the northeast by the Pryor Mountains, on the east by the Bighorn Mountains, on the south by the Owl Creek uplift, and on the west and northwest by the Absaroka Range and Beartooth Mountains, respectively (Finn and others, 2010) (figs. 1 and 2). Finn and others (2010) define the northern basin margin by a zone of structural deformation referred to as the Nye-Bowler lineament (Wilson, 1936) (fig. 2). The earliest commercial hydrocarbon production in the Bighorn Basin was in 1906, which exploited Cretaceous sandstone reservoirs (Fox and Dolton, 1996). Total production from Cretaceous and Tertiary reservoirs is about 94 million barrels of oil and 830 billion ft^3 of gas through 2010 according to Finn and others (2010). Approximately 1.8 billion barrels of oil and 2.7 trillion ft^3 of gas have been discovered as of year-end 1990 (Fox and Dolton, 1995). Production in the Bighorn Basin is

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predominantly from anticlinal structural traps in Permian and Cretaceous reservoirs (Fox and Dolton, 1995; Finn and others, 2010).

The USGS recently completed a geology-based assessment of undiscovered oil and gas resources of the Bighorn Basin (U.S. Geological Survey Bighorn Basin Province Assessment Team, 2010). Two petroleum systems were identified, each comprising characteristic petroleum source rocks, reservoir rocks, and traps: Phosphoria (Permian) and Cretaceous-Tertiary Composite (U.S. Geological Survey Bighorn Basin Province Assessment Team, 2010). The U.S. Geological Survey Bighorn Basin Province Assessment Team (2010) estimated means of 72 million barrels of recoverable undiscovered oil, 989 billion ft^3 of recoverable undiscovered natural gas, and 13 million barrels of recoverable undiscovered total natural gas liquids from the two petroleum systems. Most of the conventional, anticlinal structural traps in the Bighorn Basin have been exploited. Thus, new conventional resource potential is interpreted to be from stratigraphic traps of Permian carbonate rocks and Upper Cretaceous sedimentary rocks (U.S. Geological Survey Bighorn Basin Province Assessment Team, 2010).

Finn and others (2010) noted a limited zone of overpressure in sedimentary rocks deeper than approximately 13,000–17,000 ft below surface in the Bighorn Basin (Surdam and others, 1997; Johnson and Finn, 1998; Johnson and others, 1999). Moreover, the injection of large amounts of supercritical CO_2 into subsurface reservoir formations of the Bighorn Basin might cause large pressure increases. The resulting overpressure might promote reactivation of fractures or create new fractures that compromise seal integrity (Burruss and others, 2009). Burruss and others (2009) provide a review of overpressure in the context of CO_2 storage. Following the methodology of Brennan and others (2010), we do not consider overpressure in this assessment of potential geologic storage resources for CO_2 in the Bighorn Basin.

Present-Day Bighorn Basin Physiography

The present-day physiography of the Bighorn Basin is largely the result of Late Cretaceous to Eocene Laramide orogenesis (Dickinson and others, 1988) (figs. 1 and 2). The Laramide orogeny was characterized by a structural style of Precambrian basement-cored uplifts and intervening sedimentary basins developed over a wide area east of about 112° W. longitude (Coney, 1976; Dickinson and others, 1988) (figs. 1 and 2). Laramide basins and associated uplifts of various shapes, sizes, and orientations are distributed throughout the central Rocky Mountain region (Dickinson and others, 1988). The Bighorn Basin generally trends northwest to southeast (fig. 1). The northeastern, eastern, and southern basin margins are basement-cored uplifts of the Pryor, Bighorn, and Owl Creek Mountains, respectively (Finn and others, 2010) (figs. 1 and 2). These mountains are flanked by folded and faulted Cambrian to Paleocene sedimentary rocks (Finn and others, 2010) (fig. 1). The western basin margin is the Absaroka Range, which predominantly comprises Eocene andesitic volcanic and volcaniclastic rocks that unconformably overlie folded and faulted Paleozoic, Mesozoic, and lower Tertiary sedimentary rocks (Sundell, 1990, 1993) (fig. 1). The northwest margin of the basin is the Beartooth Mountains, which are composed of a basement-cored uplift flanked by steeply dipping to overturned sedimentary rocks (Foose and others, 1961; Finn and others, 2010). The Nye-Bowler lineament is an approximately 60-mile-long regional anticlinal trend extending east to southeast from the northern Beartooth Mountains to the Pryor Mountains (Finn and others, 2010). It is interpreted to overlie a left-lateral basement shear zone (Wilson, 1936).

Bighorn Basin Tectono-Stratigraphic Evolution

The Bighorn Basin is part of the North American Cordilleran orogenic belt, which extends for nearly 4,000 miles from southern Mexico to the Canadian Arctic and Alaska (fig. 3) (DeCelles, 2004). This Cordillera became consolidated as a coherent high-elevation orogenic basin during the Late Jurassic (DeCelles, 2004). The Cordilleran orogenic belt was constructed of sedimentary and metasedimentary rocks that were originally deposited in marine environments along the Neoproterozoic-early Paleozoic rifted western margin of Laurentia (DeCelles, 2004). These Neoproterozoic-lower Paleozoic strata are predominantly siliciclastic with some carbonate rock (DeCelles, 2004). The Proterozoic section ranges in thickness from approximately 2–6 miles (Link and others, 1993; DeCelles, 2004).

The development of the Cordillera was significantly influenced by Late Devonian-Early Mississippian Antler and Late Permian-Early Triassic Sonoma orogenies, elements of which can be traced from southwestern Nevada to southern Idaho (Miller and others, 1992; DeCelles, 2004). Following these orogenic episodes, the Triassic-Middle Jurassic succession was deposited and comprises shallow-marine to nonmarine lithofacies, including eolianites, fluvial sandstone and mudstone, and evaporites (DeCelles, 2004).

The Late Jurassic-Eocene evolution of the Cordilleran orogenic belt and foreland basin in North America took place contemporaneous with opening of the North Atlantic Ocean, subduction of oceanic plates beneath the western margin of the North American plate, closure of marginal oceanic basins, and accretion of fringing arcs along the western edge of the North American plate (DeCelles, 2004). During this period of about 100 million years, contractile deformation along the Cordilleran orogenic belt propagated greater than 600 miles eastward, culminating in the formation of the Laramide Rocky Mountains (DeCelles, 2004). During much of Cretaceous time, the part of Wyoming and Montana that is now the Bighorn Basin was located in the Western Interior Seaway and foreland basin system (fig. 3). Fluctuations in relative sea level and variations in sediment supply along the western shoreline of the Cretaceous foreland basin resulted in a complex pattern of intertonguing marine, marginal marine, and nonmarine deposits (Finn and others, 2010).

Late Cretaceous to Eocene Laramide deformation within the central Rocky Mountain region broke the Western Interior foreland basin into discrete basins that became increasingly sedimentologically isolated through time and separated by emergent basement-cored uplifts, which served as local sources of synorogenic sediment (Dickinson and others, 1988) (fig. 2). Laramide basins such as the Bighorn Basin subsided rapidly and became depocenters for nonmarine sediment. During the Eocene Epoch, many Laramide basins, including the Bighorn Basin, were filled with volcaniclastic sediment from the Yellowstone-Absaroka area to the west (Love, 1988). Volcanic activity ended by Oligocene time, but basin filling continued as Oligocene and Miocene volcaniclastic sediment spilled over the crest of the Bighorn Mountains and was deposited in the Powder River Basin to the east (McKenna and Love, 1972). During middle Miocene time, regional uplift initiated the exhumation of the Laramide uplifts and basins, which continues to the present day (Love, 1988).

Bighorn Basin Carbon Dioxide Storage Assessment

Reservoirs assessed for CO_2 storage in the Bighorn Basin include: (1) Middle Pennsylvanian to Lower Permian Tensleep Sandstone, (2) Lower Permian Ervay Member of the Phosphoria Formation, (3) Triassic Crow Mountain Sandstone of the Chugwater Group, (4) Lower Cretaceous Cloverly Formation, (5) Lower Cretaceous Muddy Sandstone, and (6) Upper Cretaceous Frontier Formation (fig. 4). The extents of storage formations are defined by the geologic characteristics of the reservoirs and overlying seals and the subsurface physical properties of CO_2 as described in Burruss and others (2009) and Brennan and others (2010). The following sections describe each of the storage assessment units defined in the Bighorn Basin.

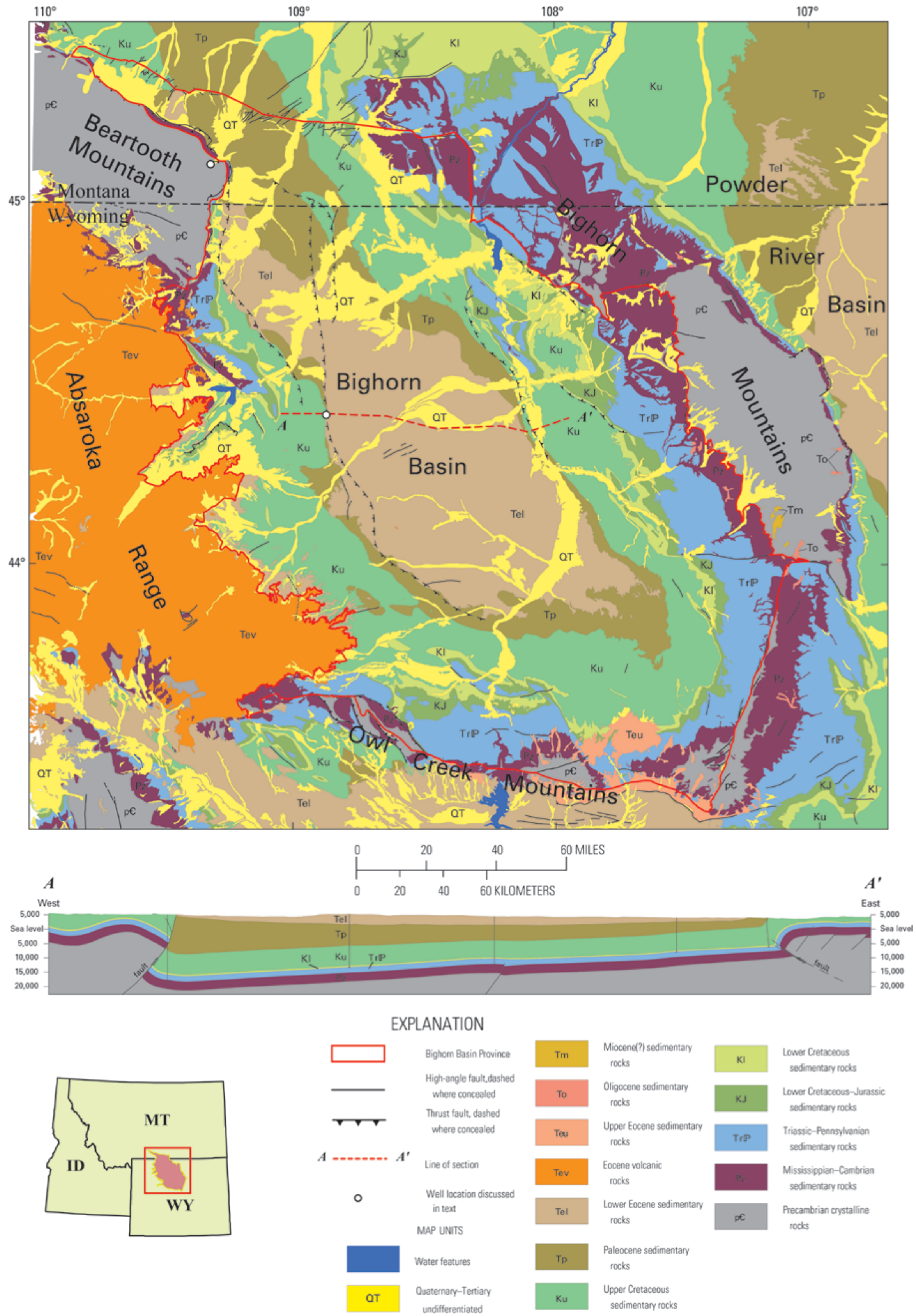

Figure 1. Geologic map and cross section of the Bighorn Basin, Wyoming and Montana (modified from Finn and others, 2010, their fig. 2). Vertical scale of cross section is in feet.

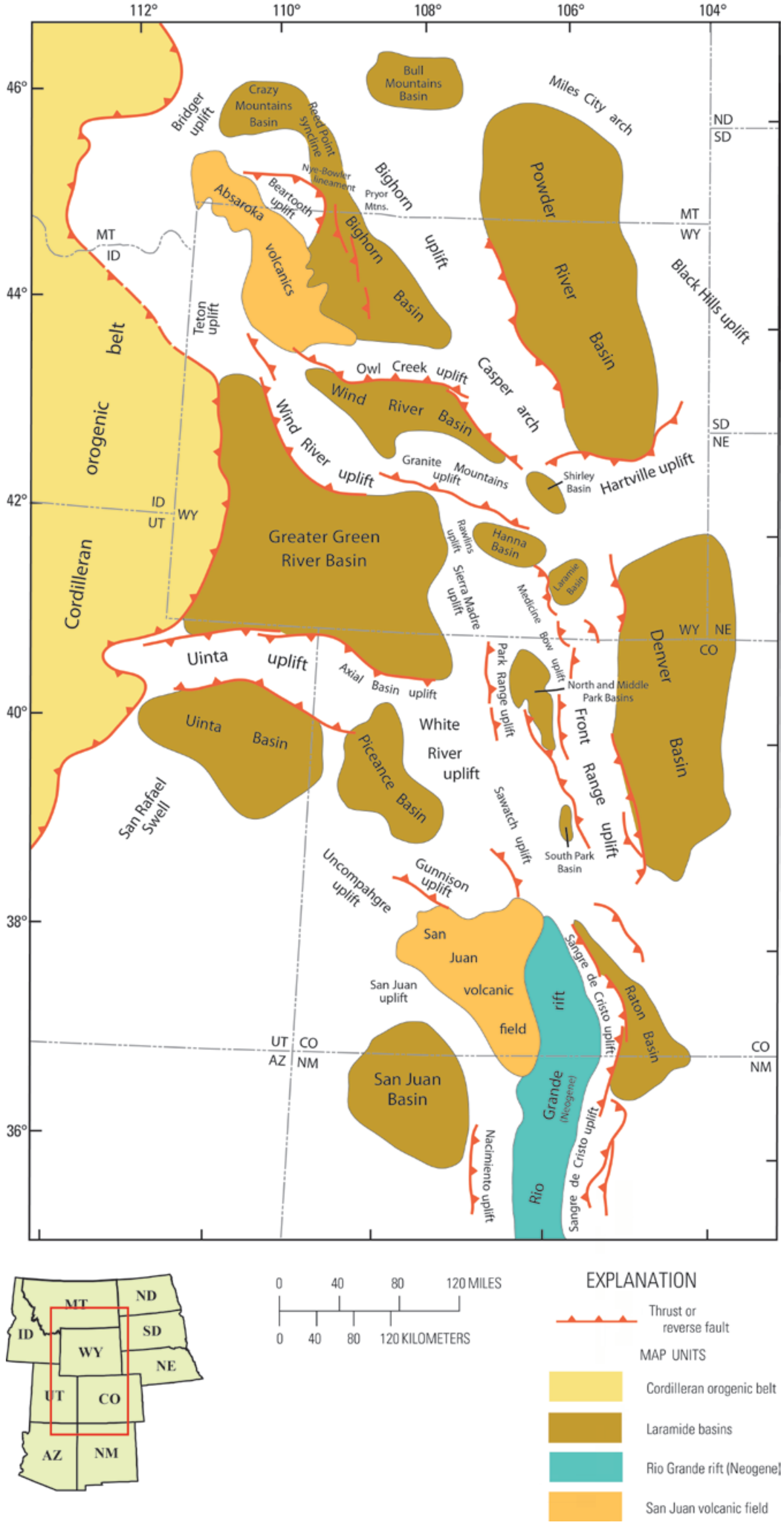

Figure 2. Map of Rocky Mountain region extending from southern Montana to northern New Mexico showing locations of Laramide sedimentary basins (in brown) and intervening uplifts (modified from Dickinson and others, 1988; from Finn and others, 2010, their fig. 4).

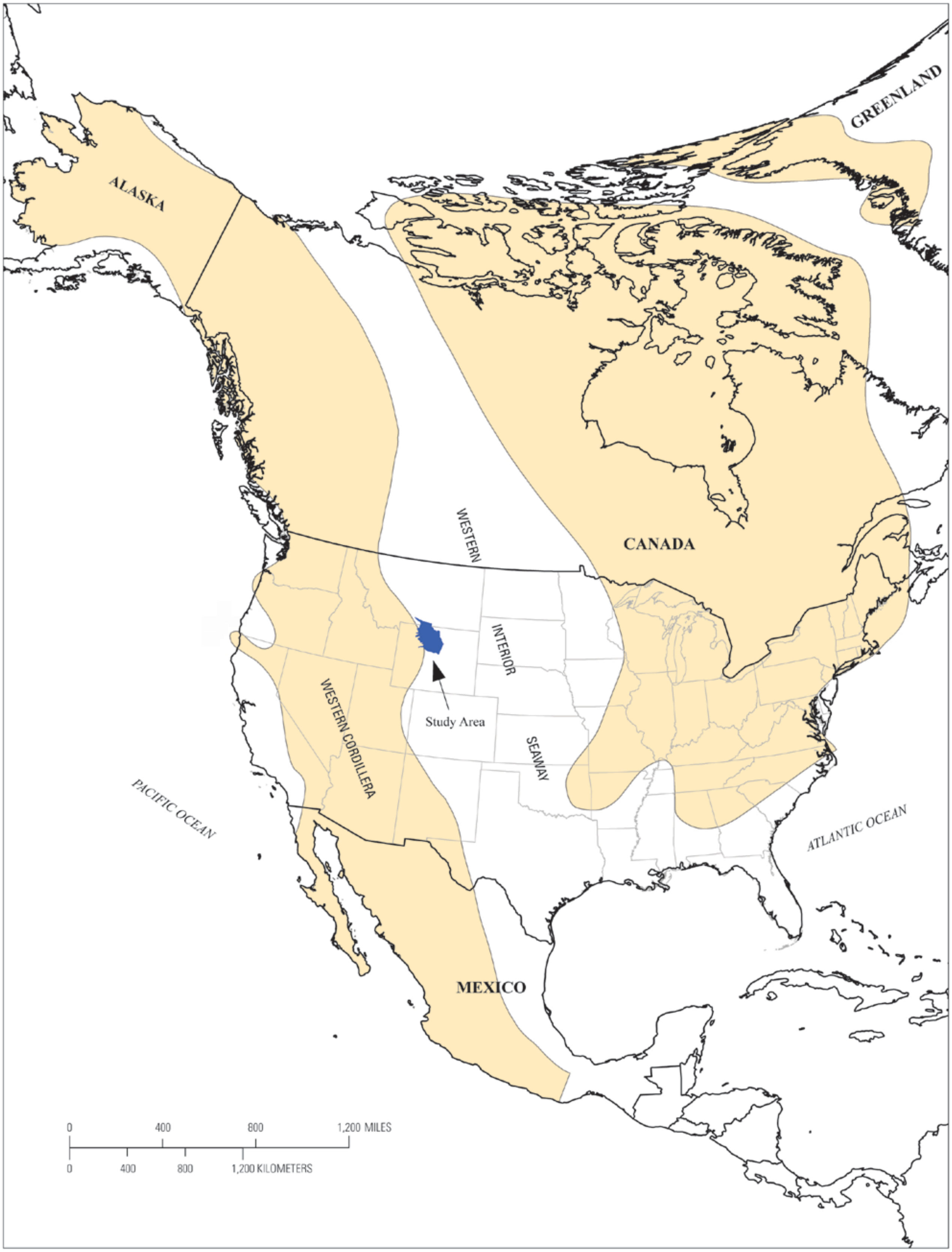

Figure 3. Map showing extent of the Western Interior Seaway during Campanian time. Tan areas show approximate geographic distribution of land areas (modified from Gill and Cobban, 1973; from Finn and others, 2010, their fig. 5).

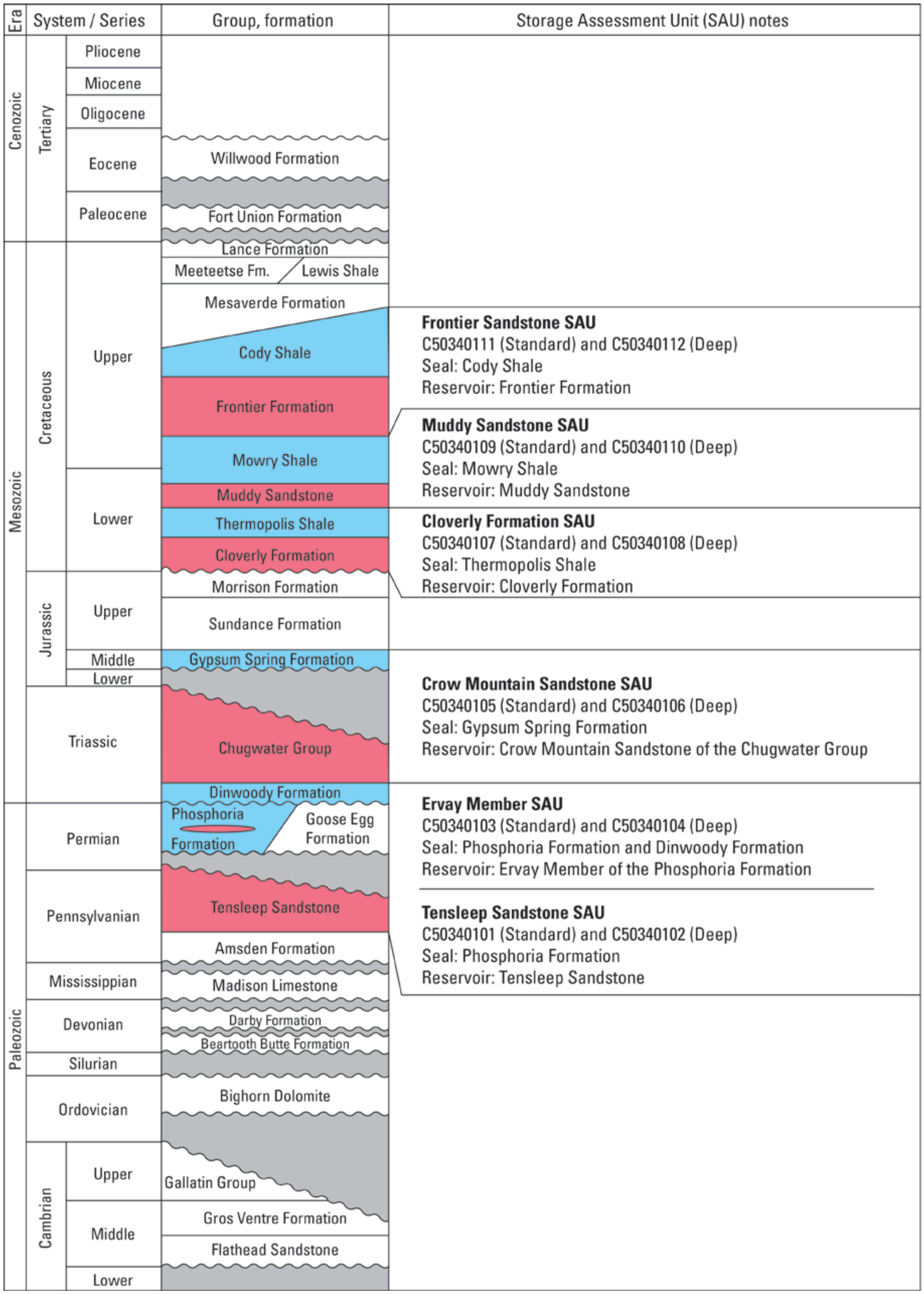

Figure 4. Generalized stratigraphic column of geologic formations in the Bighorn Basin, Wyoming and Montana. Storage assessment units consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray sections represent eroded section. In some cases, subdivisions of units are not shown (modified from Fox and Dolton, 1995).

Tensleep Sandstone C50340101 and Tensleep Sandstone Deep C50340102

By Matthew D. Merrill

The Pennsylvanian-Permian Tensleep Sandstone (figs. 4 and 5) predominantly includes fine- to medium-grained sandstone, with carbonate rocks and shale (Lawson and Smith, 1966). Uplift and denudation of the ancestral Rockies in the southeast of present-day Wyoming provided sediment to eolian dunes of the Tensleep Sandstone, which extends across central and western Wyoming (Lawson and Smith, 1966). Fine-grained rocks of the overlying Phosophoria Formation are relatively continuous and sufficiently thick (20–280 ft) to serve as a regional seal (Fox and Dolton, 1995).

The Tensleep Sandstone comprises two potential reservoir units for CO_2 storage in the Bighorn Basin: (1) between 3,000- and 13,000-ft subsurface depth, Tensleep Sandstone C50340101 and (2) below 13,000-ft subsurface depth, Tensleep Sandstone Deep C50340102 (fig. 5). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from well penetrations (IHS Energy Group, 2010), published structure contour maps (Zapp, 1956), and faults bounding the Bighorn Basin. Zapp (1956) indicates that the thickness of the Tensleep Sandstone ranges from 100–300 ft, with a general thinning to the north. The net porous interval of the Tensleep Sandstone ranges from 10–150 ft (Nehring Associates, Inc., 2010). Sandstone porosity ranges from 4–15 percent in the shallow SAU (Tensleep Sandstone C50340101) and 2–7 percent in the deep SAU (Tensleep Sandstone Deep C50340102) (Fox and others, 1975; Nehring Associates, Inc., 2010). Reservoir permeability values range from 0.1–1,000 millidarcies (mD) with 10–200 mD values most typical at depths from 3,000–13,000 ft below surface. Deeper than 13,000 ft, reservoir permeability values range from 0.1–10 mD (Fox and others, 1975). Water-quality measurements from 736 samples in the Tensleep Sandstone (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010) indicate that groundwater in the formation is predominantly fresh (less than 10,000 ppm of total dissolved solids); however, at greater depths, water quality may trend toward higher salinity. The minimum and central tendency buoyant trapping pore volumes were determined using methods described in Brennan and others (2010). Maximum buoyant trapping pore volume was calculated from the product of (1) the combined areas of structural reservoir traps interpreted from a structure map of the Tensleep Sandstone and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) the maximum net porous interval thickness, and (3) the maximum porosity (Brennan and others, 2010). Structural reservoir traps were defined by outlining areas of closure interpreted on a 1,000-ft-contour-interval structural map of the top of the Tensleep Sandstone (Zapp, 1956).

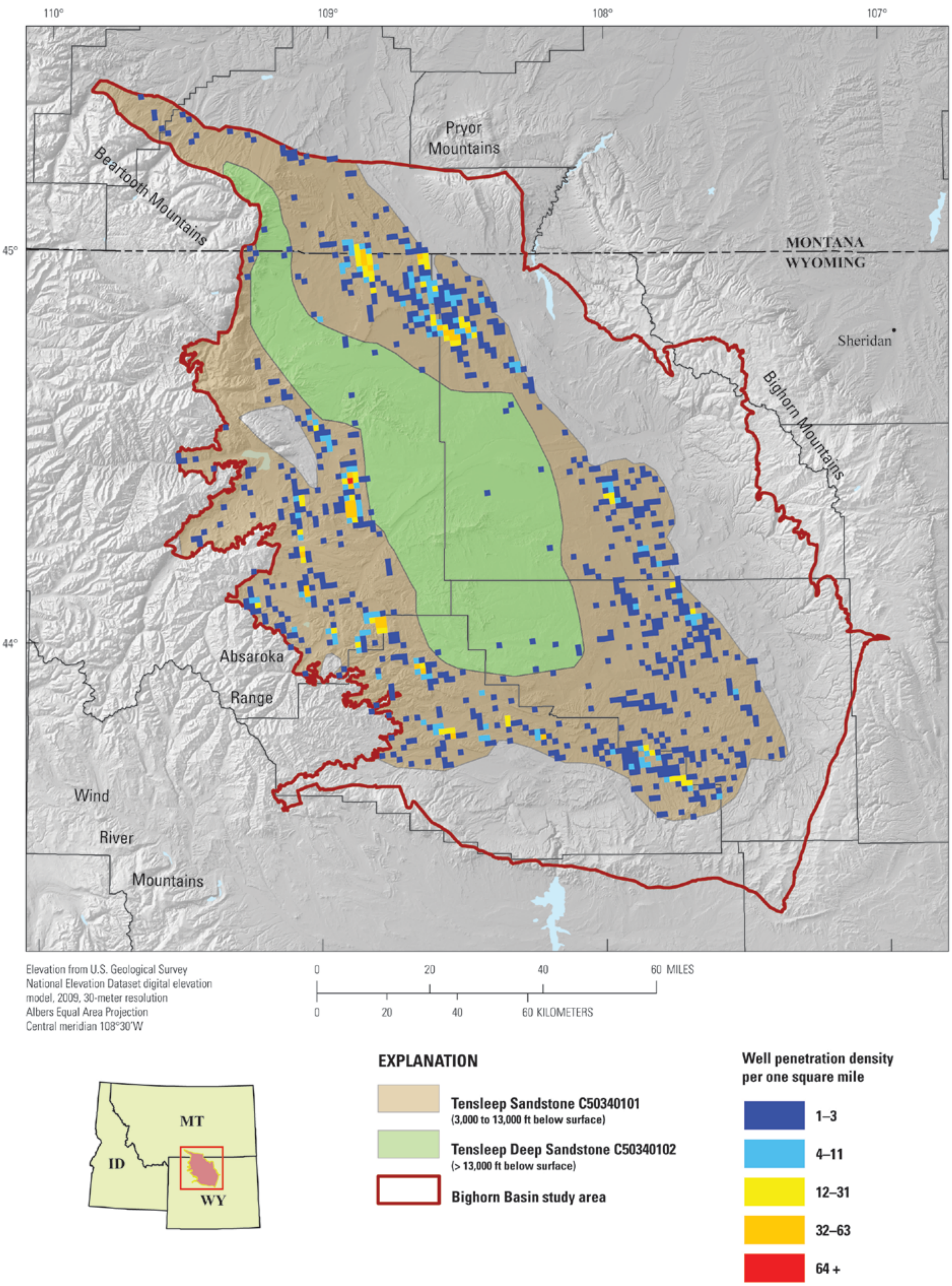

Figure 5. Map of the U.S. Geological Survey Storage Assessment boundary for the Tensleep Sandstone and Tensleep Sandstone Deep Storage Assessment Units in the Bighorn Basin, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir-formation top. Total Petroleum System boundary modified from U.S. Geological Survey Bighorn Basin Province Assessment Team (2010).

Ervay Member C50340103 and Ervay Member Deep C50340104

By Marc L. Buursink

The Permian Ervay Member of the Phosphoria Formation predominantly includes dolomite grainstone and packstone, with some siliciclastic sandstone interpreted to represent tidal deposition (figs. 4 and 6) (Coalson and Inden, 1990). Fine-grained rocks of the Phosophoria and overlying Dinwoody Formation are relatively continuous and sufficiently thick (as much as 1,000 ft) to serve as a regional seal (Campbell, 1962; Stone, 1967; Picard, 1978; Anderson and O'Connell, 1993).

The Ervay Member comprises two potential reservoir units for CO_2 storage in the Bighorn Basin: (1) between 3,000- and 13,000-ft subsurface depth, Ervay Member C50340103; and (2) below 13,000-ft subsurface depth, Ervay Member Deep C50340104 (fig. 6). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from well penetrations (IHS Energy Group, 2010). Interpretations of boundaries are supported by the Wyoming digital geologic map of Green and Drouillard (1994) and the Wyoming Precambrian basement map of Blackstone (1993). The Phosphoria Formation ranges from approximately 20–280 ft thick in the Bighorn Basin and generally thickens to the southwest (Thomas, 1965; Libra and others, 1981). Net Ervay Member sandstone ranges from approximately 12–100 ft (Tohill and Picard, 1966; High and Picard, 1969). Ervay Member sandstone porosity values range from 2–24 percent in the shallow SAU (Ervay Member C50340103) and 2–7 percent in the deep SAU (Ervay Member Deep C50340104) (Nehring Associates, Inc., 2010). These values are broadly consistent with a global compilation of Permian mixed siliciclastic and carbonate reservoir rocks (Libra and others, 1981; Ehrenberg and others, 2009). Reservoir permeability values generally range from 1–1,000 mD (Libra and others, 1981; Nehring Associates, Inc., 2010). Water-quality measurements indicate that groundwater in the Ervay Member is both fresh and saline (greater than 10,000 ppm of total dissolved solids) (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010). The minimum and central tendency buoyant trapping pore volumes were determined using methods described in Brennan and others (2010). Maximum buoyant trapping pore volume was calculated from the product of (1) the combined areas of structural reservoir traps interpreted from a structure map of the Ervay Member and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) the maximum net-porous-interval thickness, and (3) the maximum porosity (Brennan and others, 2010). Structural reservoir traps were defined by outlining areas of closure interpreted on a 1,000-ft-contour-interval structural map of the top of the Ervay Member.

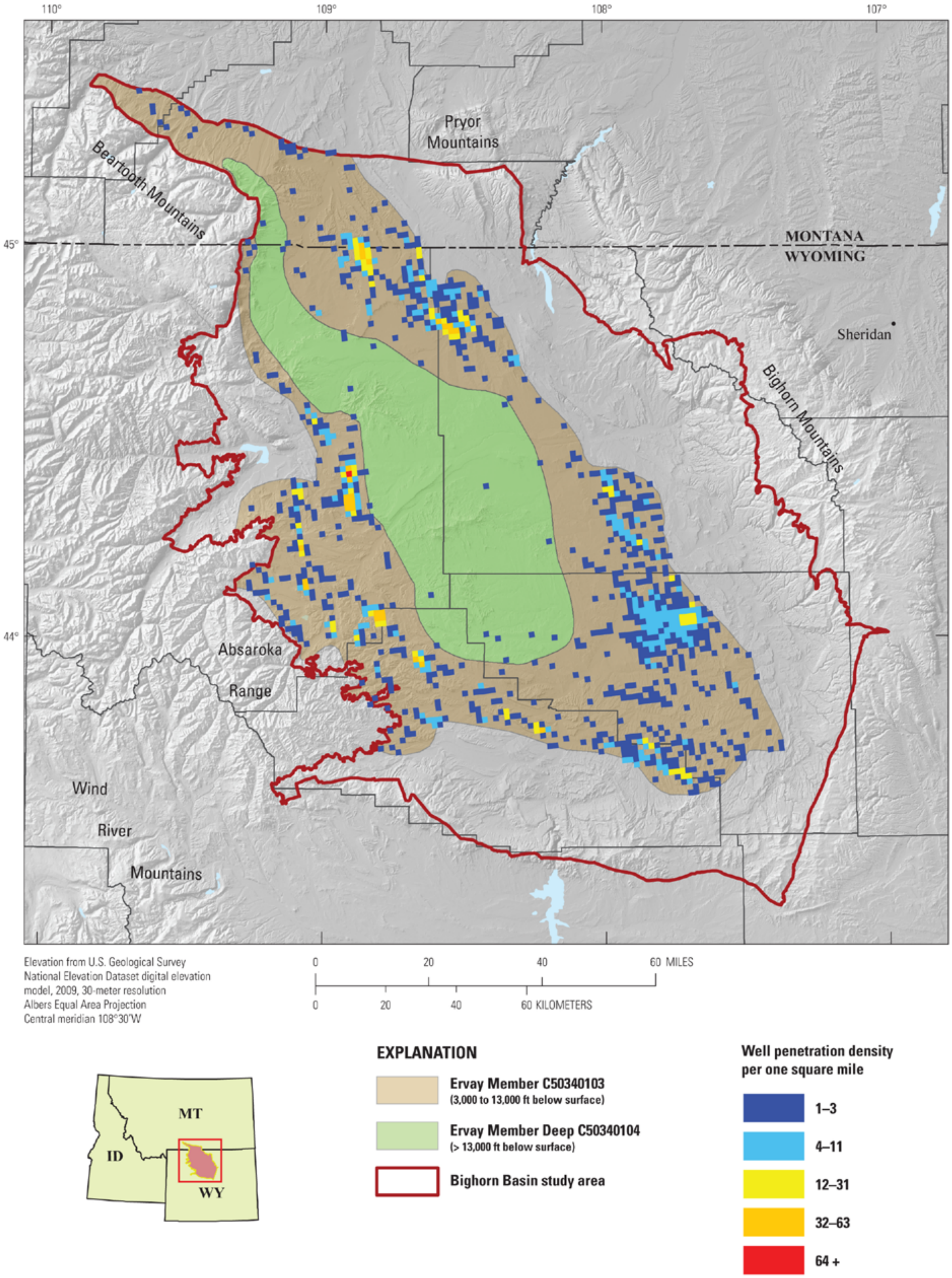

Figure 6. Map of the U.S. Geological Survey Storage Assessment boundary for the Ervay Member and Ervay Member Deep Storage Assessment Units in the Bighorn Basin, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Total Petroleum System boundary modified from U.S. Geological Survey Bighorn Basin Province Assessment Team (2010).

Crow Mountain Sandstone C50340105 and Crow Mountain Sandstone Deep C50340106

By Marc L. Buursink

The Triassic Crow Mountain Sandstone of the Chugwater Group predominantly includes fine- and medium-grained siliciclastic sandstone, which has been interpreted to represent shallow-marine deposition during a period of westward shoreline regression (figs. 4 and 7) (Tohill and Picard, 1966). Relatively fine-grained siliciclastic rocks of the overlying Triassic Popo Agie Formation (as much as 170 ft thick) (Picard, 1978; Anderson and O'Connell, 1993) and anhydrite of the Middle Jurassic Gypsum Spring Formation (80–200 ft thick; Freethey and Cordy, 1991) are relatively continuous and sufficiently thick to serve as a regional seal.

The Crow Mountain Sandstone comprises two potential reservoir units for CO_2 storage in the Bighorn Basin: (1) between 3,000- and 13,000-ft subsurface depth, Crow Mountain Sandstone C50340105; and (2) below 13,000-ft subsurface depth, Crow Mountain Sandstone Deep C50340106 (fig. 7). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from well penetrations (IHS Energy Group, 2010). Interpretations of boundaries are supported by the Wyoming digital geologic map of Green and Drouillard (1994) and the Wyoming Precambrian basement map of Blackstone (1993). The Chugwater Group ranges from approximately 500–1,100 ft thick in the Bighorn Basin and generally thickens to the southwest (Thomas, 1965; Libra and others, 1981). The net porous interval of the Crow Mountain Sandstone ranges from approximately 10–140 ft (Tohill and Picard, 1966; High and Picard, 1969). Crow Mountain Sandstone porosity values range from 5–22 percent in the shallow SAU (Crow Mountain Sandstone C50340105) and 3–10 percent in the deep SAU (Crow Mountain Sandstone Deep) (Nehring Associates, Inc., 2010). These values are broadly consistent with a global compilation of Triassic siliciclastic reservoir rocks (Ehrenberg and others, 2009). Reservoir permeability values generally range from 1–1,000 mD for both the shallow and deep SAUs (Nehring Associates, Inc., 2010). Water-quality measurements indicate that groundwater in the formation is both fresh and saline (greater than 10,000 ppm of total dissolved solids) (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010). The minimum and central tendency buoyant trapping pore volumes were determined using methods described in Brennan and others (2010). Maximum buoyant trapping pore volume was calculated from the product of (1) the combined areas of structural reservoir traps interpreted from a structure map of the Crow Mountain Sandstone and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) the maximum net porous interval thickness, and (3) the maximum porosity (Brennan and others, 2010). Structural reservoir traps were defined by outlining areas of closure interpreted on a 1,000-ft-contour-interval structural map of the top of the Crow Mountain Sandstone.

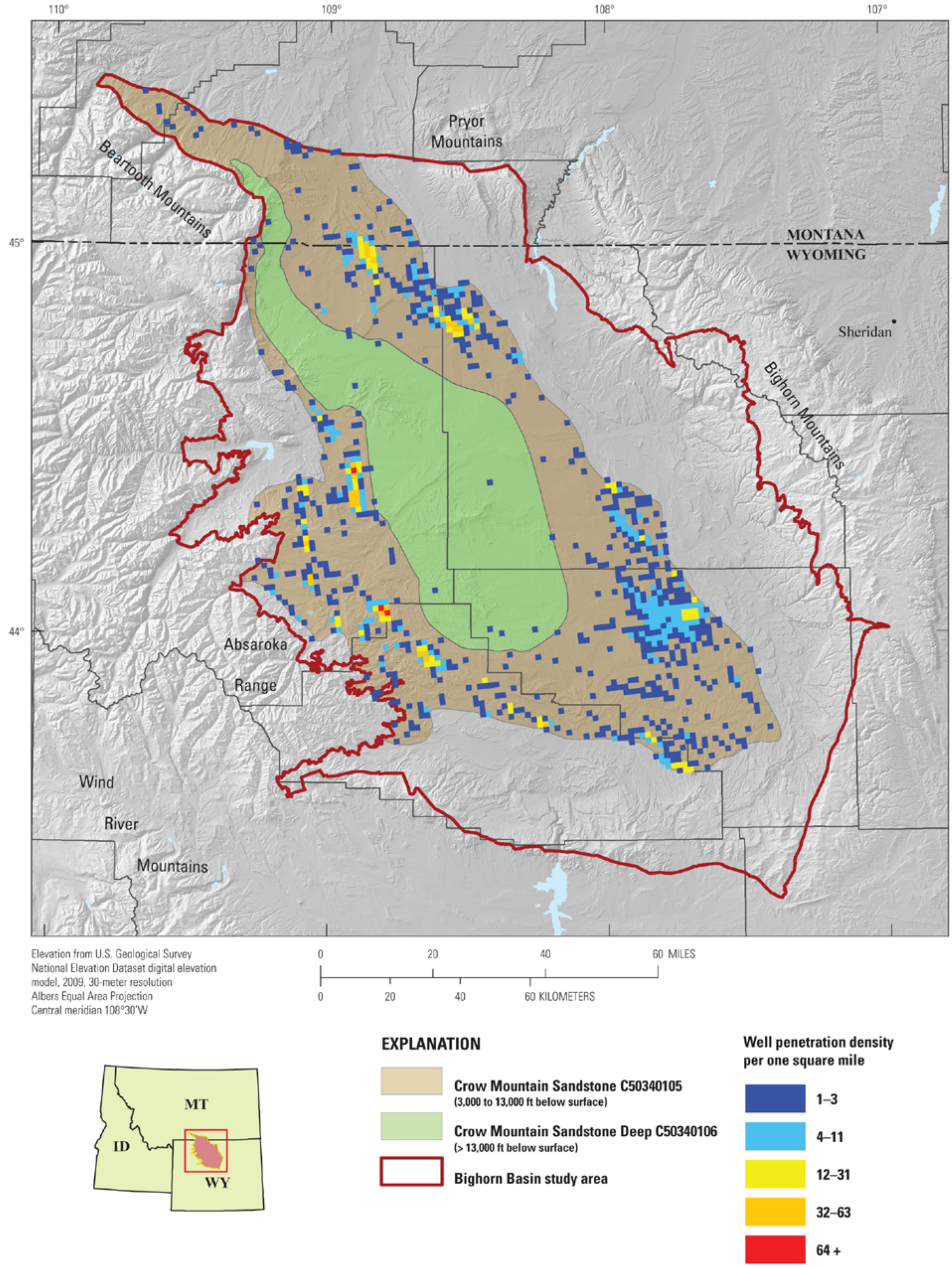

Figure 7. Map of the U.S. Geological Survey Storage Assessment boundary for the Crow Mountain Sandstone and Crow Mountain Sandstone Deep Storage Assessment Units in the Bighorn Basin, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Total Petroleum System boundary modified from U.S. Geological Survey Bighorn Basin Province Assessment Team (2010).

Cloverly Formation C50340107 and Cloverly Formation Deep C50340108

By Jacob A. Covault

The Lower Cretaceous Cloverly Formation is as much as 310 ft thick and predominantly includes siliciclastic sandstone and conglomerate (figs. 4 and 8) (Keefer and others, 1998; Finn and others, 2010). The Cloverly Formation has been subdivided into at least three members, from base to top: the Pryor Conglomerate Member (Moberly, 1960), the Greybull Sandstone Member, and the informal “rusty beds” (Love and others, 1945; Keefer and others, 1998; Finn and others, 2010). The Cloverly Formation unconformably overlies the Upper Jurassic Morrison Formation and progressively fines up-section into the Lower Cretaceous Thermopolis Shale (Finn and others, 2010). The Thermopolis Shale comprises as much as 230 ft of shale and siltstone and is interpreted to be a sealing unit for the underlying Cloverly Formation. Both the Cloverly Formation and Thermopolis Shale are regionally extensive across the Bighorn Basin (Finn, 2010). The Cloverly Formation and overlying Thermopolis Shale couplet has been interpreted to represent a landward retreat of depositional environments from predominantly nonmarine fluvial to fully marine systems in the Cretaceous Western Interior Seaway foreland basin (Finn and others, 2010).

The Cloverly Formation comprises two potential reservoir units for CO_2 storage in the Bighorn Basin: (1) between 3,000- and 13,000-ft subsurface depth, Cloverly Formation C50340107; and (2) below 13,000-ft subsurface depth, Cloverly Formation Deep C50340108 (fig. 8). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from greater than 500 well penetrations (IHS Energy Group, 2010), published structure contour maps (Roberts and others, 2008), and faults bounding the Bighorn Basin. Fault locations were approximated from structural contour maps of Roberts and others (2008) and Finn and others (2010). The range of total storage formation thickness for reservoir units was determined from regional subsurface stratigraphic correlations of Finn (2010). The thickness of the net porous interval was calculated by multiplying the total storage formation thickness by a net porous thickness to gross thickness ratio of 0.52 interpreted from gamma-ray wireline logs of Finn (2010). Finn and others (2010) indicate a porosity range from 5–30 percent and a permeability range from 0.41–150 mD (Hafenbrack and others, 1958; Tonnsen, 1985; Bartow-Campen, 1986; Cardinal and others, 1989; Nehring Associates, Inc., 2010). These data were employed in order to populate porosity and permeability ranges for the SAU C50340107 between 3,000 and 13,000 ft. A relatively small proportion of greater than 1-D permeability is interpreted for the shallow Cloverly Formation C50340107 SAU based on gravel-size sediment of the Pryor Conglomerate Member of the Cloverly Formation. Porosity and permeability values are interpreted to diminish with depth (Ehrenberg and others, 2009). Accordingly, we reduced the porosity range of the Cloverly Formation Deep C50340108 SAU by approximately 50 percent of the range of the shallower Cloverly Formation C50340107 SAU. These adjustments to petrophysical properties with depth are consistent with empirical data from Cretaceous siliciclastic sandstone reservoirs of the Rocky Mountain region (Nehring Associates, Inc., 2010). Water-quality measurements indicate that groundwater in the formation is both fresh and saline (greater than 10,000 ppm of total dissolved solids) (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010). The minimum and central tendency buoyant trapping pore volumes were determined using methods described in Brennan and others (2010). Maximum buoyant trapping pore volume was calculated from the product of (1) the combined areas of structural reservoir traps interpreted from contours of Roberts and others (2008) and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) the maximum net porous interval thickness, and (3) the maximum porosity (Brennan and others, 2010). Structural reservoir traps were defined by outlining areas of closure interpreted on a 1,000-ft-contour-interval structural map of the top of the Cloverly Formation. In the Cloverly Formation Deep C50340108 SAU, areas of structural enclosure were also interpreted in the proximal footwalls of thrust faults of the Bighorn Basin (fig. 1).

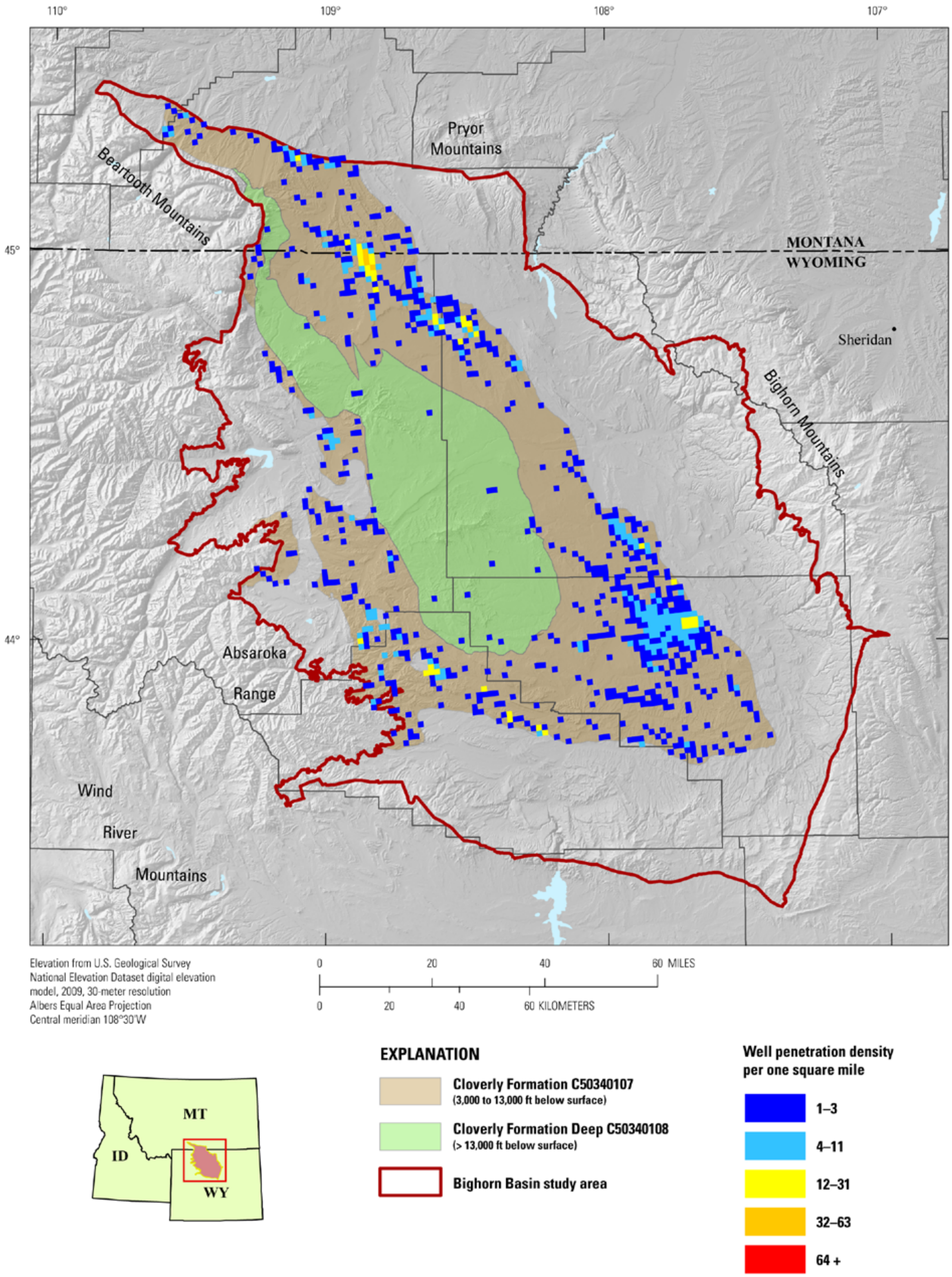

Figure 8. Map of the U.S. Geological Survey Storage Assessment boundary for the Cloverly Formation and Cloverly Formation Deep Storage Assessment Units in the Bighorn Basin, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Total Petroleum System boundary modified from U.S. Geological Survey Bighorn Basin Province Assessment Team (2010).

Muddy Sandstone C50340109 and Muddy Sandstone Deep C50340110

By Jacob A. Covault

The Lower Cretaceous Muddy Sandstone is as much as 70 ft thick and predominantly includes sandstone interbedded with mudstone (figs. 4 and 9) (Finn and others, 2010). The Muddy Sandstone unconformably overlies the Lower Cretaceous Thermopolis Shale and underlies the Lower and Upper Cretaceous Mowry Shale. The Mowry Shale is as much as 800 ft thick and is interpreted to seal the underlying Muddy Sandstone. Both the Muddy Sandstone and overlying Mowry Shale are regionally extensive across the Bighorn Basin (Finn, 2010). However, the Muddy Sandstone is thickest in the southeastern Bighorn Basin, where it is sandstone-rich, and thinnest in the north-northwestern part of the basin, where it includes sandstone encased in shale (Finn and others, 2010). The Mowry Shale increases in thickness from about 400 ft in the southeastern part of the Bighorn Basin to 800 ft in the northwestern part of the Bighorn Basin (Finn and others, 2010). The Muddy Sandstone and overlying Mowry Shale couplet has been interpreted to represent a landward retreat of depositional environments from a marginal marine fluvial and (or) incised valley system that transitions to offshore bars (Muddy Sandstone) from southeast to northwest, to fully marine systems (Mowry Shale) in the Cretaceous Western Interior Seaway and foreland basin (Paull, 1962; Dolson and others, 1991; Long, 1999; Finn and others, 2010).

The Muddy Sandstone comprises two potential reservoir units for CO_2 storage in the Bighorn Basin: (1) between 3,000- and 13,000-ft subsurface depth, Muddy Sandstone C50340109; and (2) below 13,000-ft subsurface depth, Muddy Sandstone Deep C50340110 (fig. 9). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from greater than 4,200 well penetrations (IHS Energy Group, 2010) and faults bounding the Bighorn Basin. Fault locations were approximated from structural contour maps for the underlying Cloverly Formation (Finn and others, 2010). The range of total storage formation thickness for reservoir units was determined from an isopach map of Finn and others (2010). The thickness of the net porous interval was calculated by multiplying the total storage formation thickness by a net porous thickness to gross thickness ratio of 0.64 interpreted from gamma-ray wireline logs of Finn (2010). Finn and others (2010) indicate a porosity range from 2–23 percent and a permeability range from 0.01–33 mD (Cardinal and others, 1989; Nehring Associates, Inc., 2010). These data were employed in order to populate porosity and permeability ranges for the SAU C50340109 between 3,000 and 13,000 ft. Porosity and permeability values are interpreted to diminish with depth (Ehrenberg and others, 2009). Accordingly, we reduced the porosity range of the SAU deeper than 13,000 ft below surface (C50340110) by approximately 50 percent of the range of the shallower Muddy Sandstone C50340109 SAU. These adjustments to petrophysical properties with depth are consistent with empirical data from Cretaceous siliciclastic sandstone reservoirs of the Rocky Mountain region (Nehring Associates, Inc., 2010). Water-quality measurements indicate that groundwater in the formation is both fresh and saline (greater than 10,000 ppm of total dissolved solids) (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010). The minimum and central tendency buoyant trapping pore volumes were determined using methods described in Brennan and others (2010). Maximum buoyant trapping pore volume was calculated from the product of (1) the combined areas of structural reservoir traps interpreted from a structure map of the Muddy Sandstone and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) the maximum net porous interval thickness, and (3) the maximum porosity (Brennan and others, 2010). Structural reservoir traps were defined by outlining areas of closure interpreted on a 1,000-ft-contour-interval structural map of the top of the Muddy Sandstone. In the Muddy Sandstone Deep C50340110 SAU, areas of structural enclosure were also interpreted in the proximal footwalls of thrust faults of the Bighorn Basin (fig. 1).

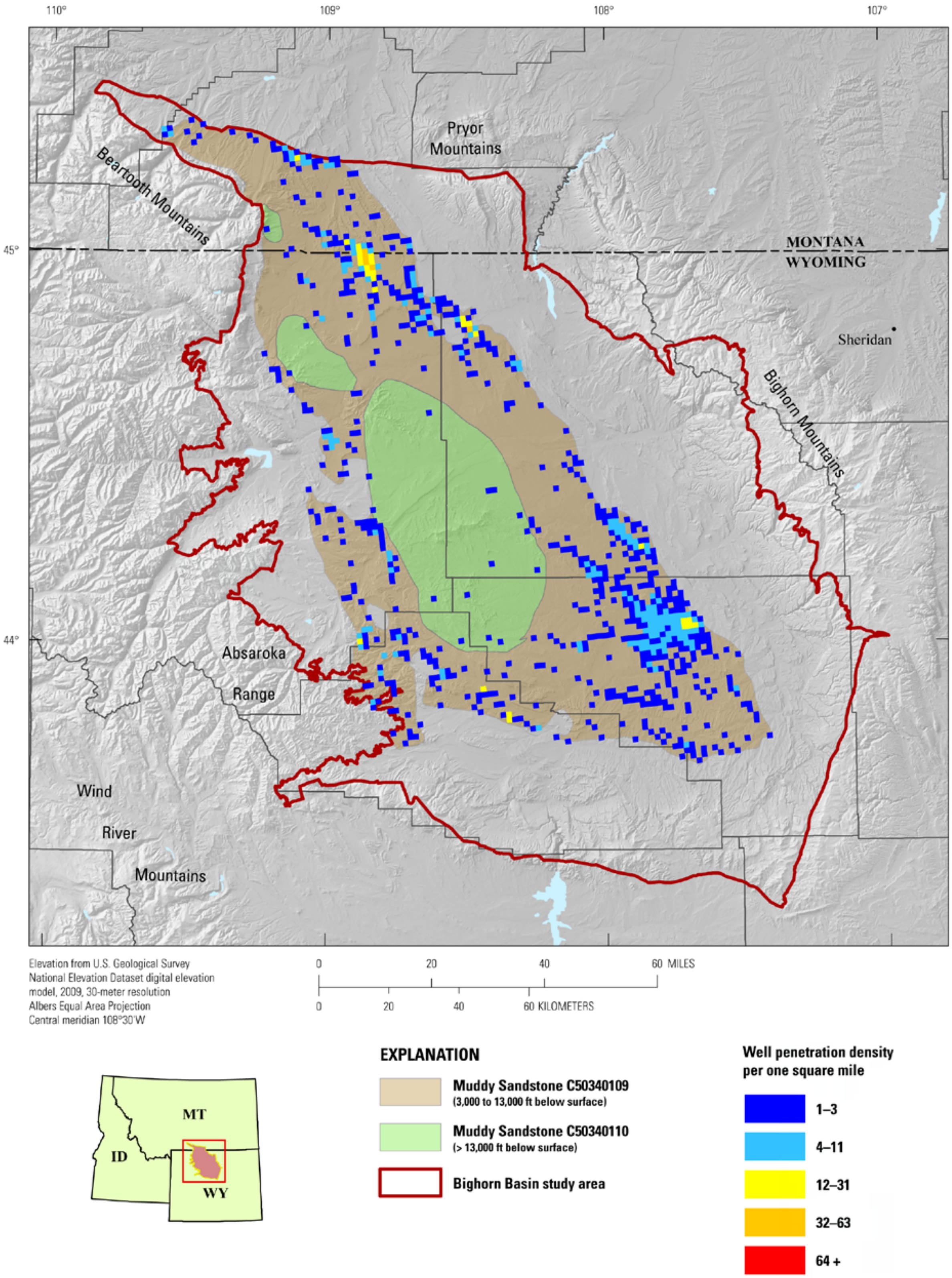

Figure 9. Map of the U.S. Geological Survey Storage Assessment boundary for the Muddy Sandstone and Muddy Sandstone Deep Storage Assessment Units in the Bighorn Basin, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Total Petroleum System boundary modified from U.S. Geological Survey Bighorn Basin Province Assessment Team (2010).

Frontier Sandstone C50340111 and Frontier Sandstone Deep C50340112

By William H. Craddock

The Upper Cretaceous Frontier Sandstone ranges from approximately 100–300 ft thick and comprises lobate packages of sandstone and siltstone interbedded with shale (figs. 4 and 10). The sandstone packages generally exhibit gradational contacts with underlying shale units, coarsen upward, and are composed of inch- or foot-scale, buff-colored sandstone and siltstone beds. Eastward, across the Bighorn Basin, sandstone packages thin, become finer grained, and interfinger with the shale units. Sandstone beds exhibit hummocky, swaley, and trough cross stratification, burrowing, and bioturbation (Bhattacharya and Willis, 2001). The formation contains abundant marine fossils and trace fossil assemblages, including skolithos and ophiomorpha (Bhattacharya and Willis, 2001). The Frontier Sandstone is overlain by the Upper Cretaceous Cody Shale, which is laterally extensive shale as much as 2,000 ft thick. A range of marine depositional environments is represented by the Frontier Sandstone, including shelf, prodelta, lower shoreface, and upper shoreface. The Cody Shale is interpreted to be a marine hemipelagic fallout deposit, which accumulated in deeper water below the storm-wave base. The formations were deposited during the early Late Cretaceous, in the western part of the Western Interior Seaway and foreland basin (fig. 3) (Barlow and Haun, 1966; Bhattacharya and Willis, 2001; Finn and others, 2010).

The Frontier Sandstone comprises two potential reservoir units for CO_2 storage in the Bighorn Basin: (1) between 3,000- and 13,000-ft subsurface depth, Frontier Sandstone C50340111; and (2) below 13,000-ft subsurface depth, Frontier Sandstone Deep C50340112 (fig. 10). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from well penetrations (Finn and others, 2010; IHS Energy Group, 2010) and faults bounding the Bighorn Basin. Fault locations were approximated from structural contour maps for the underlying Cloverly Formation (Finn and others, 2010). Regional subsurface stratigraphic correlations were used to define gross formation thickness (Finn and others, 2010). Net porous interval thickness for the Frontier Sandstone was adapted from Fox and Dolton (1996) and represents an aggregate of all beds in excess of 10 ft.

In order to assess the porosity of the Frontier Sandstone, a sandstone compaction curve was generated from 21 petroleum-reservoir-averaged porosity measurements distributed around the Bighorn Basin (Nehring Associates, Inc., 2010). In the shallow Frontier Sandstone C50340111 SAU, modal porosity is approximately 13 percent, but the range in reservoir-scale porosity values varies widely across the basin. Because no petroleum production occurs in the deepest portions of the Bighorn Basin, the porosity of the deepest rocks was estimated using a global compilation of Cretaceous siliciclastic rocks (Ehrenberg and others, 2009). The compilation suggests a modal porosity of 9 percent. Petroleum production data were also used to assess the permeability of the Frontier Sandstone (Nehring Associates, Inc., 2010). The trend of Frontier Sandstone permeability with depth suggests that the Frontier Sandstone Deep C50340112 SAU predominantly includes rocks with permeabilities less than 1 mD. Much of the Frontier Sandstone contains fresh groundwater with less than 10,000 ppm of total dissolved solids (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010); therefore, the viable storage area for the formation is restricted by U.S. Environmental Protection Agency regulations (U.S. Environmental Protection Agency, 2008). The minimum and central tendency buoyant trapping pore volumes were determined using methods described in Brennan and others (2010). Maximum buoyant trapping pore volume was calculated from the product of (1) the combined areas of structural reservoir traps interpreted from a structure map of the Frontier Sandstone and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) the maximum net porous interval thickness, and (3) the maximum porosity (Brennan and others, 2010). Structural reservoir traps were defined by outlining areas of closure interpreted on a 1,000-ft-contour-interval structural map of the top of the Frontier Sandstone. In the Frontier Sandstone Deep C50340112 SAU, areas of structural enclosure were also interpreted in the proximal footwalls of thrust faults of the Bighorn Basin (fig. 1).

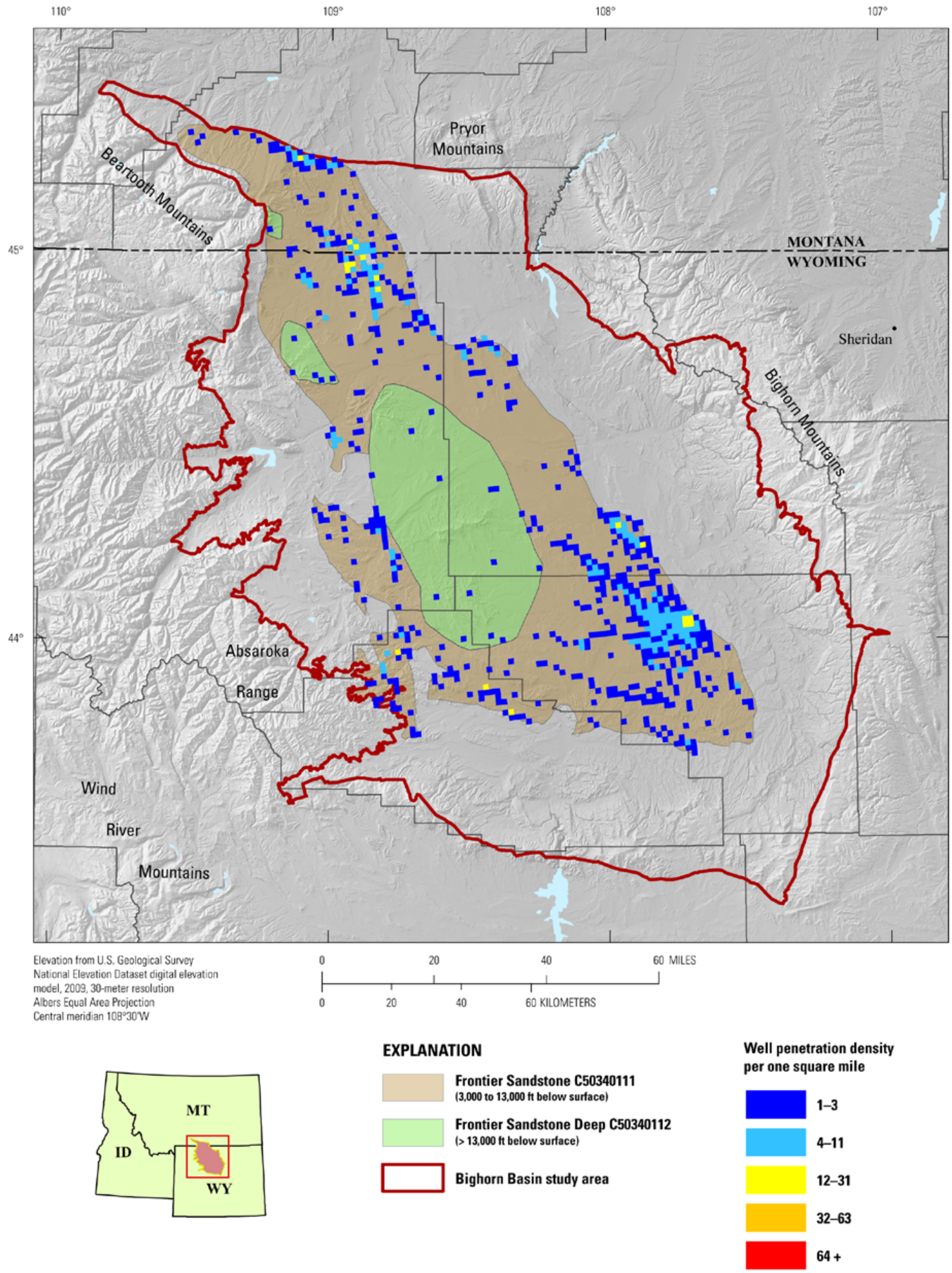

Figure 10. Map of the U.S. Geological Survey Storage Assessment boundary for the Frontier Sandstone and Frontier Sandstone Deep Storage Assessment Units in the Bighorn Basin, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Total Petroleum System boundary modified from U.S. Geological Survey Bighorn Basin Province Assessment Team (2010).

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References Cited

Anderson, T.C., and O'Connell, P.J., 1993, Structural geology of the Circle Ridge oilfield, Fremont County Wyoming, *in* Keefer, W.R., Metzger, W.J., Godwin, L.H., eds., Wyoming Geological Association Special Symposium on Oil and Gas, p. 399-418.

Barlow, J.A., and Haun, J.D., 1966, Regional stratigraphy of Frontier Formation and relations to Salt Creek field, Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2185–2196.

Bartow-Campen, E., 1986, Hydrocarbon exploration techniques in the Greybull Sandstone, northern Bighorn Basin, *in* Garrison, P.B., ed., Geology of the Beartooth uplift and adjacent basins: Yellowstone Bighorn Research Association-Montana Geological Society 50th Anniversary Guidebook, p. 225–231.

Bhattacharya, J.P., and Willis, B.J., 2001, Lowstand deltas in the Frontier Formation, Powder River Basin, Wyoming—Implications for sequence stratigraphic models: American Association of Petroleum Geologists Bulletin, v. 85, no. 2, p. 261–294.

Blackstone, D.L., Jr., 1993, Precambrian basement map of Wyoming: Outcrop and structural configuration: The Geological Survey of Wyoming, Map Series 43, scale 1:1,000,000, 1 sheet.

Breit, G.N., 2002, Produced waters database: U.S. Geological Survey online database, accessed on March 23, 2011, at *http://energy.cr.usgs.gov/prov/prodwat/*.

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., accessed March 22, 2011, at *http://pubs.usgs.gov/of/2010/1127/*.

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., accessed March 22, 2011, at *http://pubs.usgs.gov/of/2009/1035/*.

Campbell, C.V., 1962, Depositional environments of Phosphoria Formation (Permian) in southeastern Bighorn Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 46, no. 4, p. 478–503.

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: Wyoming Geological Association, 555 p.

Coalson, E.B., and Inden, R.F., 1990, Geology and oil production of the Ervay ("Phosphoria") reservoirs, eastern Big Horn Basin, Wyoming: The Mountain Geologist, v. 27, no. 3, p. 77.

Coney, P.J., 1976, Plate tectonics and the Laramide orogeny, *in* Woodward, L.A., and Northrop, A.S., eds., Tectonics and mineral deposits of southwestern North America: New Mexico Geological Society Special Publication, v. 6, p. 5–10.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, Western U.S.A.: American Journal of Science, v. 304, p. 105–168.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039.

Dolson, John, Muller, Dave, Evetts, M.J., and Stein, J.A., 1991, Regional paleotopographic trends and production, Muddy Sandstone (Lower Cretaceous), central and northern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 75, p. 409–435.

Ehrenberg, S.N., Nadeau, P.H., and Steen, Ø., 2009, Petroleum reservoir porosity versus depth—Influence of geological age: American Association of Petroleum Geologists Bulletin, v. 93, no. 10, p. 1281–1296.

Finn, T.M., 2010, Subsurface stratigraphic cross sections showing correlation of Cretaceous and lower Tertiary rocks in the Bighorn Basin, Wyoming and Montana, chap. 6 *of* U.S. Geological Survey Bighorn Basin Assessment Team, 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, 14 p., accessed March 22, 2011, at *http://pubs.usgs.gov/dds/dds-069/dds-069-v/REPORTS/69_V_CH_6.pdf*.

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, chap. 3 *of* U.S. Geological Survey Bighorn Basin Assessment Team, 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, 156 p., accessed March 22, 2011, at *http://pubs.usgs.gov/dds/dds-069/dds-069-v/REPORTS/69_V_CH_3.pdf*.

Foose, R.M., Wise, D.U., and Garbarini, G.S., 1961, Structural geology of the Beartooth Mountains, Montana and Wyoming: Geological Society of America Bulletin, v. 72, p. 1143–1172.

Fox, J.E., and Dolton, G.L., 1995, Bighorn Basin Province (034): U.S. Geological Survey Digital Data Series DDS-30, Release 2, one CD-ROM, accessed March 22, 2011, at *http://certmapper.cr.usgs.gov/data/noga95/prov34/text/prov34.pdf*.

Fox, J.E., and Dolton, G.L., 1996, 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: Wyoming Geological Association Guidebook, p. 19–39.

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: Rocky Mountain Association of Geologists Symposium, p. 185–216.

Freethey, G.W., and Cordy, G.E., 1991, Geohydrology of Mesozoic rocks in the upper Colorado River basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin: U.S. Geological Survey Professional Paper 1411–C, 188 p., accessed March 22, 2011, *http://pubs.er.usgs.gov/djvu/PP/pp_1411_c.djvu*.

Gill, J.R., and Cobban, W.A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey Professional Paper 776, 37 p.

Green, G.N., and Drouillard, P.H., 1994, The digital geologic map of Wyoming in ARC/INFO format: U.S. Geological Survey Open-File Report 94-0425, scale 1:500,000, accessed March 22, 2011, at *http://pubs.usgs.gov/of/1994/ofr-94-0425*.

Hafenbrack, J.H., Chuman, R.W., and Shannon, P., eds., 1958, Montana oil and gas fields symposium 1958: Billings Geological Society, 240 p.

High, L.R., Jr., and Picard, M.D., 1969, Stratigraphic relations within upper Chugwater Group (Triassic), Wyoming: Bulletin of American Association of Petroleum Geologists, v. 53, no. 5, p. 1091–1104.

IHS Energy Group, 2010 [includes data current as of December 23, 2009], PIDM relational U.S. well data: IHS Energy Group, database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112, U.S.A.

IHS Energy Group, 2011, ENERDEQ U.S. well data: IHS Energy Group, online database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112, U.S.A., accessed January 20, 2011., at *http://energy.ihs.com/*.

Johnson, R.C., and Finn, T.M., 1998, Is there a basin-centered gas accumulation in Upper Cretaceous rocks in the Bighorn Basin?, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association 49th Guidebook, p. 257–273.

Johnson, R.C., Crovelli, R.A., Lowell, B.A., and Finn, T.M., 1999, An assessment of in-place gas resources in the low-permeability basin-centered gas accumulation of the Bighorn Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 99–315-A, 123 p.

Keefer, W.R., Finn, T.M., Johnson, R.C., and Keighin, C.W., 1998, Regional stratigraphy and correlation of Cretaceous and Paleocene 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: Wyoming Geological Association 49th Guidebook, p. 1–30.

Lawson, D.E., and Smith, J.R., 1966, Pennsylvanian and Permian influence on Tensleep oil accumulation, Big Horn Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, no. 10, p. 2197–2220.

Libra, R., Doremus, D., and Goodwin, C., 1981, Occurrence and characteristics of groundwater in the Bighorn Basin, Wyoming: Wyoming Water Resources Research Institute, University of Wyoming, v. II-A, 104 p., 5 pls.

Link, P.K., Christie-Blick, N., Devlin, W.J., Elston, D.P., Horodyski, R.J., Levy, M., Miller, J.M.G., Pearson, R.C., Prave, A., Stewart, J.H., Winsont, D., Wright, L.A., and Wrucke, C.T., 1993, Middle and Late Proterozoic stratified rocks of the Western U.S. cordillera, Colorado Plateau, and Basin and Range province, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Ranking, D.W., Sims, P.K., and Van Schmus, W.R., eds., Precambrian—Conterminous U.S.: Boulder, Colo., Geological Society of America, The Geology of North America, v. C-2., p 463–595.

Long, M.S., 1999, Facies architecture and sequence stratigraphy of the Lower Cretaceous Muddy Formation in the southeastern Bighorn Basin, Wyoming: Provo, Utah, Brigham Young University, M.S. thesis, 86 p.

Love, J.D., 1988, Geology of the Bighorn Basin, northern Wyoming and southern Montana, *in* chap. 8, Basins of the Rocky Mountain region, *of* Sloss, L.L., ed., Sedimentary cover—North American craton, U.S.: The Geology of North America: Geological Society of America, v. D-2, p. 201–204.

Love, J.D., Thompson, R.M., Johnson, C.O., Sharkey, H.H.R., Tourtelot, H.A., and Zapp, A.D., 1945, Stratigraphic sections and thickness maps of Lower Cretaceous and nonmarine Jurassic rocks of central Wyoming: U.S. Geological Survey Oil and Gas Investigations Preliminary Chart 13.

McKenna, M.C., and Love, J.D., 1972, High-level strata containing early Miocene mammals on the Bighorn Mountains, Wyoming: American Museum Novitiates, no. 2490, 31 p.

Miller, D.M., Nilsen, T.H., and Bilodeau, W.L., 1992, Late Cretaceous to early Eocene geologic evolution of the U.S. cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran orogen; Conterminous U.S.: Geological Society of America, The Geology of North America, v. G-3, p. 205–260.

Moberly, R.M., 1960, Morrison, Cloverly, and Sykes Mountain Formations, northern Bighorn Basin, Wyoming and Montana: Geological Society of America Bulletin, v. 71, p. 1137–1176.

Nehring Associates, Inc., 2010 [data current as of December 2008], The significant oil and gas fields of the United States: Colorado Springs, Colo., Nehring Associates, Inc., database available from Nehring Associates, Inc., P.O. Box 1655, Colorado Springs, CO 80901, U.S.A.

Paull, R.A., 1962, Depositional history of the Muddy Sandstone, Bighorn Basin, Wyoming, *in* Enyert, R.L., and Curry, W.H., eds., Symposium on Early Cretaceous rocks of Wyoming and adjacent areas: Wyoming Geological Association 17th Annual Field Conference Guidebook, p. 102–117.

Picard, M.D., 1978, Stratigraphy of Triassic rocks in west-central Wyoming: Wyoming Geological Association 30th Annual Field Conference Guidebook, p. 101–130.
Roberts, L.N.R., Finn, T.M., Lewan, M.D., and Kirschbaum, M.A., 2008, Burial history, thermal maturity, and oil and gas generation history of source rocks in the Bighorn Basin, Wyoming and Montana: U.S. Geological Survey Scientific Investigations Report 2008–5037, 27 p., accessed March 22, 2011, at *http://pubs.usgs.gov/sir/2008/5037/*.
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.
Sundell, K.A., 1990, Sedimentation and tectonics of the Absaroka Basin of northwestern Wyoming, *in* Specht, R.W., ed., Wyoming sedimentation and tectonics: Wyoming Geological Association 41st Field Conference Guidebook, p. 105–122.
Sundell, K.A., 1993, A geologic overview of the Absaroka volcanic province, *in* Snoke, A.W., Steidtman, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 480–506.
Surdam, R.C., Jiao, Z.S., and Heasler, H.P., 1997, Anomalously pressured gas compartments in Cretaceous rocks of the Laramide basins of Wyoming—A new class of hydrocarbon accumulation, *in* Surdam, R.C., ed., Seals, traps, and the petroleum system: American Association of Petroleum Geologists Memoir 67, p. 199–222.
Thomas, L.E., 1965, Sedimentation and structural development of Big Horn Basin: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1867–1877.
Tohill, B., and Picard, M.D., 1966, Stratigraphy and petrology of Crow Mountain Sandstone Member (Triassic), Chugwater Formation, northwestern Wyoming: American Association of Petroleum Geologists Bulletin, v. 50, no. 12, p. 2547–2565.
Tonnsen, J.J., ed., 1985, Montana oil and gas fields symposium 1985: Montana Geological Society, 1217 p.
U.S. Environmental Protection Agency, 2008, Federal requirements under the underground injection control (UIC) program for carbon dioxide (CO_2) geologic sequestration (GS) wells: Washington, D.C., U.S. Environmental Protection Agency, proposed rule, accessed March 23, 2011, at *http://www.epa.gov/fedrgstr/EPA-WATER/2008/July/Day-25/w16626.htm*.
U.S. Geological Survey Bighorn Basin Province Assessment Team, 2010, Executive summary—Assessment of undiscovered oil and gas resources of the Bighorn Basin Province, Wyoming and Montana, 2008, chap. 1 *of* U.S. Geological Survey Bighorn Basin Province Assessment Team, 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, 7 p., accessed March 22, 2011, at *http://pubs.usgs.gov/dds/dds-069/dds-069-v/REPORTS/69_V_CH_1.pdf*.
Wilson, C.W., Jr., 1936, Geology of the Nye-Bowler lineament, Stillwater and Carbon Counties, Montana: American Association of Petroleum Geologists Bulletin, v. 20, p. 1161–1188.
Wyoming Oil and Gas Conservation Commission, 2010, Produced water database: Wyoming Oil and Gas Conservation Commission online database, accessed March 23, 2011, at *http://wogcc.state.wy.us/*.
Zapp, A.D., 1956, Structure contour map of the Tensleep Sandstone in the Big Horn Basin, Wyoming and Montana: U.S. Geological Survey Oil and Gas Investigation Map OM–182, scale 1:250,000, 1 sheet.