Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Powder River Basin, Wyoming, Montana, South Dakota, and Nebraska

By William H. Craddock, Ronald M. Drake, II, John C. Mars, Matthew D. Merrill, Peter D. Warwick, Madalyn S. Blondes, Mayur A. Gosai, Philip A. Freeman, Steven M. Cahan, Christina A. DeVera, and Celeste D. Lohr

Chapter B of
Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources
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.

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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	
acre	0.4047	hectare (ha)
acre	0.004047	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)
liter (L)	0.2642	gallon (gal)

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Abstract

This report presents ten storage assessment units (SAUs) within the Powder River Basin of Wyoming, Montana, South Dakota, and Nebraska. The Powder River Basin contains a thick succession of sedimentary rocks that accumulated steadily throughout much of the Phanerozoic, and at least three stratigraphic packages contain strata that are suitable for CO_2 storage. Pennsylvanian through Triassic siliciclastic strata contain two potential storage units: the Pennsylvanian and Permian Tensleep Sandstone and Minnelusa Formation, and the Triassic Crow Mountain Sandstone. Jurassic siliciclastic strata contain one potential storage unit: the lower part of the Sundance Formation. Cretaceous siliciclastic strata contain seven potential storage units: (1) the Fall River and Lakota Formations, (2) the Muddy Sandstone, (3) the Frontier Sandstone and Turner Sandy Member of the Carlile Shale, (4) the Sussex and Shannon Sandstone Members of Cody Shale, and (5) the Parkman, (6) Teapot, and (7) Teckla Sandstone Members of the Mesaverde Formation. For each SAU, we discuss the areal distribution of suitable CO_2 reservoir rock. We also characterize the overlying sealing unit and describe the geologic characteristics that influence the potential CO_2 storage volume and reservoir performance. These characteristics include reservoir depth, gross thickness, net thickness, porosity, permeability, and groundwater salinity. Case-by-case strategies for estimating the pore volume existing within structurally and (or) stratigraphically closed traps are presented. Although assessment results are not contained in this report, the geologic information included herein will be employed to calculate the potential storage space in the various SAUs.

Introduction

The Powder River Basin occupies a broad swath of the northeastern Rocky Mountain region and exhibits significant potential for carbon dioxide (CO_2) sequestration. The basin study area extends over approximately 100–150 mi from east to west and approximately 200 mi from north to south, and it covers portions of northeastern Wyoming, southeastern Montana, western South Dakota, and northwestern Nebraska (fig.1). The basin contains as much as 17,000 ft of sedimentary rock that accumulated throughout the Phanerozoic. A series of north- to northwest-striking structures that developed, or reactivated, during the Cretaceous and Tertiary Laramide orogeny delineates the basin margins (fig. 1). The largest of the basin-bounding structures is the Bighorn Mountains, along the western basin margin, and the Black Hills uplift, along the eastern basin margin. The interior of Powder River Basin is an asymmetric foreland-style basin in which the axis parallels, and is proximal to, the western margin (fig.1). The basin axis separates a broad, gently dipping eastern limb from a steeply dipping western limb.

A recently completed geologic assessment of undiscovered oil and gas resources highlights the prolific history of hydrocarbon production in Powder River Basin (Anna, 2010). Basinwide, known oil and gas reserves, which include both produced and proven reserves, are in excess of 3,200,000 million barrels of oil (MMBO) and 8,400,000 billion cubic feet of gas (BCFG) (Nehring Associates, Inc., 2010). Moreover, the U.S. Geological Survey estimates that approximately 600 MMBO and approximately 16,000 BCFG remain undiscovered (Anna, 2010). The large oil and gas accumulations within the basin imply that large pore volumes may be accessible for the purpose of geologic CO_2 sequestration within produced fields and, possibly, uncharged traps. At least three geochemically distinct hydrocarbon systems in Powder River Basin are associated with unique source rocks and confined to discrete stratigraphic intervals (Anna, 2010). This stratigraphic confinement of hydrocarbon systems is relevant to CO_2 sequestration because it suggests the presence of several regionally impermeable sealing units internal to the basin fill. The regional seals are a desirable feature for a CO_2 storage site because they suggest a high likelihood of containment over geologic time and a low risk of leakage from storage sites into aquifers with potable water or into the atmosphere (for example, see Wilson and others, 2003).

Powder River Basin is part of a chain of sedimentary basins that flanks the eastern Rocky Mountains and extends from Alaska to Mexico (see DeCelles, 2004). Sedimentary rocks in these basins may be divided into seven tectonostratigraphic packages. The packages are separated by regional unconformities and correspond to various phases of the tectonic evolution of western North America (fig. 2). This tectonostratigraphic framework is useful for identifying prospective reservoir intervals and robust basin-scale seals. From oldest to youngest, the packages are (1) Cambrian miogeoclinal siliciclastics, (2) Ordovician to Mississippian miogeoclinal carbonates, (3) Pennsylvanian to Triassic marine, fluvial, and eolian siliciclastics, (4) Jurassic peripheral foreland basin siliciclastics, (5) Cretaceous peripheral foreland basin siliciclastics, (6) lower Tertiary intramontane foreland basin siliciclastics, and (7) middle and upper Tertiary lacustrine deposits. Interested readers are directed to a review by DeCelles (2004) and references therein for additional information about the geologic evolution of the central and northern Rocky Mountain region and the tectonic setting of each of the aforementioned tectonostratigraphic packages.

In total, 10 formations within the Powder River Basin meet our criteria for conducting a regional assessment for CO_2 storage capacity. The potential storage units are confined to three of the previously defined stratigraphic packages, which are the (1) Pennsylvanian to Triassic, (2) Jurassic, and (3) Cretaceous rocks. In the Pennsylvanian to Triassic section, the two potential storage units are the Pennsylvanian and Permian Tensleep Sandstone and Minnelusa Formation, and the Triassic Crow Mountain Sandstone (fig. 2). In the Jurassic section, the one potential storage unit is the lower part of the Sundance Formation (fig. 2). Finally, in the Cretaceous section, the potential storage units are the Fall River and Lakota Formations, the Muddy Sandstone, the Frontier Sandstone, the Turner Sandy Member of the Carlile Shale, the Sussex and Shannon Sandstone Members of the Cody Shale, and the Parkman, Teapot, and Teckla Sandstone Members of the Mesaverde Formation (fig. 2).

In the following sections, we characterize the distribution and stratigraphic character of each prospective storage assessment unit (SAU). We briefly summarize the key information that provides the basis for calculating the capacity of each of the SAUs for buoyant and residual CO_2 storage (as described in Burruss and others, 2009; Brennan and others, 2010; a function of SAU area, thickness and porosity) as well as information that relates to the reservoir characteristics for each unit. Due to the fact that the U.S. Environmental Protection Agency (2009) stipulates that aquifers must contain groundwater with a total dissolved solids (TDS) concentration >10,000 ppm in order to be used for CO_2 storage, we present descriptions of regional trends in groundwater quality. Finally, in order to differentiate between the pore volume contained within buoyant and residual traps (see Brennan and others, 2010) for the various SAUs, we defined the pore volume enclosed within buoyant traps, which are analogous to stratigraphic and (or) structural hydrocarbon traps. For each SAU, the (a) minimum and (b) most likely pore volumes enclosed within buoyant traps were constrained on the basis of (a) the sum of the cumulative oil and gas production and the known hydrocarbon reserve volume and (b) the minimum buoyant volume plus the estimated volume of undiscovered resources (see Brennan and others, 2010; Anna, 2010). Because this method was applied to all SAUs, it is not discussed on a case-by-case basis. An upper bound for enclosed pore volume was also determined for each unit, and we describe our methods for the various SAUs on a case-by-case basis. The information derived from the data sources and methods described herein will be used in accordance with the U.S. Geological Survey (USGS) Carbon Sequestration Assessment Methodology (Brennen and others, 2010) to calculate the available storage space for CO_2 within the SAU.

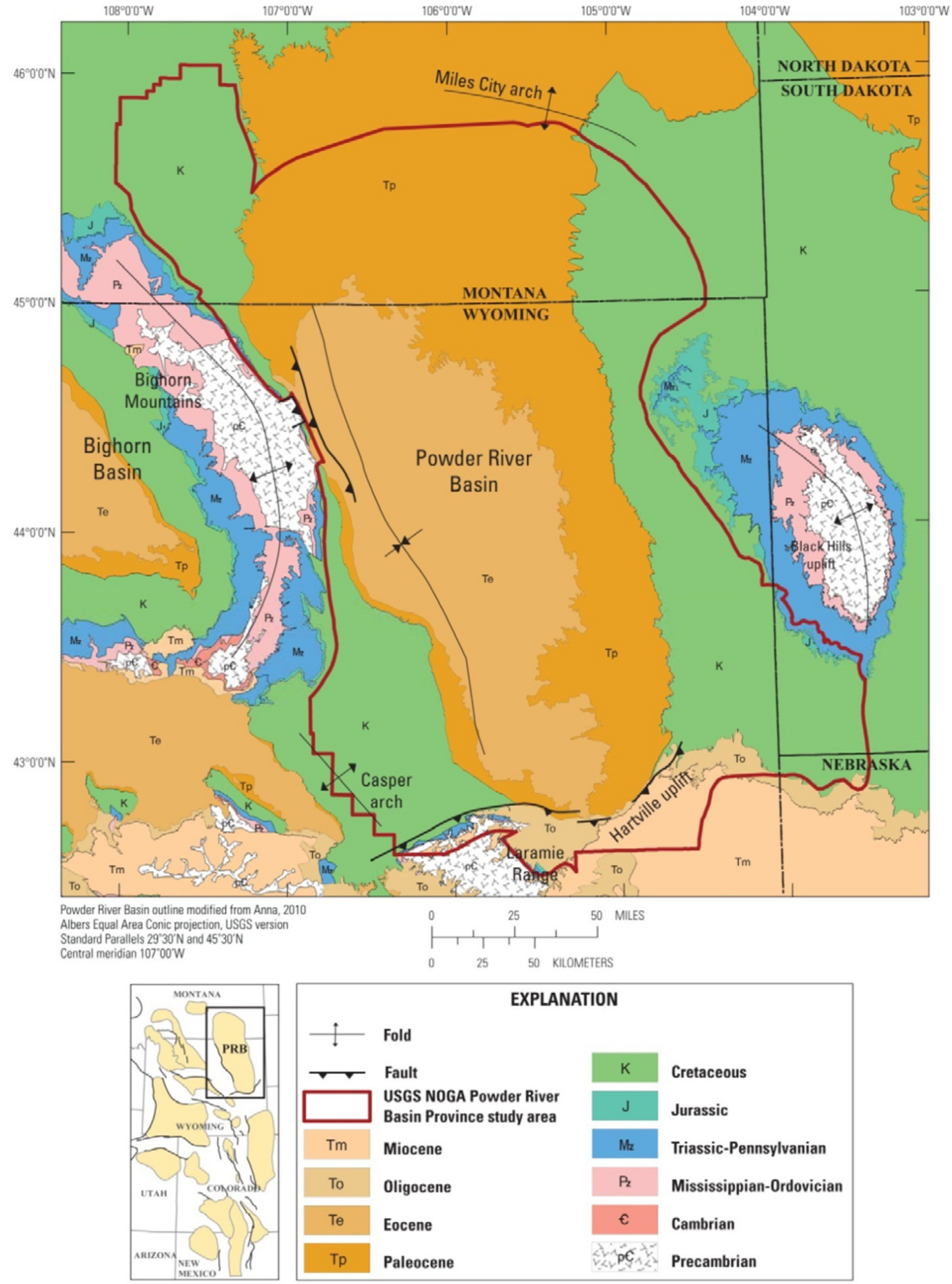

Figure 1. Geologic map of the Powder River Basin study area of Wyoming, Montana, South Dakota, and Nebraska. Geologic units are simplified from Stoeser and others (2007). Major structural features adapted from Anna (2010). In the inset on the lower left, PRB, Powder River Basin. NOGA, National Oil and Gas Assessment.

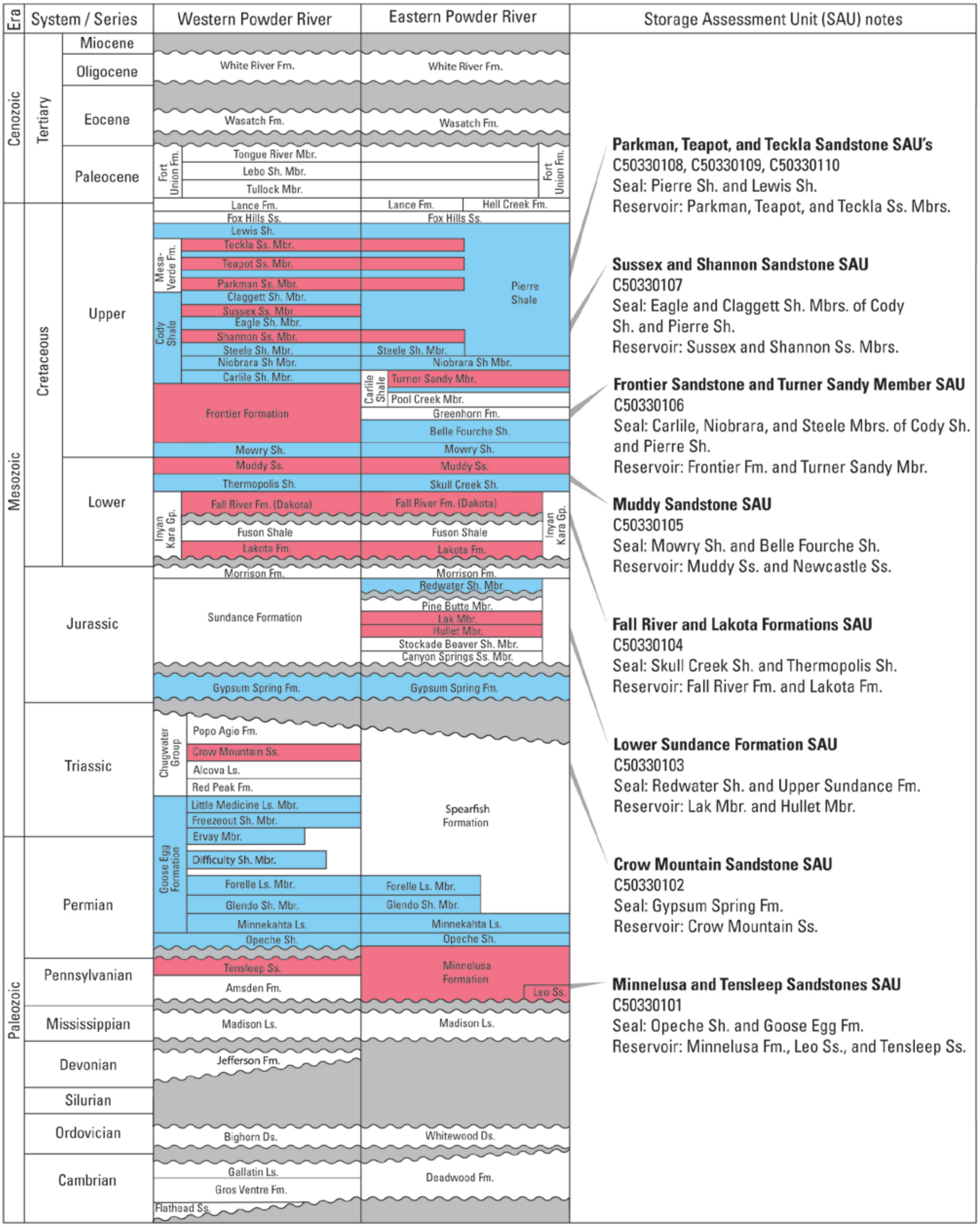

Figure 2. Stratigraphic column for the Powder River Basin study area of Wyoming, Montana, South Dakota, and Nebraska. Storage assessment units consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray areas represent unconformities. Adapted from Dolton and Fox (1995) and Anna (2010). Ss., sandstone; Sh., Shale; Ls., Limestone; Dol., Dolomite; Gp., Group; Fm.,Formation; Mbr., Member.

Minnelusa and Tensleep Sandstones SAU C50330101

By Peter D. Warwick

The Pennsylvanian and Permian Minnelusa Formation and Tensleep Sandstone and Pennsylvanian Leo Sandstone (fig. 2) are partly laterally equivalent formations, and they consist of eolian sandstones interbedded with low-porosity shallow marine dolomite, lagoonal mudstone, and evaporite from shallow marine environments (Anna, 2010). The sealing units for the Minnelusa and Tensleep Sandstones SAU are Lower Permian Opeche Shale and Lower Permian to Lower Triassic Goose Egg Formation (fig. 2), which are composed of variegated red mudstone, siltstone, sandstone, and evaporite (Benison and Goldstein, 2000; Anna, 2010). Subsurface stratigraphic correlations indicate that the seal formations are several hundreds of feet thick across the breadth of Powder River Basin (Benison and Goldstein, 2000; Anna, 2010).

The Minnelusa and Tensleep Sandstones SAU boundary is based on overburden thickness and corresponds to the area where the top of the reservoir rock is between 3,000 and 13,000 ft in depth (fig. 3). The 3,000- to 13,000-ft-depth limits were determined from formation tops in the IHS Energy Group (2010) commercial database and various structure contour maps published by Blackstone (1989), Crysdale (1990a), and Fox and Higley (1987a,b). Although a swath of the Tensleep Sandstone is deeper than 13,000 ft in the southwestern portion of the basin, this area does not exhibit exceptional CO_2 storage potential and it was not assessed.

Regional subsurface stratigraphic correlations indicate that the Minnelusa and Tensleep thicken to the west across the basin, and on average, the gross formation thickness is 300 to 600 ft (Anna, 2010; IHS Energy Group, 2010). Eolian sandstones are the best reservoir rocks in this stratigraphic interval, and they are characterized by alternating intervals of high and low permeability (Anna, 2010). Available data from Desmond and others (1984), Crysdale (1990b), Anna (2010), and Nehring Associates, Inc. (2010) suggest that on average, the net porous interval for the Minnelusa and Tensleep Sandstones SAU ranges in thickness between 75 and 150 ft, and is most likely 100 ft.

A combination of previous studies and a commercial database of petroleum production data was used to characterize the reservoir properties of the Minnelusa Formation and Tensleep Sandstone. Data from Anna (2010), Ehrenberg and others (2009), and Nehring Associates, Inc. (2010) suggest that the average porosity of the net porous interval of the SAU ranges from 14 to 20 percent with a most likely value of 16 percent. Permeability of the SAU ranges from 0.1 to 1,000 millidarcy (mD), with a most likely permeability of 100 mD (Nehring Associates, Inc., 2010).

Several databases of TDS concentrations within formation waters from around the basin indicate that there is a mix of fresh (<10,000 TDS) and saline (>10,000 TDS) water within the SAU interval (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010). Because the basin contains many accumulations of potentially potable water, only about 50 percent (at the mode; with a minimum of 30 percent and a maximum of 75 percent) of the SAU area may be suitable for subsurface storage of CO_2.

In order to calculate the maximum buoyant pore volume within structural and stratigraphic closures, we extrapolated the known closure area from the highly productive, south-central part of the basin to the entire SAU and combined this with upper bounds on regional reservoir thickness and porosity. The known closure area in the south-central part of the basin was calculated by summing petroleum field areas (Nehring Associates, Inc., 2010). An assumption underlying this calculation is that there is potential for additional uncharged or undiscovered structural and stratigraphic closures outside of regions of historical hydrocarbon production. We did not allocate uncharged or undiscovered traps to areas known to contain fresh groundwater.

In addition to the references cited above, other reports used to characterize the Minnelusa and Tensleep Sandstones SAU include Agatston (1954), Bates (1955), Wilson (1962), Bowles and Braddock (1963), Tranter and Petter (1963), Trotter (1963), Berg and Tenney (1967), Van Fossen (1970), Maughan (1980), Desmond and others (1984), Moore (1986), Ahlbrandt and others (1994), and Ciftci and others (2004).

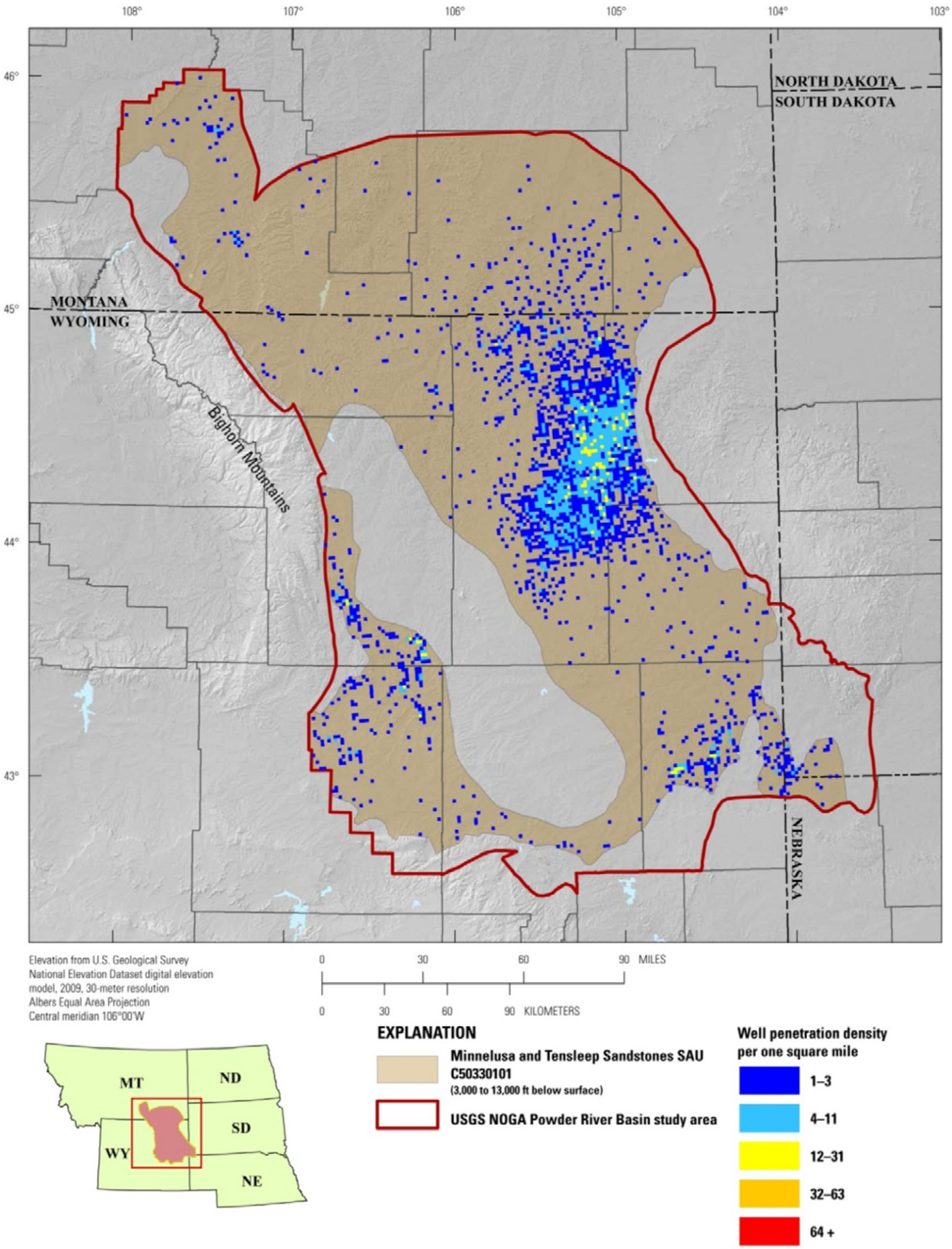

Figure 3. Map of the Minnelusa and Tensleep Sandstones Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. The area interior to the SAU contains Minnelusa Formation and (or) Tensleep Sandstone strata that are covered by overburden in excess of 13,000 ft and were not assessed. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir formation top. Powder River Basin study area modified from Anna (2010).

Crow Mountain Sandstone SAU C50330102

By Matthew D. Merrill and John C. Mars

The Upper Triassic Crow Mountain Sandstone of the Chugwater Group (fig. 2) is an eolian, fluvial, and shallow marine, fine- to medium-grained sandstone that was deposited across much of the northern Rocky Mountain Region. In the Powder River Basin region, the Crow Mountain Sandstone has been variously interpreted to be a shallow marine deposit (Cavaroc and Flores, 1991) and an eolian deposit (Irmen and Vondra, 2000). Within the basin, Crow Mountain Sandstone is only recognized in the proximity of the faulted western margin. To the east, the Spearfish Formation is likely to include some Crow Mountain-equivalent strata (fig. 2), but these were not included in the SAU because of a lack of subsurface geologic information for the Triassic strata. The Crow Mountain is overlain and sealed by the Middle Jurassic Gypsum Spring Formation, a shallow marine deposit containing gypsiferous beds, shales, and silts ranging from 50 to 150 ft thick across the SAU (Mapel and Bergendahl, 1951; IHS Energy Group, 2010). In general, a paucity of information on the Crow Mountain in the Powder River Basin has required us to rely on more robust datasets from the Wind River and Bighorn Basins and other southwest Wyoming basins as analogs in order to characterize the unit.

The SAU area (1,484,000 acres) is defined by the 3,000- to 13,000-ft overburden contours (fig. 4). The contour map was generated from formation tops, and it indicates that the most likely reservoir depth is about 5,000 ft (IHS Energy Group, 2010). Gross reservoir thickness, determined by differencing the tops of the Crow Mountain and underlying Alcova Limestone (fig. 2) for wells in which tops were identified for both formations (IHS Energy Group, 2010), appears to average between 70 and 110 ft. The most likely net sandstone thickness was calculated using net-to-gross sand ratios from analog formations from nearby Wyoming basins, and we estimate that the net sandstone in the Crow Mountain is 21–33 ft thick on average, across the SAU area.

A commercial database of petroleum production data for analog formations (Nehring Associates, Inc., 2010) was used to quantify the rock properties of the Crow Mountain Sandstone. This analysis indicates that the porosity is most likely 8–20 percent, and that the permeability ranges from 0.1 to 150 mD, with a characteristic value of around 10 mD (Nehring Associates, Inc., 2010).

Water-quality data in the Powder River Basin Crow Mountain Sandstone are sparse, making it difficult to evaluate the portion of the SAU area that may satisfy the EPA groundwater-quality requirements for CO_2 injection (see U.S. Environmental Protection Agency, 2009; Brennan and others, 2010). A limited number of TDS concentration measurements indicate the presence of relatively fresh groundwater zones (TDS <10,000 ppm), which may relate to recharge zones associated with faults near the Bighorn Mountains and the Casper arch (fig. 1) (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010). However, substantial areas lack groundwater-quality information, and these may contain formation waters that are sufficiently saline for CO_2 injection.

To date the Crow Mountain Sandstone has had little hydrocarbon production in the Powder River Basin (Nehring Associates, Inc., 2010). Only one major petroleum field exists, the Tisdale North field (located on the Casper arch; see fig. 1), which at 900 ft from the surface is not sufficiently deep for storage of CO_2 in a supercritical phase. The lack of data related to petroleum exploration and production in this stratigraphic interval make the enclosed pore space in the Crow Mountain difficult to assess. This problem is compounded by the fact that many of the traps in the Powder River Basin are stratigraphic, and the volume of stratigraphic enclosures is particularly difficult to characterize with analog data. Nevertheless, analog data from similar formations in adjacent basins were used to estimate an average field size and distribution. Stratigraphic trap closure areas were combined with upper bounds on regional thickness and porosity to obtain an estimate of the maximum pore volume that is accessible for CO_2 storage within enclosed traps.

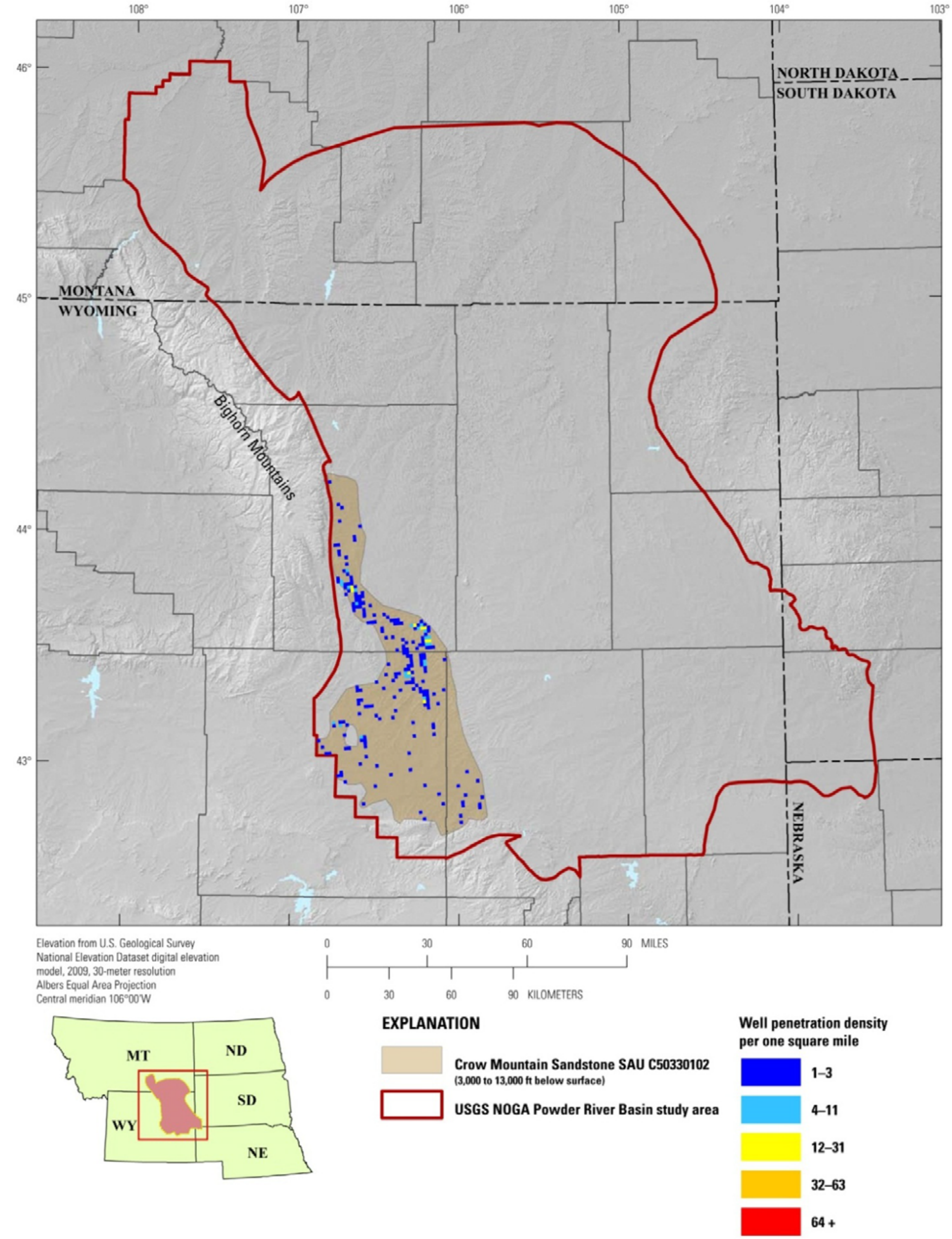

Figure 4. Map of the Crow Mountain Sandstone Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir formation top. Powder River Basin study area modified from Anna (2010).

Lower Sundance Formation SAU C50330103

By Matthew D. Merrill and John C. Mars

The Hulett and Lak Members in the lower part of the Sundance Formation (fig. 2) in the Powder River Basin constitute a northeast-trending barrier island complex that was deposited during a period of regression in the Jurassic Sundance seaway (Rautman, 1978; DeCelles, 2004). The Hulett is a silty sandstone with trough crossbedding and shale interbeds (Rautman, 1978). The Lak Member conformably overlies the Hulett (fig. 2) and consists of well-sorted silty red beds with some evaporites (Wright, 1973). The Lower Sundance Formation SAU is sealed by several marine shales, including the Redwater Shale Member in the upper part of the Sundance Formation (Rautman, 1978), as verified through our inspection of well logs from the SAU area.

A regional overburden contour map was generated using a formation tops database (IHS Energy Group, 2010), and the SAU boundary was delineated on the basis of the 3,000- and 13,000-ft overburden contours (fig. 5). The overburden contour map indicates a mode depth near 6,700 ft within the SAU area. The 11,533,000-acre extent of the SAU covers most of the basin with the exception of the far north and a swath of the southern part of the basin where overburden thickness exceeds 13,000 ft.

Hulett and Lak Members thicknesses were determined using a combination of stratigraphic top depths as well as more detailed analysis of geophysical well logs. Average total thickness for the two members is 40 to 80 ft; approximately 30–60 ft of that gross thickness represents the net porous interval in the SAU (based on interpretation of suites of geophysical logs from the IHS Energy Group in 2010). Reservoir properties from producing reservoirs, as well as analog data from Inyan Kara Group equivalent reservoirs in Powder River Basin, indicate representative porosities and permeabilities range from 16 to 24 percent and 0.1 to 500 mD, respectively (Nehring Associates, Inc., 2010). The characteristic permeability for prospective CO_2 reservoirs is likely to be around 100 mD (Nehring Associates, Inc., 2010).

Analysis of groundwater-quality measurements for the Sundance Formation from around Powder River Basin indicates that the majority of the formation water exhibits TDS concentrations <10,000 ppm (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010). This suggests that much of the SAU area would be restricted for CO_2 injection by EPA regulations (U.S. Environmental Protection Agency, 2009). However considerable areas of the SAU lack groundwater-quality information, and these areas may be suitably saline for CO_2 injection.

Oil and gas production is concentrated along the southern and western basin margins where structural closures act as the main trapping mechanism (Nehring Associates, Inc., 2010). Buoyant trapping of CO_2 should be possible in these same structural traps. Given the abundance of stratigraphic traps in Mesozoic rocks in the Powder River Basin, we speculate that the Hulett and Lak Members may contain undiscovered and (or) uncharged stratigraphic enclosures, which may be acceptable for CO_2 storage. We estimated the maximum possible number of stratigraphically and structurally enclosed traps of a characteristic size and combined the closure area with upper bounds on formation thickness and porosity in order to place an upper bound on the enclosed pore space within the SAU.

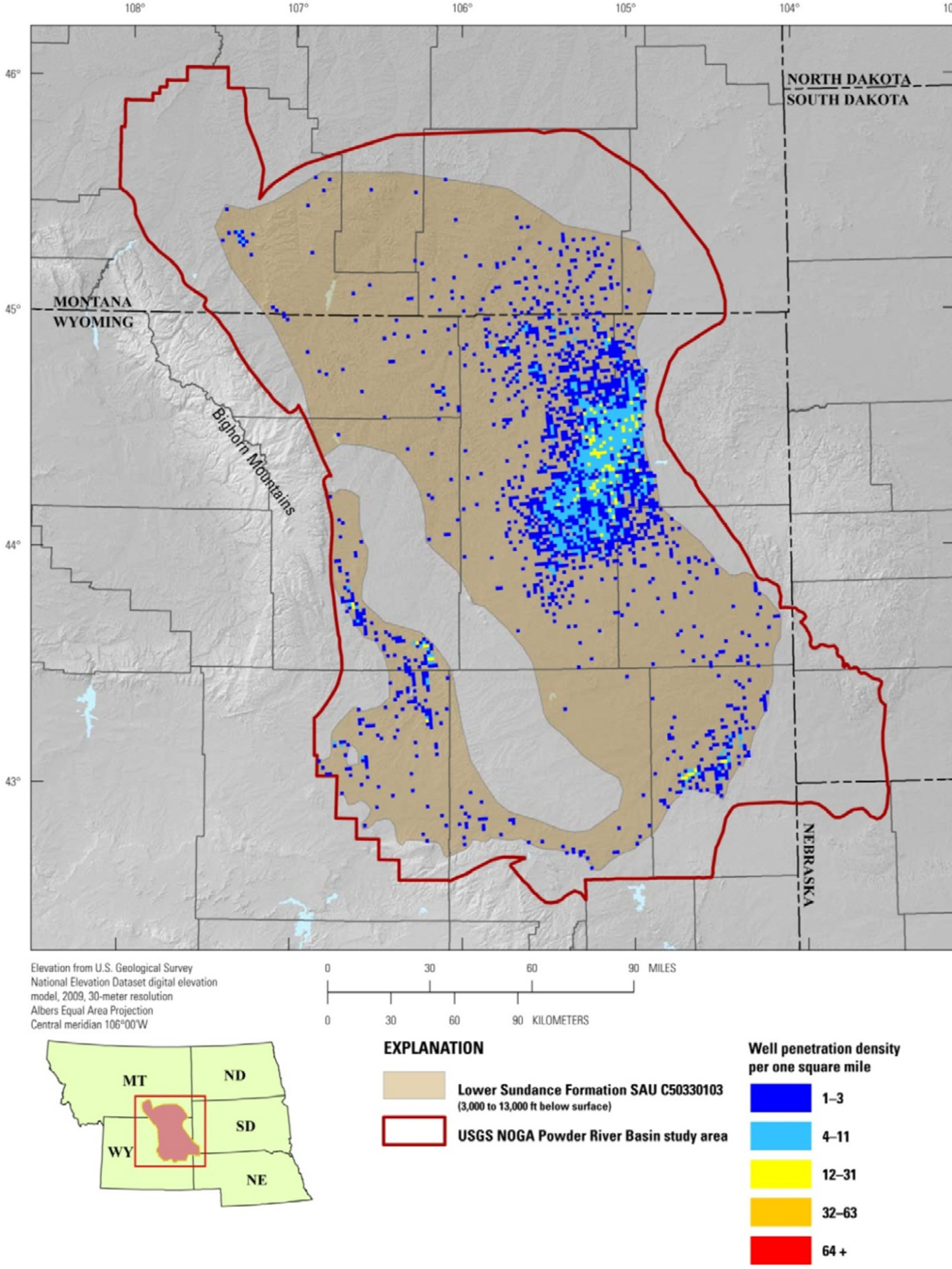

Figure 5. Map of the Lower Sundance Formation Storage Assessment Unit (SAU) (C50330103) boundary in the Powder River Basin study area. The area interior to the SAU contains the lower part of the Sundance Formation that is covered by overburden in excess of 13,000 ft and was not assessed. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir formation top. Powder River Basin study area modified from Anna (2010).

Fall River and Lakota Formations SAU C50330104

By Ronald M. Drake

The Lakota and Fall River Formations are the lowermost Cretaceous deposits in Powder River Basin (fig. 2), and they are separated by the intervening Fuson Shale. The Lakota Formation consists of discontinuous, fluvial-floodplain strata deposited within valleys associated with a north-trending drainage system that was incised into underlying Jurassic strata (Meyers and others, 1992; Anna, 2010). The Fall River Formation was deposited by a broad fluvio-deltaic system, and a number of depositional environments are represented, including incised valley and distributary channel, delta plain, and delta front (Rasmussen and others, 1985; Anna, 2010). The Lakota and Fall River Formations were combined into one SAU because the intervening Fuson Shale pinches out in the eastern part of the basin (Harris, 1976). The entire stratigraphic package is overlain by the Skull Creek and Thermopolis Shales, which are laterally equivalent, hemipelagic deposits that are hundreds of feet thick and likely to be excellent seals for CO_2 storage.

SAU boundaries for the Fall River and Lakota Formations were defined on the basis of an overburden contour map, which was generated from a borehole penetrations database of the units and existing structural contour maps (Gay, 2007; IHS Energy Group, 2010) (fig. 6). The SAU interval extends below 13,000 ft in a small area in the south-central part of Powder River Basin. This region was not assessed, because it appears to be less prospective than the shallower rocks due to its limited size and its relatively low porosity and permeability.

The thickness of the SAU was assessed using a regional isopach map generated from a network of 186 wells (Fox and Higley, 1987c). The gross thickness of the SAU ranges from about 85 ft to 360 ft across the basin, averaging approximately 160 ft (Fox and Higley, 1987c). In order to calculate the net thickness of porous strata within this interval, the gross thickness was reduced by a net-to-gross ratio of 0.6, resulting in an average net porous sand of approximately 96 ft (Bolyard and McGregor, 1966).

A commercial database of petroleum production data was used to characterize the rock properties of the SAU (Nehring and Associates, Inc., 2010). Thirty-nine petroleum-reservoir-averaged porosity values suggest significant spatial variability, but the basinwide average appears to be approximately 15 percent. Petroleum-reservoir-averaged permeability measurements were available for a subset of 26 reservoirs in the database described above. This compilation suggests that permeability ranges from 0.1 mD to 450 mD across the SAU, with a modal value that is around 100 mD.

Data from 241 measurements of TDS reveal that broad swaths of the Fall River and Lakota Formations contain potable water accumulations within the SAU area (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010), such that some areas within the SAU boundary may not be suited for CO_2 storage. The salinity of formation water increases with depth, suggesting that the best areas for CO_2 storage may be in the deep, south-central part of the basin. However, pockets of potentially potable water appear to exist even in the deepest parts of the basin.

In order to estimate the maximum pore volume that is located within structural and stratigraphic traps, we used a compilation showing the distribution of Lakota and Fall River petroleum fields and combined the apparent closure area with upper bounds on regional reservoir thickness and porosity. Oil and gas fields are heavily concentrated in the southeastern part of the basin (Anna, 2010), and we assumed that a similar density of stratigraphic and structural traps exists in less productive areas of the basin. As such, our maximum estimate of enclosed reservoir area exceeds the area of producing oil fields within the basin. Uncharged and undiscovered traps were not attributed to areas of known fresh groundwater.

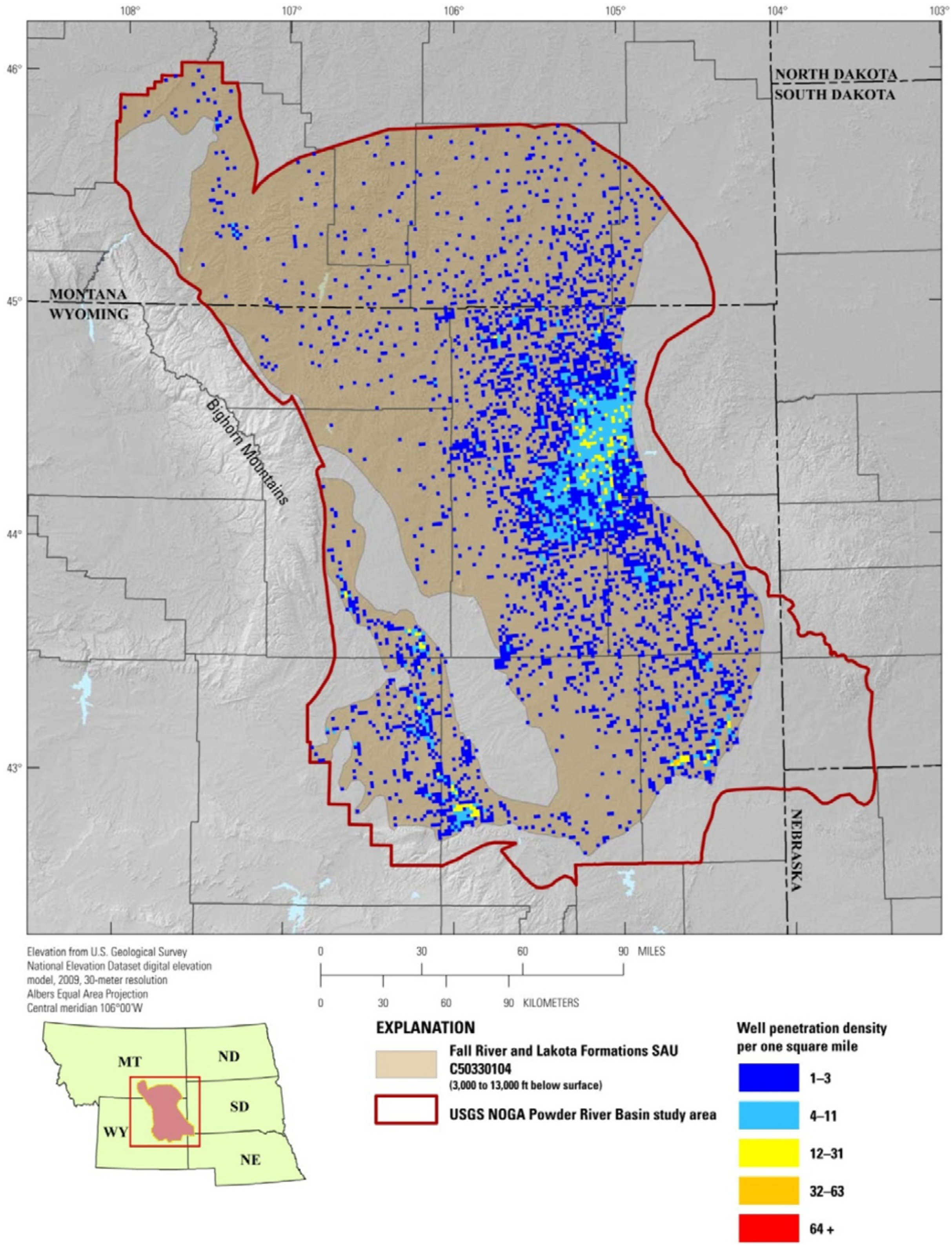

Figure 6. Map of the Fall River and Lakota Formations Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. The area interior to the SAU contains Fall River and (or) Lakota Formations stata that are covered by overburden in excess of 13,000 ft and were not assessed. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir formation top. Powder River Basin study area modified from Anna (2010).

Muddy Sandstone SAU C50330105

By Ronald M. Drake

The Lower Cretaceous Muddy Sandstone, which is equivalent to the Newcastle Sandstone in the eastern part of Powder River Basin, consists of marine and nonmarine sandstone, siltstone, and mudstone (fig. 2). This unit was primarily deposited in an incised fluvial-floodplain setting on the east side of the basin and an estuarine setting on the west side of the basin (Dolson and others, 1991, and references therein; Anna, 2010). The Muddy Sandstone is overlain by Mowry Shale in the western part of the Powder River Basin and Mowry and Belle Fourche Shale in the eastern part of the basin (fig. 2), both of which are hemipelagic deposits, and in aggregate, these formations are hundreds of feet thick and constitute an excellent sealing unit.

The SAU boundary for the Muddy Sandstone is based on the overburden thickness and the regional extent of sand-prone reservoir rock (Davis, 1970) (fig. 7). The overburden contour map was built from a database of borehole penetrations (IHS Energy Group, 2010). The areal extent of porous sand within the SAU was defined from maps of borehole penetrations of the reservoir unit, subsurface stratigraphic correlations, and surface geologic maps (Berg, 1976; Anna, 2010; IHS Energy Group, 2010). Similar to other units, the SAU excludes an area covered by greater than 13,000 ft of overburden in the southern part of the basin.

Subsurface stratigraphic correlations indicate that the average gross thickness of the Muddy Sandstone is approximately 45 ft (Anna, 2010). An analysis of geophysical logs from across the basin indicates the average net thickness of reservoir rock is approximately 25 ft (Anna, 2010).

A proprietary database of petroleum production data was used to characterize the rock properties of the SAU (Nehring Associates, Inc., 2010). A compilation of 47 Muddy Sandstone petroleum-reservoir-averaged porosity measurements from around the basin indicates that average porosity of reservoir-quality sandstone is approximately 15 percent (Nehring Associates, Inc., 2010). Likewise, 42 reservoir-averaged permeability measurements indicate a range from 0.3 mD to more than 1,000 mD, with a modal value that is around 100 mD (Nehring Associates, Inc., 2010; Anna, 2010).

In the Powder River Basin, a compilation of data from TDS measurements in the Muddy Sandstone shows that salinity varies between about 1,000 parts per million (ppm) and 67,000 ppm (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010). The freshest water in the basin is concentrated along the eastern and northeastern sides of the basin, and salinity generally increases with depth, suggesting that there are potential zones of freshwater recharge along the shoulders of the basin where the reservoir interval outcrops. Importantly, formation waters with TDS concentrations as low as 1,143 ppm exist at depths below 13,000 ft, and it appears that pockets of fresh, potable water may exist at any depth in the SAU.

The most significant oil and gas production in the Muddy Sandstone is from stratigraphic traps associated with incised valley-fill deposits in the southeastern portion of the basin (Anna, 2010). In order to estimate the maximum accessible pore volume within stratigraphic and structural traps, we estimated the total closure area across the basin based on the area encompassed by oil fields in the southeastern portion of the basin. We did not attribute undiscovered or uncharged enclosures to areas of known fresh groundwater. We combined this closure area with upper bounds on regional porosity and net reservoir thickness.

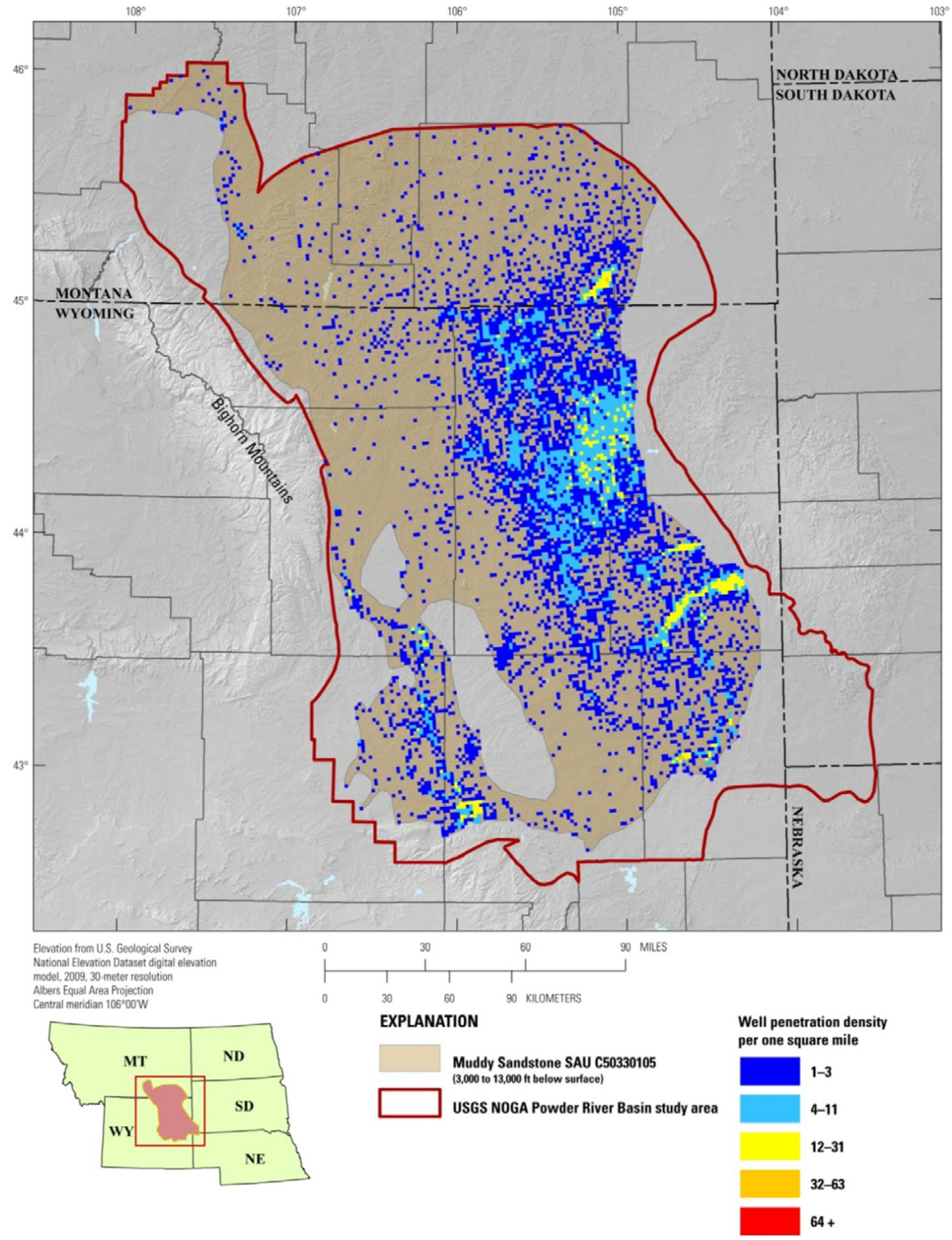

Figure 7. Map of the Muddy Sandstone Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. The area interior to the SAU contains Muddy Sandstone strata that are covered by overburden in excess of 13,000 ft and were not assessed. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir formation top. Powder River Basin study area modified from Anna (2010).

Frontier Sandstone and Turner Sandy Member SAU C50330106

By Matthew D. Merrill

The Upper Cretaceous Frontier Formation (fig. 2) was deposited as an eastward-prograding clastic wedge into the Western Interior Basin during Sevier orogenesis in Cenomanian to Turonian time (Anna, 2010). Nonmarine fluvial deposits of Frontier sandstone in the western part of the basin grade laterally eastward into shallow marine and deltaic deposits. Fluvial sands that were reworked in shallow marine waters in the eastern part of Powder River Basin are locally referred to as the Turner Sandy Member of the Carlile Shale. Both the Frontier and Turner are encased within a package of open-marine shales that includes the Carlile and Pierre Shales in the eastern part of the basin and the Carlile, Niobrara, and Steele Members of the Cody Shale in the western part. The shales are many hundreds of feet thick and laterally continuous (Fox and Higley, 1987d,e). As such, the Frontier Formation is thought to have an excellent seal for CO_2 containment.

SAU boundaries for the Frontier Sandstone and Turner Sandy Member are delineated by the 3,000- and 13,000-ft overburden contours and the spatial extent of Frontier and Turner porous sand deposits (fig. 8). A basin-scale overburden contour map was generated from a proprietary database of borehole penetrations of the Frontier Formation and Turner Sandy Member (IHS Energy Group, 2010). The spatial distribution of porous sandstone was mapped on the basis of recorded formation tops in well penetrations (IHS Energy Group, 2010) and on regional stratigraphic studies (Crews and others, 1976; Weimer and Flexer, 1985). Similar to other units, the SAU excludes an area covered by greater than 13,000 ft of overburden in the southern part of the basin.

The Frontier and Turner contain up to 10 discrete lenticular beds of sandstone, which in aggregate, exhibit a mean thickness of 100 to 150 ft (Weimer and Flexer, 1985). The broader stratigraphic interval, including the surrounding shales, typically ranges in thickness from 700–950 ft (Towse, 1952; Crews and others, 1976).

Using the database described in previous sections, we determined that the mean porosity in the Frontier and Turner falls between 10 and 16 percent, most likely about 12 percent, in the 3,000- to 13,000-ft-depth range (Charoen-Pakdi and Fox, 1989; Nehring Associates, Inc., 2010; Anna, 2010). The sands range from a fraction of 1 mD to 100 mD permeability, though values in the tens of millidarcies are most common (Charoen-Pakdi and Fox, 1989; Nehring Associates, Inc., 2010; Anna, 2010).

A compilation of TDS measurements for the reservoir interval shows that pockets of potable formation waters appear to be interspersed with relatively saline water in the southwestern portion of the basin (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010). We infer that this complexity relates to numerous structural features and possibly freshwater recharge at nearby outcrops (fig. 1). Beyond the southwestern corner of Powder River Basin, groundwater salinity has only been measured at a few sites. The sparse data suggest an eastward increase in groundwater salinity, perhaps because of increasing separation from potential freshwater recharge zones, such that this area may be better suited for CO_2 storage.

We assessed the maximum pore volume that may be accessible for buoyant storage by summing the area of hydrocarbon fields within the basin (Nehring Associates, Inc., 2010) and combining this with upper limits on basin-averaged reservoir thickness and porosity.

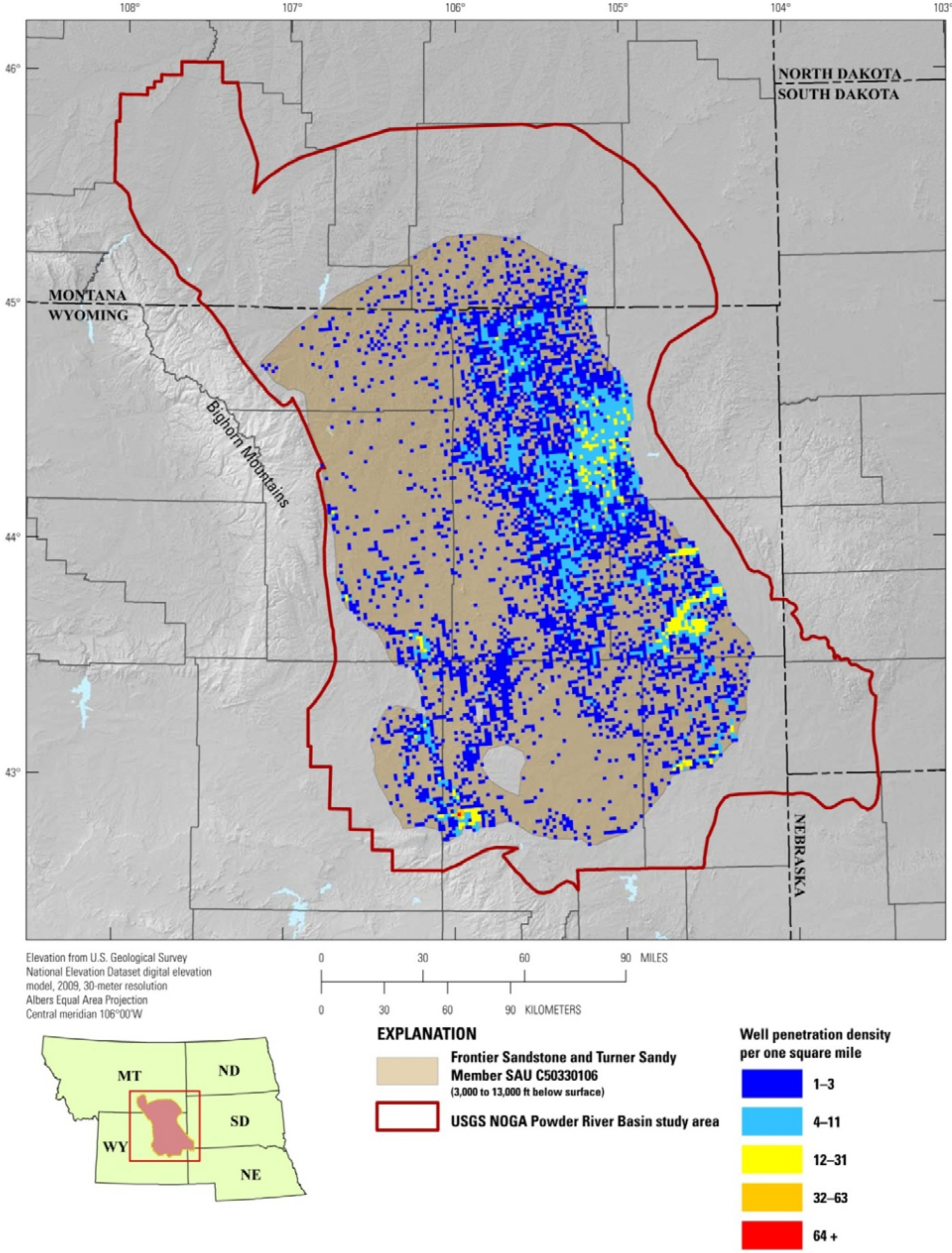

Figure 8. Map of the Frontier Sandstone and Turner Sandy Member Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. The area interior to the SAU contains Frontier Formation and Turner Sandy Member of the Carlile Shale strata that are covered by overburden in excess of 13,000 ft and were not assessed. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir top. Powder River Basin study area modified from Anna (2010).

Sussex and Shannon Sandstone Members SAU C50330107

By Matthew D. Merrill

The Upper Cretaceous Sussex and Shannon Sandstone Members of the Cody Shale (fig. 2) are primarily shoreface and nearshore marine deposits that were linked to a delta complex that developed along the western margin of the Western Interior seaway (Shurr and others, 1988; Higley and others, 1997; Anna, 2010). Sediment was derived from the Sevier highlands to the west, and the delta complex prograded orthogonal to the strike of the basin, in a south–southeast direction (Shurr and others, 1988). Similar to the other Cretaceous sandstones in Powder River Basin, the Sussex and Shannon are encased within hundreds of feet of marine shale. Locally the shale units are referred to as the Steele, Eagle, and Claggett Members of the Cody Shale; these units grade laterally to the east into the massive Pierre Shale (fig. 2). The thickness and lateral continuity of these marine shales suggest that they should constitute excellent regional seals for CO_2 storage.

The Sussex and Shannon Sandstone Members SAU boundaries are defined entirely by the 3,000-ft overburden contour, which was generated from a database of borehole penetrations (IHS Energy Group, 2010) (fig. 9). The SAU is deepest within the Cretaceous depocenter in the south-central portion of the basin, where it reaches a depth of 11,400 ft.

The gross thickness of the SAU was determined using isopach maps generated from a network of subsurface geophysical log correlations (Fox and Higley, 1987f). These correlations reveal that in the Powder River Basin, the Sussex and Shannon consist of several eastward-thinning lobes of sediment, and within the SAU boundaries, the gross thickness averages between 95 and 175 ft. Although the net sand thickness exhibits significant heterogeneity across the basin, the basinwide average is approximately 95 ± 25 ft (Parker, 1958; Crews and others, 1976; Fox, 1986a,b, 1987a–f, 1988a,b; Higley, 1992).

Petroleum production data were used to characterize the porosity and permeability of the SAU (Nehring Associates, Inc., 2010). Porosity is typical of other Cretaceous marine sandstones in the Rocky Mountain region, with an average value of 13 ± 3 percent within the reservoir depth range (Higley, 1992; Anna, 2010; Nehring Associates, Inc., 2010). A combination of 18 petroleum-reservoir-averaged measurements and analysis of 792 core plugs indicates that permeability of the Sussex and Shannon ranges widely, with values from <0.1 mD to 3,000 mD (Higley, 1992; Nehring Associates, Inc., 2010).

Data from TDS measurements for 185 samples from around the basin indicate that the members typically contain saline waters that are not suitable for drinking (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010). However, freshwater zones are prevalent in the eastern and northwestern parts of the basin. We infer that the freshwater accumulations relate to proximate surface outcrops and faults, both of which may facilitate meteoric-water recharge. The deep south-central portion of the basin and the northeastern margin of the assessed area appear to contain pockets of formation waters with TDS in excess of 10,000 ppm.

We assessed the maximum pore volume that may be accessible for buoyant storage by summing the area of hydrocarbon fields within the basin (Nehring Associates, Inc., 2010) and combining this with upper limits on basin-averaged reservoir thickness and porosity.

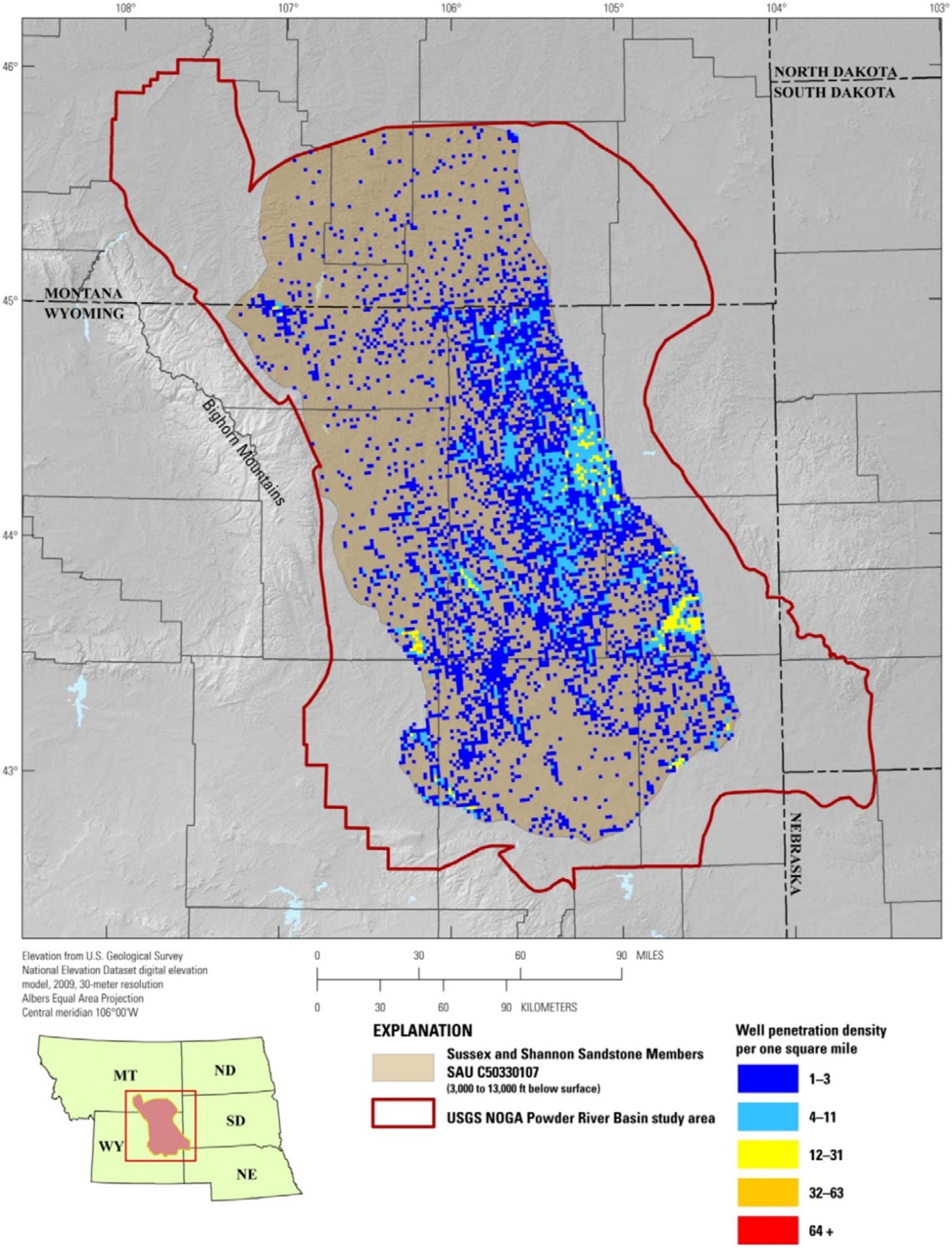

Figure 9. Map of the Sussex and Shannon Sandstone Members Storage Assessment Unit (SAU) boundary in the Powder River study area. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir top. Powder River Basin study area modified from Anna (2010).

Parkman, Teapot, and Teckla Sandstone Members SAUs C50330108, C50330109, and C50330110

By William H. Craddock

The Parkman, Teapot, and Teckla Sandstone Members are within the Upper Cretaceous Mesaverde Formation (fig. 2). The members were deposited during periodic marine regressions in the Western Interior seaway, during which eastward–southeastward prograding packages of coarse-grained sediment derived from the Sevier highlands filled the basin (for example, see McGookey, 1972; DeCelles, 2004). In the Powder River Basin region, these sandstones are generally deltaic, and a range of specific depositional environments is represented, including prodelta, lower shoreface and outer stream mouth bar, upper shoreface and inner stream mouth bar, foreshore, distributary channel, and delta plain (Hubert and others 1972; Rich, 1958; Flores, 2004). Eastward, across Powder River Basin, sandstone packages thin, fine, and interfinger with shales that were deposited in an open marine setting (Fox, 1987a-f; Flores, 2004). Sands pinch out entirely in the eastern and northern parts of the basin. The hemipelagic shales that encase these sandstone members are hundreds of feet thick and laterally continuous and should be excellent seals for CO_2 containment. These shales are referred to as the Cody, Pierre, and Lewis Shales (fig. 2).

SAU boundaries for the units are defined by the 3,000- and 13,000-ft overburden contours, faults, and the sandstone pinch outs in the eastern half of the basin (figs. 10, 11, and 12). Overburden contours were generated at 500-ft intervals using a proprietary database of borehole penetrations (IHS Energy Group, 2010). Due to the fact that the Powder River Basin is a mature and prolific hydrocarbon province, thousands of borehole penetrations distributed across the entire basin were available for each unit, such that the overburden contour maps are well constrained. The location of faults was approximated using the basement structure map for the State of Wyoming (Blackstone, 1989). Sandstone pinch outs were determined using a network of subsurface geophysical log correlations based on 188 well locations (Fox, 1986a,b, 1987a-f, 1988a,b). In general, the western and southern margins of the SAUs are defined by fault truncations, whereas the northern and eastern margins are defined by 3,000-ft overburden contours or stratigraphic pinch outs.

The sandstone members exhibit gradational contacts with underlying shales. They coarsen upward into mud-parted, and eventually amalgamated, inch- to foot-thick sandstone and siltstone beds, with aggregate thicknesses ranging from several tens to hundreds of feet. Gross unit thickness was defined on the basis of gamma ray logs from the aforementioned network of geophysical logs (Fox, 1986a,b, 1987a–f, 1988a,b; Fox and Higley, 1987g–i). The eastward-thinning, fan-shaped sandstones exhibit significant thickness changes across the basin; upper and lower bounds on basinwide average gross formation thickness for the Parkman, Teapot, and Teckla are 250–450 ft, 130–170 ft, and 125–325 ft, respectively. In order to measure the thickness of the net porous interval, gamma ray curves were also used to define sandstone and shale percentages for approximately 60 wells within the geophysical log network (Fox, 1986a,b, 1987a–f, 1988a,b). Sandstone percentages were contoured and combined with the regional isopachs. The resulting net sandstone thicknesses also exhibit a pronounced decrease from west to east across the basin, with feather edges defining the eastern extent of the three SAUs. Averaged across the SAU area, upper and lower bounds on the net porous sandstone thickness for the three sandstone members are 125–225 ft, 65–115 ft, and 70–150 ft, respectively.

The previously described petroleum production database was used to assess the porosity and permeability of the SAUs (Nehring Associates, Inc., 2010). Because the number of petroleum fields within the Mesaverde Formation is limited, fields from other Cretaceous sandstones in Powder River

Basin were integrated into our reservoir quality analysis; reservoir rocks in these fields share similar tectonic settings, depositional environments, sediment sources, and burial histories with the SAUs. Petroleum-reservoir-averaged values for 148 reservoirs in Cretaceous sandstones within the basin were plotted against reservoir depth to generate a sandstone porosity loss curve (for example, see Sclater and Christie, 1980). By comparing the porosity loss curves with our overburden contour maps, we estimated that porosity, averaged across the basin, ranges from 11–19 percent, with a most likely value of 15 percent, for all three units. Petroleum-reservoir-averaged permeability measurements from the same group of Cretaceous oil fields was used to assess the range of permeabilities across the basin (Nehring Associates, Inc., 2010). The probable permeability of prospective reservoirs ranges from 0.05 mD to 1,000 mD with most likely values of a few tens of millidarcies.

Approximately 200 TDS measurements for formation waters within the SAUs show that the formation waters are frequently <10,000 ppm, and therefore potentially potable and not available for subsurface CO_2 storage (Breit, 2002; Department of Energy National Energy Technology Laboratory, 2010; U.S. Geological Survey, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; Wyoming Oil and Gas Conservation Commission, 2010; U.S. Environmental Protection Agency, 2009). However, the deep, south-central part of the basin appears to be characterized by relatively saline formation waters, such that this area may be suited for CO_2 storage.

The maximum pore volume available for buoyant storage was assessed by multiplying the area of structural and (or) stratigraphic enclosure by upper bounds on the basin-averaged net sand thickness and porosity. Oil accumulations within Powder River Basin are often contained within approximately north–south elongate bodies of sandstone in the southern half of the basin. These ribbon-like sandstones are interpreted to be offshore bar deposits, which are encased in shale and are tilted gently westward along the broad eastern limb of the basin. We estimated the areal distribution of these bars on the basis of a dense network of borehole penetrations from the southern portion of the basin, and we speculated that similar traps may exist to the north, along depositional strike, in order to compute a maximum closure area. No uncharged or undiscovered traps were attributed to areas of known fresh groundwater (TDS <10,000 ppm).

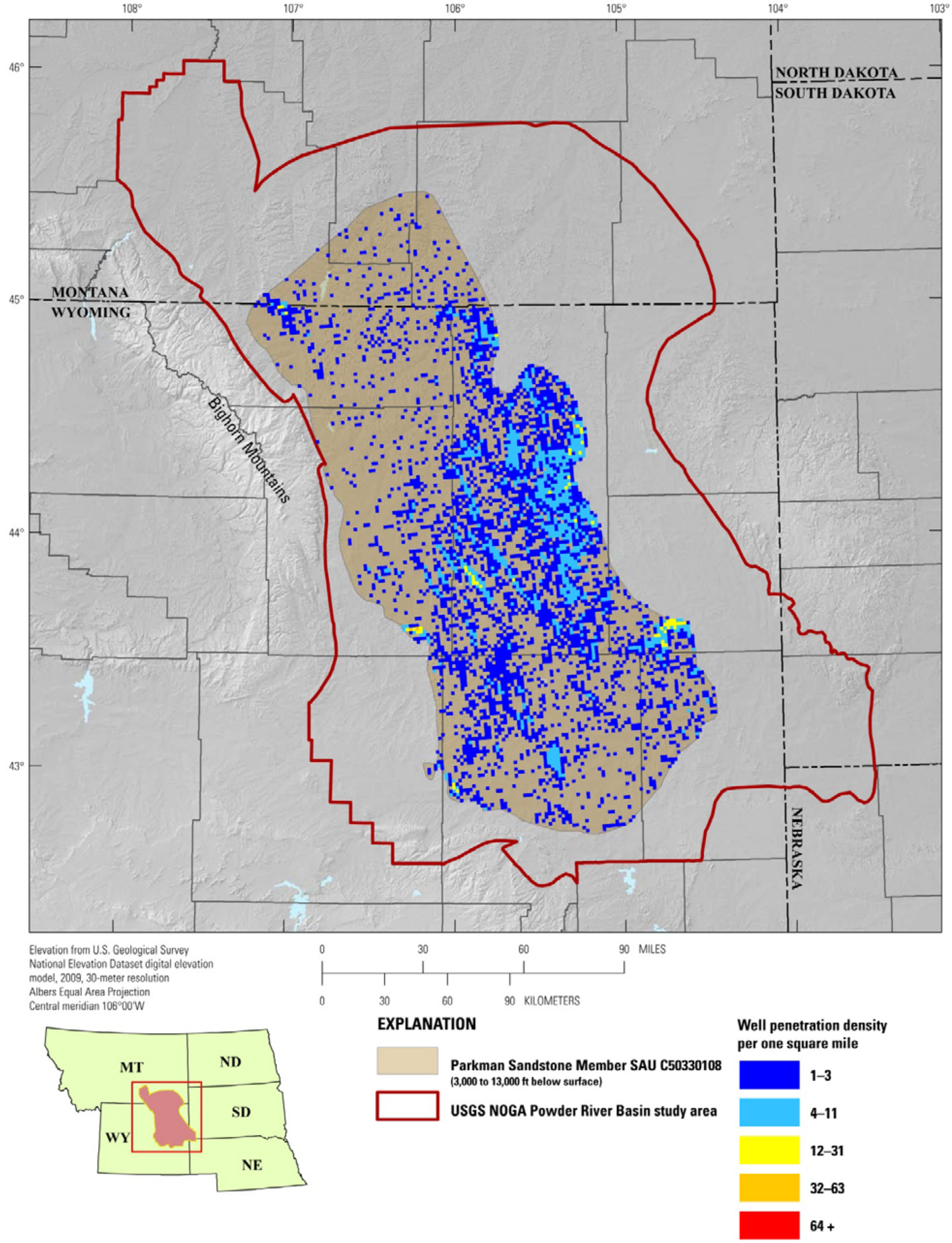

Figure 10. Map of the Parkman Sandstone Member Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir top. Powder River Basin study area is modified from Anna (2010).

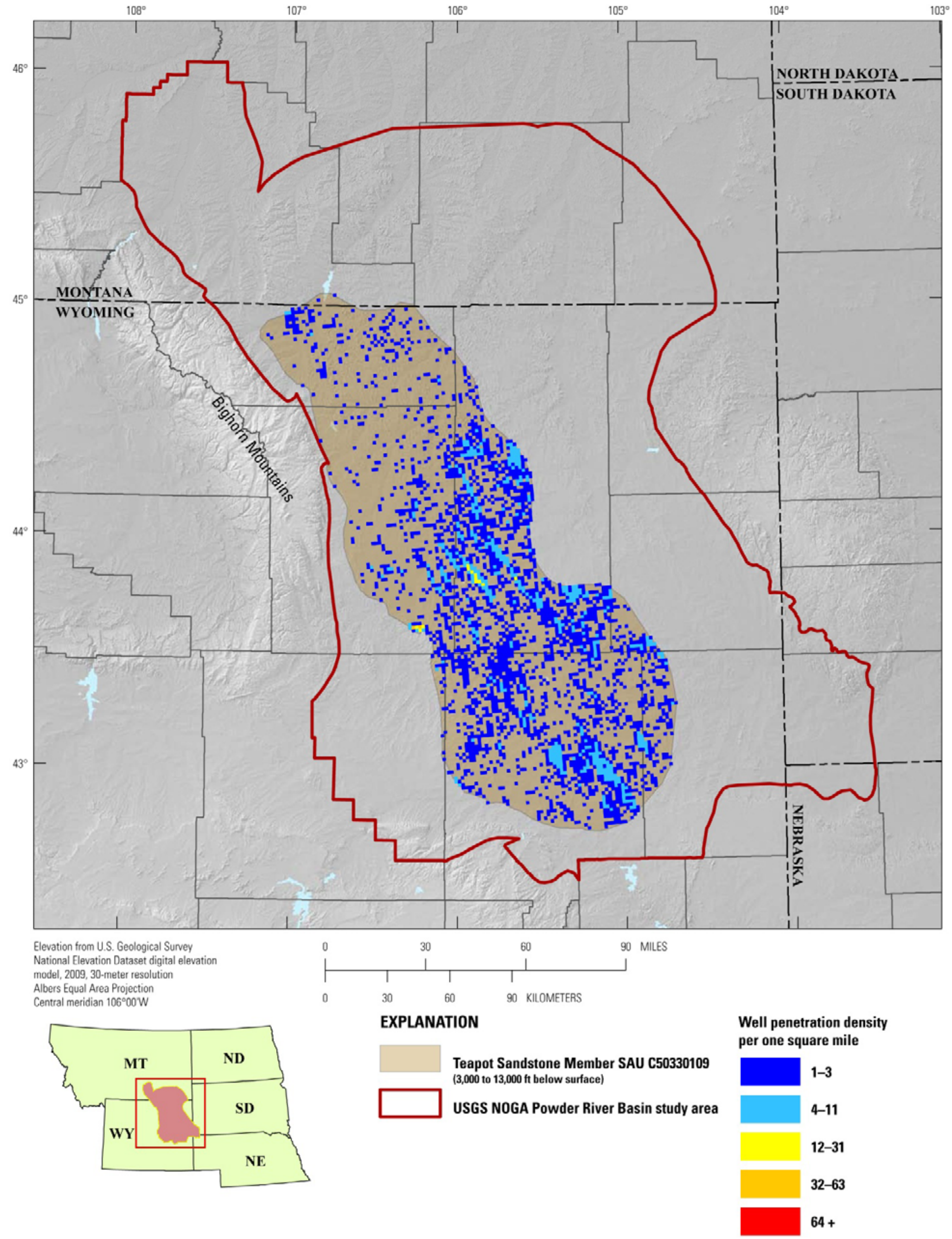

Figure 11. Map of the Teapot Sandstone Member Storage Assessment Unit (SAU) boundary in the Powder River Basin study area. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir top. Powder River Basin study area modified from Anna (2010).

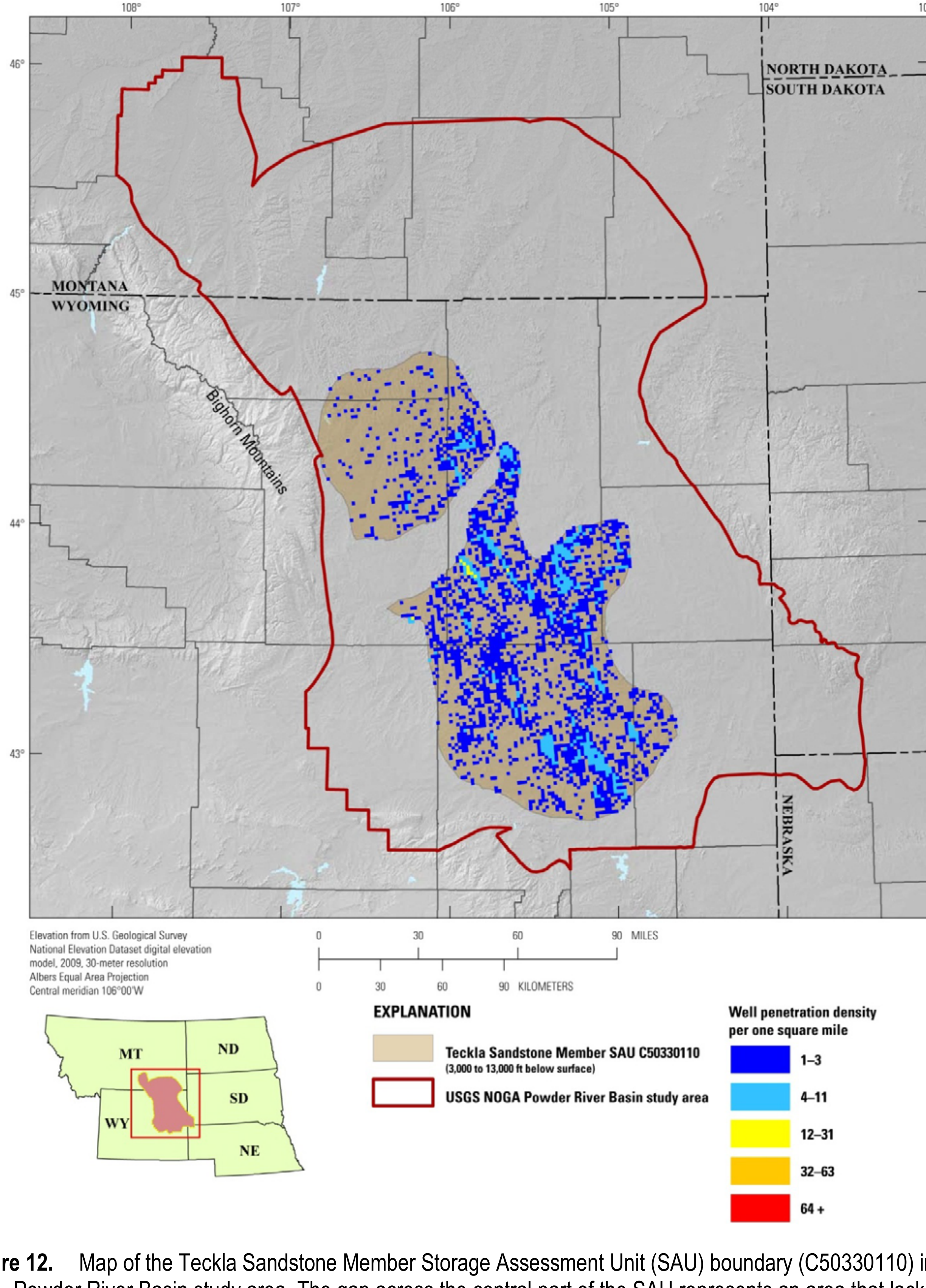

Figure 12. Map of the Teckla Sandstone Member Storage Assessment Unit (SAU) boundary (C50330110) in the Powder River Basin study area. The gap across the central part of the SAU represents an area that lacks reservoir rock. Grid cells (1 square mile) display counts of wells derived from the IHS Energy Group (2011) well database that have penetrated the reservoir formation top. Powder River Basin study area modified from Anna (2010).

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