Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Hanna, Laramie, and Shirley Basins, Wyoming

By Matthew D. Merrill, Jacob A. Covault, William H. Craddock, Ernie R. Slucher, Peter D. Warwick, Madalyn S. Blondes, Mayur A. Gosai, Philip A. Freeman, Steven M. Cahan, and Celeste D. Lohr

Chapter C 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 lower 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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Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Hanna, Laramie, and Shirley Basins, Wyoming

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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 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 rock within the Hanna, Laramie, and Shirley Basins of Wyoming. It focuses on the particular characteristics, specified in the methodology, that influence the potential CO_2 storage resource in those SAUs. Specific descriptions of 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 herein will be employed, as specified in the methodology, 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. Cell maps show the number of penetrating wells within one square mile and are derived from interpretations of incompletely attributed well data in 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 Hanna, Laramie, and Shirley Basins, formed during the Late Cretaceous to Paleocene, are Laramide orogeny structural basins. Bounded by the Laramie Mountains to the east, Rawlins uplift to the west, Medicine Bow Mountains to the south, and the Sweetwater uplift and Wind River Basin to the north, the basins are separated internally by small subbasins and uplifts that were also formed during the Laramide orogeny (fig. 1). These smaller internal structures provide the trapping mechanism for the hydrocarbons that are the target for oil and gas exploration in these basins. Though close in proximity, these basins exhibit dissimilar structural characteristics. The Hanna Basin is a rather small intermontane basin; however, it is notably deep, with depths to basement reaching 40,000 feet (ft), including as much as 15,000 ft of Upper Cretaceous and lower Tertiary rocks (Dyman and Condon, 2007). Shirley Basin, on the other hand, is a very shallow south-dipping syncline with maximum depths to basement of 7,000 ft (Blackstone, 1989). Laramie Basin is the largest of the three basins in surface area and has produced the most hydrocarbons—approximately 63 million barrels of oil (MMBO) and 18 trillion cubic feet of gas

(TCFG) (Nehring Associates, 2010)—much of it along its complex western margin. Depths to basement in the Laramie Basin are intermediate to the two other basins, reaching 10,000 ft in the central-western section of the asymmetrical basin (Blackstone, 1989).

Cambrian through Miocene strata are present in these basins; however, major sediment accumulations in the latest Cretaceous and Paleocene represent the vast majority of the basin thickness (Wroblewski, 2002). Structural evolution, stratigraphy, and hydrocarbon exploration have been discussed in great detail in the geologic literature published on these basins. For a more in-depth summary of the geology of these basins, the reader is referred to the Hanna, Laramie, and Shirley Basins USGS National Oil and Gas Assessment (Dyman and Condon, 2007) and the further detail that is available in the numerous references therein.

Hydrocarbon Exploration

The Hanna, Laramie, and Shirley Basins are not major hydrocarbon producers compared to other Wyoming basins; as of 2008, known recovery plus reserves for oil were ≈70 MMBO, and gas recovery and reserves were ≈40 TCFG in 17 fields (Nehring Associates, 2010). The majority of fields are located in the complex structural highs between the Hanna and Laramie Basins; exploration in Shirley Basin has resulted in no producing fields greater than 0.5 MMBO or 3 TCFG (Dyman and Condon, 2007). These volumes amount to approximately 5 percent and 2.5 percent of the oil production in the nearby Wind River and Bighorn Basins and roughly 0.7 percent and 2 percent of the gas production in these basins. Exploration using surface structures and local seismic surveys has already been employed; current and future exploration is focused on deeper Hanna Basin wells (Dyman and Condon, 2007).

Geologic History

At a general level, the evolution of the Hanna, Laramie, and Shirley Basins can be separated into three stages where the broad depositional environment was either favorable or not favorable for producing regionally extensive reservoir and sealing formations that are targets for CO_2 sequestration. The stages are (1) Cambrian through Mississippian carbonate-rich, highly eroded period; (2) upper Paleozoic and Mesozoic retro-arc foreland deposits and interior seaway units; and (3) uppermost Cretaceous and Paleocene orogenic regime.

The Precambrian Cheyenne belt trends northeastward through the Laramie Basin and represents the collision of the Colorado province Paleoproterozoic arc terrane with the Archean craton of the Wyoming province; some of these structures were later reactivated during the Late Cretaceous Laramide orogeny that produced the Hanna, Laramie, and Shirley Basins (Dyman and Condon, 2007).

Paleozoic strata are present in the Hanna, Laramie, and Shirley Basins, though they are not a major constituent of the sediment package (fig. 2). Eastward transgression of Cambrian seas deposited sands across much of Wyoming including the study area. Ordovician and Silurian seas produced mainly carbonate deposits; however, uplift and subsequent erosion during the Devonian have removed much of these lower Paleozoic rocks. Continued transgressions and regressions occurred in the Mississippian, with later periods of erosion removing much of the older units as well.

The Pennsylvanian-Permian assembly of the supercontinent Pangaea and the associated uplift of the Ancestral Rocky Mountains created the second phase of evolution in this area (Mallory and others, 1972; Dyman and Condon, 2007). A major source located to the west provided sediment to a regional retro-arc foreland basin that persisted until the Laramide orogeny. Shale, chert, and evaporite deposition was common throughout the Permian in the Hanna, Laramie, and Shirley Basins. In the Triassic, restricted marine input resulted in continent-derived clastic deposits of red beds, eolian sands, and evaporites. Marine transgression cycles dominated the Jurassic and Cretaceous, with seas originating first from the north and later the east, forming the Cretaceous Western Interior Seaway (McGookey and others, 1972).

Mountain building due to the Laramide orogeny beginning in the Late Cretaceous changed the major depositional environment in the Hanna, Laramie, and Shirley Basins region for the third time. The regional foreland basin was replaced by numerous structurally complex Laramide basins bounded by Precambrian thrust blocks (Dyman and Condon, 2007). The distinct Hanna, Laramie, and Shirley Basins were formed at this time. The Hanna, Laramie, and Shirley Basins area no longer received sediment on a regional marine transgression and regression scale; the basins were now localized depocenters with source areas in the recently uplifted mountains flanking the basins. The closed drainage systems of these basins led to fluvial- and lacustrine-dominated systems with restricted carbonate formation and increased clastic deposition into and throughout the Tertiary.

Hanna, Laramie, and Shirley Basins Carbon Dioxide Storage Resource Assessment

The major reservoirs and their seals in the storage assessment units (SAUs) in this assessment are in formations deposited during the Pennsylvanian to Late Cretaceous regional-scale retro-arc foreland basin development; however, some reservoir units from pre-Pennsylvanian formations are incorporated into a composite SAU. Storage assessment unit names are based specifically on the reservoir interval considered for sequestration. Often this means a formation name; however, member names or the inclusion of lithology terms are also used in an effort to refer to the specific reservoir interval assessed within a formation. For example, whereas Frontier Formation is the geologic name used in the stratigraphic column in figure 2, the SAU is called Frontier Sandstone, because much of the Frontier Formation is shale and was not considered as part of the assessed reservoir. The reader can refer to the left side of figure 2 for stratigraphic names and the right side for SAU names; the stratigraphic and SAU names may differ because SAU names are specific to the reservoir interval. SAU names, stratigraphic position, and their lithology for CO_2 storage in the Hanna, Laramie, and Shirley Basins, from oldest to youngest, include (1) Paleozoic Composite SAU consisting of carbonates and sandstones, (2) Lower Cretaceous Muddy Sandstone and Cloverly Formation SAU consisting of sandstones, (3) Upper Cretaceous Frontier Sandstone SAU, (4) Upper Cretaceous Shannon Sandstone Member SAU, (5) Upper Cretaceous Mesaverde Formation SAU consisting of sandstones, and (6) Upper Cretaceous Dad Sandstone Member SAU (fig. 2). The geographic extents of storage formations are defined by the geologic characteristics of the reservoirs and their overlying seals; they are restricted to subsurface conditions favoring supercritical phase CO_2 as described in Burruss and others (2009) and Brennan and others (2010). Wyoming groundwater quality, as indicated by total dissolved solids (TDS) content, was assembled from multiple databases in Blondes and Gosai (2011), including data from USGS Produced Waters Database (Breit, 2002), National Water Information System (U.S. Geological Survey, 2010), Wyoming Produced Water Database (Wyoming Oil and Gas Conservation Commission, 2010), Rocky Mountains Produced Water Database (National Energy Technology Laboratory, 2010), and Wyoming EOR Reservoir Database (University of Wyoming Enhanced Oil Recovery Institute, 2010). The following sections describe each of the storage assessment units defined in the Hanna, Laramie, and Shirley Basins.

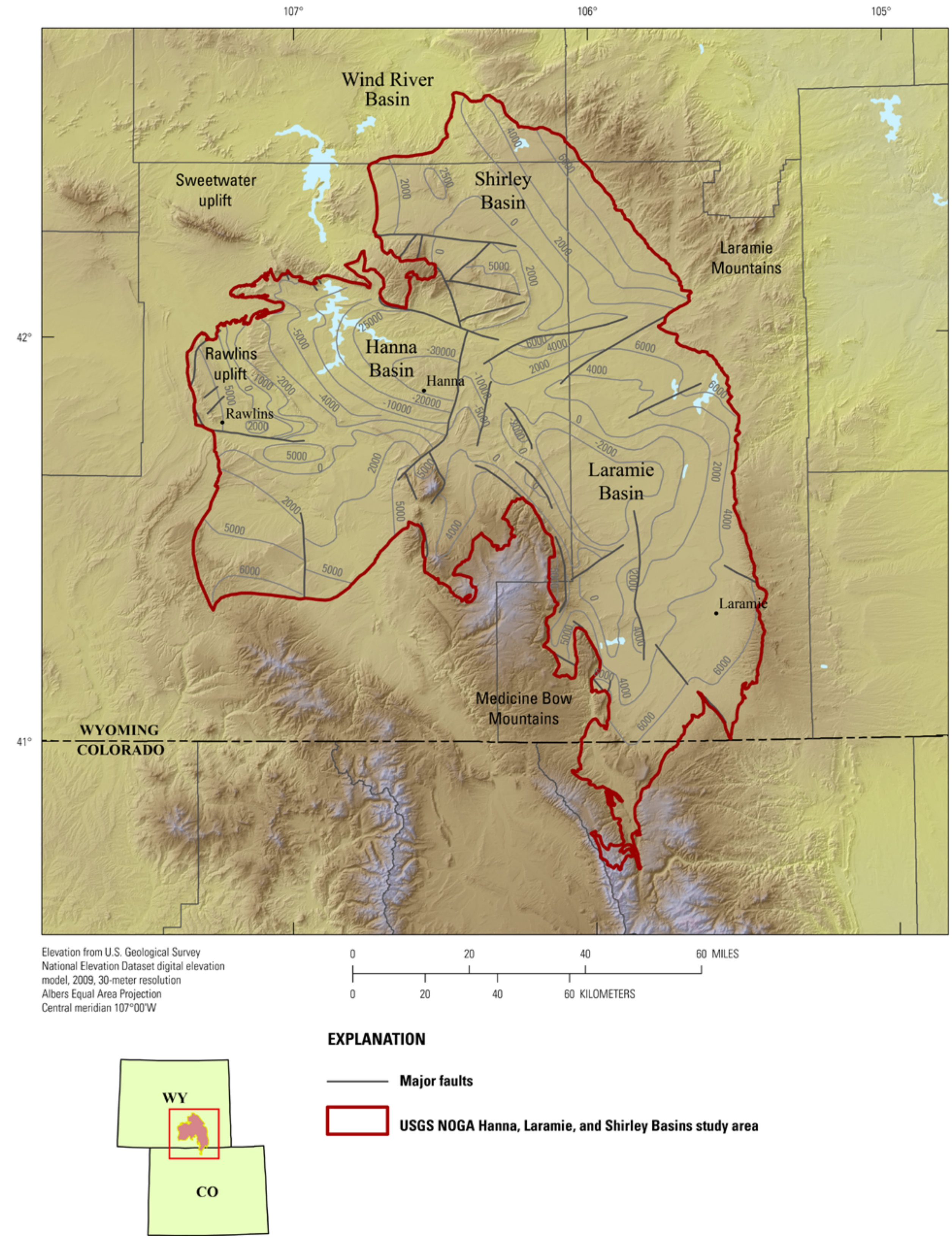

Figure 1. Map showing the Hanna, Laramie, and Shirley Basins, Wyoming, including major structural features and contours on the Precambrian basement (Blackstone, 1989) and basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005). Structure contour in feet.

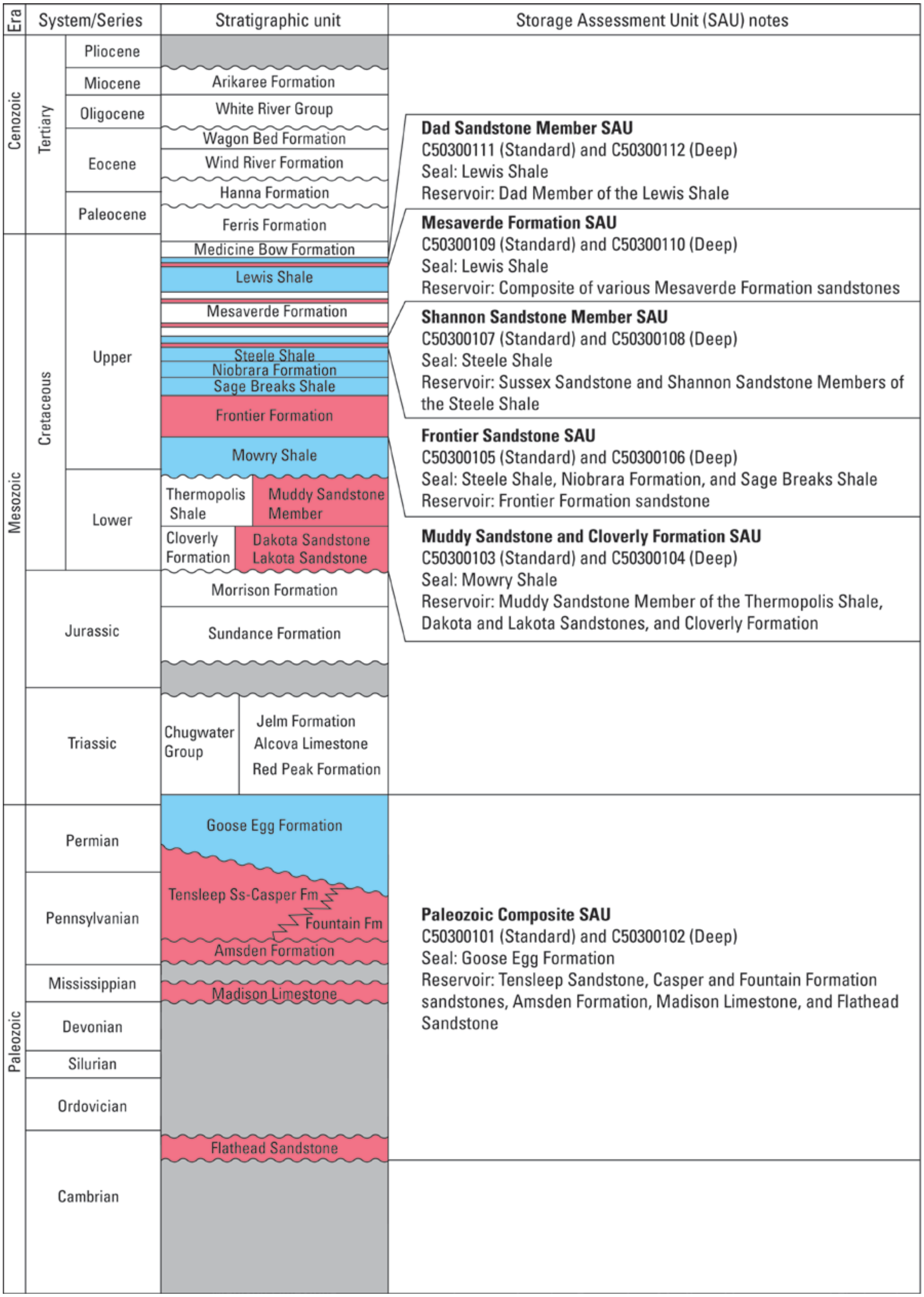

Figure 2. Generalized stratigraphic column of geologic units in Hanna, Laramie, and Shirley Basins, Wyoming (modified from Dyman and Condon, 2007). Storage assessment units consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray sections represent nonpreserved lithology. In some cases, divisions of units are not shown.

Paleozoic Composite SAU C50300101 and Paleozoic Composite Deep SAU C50300102

By Ernie R. Slucher and Peter D. Warwick

The Paleozoic Composite SAU and Paleozoic Composite Deep SAU consist of Cambrian to Permian reservoirs with primarily siliciclastic rocks with some carbonate lithologies. Most rocks in the pre-Pennsylvanian interval are absent or preserved only locally because of the regional paleogeographic setting and eustatic changes occurring during Paleozoic time. Rocks in the SAUs include, in ascending stratigraphic order, the Cambrian Flathead Sandstone (present in most of the Hanna and northwestern Shirley Basins), the Mississippian Madison Limestone (present in most of the Hanna and Shirley Basins and a small portion of northwestern Laramie Basin), and the Pennsylvanian Amsden Formation and Pennsylvanian and Permian Tensleep Sandstone (mainly in the Hanna and Shirley Basins) or their time-equivalents, the Fountain Formation and Casper Formation, respectively (mainly in the Laramie Basin) (fig. 2). Regionally, the Permian and Triassic Goose Egg Formation unconformably overlies the Tensleep or Casper and acts as the regional sealing formation. Berg (1956), Sloss and others (1960), Mitchell (1968), Mallory and others (1972), Hinckley and Heasler (1984), Dyman and Condon (2007), Anna (2010), and Love and Christiansen (2010) were the main references used to spatially define and characterize individual reservoir and seal units in the Paleozoic Composite SAUs.

The Paleozoic Composite SAU boundaries were based on the depth below the surface of the top of the Tensleep or Casper Formations (fig. 3), which are the shallowest reservoirs, and an approximation of the depth to the bottom of the sealing formation. The Paleozoic Composite SAU C50300101 boundary outlines the subsurface extent of the Tensleep Sandstone or Casper Formation between 3,000 and 13,000 ft in depth, and the Paleozoic Composite Deep SAU C50070102 boundary is where the top of the Tensleep or Casper is 13,000 ft or deeper. In addition to employing commercial database tops, the Tensleep or Casper upper surface was projected and delineated from maps of the Cretaceous Cloverly Formation (Mitchell, 1968) and Proterozoic basement (Blackstone, 1989). Gross reservoir thickness of each of the Paleozoic Composite SAUs ranges from 100–1,250 ft, with a median of 600 ft. In most of the Hanna and Shirley Basins, however, the thickness of the SAUs can vary unpredictably because of unconformities and the spatial distribution of rocks preserved in the pre-Pennsylvanian interval. Available Nehring Associates (2010) and analogous Powder River Basin data (Anna, 2010) suggest that the net porous interval for SAU C50300101 ranges between 20–520 ft, with a mode of 300 ft. Likewise, the net porous interval for SAU C50300102 ranges between 100–520 ft; 350 ft is the mode. Most thickness of both SAUs is represented by porous intervals in the Tensleep Sandstone and the Amsden, Fountain, and Casper Formations.

Petroleum production is limited, being primarily in small areas of the Hanna and Laramie Basins, even though exploration has occurred throughout the area (Dyman and Condon, 2007). Consequently, meager porosity and permeability data on units within the SAUs exist, and thus analogs from the Powder River Basin Minnelusa-Tensleep SAU (C50330101) were used, as were values presented by Geldon (2003), Ehrenberg and others (2009), and Thyne and others (2010) for other rock units. These data suggest average porosity values within the SAU range between 6–17 percent porosity with permeability ranging between 0.01–1,570 millidarcies (mD)—the occurrence and proportion of these values are mainly a function of lithology and depth.

Water-quality data (Blondes and Gosai, 2011) for the SAU exist only for areas in the standard SAU (C50330101); TDS within groundwater is both below and above the U.S. Environmental Protection Agency (EPA) underground source of drinking water (USDW) limit of 10,000 parts per million (ppm). Areas identified as being above the 10,000 ppm limit are available for CO_2 storage in the SAU. Water-quality trends in the deeper portions of the Laramie Basin and in similar units in the southwestern Wyoming basins and Wind River Basin assessments suggest that deep areas in the Hanna Basin contain groundwater with TDS values in excess of 10,000 ppm; thus, this water quality was assigned to SAU C50330102, which occurs in the Hanna Basin only. Given available data, approximately 1 percent of the areas of both SAUs was estimated to contain suitable structural or stratigraphic closure for use in the methodology's (Brennan and others, 2010) probabilistic calculation for buoyant trapping.

The attributes described herein will be used in accordance with the USGS Carbon Sequestration Assessment Methodology (Brennan and others, 2010) to calculate the available storage space for CO_2 within the two Paleozoic Composite SAUs for (1) areas occurring between 3,000–13,000 ft in depth and (2) areas greater than 13,000 ft in depth.

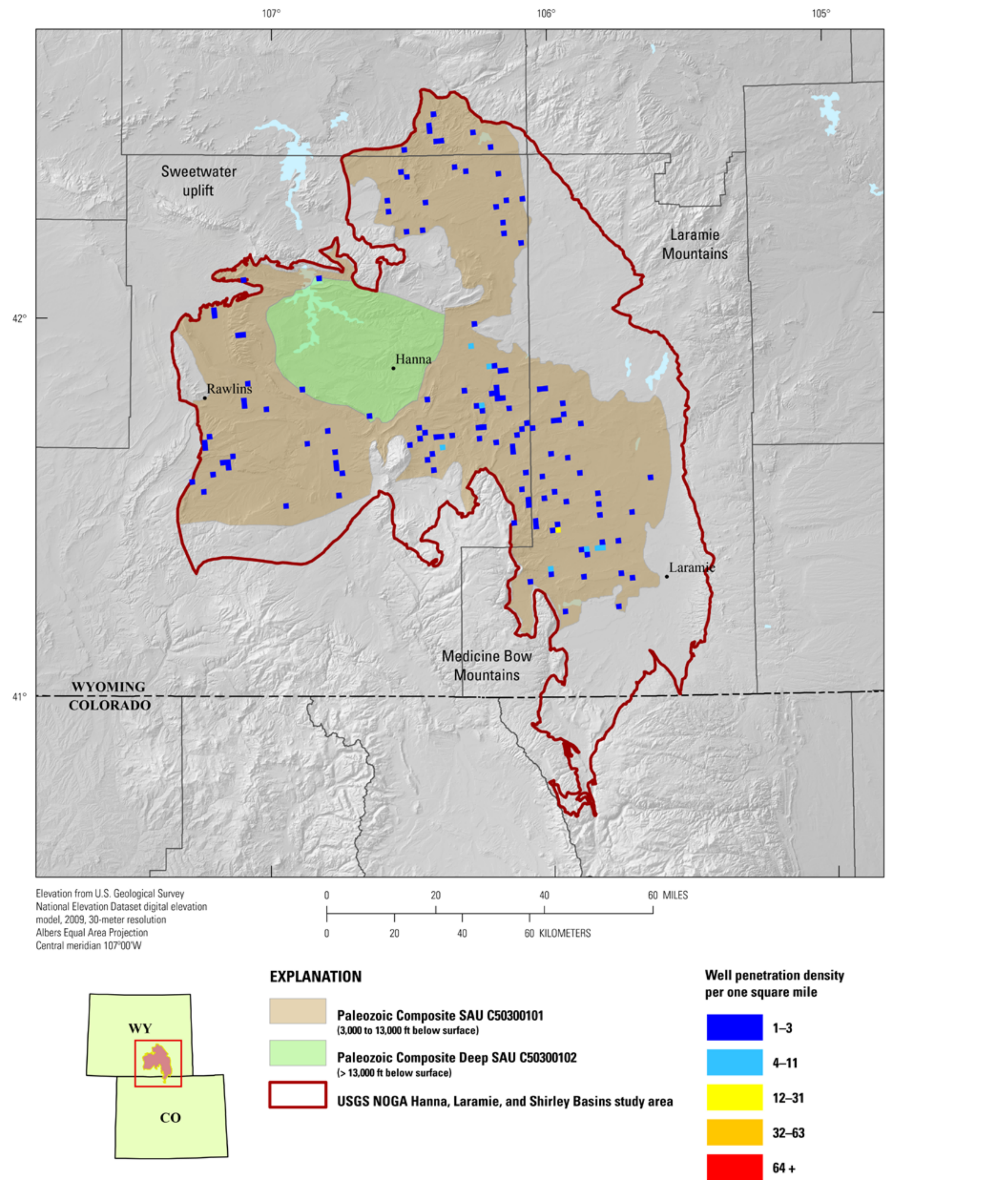

Figure 3. Map showing storage assessment unit (SAU) boundaries for the Paleozoic Composite and Paleozoic Composite Deep SAUs in the Hanna, Laramie, and Shirley Basins, Wyoming. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005).

Muddy Sandstone and Cloverly Formation SAU C50300103 and Muddy Sandstone and Cloverly Formation Deep SAU C50300104

By Jacob A. Covault

The combined Lower Cretaceous Cloverly Formation and Muddy Sandstone Member of the Thermopolis Shale constitute two potential reservoir units for CO_2 storage in the Hanna and Laramie Basins, one above and one below 13,000-ft subsurface depth. The Cloverly Formation comprises siliciclastic sandstone and gravel that thins from ≈231 ft in the Hanna Basin to <100 ft in the southern Laramie Basin (Bowen, 1917; Dobbin and others, 1929; Dyman and Condon, 2007). The Cloverly Formation includes strata equivalent to the Fuson Shale and Dakota and Lakota Sandstones (Stone, 1966; Dyman and Condon, 2007; IHS Energy Group, 2010). The Cloverly Formation unconformably overlies the Upper Jurassic Morrison Formation and progressively fines up-section into the overlying Thermopolis Shale (Dyman and Condon, 2007) (fig. 2). The Thermopolis Shale includes two predominantly fine-grained members, the Skull Creek Shale and Shell Creek Shale Members (Dyman and Condon, 2007), interstratified with coarser grained sandstone of the Muddy Sandstone Member (Eicher, 1960; Dyman and Condon, 2007). The Thermopolis Shale ranges from ≈200 ft thick in the northern Hanna and Laramie Basins to 50 ft thick in the southern Laramie Basin (Mitchell, 1968). The regionally extensive Mowry Shale overlies the Thermopolis Shale and is as much as 200 ft thick in the Hanna and Laramie Basins (Dobbin and others, 1929). The Mowry Shale is interpreted to be a sealing unit for the underlying combined Cloverly Formation and Muddy Sandstone Member potential reservoir units. Well data from IHS Energy Group (2010) indicate a maximum thickness of 455 ft from the base of the Cloverly Formation to the top of the Muddy Sandstone Member. The Cloverly Formation, Thermopolis Shale, and Mowry Shale are interpreted to be regionally extensive in the Hanna and Laramie Basins, whereas the Muddy Sandstone Member of the Thermopolis Shale is locally absent (Stone, 1966; Dyman and Condon, 2007). The relatively coarse-grained Cloverly Formation and Muddy Sandstone Member generally represent continental fluvial and marginal-marine incised valley systems, respectively, that transition up the stratigraphic section to fully marine systems of the fine-grained Skull Creek Shale Member of the Thermopolis Shale and Mowry Shale in the Cretaceous Western Interior foreland basin (Stone, 1966; Cardinal, 1970; Dolson and others, 1991; Dyman and Condon, 2007).

A subsurface-depth contour map of the top of the Muddy Sandstone Member of the Thermopolis Shale was created from Cloverly Formation structure contours of Mitchell (1968) and Rocky Mountain Map Company (1992) and from approximately 400 wells that penetrate the member (IHS Energy Group, 2010). This map provided depth ranges and areal extents of two potential reservoir units: (1) between 3,000- and 13,000-ft (C50300103) and (2) greater than 13,000-ft (C50300104) subsurface depth (fig. 4). The range of total storage formation thickness for reservoir units from the base of the Cloverly Formation to the top of the Muddy Sandstone Member was determined from IHS Energy Group (2010) wells. The thickness of the net porous interval was calculated by subtracting the thickness of the intervening Skull Creek Shale Member of the Thermopolis Shale from the total storage formation thickness and multiplying the remaining thickness by a net-to-gross sandstone ratio of 0.60 measured from maps of Cardinal (1970). Sparse petrophysical data indicate a porosity range of 8–19 percent, with an average porosity of 15 percent for the Cloverly Formation and 16 percent for the Muddy Sandstone Member. Permeability ranges from 0.10 to 138 millidarcies (mD) with an average permeability of 90 mD for the Cloverly Formation and 26 mD for the Muddy (Hollis and Potter, 1984; Dyman and Condon, 2007; Nehring Associates, 2010). Additional Cloverly and Muddy petrophysical data from the entire Rocky Mountain region (380 data points) exhibit a porosity range of ≈5–30 percent and a permeability range of 0.10 to >1,000 mD between 3,000- and 13,000-ft subsurface depth (Nehring Associates, 2010). These analog data were used in order to populate porosity and permeability ranges for the storage assessment unit between 3,000 and 13,000 ft (C50300103). Porosity and permeability values are interpreted to diminish with depth (Ehrenberg and others, 2009). Thus, we reduced the porosity range of the storage assessment unit >13,000-ft subsurface depth (C50300104) by ≈50 percent of the range of the shallower assessment unit (C50300103). These adjustments to petrophysical properties with depth are consistent with empirical data from Cretaceous siliciclastic sandstone reservoirs of the Rocky Mountain region (Nehring Associates, 2010). Maximum buoyant trapping pore volume was calculated from the product of the (1) area of structural reservoir traps mapped from a structure map created by subtracting the surface elevation from the depth-to-top map of the Muddy Sandstone Member, (2) maximum net-porous-interval thickness, and (3) maximum porosity.

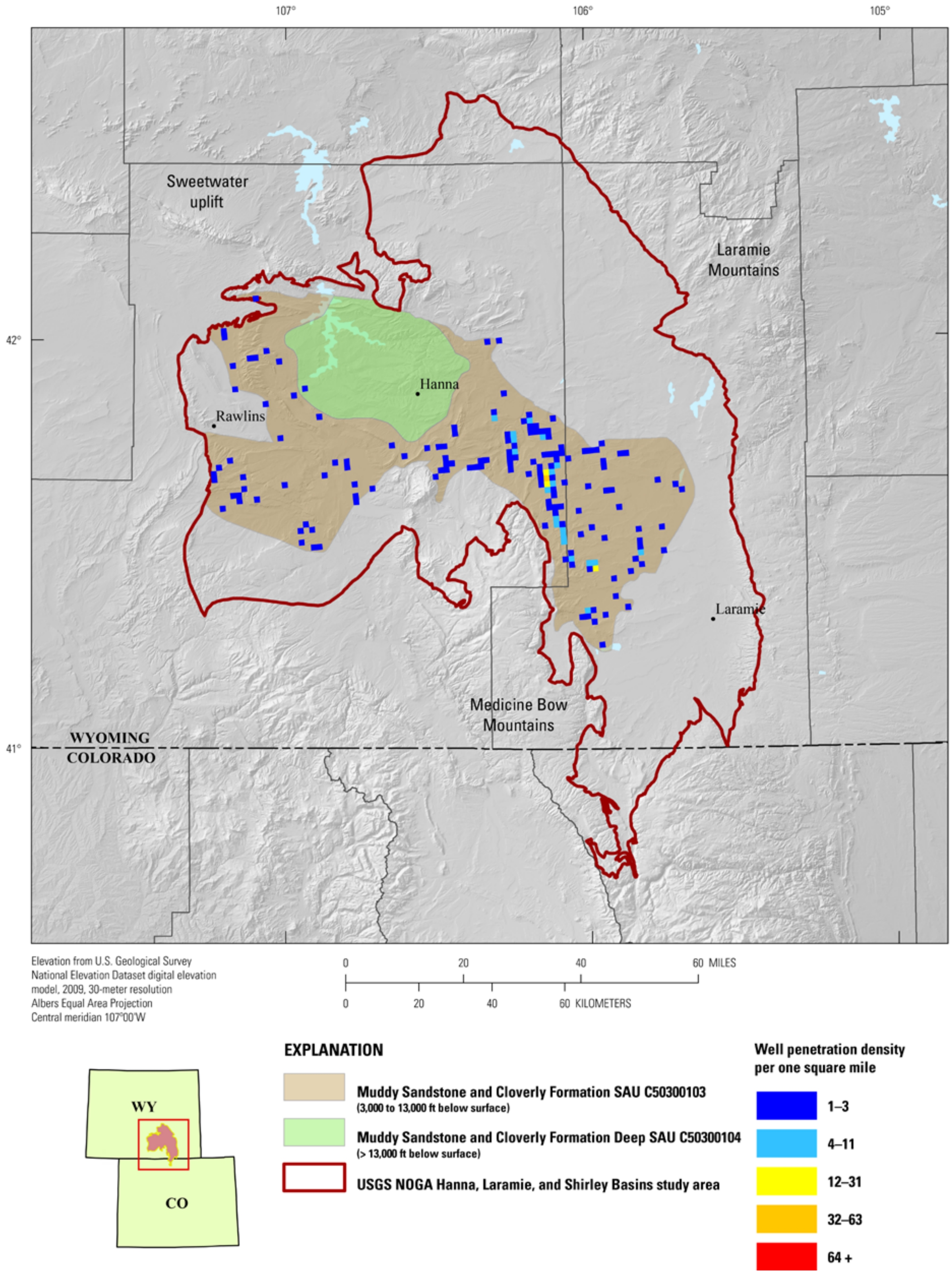

Figure 4. Map showing the storage assessment unit (SAU) boundaries for the Muddy Sandstone and Cloverly Formation and Muddy Sandstone and Cloverly Formation Deep SAUs in the Hanna, Laramie, and Shirley Basins, Wyoming. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005).

Frontier Sandstone SAU C50300105 and Frontier Sandstone Deep SAU C50300106

By Matthew D. Merrill

In the Hanna, Laramie, and Shirley Basins of Wyoming, the sandstone of the Frontier Formation is a Late Cretaceous-age (Cenomanian to Turonian) progradational clastic wedge enclosed between the underlying marine Mowry Shale and the overlying Niobrara Formation and Sage Breaks and Steele Shales (Dyman and Condon, 2007) (fig. 2).

Boundaries for the Frontier Sandstone SAU (C50300105) and Frontier Sandstone Deep SAU (C50300106) are based on the extent of the Frontier Formation at 3,000–13,000 ft depth from surface and greater than 13,000-ft depth from surface respectively (fig. 5). These boundaries were created using interpretations of formation tops in wells from a commercial database (IHS Energy Group, 2010). Structure contour maps of the Cloverly Formation from Mitchell (1968) and Rocky Mountain Map Company (1992), as well as basement structures (Blackstone, 1989), also aided in the creation of the SAU boundaries for the Frontier Formation.

Within the Frontier Sandstone SAU, formation thickness ranges from 550 to 800 ft, with net porous sand thicknesses of 25 ft in the southwestern and far eastern part of the SAU area to 110 ft in the center and northwestern part (Goodell, 1962). Within the Frontier Sandstone Deep SAU, formation thickness ranges from 680 to 725 ft with net porous sand thicknesses of 40–60 ft, with a most likely thickness of 45 ft (Goodell, 1962).

Limited hydrocarbon production from the Frontier, as well as a lack of exploration at depth, has resulted in a paucity of available rock-property information. Field averages for the Rock River field, one of few sources of data, indicate an average porosity of 12 percent (Hollis and Potter, 1984); this averaged value was supplemented with analog data in order to complete the assessment process. Frontier Formation sandstone data collected during the carbon sequestration assessments of the Wind River, Bighorn, and Powder River Basins suggest that reservoir properties such as porosity and permeability may not vary significantly between these basins. Porosity values of 10–25 percent for Frontier sandstone reservoirs at depths between 3,000–13,000 ft were present in all three analog basins, and values of 2–12 percent for Frontier sandstone reservoirs at 13,000 ft and deeper were present or projected. Permeability showed the same consistency, with values ranging from as low as 0.1 mD to around 500 mD; when projected to depths below 13,000 ft, analog basin permeabilities were essentially completely below the 1-mD level.

Water-quality data (Blondes and Gosai, 2011) for the Frontier Formation are limited; however, a majority of samples (8 of 11) collected from available databases suggests that the formation water in the 3,000–13,000 ft deep Frontier Sandstone SAU is greater than the EPA USDW limit of 10,000 ppm TDS. With additional depth, this water quality is expected to persist, if not become more saline.

The boundaries, thicknesses, rock properties, and water-quality information mentioned above will be used in accordance with the USGS CO_2 Sequestration Assessment Methodology (Brennan and others, 2010) to calculate the available storage space within the Frontier Sandstone SAU (C50300105) and Frontier Sandstone Deep SAU (C50300106).

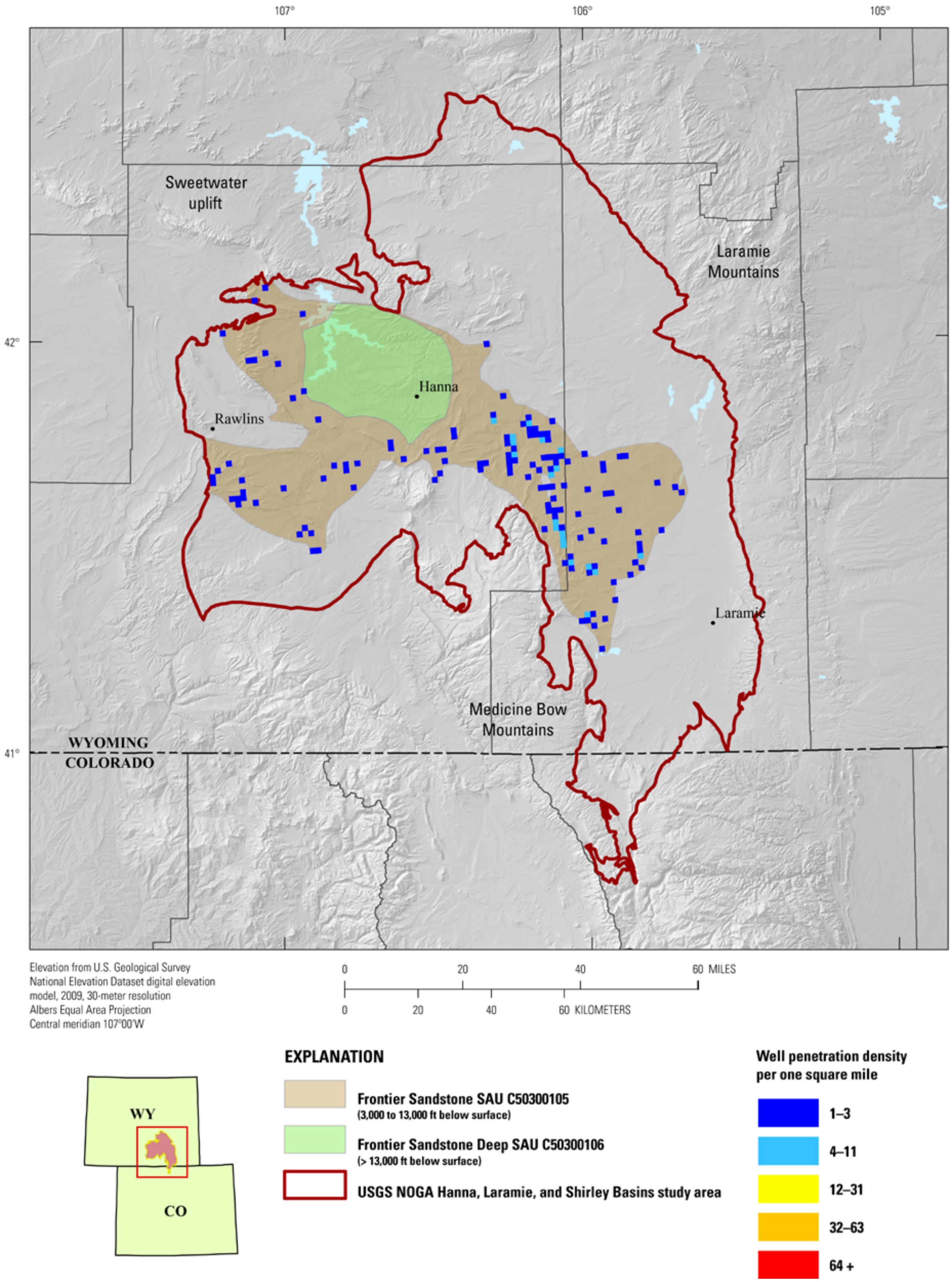

Figure 5. Map showing the storage assessment unit (SAU) boundary for the Frontier Sandstone and Frontier Sandstone Deep SAUs in the Hanna, Laramie, and Shirley Basins, Wyoming and Montana. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (HIS Energy Group, 2011) that have penetrated the reservoir formations top. Basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005).

Shannon Sandstone Member SAU C50300107 and Shannon Sandstone Member Deep SAU C50300108

By Matthew D. Merrill

In the Hanna, Laramie, and Shirley Basins of Wyoming, the Shannon Sandstone and Sussex Sandstone Members of the Steele Shale (fig. 2) were deposited in a shallow-marine to marginal-marine environment along the edge and seaward of a large delta complex (Stone, 1966). Sandstone members like the Shannon and younger Sussex are located toward the top of the Steele Shale; they have 550–1,000 ft of shale in between them, and 300–3,500 ft of Steele Shale overlies the stratigraphically higher Sussex (IHS, 2010).

Boundaries for the Shannon Sandstone Member SAU (C50300107) and Shannon Sandstone Member Deep SAU (C50300108) include both the Shannon Sandstone and the Sussex Sandstone Members. The SAU boundaries are based on the 3,000–13,000 ft subsurface isopach and the greater than 13,000-ft subsurface isopach respectively. Depth contours were created using interpretations of well tops from commercial databases (IHS Energy Group, 2010). Structure contour maps of the Cloverly Formation from Mitchell (1968) and Rocky Mountain Map Company (1992), as well as basement structures (Blackstone, 1989), also aided in the creation of the SAU boundaries (fig. 6).

Within both Shannon Sandstone Member SAUs, formation thickness ranges from 550 to 1,000 ft, with net porous sandstone thicknesses of 50–350 ft observed in nine well logs. These thicknesses are in agreement with net-porous-interval observations from the Wind River and Powder River Basins.

Limited oil and gas production from the Shannon Sandstone Member, as well as a lack of exploration at depth, has resulted in a paucity of available reservoir property information. Analog data from the Steele Shale sandstones in other basins were incorporated here in order to complete the assessment evaluation. Shannon and Sussex Members data collected during the CO_2 sequestration assessments of the Wind River and Powder River Basins suggest that porosity and permeability may not vary significantly between these basins. Analog basins suggest that porosity values of 5–25 percent for Shannon reservoirs at 3,000–13,000 ft depth and values of 3–12 percent for sandstones below 13,000 ft are realistic. Permeability showed similar consistency across basins, with values ranging from as low as 0.5 to about 400 mD in the standard SAU and exhibiting permeabilities less than 1mD in the deep SAU.

Water-quality data (Blondes and Gosai, 2011) for the Steele Shale sandstones are limited. Only two data points are present in the reservoir, and both are outside the SAU. With one sample above the EPA USDW limit of 10,000 ppm TDS and the other below, there are not enough data to attempt to quantify distinct areas of formation-water quality at this time.

The boundaries, thicknesses, rock properties, and water-quality information mentioned above will be used in accordance with the USGS Carbon Sequestration Assessment Methodology (Brennan and others, 2010) to calculate the available storage space within the Shannon Sandstone Member SAU (C50300107) and Shannon Sandstone Member Deep SAU (C50300108).

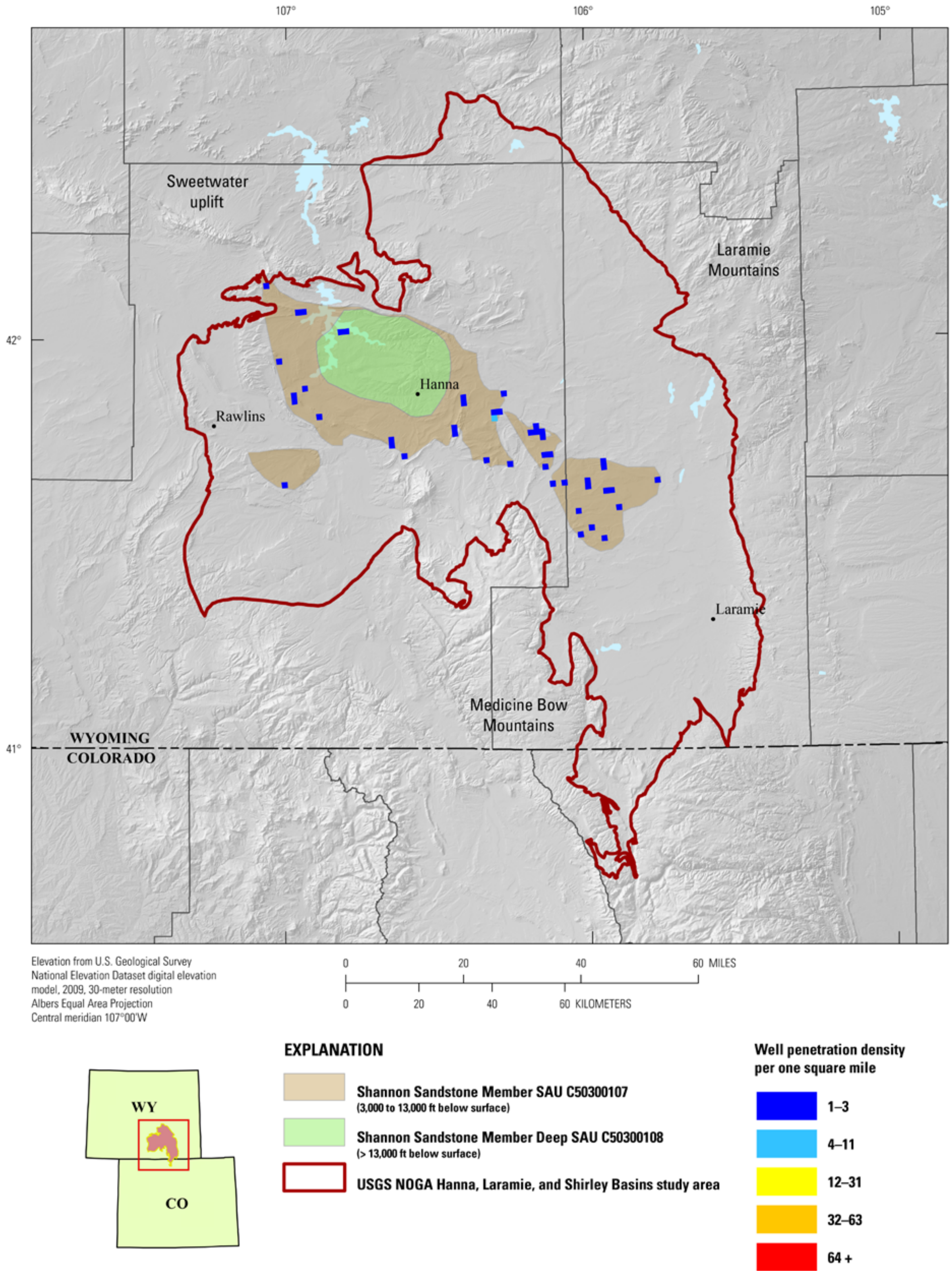

Figure 6. Map showing the storage assessment unit (SAU) boundary for the Shannon Sandstone Member and Shannon Sandstone Member Deep SAUs in the Hanna, Laramie, and Shirley Basins, Wyoming. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005).

Mesaverde Formation SAU C50300109 and Mesaverde Formation Deep SAU C50300110

By William H. Craddock

The Mesaverde Formation (fig. 2) comprises several lobate packages of fine-grained, yellowish-gray sandstone encased within sheet-like beds of black, dark-gray, or brownish-gray marine shale. The sandstones exhibit trough and hummocky cross stratification, and they contain burrows and plant debris. The shales contain marine fossils, including ammonites (Gill and others, 1970; Martinsen and others, 1993). Individual sandstones are inches to feet thick, and successions of sandstone are ≈30–100 ft thick. The mudstone-prone intervals that separate the sandstones are generally thicker than the sand successions.

A range of depositional environments is represented within the Mesaverde sandstones, including prodelta, lower shoreface, distal stream-mouth bar, upper shoreface, proximal stream-mouth bar, foreshore, distributary channel, delta plain, and incised valley fill (Gill and others, 1970; Perman, 1990; Martinsen and others, 1993; Dyman and Condon, 2007). The interfingered shale beds are hemipelagic fallout deposits. The unit was deposited during the latest part of the Cretaceous Period, in the western part of the Cretaceous Western Interior Seaway basin.

Boundaries for the Mesaverde Formation SAUs are defined by 3,000–13,000 ft subsurface contours and faults (fig. 7). One-thousand-foot structural contour maps were constructed using well tops (IHS Energy Group, 2010), a basement contour map (Blackstone, 1989), a structural contour map for Lower Cretaceous strata (Mitchell, 1968), the outcrop pattern of the units, and a seismic reflection profile that extends from north to south across the Hanna Basin (Pritchett, 1985). A map of major faults was constructed by combining structural contour maps of Lower Cretaceous strata and the basement (Mitchell, 1968; Blackstone, 1989). Gross and net thickness maps for the SAU units were constructed from outcrop-based regional stratigraphic correlations (Gill and others, 1970; Martinsen and others, 1993). The gross thickness of the Mesaverde decreases slightly from west to east. At a maximum, the unit is ≈5,000 ft thick, and at a minimum, it is 4,400 ft thick; the median thickness is 4,800 ft. Due to the fact that the Mesaverde Formation Deep SAU is confined to a small area, it exhibits less variability in thickness, ranging from 4,400 to 4,600 ft, with a median thickness of ≈4,500 ft (Gill and others, 1970; Martinsen, and others, 1993). Examination of several measured stratigraphic sections from across the region indicates that the net porous sandstone thickness decreases from west to east, ranging from 1,400 to 450 ft, and has a median value of ≈1,100 ft thick (Martinsen and others, 1993). Within the relatively small Mesaverde Formation Deep SAU, net porous sand thickness ranges from 1,050 to 1,200 ft and exhibits a median value of 1,130 ft.

Due to a paucity of information about the porosity and permeability of the Mesaverde Formation in Hanna, Laramie, and Shirley Basins, analog data from a compilation of Cretaceous rocks in the Rocky Mountain region were used to describe these two properties for the various SAUs (Nehring Associates, 2010). A sandstone compaction curve generated from these data suggests that the shallow Mesaverde is characterized by minimum, mean, and maximum porosity of 5, 15, and 35 percent, respectively. Corresponding values for the Mesaverde Formation Deep SAU are 3, 8, and 15 percent. Permeability data from Rocky Mountain Cretaceous sandstones suggest that the Mesaverde contains a small amount of rock with permeability in excess of 1,000 mD (2 percent), a large amount of rock with permeability between 1–1,000 mD (84 percent), and a small amount of rock with permeability less than 1 mD (14 percent). In contrast, the Mesaverde Formation Deep SAU contains no rock with permeability in excess of 1,000 mD and is entirely composed of rocks with permeability of 1–1,000 mD (50 percent) and less than 1 mD (50 percent).

The Mesaverde is considered to be an aquifer in the Hanna Basin (Bartos and others, 2006), such that the presence of potable water appears to restrict the area available for CO_2 storage. The standard SAU contains a mix of formation waters with TDS above and below 10,000 ppm (Bartos and others, 2006; Blondes and Gosai, 2011). The scarcity of salinity data in these aquifers, however, renders interpretation of the extent of fresh versus saline formation water equivocal. The formation exhibits a weak trend of increasing salinity with depth, such that larger swaths of the deep SAU are more likely to have formation water that is sufficiently saline to host carbon sequestration.

The Mesaverde does not produce oil or gas from within the SAU boundaries; therefore, the pore volume available within structural and stratigraphic traps is difficult to define. In order to estimate the volume that may be available for buoyant CO_2 storage, we combined upper bounds on trap size, number of traps, net sandstone thickness, and porosity. Upper bounds on trap size were based on comparison to reservoirs in the Mesaverde Formation in neighboring Powder River Basin (Nehring Associates, 2010).

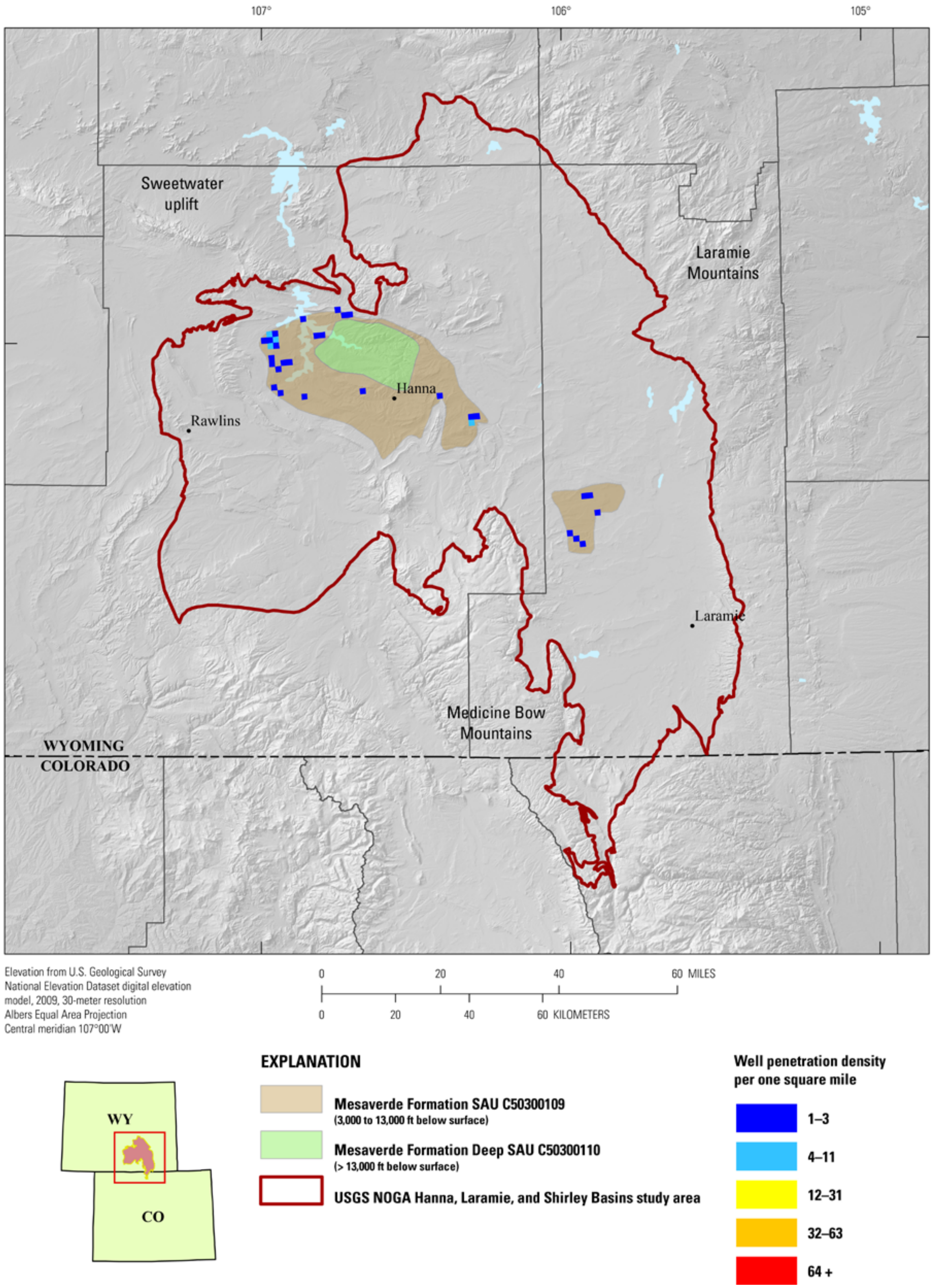

Figure 7. Map showing the storage assessment unit (SAU) boundary for the Mesaverde Formation and Mesaverde Formation Deep SAUs in the Hanna, Laramie, and Shirley Basins, Wyoming. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005).

Dad Sandstone Member SAU C50300111 and Dad Sandstone Member SAU Deep C50300112

By William H. Craddock

The Dad Member is part of the Lewis Shale (fig. 2). It is an approximately 500-ft-thick succession of light-yellowish-gray, very fine to fine-grained sandstone beds encased within, and interfingered with, a thick package of gray shale. The thickness of individual beds is similar to the underlying Mesaverde with beds on the order of inches to feet in thickness. The sandstones exhibit ripple lamination, trough and hummocky cross stratification, shale rip-ups, and contorted bedding. The unit contains marine fossils such as *Ophiomorpha* and mollusks (Gill and others, 1970).

A range of depositional environments is represented in the Dad Member, including lower and upper shoreface, foreshore, and lagoon (Gill and others, 1970; Perman, 1990; Dyman and Condon, 2007). The unit was deposited during the latest part of the Cretaceous Period in the western part of the Cretaceous Western Interior Seaway basin.

Storage assessment unit (SAU) boundaries for the unit are defined by the 3,000–13,000 ft depth from subsurface isopach contours and faults (fig. 8). One-thousand-foot structural contour maps were constructed using well tops (IHS Energy Group, 2010), a basement contour map (Blackstone, 1989), a structural contour map for Lower Cretaceous strata (Mitchell, 1968), the outcrop pattern of the units, and a seismic reflection profile that extends from north to south across Hanna Basin (Pritchett, 1985). A map of major faults was constructed by combining structural contour maps of Lower Cretaceous strata and the basement (Mitchell, 1968; Blackstone, 1989). Gross and net thickness maps for the unit were constructed from outcrop-based regional stratigraphic correlations (Gill and others, 1970). The Dad Member ranges in thickness from 440–650 ft with a median thickness of ≈500 ft. Due to the fact that the Dad Sandstone Member Deep SAU covers only a small portion of the basin, the range of thickness is relatively narrow, ranging from 440–580 ft, with a median thickness of ≈520 ft. Net sandstone thickness was determined by examining measured stratigraphic sections and reducing gross thickness by the regional trend of net sandstone to gross sandstone ratio. The standard SAU exhibits net porous sand thicknesses of 220–320 ft with a median thickness of 250 ft, and the Dad Sandstone Member Deep SAU exhibits net porous sandstone thickness of 220–280 ft with a median thickness of 250 ft.

Due to a paucity of information about the porosity and permeability of the Dad Member in Hanna, Laramie, and Shirley Basins, analog data from a compilation of Cretaceous rocks in the Rocky Mountain region were used to describe these properties for the SAUs (Nehring Associates, 2010). A sandstone compaction curve generated from these data suggests that the standard SAU is characterized by minimum, mean, and maximum porosity of 5 percent, 15 percent, and 35 percent, and corresponding values for the deep SAU are 3 percent, 8 percent, and 15 percent. Permeability data from Rocky Mountain Cretaceous sandstones suggest that a small amount of the Dad sandstone has permeability in excess of 1,000 mD (2 percent), a large amount has permeability between 1–1,000 mD (84 percent), and a small amount has permeability less than 1 mD (14 percent). In contrast, the deep SAU contains no rock with permeability in excess of 1,000 mD and is entirely composed of sandstone with permeability of 1–1,000 mD (50 percent) and less than 1 mD (50 percent).

The Lewis Shale is considered to be an aquifer in the Hanna Basin (Bartos and others, 2006), such that the presence of potable water appears to restrict the area available for CO_2 storage. The shallow SAU contains a mix of formation waters with TDS above and below 10,000 ppm (Bartos and others, 2006; Blondes and Gosai, 2011). The scarcity of salinity data from the aquifer, however, renders interpretation of the extent of fresh versus saline formation water equivocal. The formation exhibits a weak trend of increasing salinity with depth, such that larger swaths of the deep SAU are more likely to have formation water that is sufficiently saline for carbon sequestration.

The Dad Sandstone Member does not produce oil or gas from within the SAU boundaries, and the pore volume within structural and stratigraphic traps is difficult to define. In order to place upper bounds on the enclosed pore volume within the SAUs, we adapted the method described for the Mesaverde Formation to the Dad Sandstone Member.

The attributes described herein will be used in accordance with the USGS Carbon Sequestration Assessment Methodology (Brennan and others, 2010) to calculate the available storage space for CO_2 within the Dad Sandstone Member SAU for areas occurring between 3,000–13,000 ft in depth and areas greater than 13,000 ft in depth.

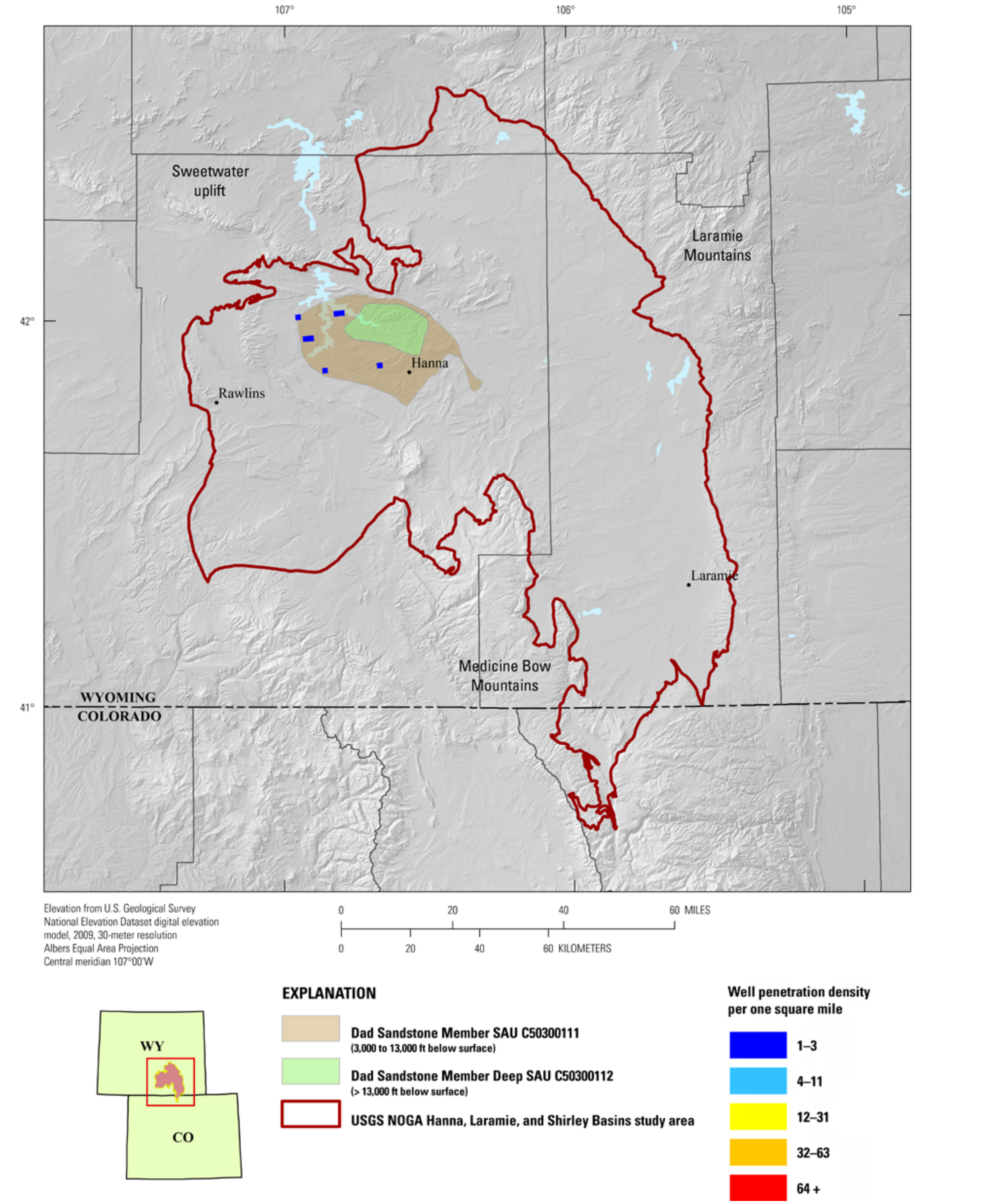

Figure 8. Map showing the storage assessment unit (SAU) boundary for the Dad Sandstone Member and Dad Sandstone Member Deep SAUs in the Hanna, Laramie, and Shirley Basins, Wyoming. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formation top. Basin boundaries modified from the U.S. Geological Survey (USGS) national oil and gas assessment (NOGA) (Dyman and others, 2005).

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