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Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Greater Green River Basin, Wyoming, Colorado, and Utah, and Wyoming-Idaho-Utah Thrust Belt

By Marc L. Buursink, Ernie R. Slucher, Sean T. Brennan, Colin A. Doolan, Ronald M. Drake II, Matthew D. Merrill, Peter D. Warwick, Madalyn S. Blondes, Philip A. Freeman, Steven M. Cahan, Christina A. DeVera, and Celeste D. Lohr

Chapter E 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 and Abbreviations

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)

Initialisms and Abbreviations

CO_2	carbon dioxide
GGRB	Greater Green River Basin
MMBO	million barrels of oil
NOGA	national oil and gas assessment
OFR	open-file report
ppm	parts per million
SAU	storage assessment unit
TCFG	trillion cubic feet of gas
TDS	total dissolved solids
USDW	underground sources of drinking water
USGS	U.S. Geological Survey
WIUTB	Wyoming-Idaho-Utah Thrust Belt

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Report Overview

This two-part open-file report (OFR) contains the geologic framework for two adjacent study areas, the Greater Green River Basin (GGRB) and the Wyoming-Idaho-Utah Thrust Belt (WIUTB), which offer significant potential for carbon dioxide sequestration. Although these study areas are contiguous, they differ in size and structural complexity. The GGRB is larger in size (about 23,000 square miles and five subbasins), whereas the WIUTB is more structurally complex (about 15,000 square miles and four thrust systems). Nevertheless, the study areas have nearly identical geologic units, and consequently, nearly similar storage assessment units (SAUs) were assessed in each basin separated by a thrust system. The study areas overlap because this thrust systems dips west thereby offsetting SAU boundaries at depth. Differences in the SAUs arise due to changing nomenclature for the stratigraphic units across the basin and due to the structural complexity of the WIUTB. Because of their similar assessments, these contiguous study areas were included in a combined geologic framework OFR. As in the previous OFR chapters of the National Assessment of Carbon Dioxide Storage Resources, assessment geologists describe their assessment work for unique SAUs, though in this OFR a separate introduction is provided for each of the two study areas.

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 by the USGS for the national CO_2 assessment follows up on previous USGS work. The methodology is non-economic and intended to be used at regional to subbasinal scales.

This report identifies and contains geologic descriptions of 14 storage assessment units (SAUs) in Ordovician to Upper Cretaceous sedimentary rocks within the Greater Green River Basin (GGRB) of Wyoming, Colorado, and Utah, and eight SAUs in Ordovician to Upper Cretaceous sedimentary rocks within the Wyoming-Idaho-Utah Thrust Belt (WIUTB). The GGRB and WIUTB are contiguous with nearly identical geologic units; however, the GGRB is larger in size, whereas the WIUTB is more structurally complex. This report focuses on the characteristics, specified in the methodology, that influence the potential CO_2 storage resource in the SAUs. Specific descriptions of the SAU boundaries, as well as their sealing and reservoir units, are included. Properties for each SAU, such as depth to top, gross

thickness, porosity, permeability, groundwater quality, and structural reservoir traps, are typically provided to illustrate geologic factors critical to the assessment. This geologic information was employed, as specified in the USGS methodology, to calculate a probabilistic distribution of potential storage resources in each SAU.

Figures in this report show SAU boundaries and cell maps of well penetrations through sealing units into the top of the storage formations. The cell maps show the number of penetrating wells within one square mile and are derived from interpretations of variably attributed well data and a digital compilation that is known not to include all drilling.

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Introduction—Greater Green River Basin

Basin Physiography

The Greater Green River Basin (GGRB) study area consists of five sedimentary subbasins and covers portions of southwestern Wyoming, northwestern Colorado, and northeastern Utah (fig. 1). The GGRB encompasses about 23,000 square miles and is about 310 miles long from northwest to southeast and 220 miles wide from southwest to northeast (Law, 1996). Interstate 80 transects the basin in an east-west direction and passes through centrally located Rocks Springs, Wyoming, the largest town in the region; the Green River and its tributaries drain the area. The GGRB is bounded by the Wind River Range and Granite Mountains on the north, by the Rawlins uplift, Sierra Madre, and Park Range on the east, by the Axial Basin uplift and Uinta Mountains on the south, and by the Wyoming-Idaho-Utah thrust belt on the west (Rocky Mountain Association of Geologists, 1972; Roehler, 1992; Johnson, 2005). Precambrian age rocks are found at altitudes of more than 13,000 ft in the uplifts bounding the basin, whereas tops of Precambrian age rocks may be found as deep as 20,000 ft below sea level in the basin subsurface (Blackstone, 1993; Love and Christianson, 2010). The thickness of Phanerozoic age rocks commonly exceeds almost 4 miles (mi), whereas locally these may exceed 6 mi in thickness (Ryder, 1988; IHS Energy Group, 2010).

The GGRB includes multiple subbasins and intrabasin uplifts including the Rock Springs uplift, which dominates the central part of the basin due to its topography (fig. 1). In addition, major intrabasin anticlines within the GGRB include (1) the northwest-trending Wamsutter arch in the east-central part, (2) the Cherokee ridge paralleling the Wyoming-Colorado State line, (3) the northwest-trending Pinedale anticline in the northwestern part, and (4) the north-trending Moxa arch with the La Barge platform thrust-faulted on its north end in the western part. The GGRB subbasins include (1) the north-trending Great Divide Basin in the northeastern, (2) the northeast-trending Washakie Basin in the east-central part, (3) the west-trending Sand Wash Basin in the southeastern part, (4) the north-trending Green River Basin proper in the west-central part, and (5) the Hoback Basin in the northwestern part. For additional details on GGRB geology, the reader is referred to the recent National Oil and Gas Assessment (NOGA) report for the study area (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005), and also to Miller and others (1992), and information available in the numerous references and maps therein.

Geologic History

The GGRB area was positioned between the North American craton to the east and an open Cordilleran sea to the west during the Paleozoic and early part of the Mesozoic Eras (DeCelles, 2004). Throughout these eras, multiple eustatic changes in sea level generated various depositional environments, which resulted in heterogeneous sedimentary deposits (Johnson, 2005) (fig. 2). These deposits include marine carbonate shelves (Mississippian Madison Limestone, for example), broad alluvial plains (in the Triassic Chugwater Group, for example), and regional dune fields (Upper Triassic to Lower Jurassic Nugget Sandstone, for example). A major uplift of the western North American craton during the Early Cretaceous produced a regional foreland basin between Cordilleran highlands on the west and the Cretaceous Western Interior Seaway on the east (Johnson, 2005). The GGRB area occupied part of this foreland basin from the Early Cretaceous to the late Paleocene. Again, throughout this time, multiple eustatic changes in sea level generated various depositional environments. The resulting sedimentary settings included marine basins (Lower Cretaceous Thermopolis Shale, for example), coastal plains (Upper Cretaceous Mesaverde Group, for example), and alluvial plains (Tertiary Fort Union Formation, for example).

Multiple uplifts and structural depressions throughout the central Rocky Mountains were generated by the Laramide orogeny, which progressed eastward during the Late Cretaceous to middle Eocene (Roehler, 1992). Laramide tectonism started with compressional deformation resulting in, for example, the complex Wyoming-Idaho-Utah Thrust Belt located west of the GGRB. Subsequently, the GGRB began to form during the early Tertiary and was completed by the middle Eocene. Therefore, post-Laramide sedimentary strata reflect GGRB deposition. However, evidence of pre-Laramide deformation exists in the region when most GGRB substructures were generated (Johnson, 2005). For additional details on GGRB geologic history, the reader is referred to Ryder (1988), Law and others (1989), Roehler (1992), Snoke and others (1993), Law (1996), and Lawton (2008).

Hydrocarbon Production and Exploration

Hydrocarbons have been produced from the GGRB since the significant discovery of the 1916 Lost Soldier field (Law, 1996). GGRB hydrocarbon fields are mainly located in and adjacent to the Rawlins uplift, the Axial Basin uplift, and the Moxa arch within the La Barge platform trend (fig. 1). Productive GGRB reservoirs, which range from Cambrian through Tertiary age, are dominantly sandstone strata, whereas carbonate reservoirs have minor production. Fields are located in both stratigraphic and structural traps associated with anticlines that developed during the Laramide orogeny (Broadhead and others, 1993; Nehring Associates, 2010; IHS Energy Group, 2011). In summary, over 60 oil and gas fields have production from 1 or more of nearly 20 Cretaceous or older units (Johnson, 2005). More than 100 fields greater than 1 million barrels of oil (MMBO) equivalent in size have been discovered, with cumulative production through end of 1991 reaching about 849 MMBO and 7.3 trillion cubic feet of gas (TCFG) (Law, 1996). In addition, the U.S. Geological Survey (USGS) Southwestern Wyoming Province Assessment Team (2005) estimated a mean of 84.6 TCFG, a mean of 131 MMBO, and a mean of 2.6 billion barrels of total natural gas liquids remaining as undiscovered technically recoverable conventional and continuous resources in nine total petroleum systems (mappable entities encompassing genetically related petroleum).

Storage Resource Assessment

The USGS regional CO_2 storage resource assessment of the GGRB resulted in 14 SAUs. Each SAU is described in the following sections and includes a storage formation and regional seal pair. The SAU name is typically based on the whole stratigraphic interval or lithology considered for storage (fig. 2). The geographic extents of the SAUs are defined by the depth to the top of the storage formation and by the geologic characteristics of the reservoir and overlying seal. Geologic characteristics described or considered for each SAU include both the seal and reservoir thickness, distribution, and the reservoir quality (such as net-to-gross ratio, porosity, and permeability). Furthermore, we identify regional trends in groundwater quality because the U.S. Environmental Protection Agency (2009; 2010) stipulates that underground sources of drinking water (USDW) with a total dissolved solids (TDS) concentration less than 10,000 mg/L (parts per million) may not be used for CO_2 storage. For the GGRB assessment, groundwater quality, based on TDS content, was compiled for Wyoming from multiple databases (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; Blondes and Gosai, 2011).

This assessment was conducted following the methodology of Burruss and others (2009), Brennan and others (2010), and Blondes and others (2013) that prescribes the geologic model employed here, a probabilistic statistical analysis, and subsurface conditions favoring supercritical phase CO_2. Subsurface conditions favoring CO_2 storage at high density include relatively high basin pressures and temperatures (Buursink, 2012). Based on the methodologies, our storage resource was allocated between residual trapping (typically larger but less certain) and buoyant trapping (typically smaller but more certain). Residual trapping occurs at the pore scale, and buoyant trapping is analogous to stratigraphic and (or) structural hydrocarbon trapping. The minimum buoyant-trapping volume is determined from cumulative oil and gas production together with the known hydrocarbon reserve volume, whereas the most likely buoyant-trapping volume adds the minimum volume and the estimated volumes of undiscovered resources (Brennan and others, 2010). The maximum buoyant resource is determined by the assessment geologist. Upon completion of the assessment, the following SAUs, listed by name and number, were described: Paleozoic Composite C50370101; Paleozoic Composite Deep C50370102; Nugget Sandstone C50370103; Nugget Sandstone Deep C50370104; Muddy Sandstone and Cloverly Formation C50370105; Muddy Sandstone and Cloverly Formation Deep C50370106; Frontier Sandstone C50370107; Frontier Sandstone Deep C50370108; Hilliard, Baxter, and Mancos Shales C50370109; Hilliard, Baxter, and Mancos Shales Deep C50370110; Mesaverde Group C50370111; Mesaverde Group Deep C50370112; Dad Member C50370113; and Dad Member Deep C50370114.

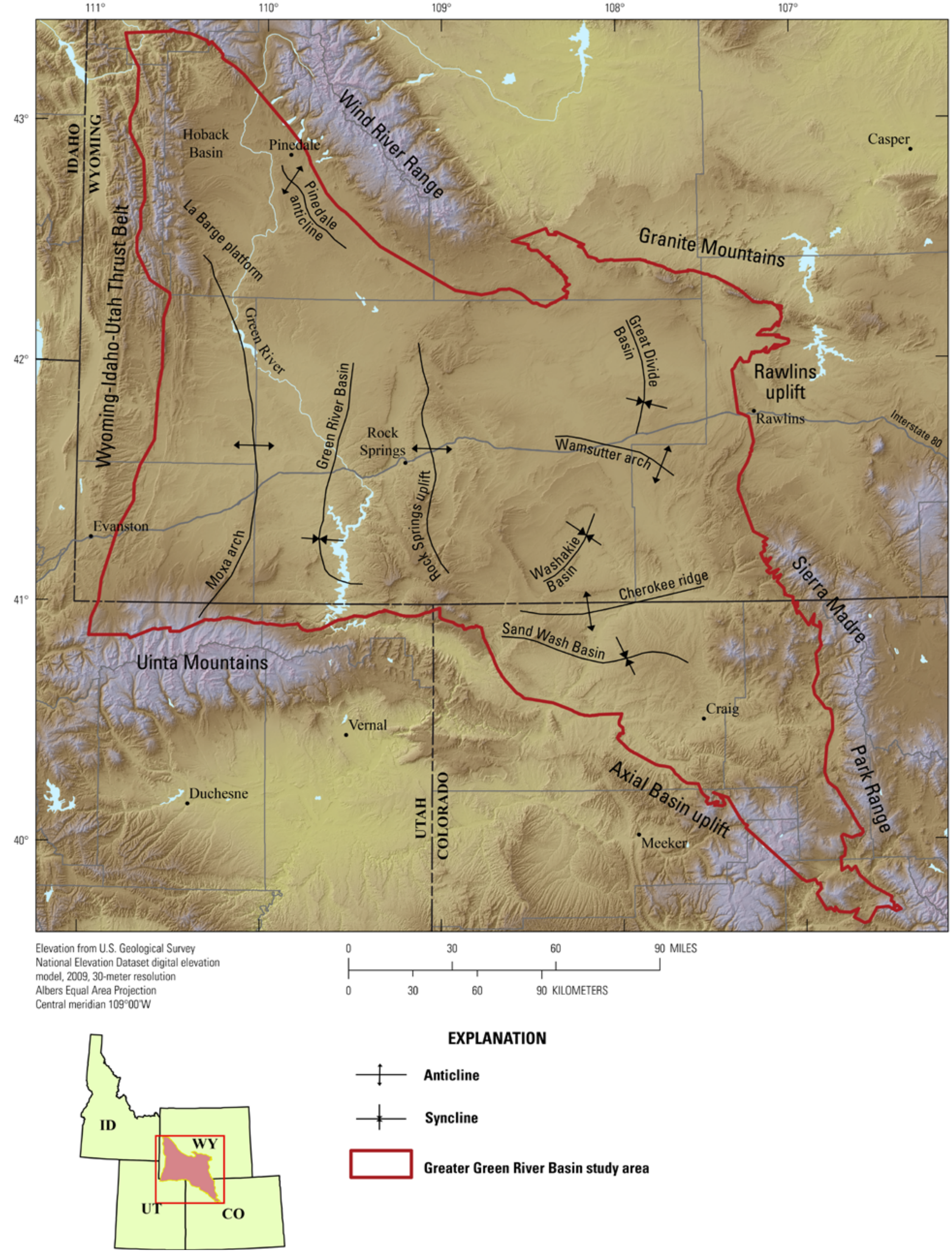

Figure 1. Map showing the Greater Green River Basin study area, Wyoming, Colorado, and Utah, including major structural features (Blackstone, 1993; U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005). Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

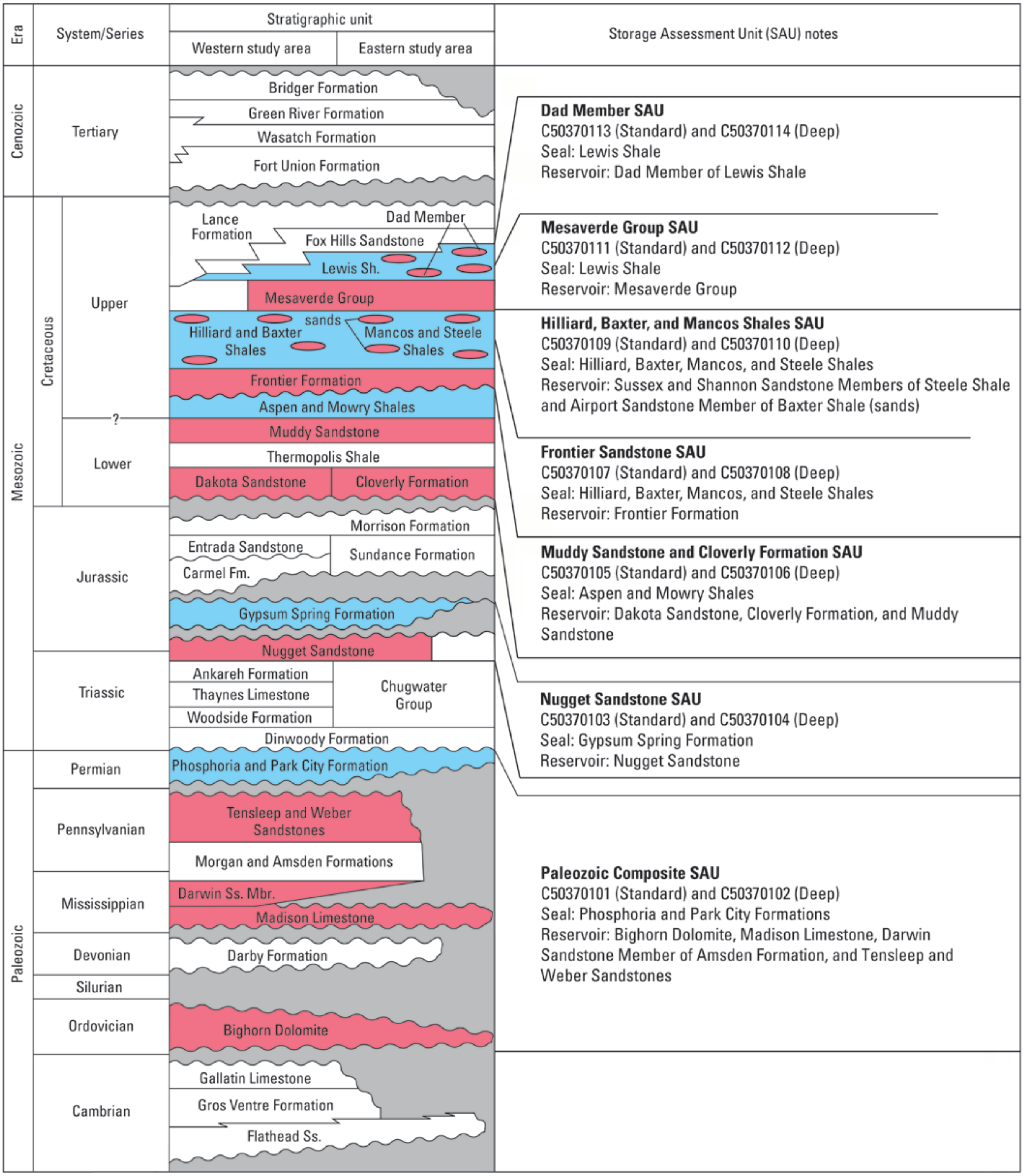

Figure 2. Generalized stratigraphic column of geologic units in the Greater Green River Basin study area, Wyoming, Colorado, and Utah (modified from U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005). Storage assessment units (SAUs) consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray areas represent unconformities or hiatuses. In some cases, subdivisions of units or lesser known correlative units are not shown. Sh., Shale; Fm., Formation; Mbr., Member; Ss., Sandstone.

Paleozoic Composite SAU C50370101 and Paleozoic Composite Deep SAU C50370102

By Ernie R. Slucher and Marc L. Buursink

The Paleozoic Composite and Paleozoic Composite Deep SAUs comprise only those portions of the preserved Middle Cambrian to Lower Permian geologic section deemed suitable as reservoirs for CO_2 storage and occurring beneath a regionally extensive seal in the GGRB (fig. 1). The suitable reservoir rocks consist of siliciclastic and carbonate lithologies and include, in ascending stratigraphic order, the Ordovician Bighorn Dolomite, the Mississippian Madison Limestone, the Mississippian Darwin Sandstone Member of the Amsden Formation, and the Pennsylvanian Tensleep Sandstone or its correlative the Weber Sandstone (Law, 1996; Johnson, 2005) (fig. 2). Regionally the Permian Phosphoria Formation and its stratigraphic equivalent, the Park City Formation, overlie the Tensleep and Weber Sandstones and function as the sealing formations (Rascoe and Baars, 1972; Peterson, 1980; Whalen, 1996). Paleozoic age rocks in the GGRB were deposited mostly on a passive continental margin and were periodically influenced by eustatic fluctuations resulting in numerous regional unconformities (Lynds and others, 2010) and preserve spatially variable thickness and lithologic changes (Geldon, 2003). The Early Mississippian Antler orogeny, west of the GGRB, and the formation of the Ancestral Rocky Mountains in the Pennsylvanian may have contributed to stratigraphic variations in the Paleozoic section (Anna, 2010).

The Paleozoic Composite and Paleozoic Composite Deep SAU boundaries are defined by the top of the uppermost storage formation and by the extent of the regional seal. Formation picks reported in a commercial database (IHS Energy Group, 2011) for the Tensleep Sandstone, or its correlative the Weber Sandstone, helped to define the top of the storage interval. The Paleozoic Composite SAU lies between 3,000 and 13,000 ft in depth and includes about a 4.5-million-acre most-likely area; and the Paleozoic Composite Deep SAU lies between 13,000 and 24,500 ft and includes about a 9.5-million-acre most-likely area (fig. 3). These interpretations are supported by the structure contours maps from Mallory and others (1972) and Bartos and Hallberg (2010) and supplemented by the Wyoming and Colorado Precambrian basement maps (Blackstone, 1993; Sims and others, 2001). Regionally, the gross thickness of the Paleozoic Composite SAU sequence ranges from tens to thousands of feet with most of the stratigraphic section being preserved and with general thickening of the interval occurring westward in the study area (Bartos and Hallberg, 2010). Analyses of the stratigraphy and net-porous intervals of individual reservoirs within each SAU were obtained from literature (Geldon, 2003; Johnson, 2005; Zhang and others, 2005; Friedman and Stamp, 2006). To assess the composite SAUs as a whole, isopach maps of individual storage formations within the SAUs were scanned, geo-referenced, and digitized; the thickness values were then scaled by a unique net-to-gross ratio derived from the literature and well logs (Geldon, 2003; Thyne and others, 2010). Finally, using a geographic information system, the net-porous interval of each composite SAU was summed (Buursink and others, 2011). The Paleozoic Composite SAU gross thickness ranges from 500 to 1,000 ft with a net thickness between 300 and 700 ft; and the Paleozoic Composite Deep SAU gross thickness ranges from 900 to 2,100 ft with a net thickness between 700 and 1,200 ft.

The overall depth of the Paleozoic interval in the GGRB generally restricts their hydrocarbon potential and thus limited well log and core data exist. Therefore, porosity and permeability trends for individual formations within the composite SAUs are estimated from relevant sandstone and carbonate analogs (Fox and others, 1975; Nelson and Kibler, 2003; Johnson, 2005; Ehrenberg and others, 2009), obtained from the Wyoming water-plan report (Geldon, 2003), and average field values are extracted from Nehring Associates (2010), a commercial oil and gas database. The Paleozoic Composite SAU porosity ranges from 5 to 13 percent and permeability ranges from 0.1 to 300 millidarcy (mD); and the Paleozoic Composite Deep SAU porosity ranges from 2 to 9 percent and permeability ranges from 0.01 to

10 mD. The occurrence and distribution of these reservoir properties in the composite SAUs is generally a function of the storage formation lithology and depths.

Water-quality data obtained from multiple published databases (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; Blondes and Gosai, 2011) for the SAU indicated mixed fresh and saline waters. Areas exist in each SAU where the groundwater TDS value is both under and above the USDW limit of 10,000 mg/L. Generally, groundwater TDS values increase slightly with depth in the SAU. Given the paucity of available hydrocarbon data, the Nehring Associates (2010) average field size was used and multiplied by a factor of five to create a probabilistic maximum volume for buoyant trapping for each SAU.

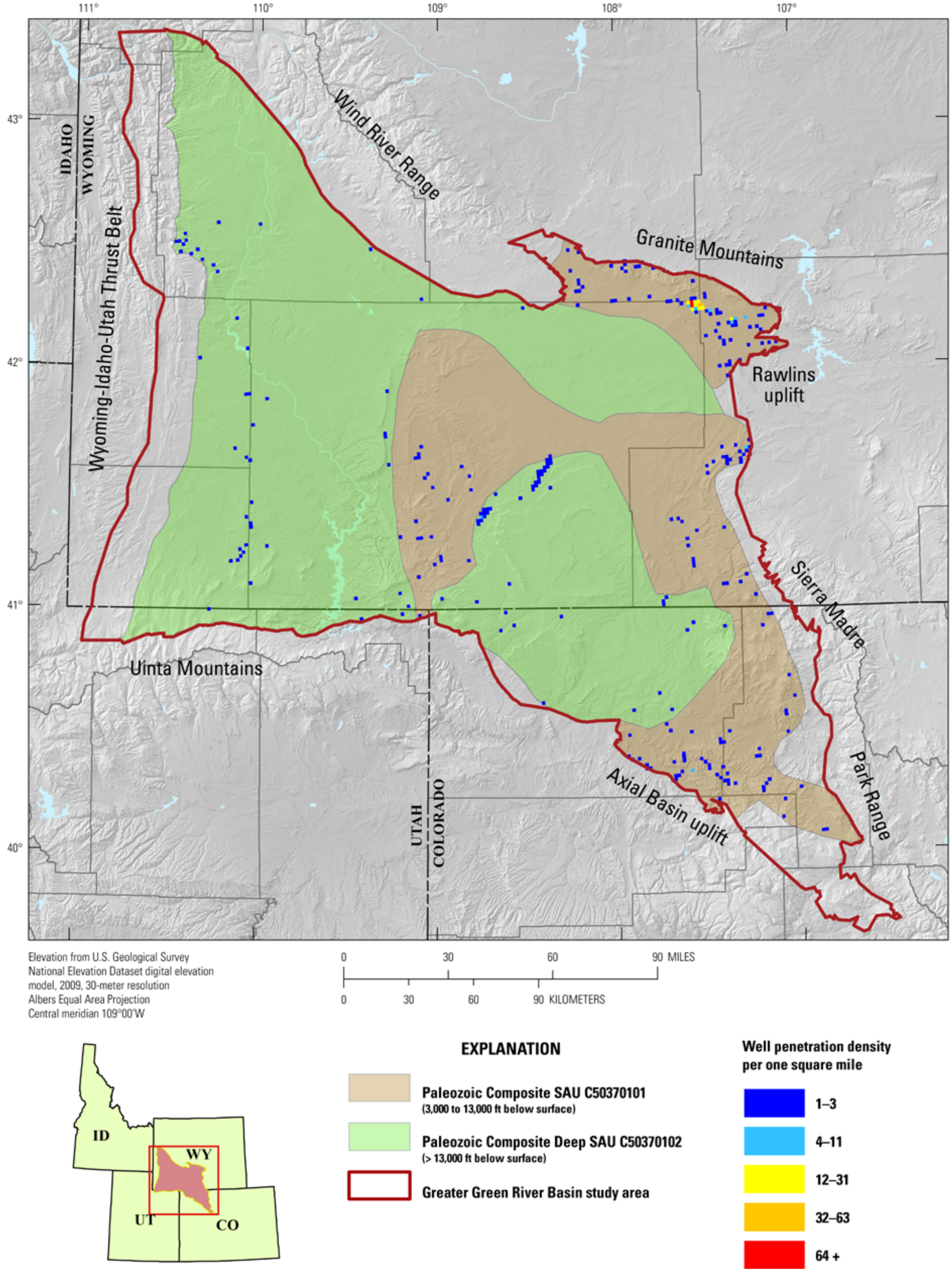

Figure 3. Map showing the Paleozoic Composite and Paleozoic Composite Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Nugget Sandstone SAU C50370103 and Nugget Sandstone Deep SAU C50370104

By Marc L. Buursink

The Nugget Sandstone SAUs consist of those portions of the preserved Upper Triassic and Lower Jurassic siliciclastic lithology deemed suitable as reservoirs for CO_2 storage and occurring beneath a regionally extensive seal in the GGRB (fig. 1). The cross-stratified Nugget Sandstone was deposited in predominantly eolian and fluvial environments and constitutes favorable reservoir rock in the Rock Springs uplift, Cherokee ridge, and Moxa arch (La Barge platform) (Picard, 1975; Law, 1996; Johnson, 2005). Regionally the Jurassic Gypsum Spring Formation, which was deposited in predominantly marginal-marine environments during repeated transgressions and regressions of Jurassic seas (Freethey and Cordy, 1991), overlies the Nugget Sandstone and functions as the sealing formation (Peterson, 1957; Law, 1996; Johnson, 2005) (fig. 2).

The SAU boundaries are defined by the depth below the surface of the uppermost storage-formation top and by the extent of the regional seal. Formation-top picks, reported in a proprietary commercial database (IHS Energy Group, 2011), for the Nugget Sandstone constrain the SAU boundary. The Nugget Sandstone SAU lies between 3,000 and 13,000 ft in depth and covers about a 700,000-acre most-likely area; and the Nugget Sandstone Deep SAU lies between 13,000 and 22,500 ft and covers about a 6-million-acre most-likely area (fig. 4). The SAUs do not extend into the eastern GGRB because the regional seal is absent. These interpretations are supported by the Wyoming digital geologic map from Green and Drouillard (1994) and supplemented by the Wyoming and Colorado Precambrian basement maps (Blackstone, 1993; Sims and others, 2001). Regionally, the gross thickness of the Nugget Sandstone ranges from tens to thousands of feet, with most of the stratigraphic section being preserved and with general thickening of the interval occurring northwestward in the study area (Bartos and Hallberg, 2010). Analyses of the stratigraphy, net-to-gross ratio, and net-porous intervals within the SAU were obtained primarily from Knapp (1978), Freethey and Cordy (1991), and supplemented by Lindquist (1988) and Johnson (2005). The Nugget Sandstone SAU gross thickness ranges from 800 to 900 ft with a net thickness between 270 and 300 ft, and the Nugget Sandstone Deep SAU gross thickness ranges from 800 to 1,200 ft with a net thickness between 270 and 400 ft.

The Nugget Sandstone is a productive hydrocarbon interval in the GGRB and reservoir-quality data is reported in multiple forms. Besides reported porosity values (Doelger, 1987; Johnson, 2005) and reported permeability values (Richter, 1981; Bartos and Hallberg, 2010), additional values are estimated from relevant sandstone analogs (Nelson and Kibler, 2003; Ehrenberg and others, 2009), and average field values are extracted from Nehring Associates (2010). The Nugget Sandstone SAU porosity ranges from 10 to 15 percent and permeability ranges from 0.1 to 200 mD; the Nugget Sandstone Deep SAU porosity ranges from 6 to 12 percent and permeability ranges from 0.01 to 10 mD.

Water-quality data obtained from multiple published databases (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; Blondes and Gosai, 2011) for the SAU indicated mixed fresh and saline waters. Areas exist in the SAU where the groundwater TDS value is both under and above the USDW limit of 10,000 mg/L. Generally, groundwater TDS values increase slightly with depth in the SAU. Storage-formation areas with groundwater below the 10,000 mg/L total TDS limit were identified and removed from each SAU. To create a probabilistic maximum volume for buoyant trapping for each SAU, both the size and location of structural features highlighted on the Precambrian basement maps (Blackstone, 1993; Sims and others, 2001), along with the Nehring Associates (2010) average field size, were used.

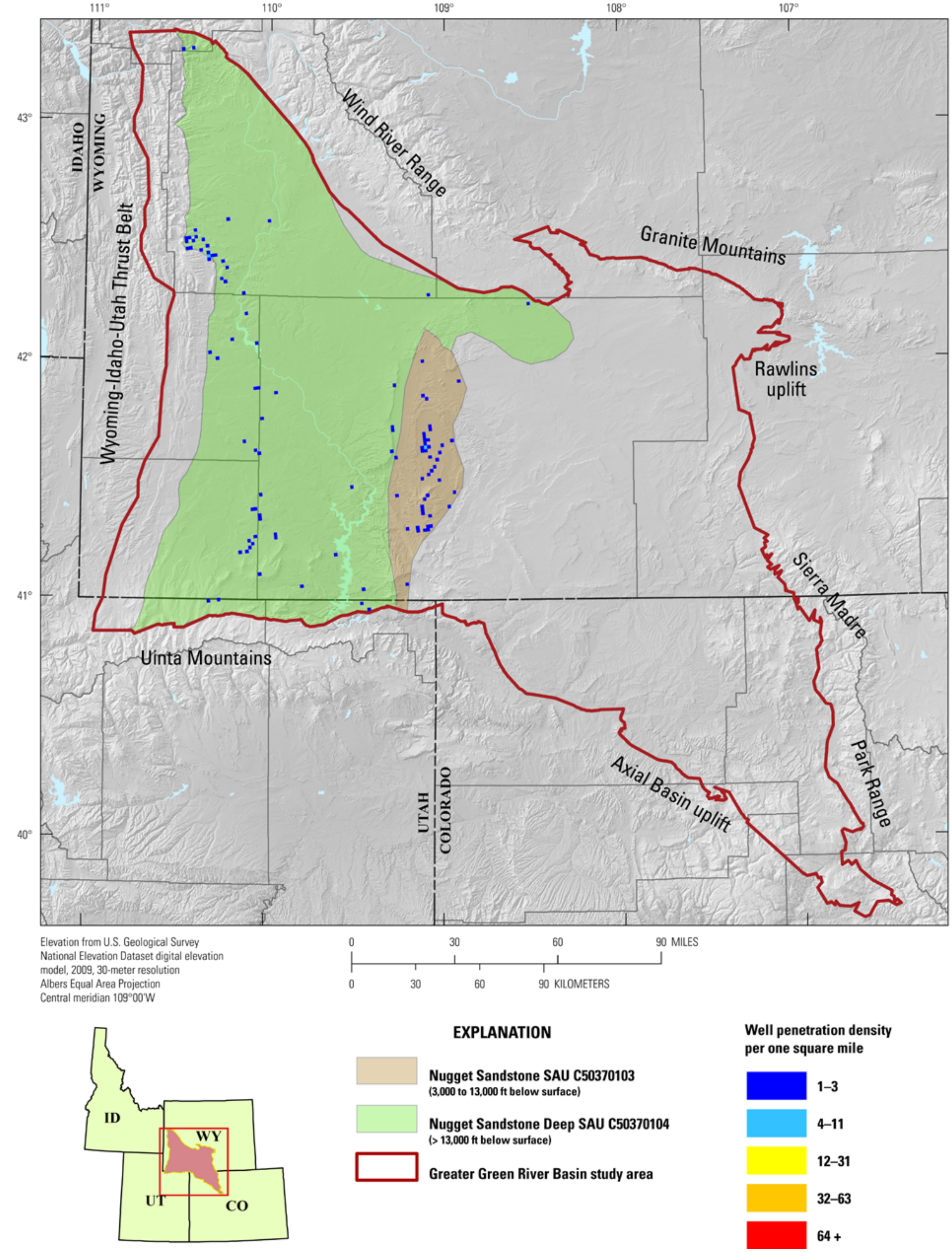

Figure 4. Map showing the Nugget Sandstone and Nugget Sandstone Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Muddy Sandstone and Cloverly Formation SAU C50370105 and Muddy Sandstone and Cloverly Formation Deep SAU C50370106

By Ronald M. Drake II

In the GGRB (fig. 1), the Lower Cretaceous Muddy Sandstone, Cloverly Formation, and correlative Dakota Sandstone (fig. 2) were combined into either the Muddy Sandstone and Cloverly Formation SAU or the Muddy Sandstone and Cloverly Formation Deep SAU. According to the 2005 National Oil and Gas Assessment (NOGA) report (Kirschbaum and Roberts, 2005a), the Muddy Sandstone is a discontinuous member of the Thermopolis Shale. These grouped units are overlain by the Aspen and Mowry Shales that form a regional top seal for the SAUs. The Muddy Sandstone and Cloverly Formation SAUs are generally composed of fluvial, shoreface, and deltaic deposits that are predominantly sandstone but may also contain lower shoreface mudrock or offshore marine shale.

SAU boundaries for the Muddy Sandstone and Cloverly Formation SAU and the Muddy Sandstone and Cloverly Formation Deep SAU are based on the area created by contouring the depth to top of the Muddy Sandstone and Cloverly Formation using interpretations of well tops from commercial databases (IHS Energy Group, 2010) and from projecting and delineating the top surface of these units from structure and depth maps of Barlow and others (1994) and Reisser and Blanke (1989) (fig. 5). The structure contour map of the base of the Mowry Shale from Barlow and others (1994) was particularly useful in the creation of the SAU boundaries. The SAU boundary for the Muddy Sandstone and Cloverly Formation SAU includes the area defined by the contours between 3,000 and 13,000 ft. The boundary for the Muddy Sandstone and Cloverly Formation Deep SAU includes the area defined by the contours greater than 13,000 ft in depth.

Within the Muddy Sandstone and Cloverly Formation SAU, formation thickness was determined from published isopach maps (Furer, 1970; Reisser and Blanke, 1989; Dolson and others, 1991) and from differencing formation-tops picks (IHS Energy Group, 2010). As a result, the SAU thickness ranges from 150 to 320 ft. Net-porous-sand thickness ranges from 60 to 128 ft, and the most likely net-porous thickness is 96 ft using a net-to-gross ratio of about 0.4 as determined from cross sections in Kirschbaum and Roberts (2005a). Within the Muddy Sandstone and Cloverly Formation Deep SAU, formation thickness was determined with the same sources and ranges from 200 to 350 ft. Net-porous-sand thickness ranges from 80 to 140 ft, and the most likely thickness is 110 ft using a net-to-gross ratio of about 0.4, also determined from cross sections in Kirschbaum and Roberts (2005a).

Water-quality data were compiled from several sources (Breit, 2002; U.S. Department of Energy National Energy Technology Laboratory, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; U.S. Geological Survey, 2010; Wyoming Oil and Gas Conservation Commission, 2010) for this assessment. The water-quality data from the Muddy Sandstone and Cloverly Formation SAU intervals were plotted on a map, and then areas were identified that contained high concentrations of TDS above the 10,000 mg/L USDW limit. A general trend of decreasing water quality appears as depth increases within the Muddy Sandstone and Cloverly Formation SAU.

In this assessment, porosity and permeability data came from Nehring Associates (2010) and from Kirschbaum and Roberts (2005a). Porosities for the Muddy Sandstone and Cloverly Formation SAU were reported as ranging from 10 to 18 percent with a most likely porosity of 15 percent. The porosities for the Muddy Sandstone and Cloverly Formation Deep SAU were reported as ranging from 7 to 14 percent with a most likely porosity of 12 percent. Permeabilities for the Muddy Sandstone and Cloverly Formation SAU were reported as ranging from 0.01 to 500 mD. Permeabilities for the Muddy Sandstone and Cloverly Formation Deep SAU were reported as ranging from 0.01 to 100 mD.

The boundaries, thicknesses, rock properties, and water-quality information previously mentioned were used in accordance with the USGS CO_2 storage resource assessment methodology (Brennan and others, 2010) to calculate the available storage volume within the Muddy Sandstone and Cloverly Formation SAUs. The maximum buoyant pore volume within structural and stratigraphic traps was estimated from apparent closure areas and available published maps of petroleum fields within the corresponding stratigraphic units (Barlow and others, 1994). These areas were combined with the upper bounds of regional reservoir thickness and porosity estimates, and a maximum buoyant storage volume was calculated.

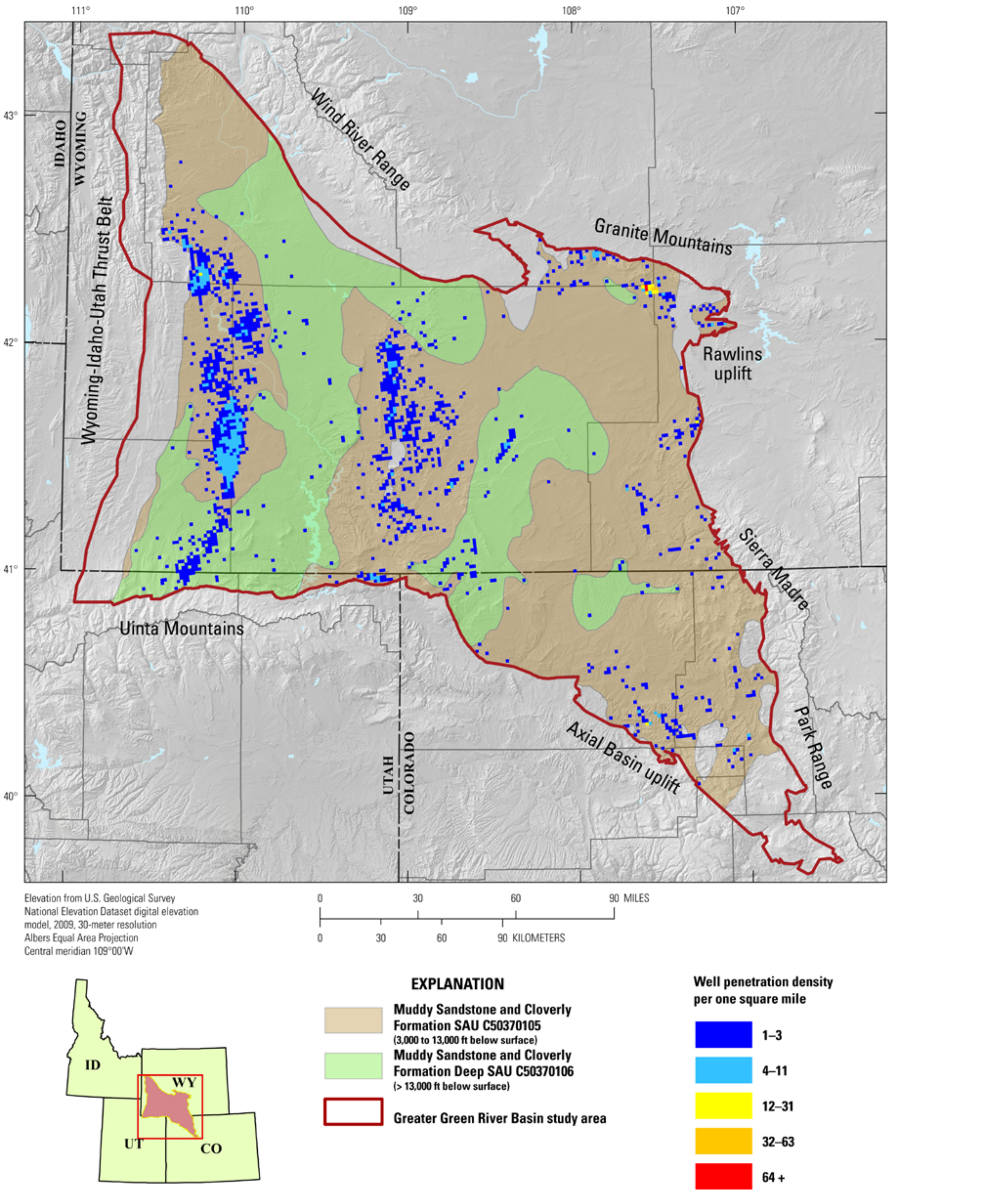

Figure 5. Map showing the Muddy Sandstone and Cloverly Formation, and Muddy Sandstone and Cloverly Formation Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Frontier Sandstone C50370107 and Frontier Sandstone Deep C50370108

By Ronald M. Drake II

In the GGRB, the Upper Cretaceous Frontier Formation (fig. 2) is composed of continental, shoreface, deltaic, and offshore deposits. These deposits include, in approximate ascending order, the Belle Fourche, Chalk Creek, Oyster Ridge Sandstone, Emigrant Gap, and Dry Hollow Members of the Frontier Formation. These members along with informal sandstone deposits of the Frontier Formation were combined into the Frontier Sandstone SAU and the Frontier Sandstone Deep SAU (see Kirschbaum and Roberts, 2005b). These grouped units are overlain by the Hilliard, Baxter, Mancos, and Steele Shales (fig. 2). These shales are 3,000 to 5,000 ft thick and form a regional top seal for the SAUs.

SAU boundaries for the Frontier Sandstone and the Frontier Sandstone Deep are based on plotted interpretations of formation tops from a commercial database (IHS Energy Group, 2010) and from depths on the Frontier Formation map of Kirschbaum and Roberts (2005b) (fig. 6). The SAU boundary for the Frontier Formation includes the area defined by depths between 3,000 and 13,000 ft. The boundary for the Frontier Sandstone Deep SAU includes the area defined by the tops' picks greater than 13,000 ft in depth and from mapped contours greater than 13,000 ft in depth from Kirschbaum and Roberts (2005b).

Within the Frontier Sandstone SAU, formation gross thickness ranges from 200 to 700 ft with net-porous-sand thickness of 50 to 200 ft and a most likely thickness of 100 ft. Within the Frontier Sandstone Deep SAU, formation thickness ranges from 200 to 600 ft with net-porous-sand thickness of 50 to 200 ft and a most likely thickness of 100 ft.

Water-quality data were compiled from several sources (Breit, 2002; U.S. Department of Energy National Energy Technology Laboratory, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; U.S. Geological Survey, 2010; Wyoming Oil and Gas Conservation Commission, 2010) for this assessment. The water-quality data from the Frontier Sandstone SAUs were plotted on a map, and areas were identified that contained high concentrations of TDS above the 10,000 mg/L USDW limit. High TDS (>10,000 mg/L) measurements are very much intermixed with low TDS measurements (<10,000 mg/L) within the Frontier Sandstone SAUs.

Porosity and permeability data were obtained from Nehring Associates (2010) and from Kirschbaum and Roberts (2005b). The most likely porosities for the Frontier Sandstone SAU were reported as ranging from 12 to 18 percent in this assessment with a most likely porosity of 15 percent. The most likely porosities for the Frontier Sandstone Deep SAU were reported as ranging from 5 to 9 percent with a most likely porosity of 7 percent. Permeabilities for the Frontier Sandstone SAU were reported as ranging from 0.01 to 250 mD. Permeabilities for the Frontier Sandstone Deep SAU were reported as ranging from 0.01 to 1 mD.

The boundaries, thicknesses, rock properties, and water-quality information previously mentioned were used in accordance with the USGS CO_2 storage resource assessment methodology to calculate the available storage volume within the Frontier Sandstone SAUs. The maximum buoyant-trapping pore volume within structural and stratigraphic traps was estimated from apparent closure areas and available published maps of petroleum fields within the relevant stratigraphic units. These areas were combined with the upper bounds of regional reservoir thickness and porosity, and a resulting maximum buoyant storage volume was calculated.

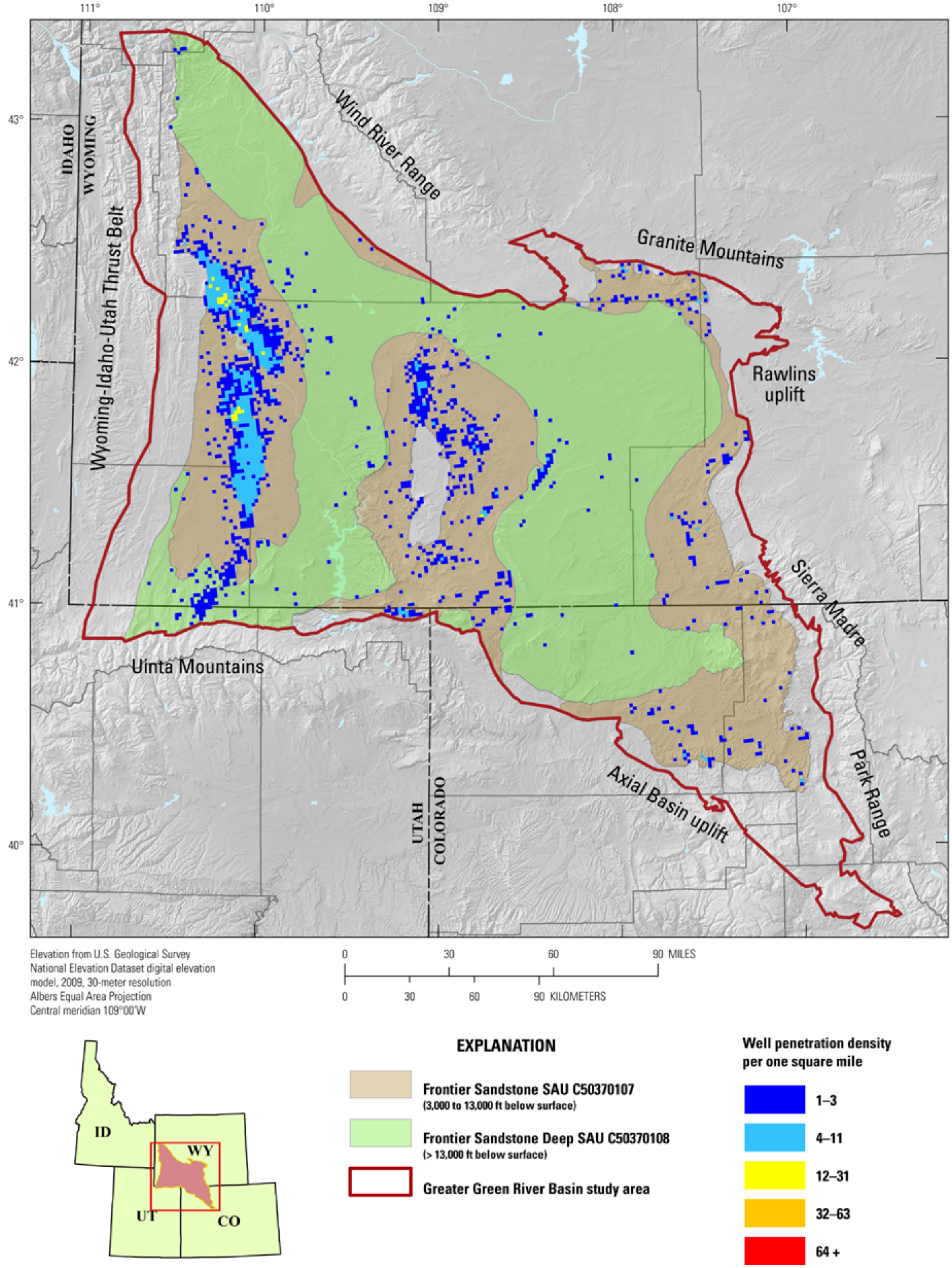

Figure 6. Map showing the Frontier Sandstone and Frontier Sandstone Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Hilliard, Baxter, and Mancos Shales SAU C50370109, and Hilliard, Baxter, and Mancos Shales Deep SAU C50370110

By Sean T. Brennan

The Hilliard, Baxter, and Mancos Shales are relatively thick, deep-water formations that were deposited within the GGRB (fig. 1) during the Late Cretaceous (Roehler, 1990; Finn and Johnson, 2005a). The undiscovered oil and gas resource in these shales was recently assessed by a USGS NOGA study (Finn and Johnson, 2005a) for the GGRB, and this CO_2 storage assessment is partially based on the research presented in NOGA. These formations are predominantly shale-rich, are broadly coeval with the Steele Shale (fig. 2), as well as the Cody Shale, which lies to the north and east of the GGRB, and are the sealing formation for the underlying Frontier Sandstone SAU (Roehler, 1990; Finn and Johnson, 2005a, 2005b) (fig. 6; Drake, this report). The Mancos and Steele Shales are present in the eastern portion of the GGRB and are underlain by the Niobrara Formation and overlain by the Haystack Mountains Formation of the lowermost part of the Mesaverde Group (Roehler, 1990; Finn and Johnson, 2005a,b). The Hilliard and Baxter Shales are present in the western portion of the GGRB, are underlain by the Frontier Formation, and overlain by the Blair Formation of the Mesaverde Group, which is another marine shale unit (Roehler, 1990; Finn and Johnson, 2005a,b). These shale formations are the sealing unit, whereas the storage formations in these SAUs are sandstones encased within these relatively thick marine shales (Finn and Johnson, 2005a). These sandstones, including the Sussex and Shannon Sandstone Members of the Steele Shale, Airport Sandstone Member of the Baxter Shale, sandstones within Haystack Mountains Formation, and many unnamed sandstone units, are discontinuous sheet sands typically 20 to 100 ft in thickness (Roehler, 1990; Finn and Johnson, 2005b). These sandstones were deposited in marine nearshore, shelf, and slope environments within the Cretaceous Western Interior Seaway (Finn and Johnson, 2005a).

The Hilliard, Baxter, and Mancos Shales SAU and Hilliard, Baxter, and Mancos Shales Deep SAU in the GGRB contain about 8,470,000 and 1,244,000 acres, respectively (fig. 7). The SAU boundaries are partially defined by the limit of sandstone extents as observed in well logs and cross sections (Finn and Johnsons, 2005b). The standard and deep SAUs were defined by the depth to the top of the shale units, as identified in a commercial well database (IHS Energy Group, 2010), because most sandstone units are not formally named and therefore are not identified in the well database (IHS Energy Group, 2010). The standard SAU was defined by the locations of tops of the shale units between 3,000 and 13,000 ft below the surface, whereas the deep SAU was defined by the locations of tops of the shale units below 13,000 ft. The deepest estimate for the top of the deep SAU was 20,000 ft below the surface. The apparent gap in the standard SAU near the Washakie and Great Divide Basins (fig. 1) is due to the lack of sandstones interpreted in well logs and published cross sections through this region (Roehler, 1990; Finn and Johnson, 2005b).

The total shale thickness ranges from 3,500 to 6,000 ft across the entire SAU (see Finn and Johnson, 2005a, b), and the net-porous interval ranges from 200 to 400 ft, which was based on the thickness of the combined sand units within the shales (Finn and Johnson, 2005b). These thicknesses were the same in the standard and deep SAUs. The porosity of the sandstone units, which averages 15 percent for the standard and 8 percent for the deep SAU, is based on reservoir porosities from the GGRB and nearby basins (Nehring Associates, 2010) and projection of the porosity trend defined by the porosity values to the base on the standard SAU and throughout the thickness of the deep SAU. The permeability ranges from 0.01 to 70 mD with a most likely permeability of 1 mD for the standard SAU and from 0.001 to 5 mD with a most likely permeability of 0.1 mD for the deep SAU. These permeability values are derived from the same sources as the porosity data (Nehring Associates, 2010) and the extrapolated trends from those permeability data. The water-quality data indicate that there are portions of the SAU with groundwater TDS greater than and less than 10,000 mg/L (see Blondes and Gosai, 2011). By plotting the TDS values and interpolating where data are sparse, it was estimated that 60 percent of the standard SAU, on average, and 80 percent of the deep SAU, on average, contained water that exceeded the 10,000 mg/L TDS USDW threshold. Assessed buoyant storage values were based on (a) hydrocarbon volumes, both known reserves (Nehring Associates, 2010), and undiscovered resource estimates (Finn and Johnson, 2005a), and (b) estimates of the areas and thicknesses of stratigraphic traps and structural closures.

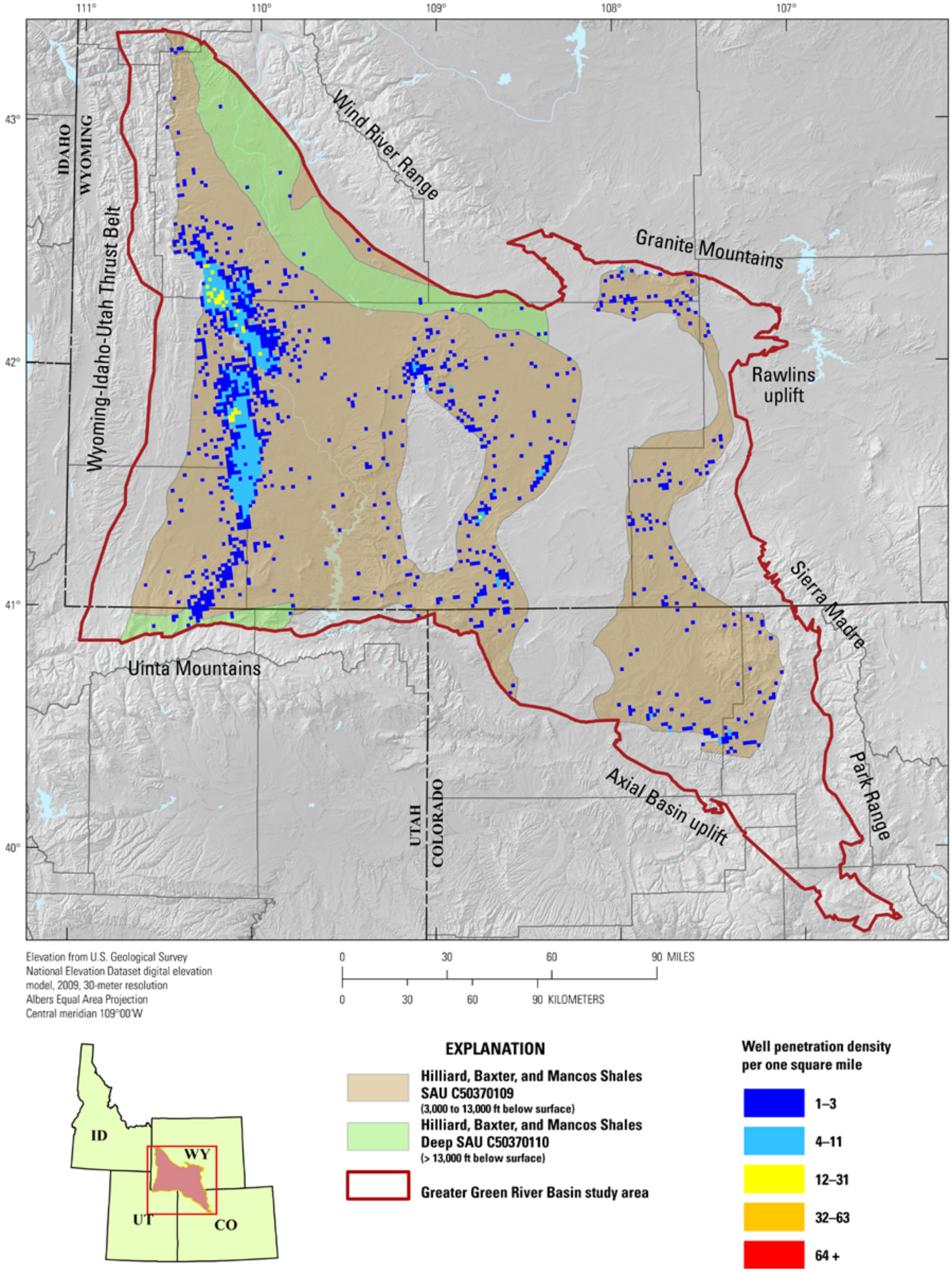

Figure 7. Map showing the Hilliard, Baxter, and Mancos Shales, and Hilliard, Baxter, and Mancos Shales Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Mesaverde Group SAU C50370111 and Mesaverde Group Deep SAU C50370112

By Peter D. Warwick

In the GGRB (fig. 1), the Mesaverde Group and Mesaverde Group Deep SAUs (fig. 8) are composed of porous, primarily sandstone, strata. These Upper Cretaceous strata are a terrestrial to marginal marine, coal-bearing sequence of mixed siliciclastic lithologies. The SAUs do not include the Blair and Haystack Mountains Formations; these formations were included in the underlying Hilliard, Baxter, and Mancos Shales SAUs (fig. 7; Brennan, this report).

The USGS recently assessed the Mesaverde Group for hydrocarbon resources, and the geologic data used in that study (Johnson and others, 2005) were incorporated into the current carbon dioxide storage assessment and report. The sealing unit for the Mesaverde Group and Mesaverde Group Deep SAUs is the Upper Cretaceous Lewis Shale (fig. 2); however, the Lewis Shale is restricted to the eastern part of the GGRB study area (Finn and Johnson, 2005b; Johnson and others, 2005). In addition, several other reports and datasets were used to spatially define and characterize the Mesaverde Group and Mesaverde Group Deep SAUs (Ryder, 1988; Blackstone, 1993; Roehler, 1990; Johnson and others, 1996; IHS Energy Group, 2010).

The Mesaverde Group and Mesaverde Group Deep SAU boundaries are based on the depth from the land surface to the top of the Mesaverde Group. These are two areas where the top of the SAU is between 3,000 and 13,000 ft, and 13,000 ft and greater, respectively (fig. 8). The Mesaverde Group and Mesaverde Group Deep SAU areas were constrained by formation tops in the IHS Energy Group (2010) commercial database and by projecting and delineating the Mesaverde Group on the structure and depth maps of Blackstone (1993) and Johnson and others (2005). The gross thickness of the Mesaverde Group in the area of the SAUs ranges from 2,000 to 3,100 ft with a most likely thickness of 2,600 ft for the standard SAU and 2,500 ft for the deep SAU (data from Finn and Johnson, 2005b; Johnson and others, 2005; IHS Energy Group, 2010). Available data from Finn and Johnson (2005b), Johnson and others (2005), IHS Energy Group (2010), and Nehring Associates (2010) suggest that the net-porous interval for the Mesaverde Group SAU ranges from 590 to 870 ft with a most likely thickness of 730 ft; and for the Mesaverde Group Deep SAU, the net-porous interval ranges from 560 to 810 ft with a most likely thickness of 700 ft. Water-quality data (see Breit, 2002; U.S. Department of Energy National Energy Technology Laboratory, 2010; University of Wyoming Enhanced Oil Recovery Institute, 2010; U.S. Geological Survey, 2010; Wyoming Oil and Gas Conservation Commission, 2010) suggest that there is a mix of both fresh (<10,000 mg/L TDS) and saline water (>10,000 mg/L TDS) within the SAU intervals. For the Mesaverde Group SAU, about 45 percent (with 25 percent as a minimum and 70 percent as maximum) of the resource may contain saline water suitable for subsurface storage of CO_2. For the Mesaverde Group Deep SAU, about 50 percent (with 25 percent as a minimum and 70 percent as maximum) of the resource may contain saline water. Data from Johnson and others (2005) and Nehring Associates (2010) suggest porosity of the net-porous interval of the Mesaverde Group SAU ranges from 10 to 16 percent with a most likely porosity of 12 percent, and for the Mesaverde Deep Group SAU, the porosity ranges from 4 to 12 percent with a most likely porosity of 8 percent. Permeability of the Mesaverde Group SAU is estimated to range from 0.1 to 100 mD with 3 mD as the most likely permeability (Nehring Associates, 2010). Permeability in the Mesaverde Group Deep SAU is estimated to range from 0.01 to 10 mD with 0.08 mD as the most likely permeability. About 1 percent of the Mesaverde Group SAU and Mesaverde Group Deep SAU areas may be impacted by structural and stratigraphic closures, and this percentage was used to estimate maximum buoyant-trapping pore volumes for the two SAUs. The attributes described herein were used in accordance with the USGS CO_2 storage resource assessment methodology (Brennen and others, 2010) to calculate the available storage volume for CO_2 within the Mesaverde and Mesaverde Deep SAUs.

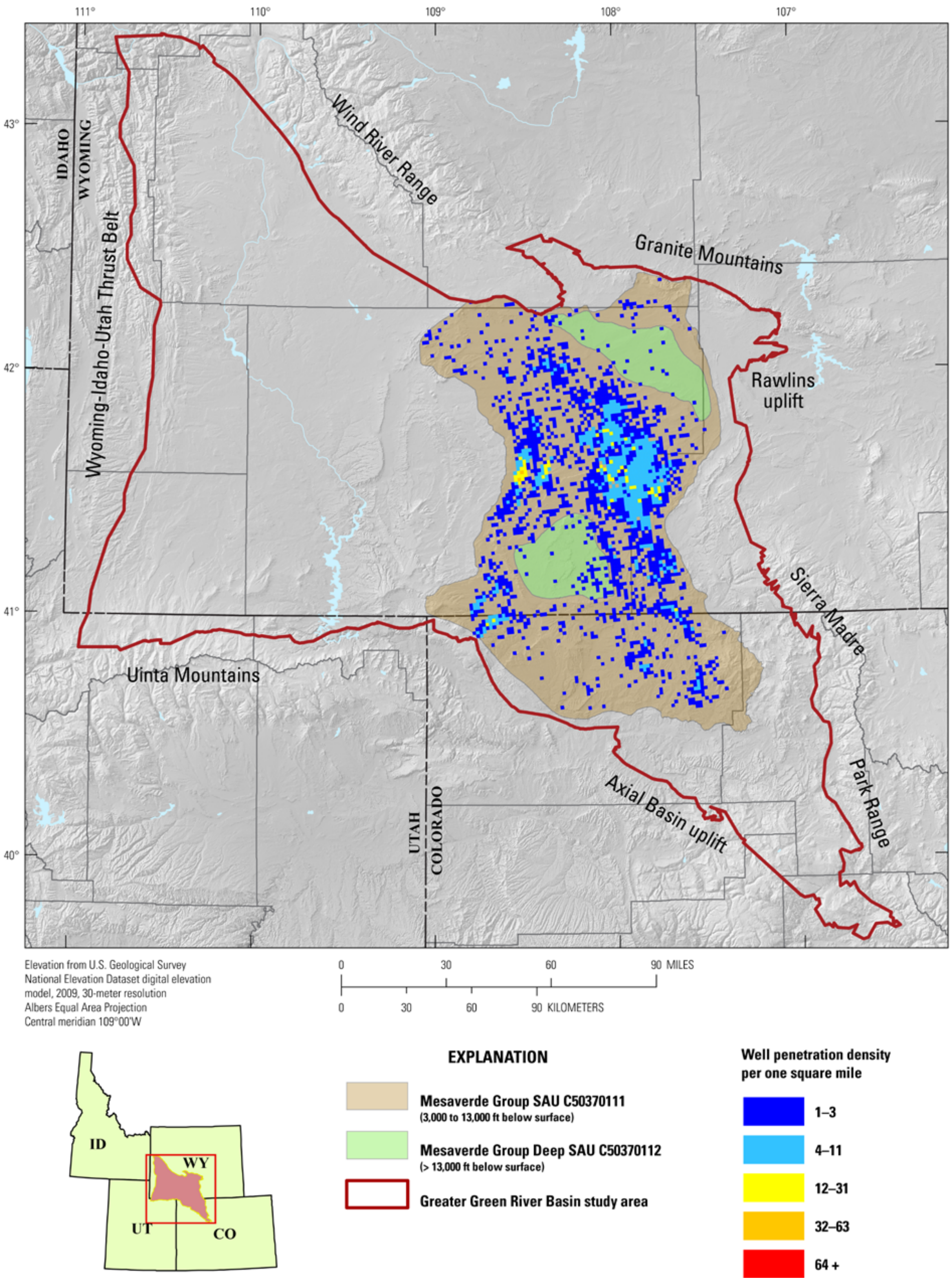

Figure 8. Map showing the Mesaverde Group and Mesaverde Group Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Dad Member SAU C50370113 and Dad Member Deep SAU C50370114

By Sean T. Brennan

In the GGRB (fig. 1), the Dad Member is part of the Lewis Shale, a marine deposit that contains evidence of deposition along deltaic, slope, and deep basin settings (Hettinger and Roberts, 2005). The undiscovered oil and gas resources of the Lewis Shale within the GGRB were recently assessed by the USGS (Hettinger and Roberts, 2005), and this CO_2 storage assessment is partially based on the research presented in that study. The Lewis Shale is underlain by fluvio-deltaic deposits of the Mesaverde Group and is overlain by nearshore and shoreface deposits of the Fox Hills Sandstone (Hettinger and Roberts, 2005) (fig. 2). The Lewis Shale is between 1,600 and 2,400 ft thick on average (Law and others, 1989; Roehler, 1992; Finn and Johnson, 2005b; Hettinger and Roberts, 2005) and is the seal formation, encasing the Dad Member, which is the storage formation. The Dad Member is located east of the Rock Springs uplift (fig. 1) and is a turbidite deposit sourced from the southwest and deposited along slope- and deep-basin settings (Perman, 1990).

The Dad Member SAU and the Dad Member Deep SAU extend on average more than 4,188,000 and 340,000 acres, respectively (fig. 9). The SAU areas were delineated based on depth to the top of the Lewis Shale and the extent of the sandstone layers. The Dad Member SAU was defined based on (a) locations of the Lewis Shale top picks between 3,000 and 13,000 ft below the surface in wells from a commercial database (IHS Energy Group, 2010), (b) an overburden map showing the thickness of the strata overlying the Lewis Shale (Hettinger and Roberts, 2005), and (c) an isopach map of the Dad Member that indicates extent of sandstone layers greater than 10 ft thick (Law and others, 1989; Hettinger and Roberts, 2005). The Dad Member Deep SAU was defined based on the overburden map by Hettinger and Roberts (2005) and verified by the Lewis Shale tops data from wells (IHS Energy Group, 2010). The top of the Lewis Shale in the Dad Member Deep SAU ranges from 13,000 to 16,600 ft below the surface (data from Hettinger and Roberts, 2005; IHS Energy Group, 2010).

The Dad Member is primarily sandstone with net-porous intervals that average 200 ft thick in the Dad Member SAU and 450 ft thick in the Dad Member Deep SAU, according to isopach maps (Law and others, 1989; Hettinger and Roberts, 2005) and cross sections (Finn and Johnson, 2005b; Hettinger and Roberts, 2005). The most likely estimate of porosity for the Dad Member SAU is 15 percent, whereas for the Dad Member Deep SAU it is 6 percent (Nehring Associates, 2010). Water-quality data for these SAUs (see Blondes and Gosai, 2011) indicate that there is a significant amount of formation water with salinities below the USDW threshold (<10,000 mg/L TDS). Based on the areal distribution of the water-quality data, it was estimated that the amount of the Dad Member and the Dad Member Deep SAUs that contained water with salinity above the threshold have most likely values of 20 percent and 35 percent, respectively. The permeabilities for the Dad Member SAU range from 0.1 to 60 mD with a most likely permeability of 3 mD (Nehring Associates, 2010). Based on the trend of the available permeability data (Nehring Associates, 2010), it was estimated that the permeability for the Dad Member Deep SAU ranges from 0.001 to 10 mD with a most likely permeability of 0.1 mD.

The SAU buoyant-resource values were based on known production from the Dad Member (Nehring Associates, 2010), estimates of the undiscovered hydrocarbon resource (Hettinger and Roberts, 2005), and estimating the volume of closures by estimating the potential number and size of both stratigraphic traps and structural closures.

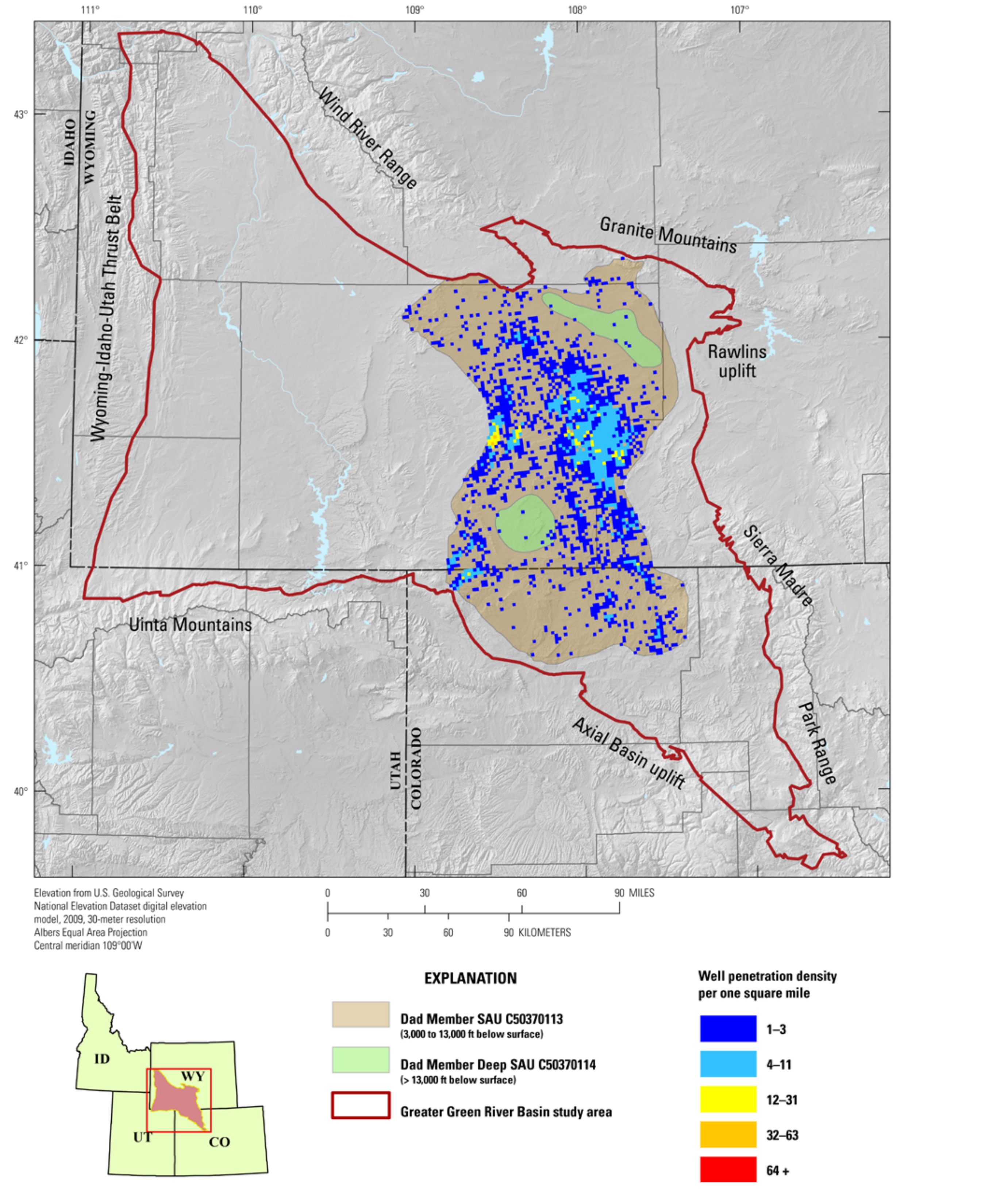

Figure 9. Map showing the Dad Member and Dad Member Deep Storage Assessment Units (SAUs) in the Greater Green River Basin, Wyoming, Colorado, and Utah. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Southwestern Wyoming Province Assessment Team, 2005).

Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Wyoming-Idaho-Utah Thrust Belt

By Marc L. Buursink, Ernie R. Slucher, Sean T. Brennan, Colin A. Doolan, Ronald M. Drake II, Matthew D. Merrill, Madalyn S. Blondes, Philip A. Freeman, Steven M. Cahan, and Christina A. DeVera

Introduction—Wyoming-Idaho-Utah Thrust Belt

Basin Physiography

The Wyoming-Idaho-Utah Thrust Belt (WIUTB) study area extends from the Uinta Mountains on the south, to the Snake River Plain and Teton Range on the north, and to the edge of the Basin and Range Province on the west (fig. 10) (Royse 1993; Powers, 1995). The eastern limit of the WIUTB may be defined by the surface trace of the Hogsback and Prospect thrust systems separating it from the relatively undisturbed and neighboring GGRB, whereas the western limit is poorly defined by the limit of identifiable eastward thrusting (Monley, 1971; Royse and others, 1975; U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004). This arcuate, north- to south-trending thrust belt covers about 15,000 square miles and is an easterly salient of the Cordilleran orogen, which spans over 5,000 miles from Alaska to Mexico in western North America (Powers, 1995). Study area altitudes range to more than 11,000 ft with many peaks and ridges exceeding 10,000 ft (Monley, 1971).

Four major thrust systems make up the structure of the WIUTB (Powers, 1995). From west to east these are the Willard-Paris (Bannock), Crawford-Meade, Absaroka, and Prospect-Darby-Hogsback thrust systems (fig. 10). The thrust faults in these systems are low angle, westward-dipping, moderately to highly imbricated, and according to seismic, aeromagnetic, and surface data, typically do not involve crystalline basement (Royse and others, 1975; Royse, 1993). The Paleozoic and Mesozoic strata that contain these thrust faults are severely deformed and are shortened with older rocks overlying younger rocks due to eastward movement of the faults (Monley, 1971). Beside the major thrust systems with associated upright to nearly recumbent folds, WIUTB deformation includes lesser thrusts and folds, tear faults, and post-thrusting extensional faults (Powers, 1995; Monley, 1971). Deformation in the WIUTB is brittle with little plastic flow or cleavage folding, and concentric folding dominates with thickness and surface area of the individual strata not changing (Royse and others, 1975). For additional details on WIUTB geology, the reader is referred to NOGA reports (Powers, 1995; U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004), the symposium on the Greater Green River Basin and overthrust belt (Miller and others, 1992), the guidebook to the thrust belt (Miller, 1987), the “Geology of Wyoming” volume by Snoke and others (1993), and information available in numerous references and maps therein.

Geologic History

During the Paleozoic and Mesozoic Eras, more than 60,000 ft of predominantly marine sediments were deposited in the WIUTB study area (Lines and Glass, 1975; Powers, 1995). Throughout these eras, multiple eustatic changes in sea level generated various depositional environments that resulted in heterogeneous sedimentary deposits (Johnson, 2005). These deposits include marine carbonate shelves (Mississippian Madison Limestone, for example), broad alluvial plains (Triassic Chugwater Group, for example), and regional dune fields (Upper Triassic to Lower Jurassic Nugget Sandstone, for example) (fig. 11). A major uplift of the western North American craton during the Early Cretaceous produced a regional foreland basin between Cordilleran highlands on the west and the Cretaceous Western Interior

Seaway on the east (Johnson, 2005). The resulting sedimentary settings included marine basins, coastal plains, and alluvial plains.

The WIUTB is part of the larger Cordilleran thrust belt in western North America that was formed during the Sevier orogeny from about 150 to 55 million years ago (Wyoming State Geological Survey, 2012). Compression, from Late Jurassic in the western to early Eocene in the eastern part of the study area, moved individual thrust sheets about 20 to 40 miles laterally, although the total movement on all faults is estimated at about 100 miles (Royse and others, 1975; Wiltschko and Dorr, 1983). Normal or extensional faulting occurred from the Eocene to the present (Armstrong and Oriel, 1965). The north-south axis of the WIUTB roughly parallels the eastern hinge line of a Paleozoic and early Mesozoic miogeosyncline with a depocenter in the current study area location (Monley, 1971). The transition from west to east of thick marine section to thinner shelf section in the WIUTB provides source and reservoir intervals and traps for hydrocarbon systems in the study area (Powers, 1995).

Hydrocarbon Production and Exploration

Hydrocarbons have been produced from the WIUTB area since the significant discovery of the 1975 Pineview field, whereas exploration dates back to the 1890s (Powers, 1995). Through 1995, almost 30 oil and gas fields, of which 24 are still productive, have been discovered in traps along three of the major thrust systems (Powers, 1995). According to Powers (1995), cumulative production from these fields, five of which he labeled as giant fields, was 253 MMBO and 5.1 TCFG to the end of 1992. As part of additional exploration, seismic surveying, and drilling, new field discoveries have been heavily concentrated in southern WIUTB (Powers, 1995). Limited access (due to topography and land ownership) and seasonal restrictions in higher altitude areas impede drilling, and thus the northern WIUTB has undergone less hydrocarbon exploration (Monley, 1971).

Nevertheless, the Mississippian Madison Limestone, the Pennsylvanian Wells Formation, the Triassic Thaynes Formation and Triassic and Jurassic Nugget Sandstone, and the Jurassic Twin Creek Limestone are all considered as potential reservoirs in the WIUTB area due to evidence of porosity and hydrocarbon shows in test wells and surface exposures (Monley, 1971). After drilling nearly 100 test wells, only a fraction of the surface anticlinal trends have been tested (Monley, 1971). Monley (1971) also explains that most of these tests were probably not drilled on crestal positions of the anticlines, because of the thrust system complexity and the lack of access to seismic data at the time.

Storage Resource Assessment

The USGS regional CO_2 storage resource assessment of the WIUTB resulted in eight SAUs. Each SAU is described in the following sections and includes both a storage-formation and regional-seal pair. The SAU name is typically based on the entire stratigraphic interval or lithology considered as the storage resource (fig. 11). The geographic extents of the SAUs are defined by the depth to the top of the storage formation and by the geologic characteristics of both the reservoir and the overlying seal. Geologic characteristics described or considered for each SAU include both seal and reservoir thickness, distribution, and reservoir quality (such as net-to-gross ratio, porosity, and permeability). Specific seismic hazards are not considered when mapping our SAU boundaries; however, seismic activity exists in the WIUTB and should be considered when locally characterizing the storage formations (Pierce and Morgan, 1992; Petersen and others, 2008). Furthermore, we identify regional trends in groundwater quality because the U.S. Environmental Protection Agency (2009, 2010) stipulates that USDWs with a TDS concentration less than 10,000 mg/L may not be used for CO_2 storage. For the WIUTB assessment, groundwater quality, based on TDS content, was compiled for Wyoming and the neighboring States from multiple databases (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; Blondes and Gosai, 2011).

This assessment was conducted following the methodology of Burruss and others (2009), Brennan and others (2010), and Blondes and others (2013) that prescribes the geologic model employed here, a probabilistic statistical analysis, and subsurface conditions favoring supercritical phase CO_2. Subsurface conditions favoring CO_2 storage at high density include relatively high basin pressures and temperatures (Buursink, 2012). Based on the methodologies, our assessed storage resource was allocated between residual trapping (typically larger but less certain) and buoyant trapping (typically smaller but more certain). Residual trapping occurs at the pore scale, and buoyant trapping is analogous to stratigraphic and (or) structural hydrocarbon trapping. The minimum buoyant-trapping volume is determined from cumulative oil and gas production together with the known hydrocarbon reserve volume, whereas the most likely buoyant-trapping volume adds the minimum volume and the estimated volumes of undiscovered resources (Brennan and others, 2010; IHS Energy Group, 2010; Nehring Associates, 2010). The maximum buoyant resource is determined by the assessment geologist. Upon completion of the assessment, the following SAUs, listed by name and number, are described: Paleozoic Composite C50360101, Paleozoic Composite Deep C50360102, Nugget Sandstone C50360103, Nugget Sandstone Deep C50360104, Bear River Formation C50360105, Bear River Formation Deep C50360106, Frontier Sandstone C50360107, and Frontier Sandstone Deep C50360108.

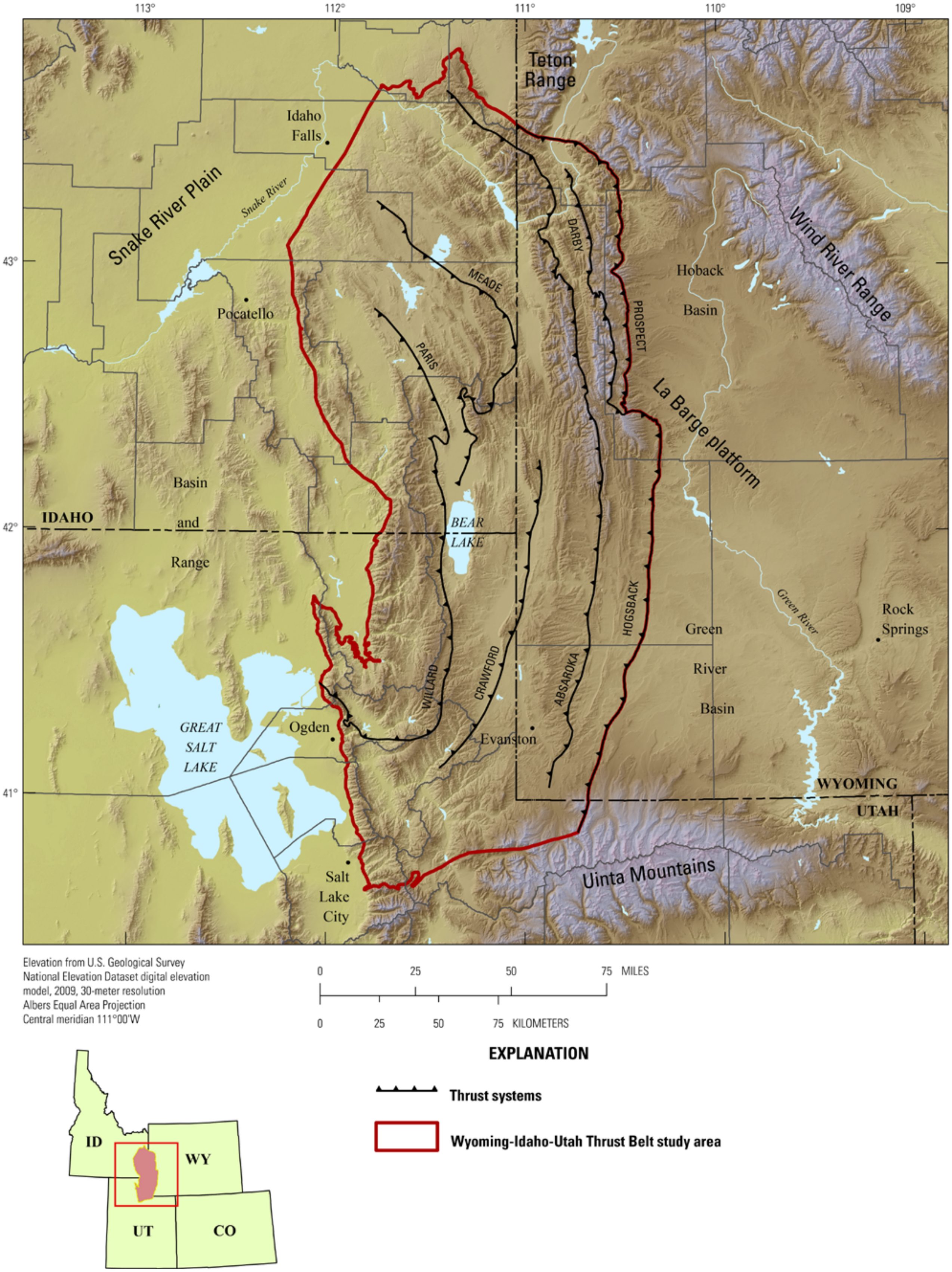

Figure 10. Map showing the Wyoming-Idaho-Utah Thrust Belt study area including major structural features (after Royse, 1993; fig. 1). Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

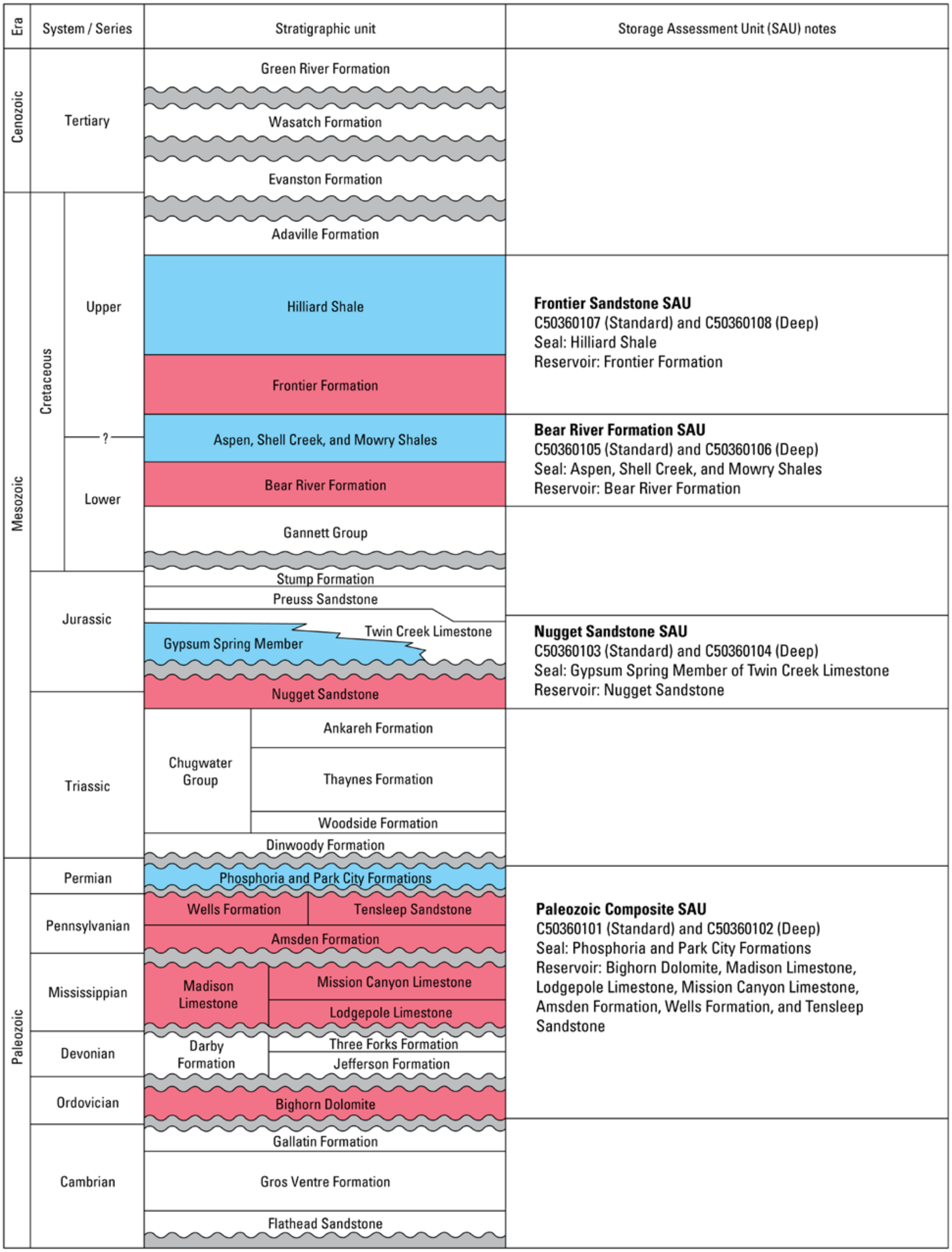

Figure 11. Generalized stratigraphic column of geologic units in the Wyoming-Idaho-Utah Thrust Belt study area (modified from Powers, 1995). Storage assessment units (SAUs) consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray areas represent unconformities or hiatuses. In some cases, subdivisions of units or lesser known correlative units are not shown.

Paleozoic Composite SAU C50360101 and Paleozoic Composite Deep SAU C50360102

By Marc L. Buursink and Ernie R. Slucher

The Paleozoic Composite SAUs comprise the Middle Cambrian to Lower Permian geologic section deemed suitable as reservoirs for CO_2 storage that occur beneath a regionally extensive seal in the WIUTB (fig. 10). The suitable reservoir rocks consist of siliciclastic and carbonate lithologies and include, in ascending stratigraphic order, the Ordovician Bighorn Dolomite, the Mississippian Madison, Lodgepole, and Mission Canyon Limestones, the Mississippian and Pennsylvanian Amsden Formation, and the Pennsylvanian Wells Formation or its correlative Tensleep Sandstone (Boyd and others, 1989; Powers, 1995; U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004) (fig. 11). Regionally, the Permian Phosphoria Formation and its stratigraphic equivalent, the Park City Formation, overlie the Wells Formation and function as the sealing formations (Rascoe and Baars, 1972; Lines and Glass, 1975; Peterson, 1980; Whalen, 1996). Paleozoic units in the WIUTB are composed of marine strata deposited in the transitional area between a syncline to the west (eastern Idaho and Utah) and a continental shelf to the east. Beginning in the Mississippian, the miogeosyncline along with the site of maximum deposition shifted eastward. The WIUTB was largely folded and thrusted eastward starting in the Late Jurassic (Lines and Glass, 1975; Powers, 1995). The Bighorn Dolomite comprises gray, fine- to medium-grained massive dolomite and dolomitic limestone; whereas the Madison Limestone is equivalent to the Mission Canyon and Lodgepole Limestones in the WIUTB and GGRB and comprises gray to brown and thin-bedded to massive deposits (Schroeder, 1969). The Amsden Formation comprises multicolored mudstone, siltstone, and sandstone. The Wells Formation comprises mainly gray and thick-bedded limestone with quartz and calcite grains, and the Tensleep Sandstone comprises white to pink, well-sorted deposits (Armstrong and Oriel, 1965). The Cambrian units in the WIUTB are not suitable storage formations, because of their poor reservoir quality (porosity and permeability).

The Paleozoic Composite and Paleozoic Composite Deep SAU boundaries (figs. 12 and 13) are constrained by the depth below the surface of the uppermost storage formation. Formation picks (IHS Energy Group, 2010) for the top of the Wells Formation, or its correlative the Tensleep Sandstone, helped to define the top of the storage area. The Paleozoic Composite SAU lies between 3,000 and 13,000 ft in depth and encompasses about a 3.3-million-acre most likely area; and the Paleozoic Composite Deep SAU lies between 13,000 and 29,000 ft and encompasses about a 5.1-million-acre most likely area. The interpretations of thickness and depth are supported by numerous published cross sections, which are based on well logs and seismic surveys (Royse and others, 1975; Dixon, 1982; Craddock and others, 1988; Dickinson and Matthews, 1993; Mitra, 1994). Regionally, the gross thickness of the composite Paleozoic SAU sequences ranges from tens to thousands of feet with most of the stratigraphic section being preserved; the interval thickens westward in the study area (Armstrong and Oriel, 1965; Lines and Glass, 1975). The Paleozoic Composite SAU gross thickness ranges from 3,000 to 5,000 ft with a net thickness from 1,000 to 1,700 ft, and the Paleozoic Composite Deep SAU gross thickness ranges from 2,500 to 4,500 ft with a net thickness from 900 to 1,600 ft. Because the storage formations are involved in thrust systems, the two Paleozoic Composite SAUs may overlap in areas of the WIUTB.

The overall depth of the Paleozoic interval in the WIUTB generally restricts the hydrocarbon potential, and thus limited well log and core data exist. Therefore, porosity and permeability trends for individual formations within the composite SAUs were estimated from relevant sandstone and carbonate analogs (Fox and others, 1975; Nelson and Kibler, 2003; Johnson, 2005; Ehrenberg and others, 2009; Thyne and others, 2010) obtained from the Wyoming water-plan report (Geldon, 2003), and average field values were extracted from Nehring Associates (2010). The Paleozoic Composite SAU porosity ranges from 5 to 13 percent, whereas the permeability ranges from 0.1 to 300 mD. The Paleozoic Composite

Deep SAU porosity ranges from 2 to 9 percent, whereas the permeability ranges from 0.01 to 10 mD. The occurrence and distribution of these reservoir properties in the composite SAUs is mainly a function of the storage-formation lithology and depths.

Water-quality data obtained from multiple published databases (Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; Blondes and Gosai, 2011) for the SAU indicated mixed fresh and saline waters in the WIUTB. Areas exist in each SAU where the groundwater TDS value is both under and above the USDW limit of 10,000 mg/L. Generally, groundwater TDS values increase slightly with depth in the assessment area. Given the paucity of available hydrocarbon data, the Nehring Associates (2010) average field size was used and multiplied by a factor of five to create a probabilistic maximum volume for buoyant trapping for each SAU.

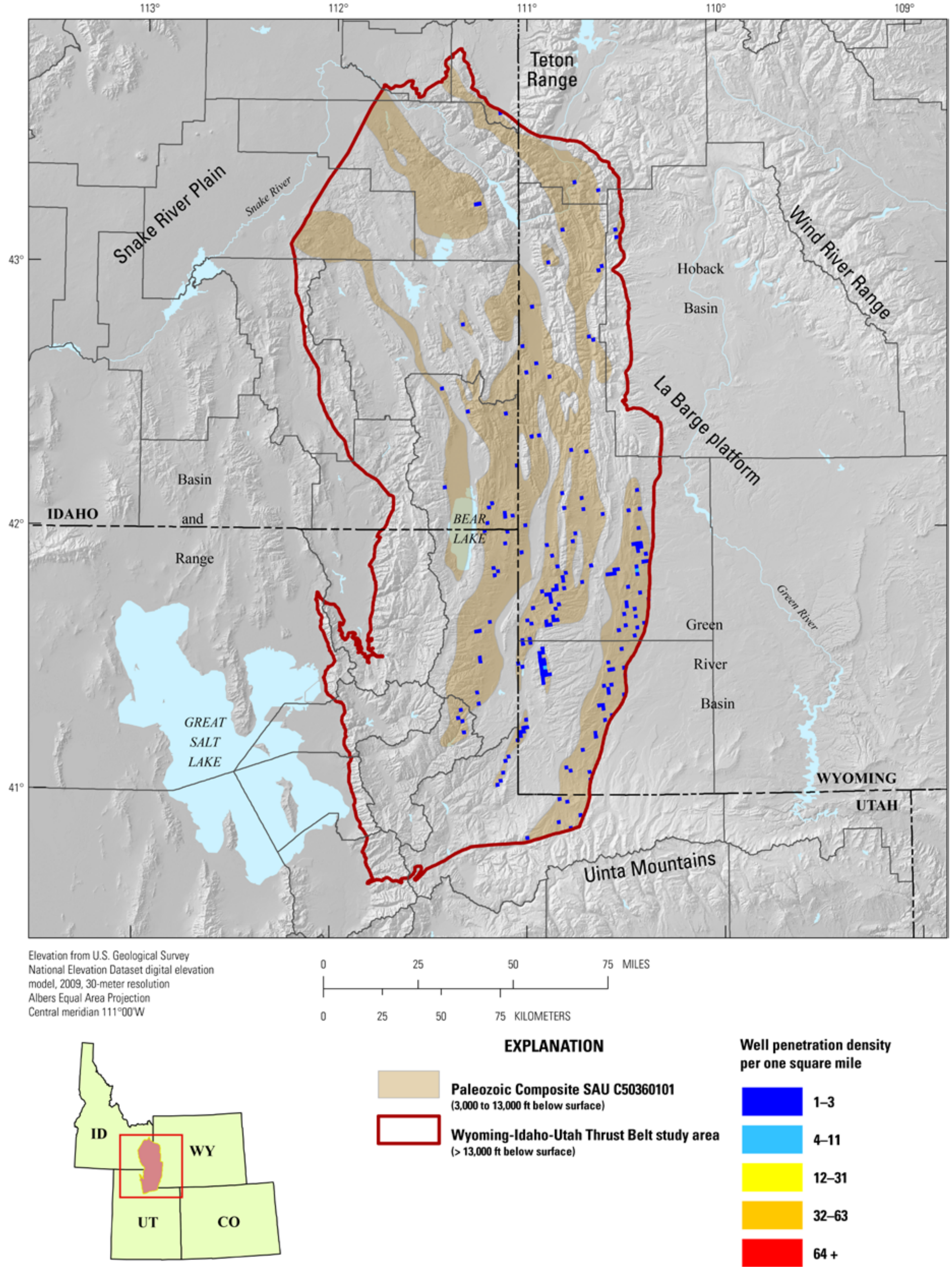

Figure 12. Map showing the Paleozoic Composite Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

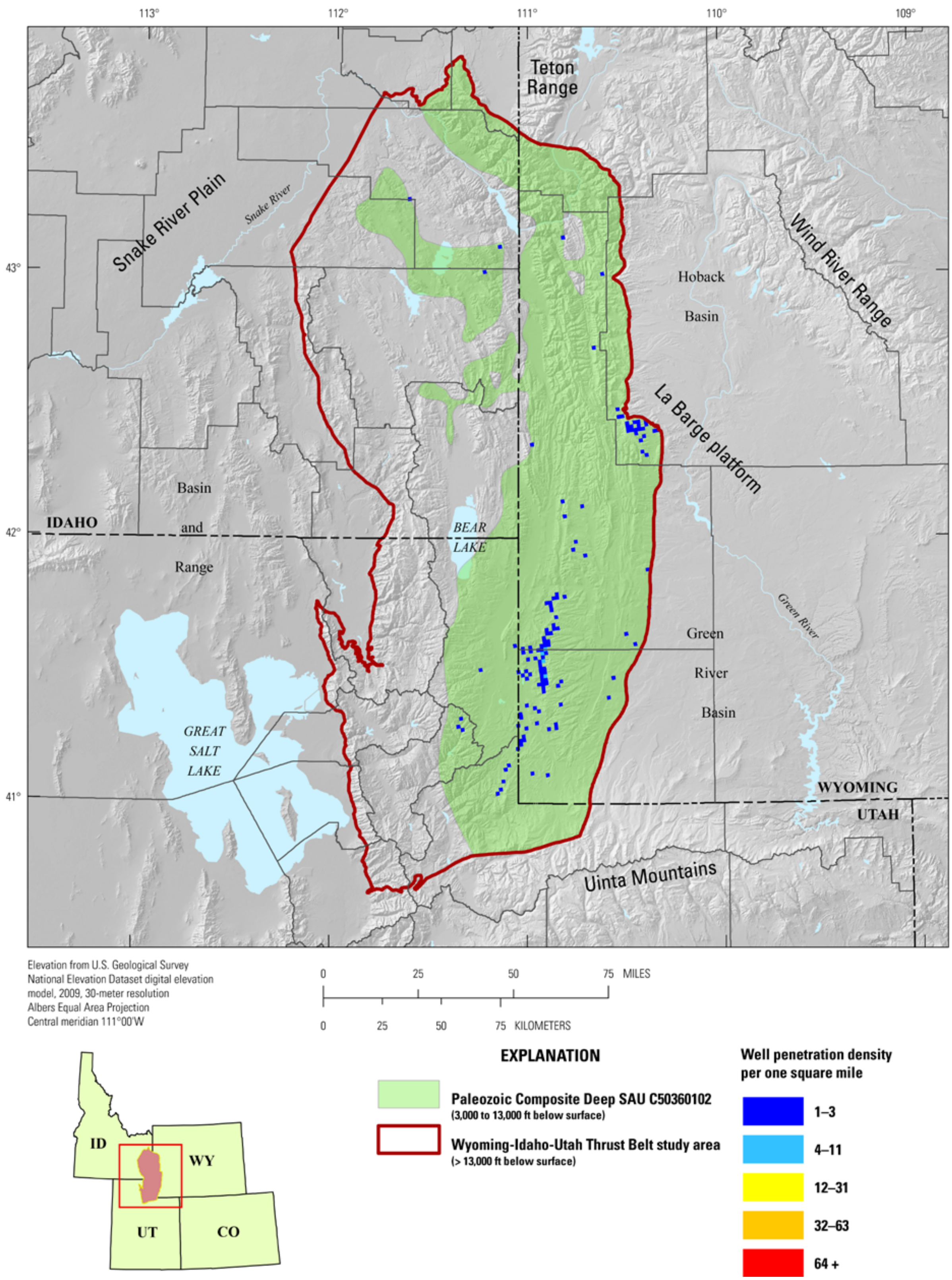

Figure 13. Map showing the Paleozoic Composite Deep Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

Nugget Sandstone SAU C50360103 and Nugget Sandstone Deep SAU C50360104

By Matthew D. Merrill and Colin A. Doolan

The Nugget Sandstone is Late Triassic to Early Jurassic in age and is a predominantly eolian deposit. In the WIUTB (fig. 10), it overlies the Triassic Ankareh Formation and is unconformably overlain by the Middle Jurassic Twin Creek Limestone, which comprises limestones, shales, and evaporites (Tillman, 1989) (fig. 11). The upper two-thirds of the roughly 1,000-ft-thick Nugget Sandstone is characterized by relatively high porosity, large-scale dunes that are generally a target for oil and gas exploration. Conversely, the basal one-third of the sandstone exhibits smaller scale eolian features that apparently were deposited in a low-relief sheet-sand environment, and these may have been affected by periods of standing water or an elevated water table (Lindquist, 1988).

The Nugget Sandstone SAU and Nugget Sandstone Deep SAU in the WIUTB comprise about 4,150,000 and 4,006,000 acres, respectively (figs. 14 and 15). SAU boundaries are limited to the interpreted extent of the basal Twin Creek Limestone's Gypsum Spring Member, a regional sealing unit that lies unconformably on top of the Nugget Sandstone (Freethey and Cordy, 1991). In the WIUTB, the Gypsum Spring Member has an average thickness of about 175 ft , which was calculated by differencing stacked formation-top depths (IHS Energy Group, 2010). In addition to being restricted to the extent of the overlying sealing formation, the SAU is also constrained by the extent of the Nugget Sandstone where its depth from surface is between 3,000 and 13,000 ft for the standard SAU and greater than 13,000 ft for the deep SAU, whose maximum depth reaches to 26,000 ft. In the WIUTB, these depth estimates are complicated by the thrust systems present in the study area that result in repeated or truncated SAU strata. As a consequence of the variable depths to the top of the Nugget Sandstone, the SAUs comprise arcuate and elongate north–south trending areas that reflect the depth of the Nugget Sandstone in the subsurface; and these roughly parallel the strike of the thrust systems (fig. 10). Furthermore, the standard and deep SAUs overlap, which is due to the overthrusted nature of the Nugget Sandstone in the WIUTB.

Total thickness of the Nugget Sandstone ranges from 800 to 1,200 ft (Frank and Gavlin, 1981; Tillman, 1989; Edman and Cook, 1992), whereas the net-porous-interval thickness exhibits a wider range from 50 to 840 ft with 500 ft as a most likely thickness (data from Sercombe, 1989; White and others 1990; Chidsey, 1993, Nehring Associates, 2010). Reservoir porosities of 5 to 18 percent occur with most likely porosities of 13 percent in the standard SAU and 8 percent in the deep SAU (data from Frank and Gavlin, 1981; Sercombe, 1989; Tillman, 1989; Nehring Associates, 2010). Permeability in the Nugget Sandstone ranges from 0.5 mD to a maximum of 600 mD with a most likely permeability of 20 mD in the standard SAU and a maximum of 65 mD with a most likely permeability of 10 mD in the deep SAU. As in neighboring Rocky Mountain basins, water quality in the Nugget Sandstone of the WIUTB is generally saline (>10,000 mg/L TDS USDW limit) due to the presence of evaporate deposits within and above the unit (Blondes and Gosai, 2011).

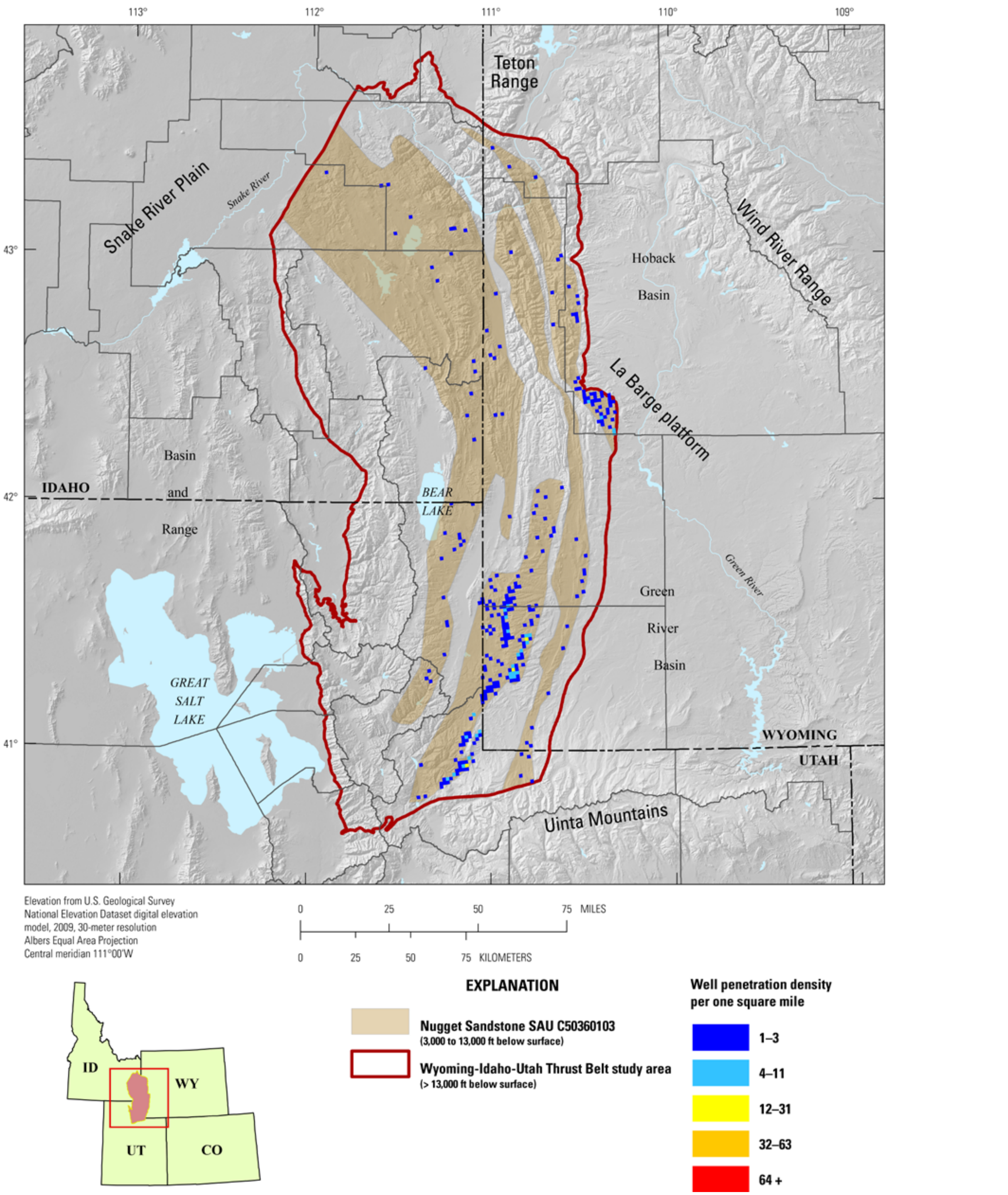

Figure 14. Map showing the Nugget Sandstone Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

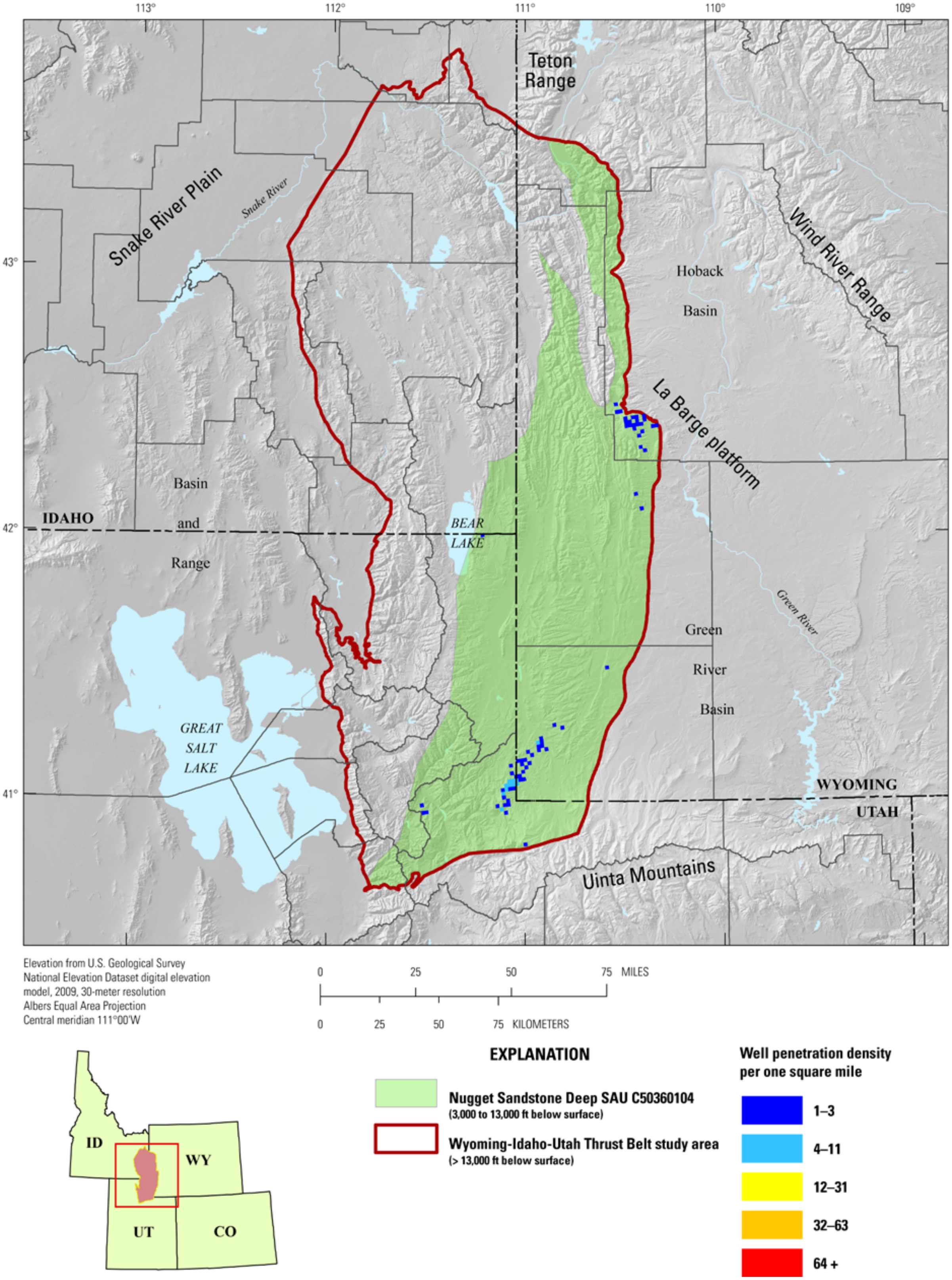

Figure 15. Map showing the Nugget Sandstone Deep Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

Bear River Formation SAU C50360105 and Bear River Formation Deep SAU C50360106

By Ronald M. Drake and Matthew D. Merrill

The Bear River Formation in the WIUTB (fig. 10) is Early Cretaceous age, and it records the initial transgression of the empiric Cretaceous seaway into southwestern Wyoming and northern Utah (Reisser and Blanke, 1989). The Bear River Formation is predominantly a fluvial and nearshore deposit and is correlative to the Dakota and Muddy Sandstones in the Bighorn and Powder River Basins. In the WIUTB, Bear River Formation overlies the Gannett Group and is overlain by the Cretaceous Aspen, Shell Creek, and Mowry Shales (Ryer and others, 1987, fig. 1) (fig. 11). These shales are 400 to 2,300 ft thick (Jordan, 1981) and form a regional top seal for the SAUs described next.

The Bear River Formation SAU and Bear River Formation Deep SAU in the WIUTB comprise areas of roughly 1,846,000 and 1,630,000 acres, respectively (figs. 16 and 17). Boundaries for the Bear River Formation SAU and Bear River Formation Deep SAU are based on plotted interpretations of formation tops from a commercial database (IHS Energy Group, 2010), published cross sections (Royse and others, 1975), and the Dakota Sandstone structure-contour map by Roehler (1977). Compared to other major basins in the Wyoming area, the WIUTB is lacking in subsurface data and in interpretive maps and cross sections of the Bear River Formation; therefore, we relied extensively on borehole data. The SAU boundary for the Bear River Formation SAU includes the area defined by boreholes with Bear River Formation (and equivalent Dakota Sandstone and Kelvin Formation) tops between 3,000 and 13,000 ft. The boundaries for the Bear River Formation Deep SAU include the area where tops of the Bear River Formation in boreholes are deeper than 13,000 ft. These SAUs form elongate, north-south, arcuate shapes that show the effects of major thrusting in the area. In some cases the storage formations are repeated at depth and the standard SAU overlies the deep SAU.

Within the Bear River Formation SAU, the formation thickness ranges from 750 to 1,200 ft with net-porous-sand thicknesses ranging from 170 to 260 ft and a most likely net-porous-sand thickness of 220 ft (data from Royse and others, 1975). Within the Bear River Formation Deep SAU, formation thickness ranges from 700 to 1,200 ft (average of 1,000 ft) with net-porous thicknesses of 150 to 260 ft and a most likely net-porous thickness of 220 ft (data from Royse and others, 1975).

Porosity and permeability data were obtained from a State database (Wyoming Oil and Gas Conservation Commission, 2010) and from NOGA (Powers, 1995). The average porosities for the Bear River Formation SAU were reported as ranging from 7 to 16 percent in this assessment with a most likely porosity of 11 percent. The average porosities for the Bear River Formation Deep SAU were reported as ranging from 5 to 10 percent with a most likely porosity of 8 percent. Permeabilities for the Bear River Formation were reported as ranging from 0.01 to 50 mD. Permeabilities for the Bear River Formation Deep SAU were reported as ranging from 0.001 to 30 mD.

Water-quality data were compiled from several sources including a State database (Wyoming Oil and Gas Conservation Commission, 2010), a university database (University of Wyoming Enhanced Oil Recovery Institute, 2010), and a compiled water-quality database (Blondes and Gosai, 2011). The water-quality data from the Bear River Formation were plotted on a map, and areas were identified that contained high concentrations of TDS above the 10,000 mg/L USDW limit. High TDS measurements are generally confined near the La Barge platform and are only found within the Bear River Formation SAU.

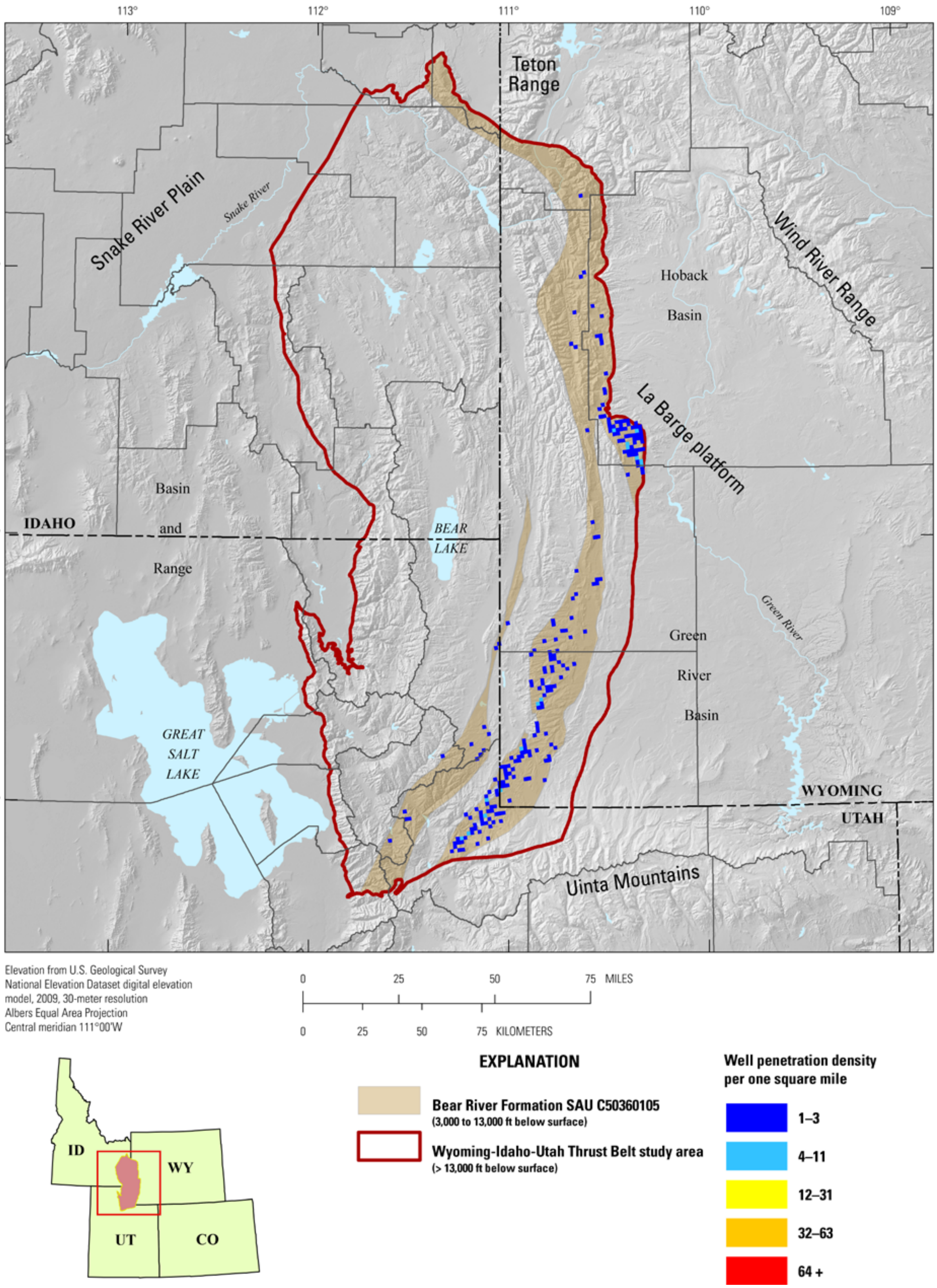

Figure 16. Map showing the Bear River Formation Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

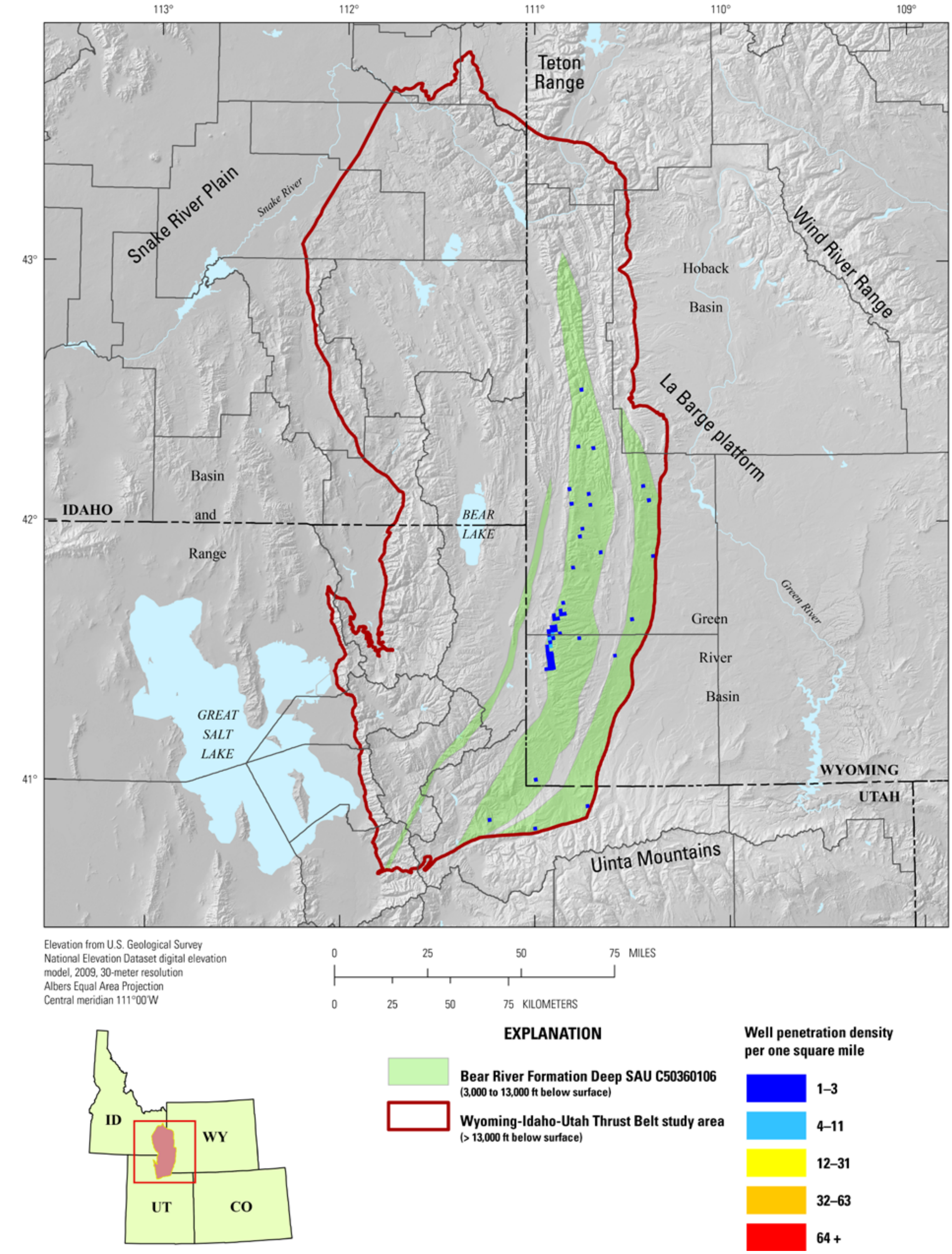

Figure 17. Map showing the Bear River Formation Deep Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

Frontier Sandstone SAU C50360107 and Frontier Sandstone Deep SAU C50360108

By Sean T. Brennan

The Frontier Formation was deposited in a nearshore environment along the western edge of the Cretaceous Western Interior Seaway. The undiscovered Cretaceous oil and gas resource was assessed by the U.S. Geological Survey within the neighboring GGRB (Kirschbaum and Roberts, 2005a), and the results of that study along with the accompanying framework geology report (Kirschbaum and Roberts, 2005b) were used extensively for this CO_2 storage resource assessment. The Frontier Formation within the WIUTB (fig. 10) comprises five members, which are, in ascending order, the Chalk Creek, Coalville, Allen Hollow Shale, Oyster Ridge Sandstone, and Dry Hollow Members (Hale, 1960; M'Gonigle and others, 1995; Kirschbaum and Roberts, 2005b) and is a marine regressive-transgressive, nearshore deposit throughout the WIUTB (Kirschbaum and Roberts, 2005a,b). The Frontier Formation is generally overlain by the marine Hilliard Shale or locally by the Baxter Shale (fig. 11). These shales, when present, are thousands of feet thick across the GGRB (Finn and Johnson, 2005b; Kirschbaum and Roberts, 2005a,b) and the neighboring WIUTB.

The WIUTB comprises a series of thrust sheets and thus contains repeat sections of stratigraphic units due to overthrust (Dixon, 1982). Erosion of the exposed overthrust stratigraphy removed the Hilliard Shale from the center to the western extent of the WIUTB, and therefore the size of both the Frontier Sandstone and Frontier Sandstone Deep SAUs was limited by the extent and presence of the Hilliard Shale (Hoffman and Kelly, 1981; Dixon, 1982; White and others, 1990; Dischinger and Mitra, 2006). Furthermore, the depth from the surface to the top of the Frontier Formation and the SAUs therein was based on well data (IHS Energy Group, 2010) (figs. 18 and 19). The most likely areas of the Frontier Sandstone and Frontier Sandstone Deep SAUs are 755,000 and 846,000 acres, respectively. The SAUs have arcuate shapes that follow thrust sheets and are discontinuous because the SAUs are on two separate thrust sheets (fig. 10).

The thickness of the Frontier Formation has a wide range within WIUTB (250 to 4,000 ft), but the average range of thickness is 600 to 1,400 ft in the Frontier Sandstone SAU and 800 to 1,600 ft in the Frontier Sandstone Deep SAU (data from Kirschbaum and Roberts, 2005b). The net-porous interval of the Frontier Sandstone SAU ranges from 250 to 400 ft thick and in the Frontier Sandstone Deep SAU ranges from 300 to 400 ft thick (data from Goodell, 1962). The porosity values from the Frontier Sandstone throughout the northern Rocky Mountains were used as an analog as there were very few reported porosity values for the Frontier Formation of the WIUTB. The range of porosities in the Frontier Sandstone SAU is from 12 to 17 percent and in the Frontier Sandstone Deep SAU is from 5 to 9 percent (Nehring Associates, 2010). The permeability values for the Frontier Formation throughout the northern Rocky Mountains (Nehring Associates, 2010) were also used as an analog for the permeability of the Frontier Formation within the WIUTB. The estimated permeabilities of the Frontier Sandstone SAU range from 0.1 to 100 mD with a most likely permeability of 1 mD, and in the Frontier Sandstone Deep SAU, permeabilities range from 0.01 to 10 mD with a most likely permeability of 0.1 mD.

Analysis of the salinity of the formation water within the Frontier Formation (Blondes and Gosai, 2011) indicates that there are areas of the SAUs that contain water greater than, and other areas that contain water less than, the USDW threshold requirements of 10,000 mg/L TDS (Brennan and others, 2010). Based on this analysis, on average, 10 percent of the Frontier Sandstone SAU and 40 percent of the Frontier Sandstone Deep SAU are available for CO_2 storage.

The buoyant resource values were based on (a) known production from the Frontier Formation (Nehring Associates, 2010), (b) estimates of the undiscovered hydrocarbon resource (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004), and (c) computing the volume of closures by estimating the potential numbers and sizes of both stratigraphic traps and structural closures.

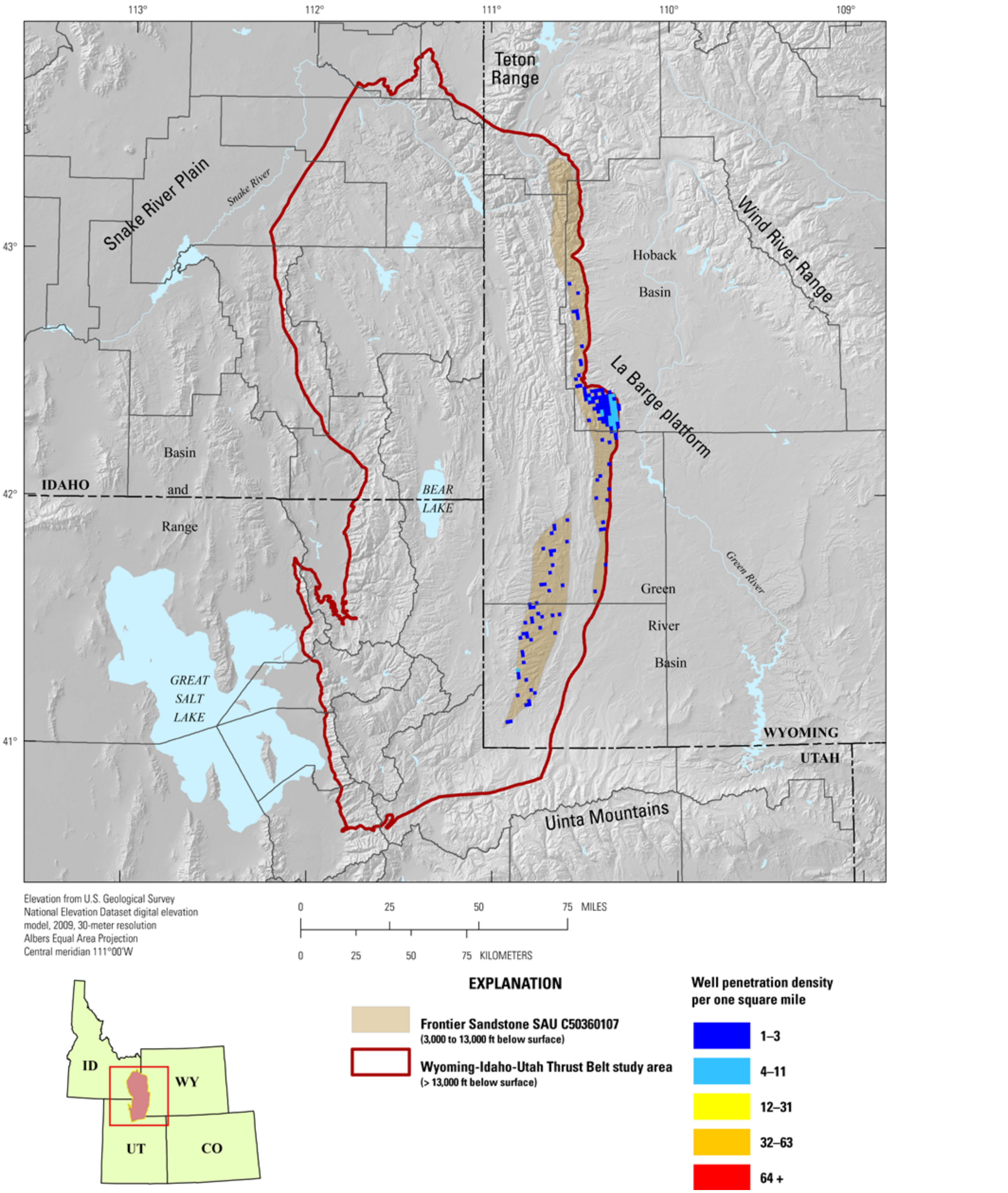

Figure 18. Map showing the Frontier Sandstone Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

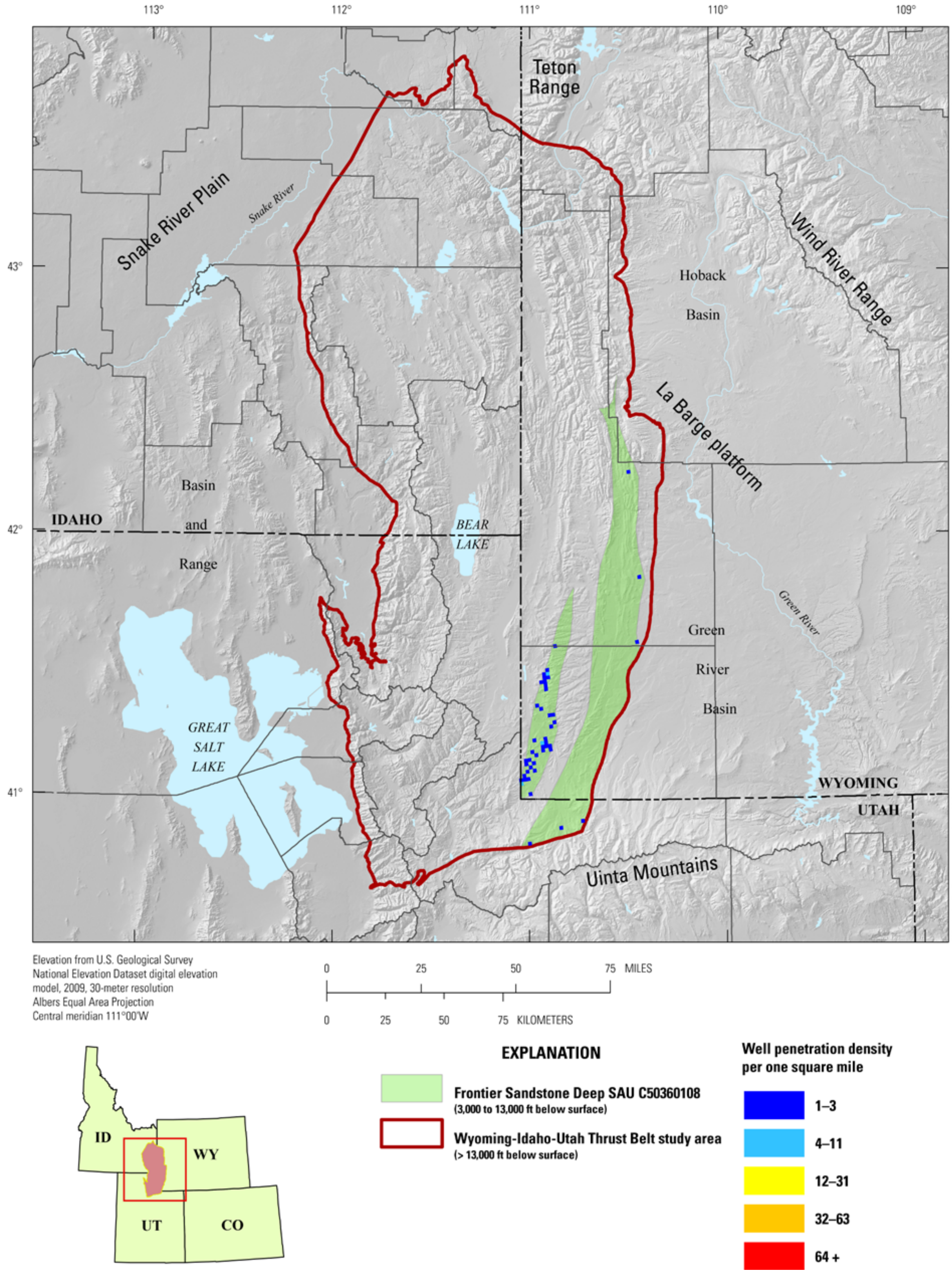

Figure 19. Map showing the Frontier Sandstone Deep Storage Assessment Unit (SAU) in the Wyoming-Utah-Idaho Thrust Belt. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the storage-formation top. Study area boundaries were modified from the U.S. Geological Survey national oil and gas assessment (NOGA) (U.S. Geological Survey Wyoming Thrust Belt Province Assessment Team, 2004).

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