Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Denver Basin, Colorado, Wyoming, and Nebraska

By Ronald M. Drake II, Sean T. Brennan, Jacob A. Covault, Madalyn S. Blondes, Philip A. Freeman, Steven M. Cahan, Christina A. DeVera, and Celeste D. Lohr

Chapter G 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 milligrams per liter (mg/L) of 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 (2010) defines the lower limit of 10,000 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 mg/L TDS are not assessed (Brennan and others, 2010; Blondes and others, 2013).

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

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
meter (m)	3.281	foot (ft)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
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)

Abbreviations

CO_2	carbon dioxide
SAU	storage assessment unit
TDS	total dissolved solids
USGS	U.S. Geological Survey

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Abstract

This is a report about the geologic characteristics of five storage assessment units (SAUs) within the Denver Basin of Colorado, Wyoming, and Nebraska. These SAUs are Cretaceous in age and include (1) the Plainview and Lytle Formations, (2) the Muddy Sandstone, (3) the Greenhorn Limestone, (4) the Niobrara Formation and Codell Sandstone, and (5) the Terry and Hygiene Sandstone Members. The described characteristics, as specified in the methodology, affect the potential carbon dioxide storage resource in the SAUs. The specific geologic and petrophysical properties of interest include depth to the top of the storage formation, average thickness, net-porous thickness, porosity, permeability, groundwater quality, and the area of structural reservoir traps. Descriptions of the SAU boundaries and the overlying sealing units are also included. Assessment results are not contained in this report; however, the geologic information included here will be used to calculate a statistical Monte Carlo-based distribution of potential storage volume in the SAUs.

Introduction

The Denver Basin is a Laramide-age, asymmetric structural foreland basin located east of the Rocky Mountain Front Range (Higley and others, 1995). The basin extends from southeastern Colorado, north to the Nebraska-South Dakota border and from the eastern edge of the Front Range to about the Colorado-Kansas border (fig. 1). The basin is elongated north–south and is about 330 miles (mi) long and about 180 mi wide. It is bounded on the northwest and northeast by the Hartville uplift and the Chadron arch, respectively, on the southeast by the Las Animas arch, on the southwest by the Apishapa uplift, and on the west by the Rocky Mountain Front Range. The basin is more than 13,000 ft deep near Denver (Martin, 1965) and is steeply dipping along the western flank and gently dipping along the eastern flank of the basin. Most of the thickness of deposits in the basin is from stratigraphic units ranging in age from Pennsylvanian to Tertiary (fig. 2).

Hydrocarbon Exploration

Wells within the Denver Basin have produced more than 1.05 billion barrels of oil and 3.67 trillion cubic feet of natural gas (Higley and Cox, 2007). Most of the oil and gas has been produced from Cretaceous rocks in the basin with most oil production from the Lower Cretaceous Muddy (“J”) Sandstone and the Upper Cretaceous “D” sandstone (Higley and Cox, 2007), which are mainly from fluvial, incised-valley, and deltaic environments. The “D” and “J” sandstones are informal economic units. There has also been production from Paleozoic-age deposits, for example, the Permian Lyons Sandstone, and there is some potential for gas from coals in the Upper Cretaceous Laramie Formation and lower Tertiary and Upper Cretaceous Denver Formation (Higley and Cox, 2007).

Geologic History

During Late Cambrian to Early Ordovician, sediments in the area of the Denver Basin were deposited in a shallow marine environment (Kent, 1972) and consisted of sands, calcareous deposits, and dolomites. The conformable Ordovician sequence (Graffin, 1992) includes, from oldest to youngest, the Manitou Formation, Harding Sandstone, and Fremont Dolomite. The Harding Sandstone was deposited in the southern portion of the basin during the Middle Ordovician and the Fremont Dolomite was deposited in western and south-central Colorado during the Late Ordovician. Some Upper Devonian shales, sandstones, and thin limestones were deposited indicating widespread shallow seas. Limestone and shale units (for example, Leadville Limestone) were deposited in the southern portion of the basin during the Mississippian. The Ancestral Rocky Mountains formed along the west side of the Denver Basin during the Pennsylvanian and subsequent deposition of great thicknesses of coarse arkosic clastic sediments (the Pennsylvanian part of the Fountain Formation) were deposited in the basin (Kent, 1972). The Ancestral Rocky Mountains continued to be eroded during the Permian and thick deposits of coarse material continued to collect adjacent to the uplift, while finer material accumulated farther away from the uplift. The Permian deposits include the upper part of the Fountain, Ingleside, and Owl Canyon Formations, Lyons Sandstone, and lower part of the Lykins Formation.

During the Triassic, mostly subaerial deposits, such as the upper part of the Lykins Formation and the Jelm Formation, were deposited in the central and northern portion of the Denver Basin (McCoy, 1953). In the Jurassic, Morrison Formation nonmarine variegated shales, freshwater limestones, and sandstones were deposited. During the Cretaceous, the Western Interior Seaway covered the basin and there were several sea level fluctuations that led to varied depositional environments and strata. The Cretaceous deposits (fig. 2) compose the majority of the Denver Basin sediment thickness, and the formations analyzed in this paper are all Cretaceous age. In the latest Cretaceous to Tertiary time, the Laramide orogeny began, and uplift occurred from Mexico to Canada (English and Johnston, 2004) and along the western edge of the Denver Basin. During the earliest of Tertiary time, the Western Interior Seaway regressed and marked the end of marine deposition in the Denver Basin.

Denver Basin Carbon Dioxide Storage Resource Assessment

Reservoirs assessed for carbon dioxide (CO_2) storage in the Denver Basin include (1) Lower Cretaceous Plainview and Lytle Formations, (2) Lower Cretaceous Muddy Sandstone, (3) Upper Cretaceous Greenhorn Limestone, (4) Upper Cretaceous Niobrara Formation and Codell Sandstone Member of the Carlile Shale, and (5) Upper Cretaceous Terry and Hygiene Sandstone Members of the Pierre Shale (fig. 2). The extents of storage formations are defined by the geologic characteristics of the reservoirs and overlying seals and the subsurface physical properties of CO_2 as described in Burruss and others (2009) and Brennan and others (2010). The following sections describe each of the SAUs in the Denver Basin.

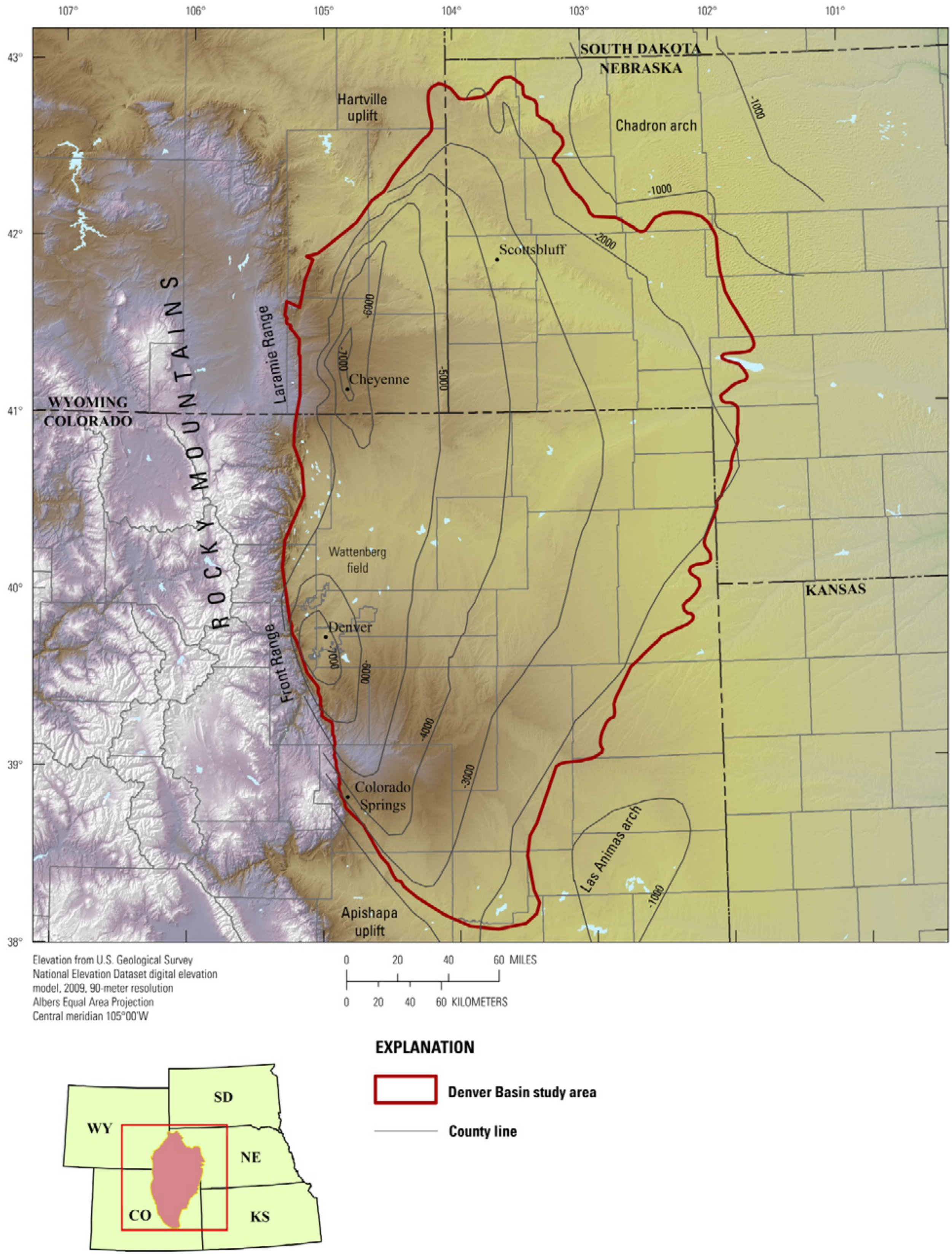

Figure 1. Map of the Denver Basin within Colorado, Wyoming, and Nebraska with structure contours on top of the Precambrian basement in feet below sea level (contour interval = 1,000 feet) from Sonnenberg (1985). Denver Basin study area boundary modified from U.S. Geological Survey National Oil and Gas Assessment project (Higley and others, 2007).

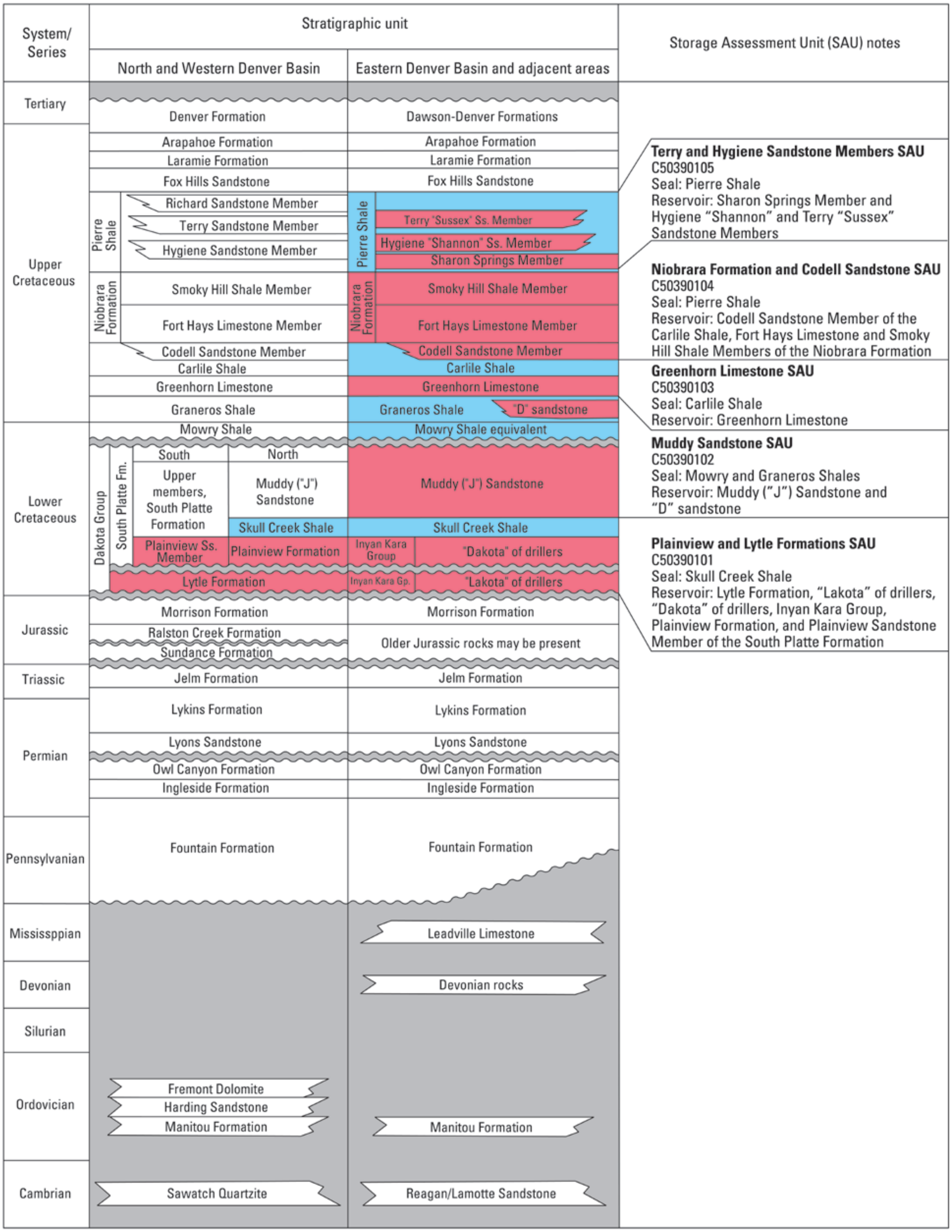

Figure 2. Generalized stratigraphic column of geologic units in the Denver Basin, Colorado, Wyoming, and Nebraska (modified from Higley and Cox, 2007). Storage assessment units consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray sections represent nonpreserved lithology. In some cases, subdivisions of units are not shown. Gp., Group; Ss., Sandstone; SAU, storage assessment unit.

Plainview and Lytle Formations SAU C50390101

By Jacob A. Covault

The Lower Cretaceous Plainview and Lytle Formations of the Dakota Group (fig. 2) average 140 ft in thickness and are predominantly very fine to medium-grained, quartz-rich, siliciclastic sandstone and conglomerate interbedded with mudstone (Haun, 1963; Gabarini and Veal, 1968; Moredock and others, 1977; Ladd, 2001; Higley and Cox, 2007). The Plainview and Lytle Formations are equivalent to the “Dakota” of driller usage, Fall River Sandstone, the “Lakota” of driller usage, and the Cheyenne Sandstone and compose the lower part of the Lower Cretaceous Dakota Group (Haun, 1963; Ladd, 2001; Higley and Cox, 2007). Within this report, the Plainview and Lytle Formations will be referred to as the lower part of the Dakota Group or the Dakota. The Dakota locally rests unconformably on the Upper Jurassic Morrison Formation (Haun, 1963). Overlying the Dakota is the Skull Creek Shale, which is equivalent to the Thermopolis Shale, and is greater than 100 ft thick across much of the Denver Basin (Haun, 1963; Moredock and others, 1977; IHS Energy Group, 2011). The Skull Creek Shale is locally thinner than 50 ft in the southern part of the Denver Basin and generally is between 50 and 100 ft thick along the western basin margin (Moredock and others, 1977; IHS Energy Group, 2011). The Skull Creek Shale is a potential hydrocarbon source rock for overlying sandstone reservoirs (for example, the Muddy Sandstone; Higley and others, 1995; Ladd, 2001; Higley and Cox, 2007) and is interpreted to be a sealing unit for the underlying Dakota. Both the Dakota and Skull Creek Shale are regionally extensive across the Denver Basin (Haun, 1963; Moredock and others, 1977; IHS Energy Group, 2011). There is a paucity of data relevant to the Dakota compared to overlying reservoir units (for example, the Muddy Sandstone). This is a result of physical separation from major petroleum source rocks and, consequently, limited production (Ladd, 2001). The Dakota and overlying Skull Creek Shale couplet has been interpreted to represent a landward retreat of depositional environments from predominantly nonmarine and marginal marine channel-filling systems (Dakota) to a fully marine system (Skull Creek Shale) in the Cretaceous Western Interior Seaway and foreland basin (Haun, 1963; Martin, 1965; Gabarini and Veal, 1968; Ladd, 2001).

The Plainview and Lytle Formations (Dakota) SAU (C50390101) is a potential reservoir unit for CO_2 storage in the Denver Basin (fig. 2) between 3,000- and 11,000-ft subsurface depths. The SAU boundary is defined by the 3,000-ft drilling depth, based on greater than 2,300 well penetrations (IHS Energy Group, 2011), and faults bounding the Denver Basin (Stoeser and others, 2007) (fig. 3). The area of the Plainview and Lytle Formations SAU is about 24,400,000 acres. The range of total storage-formation thickness for the reservoir unit was determined from using regional subsurface stratigraphic correlations of Moredock and others (1977) and isopach and net-sandstone thickness maps of Haun (1963). The thickness of the net-porous interval was from a net-sandstone thickness map of Haun (1963). Reservoir quality data for the Dakota are localized in the west-central part of the Denver Basin (Ladd, 2001). Within the Wattenberg field, porosity ranges from 1 to 13 percent and permeability ranges between 0.001 and 100 millidarcys (mD) (Ladd, 2001). Nehring Associates, Inc. (2010) indicates a single field-averaged porosity measurement of 18 percent and a permeability measurement of 150 mD. Water-quality measurements indicate that groundwater in the Dakota ranges from fresh to saline (greater than 10,000 parts per million (ppm) of total dissolved solids) (Leonard and others, 1983; Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; U.S. Geological Survey, 2011). The minimum and central tendency buoyant-trapping pore volumes were determined using methods described in Brennan and others (2010) and Blondes and others (2013). Maximum buoyant-trapping pore volume was calculated from the product of (1) the combined areas of stratigraphically analogous, overlying Muddy Sandstone reservoirs mapped by Hemborg (1993) and reservoirs of producing fields (Nehring Associates, Inc., 2010); (2) the maximum net-porous-interval thickness; and (3) the maximum porosity (Brennan and others, 2010).

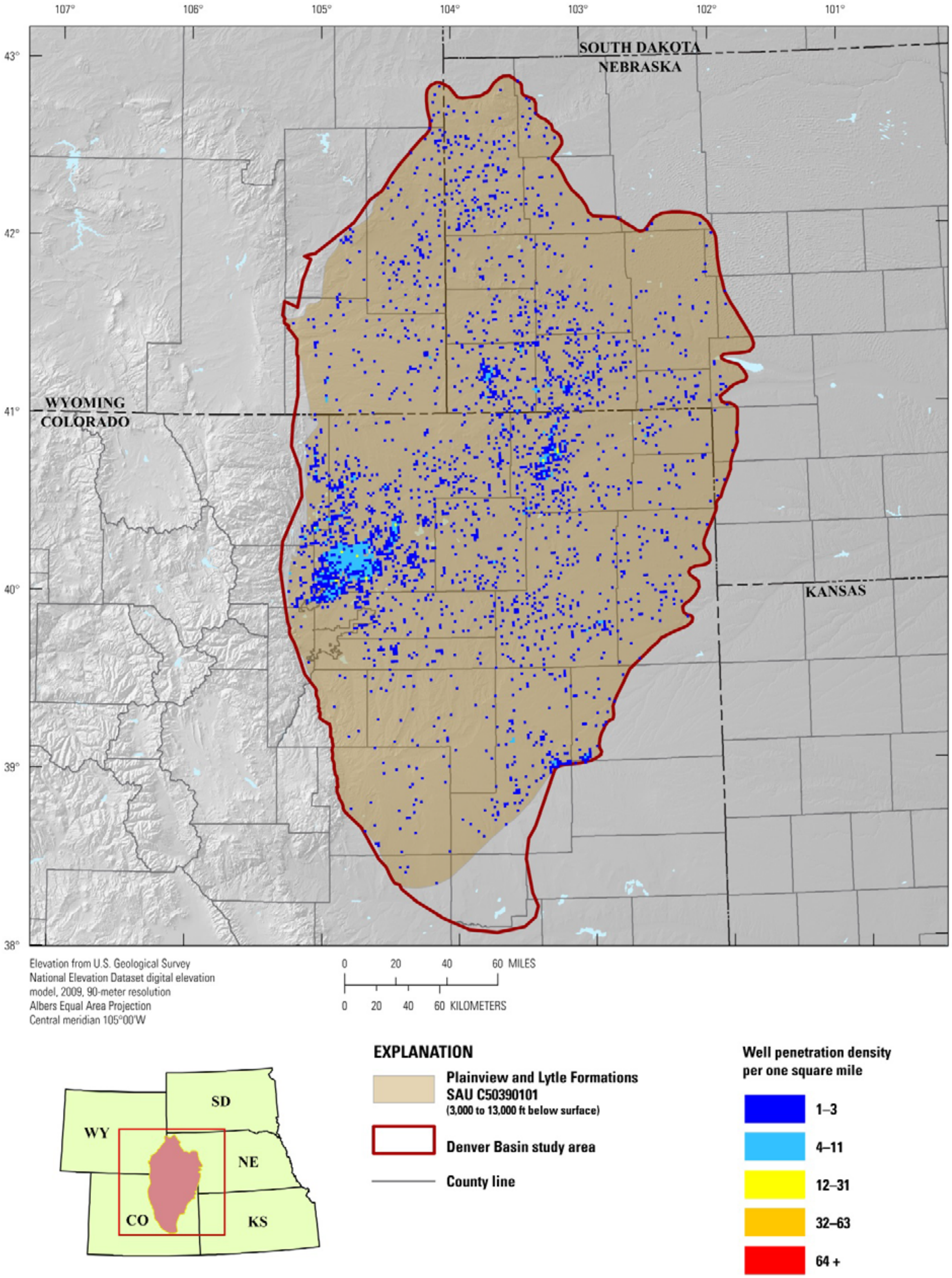

Figure 3. Map of the U.S. Geological Survey storage assessment unit (SAU) boundary for the Plainview and Lytle Formations SAU in the Denver Basin. Grid cells (one square mile) represent counts of wells derived from the ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir-formation top. Denver Basin study area boundary modified from National Oil and Gas Assessment project unit boundaries (Higley and others, 2007).

Muddy Sandstone SAU C50390102

By Jacob A. Covault

The Lower Cretaceous Muddy Sandstone averages approximately 200 ft in thickness and predominantly includes fine- to medium-grained, siliciclastic sandstone interbedded with mudstone (fig. 2) (Weimer and others, 1998; Higley and Cox, 2007). The Muddy Sandstone SAU includes Mowry Shale or the Huntsman Shale (which is not uniformly present in the subsurface of the Denver Basin) (Haun, 1963; Higley and Cox, 2007) and the overlying Graneros Shale (fig. 2). The lower part of the Muddy Sandstone SAU includes the informal “J” sandstone, and the upper part includes the informal “D” sandstone (Haun, 1963; Weimer and others, 1998; Higley and Cox, 2007). The Muddy Sandstone overlies the regionally extensive Skull Creek Shale (Haun, 1963). Overlying the Mowry Shale is the Graneros Shale, which is greater than 100 ft thick across much of the Denver Basin (Moredock and others, 1977; IHS Energy Group, 2011). The Mowry and Graneros Shales are interpreted to be the sealing units for the Muddy Sandstone SAU and are source rocks in the Denver Basin (Higley and Cox, 2007). Both the Muddy Sandstone and Graneros Shale are regionally extensive across the Denver Basin (Haun, 1963; Moredock and others, 1977; IHS Energy Group, 2011). Most of the oil and gas exploration and production in the Denver Basin has focused on the Muddy Sandstone (Higley and Cox, 2007). Muddy Sandstone reservoir strata were mainly interpreted to represent deposition in deltaic and incised-valley environments in response to shoreline regression of the Cretaceous Western Interior Seaway and foreland basin (Haun, 1963; Weimer, 1992; Weimer and others, 1998; Higley and Cox, 2007). The overlying Graneros Shale has been interpreted to represent relatively fine grained, fully marine deposition as a result of shoreline transgression (Haun, 1963; Weimer and others, 1998).

The Muddy Sandstone SAU (C50390102) is a potential reservoir unit (fig. 2) for CO_2 storage in the Denver Basin at depths between 3,000 and 10,000 ft. The SAU boundary (fig. 4) is defined by the 3,000-ft drilling depth from greater than 30,000 well penetrations (IHS Energy Group, 2011) and faults bounding the Denver Basin (Stoeser and others, 2007). The area of the Muddy Sandstone SAU is about 23,500,000 acres. The range of total storage-formation thickness for the reservoir unit was determined from more than 6,000 well penetrations (fig. 4) of the tops of the Muddy Sandstone and Skull Creek Shale (IHS Energy Group, 2011), regional subsurface stratigraphic correlations of Moredock and others (1977), and isopach and net-sandstone thickness maps of Haun (1963). The thickness of the net-porous interval was from net-sandstone thickness maps of Haun (1963). Greater than 200 reservoir-quality measurements from Nehring Associates, Inc. (2010) show an average porosity of 18 percent, with a standard deviation of 5 percent (see also Higley and Schmoker, 1989; and Schmoker and Higley, 1991). Higley and Schmoker (1989) provide constraints on the distribution of Muddy Sandstone permeability, which ranges from approximately 0.01 to 2,000 mD in their study. Water-quality measurements indicate that groundwater in the formation ranges from fresh to saline (greater than 10,000 ppm of total dissolved solids) (Leonard and others, 1983; Breit, 2002; Wyoming Oil and Gas Conservation Commission, 2010; U.S. Geological Survey, 2011). The minimum and central tendency buoyant-trapping pore volumes were determined using methods described in Brennan and others (2010) and Blondes and others (2013). Maximum buoyant-trapping pore volume was calculated from the product of (1) combined areas of Muddy Sandstone reservoirs mapped by Hemborg (1993) and reservoirs of producing fields (Nehring Associates, Inc., 2010), (2) maximum net-porous-interval thickness, and (3) maximum porosity (Brennan and others, 2010).

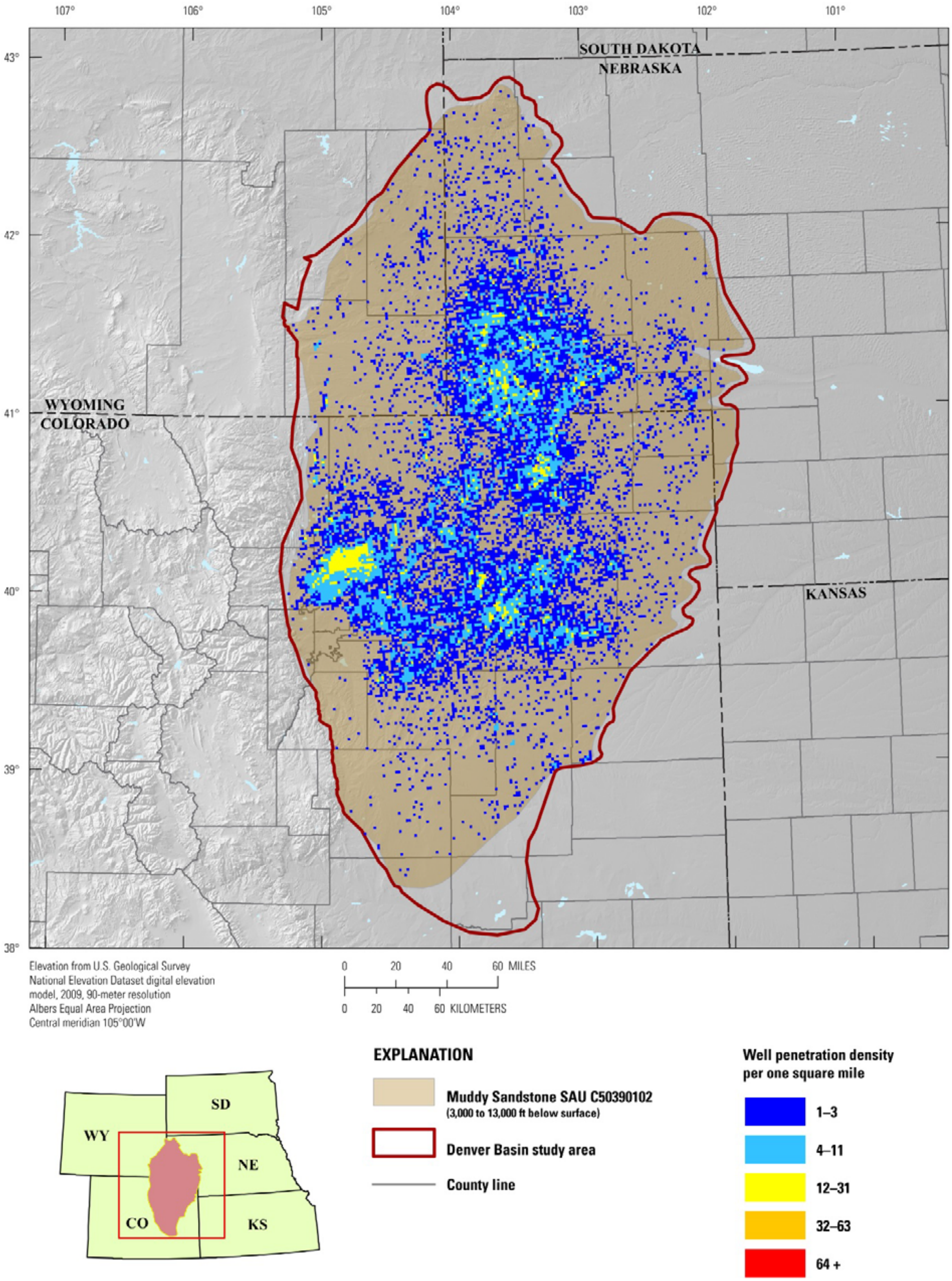

Figure 4. Map of the U.S. Geological Survey storage assessment unit (SAU) boundary for the Muddy Sandstone SAU in the Denver Basin, Colorado, Wyoming, and Nebraska. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir-formation top. Denver Basin study area boundary modified from Higley and others (2007).

Greenhorn Limestone SAU C50390103

By Ronald M. Drake II

The Upper Cretaceous Greenhorn Limestone (fig. 2) is one of the most widespread units in the Rocky Mountain region extending northward from New Mexico to Canada and from western New Mexico eastward to the South Dakota-Minnesota boundary (Hattin, 1975; Weimer and others, 1986). In central Colorado, the Greenhorn Limestone is composed of (in ascending order) the Lincoln Limestone, Hartland Shale, and the Bridge Creek Limestone Members (Sageman, 1996). Within the SAU, the Greenhorn Limestone averages approximately 125 ft in thickness (IHS Energy Group, 2010) and is composed predominantly of thin limestones, dark-gray to black organic-rich shales, and thin bentonite beds (Weimer and others, 1986; IHS Energy Group, 2011). The Greenhorn Limestone and overlying Carlile Shale were deposited in the Cretaceous Western Interior Seaway primarily as offshore muds and carbonate-rich muds deposited on a marine shelf, shelf slope, and in the deep basin (Hattin, 1975; Weimer and others, 1986). The Carlile Shale overlies the Greenhorn Limestone, and this regionally extensive unit averages about 140 ft in thickness within the SAU (IHS Energy Group, 2011); however, north and northeast of Denver, the Carlile Shale thins to less than 50 ft.

The Greenhorn Limestone SAU (C50390103) is a potential reservoir unit for CO_2 storage in the Denver Basin at depths greater than 3,000 ft below the surface. More than 1,100 well penetrations (IHS Energy Group, 2011) were used to define the SAU boundary, which is based on the top of the Greenhorn Limestone being at least 3,000 ft below the surface and the overlying sealing unit being at least 50 ft thick. There were no tops below 13,000 ft; therefore, there is no deep SAU. The area of the Greenhorn Limestone SAU is about 20,024,000 acres (fig. 5). The storage-formation thickness was calculated from boreholes penetrating both the top of Greenhorn Limestone and the top of the underlying Graneros Shale (IHS Energy Group, 2011). Regional subsurface stratigraphic correlations by Moredock and others (1977) and Weimer and others (1986), as well as an isopach map from Weimer and others (1986), were utilized to determine unit thickness. Porosity data for the Greenhorn Limestone are scarce, but available sources indicate that average porosity is about 9 percent (Hoffman and Chang, 2009; URS Corporation and others, 2009). The average net-porous thickness of 13 ft was derived from applying a net-porous thickness to gross thickness ratio estimated from available well logs (MacQuown and Millikan, 1955; Monson, 1995; Sonnenberg and Weimer, 2006). Permeability data were also scarce for the Greenhorn Limestone; therefore, permeability data were used from a report by URS Corporation and others (2009) and by using data from the overlying Niobrara Formation as an analogy with resulting permeability ranging from approximately 0.01 to 2 mD (Nehring Associates, Inc., 2010). Because of the lack of water-quality measurements from the Greenhorn Limestone, water-quality data from adjacent units were utilized and indicate that groundwater in and adjacent to the formation ranges from fresh to saline (greater than 10,000 ppm of total dissolved solids) (Breit, 2002; U.S. Geological Survey, 2011). The area of the SAU available for storage (based on water-quality restrictions) ranges between 10 and 50 percent, and the most likely value is 30 percent. The maximum buoyant-trap volume was calculated based on (1) the area of existing hydrocarbon fields and potential structures mapped within the Denver Basin, (2) maximum net-porous-interval thickness, and (3) maximum porosity (Brennan and others, 2010; Blondes and others, 2013).

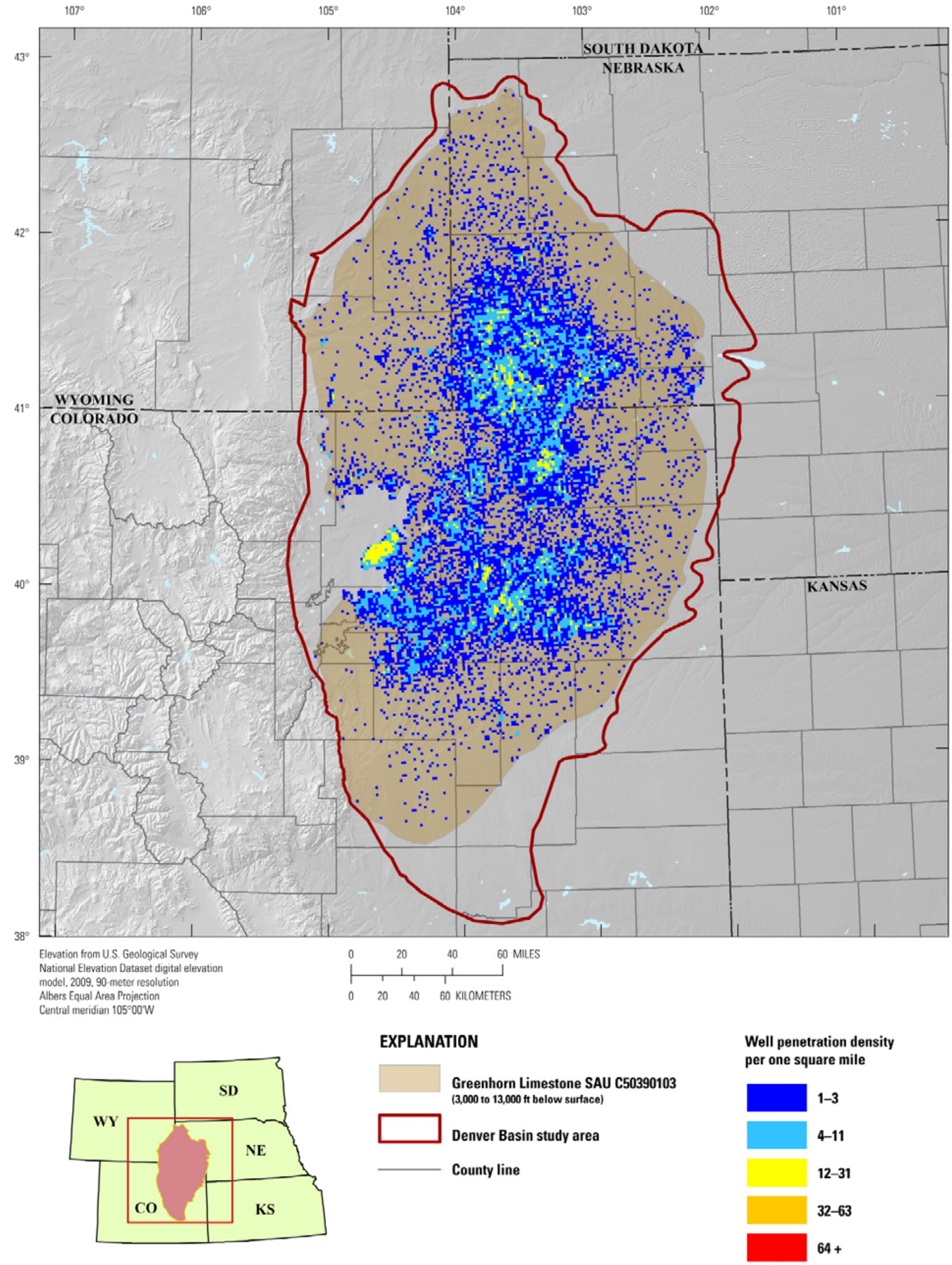

Figure 5. Map of the U.S. Geological Survey storage assessment unit (SAU) boundary for the Greenhorn Limestone SAU in the Denver Basin, Colorado, Wyoming, and Nebraska. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir-formation top. Denver Basin study area modified from Higley and others (2007).

Niobrara Formation and Codell Sandstone Member SAU C50390104

By Ronald M. Drake II

The Upper Cretaceous Niobrara Formation and Codell Sandstone SAU (C50390104) includes the Codell Sandstone Member of the Carlile Shale and the overlying Fort Hayes Limestone and Smoky Hill Shale Members of the Niobrara Formation (fig. 2). The Codell Sandstone Member was deposited in a shallow marine or brackish environment near the shoreline or on the shelf of the Cretaceous Western Interior Seaway (Weimer and Sonnenberg, 1983). Deposition of the overlying unconformable Niobrara Formation marks a sea level rise and regionally comprises four limestone (chalk) units and intervening shale units (Weimer and others, 1986). The Codell Sandstone Member and Niobrara Formation are overlain by the thick, deep-water marine Pierre Shale that seals the SAU.

The Niobrara Formation and Codell Sandstone Member SAU boundary was created using well penetration data for the top of the Niobrara Formation (IHS Energy Group, 2011). These data were used to identify the extent of the SAU where the top of the Niobrara Formation is at least 3,000 ft deep. There were no tops below 13,000 ft; therefore, there is no deep SAU. The area of the Niobrara Formation and Codell Sandstone Member SAU is about 17,039,000 acres (fig.6). Water-quality measurements from the Codell Sandstone Member and Niobrara Formation are limited; therefore, water-quality data from adjacent stratigraphic units were utilized and indicate that groundwater in and adjacent to the Codell and Niobrara ranges from fresh to saline (greater than 10,000 ppm of total dissolved solids) (Breit, 2002). The most likely percentage of the amount of the SAU available for storage is 30 percent, with a range of uncertainty between 50 and 10 percent of the SAU area.

Within the SAU, the thickness of the Niobrara Formation and Codell Sandstone Member averages 350 ft based on isopach data (Weimer and others, 1986), National Oil and Gas Assessment project data (Higley and others, 1995), and by calculating thicknesses from subtracting the top depth of the Niobrara Formation from the top depth of the underlying Carlile Shale (IHS Energy Group, 2011). The average net-porous thickness of 20 ft was derived from literature and well logs (MacQuown and Millikan, 1955; Weimer and others, 1986; Higley and others, 1995; Sonnenberg and Weimer, 2006; Higley and Cox, 2007). The porosity of the net-porous interval has a most likely value of 10 percent, with a minimum of 8 percent and a maximum of 12 percent, and the permeability values range from 0.01 to 2 mD, with a most likely value of 0.1 mD (Weimer and others, 1986; Hemborg, 1993; Higley and Cox, 2007; Nehring Associates, 2010). The maximum buoyant-trap-volume calculation was based on (1) area of existing hydrocarbon fields and potential structures mapped within the Denver Basin, (2) maximum net-porous-interval thickness, and (3) maximum porosity (Brennan and others, 2010; Blondes and others, 2013).

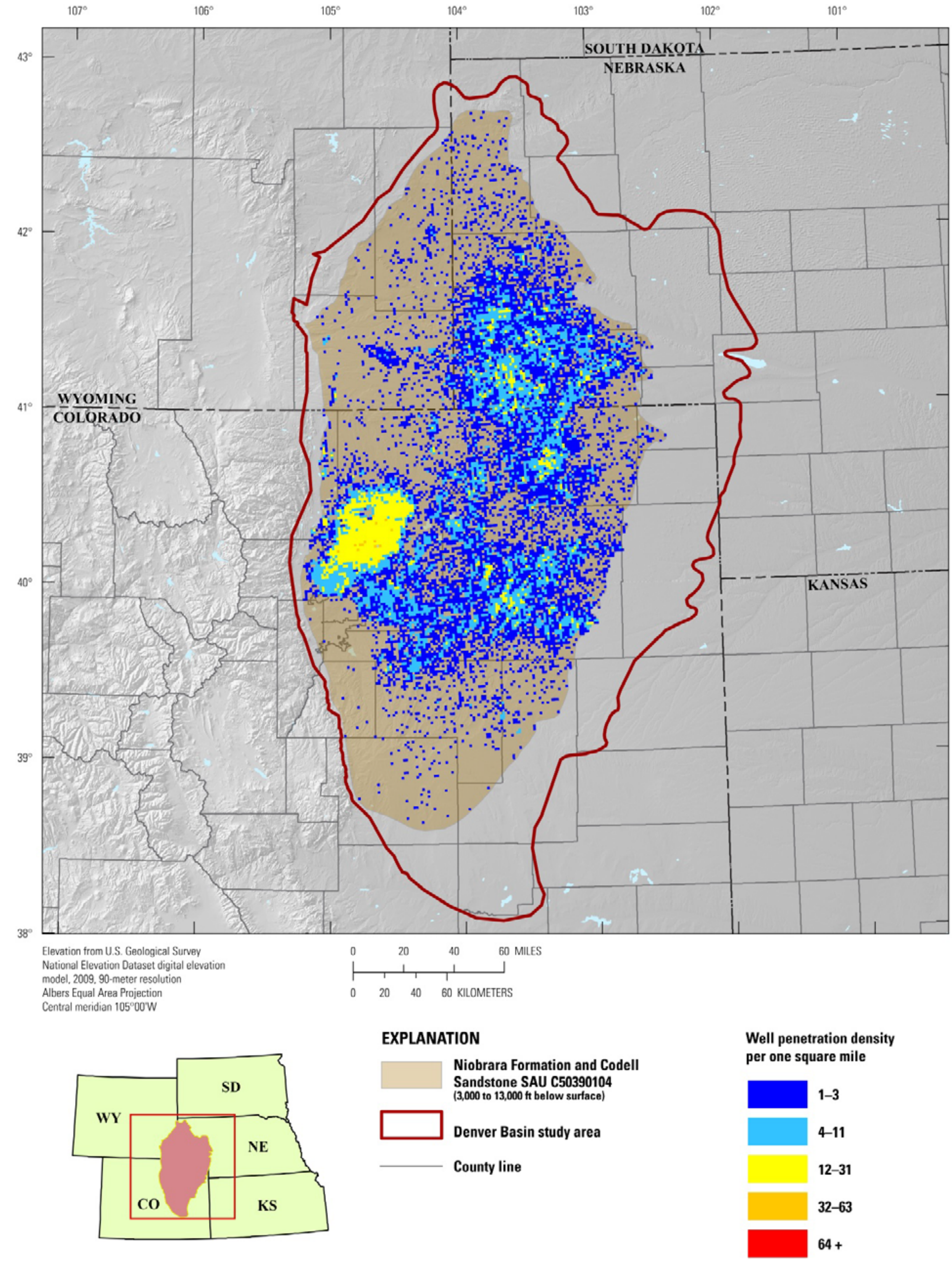

Figure 6. Map of the U.S. Geological Survey storage assessment unit (SAU) boundary for the Niobrara Formation and Codell Sandstone Member SAU in the Denver Basin, Colorado, Wyoming, and Nebraska. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir-formation top. Denver Basin study area modified from Higley and others (2007).

Terry and Hygiene Sandstone Members SAU (C50390105)

By Sean T. Brennan

The Terry and Hygiene Sandstone Members SAU (C50390105) is composed of thin linear sands within the Pierre Shale (fig. 2) of the Denver Basin. The Pierre Shale, which both hosts and seals the sandstone members, is a thick, deep-water marine shale deposited during the Late Cretaceous within the Cretaceous Western Interior Seaway (McGookey and others, 1972). The Pierre Shale is broadly correlative with other Upper Cretaceous marine shales throughout the Rocky Mountain region, such as the Cody, Steele, Hilliard, Baxter, and Mancos Shales (McGookey and others, 1972). The Pierre Shale averages 6,000 to 8,000 ft thick within the Denver Basin (Higley and Cox, 2007). The Terry and Hygiene Sandstone Members are thin, laterally continuous sandstone units that have been described as offshore shelf deposits formed during regressive shoaling events (Porter, 1989) and as stacked nearshore, high-energy beach deposits (Slatt and others, 1997).

The SAU boundaries of the Terry and Hygiene Sandstone Members (fig. 7) were defined by the well penetration data for the top of the Hygiene (IHS Energy Group, 2011). However, the stratigraphic-unit names that most drillers use in the basin are the “Sussex” for the Terry and the “Shannon” for the Hygiene (Higley and Cox, 2007). The Sussex and Shannon Sandstone Members are found within the thick, Upper Cretaceous marine shale units elsewhere throughout the Rocky Mountain basins, and they appear broadly similar, though they can have very different depositional environments (Higley and Cox, 2007). The locations of these mislabeled “Sussex” or “Shannon” tops greater than 3,000 ft (IHS Energy Group, 2011), along with isopach maps and sand extent maps of the Terry and Hygiene Sandstone Members (Kiteley, 1977), were used to identify the extent of the SAU. There were no tops below 13,000 ft; therefore, there is no deep SAU. The area of the Terry and Hygiene Sandstone Members SAU is about 6,400,000 acres. However, based on the salinity data available (Breit, 2002), there are formation waters within the SAU that are greater than and less than 10,000 ppm TDS. The average percentage of the amount of the SAU available for storage is 30 percent, with a wide range of uncertainty, with a 50-percent maximum and a 10-percent minimum value.

Within the SAU the total thickness of the Terry and Hygiene Sandstone Members averages 500 ft based on isopach thickness maps (Kiteley, 1977), with an average net-porous thickness of 35 ft. The net-porous value is derived from applying a net-porous thickness to gross thickness ratio estimated from available well logs (Pittman, 1989; Porter, 1989; Al-Raisi and others, 1996; Slatt and others, 1997), cross sections (Kiteley, 1977; Pittman, 1989; Porter, 1989), and sand extent maps (Kiteley, 1977). The porosity of the sandstone units has a most likely value of 8 percent, with a minimum of 6 percent and a maximum of 10 percent, whereas the permeability values range from 0.01 to 10 mD, with central tendency of 1 mD (Pittman, 1988; Al-Raisi and others, 1996; Slatt and others, 1997; Nehring Associates, Inc., 2010). The maximum buoyant-trap volume was determined based on existing and potential undiscovered hydrocarbon fields and structure maps within the Denver Basin.

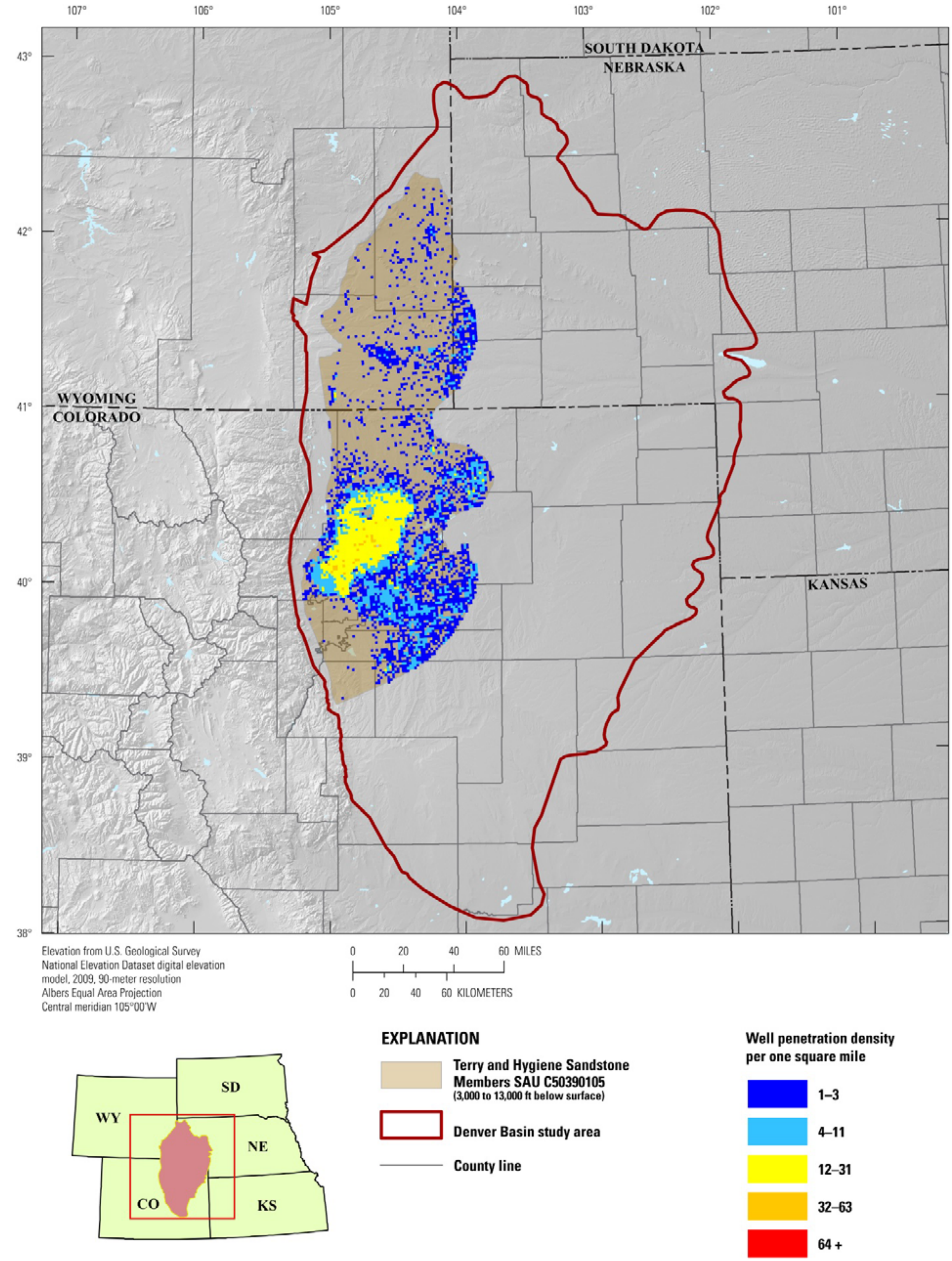

Figure 7. Map of the U.S. Geological Survey storage assessment unit (SAU) boundary for the Terry and Hygiene Sandstone Members SAU in the Denver Basin. Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir-formation top. Denver Basin study area modified from Higley and others (2007).

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