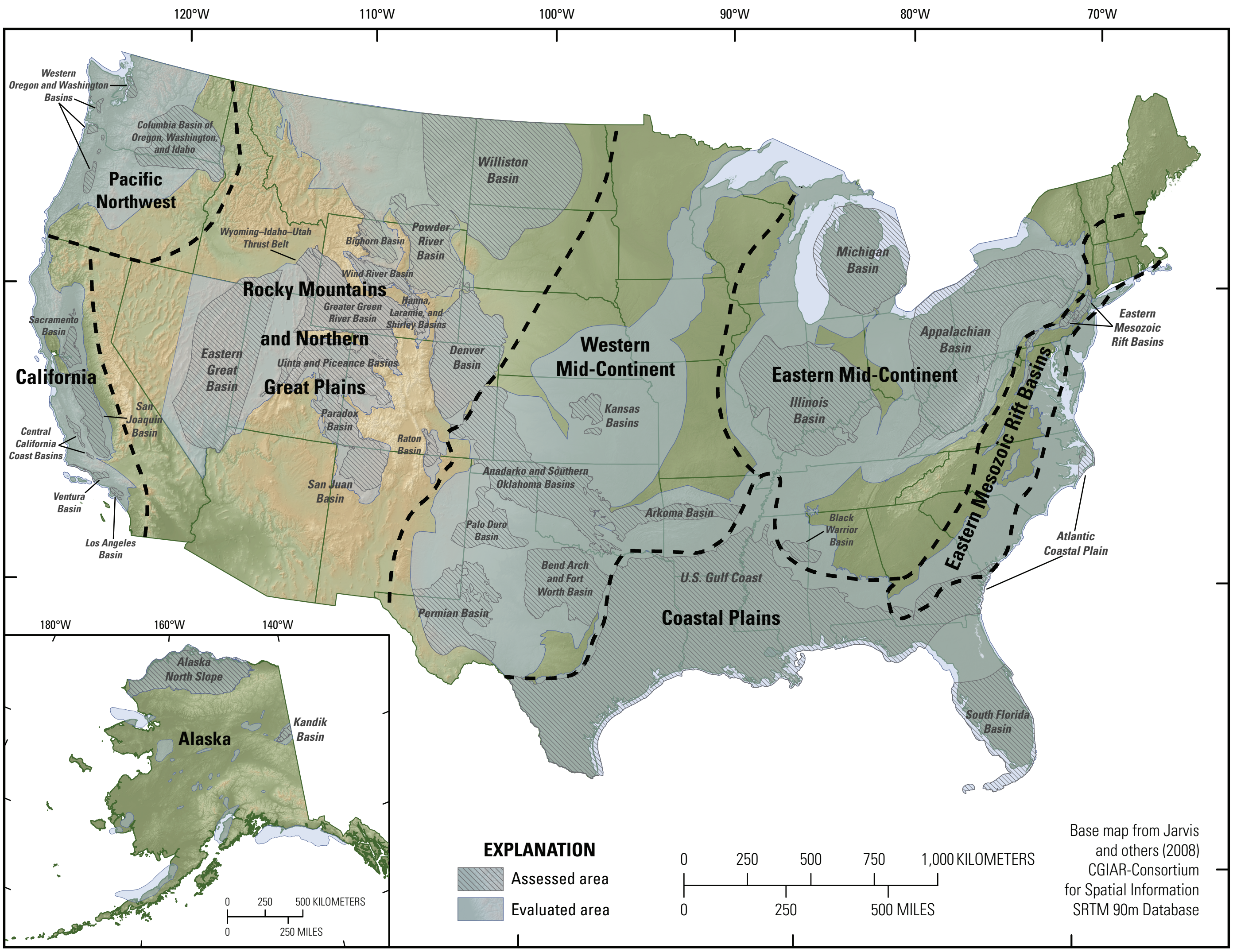
National Assessment of Geologic Carbon Dioxide Storage Resources—Data



Data Series 774
Version 1.1, September 2013

U.S. Department of the Interior
U.S. Geological Survey

Cover. Map of the conterminous United States and Alaska showing 8 regions (separated by bold dashed lines and labeled in a bold font), evaluated areas (bluish gray) that were not assessed, and 36 areas (pattern) that were assessed by the U.S. Geological Survey for carbon dioxide storage. The assessed areas contain multiple storage assessment units.

National Assessment of Geologic Carbon Dioxide Storage Resources—Data

By U.S. Geological Survey Geologic Carbon Dioxide Storage Resources
Assessment Team

Data Series 774
Version 1.1, September 2013

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013
Version 1.0 was released June 26, 2013
Version 1.1 was released September 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013, National assessment of geologic carbon dioxide storage resources—Data (ver. 1.1, September 2013): U.S. Geological Survey Data Series 774, 13 p., plus 2 appendixes and 2 large tables in separate files, http://pubs.usgs.gov/ds/774/. (Supersedes ver. 1.0 released June 26, 2013.)

Members of the U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team[1]

Peter D. Warwick, Project Chief
Madalyn S. Blondes
Sean T. Brennan
Marc L. Buursink
Steven M. Cahan
James L. Coleman
Troy A. Cook
Margo D. Corum
Jacob A. Covault
William H. Craddock
Christina A. DeVera
Colin Doolan
Ronald M. Drake II
Lawrence J. Drew
Joseph A. East
Philip A. Freeman
Christopher P. Garrity
Kevin J. Gooley
Mayur A. Gosai
Hossein Jahediesfanjani[2]
Celeste D. Lohr
John C. Mars
Matthew D. Merrill
Ricardo A. Olea
Tina L. Roberts-Ashby
William A. Rouse
Paul G. Schruben
John H. Schuenemeyer[2]
Ernie R. Slucher
Brian A. Varela
Mahendra K. Verma

[1]All members are or were with the U.S. Geological Survey unless otherwise indicated.
[2]Contractor.

Contents

Figure

Tables

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)
mile, nautical (nmi)	1.852	kilometer (km)
meter (m)	3.281	foot (ft)
	Area	
square inch (in^2)	6.452	square centimeter (cm^2)
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)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton, long (2,240 lb)	1.016	megagram (Mg)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound, avoirdupois (lb)
megagram (Mg) = 1 metric ton (t) (1,000 kg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
megaton (Mt) = 1 million metric tons	1.102	million short tons
gigaton (Gt) = 1 billion metric tons	1.102	billion short tons
	Pressure	
bar	100	kilopascal (kPa)
pound-force per square inch (lbf/in^2 or psi)	6.895	kilopascal (kPa)
kilopascal (kPa)	0.01	bar
kilopascal (kPa)	0.1450	pound-force per square inch (lbf/in^2)
	Pressure gradient	
pound-force per square inch per foot ($lbf/in^2/ft$ or psi/ft)	22.62	kilopascal per meter (kPa/m)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Permeability is given in darcies (D) and millidarcies (mD).

1 barrel of oil equivalent (BOE)	= 1 barrel of crude oil (42 gallons)
	= 6,000 cubic feet of natural gas
	= 1.5 barrels of natural gas liquids

Abbreviations, Acronyms, and Symbols

A_{SF}	area of the storage formation within the storage assessment unit
AU	assessment unit, part of the USGS National Oil and Gas Assessment
B_{PV}	buoyant trapping pore volume
B_{SE}	buoyant trapping storage efficiency
B_{SR}	buoyant trapping storage resource
B_{SV}	buoyant trapping storage volume
bbl	petroleum barrel or barrels
BLM	Bureau of Land Management
BOE	barrel of oil equivalent; see glossary
BOEM	Bureau of Ocean Energy Management
CDF	cumulative distribution function
CO_2	carbon dioxide
COTSA	CO_2 Sequestration Assessment program
D	darcy
FVF	formation volume factor
FVF_{gas}	formation volume factor for gas
FVF_{NGL}	formation volume factor for natural gas liquids
FVF_{oil}	formation volume factor for oil
GOR	gas:oil ratio
Gt	gigaton = billion metric tons
k	permeability
KR	known recovery production and reserve volumes
KR_{RES}	known recovery production volumes converted to reservoir conditions
KRR_{SR}	known recovery replacement storage resource
mD	millidarcy
MMbbl	million petroleum barrels
Mt	megaton = million metric tons
NCRDS	USGS National Coal Resources Data System
NETL	National Energy Technology Laboratory
NGL	natural gas liquids
NOGA	USGS National Oil and Gas Assessment

P_5	probability percentile—5-percent probability that the true value is less than the given value
P_{50}	probability percentile—50-percent probability that the true value is less than the given value. P_{50} is the median of the probability distribution.
P_{95}	probability percentile—95-percent probability that the true value is less than the given value
psi	pound-force per square inch
R_k	permeability distribution
R_W	the area fraction of the SAU available for storage after consideration of EPA water-quality guidelines or highly fractured seals
$R1_{PV}$	residual trapping class 1 pore volume
$R1_{SE}$	residual trapping class 1 storage efficiency
$R1_{SR}$	residual trapping class 1 storage resource
$R1_{SV}$	residual trapping class 1 storage volume
$R2_{PV}$	residual trapping class 2 pore volume
$R2_{SE}$	residual trapping class 2 storage efficiency
$R2_{SR}$	residual trapping class 2 storage resource
$R2_{SV}$	residual trapping class 2 storage volume
$R3_{PV}$	residual trapping class 3 pore volume
$R3_{SE}$	residual trapping class 3 storage efficiency
$R3_{SR}$	residual trapping class 3 storage resource
$R3_{SV}$	residual trapping class 3 storage volume
RCSP	Regional Carbon Sequestration Partnership
SAU	storage assessment unit
SE	storage efficiency
SF	storage formation
SF_{PV}	storage formation pore volume
T_{PI}	thickness of the net porous interval
TA_{SR}	technically accessible storage resource
TA_{SV}	technically accessible storage volume
TDS	total dissolved solids
USGS	U.S. Geological Survey
Z factor	critical value: standard deviations from the mean for a given probability assumption
ρ_{CO_2}	density of carbon dioxide
ϕ	porosity
ϕ_{PI}	porosity of the net porous interval

National Assessment of Geologic Carbon Dioxide Storage Resources—Data

By U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team

Abstract

In 2012, the U.S. Geological Survey (USGS) completed the national assessment of geologic carbon dioxide storage resources. Its data and results are reported in three publications: the assessment data publication (this report), the assessment results publication (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013a, USGS Circular 1386), and the assessment summary publication (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013b, USGS Fact Sheet 2013–3020). This data publication supports the results publication and contains (1) individual storage assessment unit (SAU) input data forms with all input parameters and details on the allocation of the SAU surface land area by State and general land-ownership category; (2) figures representing the distribution of all storage classes for each SAU; (3) a table containing most input data and assessment result values for each SAU; and (4) a pairwise correlation matrix specifying geological and methodological dependencies between SAUs that are needed for aggregation of results.

Introduction

In 2012, the U.S. Geological Survey (USGS) completed the national assessment of geologic carbon dioxide storage resources, hereinafter called the assessment. Its data and results are reported in three publications: the assessment data publication (this report), the assessment results publication (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013a), and the assessment summary publication (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013b). This data publication supports the results publication and contains (1) an input data form for each storage assessment unit (SAU) that was analyzed quantitatively (appendix 1), (2) empirical cumulative distribution function (CDF) plots of assessment results for each SAU (appendix 2), (3) a table containing most inputs to and outputs from the assessment (table 1), and (4) a correlation matrix for aggregation (table 2). These components are not in the results or summary publications cited above.

This data publication and the companion results report and summary report (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013a,b) are parts of a suite of USGS reports that document the development of the assessment methodology and the execution and reporting of the assessment. The assessment methodology described by Burruss and others (2009) and Brennan and others (2010) was modified slightly during the assessment, as summarized in the implementation report by Blondes, Brennan, and others (2013). Geologic descriptions of the SAUs in basins or combined basin areas were prepared during the assessment, and some have been released as chapters of a report edited by Warwick and Corum (2012).

Description of the Storage Assessment Unit Input Data Form

This section explains the 192 SAU input data forms in appendix 1 that were completed for the national assessment. The SAU is a mappable volume of rock that consists of a porous reservoir and a bounding regional sealing formation (Brennan and others, 2010). Within the SAU, the porous reservoir is defined as the storage formation (SF). Sedimentary rocks of deep saline formations and of existing oil and gas fields were evaluated. Specifically, 36 sedimentary basins, or combined basin areas, within 8 regions of the conterminous United States and Alaska were assessed. Within the assessed basins, 202 SAUs were identified as having good storage potential because of the presence of a robust regional seal, adequate reservoir rock, and sufficient areas containing saline formation waters. Ten of these SAUs did not have sufficient data to build a robust geologic model to accurately estimate the storage resource and were designated as nonquantitative SAUs. No storage resources were estimated for the 10 nonquantitative SAUs, and input forms were not prepared for them. Three basins (Central California Coast Basins; Columbia Basin of Oregon, Washington, and Idaho; and Raton Basin) contain only nonquantitative SAUs and are included in table 1 but not in the correlation matrix (table 2). For nonquantitative SAUs, surficial geographic boundaries were defined and a geologic description was prepared.

The USGS assessed the technically accessible storage resources (TA_{SR}) for carbon dioxide (CO_2) in geologic formations underlying the onshore area and State waters area of the United States; resources in federally owned offshore areas were not assessed because resource assessments in these areas are typically done by the Bureau of Ocean Energy Management (BOEM). Federally owned offshore areas generally extend from 3 or more geographic (nautical) miles from the established baseline for the coast to an outer limit of 200 geographic miles. The offshore areas on the input form are defined as State waters, or those submerged areas between the established baseline for the coast and the federally owned offshore areas.

All assessments were conducted by USGS employees to ensure the use of a consistent process and to avoid outside influence. A permanent panel of experienced assessment geologists presided over all assessment meetings and worked with the assessment geologist to arrive at a consensus for the values entered on the input data forms.

The first page of the input form (fig. 1) contains identification information and the assessment geologist's inputs; the second page contains allocation percentages of the SAU mean area to the States that are listed alphabetically and of the SAU area to five general land-ownership categories that are defined in the "Glossary" in this report: Federal lands, State lands, Tribal lands, private and other lands, and offshore areas. Each input form is identified with an SAU name and a unique SAU code number following the style established by the USGS National Oil and Gas Assessment (NOGA) publications, as explained by Blondes, Brennan, and others (2013) and the "Glossary" in this report. A list of SAU names and codes by basin is in table 1. In addition to identifying the SAU, the input form contains spaces for the assessment geologist's name, the date of assessment, and the SAU location and its relation to NOGA assessment units (AUs), if appropriate, along with any notes from the assessor. In the input forms in appendix 1, no entries are shown for the last two categories because the information about the NOGA AUs was lengthy for some SAUs and because there were no significant notes from the assessors. Information on the related NOGA AUs is in table 1.

The first page of the input data form has spaces for the geologist to indicate whether the SAU consists of formations between depths of 3,000 and 13,000 feet (914 and 3,962 meters) or of formations more than 13,000 feet below the ground surface (fig. 1). These depths distinguish a standard SAU from a deep SAU. Lines 1–9 contain depth information and input parameters for each SAU that were used to probabilistically calculate storage resources.

These input values in lines 1–9 are typically the minimum, most likely, and maximum estimates made by the assessment geologist with the help of the assessment panel for the following parameters:

Line 1: SAU depth from surface in feet

Line 2: Area of the SAU in acres

Line 3: Mean total SAU thickness in feet

Line 4: Likely SAU water quality in terms of salinity greater than or less than 10,000 milligrams per liter of total dissolved solids (mg/L TDS) as described in Blondes, Brennan, and others (2013)

Line 5: Area fraction available for storage (Blondes, Brennan, and others, 2013)

Line 6: Mean thickness of the net porous interval in feet

Line 7: Mean porosity of the net porous interval as a fraction

Line 8: Buoyant trapping pore volume in millions of barrels (MMbbl)

Line 9: Permeability of the net porous interval in millidarcies, which is used in estimating residual trapping storage characteristics

The second page of the input data form has allocations of the SAU mean area to the States that it underlies and to general land-ownership categories (fig. 1). A cartographer calculated the percentage of each SAU's mean area for each State and land-ownership category. Although volume allocations are commonly completed for basin-specific AUs in the USGS NOGA, time and data constraints for this assessment of CO_2 storage precluded this type of allocation for SAUs. Acronyms and abbreviations reduce the length of the assessment input forms; their definitions can be found in the "Abbreviations, Acronyms, and Symbols" section at the beginning of this document or the "Glossary" section at the end of this document.

Description of the Empirical Cumulative Distribution Function Plots

This section explains the empirical cumulative distribution function (CDF) plots in appendix 2 for the storage resources. The empirical CDF plots in appendix 2 are arranged alphabetically by basin name and then numerically by SAU code. A complete list of basin names, SAU names, and SAU codes is in table 1. Each page in appendix 2 shows the probabilistic results of one quantitatively assessed SAU and contains six plots, one for each assessment output. These outputs are (1) the technically accessible storage resource (TA_{SR}); (2) the buoyant trapping storage resource (B_{SR}); (3) the known recovery replacement storage resource (KRR_{SR}); (4) the residual trapping class 1 storage resource ($R1_{SR}$), for rocks with permeability greater than 1 darcy (D); (5) the residual trapping class 2 storage resource ($R2_{SR}$), for rocks with permeability between 1 millidarcy (mD) and 1 D; and (6) the residual trapping class 3 storage resource ($R3_{SR}$), for rocks with permeability less than 1 mD. In each CDF plot, the horizontal axis shows the storage resource (in millions of metric tons, Mt) and the vertical axis shows the cumulative probability between zero and one. The cumulative probability for a given percentile represents the probability that the true storage resource is *less than* the value shown. The points along the CDF are the mean and the P_5, P_{50}, and P_{95} percentiles. These values are also given in table 1. Output categories with a calculated storage resource of zero are labeled "No storage resource." For more details on the calculations used to create the empirical CDF plots, see Brennan and others (2010) and Blondes, Brennan, and others (2013).

Description of the Comprehensive Data Table

This section explains the comprehensive data presentation in table 1, which lists most inputs necessary to replicate the assessment team's probabilistic resource calculations for individual quantitative SAUs. Table 1 includes inputs from the input data forms; basin-scale parameters such as formation volume factors, storage efficiencies, and CO_2 densities; Z factors used to calculate lognormal distributions for permeability and buoyant trapping pore volume (Blondes, Brennan, and others, 2013); six assessment outputs as storage resources; and general assessment information such as the name of the assessment geologist, the date of assessment, SAU names, and SAU codes. To calculate the aggregated basin, region, and national storage resources, it is necessary to use the correlation matrix in table 2 for aggregation (Blondes, Brennan, and others, 2013; Blondes, Schuenemeyer, and others, 2013).

Description of the Correlation Matrix for Aggregation

The assessment uses a probabilistic addition, or aggregation, methodology (Blondes, Brennan, and others, 2013; Blondes, Schuenemeyer, and others, 2013) to correctly propagate uncertainty when combining SAU resources to a basin, regional, or national scale. The probabilistic aggregation methodology requires two main inputs: (1) stochastic storage resource estimates for each SAU, represented by the empirical CDFs described above, and (2) a pairwise correlation matrix specifying geological and methodological dependencies between SAUs. The correlation matrix for aggregation (table 2) contains matching column and row titles showing the region name, basin name, SAU name, and SAU code. The column and row intersection within the correlation matrix of two SAUs represents the correlation coefficient for that SAU pair. Note that the coefficient along the diagonal is always one. The SAUs are grouped by region and basin and are listed numerically by code in table 2.

Data Sources

Assessment geologists used geologic data from sources including USGS (published and unpublished) reports and maps, published literature such as journal articles and textbooks, and research-consortium-funded Web sites. Examples of USGS sources include previous NOGA publications (http://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment.aspx), the National Geologic Map Database (http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html), the Geologic Names Lexicon (http://ngmdb.usgs.gov/Geolex/), and the Publications Warehouse database (http://pubs.er.usgs.gov/). Water-quality data were obtained from many sources, including the USGS produced-waters database (Breit, 2002), various regional compilations (for example, Blondes and Gosai, 2011), the National Energy Technology Laboratory (NETL) Brine Database (Hovorka and others, 2000), and datasets available from State sources.

Additional data were obtained from cooperative agreements such as the CO_2 Sequestration Assessment (COTSA) program through the National Coal Resources Data System (NCRDS), which funded 35 State agencies to provide high-quality geologic information, and data-sharing agreements with the NETL Regional Carbon Sequestration Partnerships (RCSP). These agreements provided formal interpretive publications and summary reports, as well as unpublished data containing, for example, depth-to-top-of-formation interpretations from drilling; subsurface pressure, temperature, porosity, and permeability ranges; and thickness of the porous interval and the ratio of porous thickness to total thickness (also known as net-to-gross) estimates.

Assessment geologists used several proprietary databases to support their interpretations. The "Significant Oil and Gas Fields of the United States Database" from Nehring Associates, Inc. (2010), provided quantitative field- and reservoir-level data (current as of December 2008). It includes reservoir porosity, permeability, temperature, and pressure and hydrocarbon production data such as reserves, cumulative production, and various other types of information for most oil and gas fields and reservoirs containing more than 0.5 million barrels of oil equivalent (BOE). The Petroleum Information Data Model (PIDM) well relational database (IHS Inc., 2010) served as a source for depth-to-top-of-formation interpretations, bottom-hole temperatures, and estimated reservoir cumulative production and prorated cumulative production in States where the Nehring database provided production and reserve estimates only at the field level. The Web-based Enerdeq database (IHS Inc., 2011a) contains comprehensive well attribute sets with formation penetration data, from which drilling density estimates are derived. These databases were also used to find and identify well logs, estimate drilled intervals, find perforation intervals, and locate porosity and permeability data. Assessment geologists used the IHS Interpreted Formation Tops and Online Structure Maps (IHS Inc., 2011b) where possible; the data were current as of 2011.

STORAGE ASSESSMENT UNIT INPUT DATA FORM

Identification Information

Assessment geologist: ____________________ Date: __________

Assessment region: ____________________

Province: ____________________ Number: __________

Basin: ____________________ Number: __________

Storage Assessment Unit (SAU): ____________________ Number: __________

SAU relationship to NOGA AU: ____________________

Notes from assessor: ____________________

Characteristics of the Storage Assessment Unit

Lines 1-9 concern data for the SAU at depths of (check one):
3,000-13,000 ft __________
> 13,000 ft __________

(1) SAU depth from surface (ft): minimum: ________ most likely: ________ maximum: ________

(2) Area of the SAU (acres): minimum: ________ most likely: ________ maximum: ________

(3) Mean total SAU thickness (ft): minimum: ________ most likely: ________ maximum: ________

(4) SAU water quality (check one):

Most of the water in the SAU is saline (greater than 10,000 mg/L TDS). __________

Water in this SAU is both saline and fresh. __________

Most of the water in the SAU is fresh (less than 10,000 mg/L TDS). __________

(5) Area fraction available for storage (generally, the area where SAU pore water has more than 10,000 mg/L TDS):
minimum: ________ most likely: ________ maximum: ________

(6) Mean thickness net porous interval (ft): minimum: ________ most likely: ________ maximum: ________

(7) Mean porosity net porous interval (fraction): minimum: ________ most likely: ________ maximum: ________

Buoyant Trapping Probabilistic Calculation Inputs

(8) Buoyant trapping pore volume (MMbbl):
minimum: ________ most likely: ________ maximum: ________

Residual Trapping Probabilistic Calculation Inputs

(9) Permeability of the net porous interval (mD): minimum: ________ most likely: ________ maximum: ________

Storage Assessment Unit (SAU): ______________________ Number: __________

Allocations of the SAU to States

(1) ______________________ contains __________ % of mean SAU area

(2) ______________________ contains __________ % of mean SAU area

(3) ______________________ contains __________ % of mean SAU area

(4) ______________________ contains __________ % of mean SAU area

(5) ______________________ contains __________ % of mean SAU area

(6) ______________________ contains __________ % of mean SAU area

(7) ______________________ contains __________ % of mean SAU area

(8) ______________________ contains __________ % of mean SAU area

Allocations of the SAU to General Land-Ownership Categories

(1) Federal lands contain __________ % of mean SAU area

(2) State lands contain __________ % of mean SAU area

(3) Tribal lands contain __________ % of mean SAU area

(4) Private and other lands contain __________ % of mean SAU area

(5) Offshore areas contain __________ % of mean SAU area

Figure 1 (facing page and above). Input data form used for each storage assessment unit (SAU) that was analyzed quantitatively during the U.S. Geological Survey national assessment of geologic carbon dioxide (CO_2) storage resources. These data inputs were used in the calculations described in Brennan and others (2010) and Blondes, Brennan, and others (2013). Some of the data inputs are solely descriptive and were not used in the calculations (for example, lines 1, 3, and 4 on the first page), although they were helpful in determining other data input parameters. Completed data forms for the 192 quantitative SAUs are in appendix 1; they are arranged alphabetically by basin name and then numerically by SAU code.

Carbon dioxide storage resources were allocated to States and land-ownership categories by using State-specific geospatial data primarily from the Bureau of Land Management (BLM) (http://www.blm.gov) and secondarily from either individual State agencies or the National Atlas of the United States® (http://nationalatlas.gov/).

Acknowledgments

The U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team acknowledges the helpful reviews of this report by Kevin Jones and Michael Trippi of the USGS. Additional acknowledgements for the assessment process are included in the assessment results publication (U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013a).

References Cited

Bachu, Stefan, 2003, Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change: Environmental Geology, v. 44, p. 277–289.

Blondes, M.S., Brennan, S.T., Merrill, M.D., Buursink, M.L., Warwick, P.D., Cahan, S.M., Cook, T.A., Corum, M.D., Craddock, W.H., DeVera, C.A., Drake, R.M., II, Drew, L.J., Freeman, P.A., Lohr, C.D., Olea, R.A., Roberts-Ashby, T.L., Slucher, E.R., and Varela, B.A., 2013, National assessment of geologic carbon dioxide storage resources—Methodology implementation: U.S. Geological Survey Open-File Report 2013–1055, 26 p., accessed May 10, 2013 at http://pubs.usgs.gov/of/2013/1055/.

Blondes, M.S., and Gosai, M.A., 2011, An expanded Wyoming water quality database [abs.]: American Association of Petroleum Geologists Rocky Mountain Section, Annual Meeting, Cheyenne, Wyo., June 25–29, 2011, Abstracts, 1 p., accessed March 10, 2013, at http://www.searchanddiscovery.com/abstracts/pdf/2011/rocky/abstracts/ndx_blondes.pdf.

Blondes, M.S., Schuenemeyer, J.H., Olea, R.A., and Drew, L.J., 2013, Aggregation of carbon dioxide sequestration storage assessment units: Stochastic Environmental Research and Risk Assessment, DOI:10.1007/s00477-013-0718-x, 21 p., accessed May 31, 2013, at http://link.springer.com/article/10.1007%2Fs00477-013-0718-x.

Breit, G.N., comp., 2002, Produced waters database: U.S. Geological Survey database, accessed January 19, 2011, at http://energy.cr.usgs.gov/prov/prodwat/.

Brennan, S.T., Burruss, R.C., Merrill, M.D., Freeman, P.A., and Ruppert, L.F., 2010, A probabilistic assessment methodology for the evaluation of geologic carbon dioxide storage: U.S. Geological Survey Open-File Report 2010–1127, 31 p., accessed September 19, 2012, at http://pubs.usgs.gov/of/2010/1127.

Burruss, R.C., Brennan, S.T., Freeman, P.A., Merrill, M.D., Ruppert, L.F., Becker, M.F., Herkelrath, W.N., Kharaka, Y.K., Neuzil, C.E., Swanson, S.M., Cook, T.A., Klett, T.R., Nelson, P.H., and Schenk, C.J., 2009, Development of a probabilistic assessment methodology for evaluation of carbon dioxide storage: U.S. Geological Survey Open-File Report 2009–1035, 81 p., accessed September 19, 2012, at http://pubs.usgs.gov/of/2009/1035/.

Everitt, B.S., and Skrondal, Anders, 2010, The Cambridge dictionary of statistics (4th ed.): Cambridge, England, Cambridge University Press, 478 p.

Hovorka, S.D., Romero, M.L., Treviño, R.H., Warne, A.G., Ambrose, W.A., Knox, P.R., and Tremblay, T.A., 2000, Project evaluation, Phase II; Optimal geological environments for carbon dioxide disposal in brine-bearing formations (aquifers) in the United States: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for U.S. Department of Energy, National Energy Technology Laboratory, under contract no. DE–AC26–98FT40417, 232 p. (GCCC [Gulf Coast Carbon Center] Digital Publication Series 00–01, available at http://www.beg.utexas.edu/gccc/bookshelf/Final%20Papers/00-01-Final.pdf.)

IHS Inc., 2010, PIDM [Petroleum Information Data Model] relational U.S. well data [data current as of December 23, 2009]: Englewood, Colo., IHS Inc., database.

IHS Inc., 2011a, Enerdeq U.S. well data: Englewood, Colo., IHS Inc., database, accessed January 20, 2011, at http://energy.ihs.com/.

IHS Inc., 2011b, IHS interpreted formation tops and online structure maps [data current as of 2011]: Englewood, Colo., IHS Inc., database.

Jarvis, A., Reuter, H.I., Nelson, Andrew, and Guevara, Edward, 2008, Hole-filled SRTM [Shuttle Radar Topographic Mission] for the globe, version 4: available from the CGIAR [Consultative Group for International Agricultural Research]-Consortium for Spatial Information SRTM 90m Database; accessed January 15, 2012, at http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1#acknowledgements.

Klett, T.R., Schmoker, J.W., Charpentier, R.R., Ahlbrandt, T.S., and Ulmishek, G.F., 2005, Glossary, chap. 25 *of*

U.S. Geological Survey Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series DDS–69–D, 3 p., on CD-ROM. (Also available at http://pubs.usgs.gov/dds/dds-069/dds-069-d/.)

MacMinn, C.W., Szulczewski, M.L., and Juanes, Ruben, 2010, CO_2 migration in saline aquifers. Part 1, Capillary trapping under slope and groundwater flow: Journal of Fluid Mechanics, v. 662, p. 329–351.

Nehring Associates, Inc., 2010, Significant oil and gas fields of the United States database [data current as of December 2008]: Colorado Springs, Colo., Nehring Associates, Inc.

R Core Team, 2013, R—A language and environment for statistical computing (version 3.0.0): Vienna, Austria, R Foundation for Statistical Computing, http://www.R-project.org/.

Schlumberger, 2011, Injectivity test, [entry] *in* Schlumberger oilfield glossary: Schlumberger Web site, accessed December 20, 2012, at http://www.glossary.oilfield.slb.com/Display.cfm?Term=injectivity%20test.

Schmoker, J.W., and Klett, T.R., 2005, U.S. Geological Survey assessment concepts for conventional petroleum accumulations, chap. 19 *of* U.S. Geological Survey Southwestern Wyoming Province Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah: U.S. Geological Survey Digital Data Series, DDS–69–D, 6 p., accessed February 20, 2013, at http://pubs.usgs.gov/dds/dds-069/dds-069-d/REPORTS/69_D_CH_19.pdf.

Thormahlen, L.F., 1999, Boundary development on the outer continental shelf: Minerals Management Service Mapping and Boundary Branch, OCS report MMS 99–0006, 12 p., accessed February 21, 2013, at http://www.boem.gov/BOEM-Newsroom/Library/Publications/1999/99-0006-pdf.aspx.

U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013a, National assessment of geologic carbon dioxide storage resources—Results (ver. 1.1, September 2013): U.S. Geological Survey Circular 1386, 41 p., http://pubs.usgs.gov/circ/1386/. (Supersedes ver. 1.0 released June 26, 2013.)

U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013b, National assessment of geologic carbon dioxide storage resources—Summary (ver. 1.1, September 2013): U.S. Geological Survey Fact Sheet 2013–3020, 6 p., http://pubs.usgs.gov/fs/2013/3020/. (Supersedes ver. 1.0 released June 26, 2013.)

Warwick, P.D., and Corum, M.D., eds., 2012, Geologic framework for the national assessment of carbon dioxide storage resources: U.S. Geological Survey Open-File Report 2012–1024, accessed February 21, 2013, at http://pubs.usgs.gov/of/2012/1024/. (Chapters A–C were posted by November 1, 2012.)

Wickham, Hadley, 2009, ggplot2; Elegant graphics for data analysis: New York, Springer, 221 p.

Glossary

The following definitions are modified from Brennan and others (2010) and other sources indicated.

barrels of oil equivalent (BOE) A unit of petroleum volume in which the gas part is expressed in terms of its energy equivalent in barrels of oil. For this assessment, the energy equivalent (not the volume equivalent) of 6,000 cubic feet of natural gas equals 1 barrel of oil equivalent (Klett and others, 2005).

buoyancy Upward force on one phase (for example, a fluid) produced by the surrounding fluid (for example, a liquid or a gas) in which it is fully or partially immersed, caused by differences in density.

buoyant trapping A trapping mechanism by which CO_2 is held in place by a top and lateral seal (either a sealing formation or a sealing fault), creating a column of CO_2 in communication across pore space.

buoyant trapping pore volume (B_{PV}) A geologically determined, probabilistic distribution of the volume fraction of the storage formation (SF) that can store CO_2 by buoyant trapping. This distribution minimum is typically defined by existing plus forecast undiscovered oil and gas production volumes. The maximum is probabilistically calculated from distributions of geologic parameters describing the known trapping structures within the storage formation.

buoyant trapping storage efficiency (B_{SE}) A distribution of efficiency values that describe the fraction of buoyant trapping that can occur within a volume of porous media. The values used in the methodology for this assessment (0.2 min, 0.3 most likely, and 0.4 max) are discussed in Blondes, Brennan, and others (2013).

buoyant trapping storage resource (B_{SR}) The mass of CO_2 retained in the storage formation by buoyant trapping.

buoyant trapping storage volume (B_{SV}) The volume of CO_2 retained in the storage formation by buoyant trapping.

carbon sequestration Both natural and deliberate processes by which CO_2 is either removed from the atmosphere or diverted from emission sources and stored in the ocean, terrestrial environments (vegetation, soils, and sediment), and subsurface geologic formations.

Federal lands One of five land-ownership categories used in this assessment for allocation of resources. Federal lands are lands within the United States owned or administered by the Federal Government. These include national parks, national wildlife refuges, military reservations, Federal prisons, and public-domain land. Spatial data for this category come from the State-specific spatial resources from the BLM available at http://www.blm.gov and the National Atlas of the United States® at http://nationalatlas.gov/mld/fedlanp.html.

federally owned offshore areas Federal jurisdiction begins at 3 geographic (nautical) miles from the established baseline for the coast and extends to an outer limit of 200 nautical miles. However, there are special cases. Because of claims existing at the dates of statehood, Texas and the Gulf Coast of Florida have proprietary interest in a submerged belt of land, 9 geographic miles wide, extending seaward along the coast (Thormahlen, 1999). Resource assessments in federally owned offshore areas are typically done by the Bureau of Ocean Energy Management (BOEM).

gas:oil ratio (GOR) Ratio of gas to oil (in cubic feet per barrel) in a hydrocarbon accumulation. GOR is calculated by using volumes of gas and oil at surface conditions.

gas reservoir A subsurface accumulation of hydrocarbons primarily in the gas phase that is contained in porous or fractured rock formations. A gas accumulation is defined by the USGS (Klett and others, 2005) as having a gas:oil ratio of 20,000 cubic feet per barrel or greater.

geologic storage of CO_2 A type of carbon sequestration that utilizes the long-term retention of carbon dioxide in subsurface geologic formations.

injectivity The "Schlumberger Oilfield Glossary" (Schlumberger, 2011) defines an injectivity test as a procedure that is used to determine "the rate and pressure at which fluids can be pumped into the treatment target without fracturing the formation." Although injectivity is typically reported as a rate, the methodology used in this assessment addresses this requirement by using permeability values to divide the residual storage component of the storage formation into three classes; *see* residual trapping classes 1, 2, and 3. The permeability is a proxy for injectivity because actual CO_2 injection rate data are generally limited to enhanced-oil-recovery operations using CO_2 and are not available for various reservoir types.

known recovery production volumes The cumulative petroleum production and proved reserves for a given reservoir.

known recovery replacement storage resource (KRR_{SR}) The storage resource calculated from known recovery production volumes.

minimum size The lower limit for inclusion of oil and gas field information in assessment calculations. Following USGS oil and gas assessment methodology (Schmoker and Klett, 2005), volumetric data from accumulations with less than 0.5 million barrels of oil equivalent total production were not included in any of the calculations in the methodology used for this assessment.

National Oil and Gas Assessment (NOGA) U.S. Geological Survey National Oil and Gas Assessment, described at http://energy.usgs.gov/OilGas/AssessmentsData/NationalOilGasAssessment.aspx.

offshore areas One of five land-ownership categories used in this assessment for allocation of resources. In this assessment, offshore areas refer to State waters (*see* definition). Both State and Federal offshore area boundaries are available from the National Atlas of the United States® at http://nationalatlas.gov/mld/opdlm0p.html.

oil reservoir A subsurface accumulation of hydrocarbons composed primarily of oil that is contained in porous or fractured rock formations. An oil accumulation is defined by the USGS (Klett and others, 2005) as having a gas:oil ratio less than 20,000 cubic feet per barrel.

percentile In values sorted by increasing magnitude, any of the 99 dividers that produce exactly 100 groups with equal number of values (Everitt and Skrondal, 2010). The dividers are used to denote the proportion of values above and below them. The dividers are sequential integer numbers starting from the one between the two groups with the lowest values. For example, in the modeling of sequestration capacity, a 95th percentile of 10 gigatons (Gt) denotes that 10 Gt divides all likely values into 95 percent of them below 10 Gt and 5 percent above it.

permeability (k) A measure of the ability of a rock to permit fluids to be transmitted through it; it is controlled by pore size, pore throat geometry, and pore connectivity. Permeability is typically reported in darcies.

porosity (ϕ) The part of a rock that is occupied by voids or pores. Pores can be connected by passages called pore throats, which allow for fluid flow, or pores can be isolated and inaccessible to fluid flow. Porosity is typically reported as a volume, fraction, or percentage of the rock.

porosity of the net porous interval (ϕ_{PI}) For this assessment, three values (minimum, most likely, and maximum) were estimated for the mean porosity of each net porous interval. The determination by the assessment geologist of how much porosity was sufficient to allow storage of CO_2 was dependent on the geology of the storage formation, and this dependence did not allow for a fixed threshold.

pressure gradient The change in pore pressure per unit depth, typically in units of pound-force per square inch per foot (psi/ft), kilopascals per meter (kPa/m), or bars per meter (bar/m).

private and other lands One of five land-ownership categories used in this assessment for allocation of resources. Lands not owned by Federal, State, or Tribal entities are placed in this category of private and other lands. These lands either belong to private owners or, less commonly, belong to additional BLM-named ownership categories (such as county, city, water, and other) and are grouped together here. Spatial data for this category come from State-specific spatial resources from the BLM available at http://www.blm.gov; when data were not available from the BLM, they were obtained from individual State agencies.

residual trapping A mechanism by which CO_2 is trapped as discrete droplets, blobs, or ganglia of CO_2 as a nonwetting phase, essentially immiscible with the wetting fluid, within individual pores where the capillary forces overcome the buoyant forces.

residual trapping class 1 (*R1*) Storage formation rock with permeability greater than 1 darcy that is available for residual trapping.

residual trapping class 2 (*R2*) Storage formation rock with permeability ranging from 1 millidarcy to 1 darcy that is available for residual trapping.

residual trapping class 3 (*R3*) Storage formation rock with permeability less than 1 millidarcy that is available for residual trapping.

residual trapping pore volume (R_{PV}) A calculated value equal to the storage formation pore volume (SF_{PV}) minus the buoyant trapping pore volume (B_{PV}). The value represents the pore volume within the storage formation that can be used to store CO_2 by residual trapping; it is calculated during iterations of the Monte Carlo simulator after a value from the buoyant trapping pore volume distribution is randomly chosen by the simulator program (@RISK; version 5.7 is commercially available from Palisade Corporation: http://www.palisade.com/risk/). Calculations were made for the three residual trapping classes *R1*, *R2*, and *R3* to obtain $R1_{PV}$, $R2_{PV}$, and $R3_{PV}$.

residual trapping storage efficiency (R_{SE}) A distribution of efficiency values that describes the fraction of residual trapping that can occur within a volume of porous media. The values used in the methodology for this assessment to define the distribution were calculated for each storage assessment unit by using equations from MacMinn and others (2010) and regional pressure and temperature data (Blondes, Brennan, and others, 2013). Calculations were made for the three residual trapping classes *R1*, *R2*, and *R3* to obtain $R1_{SE}$, $R2_{SE}$, and $R3_{SE}$.

residual trapping storage resource (R_{SR}) The mass of CO_2 retained in the storage formation by residual trapping. Calculations were made for the three residual trapping classes *R1*, *R2*, and *R3* to obtain $R1_{SR}$, $R2_{SR}$, and $R3_{SR}$.

residual trapping storage volume (R_{SV}) The volume of CO_2 retained in the storage formation by residual trapping. Calculations were made for the three residual trapping classes *R1*, *R2*, and *R3* to obtain $R1_{SV}$, $R2_{SV}$, and $R3_{SV}$.

seal A geologic feature that inhibits the mixing or migration of fluids and gases between adjacent geologic units. A seal is typically a rock unit or a fault; it can be a top seal, inhibiting upward flow of buoyant fluids, or a lateral seal, inhibiting the lateral flow of buoyant fluids.

seal formation The confining rock unit within the storage assessment unit. The seal formation is a rock unit that sufficiently overlies the storage formation and where managed properly has a capillary entrance pressure low enough to effectively inhibit the upward buoyant flow of CO_2.

State lands One of five land-ownership categories used in this assessment for allocation of resources. This ownership category includes lands owned by State entities, as categorized by the BLM in State-specific land-ownership data obtained from http://www.blm.gov; when data were not available from the BLM, they were obtained from individual State agencies.

State waters State jurisdiction begins at the established baseline for the coast and extends 3 geographic (nautical) miles. However, there are special cases. Because of claims existing at the dates of statehood, Texas and the Gulf Coast of Florida have proprietary interest in a submerged belt of land, 9 geographic miles wide, extending seaward along the coast (Thormahlen, 1999).

storage assessment unit (SAU) A mappable volume of rock that includes two main components: (1) the storage formation (SF), which is the reservoir for CO_2 storage, and (2) a regional seal formation.

storage assessment unit code For each storage assessment unit, the nine-digit code identifies the USGS-specific storage assessment unit. The preceding letter "C" refers to a carbon dioxide storage assessment unit and distinguishes it from USGS National Oil and Gas Assessment (NOGA) Project assessment units that may have similar numbers. The first digit after "C" of the code denotes the world region number (5), the following three digits (034) denote the North America NOGA province number, the following two digits (C5034xx) denote the basin number (always 01 unless there is more than one basin in each province). The last two digits (C503401xx) denote the storage assessment unit number of that particular basin. In this report, the NOGA province and basin names are the same.

storage efficiency factor (B_{SE} and R_{SE}) Values representing the fraction of the total available pore space that will be occupied by free-phase CO_2. Ranges of storage efficiency are specific to trapping types. The two used in this assessment were buoyant trapping storage efficiency (B_{SE}) and residual trapping storage efficiency (R_{SE}).

storage formation (SF) The reservoir of the storage assessment unit. The storage formation consists of sedimentary rock layers that are saturated with formation water having total dissolved solids (TDS) greater than 10,000 milligrams per liter (mg/L). In the CO_2 assessment methodology, the storage formation resource calculation is the main resource calculation and consists of two parts: a buoyant trapping resource and a residual trapping resource.

storage formation pore volume (SF_{PV}) The available pore space in the storage formation calculated from the area of the storage formation within the SAU and the thickness and porosity of the net porous interval. This value was used in the calculation of the residual trapping pore volume (R_{PV}).

technically accessible storage resource (TA_{SR}) The mass of CO_2 that may be injected and stored using present-day geologic and hydrologic knowledge of the subsurface and engineering practices. This term is analogous to the term "technically recoverable resource" used in USGS oil and gas assessments.

technically accessible storage volume (TA_{SV}) The volume of CO_2 that may be injected and stored using present-day geologic and hydrologic knowledge of the subsurface and engineering practices.

thickness of the net porous interval (T_{PI}) Defined in the methodology for this assessment as the mean net stratigraphic thickness of the portion of the storage formation that the assessment geologist determined contained an appropriate lithology with sufficient porosity to store CO_2. Three values (minimum, most likely, and maximum) were estimated for the mean thickness of each net porous interval.

total dissolved solids (TDS) The quantity of dissolved material in a sample of water, usually expressed in milligrams per liter (mg/L).

trapping The physical and geochemical processes by which injected CO_2 is retained in the subsurface.

Tribal lands One of five land-ownership categories used in this assessment for allocation of resources. Indian or Tribal lands within the United States are areas with boundaries established by treaty, statute, and (or) executive or court order, recognized by the Federal Government as territory in which American Indian Tribes have primary governmental authority. Spatial data for this category come from State-specific spatial resources from the BLM available at http://www.blm.gov and the National Atlas of the United States® at http://nationalatlas.gov/mld/indlanp.html.

Tables 1 and 2

Tables 1 and 2 are in separate Excel files. Clicking on a table number below will link to the file.

Table 1. Comprehensive presentation of data used in the U.S. Geological Survey national assessment of geologic carbon dioxide storage resources.

Table 2. Correlation matrix for aggregation of data used in the U.S. Geological Survey national assessment of geologic carbon dioxide storage resources.

Appendix 1. Input Data Forms for 192 Storage Assessment Units Used in the U.S. Geological Survey National Assessment of Geologic Carbon Dioxide Storage Resources

The completed input data forms in appendix 1 are arranged alphabetically by basin name and then numerically by storage assessment unit (SAU) code. A complete list of basin names, SAU names, and SAU codes is in table 1. The first page of the input form contains identification information and the assessment geologist's inputs; it has spaces for the assessment geologist's name, the date of assessment, and the SAU location and its relation to NOGA assessment units (AUs), if appropriate, along with any notes from the assessor. In the input forms in appendix 1, no entries are shown for the last two categories because the information about the NOGA AUs was lengthy for some SAUs and because there were no significant notes from the assessors. Information on the related NOGA AUs is in table 1. The second page contains allocation percentages of the SAU mean area to the States that are listed alphabetically and of the SAU area to five general land-ownership categories that are defined in the "Glossary" in this report: Federal lands, State lands, Tribal lands, private and other lands, and offshore areas. More details about the forms are in the report text and figure 1.

Appendix 2. Empirical Cumulative Distribution Function Plots of Six Resource Types for Each of the 192 Storage Assessment Units Used in the U.S. Geological Survey National Assessment of Geologic Carbon Dioxide Storage Resources

The empirical cumulative distribution function (CDF) plots in appendix 2 are arranged alphabetically by basin name and then numerically by storage assessment unit (SAU) code. A complete list of basin names, SAU names, and SAU codes is in table 1. Each page in appendix 2 shows the probabilistic results of one quantitatively assessed SAU and contains six plots, one for each assessment output. These outputs are (1) the technically accessible storage resource (TA_{SR}); (2) the buoyant trapping storage resource (B_{SR}); (3) the known recovery replacement storage resource (KRR_{SR}); (4) the residual trapping class 1 storage resource ($R1_{SR}$), for rocks with permeability greater than 1 darcy; (5) the residual trapping class 2 storage resource ($R2_{SR}$), for rocks with permeability between 1 millidarcy (mD) and 1 darcy; and (6) the residual trapping class 3 storage resource ($R3_{SR}$), for rocks with permeability less than 1 mD. In each empirical CDF plot, the horizontal axis shows the storage resource (in millions of metric tons, Mt) and the vertical axis shows the cumulative probability between zero and one. The cumulative probability for a given percentile represents the probability that the true storage resource is *less than* the value shown. The points along the CDF are the mean and the P_5, P_{50}, and P_{95} percentiles as used in the rest of this report, although the labels on the plots lack subscripts and look like P5, P50, and P95. These values are also given in table 1. Output categories with a calculated storage resource of zero are labeled "No storage resource." Where the mean and P_{50} values are the same within rounding to two significant figures, their respective dots on the curve may be slightly offset and reflect the unrounded values. All storage resource values greater than 1 Mt are rounded to two significant figures; all storage resource values less than 1 Mt are rounded to the nearest 0.1 Mt. For plots with storage resource values less than 1 Mt, a few points do not fall on the empirical CDF curve due to rounding error. All figures were created in R (R Core Team, 2013) using the ggplot2 package (Wickham, 2009). For more details on the calculations used to create the empirical CDF plots, see Brennan and others (2010) and Blondes, Brennan, and others (2013).

USGS

U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team—**National Assessment—Data**—Data Series 774, ver. 1.1