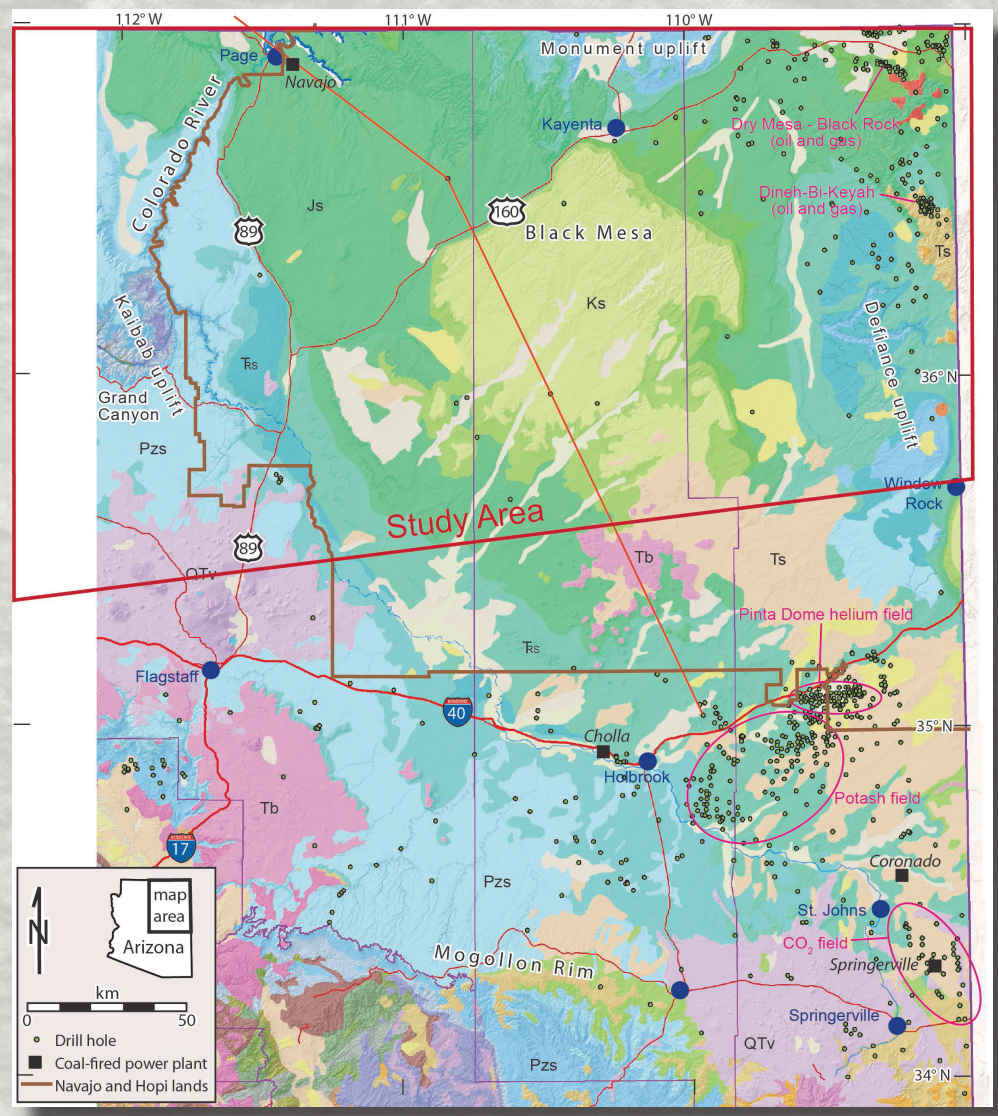
An evaluation of carbon dioxide sequestration potential of the Permian Cedar Mesa Sandstone, northeastern Arizona

Steven L. Rauzi and Jon E. Spencer
Arizona Geological Survey



Geologic map of the study area in northeastern Arizona.

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M. Lee Allison, State Geologist and Director

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An evaluation of carbon dioxide sequestration potential of the Permian Cedar Mesa Sandstone, northeastern Arizona

Steven L. Rauzi and Jon E. Spencer
Arizona Geological Survey
steve.rauzi@azgs.az.gov | jon.spencer@azgs.az.gov

Abstract

Northeastern Arizona encompasses the southwestern part of the Colorado Plateau, an area of gently dipping to slightly tilted Paleozoic and Mesozoic strata that include porous and permeable sandstone units. The Lower Permian Cedar Mesa Sandstone was identified for study as a potential target for CO_2 sequestration in order to reduce anthropogenic CO_2 emissions to the atmosphere. The Cedar Mesa Sandstone is overlain by the impermeable Organ Rock Formation, which is necessary to prevent escape of sequestered CO_2. The salinity of groundwater in the Cedar Mesa Sandstone is unknown, but must be determined before CO_2 can be sequestered because CO_2 sequestration is not permitted in potable groundwater under current regulatory conditions. Well logs for 755 drill holes were used to evaluate the extent, depth, and thickness of subsurface formations. ESRI® ArcMap™ software was then used to calculate the volume of the Cedar Mesa Sandstone where the top of the unit is below 3000 feet (915 meters) depth, which is the minimum depth necessary for CO_2 sequestration where the CO_2 is under sufficient pressure to remain in a dense, near-liquid state. Well logs were used to evaluate porosity, which was then used to calculate the amount of pore space that is theoretically available for CO_2 storage (the effective porosity). We calculate that there are between 30 km^3 and 80 km^3 of pore space in the Cedar Mesa Sandstone. The fraction of pore-space volume that is accessible to CO_2 injection is estimated to be approximately 0.5% to 5%. Applying this storage efficiency to the Cedar Mesa Sandstone indicates that 0.15 km^3 to 4.3 km^3 of pore space is accessible to injected CO_2, and that 0.114 to 3.24 billion tonnes of CO_2 could be sequestered in this pore space at a density of approximately 750 kg/m^3.

Introduction

The U.S. Department of Energy (DOE), through its National Engineering Technology Laboratory (NETL), established a national program to evaluate the feasibility of separating carbon dioxide (CO_2) from industrial sources and pumping it underground for long-term storage or disposal. This program was established in response to concerns that CO_2 emissions from fossil-fuel combustion, and from other industrial processes such as cement production from limestone, are increasing atmospheric CO_2 concentration and solar-energy absorption, thereby causing global warming. Carbon dioxide removal from industrial sources and storage in geologic reservoirs is known as "geologic sequestration." A major aspect of the DOE program is to evaluate subsurface geology to determine the potential of underground rock formations for long-term CO_2 sequestration (U.S. Department of Energy, 2010).

RMCCS (Rocky Mountain Carbon Capture and Sequestration) is a partnership of four western U.S. States (Utah, Colorado, New Mexico, and Arizona) and private industry studying the CO_2 sequestration potential of the Pennsylvanian-Permian Weber Sandstone, Jurassic Entrada Sandstone, and the Cretaceous Dakota Sandstone at a site near Craig, Colorado. The RMCCS team studied these formations regionally to help determine the CO_2 sequestration potential throughout the Colorado Plateau. The team includes the Arizona Geological Survey (AZGS), Colorado Geological Survey, New Mexico Bureau of Geology and Mineral Resources, Schlumberger Carbon Services, Shell Production Company, Tri-State Generation and Transmission, the University of Utah, and the Utah Geological Survey.

This report represents a RMCCS assessment of CO_2 storage potential in the Lower Permian Cedar Mesa Sandstone (equivalent to the Weber Sandstone farther north), the Jurassic Entrada Sandstone, and the Cretaceous Dakota Formation in Arizona. Neither the Entrada Sandstone nor the Dakota Formation are buried at sufficient depth to be considered for CO_2 sequestration, and are not considered further in this report. Funding for this study was provided by University of Utah subaward agreement to the AZGS, with funding ultimately derived from a U.S. American Recovery and Reinvestment Act award to the University of Utah.

The study area is located in northeastern Arizona, in an area that is largely owned by the Navajo and Hopi Indians (Fig. 1; Appendix A). The focus of this study is determining (1) the volume of porous and permeable Permian Cedar Mesa Sandstone where the interface with overlying impermeable capping formations is below 3000 feet (915 meters) depth, (2) the effective (accessible) pore-space volume, and (3) the presence or absence of saline water in the pore space. Basin volume below 3000 feet (915 meters) depth is important because CO_2 will remain in a dense, near-liquid state at hydrostatic pressures corresponding to such depths (provided temperatures are not abnormally high). Successful sequestration requires both adequate permeability and porosity for large-volume CO_2 injection, and an impermeable cap rock that will prevent movement of CO_2 to shallower depth and escape to the atmosphere. Data on the porosity of the Cedar Mesa Sandstone and the salinity of included groundwater are reviewed in this report, and discussed in the context of suitability for CO_2 sequestration. Data on the porosity of the Permian De Chelly Sandstone (lateral equivalent of the White Rim Sandstone in southern Utah) and the salinity of included groundwater are reviewed in Rauzi and Spencer (2012) and are not duplicated here. However, the De Chelly data were submitted to the RMCCS group at the University of Utah Energy Geoscience Institute (EGI) for capacity calculation in the EGI Storage Capacity Spreadsheet.

The AZGS purchased Neuralog software in 2011 to digitize Arizona well logs into computer usable LAS (log ASCII Standard) format to aid analysis for CO_2 sequestration potential. The digitizing effort focused on deep wells across northeastern Arizona including wells that penetrated Precambrian basement and wells in the oil and gas fields with the highest cumulative production (Appendix B). The AZGS developed a user-friendly web application to make the digitized well data available online to facilitate the widest possible access and use of the data. The online search and download map, the Arizona Oil and Gas Well Viewer, is hosted under the Online Data tab on the State of Arizona Oil and Gas Conservation Commission (AZOGCC) website. A total of 275 logs from 120 wells for a total of about 962 curves were digitized through September 30, 2013.

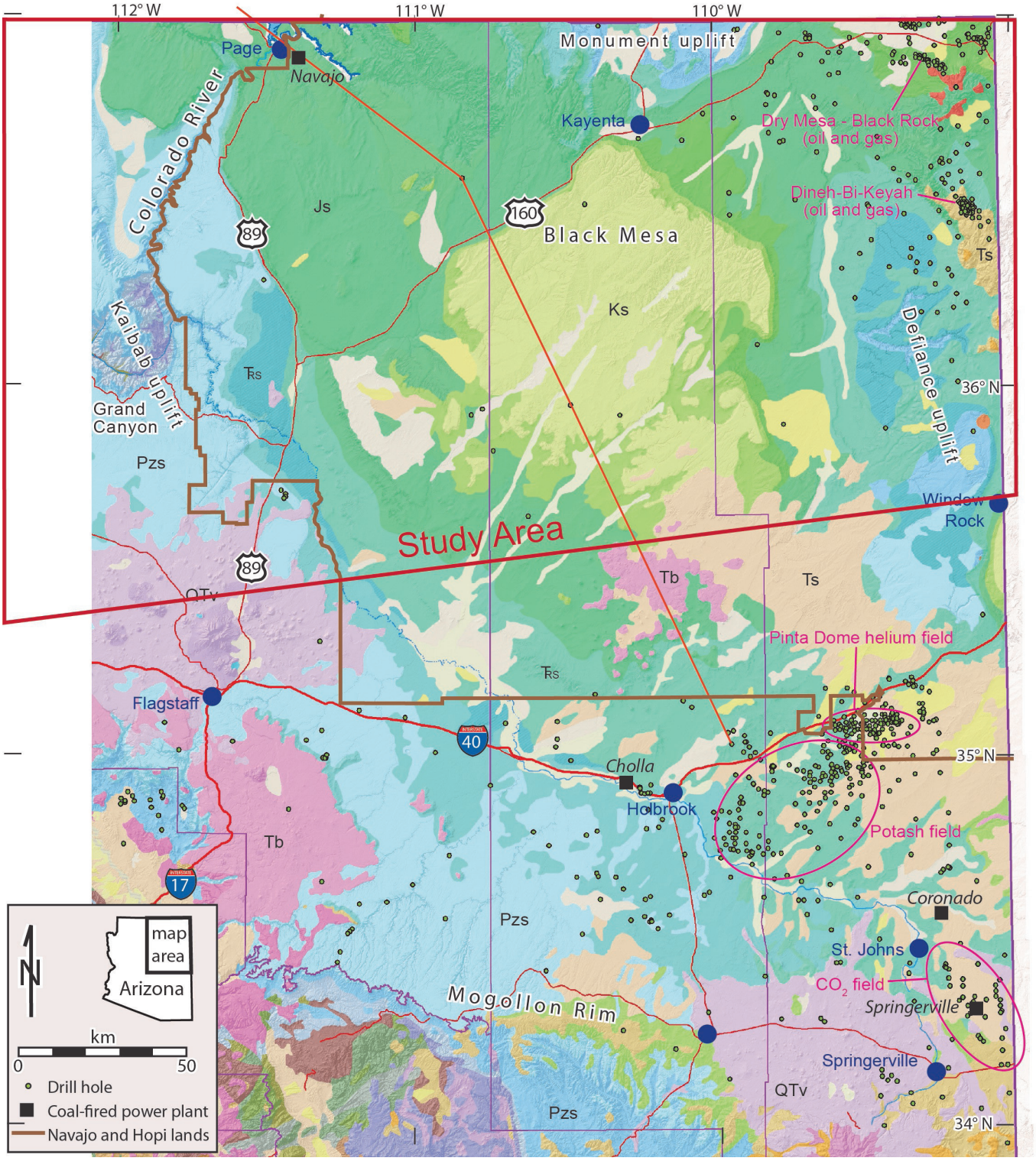

Figure 1. Map of the study area in northeastern Arizona. Colors represent rock units exposed at the surface and were derived from the geologic map of Arizona (Richard et al., 2000). Location of cross section is also shown (see Appendix A for cross section). Large blue dots represent towns. The "CO_2 field" around Springerville is under consideration for CO_2 production for use in secondary oil recovery in west Texas. Map units include Pzs – Paleozoic sedimentary rocks; Trs – Triassic sedimentary rocks; Js – Jurassic sedimentary rocks; Ks – Cretaceous sedimentary rocks, Ts – Tertiary sedimentary rocks; Tb – Tertiary basalt; QTv – Quaternary and Tertiary volcanic rocks, undivided.

Paleozoic Cedar Mesa Sandstone on the Colorado Plateau in Arizona

The Colorado Plateau in Arizona, Utah, New Mexico, and Colorado is characterized by flat-lying to gently dipping, locally gently folded Paleozoic and Mesozoic strata. These strata are most spectacularly revealed where dissected by the Colorado River in Grand Canyon or exposed in Monument Valley in northeastern Arizona. Areas surrounding the Colorado Plateau contain a similar sequence of Paleozoic strata but are more severely affected by Mesozoic and Cenozoic magmatism, folding, faulting, and erosion.

Paleozoic strata of the Colorado Plateau were deposited on the North American craton, an area of much older igneous and metamorphic rocks that had been beveled to a fairly flat surface during hundreds of millions of years of Proterozoic weathering without mountain building. Because of minimal Paleozoic igneous and tectonic activity in the American Southwest, Paleozoic sandstones are generally quartzose, with rounded quartz grains, and lack much of the fine clay and silt that would clog pore spaces in less mature sandstones (e.g., Sloss, 1988; Blakey and Knepp, 1989). As a result, Paleozoic Plateau sands are generally porous and permeable, and an obvious target for studies of CO_2 sequestration potential.

The study area is centered on Black Mesa Basin and the area to the northwest around the town of Page (Fig. 1). The Permian Cedar Mesa Sandstone that is the focus of this study (Fig. 2) is not thicker in Black Mesa basin. Rather, the unit is deformed over a large area into an approximate bowl shape, with the most deeply buried strata beneath Black Mesa on the Navajo and Hopi Nations (Fig. 1). The greater burial depth of Paleozoic strata in Black Mesa basin results from the greater preserved stratigraphic thickness of Mesozoic strata that make up Black Mesa and immediately surrounding areas. The bowl-shaped basin is bounded to the north by the Monument uplift, to the west by the Kaibab uplift, to the east by the Defiance uplift, and to the south by the slightly upturned south rim of the Colorado Plateau that is known as the Mogollon Rim (Fig. 1). These uplifts are the result of faulting and folding during the latest Cretaceous and Paleogene Laramide orogeny. The greater depth of the Cedar Mesa Sandstone to the northwest of Black Mesa Basin is the result, in part, of thick preserved Jurassic and Triassic strata that extend into Utah north of Page.

Subsurface control is from 755 wells maintained on behalf of the AZOGCC at the AZGS. Depth, thickness, and porosity data are primarily from lithologic logs prepared by the American Stratigraphic Company (AmStrat). Approximate porosity indicated on the AmStrat logs represent visual examination of cuttings and core. AmStrat logs are available for most wells drilled in the 1970s and earlier. Some depth and thickness data are from formation tops reported on completion reports submitted by well operators. In some cases, depth correlations and estimates were picked by the authors in wells for which operator-identified tops or an AmStrat log were not available or where the authors disagreed with the operator or AmStrat picks. Well data used in the report are available online at the AZOGCC website at http://welldata.azogcc.az.gov/OilGasViewer.html.

Of the three units under study by RMCCS, only the Cedar Mesa Sandstone is present in the study area at depths greater than 3000 feet (915 meters). Depth and thickness contours are based on depth below the land surface at the location of the wells and are not based on depth relative to sea level or some other horizontal datum. For example, the Cedar Mesa Sandstone is deeper in the Black Mesa Basin because of the higher surface elevation of Black Mesa relative to the surrounding terrain in northeastern Arizona. Some of the locally isolated deep spots depicted on the depth maps represent wells that were drilled on topographically high buttes and mesas, which are common in northeastern Arizona.

Sealing unit

The impermeable Permian Organ Rock Formation overlies the Cedar Mesa Sandstone (Fig. 2). The Organ Rock forms a distinctive redbed sequence that was deposited across all of northern Arizona (Blakey and Knepp, 1989). The Organ Rock Formation in the Sinclair Oil #1 Navajo well in Sec 28, T. 37 N., R. 14 E. is predominantly a tight, orange to brown very argillaceous, very fine grained sandy siltstone interbedded with thin shale. The shale is micaceous with limestone nodules. The Organ Rock Formation forms an effective seal directly above the Cedar Mesa Sandstone.

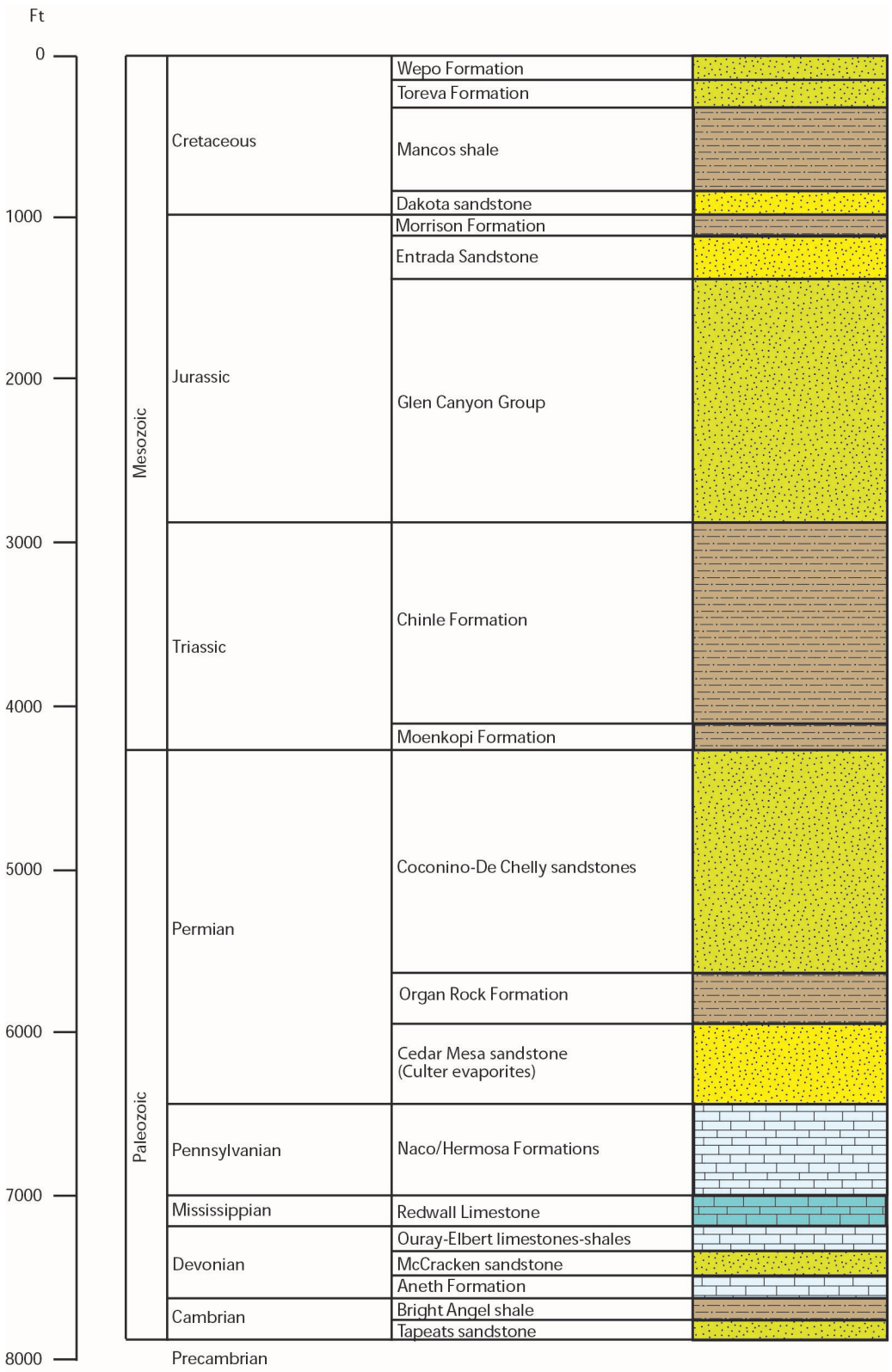

Figure 2. Stratigraphic column representing the Black Mesa and Four Corners areas. Yellow represents sandstone units under study for CO2 sequestration potential.

Formation fluid salinity

Salinity data are derived primarily from drill-stem tests or production data. Drill-stem tests are usually performed while the well is being drilled. Production data are obtained after a well is completed as a producing well. Salinity data from drill-stem tests are usually described qualitatively as “salt water”, “mud-cut salt water”, or in some instances “fresh water”. The Cedar Mesa Sandstone has not generally been the target of drilling for oil and gas exploration. As a result, only two wells in the far northeastern corner of Arizona have any data relevant to the composition of groundwater in the Cedar Mesa Sandstone. They indicate “gas-cut mud” and “slightly oil and gas cut mud.” The slight showings of hydrocarbons suggest that the formation waters in the Cedar Mesa Sandstone are not fresh because they yield minor showings of oil and gas.

Depth and thickness of the Cedar Mesa Sandstone

The Permian Cedar Mesa Sandstone pinches out to zero thickness southeastward under Black Mesa, but thickens northwestward toward the Paria Plateau west of Page where thickness is up to 700 feet (213 meters) at depths greater than 3000 feet (915 meters). The Cedar Mesa Sandstone is equivalent to the Weber Sandstone in northern Utah. To the west in the Grand Canyon region, the Cedar Mesa Sandstone is roughly equivalent to the Esplanade Member of the Supai Group. The Cedar Mesa Sandstone grades into an evaporite facies of the Cutler Group in northeastern Arizona across a line that extends generally from Flagstaff to the Four Corners. This line represents the zero thickness line on the isopach map (Fig. 5). Isolated sandbars embedded within the evaporite facies are present in northeastern Arizona north of the Defiance Uplift. These isolated sandbars provide an insignificant amount to the overall potential CO_2 sequestration capacity of the Cedar Mesa Sandstone in Arizona. The Cedar Mesa has potential for CO_2 sequestration throughout a broad area below a depth of 3000 feet (915 meters) that extends northward from the Black Mesa Basin in Arizona to the Kaiparowits Basin in Utah and between Kaibab Uplift to the west and Monument Valley and Defiance Uplift to the east. The Cedar Mesa Sandstone is absent over much of the southern part of the study area. The Cedar Mesa Sandstone increases in thickness from zero in the Four Corners area and along the western margin of the Defiance Uplift to about 500 feet (152 meters) beneath the Navajo Generating Station near Page, Arizona. The unit is between 300 and 400 feet (91 and 122 meters) thick where it crops out as the Esplanade Sandstone in eastern Grand Canyon. The Cedar Mesa Sandstone attains localized thickness of up to 500 feet (152 meters) in isolated occurrences in the Four Corners area. Maps of the distribution, depth, and thickness of the Cedar Mesa Sandstone are shown in figures 3, 4, and 5, which also show drill holes. The cross section, represented by the orange line in the map figures, is shown in Appendix A.

Navajo Generating Station.

The Navajo Generating Station (NGS) near Page is the recommended site in Arizona. The NGS is the largest coal-fired power plant and emitter of CO_2 (16 million metric tons in 2011) in Arizona. The Cedar Mesa Sandstone attains its maximum storage capacity of 138,409 metric tons per km^2 at 2% efficiency factor beneath the NGS as calculated in the EGI Storage Capacity Spreadsheet (Fig. 6). There are no deep exploratory wells in the immediate vicinity of the NGS. The depth and thickness estimates of the Cedar Mesa Sandstone beneath the NGS are based on regional hand contouring and projections from the Sinclair Oil 1 Navajo well in Arizona (Sec. 28, T. 37 N., R. 14 E.) and the Rangeland (Union Oil Company) 1 Judd Hollow well in Utah (Sec. 19, T. 43 S., R. 2 E.). The Sinclair and Rangeland wells lie approximately 38 miles southeast and 22 miles northwest of the NGS, respectively. A stratigraphic well is needed at the NGS site to determine the site-specific reservoir properties of the Cedar Mesa Sandstone and seal properties of the overlying Organ Rock Formation.

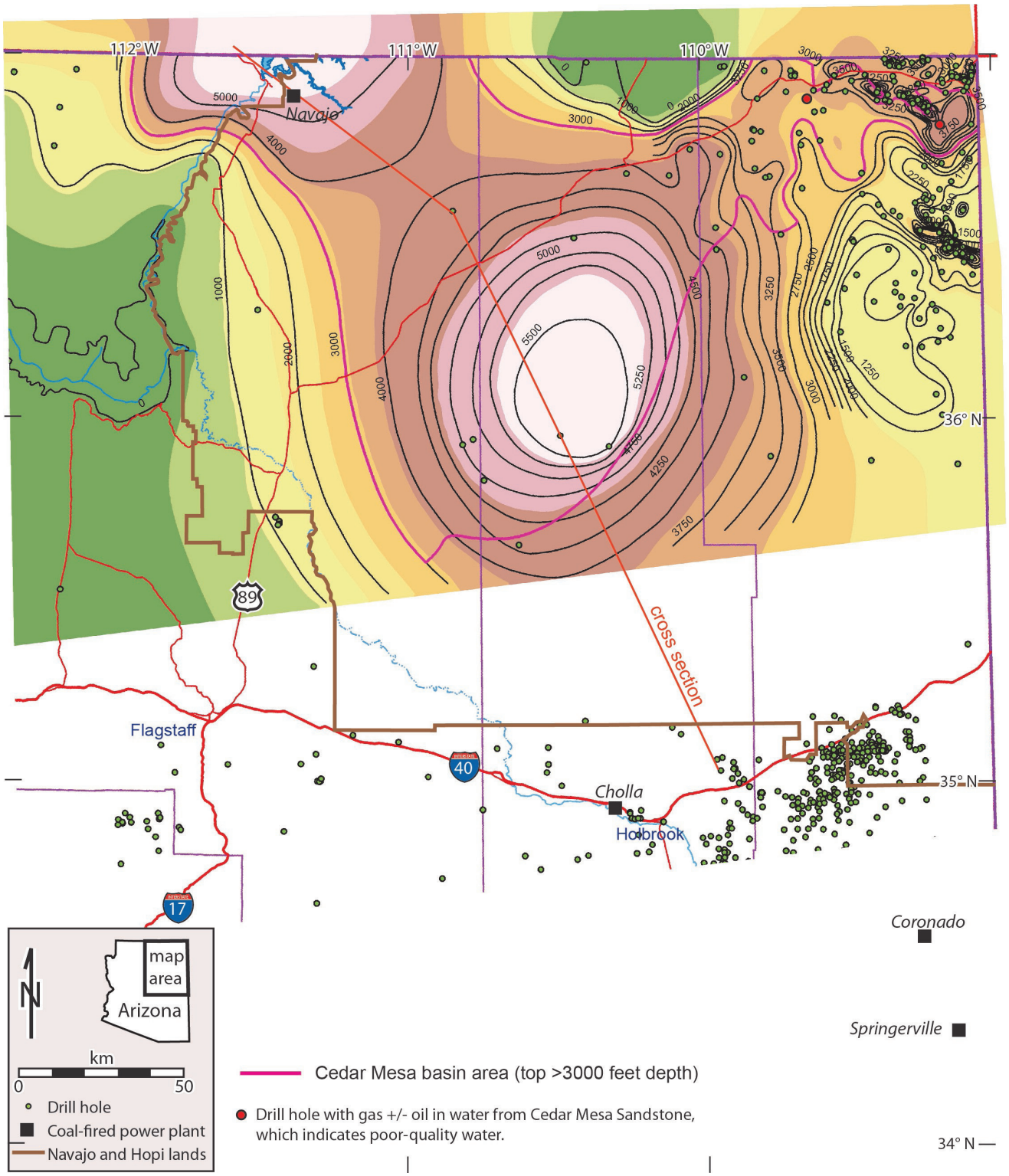

Figure 3. Depth contours (black numbered lines, in feet) represent the depth to the top of the Cedar Mesa Sandstone, and were derived from analysis of well logs. The color background maps are raster representations of the contoured surface created using ArcToolbox™ tools (see text) (color interval for raster colors is arbitrary). Magenta lines bounds areas where the top of the Cedar Mesa Sandstone is greater than 3000 feet (915 meters) deep or where the sandstone pinches out to zero thickness.

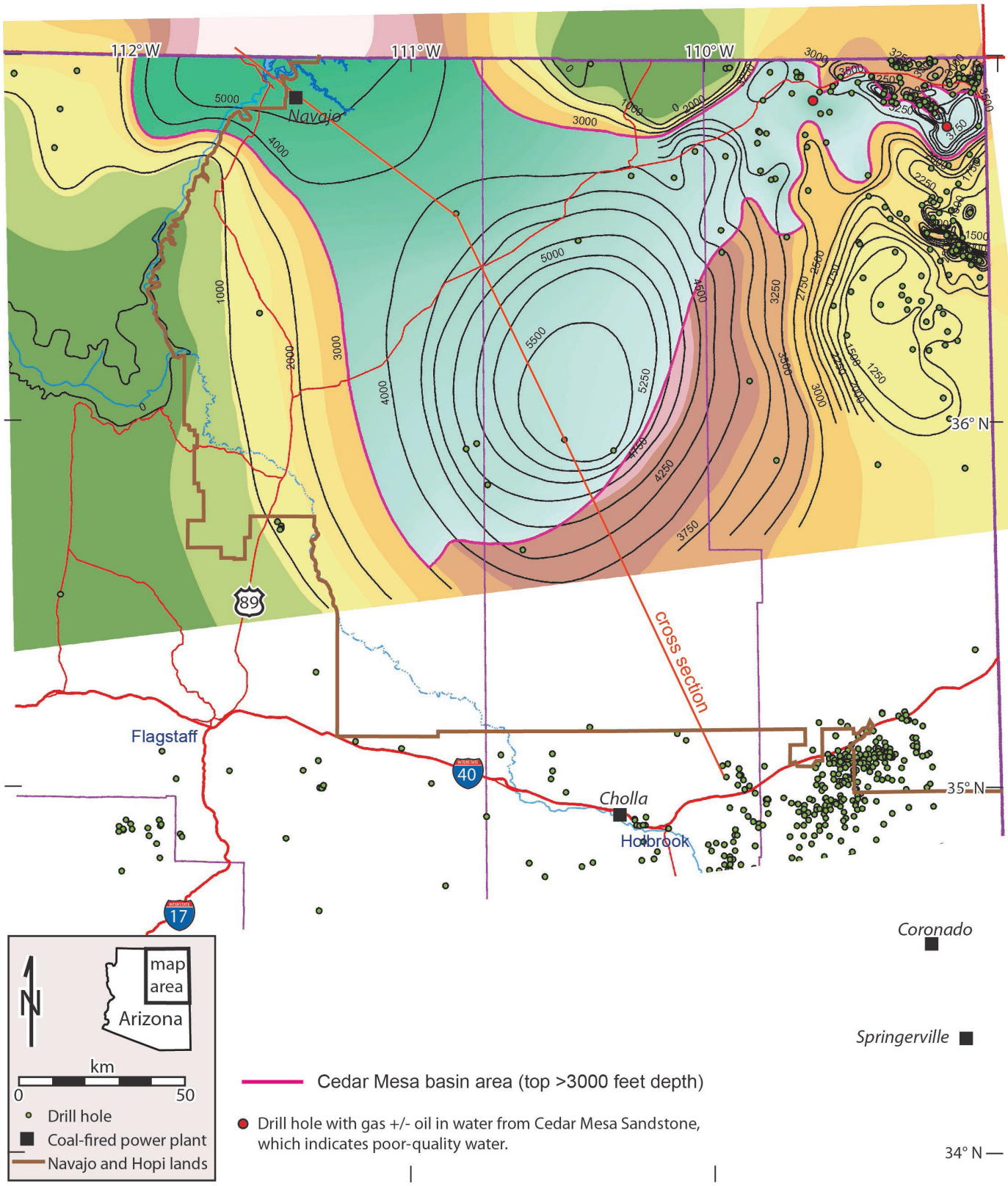

Figure 4. As in figure 3, but areas where the top of the Cedar Mesa Sandstone is below 3000 feet (915 meters) depth are colored green, with lighter green corresponding to areas where the sandstone is thinner. Depth contours are in feet.

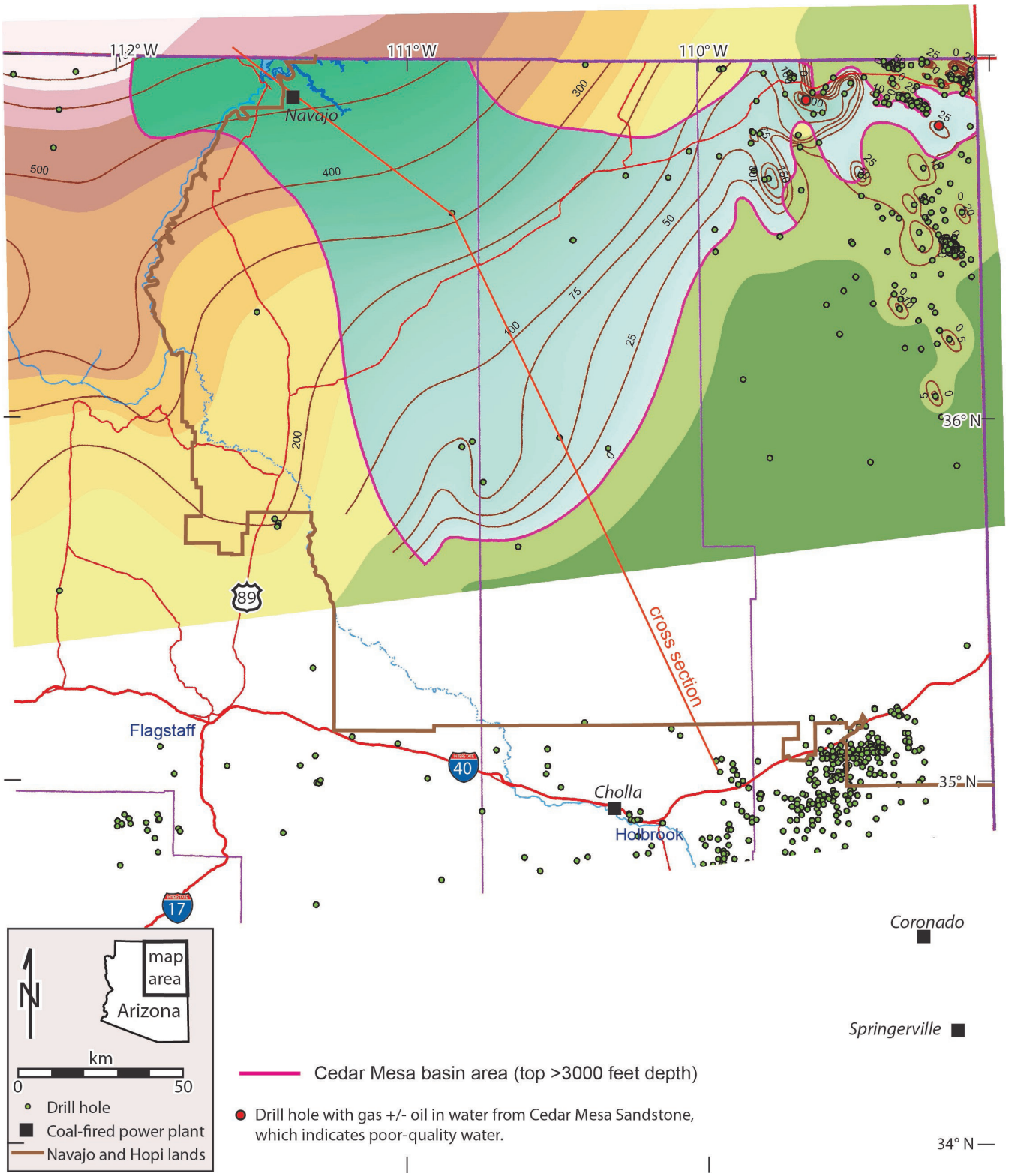

Figure 5. As in figures 3 and 4, but contours and color raster background maps represent sandstone unit thickness rather than depth (in feet). The color raster background maps represent the thickness of the Cedar Mesa Sandstone as derived from the contour map using ArcToolbox™ tools (see text) (color interval for raster colors is arbitrary). Areas where the top of the Cedar Mesa Sandstone is below 3000 feet (915 meters) depth are colored green, with lighter green corresponding to areas where the sandstone is thinner. Sandstone volume was calculated for this raster using ArcToolbox™ tools (see text and tables).

Sandstone-volume calculations - procedure

The volume Cedar Mesa Sandstone in areas where the top of the formation is >3000 feet (>915 meters) deep was determined using ESRI® ArcMap™ version 10 software. Some of this procedure followed specifications required by the RMCCS program coordinators.

(1) Contours

Well logs from a database of 755 Arizona oil and gas exploration drill holes were used to identify the depth to the stratigraphic top and base of Colorado Plateau sandstone units. Contour maps were drafted by hand (by Steve Rauzi) for formation tops and thicknesses (in feet), and then each was digitized to create a shape file with depth and thickness in feet (as text values) and in meters (as numeric values calculated from values in feet). These digitized contour maps were created in the geographic coordinate system (GCS) "North American 1983" using projection NAD83, zone 12. The Cedar Mesa Sandstone contours were used for this study. Other formations were evaluated earlier using similar methodology (Rauzi and Spencer, 2012). Digital manipulations and calculations listed below were done by J. Spencer.

(2) Coordinate system transformation

Contour maps were transformed to the geographic coordinate system (GCS) WGS_1984 with a Lambert Azimuthal Equal Area projection, as required for the NATCARB Atlas geodatabase, with the following procedure.

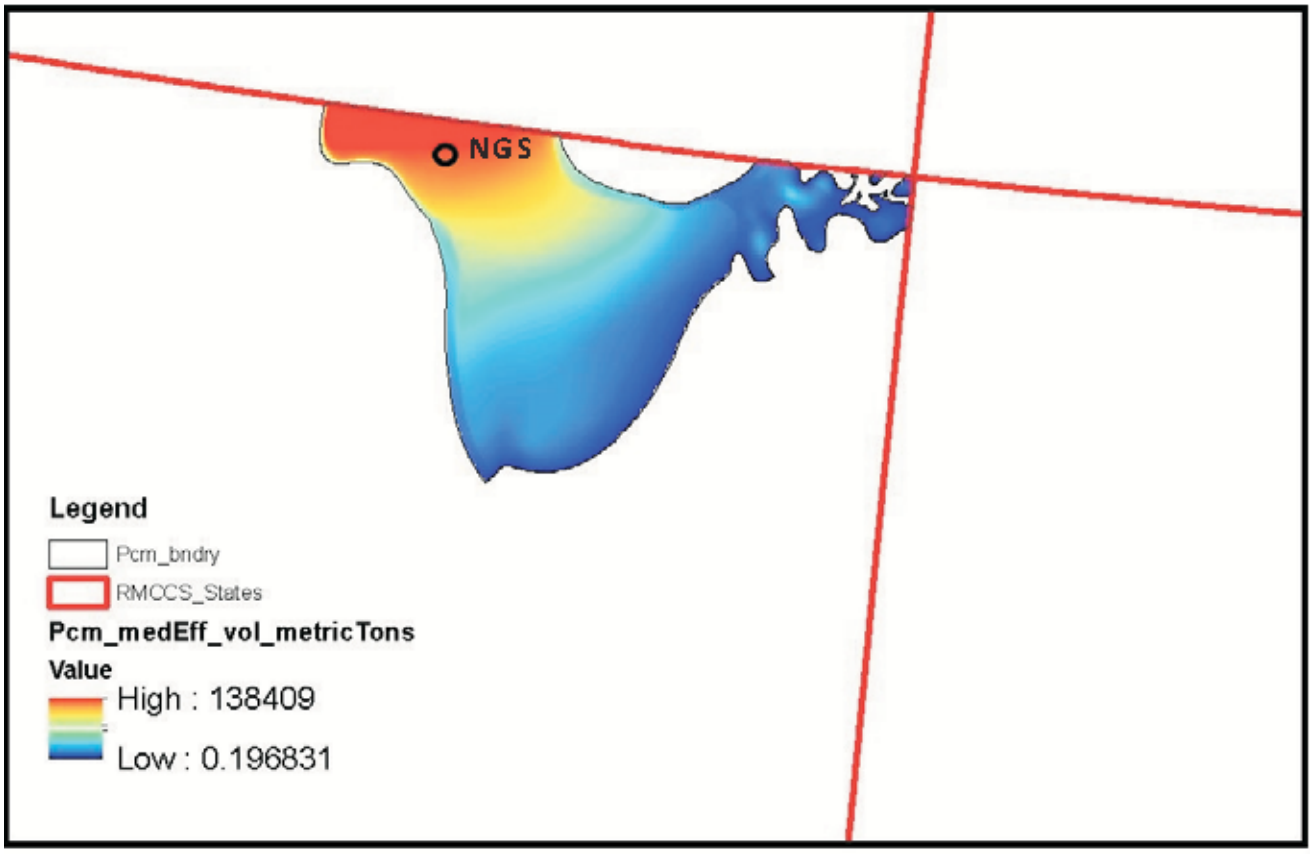

Figure 6. Map showing a CO2 storage capacity visualization of the Cedar Mesa Sandstone in Arizona as calculated in the EGI Storage Capacity Spreadsheet. Units are in metric tons per km_2 raster cell using an average porosity of 4.62% and medium efficiency volume of 2%. The values range from a high of 138,409 metric tons per km_2 to a low of 0.2 metric tons per km_2. Note that the highest storage capacity occurs beneath the Navajo Generating Station (NGS). Pcm_bndy shows where the top of the Cedar Mesa Sandstone is below a depth of 3000 feet. Input parameters for the capacity visualization included depth (ft), thickness (ft), reservoir temperature (F), porosity (%), pore volume (m_3), and CO2 density (kg/m_3).

The “Project” tool in the “Feature” toolset in the “Projections and Transformations” toolbox in the “Data Management Tools” in ArcMap v. 10.0 was opened. The “Input Dataset or Feature Class” is the original (NAD 83) shape file. A folder was created for the transformed shape files (in ArcCatalog) and used for the “Output Dataset of Feature Class” (ArcMap defaulted to the RMCCS_saline data.gdb for the output feature class, but then would fail to create the file if this default option was not changed). For “Output Coordinate System” select “Import”, then navigate to one of the feature classes in the RMCCS_saline geodatabase and select it. That should fill in “Details” window with the following information:

Projection: Lambert_Azimuthal_Equal_Area
False_Easting: 0.000000
False_Northing: 0.000000
Central_Meridian: -100.000000
Latitude_Of_Origin: 45.000000
Linear Unit: Meter (1.000000)

Geographic Coordinate System: GCS_WGS_1984
Angular Unit: Degree (0.017453292519943299)
Prime Meridian: Greenwich (0.000000000000000000)
Datum: D_WGS_1984
  Spheroid: WGS_1984
    Semimajor Axis: 6378137.000000000000000000
    Semiminor Axis: 6356752.314245179300000000
    Inverse Flattening: 298.257223563000030000

It was necessary to add a “Geographic Transformation” which is supposed to be optional. However, reprojection was not possible without selecting one of the Transformations. According to the help menu for “Project (Data Management)”, the “Geographic Transformation” corresponds to a “transform_method”, with the following information:

This method can be used for converting data between two geographic coordinate systems or datums. This initially optional parameter may be required if the input and output coordinate systems have different data.

The ArcGIS help topic “Choosing an appropriate transformation” states the following:

Converting between NAD 1983 and WGS 1984. Originally, NAD 1983 and WGS 1984 were considered coincident. To minimize coordinate changes, NAD 1983 is tied to the North American and Pacific (for Hawaii, and so on) plates. WGS 1984 is tied to the International Terrestrial Reference System (ITRF), which is independent of the tectonic plates. Over time, the two coordinate systems have become increasingly different.

NAD_1983_To_WGS_1984_1: Published accuracy from EPSG is 2 meters. This transformation applies to the entire North American continent. This transformation uses the geocentric translation method, with the transformation’s parameters (dx, dy, and dz) all equal to zeroes. This transformation treats the NAD 1983 and WGS 1984 datums as though they are equivalent. “NAD_1983_To_WGS_1984_1” was used to transform Arizona data.

(3) Contour-to-raster conversion

In a raster representation of a contour map, a surface is constructed that interpolates between contours. The surface is represented by a grid of regularly spaced points, each of which has an assigned value based on the interpolation between contours. The depth and thickness contour maps were used to build raster representations of Cedar Mesa unit-top depth and unit thickness using the “Topo to Raster” tool in the “Raster Interpolation” tool set in the “3D Analyst Tools” in ArcToolbox. To do this, each contour dataset was dragged (using the computer mouse) from the table of contents in the ArcMap project to the top line in the “Topo to Raster” tool. The “field” to represent was set to “ThicknessM” or “DepthMeter” (this must be a numeric field that indicates contour depth or thickness, here in meters). Output surface raster file name and path were specified, and output cell size was set to 1000 meters. “Output extent (optional)” was specified as using the same extent as the input contour shape file for thickness, and to the thickness contour shape file for depth so that the extent would be the same for both resultant raster files. “Drainage enforcement” was set to “NO_ENFORCE” because the contour map does not represent a landscape. The “Environments” button at the bottom of the “Topo to Raster” tool window was then used to open the “Environment Settings” window. To create a raster with raster points that are spatially coincident with the “RMCCS_1K” 1-km grid raster, the “Processing Extent” option was opened and the “Snap Raster” was identified as “RMCCS_1K” by navigating to that feature and selecting it. Also, under “Processing

Extent", the input contour file was selected (this might be redundant with the "Output extent (optional)" setting as specified in the "Topo to Raster" tool).

For the Cedar Mesa thickness-raster construction, the zero-depth line was deleted from the thickness contour map where that line is due to modern erosional removal rather than subsurface thickness changes. The areas of thickness interpolation (especially across Grand Canyon) where Cedar Mesa Sandstone is absent are ultimately irrelevant to later volume calculations because these calculations were done only for areas where the sandstone is present at significant depth. (Also, it was not necessary to calculate depth by subtracting the elevation of the formation top from surface elevation because, from the start, depth represented depth below the surface and not elevation as would be the case for a structure-contour map.)

(4) Basin area below 3000 feet (915 meters) depth and thickness-raster subset

The basin area for calculation of basin sequestration volume is the area where the top of the Cedar Mesa Sandstone is below 3000 feet (915 meters) depth, the unit has greater-than-zero thickness, and the unit is within Arizona. A single closed loop, as a feature in a shape file, was created from a copy of the 3000 foot depth contour, which was cut where it crossed the Arizona state border or the zero thickness contour, and then extended along the zero thickness contour and state border until a single closed loop was created that outlined the Cedar Mesa calculation area. The loop was then converted to a polygon using the "Feature to Polygon" tool in the "Features" tool set in the "Data Management Tools" in ArcToolbox.

The polygon was then used to extract a subset of the thickness raster for the purpose of calculating volume. This was done using the "Extract by mask" tool of the "Extraction" tool set within the "Spatial Analyst" toolbox (output file named "thick3000"). For the RMCCS multistate CO_2 sequestration atlas, this same procedure was then done for the depth raster (output file named "depth3000") so that two rasters would exist, one for thickness and one for depth, of identical areas with identical coordinates for the raster cells. (For calculations presented in the rest of this paper that were not done only for the RMCCS atlas, a very slightly corrected raster area was used, with outputs named "thick3000B" and "depth3000B".)

(5) Joined table with xy coordinates (done only for the RMCCS multistate CO_2 sequestration atlas)

Depth and thickness raster data (in two .shp files but referred to as "raster datasets" or "raster layers") were merged into a single feature class (also with a .shp file extension but referred to as a "point feature class" in the ArcMap Help menu under "raster to point") with xy coordinates. This was done in three steps: (1) The raster point data were converted using the "Raster to Point" tool in the "From Raster" toolset in the "Conversion Tools" in ArcToolbox. (2) The two resulting point-data datasets were then merged into a single point feature class using the "Spatial Join" tool in the "Overlay" toolset in the "Analysis Tools" in ArcToolbox. (3) To add coordinate data to the table of points, we used the "Add XY Coordinates" tool in the "Features" toolset in the "Data Management Tools" in ArcToolbox. This tool was used on the joined table created in the previous step to create two new fields populated with coordinate data.

(6) Export to Excel (done only for the RMCCS multistate CO_2 sequestration atlas)

The joined table with xy data was opened in ArcMap. The pull-down menu associated with the upper left button ("Table Options") at the top of the table includes "Export". Selecting this option allows export of the joined table with xy data to be exported as a .txt file to any specified folder. The table was then opened in Excel, saved as an Excel file, and sent to the RMCCS group at the University of Utah for further calculations in the EGI Storage Capacity Spreadsheet.

(7) Calculation of Cedar Mesa volume below 3000 feet (915 meters) depth (done for AZGS, not for atlas)

The Cedar Mesa thickness raster produced in step 4 above was then used to calculate basin volume below 3000 feet (915 meters) depth using the "Surface volume" tool from the "Functional surface" tool set in the "3D Analyst" toolbox. "Plane Height" was set to zero so that, if all thicknesses in the raster are greater than zero by a finite amount (i.e., every raster cell has thickness greater than zero), a reduced volume is not erroneously produced. The resulting table output data was entered in an Excel spreadsheet (Table 1), with similar data for the De Chelly Sandstone that was evaluated earlier for minimum depth of 800 meters (2624 feet) (Rauzi and Spencer, 2012).

CO_2 Storage Capacity

The estimated mass of CO_2 (G_{CO2}) that could be stored in a sandstone unit is calculated with the following equation (from Litynski et al., 2010):

$$G_{CO2} = A_t\ h_g\ \phi_{total}\ \rho\ E_{saline} \qquad (1)$$

where A_t is the total area in which the top of the saline formation is below 915m depth, h_g is the gross formation thickness, ϕ_{total} is the total porosity, ρ is the average density of CO_2 at the depths and temperatures that characterize the formation, and E_{saline} is the storage efficiency factor that represents the fraction of the total pore space that potentially will be occupied by stored CO_2. The ArcMap calculations presented in Table 1 represent formation volume with greater accuracy than formation volume calculated by simply multiplying total area At by gross thickness hg because the ArcMap calculations account for lateral changes in thickness.

Formation porosities were estimated by well loggers based on examination of drill cuttings from 79 drill holes that penetrated at least part of the Cedar Mesa Sandstone. The total porosity (ϕ_{total}) and standard deviation were determined for the sandstone (Table 2). High porosity is given at the one standard deviation level above the mean, but this was unreasonably low for the deviation below the mean due to the skewed distribution of porosity determination. Instead, we considered a porosity of 3% as the low estimate because 66 of 79 measurements indicated porosity of 3% or higher. Low, middle, and high values for total pore volume were then calculated for the Cedar Mesa Sandstone and compared to other Paleozoic sandstone unit volumes calculated previously (Table 2, last three columns).

The capacity of sandstone to store CO_2 is not equivalent to its pore volume because not all pore space is accessible to an injected fluid. The storage efficiency of a saline formation (Esaline), which is the fraction of pore space that is actually accessible to injected CO_2, is calculated from the following equation (Litynski et al., 2010):

$$E_{saline} = E_{An/At}\ E_{hn/hg}\ E_{\phi e/\phi tot}\ E_v\ E_d \qquad (2)$$

$E_{An/At}$ and $E_{hn/hg}$ are the fractions of areal extent and thickness, respectively, that have suitable physical properties for CO_2 sequestration. $E_{\phi e/\phi tot}$ is the fraction of total pore space that is interconnected and so is amenable to CO_2 sequestration. E_v represents barriers to displacement of CO_2 into formation volume, and includes such barriers as fault zones. E_d represents microscopic barriers to CO_2 movement into all pore space and includes molecular adhesion (wetting) of saline solutions to sand grains in which the saline fluids are not displaced by CO_2 influx. Storage efficiencies derived from studies of CO_2 injection into oil and gas reservoirs, and estimated by numerical simulation, are 0.51% to 5.4% for clastic rocks, with a mean value of 2.0% (Table 7 in Litynski et al., 2010). The low and high values are calculated to represent the 10% and 90% probability values.

Estimates of the mass of CO_2 that can be stored in a given pore-space volume require an estimate of the density of stored CO_2, which depends on temperature and pressure. Subsurface temperatures beneath the Colorado Plateau as measured in 430 drill holes were used to calculate average surface temperature and geothermal gradient (Fig. 7). This yielded a surface temperature of 23.57°C and a gradient of 0.0134h where h is depth in meters and gradient is given in degrees C per meter depth. Using this data set in this manner is somewhat problematic because data generally were collected during drilling operations and not after an extended period (5-15 days) of inactivity. Circulating drilling fluids carry cold fluids down and bring heat back up, which decreases bottom-hole temperature. Because of variability in the time between cessation of drill-fluid circulation and down-hole temperature measurement, some measured temperatures were possibly artificially depressed and others were not. As a result, geothermal gradient is probably slightly underestimated, and scatter in measured temperatures is increased. The significance of this bias toward low temperatures is not well known, but inasmuch as it is reflected in increased scatter in temperature measurements, it does not appear to be large. Especially telling in this regard is the fact that temperatures measured at greater depth do not show greater scatter, as would be expected for greater heat loss to drill fluids for deeper wells with greater down-hole temperatures (Fig. 7).

The calculated temperature gradient was used to estimate subsurface temperatures beneath the Colorado Plateau. Hydrostatic pressure (the weight of a column of water extending upward to the surface) is assumed for conditions of CO_2 storage (Bachu, 2003). Using a hydrostatic pressure gradient and a

temperature gradient as described above, CO_2 density was calculated by plotting P-T conditions for a range of depths as shown on Figure 8. Each blue dot represents hydrostatic pressure at depths represented by the numbers (in km) associated with each dot. The horizontal position of each dot is determined by the calculated temperature at each depth. CO_2 density at 3000 feet (915 meters) depth is estimated from the graph at 750 kg/m^3. This value was used to calculate CO_2 storage capacity for Colorado Plateau sandstone units (Table 3). Most of the volume under consideration for CO_2 storage is deeper, however, reaching depths of over 5000 feet (1524 meters) in a large area near the Navajo Generating Station near Page (Figs. 3, 4) where thickness is several hundred feet (Fig. 5). Our median estimate using ArcMap tools of the mass of CO_2 that can be stored in the Cedar Mesa Sandstone in the Arizona part of the Colorado Plateau is 0.69 billion tonnes, with low and high estimates of 0.114 and 3.24 billion tonnes, respectively (a "tonne" is a metric ton, equivalent to 1000 kg). Median estimate from the EGI Storage Capacity Spreadsheet of the mass of CO_2 that can be stored in the Cedar Mesa Sandstone in the Arizona part of the Colorado Plateau is 0.66 billion tonnes, with low and high estimates of 0.168 and 1.78 billion tonnes, respectively (Table 3). The difference in median capacity values may be due, at least in part, to the use of a CO_2 density calculation procedure that accounts for variation in depth to formation top, and

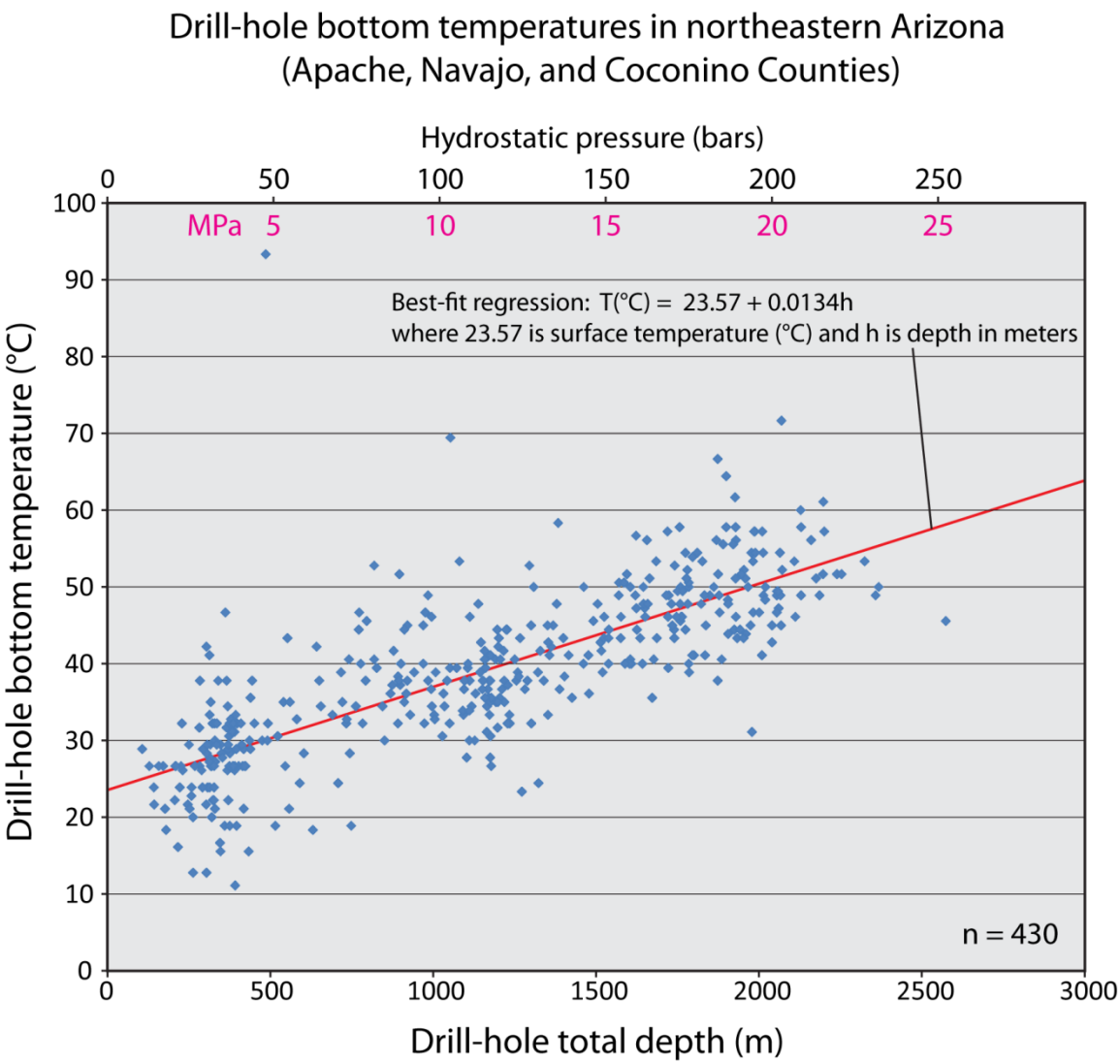

Figure 7. Drill-hole bottom temperatures from 430 bore holes in northeastern Arizona.

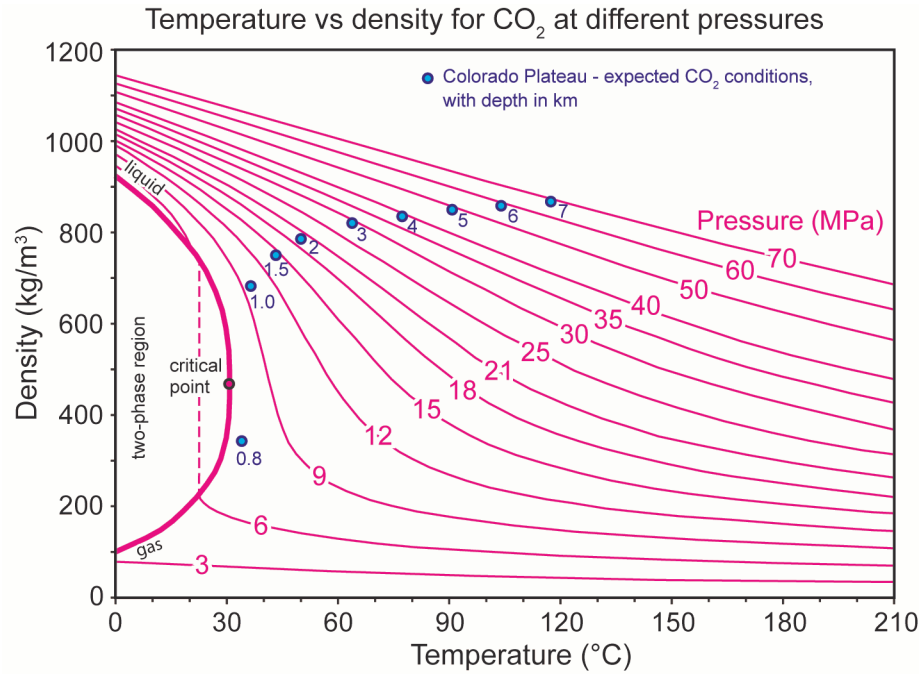

Figure 8. Temperature and density of CO2 are plotted for a range of pressures represented by the magenta isopressure lines. For appropriate pressure, and temperature below that of the critical point, CO2 coexists as both a gas and a liquid. To identify density conditions of CO2 stored in sandstone units beneath the Colorado Plateau, a range of pressure and temperature conditions were evaluated, as follows. For each storage depth, a temperature was calculated from the regression line in Figure 7, and a value for hydrostatic pressure was calculated. Each blue dot, representing a depth given by the number next to each dot, was located on this diagram by its temperature (horizontal position) and by the calculated hydrostatic pressure for each depth which was used to place the dot among the magenta isopressure lines (from Bachu, 2003). At pressure corresponding to depth less than 1 km, precise density is uncertain (for example, compare results plotted here [derived from Bachu, 2003] with those from an online CO2 density calculator at http://www.peacesoftware.de/einigewerte/co2_e.html).

hence ambient pressure, in the EGI Storage Capacity Spreadsheet. The difference in low and high capacity estimates, with a greater range of values determined by the AZGS estimate, is apparently due to the fact that AZGS estimates included low and high estimates of porosity (Table 2). The median estimate from the EGI Storage Capacity Spreadsheet of the mass of CO_2 that can be stored in the De Chelly Sandstone in the Arizona part of the Colorado Plateau is 7.1 billion tonnes (Table 3).

Conclusion

We calculate that the Cedar Mesa Sandstone has the capacity to store approximately 0.69 billion tonnes of CO_2, which is more than for any of the other Paleozoic sandstone units on the Colorado Plateau except the De Chelly sandstone beneath Black Mesa Basin (median estimate of 7.3 billion tonnes, or ten times more; Rauzi and Spencer, 2012). However, it is not known if pore waters present in the Cedar Mesa Sandstone are saline. It seems likely that groundwater in the Cedar Mesa Sandstone is saltier than that in the De Chelly Sandstone simply because the Cedar Mesa Sandstone is more deeply buried, but this will not be known until drilling and testing are done.

Table 1. ArcMap-calculated volume and area of two Paleozoic sandstone units on the Colorado Plateau in Arizona*

Basin and unit	Dataset	Plane Height	Reference	Z Factor	2D Area (m^2)	3D Area (m^2)	Volume (m^3)	2D area (km^2)	Volume (km^3)	Minimum depth
De Chelly main	..ateau2012_2\Rasters\dech_main2	0	ABOVE	1	10133348856	10133429005	3.39325E+12	10133	3393	800 m
Cedar Mesa	..GS_Atlas\ShapeFiles\thick3000B	0	ABOVE	1	16640926196	16640951452	9.93947E+11	16641	994	914 m (3000 ft)

*For depth below threshold indicated in last column

Table 2. Porosity and pore volume for two Paleozoic sandstone units on the Colorado Plateau in Arizona

Basin and unit	Area (km^2)	Volume (km^3)	Porosity low (%)*	Porosity mean (%)	Porosity high (%)*	Pore volume low (km^3)	Pore volume mean (km^3)	Pore volume high (km^3)
De Chelly main	10133	3393	9.3	14.3	19.3	315.57	485.23	654.90
Cedar Mesa	16818	994	3	4.62	8.04	29.82	45.92	79.91

*De Chelly Sandstone (n=184): Porosity range is +/- one standard deviation

Table 3. CO_2 storage capacity for two Paleozoic sandstone units on the Colorado Plateau in Arizona

Sandstone unit and basin	Pore volume low (km^3)	Pore volume mean (km^3)	Pore volume high (km^3)	Storage efficiency, low*	Storage efficiency, median*	Storage efficiency, high*	Effective pore volume, low (km^3)	Effective pore volume, median (km^3)	Effective pore volume, high (km^3)	CO_2 density (kg/m^3)	AZGS ArcMap Potential mass of stored CO_2 (tonnes), low**	EGI Storage Capacity Spreadsheet Potential mass of stored CO_2 (tonnes), low**	AZGS ArcMap Potential mass of stored CO_2 (tonnes), median**	EGI Storage Capacity Spreadsheet Potential mass of stored CO_2 (tonnes), median**	AZGS ArcMap Potential mass of stored CO_2 (tonnes), high**	EGI Storage Capacity Spreadsheet Potential mass of stored CO_2 (tonnes), high**
De Chelly main	315.57	485.23	654.90	0.0051	0.02	0.054	1.6	9.7	35.4	750	1.2071.E+09	1.8207.E+09	7.2785.E+09	7.1401.E+09	2.6523.E+10	1.9278.E+10
Cedar Mesa***	29.82	45.92	79.91	0.0051	0.02	0.054	0.152	0.92	4.32	750	1.1406.E+08	1.6810.E+08	6.8881.E+08	6.5921.E+08	3.2365.E+09	1.7799.E+09
										Total	1.32.E+09	1.99.E+09	7.97.E+09	7.80.E+09	2.98.E+10	2.11.E+10

*Values are approximations from various lithologies in the United States, as given by Litynski et al. (2010, p. 147, Table 7)

**E+09 indicates $x10^9$

***Values are for depth below 800m except for Cedar Mesa Sandstone for which value are for depth below 914m (3000 feet)

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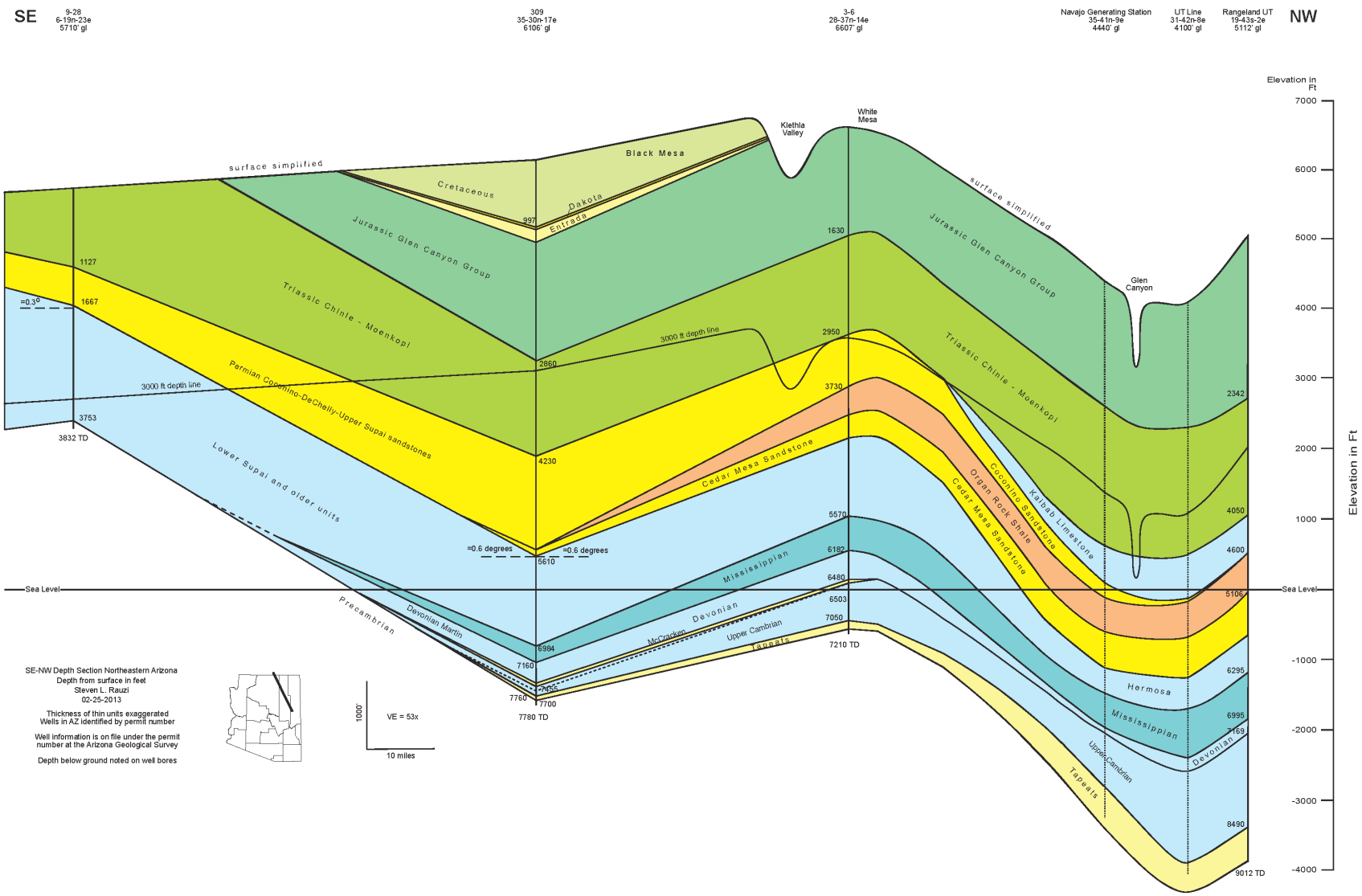
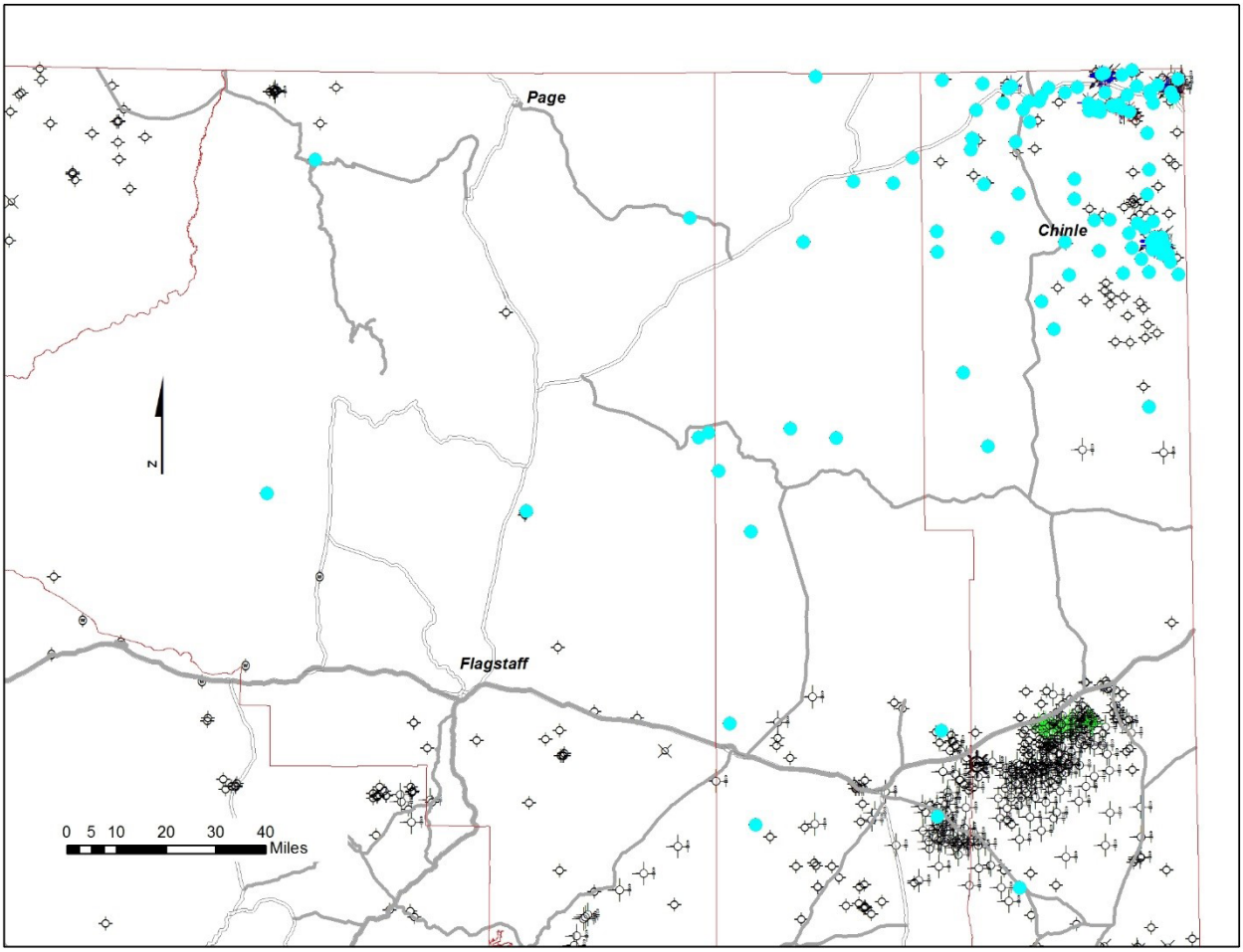
Appendix A. SE-NW Cross Section

Cross section was constructed from drill logs. Location of cross section is shown in Figures 1, 3, 4, and 5.
Locations of drill holes are shown on Figures 1, 3, 4, and 5.



Appendix B.

Blue dots represent wells digitized from raster tiff images to LAS (Log ASCII Standard) format using Neuralog. Approximately 264 logs from 116 wells for a total of about 924 curves were digitized. The AZGS developed a web application to make the LAS data available on the internet through an interactive search and download map hosted on the AZOGCC website.