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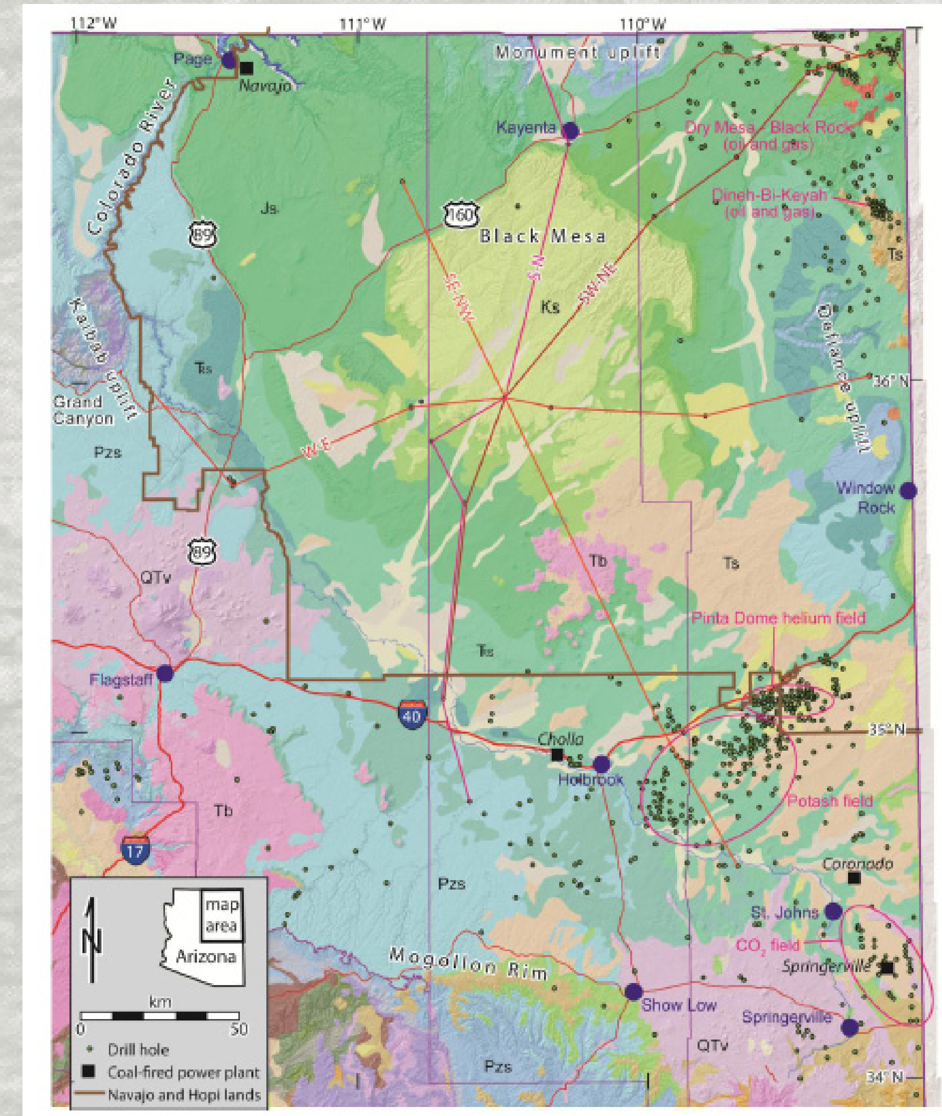

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An evaluation of CO_2 sequestration potential of Paleozoic sandstone units, northeastern Arizona

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Abstract

Northeastern Arizona is underlain by the southwestern part of the Colorado Plateau, an area of gently dipping to slightly folded Paleozoic and Mesozoic strata that include porous and permeable sandstone units. Three Paleozoic sandstone units, the Cambrian Tapeats Sandstone, Devonian McCracken Sandstone, and Permian De Chelly Sandstone, were identified for study as potential targets for CO_2 sequestration in order to reduce anthropogenic emissions to the atmosphere. Well logs for 755 drill holes were used to evaluate the extent, depth, and thickness of these sandstone units. Esri® ArcMap™ software was then used to calculate the volume of each sandstone unit where the top of each unit is below 800 m depth, which is the minimum necessary for CO_2 sequestration so that the CO_2 remains in a dense, near-liquid state. Well logs were used to evaluate porosity, which was then used to calculate effective porosity that is theoretically available for CO_2 storage. We calculate that there are 9.7 km^3 of effective pore space in the De Chelly Sandstone in Black Mesa basin, with 0.43 km^3 and 0.72 km^3 effective pore space in the Tapeats and McCracken sandstone units, respectively, in the same area. The total mass of CO_2 that, potentially, could be stored in Colorado Plateau sandstone units is calculated at 8.28 billion metric tons. Qualitative information available from well logs suggests that the Tapeats and McCracken sandstones contain saline formation waters, but the character of formation waters in the De Chelly Sandstone remains poorly known.

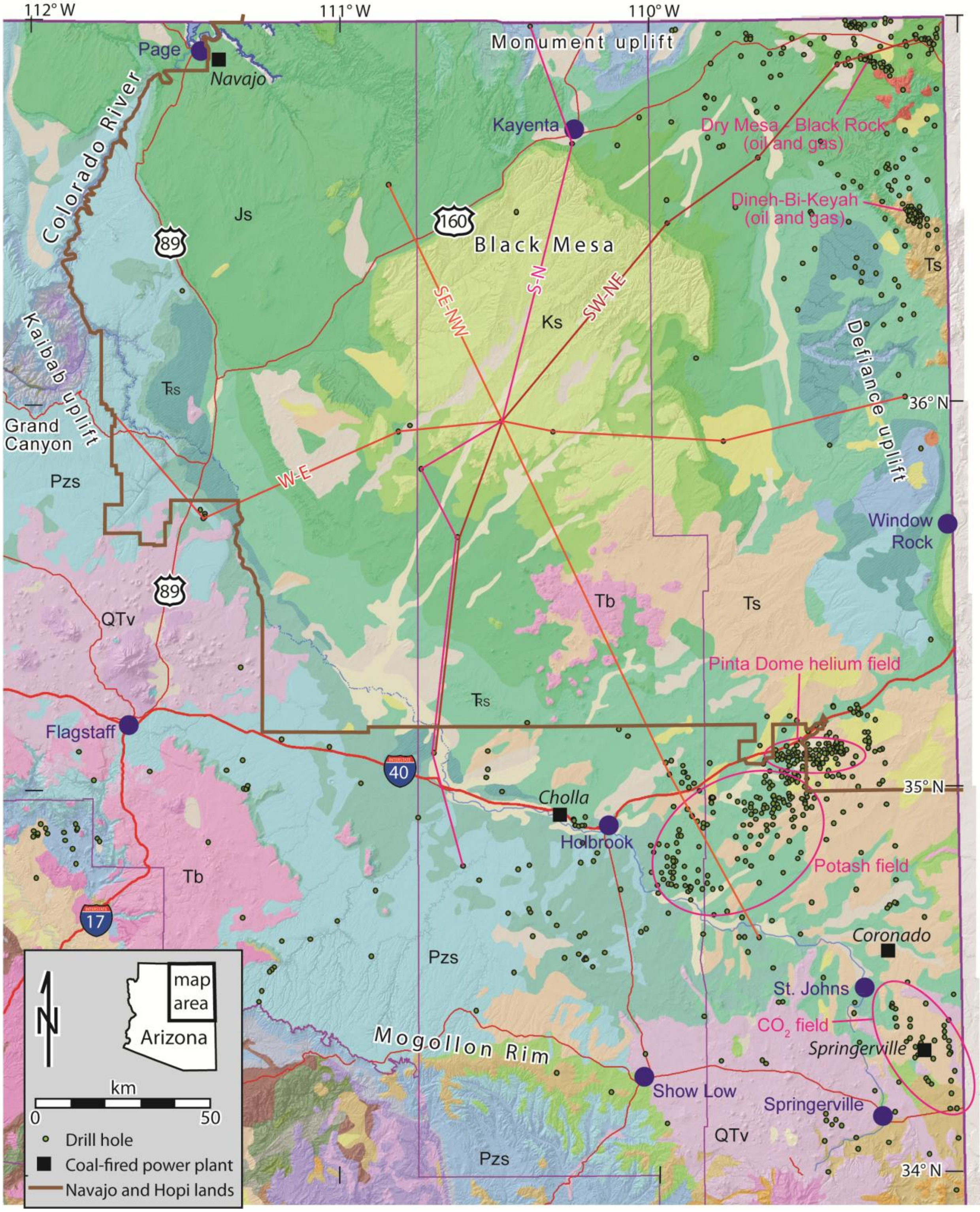
Introduction

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).

WESTCARB (West Coast Regional Carbon Sequestration Partnership) is a consortium of seven western U.S. States and one Canadian Province that is one of seven regional North American partnerships established to evaluate technical aspects of high-volume CO_2 capture and sequestration. The WESTCARB research program has members and collaborators, including more than 90 public agencies, private companies, and non-profit organizations. The Arizona Geological Survey began work in 2010 on *WESTCARB Phase III – Arizona Geological Characterization*. This report represents a WESTCARB assessment of CO_2 storage potential in Arizona's Paleozoic strata of the Colorado Plateau, and is part of Tasks 2 and 3 of Arizona WESTCARB Phase III (California Energy Commission Agreement Number 500-10-024).

The study area is northeastern Arizona, which consists largely of land owned by the Navajo and Hopi Indians (Fig. 1). The focus of this study is determining (1) the volume of porous and permeable Paleozoic sandstone units where the interface with overlying impermeable capping formations is below 800 m depth, (2) the effective (accessible) pore-space volume, and (3) the presence or absence of saline water in the pore space. The ultimate purpose of this study is to identify specific units and areas for further carbon-sequestration evaluation. Basin volume below 800 m 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 Paleozoic strata and the salinity of included groundwater are reviewed in this report, and discussed in the context of suitability for CO_2 sequestration.

Figure 1 (next page). Map of the study area, which covers the northeastern one-fourth of 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 sections is also shown (see Appendix A for cross sections). 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.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Navajo
Colorado River
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Coal-fired power plant
Navajo and Hopi lands

Paleozoic sandstone units 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 the Grand Canyon. 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, 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. 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 in northeastern Arizona. The Paleozoic sandstone units that are the focus of this study (Fig. 2) are not thicker in Black Mesa basin. Rather, they are 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; Appendix A). 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 three Plateau sandstone units targeted for CO_2 sequestration study are the Cambrian Tapeats Sandstone, Devonian McCracken Sandstone, and Permian De Chelly Sandstone (pronounced "dee-sháy" - derived from a Navajo word). The De Chelly Sandstone here includes the overlying Coconino Sandstone and the upper sandstone of the underlying Supai Group where these units are lithologically similar in well logs, which is characteristic of the Black Mesa Basin area. These units are interbedded with much less porous carbonates, siltstones, and evaporites. The study area covers ~90,000 km^2 (35,000 mi^2) of Apache, Navajo, and Coconino Counties in northeastern Arizona. The northern and eastern extent of the area is the Arizona state border. The southern extent is generally coincident with the Mogollon Rim, which is the approximate topographic margin of the Colorado Plateau. Grand Canyon and Flagstaff are the approximate western margin. (The area encompasses Townships 7 through 42 North and Ranges 8 through 31 East of the Gila and Salt River Baseline and Meridian and Townships 1 through 7 North and Ranges 6 through 10 West of the Navajo Baseline and Meridian).

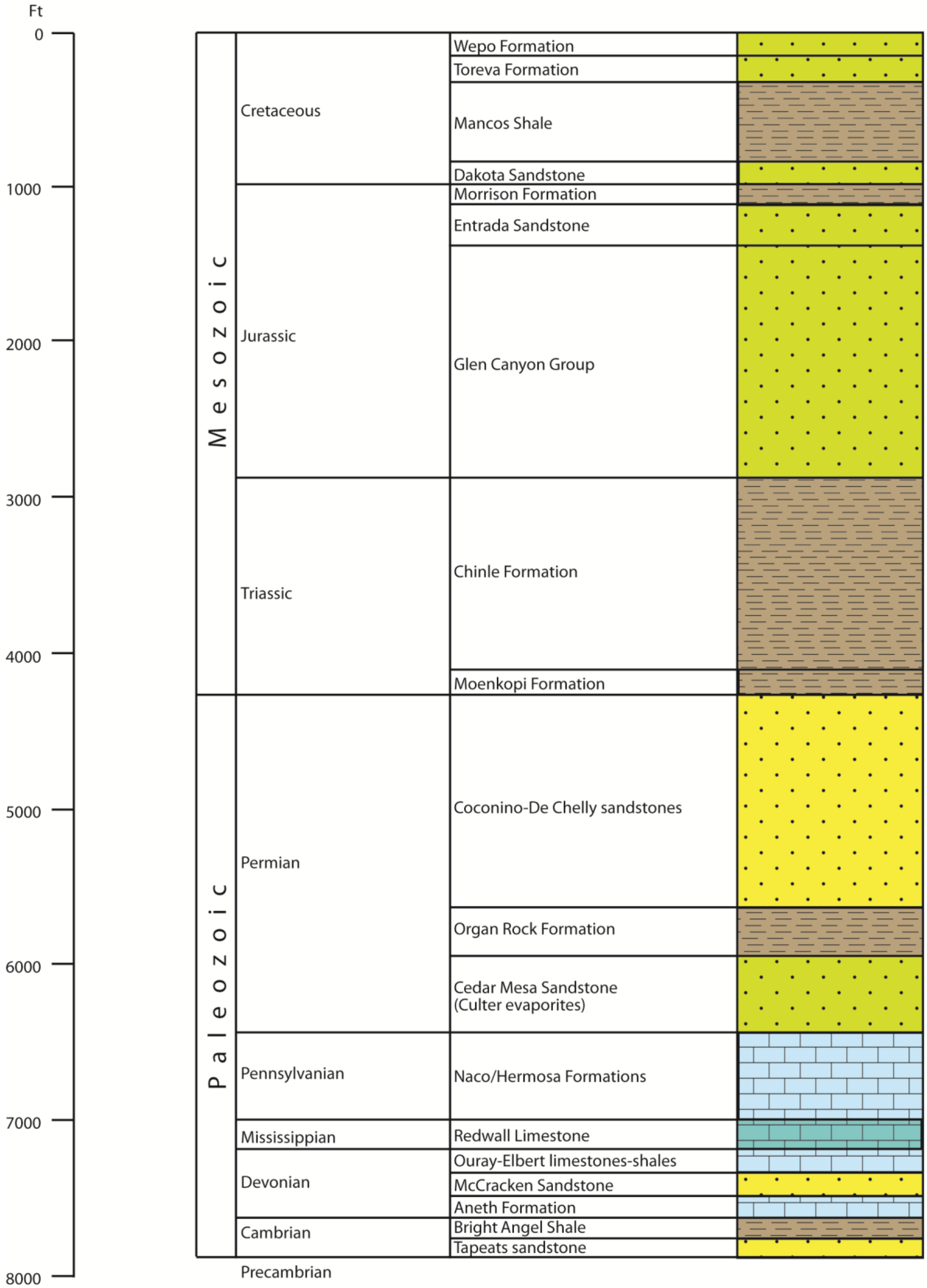

Figure 2. Stratigraphic column representing the Black Mesa and Four Corners areas. Yellow represents sandstone units under study for CO_2 sequestration potential.

Subsurface control is from 755 wells maintained on behalf of the State of Arizona Oil and Gas Conservation Commission at the Arizona Geological Survey. 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 USGIN AASG website at catalog.usgin.org/geoportal/catalog/search/search.page .

All three sandstone units are present in the study area at depths greater than 800 m below the land surface. 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 three potential storage units are 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 units. Impermeable sealing units overlie all three of the potential geologic storage units studied (Fig. 2; Appendix A). Shale and mudstone are the dominant rock types in the Triassic Moenkopi and Chinle Formations that overlie the Permian De Chelly - Coconino Sandstone. The Triassic Moenkopi and Chinle Formations are predominately thick shale, mudstone, and claystone intercalated with lenticular siltstone and sandstone across northeastern Arizona. The Moenkopi and Chinle Formations range in thickness from about 1700 feet near Winslow on the south to about 1000 feet near Lees Ferry on the north. Thick bentonitic mudstones and claystones are the most common rock type of the Chinle as expressed in outcrop in Petrified Forest National Park. Dense limestone and shale of the Devonian Elbert Formation, and shale, limestone, and marl of the Ouray limestone overlie the McCracken Sandstone. Dense limestone and shale of the Ouray and upper Elbert Formations form an ~175-foot-thick seal to oil produced from the McCracken Sandstone at the Walker Creek field in northeast Arizona. The Ouray and upper Elbert formations are about 295 feet thick in the Skelly well in the Black Mesa Basin. (The Skelly well is the central well where all cross sections intersect in Appendix A). Thin-bedded limestone and shale of the Cambrian Muav Limestone and Bright Angel Shale overlies the Tapeats Sandstone in the western part of the area. Devonian carbonate and shale and to a lesser extent Cambrian carbonate and shale overlie the Tapeats Sandstone in the northeastern part of the area. About 155 feet of dense dolomite with scattered anhydrite inclusions and green shale of the Devonian Aneth and Cambrian Bright Angel Shale provide a seal to the Cambrian Tapeats in the Skelly well in the Black Mesa Basin. About 110 feet of Bright Angel Shale and about 130 feet of dolomite in the Devonian Aneth Formation provides a seal to isolated accumulations of the Tapeats Sandstone in the Four Corners area.

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”. Actual salinity data measured from produced water in producing fields indicate that the formation-water salinity in the McCracken and Tapeats Sandstones is much greater than 10,000 total dissolved solids in the far northeastern corner of Arizona. Water salinity (Na^+ and Cl^-) from a production test of the McCracken Sandstone at the Walker Creek Field (Township 41 North, Range 25 East) is 41,000 ppm. Several tests of formation fluids in the De Chelly-Coconino sandstone in the Holbrook area indicate that total dissolved solids may be greater than 10,000 ppm in the deeper parts of the Black Mesa Basin. Fresh water is reported in some drill-stem tests in the Coconino Sandstone.

Depth and thickness of potential storage units

Tapeats Sandstone. The Tapeats Sandstone of Cambrian age is at least 3000 ft below ground surface in most of northeastern Arizona and is more than 7000 feet deep below Black Mesa (Figs. 3a, b). The Tapeats Sandstone is absent over much of the southern part of the study area, which is labeled the “Defiance paleotopographic high” on Figures 3a, b, and c. This area is inferred to have been elevated in Cambrian time so that it was a source of sand rather than an area of sand deposition. The Tapeats is mostly absent in the Four Corners area except for a few isolated accumulations or remnant deposits (Fig. 3c). There is some uncertainty as to whether basal sandstone in the Four Corners area is correlative with Tapeats or the Devonian McCracken Sandstone, especially where the Devonian Aneth Formation, which usually underlies the McCracken, is absent. The Tapeats Sandstone increases in thickness from zero in the Four Corners area and along the western margin of the Defiance uplift to over 300 ft where it crops out in the eastern Grand Canyon (Fig. 3c). The Tapeats Sandstone attains a thickness of 150 ft in a relatively isolated occurrence in the central part of the area south of the Defiance Uplift and just north of the Mogollon Rim (Fig. 3c).

McCracken Sandstone. The McCracken Sandstone is present at depths of >3000 feet below ground surface throughout much of the study area (Figs. 4a, b). The McCracken Sandstone as originally described by Knight and Cooper (1955) is restricted to the Four Corners region and Black Mesa Basin in the northeastern part of the study area. The isolated accumulations or remnants of sandstone in the Holbrook area in the southern part of the area are mapped with the McCracken Sandstone but actually represent local sandstone accumulations in the lower part of the Devonian Martin Formation rather than the McCracken Sandstone (Fig. 4c). Teichert (1965) used the term Beckers Butte member for the basal sandstone in the Devonian Martin Formation south of the Mogollon Rim in central Arizona. The sandstone exposed along the Verde River just north of Payson has been referred to by various investigators as either Cambrian Tapeats or “sandstone of Devonian age” for many years (Lausen and Wilson, 1925; Teichert, 1965, p. 14; Hereford, 1977). This sandstone is included with the Tapeats Sandstone in this study. The

McCracken Sandstone is thin to absent in the southern part of the study area but thickens northward across Black Mesa Basin to reach thicknesses of over 250 ft in the Four Corners region (Fig. 4c). The McCracken Sandstone is absent in the southeastern part of the area. Locally isolated accumulations of sandstone in the lower part of the Martin Formation range from 10 to 30 ft thick across most of the Holbrook area. The sandstone in the lower part of the Martin Formation attains a thickness of about 100 ft. between St. Johns and Show Low.

De Chelly - Coconino Sandstone. The De Chelly Sandstone in eastern Arizona and the Coconino Sandstone in Grand Canyon, both of Permian age, are treated here as one unit, commonly referred to simply as De Chelly Sandstone. Sandstone in the upper Supai Group (approximately the Esplanade Member) that directly underlies the De Chelly Sandstone in the Black Mesa Basin is also included here with the De Chelly Sandstone. The De Chelly Sandstone is present in northeastern Arizona at depths ranging from 2000 ft below ground surface in the Four Corners area to 4900 ft below ground surface in the Black Mesa Basin (Figs. 5a, b). The De Chelly Sandstone is present at depths generally < 1000 ft below ground surface in the southern part of the study area. The De Chelly is present at a depth of 2000 ft below ground surface in a relatively small area east of Holbrook. The De Chelly Sandstone crops out in Monument Valley to the northeast, Marble and Grand Canyons to the west, along the Mogollon Rim to the south, and in the Canyon De Chelly area to the east. The De Chelly Sandstone increases in thickness from about 300 ft in the Four Corners, Grand Canyon, and Mogollon Rims to as much as 1700 ft in the southern part of the Black Mesa Basin (Fig. 5c).

Sandstone-volume calculations - procedure

The volume of sandstone in each of the three sandstone units under study here was calculated for areas where the depth to the base of the overlying capping unit is >800 m (2625 feet) (this is the minimum depth for a capping unit according to NETL recommended methodology [Litynski et al., 2010]). This was done using Esri® ArcMap™ version 10 software, as follows:

(1) Well logs from a database of 755 oil and gas exploration drill holes were used to identify the depth to the stratigraphic top and base of the three sandstone units. Contour maps were drafted (in feet), by hand, for formation tops and formation thicknesses. Each of these six contour maps was then digitized to create six shape files, with depth and thickness as numeric attributes (in both feet and meters) of the contours.

(2) In a raster representation of a contour map, a surface is constructed that interpolates between contours. The depth and thickness contour maps were used to build raster representations of sandstone unit-top depths and unit thicknesses 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 “Thick_m” or “Depth _m”. “Drainage enforcement” was set to “NO_ENFORCE” because the

contour map does not represent a landscape. Raster creation was done six times, once for each depth and thickness contour set. For the Tapeats depth raster construction, the line representing the margin of the unit (zero thickness) was deleted from the depth contour map because it does not represent depth. This was done by creating a copy of the contour shape file using ArcCatalog, deleting the zero-thickness contours from the copy in ArcMap, and then using the remaining contour lines to create the raster representation of thickness. The areas of depth interpolation where Tapeats is absent in the subsurface are irrelevant to later volume calculations because these calculations were done only for areas of finite thickness.

(3) The raster representations of unit depth were then used to create a contour map with an 800m contour. This was done using the "Contour" tool in the "Raster Surface" tool set in the "3D Analysts Tools" in ArcToolbox, with a contour interval of 1312 feet (400m). These depth contour maps were copied and placed in the ArcMap Project. All contours other than the 800m contour were then deleted.

(4) The 800m lines were extended along the zero-thickness contour and along the state border, until each line formed a closed loop. Each 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 areas represented by the polygons have formation tops greater than 800m depth, thickness greater than zero, and are within Arizona. Each polygon file, representing one sandstone formation, was copied using ArcCatalog so that there were as many copies as polygons. All polygons except one were deleted from each shape file so that each shape file contained only one polygon. Each shape file (and each polygon) was then used to extract subsets of the thickness rasters for the purpose of calculating volume, as described in the next step.

(5) The parts of each thickness raster corresponding to formation-top depths below 800m, >0m thickness, and that are within Arizona, were separated into smaller rasters using the "Extract by mask" tool of the "Extraction" tool set within the "Spatial Analyst" toolbox. This produced three rasters, shown in shades of green, for the Tapeats Sandstone (Fig. 3b), one for the McCracken Sandstone (Fig. 4b), and three for the De Chelly Sandstone (Fig. 5b). The green color is darker for greater sand thickness (Figs. 3c, 4c, 5c).

(6) Each deep-basin raster area was then used to calculate basin volume below 800m 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., the minimum thickness is greater than zero), a reduced volume is not erroneously produced. Resulting table output data was compiled in an Excel spreadsheet, with three deep basins each for the De Chelly and Tapeats Sandstones, and one for the McCracken Sandstone (Table 1).

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 800m 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 A_t by gross thickness h_g because the ArcMap calculations account for lateral changes in thickness.

Formation porosities were estimated by well loggers based on examination of drill cuttings. This was done for 184 drill holes in the De Chelly Sandstone, 112 drill holes in the McCracken Sandstone, and 55 drill holes in the Tapeats Sandstone. The total porosity (ϕ_{total}) and standard deviation were determined for each formation (Table 2). Low and high porosities are given at the one standard deviation level for the De Chelly Sandstone, but for the other two formations, one standard deviation below the mean is approximately zero or negative. As a result, approximately similar representations of uncertainty are estimated at one-half standard deviation below the mean for the McCracken Sandstone, and one-third standard deviation for the Tapeats Sandstone (Table 2). These values were assigned to the respective formations over the entire study area, without determining different porosities for each subbasin in the De Chelly and Tapeats Sandstone units. Low, middle and high values for total pore volume were then calculated for each of the seven basins (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 (E_{saline}), 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. 6). This yielded a surface temperature of 23.57°C and a gradient of 0.0134*h* 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. 6).

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 7. 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. Because calculated temperature at Earth's surface on the Colorado Plateau is rather high (23.6°C), CO_2 density at 800m depth is rather low (~350 kg/m^3). Because of greater subsurface buoyancy of CO_2 at lower densities, and potential for upward flow of CO_2, the 800m minimum depth for CO_2 storage may not be sufficient for long-term storage. Most of the volume under consideration for CO_2 storage is deeper, however, reaching depths of over 2km for the Tapeats Sandstone. CO_2 density at depths of ~1-2 km is ~700 – 800 kg/m^3. A value of 750 km/m^3 was used to calculate CO_2 storage capacity for Colorado Plateau sandstone units (Table 3). Our median estimate of the mass of CO_2 that can be stored in sandstone units of the Colorado Plateau is 8.28 billion tonnes, with low and high estimates of 1.34 and 32.5 billion tonnes, respectively. We calculate that 88% of this storage capacity is present in the De Chelly Sandstone sub-basin beneath Black Mesa.

Conclusion

Of the three sandstone units on the Colorado Plateau in Arizona, the De Chelly Sandstone has ~90% of the total capacity for CO_2 sequestration (7.40 billion tonnes calculated storage capacity). This is because the De Chelly Sandstone is thicker and has higher porosity than the deeper Paleozoic units. However, it is not known if formation waters present in the De Chelly Sandstone are saline. The sub-basin of the Tapeats sandstone beneath Black Mesa has a calculated CO_2 storage capacity of 540 million tonnes, while the CO_2 storage capacity of the McCracken Sandstone is calculated at 319 million tonnes. Both of these units are more likely, based on measured formation-water salinities, to contain saline pore water. If these three formations in the Black Mesa area are considered potential targets of future investigations, it is perhaps fortunate that all three can be penetrated with a single drill hole.

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Figures 3, 4, 5. Depth and thickness of Paleozoic sandstone units, well locations, cross-section locations, and areas where the top of the sandstone units are below 800m depth.

Figures 3a, 4a, 5a. Contours shown here (black numbered lines) represent the depth to the top of each Paleozoic sandstone unit 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 each sandstone unit is greater than 800m deep or where the sandstone pinches out to zero thickness.

Figures 3b, 4b, 5b. As in figures 3a, 4a, and 5a, but areas where the top of the relevant sandstone unit is below 800m depth are colored green, with lighter green corresponding to areas where the sandstone is thinner.

Figures 3c, 4c, 5c. As in figures 3b, 4b, and 5b, but contours and color raster background maps represent sandstone unit thickness rather than depth. The color raster background maps represent the thickness of each sandstone unit as derived from the contour map using ArcToolbox™ tools (see text) (color interval for raster colors is arbitrary). Areas where the top of the relevant sandstone unit is below 800m depth are colored green, with lighter green corresponding to areas where the sandstone is thinner. Each contiguous green area represents a raster representation of thickness. Sandstone volume was calculated for each of these rasters using ArcToolbox™ tools (see text and tables).

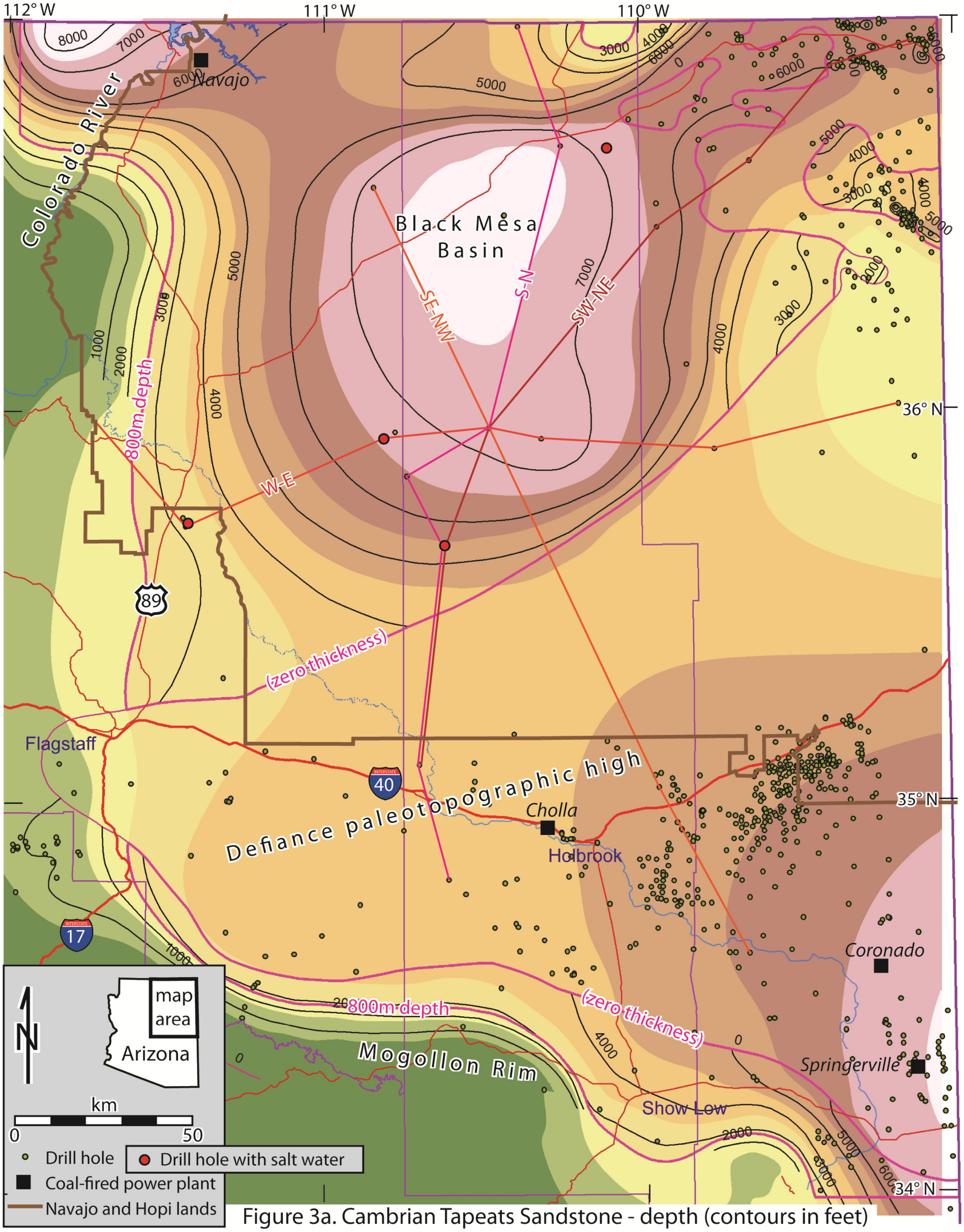

Figure 3a. Cambrian Tapeats Sandstone - depth (contours in feet)

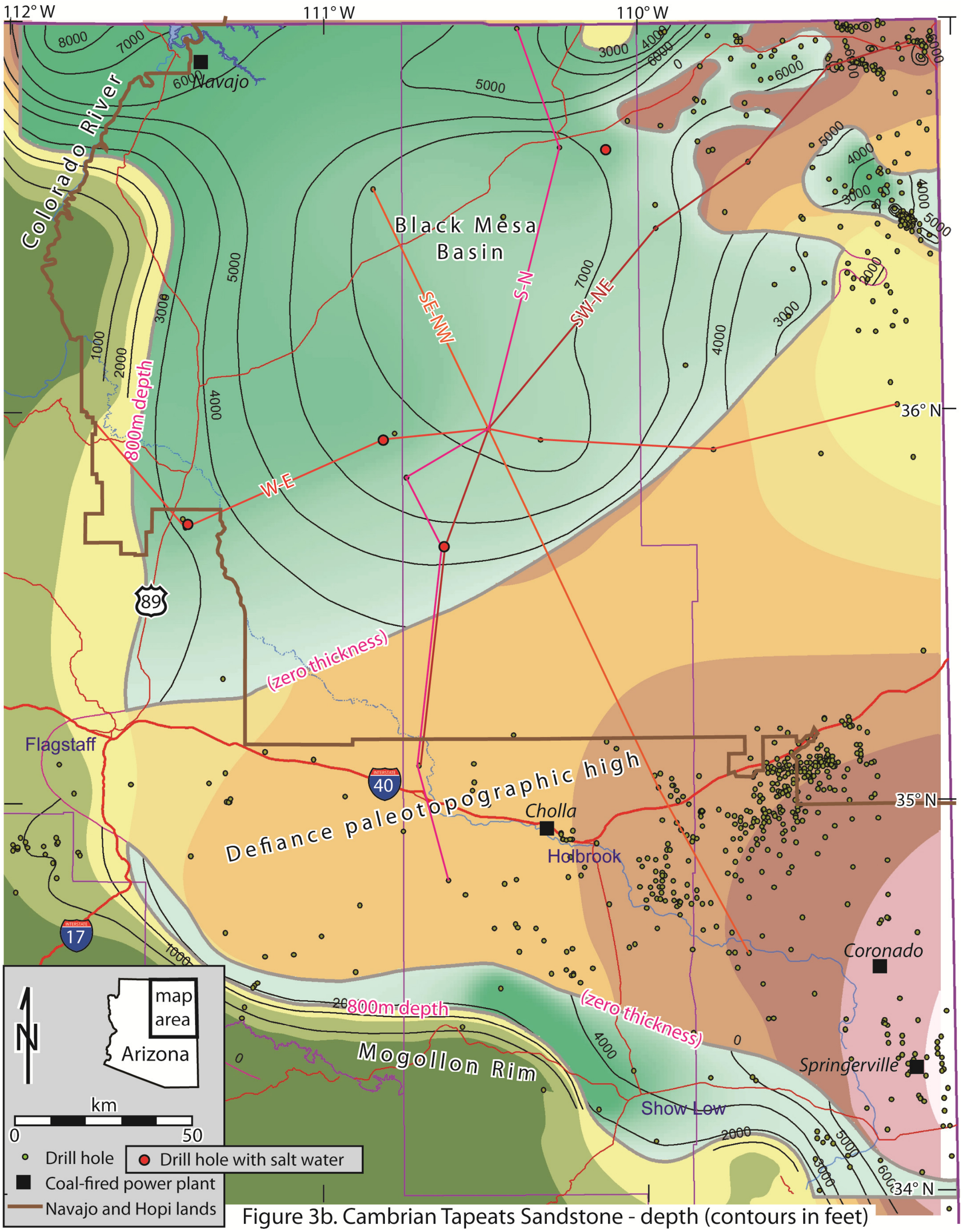

Figure 3b. Cambrian Tapeats Sandstone - depth (contours in feet)

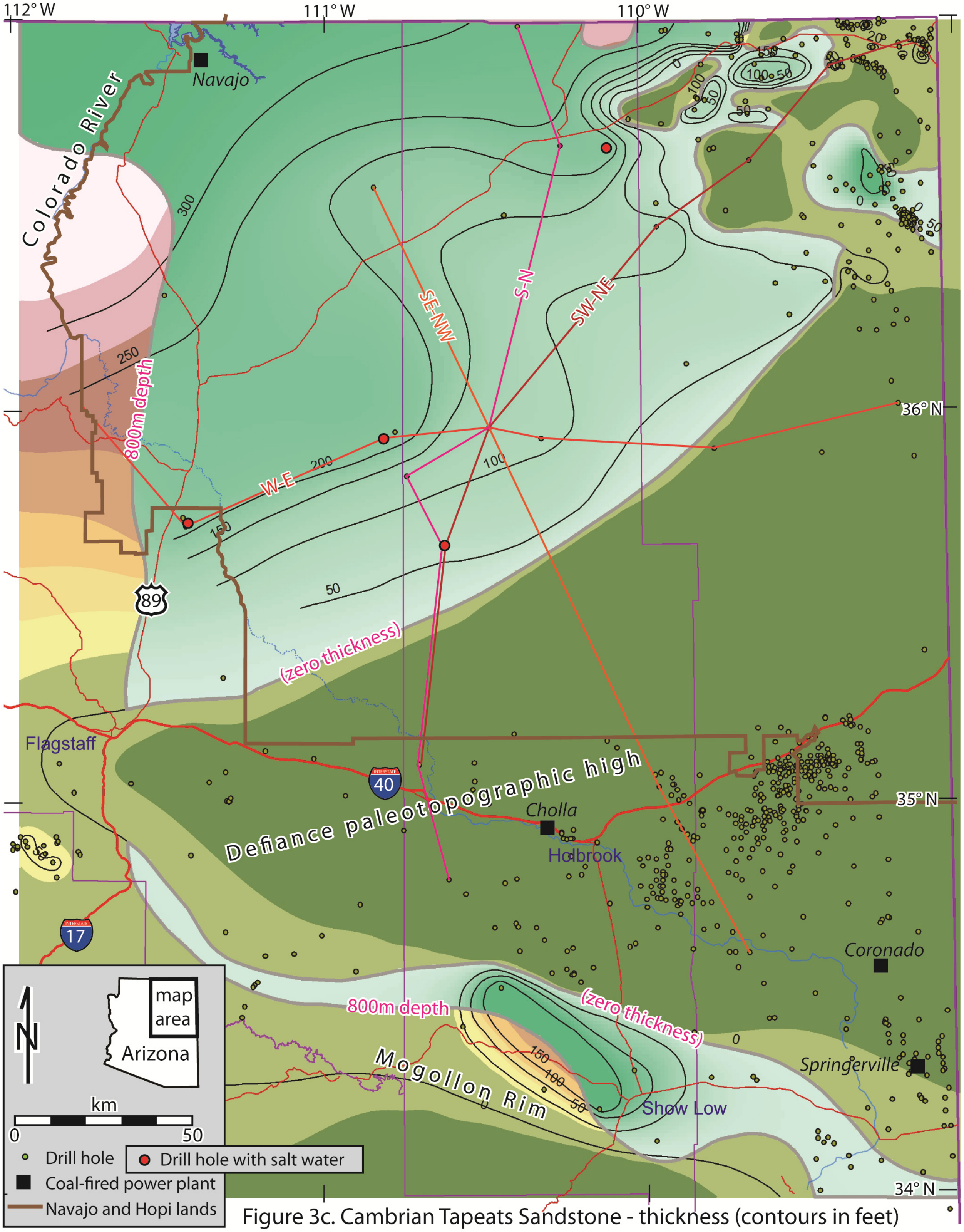

Figure 3c. Cambrian Tapeats Sandstone - thickness (contours in feet)

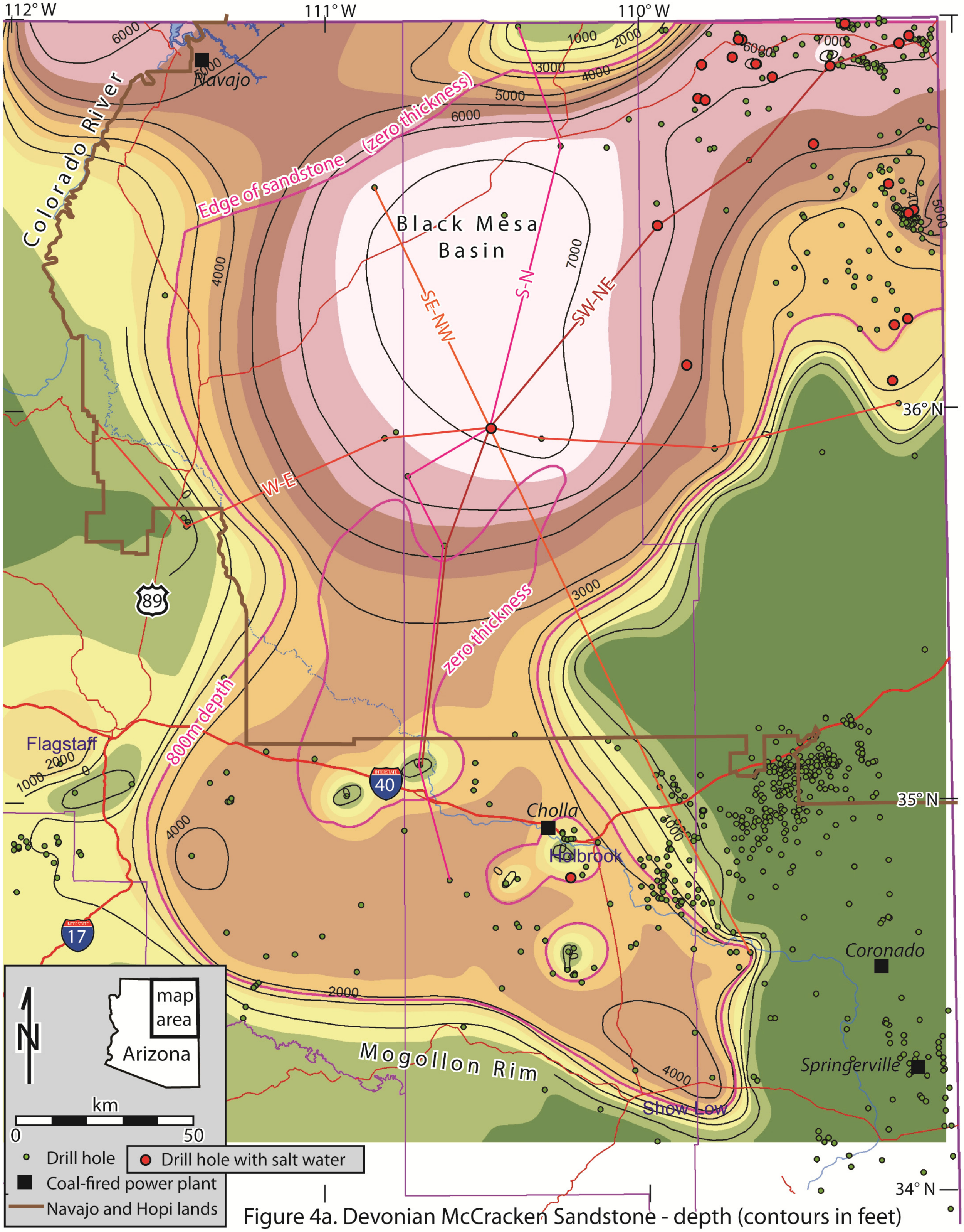

Figure 4a. Devonian McCracken Sandstone - depth (contours in feet)

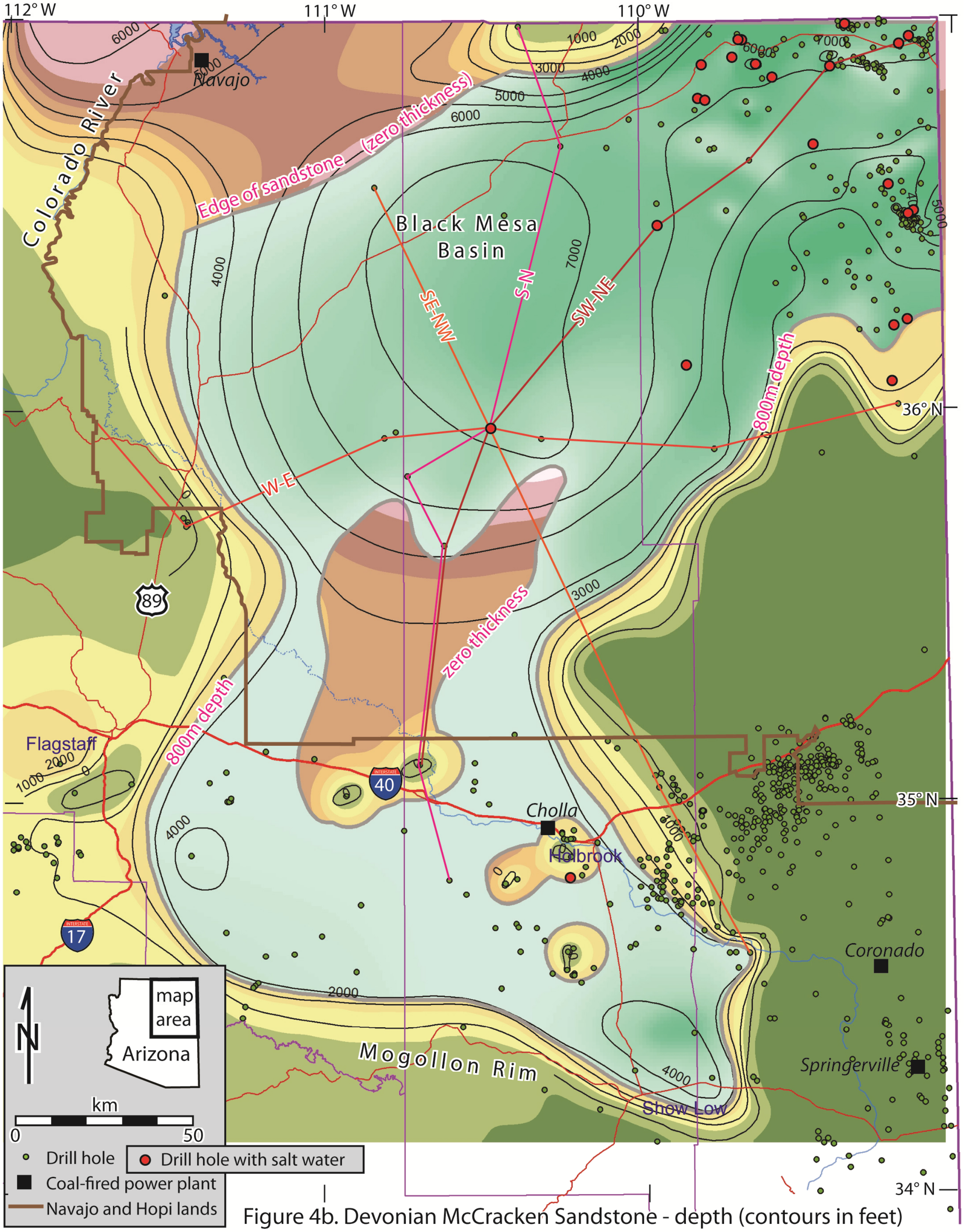

Figure 4b. Devonian McCracken Sandstone - depth (contours in feet)

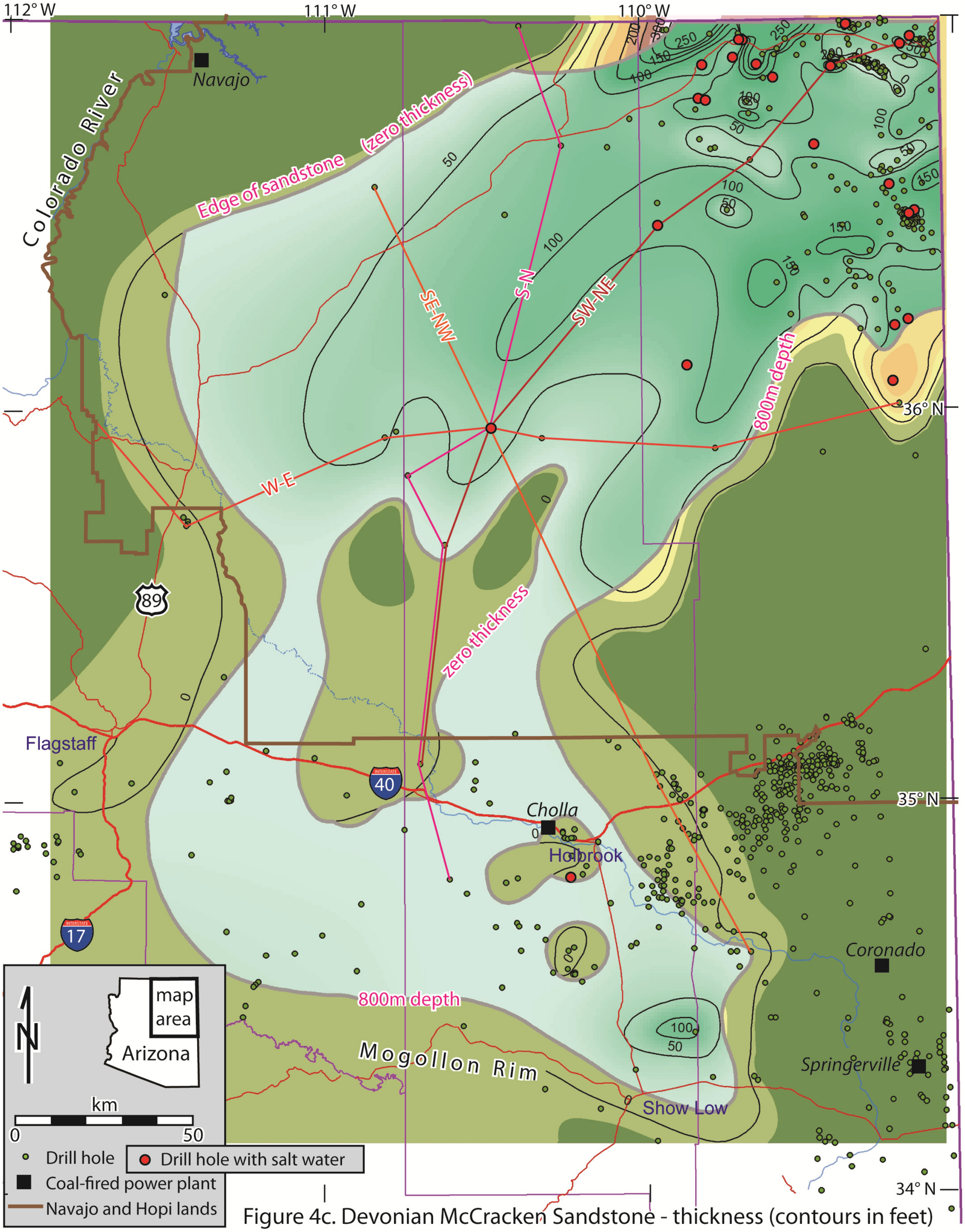

Figure 4c. Devonian McCracken Sandstone - thickness (contours in feet)

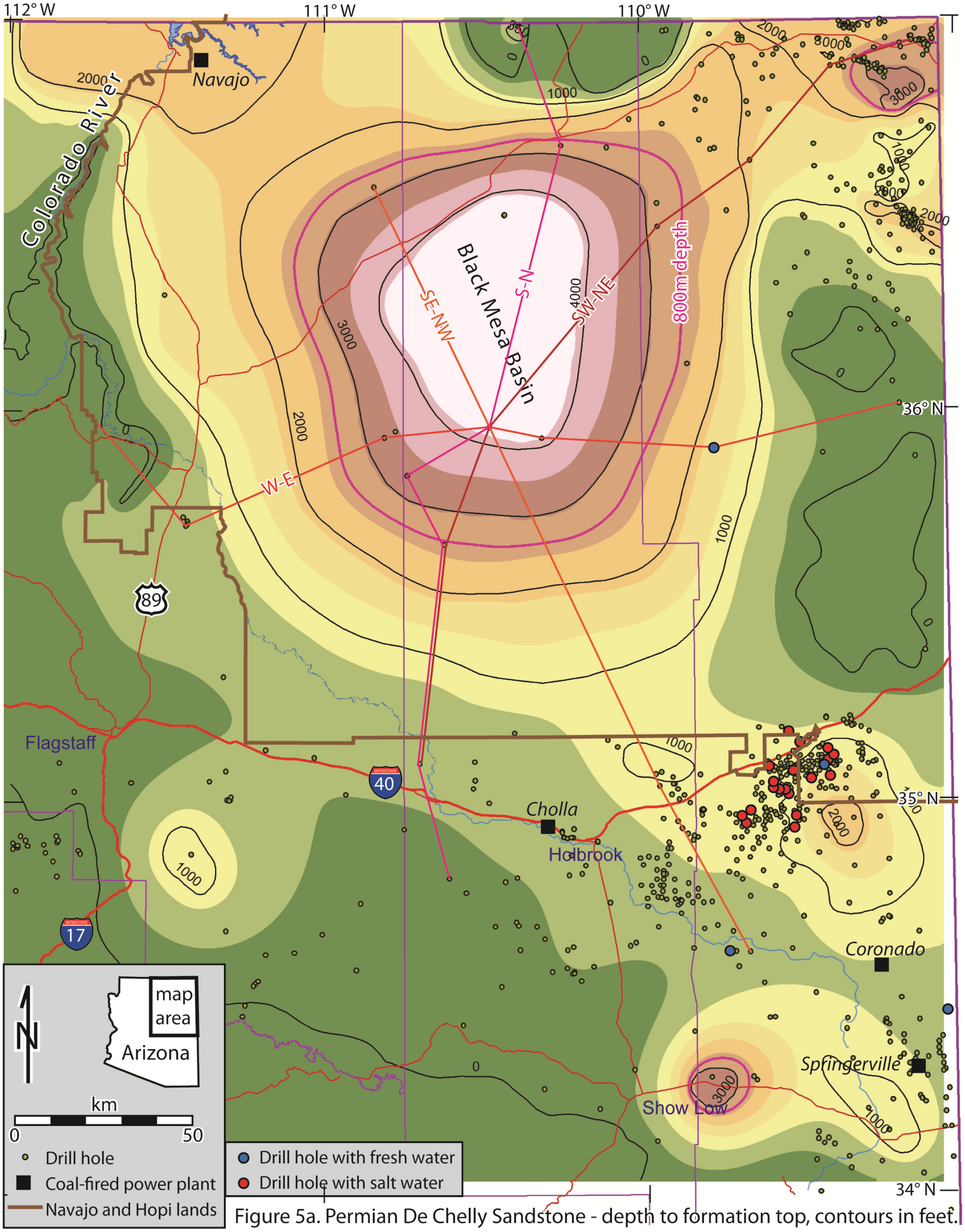

Figure 5a. Permian De Chelly Sandstone - depth to formation top, contours in feet.

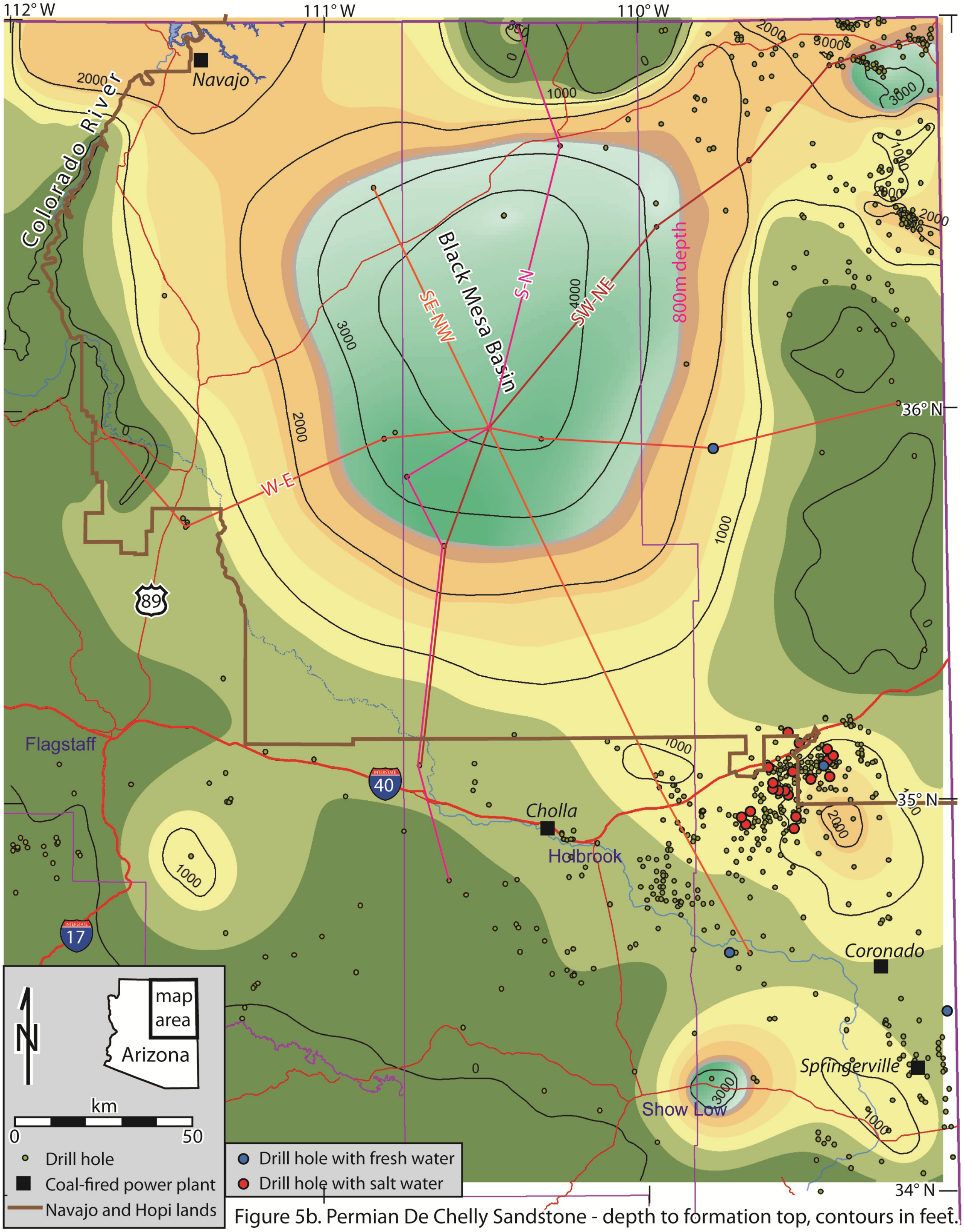

Figure 5b. Permian De Chelly Sandstone - depth to formation top, contours in feet.

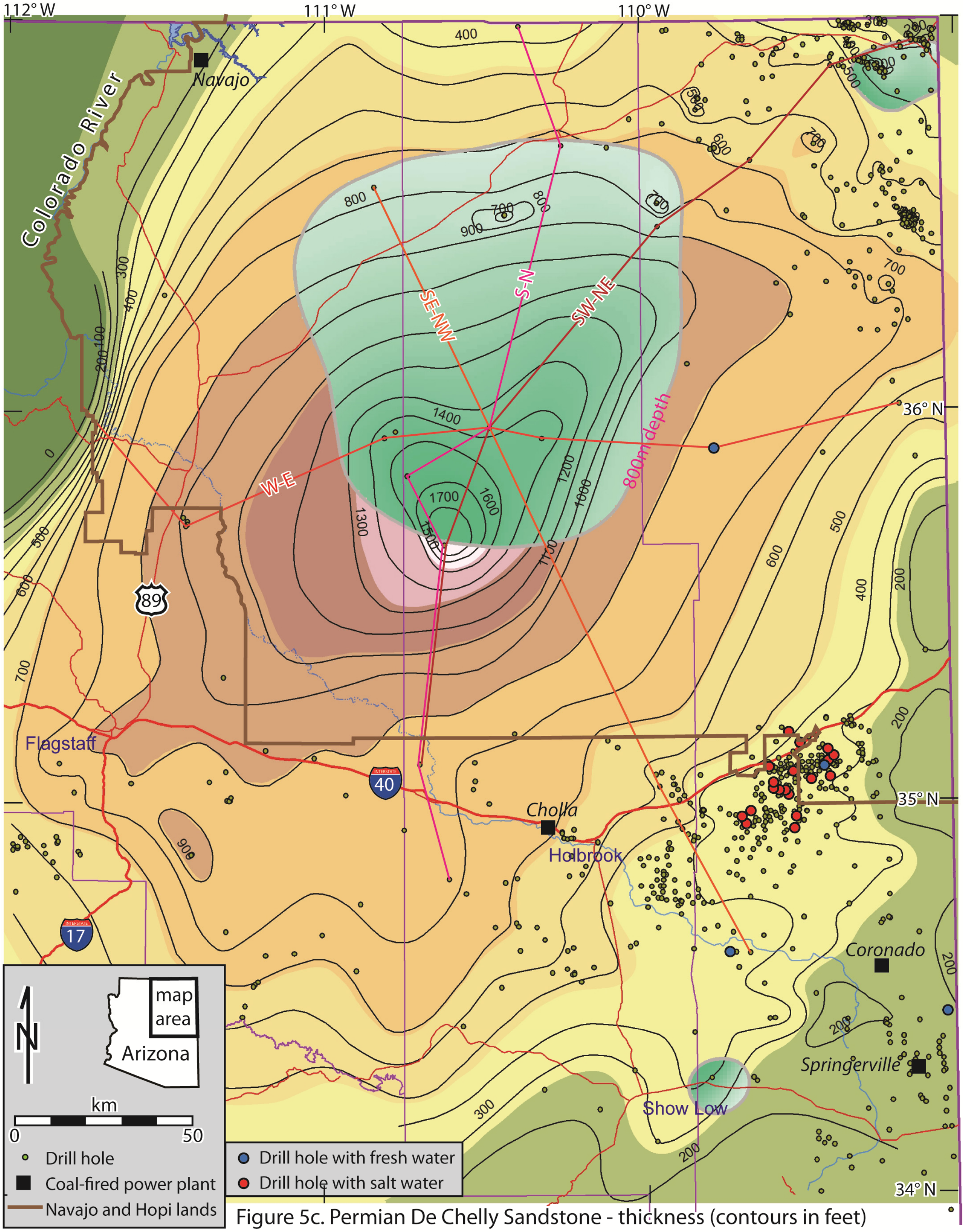

Figure 5c. Permian De Chelly Sandstone - thickness (contours in feet)

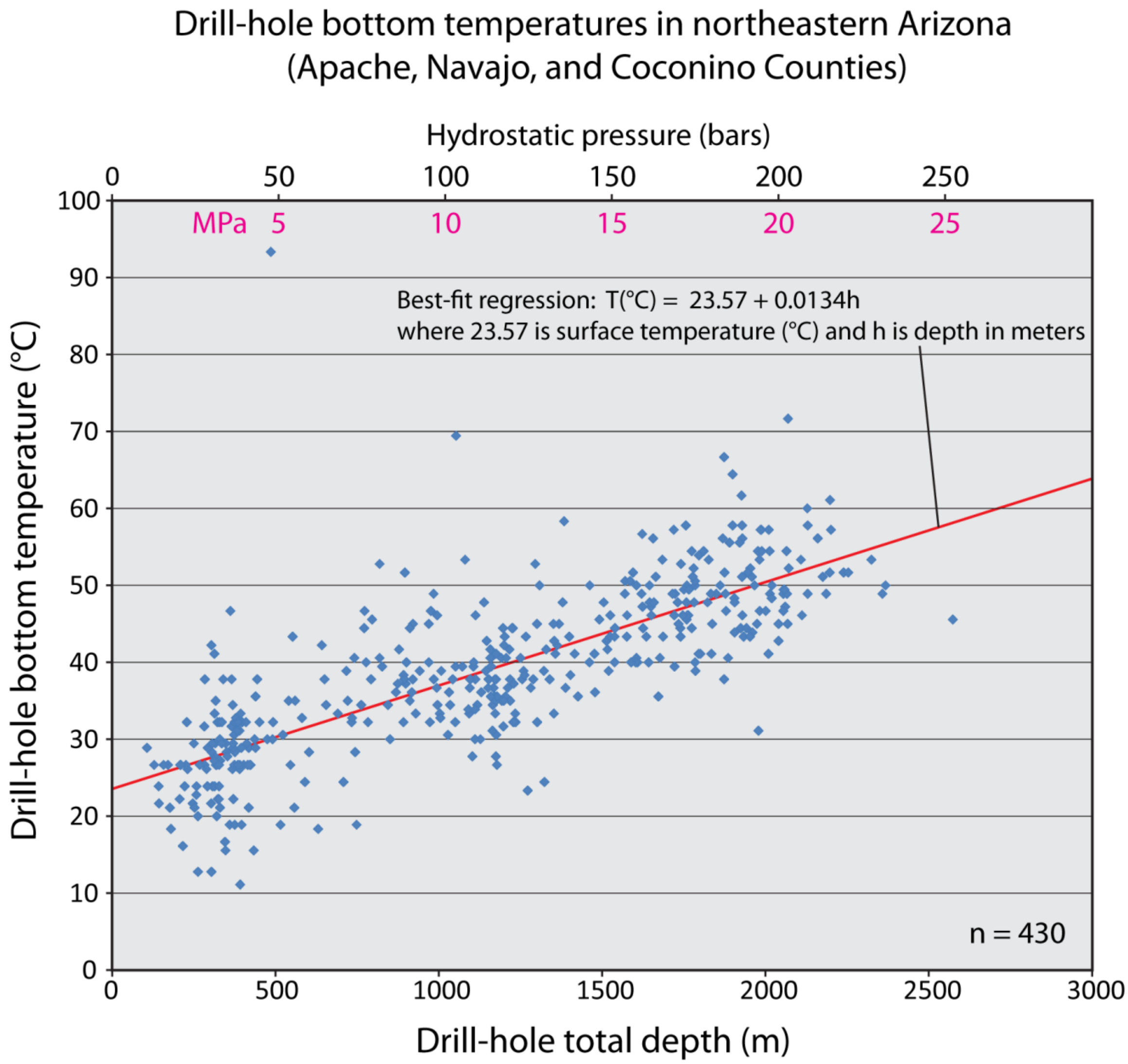

Figure 6. Drill-hole bottom temperatures from 430 bore holes in northeastern Arizona.

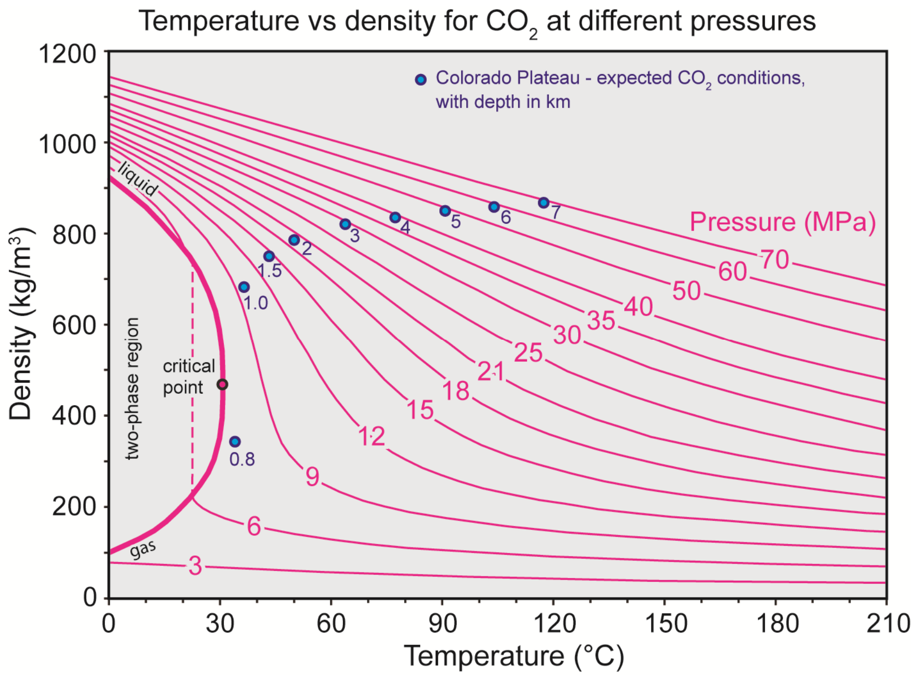

Figure 7. Temperature and density of CO_2 are plotted for a range of pressures represented by the magenta isopressure lines. For appropriate pressure, and temperature below that of the critical point, CO_2 coexists as both a gas and a liquid. To identify density conditions of CO_2 stored in sandstone 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 6, 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 CO_2 density calculator at http://www.peacesoftware.de/einigewerte/co2_e.html).

Table 1. ArcMap-calculated volume and area of Paleozoic sandstone units below 800m depth on the Colorado Plateau

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)
De Chelly main	..ateau2012_2\Rasters\dech_main2	0	ABOVE	1	10133348856	10133429005	3.39325E+12	10133	3393
De Chelly NE	..Plateau2012_2\Rasters\dech_ne2	0	ABOVE	1	344775438	344777719	36952468117	345	37
De Chelly SE	..Plateau2012_2\Rasters\dech_se2	0	ABOVE	1	172387719	172389150	18197437824	172	18
McCracken	..eau2012_2\Rasters\mccrac_main4	0	ABOVE	1	33578357384	33578387847	5.31312E+11	33578	531
Tapeats main	..au2012_2\Rasters\tapeats_main5	0	ABOVE	1	28661186925	28661225407	1.50136E+12	28661	1501
Tapeats south	..\Plateau2012_2\Rasters\tpts_s2	0	ABOVE	1	3644635937	3644645273	50082646390	3645	50
Tapeats NE	..\Plateau2012_2\Rasters\tpts_NE	0	ABOVE	1	603350972	603351717	3044647738	603	3

Table 2. Porosity and pore volume for Paleozoic sandstone units below 800m depth on the Colorado Plateau

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
De Chelly NE	345	37	9.3	14.3	19.3	3.44	5.28	7.13
De Chelly SE	172	18	9.3	14.3	19.3	1.69	2.60	3.51
McCracken	33578	531	2	4	8	10.63	21.25	42.50
Tapeats main	28661	1501	1.2	2.4	6	18.02	36.03	90.08
Tapeats south	3645	50	1.2	2.4	6	0.60	1.20	3.00
Tapeats NE	603	3	1.2	2.4	6	0.04	0.07	0.18

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

*McCracken Sandstone (n=112): Porosity range is plus one standard deviation, minus one half of one standard deviation

*Tapeats Sandstone (n=55): Porosity range is plus one standard deviation, minus one third of one standard deviation

Table 3. CO_2 storage capacity for Paleozoic sandstone units below 800m depth on the Colorado Plateau

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)	Potential mass of stored CO_2 (tonnes), low**	Potential mass of stored CO_2 (tonnes), median**	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	1.21.E+09	7.28.E+09	2.65.E+10
De Chelly NE	3.44	5.28	7.13	0.0051	0.02	0.054	0.018	0.11	0.39	750	1.31.E+07	7.93.E+07	2.89.E+08
De Chelly SE	1.69	2.60	3.51	0.0051	0.02	0.054	0.009	0.05	0.19	750	6.47.E+06	3.90.E+07	1.42.E+08
McCracken	10.63	21.25	42.51	0.0051	0.02	0.054	0.054	0.43	2.30	750	4.06.E+07	3.19.E+08	1.72.E+09
Tapeats main	18.02	36.03	90.08	0.0051	0.02	0.054	0.092	0.72	4.86	750	6.89.E+07	5.40.E+08	3.65.E+09
Tapeats south	0.60	1.20	3.00	0.0051	0.02	0.054	0.0031	0.024	0.16	750	2.30.E+06	1.80.E+07	1.22.E+08
Tapeats NE	0.04	0.07	0.18	0.0051	0.02	0.054	0.00019	0.0015	0.0099	750	1.40.E+05	1.10.E+06	7.40.E+06
										Total	1.34.E+09	8.28.E+09	3.25.E+10

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

**E+09 indicates $x10^9$