

# **Project Evaluation: Phase II: Optimal Geological Environments for Carbon Dioxide Disposal in Brine-Bearing Formations (Aquifers) in the United States**

**GCCC Digital Publication Series #00-01**

**S. D. Hovorka  
M. L. Romero  
R. H. Trevino  
A. G. Warne  
W. A. Ambrose  
P. R. Knox  
T. A. Tremblay**



**Keywords:**

**CO<sub>2</sub> Storage- Brine Formations, Brine Formation Identification, Geographic Information System (GIS), Data Digitization and Integration, CO<sub>2</sub> Storage- Site Parameters**

**Cited as:**

**Hovorka, S. D., Romero, M. L., Treviño, R. H., Warne, A. G., Ambrose, W. A., Knox, P. R., and Tremblay, T. A., 2000, Technical summary: 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 Digital Publication Series #00-01.**

## TECHNICAL SUMMARY

Brine-bearing formations have great potential for long-term storage and disposal of greenhouse gases, especially the large volumes of CO<sub>2</sub> produced as a byproduct of combustion of fossil fuels. Extensive industry experience in underground injection for enhanced oil recovery (EOR), gas storage, and deep-well waste injection demonstrates that disposal into geologic environments is feasible by using existing technology. It is also feasible that residence time for injected CO<sub>2</sub> would be adequate to prevent significant negative impact on overlying potable water or the atmosphere. One underway and several planned projects show that underground-injection technologies are transferable to injection of CO<sub>2</sub> for the purpose of reduction of greenhouse gas emissions.

However, brine formations are generally unused; therefore, documentation of the properties of the subsurface are generally not compiled in easy-to-access format. Realistic and quantitative information about the relevant characteristics of the subsurface is needed to assess feasibility, costs, and risks of various types of options for CO<sub>2</sub> disposal in brine formations. In this study, we have compiled and integrated a data base of realistic properties of brine formations. This data base is designed with a geographic structure in a geographic information system (GIS) so that it can be use to match CO<sub>2</sub> emitters with prospective sinks.

Brine formations are an attractive option as CO<sub>2</sub> sinks because (1) brine formations underlie many parts of the U.S., reducing costs and infrastructure associated with pipeline construction; (2) assuming a hydrodynamic trapping mechanism, with structural closure not required (Bachu and others, 1994), storage volumes are adequate for almost any greenhouse-gas scenario; (3) residence times are long, and accounting for volumes sequestered is straightforward; (4) scenarios for negative impacts and unintended consequences are limited; and (5) brine formations are largely unused and subsurface rights should be available.

Benefits of selecting disposal into brine formations as a greenhouse-gas-reduction method are limited by costs implicit in this method. Unlike biomass storage and various

reuse scenarios, costs of CO<sub>2</sub> extraction and injection into brine formations cannot be offset by any derived benefit. Therefore, one of the critical issues to consider in the brine-disposal option is cost. This data base provides input to model or assess a number of potential costs. For example, distance between emitter and injection well, which leads to pipeline costs, can be assessed for various sites. Distribution of exiting pipeline right-of-way may be a practical as well as a financial consideration, and the GIS format is ideal for this type of assessment. Formation injectivity, which controls the rate at which CO<sub>2</sub> can be pumped into a well, impacts construction costs. Low injectivity might require property acquisition and construction costs for more wells. Site-assessment studies are smaller but more immediate costs; basin-scale characterization provides an indication of the site-specific issues that would need to be addressed in site assessment.

Brine disposal has the potential to provide the longest residence times, as compared with other sequestration methods, on geologic time scales. However, various scenarios for leakage through the low-permeability seal above the injection horizon must be included in evaluating a candidate injection site. Leakage scenarios include (1) catastrophic escape of CO<sub>2</sub>, producing an asphyxiation hazard; (2) high fluxes of CO<sub>2</sub> from the injection site to the atmosphere, reducing the benefit of the injection; (3) displacement of large volumes of displaced brine upward, impacting potable water; and (4) other unintended negative consequences. Evaluation at a site-specific scale is required to determine seal integrity, although the basin-scale evaluation provides data for preliminary evaluation of issues involving seals.

Comparison of brine-formation properties shows that although they are present over large areas of the onshore U.S., sinks vary considerably in geological properties. Quantitative data in this data base permit future assessment of real variability impact on costs and the effectiveness of injection selection of one formation as compared with another. The GIS data base quantitatively describes some of the important geological properties of saline water-bearing formations in the U.S. and where geological conditions promote the greatest probability for success of pilot CO<sub>2</sub>-sequestration projects. This data base can be queried to match geologic saline-formation resources with critical economic

and infrastructure variables to determine the optimal locations for subsequent demonstration phases and full-scale projects. We see this data base as a proactive response to the rapid evolution of knowledge about the technologies that can be applied to CO<sub>2</sub> sequestration because the data-base format facilitates experiments and improvement of conceptual models. Furthermore, it allows stakeholders to assess multiple variables to produce a best-fit plan that unifies all land-surface variables with properties of the underlying geologic host formation.

In our phase I pilot project (Hovorka, 1999), we identified significant geological attributes that impact the feasibility of injection and containment of CO<sub>2</sub> (depth, permeability, sand-body thickness, net sand thickness, percent shale, sand-body continuity, top-seal thickness, continuity of top seal, hydrocarbon production from interval, fluid residence time, flow direction, CO<sub>2</sub> solubility in brine [P, T, and salinity], rock/water reaction, and porosity) that can be determined for saline formations by using a variety of approaches. In well-known formations in hydrocarbon-producing areas, many variables have been determined by previous researchers and can be extracted from oil and gas data sets and from previous deep-well injection studies. For other areas, more limited, direct information can be acquired from studies of basin evolution, inventories of fresh-water and brine resources, and from deep-well injection studies. The phase I pilot project determined that data sets can be compiled to determine the range of engineering characteristics of brine-bearing formations. In this study, we compiled available quantitative and spatially indexed data for 21 onshore basins.

We have been seeking venues that let us distribute these data. Identification of high-quality targets may spark interest from stakeholders in using geologic storage to reduce emissions. Stakeholders who have expressed interest in receiving the data base include oil and chemical companies, research groups and “think tanks,” and power-generation-equipment manufacturers. We expect demand to increase following release of this data base.

## CONTENTS

Technical summary .....	iii
Abstract .....	1
Introduction .....	2
Methods .....	3
Task 1. Brine-Formation Identification .....	3
Task 2. Literature and File Search for Geological Attributes of Regional Brine-Bearing Formations .....	7
Task 3. Data Digitization and Integration .....	8
Task 4. Geographic Information System Construction .....	9
Task 5. Brine-Formation Evaluation .....	14
Task 6. Reporting .....	14
Results – Target Formations .....	14
Results – Limits of Study .....	17
Results – Data Base .....	17
Results – Geologic Parameters .....	18
Results – Data Quality .....	24
Results – Optimal Brine Formations for Geologic Sequestration of Greenhouse Gases..	25
Discussion .....	24
Analysis of the Data .....	24
Target Identification .....	30
Partnerships .....	30
Further Investigation .....	31
Conclusions .....	31
Acknowledgments .....	44
References .....	34
Appendix 1. Brine-formation descriptions .....	47
Appendix 2. Citation and data quality for each parameter .....	205

## Figures

1. Distribution of power plants from FERC 432 data base showing calculated 1996 CO <sub>2</sub> emissions .....	5
2. Locations of study basins .....	16
3. Distribution of study basins and name assigned to stratigraphic interval selected for study .....	17
4. Inventory of data quality by formation and by parameter .....	26
5. Depth to top formation .....	32
6. Net sand thickness for target basins .....	34
7. Geographic distribution of porosity .....	38
8. Identification of targets .....	40

## Tables

1.	Conversion factors used to standardize parameters units .....	10
2.	GIS data structure.....	12
3.	Albers equal-area projection parameters.....	13
4.	Parameter definition .....	14
5.	Overview of selected formations .....	19
6.	Contents of the data base.....	21
7.	General rock type of sandstones .....	37
8.	Reported ranges of porosity .....	39

## ABSTRACT

Saline water-bearing formations that extend beneath much of the continental United States are attractive candidates for disposal of CO<sub>2</sub> produced during power generation or by other industrial processes. Identification of suitable targets will facilitate investigation of the potential for capture and storage of CO<sub>2</sub> from individual emitters and will help to develop the U.S. response to greenhouse gas-reduction initiatives. We have quantified the characteristics of saline formations that can be used to determine whether CO<sub>2</sub> can be efficiently injected into the selected subsurface unit and whether it will remain sequestered for suitably long time periods. A GIS data base of these geologic attributes of 21 saline formations was created to support data analysis and comparison with CO<sub>2</sub> source locations. Attributes include depth, permeability, formation thickness, net sand thickness, percent shale, sand-body continuity, top-seal thickness, continuity of top seal, hydrocarbon production from interval, fluid residence time, flow direction, CO<sub>2</sub> solubility in brine (pressure, temperature, and salinity), porosity, rock mineralogy, and water chemistry. Variations in formation properties should be considered in order to match a surface greenhouse-gas emissions-reduction operation to a suitable subsurface disposal site.

The characteristics of available sinks are highly variable from basin to basin. This data set provides the opportunity to match CO<sub>2</sub> sources with suitable sinks. We characterized 21 areas, underlying a total of 4.3 million km<sup>2</sup>. Target settings range from more than 100 m of thick, stacked sandstones to areally extensive thin sheet sands less than 10 m thick. Five sandstone targets are generally mature quartz sandstones, eight are lithic or feldspathic arkoses with moderately reactive phases, and five are mineralogical, immature sandstones containing reactive phases. Four of the targets are carbonates. We selected for high-permeability/high-porosity formations. Significant zones of more than 20-percent porosity were located in nine basins. Seals were dominated by shales, and significant thickness was found in all basins. Seals including evaporites (halite, anhydrite) were identified in three basins. Water chemistry is highly variable, from

brackish to extremely saline, and includes NaCl, CaCl, bicarbonate, and high-sulfate chemistries.

## INTRODUCTION

For CO<sub>2</sub> sequestration to be a successful component in U.S. emission-reduction strategies requires a favorable intersection of a number of variables, such as the market for electricity, fuel source, power and industrial plant design and operation, suitable geologic host for sequestration, and suitable pipeline or right-of-way from plant to injection site. The concept of CO<sub>2</sub> sequestration in brine-bearing formations (saline “aquifers”) isolated at depths below potable aquifers grew to widespread interest several years ago (Bergman and Winter, 1995) and continues to evolve. Saline formations are attractive because large volumes of prospective sink underlie many parts of the United States. Significant barriers remain, however, including high costs and potential citizen concerns about the safety and effectiveness of this process. Our contribution to the U.S. effort to reduce greenhouse-gas emission via underground sequestration is a data base of formations that have the potential for sequestering CO<sub>2</sub>. This data base can be used to (1) match CO<sub>2</sub> sources with prospective sinks and raise interest among stakeholders in areas where suitable geologic environments are present, (2) conduct preliminary feasibility analysis, (3) build various types of economic and process models, and (4) evaluate the merits of one CO<sub>2</sub> reduction plan against another. Our goal is to provide low-cost but realistic data that can support the search for viable options for CO<sub>2</sub> sequestration.

The scope of our investigations is saline water-bearing formations outside oil and gas fields. We are accepting the concept of hydrodynamic trapping (Hitchon, 1996), in which the CO<sub>2</sub> is isolated from the atmosphere and potable water supplies by very long (>1,000-yr) travel times between the injection site and these environments. A structural trap for the CO<sub>2</sub> is not required. We are also focusing on onshore sites near large or closely spaced commercial power plants and other industrial centers with point-source emissions of CO<sub>2</sub>. This definition allows exploration for large volumes of saline



formations that may be optimal injection sites near sources where sequestration could be undertaken at minimal cost. Implicit in this undertaking is an assumption that the goal is injection of large enough volumes of CO<sub>2</sub> to impact U.S. greenhouse-gas emissions. We are therefore focusing on formations with relatively high injectivity over large areas. Many other formations may be suitable for field-scale studies at a pilot scale or for sequestering output of individual emitters; however, our target is formations with the potential to scale up to store large volumes.

Many important considerations are outside the scope of this study. For example, because of the difficulty of capture, the source of the CO<sub>2</sub> is a most important cost consideration. However, determination of whether the U.S. greenhouse gas-reduction efforts should focus on one emitter over another (for example, coal burning, industrial sources, or new construction) is outside the scope of this study. Nevertheless, for geologic sequestration, intersection of a source with a suitable sink is required. We have therefore defined the characteristics of target formations over broad areas in order to maximize the potential for matches. The geologic data will also serve to help make generic assessments of rates and costs of the storage part of the process.

## METHODS

During phase II of our project, we compiled integrated, regional-scale information and quantitatively mapped the parameters identified in phase I for at least one target brine formation in 21 basins. This compilation was accomplished in six tasks: (1) brine-formation identification, (2) literature search, (3) digitizing, (4) GIS data-base construction, (5) brine-formation evaluation, and (6) reporting.

### Task 1. Brine-Formation Identification

Bergman and Winter (1995) matched the thickness of sedimentary cover and averaged rock properties and the power plant CO<sub>2</sub> emissions by state to assess the feasibility of employing brine formations as a sink for U.S. CO<sub>2</sub> emissions. This project

takes the next step in refining the assessment of feasibility by using formation-specific data to assess the feasibility and relative merits of selecting brine formations in one area or another as a sink. In the phase I feasibility study, we determined that we could assess 21 brine formations within the scope of the phase II study. This compilation included many of the very large, high-quality target formations; however, by design it is considerably short of an assessment of total capacity.

Four parameters were considered in formation selection: (1) geographic distribution of CO<sub>2</sub> sources; (2) appropriate depth, injectivity, and seal for the target; (3) adequate information to characterize the target; and (4) diverse geologic properties of the pool of selected formations. The data base is intended to describe quantitatively the realistic properties of potential targets; it is not an exhaustive list of all possible targets. We have noted in the formation descriptions (app. 1) some of the other potential targets within our study basins. Many other brine formations besides those described in this study are suitable for use as sinks; the only reasons for not including them in this study were budget and time constraints.

A comprehensive inventory of present and future U.S. point-source CO<sub>2</sub> emitters is not yet available. As a first approximation, the geographic distribution of 1996 power plant carbon emissions prepared during phase I of this study (Hovorka, 1999) was used to identify areas where CO<sub>2</sub> sinks could contribute to the national effort of reducing emissions (fig. 1). These data were extracted from 1996 fuel consumption reported in the FERC 432 data base; methods and sources of error in this calculation were reported by Hovorka (1999). Although these data are not up-to-date and may be incomplete because of the limitations of the source data base, we decided not to expend further energy on this map of power-plant emission for this phase II project because our efforts would be duplicated by in-progress U.S. Geological Survey (USGS) efforts to create a better, quality-controlled version of this plot for eventual public release (Robert Burress, USGS, personal communication, 1999).

Other parameters, such as costs of capture for various generator designs and combustion processes, peak- or base-load power generation at the plants, and plant-

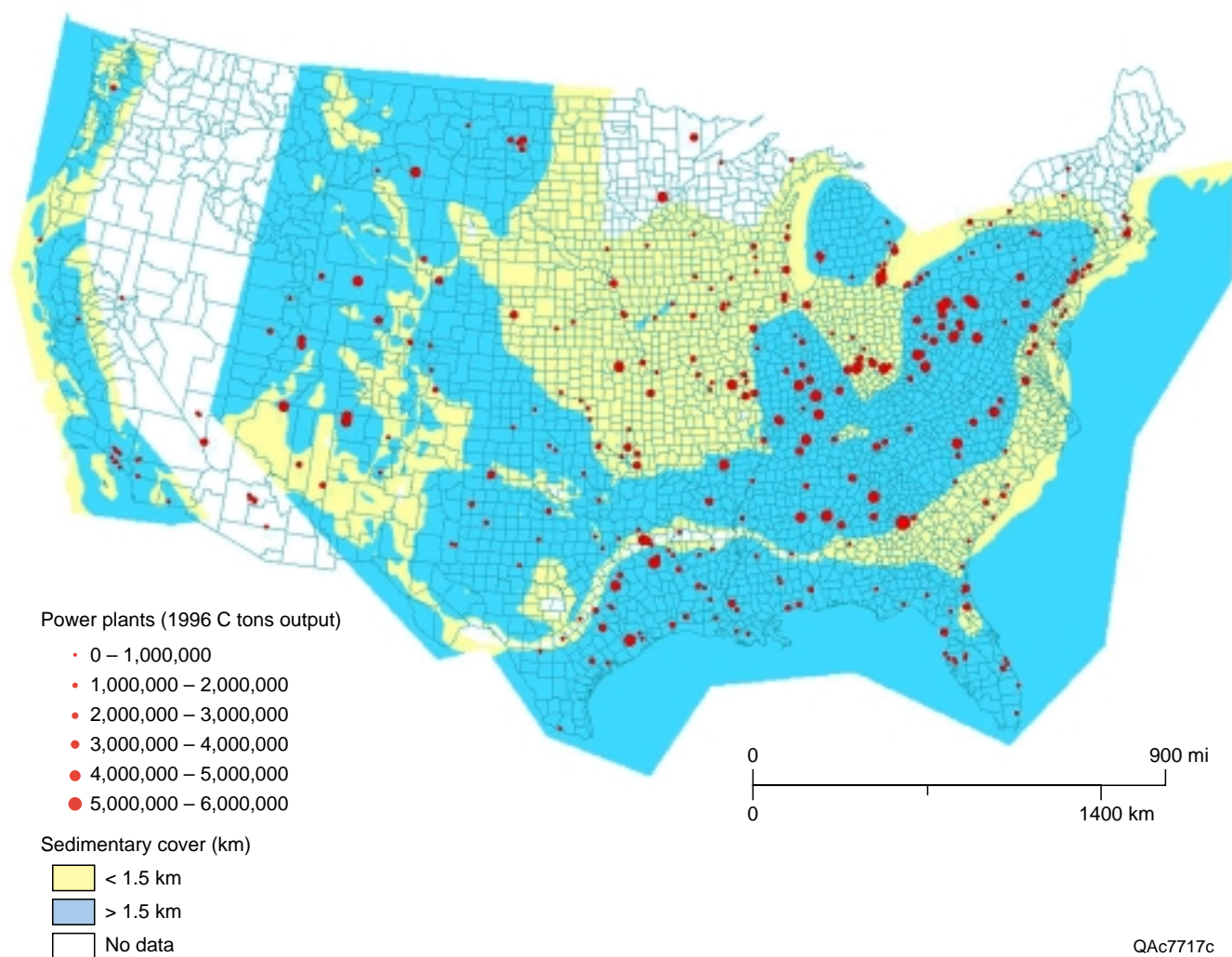


Figure 1. Distribution of power plants from FERC 432 data base showing calculated 1996 CO<sub>2</sub> emissions; intended to show approximate distribution of major power-plant releases of CO<sub>2</sub>. Colored base is gridded map of thickness of sedimentary cover (Frezon and others, 1983). Thicknesses in light-blue areas (depth < 0.8 km) are very likely too shallow to isolate targets from potable water and the surface.

specific forecasts of future evolution of power generation may have been critical to the feasibility of matching sources to sinks; these data have not been accumulated on a geographic base for the whole U.S. Geographically distributed information on other point sources of CO<sub>2</sub> besides power plants, such as oil refineries, fertilizer plants, and cement factories, are also not available. These data shortages guided us to use a generalized approach to defining sinks. We used the general trend of high 1996 power-plant CO<sub>2</sub> production to identify areas where sinks might be needed, but we captured information on sinks at a basin scale in order to increase the probabilities of matching sources to sinks. We therefore gave preference to formations with suitable properties over a large area. Proprietary or specialized power infrastructure data may also eventually be useful to match sources and pipeline right-of-way with the sinks identified in this study.

Preliminary screening criteria also included appropriate depth, injectivity, and seal for the target. We assumed that the target formation must be greater than 800 m below surface to give (1) adequate separation from potable water and (2) pressures sufficient for injection of CO<sub>2</sub> above the critical point. Assuming that basement rocks would not have sufficient injectivity, thickness of sedimentary cover provides an initial index for prospecting for suitable formations. We incorporated a digital map of thickness of sedimentary cover (Frezon and others, 1983) in our data base (fig. 1). Multiple candidate formations were noted in many basins. We assumed that costs would be minimized by selection of a shallow injection horizon. We therefore worked downward from 800 m, generally selecting the uppermost suitable horizon for characterization. We assumed that optimal target formation would have high injectivity. Injectivity is controlled by (1) near and intermediate field permeability and (2) thickness of permeable strata. The focus of our study was to identify optimal targets for low-cost injection of large volumes of CO<sub>2</sub>; we were looking for targets that approached or exceeded 100 m of permeable rock and permeability of 1 D.

These exploration goals are not cutoffs because rocks with much lower injectivity could be used for storage. Deep-well injection has effectively implaced fluids into a wide variety of geologic media, including rocks with moderate injectivity and fractured rocks

with low porosity. CO<sub>2</sub> flooding is commonly used to enhance production in reservoirs with low injectivity. However, for our compilation, we preferentially selected for high injectivity and significant porosity. The end result includes a wide spectrum of injectivities, depending on the geologic setting of each basin. Future numerical modeling can assess the validity of our assumption that injectivity is a significant component of cost. Notes on the target formation selection process for each formation are provided in appendix 1. A low-permeability barrier to vertical migration (top seal) is needed to slow upward migration of the CO<sub>2</sub> toward the surface because of buoyancy, as well as to reduce potential for upward displacement of brine was identified, along with the target injection horizon.

Because one of the purposes of our study was to quantitatively describe the properties of complex and diverse rocks that have the potential to be used for brine storage, we gave preference to units where adequate information for characterizing the target could be identified. In several basins, properties suggesting that the selected target might be not be suitable were identified during research, and our conclusion was that although another target in the basin might be more suitable, that target was poorly described and therefore not selected.

The fourth criterion was that the selected formations represent diverse geologic properties. The concepts for geologic storage are still evolving. A phase of modeling to determine optimal and acceptable requirements of the injection horizons and seal is needed and this data set is intended to support that modeling effort by supplying a realistic spectrum of formation properties. A successful pilot or full-scale CO<sub>2</sub> storage project will require a match between surface and geologic parameters; therefore, definition of the widest possible spectrum of target formations will increase the chances of a good match.

## Task 2. Literature and File Search for Geological Attributes of Regional Brine-Bearing Formations

A literature search was undertaken to populate the fields for each geologic parameter. The scope of the study limited us to about 40 hours of search per formation and seal. Our goal was to identify representative characteristics of each basin, not to compile an exhaustive bibliography for each formation. For each candidate formation, we conducted a literature search using GeoRef (<http://georef.cos.com/>) to identify the principle publications and researchers in the basin and target formation. Key words included geographic area terms and stratigraphic nomenclature. We also used previous compilations, including stratigraphic summary volumes and field guides compiled by the Geologic Society of America, Decade of North American geology (DNAG), water resource atlases compiled by USGS, indexes to oil and gas production information, and monographs on deep-well injection. A number of national data sets on specific topics (thickness of sedimentary cover, geothermal gradient) proved to be the best source of some types of basin-specific information. We used other online bibliographic resources as needed to identify other information. State geologic surveys or equivalent regulatory agencies and USGS publications proved to be rich resources in some areas. Personal contact with major researchers and state survey and regulatory agency personnel yielded important data, especially in digital format. Personal contact was also used to confirm findings of few or nonexistent data on some topics in some basins.

Relevant publications were borrowed from the Bureau of Economic Geology collections, the libraries at The University of Texas at Austin, or from interlibrary loan services. Some materials not available for loan were purchased, although the scope of this study precluded use of proprietary data. Relevant data were photocopied and filed by formation and citations prepared. Citations are listed by formation and parameter in appendix 2. In many areas, large amounts of additional site-specific data could be compiled, for example from reservoir or outcrop studies, well logs, or regulatory data.

### Task 3. Data Digitization and Integration

Map data showing the spatial distribution of each parameter were digitized. In most basins, the raw data consisted of one or more paper maps, which were scanned and georeferenced using Cartesian projection and latitude-longitude as calibration points, digitized using NDS Mapper software, attributed, and imported into ESRI ArcView GIS (geographic information system). One source of error in the data base lies in unknown projection and imprecise registration of the source maps. A few data sets were obtained in digital format (for example, from N. Gupta, Battelle Memorial Institute, USGS online sources, and an unpublished oil field data base compiled by M. Holtz, Bureau of Economic Geology). Data tables were scanned and spreadsheets prepared. During the final 2 months of the study, we will check the entire data base for consistency and accuracy.

Available data for each parameter were reviewed, evaluated, and integrated. The challenge for this project was to standardize highly unique geologic data into a format to facilitate use and comparison. In some cases, during review, our team had to use judgment in selection between disparate interpretations; these considerations are described in appendix 1. In many formations, the desired attribute was not mapped, but we were able to develop a methodology to calculate it from mapped information. For example, most structure is mapped on elevation, with a sea-level datum. We wanted to assess depth of the formation below surface. We therefore digitized the structure, gridded it, and subtracted the top formation elevation from land-surface elevation to produce a depth-below-surface map. In other cases, a map of structure on the base of the formation was used to calculate elevation of the top using the formation isopach. In some cases, data presented for several stratigraphic subdivisions were mathematically manipulated (summed, subtracted, net calculated from percent, or percent calculated from net) to determine the specified parameter the stratigraphic interval selected. For some areas, data were available for individual wells; for others well data were too dense or not readily accessible, and we used interpreted map data. Units were standardized to metric units on a spreadsheet, and the conversion factors are presented in table 1. Permeability was

Table 1. Conversion factors used to standardize parameter units. For site-specific study, we recommend examination of the methodology and units used in the original study be reviewed.

Saline aquifer properties	Convert from (headers in Arc_View)	To		Multiply by
<b>0 Clipping</b>	Clipping	Basin		
<b>1 Depth (m)</b>	Struct(ft)	To	Struct(m)	
	Altitu(ft)	To	Altitu(m)	*0.3048
<b>2 Permeability/H Conductivity(m/day)</b>	Per(md)	To	Cond(m/day)	*0.0000000966*86400
	Per(ft2)	To	Cond(m/day)	*911000*86400
	Cond(ft/S)	To	Cond(m/day)	*0.3048*86400
	Tr(ft2/S)	To	Tr(M2/day)	*0.09290304*86400
				9.87*10.7639104167097
	Per1(md)	Per2(md)		
	Cond1(m/day)	Cond2(m/day)		
	Tr1gal/D/ft	Tr2gal/D/ft		
	Tr1(ft2/day)	Tr2(ft2/day)		
<b>3 Formation thickness (m)</b>	Thickn(ft)	To	Thickn(m)	*0.3048
<b>4 Net sand thickness (m)</b>	Netsand(ft)	To	Netsand(m)	*0.3048
	Netsand(per) lithofacies			
<b>5 Percent shale (%)</b>	Shale(per)	Shale(per)		
	Netshale(ft)	To	Netshale(m)	*0.3048
	Shale1(per)	Shale2(per)		
<b>6 Sand-body continuity</b>	Continuity	Continuity		
	Contin(ft)	To	Contin(m)	*0.3048
	Netsand(ft)	To	Netsand(m)	*0.3048
	Thickn(ft)			
	Facies			
<b>7 Top-seal thickness (m)</b>	Seal(ft)	To	Seal(m)	*0.3048
	Struct(ft)			
<b>8 Continuity of top seal</b>	Contiseal	Contiseal		
	Contin(Min)	Contin(Max)		
	Topsand(per)			
	Cond(ft/D)	To	Cond(m/day)	*0.3048
	Struct(ft)	To	Struct(m)	*0.3048
	Netsand(ft)	To	Netsand(m)	*0.3048
	Evapori(per)			
	Thickn(ft)	To	Thickn(m)	*0.3048
<b>9 Hydrocabon production from interval</b>	Produc(Age)	Produc(Age)		
	Oil_fields			
	Oil_Gas			
<b>10 Fluid residence time</b>	Fluidresid	Fldrate(m/y)		
	Fires1(m/y)	Fires2(m/y)		
	Fluidresi1	Fluidresi2		
	RFLrate(m/y)			
<b>11 Flow direction elevation (m)</b>	Potenc(ft)	To	Potenc(m)	*0.3048
	Flowdirec			
<b>12 Co2 solubility brine</b>				
<b>12a Temperature C</b>	Tempera(F)	To	Tempera(C)	(Y-32)*0.5555
	Tempera(C)	To	Tempera(F)	(Y/0.5555)+32
	GeGr(F/100f)			
<b>12b Pressure (PSI)</b>	Pressu(Psi)	To	Press(Atm)	(Y*1/14.7)/12
	PrGr(psi/f)			
<b>12c Salinity (mg/l)</b>	TDS(ppm)			
	TDS(mg/L)			
	TDS1(ppm)	TDS2(ppm)		
	TDS1(mg/l)	TDS2(mg/l)		
	Altitu(ft)	To	Altitu(m)	*0.3048
<b>13 Rock/ water reaction</b>	Rock/Water			
<b>14 Porosity (percentage)</b>	Porosi(per)			
	Poros1(per)	Poros2(per)		
	Thickn(ft)	to	Thickn(ft)	*0.3048
<b>15 Water chemistry</b>	WaterChemistry			
<b>16 Rock mineralogy</b>	RockMineralogy			



standardized to hydraulic conductivity and pressure to psi at top target interval. These parameters are sensitive to fluid properties (change with salinity); therefore, for any future rigorous calculations we recommend that the methodology presented by the source publication be critically evaluated. Source data, intermediate calculations, and calculated results were preserved in the data base and are outlined in appendix 1 so that future users can retrace our calculations.

We ranked the quality of data for each parameter as follows: (1) detailed data digitized from the cited source, (2) generalized or schematic data from the cited source, (3) detailed data interpreted during this project, (4) sparse or descriptive data interpreted during this project, and (5) few or no data, values based on analog data. Data-quality ranks are presented in appendix 2.

#### **Task 4. Geographic Information System Construction**

GIS data-base structure is presented in table 2. Data sets are organized into (1) data of national extent and (2) formations within basins. Within each of the 21 formations, we show (1) source data, projected to Albers equal-area projection and standardized to common units shown in table 1, and (2) calculated, gridded parameters. Albers projection parameters are shown in table 3. Naming convention is the parameter number with which the data are related, followed by an abbreviated formation name. Parameter numbers are indexed in table 4. A c preceding the parameter number indicates calculated values, and a g at the end of the formation name indicates that the values have been gridded. Formation names are annotated in appendix 1.

Map data (polygons, arcs, and points) were imported from NDS Mapper into ArcView as shape files (.shp) and standardized data-base files (.dbf). Files projected to Albers equal-area were then manipulated in GIS and spreadsheet software to standardize highly variable source data. Shapefiles were exported to Arc/Info for gridding by using the ARC/INFO TOPOGRID algorithm, and ARC GRID was used for grid algebra. We used a coarse, 5-km grid cell to facilitate rapid review of regional data, except in small

complex areas like the Los Angeles Basin, where a 0.5-km cell size was used. Most data sets are sufficiently detailed to be more finely gridded.

Variability in original data is the major source of error in the data set; however, standardization is necessary for interbasinal comparisons, and we think that the precision of these data is adequate for the intended purpose of supporting the search for CO<sub>2</sub> sequestration options. Site-specific follow-up studies will be required at any potential sequestration prospect to confirm relationships observed at the regional scale.

Table 2. GIS data structure.

National
----US counties (shapefile)
----Thickness of sedimentary cover (grid)
----Study areas (shapefile)
----Power plants (shapefile)
----Elevation model (grid)
Formation
----arbuckle
----basinfcarb
----capefear
----cedarkey
----foxhills
----frio
----glencanyon
----granitewash
----jasper
----lyons
----madison
----morrision
----mtsimon
----oriskany
----paluxy
----potomac
----pottsville
----repetto
----stpeter
----tuscaloosa
----woodbine
Contents of each formation file
-----Source (includes ArcView.shp.shx.dbf and associated files
-----0 basin outline
-----1 structure maps as specified
-----2 permeability
-----3 thickness
-----4 net sand
-----5 percent shale
-----6 heterogeneity index (facies or proxy)
-----7 seal thickness
-----8 discontinuities in seal
-----9 production
-----10 fluid residence time
-----11 flow direction (potentiometric map)

-----12a formation temperature
-----12b formation pressure
-----12c formation salinity
-----13 potential for reaction with high CO <sub>2</sub> brine
-----14 porosity
-----15 target mineralogy
-----16 brine chemistry
-----Calculations (grid files)
-----c1 gridded formation depth below land surface
-----c3 gridded formation thickness
-----c4 gridded porosity
-----c5 calculated percent shale
-----c7 gridded seal thickness
-----c12a gridded temperature at formation depth
-----c12b gridded pressure at formation depth
-----c12c brine salinity
-----14 gridded porosity

Table 3. Albers equal-area projection parameters.

Projection	Albers equal-area conic
Spheroid	Clark 1866
Central meridian	−96.0
Reference latitude	37.5
1 <sup>st</sup> standard parallel	29.5
2 <sup>nd</sup> standard parallel	45.5
Map units	meters

Table 4. Parameter definition.

0	Basin outline	Boundary of data
1	Structure maps	Structure contours on top formation, elevation of top formation in wells, or isopachs on another horizon from which top formation is calculated
2	Permeability	Hydraulic conductivity from numerical models, well tests, or core analysis
3	Thickness	Formation isopachs or well data, structure on base formation from which thickness can be calculated
4	Net sand	Contoured net-sand maps, polygons with associated discretized descriptive data. Not applicable to carbonates
5	Percent shale	Mapped percent shale, or calculated from parameter 4/3; not applicable to carbonates
6	Heterogeneity index (facies or proxy)	Subjective estimate of continuity of sand bodies, high, medium, low, based on percent shale or facies description
7	Seal thickness	Isopach or well data on thickness of low-permeability horizon on top of target formation
8	Discontinuities in seal	Mapped faults, pinch-outs, high-permeability zones, domes, and diapers
9	Production	Oil and gas fields producing from target formation or below
10	Fluid residence time	Estimated brine ages and hydrodynamics of brine formation
11	Flow direction	Potentiometric map, qualitative description
12a	Formation temperature	Well tests or temperature gradient from this target formation temperature can be calculated from depth
12b	Formation pressure	Well tests, gradient, or observed over- or underpressure
12c	Formation salinity	Contoured data, sampled formation water, or inferred salinity gradient
13	Potential for reaction with high-CO <sub>2</sub> brine	High, medium, low potential for significant reaction with high CO <sub>2</sub> in brine; based on rock mineralogy and work of Perkins and Gunter (1996)
14	Porosity	Percent porosity from well samples, inferred from semiquantitative descriptions assigned to polygons
15	Brine chemistry	Brine analysis, generalized discretized water classification; detailed data where available are included as a nongeoreferenced dbf file
16	Target mineralogy	Point-count, thin-section, and facies-description data; detailed data where available are included as a nongeoreferenced dbf file

## Task 5. Brine-Formation Evaluation

We have used the GIS data base to demonstrate a number of evaluations to identify optimal sites in various U.S. saline formations. These evaluations fall into three categories: (1) provide information in areas where sites for sequestration activities are under consideration by industry or other researchers, (2) highlight other areas that are potentially excellent prospects, and (3) demonstrate how the data base can be used to evaluate future scenarios. These demonstrate a few of the possible ways that the data base can be used but represent only a small fraction of the utilization that is possible.

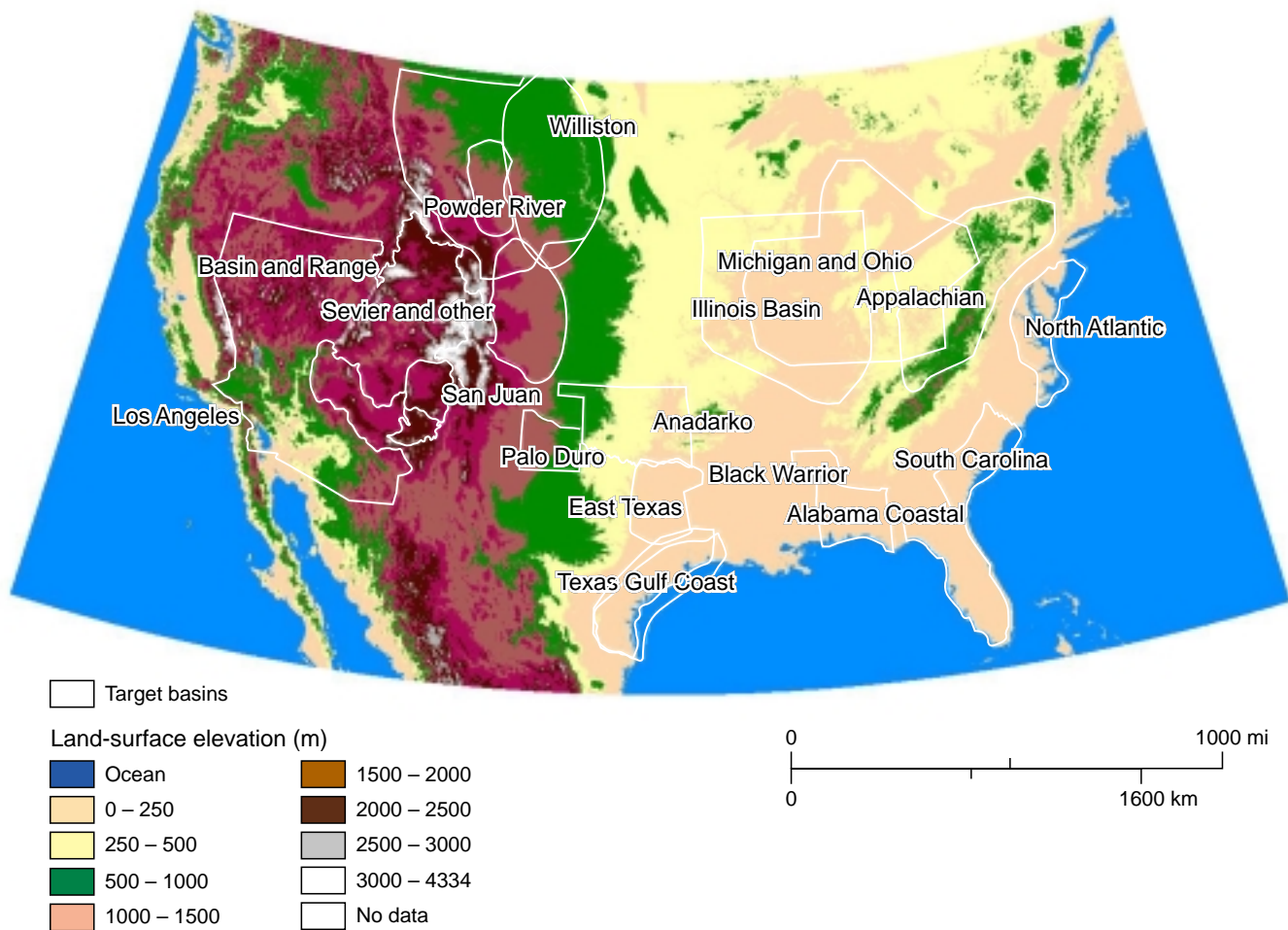
## Task 6. Reporting

One goal of our project is data exchange, with two objectives: (1) make the data as useful as possible to stakeholders and (2) facilitate implementation by engaging in data exchange with potential users of the data base. We have attended meetings, made presentations, exchanged data with other DOE contractors, and have begun dialog with potential industry partners.

We will make the results available on the internet as a web report ([www.beg.utexas.edu](http://www.beg.utexas.edu)) and a downloadable PDF file. We will make the data base available as a CD or an FTP file. We are investigating the potential to serve the GIS data to clients using a map server.

## RESULTS – TARGET FORMATIONS

Figure 2 shows the distribution of study basins, and figure 3 identifies the stratigraphic interval selected for study. Twenty-one areas underlying various parts of the onshore U.S. were investigated. The largest study area ( $0.6 \text{ million km}^2$ ) was in the areally extensive and structurally relatively simple arches and basins area of the Midwest, where we compiled descriptive data on the Mt. Simon Formation. The smallest study area ( $1,580 \text{ km}^2$ ) was the Repetto Formation in the Los Angeles Basin, which was



QAc7718c

Figure 2. Locations of study basins. Outlines shown are boundaries of data sets and do not necessarily follow any particular geologic feature. The base is a processed and gridded digital elevation map (Digital Terrain Elevation Data downloaded from National Imagery and Mapping Agency, 2000).

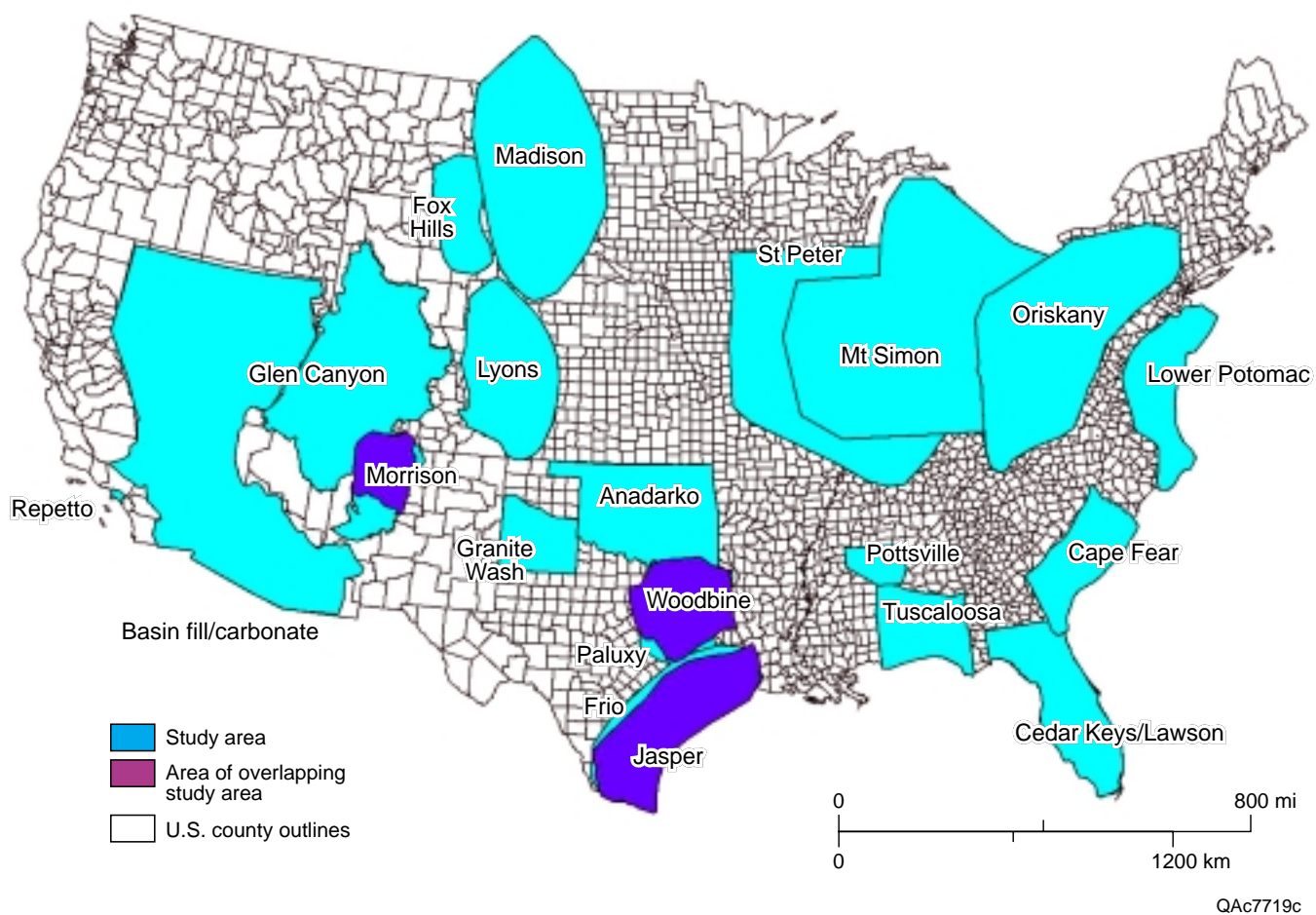


Figure 3. Distribution of study basins and name assigned to stratigraphic interval selected for study. Outlines shown are boundaries of the data sets and do not necessarily follow any particular geologic feature. Formation names have been somewhat simplified; see app. 1 for discussion.



bounded both depositionally and structurally by complex deformation. We characterized 4.3 million km<sup>2</sup> of aquifer. If the areas of overlap are eliminated, the aquifer potential beneath 3.5 million km<sup>2</sup> was characterized.

Depositional environments are also diverse, including submarine fan, marine, deltaic and delta, beach/barrier, fluvial, and carbonate platform. Seal lithologies are biased toward shale, reflecting our untested concept that this lithology is the optimal seal; however, two evaporite seals and an evaporite and tuffaceous mudstone are included.

The quantitative multicomponent characterization of brine formations will facilitate exploration for suitable CO<sub>2</sub> sinks in many areas of the onshore U.S. Table 5 summarizes the diverse types of formations and seals described. We described 4 carbonate formations and 17 sandstones. The target in the Basin and Range area includes both carbonates and sandstone. Sandstones are diverse, including conglomeritic facies (Repetto) and silty units (Cape Fear). Our selection criteria led to a bias toward younger formations in an area; however, limited thickness of sedimentary cover in platformal areas forced selection of older units. We characterized nine Mesozoic units (seven are Cretaceous) and three Tertiary units. Paleozoic formations range from Cambrian to Permian. Young formations were preferentially selected because (1) we generally selected the uppermost attractive formation in each basin, using the untested assumption that shallow injection would limit construction and compression costs; (2) high porosity tends to be preserved in young rocks at shallow burial; in most basins porosity is lost by cementation and compaction with depth; and (3) more data are generally available for shallower formations. In four areas (Midwest, East Texas, Colorado Plateau, and Gulf Coast) we characterized two formations with partly overlapping aerial extent, which could be repeated more generally on most basins.

Table 5. Overview of selected formations.

Formation	Lithology	Age	Facies	Seal	Seal lithology
Arbuckle	Karstic dolomite	Late Cambrian and Ordovician	Platform carbonate	Woodford	Shale
Mojave	Sandstone	Tertiary	Complex	Unnamed	Lacustrine fill and playa
Mojave	Carbonate	Paleozoic	Complex	Unnamed	Marine shales, siliceous siltstone, and evaporites
Cape Fear	Sandstone	Cretaceous	Marine	Unnamed	Shale
Cedar Keys/Lawson	Carbonate	Cretaceous	Carbonate platform	Upper Cedar Keys	Anhydrite
Fox Hills	Sandstone	Cretaceous	Marine/marine marginal	Lance/Lewis	Mudstone, shale
Frio	Sandstone	Oligocene	Fluvial/strandplain	Anahuac	Shale
Glen Canyon	Sandstone	Jurassic	Eolian	Carmel –Twin Creeks	Carbonates, evaporites, and shales
Granite Wash	Sandstone	Pennsylvanian	Alluvial fans and fan deltas	Wichita	Evaporites and fine-grained redbeds
Jasper	Sandstone	Miocene	Beach, barrier island	<i>Amphistegina</i> /Burkville	Shale
Lyons	Sandstone	Permian	Fluvial to normal marine	Lynkis	Redbeds, evaporites, carbonate
Madison	Carbonate		Carbonate platform	Big Snowy and Charles	Shale with minor limestone, sandy shale, sandstone
Morrison	Sandstone	Jurassic	Fluvial/marine	Brushy Basin Member	Tuffaceous mudstone
Mt. Simon	Sandstone	Cambrian	Basal transgressive tidal	Eau Claire	Silty dolomites, dolomitic sandstones and shales
Oriskany	Sandstone	Devonian	Fluvial deltaic	Middle Devonian	Black shale
Paluxy	Sandstone	Cretaceous	Deltaic	Kiamichi	Calcareous shale
Potomac	Sandstone	Cretaceous	Marine	Confining	Shale
Pottsville	Sandstone	Pennsylvanian	Fluvial/marine marginal	Cretaceous	Shale
Repetto	Sandstone, conglomerate	Pliocene	Submarine fan	Lower Pico Formation	Inner neritic to upper bathyal shales
St. Peter	Sandstone	Middle Ordovician	Marine transgressive	Maquoketa	Shale
Tuscaloosa	Sandstone	Cretaceous	Marine	Selma, middle Tuscaloosa	Chalk, shale
Woodbine	Sandstone	Cretaceous	Deltaic	Eagle Ford	Shale

## RESULTS – LIMITS OF STUDY

We selected only one formation in most areas as a target so that our results would not be a capacity assessment. We also did not attempt to be comprehensive; if the geologic parameters of a brine formation beneath a CO<sub>2</sub> source were not suitable, another shallower or deeper formation might be an ideal target. However, we did characterize many of the major, regionally extensive brine aquifers to improve the chance of matching as many sites as possible. Regional data likewise limit site-specific investigations. In all cases this data base should be utilized for regional screening; upon site identification site-specific study will be required as follow-up to confirm and refine the preliminary conclusions based on regional data. Data quality is highly variable; in all cases we recommend that the user examine the data quality in appendix 2 and refer to methods section of the original sources cited as needed to understand the limits of the data presented.

## RESULTS – DATA BASE

The data base itself is our main product. The data base is composed of shapefiles and grids suitable for viewing using ESRI software. The ArcExplorer viewer software can be downloaded at no cost from ESRI website ([www.esri.com](http://www.esri.com)). ArcView software can be purchased from the same provider. For this draft report, we have included grids created using ARC/INFO GRID. Viewing this file type requires the Spatial Analyst extension to ArcView. To broaden the accessibility of the product, we will experiment with serving the maps from our website. Data can also be downloaded and exported to other GIS and spreadsheet formats via FTP. We have also presented the data base in an html report viewable with an internet browser.

Table 6 indexes the data collected for each parameter and each formation. This data table is the index to the GIS data base. The volume of data compiled in this data base is large, and some of the data tables are content rich. We therefore have not attempted to

Table 6. Contents of data base.

Formation(Fm), Group (Gr), Sandstone /Snd/	Basin, Area, Region	0 Clipping	1 Depth (m)	2 Permeability/Hydraulic Conductivity(m/day)	3 Formation Thickness (m)	4 Net Sand Thickness (m)	5 Percent Shale (percent)	6 Continuity	7 Top Seal Thickness (m)	8 Continuity of top seal
Arbuckle Gr	Oklahoma	X	T <sub>X</sub> Depth	X	X	NA	T	xx	xx	T <sub>X</sub>
Basin Fill / Carbonates	Basin and Range, Arizona- Nevada-California	X	X <sub>just Arizona</sub>	X <sub>Low K</sub>			X <sub>just Arizona</sub>	X		
Cape Fear Fm	South Carolina Coastal Plain	X	X <sub>Structural</sub>	X	X <sub>Base Calculate</sub>	X	X	X	X	X
Cedar Keys_Lawson	Central Florida Region	X	X <sub>Structural</sub>	X	X	X	X	X	X	X
Fox Hills_Lower Hell Creek	Powder River Basin	X	X <sub>Structural</sub>	X <sub>one data point</sub>	X	X <sub>Percent</sub>	Calculate from 3 and 4	cross sec	X	X <sub>Percent</sub>
Frio Fm	Texas Gulf Coast	X	X	X <sub>Holz' Database</sub>	X	X <sub>X,X,X</sub> Add	X <sub>X,X,X</sub> Add	X		X
Glen Canyon Gr	Sevier- Kaiparowits Bench	X	X	X <sub>Conduct</sub>	X	X <sub>Navajo</sub> and X <sub>Navajo small area</sub>	X	X	X	X
Granite Wash	Palo Duro Basin	X	X <sub>Structural</sub>	X <sub>Wells and Tables</sub>	X <sub>X,X</sub> Add	X	X <sub>X</sub> add and calculate(mestone+shale)	T XX	xx	X
Jasper Interval	East Texas Gulf Coast	X	X <sub>Structural</sub>	X <sub>X'Holz' Database</sub>	X	X <sub>lag</sub> ,X <sub>Oak</sub> add	X <sub>lag</sub> ,X <sub>Oak</sub> add	X <sub>small area</sub>	X	X
Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	X	X <sub>Structural</sub>	X	X <sub>Base Calculate</sub>	X	X	X	X	X
Lyons Fm	Denver Basin	X	X <sub>Depth</sub>	X	X	X	NA	X	X	X
Madison Gr	Williston Basin	X	X <sub>Structural</sub>	X	X	NA	NA	X	X	xxx
Morrison Fm	San Juan Basin	X	X <sub>Depth</sub>	X	X	X <sub>south area</sub>	X <sub>south area calculate</sub>	xx	T <sub>X</sub>	xx
Mt Simon Fm	Michigan Basin and Ohio Areas	X	X <sub>Gupta Wells do contouring</sub>	X <sub>map one point and Table the same well</sub>	X <sub>Gupta Wells do contouring</sub> X	NA	NA	NA	x	T
Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	X	X <sub>Structural</sub>	X	X	X	X	X	X	X
Paluxy Snd	East Texas Basin	X	X <sub>Structural</sub>	X <sub>Holz' Database</sub>	X	X	Calculate from 3 and 4	X	X	X <sub>salt</sub> X <sub>fits from 1</sub>
Pottsville Fm	Black Warrior Basin	X	X <sub>Structural</sub>	X	X	X	T	X		X <sub>Faults</sub>
Repetto Fm	Los Angeles Basin	X	X <sub>Structural Base</sub>	X <sub>Rappeto fields book</sub>	X	X	X	X		X
St Peter Snd	Illinois Basin	X	X <sub>Structural</sub>	X <sub>converted</sub>	X	X	X <sub>One data point average</sub>	X	X	X
Tuscaloosa Gr	Alabama Gulf Coastal Plain	X	X <sub>Structural</sub>	X <sub>Table</sub>	X	X	X	X	X <sub>Depth-Top Seal</sub>	?X <sub>Structural</sub>
Woodbine Fm	East Texas Basin	X	X	X <sub>Holz' Database</sub>	X	X		X	X	xx

Table 6. continued.

Formation/Fm_Group (Gr, Sandstone/Snd)	Basin_Area_Region	9 Hydrocarbon Production	10 Fluid Residence Time	11 Flow Direction Elevation (m)	12 Co2 Solubility Brine			13 Rock-Water Reaction	14 Porosity (percent)	15 Water Chemistr	16 Rock Mineralogy
					12a Temperature C	12b Pressure (kg/cm2)	12c Salinity (mg/l) (ppm)				
Arbuckle Gr	Oklahoma	X <sub>(OGS map)</sub>	T	X	/ <sub>(Geothermal gradient map)</sub>	X	X	NA	T	T	X
Basin Fill / Carbonates	Basin and Range, Arizona- Nevada-California		T	X <sub>Arrows and Map</sub>			X	T <sub>saturation indices</sub>			
Cape Fear Fm	South Carolina Coastal Plain	NA <sub>no map</sub>	X	X	/ <sub>Depth*gradient</sub>	X <sub>Depth*gradient</sub>	X	X	X	X <sub>just dbf file</sub>	T
Cedar Keys_Lawson	Central Florida Region	X	X	X	X	X	X	X	X	X <sub>table</sub>	
Fox Hills_Lower Hell Creek	Powder River Basin	X	X <sub>Table</sub>	X <sub>two maps</sub>	X <sub>wells tableX<sub>map</sub></sub>		X <sub>two maps</sub>		X <sub>one data point</sub>	X <sub>Table</sub>	
Frio Fm	Texas Gulf Coast	X		X		X <sub>Holz' Database</sub>	XX <sub>table and map</sub>	X <sub>table</sub>	X <sub>Holz' Database</sub>	X <sub>table</sub>	
Glen Canyon Gr	Sevier- Kaiparowits Bench		/ <sub>just dbf file</sub>	X			X		X	T <sub>Pie</sub>	
Granite Wash	Palo Duro Basin	X	T	X	X <sub>table no map</sub>	/ <sub>Depth*gradient</sub>	X <sub>Wells do contouring</sub>	NA	T	X <sub>table no map</sub>	? <sub>ternary diagram</sub>
Jasper Interval	East Texas Gulf Coast	X		X	X	X <sub>Holz' Database, / <sub>Depth*gradient</sub></sub>	X		X <sub>Small area, X<sub>Holz' Database</sub></sub>		X
Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	T	X	X	/ <sub>Depth*gradient</sub>	/ <sub>Depth*gradient</sub>	X	X	X	XXX <sub>Table</sub>	X <sub>Table</sub>
Lyons Fm	Denver Basin	X	T	X	/ <sub>Depth*gradient</sub>	/ <sub>Depth*gradient</sub>	T <sub>No Data</sub>	T	X	/	/
Madison Gr	Williston Basin	X	X	X	X	T <sub>No Data</sub>	X	X	X	X	/
Morrison Fm	San Juan Basin	X	NA	X	X	NA	X	T	T	X <sub>and T<sub>stiff</sub> diagram</sub>	T
Mt Simon Fm	Michigan Basin and Ohio Areas	X	NA	X	X <sub>Michigan Geological Survey database, X<sub>Depth*gradient</sub></sub>	X <sub>Michigan Geological Survey database, / <sub>Depth*gradient</sub></sub>	NA,X <sub>Gupta Wells do contouring</sub>	NA	X <sub>map one point and Table the same well</sub>	NA	X <sub>map one point and Table the same well</sub>
Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	X	X	X	/ <sub>Depth*gradient</sub>	/ <sub>Depth*gradient</sub>	X	X	X	X	X
Paluxy Snd	East Texas Basin	X <sub>just Paluxy</sub>	T	T	/ <sub>Depth*gradient</sub>	X <sub>Holz' Database, / <sub>Depth*gradient</sub></sub>	X	T	X <sub>Holz' Database, X<sub>one data point</sub></sub>	X	X
Pottsville Fm	Black Warrior Basin	X		X	/ <sub>Depth*gradient</sub>	/ <sub>Depth*gradient</sub>	X <sub>Depth of Saline water</sub>		X	/	/
Repetto Fm	Los Angeles Basin	X		? <sub>Arrows flow direction</sub>	X <sub>Repetto fields book</sub>	X <sub>Repetto fields book</sub>	X <sub>Repetto fields book</sub>		X <sub>Repetto fields book</sub>		
St Peter Snd	Illinois Basin	X	X	X	/ <sub>Depth*gradient</sub>	/ <sub>Depth*gradient</sub>	X	X	/ <sub>Calculate</sub>	X <sub>Table</sub>	? <sub>charts</sub>
Tuscaloosa Gr	Alabama Gulf Coastal Plain	X	X	? <sub>Arrows flow direction</sub>	/ <sub>Depth*gradient</sub>	/ <sub>Depth*gradient</sub>	X	X	X <sub>Table</sub>	X <sub>Table</sub>	XX <sub>Table</sub>
Woodbine Fm	East Texas Basin			NA		X <sub>mapX<sub>Holz' Database</sub></sub>	X		X <sub>Holz' Database</sub>	X	/ <sub>Table</sub>

reproduce the data-base content on paper. The analysis presented below is an overview of the data base.

## RESULTS – GEOLOGIC PARAMETERS

During the feasibility phase of evaluation of parameters that describe the properties of reservoirs and seals in potential sinks, we decided that the state of the science was too immature to determine at this time which variables are critical. We therefore decided to compile diverse data. Variables were selected either because other workers used them for models or basin assessment (for example Hendriks and Blok, 1995; Holloway and van der Straaten, 1995; Koide and others, 1995; Hitchon, 1996; van der Meer, 1996; Weir and others, 1996; Gupta and others 1998) or because they are commonly used in reservoir evaluation or for underground waste-disposal-site evaluation. These diverse data sets will then facilitate further evaluation and modeling, and quantitative analysis can be used to determine which parameters are critical with respect to feasibility, cost, regulatory considerations, and potential for negative impacts. Table 4 shows the geologic parameters identified in phase I to characterize brine formations.

Six parameters were selected primarily to describe injectivity (table 4) Injectivity controls how fast CO<sub>2</sub> can be injected into the saline formation without excessive pressure buildup. Depth is a primary constraint on the density of the injected CO<sub>2</sub>. At typical temperature and pressure, 800-m depth approximates the critical point, above which CO<sub>2</sub> requires less volume. Permeability and formation thickness are the rock variables that determine the flow rate from a well. Net sand (net high-permeability strata) describes the thickness of the strata that accept fluid and are used for capacity assessment. Percent shale and sand-body continuity are indexes to the internal heterogeneity of the injection unit; they are needed to model the behavior of the CO<sub>2</sub> after it is injected.

Ten parameters were collected primarily to assess how effective the unit would be at trapping the CO<sub>2</sub>. Under most conditions, CO<sub>2</sub> at critical point will be buoyant in brine.

The top seal is defined as the low-permeability unit above the prospective injection unit that will limit leakage of the injected CO<sub>2</sub> upward into potable water and the atmosphere. The thickness of the top seal, as well as its continuity, can be used to calculate the rate of escape of CO<sub>2</sub> to assure that trapping will be effective. Examples of variable-quality seals are faults in the Frio, Jasper, and Repetto Formations; salt domes may provide a zone where leakage may occur in the Paluxy, Woodbine, and Frio; and variable seal quality can appear elsewhere, for example, variations in sand content in the Lance Formation overlying the Fox Hills.

Formation depth is also a key component in assuring suitably low upward flux of CO<sub>2</sub> and displaced brine. In most areas, 800 m is beneath the downdip limit of fresh water. Regulations typically classify water having more than 10,000 TDS as suitable for use as disposal horizons, and less-saline water is protected. This data base provides a basin-specific test of salinity in the target interval. The seal provides some thickness of low-permeability strata between the injection horizon and potable water for protection of water quality. Production of oil or gas from the interval can provide a pathway for more rapid release of CO<sub>2</sub> to the atmosphere; pragmatically, injection near production raises issues of mineral rights. Injection of CO<sub>2</sub> in producing intervals can be beneficial to production, maintaining pressure, and helping to mobilize oil. Use or reuse of hydrocarbon reservoirs for CO<sub>2</sub> sequestration has been considered in a number of studies, such as Bergman and others (1997) and Holtz and others (1998), and is therefore not the focus of our study. Because we are using a hydrodynamic-trapping assumption, fluid residence time and flow direction are important in assessing effectiveness of lateral trapping in the formation and identifying potential short, lateral paths for leakage to fresh water or the atmosphere. Temperature, pressure, and salinity are major variables in calculating CO<sub>2</sub> solubility in brine. Mineral trapping, in which CO<sub>2</sub> reacts with minerals in the rock can also provide a very long term trapping mechanism (Hitchon, 1996); therefore, we compiled rock mineralogy and brine chemistry to assess the role of this process. Porosity is a variable for assessing the total volume of storage in the saline formation.

## RESULTS – DATA QUALITY

Quality of the data is highly variable. We have ranked the data (app. 2) according to the following criteria: 1 = detailed data digitized from the cited sources; 2 = generalized or schematic data digitized from the cited sources; 3 = detailed data interpreted during this project; 4 = sparse or descriptive data; 5 = few or no data, values based on analogs or assumptions. Note that many parameters are derived from several sources—for example, several types of leaks such as faults, domes, channels in the seal. Ranking of 1, 2, and 3 indicates that the property is well known or moderately well known at a regional scale. Ranking of 4 or 5 indicates that the property is poorly known. In inventorying data quality for formations, we find that most properties in most formations fall into well-known categories (fig. 4a). The best-known formations are those with extensive oil production: Lyons, Frio, Oriskany, Arbuckle, and Paluxy. Formations that are more poorly known are Cedar Keys, Tuscaloosa, and Fox Hills. The Mt. Simon Formation, although extensively used for deep-well injection, is also relatively poorly known. Examination of injection permits might remedy this situation, at least on a site scale.

We can also rank data quality by property (fig. 4b). Basic descriptive properties of target horizons, such as 1 depth and 3 thickness, are relatively well known in all formations. Basic properties of seals, including 7 thickness and 8 potential leaks, are also well known. Detailed information about injectivity, such as 4 net sand, 5 percent sand, and 6 sand-body continuity, are more poorly known, although excellent regional and site-specific data are available in areas of hydrocarbon production and in a few outcrop areas. Reservoir characteristics that provide information about trapping, 10 fluid residence time, 11 flow direction, 13 potential for mineral trapping, and 14 detailed porosity data, are poorly known in about half the basins. We did not attempt to collect detailed information on the seals, such as mineralogy or bulk hydrologic properties; inspection of literature indicates that information on detailed properties of low-permeability units is one of the areas where very little basin-specific information exists.



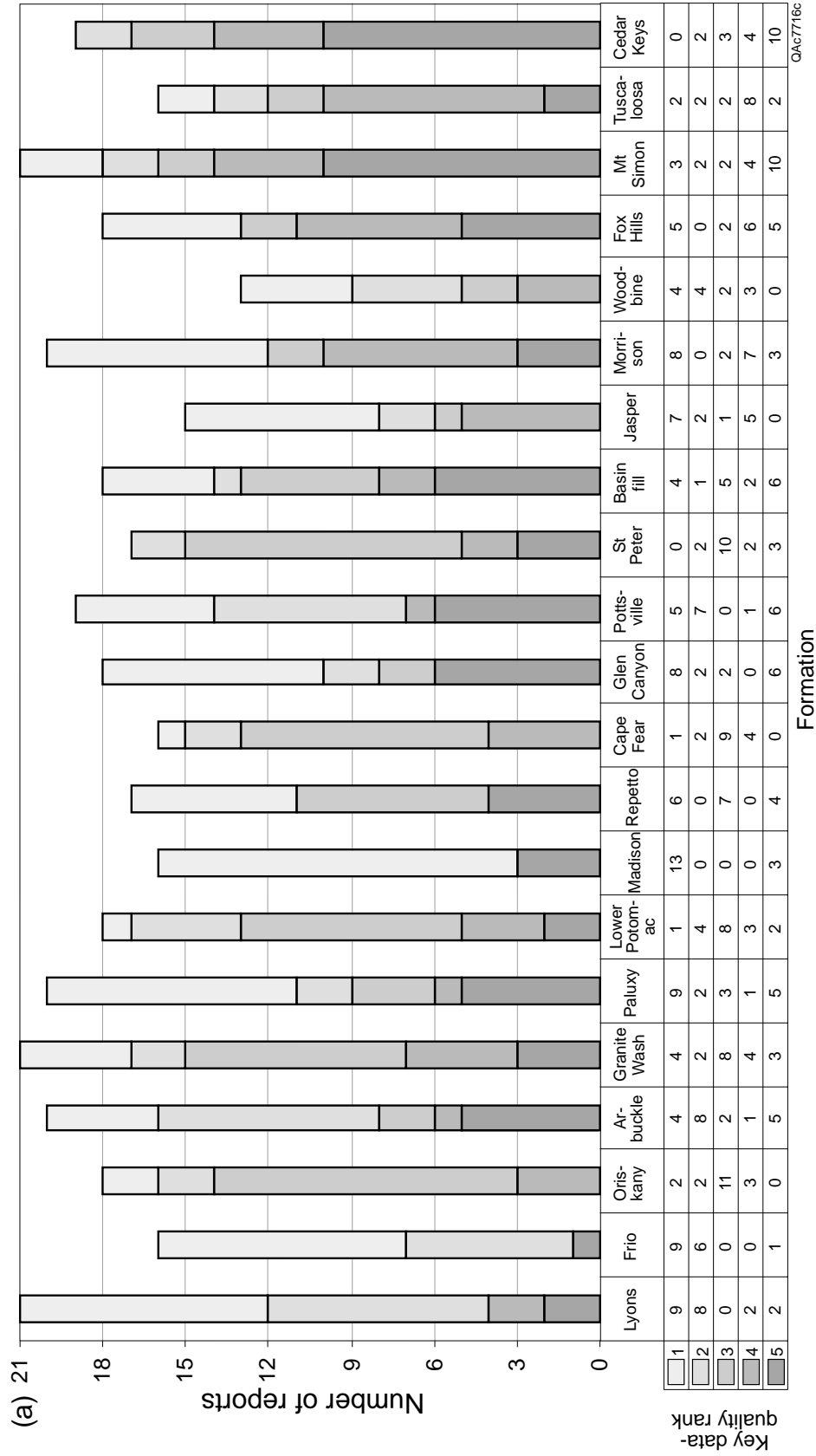
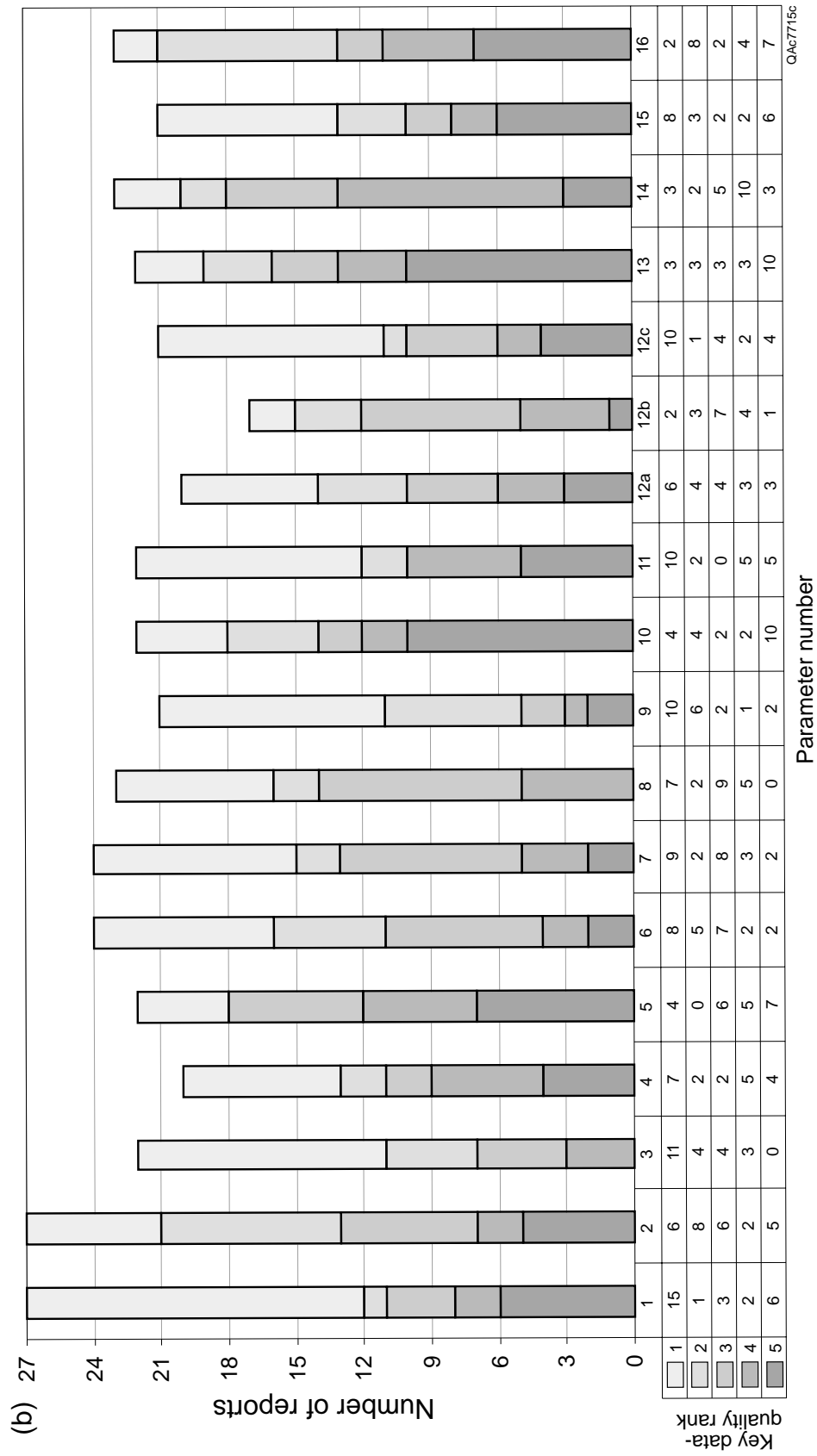


Figure 4. Inventory of data quality by (a) formation and (b) parameter (.dbf files in data base).  
More than one data set was used for some data.



## RESULTS – OPTIMAL BRINE FORMATIONS FOR GEOLOGIC SEQUESTRATION OF GREENHOUSE GASES

One goal of this project was to provide information in areas where sites for sequestration activities are under consideration by industry or other researchers, to highlight other areas that are potentially excellent prospects, and to demonstrate how the data base can be used to evaluate future scenarios. In this study, we selected four areas in response to informal discussions with representatives of the chemical and refinery industry, who identified Texas City Texas, Los Angeles, California, coastal South Carolina, and Chicago, Illinois, as areas where there was potential need for future greenhouse-gas reduction. In each case, a viable injection target was identified. We identified the Jasper (Miocene) in Texas City, the Repetto Formation in Los Angeles, the Cape Fear Formation in South Carolina, and the Mt. Simon in the Chicago area. In other areas we selected various formations to characterize the variability; several examples are discussed in the text, and details are provided for all in appendix 1 and the GIS and html presentations.

The Jasper (app. 1), a typical, well-known Gulf Coast Sandstone, contains 330 m of thick, highly permeable (500 to 2,300 md) sands interbedded with shale. Sand deposited in beach and barrier-island settings is relatively well understood. The top formation seal is a thick, continuous transgressive shale; however, site-specific detail for describing the permeability structure within the barrier and the capacity for growth faults to transmit gas or brine through the seal will be needed. Fluid residence time and flow direction have been highly perturbed by pumping. Salinity is high enough to qualify as brine, which could be permitted in Texas to receive waste (>10,000 TDS). Rocks are porous enough (23 to 28 percent) to store large volumes of CO<sub>2</sub> and mineralogically immature enough to have the potential for mineralogical trapping. This formation is assessed as a high-quality prospect.

The Repetto Formation (app. 1) is a typical deposit from a structurally complex area. Highly heterogeneous, sandy deposits are locally highly permeable (2,300 md) and as thick as 600 m; however, the thicker submarine fans are less permeable than the

thinner suprafan facies. Seal thickness is highly variable, and faults are abundant, indicating that site-specific characterization of these parameters is needed. Likewise, basin hydrology is poorly known, although analysis of production data may provide the potential for assessing this parameter. Rocks are porous enough (22 to 34 percent) to store large volumes of CO<sub>2</sub> and mineralogically immature enough, containing igneous rock fragments and glauconite, to have the potential for mineralogical trapping. This brine formation is assessed as a good-quality prospect.

Shallow depth to basement is the limiting variable in the South Carolina coastal area, with the top formation lying below 800 m only in the south part of the area, and salinity is greater than 10,000 ppm only on the south edge of the area. This unit is poorly known relative to the population of formations considered in our study. Sands are thin (< 20 m for individual sands, and > 100 m total only in the southeast part of the area) in this silt-rich sequence. However, permeability is interpreted as high, 1,000 to 6000 md. Although the properties of the seal are poorly known, it is interpreted as an effective confining unit. Ground-water flow is inferred to be northward, so flowpaths would be long from an injection site along the southern coast. Salinity is adequate to permit use for disposal. Sands are immature and have a moderate potential for mineralogical trapping. This formation may be useful because it is the only available target in the area; however, more assessment is needed to refine the quantitative parameters. Modeling is needed to assess the impacts of limited sand on injectivity and costs.

The Mt. Simon was identified as a target in a wide area of the Midwest, including the Chicago area. Depth of the formation top is more than 1,000 m. Most of the information found was for the Michigan Basin and Ohio area (app. 1); however, these areas only have 50 to 500 m of thickness. Little information was found anywhere about reservoir quality. Data on flow direction are somewhat conflicting, but it may be toward the basin center. The Chicago area would also require more detailed study to compare it with better known basins.

One of the most favorable units that we assessed is the Frio Formation of the Gulf Coast, with 300 m of sand over wide areas and 28- to 35-percent porosity (app. 1).

Numerous field studies provide site-specific data, and researchers have accumulated these into a detailed regional synthesis so that site comparison can be done with a high degree of confidence. One interesting data shortcoming is an assessment of the Anahuac Formation seal horizon, although numerous cross sections show the regional extent of the thick clay wedge. Growth faults and salt domes penetrate the seal, and site-specific information on the potential for leaks from these features would have to be conducted. Like in the Jasper, extensive oil production has modified the fluid residence time and flow direction so that flow is now generally toward pumping centers. Thermal and salinity structure is complex in the Gulf Coast because of geopressure. Although these parameters are well known, because of depth dependence we did not try to present them in this reconnaissance GIS. Highly reactive sand composition may be favorable to mineral trapping.

In contrast, we investigated the Glen Canyon Group from the Four Corners area. Several large coal-burning power plants are found in this area. Only in a few parts of the area does the Glen Canyon Group lie at adequate depths and contain adequately saline brine; however, interpolation of data from shallower and better studied areas suggests that reservoir quality might be very good, with areas of 20-percent porosity (app. 1) and sand-body thickness of 50 to 100 m. Flow direction appears to be toward the deeper parts of the basin. Seal thickness appears adequate, but variation in lithology at a regional scale may be a limiting factor. The data base contains an adequate number of data to encourage further investigation of this area; however, it is apparent that in this basin the brine formations are poorly known and would require significant investment to explore the potential.

These descriptions are examples. The reader is referred to appendix 1 and the GIS and html presentations for equivalent descriptions of each formation.

## DISCUSSION

When we proposed this study, we thought that saline formations were generally poorly known because they are unused. We expected to have to interpolate information from oil- and gas-producing areas and aquifers. However, during the feasibility phase, as well as the assessment phase, we found that data describing saline formations at a regional scale are moderately abundant. Table 6 shows the parameter fields that were successfully populated, and appendix 2 documents the source and quality of the data. Data are derived from regional studies integrating areas productive for resources, as well as assessment of saline formations themselves as potentials for deep-well injection of waste or saline-water resources. In many places more detail can be extracted from sources, such as well records and regulatory information from various types of injection, including waste and gas storage.

We did not attempt a comprehensive survey of potential saline formations; therefore, our study is not intended as a refinement of the total-volume assessment of Bergman and Winter (1995) or as a tool for evaluating all the sequestration options at a given site. It is, however, suitable for meeting our goal of providing realistic data that can support the search for viable options for CO<sub>2</sub> sequestration. In addition, our study provides a template for additional data compilation to create a detailed national assessment of capacity. This flexible data base can be used for construction of other scenarios—for example, combination of CO<sub>2</sub> utilization and geologic sequestration.

### Analysis of the Data

Opportunities for CO<sub>2</sub> sequestration in different basins is highly variable in detail; however, we were successful in defining a potential target in all of the basins. The data provided by this study will facilitate preliminary evaluation of feasibility. It will also provide some basis for prospect comparison.

Depth (parameter 1) is a limiting parameter in some parts of the U.S. where the thickness of sedimentary cover limits target horizon depth. A composite of the depth to

top formation (fig. 5) shows where target is too shallow (yellow, < 800 m), favorable depth (green), or too deep (blue). Depth is a notable limitation in target along the eastern seaboard and where basement is exposed in the Appalachians. Depths are marginal in parts of the Midwest and Great Plains. In these areas, we selected the basal transgressive sandstones as targets to maximize depths; depth therefore limits potential. Summing depth (parameter 1) and thickness (parameter 3) gives the maximum depth of the formation; this depth may expand the target area somewhat. We retained data from shallow parts of the saline formation because this information may be useful in explaining basin dynamics and the potential for lateral/updip displacement of brine or CO<sub>2</sub>. In other areas, our selected units were at probably excessive depths. We were successful in obtaining this parameter in every basin (fig. 4)

In the western U.S., structural complexity limiting basin size (parameter 0) is a factor. Description of these basins is very labor intensive per unit area, and it is difficult to make interpolations for widely spaced well data because of structural, and in some places depositional, heterogeneity. We inventoried two formations representative of targets in this type of basin, the Repetto Formation, Los Angeles Basin, and the carbonate and basin-fill formations in the Basin and Range area. These examples show that prospective targets can be identified in additional areas; however, as basin size decreases, characterization becomes more difficult and less certain.

Permeability (parameter 2) is difficult to characterize at a whole formation/whole basin scale. We have captured two disparate types of permeability data: (1) output from numerical models, which estimates bulk formation hydraulic conductivity (m/day) of large rock volumes, and (2) intrinsic permeability (darcys) from measurements on core samples. The scaling effects apparent between bulk and sample measurements are well known. In addition, samples analyzed for intrinsic permeability are from productive intervals; they are almost certainly biased toward high permeability. We normalized intrinsic permeability to hydraulic conductivity, assuming fresh water (table 1). However, we do not recommend using these data to interpolate over wide areas. We recommend extracting permeability for specific depositional facies or matching permeability to net

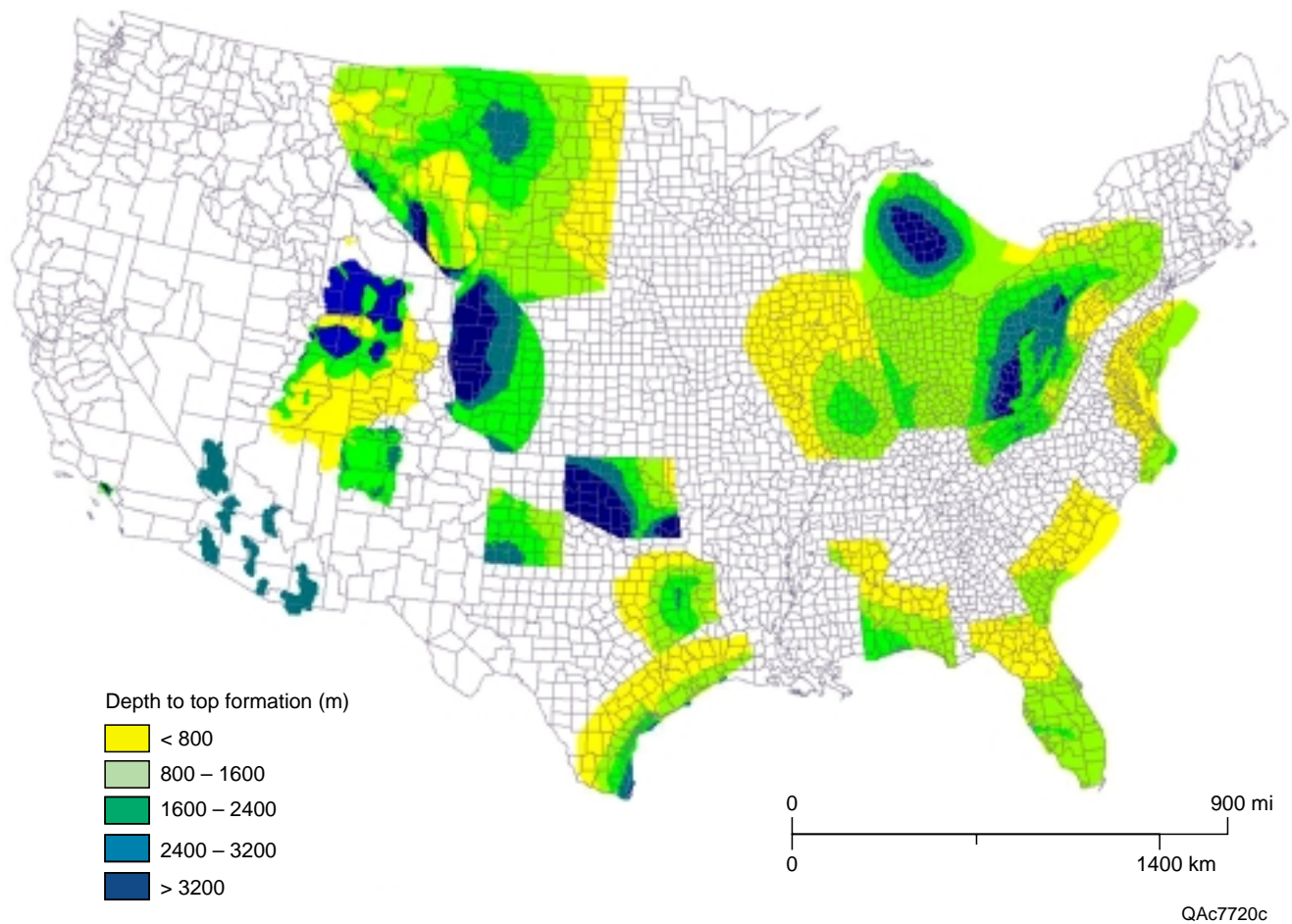


Figure 5. Depth to top formation. Yellow = too thin; green = good potential; blue = too deep. Note that using the GIS, one can “zoom in” to a basin-specific scale, which is the scale at which the data were digitized.



sand as an initial approach to characterizing target permeability. Parameter 6 provides an estimate of heterogeneity that is expected in the system.

Formation thickness (parameter 3) provides a coarse measure of the target volume. In some ways, this parameter is misleading because a formation definition does not always describe hydrologic units. In a number of cases, we considered the top of the formation as part of the seal. Net sand is a more useful estimate of the usable capacity of the target; however, these data are not available for some formations.

Net sand (parameter 4) provides an index of the total capacity of the target (fig. 6). Net-sand maps are prepared by summing the sand beds within the formation and contouring the values. Net sand also provides an initial indicator of bulk depositional facies, which may be an indicator of reservoir heterogeneity. We found net-sand maps for many formations; for a few formations we calculated net sand by multiplying decimal percent sand by formation thickness. In other areas we estimated net sand from semiquantitative descriptions. For carbonates, no simple variable equivalent is available for assessing permeable rock volume. In most carbonates characterized in this study, fractures and karst-enlarged conduits played a role in permeability. Figure 5 shows the distribution of net sand. Note that some targets, notably the Frio and Jasper, Woodbine and Paluxy, and St. Peter, Mt. Simon, and Oriskany overlap. It would be possible to sum all sand thickness; however, inspection of figure 3 shows that depth considerations may limit the usefulness of all this sand. Formation thickness is shown for carbonate formations. Note that these are not equivalent indicators of the distribution of permeable strata.

Percent shale (parameter 5) is an indicator of reservoir heterogeneity. Recent 3-D seismic evaluation of CO<sub>2</sub> injection at the Sleipner Vest project (B. van der Meer, NTO Institute of Applied Geoscience, personal communication, 2000) shows that minor amounts of shale (0 to 10 percent) may impact the evolution of the CO<sub>2</sub> flood over the short term. Modeling is needed to determine the effect of moderate shale contents on the CO<sub>2</sub> flood. High-percent shale (> 50 percent, J. Jennings, Bureau of Economic Geology, personal communication, 2000) may increase cost of site characterization because the

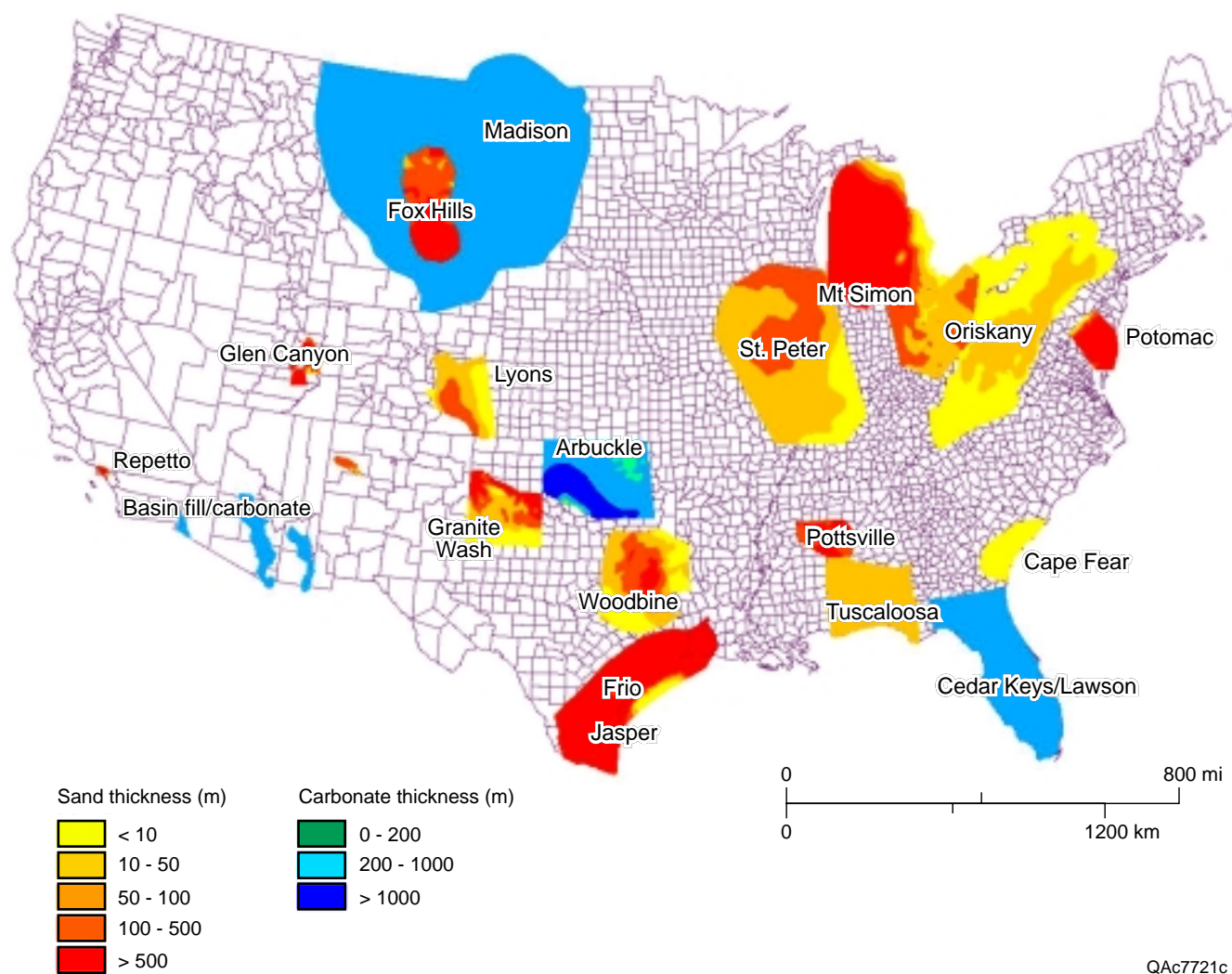


Figure 6. Net sand thickness of target basins. For sandstone targets, yellow = 0 to 10 m; light orange = 10 to 50 m; medium orange = 50 to 100 m; dark orange = 100 to 500; red = 500 m. For carbonate targets, formation thickness is shown. Light blue = 100 to 200 m; dark blue = 200 to 1,000 m

chance of sand bodies being discontinuous in three dimensions increases. On the positive side, limitation on the three dimensional interconnection of sand beds may trap or provide substantial lag on the dispersion of the CO<sub>2</sub> volume, possibly increasing the performance of the reservoir for isolation.

Sand-body continuity (parameter 6) is a qualitative estimate of reservoir-scale heterogeneity. We used depositional facies, percent shale, and descriptive information to populate this parameter and ranked brine formations as low, moderate, or high heterogeneity. For a number of basins that do not produce hydrocarbons, data were insufficient to populate this field. Reservoir-scale data collection and modeling are needed to assess the significance of this parameter at a site scale.

Seal thickness (parameter 7) is an estimate of the thickness of the seal. The seal is a low-permeability unit overlying the target horizon. Like formation thickness (parameter 3), these data are somewhat misleading because of oversimplification. The entire formation probably does not function as a homogeneous seal, and overlying formations may be functionally part of the aquitard. In fact, a layered unit is sometimes considered to be more effective in retarding upward flow of fluid or CO<sub>2</sub> (Ben Knappe, TNRCC, personal communication, 2000) because sand layers within the seal may bleed off pressure. Data on fine-grained units are very limited. We preferentially selected shales as seal horizons; however, evaporites, carbonates, and mudstones are included in our summary. Although thickness data were found, seal description is the weakest area of the data base

Continuity of the seal (parameter 8) is a category populated mostly by graphic data. We identify faults, salt domes, outcrop area, and breached seals in category 8. Basin- and site-specific study is needed to determine whether these features are in fact potential leaks. Oil and gas commonly accumulate adjacent to faults and salt domes, demonstrating that these features can be tight over geologic time; however, in other areas upward flow is focused at faults and domes. Distance to outcrop is a significant fracture in a hydrodynamic trapping model.

Parameter 9, production from target interval, was a fairly straightforward parameter. We limited ourselves to digitizing published generalized information. Some areas are generalized by field, lease, or play. Detailed well and reservoir information is available from proprietary sources, as well as public files. Issues such as failed well plugs or unplugged wells (potential leaks, possibly at high rates), mineral rights, and positive and negative interaction with production activities must be considered near oil and gas fields. Although our study focuses on storage in brine, some of the same data can be used in reverse to identify fields in areas favorable to enhanced oil recovery (EOR) or storage in abandoned oil fields.

Residence time (parameter 10) provides an index of natural isolation of the brine. This parameter was not available for some basins.

Flow direction (parameter 11) can be inferred from pressure gradients; however, great care must be taken to correctly interpret pressure in variable density fluids (Kreitler and others, 1990). We captured available data in various formats; the user should consider the data source. Zones of underpressure because of unloading or pumping show isolation of the brine and may help to offset pressure increase and buoyancy resulting from CO<sub>2</sub> injection.

Brine temperature, pressure, and salinity are needed to calculate CO<sub>2</sub> solubility and input into equations of state. Data are from well data and calculated from regional gradients.

Parameter 13 is a subjective evaluation of the potential for mineral sequestration using the criteria of Perkins and Gunter (1996). More rigorous analysis can be undertaken using rock mineralogy and brine chemistry data (parameters 15 and 16).

Table 7. General rock type of sandstones.

Mature	Lithic	Arkosic	Immature/reactive
Glen Canyon	Pottsville	Fox Hills	Repetto
Tuscaloosa	Jasper	Cape Fear	Basin fill
Oriskany	Woodbine	Potomac	Frio
St. Peter		Mt. Simon	Morrison
Lyons		Granite Wash	
Paluxy			

Porosity (parameter 14) is derived from core-sand outcrop samples, calculated from wireline logs, and inferred from facies, burial depth, and age. We attempted to identify highly permeable and porous formations and were generally successful (table 8). Note that porosity is from selected samples, probably from porous productive intervals, and probably cannot be extrapolated over the entire formation. Extrapolation guided by facies or net sand may be acceptable (fig. 7).

Table 8. Reported ranges of porosity.

0 -10	10-20	20-30
Oriskany	Woodbine	Repetto
<b>Arbuckle</b>	Pottsville	Fox Hills
<b>Basin carbonate</b>	Lyons	Glen Canyon
	Morrison	Basin-fill sandstone?
	Granite Wash	Jasper
	Madison	Cape Fear
	Mt. Simon	Potomac
	St. Peter	Frio
	Paluxy	<b>Cedar Key/Lawson</b>
		Tuscaloosa

**Bold** indicates carbonate

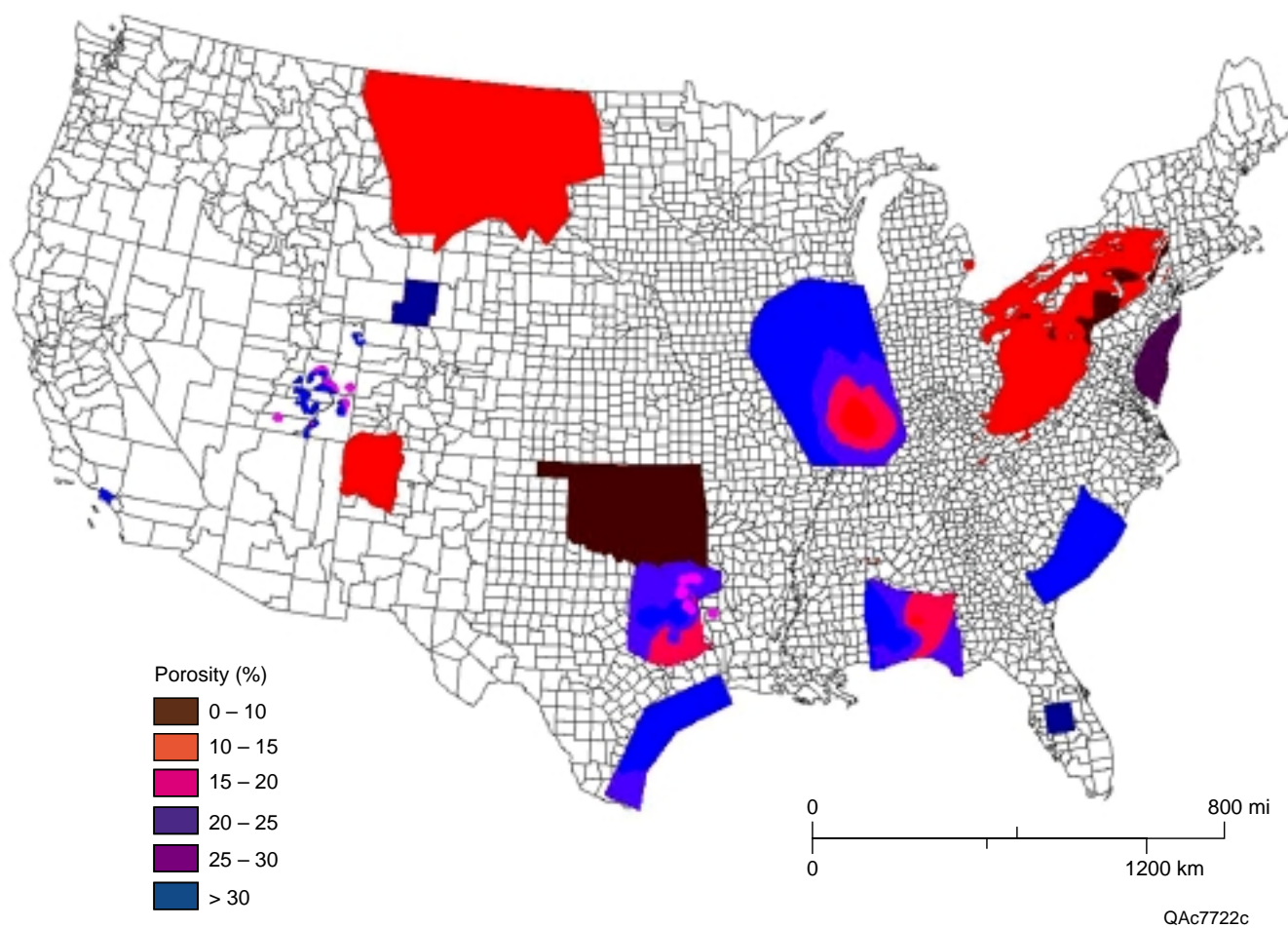


Figure 7. Geographic distribution of porosity. Some data are not spatially referenced. Other data are at a very local scale not visible on a national overview.

## Target Identification

Figure 8 shows the match between target formations and 1996 carbon emission from power plants (red dots). We note four populations of power plants: (1) areas where the target is too shallow (yellow), (2) areas where targets of suitable depth were identified (green), (3) areas where thickness of sedimentary cover appear to be adequate but no formation was characterized for this study, and (4) structurally complex areas where site-specific data are needed. Using the GIS, the user can “zoom in” to investigate storage prospects in a selected area in more detail. The locations of additional features—for example, chemical industries with the potential for demonstration project development or pipeline rights-of-way—can be posted in this data base to explore options.

## Partnerships

This project is not intended as a stand-alone end result. During the project, we have worked toward developing partnerships for help in using the data to move the U.S. CO<sub>2</sub>-emissions-reduction plan forward. We made presentations at the IEA workshop on Geological Storage of CO<sub>2</sub> in saline aquifers sponsored by Statoil in the Netherlands, Spring 2000, the Energex Conference, Las Vegas, July 2000, and the American Chemical Society symposia on greenhouse-gas reduction methods, Washington DC, July 2000. We attended a number of workshops as well, including the fall 1999 workshop sponsored by PB and DOE.

We have formed one partnership with the Lawrence Livermore-led GEOSEQ project to supply them with materials evolved from this project. In addition, we are working toward participating in two industry-led collaborations, one with Shell and one with BP.

Potential for further collaboration is large. We have received and responded to requests for information from a number of stakeholders, including Texas legislators, oil-field independents, small operators, major oil companies, providers to the oil industry,

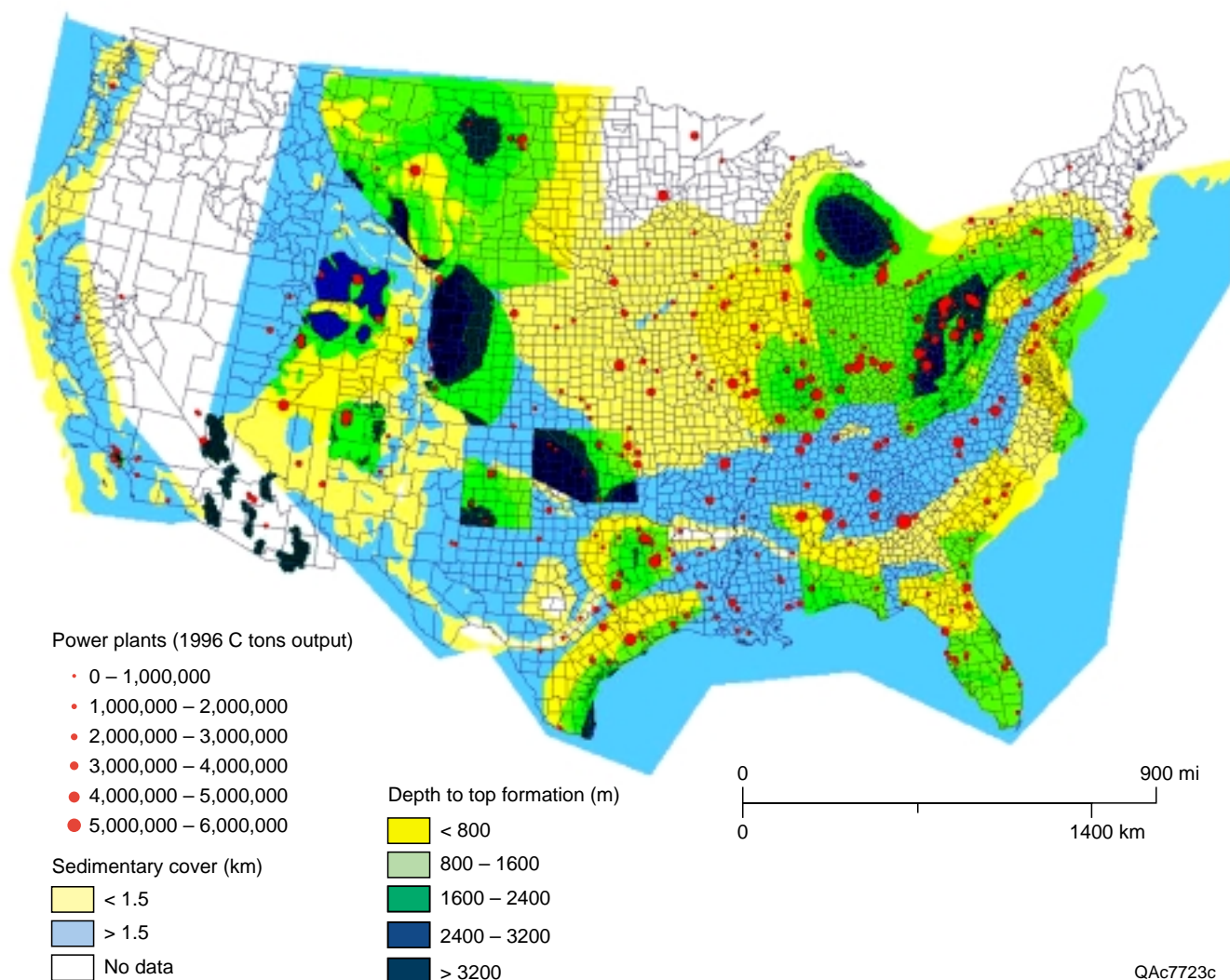


Figure 8. Identification of targets. Power plants (dot size proportional to 1996 carbon emissions calculated from fuel consumption, FERC 432 database). Note that these are not all the point sources of carbon; however, populations of emitters provided. Depth to top formation in the study basins is shown by: yellow = target too shallow; green = suitable target; blue-green = target too deep. The sedimentary cover image was created by gridding a ARC/INFO coverage provided by FTP (David Ferderer USGS, Energy Resources Survey Team, 2000) of a map (Frezon and others, 1983); light yellow = areas that are too thin; blue = rocks at depths suitable to be considered targets.



providers to the electricity industry, and private and government think-tanks. We are engaged in data exchange with the European GESTCO project, as well as the Australian GEODISC project.

During the final phase of the project, we plan to disseminate the data and provide education to stakeholders on the potential for geologic storage.

### Further Investigation

This data base is a low-cost start on matching sources and sinks. Additional data are needed on distribution of sources where capture is feasible. Modeling injectivity, including costs, is needed to constrain the assumptions made about injectivity, depth, and seal properties. This data base can help with these efforts, by providing realistic constraints on models and focusing on attractive prospects.

The user is invited to experiment with scenario building to intersect parameters—for example, matching porosity data and sand thickness to calculate total brine volume as an input into capacity assessment. Formations can be screened—for example, to determine which basins are limited by the EPA cutoff for salinity.

A large number of additional data are available to characterize the target formations, both those selected for our project in more detail and those found when extending the work into areas that were not covered or for which the selected formation was not suitable. We hope that this project will help focus these activities.

### CONCLUSIONS

Variations in formation properties should be considered in order to match a surface greenhouse-gas-emissions reduction operation with a suitable subsurface disposal site. In this environment, where cost is a critical limiting factor, matching CO<sub>2</sub> capture processes with an optimal subsurface site for sequestration can be essential. This data base provides

a vehicle for assessing the interaction between surface variables, such as the nature of the source and type of capture and infrastructure and subsurface geologic variables.

We identified 21 candidate formations in onshore U.S. basins, including Los Angeles, Powder River, Sevier, Mojave, South Carolina, Alabama, North Carolina, Appalachian, Illinois, Texas Gulf Coast, East Texas, Florida, Black Warrior, Denver, Williston, Michigan, San Juan, Palo Duro, and Anadarko. Data sets of 16 parameters for the target saline formation in each basin have been compiled and digitized. In many basins, several potential prospects were identified. We selected one or two formations to characterize in this study and note the potential for additional resource in overlying and underlying formations.

One of the major problems to be resolved for underground sequestration of CO<sub>2</sub> is how to identify optimal saline water-bearing formations. The “quality” of the water-bearing formation is a critical variable in the economic success of a sequestration project because it controls the effective rate of CO<sub>2</sub> input, the ultimate total volume of CO<sub>2</sub> sequestered, and the rate and processes of release of CO<sub>2</sub> back to the atmosphere. The reliability of the confinement of CO<sub>2</sub> is also a critical safety concern and may be crucial in permitting a facility. However, the same attributes that make saline water-bearing formations desirable as disposal sites (isolation, low potential for economic usage, and few well penetrations) are those for which we have little direct information. At the present, selection of a saline water-bearing formation for CO<sub>2</sub> disposal is analogous to a wildcat drilling venture in an unexplored basin. Selection of an appropriate saline water-bearing system might mean the difference between success and failure for a pilot sequestration project; therefore, flexible and creative matches between infrastructure (power plants and other surface facilities) and the geologic host media are crucial to the success of the program.

Identification of sites and saline water-bearing formations for operational CO<sub>2</sub> sequestration facilities and demonstration projects to date has been driven mostly by opportunities associated with hydrocarbon production. This data base will allow users to systematically screen water-bearing formations beneath CO<sub>2</sub>-producing areas of the

continental U.S. in order to optimize the process of matching suitable saline water-bearing formations with CO<sub>2</sub>-producing areas. The users of the saline-formation data base resulting from this study would be DOE contractors and industry-funded groups seeking optimal areas for demonstration projects. We think that optimizing the choice of formation would greatly improve the chances of success in an environment where cost is critical.

The relatively low cost-assessment techniques using existing data bases can increase the probability of success for modeling efforts and demonstration projects to identify optimal saline water-bearing formations for storage. This is not intended to be a stand-alone process but to complement and support other engineering and modeling-based efforts by examining the real variability in potential water-bearing formations. The geologic variability observed is expected to have both positive and negative effects on the economics and feasibility of injection. Positive effects may include multiple injection horizons and improved trapping mechanics. Negative effects of the real complexity as compared with idealized sandstone water-bearing formations can be decreased assumptions about overall permeability of sandstone bodies and reduced volumes of permeable sandstones.

## ACKNOWLEDGMENTS

We thank John Andrews for help with the more arcane parts of ARC/INFO and ArcView data-base construction and data management. Scott Rodgers made the CD.

## REFERENCES

- Bachu, S., Gunter, W. D., and Perkins, E. H., 1994, Aquifer disposal of CO<sub>2</sub>: hydrodynamic and mineral trapping: *Energy Conversion and Management*, v. 35, no. 4, p. 269–279.
- Bergman, P. D., and Winter, E. M., 1995, Disposal of carbon dioxide in aquifers in the U.S.: *Energy Conversion and Management*, v. 36 nos. 6–9, p. 523–526.
- Bergman, P. D., Winter, E. M., and Chen, Z.-Y., 1997, Disposal of CO<sub>2</sub> in depleted oil and gas reservoirs in Texas: *Energy Conversion and Management*, v. 38, p. 211–216.
- Frezon, S. E., Finn, T. M., and Lister, J. H., 1983, Total thickness of sedimentary rocks in the conterminous United States: U.S. Geological Survey, Open-File Report 83-920, digital data via FTP from David Ferderer, USGS, Energy Resources Survey Team.
- Gupta, Neeraj, Naymik, T. G., and Bergman, Perry, 1998, Aquifer disposal of carbon dioxide for greenhouse effect mitigation: Proceedings of the 23rd International Conference on Coal Utilization and Fuel Systems, March 9–13, Clearwater, Florida.
- Hendriks, C. A., and Blok, Kornelis, 1995, Underground storage of carbon dioxide: *Energy Conversion and Management* v. 36, p. 539–542.
- Hitchon, Brian, ed., 1996, Aquifer disposal of carbon dioxide: hydrodynamic and mineral trapping—proof of concept: Alberta, Canada, Geoscience Publishing Ltd., 165 p.
- Holloway, Sam, and van der Straaten, Rieks, 1995, The Joule II project: the underground disposal of carbon dioxide: *Energy Conservation and Management*, v. 36, nos. 6–9, p. 519–522.
- Holtz, M. H., Nance, P. K., and Finley, R. J., 1998, Reduction of greenhouse gas emissions through underground CO<sub>2</sub> sequestration in Texas oil and gas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, draft report, 84 p.
- Hovorka, S. D., 1999, Project evaluation: phase I: optimal geological environments for carbon dioxide disposal in saline water-bearing formations in the United States: The University of Texas, Bureau of Economic Geology, final report prepared for U.S. Department of Energy, Federal Technology Center, under contract no. DE-AC26-98FT40417, 55 p.
- Koide, H., Takahashi, M., Tsukamoto, H., and Shindo, Y., 1995, Self-trapping mechanism of carbon dioxide in aquifer: *Energy Conservation and Management*, v. 36, p. 505–508.

- Kreitler, C. W., Akhter, M. S., and Donnelly, A. C. A., 1990, Hydrologic hydrochemical characterization of Texas Frio Formation used for deep-well injection of chemical wastes: *Environmental Geology and Water Sciences*, v. 16, no. 2, p. 107–120.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Perkins, E. H., and Gunter, W. D., 1996, Mineral traps for carbon dioxide, *in* Hitchon, Brian, ed., *Aquifer disposal of carbon dioxide: hydrodynamic and mineral trapping—proof of concept: Alberta, Canada*, Geoscience Publishing Ltd., Chapter 7, p. 93–113.
- van der Meer, L. G. H., 1996, Computer modeling of underground CO<sub>2</sub> storage: *Energy Conversion and Management*, v. 37, nos. 6–8, p. 1155–1160.
- Weir, G. J., White, S. P. and Kissling, W. M., 1996, Reservoir storage and containment of greenhouse gasses: transport in porous media, v. 23, p. 37–60.

## APPENDIX 1. BRINE-FORMATION DESCRIPTIONS

Arbuckle Group, Oklahoma .....	49
Basin-Fill Sandstone and Carbonate Aquifers in the Basin and Range, Arizona–Nevada–California.....	55
Cape Fear Formation, South Carolina Coastal Plain.....	61
Cedar Keys/Lawson, Central Florida Region.....	69
Fox Hills –Lower Hell Creek, Powder River Basin .....	79
Frio Formation, Texas Gulf Coast.....	87
Glen Canyon Group, Sevier Basin and Kaiparowits Bench.....	93
Granite Wash, Palo Duro Basin, Texas.....	99
Jasper Interval, East Texas Gulf Coast .....	105
Lower Potomac Group, Eastern Coastal Plain of Maryland, Delaware, and New Jersey.....	115
Lyons Sandstone, Denver Basin .....	125
Madison Group – Williston Basin.....	131
Morrison Formation, San Juan Basin.....	137
Mt. Simon Formation, Michigan Basin and Ohio Area .....	143
Oriskany Formation, Appalachian Basin, Western Pennsylvania, Eastern Ohio, and Eastern Kentucky.....	149
Paluxy Sandstone, East Texas Basin.....	159
Pottsville Formation, Black Warrior Basin, Alabama/Mississippi.....	165
Repetto Formation, Los Angeles Basin .....	171
St. Peter Sandstone, Illinois Basin .....	179
Tuscaloosa Group, Alabama Gulf Coastal Plain .....	189
Woodbine Formation, East Texas Basin.....	199



## ARBUCKLE GROUP, OKLAHOMA

### General Setting

The Arbuckle Group of Late Cambrian and Ordovician age was deposited in the Oklahoma basin in a broad epicontinental sea that extended across the southern Mid-Continent. The region was stable throughout Arbuckle deposition, as evidenced by the lateral continuity of the strata (Johnson, 1991a). In fact, the Arbuckle was deposited as part of an even larger carbonate (limestones and dolomites) platform that extended from West Texas to eastern North America. The Arbuckle and its equivalents are all composed of very thick, almost pure carbonate successions that are often dolomitized. These successions consist of several hundred upward-shoaling, meter-thick, tidal-flat cycles or parasequences (Wilson, 1994). Extensive karst and solution-collapse brecciation (ancient cave systems) developed within these carbonates as a result of meteoric water infiltration during the widespread post-Sauk unconformity (Wilson, 1994). It is these karsted zones that contain significant amounts of porosity and permeability in what are otherwise low-porosity and low-permeability rocks. The high-porosity and -permeability karsted zones can be targets for CO<sub>2</sub> sequestration when they subcrop beneath competent seals, such as the ubiquitous Devonian-age Woodford Formation.

### Comments on Geologic Parameters

1arbuckle: Depth. Generalized depth map to the top of the Arbuckle Group (Johnson, 1991a).

2arbuckle: Permeability / hydraulic conductivity. The permeability map that we chose comes from a numerical ground-water flow model developed by Jorgensen and others (1996). The rock matrix consists of low-porosity mudstones and dolomudstones. However, the permeability map of Jorgensen and others (1996) is regional in scope and does not reflect local differences in porosity and permeability. Therefore, one must realize that because of dissolution and



dolomitization, the Arbuckle Group rocks are locally some of the most porous and permeable in the Mid-Continent region. It is often true that reported porosity and permeability values are much lower than the true values (Puckette, 1996).

Puckette offered two examples of this phenomenon. The producing section of Cottonwood Creek field, Carter County, Oklahoma, has produced more than 4,000 bopd. Yet the reported porosity and permeability are 2 to 3 percent and less than 0.01 millidarcy, respectively (after Read and Richmond, 1993). In large part this is due to the nature of the karsted rock, which during coring yields proportionately much more of the low-porosity rock than the porous, sometimes brecciated and cavernous zones (Puckette, 1996).

3arbuckle: Formation thickness. Generalized thickness map of the Arbuckle *and* Timbered Hills Groups from Johnson (1991b) was gridded in 5-km cells.

4arbuckle: Net sand thickness. Thickness of the permeable units are highly variable because of karst origin.

5arbuckle: Percent shale. “The paucity of shales in the Arbuckle Group prevented the generation of stratabound seals that were barriers to vertical fluid movement. The widespread distribution of dolomitized grain-rich facies in combination with karstic dissolution contributed to the evolution of regionally extensive reservoirs in the Arbuckle” (Puckette, 1996, p. 73). We did not find any quantitative data concerning percent shale in the Arbuckle.

6arbuckle: Continuity. “The tendency for liquids to freely migrate within this aquifer (no lateral seals) make[s] it unsuitable for the disposal of extremely toxic wastes” (Puckette, 1996, p. 158). The recharge area for the Arbuckle Group includes the Arbuckle Mountains of southern Oklahoma (Henry, 1991) and the Ozark Plateau of Arkansas and Missouri. Karst permeability can be very complex and would require detailed site-specific study. We digitized a map of faults and zero contours on the Arbuckle Group.

7arbuckle: Top-seal thickness. We combined the isopach maps of Hester and Schmoker (1993) and Amsden (1975) to derive a thickness map for the Woodford Shale—the unit that we identify as the best potential seal for the Arbuckle—and gridded it

- (s7arbuckle). Johnson (1991b) mentioned that by the early 1990's all ten of the hazardous waste-disposal wells then operating in Oklahoma were using the Arbuckle or Arbuckle-Simpson as the recipient reservoir. Significantly, either the Woodford Shale (in the Tulsa area) or truncating Pennsylvanian-age shales (in the Oklahoma City area) acted as the confining units. This fact suggests that, at least in the cases where hazardous waste is involved, the intervening Silurian- and Devonian-age rocks may not be sufficiently low in permeability to act as seals for either the Arbuckle or the Simpson.
- 8arbuckle: Continuity of top seal. We digitized the faults from Amsden's (1975) isopach map of the Woodford Shale as a means to define the continuity of the unit.
- 9arbuckle: Hydrocarbon production. Proprietary detailed production data are available from the Geomap Company. We used a public-domain map (Burchfield, 1985) showing the oil and gas fields of Oklahoma.
- 10arbuckle: Fluid residence time. Jorgensen and others (1996) generated a vector lateral-flow velocity map. The vectors show slow velocity of flow in the Western Interior Plains aquifer system (Jorgensen, and others, 1996). Jorgensen and others (1996) included all of the rock units below the Woodford Shale and above basement in what they called the "Western Interior Plains aquifer system." This aquifer system includes the Arbuckle. Because of the vector nature of the data, we could not quantitatively incorporate the map into our analyses.
- 11arbuckle: Flow direction. Potentiometric surface map from Puckette (1996).
- 12aarbuckle: Formation temperature. Thermal gradient map of the United States from website: <http://icsbep.inel.gov/geothermal/fy97/explore/exp-16.html# Fig2> (Blackwell and others, 1997).
- 12barbuckle: Formation pressure. Pressure-depth gradient map from Puckette (1996).
- 12carbuckle: Formation-water salinity. Dissolved-solid concentrations map of the "lower units in the Western Interior Plains aquifer system" (including the Arbuckle) of Jorgensen and others (1996).
- 13arbuckle: Rock / water reaction. Dolomite and chert are minerals that would react with high-CO<sub>2</sub> brine.

- 14arbuckle: Porosity. Data are from the same source as 2arbuckle permeability.
- 15arbuckle. Water chemistry. The water is a calcium bicarbonate type, usually a calcium-magnesium bicarbonate (Ryder, 1996).
- 16arbuckle: Rock mineralogy. Dolomite, cherty dolomite, and calcite (bedded limestone), with minor amounts of quartz sand (both bedded and dispersed grains) (Derby and others, 1991; Ragland and Donovan, 1991). Rare bedded chert in the Cool Creek Formation (Ragland and Donovan, 1991). “Calcite, dolomite, silica, and minor feldspar cements” (Ragland and Donovan, 1991, p. 14). See also the generalized lithology map of Johnson (1991b).

## References

- Amsden, T. W., 1975, Panel 4—Isopach map of Woodford Shale, *in* Hunton Group (late Ordovician, Silurian, and early Devonian) in the Anadarko Basin of Oklahoma: Oklahoma Geological Survey Bulletin, v. 121, 214 p.
- Blackwell, D. D., Wisian, K. W., and Steele, J. L., 1997, Geothermal resource/reservoir investigations based on heat flow and thermal gradient data for the United States: U.S. Department of Energy Geothermal Energy, <http://icsbep.inel.gov/geothermal/fy97/explore/exp-16.html#Fig2>.
- Burchfield, M. R., 1985, Map of Oklahoma oil and gas fields: Oklahoma Geological Survey, Map GM-28.
- Derby, J. R., Hinch, H. H., and Repetski, J. R., 1991, Lithology, stratigraphy, and age of the Arbuckle Group in the Amoco Shads No. 4, a continuous core from grassroots into basement, Rogers County, Oklahoma, *in* Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey, Special Publication 91-3, p. 69–82.
- Henry, M. E., 1991, Subsurface structure map of the Arbuckle Group, south-central Oklahoma, *in* Johnson, K. S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 Symposium: Oklahoma Geological Survey, Circular 92, p. 218–219.
- Hester, T. C., and Schmoker, J. W., 1993, Regional geology of the Woodford Shale—Anadarko Basin, Oklahoma: an overview of relevance to horizontal drilling, *in* Johnson, K. S., and Campbell, J. A., eds., Petroleum—reservoir geology in the southern Midcontinent, 1991 Symposium: Oklahoma Geological Survey, Circular 95, p. 74–81.

- Johnson, K. S., 1991a, Geologic setting of the Arbuckle Group in Oklahoma, *in* Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey, Special Publication 91-3, p. 1–7.
- \_\_\_\_\_, 1991b, Geologic overview and economic importance of Late Cambrian and Ordovician age rocks in Oklahoma, *in* Johnson, K. S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 Symposium: Oklahoma Geological Survey, Circular 92, p. 3–14.
- Jorgensen, D. G., 1993, Paleohydrology of the Central United States: U.S. Geological Survey, Bulletin 1989-D, 32 p.
- Jorgensen, D. G., Helgesen, J. O., Signor, D. C., Leonard, R. B., Imes, J. L., and Christenson, S. C., 1996, Analysis of regional aquifers in the central midwest of the United States in Kansas, Nebraska and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Summary: U.S. Geological Survey, Professional Paper 1414-A, 67 p.
- Puckette, J. O., 1996, Evaluation of underpressured reservoirs as potential repositories for liquid waste: Oklahoma State University, Ph.D. dissertation, 274 p.
- Ragland, D. A., and Donovan, R. N., 1991, Sedimentology and diagenesis of the Arbuckle Group in outcrops of southern Oklahoma, *in* Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey, Special Publication 91-3, p. 9–30.
- Read, D. L., and Richmond, G. L., 1993, Geology and reservoir characteristics of the Arbuckle Brown zone in the Cottonwood Creek field, Carter County, Oklahoma, *in* Johnson, K. S., and Campbell, J. A., eds., Petroleum reservoir geology in the southern Midcontinent: Oklahoma Geological Survey, Circular 95, p. 113–125.
- Ryder, P. D., 1996, Ground water atlas of the United States—segment 4, Oklahoma, Texas, *in* U.S. Geological Survey, Hydrologic Investigations Atlas 730-E, p. E27.
- Wilson, J. L., 1994, The Lower Ordovician great American bank of the southwestern United States, *in* Keller, D. R., and Reed, C. L., eds., Paleokarst, karst-related diagenesis, reservoir development, and exploration concepts; examples from the Paleozoic section of the southern Mid-Continent: SEPM (Society for Sedimentary Geology), SEPM Guidebook 93-34, p. 35–43.

Prepared by Ramón Treviño.



## BASIN-FILL SANDSTONE AND CARBONATE AQUIFERS IN THE BASIN AND RANGE, ARIZONA-NEVADA-CALIFORNIA

### General Setting

The Mojave Basin in northwestern Arizona, southeastern California, and southern Nevada contains unconsolidated Tertiary sandstones in block-faulted basins and deeper Paleozoic carbonates. Neither of these two formations, individually, is ideal for CO<sub>2</sub> sequestration. The basin-and-range Tertiary sandstones are very shallow in many parts of the basin and contain fresh water, whereas the carbonates are locally fractured, making predictions of projected fluid paths difficult. However, areas where Tertiary sandstones are deep and where the carbonates are minimally fractured may be potential sites for CO<sub>2</sub> storage. Because the Paleozoic carbonates are so extensive in the southern basin-and-range structural province, the Mojave study area was extended to central and eastern Nevada, as well as western Utah in the vicinity of the Sevier Basin.

### Information Search and Selection

The major sources of data for basin-and-range and deep carbonate aquifers in the region of the Mojave Basin are Brown (1976), Pool (1985), Thomas and others (1986), Harrill and others (1988), Anderson and others (1992), Prudic and others (1995), Dettinger and others (1995), Thomas and others (1996), Planert (1996), and Robson (1996). Major parameters for these formations are briefly described, with notes pertaining to the suitability of these stratigraphic units to be included as data sources.

## Comments on Geologic Parameters

- 1mojave: Depth. Depth of basin-fill and carbonate aquifers in the Mojave Basin and adjacent areas was discussed by Planert (1996) and Robson (1996). Depth to basement in the Arizona part of the Mojave Basin was shown by Pool (1985).
- 2mojave: Permeability/hydraulic conductivity. Simulated transmissivity values, from which permeability is inferred, were presented for carbonate aquifers in Nevada by Prudic and others (1985). The distribution of low-permeability consolidated rock, including tuff layers and intrusive bodies was shown by Harrill and others (1988).
- 3mojave: Formation thickness. Brown (1976) presented formation-thickness data for the Tertiary basin-and-range aquifers. Formation-thickness maps of the deep carbonate aquifers are unavailable; however, total formation thickness of the carbonates in the Mojave Basin is typically several thousand feet and exceeds 10,000 ft (3,048.8 m) in eastern Nevada (Prudic and others, 1995). Actual thickness and distribution of carbonate-rock types at depth are poorly understood because the region is structurally complex because of thrust faults that affect the carbonate section and normal faults that offset Paleozoic and younger strata. Moreover, granite bodies are more extensive at depth than they are in outcrops in the region (Prudic and others, 1995).
- 4mojave: Net sand thickness. Net-sand-thickness maps of the Tertiary basin-and-range aquifers are not documented for the entire Mojave Basin and adjacent areas. However, local accumulations of more than several hundred feet of net sand are common in areas where the net upper-basin-fill thickness is more than 1 mi (>1.6 km) (Brown, 1976).
- 5mojave: Percent shale. Percent shale of the Tertiary basin fill in the Arizona part of the Mojave Basin is inferred from maps in Anderson and others (1992).
- 6mojave: Continuity. Sand-body continuity of the Tertiary basin-fill aquifers is inferred from data in Robson (1996). Sand-body continuity in these aquifers is typically very high within each fault-bounded basin, but poor between basins because of the complex structure.

7mojave: Top-seal thickness. Top-seal-thickness maps are lacking for the two principal hydrologic units in the Mojave Basin. Top seals for the deeply buried carbonate aquifers are a combination of upper Paleozoic marine shales, siliceous siltstone, and evaporites. The hydraulic conductivity of these noncarbonate rocks is commonly only 0.01 ft/d (Dettinger and others, 1995; Thomas and others, 1996). Although these noncarbonate seal facies are up to 200 ft (61 m) thick in north-central Nevada, they exhibit pinch-outs. Interbedded tuffaceous sediments and central-basin fine-grained sediments (lacustrine-fill and playa) are the main seals for the Tertiary basin-and-range aquifers (Freethey and others, 1986; Harrill and others, 1988; Prudic and others, 1995).

8mojave: Continuity of top seal. Maps of top-seal continuity of aquifers in the Mojave Basin and adjacent areas were not found during our search. However, schematic cross sections of Paleozoic carbonates in Nevada in Prudic and others (1995) show that shaly limestone top seals are several miles in extent. However, the continuity of these top seals is commonly disrupted by subsurface fracture systems, faults, and intrusive igneous bodies (Planert, 1996). Cross sections in the basin-and-range province in Arizona show locally extensive continuity of fine-grained central-basin siltstones and mudstones above alluvial-fan wedges (Freethey and others, 1986).

9mojave: Hydrocarbon production. There is no hydrocarbon production from the shallow Tertiary basin-fill sandstones in the region. Several exploratory wells have been drilled in the deep Paleozoic section in southwestern and west-central Utah to test its potential for hydrocarbon production (Mitchell and McDonald, 1986).

10mojave: Fluid residence time. Thomas and others (1996) presented several types of maps that display fluid residence time for the carbonate aquifers in Nevada. These maps are derived from carbon-13 and carbon-14 compositions of ground water. Flow rates are shown for Tertiary basin-and-range aquifers in Nevada in Harrill and others (1988).

11mojave: Flow direction. Flow directions are inferred from potentiometric contour maps of the carbonate aquifers in Nevada in Prudic and others (1995) and Thomas and



- others (1986). Arrows indicating preferred ground-water flow directions in Tertiary basin-fill sandstones in northwestern Arizona and southwestern Utah are shown in Robson (1996).
- 12amojave: Formation temperature. No maps are available that show temperature for the deeply buried carbonate aquifers because of sparse well penetrations. Similar maps are also lacking of Tertiary basin-fill aquifers.
- 12bmojave: Formation pressure. No maps are available that show formation pressure for the deeply buried carbonate aquifers because of sparse well penetrations. Formation-pressure data are also lacking of Tertiary basin-fill aquifers.
- 12mojave: Formation-water salinity. Formation-water salinity data for Tertiary basin-fill aquifers are provided in Robson (1996) and the U.S. Geological Survey (1996). Concentrations of greater than 3,000 ppm of total dissolved solids are limited to elongate, fault-bounded areas.
- 13mojave: Rock/water reaction. Data on rock/water reaction in the deep carbonate aquifers were provided by Thomas and others (1996). Immature mineralogy of Tertiary sandstones may have moderate reaction with high CO<sub>2</sub> brines.
- 14mojave: Porosity. Porosity values for the shallow Tertiary basin-and-range sands are not mapped regionally but are presumed to be very high owing to their unconsolidated nature. In contrast, porosity values for the deep carbonates are typically low because they are heavily dolomitized. However, hydraulic conductivity in these carbonates is as much as 940 ft/d (Thomas and others, 1996), where it is greatly enhanced by fracturing.
- 15mojave: Water chemistry. Brine chemistry data of the carbonate aquifers were summarized in tables by Thomas and others (1996), who focused on both geochemistry and isotope hydrology.
- 16mojave: Rock mineralogy. Detailed mineral constituents of the carbonate aquifers in Nevada were provided in tables by Thomas and others (1996). These minerals include calcite, dolomite, gypsum, halite, albite, kaolinite, and K-feldspar. Minor amounts of chalcedony, analcime, and clinoptilolite are reported. Mineralogy of

the shallow basin-fill sediments is primarily a reflection of granitic and metamorphic sources (Pool, 1985).

## References

- Anderson, T. W., Freethey, G. W., and Tucci, Patrick, 1992, Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent states: U.S. Geological Survey Professional Paper 1406-B, 67 p.
- Brown, S. G., 1976, Preliminary maps showing ground-water resources in the lower Colorado River region, Arizona, New Mexico, and Utah: U.S. Geological Survey Hydrologic Investigations Atlas HA-542, 3 sheets.
- Dettinger, M. D., Harrill, J. R., Schmidt, D. L., and Hess, J. W., 1995, Distribution of the carbonate rock aquifers and the potential for their development, southern Nevada and adjacent parts of California, Arizona, and Utah: U.S. Geological Survey Water-Resources Investigations WRI 91-4146, 100 p., 2 sheets.
- Freethey, G. W., Pool, D. R., Anderson, T. W., and Tucci, Patrick, 1986, Description and generalized distribution of aquifer materials in the alluvial basins of Arizona and adjacent parts of California and New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA-663, scale 1:500,000, 4 sheets.
- Harrill, J. R., Gates, J. S., and Thomas, J. M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-C, scale 1:1,000,000, 1 sheet.
- Mitchell, G. C., and McDonald, R. E., 1986, History of Cenozoic extension in Central Sevier Desert, west-central Utah, from COCORP seismic reflection data: discussion: American Association of Petroleum Geologists Bulletin, v. 70, no. 8, p. 1015–1021.
- Planert, M., 1996, Ground water atlas of the United States, Segment 1: California and Nevada: U.S. Geological Survey Atlas.
- Pool, D. R., 1985, Aquifer geology of alluvial basins of Arizona, *in* Anderson, T. W., and Johnson, A. I., eds., Regional aquifer systems of the United States, southwest alluvial basins of Arizona: American Water Resources Association Monograph 7, p. 25–36.
- Prudic, D. E., Harrill, J. R., Burbey, and Thomas J., 1995, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper P-1409-D, 102 p.
- Robson, S. G., 1996, Ground water atlas of the United States, Segment 2: Colorado, Nevada, and New Mexico: U.S. Geological Survey Atlas.

Thomas, J. M., Mason, J. L., and Crabtree, J. D., 1986, Ground-water levels in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-B, 2 sheets.

Thomas, J. M., Welch, A. H., and Dettinger, M. D., 1996, Geochemistry and isotope hydrology of representative aquifers in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-C, p. C1-C100.

U.S. Geological Survey, 1996, Ground water atlas of the United States, Segment 1.

Prepared by William Ambrose.

## CAPE FEAR FORMATION, SOUTH CAROLINA COASTAL PLAIN

### General Setting

The South Carolina coastal plain consists of a seaward-dipping and seaward-thickening wedge of Cretaceous through Pleistocene sediments. Most stratigraphic units outcrop in belts generally parallel to the coast, where they receive precipitation, which then infiltrates and flows downdip to become ground water. South Carolina receives abundant rainfall, and a number of the shallow aquifers provide ample domestic and industrial water.

### Information Search and Selection

The deeper portions of the eastern coastal plain are the focus of this investigation because this area contains strata that are sufficiently deep, porous and permeable, and hydraulically isolated from fresh-water aquifers to make potential CO<sub>2</sub> sequestration targets. This area was identified to explore for a potential target for capture and storage of CO<sub>2</sub> from industrial activities in this region. However, depth to basement in eastern South Carolina is shallow, largely because of the Cape Fear Arch to the north (Manheim and Horn, 1968; Colquhoun and others, 1983; Aucott and others, 1987; Miller, 1990), which limits the area within South Carolina where aquifers are sufficiently deep to be candidates for CO<sub>2</sub> sequestration.

The subsurface of this area has been moderately characterized, but deep aquifers are poorly known because shallow aquifers generally provide sufficient water. There is very little potential for hydrocarbon production along coastal South Carolina, and because the state currently has laws prohibiting subsurface liquid waste disposal, there has been little subsurface research related to petroleum exploration and subsurface disposal of industrial liquid wastes.

Because the basement is so shallow in eastern South Carolina, the only potential candidate for CO<sub>2</sub> sequestration is the Upper Cretaceous Cape Fear Formation, which

directly overlies the igneous/metamorphic basement in the region (Manheim and Horn, 1968; Colquhoun and others, 1983; Aucott and others, 1987; Miller, 1990). Farther south, in eastern Georgia, the depth to basement is greater, and, therefore, many of the data presented later extend into this region. Note that the aquifer unit described later is referred to by several names in the literature: some call it Cape Fear Formation (Manheim and Horn, 1968; Aucott and others, 1987), others call it Middendorf Formation (Colquhoun and others, 1983), and other regional studies assign it a symbol, such as A4 or Unit E (Brown and others, 1979; Miller and others, 1986). Miller (1990), in his regional study, referred to this interval as the Black Warrior River aquifer.

### Comments on Geologic Parameters

Each of the 16 parameters for the Cape Fear Formation is now briefly described, and the reasons for selection of the map or data source for the GIS are outlined. The reference list at the end of this summary includes documents that are relevant to the South Carolina coastal plain and Cape Fear hydrostratigraphic interval.

1capefear: Depth. A number of maps show the elevation at the top of the Cape Fear Formation (Brown and others, 1979; Colquhoun and others, 1983; Aucott and others, 1987; Renkin and others, 1989; Miller, 1990). We chose to use the maps of Renkin and others (1989) because they provided a detailed, regional map of the top of the Cape Fear aquifer, and they clearly documented the stratigraphic position of the top of the unit. We then used a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid (c1capefear) the depth to top of the Cape Fear brine formation.

2capefear: Permeability/hydraulic conductivity. There are few studies that provide estimates of hydraulic conductivity or permeability for the Cape Fear interval. Temples and Waddell (1996) reported permeabilities ranging from 1,000 to 6,000 millidarcys. Aucott (1988), in his modeling studies of regional aquifers, presented a map showing spatial distribution of transmissivities in the Cape Fear interval. We used his transmissivity values. Recalling  $\text{Hydraulic Conductivity} = \text{Transmissivity} / \text{Aquifer Thickness}$ , we used the Cape Fear aquifer thickness GIS

data layer to convert Aucott's (1988) transmissivity values to hydraulic conductivity.

3capefear: Formation thickness. There is no published map showing the thickness distribution of the Cape Fear Formation (T. Temples, DOE, Savannah River, personal communication, 2000; B. Hockensmith, South Carolina Department of Natural Resources, personal communication, 2000). Therefore we used the GIS to calculate the difference in elevation at top of the Cape Fear Formation and the top of basement (Colquhoun and others, 1983; Aucott and others, 1987) to calculate a Cape Fear Formation thickness map.

4capefear: Net sand thickness. A number of studies present cross sections of the Cape Fear interval that include geophysical logs (gamma ray, spontaneous potential) (Colquhoun and others, 1983; Aucott and others, 1987; Temples and Waddell, 1996). These logs are a source of semiquantitative estimates of sand thickness in the Cape Fear interval. Brown and others (1979) provided actual sand thickness for the Cape Fear interval (their Unit E), but these estimates are from wells in Georgia. Gohn and others (1977) presented results of textural and mineralogical analyses of the Cape Fear Formation conducted on samples from a well near Charleston. Their analyses indicate that the Cape Fear interval is primarily silt, but there are some sand intervals. Sand-thickness estimates are considerably lower than estimates derived from the geophysical logs (which are typically 50 ft). We attribute the difference to the geophysical-log response to silt intervals being similar to that of sand. Temples and Waddell (1996) reported that for the Middendorf and Cape Fear aquifers in southeasternmost South Carolina, between 2,770 and 3,763, there is 381 ft of aquifer sand. Brown and others (1979) determined that the sands in the Cape Fear interval (their unit E) in Georgia generally range from 40 to 58, with an average of 49. We attribute the thicker sands in southeasternmost South Carolina and in Georgia to a deeper basement and thicker Cape Fear interval. For the GIS we combined sand-thickness information of Gohn and others (1977), Brown and others (1979), and Temples and Waddell (1996).

5capefear: Percent shale. A number of studies present cross sections of the Cape Fear interval that include geophysical logs (gamma ray, spontaneous potential) (Colquhoun and others, 1983; Aucott and others, 1987; Temples and Waddell, 1996). These logs are a source of semiquantitative estimates of percent shale in the Cape Fear interval. Brown and others (1979) provided actual percentages for the Cape Fear interval (their Unit E), but these estimates are from wells in Georgia. Gohn and others (1977) presented results of textural and mineralogical analysis of the Cape Fear Formation conducted on samples from a well near Charleston. Their analyses indicate that the Cape Fear interval is primarily silt and that shale composes between 20 and 40 percent of the unit. For the GIS, we combined the analysis of Gohn and others (1977; their fig. 3) and Brown and others (1979). These shale percentages generally agree with the estimates derived from the geophysical logs.

6capefear: Continuity. A number of studies present cross sections of the Cape Fear interval that include geophysical logs (gamma ray, spontaneous potential) (Colquhoun and others, 1983; Aucott and others, 1987; Temples and Waddell, 1996). These cross sections indicate that sands are generally discontinuous (R. Willoughby, South Carolina Geological Survey, personal communication, 2000). Brown and others, (1979; their table 7) determined that the thickest potential reservoir sand in the Cape Fear interval ranges from 40 to 58, with an average of 49. These thicker sands tend to be more continuous. For the GIS, we chose to use the thickness of reservoir sand as determined by Brown and others (1979).

7capefear: Top-seal thickness. Several studies characterize the confining unit above the Cape Fear Formation as a tight marine shale (Aucott and others, 1987; Aucott, 1988; Miller, 1990), and the shale interval is apparent in published cross-sections (Colquhoun and others, 1983; Aucott and others, 1987). However, there is no published map showing thickness of the Cape Fear confining unit. On the basis of evaluation of logs in published cross sections, we determined that the thickness of the confining unit is consistent across southeastern South Carolina and averages about 50 ft.

- 8capefear: Continuity of top seal. Several studies characterize the confining unit above the Cape Fear Formation as a tight marine shale (Aucott and others, 1987; Aucott, 1988; Miller, 1990), and the shale interval is easy to recognize in published cross sections (Colquhoun and others, 1983; Aucott and others, 1987). Aucott (1988) provided a map showing the distribution leakage coefficient of the Cape Fear confining unit. He defined the leakage coefficient as the vertical hydraulic conductivity ( $\sim 2 \times 10^{-7}$  ft/day) divided by the confining unit thickness ( $\sim 50$  ft). The map in the GIS is from Aucott (1988; his fig. 31).
- 9capefear: Hydrocarbon production. Several hydrocarbon exploration wells have been drilled in the Atlantic coastal plain without success (Maher and Applin, 1971).
- 10capefear: Fluid residence time. Several authors have characterized ground-water flow in the Cape Fear interval (Aucott and Speiran, 1985; Miller and others, 1986; Aucott, 1988; Miller, 1990). A number of authors determined that the deep aquifers directly below the coast is a marine/terrestrial ground-water interface zone in which waters tend to be stagnant. Miller and others (1986; their fig. 5) showed that the Na<sup>+</sup> concentrations increase with distance along the aquifer flow path, and several authors showed that the Cape Fear aquifer in southeastern South Carolina contains relatively high concentrations of Na<sup>+</sup> (Miller and others, 1986; Miller, 1990). On the basis of these data, we conclude that residence times in the Cape Fear aquifer of southeastern South Carolina are long, and may be as much as 5,000 yr.
- 11capefear: Flow direction. Several authors have characterized ground-water flow in the Cape Fear interval (Aucott and Speiran, 1985; Miller and others, 1986; Aucott and others, 1987; Aucott, 1988; Miller, 1990). A number of authors determined that the deep aquifers directly below the coast are a marine/terrestrial ground-water interface zone in which waters tend to be stagnant. These studies demonstrate that ground-water flow is parallel to the coast. We chose to use the map of Miller (1990) for the GIS because it is regional in perspective but generally shows the same information for South Carolina that several authors have presented.



12acapefear: Formation temperature. Little information is available for geothermal gradients associated with deep aquifers, primarily because there are few wells that have been drilled to the deep aquifers. Temples and Waddell (1996) reported temperature data for a deep well on Hilton Head Island. However, we chose to use the geothermal gradient data from Kinney (1976) in which they showed a geothermal gradient of about 1.38° F/100 ft (25.5° C/km) for southeastern South Carolina.

12bcapefear: Formation pressure. There currently are no published data regarding geopressure gradients or maps showing formation pressures. We used pressure data from Temples and Waddell (1996; their table 3) to generate a graph showing the relationship between pressure and depth. The data show a clear gradient of 0.45 psi/ ft. This gradient was used in conjunction with the depth to top of Cape Fear Formation to derive the formation-pressure distribution map presented in the GIS.

12ccapefear: Formation-water salinity. Several researchers have reported that salinity in the Cape Fear aquifer is moderately high but below 10,000 mg/L (Manheim and Horn, 1968; Brown and others, 1979; Lee, 1985; Miller and others, 1986; Miller, 1990). However, there has not been a systematic study of water chemistry in southeastern South Carolina because of low prospect for use. We used the map of Lee (1985) for the GIS, who referred to the Cape Fear hydrostratigraphic interval as the middle water-bearing zone of the A4 regional aquifer. We chose this map to grid (c12capefear) because it shows the regional distribution of dissolved solids.

13capefear: Rock/water reaction. The Cape Fear Formation contains substantial volumes of clays and labile minerals that can potentially react with ground water (Gohn and others, 1977). Miller and others (1986) provided an excellent discussion of sediment/water interaction as a function of ground-water residence time in southeastern U.S. coastal plain aquifers. For the GIS we used information from Miller and others (1986) to characterize rock/water reactions that can be expected

- in the Cape Fear hydrostratigraphic interval. Immature sands may have moderate potential for interaction with high-CO<sub>2</sub> fluids.
- 14capefear: Porosity. Temples and Waddell (1996; their table 2) are the only researchers that have published porosity data on the Cape Fear aquifer. Their data are presented in the GIS.
- 15capefear: Water chemistry. Temples and Waddell (1996) provided the results of chemical analysis of water samples from the Cape Fear interval from a well on Hilton Head Island. Their results are presented in the GIS. Their results indicate that salinities are very low for the interval.
- 16capefear: Rock mineralogy. Gohn and others (1977) described sediment samples of the Cape Fear Formation derived from a well near Charleston. Their analysis of the sands (their figure 4) indicates that the sands are immature and contain between 2- and 35-percent feldspar.

## References

- Aucott, W. R., 1988, The predevelopment ground-water flow system and hydrologic characteristics of the Coastal Plain aquifers of south Carolina: U.S. Geological Survey, Water-Resources Investigations Report 86-4347, 66 p.
- Aucott, W. R., Davis, M. E., and Speiran, G. K., 1987, Geohydrologic framework of the Coastal Plain aquifers of South Carolina: U.S. Geological Survey, Water-Resources Investigations Report 85-4271, 7 sheets.
- Aucott, W. R., and Speiran, G. K., 1985, Ground-water flow in the coastal plain aquifers of South Carolina: *Ground Water*, v. 23, p. 736-745.
- Brown, P. M., Brown, D. L., Reid, M. S., and Lloyd, O. B., Jr., 1979, Evaluation of the geologic and hydrologic factors related to the water-storage potential of Mesozoic aquifers in the southern part of the Atlantic coastal plain, South Carolina and Georgia: U.S. Geological Survey, Professional Paper 1088, 37 p., 11 plates.
- Colquhoun, D. J., Woollen, L. D., Van Nienwenhuise, D. S., Padgett, G. G., Oldham, R. W., Boylan, D. C., Bishop, J. W., and Howell, P. D., 1983, Surface and subsurface stratigraphy, structure and aquifers of the South Carolina Coastal Plain: Columbia, SC, State of South Carolina, Office of the Governor, 78 p.
- Gohn, G. S., Higgins, B. B., Smith, C. C., and Owens, J. P., 1977, Lithostratigraphy of the deep corehole (Clubhouse Crossroads Corehole 1) near Charleston, South Carolina: U.S. Geological Survey, Professional Paper 1028E, p. 59-70.

- Kinney, D. M., ed., 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U.S. Geological Survey Publication G74014, 2 maps.
- Lee, R. W., 1985, Water-quality maps for selected Upper Cretaceous water-bearing zones in the southeastern coastal plain: U.S. Geological Survey Water Resources Investigations 85-4193.
- Maher, J. C., and Applin, E. R., 1971, Geologic framework and petroleum potential of the Atlantic coastal plain and continental shelf: U.S. Geological Survey Professional Paper 659, 98 p., 17 plates.
- Manheim, F. T., and Horn, M. K., 1968, Composition of deeper subsurface waters along the Atlantic continental margin: *Southeastern Geology*, v. 9, p. 215–236.
- Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey Hydrologic Investigations Atlas No. HA-730-G, 28 p.
- Miller, J. A., Barker, R. A., and Renkin, R. A., 1986, Hydrology of the Southeastern Coastal Plain Aquifer System, *in* Vecchioli, J., and Johnson, A. I., eds., Regional aquifer systems of the United States: aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph Series No. 9, p. 53–77.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Renkin, R. A., Mahon, G. L., and Davis, M. E., 1989, Hydrogeology of clastic Tertiary and Cretaceous regional aquifers and confining units in the southeastern coastal plain aquifer system of the United States: U.S. Geological Survey Hydrologic Investigations Atlas HA-701, 3 sheets.
- Richards, H. G., 1974, Structural and stratigraphic framework of the Atlantic coastal plain, in Post-Miocene stratigraphy, central and southern Atlantic coastal plain, *in* Oaks, R. Q., Jr., and DuBar, J. R., eds., Post-Miocene stratigraphy, central and southern Atlantic coastal plain: Logan UT, Utah State University Press, p. 11–19.
- Speiran, G. K., 1986, Relation of aqueous geochemistry to sediment depositional environment, Middendorf Aquifer, South Carolina, *in* Vecchioli, J., and Johnson, A. I., eds., Regional aquifer systems of the United States aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph Series No. 9, p. 79–96.
- Temples, T. J., and Waddell, M. G., 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: *Ground Water*, v. 34, p. 523–531.

Prepared by Andrew Warne.

## CEDAR KEYS/LAWSON, CENTRAL FLORIDA REGION

### General Setting

Central Florida is underlain by a thick (>2,500 m) sequence of Cretaceous and Tertiary carbonates (Randazzo, 1997). This carbonate sequence consists of a variety of lithologies, including limestone, dolostone, mudstones, and evaporites. Subsequent to deposition of the Tertiary carbonates, extensive dissolution cavities developed, which now form the Floridan aquifer (Miller, 1986, 1997). Particularly prominent, cavernous intervals and/or Boulder Zones have been reported in the Lower Cretaceous Pine Key and/or Lawson and the Tertiary Cedar Keys and Avon Park Formations (Miller, 1997; J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000). Note that in the correlation chart of Randazzo and Jones (1997, inside back cover), the Lawson Formation correlates with the upper Pine Key Formation. In this report, we will refer to the porous hydrostratigraphic interval as the Cedar Key/Lawson Dolomite.

Injection wells are used in several places in Florida to dispose of municipal and industrial wastes (Miller, 1997). The wastes are mostly injected into highly permeable zones in the lower Floridan aquifer, known as the Boulder Zone. About 208 Mgal/d was injected in 1988; Boulder Zone depths in south central Florida are typically 1,500 to 2,000 ft. Some wells, such as those in Polk County, inject wastes into the permeable, Upper Cretaceous Cedar Keys and Lawson Dolomites, which are below the Floridan aquifer. The Cedar Keys and Lawson Dolomites are generally 4,000 to 5,000 ft deep in central Florida.

### Information Search and Selection

Central Florida is the focus of this regional assessment because the lower Cedar Keys and Lawson Dolomites appear to contain a laterally extensive porous zone that is overlain by an anhydrite-dolomite sequence in the middle Cedar Keys Formation that is about 700 ft thick, forming an effective top seal (J. Haberfeld, Florida Department

of Environmental Protection, personal communication, 2000). Currently the lateral extent of this potential CO<sub>2</sub> reservoir is not known. Winston (1977) indicated that southwestern Florida was a vast back-barrier reef area during deposition of the Lawson and Cedar Keys Dolomites, which implies that the lithologies within these mixed carbonate and evaporite units are laterally extensive.

The Boulder Zones of the lower Floridan Aquifer are not presented in the GIS because they are generally too shallow, and the confining horizon within the middle and upper Oldsmar and lower Avon Park Formations generally has too high a leakage rate to be expected to retain gases (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000), particularly along fracture zones.

The Floridan aquifer, which generally comprises the Paleocene upper Cedar Keys, the Eocene Oldsmar, Avon Park and Ocala, and the Oligocene Suwannee Formations, has been extensively studied (Miller, 1986, 1997). However, little has been published on the Cretaceous Cedar Keys and Lawson Dolomites below the Floridan aquifer (Winston, 1994, 1996). There is oil and gas production from the Lower Cretaceous Sunniland Limestone in southeastern Florida, but no information has been published on the overlying Lawson and Cedar Keys Dolomites. However, geophysical logs from this area, or any area in Florida where the Lower Cretaceous has been drilled can provide information regarding the physical properties of the Lawson and Cedar Keys Dolomites. In general, however, there is currently very little information available. Nonetheless, Florida is a rapidly developing area, and the Lawson and Cedar Keys Dolomites are potential reservoirs for CO<sub>2</sub> sequestration, and, therefore, the information that is currently available for these Cretaceous strata are presented in the GIS.

#### Comments on Geologic Parameters

Each of the 16 parameters for the lower Cedar Keys and Lawson Dolomites are now briefly described, and the reasons for selection of the map or data source for the GIS are outlined. The reference list at the end of this summary includes documents that are relevant to the lower Floridan Aquifer and the Cretaceous Cedar Keys and Lawson Dolomites in Florida.

1cedarkeys: Depth. In the Polk County Florida area, the lower Cedar Keys and Lawson Dolomites occur between 4005- and 4495-ft depth (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000). Chen (1965) presented a map showing the elevation of the top of the Upper Cretaceous, which is the top of the Lawson Dolomite, and we used this map for the GIS. We then used a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid (c1cedarkeys) the depth to top of the lower Cedar Keys/Lawson Formation

2cedarkeys: Permeability/hydraulic conductivity. Permeability has been determined for the Lawson Dolomite in a liquid waste-disposal well located in Mulberry, Polk County, Florida (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000). The permeabilities were determined by Core Lab, Incorporated, from sidewall cores. Permeabilities from eight samples range from 5 to 28 millidarcys. Because we lack any other permeability, we assign this range for all of southern Florida. More permeability data are available from geophysical logs taken for petroleum exploration and production from Lower Cretaceous horizons. It is surprising that reported permeabilities are so low, considering that porosities are 24 to 28 percent.

3cedarkeys: Formation thickness. Currently no maps show the thickness distribution of the Cedar Keys and/or Lawson Dolomites (although Winston [1994] presented thickness maps of various units within the Cedar Keys Formation). A lithologic log from a waste-disposal well in Mulberry, Polk County, Florida, records a thickness of 1,260 ft for the lower Cedar Keys and Lawson Dolomites. Randazzo (1997; his fig. 4.2c) presented a map showing the thickness distribution of the Upper Cretaceous interval across the Florida Peninsula. His map shows that (1) the entire Upper Cretaceous interval in Polk County is about 2,400 ft and (2) the thickness of the Upper Cretaceous does not vary that much across Florida. The lower Cedar Keys and Lawson Dolomite compose about half of the Upper Cretaceous section. We use the Upper Cretaceous isopach map of Randazzo

(1997) and proportionally scale it to reflect the thickness distribution of the lower Cedar Keys and Lawson Dolomites.

4cedarkeys: Net sand thickness. These are dolomites and contain virtually no sand. As is typical in carbonates, the thickness of permeable strata requires more detailed study.

5cedarkeys: Percent shale. Although we have no direct evidence, we do know that the lower Cedar Keys and Lawson Dolomites are platform carbonates, and therefore we conclude that the clay content is low (<5 percent). It would be possible to calculate clay percent from geophysical logs that penetrate this interval.

6cedarkeys: Continuity. The lower Tertiary and Upper Cretaceous carbonate units are continuous across central Florida (Randazzo, 1997). Moreover, it has been clearly and thoroughly demonstrated that the highly permeable intervals, including the Boulder Zones, in the Floridan aquifer are regionally continuous (Miller, 1986, 1997; Winston, 1996). However, there is no published information regarding the continuity of permeable zones in the lower Cedar Keys and upper Lawson Dolomites. Winston (1977) stated that porosity in the Lawson Dolomite in central Florida is occasionally present and can be quite high. Applin and Applin (1944, 1967), Vernon (1951), and Winston (1994) indicated that this interval is permeable. The cross sections of Chen (1965, his figs. 20, 21) are perhaps the best published information regarding the lithologic variability in these units. On the basis of the variation in lithologic descriptions from this interval, we infer that permeability varies in these units as a function of both sedimentologic and diagenetic processes, which is characteristic of carbonate units. It is possible to map the continuity of porous/permeable zones using geophysical logs but is beyond the scope of the present project.

7cedarkeys: Top-seal thickness. The top seal for the lower Cedar Keys and Lawson Dolomites is the middle Cedar Keys Formation. This unit is composed of massively bedded anhydrite, and it is the lower confining unit for the Floridan aquifer in southern Florida (Miller, 1986). A lithologic well log from Mulberry, Polk County, Florida, reports that this anhydrite-rich unit is 670 ft thick. Cross

sections by Miller (1986), which span southern Florida, indicate that this confining unit is as much as 1,000 ft thick. We use GIS technology to combine the Cedar Keys Formation thickness and percent-anhydrite maps of Chen (1965) to derive an anhydrite-thickness map for the Cedar Keys. Winston (1994) also presented evaporite isolith maps of the middle Cedar Keys interval. We think that these anhydrites, which are more than 800 ft thick in places, would make a very effective top seal for sequestration of CO<sub>2</sub>.

8cedarkeys: Continuity of top seal. As mentioned earlier, the middle Cedar Keys Formation, which makes up the top seal for the lower Cedar Keys and Lawson Dolomites, is a laterally continuous unit composed of massively bedded anhydrite (Miller, 1986; J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000). Miller (1986) provided numerous cross sections across southern Florida, demonstrating that this unit is laterally continuous. Although basement faults have been reported by numerous authors (Randazzo, 1997) across southern Florida, they should not regionally affect the hydraulic integrity of this anhydrite unit. To characterize the continuity of the top seal, we chose the map of Chen (1965), which shows the percent evaporites in the Paleocene Cedar Keys Dolomite. Winston (1994) also discussed evaporite distribution in the middle Cedar Keys interval (c8cedarkey). This map shows that the evaporites compose at least 20 percent of the Cedar Keys Dolomite throughout south central Florida.

9cedarkeys: Hydrocarbon production. Hydrocarbon production in southern Florida is from the Lower Cretaceous. None has been reported from the Cedar Keys and Lawson Dolomites. We used the oil-field location map of Meyer (1989) to show the locations of Lower Cretaceous production areas. Note that these Lower Cretaceous horizons produce large volumes of brines and that a portion of the brines are injected into boulder zones above the lower Cedar Keys and upper Lawson Dolomites.

10cedarkeys: Fluid residence time. There are essentially no data on ground-water flow rates and directions in the lower Cedar Keys and upper Lawson Dolomites.



However, Meyers (1989, his fig. 13) showed that ground water in the lower Floridan aquifer are 10,000 yr old. In all probability the ground waters in the underlying lower Cedar Keys and upper Lawson Dolomites are significantly older. Therefore, we assign a date of more than 20,000 yr for fluid residence time in the lower Cedar Keys and upper Lawson Dolomites of southern Florida.

11cedarkeys: Flow direction. There is essentially no information regarding flow direction for the hydrostratigraphic units below the Floridan aquifer. For the GIS, we used the map of Meyer (1989), which characterizes flow in the Floridan. Flow in the lower Cedar Keys and upper Lawson Dolomite is unknown.

12acedarkeys: Formation temperature. Smith and Lord (1997; their fig. 2.10) presented a map showing geothermal gradients across Florida. Their map, in combination with the depth to formation, was used to derive the formation-brine temperature distribution in the GIS. Note that the geothermal gradients of Smith and Lord closely match those of Blackwell and others (2000). Vernon (1970) reported some significant decreases in temperature with depth in some wells and attributed these reversals to fresh-water flow thorough cavernous zones.

12bcdarkeys: Formation pressure. Meyer (1989) provided a discussion of pressure versus depth of wells in southern Florida and determined that the pressure gradient for the saltwater portion of the section is 0.44426 psi/ft. We used this gradient in combination with the depth to formation information to generate the pressure-distribution map presented in the GIS.

12ccedarkeys: Formation-water salinity. Vernon (1970, his app. I) demonstrated that salinity within the Floridan aquifer increases with depth and at about 2,900 ft (in the Coral Gables area) that total dissolved solids (TDS) is 35,000 mg/L. Brines from oil fields that produce from the Lower Cretaceous Sunniland Limestone have TDS concentrations of about 200,000 mg/L (Meyer, 1989, his table 11). We therefore conclude that TDS concentrations in the lower Cedar Keys and upper Lawson Dolomites are between 35,000 and 200,000 mg/L, which is shown in the GIS.

13cedarkeys: Rock/water reaction. Published lithologic descriptions of the lower Cedar Keys and Lawson Dolomites vary (Applin and Applin, 1944, 1967; Vernon, 1951; Chen, 1965), indicating that (1) the boundaries of these units remain poorly defined and/or (2) these units vary laterally. Difference in lithology is primarily degree of dolomitization, crystal size, and relative proportion of anhydrite. As discussed earlier, the formation waters are saline, have been in place for many millennia, and therefore have probably approached equilibrium with the surrounding rock mass. Relatively clean carbonates are the phases that would react with injected CO<sub>2</sub>.

14cedarkeys: Porosity. Core Laboratory (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000) determined porosity of sidewall core samples from 4,500 to 4,950 in the Lawson Dolomite from the Kaiser Mulberry waste-injection well in Polk County, central Florida (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000). Their analysis shows that porosity varies between 24.5 and 28.0 percent. For lack of other data, we used this range for the GIS. However, descriptions of the lower Cedar Keys and upper Lawson Dolomites indicate that because porosity varies vertically and horizontally in these units, so this range may not be representative throughout central and southern Florida.

15cedarkeys: Water chemistry. Few data were available on the chemistry of brines in the deep subsurface. We chose to use the data of Vernon (1970), who presented water-chemistry-analysis results from selected oil fields in the Coral Gables area.

16cedarkeys: Rock mineralogy. Published lithologic descriptions of the lower Cedar Keys and Lawson Dolomites vary (Applin and Applin, 1944, 1967; Vernon, 1951; Chen, 1965), indicating that (1) the boundaries of these units remain poorly defined and/or (2) these units vary laterally. Difference in lithology is primarily degree of dolomitization, crystal size, and relative proportion of anhydrite. Winston (1977) gave perhaps the best summary of lower Cedar Keys and upper Lawson Dolomite composition. He stated that the lower Cedar Keys was tan, microolitic or micropetal dolomite of varying thickness and cemented by clear

calcium sulfate, whose mineralogy has not been determined. He described the upper Lawson Dolomite as very fine to fine crystalline anhedral or euhedral dolomite with occasional streaks of very fine to fine-grained skeletal dolomite. Applin and Applin (1944) and Vernon (1951) reported gypsum in the upper Lawson Dolomite.

## References

- Applin, P. L., and Applin, E. R., 1944, Regional subsurface stratigraphy and structure of Florida and southern Georgia: American Association of Petroleum Geologists, v. 28, p. 1673–1753.
- \_\_\_\_\_. 1967, The Gulf Series in the subsurface in northern Florida and southern Georgia: U.S. Geological Survey, Professional Paper 524-G, 35 p., 8 plates.
- Blackwell, D. W., Wisian, K. W., and Steele, J. L., 2000, Geothermal resource/reservoir investigations based on heat flow and thermal gradient data for the United States: <http://icsbep.inel.gov/geothermal/fy97/explore/exp-16.html>.
- Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.
- Kinney, D. M., ed., 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U.S. Geological Survey, Publication G74014, 2 maps.
- Meyer, F. W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan Aquifer system in southern Florida: U.S. Geological Survey, Professional Paper 1403-G, 59 p.
- Miller, J. A., 1986, Hydrogeologic framework of the Floridan Aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey, Professional Paper 1403-B, 91 p., 33 plates.
- \_\_\_\_\_. 1997, Hydrogeology of Florida, *in* Randazzo, A. F., and Jones, D. S., eds., The geology of Florida: Tallahassee, University of Florida Press, p. 69–88.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Randazzo, A. F., 1997, The sedimentary platform of Florida: Mesozoic to Cenozoic, *in* Randazzo, A. F., and Jones, D. S., eds., The geology of Florida: Tallahassee, University of Florida Press, p. 39–56.

- Randazzo, A. F., and Jones, D. S., eds., 1997, *The geology of Florida*: Tallahassee, University of Florida Press, 327 p.
- Smith, D. L., and Lord, K. M., 1997, Tectonic evolution and geophysics of the Florida basement, *in* Randazzo, A. F., and Jones, D. S., eds., *The geology of Florida*: Tallahassee, University of Florida Press, p. 13–26.
- Vernon, R. O., 1951, *The geology of Citrus and Levy counties, Florida*: Florida Geological Survey Bulletin 33, 256 p.
- \_\_\_\_\_. 1970, The beneficial uses of zones of high transmissivities in the Florida subsurface for water storage and waste disposal: Florida Geological Survey, Information Circular No. 70, 39 p.
- Winston, G. O., 1977, Cotype wells for the five classic formations in peninsular Florida: *Gulf Coast Association of Geological Societies Transactions*, v. 27, p. 421–427.
- \_\_\_\_\_. 1994, *The Paleogene of Florida*, v. 3. Lithostratigraphy of the Cedar Keys Formation of the Paleocene and Upper Cretaceous age—Peninsular Florida and environs: Miami Geological Survey, 52 p.
- \_\_\_\_\_. 1996, *The Boulder Zone dolomites of Florida*, v. 2, Paleogene zones of the southwestern peninsula: Miami Geological Society, 62 p.

Prepared by Andrew Warne.



## FOX HILLS –LOWER HELL CREEK, POWDER RIVER BASIN

### General Setting

The Powder River Basin is a Rocky Mountain foreland basin in northeastern Wyoming and southeastern Montana. It is a highly asymmetrical basin, with a gently sloping eastern margin and steeply dipping western and southern margins, where folding and overturned strata are common. The Powder River Basin contains fewer structurally defined fields than other basins of western and southwestern Wyoming. The major gas-productive reservoirs, occurring in the Sussex and Shannon Sandstones, the Frontier Formation, and the Dakota Sandstone, contain abundant stratigraphic traps (Mullen and Barlow and Haun, Inc., 1993).

### Information Search and Selection

Subsurface formations in the Powder River Basin are well documented, with the majority of the hydrocarbon-producing zones from numerous stratigraphic Cretaceous intervals, with additional zones in the Jurassic, Permian, and Pennsylvanian (Gluskoter and others, 1991). A variety of studies have been made of individual formations and groups, both hydrocarbon and nonhydrocarbon productive, in the Powder River Basin (Cloverly Group [Hooper, 1961], Tekla Sandstone [George, 1974], Fort Union Formation [Ayers and Kaiser, 1984], Sussex and Shannon Sandstones [Tillman and Martinsen, 1984; 1987], Muddy Sandstone [Gustason, 1988], and Lance Formation [Connor, 1991], but many of these studies have focused on potential for hydrocarbon production or coal distribution, with only minor attention paid to brine disposal or aquifer geometry.

Several formations contain permeable and continuous sandstone bodies in the Powder River Basin. Of these formations, the Lower Cretaceous Lakota Formation was initially considered to be a potentially excellent candidate because it contains continuous sandstone bodies, is deeply buried (more than 2,500 ft [ $>762.2$  m]) in most of the Powder River Basin, and contains relatively little hydrocarbon production (Gluskoter and others,

1991). However, critical information such as gross sandstone, formation isopach, top-seal thickness, and potentiometric surface on a regional scale is lacking for the Lakota Formation, and the Upper Cretaceous Fox Hills Sandstone was therefore chosen for characterization.

The Fox Hills Sandstone contains regionally continuous, marine and marginal-marine sandstones overlain by muddy, lower-coastal-plain sandstones of the Lance Formation (Connor, 1991). Because the Fox Hills Sandstone has little or no hydrocarbon production in the Powder River Basin, its characteristics as a hydrogeologic unit have been relatively well described (Henderson, 1985). However, there are some limitations of the Fox Hills Sandstone that may decrease its potential for CO<sub>2</sub> sequestration. Although the upper Cretaceous Fox Hills Sandstone meets the minimum depth criterion of 800 m for suitability as a formation for injection of CO<sub>2</sub>, it may be marginally suitable from the standpoint of salinity. For a large part of the Powder River Basin, the salinity of the Fox Hills Sandstone is less than 3,000 ppm, reaching brackish conditions in the deep, western part of the basin.

The major sources of data for the Fox Hills Sandstone in the Powder River Basin are derived from Lewis and Hotchkiss (1981) and Henderson (1985) in studies of the Upper Cretaceous Hell Creek and Lance-Fox Hills aquifers. Major parameters for the Fox Hills Sandstone are briefly described, with notes pertaining to the suitability of this stratigraphic unit for being included as a data source.

### Comments on Geologic Parameters

1foxhills: Depth. The principal source for mapping formation depth of the Fox Hills Sandstone in the Powder River Basin is Lewis and Hotchkiss (1981), who presented a structure map on the top of the Fox Hills Sandstone; it reaches a maximum depth of more than 3,000 ft (>910 m) in the steeply dipping, western part of the basin, west of Gillette. We subtracted the subsea elevation of the formation top from the gridded land-surface elevation from a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate depth to top Fox Hills (c1foxhillsg).

- 2foxhills: Permeability/hydraulic conductivity. Permeability data are very limited for the Fox Hills Sandstone. Mullen and Barlow and Haun, Inc. (1993), indicated a permeability of 49 md of the Fox Hills Sandstone in the West Side Canal reservoir in Carbon County in the Greater Green River Basin. By comparison with similar facies in the Powder River Basin, a typical permeability value of 50 md can be inferred for the Fox Hills Sandstone there, but the permeability distribution is unknown.
- 3foxhills: Formation thickness. Lewis and Hotchkiss (1981) documented the thickness of the Fox Hills Sandstone over the entire Powder River Basin. The Fox Hills Sandstone, commonly 500 to 1,000 ft thick (152.4 to 304.8 m) in the north part of the basin in Montana, reaches a maximum thickness of more than 2,500 ft (>762.2 m) in the extreme south part of the basin near Douglas. The isopach was gridded (c3foxhillsg).
- 4foxhills: Net sand thickness. The net sandstone thickness of the Fox Hills Sandstone is calculated from formation isopach and percent-sand data from Lewis and Hotchkiss (1981). Percent sand values of the Fox Hills Sandstone are more than 70 percent in Montana and decrease to 40 to 50 percent in the south part of the basin. The net-sand contour map was gridded (c4foxhillsg).
- 5foxhills: Percent shale. Percent shale (c5foxhills) of the Fox Hills Sandstone was calculated from the gridded percent-sandstone map of Lewis and Hotchkiss (1981). Greatest percent-shale values occur in the south part of the basin.
- 6foxhills: Continuity. Maps of Fox Hills sand-body continuity are not encountered in the literature. However, generalized sand-body continuity can be inferred from maps of percent sand (Lewis and Hotchkiss, 1981) and from the regional facies distribution. The Fox Hills paleoshoreline is interpreted to have prograded from north to south in south-central Wyoming (Van Horn and Shannon, 1989). Sand-body geometry in the north part of the Powder River Basin is inferred to be dominated by narrow, dip-elongate, fluvial- and distributary-channel sandstones, where the Fox Hills Sandstone grades into nonmarine deposits of the Lance Formation (Connor, 1991), whereas strike-elongate (east-west-trending), wave-



dominated shoreface and delta-front Fox Hills sandstones are inferred to be present in the central part of the basin. These shorezone sandstones pinch out southward into shelf mudstones in the south part of the basin, where percent-sandstone values are commonly less than 50 percent (Lewis and Hotchkiss, 1981).

7foxhills: Top-seal thickness. The Fox Hills Sandstone has a regionally extensive top seal known as the Upper Hell Creek Confining Layer. The thickness of this top seal is well documented across the entire Powder River Basin (Lewis and Hotchkiss, 1981). The thickness of the top seal increases from approximately 200 ft (61 m) in Montana to more than 1,000 ft (>304.9 m) in the south part of the basin, where distal-shoreface and shelf Fox Hills Sandstones intertongue and are overlain by marine mudstones in the Lewis Shale. The seal-thickness isopach was gridded (c7foxhillsg).

8foxhills: Continuity of top seal. Marginal-marine deposits of the Fox Hills Formation have an intertonguing relationship with the overlying Lance Formation (Connor, 1991) and laterally with the Lewis Shale (Asquith, 1970). The Fox Hills-Lance contact is gradational and is defined as the transitional interval from upward-coarsening, progradational, marine sandstone wedges and aggradational sandstones with blocky and upward-fining log responses. In the Powder River Basin, shales in this transitional interval vary from less than 20 ft (<6 m) in proximal depositional settings in the north part of the basin, where they pinch out with sandy sequences, to as much as 150 ft (45.6 m) in thickness toward the south (Connor, 1991, his plate 3). However, the top of the Fox Hills Formation in the Powder River Basin and other basins in Wyoming is not a single shale bed, but multiple shale beds overlying several progradational Fox Hills sandstone wedges that pinch out into the Lewis Shale. These shale beds range in continuity from less than 3 mi (<4.8 km) in the proximal part of the Greater Green River Basin, to more than 10 mi (>16 km) in the distal part of the basin (Asquith, 1970, his fig. 20). A percent-sandstone map of the Upper Hell Creek Confining Layer (Lewis and Hotchkiss, 1991) shows great variability in the sand content of the Fox Hills top seal, but locally high values of more than 70 percent sandstone

- occur in the north part of the basin, and lower percent-sandstone values of less than 40 percent are more common in the south part of the basin, where individual sandy Fox Hills progradational wedges pinch out into the Lewis Shale.
- 9foxhills: Hydrocarbon production. The Fox Hills has negligible volumes of hydrocarbon production in the Powder River Basin (Gluskoter and others, 1991), although distal equivalent sandstone facies encased in the Lewis Shale are productive in the southeast part of the basin (Mullen and Barlow and Haun, Inc., 1993).
- 10foxhills: Fluid residence time. We were unable to locate maps that show residence time for the Fox Hills Sandstone in the Powder River Basin. However, Henderson (1985) calculated flow rates of 0.16 to 1.08 m/yr from sample data in the northeast part of the basin.
- 11foxhills: Flow direction. Flow directions inferred from potentiometric contour maps of the Fox Hills Sandstone in the northeast part of the Powder River Basin were documented by Henderson (1985). These inferred flow paths are north and northwestward. However, these maps represent only a limited part of the basin.
- 12afoxhills: Formation temperature. Temperature data from Fox Hills brine samples were presented in tabular form from the northeast part of the basin by Henderson (1985). These data indicate low brine temperatures of 9 to 38.9° C.
- 12bnodata: Formation pressure. There currently is no published information regarding geopressure gradients or maps showing formation-pressure distribution in the Fox Hills Sandstone.
- 12cfoxhills: Formation-water salinity. The Fox Hills Sandstone typically has water-salinity values under 3,000 ppm (U.S. Geological Survey, 1996). Greatest salinity values occur in the deep, west and southwest parts of the basin.
- 13foxhills: Rock/water reaction. Data on rock/water reaction were provided by Henderson (1985). These data are in tabular form and in Stiff diagrams, indicating that coalification processes along the Lance-Fox Hills contact may provide preexisting influxes of CO<sub>2</sub> in the basin. Complex mineralogy, including plagioclase and interbedded coal and suggesting the potential for mineral reaction with high CO<sub>2</sub> brines, is moderate to high.

- 14foxhills: Porosity. Porosity data are very limited for the Fox Hills Sandstone. Mullen and Barlow and Haun, Inc. (1993), showed a porosity value of 21 percent in West Side Canal field in the Greater Green River Basin. This value is inferred to be typical of Fox Hills porosity values in the Powder River Basin in similar shorezone facies. However, the porosity distribution is unknown.
- 15foxhills: Water chemistry. Fox Hills brine chemistry data, summarized by Henderson (1985), show that dissolved-solid concentrations increase downflow from initially low values in the northern recharge area. A plume of intermediate dissolved solids content is controlled by mixing of recharge waters with older, northwest-trending waters. Deep-basin Fox Hills waters are predominantly sodium bicarbonate, sulfate, and chloride.
- 16foxhills: Formation mineralogy. Fox Hills mineralogy data from X-ray diffraction analysis were presented in Henderson (1985; his tables 18, 19). Dominant minerals in the Fox Hills Sandstone are quartz, albite, microcline, muscovite, calcite, and dolomite. Clay cements consist of kaolinite, smectite, and chlorite.

## References

- Asquith, D. O., 1970, Depositional topography and major marine environments, Late Cretaceous, Wyoming: American Association of Petroleum Geologists Bulletin, v. 54, no. 7, p. 1184–1224.
- Ayers, W. B., Jr., and Kaiser, W. R., 1984, Lacustrine interdeltaic coal in the Fort Union Formation (Palaeocene), Powder River Basin, Wyoming and Montana, U.S.A., in Rahmani, R. A., and Flores, R. M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists, Special Publication 7, p. 61–84.
- Connor, C. W., 1991, The Lance Formation—petrography and stratigraphy, Powder River Basin and nearby basins, Wyoming and Montana: U.S. Geological Survey, Bulletin 1917-I, 17p. and 8 plates.
- George, G. R., 1974, Poison Draw field, Converse County, Wyoming: Wyoming Geological Association, Earth Science Bulletin, v. 7, no. 3, p. 3–19.
- Gluskoter, H. J., Rice, D. D., and Taylor, R. B., 1991, eds., Economic geology, the geology of North America: Geological Society of America, v. 2.

- Gustason, E. R., 1988, Depositional and tectonic history of the Lower Cretaceous Muddy Sandstone, Lazy B field, Powder River Basin, Wyoming: Wyoming Geological Association, Guidebook to 39th Field Conference, p. 129–146.
- Henderson, T., 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey, Professional Paper 1402-C, p. C1-C84.
- Hooper, W. F., 1961, Lower Cretaceous of Casper Arch, Wyoming: American Association of Petroleum Geologists Bulletin, v. 45, no. 8, p. 1523–1544.
- Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.
- Mullen, D. M., and Barlow and Haun, Inc., 1993, Powder River Basin (Section FS-1), *in* Hjellming, C. A., ed., Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, Geological Survey of Wyoming, Colorado Geological Survey, Utah Geological Survey, Barlow and Haun, Intera, and Methane Resources Group, Ltd., p. 70.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Tillman, R. W., and Martinsen, R. S., 1984, The Shannon shelf-ridge sandstone complex, Salt Creek Anticline area, Powder River Basin, Wyoming: Society of Economic Paleontologists and Mineralogists, Special Publication 34, p. 85–142.
- \_\_\_\_\_, 1987, Sedimentological model and production characteristics of Hartzog Draw field, Wyoming, a Shannon shelf-ridge sandstone: Society of Economic Paleontologists and Mineralogists, Special Publication 40, p. 15–112.
- U.S. Geological Survey, 1996, Ground water atlas of the United States: Segment 8: Montana, North Dakota, South Dakota, and Wyoming, p. 117.
- Van Horn, M. D., and Shannon, L. T., 1989, Hay reservoir field: a submarine fan gas reservoir within the Lewis Shale, Sweetwater County, Wyoming: Wyoming Geological Association, Guidebook to 40th Field Conference, p. 155–180.

Prepared by William Ambrose.



## FRIO FORMATION, TEXAS GULF COAST

### General Setting

The Gulf Coast is an attractive target for CO<sub>2</sub> sequestration because of the coincidence of emitters (industrial and power-generation facilities) and potential sinks in a thick young wedge of sand-rich sediment. Gulf Coast sandstones are also extensively used for underground injection of chemical and other wastes (Kreitler and others, 1988). During the Tertiary Period, wedges of sediments shed from the rising mountains of the western U.S. and Mexico were deposited in coastal-plain and offshore environments. Sand-rich facies include river-channel, delta-mouth-bar, barrier, slope-channel, and fan environments. Growth faulting resulting from loading of clays by sand created accommodation for accumulation of exceptionally thick sands. Episodes of relative sea-level rise flooded the area and caused widespread accumulation of clay. Complex interactions among sea level, coastal process, and sediment supply have led to complexity within this thick sedimentary unit.

### Selection and Information Search

The number of possible sinks along the Gulf coast is a challenge for this project because the total sand volume and the diversity of potential targets are very large. We selected two units, the upper Frio and the Oakville-Lagarto, as examples of good targets. As is true of other basins in this study, a number of formations are potential targets in the area; Wilcox, Claiborne, and Jackson Groups beneath the Frio contain numerous suitable targets in the updip (western and northern parts of the Gulf Coast basin), and Pliocene and Pleistocene units may be thick enough to be considered near the coast. Nomenclature is a barrier to understanding the options in target selection. Because of the areal extent of the depositional basin, complex depositional environments, and stratigraphic complexities resulting from growth faulting, definition of stratigraphic units is complex and controversial. We have followed the stratigraphy of Galloway and others (1982),

which includes the Texas Catahoula, Frio, and Vicksburg as part of one major genetic unit. We incorporated four large volumes of information about the Frio at regional and field scales; the challenge was to extract suitable and reasonably consistent basin-scale information. In this highly heterogeneous and complex formation, field-specific information is required as a follow-up to this regional-scale study.

### Comments on Geologic Parameters

1frio: Depth. Structure on top of the Frio was digitized from a generalized plate from Galloway and others (1982). Proprietary small-scale maps showing complexities at a reservoir scale are available for much of the Gulf coast from Geomap Inc., Plano, Texas. Field-specific maps are available from various sources. For examples see Galloway and others (1983). We then used land-surface elevation from a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid (c1frio) the depth to top of the Frio Formation.

2frio: Permeability/hydraulic conductivity. Controls on the distribution of permeability in the Frio Formation have been extensively studied and related to its impacts on oil production, as well as exploration for geothermal energy. Rich data sets are available that could be used for analysis of the impacts of heterogeneity on CO<sub>2</sub> injection at a reservoir scale. Porosity is primarily related to depositional facies, with very high permeability in clean sandstone. Compaction and burial diagenesis cause decreased sandstone permeability with depth (Loucks and others, 1984). A generalized trend lies between 1,000 md at 800 m to 0.3 md at 5,000 m; however, samples with permeability between 1,000 and 10,000 md are reported at all depths (Loucks and others, 1984). A smaller data base of data from oil fields (Holtz, 1997) is in the GIS.

3frio: Formation thickness. Thickness of the Frio Formation was digitized from a plate in Galloway and others (1982) and gridded in 5-km cells (c3frio).

4frio: Net sand thickness. Net sand was digitized from three stratigraphic intervals (upper, middle, and lower) as defined by Galloway and others (1982), gridded in

- coarse 5-km cells (c4frio), and the three layers summed to produce gridded cumulative net sand.
- 5frio: Percent shale. Percent shale was also digitized from percent-sandstone maps of the upper, middle, and lower as defined by Galloway and others (1982), which provides an index to the heterogeneity of the system.
- 6frio: Continuity. Compartmentalization is related to depositional facies and percent shale. A recent analysis of the south Texas Frio fluvial-deltaic play (Knox and others, 1996) provides a strong model for how to determine reservoir heterogeneity using facies and play analysis.
- 7frio: Top-seal thickness. The Anahuac Formation is the top seal on the Frio Formation. It is a thick, shale-rich unit deposited during widespread transgression. Surprisingly, we failed to find an isopach of the Anahuac, perhaps because of stratigraphic uncertainty. Seal quality is an issue; the Anahuac pinches out updip. Many shale beds within the Frio serve as traps for hydrocarbons and would most likely similarly trap CO<sub>2</sub>; these units must be mapped at a more local scale than we used.
- 8frio: Continuity of top seal. The integrity of both within-Frio seals and the Anahuac is impacted by growth faults and salt diapirs that penetrate the section. The Anahuac pinches out toward outcrop and the permeable Oakville-Fleming overlies the updip equivalent of the Frio, the Catahoula Formation. Upward leakage along the flanks of at least some salt domes at geologic rates is well documented by fluid chemistry (Macpherson, 1992) and mineralization on dome flanks. Brine leakage through microfractures in shales has been documented (Harrison and Summa, 1991; Macpherson, 1992; Capuano, 1993). In addition, production within and below the Frio should be considered in terms of potential for upward flow along failed casings or improperly plugged wells, as well as in terms of mineral rights and potential for negative impact on production and maintenance. Potentially this area might serve as a fruitful area for investigation of rates of CO<sub>2</sub> flux across shales.



- 9frio: Hydrocarbon production. The Frio is a very productive unit. We digitized a generalized map of Frio production from Galloway and others (1982).
- 10frio: Fluid residence time.
- 11frio: Flow direction. Flow direction within the Frio is complex, and interpretation of major- and minor-element chemistry does not unequivocally support a single interpretation of brine origin. Generally fluids are being expelled from the Gulf Coast basin because of compaction in this depocenter, and deeper sections are overpressured. Overprinted on this system is fresh water moved downdip during higher hydrologic gradients during Pleistocene sea-level lowstand and depressurizing as a result of oil and associated brine production.
- 12afrio: Formation temperature. Temperature data for fields producing from the Frio were extracted from Macpherson (1992) and georeferenced to the field outlines. Because of structural complexity related to salt diapirs and growth faults, heterogeneity at a fine scale is expected.
- 12bfrio: Formation pressure. Kreitler and others (1988) used final shut-in pressures from drill-stem tests and bottom-hole pressures to construct pressure-depth profiles and potentiometric surfaces to determine flow gradients. In order to characterize this thick formation with heterogeneous salinity, Kreitler and others (1988) plotted averaged Frio data slices defined on depth. We include the output from 4,000 to 6,000 ft and 6,000 to 8,000 ft as best matching our target. Data quality is an issue with this data set, as are large vertical and horizontal variables related to natural overpressure and pumpage-induced underpressure.
- 12cfrio: Formation-water salinity. Salinity has been mapped in Frio oil fields by Morton and Land (1987), as have major- and minor-element ratios. Significant vertical and lateral variation in fluid chemistry is well documented in the Gulf Coast basin and reflects the dynamic evolution of this thick sediment wedge (Macpherson, 1992).
- 13frio: Rock/water reaction. The Frio Formation is one of the most mineralogically immature and reactive units in our study. Composition of anorthite (20 percent) and K-feldspar (30 percent) (Land and Macpherson, 1992) reflects high volcanic

- input into the sedimentary environment. This unit has high potential for reacting with high CO<sub>2</sub> brine.
- 15frio: Water chemistry. Brine chemistry in the Gulf Coast basin is relatively well known because of the brine of hydrocarbon production. We have selected a high-quality, formation-specific data set (Macpherson, 1992); other data are available (for example, Kreitler and Richter, 1986; Kreitler and others, 1988).
- 16frio: Rock mineralogy. Mineralogic composition of the Gulf Coast Oligocene Frio was summarized by Land and Macpherson (1992). This compilation represents the productive intervals and may not be representative of fine-grained intervals. Detailed data on which this summary is based are available in spreadsheet format (K. Milliken, The University of Texas at Austin, personal communication, 2000).

## References

- Capuano, R. M., 1993, Evidence of fluid flow in microfractures in geopressed shales: American Association of Petroleum Geologists Bulletin, v. 77, no. 8, p. 1303–1314.
- Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, Noel, and Bebout, D. G., 1983, Atlas of major Texas oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 139 p.
- Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.
- Harrison, W. J., and Summa, L. L., 1991, Paleohydrology of the Gulf of Mexico basin: American Journal of Science, v. 291, p. 109–176.
- Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.
- Knox, P. R., Holtz, M. H., McRae, L. E., Hentz, T. F., Paine, J. G., White, W. G., and Chang, C.-Y., 1996, Revitalizing a mature oil play: strategies for finding and producing unrecovered oil in Frio fluvial-deltaic sandstone reservoirs of South Texas: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for U.S. Department of Energy, Bartlesville Project Office, under contract no. DE-FC22-93BC14959, 178 p.

- Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A, and Wood, W. T., 1988, Hydrology of formations for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, unpublished contract report, 204 p.
- Kreitler, C. W., and Richter, B. C., 1986, Hydrochemical characterization of the saline aquifers of the Texas Gulf Coast used for disposal of industrial waste: The University of Texas at Austin, Bureau of Economic Geology, unpublished contract report, 164 p.
- Land, L. S., and Macpherson, G. L., 1992, Origin of saline formation waters, Cenozoic section, Gulf of Mexico sedimentary basin: American Association of Petroleum Geologists Bulletin v. 76, p. 1344–1362.
- Loucks, R. G., Dodge, M. M., and Galloway, W. E., 1984, Regional controls on diagenesis and reservoir quality in lower Tertiary sandstones along the lower Texas Gulf Coast, *in* McDonald, D. A., and Surdam, R. C., eds., *Clastic diagenesis*: American Association of Petroleum Geologists Memoir 37, p. 15–46.
- Macpherson, G. L., 1992, Regional variation in formation water chemistry; major and minor elements, Frio Formation fluids, Texas: American Association of Petroleum Geologists Bulletin, v. 76, no. 5, p. 740–757.
- Morton, R. A., and Land, L. S., 1987, Regional variations in formation water chemistry, Frio Formation (Oligocene), Texas Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 71, no. 2, p. 191–206.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.

Prepared by S. Hovorka.

## GLEN CANYON GROUP, SEVIER BASIN AND KAIPAROWITS BENCH

### General Setting

The Glen Canyon Group is developed in the subsurface in the Kaiparowits Basin area in south-central Utah in the southwest part of the Colorado Plateau. It is also present in the subsurface in the east part of the Sevier Basin, a foreland basin in southwestern Utah, and the Uinta Basin in northeastern Utah (U.S. Geological Survey, 1996). The Glen Canyon Group encompasses the Jurassic Navajo Sandstone, Kayenta Formation, and Wingate Sandstone. These stratigraphic units consist mainly of clean, well-sorted eolian sandstones (Stanley and others, 1971; Kocurek and Dott, 1983; However, the Kayenta Formation contains sandstone with various amounts of siltstone, mudstone, claystone, and limestone (U.S. Geological Survey, 1996). The top seal is represented by the Carmel Formation, part of the Carmel–Twin Creek confining unit. The Carmel Formation, consisting of mudstone and evaporites, is present throughout the southwestern Colorado Plateau and the Sevier Basin (Wright and Dickey, 1963; Imlay, 1967; Kocurek and Dott, 1983).

### Information Search and Selection

A wide variety of sources of aquifer data for the Glen Canyon Group include, in order of amount of information available, Freethey and Cordy (1991), Freethey and others (1988), The U.S. Geological Survey (1996), Hood and Danielson (1981), Hood and Patterson (1984), and Heilweil and Freethey (1992). Basic geologic data of the Navajo Sandstone and Carmel Formation were provided by Wright and Dickey (1963), Imlay (1967), Stanley and others (1971), Freeman and Visser (1975), Peterson and Pippingos (1979), Taylor (1981), Blakey and others (1983), and Kocurek and Dott (1983). Major parameters for the Glen Canyon Group are briefly described, with notes pertaining to the suitability of this stratigraphic unit to be included as a data source.

## Comments on Geologic Parameters

- 1glencanyon: Depth. The principal sources for inference of formation depth of the Glen Canyon Group are Freethey and Cordy (1991) and Freethey and others (1988). A generalized map of formation-depth ranges in polygon format was provided by the U.S. Geological Survey (1996).
- 2glencanyon: Permeability/hydraulic conductivity. Permeability values of the Glen Canyon Group are not available. However, maps of transmissivity and hydraulic conductivity in the Kaiparowits Basin and northeast Utah were presented by Freethey and Cordy (1991).
- 3glencanyon: Formation thickness. Formation thickness maps of the Navajo Sandstone, the principal component of the Glen Canyon Group, were digitized from Freethey and others (1988) and gridded (c3glencanyon).
- 4glenconyon: Net sand thickness. Regional net-sand-thickness maps of the Navajo Sandstone are poorly documented in the literature. However, detailed net sand thickness of the Navajo Sandstone in the southeast part of Utah (Kaiparowits Basin and San Rafael Swell) were provided by Hood and Patterson (1984).
- 5glencanyon: Percent shale. Simplified maps of percent shale of the Navajo Sandstone over the entire study area were presented by Stanley and others (1971) and Kocurek and Dott (1983). Freethey and Cordy (1991) displayed a general lithofacies map of the Navajo Sandstone in eastern Utah, from which shale percentages were derived.
- 6glencanyon: Continuity. General sand-body continuity maps of the Navajo Sandstone throughout Utah were presented by Stanley and others (1971) and Kocurek and Dott (1983). These maps are schematic and do not display sand-body pinch-outs where the Navajo Sandstone intertongues with the Carmel Formation top seal.
- 7glencanyon: Top-seal thickness. The most detailed maps of top-seal thickness (isopach of the Carmel–Twin Creek confining unit) were presented by Freethey and Cordy (1991). However, their map covers only the east half of Utah and does not include the Sevier Basin. Regional maps of the Carmel Formation (Kocurek and Dott, 1983), however, suggest that the top seal is equally thick in western Utah.

- 8glencanyon: Continuity of top seal. These data for both the Kaiparowits Bench and Sevier Basin were provided by Kocurek and Dott (1983) in regional lithofacies maps of the Carmel Formation. Various lithotypes in the top seal are differentiated and mapped, including carbonates, evaporites, and shales.
- 9glencanyon: Hydrocarbon production. There is no documented hydrocarbon production from the Glen Canyon Group in Utah.
- 10glencanyon: Fluid residence time. We were unable to locate maps of fluid residence time for the Glen Canyon Group. However, Heilweil and Freethey (1992) presented data from the Navajo Sandstone in southwestern Utah (southern Sevier Basin), northwestern Arizona, and southeast Utah (Kaiparowits Basin) that provide estimated flow rates and ground-water budgets.
- 11glencanyon: Flow direction. Flow directions inferred from potentiometric contour maps of the Glen Canyon Group were displayed in a regional map by the U.S. Geological Survey (1996). Detailed data in eastern Utah were shown by Freethey and Cordy (1991).
- 12a, bglen canyon: Formation temperature and formation pressure. No maps are available that show formation brine temperature and pressure. These values are probably low because the Glen Canyon Group is not deeply buried, except for parts of the Sevier Basin, where it is steeply dipping.
- 12cglencanyon: Formation-water salinity. Formation-water salinity in the Glen Canyon Group is greatest in northeastern Utah (more than 35,000 ppm) but low to moderate in southeastern Utah, where it is less than 3,000 ppm (Freethey and Cordy, 1991; U.S. Geological Survey, 1996).
- 13glencanyon: Rock/water reaction. Some data on rock/water reaction were provided by Freethey and Cordy (1991), but the emphasis of their research is on ground-water chemistry. Potential for mineral interaction with high-CO<sub>2</sub> brines is low in these mature sandstones.
- 14glencanyon: Porosity. The distribution of porosity values in the Navajo Sandstone in eastern Utah was presented by Freethey and Cordy (1991). Values of 20 to 30 percent are typical for these mature eolian sandstones.

- 15glencanyon: Water chemistry. Glen Canyon brine chemistry data were summarized by Freethey and others (1988) and Freethey and Cordy (1991), who presented a variety of stiff diagrams and pie charts. Chloride, carbonate+bicarbonate, and sodium+potassium are the chief chemical constituents in brines in the Navajo Sandstone.
- 16glencanyon: Rock mineralogy. The mineralogy of the Page Sandstone, interpreted to have been derived from reworking of the Navajo Sandstone, was described by Blakey and others (1983). Detailed petrographic description of the Carmel Formation was provided by Taylor (1981).

### References

- Blakey, R. C., Peterson, F., Caputo, M. V., Voorhees, B. J., and Geesaman, R. C., 1983, Paleogeography of Middle Jurassic continental, shoreline and shallow marine sedimentation, southern Utah, *in* Reynolds, M. W., and Dolly, E. D., eds., Mesozoic paleogeography of the West-Central United States: Rocky Mountain paleogeography symposium: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, March, v. 2, p. 77–100.
- Freeman, W. E., and Visser, G. S., 1975, Stratigraphic analysis of the Navajo Sandstone: *Journal of Sedimentology Petrology*, v. 45, no. 3, p. 651–668.
- Freethey, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.
- Freethey, G. W., Kimball, B. A., Wilberg, D. E., and Hood, J. W., 1988, General hydrogeology of the aquifers of Mesozoic age, upper Colorado River basin—excluding the San Juan Basin—Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey, Hydrologic Investigations Atlas HA-698, scale 1:2,500,000, 2 sheets.
- Heilweil, V. M., and Freethey, G. W., 1992, Hydrology of the Navajo aquifer in southwestern Utah and northwestern Arizona, including computer simulation of ground-water flow and water-level declines that could be caused by proposed withdrawals, *in* Harty, K. M., ed., Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 213–223.
- Hood, J. W., and Danielson, T. W., 1981, Bedrock aquifers in the lower Dirty Devil River basin, Utah, with emphasis on the Navajo Sandstone: Utah Department of Natural Resources Technical Publication 68, 143 p.

- Hood, J. W., and Patterson, D. J., 1984, Bedrock aquifers in the northern San Rafael Swell area, Utah, with special emphasis on the Navajo Sandstone: Utah Department of Natural Resources Technical Publication 78, 128 p.
- Imlay, R. W., 1967, Twin Creek Limestone (Jurassic) in the Western Interior of the United States: U.S. Geological Survey, Professional Paper 540, 105 p.
- Kocurek, G., and Dott, R. H., Jr., 1983, Jurassic paleogeography of the central and southern Rocky Mountains region, *in* Reynolds, M. W., and Dolly, E. D., eds., Mesozoic paleogeography of the West-Central United States: Rocky Mountain paleogeography symposium: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, v. 2, p. 101–116.
- Peterson, F., and Pipiringos, G. N., 1979, Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona: U.S. Geological Survey Professional Paper 1035-B, p. B1–B43.
- Richards, H. G., 1958, Cyclic deposition in the Jurassic Carmel Formation of eastern Utah: *Journal of Sedimentary Petrology*, v. 28, no. 1, p. 40–45.
- Stanley, K. O., Jordan, W. M., and Dott, R. H., Jr., 1971, New hypothesis of early Jurassic paleogeography and sediment dispersal for western United States: *American Association of Petroleum Geologists Bulletin*, v. 55, no. 1, p. 10–19.
- Taylor, D. W., 1981, Carbonate petrology and depositional environments of the limestone member of the Carmel Formation, near Carmel Junction, Kane County, Utah: *Geology Studies*, Brigham Young University, v. 28, no. 3, p. 117–133.
- U.S. Geological Survey, 1996, Ground water atlas of the United States: Segment 2: Arizona, Colorado, New Mexico, and Utah.
- Wright, J. C., and Dickey, D. D., 1963, Relations of the Navajo and Carmel formations in Southwest Utah and adjoining Arizona: U.S. Geological Survey Professional Paper 450-E, p. E63–E67.

Prepared by William Ambrose.





## GRANITE WASH, PALO DURO BASIN, TEXAS

### General Setting

The Palo Duro Basin of the Texas Panhandle may be considered a northern extension of the Permian Basin of West Texas and eastern New Mexico. A basement high called the Matador Arch separates the two basins. The Matador Arch and other block-faulted Precambrian basement highs to the north, such as the Amarillo Uplift and the Bravo Dome, form the boundaries of the basin. The target reservoir in this basin, the Pennsylvanian Granite Wash, was deposited in a series of alluvial fans and fan deltas that formed rims around these structural highs that developed during the Pennsylvanian Period in response to major continental collision associated with the Ouachita Orogeny (Dutton and others, 1982a). Conversely, units of early Paleozoic age (older than the Granite Wash) were deposited on a stable, shallow shelf periodically covered by epicontinental seas. Eventually erosion of the basement uplifts led to their planation and burial, which was followed by deposition of a series of Permian-age red-bed and evaporite facies. It is these evaporites that form the top seal for the Granite Wash.

### Information Search and Selection

In some cases, we did not find data for the Granite Wash as a separate hydrologic unit. However, there may have been data available for a unit called the “deep brine aquifer,” which includes the Granite Wash and time-equivalent carbonates. In such instances, we have specifically mentioned that the data are for the deep brine aquifer as a whole. Granite Wash is locally used for deep-well injection.

1granitewash: Depth. We digitized a structure-contour map of the top of the

Pennsylvanian section (Budnik and Smith, 1982). Strictly speaking this is not equivalent to the top of the Granite Wash because Granite Wash deposition diminished but continued until the end of the Wolfcampian, the early part of the Permian. The top of the Pennsylvanian map is a close approximation of a top of

- Granite Wash structural map. We gridded the top structure map, subtracted it from land surface elevation (National Imagery and Mapping Agency, 2000) to calculate gridded depth to Granite Wash (c1granitewash).
- 2granitewash: Permeability / hydraulic conductivity. Permeability varies from 1,450 to less than 0.1 md (Dutton, 1982a). “Vertical permeability in the lower Permian and Pennsylvanian strata is assumed to be two orders of magnitude lower than horizontal permeability” because of extensive horizontal stratification. “Proximal granite-wash deposits near the Amarillo Uplift and Bravo Dome apparently have higher permeabilities than distal granite-wash deposits near the center of the basin.” (Senger, and others, 1987, p. 10). There was only one Granite Wash well in the SLERO Oil Information data base (Holtz, 1997), and this well was located in the Anadarko Basin but had no permeability data.
- 3granitewash: Formation thickness. The Granite Wash gridded formation-thickness map results from adding the Pennsylvanian System and the Wolfcampian Series isolith maps of Dutton (1982a) (c3granitewash). Then the areas where the percent carbonate is greater than 40 percent and the Granite Wash percent is less than 30 percent, the maps of Budnik and Smith (1982) are subtracted from the areas defined as Granite Wash. The two cutoffs, 40 percent carbonate and 30 percent granite wash, are chosen because they are the lowest percentages for each of the lithologies, respectively. The main assumption here is that the shale percentage (for which there is no map) is included as part of the total Granite Wash isopach.
- 4granitewash: Net sand thickness. The data used to define the net-sandstone map for the Granite Wash consist of all clastic sediments that are sand size or greater (Dutton, 1980), including granite fragments and feldspar grains derived from the granitic uplifts that define the basin margins (for example, the Amarillo Uplift). This is actually a net-isolith map. The sand isolith was gridded (c4granitewash).
- 5granitewash: Percent shale. Percent shale was computed from facies-distribution maps (Budnik and Smith, 1982) of the Lower and Upper Pennsylvanian-age rocks, respectively. The main assumption we made here was that the Granite Wash included only shale and coarser grained clastics but no bedded carbonates. This is,

- of course, not strictly true, but Dutton (1982a) did present several figures that imply relatively minor amounts of carbonate interbedded with the Granite Wash. Therefore, this map can more correctly be called “percent shale and carbonate.”
- 6granitewash: Continuity. Well spacing is inadequate to describe the highly heterogeneous sand bodies in this nonproductive area. Detailed facies studies of a similar depositional setting on the north side of the Amarillo Uplift (Dutton, 1982b) provide information on the expected scale of complexities.
- 7granitewash: Top-seal thickness. We found no thickness map of the entire evaporite aquitard that overlies the Granite Wash. However, adding the gridded isopach maps of the San Andres / Blaine Formations and the genetic unit above them results in thicknesses that approach or exceed 2,000 ft, ample seal thickness. (c7granitewash)
- 8granitewash: Continuity of top seal. Similar to property number 7, top-seal thickness, we did not find a net-salt map of the entire aquitard. Therefore, we used a net-salt map of the San Andres Formation cycle 4 (Presley, 1979) as an example of the continuity of part of the aquitard.
- 9granite wash: Hydrocarbon production. There is only very minor hydrocarbon production from the Palo Duro Basin in general and the Granite Wash in particular. The few oil fields are located on margins along basement uplifts.
- 10granitewash: Fluid residence time. Estimated travel times from the westernmost recharge area in New Mexico to the eastern boundary range from 1.2 to 4 Ma, depending on the flow path and average porosity of the different units (Senger 1991). Remember that permeability values assigned to the different hydrostratigraphic units are average values representing heterogeneous systems. (Senger and others, 1987, p. 27)
- 11granitewash: Flow direction. The potentiometric surface map by Orr and others (1985) shows a general flow from west-southwest to east-northeast.
- 12agranitewash: Formation temperature. These data are contained in a table from Bassett and Bentley (1983), who did not provide well locations. However, they did furnish county locations, all located in the Anadarko or Dalhart Basins. Because

Basset and Bentley (1983) stated that the data came from tests conducted in the Palo Duro Basin, we have assumed that the authors thought that the data were, therefore, representative of the Palo Duro Basin.

12granitewash: Formation pressure. After reviewing the pressure-data analyses presented by Orr and others (1985), we chose to use 0.403 psi/ft as the slope of the pressure function for the deep brine aquifer (Granite Wash) of the Palo Duro Basin. We chose this value because it derives from the most consistent data (“Class A”) presented by Orr and others (1985). They defined “Class A” pressure data as those values for which both initial and final shut-in pressures were available and that agreed within 10 percent. The original data came from drill-stem tests of petroleum exploration wells. Orr and others (1985) obtained them from Petroleum Information Service, Inc. Note that this value, 0.403 psi/ft, is below the estimated hydrostatic gradient of deep-basin brines, 0.466 psi/ft. By choosing only the “Class A” data of Orr and others, we hope to eliminate one possible reason for the underpressuring of the saline aquifer, poor-quality drill-stem tests. Therefore, according to Orr and others, there are two other possible reasons for this underpressuring: (1) isolation from shallower, hydrostatically pressured aquifers or (2) potential for downward flow within the aquifer. Orr and others presented evidence for both cases in the deep brine aquifer of the Palo Duro Basin.

12cgranitewash: Formation-water salinity. The total dissolved solids values for this map (Bassett and Bentley, 1983) are in units of g/L.

13granitewash: Rock / water reaction. These immature arkosic sandstones are mostly derived from erosion of granite basement uplifts. Potential for mineral reaction with high-CO<sub>2</sub> brines is estimated to be moderate.

14granitewash: Porosity. Porosity measured in thin sections varies from 14 percent in uncemented sandstones to zero in tightly cemented sandstones (Dutton, 1982a).

15granitewash: Water chemistry. These data are contained in a table from Bassett and Bentley (1983), who did not provide well locations. However, they did furnish county locations, all located in the Anadarko or Dalhart Basins. Because Basset and Bentley (1983) stated that the data came from “tests conducted in the Palo

Duro Basin,” we have assumed that the authors thought that the data were, therefore, representative of the Palo Duro Basin.

16granitewash: Rock mineralogy. Most of the Granite Wash falls into the categories of arkose or lithic arkose, with smaller percentages being feldspathic litharenite and minor amounts of subarkose (Dutton, 1980, p. 13).

## References

- Bassett, R. L., and Bentley, M. E., 1983, Deep brine aquifers in the Palo Duro Basin: regional flow and geochemical constraints: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 130, 59 p.
- Budnik, R., and Smith, D., 1982, Regional stratigraphic framework of the Texas Panhandle, *in* Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., *Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 38–86.*
- Dutton, S. P., 1980, Depositional systems and hydrocarbon resource potential of the Pennsylvanian System, Palo Duro and Dalhart Basins, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 80-8, 49 p.
- \_\_\_\_\_, 1982a, Depositional history and reservoir quality of Granite Wash, *in* Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., *Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 87–90.*
- Dutton, S. P., 1982b, Pennsylvanian fan-delta and carbonate deposition, Mobeetie Field, Texas Panhandle: *American Association of Petroleum Geologists Bulletin*, v. 66, p. 389–407.
- Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.

- Handford, C. R., and Dutton, S. P., 1980, Pennsylvanian-Lower Permian depositional systems and shelf-margin evolution, paleogeography, and petroleum potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 102, 31 p.
- Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Orr, E. D, Kreitler, C. W., and Senger, R. K., 1985, Investigation of the underpressuring in the deep-brine aquifer, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 85-1, 44 p.
- Presley, M. W., 1979, Upper Permian evaporites and red beds, *in* Dutton, S. P., Finley R. J., Galloway, W. E., Gustavson, T. C., Handford, C. R., and Presley, M. W., Geology and hydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of nuclear waste isolation feasibility studies, 1978: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 79-1, p. 39–49.
- Senger, R. K., 1991, Regional hydrodynamics of variable-density flow systems, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 202, 54 p.
- Senger, R. K., Fogg, G. E., and Kreitler, C. W., 1987, Effects of hydrostratigraphy and basin development on hydrodynamics of the Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 165, 48 p.
- Smith, D. A., 1983, Permeability of the deep-basin aquifer system, Palo Duro Basin, *in* Gustavson, T. C., Kreitler, C. W., Bassett, R. L., Budnik, R. T., Ruppel, S. C., Baumgardner, R. W., Jr., Caran, S. C., Collins, E. W., Dutton, A. R., Dutton, S. P., Fisher, R. S., Fogg, G. E., Hovorka, S. D., Kolker, A., McGookey, D. A., Orr, E. D., Roberts, M. P., Senger, R. K., Smith, Dale, A., and Smith, D. Anderson, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1982: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 83-4, 156 p.

Prepared by Ramón Treviño.

## JASPER INTERVAL, EAST TEXAS GULF COAST

### General Setting

The Jasper interval, East Texas Gulf Coast, was identified as the uppermost potential target area beneath Texas City, Galveston Bay, within the coastal plain the Gulf of Mexico. Texas City has a high concentration of refineries and therefore has the potential to be considered for pilot sequestration projects using high-pressure CO<sub>2</sub> available from some industrial processes. Texas City is underlain by a thick (>10,000 m) sequence of Cenozoic clastic strata that generally deepen and thicken seaward. Stratigraphic units are interrupted by numerous growth faults.

### Information Search and Selection

The subsurface of this area has been well studied, driven by the search for domestic and industrial water supplies, petroleum, uranium, and geopressured-geothermal energy.

Because Texas City is underlain by a large number of sand units that have the porosity, permeability, and lateral continuity to potentially sequester CO<sub>2</sub>, depth, salinity, and presence of an effective top seal were principal criteria in selecting a target interval. The middle and lower Miocene interval was selected as the primary interval for CO<sub>2</sub> sequestration in the Texas City area because it ranges in depth from about 1,300 to 2,000 m below mean sea level (bmsl), and the interval is directly overlain by a laterally continuous aquitard. Sands within the deeper Frio Formation are potential candidates throughout the Texas Gulf Coast, where we are assessing the potential for targeting a shallower unit in the most gulfward part of the coastal plain

Several names are used for this interval. The name Jasper aquifer comes from the shallow and landward (updip) parts of this unit, where it contains abundant fresh water (Baker, 1986). Along the coast the formation waters, too saline to be used for domestic and industrial water supply, may be considered for CO<sub>2</sub> sequestration. Stratigraphically



the interval is composed of a progradational wedge of sediments of the Miocene Lagarto and Oakville Formations deposited in the coastal and nearshore zone along the margin of a large delta complex that was centered along the Texas–Louisiana border (Galloway and others, 1986). The sands of the Lagarto and Oakville Formations accumulated as beach and barrier-island deposits along a shoreline that generally parallels the present coast. These deposits accumulated during a delta progradational period, probably related to a relative lowering of sea level. These deposits were later partly offset by faults that generally parallel the coast and are the result of loading and basinward failure of the thick Cenozoic sedimentary prism. These sediments have not been deeply buried, they remain unconsolidated, and they have not been subject to significant diagenetic processes that would affect porosity and permeability.

#### Comments on Geologic Parameters

Next, each of the 14 parameters is briefly described, and the reasons for selection of the map or data source for the GIS are outlined. The reference list at the end of this summary summarizes documents that are relevant to the Fleming Formation in the study area.

1jasper: Depth. The top of the Fleming (or Lagarto/Oakville) Formation occurs at about 1,200- to 1,300-m depth in the Texas City area and generally deepens seaward. The map depicting the altitude of the top of the Jasper aquifer (feet below mean sea level) in Baker (1986) was used in the GIS because it most clearly shows the top of the hydrogeologic unit of interest. Although this map provides an excellent regional perspective, it does not show local offsets associated with faulting, which will need to be considered when specific CO<sub>2</sub> sequestration sites are located (see later discussion of parameter 8, continuity of top seal, for more information regarding the nature of faulting within the Miocene interval in the Texas City area). We gridded the structure map on top of the Jasper and then calculated depth to top Jasper (c1jasper) by subtracting subsea elevation of the top Jasper from land-surface elevation of a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000).

2jasper: Permeability/hydraulic conductivity. Very little direct information is currently available on permeability of the Miocene sands beneath the Texas City area. Most permeability estimates are generated from geophysical logs of oil and gas wells or from outcrops in the coastal plain to the east. A major drawback of using geophysical logs for permeability estimates is that a number of assumptions must be made (pore-water chemistry, formation mineralogy). Drawbacks of using permeability information from outcrop studies are primarily because these outcropping deposits were deposited in more fluvial environments than the coastal deposits beneath Texas City (Galloway and others, 1986). The permeability data from Kreitler and others (1988) were used for the GIS because it is the most comprehensive and systematic study of permeability of the Miocene interval that is currently available. Kreitler and others (1988) used a combination of data from brine-injection well reports and from pressure data from petroleum wells and reported intrinsic permeability in millidarcys.

3jasper: Formation thickness. Although there is ample stratigraphic information on the Miocene interval in the Texas City area, a map showing the overall thickness distribution of the Fleming interval was surprisingly difficult to locate. Several maps show the interval-thickness distribution to the southwest and west of Texas City, and a number of subsurface cross sections are available through the Texas City area (Baker, 1979, 1986; Ambrose and others, 1990). The regional thickness map of the middle Miocene interval by Galloway and others (1991) was used because it provides the only available compilation of data currently available for the area. The isopach was coarsely gridded by using a 5-km cell size (c3jasper).

4jasper: Net sand thickness. Galloway and others (1986) compiled excellent maps showing sand-thickness distribution in both the Lagarto and Oakville Formations along the Gulf Coast of Texas. These maps show (1) the thickening of sands around the depocenter, especially during Lagarto deposition, and (2) elongation of (beach and barrier-island) sand bodies generally parallel to the present coast. In the GIS, sand-thickness isopach maps of the Oakville and Lagarto were gridded and the two formations summed (c4jasper).

- 5jasper: Percent shale. Galloway and others (1986) also compiled excellent maps showing percent sand of both the Lagarto and Oakville Formations. These maps show (1) the thickening of sands around the depocenter, especially during Lagarto deposition; (2) elongation of (beach and barrier-island) sand bodies generally parallel to the present coast; and (3) the interval containing abundant sand.
- 6jasper: Continuity. These sands are largely winnowed beach and barrier-island deposits, and therefore sand continuity in the thicker units is excellent (Ambrose, 1990). Local faulting, however, significantly influences sand-body continuity in the Texas City area. The net-sand map of the lower Miocene (6,150 ft) interval, as mapped by Ambrose (1990), was selected for use in the GIS because it highlights the continuity of the sand bodies in an orientation parallel to the present shoreline and because it highlights the importance of local faults in controlling the lateral continuity of these beach/barrier-island sands.
- 7jasper: Top-seal thickness. A number of studies have identified the upper portion of the Lagarto Formation as a laterally continuous shale known as the *Amphistegina* Shale (Galloway and others, 1986) or the Burkeville confining system (Baker, 1979, 1986). The Burkeville confining system is deep-water shale that was deposited during a eustatic rise in sea level, and therefore it is laterally continuous and generally homogeneous. The thickness isopach of the Burkeville confining system of Baker (1986) was selected and gridded (c7jasper) for use in the GIS because Baker mapped the area to characterize hydrogeologic characteristics of the subsurface.
- 8jasper: Continuity of top seal. As discussed earlier, local faulting significantly influences the continuity of the Tertiary strata in the Texas City area, including the Burkeville confining layer. Baker (1986) reported that the Burkeville shale is generally thick enough not to be completely offset by faults, and therefore this interval remains an effective seal. A map showing the elevation at the approximate base of the Burkeville confining unit, as mapped by Ambrose (1990), was selected for use in the GIS because it highlights the importance of faulting and amount of offset associated with the top seal

9jasper: Hydrocarbon production. The Tertiary deposits of the Texas Gulf Coast, including the Texas City area, have been extensively drilled for gas and oil. Several published atlases summarize oil and gas drilling and production activity along the Texas Gulf Coast, including those of Galloway and others (1983) and Kisters and others (1989). Principal petroleum targets in the Texas City area are within the Frio Formation, although there is production from the Oakville Formation as well. The oil- and gas-field maps of Galloway and others (1983) and Kisters and others (1989) were used in the GIS because they provide a summary of where oil and gas wells are concentrated. Because of the large number of wells in the Texas City area that penetrate the Lagarto/Oakville interval, locations of all existing and plugged wells should be considered when determining the location of CO<sub>2</sub> sequestration wells. Proprietary maps compiled by Geomap (<http://geomap.com>) provide more detailed information regarding well and field locations in the Texas City area.

10jasper: Fluid residence time. Very few data are available to determine fluid residence times in the Lagarto/Oakville interval. The laterally continuous Burkeville confining interval promotes protracted fluid residence times within the Lagarto/Oakville Formation. More detailed analyses of hydraulic heads from this interval are needed to determine flow direction and rates and, from this information, to infer fluid residence times.

11jasper: Flow direction. Ground-water-flow direction is typically determined by first determining the hydraulic-head of ground water in the interval in a series of wells. The distribution of hydraulic-head data from the Lagarto/Oakville Formation must be compiled and potentiometric surface and gradients defined to determine ground-water flow and direction.

12jasper: Formation temperature. As part of their Gulf Coast Regional Aquifer System Analysis program, the U.S. Geological Survey (Pettijohn and others, 1988) mapped the distribution of temperature and salinity of formation water in several Tertiary subsurface intervals of the Gulf Coast region, including the Texas City area. These maps, including the middle and lower Miocene interval, are used for

- the GIS. Temperatures are reported in degrees Celsius, and temperatures in the Lagarto/Oakville interval typically range from 50 to 70° C in the Texas City area.
- 12bjasper: Formation pressure. Studies by Kreitler and others (1988; their figure 62) demonstrate that pressure increases uniformly with depth for the Miocene formations of the Texas Gulf Coastal Plain. They determined that the regional pressure gradient for the Miocene formations is 0.465 psi/ft. With this information we calculated pressure at formation depth (c12bjasper) to determine the aerial distribution of pressures within this middle and lower Miocene interval. In the Texas City area, the Lagarto/Oakville interval is at 1,860 to 3,022 psi.
- 12cjasper: Formation-water salinity. As part of their Gulf Coast Regional Aquifer System Analysis program, the U.S. Geological Survey (Pettijohn and others, 1988) mapped temperature and salinity of formation water in several Tertiary subsurface intervals of the Gulf Coast region, including the Texas City area. These maps include the middle and lower Miocene interval and are used for the GIS. Salinities are reported in milligrams per liter, and brine concentrations in the Lagarto/Oakville interval typically range from 35,000 to 150,000 mg/L in the Texas City area.
- 13jasper: Rock/water reaction. Rock/water reactions are largely a function of formation mineralogy and (if applicable) cement composition. Pore-water chemistry and pore-water residence also significantly influence rock/water reactions. Land and Macpherson (1992) summarized the composition of Miocene sandstones in the Gulf Coast, showing that they are the most immature and potentially reactive in our study. Published data are available from outcrop studies of the Fleming Formation to the west (Ragsdale, 1960). Ragsdale's data show that the sands are primarily composed of quartz, carbonate rock fragments, and chert. Sediments of these outcrops were probably deposited in a more fluvial environment than those of the subsurface in the Texas City area, and so mineralogic differences may exist. Potential for significant interaction with CO<sub>2</sub>-rich fluids appears moderate. Samples from four wells in Galveston county that include the Lagarto/Oakville interval are available for mineralogical analysis at The University of Texas at

- Austin, Bureau of Economic Geology, Core Research Center, if the need arises for more detailed investigations of rock/water reactions in the Texas City area. A limited number of pore-fluid chemistry data for the Miocene interval of Galveston County are available in the Core Laboratories (1972a).
- 14jasper: Porosity. Although only limited published information regarding porosity of the Lagarto/Oakville interval is available (Core Laboratories, 1972b; Wallace and others, 1979; Kreitler and others, 1988), most agree that the thicker sand intervals range between 23 and 28 percent porosity. Muddier and siltier sands are more typically 16 percent. To represent porosity in the GIS we used the net-sand map of the lower Miocene (6,150 ft) interval, as mapped by Ambrose (1990), in which we assign a value of 27 percent porosity to the thicker (barrier-island facies) sands and 16 percent porosity to the thinner (barrier-island flank facies) sands. For more detailed analysis of porosity within the Lagarto and Oakville Formations in the Texas City area, geophysical logs from gas and oil wells can be an excellent source of data for determining and mapping porosity distribution.
- 16jasper: Rock mineralogy. Mineralogic composition of the Gulf Coast was summarized by Land and Macpherson (1992). This summary represents the productive intervals and may not be representative of fine-grained intervals. Detailed data on which this summary is based are available in spreadsheet format (K. Milliken, The University of Texas at Austin, personal communication, 2000).

## References

- Ambrose, W. A., 1990, Facies heterogeneity and brine-disposal potential of Miocene barrier-island, fluvial, and deltaic systems: examples from northeast Hitchcock and Alta Loma Fields, Galveston County, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 90-4, 35 p.
- Baker, E. T., Jr., 1979, Stratigraphic and hydrogeologic framework of part of the coastal plain of Texas: Texas Department of Water Resources, Report 236, 43 p.
- \_\_\_\_\_, 1986, Hydrology of the Jasper Aquifer in the southeast Texas coastal plain: Texas Water Development Board, Report 295, 64 p.

- Core Laboratories, 1972a, A survey of the subsurface saline water of Texas: Volume 2 chemical analysis of saline water: Texas Water Development Board, Report 157, 378 p.
- \_\_\_\_\_ 1972b, A survey of the subsurface saline water of Texas: Volume 3 aquifer rock properties: Texas Water Development Board, Report 157, 364 p.
- Doyle, J. D., 1979, Depositional patterns of Miocene facies, middle Texas Coastal Plain: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 99, 28 p.
- Gabrysch, R. K., 1980, Development of ground water in the Houston District, Texas, 1970-74: Texas Department of Water Resources, Report 241, 49 p.
- Galloway, W. E., 1988, Depositional framework and hydrocarbon resources of the early Miocene (Fleming) episode, northwest Gulf Coast basin: *Marine Geology*, v. 90, p. 19-29.
- Galloway, W. E., Bebout, D. G., Fisher, W. L., Dunlap, J. B., Jr., Cabrera-Castro, R., Lugo-Rivera, J. E., and Scott, T. M., 1991, Cenozoic, *in* Salvador, A., ed., The geology of North America, v. J. The Gulf of Mexico Basin: Geological Society of America, p. 245-324.
- Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, N., and Bebout, D. G., 1983, Atlas of major Texas oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 139 p.
- Galloway, W. E., Jirik, L. A., Morton, R. A., and Dubar, J. R., 1986, Lower Miocene (Fleming) depositional episode of the Texas coastal plain and continental shelf: structural framework, facies, and hydrocarbon resources: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 150, 50 p.
- Grubb, H. F., 1984, Planning report for the Gulf Coast regional aquifer-system analysis in the Gulf of Mexico coastal plain, United States: U.S. Geological Survey Water-Resources Investigations Report 84-4219, 30 p.
- Kiatta, H. W., 1971, The stratigraphy and petroleum potential of the lower Miocene, offshore Galveston and Jefferson Counties, Texas: *Gulf Coast Association of Geological Societies Transactions*, v. 21, p. 257-270.
- Kosters, E. C., Bebout, D. G., Seni, S. J., Garrett, C. M., Jr., Brown, L. F., Jr., Hamlin, H. S., Dutton, S. P., Ruppel, S. C., Finley, R. J., and Tyler, N., 1989, Atlas of major Texas gas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 161 p.
- Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A., and Wood, W. T., 1988, Hydrogeology of formations used for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, open-file report prepared for U.S. Environmental Protection Agency under Cooperative Agreement ID No. CR812786-01, 204 p.

- Kreitler, C. W., Guevara, E., Granata, G., and McKalips, D., 1977, Hydrogeology of gulf coast aquifers, Houston-Galveston area, Texas: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 72–89.
- Land, L. S., and Macpherson, G. L., 1992, Origin of saline formation waters, Cenozoic section, Gulf of Mexico sedimentary basin: American Association of Petroleum Geologists Bulletin, v. 76, p. 1344–1362.
- Morton, R. A., Jirik, L. A., and Foote, R. G., 1985, Structural cross sections, Miocene series, Texas Continental Shelf: The University of Texas at Austin, Bureau of Economic Geology, Open-File Report.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Pettijohn, R. A., Weiss, J. S., and Williamson, A. K., 1988, Distribution of dissolved-solids concentrations and temperature in ground water of the gulf coast aquifer systems, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4082.
- Ragsdale, J. A., 1960, Petrology of Miocene Oakville Formation, Texas Coastal Plain: University of Texas, Austin, Master's thesis, 196 p.
- Sharp, J. M., Kreitler, C. W., and Lesser, J., 1991, Ground water, *in* Salvador, A., ed., The geology of North America, v. J. The Gulf of Mexico Basin: Geological Society of America, p. 529–543.
- Turcan, A. N., Jr., Wesselman, J. B., and Kilburn, C., 1966, Interstate correlation of aquifers, southwestern Louisiana and southeastern Texas: U.S. Geological Survey, Professional Paper 550-D, p. D231–D236.
- Wallace, R. H., Kraemer, T. F., Taylor, R. E., and Wesselman, J. B., 1979, Assessment of geopressured-geothermal resources in the northern Gulf of Mexico basin: U.S. Geological Survey, Circular 790, 132–155.
- Wilson, T. A., and Hosman, R. L., 1987, Geophysical well-log data base for the Gulf Coast aquifer systems, south-central United States: U.S. Geological Survey, Open-File Report 87-677, 213 p.

Prepared by Andrew Warne.





## LOWER POTOMAC GROUP, EASTERN COASTAL PLAIN OF MARYLAND, DELAWARE, AND NEW JERSEY

### General Setting

The north central Atlantic coastal plain, which includes eastern Maryland, Delaware, and New Jersey, consists of a seaward-dipping and seaward-thickening wedge of Cretaceous through Pleistocene sediments (Trapp and others, 1984; Olsson and others, 1988). Most stratigraphic units outcrop in belts generally parallel to the coast, where they receive precipitation, which then infiltrates and flows downdip to become ground water. Eastern Maryland, Delaware and New Jersey receive abundant rainfall, and a number of the shallow aquifers provide ample domestic and industrial water.

### Information Search and Selection

The deeper portions of the eastern coastal plain are the focus of this investigation because this area contains strata that are sufficiently deep, porous and permeable, and hydraulically isolated from fresh-water aquifers to serve as potential CO<sub>2</sub> sequestration targets. In addition, there are several major CO<sub>2</sub> producers in this region (fig. 1). However, depth to basement in the region is variable and is generally shallow in northern New Jersey and becomes deep (>7,000 ft) in the Maryland coastal plain (Manheim and Horn, 1968; Brown and others, 1972). Hence, depth-to-basement limits areas within the north central Atlantic coastal plain where aquifers are sufficiently deep to be candidates for CO<sub>2</sub> sequestration.

The deep subsurface of this area has only been moderately studied because shallow aquifers generally provide sufficient water. There is very little potential for hydrocarbon production along the northern Atlantic coastal plain, and the subsurface liquid waste disposal has been limited to shallow injection of secondarily treated wastewater (Maria Conicelli, U.S. Environmental Protection Agency, personal communication, 2000; Ching-Tzone Tienn, Maryland Department of the Environment,

personal communication, 2000). However, a number of deep hydrocarbon exploration wells were drilled and analyzed, which provide valuable information on deep-aquifer properties (Anderson, 1948; Kasabach and Scudder, 1961; Maher and Applin, 1971; Trapp and others, 1984; Benson and others, 1985). A number of reports were generated to describe deep-aquifer properties as potential subsurface-waste disposal sites (Hansen, 1984). Regional aquifer analyses commonly include deeper horizons (Manheim and Horn, 1968; Brown and others, 1972; Trapp and Meisler, 1992).

Because the basement is relatively shallow in eastern New Jersey, Delaware and Maryland, the only regional candidate for CO<sub>2</sub> sequestration is the Lower Cretaceous Group, which is widely recognized as a major aquifer system in the northern Atlantic coastal-plain horizons (Manheim and Horn, 1968; Brown and others, 1972; Trapp and Meisler, 1992). The Potomac Group directly overlies the igneous and metamorphic basement in most of the area of interest. However, there are some areas where the Potomac Group is underlain by sediments of Jurassic(?) age (Manheim and Horn, 1968; Brown and others, 1972). Several authors recognized an upper, middle, and lower Potomac aquifer (for example, Trapp and Meisler, 1992). The GIS is based on the lower Potomac aquifer. Although the GIS generally covers the eastern coastal plain of New Jersey, Delaware, and Maryland, eastern Maryland and southeasternmost Delaware appear to be especially suitable for CO<sub>2</sub> sequestration: there are significant CO<sub>2</sub> producers in the area (fig. 1), basement in that area is relatively deep, and there is a well-defined sandy unit, the Waste Gate Formation, in the lower Potomac Group (Hansen, 1984) that has good reservoir properties for sequestering CO<sub>2</sub>.

### Comments on Geologic Parameters

Each of the 14 parameters for the lower Potomac aquifer is now briefly described, and the reasons for selection of the map or data source for the GIS are outlined. The reference list at the end of this summary includes documents that are relevant to the New Jersey, Delaware, and Maryland coastal plain and the Potomac hydrostratigraphic interval.

1potomac: Depth. A number of maps show the elevation at the top of the Potomac aquifer (Gill and Farlekas, 1969; Brown and others, 1972; Trapp and Meisler (1992; Trapp, 1992). We chose to use the map of Trapp and Meisler (1992; their plate 7B) because it covers the entire region and clearly defines the hydrostratigraphic unit. We then used a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid the depth to top of the Potomac brine formation (c1potomac).

2potomac: Permeability/hydraulic conductivity. A number of studies provide information on lower Potomac aquifer permeability or hydraulic conductivity (Hansen, 1969, 1984; Trapp and others, 1984; Trapp, 1992; Leahy and Martin, 1993; Pope and Gordon, 1999). However, only Pope and Gordon (1999) provided a map showing distribution of hydraulic conductivity (transmissivity) for the eastern coastal plain, and it is used for the GIS. The Pope and Gordon (1999) map is limited to the New Jersey coastal plain, and so another data point available from the Waste Gate Formation of eastern Maryland (Hansen, 1984) is also included in the GIS.

3potomac: Formation thickness. There is no published map showing the thickness distribution of the lower Potomac aquifer in the eastern coastal plain of New Jersey, Delaware, and Maryland (D. Pope, U.S. Geological Survey, personal communication, 2000). Hansen (1984) provided thickness-distribution information for the Waste Gate Formation in eastern Maryland. We used the GIS to calculate the difference in elevation at top of the lower Potomac aquifer (Trapp and Meisler, 1992) and top of basement (Brown and others, 1972) to calculate lower Potomac aquifer thickness distribution (c3potomacg).

4potomac: Net sand thickness. A number of studies present cross sections that include geophysical logs (gamma ray, spontaneous potential, resistivity) that can be used to derive a semiquantitative estimate of net sand thickness in the lower Potomac aquifer (Hansen, 1968; Brown and others, 1972; Cushing and others, 1973; Trapp and others, 1984). Anderson (1948) and Benson and others (1985) provided grain-size analysis results from cores that can also be used to evaluate net sand thickness in the lower Potomac aquifer. Otton and Mandle (1984) and Hansen

(1984) provided information regarding areal distribution of sands within the Potomac Group, and these data were gridded and used in the GIS (c4potomacg).

5potomac: Percent shale. A number of studies present cross sections that include geophysical logs (gamma ray, spontaneous potential, resistivity) that can be used to derive a semiquantitative estimate percent shale within the lower Potomac aquifer (Hansen, 1968; Brown and others, 1972; Cushing and others, 1973; Trapp and others, 1984). Anderson (1948) and Benson and others (1985) provided grain-size analysis results from cores that can also be used to evaluate percent shale within the lower Potomac aquifer. Otton and Mandle (1984) and Hansen (1984) provided information regarding distribution of shale within the Potomac Group, but their maps cover only a portion of the area of interest. Brown and others (1972) provided a percent-shale map of the lower Potomac stratigraphic interval that covers the entire area of interest, and this map is used for the GIS.

6potomac: Continuity. A number of studies present cross sections that include geophysical logs (gamma ray, spontaneous potential, resistivity) that can be used to evaluate sand-body continuity within the lower Potomac aquifer (Hansen, 1968; Brown and others, 1972; Cushing and others, 1973; Trapp and others, 1984). These cross sections indicate that a number of thicker sands are continuous. Cushing and others (1973, their plate 2) generated a map showing the thickness distribution of a major sand unit in the Potomac aquifer. This map, which is gridded for the GIS (c6potomacg), demonstrates that the major sand bodies are continuous, and for this particular interval, are more than 50 ft thick across the entire Delmarva Peninsula.

7potomac: Top-seal thickness. Several studies define the confining unit above the lower Potomac aquifer (Trapp, 1992; Trapp and Meisler, 1992). It is generally composed of “tough” or “hard” clay and sandy clay beds. It is regionally continuous from North Carolina to New Jersey and generally ranges in thickness from 50 to 100 ft but exceeds 1,000 ft toward the mouth of Delaware Bay (Trapp, 1992). Trapp (1992) provided a map showing the thickness distribution of the

- lower Potomac confining unit across the area of interest, and this map is gridded for the GIS (c7potomacg).
- 8potomac: Continuity of top seal. The lower Potomac confining unit is regionally continuous from North Carolina to New Jersey and generally ranges in thickness from 50 to 100 ft but exceeds 1,000 ft toward the mouth of Delaware Bay (Trapp, 1992). Vertical leakage generally ranges from  $1 \times 10^{-8}$  to  $1 \times 10^{-4}$  (ft/day) (Trapp, 1992). Pope and Gordon (1999) presented a map showing the leakage distribution of the lower Potomac confining unit across southeastern New Jersey, and this map is used for the GIS.
- 9potomac: Hydrocarbon production from the interval. Several hydrocarbon exploration wells have been drilled in the Atlantic coastal plain without success (Anderson, 1948; Kasabach and Scudder, 1961; Manheim and Horn, 1968; Maher and Applin, 1971; Trapp and others, 1984; Benson and others, 1985). There is no production in the area.
- 10potomac: Fluid residence time. Several authors characterized regional ground-water flow in the lower Potomac interval (Trapp and Meisler, 1992; Leahy and Martin, 1993; Trapp and Horn, 1997; Pope and Gordon, 1999). However, these studies focus on measuring and/or modeling hydraulic head in areas where the lower Potomac aquifer is shallow and contains fresh water, and their maps cover only areas that are inland (up dip) of the area of interest in this study. Meisler and others (1984) analyzed the effect of Pleistocene sea-level change on the saltwater/fresh-water interface in deep aquifers below the coastal plain. They concluded that the saltwater/fresh-water interface moves very little with major sea-level changes, which implies that the fluid residence times in these deep aquifers is very long and undoubtedly exceeds the age of the last major sea-level low, which was about 18,000 yr BP. Hence, in the GIS, we represent fluid residence times across eastern New Jersey, Delaware, and Maryland as more than 18,000 yr.
- 11potomac: Flow direction. Several authors characterized ground-water flow in the lower Potomac interval (Trapp and Meisler, 1992; Leahy and Martin, 1993; Trapp and

Horn, 1997; Pope and Gordon, 1999). However, these studies focus on measuring and/or modeling hydraulic head in areas where the lower Potomac aquifer is shallow and contains fresh water, and their maps cover only areas that are inland (up dip) of the area of interest in this study. We used the combined information from Trapp and Meisler (1992), Leahy and Martin (1993), Trapp and Horn (1997), and Pope and Gordon (1999) to generate the hydraulic head/flow direction map presented in the GIS.

12apotomac: Formation temperature. Trapp and others (1984) and Hansen (1984) provided temperature versus depth information from deep wells in the coastal plain of Maryland. Both studies determine a normal geothermal gradient of about 1.5° F/100 ft. This compares well with the geothermal gradient data of Kinney (1976) in which a geothermal gradient of about 1.38° F/100 ft (25.5° C/km) is shown for the eastern New Jersey, Delaware, and Maryland coastal-plain area.

12bpotomac: Formation pressure. Hansen (1984) and Trapp and others (1984) provided discussions of pressure gradients for the lower Potomac Group (Waste Gate Formation) of eastern Maryland. They found that observed pressures generally follow a normal lithostatic pressure gradient of 0.45 psi/ft. To derive a pressure distribution map for the GIS, we took the 0.45 psi/ft and multiplied the depth to the top of the lower Potomac aquifer (c12bpotomac).

12cpotomac: Formation-water salinity. Several researchers reported that salinities for the lower Potomac aquifer interval of eastern New Jersey, Delaware, and Maryland (Manheim and Horn, 1968; Hansen, 1984; Trapp and others, 1984; Meisler, 1989; Trapp and Horn, 1997; Pope and Gordon, 1999). We combined information presented by Hansen (1984) and Pope and Gordon (1999) for the GIS.

13potomac: Rock/water reaction. Several authors presented descriptions of the mineral composition of the lower Potomac interval (Anderson, 1948; Kasabach and Scudder, 1961; Maher and Applin, 1971; Trapp and others, 1984; Benson and others, 1985). These studies indicate that the sands of the lower Potomac aquifer contain low proportions of reactive minerals such as calcium plagioclase and calcite; however, glauconite is present. In addition, studies indicate that because

the formation waters have been in place for >15,000 yr, they have most likely approached equilibrium with the surrounding formations. We therefore conclude that the potential for significant rock/water reactions with high CO<sub>2</sub> fluids for eastern New Jersey, Delaware, and Maryland are low to moderate.

14potomac: Porosity. Hansen (1984) provided information regarding porosity in the lower Potomac aquifer (Waste Gate Formation) of eastern Maryland. He reported that porosities generally range from 19 to 27 percent. This range is reported in the GIS.

15potomac: Water chemistry. Gill and others (1963), Trapp and others (1984), and Hansen (1984) provided the results of chemical analyses of water from the lower Potomac aquifer. Their results indicate that waters are saline (>20,000 mg/L dissolved solids), although the chemistry varies. Their data are presented in the GIS.

16potomac: Rock mineralogy. Several authors presented descriptions of the mineral composition of the lower Potomac interval (Anderson, 1948; Kasabach and Scudder, 1961; Gill and others, 1963; Maher and Applin, 1971; Trapp and others, 1984; Benson and others, 1985). Review of these reports indicates that the mineralogy is quite variable: Anderson (1948), Hansen (1984), and Trapp and others (1984) reported that feldspar comprises between 20 and 50 percent of the light minerals, but Gill and others (1963) and Benson and others (1985) reported that the Potomac Group sands are quartzose with very little feldspar. The lithologic descriptions of Gill and others (1963) indicate high percentages of calcite and shell fragments, but those of Anderson (1948), Trapp and others (1984), and Benson and others (1985) indicate low to moderate amounts of calcite and shell. Most reported lignite and/or glauconite. The heavy minerals typically comprise less than 1 percent (by weight) of the sand fraction and are predominantly composed of epidote, garnet, staurolite, zircon, and tourmaline. We attribute the variability in mineralogy to deposition of the sands in a variety of fluvial and deltaic environments. To typify the mineralogy, we present data from



Trapp and others (1984, their table 13) in the GIS. However, the other references cited earlier provide additional information.

## References

- Anderson, J. L., 1948, Cretaceous and Tertiary subsurface geology: State of Maryland Board of Natural Resources, Bulletin 2, 456 p.
- Benson, R. N., Jordan, R. R., and Spoljaric, N., 1985, Geological studies of Cretaceous and Tertiary section, test well Je32-04, central Delaware: Delaware Geological Survey Bulletin No. 17, 69 p., 3 plates.
- Brown, P. M., Miller, J. A., and Swain, F. M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic coastal plain, North Carolina to New York: U.S. Geological Survey, Professional Paper 796, 79 p., 59 plates.
- Cushing, E. M., Kantrowitz, I. H., and Taylor, K. R., 1973, Water resources of the Delmarva Peninsula: U.S. Geological Survey, Professional Paper 822, 58 p.
- Gill, H. E., and Farlekas, G. M., 1969, Geohydrologic maps of the Potomac-Raritan-Magoth aquifer system in the New Jersey coastal plain: U.S. Geological Survey, Hydrologic Investigations Atlas HA-557, 2 sheets
- Gill, H. E., Seabar, P. R., Vecchioli, J., and Anderson, H. R., 1963, Evaluation of geologic and hydrologic data from the test-drilling program at Island Beach State Park, N.J.: New Jersey Department of Conservation and Economic Development, Water Resources Circular 12, 25 p.
- Hansen, H. J., 1968, Geophysical log cross-section network of the Cretaceous sediments of southern Maryland: Maryland Geological Survey Report of Investigation No. 7, 33 p.
- \_\_\_\_\_ 1969, Depositional environments of subsurface Potomac Group in southern Maryland: American Association of Petroleum Geologists Bulletin, v. 53, p. 1923–1937.
- \_\_\_\_\_ 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.
- Kasabach, H. F., and Scudder, R. J., 1961, Deep wells of the New Jersey coastal plain: New Jersey Geological Survey Report GSR 3, 62 p.
- Kinney, D. M., ed., 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U.S. Geological Survey Publication G74014, 2 maps.

- Leahy, P. P., and Martin, Mary, 1993, Geohydrology and simulation of ground-water flow in the Northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404-K, 81 p.
- Leahy, P. P., Martin, M., and Meisler, H., 1986, Hydrogeologic definition of the northern Atlantic Coastal Plain Aquifer System based on regional simulation, *in* Vecchioli, J., and Johnson, A. I., eds., Regional aquifer systems of the United States aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association, Monograph Series No. 9, Bethesda, MD, p. 7–24.
- Maher, J. C., and Applin, E. R., 1971, Geologic framework and petroleum potential of the Atlantic coastal plain and continental shelf: U.S. Geological Survey Professional Paper 659, 98 p., 17 plates.
- Manheim, F. T., and Horn, M. K., 1968, Composition of deeper subsurface waters along the Atlantic continental margin: *Southeastern Geology*, v. 9, p. 215–236.
- Meisler, Harold, 1989, The occurrence and geochemistry of salty ground water in the northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper P 1404-D, p. D1–D51.
- Meisler, H., Leahy, P. P., and Knobel, L. L., 1984, Effect of eustatic sea-level changes on salt-water-freshwater in the northern Atlantic coastal plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Olsson, R. K., Gibson, T. G., Hansen, J. J., and Owens, J. P., 1988, Geology of the Atlantic coastal plain: Long Island to Virginia, *in* The geology of North America, v. 1-2, the Atlantic continental margin: Geological Society of America, p. 87–105.
- Otton, E. G., and Mandle, R. J., 1984, Hydrogeology of the upper Chesapeake Bay area, Maryland with emphasis on aquifers in the Potomac Group: Maryland Geological Survey Report of Investigations No. 39, 62 p.
- Pope, D. A., and Gordon, A. D., 1999, Simulation of ground-water flow and movement of the freshwater-saltwater interface in the New Jersey coastal plain: U.S. Geological Survey Water-Resources Investigations Report 98-4216, 159 p.
- Richards, H. G. 1974, Structural and stratigraphic framework of the Atlantic coastal plain, *in* Oaks, R. Q., Jr., and DuBar, J. R., eds., Post-Miocene stratigraphy, central and southern Atlantic coastal plain: Logan UT, Utah State University Press, p. 11–19.
- Trapp, H., Jr., 1992, Hydrogeologic framework of the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404-G, 59 p., 13 plates.

- Trapp, H., Jr., and Horn, M. A., 1997, Ground water atlas of the United States—segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia: U.S. Geological Survey Hydrologic Investigations, Atlas No. HA-730-L, 30 p.
- Trapp, H., Jr., Knobel, L. L., Meisler, H., and Leahy, P. P., 1984, Test well DO-CE 88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey, Water-Supply Paper 2229, 48 p.
- Trapp, H., Jr., and Meisler, H., 1992, The regional aquifer underlying the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York—summary: U.S. Geological Survey, Professional Paper 1404A, 33 p., 11 plates.

Prepared by Andrew Warne.

## LYONS SANDSTONE, DENVER BASIN

### General Setting

The Denver Basin is an elongated, asymmetric structure. The east flank has a west dip of about 30 to 50 ft/mi, and the west flank has a steep east dip, interrupted by large anticlines. The axis runs from north to south parallel to the Front Range. The deepest part of the basin lies near Denver, Colorado, with a sedimentary cover of about 13,500 ft (~4,100 m) and 12,000 ft (~3,700 m) near Cheyenne, Wyoming. The basin is bounded on the west by the Laramide and the Front Range Uplifts, on the east by the Chadron and Cambridge Arches, and on the south and southeast by the Apishapa and Las Animas Arches.

### Information Search and Selection

One of the main considerations in selecting the Lyons Sandstone in the Denver Basin was its depth and its isolation for preventing CO<sub>2</sub> contamination of natural resources such as potable ground water, gas, or oil.

The Permian Lyons Sandstone has the greatest potential for being injected with CO<sub>2</sub> in the south-central part of the basin, and some areas to the east should be eliminated because of oil production. Besides the Lyons Sandstone, the porous sandstone reservoir from the Triassic (Dockum sandstone), the Triassic-Jurassic (Jelm-Entrada sandstone), and sandstone units in the Cretaceous Dakota Group may have conditions favorable for storing CO<sub>2</sub>.

### Comments on Geologic Parameters

Each of the geologic parameters selected for the GIS data base is now briefly described. The reference list at the end summarizes some of the documents that are relevant to the Lyons Sandstone in the study area.

- 1lyons: Depth. Even though several dip and strike cross sections that include the Lyons Sandstone are found in the literature, one complete depth map of the Lyons Sandstone for the entire basin was not found. The depth map was estimated by using the depth map of the Dakota, as suggested by Garbarini and Veal (1968, p. 176). They mentioned that the depth to the Lyons can be estimated by adding amounts ranging from approximately 700 ft (Apishapa Uplift) and 1,000 ft (central basin) to the Dakota depths. The depth map in GIS shows depths ranging from 2,000 ft to the east to 10,000 ft at the axis of the basin. Levandowski and others (1973) presented structural maps of the Lyons Formation in producing oil fields.
- 2lyons: Permeability/hydraulic conductivity. Several pieces of permeability information were gathered. Measurements from core data show intrinsic permeability for the Lyons between 0.1 and 3,000 md (Belitz and Bredehoeft, 1988). According to oil-field data in the subsurface, Lyons average permeability ranges from 0.9 to 88 md/ft (Levandowski and others, 1973). A transmissivity-simulated map (Belitz and Bredehoeft, 1988) was added to the GIS data base.
- 3lyons: Formation thickness. Two different maps were found for the Lyons Formation for the north part of the basin. One map was published by Sonnenberg (1981) and one by Levandowski and others (1973). The maps have some discrepancies, so we decided to use the latest because this publication also contains permeability data used in this study. In addition, a map from the south part, published by Garbarini and Veal (1968), was combined with the map from the north part, gridded (c3lyons) and added to the GIS data base. The mapped maximum thickness of the Lyons Sandstone is 300 ft.
- 4lyons: Net sand thickness. The thickness map approximates the net-sandstone map (c4lyonsg) in the west part of the area because the Lyons Sandstone should be close to 95 percent sand. The amount of sand should decrease to the east where the Lyons consists primarily of interbedded red beds and evaporates, as is described later in the sand-body continuity section.

5lyons: Percent shale. As described in 4lyons, no detailed lithology mapping of the Lyons Formation was identified.

6lyons: Continuity. The Lyons Sandstone of Leonardian age crops out along the east side of the Colorado Front Range. During the Permian, a broad sea intermittently covered an area of low relief, where sediments, including the Lyons, were deposited in environments ranging from fluvial to normal marine to hypersaline. To the west, the Lyons lies conformably on the Fountain Formation of Pennsylvanian age, and to the east the red beds of the Lyons thin, become finer grained and pinch out into a siltstone, shale, and evaporitic facies. The evaporites were accumulated in two major subbasins present in the Permian. The Alliance Basin to the north and the Sterling Basin (Lee and Bethke, 1994). The Lyons Sandstone formed as a nearshore deposit, showing evidence of both shore and eolian processes, and was deposited along a band between the emergent ancestral Rocky Mountains and the evaporite basins, as is shown in the lithofacies map prepared for the GIS data base.

7lyons: Top-seal thickness. The Lynkis Formation of Triassic age lies conformably on the Lyons Formation. The gridded isopach map of the Lynkis Formation shows thickness that ranges from 250 to 500 ft (c7lyons). The Lynkis Formation is composed of red shale and siltstone, evaporite, and carbonate. The digitized map comes from the *Geological Atlas of the Rocky Mountain Region* (1972).

8lyons: Continuity of top seal. Faulting is scarce in the basin except at the west margin, where a mayor fault system marks the border between the basin and the Front Range Uplift. Smaller uplifts limit the basin on the south, east and north. For example, the Las Aminas Arch and the Apichapa Uplift bound the basin on the southeast. The diagenetic cementation presented in the Lyons Sandstone seems to act as a barrier, limiting the vertical flow.

9lyons: Hydrocarbon production. The primary producing plays in the Denver Basin are the Dakota Group (Combined D and J Sandstones) and the J Sandstone Deep Gas (Wattenberg). Approximately 90 percent of the 800 MMbbl and 1.2 Tcf produced from the basin has been from the J sandstone. Oil was discovered in the Lyons

Sandstone in 1953 at Keaton field. The largest fields are Black Hollow and Pierce in Weld County, Colorado, which have each produced more than 10 MMbbl. Four fields are located in the Lyons Sandstone—Berthoud, Black Hollow, New Windsor, and Pierce. Average porosity and permeability for fields are about 9 to 12 percent and 21 to 88 md, respectively.

10lyons: Fluid residence time. Several simulation models have been run for the Denver Basin. Lee and Bethke (1994) simulated ground-water flow resulting from the Eocene Uplift on the Front Range. As the Front Range merged from the Laramide deformation, basin fluids migrated to the east in response to the hydraulic gradient created by the water table. Ground-water flow is active today (Belitz and Bredehoeft, 1988 in Lee and Bethke, 1994). Present-day flow velocities are not known, but the model calculated by Lee and Bethke (1994) estimates a rate of about 20 m/yr in the Lyons Sandstone. The rate should be slower because the Lyons pinches out to the east, and it also is not hydraulically continuous across the basin.

11lyons: Flow direction. The hydraulic potential and the modeled flow regime in the underlying Fountain Formation (Lee and Bethke, 1994) show that fluids in the Fountain Formation flow along the basin's axis. As the Fountain flowpath pinches out, brine discharges upward into the Lyons, mixes with ground waters, and then migrates to the east. The potential simulated map added to the GIS data base of the Triassic-Permian unit by Belitz and Bredehoeft (1988) also shows flow movement to the east.

12alyons: Formation temperature. The geothermal gradient in the Denver Basin ranges from 30° to 40° C/km (1.65° to 2.2° F/100 ft) (Sorey and Reed, 1984, in Belitz and Bredehoeft, 1988). The depth map of the Lyons Sandstone was used with the geothermal gradient to calculate the brine temperature for the Lyons Sandstone in the GIS data base.

12blyons: Formation pressure. Limited data indicate that the Lyons Sandstone reservoir has abnormally low pressures, at least locally in the Apishapa Uplift to the south. Pressures of less than 50 psi have been recorded at a depth of 1,100 ft. The

subnormal fluid pressure in the Denver Basin has been explained as a consequence of the steady-state regional ground-water flow (Belitz and Bredehoeft, 1988).

12 Lyons: Formation-water salinity. No salinity map was found for the Lyons Sandstone.

13 Lyons: Rock/water reaction. The Lyons is a quartzose sandstone ranging from red to gray, with fine to coarse, well-sorted grains. Cement includes silica, anhydrite, and calcite. The red facies contains iron oxide, quartz overgrowths, and calcite cements (Hubert, 1960). The gray facies that occurs deep in the basin has dolomite and anhydrite cement and little iron oxide and calcite (Lee and Bethke, 1994). The gray facies formed by ground-water flow resulting from the Laramide Uplift of the Front Range during the Tertiary. In the Ming-Kuo and Bethke (1994) model, the saline ground water flowed eastward through the Pennsylvanian Fountain Formation and then discharged into the Lyons Sandstone. The saline water mixed with the ground water in the Lyons Formation, driving a reaction that dissolved calcite and precipitated dolomite and anhydrite. The distribution of petroleum reservoirs is related to diagenetic cementation patterns (Levandowski and others, 1973).

14 Lyons: Porosity. The Lyons Sandstone has very low matrix porosity but fair to good fracture porosity. In outcrop, the porous beds are discontinuous, but in the subsurface, according to oil-field data, Lyons porosities range from 4.4 to 26.1 percent. (Levandowski and others, 1973)

## References

- Belitz, K., and Bredehoeft, J., 1988, Hydrodynamics of Denver Basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, v. 72, no. 11, p. 1334–1359.
- Clayton, J., and Swetland, P., 1988, Petroleum generation and migration in Denver Basin: American Association of Petroleum Geologists Bulletin, v. 64, no. 10, p. 1613–1633.
- Garbarini, G., and Veal, H. K., 1968, Potential of Denver Basin for disposal of liquid wastes, subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir, p. 165–185.



Geological Atlas of the Rocky Mountain Region, 1972, Rocky Mountain Association of Geologists.

Hubert, J. F., 1960, Petrology of the Fountain and Lyons formations, Front Range, Colorado: Colorado School of Mines Quarterly, v. 55, no. 1, p. 1–242.

Lee, M. L., and Bethke, C., 1994, Groundwater flow, late cementation and petroleum accumulation in the Permian Lyons Sandstone, Denver Basin: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 227–237.

Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217–2244.

Martin, C., 1965, Denver Basin: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1908–1925.

Sonnenberg, S., 1981, Tectonics, sedimentation and petroleum potential, northern Denver Basin, Wyoming, and Nebraska: Colorado School of Mines Quarterly, v. 72, no. 2, p. 215.

Prepared by Martha Romero.

## MADISON GROUP – WILLISTON BASIN

### General Setting

The Williston Basin is an elliptical-shaped, small topographic-relief intracratonic basin that extends from the northern Great Plains of the U.S. into Canada. The basin occupies most of North Dakota, northwestern South Dakota, eastern Montana, and a part of southern Manitoba and Saskatchewan in Canada. The basin is bordered on the east and southeast by the Canadian Shield and the Sioux Uplift. The western and southwestern border limits include the Black Hills Uplift, Miles City Arch, Porcupine Dome, and Bowdoin Dome. The U.S. part of the basin presents a maximum Phanerozoic thickness of 16,000 ft in North Dakota. Sedimentary rocks of Cambrian through Holocene age are present in the basin. The basin began subsiding during Late Cambrian or Early Ordovician time and has continued to subside through time. The style of deformation has been explained as horizontal compression, vertical tectonics, and wrench-fault tectonics. Present structure has been controlled by the Precambrian structure that was modified by the Laramide deformation. Even though Paleozoic and Mesozoic rocks are exposed, most studies are of subsurface data (Gerhard and Anderson, 1988; Peterson, 1988;).

### Information Search and Selection

Formation properties in the Williston Basin are unusually well documented. Maps of different formations capable of storing CO<sub>2</sub> in sandstone and carbonate brine formations from Cambrian to Lower Cretaceous can be found in the literature.

Subsurface disposal in the Williston Basin is restricted to three main divisions: the lower siliciclastic division (Middle to Upper Cambrian Ordovician), about 1,600 ft thick, the middle carbonate-evaporitic division (Ordovician to Mississippian), about 4,800 ft, and the upper siliciclastic division (Jurassic to Holocene), 5,300 ft. The Mississippian Madison carbonate–evaporitic group was selected for this study (even though it is one of the main oil producers in the basin) not only because of its depth and the presence of a high-

density brine on the northeastern flank of the basin but also because of the presence of other good CO<sub>2</sub> storage characteristics that are described later.

Almost the entire set of maps that was used for the GIS data base for the 14 properties was published by Downey (1984, 1986). Only two formation property maps came from others sources.

### Comments on Parameters

Each of the 14 parameters, for the U.S. part of the basin only, is now briefly described, and a reference list that summarizes the documents that are relevant to the Madison Group is presented at the end.

- 1madison: Depth. A map by Peterson (1988) was used for this study and gridded (c1madison.g). The map shows maximum depth of about 6,000 ft to the north.
- 2madison: Permeability/hydraulic conductivity. The development of karst, sink holes, caves, and solution breccias is common in the Madison Group, modifying the permeability. Movement along major faults and lineaments may have affected permeability over a large area and through time. Madison permeability is secondary to fracture permeability (Downey, 1984, 1986). Flow-net analysis assumes that a steady-state flow condition exists and no leakage is occurring from or to adjacent aquifers. The transmissivity is about 0,013 ft<sup>2</sup>/s (Konikow in Downey, 1984, 1986). Other studies suggest that some leakage from overlying rocks may be present and that the transmissivity value should be less than 0,013 ft<sup>2</sup>/s. According to Downey (1984, 1986), the variation in transmissivity values reported by several scientists is the result of local conditions and may not reflect the average on a regional scale. As a result of his analysis, Downey found that transmissivity values are related to porosity (fracturing porosity). A simulated transmissivity map by Downey (1986) was therefore added to the GIS data base.
- 3madison: Formation thickness. A map by Peterson (1981, in Downey, 1984, 1986) was used for this study. The gridded map shows thickness ranging from 0 to 2,800 ft to the north (c3madison).

- 4madison: Net sand thickness. This property is not applicable to the Madison Group because it is a carbonate-evaporite sequence.
- 5madison: Percent shale. This property is not applicable to the Madison Group because it is a carbonate-evaporite sequence.
- 6madison: Continuity. The Madison carbonate-evaporite system was deposited in carbonate-platform environments that graded laterally and vertically to deep-water facies. The Madison Group is formed by the Lodgepole Limestone (cyclic carbonate sequence), Mission Canyon Limestone (coarse limestone to finer limestone and evaporates at the top), and the Charles Formation (evaporite sequence, anhydrite, and halite). Vertical leakage is restricted by shale, halite beds, and stratigraphic traps or low-permeability zones.
- 7madison: Top-seal thickness. The Big Snowy Group and the Charles are the top seal for the Madison Group. The top-seal map (Peterson, 1981, in Downey, 1986) shows maximum thickness for the Big Snowy Group of about 1,000 ft.
- 8madison: Continuity of top seal. The Big Snowy Group top seal has a restricted extent and is present only in part of Montana and the east part of North Dakota. Fracture systems and lineaments affect the fluid flow by performing either as barriers or as conduits. A facies map for the Big Snowy Group, a Paleozoic structural fault map, and the lineament pattern map were added to the GIS data base for this area.
- 9madison: Hydrocarbon production. Exploration in the Williston Basin started with the discovery of gas in the Upper Cretaceous Eagle Sandstone on the Cedar Creek Anticline in southeastern Montana in the earliest 1900's. Hydrocarbons have been produced from reservoirs of Cambrian, Ordovician (Red River), Silurian, Devonian (Pre-Bakken–Post-Prairie Salt, Pre-Prairie Middle Devonian and Silurian, Mississippian (Madison), Pennsylvanian, and Triassic ages. Unconventional continuous-type plays are also important in the Williston Basin.
- 10madison: Fluid residence time. An area of minimal ground-water flow on the northeastern flank of the Williston Basin coincides with the area of high concentration of dissolved solids, as shows on the map by Downey (1986),

digitized for this parameter. Rate of movement of about 2 ft/yr is calculated for this north area.

11madison: Flow direction. The final potentiometric map by Downey (1986) and used in this project was the result of a detailed analysis also using the previous potentiometric maps contoured for the Madison Group by Miller and Strausz (1980, in Downey, 1986).

12amadison: Formation temperature. Water in the area varies significantly in temperature and in dissolved solids concentration, and as a result the density and viscosity vary from area to area. Available data for the ground-water temperature of the Madison Group show variations between 46° F in or near outcrop areas to about 300° F in some deeper parts of the basin. The units for the water-temperature map by Downey (1986) (modified from MacCay, 1984) are in degrees Celsius.

12bmadison: Formation pressure. No pressure data were found.

12cmadison: Formation salinity. Water in the area varies significantly in dissolved solids concentration and in temperature, and the density and viscosity vary from area to area. The highest TDS concentrations of about 10,000 to 300,000 mg/L are on the northeast side of the basin, as shown in the concentration of dissolved solids on the GIS map by Busby (1981, in Downey, 1984, 1986).

13madison: Rock/water reaction. The development of karst, sink holes, caves, and solution breccias is common in the Madison Group. A map of three main chemical facies distributions for water (bicarbonate, sulfate, and chloride facies) by Busby (1982, in Downey, 1986) represents this property in the GIS data base.

14madison: Porosity. Movement along major faults and lineaments may affect porosity over a large area and through time, making porosity fracture important in the area. Contours in the porosity map represent the thickness of rock having porosity greater than or equal to 10 percent.

## References

- Busby, J., Plummer, L., and Hansshaw, B., 1991, Geochemical evolution in the Madison in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1272-f, 89 p.
- Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.
- 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.
- Downey, J. S., and Dinwiddie, G. A., 1988, The regional aquifer system underlying the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-A, 64 p.
- Gerhard, L. C., and Anderson, S. B., 1988, Geology of the Williston Basin (United States portion): The Geology of North America, v. D-2, Sedimentary Cover—North America Craton: U.S.: Geological Society of America, p. 221–240.
- MacCay, L. M., 1984, Apparent water resistivity, porosity and water temperature in the Madison Limestone and underlying rocks in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-D, 14 p.
- Peterson, J. A., 1988, Geologic summary and hydrocarbon plays, Williston Basin, Montana, North and South Dakota, and Sioux Arch, South Dakota and Nebraska, U.S.: U.S. Geological Survey Open-File Report 87-450-N, 43 p.
- Peterson, J. A., Longman, M. W., Anderson, S. B., Pilatzke, R. H., and Kent, D. M., 1987, Williston Basin, anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, 440 p.

Prepared by Martha Romero.



## MORRISON FORMATION, SAN JUAN BASIN

### General Setting

The San Juan Basin formed during the Late Cretaceous-early Tertiary Laramide orogeny as an asymmetric syncline that steepens the northwest limb (Kernodle, 1996). In most areas, the basin is well defined by bounding faults and other structural features (for example, the Defiance and Nutria Monoclines). However, in some areas (for example, the Gallup and Acoma Sags and the Four Corners Platform), the boundary from the San Juan to adjacent basins is much less distinct (Kernodle, 1996).

Anderson and Lucas (1995), called into question the previously accepted stratigraphic definition of the Morrison. They instead defined the Morrison Formation as a two-member unit with a base of Morrison coincident with the “J-5” sequence boundary, thus excluding the Recapture Member from the Morrison and including it in the older San Rafael Group. Anderson and Lucas (1995) also proposed that the so-called “Westwater Canyon Member” is actually equivalent to the Salt Wash Member. They proposed that the base of the Morrison occurs at a regionally traceable scour surface. In the northwest San Juan Basin, this change is significant because the base of the Morrison, as now defined, is the base of what had been called the “Westwater Canyon Sandstone Member” but which Anderson and Lucas consider to be the Salt Wash Member. As early as 1980, Green (1980) identified and mapped this unconformity and suggested that it was a significant surface because, among other things, no uranium ore deposits existed below the unconformity. However, the U.S. Geological Survey study by Kernodle (1996), from which we have taken many data, specifically includes the Recapture and Westwater Canyon Members as part of the Morrison.

Regardless of the sequence stratigraphic interpretation of the Morrison Formation, the literature (for example, Kernodle, 1996) suggests that there is a confined aquifer in the San Juan Basin roughly equivalent to the lower portion of the Morrison. This aquifer is overlain by a less-permeable unit composed of green, olive, and maroon mudstone interbedded with tuff beds (Aubrey, 1992) known as the Brushy Basin Member.



Therefore, with regard to the current study, the main consequence of this stratigraphic controversy is not whether there is a potential CO<sub>2</sub> sequestration target but whether it includes or excludes certain members. The user should be aware that the maps of Dam and others (1990) and Kernodle (1996) used in this study include the Recapture Member in the Morrison Formation.

### Comments on Geologic Parameters

1morrison: Depth. We digitized depth to top of the Morrison ( Dam and others, 1990) from the U.S. Geological Survey hydrologic investigations atlas and gridded it (g1morrison).

2morrison: Permeability / hydraulic conductivity. Permeability / hydraulic conductivity is from Dam and others (1990), U.S. Geological Survey hydrologic investigations atlas.

3morrison: Formation thickness. Formation thickness is from Dam and others (1990), U.S. Geological Survey hydrologic investigations atlas. Isopach was gridded in 5-km cells (c3morrison).

4morrison: Net sand thickness. The net-sand-thickness map of the Grants uranium district (Kirk and Condon, 1986) offers an approximation of the net sand for the Morrison Formation in that area that was gridded (c4morrison). We did not identify a net-sand map for the entire basin.

5morrison: Percent shale. The percent-sandstone map of the Grants uranium district (Kirk and Condon, 1986) offers an approximation of the percent shale (1 percent) for the Morrison Formation in that area. The only other number we encountered was a value of “>25% fines” (Freethey, 1987b, his fig. 2, p. 85). We found no percent-shale map for the Morrison Formation in the entire basin.

6morrison: Continuity. The continuity of the Morrison aquifer can be estimated from the sandstone isolith map of Galloway (1980), in addition to the outcrop patterns and faults on the edge of the basin. These fluvial sandstones are highly heterogeneous.

7morrison: Top-seal thickness. The Brushy Basin Member of the Morrison Formation consists mostly of a mudstone and claystone lithology composed to varying

degrees of smectitic clays (Turner and Fishman, 1991). We propose this unit as the regional seal for the sand-dominated units that compose the brine formation selected for consideration of CO<sub>2</sub> sequestration. We found an isopach map for the Brushy Basin Member only in a small area of the Grants uranium district, but Turner and Fishman (1991) did provide a map of the different clay mineralogies of the unit. By extrapolation, we present this map as a first-order approximation of the continuity of the Brushy Basin Member. Turner and others (1991) also presented a cross section (their fig. 1, A–A') that contains measured sections at Beclabito (west of Shiprock, NM) and Piedra River (east of Durango, CO). The sections contain more than 50 and 90 m (gross), respectively, of the Brushy Basin Member. The Piedra River section contains at least 40 m of authigenic albite tuffs. Presumably these tuffaceous and altered tuffaceous deposits thin southwestward toward the Beclabito section, where tuffaceous material composes much less (<20 percent) of the section (fig. 4, Turner and others, 1991). We assume that the claystone and tuffaceous lithologies constitute the aquitard that confines the underlying aquifer.

8morrison: Continuity of top seal. In his paper on ground-water resources of the upper Colorado River Basin, Freethey (1987a, p. 61) identified the Brushy Basin as the confining unit of the Morrison aquifer. Even though Freethey's assessment is only for Colorado, Utah, and Arizona, the literature (for example, Turner and others, 1991) suggests that this general configuration is also appropriate for the San Juan Basin. Freethey (1987a) described the confining units in his study (including the Brush Basin Member) as leaky. Additional characterization is needed.

9morrison: Hydrocarbon production. Oil- and gas-field outlines and age of producing horizon from Fassett (1991).

10no data: Fluid residence time. We found no data on fluid residence time in the Morrison Formation of the San Juan Basin.

11morrison: Flow direction. The flow of fluids in the Morrison aquifer is generally from the recharge areas rimming the San Juan Basin toward the center of the basin (Dam and others, 1990).

- 12amorrison: Formation temperature. Formation temperature from Dam and others (1990), U.S. Geological Survey hydrologic investigations atlas.
- 12bnodata: Formation pressure. We did not find any pressure data for the Morrison Formation.
- 12cmorrison: Formation-water salinity. Salinity from Dam and others (1990), U.S. Geological Survey hydrologic investigations atlas.
- 13morrison: Rock / water reaction. These immature and tuffaceous sandstones have the potential to react with high-CO<sub>2</sub> brine.
- 14morrison: Porosity. The only porosity values we found for the Morrison Formation were in an article by Freethey (1987a, p. 63), in which he offered a diagram of effective porosity for the five aquifers (including the Morrison) that he studied in the Colorado Plateau region, exclusive of the San Juan Basin. The mean value for the Morrison is near 13.5 percent, with a standard deviation of approximately 12.5 percent. We took these values directly from the diagram because they were not mentioned in Freethey's (1987a) text. Freethey calculated these values from a total of 22 samples. None of the samples is from our study area, but by extrapolation they provide a general approximation of the porosity in the Morrison of the San Juan Basin.
- 15morrison: Water chemistry. We located maps from Dam and others (1990) showing chemical-constituent diagrams on a map of the basin; however, these were not suitable for digitization. Also, Freethey (1987a) mentioned that the water is typically a sodium chloride type where concentrations exceed 35,000 mg/L and a calcium bicarbonate type where concentrations are less than 2000 mg/L.
- 16morrison: Rock mineralogy. The framework grains of the coarser grained sandstone of the "Westwater Canyon" ("Salt Wash" of Anderson and Lucas, 1995) Member consist mostly of quartz, microcline, sodium plagioclase, and lithic fragments of various types. The finer grained beds often consist of fine-grained sandstone, mudstone, and rare limestone nodules and lenses, but locally they are greenish-gray smectitic mudstones (Turner-Peterson, 1987). The Brushy Basin Member has similar lithology, but the ratio of coarse-grained beds versus finer grained

material is significantly lower. Also, tuff beds containing a variety of authigenic minerals constitute a significant fraction of the Brushy Basin Member (Turner-Peterson, 1987). These authigenic minerals include mixed-layer illite-smectite, clinoptilolite, analcime, potassium feldspar, albite, silica in the form of quartz and chalcedony, and calcite. Much of the mudstone in the Brushy Basin Member is bentonitic. (Turner-Peterson, 1987).

## References

- Anderson, O. J., and Lucas, G., 1995, Base of the Morrison Formation, Jurassic, of northwestern New Mexico and adjacent areas, *New Mexico: Geology*, v. 17, no. 3, p. 44–53.
- Aubrey, W. M., 1992, New interpretations of the stratigraphy and sedimentology of uppermost Jurassic to lowermost Upper Cretaceous strata in the San Juan Basin of northwestern New Mexico: *U.S. Geological Survey Bulletin B 1808-J*, p. J1–J17.
- Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: *U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J*, 2 sheets.
- Fassett, J. E., 1991, Oil and gas resources of the San Juan basin, New Mexico and Colorado, *in* Gluskoter, H. J., Rice, D. D., and Taylor, R. B., eds., *The decade of North American geology*, v. P-2, *Economic Geology*, U.S.: Geological Society of America, p. 357–372.
- Freethy, G. W., 1987a, Upper Colorado River Basin regional aquifer-systems analysis—Mesozoic rocks in Colorado, Utah and Wyoming, Arizona, and New Mexico, *in* McLean, J. S., and Johnson, A. I., eds., *Regional aquifer systems of the United States—aquifers of the western mountain area: 23<sup>rd</sup> Annual American Water Resources Association (AWRA) Conference and Symposium*, Salt Lake City: AWRA Monograph Series No. 14, p. 57–70.
- \_\_\_\_\_, 1987b, Lithologic and hydrologic properties of Mesozoic rocks in the Upper Colorado River Basin, Mexico, *in* McLean, J. S., and Johnson, A. I., eds., *Regional aquifer systems of the United States—aquifers of the western mountain area: 23<sup>rd</sup> Annual American Water Resources Association (AWRA) Conference and Symposium*, Salt Lake City: AWRA Monograph Series No. 14, p. 81–100.
- Galloway, W. E., 1980, Deposition and early hydrologic evolution of the Westwater Canyon and other fluvial fan systems, *in* Rautman, C. A., compiler, *Geology and mineral technology of the Grants uranium region*: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 59–69.

- Green, M. W., 1980, Disconformities in Grants mineral belt and their relationship to uranium deposits, *in* Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 70–74.
- Kernodle, J. M., 1996, Hydrogeology and steady-state simulation of ground-water flow in the San Juan Basin, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey, Water-Resources Investigations Report 95-4187, 117 p.
- Kirk, A. R., and Condon, S. M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—a subsurface study, *in* Turner-Peterson, C. E., Santos, E. S., and Fishman, N. S., eds., A basin analysis case study: the Morrison Formation Grants uranium region New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 105–143.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Turner, C. E., and Fishman, N. S., 1991, Jurassic Lake T'oo'dichi': a large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, no. 4, p. 538–558.
- Turner-Peterson, C. E., 1987, Sedimentology of the Westwater Canyon and Brushy Basin Members, Upper Jurassic Morrison Formation, Colorado Plateau, and relationship to uranium mineralization: University of Colorado, Ph.D. dissertation, 169 p.

Prepared by Ramón H. Treviño.

## MT. SIMON FORMATION, MICHIGAN BASIN AND OHIO AREA

### General Setting

The oval Michigan Basin developed mostly during the Silurian as an intra-cratonic sag basin (Fisher, and others, 1988). The Mt. Simon Sandstone is the basal unit in most of the basin, and it unconformably overlies the Precambrian basement. However, because of the relatively few wells drilled to or through the formation, most of what is known about the Mt. Simon comes from outcrop studies. Driese and others (1981) described the Mt. Simon in Wisconsin as a basal quartz arenite (> 95 percent quartz) that is 0 to 65 m thick and submature to mature. They interpreted the formation as a largely progradational (regressive), shoaling- and fining-upward tidal sequence containing widespread marine trace fossils. The Mt. Simon Formation lies unconformably upon Precambrian igneous and metamorphic rocks and grades upward into fine-grained sandstones and shales of the Eau Claire Formation (Driese, and others, 1981). Gupta and Blair (1997, p. 1985) mentioned that “the only known commercial use for the Mt. Simon Formation in the mid-continent basins and arches area is as a reservoir for the disposal of hazardous-liquid wastes.”

### Information Search and Selection

The main problem in assessing the Mt. Simon as a target reservoir for CO<sub>2</sub> sequestration in the Michigan Basin is the depth of the formation. As the deepest extensive rock unit in the basin, there are relatively few wells drilled to or through the formation, especially in the central, deeper parts of the basin. Therefore, a paucity of data is available to evaluate the Mt. Simon, and any assessment of the Mt. Simon, including this one, takes this into consideration. Nonetheless, the available data do allow for some general understanding of the Mt. Simon Formation and the aquifer that it contains. The content of this data base profited greatly from data developed by N. Gupta, Battelle

Memorial Institute, and sent to us in digital form. The reader is referred to his work for additional details assessing the suitability of the Mt. Simon for CO<sub>2</sub> storage.

### Parameter Description

1mtsimon: Depth. We received a digital data base giving structural elevation of the top of the Mt. Simon in wells from N. Gupta, Battelle Memorial Institute (digital communication, 1999), and we gridded his point coverage (5-km cells) rather than piecing together structure-contour data. These data could be refined by using numerous high-resolution structure maps on basement and shallower horizons. Depth to top formation (c1mtsimon) was calculated by subtracting gridded elevation from a gridded DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000).

2mtsimon: Permeability / hydraulic conductivity. Vugrinovich (1986) stated that core analyses near the rim of the basin “show high permeabilities,” but “the only drill stem test of the Mt. Simon in the central basin indicated low permeability over approximately 94 meters of section.” Briggs (1968, p. 139) stated that “as the proportions of limestone, dolomite, and carbonate-mineral cement increase toward the south and east in the Michigan Basin, the porosity and permeability of the sandstone should decrease proportionally.” However, we were only able to obtain permeability data for one well (Briggs, 1968), and we utilized the average permeability in the Mt. Simon for that well.

3mtsimon: Formation thickness. We digitized and gridded (c3stsimong) an isopach map of thickness of the Mt. Simon (Catacosinos and others, 1986) in the Michigan Basin and gridded a point coverage of thickness of the Mt. Simon derived from the data base of Gupta (digital communication, 1999) for the Ohio area.

4no data: Net sand thickness. We were unable to locate a net-sand map of the Mt. Simon Formation. Vugrinovich (personal communication, 2000) stated that to his knowledge, no maps exist for net sand thickness.

5no data: Percent shale. We were unable to identify data suitable for quantifying net shale.

- 6nodata: Continuity. Just as for net sand and percent shale, no maps were located.
- 7mtsimon: Top-seal thickness. We gridded the isopach map of the Cambrian silty dolomites, dolomitic sandstones, and shales of the Eau Claire Formation from Catacosinos and others (1986) (c7mtsimong). Overlying low-permeability carbonate units may also retard upward communication.
- 8mtsimon: Continuity of top seal. According to Vugrinovich (1986), the “Upper Cambrian silty dolomites, dolomitic sandstones and shales” function as an aquitard. We interpret this to mean that they are a regional aquitard. The isopach map of Catacosinos and others (1986) does show one area in south-central Michigan where the Eau Claire thins to a thickness of zero.
- 9mtsimon: Hydrocarbon production. We found no specific mention of hydrocarbon production from the Mt. Simon in the Michigan Basin. However, Catacosinos and others (1991) provided maps showing fields that have produced from Cambrian as well as younger units in the basin.
- 10nodata: Fluid residence time. Vugrinovich (personal communication, 2000) stated that to his knowledge, no fluid-residence-time data exist. We found no data of this type.
- 11mtsimon: Flow direction. Flow direction inferred from maps of Vugrinovich (1986) and other workers in the Mid-Continent basins and arches region are paradoxical with respect to developing a conceptual model of flow for the region. The inferred flow directions from maps based on equivalent freshwater heads have flow moving updip, out of the Michigan Basin, whereas inferred flow directions from maps based on variable-density heads have flow moving downdip into the basin (Gupta and Blair, 1997). Because his map contains the most data points in the Michigan Basin, we have used Vugrinovich’s map of hydraulic head for the Mt. Simon.
- 12amtsimon: Formation temperature. According to Sass and others (1998) and Vugrinovich (personal communication, 2000), temperature measurements of the Mt. Simon are very scarce. Therefore, we have used the generally accepted temperature gradient for the Michigan Basin, 25° C / km (Cercione, 1984). We



- also have used one data point obtained from Vugrinovich (personal communication, 2000).
- 12bmtsimon: Formation pressure. We calculated a pressure gradient of 0.0095 Mpa/m from a pressure vs. depth diagram (Vugrinovich, 1986). Additionally, we added 16 pressure data points supplied to us by Vugrinovich, (personal communication, 2000) in our analysis. Gridded data are presented in c12bmtsimon.
- 12cnodata: Formation-water salinity. We did not find any salinity data. In a personal communication (2000), Vugrinovich stated that “the water compositional data for the Mt. Simon is [sic] really not to be trusted and in any case, only one or two analyses are available.” Therefore, we have not included any in our study.
- 13mtsimon: Rock / water reaction. The Mt. Simon is a feldspathic quartz sandstone. Potential for reaction of the minerals with high-CO<sub>2</sub> brine is low.
- 14mtsimon: Porosity. Vugrinovich (1986) stated that core analyses of the Mt. Simon near the rim of the basin show porosities that are “quite high.” In a personal communication, Vugrinovich (2000) stated that the disposal wells in the southern Lower Peninsula and the oil and gas tests penetrating the Mt. Simon were logged with porosity tools. The data are available in the form of hard-copy logs. However, no one has ever attempted to compile a regional (or even local) porosity distribution map. In addition, “there is no demonstrable relationship between depth in the sandstone interval and porosity or permeability.” However, there is a high correlation coefficient (0.86) between porosity and permeability (Briggs, 1968; p. 140).
- 15mtsimon: Water chemistry. (See comment of Vugrinovich [personal communication, 2000] in 12c.) Therefore, we have not included any water chemistry analyses for the Mt. Simon in our study.
- 16mtsimon: Rock mineralogy. In cores and cuttings of the Mt. Simon sandstone in the subsurface of Michigan and from outcrops in adjacent areas, the rock is a feldspathic quartzose sandstone, and most is arkose. “Many of the quartz and feldspar grains have authigenic overgrowths of secondary-mineral cement.” (Briggs, 1968; p.141). However, one should keep in mind that Briggs had a very

small data set to choose from. The outcrop observations of Driese and others (1981) (that the Mt. Simon is a quartz arenite) must be taken into account as well. Nonetheless, Briggs (1968) provided a table of rock mineralogy from the Consumers Power Company Brine Disposal No. 139, and we have included it in our analysis.

## References

- Briggs, L. I., 1968, Geology of subsurface waste disposal in Michigan Basin, *in* Galley, J. E., ed., *Subsurface disposal in geologic basins—a study of reservoir strata*: American Association of Petroleum Geologists Memoir 10, p. 128–153.
- Catacosinos, P. A., and Daniels, P. A., Jr., 1986, Stratigraphy of middle Proterozoic to Middle Ordovician formations of the Michigan Basin, *in* Catacosinos, P. A., and Daniels, P. A., Jr., eds., *Early sedimentary evolution of the Michigan Basin*: Geological Society of America, Special Paper 256, p. 53–71.
- Catacosinos, P. A., Harrison, W. B., III, and Daniels, P. A., Jr., 1991, Structure, stratigraphy, and petroleum geology of the Michigan Basin, Chapter 30, *in* Leighton, M. W., Kolata D. R., Oltz, D. F., and Eidel, J. J., eds., *Interior cratonic basins*: American Association of Petroleum Geologists Memoir 51, p. 561–601.
- Cercone, K. R., 1984, Thermal history of the Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 68, no. 2, p. 130–136.
- Driese, S. G., Byers, C. W., and Dott, R. H., Jr., 1981, Tidal deposition in the basal upper Cambrian Mt. Simon Formation in Wisconsin: *Journal of Sedimentary Petrology*, v. 51, no. 2, p. 367–381.
- Fisher, J. H., Barratt, M. W., Droste, J. B., and Shaver, R. H., 1988, Michigan Basin, *in* *The Geology of North America*, v. D-2, *Sedimentary Cover—North American Craton*: U.S.: Geological Society of America, p. 361–382.
- Gupta, Neeraj, 1993, Geologic and fluid-density controls on the hydrodynamics of the Mt. Simon Sandstone and overlying geologic units in Ohio and surrounding states, Columbus, Ohio State University, Ph.D. dissertation, 266 p.
- Gupta, N., and Blair, E. S., 1997, Variable-density flow in the mid-continent basins and arches region of the United States: *Water Resources Research*, v. 33, no. 8, p. 1785–1802.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.

- Reszka, C. R., Jr., 1991, The Michigan Basin, *in* Gluskoter, H. J., Rice, D. D., and Taylor, R. B., The Geology of North America, v. P-2, Economic geology, U.S.: Geological Society of America, p. 287–300.
- Sass, B., Gupta, N., Sminchak, J., and Bergman, P., 1998, Geochemical modeling to assess the capacity of a Midwestern United States geologic formation for CO<sub>2</sub> sequestration, *in* Proceedings of the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland: GHGT-4, p. 1079–1086.
- Vugrinovich, Raymond, 1986, Patterns of regional subsurface fluid movement in the Michigan Basin: Michigan Department of Natural Resources, Geological Survey Division, Open File Report 86-6.

Prepared by Ramón H. Treviño.

## ORISKANY FORMATION, APPALACHIAN BASIN, WESTERN PENNSYLVANIA, EASTERN OHIO, AND EASTERN KENTUCKY

### General Setting

The Appalachian Basin is part of an ancient foreland basin in the eastern United States that contains a thick sequence of relatively undeformed Paleozoic strata. The basin, approximately 300 mi wide (in the north) and 600 mi long, encompasses a broad area between the Allegheny front to the east, the Cincinnati and other contiguous arches to the west, and the Canadian Shield to the north. The south portion of the basin (which is not covered in the GIS) narrows between the Nashville Dome and the Pine Mountain thrust (Schumaker, 1996). The region around Pittsburgh, Morgantown, and Cleveland is near the axis of the basin and is therefore underlain by a thick succession (>10,000 ft) of strata. Because a number of these strata are porous and permeable sandstones that are regionally continuous (Milici, 1996), they are potential targets for CO<sub>2</sub> sequestration. Moreover, the Pittsburgh/Morgantown/Cleveland vicinity has a large concentration of CO<sub>2</sub>-producing power plants (fig. 1).

### Information Search and Selection

The subsurface of this area has been well studied, the research driven by the search for domestic and industrial water supplies, petroleum, and brine disposal. Because shallow aquifers in the area contain copious water supplies, there is little need for hydrogeologic studies of deeper brine aquifers. However, oil and gas exploitation has a long history in this area and has promoted research and analysis of Appalachian Basin stratigraphy (Oliver and others, 1967; Roen and Walker, 1996).

A number of potential porous, permeable, and continuous sand units are beneath the area that could potentially be used for CO<sub>2</sub> sequestration. These strata tend to be shallow in the west, and they progressively deepen eastward toward the Allegheny Front (east of the Allegheny Front the strata are folded and faulted). Therefore, optimal

sequestration horizons vary according to the position in the basin; optimal horizons are typically older on the flanks (such as the Tuscarora, Keefer, and Oriskany Sandstones) and younger in the central basin (such as the Oriskany, Pocono, Berea, and Princeton Sandstones) (Dennison, 1975; Roen and Walker, 1996).

We selected the Lower Devonian Oriskany Sandstone to characterize in the GIS because it is widespread and porous and it occurs at a depth range conducive to CO<sub>2</sub> sequestration over a large portion of the Appalachian Basin. Note that there are a large number of potential horizons, the Appalachian Basin stratigraphy and structure are well known (Roen and Walker, 1996), and there are a number of areas where CO<sub>2</sub> emissions are high (fig. 1). Moreover, because the Oriskany is the principal horizon for brine disposal in western Pennsylvania, it is a proven reservoir for subsurface disposal (Steve Platt, U.S. Environmental Protection Agency, personal communication, 2000).

### Parameter Description

Each of the geologic parameters for the Oriskany Sandstone is now briefly described, and the reasons for selection of the map or data source for the GIS are outlined. The reference list at the end of this summary lists documents that are relevant to the Appalachian Basin stratigraphy and, in particular, the Oriskany Sandstone.

- 1oriskany: Depth. A number of maps show the depth to top of the Oriskany Sandstone, including Diecchio and others (1984) and Harper and Patchen (1996), Opritza (1996), and Patchen and Harper (1996). Only Diecchio and others (1984) provided a regional structural contour map on top of the Oriskany Sandstone, and therefore it was used for the GIS. We then used a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid the depth to top of the Oriskany Sandstone (c1oriskanyg).
- 2oriskany: Permeability/hydraulic conductivity. Because of the high potential (in some areas) for natural gas production in the Oriskany Sandstone, there are a large number of reports, articles, and theses that report permeability in this stratigraphic interval (Headlee and Joseph, 1945; Harper and Patchen, 1996). Moreover, there are many geophysical logs available for the Oriskany Sandstone interval from

which formation permeability can be calculated (Asquith, 1982) if a more detailed assessment is desired. For the GIS, we combined the sand/shale/limestone map of Diecchio and others (1984; their fig. 4) with permeability information from Headlee and Joseph (1945) and Harper and Patchen (1996) to characterize permeability distributions of the Oriskany Sandstone. Permeability was converted to hydraulic conductivity.

3oriskany: Formation thickness. A number of reports and publications map Oriskany Sandstone thickness on a local basis (Stow, 1938; Cate, 1961; Abel and Heyman, 1981; Diecchio and others, 1984). Moreover, there are numerous geophysical logs available of the Oriskany Sandstone interval, from which formation-thickness distribution can be accurately mapped. We gridded the map of Harper and Patchen (1996) to characterize Oriskany Sandstone thickness distribution because it covers the entire northern basin (c3oriskany).

4oriskany: Net sand thickness. There currently is no published Oriskany Sandstone net-sand-thickness distribution for the region, although there are numerous reports showing local sand-thickness distribution (related to hydrocarbon exploration). There are numerous geophysical logs available for the Oriskany Sandstone interval, from which net-sand-thickness distribution can be accurately mapped (Asquith, 1982). Diecchio and others (1984; their fig. 4) presented a map showing general distribution of lithologies (>50 percent sand, >50 percent shale, >50 percent limestone) and formation thickness for the Oriskany Sandstone horizon; their map was used to characterize net sand thickness.

5oriskany: Percent shale. There currently is no published Oriskany Sandstone percent-shale distribution for the region, although there are numerous reports showing local sand thickness and percentage distribution (related to natural gas exploration). There are numerous geophysical logs available for the Oriskany Sandstone interval from which percent shale can be accurately mapped (Asquith, 1982). Diecchio and others (1984; their fig. 4) presented a map showing general distribution of lithologies (>50 percent sand, >50 percent shale, >50 percent

limestone) and formation thickness for the Oriskany Sandstone horizon; their map was used to characterize shale content.

6oriskany: Continuity. Numerous cross sections of the Lower Devonian interval of the central Appalachian Basin (Abel and Heyman, 1981; Diecchio and others, 1984; Harper and Patchen, 1996; Opritza, 1996; Patchen and Harper, 1996) demonstrate that the Oriskany Sandstone interval is generally continuous. The Oriskany has been interpreted as a transgressive sand unit (Diecchio and others, 1984), and these types of sandstones tend to be highly continuous. However, the upper boundary of the Oriskany is an erosional unconformity, which resulted in significant thinning and, in places, removal of the sandstone unit (Abel and Heyman, 1981; Diecchio and others, 1984). To characterize sand-body continuity, we used the map of Diecchio and others, (1984; their fig. 4), which shows a combination of formation thickness and sandstone percentage. Specifically we characterize sand-body continuity as generally good for areas on this map where the formation is more than 50 ft thick and sand content is more than 50 percent. Other areas of Oriskany where the unit is more than 50 ft thick and/or shale and limestone content is more than 50 percent, sandstone continuity is mapped as fair to poor. Note that areas along the western and northwestern boundaries of the mapped generally-good-sand-body continuity may also have good sand-body continuity; sand intervals in these areas are only slightly less than 50 ft thick. The abundant geophysical well logs can be used in specific areas to further define sand-body continuity.

7oriskany: Top-seal thickness. The Oriskany Sandstone is overlain by a cherty Onadaga Limestone and/or the Needmore Shale (Oliver and others, 1967; Milici, 1996). This interval is somewhat effective as a top seal, but it may be permeable in areas because of fracturing. However, the Onadaga Limestone/Needmore Shale interval is overlain by a thick section of Middle Devonian black shale, which makes an excellent regional confining layer. For the GIS, we gridded the map of Oliver and others (1967; their fig. 8), which shows the thickness distribution of the Middle Devonian black-shale interval (c7oriskany).

8oriskany: Continuity of top seal. The Oriskany Sandstone is overlain by a cherty Onadaga Limestone and/or the Needmore Shale (Oliver and others, 1967; Milici, 1996). This interval is somewhat effective as a top seal, but it may be permeable in areas because of fracturing. However, the Onadaga Limestone/Needmore Shale interval is overlain by a thick section of Middle Devonian black shale, which makes an excellent regional confining layer. For the GIS, we chose the map of Oliver and others (1967; their fig. 8), which shows the distribution of lithologies of the Middle Devonian black-shale sequence. This sequence is widely interpreted to be laterally continuous, deep-water black shales (Oliver and others, 1967; Roen and Walker, 1996).

9oriskany: Hydrocarbon production. The Oriskany Sandstone has a long history of hydrocarbon production (Diecchio and others, 1984; Harper and Patchen, 1996; Opritz; 1996; Patchen and Harper, 1996). We used the map of Diecchio and others (1984; their fig. 7) to characterize hydrocarbon production from the Oriskany Sandstone. This map identifies fields and pools, but there are numerous exploration wells not identified, as well as wells drilled to deeper horizons (Roen and Walker, 1996). Therefore, more detailed assessments would be needed if actual CO<sub>2</sub> sequestration sites were to be sought out and evaluated.

10oriskany: Fluid residence time. Headlee and Joseph (1945) and Dressel (1985) discussed brines in the Oriskany. Plots of sodium and chloride versus bromide and versus MCl<sub>2</sub> indicate that the source of the brine is seawater (Dressel, 1985). Moreover, Trapp and Horn (1997) stated that rocks of the Appalachian Plateaus are only mildly deformed. The lower geologic section is unable to receive fresh water as recharge or to readily discharge entrapped fluids such as brine. This statement implies that fluid residence times are extremely long, probably on the order of millions of years. Hence, we put fluid residence times for the Oriskany Sandstone brines across the central Appalachian Basin at more than 1,000,000 yr.

11oriskany: Flow direction. Ground-water flow direction is typically determined by first determining the hydraulic head (essentially water pressure) of ground water in the target interval and mapping change in hydraulic head over an area. However,



there are no published maps showing hydraulic head or hydraulic gradients in the Oriskany because it is not a water-supply aquifer in the central Appalachian Basin. Trapp and Horn (1997) stated that the fractures in Appalachian Basin sediments decrease in number with depth, and that the circulation of water likewise decreases with depth. The implication is that flow is negligible. Therefore, for the GIS, we put “No significant flow” for the Oriskany Sandstone of the central Appalachian Basin.

12aoriskany: Formation temperature. Opritz (1996) and Patchen and Harper (1996) provided temperature versus depth data for the Oriskany Sandstone of the central Appalachian Basin. We plotted their data, which formed a definite gradient such that  $63 + 0.0092 \text{ Depth} = \text{formation temperature (in } ^\circ\text{F)}$ . To derive a temperature-distribution map for the GIS, the temperature gradient at formation depth was calculated (c12oriskanyg).

12boriskany: Formation pressure. Harper and Patchen (1996, their fig. Dos-11) presented a graph showing original reservoir pressures versus drilling depth for 68 Oriskany fields and pools in New York, Pennsylvania, and West Virginia. Although there is some scatter, their data indicate that pressures follow the hydrostatic gradient of 0.44 psi/ft. To derive a pressure-distribution map for the GIS, we multiplied the formation depth by the pressure gradient (0.44 psi/ft) (c12boriskanyg).

12coriskany: Formation-water salinity. Headlee and Joseph (1945), Rosenfeld (1954), and Dressel (1985) provided data regarding Oriskany formation-water salinity. Dressel (1985) reported that total dissolved solids (TDS) in Oriskany brines of northwestern and west-central Pennsylvania range from 9,990 to 343,000 mg/L. Headlee and Joseph (1945) reported brine-salt content at 250,00 mg/L in western West Virginia. For the GIS, we put the range of 9,900 to 343,000 mg/L.

13oriskany: Rock/water reaction. Stow (1938) and Rosenfeld (1954) summarized the mineral composition of the Oriskany Sandstone. Stow (1938) emphasized the variability. However, petrographic analyses indicate that Oriskany is typically composed primarily of quartz (~85 percent), with 11 percent calcareous minerals and shell and about 4 percent (or less) plagioclase, orthoclase, and microcline.

Heavy minerals typically compose 0.2 percent of samples analyzed (Stow, 1938, his table 1), but in one sample were 5 percent. The Oriskany is widely interpreted to be a transgressive sand composed of reworked sediments (Diecchio and others, 1984) and therefore tends not to contain high proportions of labile minerals. Hence, we conclude that, although the Oriskany may vary in mineral content, it is consistently low in labile minerals and therefore has a low potential for rock/water reaction under conditions of increased CO<sub>2</sub>. However, CaCO<sub>3</sub> is a common to abundant component of the Oriskany interval.

14oriskany: Porosity. Because of the high potential for hydrocarbon production in some parts of the Oriskany Sandstone, a large number of reports, articles, and theses report porosity in this stratigraphic interval (Headlee and Joseph, 1945; Harper and Patchen, 1996). Porosity ranges from less than 2 to 12 percent but is generally more than 5 percent in the sandstone intervals. For the GIS, the sand/shale/limestone map of Diecchio and others (1984; their fig. 4) was combined with porosity information from Headlee and Joseph (1945) and Harper and Patchen (1996) to characterize porosity distribution in the Oriskany Sandstone. There are many geophysical logs available for the Oriskany Sandstone interval from which formation porosity can be calculated (Asquith, 1982), if a more detailed assessment is desired.

15oriskany: Water chemistry. Dressel (1985) presented an excellent analysis of the chemistry of Oriskany formation waters from northwestern and west-central Pennsylvania. His results are presented in the GIS.

16oriskany: Rock mineralogy. Stow (1938) and Rosenfeld (1954) presented summaries of the mineralogy of the Oriskany. A number of master's theses also present the results of mineralogic analyses. These theses, which appear on GEOREF computer searches, would require visits to respective universities for examination and copying because they are generally not available through Interlibrary Loan services. The results of Stow (1938) were used for the GIS. Although his results appear thorough and systematic, there is a noticeable lack of calcite in his results. Personal observation of the Oriskany Sandstone in numerous outcrops in the

central Appalachian Basin, as well as the results of Rosenfeld (1954) and Diecchio and others (1984, their fig. 4), demonstrates that the Oriskany interval commonly contains shell material and calcite cement and grades into sandy limestone in places.

## References

- Abel, K. D., and Heyman, L., 1981, The Oriskany Sandstone in the subsurface of Pennsylvania: Pennsylvania Geological Survey, Mineral Resources Report 81, 9 p.
- Asquith, G., 1982, Basic well log analysis for geologists: Tulsa, American Association of Petroleum Geologists, 216 p.
- Cate, A. S., 1961, Subsurface structure of plateau region of north-central and western Pennsylvania on top of the Oriskany Formation: Pennsylvania Geological Survey, Map 9.
- Dennison, J. M., 1975, Stratigraphy of Precambrian through Cretaceous strata of probable fluvial origin in southeastern United States and their potential as uranium host rocks: Southeastern Geology, Special Publication No. 5, 210 p.
- Diecchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.
- Dressel, P. E., 1985, The geochemistry of oilfield brines from western Pennsylvania: Pennsylvania State University, Master's thesis, 128 p.
- Fetter, C. W., 1988, Applied hydrogeology, 2<sup>nd</sup> ed.: New York, Macmillan Publishing Company, 592 p.
- Hall, J. F., 1952, Oriskany sand study: Ohio Geological Survey Report of Investigation 13, Petroleum and Natural Gas Series, Part 2, p. 39–58.
- Harper, J. A., and Patchen, D. G., 1996, Play Dos: the Lower Devonian Oriskany Sandstone structural play, *in* Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 109–117
- Headlee, A. J. W., and Joseph, J. S., 1945, Permeability, porosity, and water content of natural gas reservoirs, Kanawha-Jackson and Campbells Creek Oriskany fields: West Virginia Geological Survey Bulletin No. 8, 16 p.
- Milici, R. C., 1996, Stratigraphic history of the Appalachian Basin, *in* Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 4–7.

- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Oliver, W. A., DeWitt, W., Jr., Dennison, J. M., Hoskins, D. M., and Huddle, J. W., 1967, The Appalachian Basin, United States, *in* Oswald, D. H., ed., International Symposium on the Devonian System: Calgary, Canada, Alberta Society of Petroleum Geologists, p. 1001–1040.
- Opritz, S. T., 1996, Play Dop: the Lower Devonian Oriskany Sandstone updip permeability pinchout, *in* Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 126–129.
- Patchen, D. G., and Harper, J. A., 1996, Play Doc: the Lower Devonian Oriskany Sandstone combination traps play, *in* Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 118–125.
- Roen, J. B., and Walker, B. J., eds., 1996, The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, 201 p.
- Rosenfeld, M. A., 1954, Petrographic variation in the Oriskany Sandstone: American Association of Petroleum Geologists Bulletin, v. 65, p. 1298–1299.
- Schumaker, R. C., 1996, Structural history of the Appalachian Basin, *in* Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 8–22.
- Stow, M., 1938, Conditions of sedimentation and sources of the Oriskany Sandstone as indicated by petrology: American Association of Petroleum Geologists Bulletin, v. 2, p. 541–564.
- Trapp, H., Jr., and Horn, M. A., 1997, Ground water atlas of the United States—segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia: U.S. Geological Survey Hydrologic Investigations Atlas No. HA-730-L, 30 p.

Prepared by Andrew Warne.



## PALUXY SANDSTONE, EAST TEXAS BASIN

### General Setting

The deposition of the Cretaceous Paluxy Sand in the East Texas Basin occurred during the second phase of the basin's tripartite tectonic development. During this second phase of deposition, the basin experienced steady, slow subsidence. Significantly, it was during this tectonic phase that the growth of salt structures (salt domes, for example) was at its peak (Seni and Kreitler, 1981) and the presence and growth of these structures influenced the deposition of the Paluxy. The isopach map of the Paluxy shows the thinning of the formation over penecontemporaneous salt structures.

In the northern part of the East Texas Basin, the Paluxy consists of interbedded sandstone and shale with minor conglomerates. Toward the south, basinward, the formation grades into dark-gray shales and micritic limestones (Kreitler and others, 1983, *after* Nichols and others, 1968). The Paluxy Sandstone was deposited in fluvial, deltaic, and offshore environments. Progradation was from the north.

### Parameter Description

1paluxy: Depth. The depth map is derived from a structure map of the top of the Paluxy sand (Core Laboratories, 1972). This map also shows the effect of salt structures on the Paluxy Formation. We then used a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid the depth to top formation (c1paluxyg).

2paluxy: Permeability / hydraulic conductivity. Permeability data were extracted from the oil-field data base of Holtz (1997). These data were extracted from Railroad Commission of Texas files and normalized to hydraulic conductivity.

3paluxy: Formation thickness. The isopach map of Seni (1981) shows thinning of the Paluxy over salt structures and thickening in areas away from the structures. The formation-thickness isopach was gridded at 5-km cells (c3paluxyg).

4paluxy: Net sand thickness. The effect of the salt structures is not as apparent on the net-sand-thickness map of the Paluxy (Core Laboratories, 1972) as it is in the formation-thickness map. Therefore, the salt structures affected both coarse- and finer grained clastics essentially equally. The Paluxy net-sand map was gridded in 5-km cells (c4paluxyg).

5paluxy: Percent shale. Dividing net sand thickness by formation thickness derived a percent-sand map. Then subtraction of percentage of sand from formation thickness generated the percent-shale map.

6paluxy: Continuity. Sand-body continuity was related to the depositional systems and facies map (Caughey, 1977) and a map of the salt structures (domes, diapirs, etc.) in the East Texas Basin (Jackson and Seni, 1984) as a means to determine the continuity of the Paluxy Formation.

7paluxy: Top-seal thickness. There are several low permeability units above the Paluxy sand in the area of interest, including the Goodland Formation and Edwards Limestone. However, argillite/carbonate facies in these units are not mapped in detail in this area. Therefore, we have chosen the Kiamichi Formation as the top seal for the Paluxy aquifer. The Kiamichi is widespread throughout the area. In electric-log cross sections presented by Anderson (1989) it appears to be a fine-grained, low-resistivity unit. Anderson mentioned that it is composed of terrigenous clastics. Neeley (1991) described the Kiamichi in southeastern Oklahoma outcrops as being composed of mostly argillaceous oyster biostromes with minor interbedded, dark-gray clay and shale and a few hard, argillaceous limestone beds. We assume that basinward (in the study area), the Kiamichi consists of mostly clay and shale. Thus, we identified the Kiamichi as a seal for the Paluxy and gridded the data (c7paluxyg).

8paluxy: Continuity of top seal. The Kiamichi may be discontinuous at faults and along the flanks of diapirs.

9paluxy: Hydrocarbon production. The delineation of oil and gas fields that produce from the Paluxy comes from a map by Caughey (1977).

10paluxy: Fluid residence time. Fluid residence time for the Paluxy is probably in the tens of millions of years, judging from the following: “The presence of meteoric water throughout the (East Texas) basin does not infer [sic] that the flushing is recent or is occurring at a rapid hydrologic rate. The timing of fluid movement in the basin is interesting but not resolvable at this point.” (Kreitler and others, 1983, p. 34). However, isotopic compositions imply that the basin fluids were originally recharged as continental meteoric waters, which probably occurred mostly during Cretaceous time. Therefore, the waters are very old.” (Kreitler and others, 1983, p. 1).

11paluxy: Flow direction. In their nuclear waste-disposal feasibility studies, Kreitler and others (1983, p.105) concluded that their pressure data base was not good enough to generate potentiometric surfaces for any of the formations (including the Paluxy) that they studied, and therefore, they could not make any conclusions regarding flow directions or velocities.

12apaluxy: Formation temperature. The average geothermal gradient for the area is 1.6° F (0.9° C/100 ft) (Kreitler and others, 1983).

12bpaluxy: Formation pressure. Kreitler and others (1983) did not include the raw data they used to analyze the hydraulic pressure regime in the East Texas basin because those data were proprietary drill-stem tests and scout cards from Petroleum Information Corporation. They also alluded to the relatively low quality of the data. However, because their analysis of the data is the only pressure data that we found for the Paluxy formation, we have included that analysis in this report. Kreitler and others (1983) concluded from the pressure (proprietary data not available from Kreitler’s report) and water chemistry data that the Paluxy is a “mixing zone for the Upper Cretaceous hydrologic system and the deeper saline system. The depth of the Paluxy pressure data is” the point on the graph “where the pressure/depth slope starts rising above the brine hydrostatic” (Kreitler and others, 1983, p. 105).



12cpaluxy: Formation-water salinity. The salinity map from Core Laboratories (1972) shows very high salinities in the Paluxy aquifer (greater than 120,000 parts per million) in the central portion of the basin.

13paluxy: Rock / water reaction. Kreitler and others (1983) categorized the formation waters of the East Texas basin into two broad groups—shallow formations (Woodbine, Eagle Ford, and Nacatoch) and deeper formations (Glen Rose and Travis Peak). The Paluxy Formation is transitional between these two groups in terms of depth, water chemistry, and rock / water reaction. “The ionic solutes in the deep-basin brines result initially from the dissolution of salt domes by meteoric ground water” (Kreitler and others, 1983, p. 84). Kreitler and others interpreted the Na and Cl in the brines to come from the dissolution of salt domes in the basin throughout geologic time. Therefore, the Na/Cl molar ratio of approximately 1 in the shallower formations “indicates minimal water-rock interactions.” Conversely, the brines in the deeper formations have a Na/Cl molar ratio of approximately 0.7. “The increase in calcium . . . and loss of Na . . . are attributed to albitization. In this reaction, sodium in solution is exchanged for calcium in the plagioclase” (Kreitler and others, 1983, p. 88). Furthermore, the Paluxy is the first formation in which the higher Ca concentrations are encountered with increasing depth (Kreitler and others, 1983, p. 71). Similarly, Kreitler and others noted an increase in potassium concentration with depth, which they attributed to the dissolution of K-feldspars or the transformation of (“albitization”) K-feldspars to albite. Therefore, the waters of the deeper formations, including to some degree the Paluxy, are Na-Ca-Cl type waters that have evolved from Na-Cl waters (Kreitler and others, 1983, p. 67). Immature sandstone composition and high-Ca brine suggest moderate potential for rock/water reaction with injection of CO<sub>2</sub>.

14paluxy: Porosity. Porosity data are derived from an oil-field data base (Holtz, 1997). Kreitler and others (1983) presented an average porosity.

15paluxy: Water chemistry. “The chemical composition of the Paluxy water is variable. Some of the waters are NaCl water, similar to Woodbine, whereas others are Na-

Ca-Cl waters and appear intermediary between the chemical composition of Woodbine waters and Travis Peak or Glen Rose waters. The chemistry and hydrology suggest that waters from the Glen Rose and Travis Peak Formations are leaking into the Paluxy” (Kreitler and others, 1983, p. 105).

16paluxy: Rock mineralogy. According to Owen’s (1979) outcrop study of the Paluxy sand in north central Texas, the Paluxy is a quartzarenite consisting of medium to very fine quartz sand and coarse silt, with variable amounts of limonite, hematite, pyrite, and magnetite and insignificant amounts of tourmaline and feldspar. The Paluxy also contains significant amounts (as much as 50 percent in Hood, Parker, and Tarrant Counties) of clay. In general the clay fraction consists of 40 to 50 percent quartz, 5 to 25 percent feldspar, 30 to 40 percent montmorillonite, and less than 10 percent illite and kaolinite. Most of the quartz is of plutonic origin, with lesser amounts of volcanic and vein quartz.

#### References

- Anderson, L. M., 1989, Stratigraphy of the Fredericksburg Group, East Texas Basin: Baylor Geological Studies, Bulletin 47, 40 p.
- Caughey, C. A., 1977, Depositional systems in the Paluxy Formation (Lower Cretaceous), Northeast Texas; oil, gas, and groundwater resources: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 77-8, 59 p.
- Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157 (1), 12 p.
- Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.
- Jackson, M. P. A., and Seni, S. J., 1984, Atlas of salt domes in the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 140, 102 p.
- Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.

- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Neeley, R. A., 1991, Facies analysis of the Lower Cretaceous (Albian) Goodland and lower Kiamichi Formations of Southeast Oklahoma: *Shale Shaker*, v. 41, no. 5, p. 116–145.
- Nichols, P. H., Peterson, G. E., and Wercestner, C. E., 1968, Summary of subsurface geology of northeast Texas, *in* Beebe, B. W., and Curtis, B. F., eds., *Natural gases of North America: American Association of Petroleum Geologists Memoir 9*, v. 2, p. 982–1004.
- Owen, M. T., 1979, The Paluxy sand in north central Texas: *Baylor Geological Studies, Bulletin No. 36*, 36 p.
- Seni, S. J., 1981, Depositional systems of the Lower Cretaceous Paluxy Formation, East Texas Basin, *in* Kreitler, C. W., Collins, E. W., Davidson, E. D., Jr., Dix, O. R., Donaldson, G. A., Dutton, S. P., Fogg, G. E., Giles, A. B., Harris, D. W., Jackson, M. P. A., Lopez, C. M., McGowen, M. K., Muehlberger, W. R., Pennington, W. D., Seni, S. J., Wood, D. H., and Wuerch, H. V., *Geology and geohydrology of the East Texas Basin; a report on the progress of nuclear waste isolation feasibility studies: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 81-7*, p. 12–20.
- Seni, S. J., and Kreitler, C. W., 1981, Evolution of the East Texas Basin, *in* Kreitler, C. W., Collins, E. W., Davidson, E. D., Jr., Dix, O. R., Donaldson, G. A., Dutton, S. P., Fogg, G. E., Giles, A. B., Harris, D. W., Jackson, M. P. A., Lopez, C. M., McGowen, M. K., Muehlberger, W. R., Pennington, W. D., Seni, S. J., Wood, D. H., and Wuerch, H. V., *Geology and geohydrology of the East Texas Basin; a report on the progress of nuclear waste isolation feasibility studies: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 81-7*, p. 48–52.

Prepared by Ramón H. Treviño.

## POTTSVILLE FORMATION, BLACK WARRIOR BASIN, ALABAMA/MISSISSIPPI

### General Setting

The Black Warrior Basin of northwestern Alabama and northeastern Mississippi is a foreland basin, containing Paleozoic sedimentary rocks. The Black Warrior Basin is bounded by the Cincinnati Arch, Appalachian Basin, Louisiana-Mississippi Salt Basins, and the Mississippi Embayment part of the Illinois Basin. The basin is formed by a complex fault-block homocline of Paleozoic strata dipping to the southwest. The oldest sedimentary rocks in the basin are of Cambrian age, and the youngest are Pennsylvanian. The Pennsylvanian is unconformably overlain by Cretaceous strata in the west part of the basin and are exposed in the east part. Frontal thrust faults of the Appalachian and Ouachita orogenic belts cut the southeastern and southwestern margins of the basin, respectively. Most of the basin, including its thrust-faulted margins, is buried beneath a veneer of Cretaceous and Tertiary strata of the Mississippi Embayment and Gulf Coastal Plain.

### Information Search and Selection

In the past, the Pottsville Formation was the target of underground injection of large volumes of disposal waters associated with the production of coalbed methane. Currently, however, few injector wells are active in the basin (Ortiz and others, 1993). Because of the high potential for storing CO<sub>2</sub>, the Pottsville Formation was selected for this study. The south and southwest parts of the basin have high salinity and sufficient depth to be a target for CO<sub>2</sub> sequestration. Here we consider the properties of brine formation separately from coal, which is also a target for CO<sub>2</sub> sequestration.

The Upper and the Lower Pottsville are characterized together. The Upper Pottsville that contains the producible coal should not be used for injection of CO<sub>2</sub>;

however, because of the lack of more detailed information, we could not separate the Lower Pottsville interval.

#### Comments on Geologic Parameters

1pottsville: Formation depth. The sequence is deeper to the southwest. The structural map by Borland and Minihan (1977, in Hewitt, 1984), was gridded to represent this property in the GIS data base. We used the DEM generated from National Imagery and Mapping Agency (2000) to calculate and grid the depth to top Pottsville (c1pottsville).

2pottsville: Permeability/hydraulic conductivity. Permeability data from oil fields (Galicki, 1986; Beard and Meyland 1987; E. Doherty, personal communication, 1999) are presented on the 2pottsville GIS map. Permeability values range from 0.06 to 54 md. Permeability also appears to occur in fracture-enhanced sands and silts (Ortiz and others, 1993). The normal faulting and lineaments present in the basin are the main factors that seem to control the permeability. Two types of lineaments are characteristic of the N30-60E and N30-60W areas. Some disposal wells have shown good injection rates. But because the permeability is not associated with the rock matrix, injection zones into fractures may have to be determined during drilling with loss of circulation (Ortiz and others, 1993).

3pottsville: Formation thickness. The Pottsville Formation of the Black Warrior Basin comprises as much as 12,000 ft of shale, sandstone, and coal (Cleaves and Broussard, 1980). The sequence has a southwestward thickening, which represents the thick clastic wedge shed from the Ouachita Orogenic Belt. The Lower Pottsville thickens from 1,000 to 1,500 ft in the north to 2,000 ft in the southwest. Thickness was gridded (c3pottsville).

4pottsville: Net sand thickness. Only the partial net sand map for the Lower Pennsylvanian (Cleaves, 1983) was found and gridded (c4pottsvilleg).

5pottsville: Percent shale. Percent shale was not determined because of depositional complexity and limited information; more detailed studies are needed.

6pottsville: Continuity. The Lower Pottsville strata (800 to 1,000 ft thick) contain orthoquartzitic sandstone, shale, and coal interpreted as the deposits of barrier-bar, tidal-flat, and lagoonal sediments in a north-northeast progradational system of a massive clastic wedge shed from the Ouachita orogen (Cleaves and Broussard, 1980). The Upper Pottsville consists of lithoarenite, shale, coal, and minor amounts of orthoquartzite and represents a lateral gradation from lower delta-plain distributary channels, to interdistributary bays, to a barrier bar. The Lower and the Upper Pottsville sediments were deposited in two different delta systems (Horsey, 1981). The Pottsville in the north is exposed and has been eroded as a result of upwarping of the Nashville Dome. Approximately 35 separate coal beds occur in the Pottsville Formation; most are fairly local seams, but few are extensive and have been used to define seven coal groups in the Upper Pottsville. Several authors have stratigraphically divided the Pottsville; however, because of limited information, we have characterized the whole interval.

7pottsville: Top-seal thickness. To the northeast, the Pottsville is exposed, and the south half of the basin is unconformably covered by the Cretaceous Tuscaloosa Group and younger sediments of the Gulf Coastal Plain (Thomas, 1988). The Mesozoic rocks reflect deposition in coastal-plain to shallow-marine environments.

8pottsville: Continuity of top seal. A northwest-trending, high-angle normal fault, which probably formed in response to the compressional forces associated with the Ouachita Orogenic Belt, is the main structural feature of the basin. Two major lineaments are also present. One trend, N30-60E, is parallel to the main trend of normal faults (Pashin and others, 1991). The faulting influenced sediment deposition and induced natural fractures that often enhance permeability and affect diagenesis.

9pottsville: Hydrocarbon production. Gas production in the Black Warrior Basin is from Pennsylvanian and Upper Mississippian sandstones. The Upper Mississippian also has some noncommercial oil accumulations. Coalbed gas production was first established in the basin from the Mary Lee/Blue Creek and Pratt coal beds in the

Lower Pennsylvanian Pottsville Formation. Gas production from this unconventional reservoir accounted for 75 percent of the gas produced in the basin. In the Alabama part of the basin, 90 conventional nonassociated gas fields, 15 coalbed gas fields, and 20 oil-associated gas fields have been discovered. In the Mississippi part of the basin, 27 conventional nonassociated gas fields, 28 conventional gas-associated oil fields, and 9 oil fields have been discovered. The dominant reservoirs of the conventional gas fields in both parts of the basin (Mississippi and Alabama) are the Carter and Sanders sandstones of Late Mississippian age. The following conventional plays are recognized in the Black Warrior Basin: Cambrian and Ordovician Carbonate Play, Upper Mississippian Sandstone Play, Pennsylvanian Sandstone Play, and Devonian Chert and Carbonate Play. A detailed map by play was found for each side of the basin, and all were combined for the GIS data base (Masingill, 1992; Petroleum Frontiers, 1986).

- 10pottsville: Fluid residence time. Very few data are available to determine fluid residence times in Pottsville Formation. More detailed analyses of hydraulic heads from this interval are needed to determine flow direction and rates, and, from this information, to infer fluid residence times.
- 11pottsville: Flow direction. Maps of the Upper Pottsville potentiometric surface between 400 and 10,000 ft by Pashin and others (1991) were used in the GIS because they provide the only flow direction information found for the Pottsville Formation.
- 12apottsville: Formation temperature. Data from the U.S. Geothermal Gradient map (Kron and Stix, 1982) was used with the depth map to determine average brine temperature for the Pottsville Formation.
- 12bpottsville: Formation pressure. Two data points from oil fields were found for the Pottsville Formation (Galicki, 1986; Beard and Meyland, 1987), 775 psi for Coal Fire Creek field and 1,235 psi for Corrine field.
- 12cpottsville: Formation-water salinity. Ortiz and others (1993) presented a subsea-depth map of waters containing 10,000 mg/L of TDS provided by the Alabama

Department of Environmental Management (ADEM). Although this map covers only the Alabama side of the Black Warrior Basin, it can be combined with the depth map (1pottsville) in the GIS data base to infer salinity throughout the Pottsville Formation.

13pottsville: Rock/water reaction. These moderately mature sandstones have low potential for reaction with high-CO<sub>2</sub> brines. However, if abundant coal in the section may trap CO<sub>2</sub>, a mixed brine/coal sequestration method might be considered for this basin.

14pottsville: Porosity. Different literature sources were used to find porosity information for the Pottsville Formation (Galicki, 1986; Beard and Meyland, 1987; E. Doherty, personal communication, 1999). This information from the oil fields was added to one of the oil- and gas-field maps. Although porosity data from oil fields range between 1.2 and 15 percent, normal faulting and lineaments present in the basin are the main factors that seems to control both porosity and permeability (Ortiz and others, 1993).

## References

- Beard, R. H., and Meylan, M. A., 1987, Petrology and hydrocarbon reservoir potential of subsurface Pottsville (Pennsylvanian) sandstones, Black Warrior Basin, Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 11–23.
- Cleaves, A., 1983, Carboniferous terrigenous clastic facies, hydrocarbon production zones, and sandstone provenance, northern shelf of Black Warrior Basin: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 41–52
- Cleaves, A., and Broussard, M., 1980, Chester and Pottsville depositional systems, outcrops and subsurface, in the Black Warrior Basin: Gulf Coast Association of Geological Societies Transactions, v. 30, p. 49–59
- Galicki, S., 1986, Mesozoic-Paleozoic producing areas of Mississippi and Alabama: Mississippi Geological Society.
- Hewitt, J., 1984, Geologic overview, coal, and coalbed methane resources of the Black Warrior Basin—Alabama and Mississippi, *in* Rightmire, C., Eddy, G., and Kirr, J., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists, Studies in Geology Series 17, p. 73–104.



- Horsey, C., 1981 Depositional environment of the Pennsylvanian Pottsville Formation in the Black Warrior Basin of Alabama: *Journal of Sedimentary Petrology*, v. 51, no. 3, p. 799–806.
- Kron, A., and Stix, J., 1982, U.S. geothermal gradient map of the United States, exclusive of Alaska and Hawaii: National Oceanic and Atmospheric Administration, National Geophysical Data Center, scale 1:2,500,000, two sheets.
- Masingill, J., 1992, The petroleum industry in Alabama: Geological Survey of Alabama, Oil and Gas Report 3-P, 127 p.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Ortiz, I., Weller, R., and others, 1993, Disposal of produced waters: underground injection option in the Black Warrior Basin: *Proceedings of the 1993 International Symposium: The University of Alabama/Tuscaloosa*, p. 339–364.
- Pashin, J. C., and others, 1991, Structure, sedimentology, coal quality and hydrology of the Black Warrior Basin in Alabama: controls on the occurrence and producibility of coal methane: The University of Texas at Austin and Geological Survey of Alabama, Bureau of Economic Geology, GRI Contract Number 1544, 187 p.
- Petroleum Frontiers, 1986, The Black Warrior Basin: proving the potential of the southeast: v. 3, no. 3, 62 p.
- Thomas, W. A., 1988, The Black Warrior Basin: The Geology of North America, v. D-2, Sedimentary Cover—North American Craton: U.S.: The Geological Society of America, Chapter 16, p. 471–492, 1 plate.

Prepared by Martha Romero.

## REPETTO FORMATION, LOS ANGELES BASIN

### General Setting

The Los Angeles Basin is a structurally complex, polyphase Neogene basin in a tectonically active margin along the North American and Pacific plates in Southern California. The early basin development was in the mid-Miocene during an extensional phase associated with strike slip and rotation of the Transverse Ranges (Biddle, 1991). Extension continued throughout the late Miocene and early Pliocene, followed by folding and thrusting from the early Pliocene to recent times.

A substantial fraction of the oil and gas production from the Los Angeles Basin is derived from multiple fields in the Pliocene Repetto Formation. The Repetto Formation is interpreted to have been deposited in a submarine-fan setting (Conrey, 1967; Redin, 1991). Lithofacies of the Repetto Formation consist of conglomeratic and sandy submarine channel-fill facies, flanked by sandy and silty levee and lobe facies. Reservoir heterogeneity is extreme, with abrupt lateral sandstone and conglomerate pinch-outs into silty mudstones. Vertical seal of reservoir facies is provided by abyssal mudstone drapes.

There is an abundance of basic lithologic and fluid data from this stratigraphic unit as a potential target for CO<sub>2</sub> injection. The trapping mechanism for Repetto fields is dominantly structural, with many fields occurring on anticlines and in overturned strata along fault zones (Yeats and Beall, 1991). Secondary hydrocarbon accumulations occur in stratigraphic traps where deep-sea fan deposits pinch out in mudstones (Redin, 1991).

### Information Search and Selection

Subsurface data from the Repetto Formation are well documented. Primary sources of formation structure, depth, thickness, and lithology data are derived from Conrey (1967), Henry (1987), Redin (1991), and Wright (1991). Permeability, porosity, pressure, temperature, and water-chemistry data are provided chiefly by the California

Department of Conservation (1991). The principal parameters for the Repetto Formation are briefly described below.

### Comments on Geologic Parameters

1repetto: Depth. Formation depth data are calculated from the structure map on the base of the Repetto Formation from Wright (1991). The deepest part of the Repetto Formation in the Los Angeles Basin (more than 10,000 ft [ $>3,048.8$  m]) occurs in an elongate, northwest-trending, fault-bounded trough in the central part of the basin. We digitized the map of structure on the base Repetto and gridded it with a 0.5-km cell size. In ARC/INFO GRID, we added the gridded thickness of the Repetto (3repetto) to the base elevation to calculate elevation of the top. We then subtracted the subsea elevation of the formation top from the gridded land surface elevation from a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate depth to top Repetto.

2repetto: Permeability/hydraulic conductivity. Permeability data of the Repetto Formation in the major oil fields of the Los Angeles Basin are listed in the California Department of Conservation (1991). Repetto permeability values exhibit a wide range, with values as high as 2,300 md in the Huntington Beach oil field. Variations in permeability in the Repetto Formation are related partly to the extreme lithologic heterogeneity, with reservoir facies consisting of conglomerates and sandstones in a silty and muddy nonreservoir matrix (Conrey, 1967).

3repetto: Formation thickness. The Repetto Formation is over 3,500 ft ( $>1,067.1$  m) thick in the structurally deep central trough in the Los Angeles Basin (Conrey, 1967). The Repetto Formation pinches out to the southeast toward the San Joaquin Hills and is less than 1,000 ft ( $<304.9$  m) thick to the southwest and northwest of the central structural trough. Repetto thickness was gridded (c3repetto).

4repetto: Net sand thickness. Net sandstone thickness of the Repetto Formation is structurally controlled, with maximum thickness of over 2,000 ft ( $>609.8$  m) in the deepest part of the Los Angeles Basin, coinciding with deep submarine-fan

- depocenters (Conrey, 1967; Redin, 1991). Sandstone thickness was gridded (c4repettog).
- 5repetto: Percent shale. Percent shale of the Repetto Formation is calculated from the isopach of the nonsandstone fraction, termed “siltstone-silty shale” by Conrey (1967). The greatest percentage of shale occurs in the east part of the Los Angeles Basin, where there are more than 3,000 ft (>914.6 m) of fine-grained deposits. Percent shale decreases toward the north part of the basin, near the conglomeratic mid- to upper fan facies (Redin, 1991).
- 6repetto: Continuity. The sandy deposits of the Repetto Formation, consisting of channel-fill deposits in suprafan facies, are distributed in the central structural trough north and east of the Palos Verdes Hills (Redin, 1991). These sandstones were sourced from the northeast, from conglomeratic mid- to upper-channelized fan deposits. Repetto sandstones grade southward from the suprafan facies into distal submarine-fan facies into offshore areas.
- 7repetto: Top-seal thickness. The top seal for the Repetto Formation in the Los Angeles Basin consists of inner neritic to upper bathyal shales in the Lower Pico Formation. Factors controlling the top-seal thickness of the Repetto Formation are a combination of the Repetto facies distribution and relief on the angular unconformity at the base of the overlying Pico Formation (Henry, 1987). The top-seal thickness was measured from electric logs on structural cross sections of the Repetto and younger formations in the Los Angeles Basin (Henry, 1987). These top-seal values, contoured from approximately 40 data points, display extreme variability, ranging from 0 to 800 ft (0 to 243.9 m). Locally there is no Repetto top seal where Pico sandstones are in direct contact with underlying Repetto sandstones; however, these areas of no top seal are limited in areal extent.
- 8repetto: Continuity of top seal. The reason for the enormous variability in continuity of the Repetto top seal is that the overlying Pico Formation is in unconformable contact with the Repetto Formation, exhibiting hundreds of feet of erosional relief (Henry, 1987, his plate 3). For example, in the northwest part of the basin in the Torrance and Wilmington Onshore areas, basal sandstones of the Pico Formation

are in direct contact with upper Repetto sandstones, with consequently little potential for vertical seal. However, in the Wilmington Offshore area, there is approximately 100 ft (30.5 m) of continuous shale above the Repetto Formation. Farther to the southeast in the Belmont Offshore area, the basal Pico unconformity rises with respect to the Repetto Formation, resulting in preservation of additional upper Repetto strata and introduction of extreme variability in the lithologic nature of the Pico-Repetto contact. In the West Newport fault block, there is continuous shale top seal above the Repetto Formation, 100 to 200 ft thick (30.5 to 61.0 m). Toward the northeast (Sunset Beach area), the basal section of the Pico Formation commonly consists of a 100- to 200-ft (30.5- to 61.0-m) sandstone above a sandy section of the upper Repetto (Henry, 1987, his plate 2). Farther northward in the West Coyote, Leffingwell, Santa Fe Springs, and Montebello areas, the upper Repetto Formation is shalier, consisting of multiple upward-coarsening parasequences separated by hundreds of feet of shale. Consequently this part of the basin is inferred to contain a higher potential for top seal of injected gases.

9repetto: Hydrocarbon production. There are approximately 20 oil fields in the Los Angeles Basin that produce out of the Repetto Formation (Redin, 1991; Wright, 1991). Many of these fields are structurally controlled. For example, Inglewood, Potrero, Rosecrans, Dominguez, Long Beach, Seal Beach, and Huntington Beach fields occur along the Inglewood Fault. Other fields, including Whittier and Brea fields, are associated with the Whittier Fault. Production data, including data of basic reservoir parameters, are listed in detail by the California Department of Conservation (1991).

10repetto: Fluid residence time. Maps of fluid residence time from Repetto aquifers are not documented in the literature. However, faults that have been mapped extensively in the Los Angeles Basin are inferred to be barriers to fluid flow in the Repetto Formation (Redin, 1991; Wright, 1991), which are inferred to impact fluid residence time significantly.

- 11repetto: Flow direction. No aquifer studies have been done of the Repetto Formation in the Los Angeles Basin, and therefore flow directions are poorly understood. However, models of other formations in the basin (U.S. Geological Survey, 1996) indicate southwestward fluid flow into the deep part of the basin from the shallow recharge area from the northeast. The direction of ground-water movement in these formations is inferred to be diverted by northwest-trending faults such as the Inglewood Fault.
- 12arepetto. Formation temperature. Temperature data are published by the California Department of Conservation (1991). Values of 100 to 125° F are typical, although values as high as 175° F are known from Inglewood field.
- 12brepetto: Formation pressure. The Repetto Formation does not exhibit abnormal overpressure, having typical original formation pressures of 1,500 to 1,800 psi (California Department of Conservation, 1991). Original formation pressure in Olive field is rather higher, with more than 2,000 psi.
- 12crepetto: Formation-water salinity. Formation-water salinity in the Repetto Formation indicates saline conditions. Values of more than 20,000 ppm are common for most Repetto oil fields (California Department of Conservation, 1991). Lower values of fewer than 9,000 ppm have been reported from Potrero field. In contrast, Rosecrans field, located along the Inglewood Fault, features salinity values in excess of 34,000 ppm.
- 13repetto: Rock/water reaction. Mineralogy data are presented in Conrey (1967), and water-chemistry data are listed in the California Department of Conservation (1991). Reactive phases such as feldspar and glauconite suggest that the potential for reaction of minerals with high CO<sub>2</sub> brine is moderate to high, depending on amount and composition of feldspar.
- 14repetto: Porosity. An extensive set of Repetto porosity data was published by the California Department of Conservation (1991). Porosity values, reported for hydrocarbon-producing zones (hence, better reservoir-quality sandstones), range from 22 percent in Olive field to 34 percent in Huntington Beach field. Porosity

values in Seal Bach oil field, at 28 percent, are near the median value for this reservoir parameter.

15repetto: Formation-water chemistry. Total dissolved solids in Repetto Formation waters, presented in the California Department of Conservation (1991), are reported to be 25,200 ppm from Cheviot Hills field and more than 42,000 ppm in Inglewood field. However, data on specific ion concentrations are not presented.

16repetto: Rock mineralogy. Repetto mineralogy is complex, reflecting its complicated depositional history. The coarse-grained fraction, found in pebbles and granules, consists of igneous and metamorphic rock fragments, with minor amounts of sedimentary rock fragments. Carbonate materials, primarily in the form of foraminiferal tests, and glauconite are also present in the basin (Conrey, 1967). However, quartz and feldspar are predominant over calcite and other carbonate minerals in the Repetto Formation.

## References

- Biddle, K. T., 1991, The Los Angeles Basin: an overview, *in* Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 5–24.
- California Department of Conservation (Division of Oil and Gas), 1991, California oil and gas fields, v. 2: Southern, central coastal, and offshore California, 689 p.
- Conrey, B. L., 1967, Early Pliocene sedimentary history of the Los Angeles Basin, California: California Division of Mines and Geology Special Report 93, 63 p.
- Henry, M. J., 1987, Los Angeles Basin—an overview, *in* Clarke, D., and Henderson, C., eds., Oil-producing areas in Long Beach: American Association of Petroleum Geologists Field Trip Guidebook, Pacific Section, p. 1–29.
- Redin, T., 1991, Oil and gas production from submarine fans of the Los Angeles Basin, *in* Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 239–260.
- U.S. Geological Survey, 1996, Ground water atlas of the United States: segment 1: California.
- Wright, T. L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, *in* Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 35–134.

Yeats, R. S., and Beall, J. M., 1991, Stratigraphic controls of oil fields in the Los Angeles Basin, *in* Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 221–238.

Prepared by William Ambrose.





## ST. PETER SANDSTONE, ILLINOIS BASIN

### General Setting

The Illinois Basin is an elongate intracratonic basin located mostly in central and southern Illinois, southwestern Indiana, and western Kentucky (Collinson and others, 1988). It extends some 600 km northwest to southeast and 320 northeast to southwest. The greatest thickness of sedimentary fill is in southern Illinois and western Kentucky, where a maximum of 7,000 m of Paleozoic sedimentary fill occurs.

### Information Search and Selection

The deeper portions of the Illinois Basin are the focus of this investigation because this area contains strata that are sufficiently deep, porous and permeable, and hydraulically isolated from fresh-water aquifers to make potential CO<sub>2</sub> sequestration targets. Moreover, southern Illinois and western Kentucky are areas with major CO<sub>2</sub> producers (fig. 1).

The subsurface of this area has been well studied, the research driven by the search for domestic and industrial water supplies, petroleum, and, to a minor extent, subsurface disposal of industrial liquid wastes. However, the majority of study has been associated with relatively shallow (fresh-water) aquifers and shallow (Mississippian) hydrocarbon-bearing horizons. There have only been a few brine-aquifer waste-disposal studies in the region (Bergstrom, 1968; Cartwright and others, 1981; Roy and others, 1988). Although these provide excellent, site-specific information, they do not provide information regarding spatial distribution of deep-brine-aquifer characteristics.

A number of potential porous, permeable and continuous sand units within the southern Illinois Basin area could potentially be used for CO<sub>2</sub> sequestration. Some of these include the Cambrian Mount Simon, Eau Claire, Gatesville, and Ironton Sandstones, as well as the Lower Ordovician Gunter and New Richmond Sandstones. However, we chose to focus on the Middle Ordovician St. Peter Sandstone for inclusion

in the GIS because this unit is a regionally continuous porous and permeable sandstone that is overlain by the thick, impermeable, regionally extensive, Maquoketa Shale Group, which serves as an aquiclude (Young, 1992a, b). The Mt. Simon Sandstone is also characterized for study in this area in the GIS.

The St. Peter Sandstone has been studied in the region for both hydrocarbon and liquid waste-disposal potential (Hoholick, 1980; Kreutzfeld, 1982; Zuppeman and Keith, 1988). There have been a number of regional studies addressing the hydrogeologic properties of the St. Peter Sandstone to the north in northern Illinois, Minnesota, and Wisconsin, where the unit is shallower and contains fresh water (Burkart and Buchmiller, 1990; Mandle and Kontis, 1992; Young, 1992a, b). Although these hydrogeologic studies provide some useful information about aquifer parameters, they do not include the central Illinois Basin region.

#### Comments on Geologic Parameters

Each of the geologic parameters for the lower St. Peter Sandstone is now briefly described, and the reasons for selection of the map or data source for the GIS are outlined. The reference list at the end of this summary includes documents that are relevant to the St. Peter Sandstone in the study area.

1stpeter: Depth. A number of maps show the elevation at the top of the St. Peter Sandstone, including those of Cram (1971), Hoholick (1980), Kreutzfeld (1982), and Young (1992a, b). The map of Hoholick (1980) was used in the GIS because it is regionally extensive. We then used a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate and grid the depth to top of the St. Peter Sandstone (c1stpeter).

2stpeter: Permeability/hydraulic conductivity. A number of studies have evaluated hydraulic conductivity, permeability, and transmissivity of the St. Peter Sandstone, including Kreutzfeld (1982) and Mandle and Kontis (1992). We chose to use a combination of results from Kreutzfeld (1982) and Mandle and Kontis (1992). Kreutzfeld (1982) derived permeability data from core samples and his data cover central and southern Illinois. Mandle and Kontis (1992) derived

hydraulic conductivity data from well-test data, which cover northern and central Illinois, northern and central Indiana, and northern Missouri. Because Kreutzfeld's (1982) data were derived from individual core samples, they were much more variable than those of Mandle and Kontis (1992).

3stpeter: Formation thickness. A number of published maps show the thickness distribution of the St. Peter Sandstones, including Hoholick (1980), Collinson and others (1988), and Kolata and Noger (1990). We chose to use the map of Collinson and others (1988) because it shows thickness at 50 (rather than 100) ft intervals. Kreutzfeld (1982) pointed out that the thickness of the St. Peter Sandstone is much more variable than the formation-thickness map indicates. The variation in thickness is due to postdepositional erosion and its highly irregular lower boundary. The base of the St. Peter Sandstone is a major regional unconformity (Collinson and others, 1988; Young, 1992b). The isopach was gridded (c3stpeterg).

4stpeter: Net sand thickness. The St. Peter Sandstone is a mature quartz arenite that contains little or no silt and clay, except near its perimeter. Lamar (1928; his fig. 10) provided results of grain-size analysis for a number of St. Peter Sandstone samples in which the percent clay ranged from 0 to 5.8, with a mean of about 2.5 percent. Because clay and silt are minor constituents of the St. Peter Sandstone, we calculate net sand thickness (c4stpeterg) as

$$\text{Total St. Peter sandstone thickness} - (\text{total St. Peter sandstone thickness} \cdot 0.025).$$

5stpeter: Percent shale. The St. Peter Sandstone is a mature quartz arenite that contains little or no silt and clay, except near its perimeter. Lamar (1928; his fig. 10) provided results of grain-size analysis for a number of St. Peter Sandstone samples in which the percent clay ranged from 0 to 5.8 with a mean of about 2.5 percent. Because clay is a minor constituent of the St. Peter Sandstone, we simply assign the percent shale to be 2.5 throughout the central Illinois Basin.

6stpeter: Continuity. Several authors indicated that the sands within the St. Peter Sandstone are continuous, especially in the middle portions of the unit (Kreutzfeld, 1982; Barnes and others, 1992). The St. Peter Sandstone is partially

offset by a number of faults, and these faults can significantly affect sand-body continuity. Therefore, we chose to use the map of Collinson and others (1988), which shows the locations of major faults that offset the St. Peter Sandstone to characterize sand-body continuity, because faulting rather than lithology is the principal factor influencing sand-body continuity of the St. Peter in the central Illinois Basin.

7stpeter: Top-seal thickness. Young (1992a) identified the Upper Ordovician Maquoketa Shale as the primary confining unit of the Cambrian-Ordovician aquifer in the northern Midwest. The dolomite and shales of the Galena, Decorah, Platteville, and Glenwood Formations, which occur between the St. Peter Sandstone and the Maquoketa Shale, also serve as confining layers (Young, 1992a). The Maquoketa Shale is regionally continuous and lithologically homogeneous, and therefore provides an effective aquiclude across the central Illinois Basin. Young (1992a), Collinson and others (1988) and Kolata and Noger (1990) provided thickness-distribution maps of the Maquoketa Shale; we chose to grid the map of Collinson and others (1988) in the GIS because it covers the entire Illinois Basin (c7stpeterg).

8stpeter: Continuity of top seal. The Maquoketa Shale and the underlying Galena, Decorah, Platteville, and Glenwood Formations are an effective aquiclude between the St. Peter Sandstone and overlying Silurian and younger strata. To characterize the continuity of the Maquoketa Shale in the GIS, we chose the map of Mandle and Kontis (1992), which shows vertical hydraulic conductivity values for the confining unit. Note that these data do not account for the effectiveness of the Galena, Decorah, Platteville, and Glenwood Formations as aquicludes, which also serve to hydraulically isolate the St. Peter Sandstone from overlying units.

9stpeter: Hydrocarbon production. Most hydrocarbon production in the Illinois Basin is from Mississippian-age units. Zuppemann and Keith (1988) provided a map showing the locations of gas and oil fields in Cambrian/Ordovician units, which was used in the GIS. This map shows that oil and gas production from the Cambrian/Ordovician units is limited and probably not a major concern for CO<sub>2</sub> sequestration.

10stpeter: Fluid residence time. The general model of Illinois ground-water hydrology depicts water infiltrating from the surface along the flanks of the basin and moving downdip, basinward over time (Selkregg and others, 1957; Mandle and Kontis, 1992; Young, 1992a, b). Several authors indicated that formation waters in the St. Peter Sandstone in the southern Illinois, western Kentucky area are highly mineralized (Meents and others, 1952; Hoholick, 1980; Cartwright and others, 1981), which indicates that the formation waters have resided in the formation for extended periods. On the basis of flow paths depicting ground-water flow in the St. Peter Sandstone to the central Illinois Basin that are typically more than 200 mi, and St. Peter Sandstone formation waters that are highly mineralized, we infer that fluid residence times are long, more than 10,000 yr for southern Illinois and western Kentucky.

11stpeter: Flow direction. Mandle and Kontis (1992) and Young (1992a, b) provided the most comprehensive map of ground-water flow in the St. Peter-Prairie du Chien-Jordon aquifer in the region. Although their map does not explicitly cover south Illinois and western Kentucky, it clearly indicates that ground-water flow is downdip. Currently, ground-water flow in St. Peter Sandstone in the deepest portions of the basin is not well understood.

12astpeter: Formation temperature. Davis (1990) provided geothermal gradients derived from a number of deep wells drilled near the Illinois Basin center. For the five wells, gradients ranged from 0.83° F/100 ft to 1.27° F/100 ft, with a mean of 1.03° F/100 ft. These gradients are slightly less than those of Kinney and others (1976). We used the mean of 1.03° F/100 ft in combination with the depth to the top of the St. Peter Sandstone to derive a formation temperature distribution map for the GIS.

12bstpeter: Formation pressure. There currently is no published information regarding geopressure gradients or maps showing formation-pressure distribution. We used well-completion information from Bell and Kline (1952) to determine the relationship between depth and formation pressure. The data demonstrated a geopressure gradient of about 39.2 psi/100 ft. We used this gradient in

- combination with the depth to the top of the St. Peter Sandstone to generate a pressure-distribution map for the GIS.
- 12cstpeter: Formation-water salinity. Formation waters in the St. Peter Sandstone in the southern Illinois, western Kentucky, area are highly mineralized (Meents and others, 1952; Hoholick, 1980; Cartwright and others, 1981). We used the salinity-distribution map of Hoholick (1980) in the GIS because it is the most current and covers a broad region.
- 13stpeter: Rock/water reaction. The St. Peter Sandstone is a mature quartz arenite that contains little or no silt and clay, except near its perimeter. Therefore, we conclude that the potential for rock/water reaction with high CO<sub>2</sub> brine is low.
- 14stpeter: Porosity. Thiel (1935), Hoholick and others (1984), Kreuzfeld (1982), and Barnes and others (1992) generated porosity data for the St. Peter Sandstone. The porosity-versus-depth curve of Hoholick and others (1984), in combination with the depth to top of the St. Peter Sandstone, was used to generate the porosity-distribution map in the GIS.
- 15stpeter: Water chemistry. Meents and others (1952) reported brine chemistry for the St. Peter Sandstone in the central Illinois Basin, and their results are presented in the GIS. Their data show an increase in total dissolved solids concentration with depth.
- 16stpeter: Rock mineralogy. A number of authors characterized the mineral and chemical composition of the St. Peter Sandstone (Thiel, 1935; Odom and others, 1976, 1977; Barnes and others, 1992). All authors agreed that the St. Peter Sandstone is a quartzarenite, but some found intervals with appreciable feldspar content (Odom and others, 1976; Barnes and others, 1992). Hoholick and others (1984, their fig. 5) indicated that calcite is the major cement in the central Illinois Basin. Thiel (1935) reported less than 0.05 weight percent of heavy minerals. To characterize the mineralogy, we chose to present a set of graphs from Odom and others (1976). These graphs, which are from samples from Upper Mississippi Valley outcrops, show the proportions of quartz and feldspar and their variation with grain size.

These graphs are representative of the proportions of quartz and feldspar presented by other authors.

## References

- Barnes, D. A., Lundgren, C. E., and Longman, M. W., 1992, Sedimentology and diagenesis of the St. Peter Sandstone, central Michigan Basin, United States: American Association of Petroleum Geologists Bulletin, v. 76, p. 1507–1532.
- Bell, A. H., and Kline, V., 1952, Oil and gas development in Illinois during 1951: Illinois Geological Survey, Illinois Petroleum 67, 53 p.
- Bergstrom, R. E., 1968, Feasibility of subsurface disposal of industrial wastes in Illinois: Illinois Geological Survey, Circular C 26, 18 p.
- Burkart, M. R., and Buchmiller, R. C., 1990, Regional evaluation of hydrologic factors and effects of pumping, St. Peter-Jordan Aquifer, Iowa: U.S. Geological Survey, Water-Resources Investigations Report 90-4009, 44 p.
- Cartwright, K., Gilkeson, R. H., Griffin, R. A., Johnson, T. M., Lindorff, D. E., and DuMontelle, P. B., 1981, Considerations in hazardous waste disposal in Illinois: Illinois Geological Survey, Geological Note GN 94, 20 p.
- Collinson, C., Sargent, M. L., and Jennings, J. R., 1988, Chapter 14: Illinois Basin region, *in* Sloss, L. L., ed., The Geology of North America, v. D-2, Sedimentary Cover—North American Craton: U.S.: Decade of North American Geology: Geological Society of America, p. 383–426.
- Cram, I. H., ed., 1971, Future petroleum provinces of the United States—their geology and potential: American Association of Petroleum Geologists Memoir 15, 691 p.
- Davis, H. G., 1990, Pre-Mississippian hydrocarbon potential of the Illinois Basin, *in* Leighton, M. W., Kolata, D. R., Oltz, D. F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 473–489.
- Hoholick, D. J., 1980, Porosity, grain fabric, water chemistry, cement, and depth of the St. Peter Sandstone in the Illinois Basin: University of Cincinnati, Master's thesis, 72 p.
- Hoholick, J. D., Metarko, T., and Potter, P. E., 1984, Regional variations of porosity and cement: St. Peter and Mount Simon Sandstones in Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 68, p. 753–764.
- Kinney, D. M., ed., 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U.S. Geological Survey Publication G74014, 2 maps.



- Kolata, D. R., and Noger, M. C., 1990, Tippecanoe I sequence Middle and Upper Ordovician Series, *in* Leighton, M. W., Kolata, D. R., Oltz, D. F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 89–99.
- Kreutzfeld, J. E., 1982, Pore geometry and permeability of the St. Peter Sandstone in the Illinois Basin: University of Toledo, Master's thesis, 353 p.
- Lamar, J. E., 1928, Geology and economic resources of the St. Peter Sandstone of Illinois: Illinois Geological Survey Bulletin No. 53, 175 p.
- Lloyd, O. B., and Lyke, W. L., 1995, Ground water atlas of the United States—segment 10, Illinois, Indiana, Kentucky, Ohio, Tennessee: U.S. Geological Survey, Hydrologic Investigations Atlas No. HA-730-K, 30 p.
- Mandle, R. J., and Kontis, A. L., 1992, Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-C.
- Meents, W. F., Bell, A. H., Rees, O. W., and Tilbury, W. G., 1952, Illinois oil-field brines, their geologic occurrence and chemical composition: Illinois Geological Survey, Illinois Petroleum No. 66, 38 p.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Odom, I. E., Doe, T. W., and Dott, R. H., Jr., 1976, Nature of feldspar-grain size relations in some quartz-rich sandstones: *Journal of Sedimentary Petrology*, v. 46, p. 862–870.
- Odom, I. E., Willand, T. M., and Lassin, R. J., 1977, Paragenesis of authigenic minerals in St. Peter Sandstone: *American Association of Petroleum Geologists Bulletin*, v. 61, p. 1384–1385.
- Roy, W. R., Mravik, S. C., Krapac, I. G., Dickerson, D. R., and Griffin, R. A., 1988, Geochemical interactions of hazardous wastes with geological formations in deep-well systems: Illinois Geological Survey, Environmental Geology Note EGN130, 52 p.
- Selkregg, L. F., Pryor, W. A., and Kempton, J. P., 1957, Groundwater geology in south-central Illinois—a preliminary geologic report: Illinois Geologic Survey, Circular 225, 30 p.
- Thiel, G. A., 1935, Sedimentary and petrographic analysis of the St. Peter Sandstone: *Geological Society of America Bulletin*, v. 46, p. 559–614.
- Willman, H. B., Atherton, E., Buschbach, T. C., Collinson, C., Frye, J. C., Hopkins, M. E., Lineback, J. A., and Simon, J. A., 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey, Bulletin 95, 261 p.

Young, H. L., 1992a, Summary of ground water hydrology of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-A, 55 p.

\_\_\_\_\_ 1992b, Hydrogeology of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-B, 99 p.

Zuppemann, C. W., and Keith, B. D., eds., 1988, Geology and petroleum production of the Illinois Basin, v. 2: Mt. Vernon, IL, Illinois and Indiana–Kentucky Geological Societies, joint publication, 272 p.

Prepared by Andrew Warne.



## TUSCALOOSA GROUP, ALABAMA GULF COASTAL PLAIN

### General Setting

Mobile, Alabama, is located along a major embayment within the coastal plain of the Gulf of Mexico. Mobile is underlain by more than 10,000 ft of Tertiary and Mesozoic strata that generally dip and thicken seaward. A number of structural features and faults in the area (particularly the Mobile Graben) offset and alter the stratigraphy of many aquifers in the Mobile area

### Selection and Information Search

The subsurface of this area has been well studied, driven by the search for domestic and industrial water supplies, petroleum, and subsurface disposal of industrial liquid wastes. However, because shallow aquifers in the area contain copious water supplies, there is little need for hydrogeologic studies of deeper brine aquifers. Essentially all of the interest in petroleum exploration and development in the Mobile area is in the Jurassic Norphlet and Smackover Formations, whose depths exceed 10,000 ft in the Mobile area. There have been only a few brine-aquifer waste-disposal studies (Averson, 1970; Tucker and Kidd, 1973). Although these provide excellent site-specific information, they do not provide information regarding spatial distribution of deep brine-aquifer characteristics.

A number of potential porous, permeable and continuous sand units are beneath the Mobile area that could potentially be used for CO<sub>2</sub> sequestration. Some of these include sands within the Eocene/Paleocene Wilcox and the Paleocene Midway Groups. However, we selected the Upper Cretaceous Tuscaloosa Group because the lower Tuscaloosa Group contains highly porous and permeable sands that are regionally extensive, and the unit is overlain by the thick, impermeable, regionally extensive Selma Chalk, which serves as an aquiclude. The Upper Cretaceous Eutaw Formation, which immediately overlies the Tuscaloosa Group, is another potential brine formation for CO<sub>2</sub>

sequestration, although it is much thinner than the Tuscaloosa sands. We suggest that the Wilcox, Midway, and Eutaw intervals be studied in more detail if CO<sub>2</sub> sequestration becomes a serious possibility in the region.

The Tuscaloosa Group has been studied in the region for both hydrocarbon liquid and waste-disposal potential (Averson, 1970; Tucker and Kidd, 1973; Mancini and others, 1987). Miller (1990) provided a general summary of the hydrogeologic properties of this unit and referred to this subsurface interval as the Black Warrior River aquifer. The Tuscaloosa Group is commonly subdivided into a sandy upper, a clayey middle, and a sandy lower unit (Raymond and Copeland, 1987). The depth of the Tuscaloosa is commonly mapped by using the distinctive and widespread middle clay unit. The sands of the lower Tuscaloosa tend to be more porous, permeable, and continuous than those of the upper Tuscaloosa (Averson, 1970). The depth of the lower Tuscaloosa Group generally ranges from 1,500 to 22 m in the Mobile region.

#### Comments on Geologic Parameters

Each of the geologic parameters for the lower Tuscaloosa sandy interval is now briefly described, and the reasons for selection of the map or data source for the GIS are outlined.

1tuscaloosa: Depth. A number of maps show the depth to the middle Tuscaloosa clay, including Alverson (1970) and Moore (1971). Moffett and others (1984a) and Miller (1990) generated maps showing the elevation of the top of the Tuscaloosa Group. We chose the map of Moffett and others (1984a) because it covers most of the area. The Moore (1971) study contains more detail and generally represents the top of the lower Tuscaloosa sandy interval but covers only a small part of the area. We then used land-surface elevation from a DEM generated from Digital Terrain Elevation Data (National Imagery and Mapping Agency, 2000) to calculate the depth to top of the lower Tuscaloosa (c1tuscaloosag).

2tuscaloosa: Permeability/hydraulic conductivity. Permeability data come from two sources, hydrocarbon and waste-disposal-potential assessments (Tucker and Kidd, 1973; Mancini and others, 1987). The data from Tucker and Kidd (1973; their

table 2) are primarily used for the GIS. The data in the GIS are ranges of their data. A large number of geophysical logs that penetrate the Tuscaloosa Group are available. From these logs, it would possible to construct a more accurate spatial distribution of permeability, if CO<sub>2</sub> sequestration in the area becomes a serious possibility.

3tuscaloosa: Formation thickness. There currently is no published map of Tuscaloosa Group thickness distribution for the Mobile region (Jack Pashin, Alabama Geological Survey, personal communication, April 2000). We used the thickness information from the cross sections of Mancini and others (1987) to generate the lower Tuscaloosa Group thickness-distribution map for the GIS. We also digitized unpublished data supplied by Jack Pashin (Alabama Geological Survey, personal communication, 2000) and gridded the result (c3tuscaloosag).

4tuscaloosa: Net sand thickness. There currently is no published map of Tuscaloosa Group net-sand-thickness distribution for the Mobile region (Jack Pashin, Alabama Geological Survey, personal communication, April 2000). We used the geophysical logs from the cross sections of Mancini and others (1987) to generate a semiquantitative estimate of net sand thickness of the lower Tuscaloosa Group (c4tuscaloosag). A large number of geophysical logs that penetrate the Tuscaloosa Group are available. From these logs, it would possible to construct a more accurate spatial distribution of sands in a future study.

5tuscaloosa: Percent shale. There currently is no published map of Tuscaloosa Group percent-shale distribution for the Mobile region (Jack Pashin, Alabama Geological Survey, personal communication, April 2000). We used the geophysical logs from the cross sections of Mancini and others (1987) to generate a semiquantitative estimate of percent shale within the lower Tuscaloosa Group. A large number of geophysical logs that penetrate the Tuscaloosa Group are available. From these logs, it would possible to construct a more accurate shale distribution, if CO<sub>2</sub> sequestration in the area becomes a serious possibility.

6tuscaloosa: Continuity. Several authors have indicated that the sands in the lower Tuscaloosa Group are regionally continuous (Tucker and Kidd, 1973; Mancini

and others, 1987). Alverson (1970) referred to lower Tuscaloosa Groups as a regionally continuous sand reservoir. The cross sections of Mancini and others (1987) provide direct evidence of the degree of sand-body continuity in the Lower Tuscaloosa Group. A large number of geophysical logs that penetrate the Tuscaloosa Group are available. From these logs, it would be possible to determine sand-body continuity for the region, if CO<sub>2</sub> sequestration in the area becomes a serious possibility.

7tuscaloosa: Top-seal thickness. The Selma Chalk, which overlies the Tuscaloosa Group is widely recognized as a regional aquiclude. In the Mobile area, it generally ranges in thickness from 300 to 400 m (Raymond and others, 1988; Pashin and others, 1998). There currently is no published thickness map for the Selma Chalk. However, there are published maps of the top of the Selma and Eutaw Formations. (Hinkle and others, 1983; Moffett and others, 1984a). These were gridded and the top Tuscaloosa subtracted to determine the thickness of the Selma Chalk (c7tuscaloosag).

8tuscaloosa: Continuity of top seal. The Selma Chalk is thick and generally impermeable. However, Pashin and others (1998) demonstrated that fault-induced fracturing can greatly enhance fracturing in the Selma interval. Therefore, we used a map showing the configuration of the top of the Selma (Moffett and others, 1984a), which shows the location of major faults, to characterize the continuity of the top seal.

9tuscaloosa: Hydrocarbon production. There are a limited number of wells producing from the Tuscaloosa Group in southwestern Alabama (Mancini and others, 1987; J. Pashin, Alabama Geological Survey, personal communication, April, 2000). In the Mobile area, a relatively large number of wells have penetrated the Tuscaloosa during the process of drilling to the Jurassic Smackover and Norphlet Formations. The petroleum atlas of southwestern Alabama was used to summarize petroleum wells that produce from or penetrate the Tuscaloosa Group in the Mobile region (Bolin and others, 1989). Because drilling has continued in the Mobile area, especially hydrocarbon production from the Smackover and

Norphlet Formations, and because the petroleum atlas (Bolin and others, 1989) does not show dry-well locations, we recommend a more thorough investigation of hydrocarbon exploration and production activity if CO<sub>2</sub> sequestration becomes a serious possibility in the area.

10tuscaloosa: Fluid residence time. Few data are available to determine fluid residence times in the Tuscaloosa Group in the Mobile area. Miller (1990) generally described ground-water flow through the Black Warrior River aquifer (Tuscaloosa Group). He determined that water infiltrates from the surface outcrop belt into the Tuscaloosa Group. The ground water generally flows downdip toward the coast. Miller (1990) determined that the increase in dissolved solid concentration (DSC) in the subsurface water with depth (that is, distance downdip from the outcrop area) is a direct function of fluid residence time. In addition, Miller (1990) concluded that as the ground water encounters the marine water beneath the coastal zone, stagnant conditions prevail. Because the ground water in the Tuscaloosa Group is highly saline (Alverson, 1970; Tucker and Kidd, 1973; Miller, 1990), we determined that the ground water in the Mobile area has protracted residence times. Tuscaloosa ground water in the Mobile area is perhaps as old as 18,000 yr. At that time sea level was about 120 m lower than the present level, the shoreline was near the present shelf edge, and ground-water flow in the Tuscaloosa Formation (in the Mobile area) was more active and not influenced by the marine saltwater wedge. We used a modified version of the Black Warrior River ground-water-flow map of Miller (1990) to describe fluid residence times in the GIS.

11tuscaloosa: Flow direction. Ground-water-flow direction is typically found by determining the hydraulic head (essentially water pressure) of ground water in the target interval and mapping its change over an area. Published maps of hydraulic-head distribution in the Tuscaloosa Group in the Mobile area are not available. On the basis of regional assessments of deep aquifers, Miller (1990) determined that ground water generally flows downdip toward the coast. Miller (1990) concluded



that as the ground water encounters the marine water beneath the coastal zone, stagnant conditions prevail or that ground water flows parallel to the coast.

12atuscaloosa: Formation temperature. In their summary report of geothermal data for southwest Alabama, Wilson and Tew (1985) inferred that geothermal gradients for the Gulf Coastal Plain strata are low to moderate. We used figure 10 of Wilson and Tew (1985) to determine a geothermal gradient of 1.3° F/100 ft for the Tuscaloosa Formation in the Mobile area. To derive temperatures we combined the temperature gradient with the depth to the middle Tuscaloosa Group mapping horizon by Moffet and others (1984a).

12btuscaloosa: Formation pressure. Tucker and Kidd (1973; their fig. 6) provided a summary of fluid pressure versus depth relationships for the coastal-plain strata of southwest Alabama. To determine pressure distribution within the Tuscaloosa Group, we used Tucker and Kidd's (1973) gradient of 0.482 psi/ft and the map showing depth to the middle Tuscaloosa Group (Moffet and others, 1984a).

12ctuscaloosa: Formation-water salinity. A number of authors have reported that DSC in the Tuscaloosa Group in southwestern Alabama is high (Alverson, 1970; Tucker and Kidd, 1973; Miller, 1990) However, there are few published numbers (see Tucker and Kidd (1973; their table 3 in which they report one calculated DSC for the Tuscaloosa Group of 151,000 mg/L). For the GIS, we used a map of Miller (1990), which shows the portion of southwest Alabama, Tuscaloosa Group (Black Warrior River aquifer), in which formation waters are more than 10,000 mg/L.

13tuscaloosa: Rock/water reaction. Rock/water reactions are largely a function of formation mineralogy and (if applicable) cement composition. Pore-water chemistry and pore-water residence also significantly influence rock/water reactions. Little information is available regarding the mineralogic composition of the Tuscaloosa Group in the subsurface of southwest Alabama. Alverson (1970; his appendix ) and Tucker and Kidd (1973; their appendix C) provided sample descriptions of the Tuscaloosa Group from two wells. These descriptions indicate that the Tuscaloosa Group sands are mostly composed of rather mature, siliceous sand. Some mica and lignite are reported. Some shell and calcareous material is

also reported. From this limited information, we conclude that the potential for significant rock/water reaction with injected CO<sub>2</sub> is low.

14tuscaloosa: Porosity. Porosity data come from two sources, hydrocarbon and waste-disposal-potential assessments (Tucker and Kidd, 1973; Mancini and others, 1987). The data from Tucker and Kidd (1973; their table 2) are primarily used for the GIS. The data in the GIS are ranges of their data. A large number of geophysical logs that penetrate the Tuscaloosa Group are available. From these logs, it would possible to construct a more accurate spatial distribution of porosity, if CO<sub>2</sub> sequestration in the area becomes a serious possibility.

### References

- Alverson, R. M., 1970, Deep well disposal study for Baldwin, Escambia and Mobile Counties, Alabama: Alabama Geological Survey, Circular 58, 49 p.
- Arthur, K., and Taylor, R. E., 1998, Ground-water analysis of the Mississippi Embayment Aquifer System, south-central United States: U.S. Geological Survey, Professional Paper 1416-I, 46 p.
- Bolin, D. E., Mann, S. D., Burroughs, D., Moore, H. E., Jr., and Powers, T. J., 1989, Petroleum atlas of southwestern Alabama: Alabama Geological Survey, Atlas 23, 218 p.
- Copeland, C. W., 1968, Geology of the Alabama coastal plain: Alabama Geological Survey, Circular 47, 97 p., 3 plates.
- Epsman, M. L., Moffett, T. B., Hinkle, F., Wilson, G. V., and Moore, J. D., 1983, Depths to ground waters with approximately 10,000 milligrams per liter of total dissolved solids in parts of Alabama: Alabama Geological Survey, Map 199C, 1 sheet.
- Grubb, H. F., 1998, Summary of hydrology of the Regional Aquifer Systems, Gulf Coastal Plain, south-central United States: U.S. Geological Survey, Professional Paper 1416-A.
- Hinkle, F., Moffett, T. B., Epsman, M. L., Wilson, G. V., and Moore, J. V., 1983, Configuration of the top of the Eutaw Formation in Alabama: Alabama Geological Survey, Map 199A, 1 sheet.
- Hosman, R. L., 1996, Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, south-central United States: U.S. Geological Survey, Professional Paper 1416-G, 35 p.

- Mancini, E. A., Mink, R. M., Payton, J. W., and Bearden, B. L., 1987, Environments of deposition and petroleum geology of the Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128–1142.
- Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey, Hydrologic Investigations Atlas No. HA-730-G, 28 p.
- Moffett, T. B., Hinkle, F., Epsman, M. L., and Wilson, G. V., 1984a, Configuration of the top of the Selma Group in Alabama: Alabama Geological Survey, Map 199CB, 1 sheet.
- \_\_\_\_\_, 1984b, Configuration of the top of the Tuscaloosa Group in Alabama: Alabama Geological Survey, Map 199C, 1 sheet.
- Moore, D. B., 1970, Subsurface geology of southwest Alabama: Alabama Geological Survey, Map 99, 1 sheet.
- \_\_\_\_\_, 1971, Subsurface geology of southwest Alabama: Alabama Geological Survey, Bulletin 99, 80 p., 11 plates.
- National Imagery and Mapping Agency, 2000, Digital terrain elevation data (DTED Level 0), <http://www.gisdatadept.com>.
- Pashin, J. C., Raymond, D. E., Rindsberg, A. K., Alabi, G. G., Carroll, R. E., Groshong, R. H., and Jin, G., 1998, Area balance and strain in an extensional fault system: strategies for improved oil recovery in fractured chalk, Gilbertown Field, southwestern Alabama: U.S. Department of Energy Report DOE/PC/91008-20 (DE98000499), National Petroleum Technology Office, 221 p.
- Raymond, D. E., and Copeland, C. W., 1987, Selected columnar sections for the Coastal Plain, Appalachian Plateaus, Interior Lowland Plateaus, and Valley and Ridge Provinces in Alabama: Alabama Geological Survey, Atlas 20, 43 p.
- Raymond, D. E., Copeland, C. W., and Rindsberg, 1993, Post-Miocene sediments of the shallow subsurface of coastal Alabama: Alabama Geological Survey, Circular 168, 93 p.
- Raymond, D. E., Osborne, W. E., Copeland, C. W., and Neathery, T. L., 1988, Alabama stratigraphy: Alabama Geological Survey, Circular 140, 97 p.
- Reed, P. C., and McCain, J. F., 1972, Water availability in Mobile County, Alabama: Alabama Geological Survey, Map 121, 45 p.
- Riccio, J. F., Hardin, J. D., Lamb, G. M., Scarborough, L., and Hanby, K. P., 1973, Development of the hydrologic concept for the Greater Mobile metropolitan-urban environment: Alabama Geological Survey, Bulletin 106, 171 p., 10 plates.

- Tucker, W. E., 1971, Subsurface disposal of liquid industrial wastes in Alabama—a current status report: *Ground Water*, v. 9, no. 6, p. 10–16.
- Tucker, W. E., and Kidd, R. E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey, Bulletin 104, 229 p., 4 plates.
- Wilson, G. V., and Tew, B. H., 1985, Geothermal data for southwest Alabama: correlations to geology and potential uses: Alabama Geological Survey, Oil and Gas Report 10, 156 p.

Prepared by Andrew Warne.



## WOODBINE FORMATION, EAST TEXAS BASIN

### General Setting

The Cretaceous Woodbine Formation is a clastic progradational wedge deposited into the East Texas Basin, one of the salt basins formed marginal to the Gulf of Mexico during the early Mesozoic. About 6,000 m of Mesozoic and Tertiary sediment was deposited in this basin. Salt tectonics and sedimentary loading have had a long-term effect on this basin. Woodbine sediments deposited in fluvial and deltaic settings mark the highest accommodation (thickest sediments) during this phase of basin evolution. Excellent-quality reservoirs formed by winnowing of these sediments during the waning phases of Woodbine deposition. Fine-grained seal strata of the shale-rich Eagle Ford and carbonate Austin Chalk formed during global sea-level rise. Uplift of the Sabine Arch at the east edge of the basin truncates the Woodbine; the Austin Chalk unconformably covers the uplift. A large-scale, regressive Tertiary sequence of clastics overlies the Cretaceous section and dips gently gulfward. Salt pillows and diapirs formed during the Cretaceous; during the Cenozoic diapirs have risen more slowly by basal necking (Seni and Jackson, 1984). Faults of the Mexia-Talco and Elkhart-Mt. Enterprise fault zones have isolated Woodbine sandstones within the basin from recharge zones in Woodbine outcrops on the east and north basin edges (Kreitler and others, 1984). This may create a large but isolated trap for CO<sub>2</sub> storage.

### Selection and Information Search

The reservoir properties of the Woodbine Formation are well known. Production from a number of reservoirs gives us a view of the sandstone properties and fluid behavior within the system (for example, Galloway and others, 1983, p. 54–64). This long production history is one of the reasons for selection of this brine formation for characterization. One scenario proposed for reuse of oil and gas infrastructure (pipelines or pipeline right-of-way, wells, mineral rights) would be use of abandoned reservoirs for

CO<sub>2</sub> storage. Severe pressure depletion because of historic production practices in Woodbine field might increase CO<sub>2</sub> storage capacity.

Extensive analysis of the stratigraphic and structural framework was completed in the 1980's, when salt domes in this basin were under consideration for disposal of high-level nuclear waste (for example Kreitler and others, 1984; Seni and Jackson, 1984). These resources provide data that would otherwise not be available.

In addition, the Woodbine has been the subject of a number of theses and dissertations, especially from Baylor University. The Woodbine Formation is locally used for deep well injection.

### Comments on Geologic Parameters

1woodbine: Depth. Structure on top of the Woodbine was digitized from Core Labs (1972). Contours were gridded by using the Grid algorithms in ARC/INFO, and depth below land surface was calculated by using the U.S. Geological Survey digital elevation model (c1woodbineg). A more detailed, large, plate-size structure map was presented by Calavan (1985).

2woodbine. Permeability/hydraulic conductivity. Permeability data for producing fields were summarized by Galloway and others (1983), but we have used the raw data extracted from the Railroad Commission of Texas well files (Holtz, 1997) to provide an overview of the properties of Woodbine producing intervals.

3woodbine: Formation thickness. We digitized the formation-thickness map of Calavan (1985).

4woodbine: Net sandstone thickness. We digitized (c4woodbineg) and gridded the generalized net-sandstone map presented by Oliver (1971). More detailed data are available at field scale and by interpreting finer stratigraphic elements within the Woodbine.

5woodbine. Percent shale: Percent shale was calculated:  $5\text{woodbine} = 1 - (4\text{woodbine}/3\text{woodbine})$ .

6woodbine. Continuity. Sand-body continuity can be found by using a generalized map of depositional systems (Oliver, 1971). A more detailed facies map is available

(Calavan, 1985). Site studies are needed to assess the site-specific complexity of this heterogeneous system.

- 7woodbine: Thickness of seal. The Eagle Ford shale is the low-permeability unit immediately on top of the Woodbine. A thickness map was digitized from Surles (1986) and gridded (c7woodbineg). More regional-scale stratigraphic and facies information is available from this source. The Eagle Ford has been eroded over the Sabine Uplift in the eastern part of the study area; however, the low-transmissivity Austin Chalk extends over this area.
- 8woodbine: Continuity of seal. The Eagle Ford has been eroded over the Sabine Uplift in the eastern part of the study area (see 7woodbine); however, the low-transmissivity Austin Chalk extends over this area. Faults of the Mexia-Talco and Elkhart-Mt. Enterprise fault zones cut the seals. These faults create traps for oil fields, the extent to which they may locally leak unknown. Fault zones have isolated Woodbine sandstones within the basin from recharge zones in Woodbine outcrops on the east and north basin edges (Kreitler and others, 1984). If these faults can be shown to be tight to CO<sub>2</sub>, this geometry may create a desirably large but hydrologically isolated brine volume. Salt diapirs penetrate the Cretaceous section, and there is some evidence of at least geologic rates of discharge up some dome flanks (Kreitler and others, 1984). In the structurally and stratigraphically complex areas around salt diapirs, site-specific data on the potential for leakage are needed. Nonpenetrative salt pillows may also impact flow at depth.
- 9woodbine: Hydrocarbon production. We digitized a generalized map of East Texas production (Kreitler and others, 1984). More detailed proprietary data are available from Geomap, Plano, Texas.
- 10woodbine: Fluid residence time. Kreitler and others (1984, p. 117) stated in their summary of the hydrology of deep aquifers in the East Texas Basin “Recharge probably occurred during Cretaceous time; therefore the waters are very old.”
- 11woodbine: Flow direction. Kreitler and others (1984, p. 119) stated “The waters are very old, and there are no major discharge points from the basin. There is,



- however, no way to predict flow paths or travel times because there are insufficient data to construct potentiometric maps.”
- 12awoodbine: Formation temperature. We calculated temperature at formation depth from representative geothermal gradients for the East Texas Basin (Kron and Stix, 1982).
- 12bwoodbine: Formation pressure. The Woodbine Formation was originally at hydrostatic pressure, but it has been extensively depressurized by production (Kreitler and others, 1984, their fig. 44).
- 12cwoodbine: Formation-water salinity. We digitized a salinity map from Core Labs (1972).
- 13woodbine: Rock/water reaction. Field-specific petrographic descriptions of the Woodbine (Wagner, 1978) show fairly mature mineralogic compositions, the potential for reaction with high CO<sub>2</sub> brine is low.
- 14woodbine: Porosity. We present porosity data from the oil-field data base of Holtz (1997). Note that these values are representative of productive intervals.
- 15woodbine: Water chemistry. We digitized Kreitler and others (1984, their table 1) chemical analyses of produced waters.
- 16woodbine: Rock mineralogy. Field-specific petrographic descriptions of the Woodbine (Wagner, 1978) show fairly mature mineralogic compositions, sublitharenite to litharenite. Quartz is the dominant mineral and feldspar, clay, shell fragments, and chlorite is present. Accessory minerals reported include pyrite, organic materials, and micas. Albite is present but volumes were not quantified.

## References

- Calavan, C. W., 1985, Depositional environments and basinal setting of the Cretaceous Woodbine Sandstone, Northeast Texas: Baylor University, Master's thesis, 225 p.
- Core Labs (Texas Water Development Board), 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157, v. 1, 113 p.
- Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, Noel, and Bebout, D. G., 1983, Atlas of major Texas oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 139 p.

- Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.
- Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M. P. A., and Seni, S. J., 1984, Hydrogeological characterization of the saline aquifers, East Texas Basin—implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for U.S. Department of Energy, under contract no. DE-AC97-80ET46617, 156 p.
- Kron, Andrea, and Stix, John, 1982, U.S. Geothermal Gradient Map of the United States, exclusive of Alaska and Hawaii: National Oceanic and Atmospheric Administration, National Geophysical Data Center, scale 1:2,500,000, 2 sheets.
- Oliver, W. B., 1971, Depositional systems in the Woodbine Formation (Upper Cretaceous) northeast Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 73, 28 p.
- Phillips, Sandra, 1987, Shelf sedimentation and depositional sequence stratigraphy of the Upper Cretaceous Woodbine-Eagle Ford groups, East Texas: Ithaca, Cornell University, Ph.D. dissertation, 507 p.
- Seni, S. J., and Jackson, M. P. A., 1984, Sedimentary records of Cretaceous and Tertiary salt movement, East Texas Basin: times, rates, and volumes of flow, implications to nuclear waste isolation and petroleum exploration: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 139, 89 p.
- Surles, M. A., 1986, Stratigraphy of the Eagle Ford Group (Upper Cretaceous) and its source-rock potential in the East Texas Basin: Baylor University, Master's thesis, 219 p.
- Wagner, W. O., 1987, Reservoir study of Cretaceous Woodbine fields in the northern East Texas Basin: Baylor University, Master's thesis, 139 p.

Prepared by S. Hovorka.

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
1	Arbuckle Gr	Oklahoma	Johnson, K. S., 1991a, Geologic setting of the Arbuckle Group in Oklahoma, in Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey, Special Publication 91-3, p. 1-7.	2
2	Arbuckle Gr	Oklahoma	Jorgensen, D. G., Helgesen, J. O., Signor, D. C., Leonard, R. B., Imes, J. L., and Christenson, S. C., 1996, Analysis of regional aquifers in the central midwest of the United States in Kansas, Nebraska and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Summary: U.S. Geological Survey, Professional Paper 1414-A, 67 p.	2
2	Arbuckle Gr	Oklahoma	Puckette, J. O., 1996, Evaluation of underpressured reservoirs as potential repositories for liquid waste: Oklahoma State University, Ph.D. dissertation, 274 p.	2
3	Arbuckle Gr	Oklahoma	Johnson, K. S., 1991b, Geologic overview and economic importance of Late Cambrian and Ordovician age rocks in Oklahoma, in Johnson, K. S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 Symposium: Oklahoma Geological Survey, Circular 92, p. 3-14.	2
4	Arbuckle Gr	Oklahoma	Not Applicable	5
5	Arbuckle Gr	Oklahoma	Puckette, J. O., 1996, Evaluation of underpressured reservoirs as potential repositories for liquid waste: Oklahoma State University, Ph.D. dissertation, 274 p.	5
6	Arbuckle Gr	Oklahoma	Henry, M. E., 1991, Subsurface structure map of the Arbuckle Group, south-central Oklahoma, in Johnson, K. S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 Symposium: Oklahoma Geological Survey, Circular 92, p. 218-219.	2
6	Arbuckle Gr	Oklahoma	Puckette, J. O., 1996, Evaluation of underpressured reservoirs as potential repositories for liquid waste: Oklahoma State University, Ph.D. dissertation, 274 p.	2
7	Arbuckle Gr	Oklahoma	Hester, T. C., and Schmoker, J. W., 1993, Regional geology of the Woodford Shale—Anadarko Basin, Oklahoma: an overview of relevance to horizontal drilling, in Johnson, K. S., and Campbell, J. A., eds., Petroleum—reservoir geology in the southern Midcontinent, 1991	3
7	Arbuckle Gr	Oklahoma	Amsden, T. W., 1975, Panel 4—Isopach map of Woodford Shale, in Hunton Group (late Ordovician, Silurian, and early Devonian) in the Anadarko Basin of Oklahoma: Oklahoma Geological Survey Bulletin, v. 121, 214 p.	3
8	Arbuckle Gr	Oklahoma	Amsden, T. W., 1975, Panel 4—Isopach map of Woodford Shale, in Hunton Group (late Ordovician, Silurian, and early Devonian) in the Anadarko Basin of Oklahoma: Oklahoma Geological Survey Bulletin, v. 121, 214 p.	1
9	Arbuckle Gr	Oklahoma	Burchfield, M. R., 1985, Map of Oklahoma oil and gas fields: Oklahoma Geological Survey, Map GM-28.	2
10	Arbuckle Gr	Oklahoma	Jorgensen, D. G., Helgesen, J. O., Signor, D. C., Leonard, R. B., Imes, J. L., and Christenson, S. C., 1996, Analysis of regional aquifers in the central midwest of the United States in Kansas, Nebraska and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Summary: U.S. Geological Survey, Professional Paper 1414-A, 67 p.	5
11	Arbuckle Gr	Oklahoma	Puckette, J. O., 1996, Evaluation of underpressured reservoirs as potential repositories for liquid waste: Oklahoma State University, Ph.D. dissertation, 274 p.	1
12a	Arbuckle Gr	Oklahoma	Blackwell, D. D., Wisian, K. W., and Steele, J. L., 1997, Geothermal resource/reservoir investigations based on heat flow and thermal gradient data for the United States: U.S. Department of Energy Geothermal Energy, <a href="http://icsbep.inel.gov/geothermal/fy97/explore/exp-16.html#Fig2">http://icsbep.inel.gov/geothermal/fy97/explore/exp-16.html#Fig2</a> .	2
12b	Arbuckle Gr	Oklahoma	Jorgensen, D. G., Helgesen, J. O., Signor, D. C., Leonard, R. B., Imes, J. L., and Christenson, S. C., 1996, Analysis of regional aquifers in the central midwest of the United States in Kansas, Nebraska and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Summary: U.S. Geological Survey, Professional Paper 1414-A, 67 p.	1
12c	Arbuckle Gr	Oklahoma	Jorgensen, D. G., 1993, Paleohydrology of the Central United States: U.S. Geological Survey, Bulletin 1989-D, 32 p.	1
13	Arbuckle Gr	Oklahoma	Not Applicable	5
14	Arbuckle Gr	Oklahoma	Puckette, J. O., 1996, Evaluation of underpressured reservoirs as potential repositories for liquid waste: Oklahoma State University, Ph.D. dissertation, 274 p.	4
15	Arbuckle Gr	Oklahoma	Ryder, P. D., 1996, Ground water atlas of the United States—segment 4, Oklahoma, Texas, in U.S. Geological Survey, Hydrologic Investigations Atlas 730-E, p. E27.	5
16	Arbuckle Gr	Oklahoma	Derby, J. R., Hinch, H. H., and Repetski, J. R., 1991, Lithology, stratigraphy, and age of the Arbuckle Group in the Amoco Shads No.4, a continuous core from grassroots into basement, Rogers County, Oklahoma, in Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey, Special Publication 91-3, p. 69-82.	2
16	Arbuckle Gr	Oklahoma	Ragland, D. A., and Donovan, R. N., 1991, Sedimentology and diagenesis of the Arbuckle Group in outcrops of southern Oklahoma, in Arbuckle Group Core Workshop and Field Trip: Oklahoma Geological Survey, Special Publication 91-3, p. 9-30.	2
16	Arbuckle Gr	Oklahoma	Johnson, K. S., 1991b, Geologic overview and economic importance of Late Cambrian and Ordovician age rocks in Oklahoma, in Johnson, K. S., ed., Late Cambrian-Ordovician geology of the southern Midcontinent, 1989 Symposium: Oklahoma Geological Survey, Circular 92, p. 3-14.	2
1	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Pool, D. R., 1985, Aquifer geology of alluvial basins of Arizona, in Anderson, T. W., and Johnson, A. I., eds., Regional aquifer systems of the United States, southwest alluvial basins of Arizona: American Water Resources Association Monograph 7, p. 25-36.	3

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm),Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
2	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Prudic, D. E., Harrill, J. R., Burbey, and Thomas J., 1995, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper P-1409-D, 102 p.	3
3	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Brown, S. G., 1976, Preliminary maps showing ground-water resources in the lower Colorado River region, Arizona, New Mexico, and Utah: U.S. Geological Survey Hydrologic Investigations Atlas HA-542, 3 sheets.	1
4	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Brown, S. G., 1976, Preliminary maps showing ground-water resources in the lower Colorado River region, Arizona, New Mexico, and Utah: U.S. Geological Survey Hydrologic Investigations Atlas HA-542, 3 sheets.	5
5	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Anderson, T. W., Freethey, G. W., and Tucci, Patrick, 1992, Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent states: U.S. Geological Survey Professional Paper 1406-B, 67 p.	3
6	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Planert, M., 1996, Ground water atlas of the United States, Segment 1: California and Nevada: U.S. Geological Survey Atlas.	1
7	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Freethey, G. W., Pool, D. R., Anderson, T. W., and Tucci, Patrick, 1986, Description and generalized distribution of aquifer materials in the alluvial basins of Arizona and adjacent parts of California and New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA-663, scale 1:500,000, 4 sheets.	4
8	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Freethey, G. W., Pool, D. R., Anderson, T. W., and Tucci, Patrick, 1986, Description and generalized distribution of aquifer materials in the alluvial basins of Arizona and adjacent parts of California and New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA-663, scale 1:500,000, 4 sheets.	4
9	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Mitchell, G. C., and McDonald, R. E., 1986, History of Cenozoic extension in Central Sevier Desert, west-central Utah, from COCORP seismic reflection data: discussion: American Association of Petroleum Geologists Bulletin, v. 70, no. 8, p. 1015-1021	5
10	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Thomas, J. M., Welch, A. H., and Dettinger, M. D., 1996, Geochemistry and isotope hydrology of representative aquifers in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-C, p. C1-C100.	3
11	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Prudic, D. E., Harrill, J. R., Burbey, and Thomas J., 1995, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper P-1409-D, 102 p.	1
12a	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California		
12b	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California		
12c	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Planert, M., 1996, Ground water atlas of the United States, Segment 1: California and Nevada: U.S. Geological Survey Atlas.	1
13	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Thomas, J. M., Welch, A. H., and Dettinger, M. D., 1996, Geochemistry and isotope hydrology of representative aquifers in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-C, p. C1-C100.	3
14	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Thomas, J. M., Welch, A. H., and Dettinger, M. D., 1996, Geochemistry and isotope hydrology of representative aquifers in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-C, p. C1-C100.	5
15	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California	Pool, D. R., 1985, Aquifer geology of alluvial basins of Arizona, in Anderson, T. W., and Johnson, A. I., eds., Regional aquifer systems of the United States, southwest alluvial basins of Arizona: American Water Resources Association Monograph 7, p. 25-36.	2
16	Basin Fill and Carbonates	Basin and Range, Arizona-Nevada-California		
1	Cape Fear Fm	South Carolina Coastal Plain	Renkin, R. A., Mahon, G. L., and Davis, M. E., 1989, Hydrogeology of clastic Tertiary and Cretaceous regional aquifers and confining units in the southeastern coastal plain aquifer system of the United States: U.S. Geological Survey Hydrologic Investigations Atlas HA-701, 3 sheets.	1
2	Cape Fear Fm	South Carolina Coastal Plain	Aucott, W. R., 1988, The predevelopment ground-water flow system and hydrologic characteristics of the Coastal Plain aquifers of south Carolina: U.S. Geological Survey, Water-Resources Investigations Report 86-4347, 66 p.	2
3	Cape Fear Fm	South Carolina Coastal Plain	Aucott, W. R., Davis, M. E., and Speiran, G. K., 1987, Geohydrologic framework of the Coastal Plain aquifers of South Carolina: U.S. Geological Survey, Water-Resources Investigations Report 85-4271, 7 sheets.	3
3	Cape Fear Fm	South Carolina Coastal Plain	Colquhoun, D. J., Woollen, L. D., Van Nienwenhuise, D. S., Padgett, G. G., Oldham, R. W., Boylan, D. C., Bishop, J. W., and Howell, P. D., 1983, Surface and subsurface stratigraphy, structure and aquifers of the South Carolina Coastal Plain: Columbia, SC, State of South Carolina, Office of the Governor, 78 p.	3
4	Cape Fear Fm	South Carolina Coastal Plain	Gohn, G. S., Higgins, B. B., Smith, C. C., and Owens, J. P., 1977, Lithostratigraphy of the deep corehole (Clubhouse Crossroads Corehole 1) near Charleston, South Carolina: U.S. Geological Survey, Professional Paper 1028E, p. 59-70.	4
4	Cape Fear Fm	South Carolina Coastal Plain	Brown, P. M., Brown, D. L., Reid, M. S., and Lloyd, O. B., Jr., 1979, Evaluation of the geologic and hydrologic factors related to the water-storage potential of Mesozoic aquifers in the southern part of the Atlantic coastal plain, South Carolina and Georgia: U.S. Geological Survey, Professional Paper 1088, 37 p., 11 plates.	4
4	Cape Fear Fm	South Carolina Coastal Plain	Temples, T. J., and Waddell, M. G., 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: Ground Water, v. 34, p. 523-531.	4

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm),Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
5	Cape Fear Fm	South Carolina Coastal Plain	Gohn, G. S., Higgins, B. B., Smith, C. C., and Owens, J. P., 1977, Lithostratigraphy of the deep corehole (Clubhouse Crossroads Corehole 1) near Charleston, South Carolina: U.S. Geological Survey, Professional Paper 1028E, p. 59–70.	4
5	Cape Fear Fm	South Carolina Coastal Plain	Brown, P. M., Brown, D. L., Reid, M. S., and Lloyd, O. B., Jr., 1979, Evaluation of the geologic and hydrologic factors related to the water-storage potential of Mesozoic aquifers in the southern part of the Atlantic coastal plain, South Carolina and Georgia: U.S. Geological Survey, Professional Paper 1088, 37 p., 11 plates.	4
6	Cape Fear Fm	South Carolina Coastal Plain	Brown, P. M., Brown, D. L., Reid, M. S., and Lloyd, O. B., Jr., 1979, Evaluation of the geologic and hydrologic factors related to the water-storage potential of Mesozoic aquifers in the southern part of the Atlantic coastal plain, South Carolina and Georgia: U.S. Geological Survey, Professional Paper 1088, 37 p., 11 plates.	4
7	Cape Fear Fm	South Carolina Coastal Plain	Aucott, W. R., Davis, M. E., and Speiran, G. K., 1987, Geohydrologic framework of the Coastal Plain aquifers of South Carolina: U.S. Geological Survey, Water-Resources Investigations Report 85-4271, 7 sheets.	3
7	Cape Fear Fm	South Carolina Coastal Plain	Colquhoun, D. J., Woollen, L. D., Van Nienwenhuise, D. S., Padgett, G. G., Oldham, R. W., Boylan, D. C., Bishop, J. W., and Howell, P. D., 1983, Surface and subsurface stratigraphy, structure and aquifers of the South Carolina Coastal Plain: Columbia, SC, State of South Carolina, Office of the Governor, 78 p.	3
8	Cape Fear Fm	South Carolina Coastal Plain	Aucott, W. R., 1988, The predevelopment ground-water flow system and hydrologic characteristics of the Coastal Plain aquifers of south Carolina: U.S. Geological Survey, Water-Resources Investigations Report 86-4347, 66 p.	3
9	Cape Fear Fm	South Carolina Coastal Plain	Maher, J. C., and Applin, E. R., 1971, Geologic framework and petroleum potential of the Atlantic coastal plain and continental shelf: U.S. Geological Survey Professional Paper 659, 98 p., 17 plates.	3
10	Cape Fear Fm	South Carolina Coastal Plain	Miller, J. A., Barker, R. A., and Renkin, R. A., 1986, Hydrology of the Southeastern Coastal Plain Aquifer System, in Vecchioli, J., and Johnson, A. I., eds., Regional aquifer systems of the United States: aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph Series No. 9, p. 53–77.	3
10	Cape Fear Fm	South Carolina Coastal Plain	Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey Hydrologic Investigations Atlas No. HA-730-G, 28 p.	3
11	Cape Fear Fm	South Carolina Coastal Plain	Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey Hydrologic Investigations Atlas No. HA-730-G, 28 p.	2
12a	Cape Fear Fm	South Carolina Coastal Plain	Kinney, D. M., ed., 1976, Geothermal gradient map of North America: American Association of Petroleum Geologists and U.S. Geological Survey Publication G74014, 2 maps.	3
12b	Cape Fear Fm	South Carolina Coastal Plain	Temples, T. J., and Waddell, M. G., 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: Ground Water, v. 34, p. 523–531.	3
12c	Cape Fear Fm	South Carolina Coastal Plain	Lee, R. W., 1985, Water-quality maps for selected Upper Cretaceous water-bearing zones in the southeastern coastal plain: U.S. Geological Survey Water Resources Investigations 85-4193.	3
13	Cape Fear Fm	South Carolina Coastal Plain	Miller, J. A., Barker, R. A., and Renkin, R. A., 1986, Hydrology of the Southeastern Coastal Plain Aquifer System, in Vecchioli, J., and Johnson, A. I., eds., Regional aquifer systems of the United States: aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph Series No. 9, p. 53–77.	3
14	Cape Fear Fm	South Carolina Coastal Plain	Temples, T. J., and Waddell, M. G., 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: Ground Water, v. 34, p. 523–531.	4
15	Cape Fear Fm	South Carolina Coastal Plain	Gohn, G. S., Higgins, B. B., Smith, C. C., and Owens, J. P., 1977, Lithostratigraphy of the deep corehole (Clubhouse Crossroads Corehole 1) near Charleston, South Carolina: U.S. Geological Survey, Professional Paper 1028E, p. 59–70.	3
16	Cape Fear Fm	South Carolina Coastal Plain	Temples, T. J., and Waddell, M. G., 1996, Application of petroleum geophysical well logging and sampling techniques for evaluating aquifer characteristics: Ground Water, v. 34, p. 523–531.	4
1	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.	4
2	Cedar Keys_Lawson	Central Florida Region	Haberfeld (Florida Department of Environmental Protection, personal communication, 2000)	4
3	Cedar Keys_Lawson	Central Florida Region	Randazzo, A. F., 1997, The sedimentary platform of Florida: Mesozoic to Cenozoic, in Randazzo, A. F., and Jones, D. S., eds., The geology of Florida: Tallahassee, University of Florida Press, p. 39–56.	4
4	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.	5

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm),Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
5	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.	5
5	Cedar Keys_Lawson	Central Florida Region	Winston, G. O., 1977, Cotype wells for the five classic formations in peninsular Florida: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 421–427.	
6	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.Winston, G. O., 1977,	5
6	Cedar Keys_Lawson	Central Florida Region	Winston, G. O., 1977, Cotype wells for the five classic formations in peninsular Florida: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 421–427.	
7	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.	3
8	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.	3
9	Cedar Keys_Lawson	Central Florida Region	Meyer, F. W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan Aquifer system in southern Florida: U.S. Geological Survey, Professional Paper 1403-G, 59 p.	5
10	Cedar Keys_Lawson	Central Florida Region	Meyer, F. W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan Aquifer system in southern Florida: U.S. Geological Survey, Professional Paper 1403-G, 59 p.	5
11	Cedar Keys_Lawson	Central Florida Region	Meyer, F. W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan Aquifer system in southern Florida: U.S. Geological Survey, Professional Paper 1403-G, 59 p.	5
12a	Cedar Keys_Lawson	Central Florida Region	Smith, D. L., and Lord, K. M., 1997, Tectonic evolution and geophysics of the Florida basement, in Randazzo, A. F., and Jones, D. S., eds., The geology of Florida: Tallahassee, University of Florida Press, p. 13–26.	2
12b	Cedar Keys_Lawson	Central Florida Region	Meyer, F. W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan Aquifer system in southern Florida: U.S. Geological Survey, Professional Paper 1403-G, 59 p.	3
12c	Cedar Keys_Lawson	Central Florida Region	Vernon, R. O., 1970, The beneficial uses of zones of high transmissivities in the Florida subsurface for water storage and waste disposal: Florida Geological Survey, Information Circular No. 70, 39 p.	5
13	Cedar Keys_Lawson	Central Florida Region	Vernon, R. O., 1951, The geology of Citrus and Levy counties, Florida: Florida Geological Survey Bulletin 33, 256 p.	5
13	Cedar Keys_Lawson	Central Florida Region	Applin, P. L., and Applin, E. R., 1944, Regional subsurface stratigraphy and structure of Florida and southern Georgia: American Association of Petroleum Geologists, v. 28, p. 1673–1753.	5
13	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.	5
13	Cedar Keys_Lawson	Central Florida Region	Winston, G. O., 1977, Cotype wells for the five classic formations in peninsular Florida: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 421–427.	5
14	Cedar Keys_Lawson	Central Florida Region	Haberfeld (Florida Department of Environmental Protection, personal communication, 2000)	4
15	Cedar Keys_Lawson	Central Florida Region	Vernon, R. O., 1951, The geology of Citrus and Levy counties, Florida: Florida Geological Survey Bulletin 33, 256 p.	5
15	Cedar Keys_Lawson	Central Florida Region	Applin, P. L., and Applin, E. R., 1944, Regional subsurface stratigraphy and structure of Florida and southern Georgia: American Association of Petroleum Geologists, v. 28, p. 1673–1753.	5
15	Cedar Keys_Lawson	Central Florida Region	Chen, S. C., 1965, The regional stratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin No. 45, 105 p.Winston, G. O., 1977,	5
15	Cedar Keys_Lawson	Central Florida Region	Winston, G.O., 1977. Cotype wells for the five classic formations in peninsular Florida: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 421–427.	5
16	Cedar Keys_Lawson	Central Florida Region	Vernon, R. O., 1970, The beneficial uses of zones of high transmissivities in the Florida subsurface for water storage and waste disposal: Florida Geological Survey, Information Circular No. 70, 39 p.	5
1	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	1
1	Fox Hills_Lower Hell Creek	Powder River Basin	Fox, J., and Higley, D., 1987, Structural at the Base of the Upper Cretaceous Fox Hills Sandstone, Power River Basin, Wyoming and Montana. USGS OFR 8	1
2	Fox Hills_Lower Hell Creek	Powder River Basin	Mullen, D. M., and Barlow and Haun, Inc., 1993, Powder River Basin (Section FS-1), in Hjellming, C. A., ed., Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, Geological Survey of Wyoming, Colorado Geological Survey, Utah Geological Survey, Barlow and Haun, Intera, and Methane Resources Group, Ltd., p. 70.	5
3	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
4	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	1
5	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	1
6	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	3
7	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	3
8	Fox Hills_Lower Hell Creek	Powder River Basin	Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1317, 6 sheets.	1
9	Fox Hills_Lower Hell Creek	Powder River Basin	Mullen, D. M., and Barlow and Haun, Inc., 1993, Powder River Basin (Section FS-1), in Hjellming, C. A., ed., Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, Geological Survey of Wyoming, Colorado Geological Survey, Utah Geological Survey, Barlow and Haun, Intera, and Methane Resources Group, Ltd., p. 70.	4
10	Fox Hills_Lower Hell Creek	Powder River Basin	Henderson, T., 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey, Professional Paper 1402-C, p. C1-C84.	4
11	Fox Hills_Lower Hell Creek	Powder River Basin	Henderson, T., 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey, Professional Paper 1402-C, p. C1-C84.	4
12a	Fox Hills_Lower Hell Creek	Powder River Basin	Henderson, T., 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey, Professional Paper 1402-C, p. C1-C84.	4
12b	Fox Hills_Lower Hell Creek	Powder River Basin		
12c	Fox Hills_Lower Hell Creek	Powder River Basin	Henderson, T., 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey, Professional Paper 1402-C, p. C1-C84.	4
13	Fox Hills_Lower Hell Creek	Powder River Basin	Henderson, T., 1985, Geochemistry of ground-water in two sandstone aquifer systems in the northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey, Professional Paper 1402-C, p. C1-C84.	4
14	Fox Hills_Lower Hell Creek	Powder River Basin	Mullen, D. M., and Barlow and Haun, Inc., 1993, Powder River Basin (Section FS-1), in Hjellming, C. A., ed., Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, Geological Survey of Wyoming, Colorado Geological Survey, Utah Geological Survey, Barlow and Haun, Intera, and Methane Resources Group, Ltd., p. 70.	5
15	Fox Hills_Lower Hell Creek	Powder River Basin		
16	Fox Hills_Lower Hell Creek	Powder River Basin		
1	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	1
2	Frio Fm	Texas Gulf Coast	Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.	1
3	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	1
4	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm),Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
5	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	1
6	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	2
7	Frio Fm	Texas Gulf Coast	No Data	
8	Frio Fm	Texas Gulf Coast	No Data	
9	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	2
10	Frio Fm	Texas Gulf Coast	Harrison, W. J., and Summa, L. L., 1991, Paleohydrology of the Gulf of Mexico basin: American Journal of Science, v. 291 p. 109–176.	2
11	Frio Fm	Texas Gulf Coast	Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A., and Wood, W. T., 1988, Hydrology of formations for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, unpublished contract report, 204 p.	1
12a	Frio Fm	Texas Gulf Coast	complex	
12b	Frio Fm	Texas Gulf Coast	Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A., and Wood, W. T., 1988, Hydrology of formations for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, unpublished contract report, 204 p.	1
12c	Frio Fm	Texas Gulf Coast	Morton, R. A., and Land, L. S., 1987, Regional variations in formation water chemistry, Frio Formation (Oligocene), Texas Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 71, no. 2, p. 191–206.	2
13	Frio Fm	Texas Gulf Coast	Land, L. S., and Macpherson, G. L., 1992, Origin of saline formation waters, Cenozoic section, Gulf of Mexico sedimentary basin: American Association of Petroleum Geologists Bulletin v. 76, p. 1344–1362.	1
14	Frio Fm	Texas Gulf Coast	Galloway, W. H., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coast Basin—depositional systems, structural framework, hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.	2
14	Frio Fm	Texas Gulf Coast	Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.	2
15	Frio Fm	Texas Gulf Coast	Kreitler, C. W., and Richter, B. C., 1986, Hydrochemical characterization of the saline aquifers of the Texas Gulf Coast used for disposal of industrial waste: The University of Texas at Austin, Bureau of Economic Geology, unpublished contract report, 164 p.	1
16	Frio Fm	Texas Gulf Coast	Land, L. S., and Macpherson, G. L., 1992, Origin of saline formation waters, Cenozoic section, Gulf of Mexico sedimentary basin: American Association of Petroleum Geologists Bulletin v. 76, p. 1344–1362.	2
1	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethy, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
2	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethy, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
3	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethy, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
4	Glen Canyon Gr	Sevier- Kaiparowits Bench	Hood, J. W., and Patterson, D. J., 1984, Bedrock aquifers in the northern San Rafael Swell area, Utah, with special emphasis on the Navajo Sandstone: Utah Department of Natural Resources Technical Publication 78, 128 p.	1 (Limited area)
5	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethy, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	3
6	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethy, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	3
7	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethy, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
8	Glen Canyon Gr	Sevier- Kaiparowits Bench	Kocurek, G., and Dott, R. H., Jr., 1983, Jurassic paleogeography of the central and southern Rocky Mountains region, in Reynolds, M. W., and Dolly, E. D., eds., Mesozoic paleogeography of the West-Central United States: Rocky Mountain paleogeography symposium: Denver, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, v. 2, p. 101–116.	2
9	Glen Canyon Gr	Sevier- Kaiparowits Bench		



APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_ Area_ Region	Citation	Data-Quality Rank
10	Glen Canyon Gr	Sevier- Kaiparowits Bench	Heilweil, V. M., and Freethey, G. W., 1992, Hydrology of the Navajo aquifer in southwestern Utah and northwestern Arizona, including computer simulation of ground-water flow and water-level declines that could be caused by proposed withdrawals, in Harty, K. M., ed., <i>Engineering and environmental geology of southwestern Utah</i> : Utah Geological Association Publication 21, p. 213-223.	2
11	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethey, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
12a	Glen Canyon Gr	Sevier- Kaiparowits Bench		
12b	Glen Canyon Gr	Sevier- Kaiparowits Bench		
12c	Glen Canyon Gr	Sevier- Kaiparowits Bench	U.S. Geological Survey, 1996, Ground water atlas of the United States: Segment 2: Arizona, Colorado, New Mexico, and Utah.	1
12c	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethey, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
13	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethey, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
14	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethey, G. W., and Cordy, G. E., 1991, Geohydrology of Mesozoic rocks in the Upper Colorado River Basin—excluding the San Juan Basin—in Arizona, Colorado, New Mexico, Utah, and Wyoming: U.S. Geological Survey, Professional Paper 1411-C, 118 p.	1
15	Glen Canyon Gr	Sevier- Kaiparowits Bench	Freethey, G. W., Kimball, B. A., Wilberg, D. E., and Hood, J. W., 1988, General hydrogeology of the aquifers of Mesozoic age, upper Colorado River basin—excluding the San Juan Basin—Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey, Hydrologic Investigations Atlas HA-698, scale 1:2,500,000, 2 sheets.	1
16	Glen Canyon Gr	Sevier- Kaiparowits Bench		
1	Granite Wash	Palo Duro Basin	Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.	3
1	Granite Wash	Palo Duro Basin	Budnik, R., and Smith, D., 1982, Regional stratigraphic framework of the Texas Panhandle, in Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., <i>Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981</i> : The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 38-86.	3
2	Granite Wash	Palo Duro Basin	Smith, D. A., 1983, Permeability of the deep-basin aquifer system, Palo Duro Basin, in Gustavson, T. C., Kreidler, C. W., Bassett, R. L., Budnik, R. T., Ruppel, S. C., Baumgardner, R. W., Jr., Caran, S. C., Collins, E. W., Dutton, A. R., Dutton, S. P., Fisher, R. S., Fogg, G. E., Hovorka, S. D., Kolker, A., McGookey, D. A., Orr, E. D., Roberts, M. P., Senger, R. K., Smith, Dale, A., and Smith, D. Anderson, <i>Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1982</i> : The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 156-166.	5
2	Granite Wash	Palo Duro Basin	Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.	5
3	Granite Wash	Palo Duro Basin	Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.	3
3	Granite Wash	Palo Duro Basin	Budnik, R., and Smith, D., 1982, Regional stratigraphic framework of the Texas Panhandle, in Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., <i>Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981</i> : The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 38-86.	3
4	Granite Wash	Palo Duro Basin	Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
5	Granite Wash	Palo Duro Basin	Budnik, R., and Smith, D., 1982, Regional stratigraphic framework of the Texas Panhandle, in Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 38–86.	4
6	Granite Wash	Palo Duro Basin	Budnik, R., and Smith, D., 1982, Regional stratigraphic framework of the Texas Panhandle, in Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 38–86.	3
7	Granite Wash	Palo Duro Basin	Presley, M. W., 1979, Upper Permian evaporites and red beds, in Dutton, S. P., Finley R. J., Galloway, W. E., Gustavson, T. C., Handford, C. R., and Presley, M. W., Geology and hydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of nuclear waste isolation feasibility studies, 1978: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 79-1, p. 39–49.	3
8	Granite Wash	Palo Duro Basin	Presley, M. W., 1979, Upper Permian evaporites and red beds, in Dutton, S. P., Finley R. J., Galloway, W. E., Gustavson, T. C., Handford, C. R., and Presley, M. W., Geology and hydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of nuclear waste isolation feasibility studies, 1978: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 79-1, p. 39–49.	3
9	Granite Wash	Palo Duro Basin	Dutton, S. P., Goldstein, A. G., and Ruppel, S. C., 1982, Petroleum potential of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 123, 87 p.	1
10	Granite Wash	Palo Duro Basin	Senger, R. K., 1991, Regional hydrodynamics of variable-density flow systems, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 202, 54 p.	2
11	Granite Wash	Palo Duro Basin	Orr, E. D, Kreitler, C. W., and Senger, R. K., 1985, Investigation of the underpressuring in the deep-brine aquifer, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 85-1, 44 p.	1
12a	Granite Wash	Palo Duro Basin	Bassett, R. L., and Bentley, M. E., 1983, Deep brine aquifers in the Palo Duro Basin: regional flow and geochemical constraints: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 130, 59 p.	4
12b	Granite Wash	Palo Duro Basin	Orr, E. D, Kreitler, C. W., and Senger, R. K., 1985, Investigation of the underpressuring in the deep-brine aquifer, Palo Duro Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 85-1, 44 p.	3
12c	Granite Wash	Palo Duro Basin	Bassett, R. L., and Bentley, M. E., 1983, Deep brine aquifers in the Palo Duro Basin: regional flow and geochemical constraints: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 130, 59 p.	1
13	Granite Wash	Palo Duro Basin	Not Applicable	5
14	Granite Wash	Palo Duro Basin	Dutton, S. P., 1982a, Depositional history and reservoir quality of Granite Wash, in Gustavson, T. C., Bassett, R. L., Budnik, R., Finley, R., Goldstein, A. G., McGowen, J. H., Roedder, E., Ruppel, S. C., Baumgardner, R. W., Jr., Bentley, M. E., Dutton, S. P., Fogg, G. E., Hovorka, S. D., McGookey, D. A., Ramondetta, P. J., Simpkins, W. W., Smith, D., Smith, D. A., Duncan, E. A., Griffin, J. A., Merritt, R. M., and Naiman, E. R., Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of the nuclear waste isolation feasibility studies, 1981: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-7, p. 87–90.	4
15	Granite Wash	Palo Duro Basin	Bassett, R. L., and Bentley, M. E., 1983, Deep brine aquifers in the Palo Duro Basin: regional flow and geochemical constraints: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 130, 59 p.	4
16	Granite Wash	Palo Duro Basin	Dutton, S. P., 1980, Depositional systems and hydrocarbon resource potential of the Pennsylvanian System, Palo Duro and Dalhart Basins, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 80-8, 49 p.	2
1	Jasper Interval	East Texas Gulf Coast	Baker, E. T., Jr., 1986, Hydrology of the Jasper Aquifer in the southeast Texas coastal plain: Texas Water Development Board, Report 295, 64 p.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
2	Jasper Interval	East Texas Gulf Coast	Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A., and Wood, W. T., 1988, Hydrogeology of formations used for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, open-file report prepared for U.S. Environmental Protection Agency under Cooperative Agreement ID No. CR812786-01, 204 p.	3
3	Jasper Interval	East Texas Gulf Coast	Galloway, W. E., Bebout, D. G., Fisher, W. L., Dunlap, J. B., Jr., Cabrera-Castro, R., Lugo-Rivera, J. E., and Scott, T. M., 1991, Cenozoic, in Salvador, A., ed., The geology of North America, v. J. The Gulf of Mexico Basin: Geological Society of America, p. 245–324.	4
4	Jasper Interval	East Texas Gulf Coast	Galloway, W. E., Jirik, L. A., Morton, R. A., and Dubar, J. R., 1986, Lower Miocene (Fleming) depositional episode of the Texas coastal plain and continental shelf: structural framework, facies, and hydrocarbon resources: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 150, 50 p.	1
5	Jasper Interval	East Texas Gulf Coast	Galloway, W. E., Jirik, L. A., Morton, R. A., and Dubar, J. R., 1986, Lower Miocene (Fleming) depositional episode of the Texas coastal plain and continental shelf: structural framework, facies, and hydrocarbon resources: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 150, 50 p.	1
6	Jasper Interval	East Texas Gulf Coast	Ambrose, W. A., 1990, Facies heterogeneity and brine-disposal potential of Miocene barrier-island, fluvial, and deltaic systems: examples from northeast Hitchcock and Alta Loma Fields, Galveston County, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 90-4, 35 p.	2
7	Jasper Interval	East Texas Gulf Coast	Baker, E. T., Jr., 1986, Hydrology of the Jasper Aquifer in the southeast Texas coastal plain: Texas Water Development Board, Report 295, 64 p.	1
8	Jasper Interval	East Texas Gulf Coast	Ambrose, W. A., 1990, Facies heterogeneity and brine-disposal potential of Miocene barrier-island, fluvial, and deltaic systems: examples from northeast Hitchcock and Alta Loma Fields, Galveston County, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 90-4, 35 p.	4
9	Jasper Interval	East Texas Gulf Coast	Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, N., and Bebout, D. G., 1983, Atlas of major Texas oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 139 p.	1
9	Jasper Interval	East Texas Gulf Coast	Kosters, E. C., Bebout, D. G., Seni, S. J., Garrett, C. M., Jr., Brown, L. F., Jr., Hamlin, H. S., Dutton, S. P., Ruppel, S. C., Finley, R. J., and Tyler, N., 1989, Atlas of major Texas gas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 161 p.	1
10	Jasper Interval	East Texas Gulf Coast		5
11	Jasper Interval	East Texas Gulf Coast	Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A., and Wood, W. T., 1988, Hydrogeology of formations used for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, open-file report prepared for U.S. Environmental Protection Agency under Cooperative Agreement ID No. CR812786-01, 204 p.	4
12a	Jasper Interval	East Texas Gulf Coast	Pettijohn, R. A., Weiss, J. S., and Williamson, A. K., 1988, Distribution of dissolved-solids concentrations and temperature in ground water of the gulf coast aquifer systems, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4082.	1
12b	Jasper Interval	East Texas Gulf Coast	Kreitler, C. W., Akhter, M. S., Donnelly, A. C. A., and Wood, W. T., 1988, Hydrogeology of formations used for deep-well injection, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, open-file report prepared for U.S. Environmental Protection Agency under Cooperative Agreement ID No. CR812786-01, 204 p.	2
12c	Jasper Interval	East Texas Gulf Coast	Pettijohn, R. A., Weiss, J. S., and Williamson, A. K., 1988, Distribution of dissolved-solids concentrations and temperature in ground water of the gulf coast aquifer systems, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 88-4082.	1
13	Jasper Interval	East Texas Gulf Coast	Ragsdale, J. A., 1960, Petrology of Miocene Oakville Formation, Texas Coastal Plain: University of Texas, Austin, Master's thesis, 196 p.	4
14	Jasper Interval	East Texas Gulf Coast	Ambrose, W. A., 1990, Facies heterogeneity and brine-disposal potential of Miocene barrier-island, fluvial, and deltaic systems: examples from northeast Hitchcock and Alta Loma Fields, Galveston County, Texas: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 90-4, 35 p.	4
15	Jasper Interval	East Texas Gulf Coast		
16	Jasper Interval	East Texas Gulf Coast		

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
1	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., 1992, Hydrogeologic framework of the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404-G, 59 p., 13 plates.	1
2	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Pope, D. A., and Gordon, A. D., 1999, Simulation of ground-water flow and movement of the freshwater-saltwater interface in the New Jersey coastal plain: U.S. Geological Survey Water-Resources Investigations Report 98-4216, 159 p.	3
3	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Brown, P. M., Miller, J. A., and Swain, F. M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic coastal plain, North Carolina to New York: U.S. Geological Survey, Professional Paper 796, 79 p., 59 plates. Trapp, H., Jr., and Meisler, H., 1992, The regional aquifer underlying the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York—summary: U.S. Geological Survey Professional Paper 1404A, 33 p., 11 plates.	3
4	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Otton, E. G., and Mandle, R. J., 1984, Hydrogeology of the upper Chesapeake Bay area, Maryland with emphasis on aquifers in the Potomac Group: Maryland Geological Survey Report of Investigations No. 39, 62 p. Hansen, H. J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.	5
5	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Brown, P. M., Miller, J. A., and Swain, F. M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic coastal plain, North Carolina to New York: U.S. Geological Survey, Professional Paper 796, 79 p., 59 plates.	5
6	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Cushing, E. M., Kantrowitz, I. H., and Taylor, K. R., 1973, Water resources of the Delmarva Peninsula: U.S. Geological Survey, Professional Paper 822, 58 p.	4
7	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., 1992, Hydrogeologic framework of the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404-G, 59 p., 13 plates.	2
8	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Pope, D. A., and Gordon, A. D., 1999, Simulation of ground-water flow and movement of the freshwater-saltwater interface in the New Jersey coastal plain: U.S. Geological Survey Water-Resources Investigations Report 98-4216, 159 p.	2
9	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Maher, J. C., and Applin, E. R., 1971, Geologic framework and petroleum potential of the Atlantic coastal plain and continental shelf: U.S. Geological Survey Professional Paper 659, 98 p., 17 plates.	3
10	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Meisler, H., Leahy, P. P., and Knobel, L. L., 1984, Effect of eustatic sea-level changes on salt-water-freshwater in the northern Atlantic coastal plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.	4
11	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., 1992, Hydrogeologic framework of the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404-G, 59 p., 13 plates.	4
11	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Leahy, P. P., and Martin, Mary, 1993, Geohydrology and simulation of ground-water flow in the Northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404-K, 81 p.	4
11	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., and Horn, M. A., 1997, Ground water atlas of the United States—segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia: U.S. Geological Survey Hydrologic Investigations, Atlas No. HA-730-L, 30 p.	4

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
11	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Pope, D. A., and Gordon, A. D., 1999, Simulation of ground-water flow and movement of the freshwater-saltwater interface in the New Jersey coastal plain: U.S. Geological Survey Water-Resources Investigations Report 98-4216, 159 p.	4
12a	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., Knobel, L. L., Meisler, H., and Leahy, P. P., 1984, Test well DO-CE 88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey, Water-Supply Paper 2229, 48 p.	3
12a	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Hansen, H. J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.	3
12b	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Hansen, H. J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.	3
12b	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., and Meisler, H., 1992, The regional aquifer underlying the northern Atlantic coastal plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York—summary: U.S. Geological Survey, Professional Paper 1404A, 33 p., 11 plates.	3
12c	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Hansen, H. J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.	3
12c	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Pope, D. A., and Gordon, A. D., 1999, Simulation of ground-water flow and movement of the freshwater-saltwater interface in the New Jersey coastal plain: U.S. Geological Survey Water-Resources Investigations Report 98-4216, 159 p.	3
13	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Anderson, J. L., 1948, Cretaceous and Tertiary subsurface geology: State of Maryland Board of Natural Resources, Bulletin 2, 456 p.	3
13	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Kasabach, H. F., and Scudder, R. J., 1961, Deep wells of the New Jersey coastal plain: New Jersey Geological Survey Report GSR 3, 62 p.	3
13	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Maher, J. C., and Applin, E. R., 1971, Geologic framework and petroleum potential of the Atlantic coastal plain and continental shelf: U.S. Geological Survey Professional Paper 659, 98 p., 17 plates.	3
13	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., Knobel, L. L., Meisler, H., and Leahy, P. P., 1984, Test well DO-CE 88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey, Water-Supply Paper 2229, 48 p.	3
13	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Meisler, H., Leahy, P. P., and Knobel, L. L., 1984, Effect of eustatic sea-level changes on salt-water-freshwater in the northern Atlantic coastal plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.	3
13	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Benson, R. N., Jordan, R. R., and Spoljaric, N., 1985, Geological studies of Cretaceous and Tertiary section, test well Je32-04, central Delaware: Delaware Geological Survey Bulletin No. 17, 69 p., 3 plates.	3

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
14	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Hansen, H. J., 1969, Depositional environments of subsurface Potomac Group in southern Maryland: American Association of Petroleum Geologists Bulletin, v. 53, p. 1923-1937.	3
15	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., Knobel, L. L., Meisler, H., and Leahy, P. P., 1984, Test well DO-CE 88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey, Water-Supply Paper 2229, 48 p.	2
16	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Trapp, H., Jr., Knobel, L. L., Meisler, H., and Leahy, P. P., 1984, Test well DO-CE 88 at Cambridge, Dorchester County, Maryland: U.S. Geological Survey, Water-Supply Paper 2229, 48 p.	2
16	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Hansen, H. J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.	2
16	Lower Potomac Gr	Eastern Coastal Plain of Maryland, Delaware, and New Jersey	Gill, H. E., Seabar, P. R., Vecchioli, J., and Anderson, H. R., 1963, Evaluation of geologic and hydrologic data from the test-drilling program at Island Beach State Park, N.J.: New Jersey Department of Conservation and Economic Development, Water Resources Circular 12, 25 p.	2
1	Lyons Fm	Denver Basin	Garbarini, G., and Veal, H. K., 1968, Potential of Denver Basin for disposal of liquid wastes, subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir, p. 165-185	4
2	Lyons Fm	Denver Basin	Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217-2244.	2
2	Lyons Fm	Denver Basin	Belitz, K., and Bredehoeft, J., 1988, Hydrodynamics of Denver Basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, v. 72, no. 11, p. 1334-1359.	2
3	Lyons Fm	Denver Basin	Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217-2244.	2
3	Lyons Fm	Denver Basin	Garbarini, G., and Veal, H. K., 1968, Potential of Denver Basin for disposal of liquid wastes, subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir, p. 165-185	2
4	Lyons Fm	Denver Basin	Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217-2244.	4
4	Lyons Fm	Denver Basin	Garbarini, G., and Veal, H. K., 1968, Potential of Denver Basin for disposal of liquid wastes, subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir, p. 165-185	4
5	Lyons Fm	Denver Basin	No Data	
6	Lyons Fm	Denver Basin	Sloss, I., 1988. Sedimentary cover North America Craton: US. The Geology of North America D-2. Geological Society of America. The Decade of North American Geology DNAG. P189	1
7	Lyons Fm	Denver Basin	Geological Atlas of the Rocky Mountain Region, 1972, Rocky Mountain Association of Geologists.	1
8	Lyons Fm	Denver Basin	Geological Atlas of the Rocky Mountain Region, 1972, Rocky Mountain Association of Geologists.	1
8	Lyons Fm	Denver Basin	Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217-2244.	1
9	Lyons Fm	Denver Basin	Clayton, J., and Swetland, P., 1988, Petroleum generation and migration in Denver Basin: American Association of Petroleum Geologists Bulletin, v. 64, no. 10, p. 1613-1633.	1
9	Lyons Fm	Denver Basin	Geological Atlas of the Rocky Mountain Region, 1972, Rocky Mountain Association of Geologists.	1
10	Lyons Fm	Denver Basin	Lee, M. L., and Bethke, C., 1994, Groundwater flow, late cementation and petroleum accumulation in the Permian Lyons Sandstone, Denver Basin: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 227-237.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
10	Lyons Fm	Denver Basin	Belitz, K., and Bredehoeft, J., 1988, Hydrodynamics of Denver Basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, v. 72, no. 11, p. 1334-1359.	1
11	Lyons Fm	Denver Basin	Lee, M. L., and Bethke, C., 1994, Groundwater flow, late cementation and petroleum accumulation in the Permian Lyons Sandstone, Denver Basin: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 227-237.	1
11	Lyons Fm	Denver Basin	Belitz, K., and Bredehoeft, J., 1988, Hydrodynamics of Denver Basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, v. 72, no. 11, p. 1334-1359.	1
12a	Lyons Fm	Denver Basin	Belitz, K., and Bredehoeft, J., 1988, Hydrodynamics of Denver Basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, v. 72, no. 11, p. 1334-1359.	1
12b	Lyons Fm	Denver Basin	Belitz, K., and Bredehoeft, J., 1988, Hydrodynamics of Denver Basin: explanation of subnormal fluid pressures: American Association of Petroleum Geologists Bulletin, v. 72, no. 11, p. 1334-1359.	2
12c	Lyons Fm	Denver Basin	No Data	
13	Lyons Fm	Denver Basin	Lee, M. L., and Bethke, C., 1994, Groundwater flow, late cementation and petroleum accumulation in the Permian Lyons Sandstone, Denver Basin: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 227-237.	2
13	Lyons Fm	Denver Basin	Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217-2244.	2
14	Lyons Fm	Denver Basin	Levandowski, D., Kaley, M., and Smalley, R., 1973, Cementation in the Lyons Sandstone and its role in oil accumulation, Denver Basin, Colorado: American Association of Petroleum Geologists Bulletin, v. 57, no. 11, p. 2217-2244.	2
15	Lyons Fm	Denver Basin	Lee, M. L., and Bethke, C., 1994, Groundwater flow, late cementation and petroleum accumulation in the Permian Lyons Sandstone, Denver Basin: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 227-237.	1
16	Lyons Fm	Denver Basin	Adams, J., and Patton, J., 1978, Sebkhah Dune Deposition in the Lyons Formation (Permian) Northern Front Range, Colorado.	1
1	Madison Gr	Williston Basin	Peterson, J. A., Longman, M. W., Anderson, S. B., Pilatzke, R. H., and Kent, D. M., 1987, Williston Basin, anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, 440 p.	1
2	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
2	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
3	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
3	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
4	Madison Gr	Williston Basin	Not Applicable	
5	Madison Gr	Williston Basin	Not Applicable	
6	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
6	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
7	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
7	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
8	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
8	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
9	Madison Gr	Williston Basin	Geological Atlas of the Rocky Mountain Region. Rocky Mountain Association of Geologists. Denver Colorado 1972.	1
10	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
10	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
11	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
11	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
12a	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
12a	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
12b	Madison Gr	Williston Basin	No Data	
12c	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
12c	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
13	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
13	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
14	Madison Gr	Williston Basin	Downey, J. S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1402-E, 87 p.	1
14	Madison Gr	Williston Basin	Downey, J. S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 47 p.	1
15	Madison Gr	Williston Basin	Busby, J., Plummer, L., and Hanshaw, B., 1991, Geochemical evolution in the Madison in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1272-f, 89 p.	1
16	Madison Gr	Williston Basin	Busby, J., Plummer, L., and Hanshaw, B., 1991, Geochemical evolution in the Madison in parts of Montana, North Dakota, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1272-f, 89 p.	1
1	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
2	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
3	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
4	Morrison Fm	San Juan Basin	Kirk, A. R., and Condon, S. M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—a subsurface study, in Turner-Peterson, C. E., Santos, E. S., and Fishman, N. S., eds., A basin analysis case study: the Morrison Formation Grants uranium region New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 105–143.	3
5	Morrison Fm	San Juan Basin	Kirk, A. R., and Condon, S. M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—a subsurface study, in Turner-Peterson, C. E., Santos, E. S., and Fishman, N. S., eds., A basin analysis case study: the Morrison Formation Grants uranium region New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 105–143.	4
6	Morrison Fm	San Juan Basin	Galloway, W. E., 1980, Deposition and early hydrologic evolution of the Westwater Canyon and other fluvial fan systems, in Rautman, C. A., compiler, Geology and mineral technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 59–69.	3



APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
7	Morrison Fm	San Juan Basin	Kirk, A. R., and Condon, S. M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—a subsurface study, in Turner-Peterson, C. E., Santos, E. S., and Fishman, N. S., eds., A basin analysis case study: the Morrison Formation Grants uranium region New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 105–143.	4
7	Morrison Fm	San Juan Basin	Freethy, G. W., 1987a, Upper Colorado River Basin regional aquifer-systems analysis—Mesozoic rocks in Colorado, Utah and Wyoming, Arizona, and New Mexico, in McLean, J. S., and Johnson, A. I., eds., Regional aquifer systems of the United States—aquifers of the western mountain area: 23rd Annual American Water Resources Association (AWRA) Conference and Symposium, Salt Lake City: AWRA Monograph Series No. 14, p. 57–70.	4
8	Morrison Fm	San Juan Basin	Turner-Peterson, C. E., 1987, Sedimentology of the Westwater Canyon and Brushy Basin Members, Upper Jurassic Morrison Formation, Colorado Plateau, and relationship to uranium mineralization: University of Colorado, Ph.D. dissertation, 169 p.	4
8	Morrison Fm	San Juan Basin	Kirk, A. R., and Condon, S. M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—a subsurface study, in Turner-Peterson, C. E., Santos, E. S., and Fishman, N. S., eds., A basin analysis case study: the Morrison Formation Grants uranium region New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 105–143.	4
9	Morrison Fm	San Juan Basin	Fassett, J. E., 1991, Oil and gas resources of the San Juan basin, New Mexico and Colorado, in Gluskoter, H. J., Rice, D. D., and Taylor, R. B., eds., The decade of North American geology, v. P-2, Economic Geology, U.S.: Geological Society of America, p. 357–372.	1
10	Morrison Fm	San Juan Basin	Not Applicable	5
11	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
12a	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
12b	Morrison Fm	San Juan Basin	Not Applicable	5
12c	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
13	Morrison Fm	San Juan Basin	Not Applicable	5
14	Morrison Fm	San Juan Basin	Freethy, G. W., 1987b, Lithologic and hydrologic properties of Mesozoic rocks in the Upper Colorado River Basin, Mexico, in McLean, J. S., and Johnson, A. I., eds., Regional aquifer systems of the United States—aquifers of the western mountain area: 23rd Annual American Water Resources Association (AWRA) Conference and Symposium, Salt Lake City: AWRA Monograph Series No. 14, p. 81–100.	4
15	Morrison Fm	San Juan Basin	Dam, W. L., Kernodle, J. M., Thorn, C. R., Levings, G. W., and Craig, S. D., 1990, Hydrogeology of the Morrison Formation in the San Juan structural basin, New Mexico, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-0720-J, 2 sheets.	1
16	Morrison Fm	San Juan Basin	Turner-Peterson, C. E., 1987, Sedimentology of the Westwater Canyon and Brushy Basin Members, Upper Jurassic Morrison Formation, Colorado Plateau, and relationship to uranium mineralization: University of Colorado, Ph.D. dissertation, 169 p.	4
1	Mt Simon Fm	Michigan Basin	Gupta, Neeraj, 1999, Battelle Memorial Institute, Columbus, OH: personal communication.	1
2	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 1986, Patterns of regional subsurface fluid movement in the Michigan Basin: Michigan Department of Natural Resources, Geological Survey Division, Open File Report 86-6.	5
2	Mt Simon Fm	Michigan Basin	Briggs, L. I., 1968, Geology of subsurface waste disposal in Michigan Basin, in Galley, J. E., ed., Subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir 10, p. 128–153.	5
3	Mt Simon Fm	Michigan Basin	Catacosinos, P. A., and Daniels, P. A., Jr., 1986, Stratigraphy of middle Proterozoic to Middle Ordovician formations of the Michigan Basin, in Catacosinos, P. A., and Daniels, P. A., Jr., eds., Early sedimentary evolution of the Michigan Basin: Geological Society of America, Special Paper 256, p. 53–71.	1
4	Mt Simon Fm	Michigan Basin	Not Applicable	5
5	Mt Simon Fm	Michigan Basin	Not Applicable	5
6	Mt Simon Fm	Michigan Basin	Not Applicable	5

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm),Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
7	Mt Simon Fm	Michigan Basin	Catacosinos, P. A., Harrison, W. B., III, and Daniels, P. A., Jr., 1991, Structure, stratigraphy, and petroleum geology of the Michigan Basin, Chapter 30, in Leighton, M. W., Kolata D. R., Oltz, D. F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 561–601.	1
8	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 1986, Patterns of regional subsurface fluid movement in the Michigan Basin: Michigan Department of Natural Resources, Geological Survey Division, Open File Report 86-6.	3
8	Mt Simon Fm	Michigan Basin	Catacosinos, P. A., and Daniels, P. A., Jr., 1986, Stratigraphy of middle Proterozoic to Middle Ordovician formations of the Michigan Basin, in Catacosinos, P. A., and Daniels, P. A., Jr., eds., Early sedimentary evolution of the Michigan Basin: Geological Society of America, Special Paper 256, p. 53–71.	3
9	Mt Simon Fm	Michigan Basin	Catacosinos, P. A., Harrison, W. B., III, and Daniels, P. A., Jr., 1991, Structure, stratigraphy, and petroleum geology of the Michigan Basin, Chapter 30, in Leighton, M. W., Kolata D. R., Oltz, D. F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 561–601.	2
10	Mt Simon Fm	Michigan Basin	Not Applicable	5
11	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 1986, Patterns of regional subsurface fluid movement in the Michigan Basin: Michigan Department of Natural Resources, Geological Survey Division, Open File Report 86-6.	1
12a	Mt Simon Fm	Michigan Basin	Cercone, K. R., 1984, Thermal history of the Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 68, no. 2, p. 130–136.	5
12a	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 2000, Senior Geologist, Michigan Department of Environmental Quality, Geological Survey Division, personal communication.	5
12b	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 1986, Patterns of regional subsurface fluid movement in the Michigan Basin: Michigan Department of Natural Resources, Geological Survey Division, Open File Report 86-6.	4
12b	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 2000, Senior Geologist, Michigan Department of Environmental Quality, Geological Survey Division, personal communication.	4
12c	Mt Simon Fm	Michigan Basin	Not Applicable	5
13	Mt Simon Fm	Michigan Basin	Not Applicable	5
14	Mt Simon Fm	Michigan Basin	Briggs, L. I., 1968, Geology of subsurface waste disposal in Michigan Basin, in Galley, J. E., ed., Subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir 10, p. 128–153.	4
14	Mt Simon Fm	Michigan Basin	Vugrinovich, Raymond, 2000, Senior Geologist, Michigan Department of Environmental Quality, Geological Survey Division, personal communication.	4
15	Mt Simon Fm	Michigan Basin	Not Applicable	5
16	Mt Simon Fm	Michigan Basin	Briggs, L. I., 1968, Geology of subsurface waste disposal in Michigan Basin, in Galley, J. E., ed., Subsurface disposal in geologic basins—a study of reservoir strata: American Association of Petroleum Geologists Memoir 10, p. 128–153.	2
1	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	1
2	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	3
3	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Harper, J. A., and Patchen, D. G., 1996, Play Dos: the Lower Devonian Oriskany Sandstone structural play, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 109–117.	2
4	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	3
5	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	3

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
6	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	3
7	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Oliver, W. A., DeWitt, W., Jr., Dennison, J. M., Hoskins, D. M., and Huddle, J. W., 1967, The Appalachian Basin, United States, in Oswald, D. H., ed., International Symposium on the Devonian System: Calgary, Canada, Alberta Society of Petroleum Geologists, p. 1001–1040.	3
8	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Oliver, W. A., DeWitt, W., Jr., Dennison, J. M., Hoskins, D. M., and Huddle, J. W., 1967, The Appalachian Basin, United States, in Oswald, D. H., ed., International Symposium on the Devonian System: Calgary, Canada, Alberta Society of Petroleum Geologists, p. 1001–1040.	3
9	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	2
10	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Trapp, H., Jr., and Horn, M. A., 1997, Ground water atlas of the United States— segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia: U.S. Geological Survey Hydrologic Investigations Atlas No. HA-730-L, 30 p.	3
11	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Trapp, H., Jr., and Horn, M. A., 1997, Ground water atlas of the United States— segment 11, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia: U.S. Geological Survey Hydrologic Investigations Atlas No. HA-730-L, 30 p.	4
12a	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Opritz, S. T., 1996, Play Dop: the Lower Devonian Oriskany Sandstone updip permeability pinchout, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 126–129.	4
12a	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Patchen, D. G., and Harper, J. A., 1996, Play Doc: the Lower Devonian Oriskany Sandstone combination traps play, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 118–125.	4
12b	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Harper, J. A., and Patchen, D. G., 1996, Play Dos: the Lower Devonian Oriskany Sandstone structural play, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 109–117	3
12c	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Headlee, A. J. W., and Joseph, J. S., 1945, Permeability, porosity, and water content of natural gas reservoirs, Kanawha-Jackson and Campbells Creek Oriskany fields: West Virginia Geological Survey Bulletin No. 8, 16 p. Dressel, P. E., 1985, The geochemistry of oilfield brines from western Pennsylvania: Pennsylvania State University, Master's thesis, 128 p.	4
13	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Stow, M., 1938, Conditions of sedimentation and sources of the Oriskany Sandstone as indicated by petrology: American Association of Petroleum Geologists Bulletin, v. 2, p. 541–564.	3
13	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Rosenfeld, M. A., 1954, Petrographic variation in the Oriskany Sandstone: American Association of Petroleum Geologists Bulletin, v. 65, p. 1298–1299.	3
14	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Headlee, A. J. W., and Joseph, J. S., 1945, Permeability, porosity, and water content of natural gas reservoirs, Kanawha-Jackson and Campbells Creek Oriskany fields: West Virginia Geological Survey Bulletin No. 8, 16 p. Diechchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates. Harper, J. A., and Patchen, D. G., 1996, Play Dos: the Lower Devonian Oriskany Sandstone structural play, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 109–117	3

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from cited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
14	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Diecchio, R. J., Jones, S. E., and Dennison, J. M., 1984, Oriskany Sandstone regional stratigraphic relationships and production trends: West Virginia Geological and Economic Survey Map WV-17, 8 plates.	3
14	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Harper, J. A., and Patchen, D. G., 1996, Play Dos: the Lower Devonian Oriskany Sandstone structural play, in Roen, J. B., and Walker, B. J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 109–117.	3
15	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Dressel, P. E., 1985, The geochemistry of oilfield brines from western Pennsylvania: Pennsylvania State University, Master's thesis, 128 p.	1
16	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Stow, M., 1938, Conditions of sedimentation and sources of the Oriskany Sandstone as indicated by petrology: American Association of Petroleum Geologists Bulletin, v. 2, p. 541–564.	3
16	Oriskany Fm	Appalachian Basin W Pennsylvania, E Ohio, and E Kentucky	Rosenfeld, M. A., 1954, Petrographic variation in the Oriskany Sandstone: American Association of Petroleum Geologists Bulletin, v. 65, p. 1298–1299.	3
1	Paluxy Snd	East Texas Basin	Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157 (1), 12 p.	1
2	Paluxy Snd	East Texas Basin	Not Applicable	5
3	Paluxy Snd	East Texas Basin	Seni, S. J., 1981, Depositional systems of the Lower Cretaceous Paluxy Formation, East Texas Basin, in Kreitler, C. W., Collins, E. W., Davidson, E. D., Jr., Dix, O. R., Donaldson, G. A., Dutton, S. P., Fogg, G. E., Giles, A. B., Harris, D. W., Jackson, M. P. A., Lopez, C. M., McGowen, M. K., Muehlberger, W. R., Pennington, W. D., Seni, S. J., Wood, D. H., and Wuerch, H. V., Geology and geohydrology of the East Texas Basin; a report on the progress of nuclear waste isolation feasibility studies: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 81-7, p. 12–20.	1
4	Paluxy Snd	East Texas Basin	Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157 (1), 12 p.	1
5	Paluxy Snd	East Texas Basin	Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157 (1), 12 p.	3
5	Paluxy Snd	East Texas Basin	Seni, S. J., 1981, Depositional systems of the Lower Cretaceous Paluxy Formation, East Texas Basin, in Kreitler, C. W., Collins, E. W., Davidson, E. D., Jr., Dix, O. R., Donaldson, G. A., Dutton, S. P., Fogg, G. E., Giles, A. B., Harris, D. W., Jackson, M. P. A., Lopez, C. M., McGowen, M. K., Muehlberger, W. R., Pennington, W. D., Seni, S. J., Wood, D. H., and Wuerch, H. V., Geology and geohydrology of the East Texas Basin; a report on the progress of nuclear waste isolation feasibility studies: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 81-7, p. 12–20.	3
6	Paluxy Snd	East Texas Basin	Jackson, M. P. A., and Seni, S. J., 1984, Atlas of salt domes in the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 140, 102 p.	1
6	Paluxy Snd	East Texas Basin	Caughey, C. A., 1977, Depositional systems in the Paluxy Formation (Lower Cretaceous), Northeast Texas; oil, gas, and groundwater resources: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 77-8, 59 p.	1
7	Paluxy Snd	East Texas Basin	Anderson, L. M., 1989, Stratigraphy of the Fredericksburg Group, East Texas Basin: Baylor Geological Studies, Bulletin 47, 40 p.	1
7	Paluxy Snd	East Texas Basin	Neeley, R. A., 1991, Facies analysis of the Lower Cretaceous (Albian) Goodland and lower Kiamichi Formations of Southeast Oklahoma: Shale Shaker, v. 41, no. 5, p. 116–145.	1
8	Paluxy Snd	East Texas Basin	Jackson, M. P. A., and Seni, S. J., 1984, Atlas of salt domes in the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 140, 102 p.	3
9	Paluxy Snd	East Texas Basin	Caughey, C. A., 1977, Depositional systems in the Paluxy Formation (Lower Cretaceous), Northeast Texas; oil, gas, and groundwater resources: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 77-8, 59 p.	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
10	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	5
11	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	5
12a	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	5
12b	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	4
12c	Paluxy Snd	East Texas Basin	Core Laboratories, Inc., 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157 (1), 12 p.	1
13	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	2
14	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	5
15	Paluxy Snd	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M., and Seni, S. J., 1983, Hydrogeologic characterization of the saline aquifers, East Texas Basin: implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy under contract no. DE-AC97-80ET46617.	2
16	Paluxy Snd	East Texas Basin	Owen, M. T., 1979, The Paluxy sand in north central Texas: Baylor Geological Studies, Bulletin No. 36, 36 p.	2
1	Pottsville Fm	Black Warrior Basin	Hewitt, J., 1984, Geologic overview, coal, and coalbed methane resources of the Black Warrior Basin—Alabama and Mississippi, in Rightmire, C., Eddy, G., and Kirr, J., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists, Studies in Geology Series 17, p. 73–104.	1
1	Pottsville Fm	Black Warrior Basin	Pashin, J. C., and others, 1991, Structure, sedimentology, coal quality and hydrology of the Black Warrior Basin in Alabama: controls on the occurrence and producibility of coal methane: The University of Texas at Austin and Geological Survey of Alabama, Bureau of Economic Geology, GRI Contract Number 1544, 187 p.	2
2	Pottsville Fm	Black Warrior Basin	Beard, R. H., and Meylan, M. A., 1987, Petrology and hydrocarbon reservoir potential of subsurface Pottsville (Pennsylvanian) sandstones, Black Warrior Basin, Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 11–23.	2
2	Pottsville Fm	Black Warrior Basin	Galicki, S., 1986, Mesozoic-Paleozoic producing areas of Mississippi and Alabama: Mississippi Geological Society.	2
2	Pottsville Fm	Black Warrior Basin	Doherty, E., 1999, Report of Investigation. Bureau of Economic Geology.	2
3	Pottsville Fm	Black Warrior Basin	Cleaves, A., 1983, Carboniferous terrigenous clastic facies, hydrocarbon production zones, and sandstone provenance, northern shelf of Black Warrior Basin: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 41–52	1
4	Pottsville Fm	Black Warrior Basin	Cleaves, A., 1983, Carboniferous terrigenous clastic facies, hydrocarbon production zones, and sandstone provenance, northern shelf of Black Warrior Basin: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 41–52	2
5	Pottsville Fm	Black Warrior Basin	No data	
6	Pottsville Fm	Black Warrior Basin	Cleaves, A., and Broussard, M., 1980, Chester and Pottsville depositional systems, outcrops and subsurface, in the Black Warrior Basin: Gulf Coast Association of Geological Societies Transactions, v. 30, p. 49–59	1

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
7	Pottsville Fm	Black Warrior Basin		
8	Pottsville Fm	Black Warrior Basin	Pashin, J. C., and others, 1991, Structure, sedimentology, coal quality and hydrology of the Black Warrior Basin in Alabama: controls on the occurrence and producibility of coal methane: The University of Texas at Austin and Geological Survey of Alabama, Bureau of Economic Geology, GRI Contract Number 1544, 187 p.	4
9	Pottsville Fm	Black Warrior Basin	Masingill, J., 1992, The petroleum industry in Alabama: Geological Survey of Alabama, Oil and Gas Report 3-P, 127 p.	1
9	Pottsville Fm	Black Warrior Basin	Petroleum Frontiers, 1986, The Black Warrior Basin: proving the potential of the southeast: v. 3, no. 3, 62 p.	1
9	Pottsville Fm	Black Warrior Basin	Epsman, M., 1987, Subsurface geology of selected oil and gas fields in the Black Warrior basin of Alabama, 255 p., 1 app., 8 figs., 1 table.	1
10	Pottsville Fm	Black Warrior Basin	No data	5
11	Pottsville Fm	Black Warrior Basin	Pashin, J. C., and others, 1991, Structure, sedimentology, coal quality and hydrology of the Black Warrior Basin in Alabama: controls on the occurrence and producibility of coal methane: The University of Texas at Austin and Geological Survey of Alabama, Bureau of Economic Geology, GRI Contract Number 1544, 187 p.	2
12a	Pottsville Fm	Black Warrior Basin	Kron, A., and Stix, J., 1982, U.S. geothermal gradient map of the United States, exclusive of Alaska and Hawaii: National Oceanic and Atmospheric Administration, National Geophysical Data Center, scale 1:2,500,000, two sheets.	1
12b	Pottsville Fm	Black Warrior Basin	Beard, R. H., and Meylan, M. A., 1987, Petrology and hydrocarbon reservoir potential of subsurface Pottsville (Pennsylvanian) sandstones, Black Warrior Basin, Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 11-23.	2
12b	Pottsville Fm	Black Warrior Basin	Galicki, S., 1986, Mesozoic-Paleozoic producing areas of Mississippi and Alabama: Mississippi Geological Society.	2
12c	Pottsville Fm	Black Warrior Basin	Ortiz, I., Weller, R., and others, 1993, Disposal of produced waters: underground injection option in the Black Warrior Basin: Proceedings of the 1993 International Symposium: The University of Alabama/Tuscaloosa, p. 339-364.	2
13	Pottsville Fm	Black Warrior Basin	No data	
14	Pottsville Fm	Black Warrior Basin	Beard, R. H., and Meylan, M. A., 1987, Petrology and hydrocarbon reservoir potential of subsurface Pottsville (Pennsylvanian) sandstones, Black Warrior Basin, Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 11-23.	2
14	Pottsville Fm	Black Warrior Basin	Galicki, S., 1986, Mesozoic-Paleozoic producing areas of Mississippi and Alabama: Mississippi Geological Society.	2
15	Pottsville Fm	Black Warrior Basin		
16	Pottsville Fm	Black Warrior Basin		
1	Repetto Fm	Los Angeles Basin	Wright, T. L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, in Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 35-134.	1
2	Repetto Fm	Los Angeles Basin	California Department of Conservation (Division of Oil and Gas), 1991, California oil and gas fields, v. 2: Southern, central coastal, and offshore California, 689 p.	3
3	Repetto Fm	Los Angeles Basin	Conrey, B. L., 1967, Early Pliocene sedimentary history of the Los Angeles Basin, California: California Division of Mines and Geology Special Report 93, 63 p.	1
4	Repetto Fm	Los Angeles Basin	Conrey, B. L., 1967, Early Pliocene sedimentary history of the Los Angeles Basin, California: California Division of Mines and Geology Special Report 93, 63 p.	1
5	Repetto Fm	Los Angeles Basin	Conrey, B. L., 1967, Early Pliocene sedimentary history of the Los Angeles Basin, California: California Division of Mines and Geology Special Report 93, 63 p.	1
6	Repetto Fm	Los Angeles Basin	Conrey, B. L., 1967, Early Pliocene sedimentary history of the Los Angeles Basin, California: California Division of Mines and Geology Special Report 93, 63 p.	1
7	Repetto Fm	Los Angeles Basin	Henry, M. J., 1987, Los Angeles Basin—an overview, in Clarke, D., and Henderson, C., eds., Oil-producing areas in Long Beach: American Association of Petroleum Geologists Field Trip Guidebook, Pacific Section, p. 1-29.	3
8	Repetto Fm	Los Angeles Basin	Henry, M. J., 1987, Los Angeles Basin—an overview, in Clarke, D., and Henderson, C., eds., Oil-producing areas in Long Beach: American Association of Petroleum Geologists Field Trip Guidebook, Pacific Section, p. 1-29.	3
9	Repetto Fm	Los Angeles Basin	Redin, T., 1991, Oil and gas production from submarine fans of the Los Angeles Basin, in Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 239-260.	1
10	Repetto Fm	Los Angeles Basin	Redin, T., 1991, Oil and gas production from submarine fans of the Los Angeles Basin, in Biddle, K. T., ed., Active margin basins: American Association of Petroleum Geologists Memoir 52, p. 239-260.	5
11	Repetto Fm	Los Angeles Basin	U.S. Geological Survey, 1996, Ground water atlas of the United States: segment 1: California.	4

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
12a	Repetto Fm	Los Angeles Basin	California Department of Conservation (Division of Oil and Gas), 1991, California oil and gas fields, v. 2: Southern, central coastal, and offshore California, 689 p.	3
12b	Repetto Fm	Los Angeles Basin	California Department of Conservation (Division of Oil and Gas), 1991, California oil and gas fields, v. 2: Southern, central coastal, and offshore California, 689 p.	3
12c	Repetto Fm	Los Angeles Basin	California Department of Conservation (Division of Oil and Gas), 1991, California oil and gas fields, v. 2: Southern, central coastal, and offshore California, 689 p.	3
13	Repetto Fm	Los Angeles Basin	Conrey, B. L., 1967, Early Pliocene sedimentary history of the Los Angeles Basin, California: California Division of Mines and Geology Special Report 93, 63 p.	5
14	Repetto Fm	Los Angeles Basin	California Department of Conservation (Division of Oil and Gas), 1991, California oil and gas fields, v. 2: Southern, central coastal, and offshore California, 689 p.	3
15	Repetto Fm	Los Angeles Basin		
16	Repetto Fm	Los Angeles Basin		
1	St Peter Snd	Illinois Basin	Hoholick, D. J., 1980, Porosity, grain fabric, water chemistry, cement, and depth of the St. Peter Sandstone in the Illinois Basin: University of Cincinnati, Master's thesis, 72 p.	3
2	St Peter Snd	Illinois Basin	Kreutzfeld, J. E., 1982, Pore geometry and permeability of the St. Peter Sandstone in the Illinois Basin: University of Toledo, Master's thesis, 353 p.	3
2	St Peter Snd	Illinois Basin	Mandle, R. J., and Kontis, A. L., 1992, Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-C.	3
3	St Peter Snd	Illinois Basin	Collinson, C., Sargent, M. L., and Jennings, J. R., 1988, Chapter 14: Illinois Basin region, in Sloss, L. L., ed., The Geology of North America, v. D-2, Sedimentary Cover—North American Craton: U.S.: Decade of North American Geology: Geological Society of America, p. 383–426.	3
4	St Peter Snd	Illinois Basin	Lamar, J. E., 1928, Geology and economic resources of the St. Peter Sandstone of Illinois: Illinois Geological Survey Bulletin No. 53, 175 p.	4
5	St Peter Snd	Illinois Basin	Lamar, J. E., 1928, Geology and economic resources of the St. Peter Sandstone of Illinois: Illinois Geological Survey Bulletin No. 53, 175 p.	4
6	St Peter Snd	Illinois Basin	Collinson, C., Sargent, M. L., and Jennings, J. R., 1988, Chapter 14: Illinois Basin region, in Sloss, L. L., ed., The Geology of North America, v. D-2, Sedimentary Cover—North American Craton: U.S.: Decade of North American Geology: Geological Society of America, p. 383–426.	3
7	St Peter Snd	Illinois Basin	Collinson, C., Sargent, M. L., and Jennings, J. R., 1988, Chapter 14: Illinois Basin region, in Sloss, L. L., ed., The Geology of North America, v. D-2, Sedimentary Cover—North American Craton: U.S.: Decade of North American Geology: Geological Society of America, p. 383–426.	3
8	St Peter Snd	Illinois Basin	Mandle, R. J., and Kontis, A. L., 1992, Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-C.	3
9	St Peter Snd	Illinois Basin	Zuppann, C.W., and Keiith, B.D. (eds.), 1988, Geology and petroleum production of the Illinois Basin, Volume 2: Joint Publication of the Illinois and Indiana-Kentucky Geological Societies, Mt. Vernon, IL, 272p.	2
10	St Peter Snd	Illinois Basin	Selkregg, L. F., Pryor, W. A., and Kempton, J. P., 1957, Groundwater geology in south-central Illinois—a preliminary geologic report: Illinois Geologic Survey, Circular 225, 30 p.	5
10	St Peter Snd	Illinois Basin	Mandle, R. J., and Kontis, A. L., 1992, Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-C.	5
10	St Peter Snd	Illinois Basin	Young, H. L., 1992a, Summary of ground water hydrology of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-A, 55 p.	5
10	St Peter Snd	Illinois Basin	Meents, W. F., Bell, A. H., Rees, O. W., and Tilbury, W. G., 1952, Illinois oil-field brines, their geologic occurrence and chemical composition: Illinois Geological Survey, Illinois Petroleum No. 66, 38 p.	5
10	St Peter Snd	Illinois Basin	Collinson, C., Sargent, M. L., and Jennings, J. R., 1988, Chapter 14: Illinois Basin region, in Sloss, L. L., ed., The Geology of North America, v. D-2, Sedimentary Cover—North American Craton: U.S.: Decade of North American Geology: Geological Society of America, p. 383–426.	5
11	St Peter Snd	Illinois Basin	Mandle, R. J., and Kontis, A. L., 1992, Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-C.	5
11	St Peter Snd	Illinois Basin	Young, H. L., 1992a, Summary of ground water hydrology of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey, Professional Paper 1405-A, 55 p.	5

APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
<b>12a</b>	St Peter Snd	Illinois Basin	Davis, H. G., 1990, Pre-Mississippian hydrocarbon potential of the Illinois Basin, in Leighton, M. W., Kolata, D. R., Oltz, D. F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 473–489.	2
<b>12b</b>	St Peter Snd	Illinois Basin	Bell, A. H., and Kline, V., 1952, Oil and gas development in Illinois during 1951: Illinois Geological Survey, Illinois Petroleum 67, 53 p.	4
<b>12c</b>	St Peter Snd	Illinois Basin	Hoholick, D. J., 1980, Porosity, grain fabric, water chemistry, cement, and depth of the St. Peter Sandstone in the Illinois Basin: University of Cincinnati, Master's thesis, 72 p.	3
<b>13</b>	St Peter Snd	Illinois Basin	Odom, I. E., Doe, T. W., and Dott, R. H., Jr., 1976, Nature of feldspar-grain size relations in some quartz-rich sandstones: Journal of Sedimentary Petrology, v. 46, p. 862–870.	5
<b>13</b>	St Peter Snd	Illinois Basin	Odom, I. E., Willand, T. M., and Lassin, R. J., 1977, Paragenesis of authigenic minerals in St. Peter Sandstone: American Association of Petroleum Geologists Bulletin, v. 61, p. 1384–1385.	5
<b>14</b>	St Peter Snd	Illinois Basin	Hoholick, J. D., Metarko, T., and Potter, P. E., 1984, Regional variations of porosity and cement: St. Peter and Mount Simon Sandstones in Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 68, p. 753–764.	3
<b>15</b>	St Peter Snd	Illinois Basin	Odom, I. E., Doe, T. W., and Dott, R. H., Jr., 1976, Nature of feldspar-grain size relations in some quartz-rich sandstones: Journal of Sedimentary Petrology, v. 46, p. 862–870.	3
<b>16</b>	St Peter Snd	Illinois Basin	Meents, W. F., Bell, A. H., Rees, O. W., and Tilbury, W. G., 1952, Illinois oil-field brines, their geologic occurrence and chemical composition: Illinois Geological Survey, Illinois Petroleum No. 66, 38 p.	3
<b>1</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Moore, D. B., 1970, Subsurface geology of southwest Alabama: Alabama Geological Survey, Map 99, 1 sheet.	1
<b>2</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Tucker, W. E., and Kidd, R. E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey, Bulletin 104, 229 p., 4 plates.	4
<b>3</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Mancini, E. A., Mink, R. M., Payton, J. W., and Bearden, B. L., 1987, Environments of deposition and petroleum geology of the Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128–1142.	4
<b>4</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Mancini, E. A., Mink, R. M., Payton, J. W., and Bearden, B. L., 1987, Environments of deposition and petroleum geology of the Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128–1142.	4
<b>5</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Mancini, E. A., Mink, R. M., Payton, J. W., and Bearden, B. L., 1987, Environments of deposition and petroleum geology of the Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128–1142.	4
<b>6</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Mancini, E. A., Mink, R. M., Payton, J. W., and Bearden, B. L., 1987, Environments of deposition and petroleum geology of the Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128–1142.	3
<b>7</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Moffett, T. B., Hinkle, F., Epsman, M. L., and Wilson, G. V., 1984a, Configuration of the top of the Selma Group in Alabama: Alabama Geological Survey, Map 199CB, 1 sheet.	2
<b>8</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Moffett, T. B., Hinkle, F., Epsman, M. L., and Wilson, G. V., 1984a, Configuration of the top of the Selma Group in Alabama: Alabama Geological Survey, Map 199CB, 1 sheet.	4
<b>9</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Bolin, D. E., Mann, S. D., Burroughs, D., Moore, H. E., Jr., and Powers, T. J., 1989, Petroleum atlas of southwestern Alabama: Alabama Geological Survey, Atlas 23, 218 p.	1
<b>10</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey, Hydrologic Investigations Atlas No. HA-730-G, 28 p.	5
<b>11</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey, Hydrologic Investigations Atlas No. HA-730-G, 28 p.	5
<b>12a</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Wilson, G. V., and Tew, B. H., 1985, Geothermal data for southwest Alabama: correlations to geology and potential uses: Alabama Geological Survey, Oil and Gas Report 10, 156 p.	2
<b>12b</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Tucker, W. E., and Kidd, R. E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey, Bulletin 104, 229 p., 4 plates.	3
<b>12c</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Miller, J. A., 1990, Ground water atlas of the United States—segment 6, Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey, Hydrologic Investigations Atlas No. HA-730-G, 28 p.	45
<b>13</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Alverson, R. M., 1970, Deep well disposal study for Baldwin, Escambia and Mobile Counties, Alabama: Alabama Geological Survey, Circular 58, 49 p.	5
<b>14</b>	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Mancini, E. A., Mink, R. M., Payton, J. W., and Bearden, B. L., 1987, Environments of deposition and petroleum geology of the Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128–1142.	4



APPENDIX 2. Citation and data quality for each parameter. 1 = detailed data digitized from cited source; 2 = generalized or schematic data from sited source; 3 = detailed data interpreted during project; 4 = sparse or descriptive data interpreted during project; 5 = few or no data; values based on analog data; see text for details.

Property	Formation(Fm), Group (Gr), Sandstone (Snd)	Basin_Area_Region	Citation	Data-Quality Rank
14	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Tucker, W. E., and Kidd, R. E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey, Bulletin 104, 229 p., 4 plates.	
15	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Alverson, R. M., 1970, Deep well disposal study for Baldwin, Escambia and Mobile Counties, Alabama: Alabama Geological Survey, Circular 58, 49 p.	4
16	Tuscaloosa Gr	Alabama Gulf Coastal Plain	Tucker, W. E., and Kidd, R. E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey, Bulletin 104, 229 p., 4 plates.	4
1	Woodbine Fm	East Texas Basin	Core Labs (Texas Water Development Board), 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157, v. 1, 113 p.	1
2	Woodbine Fm	East Texas Basin	Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.	1
3	Woodbine Fm	East Texas Basin	Calavan, C. W., 1985, Depositional environments and basinal setting of the Cretaceous Woodbine Sandstone, Northeast Texas: Baylor University, Master's thesis, 225 p.	1
4	Woodbine Fm	East Texas Basin	Oliver, W. B., 1971, Depositional systems in the Woodbine Formation (Upper Cretaceous) northeast Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 73, 28 p.	2
5	Woodbine Fm	East Texas Basin	calculated 5woodbine = 1 - (4woodbine/3woodbine)	3
6	Woodbine Fm	East Texas Basin	Oliver, W. B., 1971, Depositional systems in the Woodbine Formation (Upper Cretaceous) northeast Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 73, 28 p.	2
7	Woodbine Fm	East Texas Basin	Surles, M. A., 1986, Stratigraphy of the Eagle Ford Group (Upper Cretaceous) and its source-rock potential in the East Texas Basin: Baylor University, Master's thesis, 219 p.	1
8	Woodbine Fm	East Texas Basin	Seni, S. J., and Jackson, M. P. A., 1984, Sedimentary records of Cretaceous and Tertiary salt movement, East Texas Basin: times, rates, and volumes of flow, implications to nuclear waste isolation and petroleum exploration: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 139, 89 p.	1
9	Woodbine Fm	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M. P. A., and Seni, S. J., 1984, Hydrogeological characterization of the saline aquifers, East Texas Basin—implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for U.S. Department of Energy, under contract no. DE-AC97-80ET46617, 156 p.	2
10	Woodbine Fm	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M. P. A., and Seni, S. J., 1984, Hydrogeological characterization of the saline aquifers, East Texas Basin—implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for U.S. Department of Energy, under contract no. DE-AC97-80ET46617, 156 p.	2
11	Woodbine Fm	East Texas Basin	No Data	5
12a	Woodbine Fm	East Texas Basin	Kron, Andrea, and Stix, John, 1982, U.S. Geothermal Gradient Map of the United States, exclusive of Alaska and Hawaii: National Oceanic and Atmospheric Administration, National Geophysical Data Center, scale 1:2,500,000, 2 sheets.	3
12b	Woodbine Fm	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M. P. A., and Seni, S. J., 1984, Hydrogeological characterization of the saline aquifers, East Texas Basin—implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for U.S. Department of Energy, under contract no. DE-AC97-80ET46617, 156 p.	1
12c	Woodbine Fm	East Texas Basin	Core Labs (Texas Water Development Board), 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board, Report 157, v. 1, 113 p.	1
13	Woodbine Fm	East Texas Basin	Wagner, W. O., 1987, Reservoir study of Cretaceous Woodbine fields in the northern East Texas Basin: Baylor University, Master's thesis, 139 p.	4
14	Woodbine Fm	East Texas Basin	Holtz, M. H., 1997, Oil atlas database of major Texas reservoirs: The University of Texas at Austin, Bureau of Economic Geology, Internal Report.	4
15	Woodbine Fm	East Texas Basin	Kreitler, C. W., Collins, E. W., Fogg, G. E., Jackson, M. P. A., and Seni, S. J., 1984, Hydrogeological characterization of the saline aquifers, East Texas Basin—implications to nuclear waste storage in East Texas salt domes: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for U.S. Department of Energy, under contract no. DE-AC97-80ET46617, 156 p.	1
16	Woodbine Fm	East Texas Basin	Wagner, W. O., 1987, Reservoir study of Cretaceous Woodbine fields in the northern East Texas Basin: Baylor University, Master's thesis, 139 p.	4