Final Contract Report

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

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EXECUTIVE SUMMARY

This study focuses on one of the options proposed to reduce United States CO_2 emissions by extracting CO_2 from power-plant exhaust and pumping it down boreholes into deeply buried saline formations. Developing a method for compiling realistic information to identify, assess, and compare saline formations to "prospect" for those with the optimum capacity for sequestration is the purpose of this study. The target is defined as saline-water-bearing formations isolated from the atmosphere and potable water supplies by very long traveltimes, which allows for exploration for large volumes of saline formations near high CO_2 output power plants.

This study was undertaken in four tasks: (1) a literature search to define properties to evaluate a saline-water-bearing formation, (2) identification of prospective study areas for this pilot study using 1996 carbon output from power plants, (3) review of literature to extract information to create case studies of saline-water-bearing formations, and (4) tabulation of information and demonstration of the utility of the data compiled using a GIS.

We identified 14 attributes of saline formations that are commonly considered to be relevant, persuasively presented as being important by at least one researcher, or that can be extracted from geologic descriptions, reservoir characterization, or play-analysis data sets that can be used to infer variables such as available storage volumes and near- and far-field permeability distribution. Two main themes are used to describing the characteristics of optimal geologic environments: (1) injectivity and (2) effective trapping. Six formation properties that effect optimal injectivity are identified: depth, permeability, formation thickness, net sand thickness, percent shale, and sand-body continuity. Eight formation properties related to effective trapping are inventoried: (1) top seal thickness, (2) continuity of top seal, (3) hydrocarbon production from interval, (4) fluid residence time, (5) flow direction, (6) CO_2 solubility in brine (pressure, temperature, and salinity), (7) rock/water reaction, and (8) porosity.

Many potentially relevant formation properties that could then be subject to sensitivity analysis during modeling or project design phases are included. This compilation is intended to be a listing of information that is commonly available and can be used to compare the relevant attributes of two different formations or different areas of the same formation. Some significant variables such as power-plant engineering, proximity to pipelines or pipeline right-of-way, or the potential for CO_2 injection to precipitate microseismic events were considered too difficult to use as an initial screening criteria.

A map showing calculated 1996 carbon emissions was produced in a GIS and used to identify a list of prospective study areas. For four of the selected areas, the Gulf Coast of Texas, the East Texas Basin, the Four Corners Area, and the Black Warrior Basin of Alabama, demonstration descriptions of potential host saline-water-bearing formations were prepared, completing the 14-parameter matrix using either direct data or inference. For two areas we created a prototype GIS to demonstrate how these data can be used to explore the optimal locations for CO_2 injection. The literature search was more successful than expected at identifying data in each pilot area, with an average of 54 citations for each formation, and relevant previous work describing the subsurface facies distribution in some detail was found in all four pilot basins. Regional exploration of geologic plays for oil and gas exploration and improved recovery produces rich data sets useful for characterization of the suitability of saline formations for CO_2 sequestration. Studies of the suitability of saline formations for deep-well injection and waste disposal found in three of the four basins examined in this pilot study proved to be very useful. Where detailed data are lacking, geologic analogs and play approaches that group similar geologic environments are useful in screening for optimal formations for sequestration, and can be used effectively to identify targets for further analysis as well as identify areas where chances of high-quality injection targets are low. Each area presented a different type of problem for data compilation. The Oligocene Frio Formation of the Gulf Coast is thick and regionally extensive with abundant oil production. The challenge of this unit is to select appropriate synthesis from abundant data. The Woodbine Formation (Cretaceous of East Texas) and the Pottsville Formation (Pennsylvanian of the Black

Warrior Basin) have less oil production, the data are more incomplete, and more geologic inference is required to fill in the matrix. The Navajo Formation (Jurassic, Utah) is well-known because of extensive outcrops, but little is known about the hydrology of basins where it occurs in the subsurface.

To demonstrate how this data can be used to meet the needs of evolving concepts for CO_2 sequestration, we input the selected formation properties for the Frio and Woodbine into a GIS. Using the GIS, different data sets from various sources can be overlaid at a common scale, various combinations of parameters can be selected and information extracted, and quantitative results and maps can be directly output. For the Frio Formation in the Houston area, we mapped regional geologic factors to identify areas useful to prospecting for CO_2 injection sites. For the Woodbine demonstration, we quantified the available formation properties near selected power plants in East Texas.

On the basis of the pilot evaluations undertaken for this project, a GIS data-base design is recommended as a mechanism for compiling information to facilitate identification and evaluation of settings that may be optimal for CO_2 sequestration in saline formations. Data tables generated in this data structure can then be joined, or the areas with desirable or negative characteristics intersected in order to prospect for optimal settings in the manner demonstrated by the pilot-study examples. These data sets can also be used as sources of realistic data sets containing needed statistical data on formation properties to simulate injection scenarios.

ABSTRACT

Recent research and applications have demonstrated technologically feasible methods, defined costs, and modeled processes needed to sequester carbon dioxide (CO_2) in saline-water-bearing formations (aquifers). One of the simplifying assumptions used in previous modeling efforts is the effect of real stratigraphic complexity on transport and trapping in saline aquifers. In this study we have developed and applied criteria for characterizing saline aquifers for very long-term sequestration of CO_2. The purpose of this pilot study is to demonstrate a methodology for optimizing matches between CO_2 sources and nearby saline formations that can be used for sequestration.

This project identified 14 geologic properties used to prospect for optimal locations for CO_2 sequestration in saline-water-bearing formations. For this demonstration, we digitized maps showing properties of saline formations and used analytical tools in a geographic information system (GIS) to extract areas that meet variably specified prototype criteria for CO_2 sequestration sites. Through geologic models, realistic aquifer properties such as discontinuous sand-body geometry are determined and can be used to add realistic hydrologic properties to future simulations. This approach facilitates refining the search for a best-fit saline host formation as our understanding of the most effective ways to implement sequestration proceeds.

Formations where there has been significant drilling for oil and gas resources as well as extensive characterization of formations for deep-well injection and waste disposal sites can be described in detail. Information to describe formation properties can be inferred from poorly known saline formations using geologic models in a play approach. Resulting data sets are less detailed than in well-described examples but serve as an effective screening tool to identify prospects for more detailed work.

INTRODUCTION

Various options for the United States response to international CO_2 emissions reductions have been the topic of recent extensive investigations (table 1). This study focuses on one of the many options, to extract CO_2 from power-plant exhaust and pump it down boreholes into deeply buried saline formations. Several advantages of this method are noted: (1) CO_2 sequestration in saline formations utilizes existing technologies in deep-well injection for waste disposal, and CO_2 flooding of oil reservoirs for enhanced oil recovery (EOR) have been in use for several decades. CO_2 sequestration from produced gas is already underway in an offshore saline formation in the North Sea (Baklid and others, 1996); and (2) suitable saline formations are available over much of the continental United States and have the capacity to store large volumes of CO_2 over a long period of time. By considering the natural trapping capacity of saline formations because they are hydrologically sluggish and isolated from fresh water, the requirement of a structural trap for CO_2 is eliminated, greatly expanding the useable volume and geographic extent of the resource and decreasing the need for detailed site characterization.

Disadvantages of CO_2 sequestration in saline formations are (1) costs associated with the separation of CO_2 from power-plant waste stream and preparation for injection, and (2) saline formations are commonly poorly known. The purpose of this study is to develop approaches to address the second disadvantage.

In order for CO_2 sequestration to be a successful component in United States emission-reduction strategies requires a favorable intersection of a number of variables, such as the market for electricity, fuel source, power-plant design and operation, a suitable geologic host for sequestration, and pipeline or right-of-way from the plant to the injection site. The understanding within the energy-producing community of the optimal method for United States emissions reduction continues to evolve as worldwide efforts to develop the needed technologies proceed. Widespread interest of the concept of CO_2 sequestration in saline water-bearing formations (saline "aquifers") isolated at depths below potable aquifers increased approximately 6 years ago and is in

Table 1. Selected recent reviews of United States options for reducing CO_2 emissions.

Option	Citation
Emission reduction/alternative energy	Holmes, 1997; Coghlan, 1997
Emission reduction/improved technology	Gessinger, 1997; Lashof, 1996
Subsurface disposal in saline formations	Gupta and others, 1998; Nadis, 1997, Bergman and Winter, 1995
Subsurface disposal in abandoned oil/gas fields	Bergman and others, 1997
Deep sea disposal	Schneider, 1998; Koide and others, 1997
Biological trapping	Ciesla, 1997; Usui and Ikenouchi, 1997; Yokoyama, 1997; Monastersky, 1995
Mineralogical trapping	Murray and Wilson, 1997; Perkins and Gunter, 1996,
Reuse of CO_2 for EOR	Holtz and others, 1998; Bondor, 1992
Other reuse of CO_2	Aresta and Tommasi, 1997
Various other	Anonymous, 1996; Anonymous, 1997

the process of maturing from a general concept to becoming one of the options in use by oil and gas producers to isolate excess produced CO_2.

In this study, we are investigating saline-water-bearing formations outside of oil and gas fields. We are accepting the concept of hydrodynamic trapping (Hitchon, 1996), in which the CO_2 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_2 is not required. We are also focusing on onshore sites near large or closely spaced commercial power plants. This definition allows for exploration for large volumes of saline formations to seek optimal injection sites near power plants where sequestration could be undertaken at minimal cost.

PURPOSE

The purpose of this project is to design an efficient and effective way to "prospect" for potential geologic hosts that will meet the needs of various engineering scenarios that utilize saline-water-bearing formations to sequester CO_2 over a long period of time. The GIS data base describing the geologic hosts created for this project will allow stakeholders to repeatedly recast scenarios in order to seek the optimal intersection of variables, both in terms of saline-formation properties and in terms of spatial relationships between infrastructure and the geologic hosts. This data base should facilitate investigation of various options and increase the likelihood that an optimal site will be selected for modeling, demonstration, and pilot projects.

The Phase I project was a test to determine (1) what kinds of geologic data are needed in predicting the optimal conditions for CO_2 sequestration in saline-water-bearing formations, and (2) whether suitable and sufficient data resources exist for completing these analyses in targeted basins of the United States.

METHODS

Data collection and analysis for this study was undertaken in four tasks: (1) definition of formation properties that should be known in order to evaluate a saline-water-bearing formation, (2) identification of prospective study areas for this pilot study, (3) review of literature to extract information to create case studies of saline-water-bearing formations, and (4) tabulation of information and demonstration of the utility of the data compiled.

Define Formation Properties

The first step was to identify a matrix of geologic information that should be known about a saline water-bearing formation in order to evaluate the engineering requirements and costs. This evaluation was based on literature review. Search strategies included searching the American Geological Institute GEOREF data base, using carbon dioxide and CO_2 as search terms, searching proceedings of recent symposia and collections, and engaging in dialog with other workers in the field. The inventory is intended to be representative and not exhaustive.

Identify Prospective Study Areas

For this project, we undertook a revision of the work of Bergman and Winter (1995) to create a plot of annual carbon emissions from individual power plants on a GIS data base. The distribution was used to nominate areas within geologic basins for further investigation.

The data sets used in calculation and location of power plants are as follows:

- Electric power plant locations (Warwick and others, 1997): ft.//ncrds.er.usgs.gov/pub/OPEN_FILES/OF_97_172/Us_powerplant.e00.
- Federal Energy Regulatory Commission (FERC) form 423 data base http://www.ferc.fed.us/electric/f423/F423annual.htm

- EIA (1996) Emissions of greenhouse gasses in the United States, 1996, Appendix B: http://www.eia.doe.gov/oiaf/1605/gg97/
- Hong, B. D. and Slatick, 1994, Carbon dioxide emission factors for coal: http://www.eia.gov.cneaf/coal/quartert
- 1998 five-digit ZIP code centroids purchased from CD Light Inc.

Electric power-plant locations (Warwick and others, 1997) were downloaded as a digital file in Arc/Info format. Comparing the plant codes on the Warwick and others (1997) data base with the Federal Energy Regulatory Commission (FERC) form 423 data base identified missing locations. Additional locations for 67 plants on the Federal Energy Regulatory Commission (FERC) form 423 data base that were not in the United States Geological Survey (USGS) data base were generated from 1998 five-digit zip-code centroids purchased from CD Light Inc. No quality assurance procedures were applied to location data.

For calculation of representative annual carbon emissions from electric power utilities, we used fuel purchases and BTU as reported on FERC form no. 423 for 1996. Data for 706 electric power producers required to submit this form were downloaded and entered into an Excel spreadsheet. Public-utility companies whose total steam turbine electric generation capacity is 50 or more megawatts (MW) are required to submit this form. This data set therefore captures many but not all of the CO_2 emissions from power plants.

For hydrocarbon fuels, carbon emissions factors K_e for each fuel type in million metric tons/quadrillion Btu for 1996 were extracted from EIA (1996), appendix B. For coal, average CO_2 emission factors K_{CO_2} for each grade of coal and source by state were extracted from Hong and Slatic (1994) and converted to K_e for each fuel type in million metric tons/quadrillion Btu:

$$K_e = K_{CO_2} \times 0.2729 \text{ lb C/ lb } CO_2 \times 0.0045359 \text{ metric ton/lb} \qquad (1)$$

Carbon emissions L_C in metric tons for each reported fuel purchase were then calculated for each fuel category, depending on reported units:

$$L_C = 0.002 \times F_{coal} \times G_{coal} \times K_e \qquad (2)$$

$$L_C = 0.000042 \times F_{oil} \times G_{oil} \times K_e \quad (3)$$

$$L_C = 0.001 \times F_{NG} \times G_{NG} \times K_e \quad (4)$$

where F_{coal} = coal in 10^3 tons;

F_{oil} = oil in 10^3 barrels;

F_{NG} = gas Mcf;

G_{coal} = Btu/lb as reported in FERC form No. 423 for that purchase;

G_{oil} = Btu/gal as reported in FERC form No. 423 for that purchase; and

G_{NG} = Btu/cuft as reported in FERC form No. 423 for that purchase.

Total carbon content of all reported 1996 purchases were then summed for each plant and imported into ArcVeiw GIS and linked to power-plant locations.

EIA (1996) calculated the total 1996 electric utility emissions as 513 million metric tons (http://www.eia.doe.gov/oiaf/1605/flash/flash.html). The total for this project is 509 million metric tons, a shortfall of 4 million metric tons (0.8 percent). This is most likely because carbon emission was not known for a few of the fuel types (wood, refuse, BFG, CTO).

The data-base approach has advantages because in future versions other salient information such as peak load or fuel type can be added easily.

Review Literature to Extract Information about Selected Saline Formations

From the distribution of power-plant carbon emission, we selected a list of prototype study areas to develop the methods for extracting information. During the study period, we completed preliminary evaluation of four areas: Texas Gulf Coast, East Texas Basin, Four Corners area, and Black Warrior Basin of Alabama.

We selected two formations from areas that have both high output of carbon from power plants and extensive utilization for oil production and deep-well injection: the Frio Formation of Texas Gulf Coast and the Woodbine Formation of the East Texas Basin. For these formations, we expected to find rich data sets that can document the "best case" for completely characterized saline-water-bearing formations. The purpose of this data collection is to demonstrate the utility of the product. We also identified two other areas on the basis of power-plant distribution to survey and inventory information on depositional systems to attempt to extrapolate formation properties from explored areas to less well-known target areas.

Tabulate Information and Demonstrate the Utility of the Data Compiled

For this study, we evaluated the extent to which the information needed to optimize formation selection was available in well and poorly known basins. We compiled information for each selected formation as layers in the GIS and data tables in Microsoft Excel.

Because good data were acquired for two formations in a timely manner, we proceeded to construct a prototype GIS to demonstrate the analytical uses that this powerful tool allows. The data base was constructed using ESRI products Arc/Info, ArcView, Grid, and Spatial Analyst on a Sun workstation, but the data base can also be used in a PC environment. This is a prototype effort for the GIS data-base construction proposed for Phase II work.

RESULTS

Selection of the Formation Properties

The first major undertaking of this project was to identify the data that are desirable when siting a CO_2 sequestration project. Our goal was not to match the needs of any one project or modeling strategy but to identify the attributes of saline formations that are either (1) commonly considered to be relevant, or (2) persuasively presented as being important by at least one researcher. In addition, we have listed formation properties that can be extracted from geologic descriptions, reservoir characterization, or play-analysis data sets that we think can be used to infer variables such as available storage volumes and near- and far-field permeability distribution. For this exercise, we reviewed 27 recent publications from 6 of the major research groups that have worked on various aspects of using saline-water-bearing formations to sequester CO_2 (table 2). We tabulated the geologic-formation properties used in numerical simulations or in describing site-selection procedures. The saline-formation characterization in the Alberta Basin of Canada (Hitchon, 1996) is a complete and well-documented analysis and provides a useful starting place for the United States formation characterization undertaken in this study.

In addition to reviewing the CO_2 sequestration literature, we examined reservoir-characterization studies undertaken to support the use of CO_2 injection into oil reservoirs for enhanced oil recovery (EOR) operations. Many of the EOR formation properties are not important when the project goals are to sequester CO_2. For example, CO_2 miscibility in oil, a critical parameter in EOR (Baviere, 1991; Holtz and others, 1998), is irrelevant in CO_2-brine systems in saline formations. However, this literature provides a rich source of information about the injectivity of nonuniform geologic media.

We find it helpful to identify two main themes in describing the characteristics of optimal geologic environments: (1) injectivity and (2) effective trapping.

Injectivity controls the rate at which CO_2 can be put into the aquifer. High injectivity allows the CO_2 bubble to rapidly displace water and move out from the injection point with low-pressure buildup. High injectivity correlates with few injection points and, therefore, with low cost. The Sleipner West CO_2 sequestration project selected a high-injectivity unit (Baklid and others, 1996). However, moderate injectivity may be desired for some engineering approaches. Six formation properties that effect optimal injectivity are identified: depth, permeability, formation thickness, net sand thickness, percent shale, and sand-body continuity. Effective trapping is necessary to isolate the CO_2 from the atmosphere, to prevent contamination of potable water, and to prevent catastrophic leaks of CO_2 that might endanger human health and safety.

Eight formation properties related to effective trapping are inventoried: top seal thickness, continuity of top seal, hydrocarbon production from interval, fluid residence time, flow direction,

Table 2. Geologic formation properties used in site selection and modeling efforts.

	Alberta	Sleipner West	St. Simon	NA	British	Japan	Dutch	US DOE
Citation	Bachu, 1996; Bachu and others, 1994; Gunter and others, 1993	Baklid and others, 1997; Korbøl and Kaddour, 1995; Holt and Lindeberg, 1995; Langeland and Wihelmsen, 1993	Gupta and others, 1998	Weir and others, 1996	Holloway and van der Straaten, 1995; Holloway and Savage, 1993	Koide and others, 1995; Koide and others, 1993	van der Meer, 1996, 1995, 1993, 1992; Hendriks and Blok, 1995, 1993; Van Engelbar and Blok, 1993	Bergman and Winter, 1995
Study type	Characterization	Characterization	Characterization	Modeling	Characterization	Characterization	Modeling	Assessment
Depth	X	X	X	X	X		X	X
Permeability	Matrix, hydrologic	X		X			X	X
Unit thickness	X	X		X			X	X
Net sand								
Percent shale								
Sand-body continuity		Compartmentalization?			X (because of faulting)			
Top seal thickness				X			X, vertical permeability	
Continuity of top seal		X (trap)	X					
Hydrocarbon production from interval		X					X	
Fluid residence time, flow direction	Detail	X	X					
Pressure, temperature, salinity	X	X	X		X		X	X
Rock/water reaction	Details	X	X		X	X		
Porosity	X	X		X	X			
Other			Seismic	Vertical permeability of the seal	Overpressuring, seismicity	Methane recovery from aquifers	Area of trap, extent of aquifer, rock compress-ibility	

CO_2 solubility in brine (pressure, temperature, and salinity), rock/water reaction, and porosity. The role of each variable in citing a sequestration facility is described below.

Depth

The depth of the host saline formation is one of the basic, most commonly available screening factors. Depth is important because (1) it is the dominant influence on reservoir pressure and, therefore, controls the required CO_2 injection pressure; (2) injection at depth is a factor in the isolation of the injected CO_2 from fresh-water aquifers; and (3) drilling and installing wells to the selected injection depth is a significant cost that increases with depth.

Pressure is related to the engineering processes to inject the CO_2 and is also related to its properties in the host strata. Unlike the case of EOR (Bergman and others, 1997), where pressure is critical in controlling miscibility, there is no stringent depth requirement for CO_2 sequestration. In fact, the horizon selected for CO_2 disposal at the Sleipner West field is 800 to 1,000 m, and the CO_2 is subcritical (Korbøl and Kaddour, 1995). Depths of more than 800 m (>2,500 ft) are commonly considered the upper ranges of possible depths. Greater depths may be desired or tolerated in some sequestration scenarios. We collected information on the depth range of 800 to 3,000 m (2,500 to 10,000 ft).

Permeability

Flow of CO_2 away from the well bore into the formation is a potentially critical element in the economics of injection-well field installation and maintenance. The Sleipner West injection facility selected a very high permeability (in the

nge of 1 Darcy). Injectivity is related to transmissivity, which can be calculated as:

$$T = C \times k \times h, \quad (5)$$

where T = transmissivity (L^2/T),

k = permeability (L^2),

h = thickness of the permeable unit (L), and

C = constant-based fluid properties.

Permeability in this usage is a small-scale rock property measured by core and plug analysis.

Formation Thickness

Formation thickness is a property commonly reported and used in modeling (table 2) as equivalent to h in equation 5. Examination of reservoir and CO_2-injection literature indicates that net sandstone (described in the next section) is a better choice for h because many formations contain thick interbeds of low-permeability strata. In this report we collected formation thickness to use (1) for calculating pressure gradients from the base to the top of the formation, and (2) as a proxy or an input value for calculating net sandstone where mapped net sandstone values are not available.

Net Sandstone

Net sandstone is a very basic rock property commonly calculated from wireline logs and is mapped regionally. It gives a direct measurement of the thickness of the high-permeability facies within a heterogeneous medium. Net sandstone also provides other information about probable flow paths in anisotropic rocks and is used to infer other geologic attributes, such as depositional facies. In this study we advocate using net sandstone for h, where it can be identified or calculated.

Sources for net sandstone data are (1) well-log analyses, (2) outcrop studies of the equivalent facies, or (3) analogue comparison to rocks that originated in a similar depositional setting.

Percent Shale

Percent shale is the inverse of net sandstone (net shale) normalized by dividing by formation thickness. In the absence of reservoir characterization, we use it to infer the probable ranges of isolation or interconnectedness of sand bodies. Many formations are highly heterogeneous, with sandstone bodies interbedded with shale or other low-permeability rocks. The geometry of interconnectedness is a critical variable in oil recovery and, especially, EOR. In a reservoir that has high heterogeneity, sandstone bodies can be isolated from each other so that injected fluids do not access some compartments, and poor oil recovery results from low sweep efficiency. High sweep efficiency is not critical for successful CO_2 sequestration because the isolated untapped compartments would be bypassed as the CO_2 bubble moves onward into better connected compartments. Poorly connected compartments have the effect of reducing *h*. Loss of effective formation thickness will influence the lateral extent of the bubble and, depending on the variability of permeability in the formation, may decrease transmissivity and injectivity on a field scale (away from the well bore but within the several-kilometer diameter of the CO_2 bubble). Interconnectedness of sand bodies decreases as percent shale increases. We estimate that 50 percent of net shale is a significant break between well-connected and poorly connected sandstones. Areas in a formation having a percent of shale higher than 50 may have decreased injectivity.

Sand-Body Continuity

Sand-body continuity is a measure of (1) how large the CO_2 bubble can be before injectivity is decreased because of intersection of the bubble with the edges of the highly permeable strata, and (2) the dimensions of near- and far-field permeability contrast (Law, 1996). Isolated sandstone bodies may provide a trap or baffle inducing slow flow of CO_2 away from the bubble, improving the trap; however, they require more characterization than larger sandstone bodies and may limit the total volume of CO_2 that can be injected at a given well.

Top Seal Thickness

A low-permeability seal unit above the injection interval is important to isolating the CO_2 to prevent contamination of ground water or rapid return of CO_2 to the atmosphere. Equation 5 is once again relevant here, where k is the vertical permeability of the trapping bed and h is its thickness. Modeling (Weir and others, 1996) showed that of 10 m (30 ft) of 0.01 md seal material is a critical rate controlling the value for vertical escape of CO_2.

Stratigraphy of units above the injection interval may be more important for predicting performance than the thickness of a single sealing stratum (Chia, 1992). Modeling of leakage of injected waste under pressure up the fractured zone that may be created around a borehole show that leakage to the surface does not occur where a permeable unit overlies the leaking seal unit. Leaking fluid is bled off into the permeable unit and does not travel further upward. If this upper permeable unit is isolated from potable water by an overlying confining zone, it might be considered part of the design and function as a double seal.

Continuity of Top Seal

The continuity of the top seal is important to the suitability of the formation as a host for CO_2 sequestration. Flaws in the seal include (1) regionally discontinuous seal strata, (2) nonsealing faults along which vertical transport could occur, and (3) features that puncture the seal strata; for example, salt diapers. These features might allow upward leakage of buoyant CO_2 from the bubble or from contaminated and pressurized saline water.

Hydrocarbon Production from Interval

Hydrocarbon production is a special case of flaws in the continuity of the top seal because (1) some of the numerous active or abandoned well bores may have poor casing, poor original cement jobs, or improper plugging, and (2) the subsurface formations near oil fields are already in use as producing strata or as sources for water or pressure drive. Wells with failed casing, bad cement, or improper plugging may provide conduits for CO_2 injected at higher than hydrostatic pressures to escape to fresh-water aquifers or to the surface (Javandel and others, 1988). CO_2 injection near oil reservoirs might impact reservoir engineering and subsurface mineral rights would have to be considered for use of formations in these areas.

Fluid Residence Time and Flow Direction

Fluid residence time is a required parameter for the concept of hydrodynamic trapping of sequestered CO_2 (Bachu, 1996). This concept recognizes that a bubble of CO_2 is to some degree isolated from the atmosphere and potable water supplies if it is injected into a saline-water-bearing formation at depths greater than 800 m (>2,500 ft). A structural or stratigraphic trap limiting the bubble migration away from the injection site is not required. In the absence of a structural or stratigraphic trap, the fluid residence time and flow direction, interacting with CO_2 fluid properties, are dominant controls on the ultimate fate of the CO_2. Fluid residence time is commonly determined in many waste-injection scenarios to determine transport to the accessible environment. Very slow velocities are typical of saline formations. Flow direction can be either out of the basin (in response to overpressuring driven by compaction), toward the basin center because of unloading, or toward underpressured areas formed as a result of oil and gas production.

CO_2 Solubility in Brine (Pressure, Temperature, and Salinity)

Geochemical controls on the rate and process of the CO_2 bubble dissolution are other controls on trapping. At the edge of the bubble, CO_2 is dissolved into the brine. Solution rates can be used to determine the long-term fate of the bubble and assess the probability of CO_2 escape before the bubble dissolves.

Rock/Water Reaction

Mineral traps for CO_2 are other long-time-frame mechanisms for preventing or limiting the ultimate release of CO_2 (Perkins and Gunter, 1996). Over a long period of time, CO_2 in solution can react with the saline brines in equilibrium with their host mineralogy and form clays or zeolites, removing CO_2 from the system. Geochemical modeling shows that high-calcium and -magnesium sandstones are the most effective trappers, and the volumes trapped can be estimated (Perkins and Gunter, 1996). Over a sufficiently long period of time, most of the CO_2 could be fixed in mineral phases.

Porosity

Porosity influences the amount of CO_2 that can be stored in a volume of host formation and is also used in flow and engineering calculations. Effective (connected porosity) may be less than total porosity and would affect injectivity.

Other Variables

Other significant variables such as power-plant engineering, economics and transportation issues (proximity to pipelines or pipeline right-of-way) are important variables outside the scope of this study. Other geologic issues, for example, the potential for CO_2 injection to precipitate microseismic events (Ahmad and Smith, 1998; Gupta and others, 1998), were considered too difficult to use as an initial screening criteria at the scale of the entire United States, but techniques could be developed to screen for higher-than-average risk of fault reactivation.

Because many scenarios are under consideration, the optimal saline host formation for CO_2 sequestration may be different in different scenarios, and as our knowledge increases during the course of this program, and as other investigations proceed internationally, the importance of various parameters may change. In response to this challenge, our approach has been to collect all the desirable information so that the scenario can be changed as needed.

Significance of Ranking the Formation Properties

The importance of each variable is unique to each modeling run or project design. At this point in the project, we decided that the most conservative and cost-effective approach was to include many potentially relevant formation properties that could then be subject to sensitivity analysis during modeling or project design phases. The rationales for this approach are (1) CO_2 sequestration is a rapidly evolving topic, and we expect that the importance of each variable will rise or fall in the hierarchy of selection criteria as knowledge evolves; and (2) many of these formation properties are interrelated and were collected together, or can be developed from the same basic data sets and can be assembled at the same time in a cost-effective manner. We decided, therefore, to defer ranking the formation properties and assemble a data base that can be used in various assessments. However, this is not intended to be an exhaustive data set including all potential information of use during model construction or site selection. Instead, this product is intended to be a listing of information that is commonly available and can be used to compare the relevant attributes of two different formations or different areas of the same formation.

Identification of Prospective Study Areas

In the initial phase of the study, we realized that more detailed information about the geographic distribution of power plants was needed in order to determine the locations within states corresponding to parts of geologic basins that might be most useful. This analysis paralleled the approach of Bergman and Winter (1995), but instead of cumulating data by state, we used digital power-plant locations (Warwick and others, 1997). The map produced (fig. 1) is a prototype for demonstration purposes and could be reproduced from various data sets, including future power-plant construction plans or various types of screenings by fuel type or plant-operation

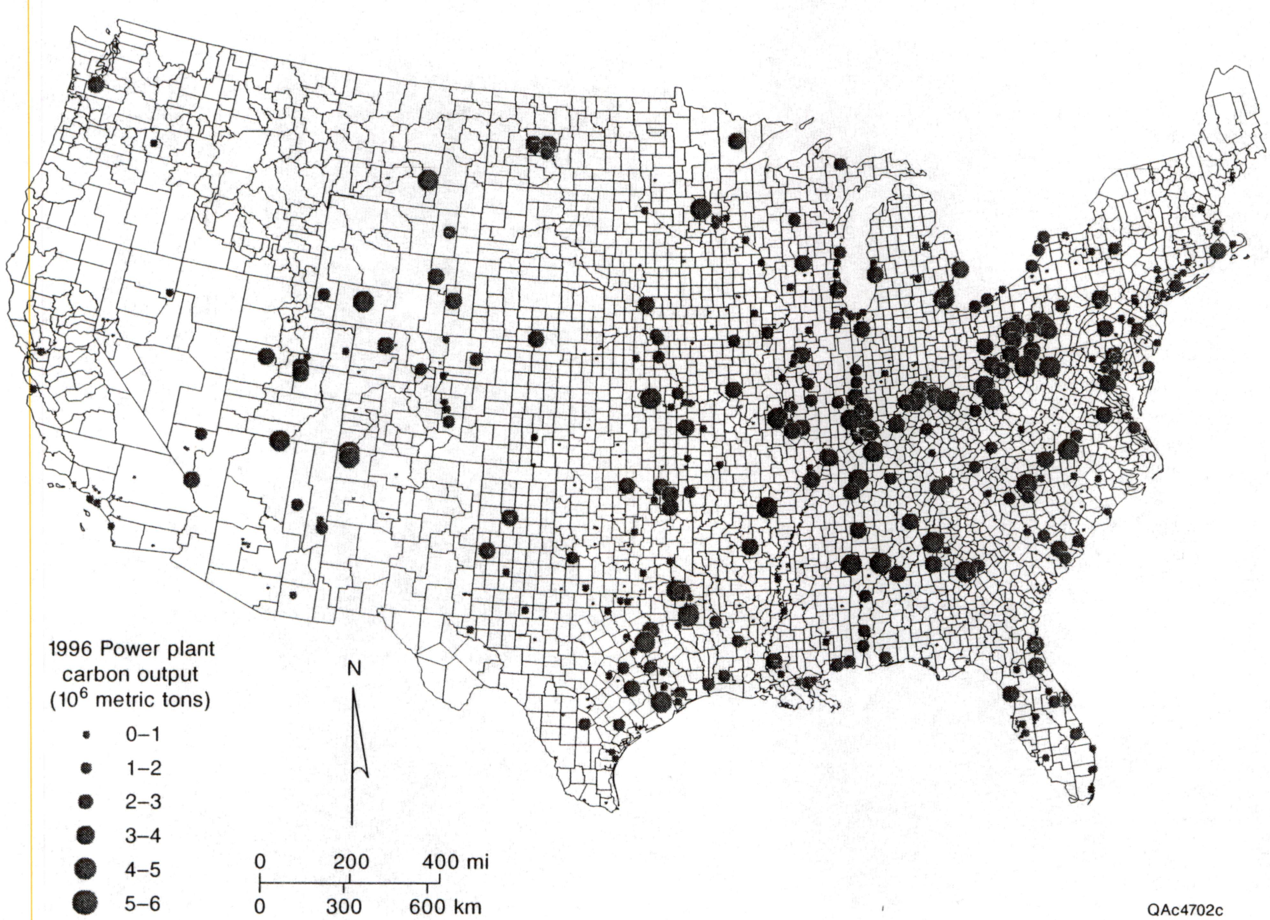

Figure 1. Printout from the GIS data base of annual carbon emissions from individual power plants.

parameters. The GIS approach lends itself to merging additional types of infrastructure information; for example, location of pipelines suitable for transporting CO_2.

Characterization of Saline-Water-Bearing Formations

The next tasks were designed to determine how much information could be assembled both from well-known and typical saline formations. Each of the identified formation properties in each geologic unit can be determined at five general levels of accuracy/precision. Formation properties can be (1) available in sufficient abundance and with a distribution that allows the property to be mapped at a regional or local scale, (2) available in sufficient abundance for the property to be described statistically, (3) inferred by combining limited measurements with a play approach, (4) inferred by comparison to a geologic analog, and (5) insufficient data to make an inference.

Literature searches for the 14 formation properties were more successful than expected. Three data sources yielded high-quality data:

(1) Data sets generated for regional evaluation of geologic plays for oil and gas exploration/improved recovery contained most of the formation properties that we evaluated as useful for characterization of the suitability of saline formations for CO_2 sequestration.

(2) Studies of the suitability of saline formations for deep-well injection and waste for both of the selected Texas formations contained detailed information that lent itself immediately to analysis for suitable optimal sites for sequestration.

(3) Analyses of the injectivity of depositional environment for CO_2 injection for EOR was conducted in a sister project also funded by the U.S. Department of Energy (Holtz and others, 1998).

Because high-quality summary reports were found in two of our prototype areas, we did not conduct a file search for deep-well injection data. However, we predict that in basins outside Texas, more time will be needed to locate and extract these kinds of data, available only as permit data or unpublished contract reports. We proceeded to create a prototype GIS to demonstrate how these data can be used to explore for the optimal locations for CO_2 injection.

Some potential sources proved to be of little use. In particular, most of the literature index hits on "saline aquifers," and numerous saline-aquifer evaluations funded in the past by the U.S. Geological Survey (for example, Winslow and others, 1968) proved to be not very useful to the CO_2 sequestration study because their focus is on slightly saline water that may be tapped for industrial uses to supplement fresh water. These shallow, slightly saline units may be in hydrologic communication with fresh-water aquifers. This result supports the terminology change in this report from "saline aquifer" to saline-water-bearing formation. One exception is the survey of subsurface saline water of Texas (Texas Water Development Board, 1972), which contains very useful information about many of the parameters for saline formations throughout Texas.

Evaluation of Representative Formations

For this pilot phase of the study, we used the carbon emissions map (fig. 1) to identify a list of prospect areas. For four of the selected areas, the Gulf Coast of Texas, the East Texas Basin, the Four Corners Area, and the Black Warrior Basin of Alabama, demonstration descriptions of potential host saline-water-bearing formations were prepared, completing the 14-parameter matrix using either direct data or inference.

Frio Formation, Texas Gulf Coast

The Frio Formation (Oligocene) is part of a thick wedge of fluvial and deltaic units that have built up from the North American craton into the Gulf of Mexico. The Frio Formation contains extensive hydrocarbon resources and has been the subject of numerous regional and field-specific studies. A bibliographic search identified 75 references describing various attributes of the Frio Formation, from regional depositional system characterization to studies of diagenesis. The Frio Formation is also used for deep-well disposal injection of industrial waste, and characterization studies for this usage are very useful resources for evaluation. Table 3 lists the major data sources used for the Frio examples, and table 4 shows the information accumulated for the each of the 14 formation properties.

The Frio Formation is a well described, highly heterogeneous unit that crops out in the Texas coastal plain and dips gulfward to depths of more than 10,000 ft (>3,000 m) below sea level near the Gulf Coast (fig. 2). Depositional-system identification has been completed at regional and field scales (fig. 3). For each depositional facies, permeability and porosity can be evaluated statistically using large data bases of data from producing oil fields. For this pilot study, we selected the most generalized depositional systems framework and collected the geometric average permeability and average porosity (figs. 4 and 5). In a mature analysis, a complete spectrum of spatial and statistical analyses could be done using the digital data bases. The formation thickens from a few hundred feet at outcrop to more than 9,000 ft (>2,700 m) near the coast. Detailed net sandstone maps have been prepared for lower, middle, and upper divisions, as have percent sand maps (Galloway and others, 1982), and a spectrum of statistical data to describe vertical and lateral sand-body continuity in each facies has been generated (Galloway and others, 1982, table 1; Knox and others, 1996, fig. 14). For example, sand-body thickness in fluvial facies is typically 10 to 30 ft (3–10 m); however, sandstone bodies are commonly stacked, producing 100 ft (30 m) of vertically interconnected sand. Delta sandstones are typically thicker, averaging 28 ft, but seaward-stepping geometry causes the separation of sand bodies by an average of 66 ft (20 m) of shale. Although these data are from various geographic areas, statistical similarities are noted when the quantitative description is tied to depositional system. From this data compilation, it is possible to describe each part of the Frio Formation in terms of properties needed to compare injectivity among sites or construct realistic simulations of injectivity.

The top seal on the Frio Formation is the Anuhac Formation, which pinches out away from the Gulf of Mexico. Compartmentalization by shales within the Frio Formation may be equally significant to the top seal, and the Frio in most areas qualifies as a unit with multiple seals separating several permeable units. Potential leaks of concern are piercement salt domes and

Table 3. Data sources for the Frio and Woodbine Formation properties.

Formation Property	Frio Formation	Woodbine Formation
Depth	Galloway, 1982	TWDB, 1972
Permeability	Holtz and others, 1998; Holtz, unpublished data table, 1999; Galloway and others, 1983	Holtz and others, 1998; Holtz, unpublished data table, 1999; Galloway and others, 1983
Formation thickness	Galloway and others, 1982	TWDB, 1972
Net sand thickness	Galloway and others, 1982; Galloway, 1986; Hamlin, 1989	Oliver, 1971
Percent shale	Galloway and others, 1982	na
Sand-body continuity	Knox and others, 1996	Oliver, 1971; Calavan, 1985
Top seal thickness	na	TWDB, 1972
Continuity of top seal	Domes and faults: Galloway and others, 1983	Domes: Jackson and Seni, 1984; Kreitler and others, 1984; faults: TWDB, 1972
Hydrocarbon production from interval	Galloway and others, 1982	Geomap, 1992
Fluid residence time, flow direction	Kreitler and others, 1986	Kreitler and others, 1984
CO_2 solubility in brine (pressure, temperature, and salinity)	Kreitler and others, 1986; Kreitler and others, 1988; Kreitler and others, 1990	Kreitler and others, 1984
Rock/water reaction	Morton and Land, 1987; Land and others, 1997	Kreitler and others, 1984; Uziemblo and Petersen, 1983; Wagner, 1987
Porosity	Galloway and others, 1983; Holtz, unpublished data table, 1999	Galloway and others, 1983; Holtz, unpublished data table, 1999

Table 4. Information accumulated for the 14 formation properties from the Frio and Woodbine Formations.

Optimal injectivity	**Frio Formation**	**Woodbine Formation**
Depth	Contour map	Contour map
Permeability	K data set, K-depositional system cross plot, statistics	K data set, K-depositional system cross plot, statistics
Formation thickness	Mapped	Mapped
Net sand thickness	Contour map	Contour map
Percent shale	Contour map	Not available
Sand-body continuity	Bed-thickness statistics	Facies descriptions as a proxy, not quantitative
Effective trapping		
Top seal thickness	Range, complex seal	Mapped
Continuity of top seal	Mapped discontinuities at domes, faults	Mapped discontinuities at domes
Hydrocarbon production from interval	Producing fields mapped, well data can be purchased	Producing fields mapped, well data can be purchased
Fluid residence time	Estimated	Estimated
CO_2 solubility in brine		
Temperature	Mapped	Estimated
Pressure	Head mapped	Pressure depletion mapped
Salinity	Mapped	Mapped
Rock/water reaction	Mineralogy and water chemistry known	Mineralogy and water chemistry known
Porosity	Statistics by depositional system	Statistics by depositional system

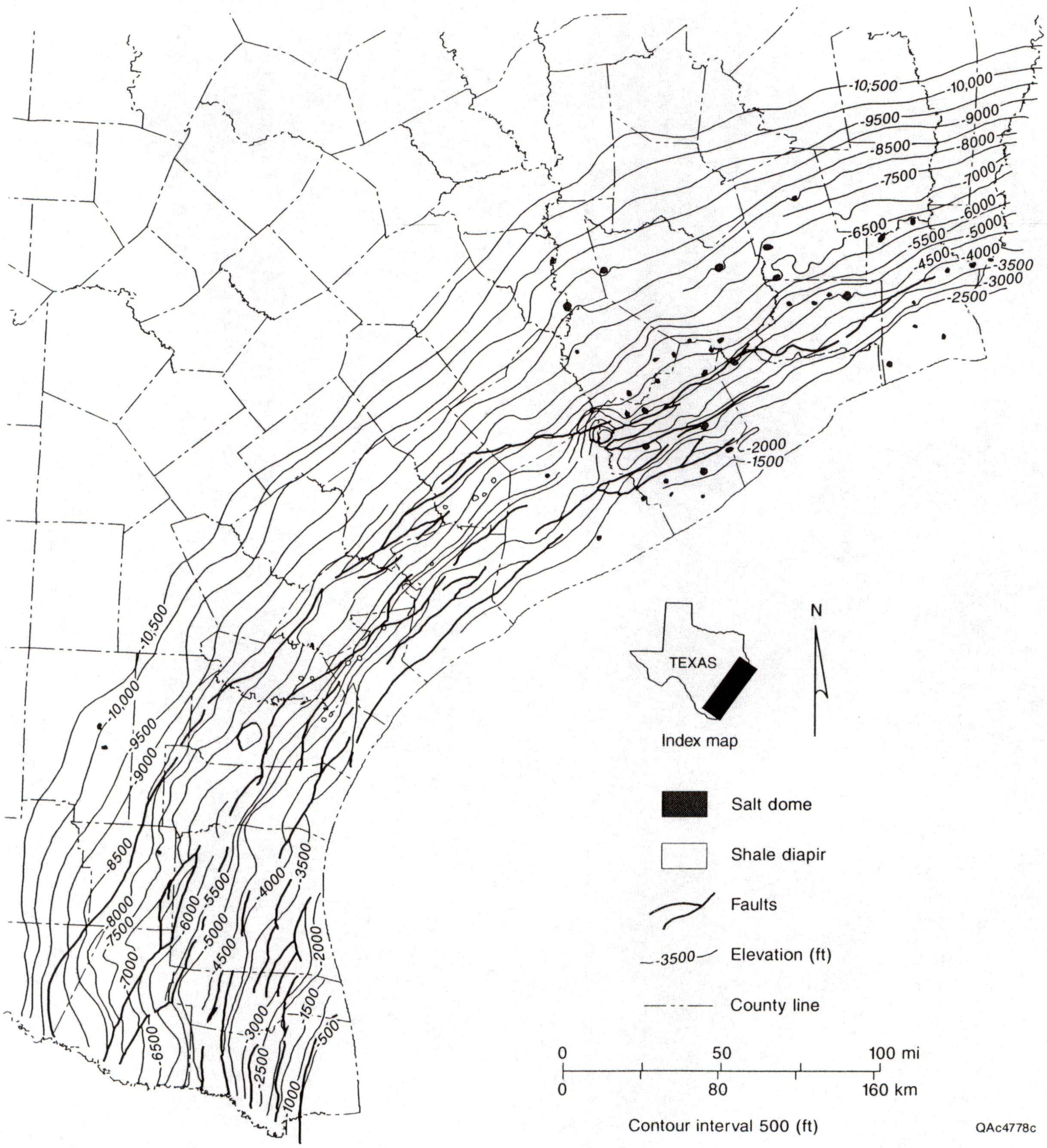

Figure 2. Printout from the GIS data base showing subsea depths of the top of the Frio Formation and location of major growth faults.

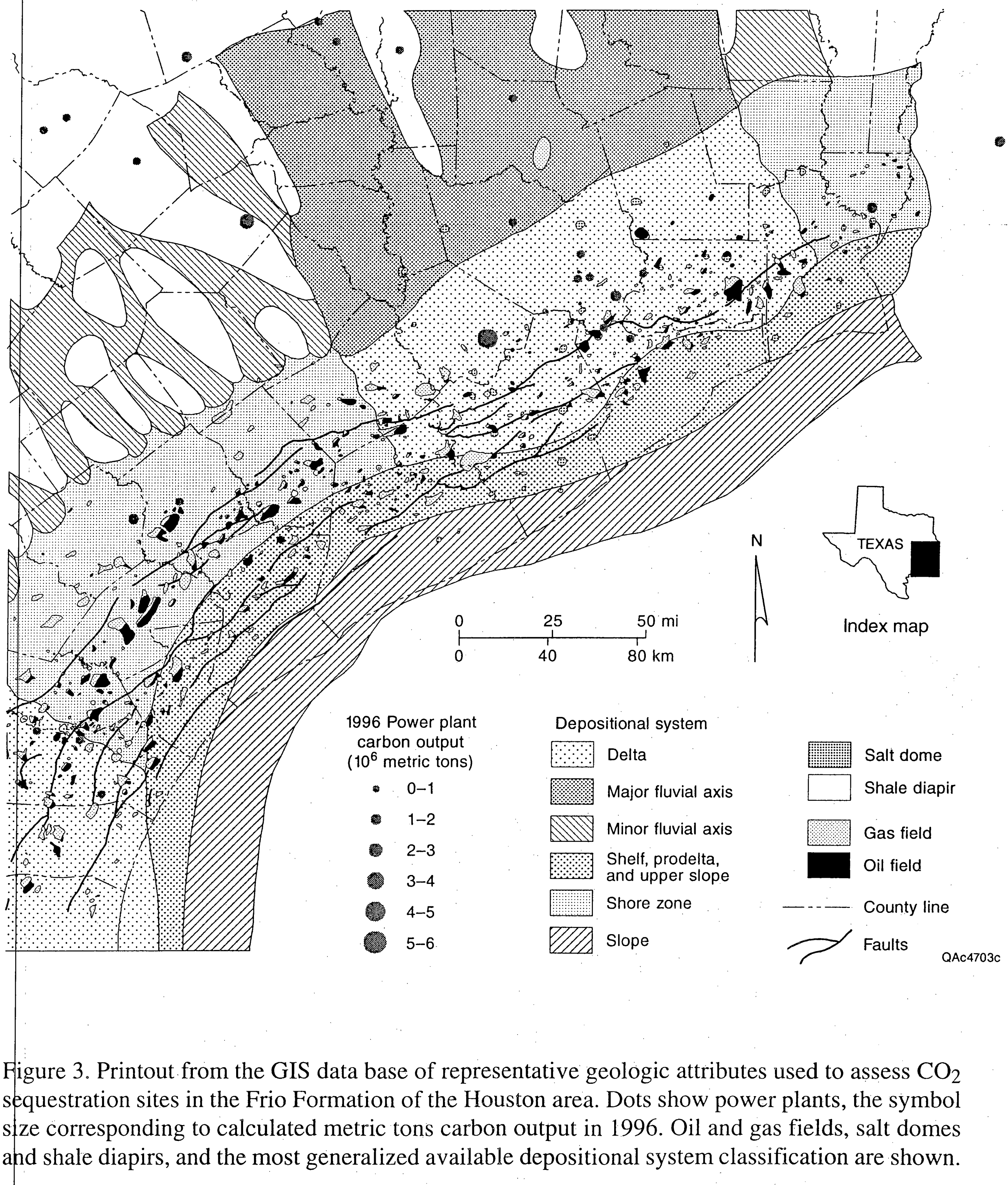

Figure 3. Printout from the GIS data base of representative geologic attributes used to assess CO_2 sequestration sites in the Frio Formation of the Houston area. Dots show power plants, the symbol size corresponding to calculated metric tons carbon output in 1996. Oil and gas fields, salt domes and shale diapirs, and the most generalized available depositional system classification are shown.

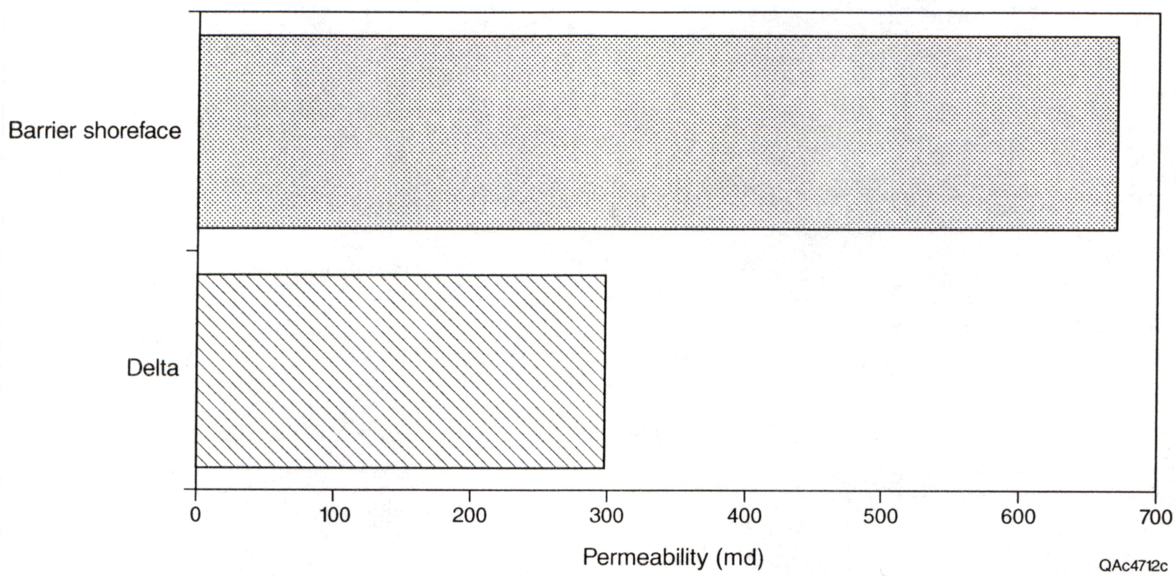

Figure 4. Geometric average sandstone permeability in the Frio oil fields, grouped by depositional facies. N = 283. Data from Holtz (1999) unpublished data base.

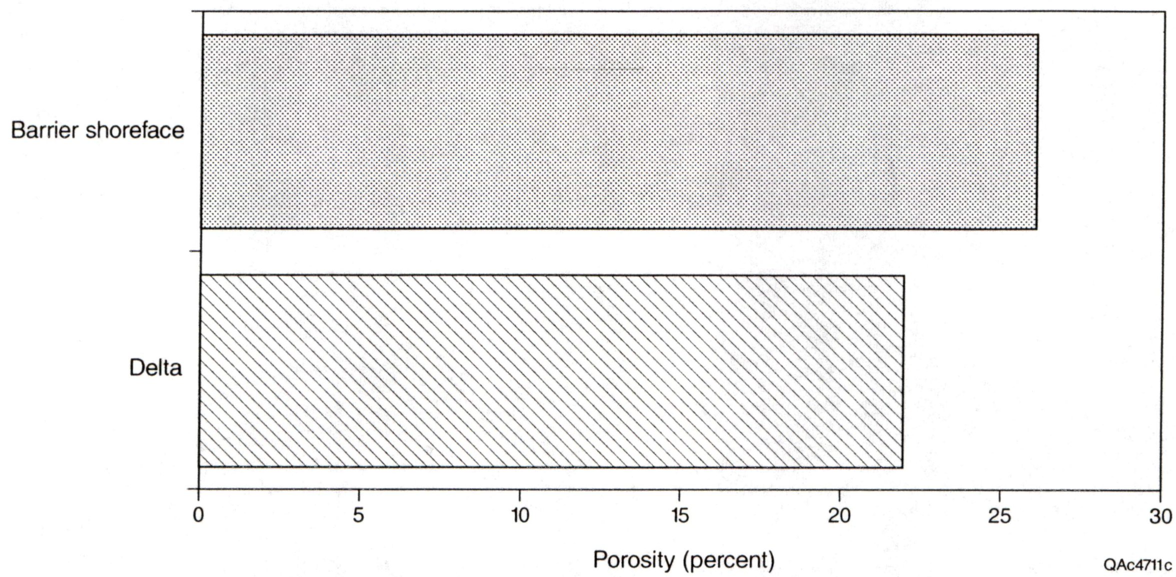

Figure 5. Average sandstone porosity in the Frio oil fields, grouped by depositional facies. N = 240. Data from Holtz (1999) unpublished data base.

growth faults (fig. 3). Upward leakage of fluids along the flanks of domes and along fault plains is known to occur locally in the Gulf Coast and, therefore, the potential impact of these features on sequestered CO_2 must be assessed. In addition, oil and gas is produced from the Frio in more than 300 fields in the Gulf Coast, and the Frio Formation is penetrated by wells producing from deeper horizons.

Fluid flow in the brine hydrostatic section of the Frio Formation has been strongly affected by depressuring because of hydrocarbon production (Kreitler and others, 1988). In a site-specific study, Kreitler and others (1988) sampled the range of average linear velocities between 0.2 and 104 ft/yr (0.06 to 31.6 m/yr), typically toward an oil field, and emphasized the need for site-specific evaluation because of large contrasts in gradient and permeability. Temperature, pressure from corrected drill-stem test data, and salinity have been mapped (Kreitler and others, 1986, 1988, 1990). From these variables, CO_2 solubility can be estimated.

The Frio Formation is composed of high Ca and Mg lithic arkoses and contains moderate to high calcium NaCl brines. Brine chemical facies have been mapped geographically and with depth over the Gulf Coast region (Morton and Land, 1987; Land and others, 1997). The capacity of this unit for fixing CO_2 in a mineral phase is high, and data exist to quantitatively evaluate the effectiveness of this process using the methods of Perkins and Gunter (1996).

Woodbine Formation

The Woodbine Formation of East Texas (Upper Cretaceous) is a fluvial and deltaic formation that prograded from the north into the East Texas Basin. The Woodbine Formation contains hydrocarbon resources, including the prolific East Texas. Less information has been published about the Woodbine Formation than the Frio, with 42 references containing Woodbine data identified. The East Texas Basin was considered as a site for disposal of high-level waste, and the basin-hydrology research conducted during the characterization of East Texas salt domes provides very useful information about the Woodbine Formation (Kreitler and others, 1984). Table 3 lists the major sources of data about the Woodbine Formation, and table 4 shows the information accumulated for each of the 14 formation properties.

The Woodbine Formation is a heterogeneous unit that crops out around the north and west margin of the East Texas Basin and dips toward the basin center to depths of as much as 4,000 ft (1,200 m) below sea level (fig. 6). Local structural depressions of more than 10,000 ft (>3,000 m) below sea level are bound in salt withdrawal basins. Depositional-system identification has been completed at regional scales (fig. 7) and field scales in some fields (Galloway and others, 1983). As we did in the Frio Formation for each depositional facies, permeability and porosity were evaluated statistically using data from producing oil fields (figs. 8 and 9). Hydrologic study of the Woodbine in outcrop yields transmissivity measurements at a larger scale (Macpherson, 1983). The formation thickens from a few hundred feet at outcrop to more than 900 ft (>270 m) down dip, and has been truncated by erosion on the east side of the East Texas Basin along the Sabine uplift. Regional net sandstone maps show thick aggregates of channel sandstones as much as 400 to 600 ft (120 to 182 m) thick in the meander-belt facies. Delta facies include 80-ft- (24-m-) thick coastal-barrier sandstones and more lenticular, compartmentalized channel-mouth-bar and delta-front sandstones (Oliver, 1971; Galloway and others, 1983, p. 54-64; Calavan, 1985). These data permit quantitative description of each part of the Woodbine Formation in terms of properties needed to compare injectivity among sites or construct realistic simulations of injectivity.

The nature of the top seal on the Woodbine Formation varies regionally because of erosional truncation, but a sequence of as much as 800 to 2,000 ft (250 to 600 m) of upper Cretaceous low-permeability units, including the Eagle Ford Formation, Austin Chalk, and Taylor Marl, overlie the unconformity. Moderate-permeability sandstones within the seal units may allow this formation to qualify as a unit having multiple seals separating several permeable units. As in the Frio Formation, piercement salt domes and faults and areas having a potential of upward leakage are identified (fig. 10). Mineralization and historical records were interpreted as evidence of past upward leakage of fluids along the flanks of domes and are associated with several domes (Kreitler and others, 1984, p. 107-117). Fault zones rim the East Texas Basin on the north, west, and

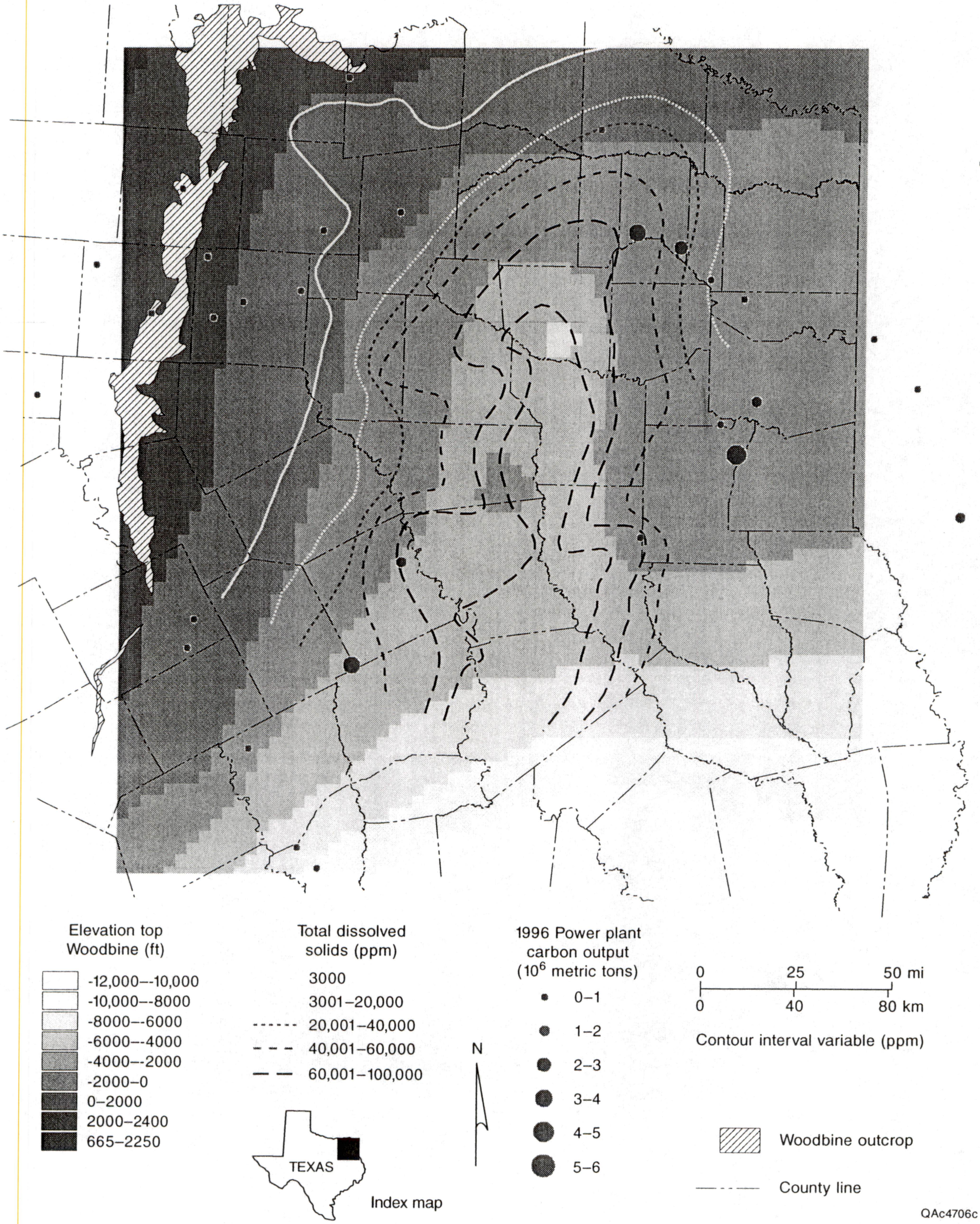

Figure 6. Printout from the GIS data base of representative geologic attributes used to assess CO_2 sequestration sites in the Woodbine Formation of East Texas. Elevation (altitude in feet above sea level) is gridded and salinity is contoured (in ppm 10^{-1}). Data sources are listed in table 3.

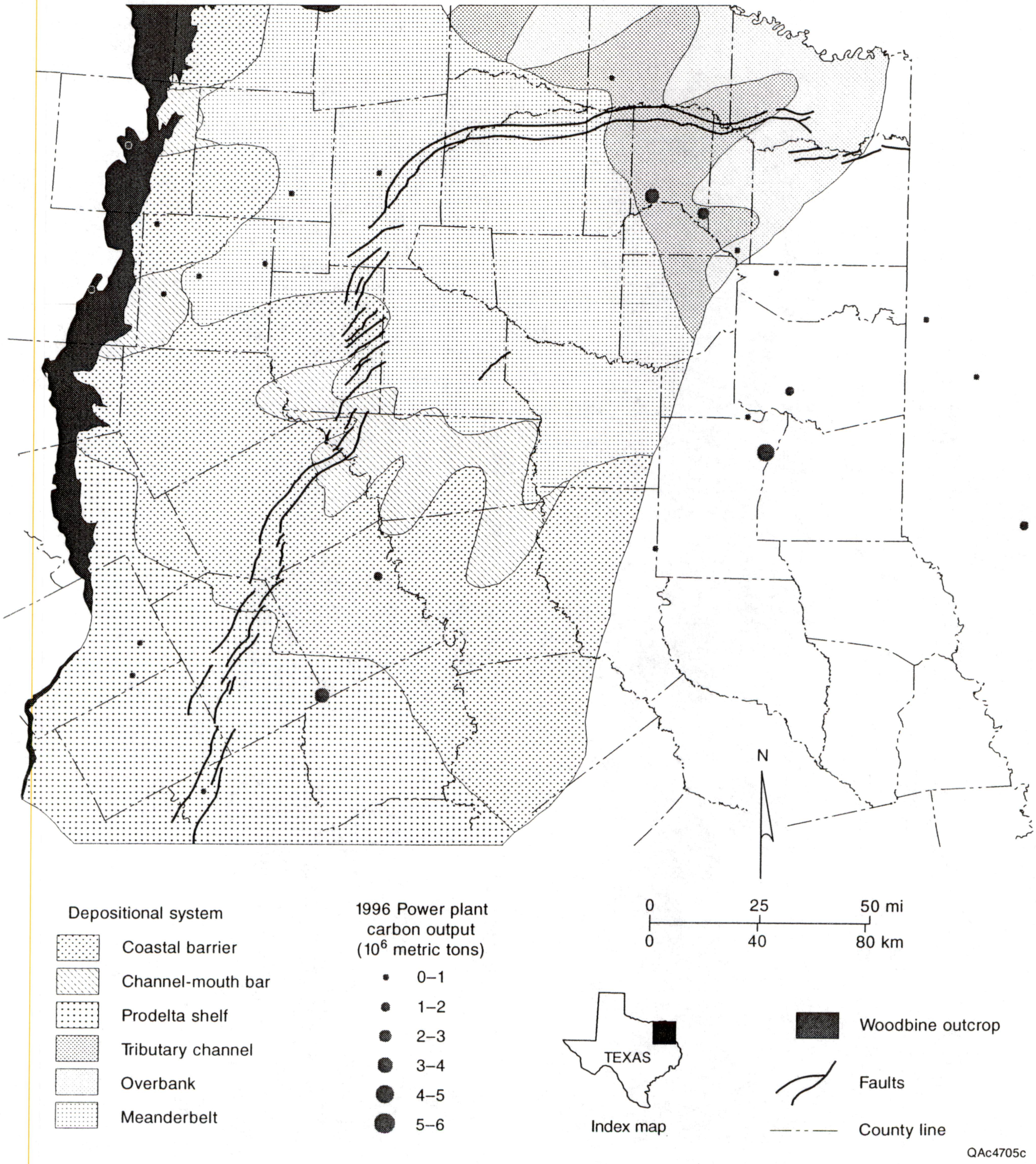

Figure 7. Printout from the GIS data base of representative geologic attributes used to assess CO_2 sequestration sites in the Woodbine Formation of East Texas. Dots show power plants, the symbol size corresponding to calculated metric tons carbon output in 1996. Depositional system classification is shown. Data sources are listed in table 3.

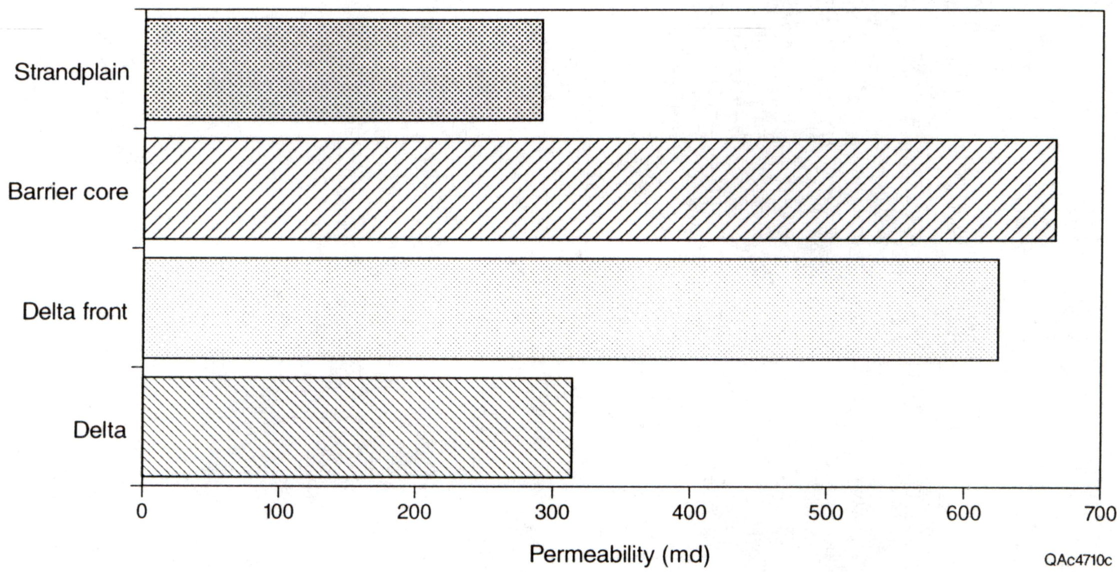

Figure 8. Geometric average sandstone permeability in the Woodbine oil fields, grouped by depositional facies. N = 29. Data from Holtz (1999) unpublished data base.

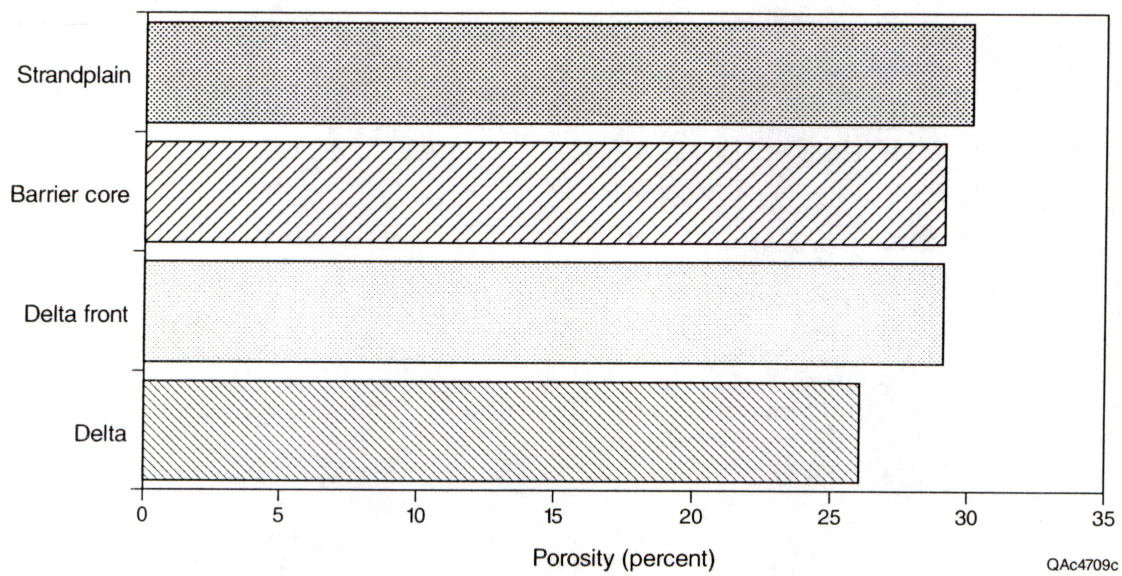

Figure 9. Average sandstone porosity in the Woodbine oil fields, grouped by depositional facies. N = 31. Data from Holtz (1999) unpublished data base.

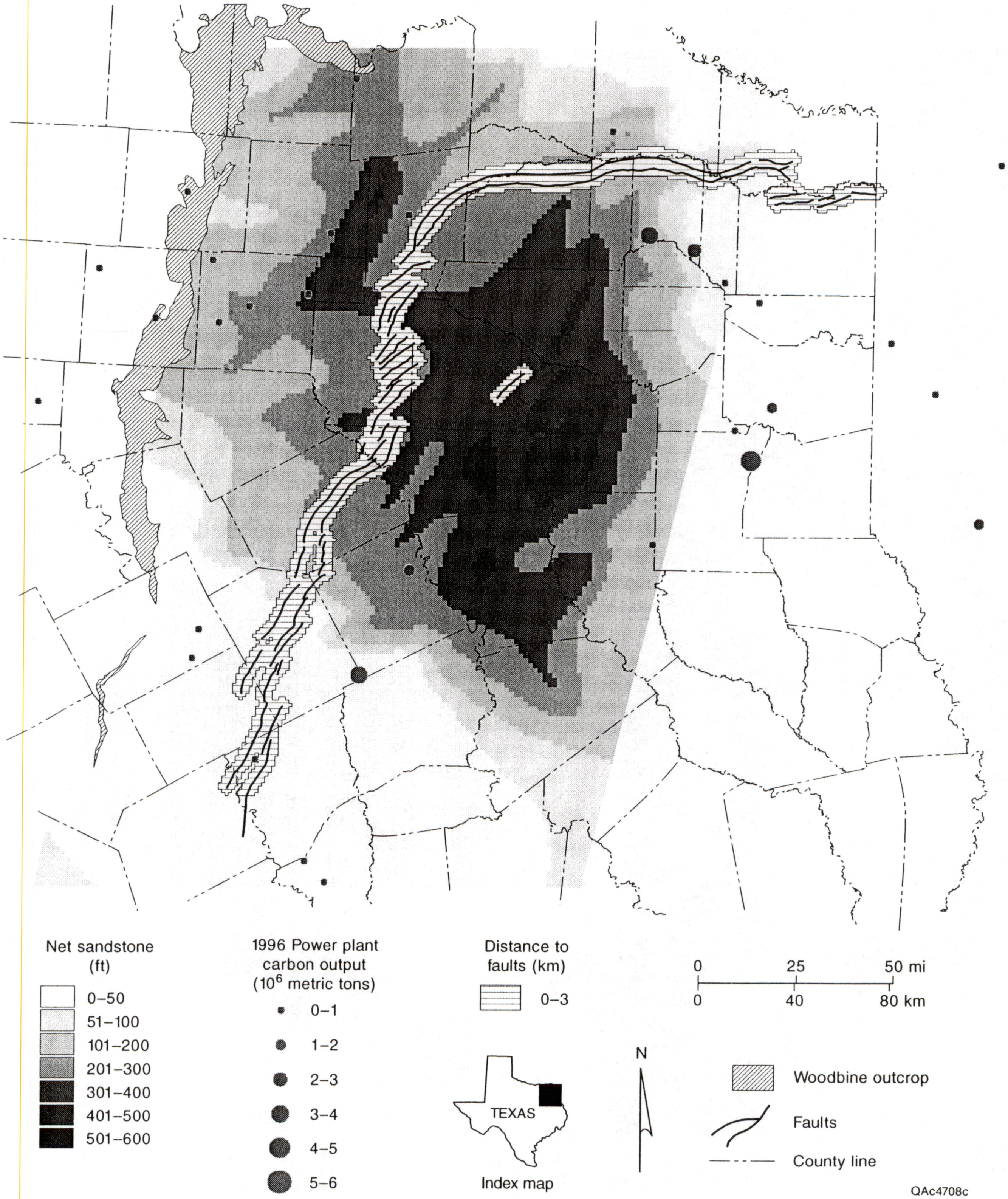

Figure 10. Printout from the GIS data base of representative geologic attributes used to assess CO_2 sequestration sites in the Woodbine Formation of East Texas. Dots show power plants, the symbol size corresponding to calculated metric tons carbon output in 1996. Measured net sandstone is gridded, and the 3-km buffer is shown around the location of faults. Data sources are listed in table 3.

south, as well as in areas associated with domes (Kreitler and others, 1984), and the potential for leakage of CO_2 along these faults has not been assessed. Oil and gas is produced from the 12 Woodbine fields in the East Texas Basin, and the impact of CO_2 injection on these fields should be evaluated. As old fields go out of production, recycling of infrastructure in areas within or adjacent to the field for CO_2 sequestration is an option. Oil is produced from the deeper Glen Rose Formation in several other areas, and the leakage up improperly completed wells in these fields is a risk. Analysis of hydrology and geochemistry of the East Texas Basin leads to the conclusion that the saline formations are essentially stagnant because of isolation of basin sediments from recharge areas by faults rimming the basin, and low topographic relief.

The Woodbine Formation has been strongly depressured as a result of long-term oil production and, therefore, pressures are subhydrostatic across the entire East Texas Basin. Drill-stem pressure data is poor quality, but pressure decline has been estimated (Kreitler and others, 1984, fig. 44) and salinity has been plotted in cross section. We did not locate a Woodbine-specific temperature map and, therefore, temperature must be calculated from depth and geothermal gradient. From these variables, CO_2 solubility can be estimated.

The Woodbine Formation is composed of arkosic quartzarenites having calcite, dolomite, ankerite, quartz, kaolinite, illite, and smectite as the dominant diagenetic phases (Uziemblo and Petersen, 1983; Wagner, 1987), and contains NaCl brines (Kreitler, 1984). The capacity of this unit for fixing CO_2 in a mineral phase is probably moderate and could be quantified using the methods of Perkins and Gunter (1996).

Navajo Formation

The Navajo Formation, Lower Jurassic of the Four Corners (Arizona, New Mexico, Colorado, and Utah) area, was selected as a challenge to test methods for evaluating the sequestration potential in areas of limited subsurface data. Table 5 outlines the techniques being used to estimate formation properties from general geologic information in a play approach where

Table 5. Techniques used to estimate formation properties from general geologic information in a play approach where these properties have not been mapped.

Formation Property	Tool
Depth	Surface geology and thickness of overlying units; regional cross sections, interpolated from other subsurface structure maps
Permeability	Extract range from analog studies, match lithology, depositional facies, grain size, burial history, and age
Formation thickness	Infer from surface mapping, measured sections
Net sand thickness	Infer range from depositional system
Percent shale	Infer range from depositional system
Sand-body continuity	Infer range from depositional system
Top seal thickness	Infer from surface mapping, measured sections
Continuity of top seal	Identify faults from surface mapping, facies pinch out from depositional system
Hydrocarbon production from interval	Generally mapped in detail
Fluid residence time, flow direction	Difficult to infer
CO_2 solubility in brine (pressure, temperature, and salinity)	Pressure and temperature can be approximated from burial depth, basin history, and geothermal gradient; salinity is difficult to infer
Rock/water reaction	Infer from lithologic and diagenetic descriptions, or from analogs
Porosity	Extract range from analog studies, match lithology, depositional facies, grain size, burial history, and age

these properties have not been mapped, and table 6 presents the data sources identified for the Navajo Formation.

The Navajo Sandstone, deposited in eolian environments (erg and associated extra-erg and interdune facies) crops out over much of the Four Corners area and, therefore, excellent information is available about its facies, thicknesses, and interrelationships with associated units. A bibliographic search yielded 43 citations about the Navajo Sandstone and related units. Little information is available about the Navajo Sandstone in the subsurface, and more time must be spent compiling information from local ground-water studies to determine the extent of saline water in the subsurface to map out areas of saline water potentially useful for sequestration. Table 6 lists the data sources compiled. Three modern structural basins were identified for further consideration: the Henry Mountains Basin of Utah, the Kaiparowits Bench Basin on the Utah–Arizona State line, and the Black Mesa Basin in Arizona. In these areas, the Jurassic is overlain by Cretaceous units, and the total thickness of the Phanerozoic is as much as 5,000 to 10,000 ft (1,500 to 3,000 m) (Woodward, 1984). These shallow basins, having extensive outcrop of the Navajo Formation, are probably a limiting factor in the usefulness of the formation for sequestering CO_2. Permeability of the Navajo Sandstone is excellent (Blanchard, 1987; Weiss, 1987; Heilweil and Freethy, 1992), and the unit is one of the thickest and most homogeneous sandstones in the United States. A detailed permeability study of the Jurassic Page Sandstone that relates permeability to depositional facies (Chandler and others, 1989) can be used as an analog for the Navajo sandstone. The effect of structure on permeability has been analyzed by Antonellini and Aydin (1994).

Large amounts of the Navajo are unusable for sequestration because of the absence of an effective seal and high probability that fluid residence time is low. The low-permeability stratigraphic unit above the Navajo is the Carmel Formation (Peterson, 1988; Blakey, 1994). We found no measurements of the vertical permeability of this unit and, therefore, estimated ranges are assigned for each of the sabkha, limestone, and gypsum facies of this units. The quality of the seal, which varies in thickness, may be a critical screening parameter. Fracturing and faulting in this area of complex deformation may also be critical. A number of hydrologic studies of small

Table 6. Data sources for the Navajo Sandstone and Black Warrior Basin Pennsylvanian properties.

Formation Property	Navajo Formation	Pennsylvanian
Depth	Estimated from Peterson, 1988, structure on the base of the Dakota Formation, and Peterson, 1994, thickness of Phanerozoic, and Woodward, 1984, structure on top Precambrian	Thomas, 1988, Plate 8
Permeability	Blanchard, 1987; Weiss, 1987; Chandler and others, 1989; Heilweil and Freethy, 1992; Antonellini and Aydin, 1994	Estimated from analogs
Formation thickness	Peterson, 1972	Cleaves, 1983
Net sand thickness	Blakey, 1994	Cleaves, 1983;Thomas, 1988
Percent shale	Blakey, 1994	Cleaves, 1983
Sand-body continuity	Blakey and others, 1988; Blakey, 1994	Cleaves, 1983;Thomas, 1988
Top seal thickness	Peterson, 1988; Blakey, 1994	Thomas, 1988
Continuity of top seal	Peterson, 1988; Blakey, 1994	Cleaves, 1983;Thomas, 1988
Hydrocarbon production from interval	Hill and Bereskin, 1993	Thomas, 1988
Fluid residence time, flow direction	Not available	Not determined
CO_2 solubility in brine (pressure, temperature, and salinity)	Not available	Not determined
Rock/water reaction	Not identified	Cleaves, 1983
Porosity	Blanchard, 1987	Estimated from analogs

areas can be merged in a GIS format to define the distribution and complex flow paths of fresh water and provide information by inference about more saline settings.

Pottsville Formation of the Black Warrior Basin

The fourth selected area for a demonstration project was placed on an area, including parts of Mississippi, Alabama, Georgia, and Tennessee (fig. 1), having a high density of large power plants. Rapid reconnaissance of the area brought our focus to the Pennsylvanian Pottsville fluvial-deltaic rocks of the Black Warrior Basin of west-central Alabama and east-central Mississippi.

The Pottsville Formation (Lower Pennsylvanian) of the Black Warrior Basin is part of a wedge of fluvial and deltaic units that syndepositionally filled the foreland basin. A bibliographic search identified 57 references describing various attributes of the Mississippian–Pennsylvanian strata, dominantly regional depositional-system characterization. The Black Warrior Basin has also been characterized for deep-well disposal of water coproduced with coalbed methane (Ortiz and others, 1993). Table 6 lists the major data sources used to determine the 14 formation properties for Pottsville Formation.

Structure contours on the top of the Mississippian show structural displacement along a southward-dipping homocline and faults from outcrop near the Tennessee state line to depths of more than 12,000 ft (>3,600 m) below sea level near the south edge of the basin, at the Ouachita thrust belt. The depositional system in the Pottsville Formation includes thick sands of the barrier island complex, lagoonal muds, and delta and delta-plain sandstones (Thomas, 1988). During this pilot-phase study, porosity and permeability data specific to these facies were not located, so that facies-equivalent data from various Pennsylvanian deltaic and barrier-island facies were used (Holtz, 1999, unpublished data base). Further searching in order to match sandstone provenance may be desirable. The Pottsville Formation thickens from the erosional limit at the north edge of the basin to as much as 11,000 ft (3,400 m) in the south part of the basin. Net sandstone maps have been prepared for various sand units in the Pottsville (Cleaves, 1983; Thomas, 1988).

Sand-body geometry specific to the Pottsville was not identified and, therefore, analog data from Pennsylvanian shelf sandstones in north-central Texas and elsewhere in the Appalachian Basin are used.

The top seal on the Pennsylvanian strata is made up of the Cretaceous to lower Tertiary units of the Mississippi Embayment and Gulf Coast, which thicken from the erosional limit toward the structural basin center. Overlaying the thickness of the seal strata on depth and sandstone facies provides a first-cut screening tool for parts of the Pottsville that contain potentially useful environments for CO_2 sequestration. Although faults do not cut the Cretaceous strata, the seal is penetrated by 1,200 oil and gas wells producing from the Mississippian (Thomas, 1988). Temperature and pressure are calculated from estimated depth and geothermal gradient. Salinity and water chemistry data were not located during a reconnaissance literature search. Sandstone composition is arkosic litharenite (Cleaves, 1983), which would provide good potential for geochemical trapping of CO_2 by rock–water reaction.

DEMONSTRATION OF THE USES OF THESE DATA IN A GIS FRAMEWORK

To meet the needs of evolving concepts for CO_2 sequestration, we input the formation properties into a GIS. For this demonstration, we selected the elements of the Frio and Woodbine examples and input them into a GIS (table 7). The powers of this tool are that (1) different data sets from various sources can be overlaid at a common scale, (2) the scale can be varied from the entire United States to a single county, (3) any combination of parameters can be selected and information extracted, and (4) quantitative results and maps can be directly output. GIS expedites experimenting with various options. The examples presented here are not "answers"; rather, they are examples of how the tool can be used to answer various questions. A typical objective for site selection might be to find the areas where all the conditions on a list are met. For model construction, the objective might be to elicit the range and variability of values for each input parameter in a selected subset of the data. For this report we have selected two examples—one

Table 7. GIS coverages created for this project.

Theme	Theme name	Derived coverages
County line base	cnty24	county1.dbf; county1.shp; county1.shx; countylns.dbf; countylns.shp; countylns.shx
Power-plant locations	us_powerplants.e00plantsutm	plantsutm.dbf; plantsutm.sbn; plantsutm.sbx; plantsutm.shp; plantsutm.shx; powerplants.avl
1996 C output		25km.dbf; 25km.shp; 25km.shx
Structure on top Woodbine	altitude	altint; Altgrid; altpoly
Woodbine outcrop	woutcrop	
Woodbine depositional systems	depsys	depsys.dbf; depsys.shp; depsys.shx; altdeps
Woodbine net sandstone	sandis	sandep; sandep.dbf; sandep.sbn; sandep.sbx; sandep.shp; sandep.shx; sandgrid; sandint; sandpoly
Faults in East Texas Basin	faults	
TDS Woodbine	dissolve	dissgrid
Structure on top Frio	elevation	elevation.trans; elevationutm; eldepunion; frioelpoly; del4-6; del4-6.dbf; del4-6.shp; del4-6.shx
Frio outcrop	outcrop	outcrop.trans; outcroputm
Frio depositional systems	deposit	deposit.trans; depositutm
Leaks in seal	dome; fault; field	dome.trans; domebuf; domeutm; fault.trans; faultutm; faultbuf; field.trans; fieldutm; fieldbuf; leaks; leakclip.dbf; leakclip.shp; leakclip.shx; leaks.dbf; leaks.shp; leaks.shx; leaksclip; leaksclip.dbf; leaksclip.shp; leaksclip.shx
Potentiometric surface 4,000–6,000 ft	potent	potent.trans; potentutm

from the Cretaceous Woodbine Formation of the East Texas Basin and one from the Oligocene Frio Formation of the Gulf Coast.

Frio Example

For the Frio Formation in the Houston area we looked at regional geologic factors to identify areas useful to prospecting for CO_2 injection sites. For our example, we selected the depositional system that had the highest ranked injectivity available (Holtz and others, 1998, p. 28). In the Frio Formation, this is the fluvially dominated deltaic depositional system (Galloway, 1986), with a geometric mean permeability of 422 md (fig. 4). We arbitrarily selected a depth of as much as -4,000 to -6,000 ft (1,200 to 1,800 m) and used ARC/INFO and ArcView software to intersect these two data sets and identify a prospect where deltaic facies occur at the specified depth range. In the Houston area, this selected prospect underlies five power plants and is within 10 mi (16 km) of three more. These eight plants produced a total 1996 carbon output of 6.8×10^6 metric tons. The selected host underlies a 6,375-km^2 (2,490-mi^2) area (fig. 11). However, not all of this area may be suitable for sequestration because oil and gas fields, salt domes, and major fault segments have the potential to at least locally breach the several trapping units above the Frio Formation. Because our proposed trapping mechanism is hydrodynamic, we assumed that the injection site should be 3 km away from potential leaks. We therefore created a 3-km (1.8-mi) buffer around these features (fig. 11) and subtracted this “leaky” area of 2,061-km^2 (805-mi^2) from the total, leaving 4,314 km^2 (1,685 mi^2) of prospect area. First-cut estimates of average porosity of 30 percent for the Frio deep salt dome play in this area can be extracted from Galloway and others (1983). Average net sandstone thickness of just the upper Frio was estimated at 250 ft (75 m). Estimated total pore volume storage for CO_2 in the upper Frio in the selected three-dimensional rock volume is 9.7 km^3 (2.3 mi^3).

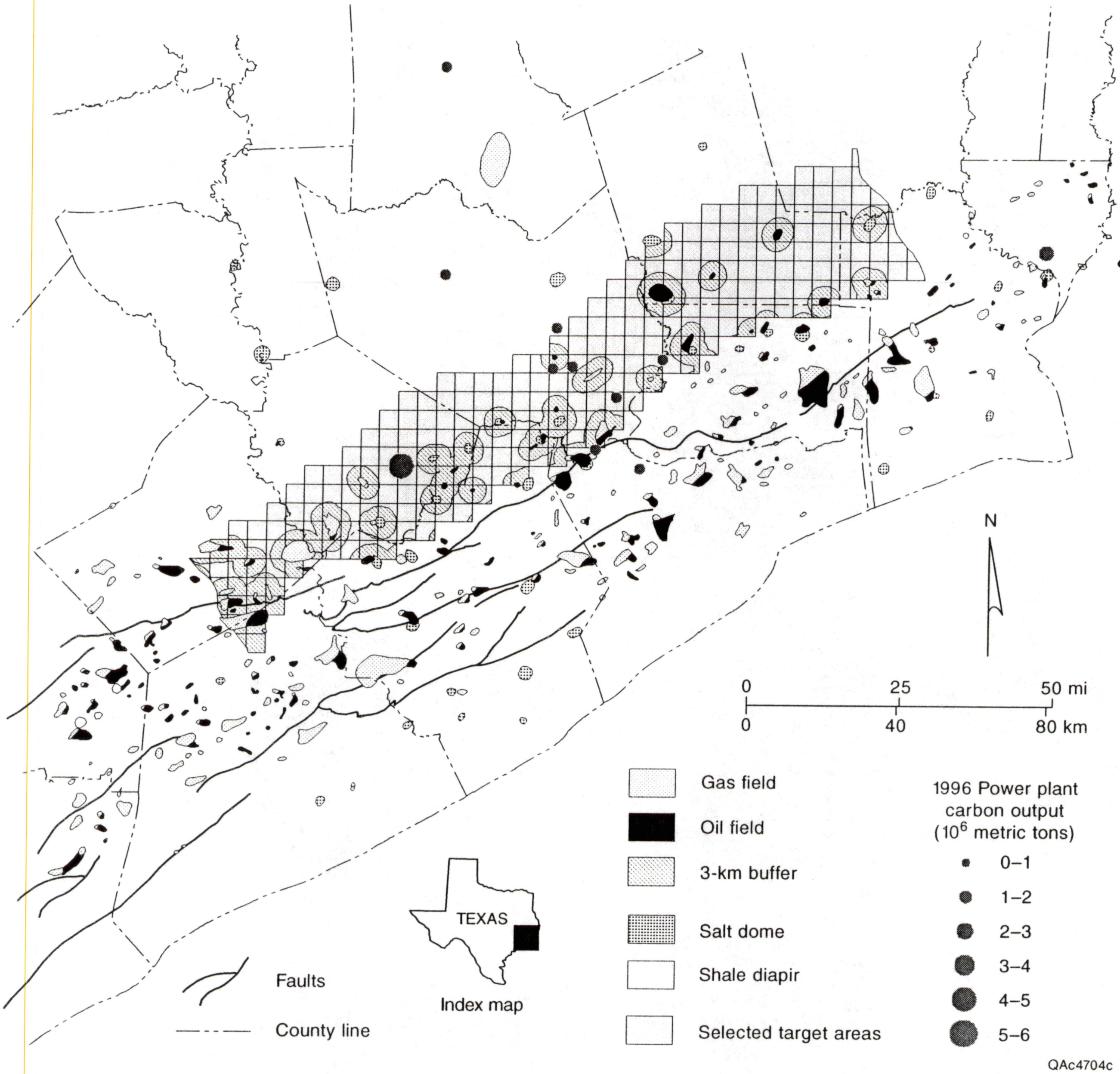

Figure 11. Printout from the GIS data base of one assessment of CO_2 sequestration sites. The selected target area is underlain by high-permeability Frio deltaic sandstones at depths of -4,000 to -6,000 ft. Patterned areas are 3-km buffers around potential leaks. Four power plants (dots) overlie this selected target.

Woodbine Example

For the Woodbine demonstration, our example objective was to depict the available formation properties near selected power plants in East Texas. Of the 23 plants that are in the area underlain by the Woodbine Formation, we chose the 2 plants having the largest CO_2 output (Limestone and Big Brown, having a total of 4.8 10^6 metric tons of carbon output in 1996). Our exercise was to provide model input parameters for these two plants from geologic data sets (figs. 7 and 10). Using the data sets, we rapidly screened for suitable areas within 25 km (15 mi) of the power plants (fig. 12). The Limestone power plant lies near the edge of the Woodbine delta facies, and an injection facility would have to be located at least 10 mi away. Big Brown power plant, however, overlies coastal barrier facies. Net sandstone beneath the Big Brown plant is 250 ft (75 m), depth is -4,000 ft (-150 m), and TDS is 60,000 ppm, moderate for this basin. This tool facilitates a rapid comparison of the geological properties of prospective host strata near power plants. Table 8 shows Woodbine formation properties within 25 km (15 mi) of power plants. A future analysis might use existing pipelines instead of a circular buffer to match plant output, transportation infrastructure, and geologic environments in a best fit.

CONCLUSIONS

Literature data searches for site specific data were more successful than expected, and relevant previous work describing the subsurface facies distribution in some detail was found in all four pilot basins. Regional exploration of geologic plays for oil and gas exploration and improved recovery produces rich data sets useful for characterization of the suitability of saline formations for CO_2 sequestration. In addition, studies of the suitability of saline formations for deep-well injection and waste disposal proved to be very useful, as we found in three of the four basins examined in this pilot study.

Where detailed data are lacking, geologic analogs and play approaches that group similar geologic environments are useful in screening for optimal formations for sequestration. Using

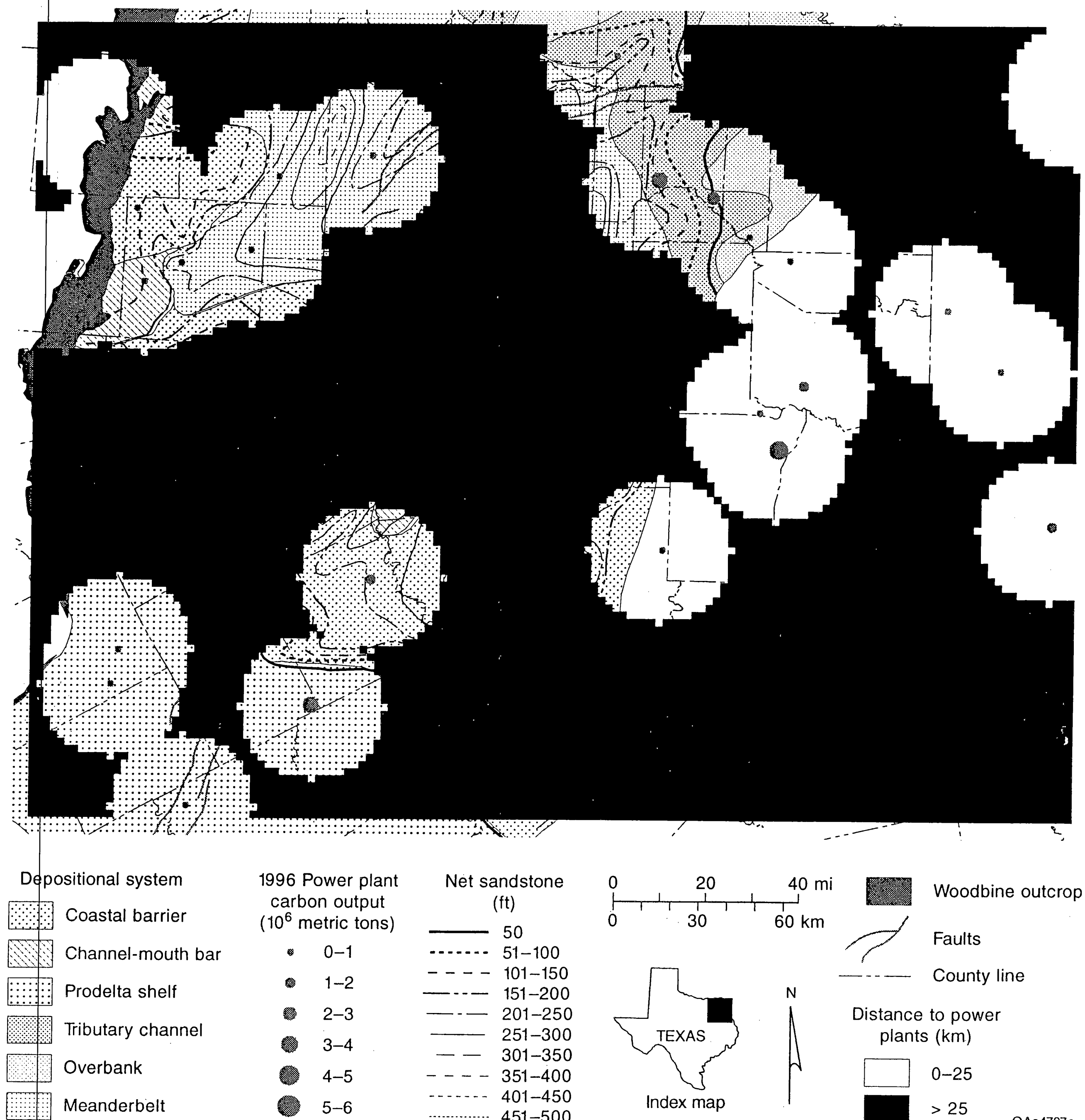

Figure 12. Printout from the GIS data base of screening for aquifer characteristics within 25 km (16 mi) of power plants. Aquifer properties in the vicinity of the power plants can be compared and injection feasibility ranked.

Table 8. Woodbine formation properties within 25 km (15 mi) of power plants.

Facies number	Facies name	Average net sand thickness
1	Coastal barrier	60
2	Channel-mouth bar	52
3	Prodelta shelf	11
4	Tributary channel	36
5	Overbank	16
6	Meander belt	83

these inferences does not permit as fine a spatial resolution as in areas with detailed subsurface data; however, it can be used effectively to identify targets for further analysis as well as identify areas where chances of high-quality injection targets are low.

RECOMMENDATIONS FOR FURTHER WORK

A GIS data base approach is recommended as a mechanism for compiling information to facilitate identification and evaluation of settings that may be optimal for CO_2 sequestration in saline formations. On the basis of the pilot evaluations undertaken for this project, table 9 outlines the recommended content and data structure for the GIS coverages. Data tables generated in this data structure can then be joined, or the areas with desirable or negative characteristics intersected, in order to prospect for optimal settings in the manner demonstrated by the pilot-study examples. These data sets can also be used as sources of realistic data sets containing needed statistical data on formation properties to simulate injection scenarios.

We found more formation-specific data than we expected for each of our pilot basins. Much of the most applicable information was found in unpublished contract reports and data archives dealing with injection permits and studies. For Phase II we recommend allocating more time than we budgeted in the pilot study for archive search and interviewing of personal contacts in order to retrieve this highly pertinent information.

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Table 9. Proposed GIS data structure for saline formation characterization.

Formation property	Preferred source data	Other data source	Derived coverage	Product
Depth	Structure contour on top of formation	Structure on other marker, isopach	Structure on top of formation	Gridded structure
Permeability	Mapped permeability	Depositional system, facies, lithology, facies/permeability relationship	Mapped permeability	Gridded permeability
Formation thickness	Formation thickness	Top underlying formation	Structure on base formation	Gridded isopach
Net sand thickness	Net sand thickness	Outcrop of field descriptions	Net sand thickness	Grid
Percent shale	Percent shale	Outcrop or field descriptions	Percent shale	Mapped areas
Sand-body continuity	Derived from depositional system	Outcrop or field descriptions	Sand-body continuity	Mapped areas
Top seal thickness	Top seal isopach	Local measurements	Top seal isopach	Gridded isopach
Continuity of top seal	Mapped location of potential leaks, hydrocarbon production, faults	Estimated density and type of leak	Mapped leaks	Mapped areas
Hydrocarbon production from interval	Field maps	Well locations, well density	Mapped production	Mapped areas
Fluid residence time	Mapped residence time	Proxy, local measurements, or whole basin estimate	Fluid residence time	Mapped areas
Flow direction	Mapped flow direction	Proxy, local measurements, or whole basin estimate	Flow direction	Mapped areas with noted flow direction
Pressure	Head map	Calculated pressure from depth	Pressure map	Grid
Temperature	Borehole temperature map	Calculated temperature from depth and geothermal gradient	Temperature map	Grid
Salinity	Formation fluid salinity map	regional estimate	Formation fluid salinity map	Formation fluid salinity map
Rock/water reaction	Formation mineralogic composition	Formation mineralogic composition	Ranked CO_2 rock-water-reaction capacity	Mapped areas
Porosity	Porosity map	Facies/porosity transform	Mapped porosity	Mapped porosity

REFERENCES

Ahmad, M. U., and Smith, J. A., 1998, Earthquakes, injection wells, and the Perry nuclear power plant, Cleveland, Ohio: Geology, v. 16, p. 739–742.

Anonymous, 1996, Just add iron and stir (geo-engineering projects on "fixing" global warming): New Scientist, v. 152, 3 p.

Anonymous, 1997, Trading places, U.S. "joint implementation" proposal for reducing greenhouse gas emissions): New Scientist, v. 156, p. 7.

Antonellini, Marco, and Aydin, Atilla, 1994, Effect of faulting on fluid flow in porous sandstones; petrophysical properties: American Association of Petroleum Geologists Bulletin, v. 78, p. 355–377.

Aresta, M., and Tommasi, I., 1997, Carbon dioxide utilization in the chemical industry: Energy Conversion and Management, v. 38, Supplement, p. S373–S378.

Bachu, Stefan, 1996, Hydrogeology, *in* Hitchon, Brian, ed., Aquifer disposal of carbon dioxide: hydrodynamic and mineral trapping—proof of concept: Geoscience Publishing Ltd, Alberta, Canada, p. 29–58.

Bachu, Stefan, Gunter, W. D., and Perkins, E. H., 1994, Aquifer disposal of CO_2; hydrodynamic and mineral trapping: Energy Conversion and Management, v. 35, no. 4, p. 269–279.

Baklid, Alan, Korbøl, Ragnhild, and Owren, Gier, 1997, Sleipner vest CO_2 disposal, CO_2 injection into a shallow underground aquifer: Society of Petroleum Engineers Paper No. 36600, reprinted in Sleipner carbon dioxide storage workshop, Trondheim, Norway, IEA Greenhouse Gas R&D Programme Report PH3/1, not paginated.

Baviere, Marc, ed., 1991, Basic concepts in enhanced oil recovery processes: Elsevier Applied Science, 412 p.

Bergman, P. D., and Winter, E. M., 1995, Disposal of carbon dioxide in aquifers in the U.S.: Energy Conversion and Management, v. 36, no. 6-9, p. 523–526.

Bergman, P. D., Winter, E. M., and Chen, Z.-Y., 1997, Disposal of CO_2 in depleted oil and gas reservoirs in Texas: Energy Conversion and Management, v. 38, p. 211–216.

Blakey, R. C., 1994, Paleogeographic and tectonic controls on some lower and middle Jurassic erg deposits, Colorado Plateau, *in* Caputo, M. V., Peterson, J. A., and Franczyk, K. J., eds., Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, p. 273–298.

Blakey, R. C., Peterson, F., and Kocurek, G. 1988, Synthesis of late Paleozoic and Mesozoic eolian deposits of the Western Interior of the United States: Sedimentary Geology, v. 56, p. 3–125.

Blanchard, P. J., 1987, Hydrology of the Navajo Sandstone in southeastern and southern Utah, *in* McLean, J. S., and Johnson, A. I., eds., Regional aquifer systems of the United States; aquifers of the western mountain area: American Water Resources Association Monograph Series 14, p. 101–119.

Bondor, P. L., 1992, Applications of carbon dioxide in enhanced oil recovery: Energy Conversion and Management, v. 33, no. 5-8, p. 579–586.

Calavan, C. W, 1985, Depositional environments and basinal setting of the Cretaceous Woodbine Sandstone, Northeast Texas: Baylor University, Master's thesis, 225 p.

Chandler, M. A., Kocurek, Gary, Goggin, D. J., and Lake, L. W., 1989, Effects of stratigraphic heterogeneity on permeability in eolian sandstone sequence, Page Sandstone, northern Arizona: American Association of Petroleum Geologists Bulletin, v. 73, no. 5, p. 658–668.

Chia, Yeeping, 1992, Analysis of hydrogeologic conditions for containment of deep-well injected waste: Journal of the Geological Society of China, 36 (3), p. 291–309.

Ciesla, W. M., 1997, Forestry options for mitigating predicted climate change, *in* Adger, W. N., Pettenella, D., and Whitby, M., eds., Climate-change mitigation and European land-use policies, p. 35–47.

Cleaves, A. W., 1983, Carboniferous terrigeneous clastic facies, hydrocarbon producing zones and sandstone provenance, northern shelf of Black Warrior Basin: Transactions, Gulf Coast Association of Geological Societies, v. 33, p. 41–53.

Coghlan, Andy, 1995, Sunlight could recycle greenhouse gas: New Scientist, v. 146, p. 22.

EIA, 1996, Emissions of greenhouse gases in the Untied States: downloadable PDF files at http://www.eia.doe.gov/oiaf/1605/gg97/

Federal Energy Regulatory Commission (FERC) data base, http://www.ferc.fed.us/electric/f423/F423annual.htm

Galloway, W. E., 1986, Depositional and structural framework of the distal Frio Formation, Texas coastal zone and shelf: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 86-8, 16 p.

Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, N., and Bebout, D. G., 1983, Atlas of major oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, p. 54–64.

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.

Geomap, 1992, Executive map of East Texas Basin, one sheet.

Gessinger, G., 1997, Lower CO_2 emissions through better technology: Energy Conversion and Management, v. 38, supplement, p. S25–S30.

Gunter, W. D., Perkins, E. H., and McCann, T. J., 1993, Aquifer disposal of CO_2-rich gases: reaction design for added capacity: Energy Conversion and Management 34, p. 941–948.

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, Clearwater, Florida.

Hendriks, C. A., and Blok, Kornelis, 1993, Underground storage of carbon dioxide: Energy Conversion and Management, v. 34, p. 949–957.

__________ 1995, Underground storage of carbon dioxide: Energy Conversion and Management, v. 36, p. 539–542.

Heilweil, V. M., and Freethey, G. W., 1992, Simulation of ground-water flow and water-level declines that could be caused by proposed withdrawals, Navajo Sandstone, southwestern Utah and northwestern Arizona: Water-Resources Investigations WRI 90-4105, U.S. Geological Survey, 51 p., 3 sheets.

Hill, B. G., and Bereskin, S. R., eds., 1993, Oil and gas fields of Utah: Utah Geological Survey, UGA-22, 192 p.

Hitchon, Brian, ed., 1996, Aquifer disposal of carbon dioxide: hydrodynamic and mineral trapping—proof of concept: Geoscience Publishing Ltd, Alberta, Canada, 165 p.

Holloway, Sam, and Savage, David, 1993, The potential for aquifer disposal of carbon dioxide in the UK: Energy Conservation Management, v. 34, p. 925–932.

Holloway, Sam, and van der Straaten, Rieks, 1995, The Joule II project: the underground disposal of carbon dioxide: Energy Conversion and Management, v. 36, no. 6-9, p. 519–522.

Holmes, Bob, 1997, The ice car cometh (nitrogen fuelled cars could solve a global warming): New Scientist, v. 155, p. 12.

Holt, T., Jensen, J.-I., and Lindeberg, E., 1995, Underground storage of CO_2 in aquifers and oil reservoirs: Energy Conservation Management, v. 36, no. 6-9, p. 535–538.

Holtz, M. H., 1999, OILINFO, Access date base, unpublished.

Holtz, M. H., Nance, P. K., and Finley, R. J., 1998, reduction of greenhouse gas emissions through underground CO_2 sequestration in Texas oil and gas reserves: The University of Texas at Austin, Bureau of Economic Geology, draft report, 84 p.

Hong, B. D., and Slatick, 1994, Carbon dioxide emission factors for coal: http://www.eia.gov.cneaf/coal/quartert

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.

Javandel, Iraj, Tsang, C. F., Witherspoon, P. A., and Morganwalp, David, 1988, Hydrologic detection of abandoned wells near proposed injection wells for hazardous waste disposal: Water Resources Research, v. 24, no. 2, p. 261–270.

Knox, R. P., Holtz, M. H., McRae, L. E., Hentz, T. F., Paine, J. G., White, Gerald, and Chang, Chun-Yen, 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 contract report, 178 p.

Koide, H., Shindo, Y., Tazaki, Y. Iijima, M., Ito, K., Kimura, N., and Omata, K., 1997, Deep sub-seabed disposal of CO_2—the most protective storage: Energy Conversion and Management, v. 38, supplement, p. S253–S258.

Koide, H., Takahashi, M., Tsukamoto, H., and Shindo, Y., 1995, Self-trapping mechanism of carbon dioxide in aquifer: Energy Conversion and Management, v. 36, p. 505–508.

Koide, H., Tazaki, Y., Noguchi, Y., Iijima, M., Ito, K., and Shindo, Y., 1993, Carbon dioxide injection into useless aquifers and recovery of natural gas dissolved in fossil water: Energy Conversion Management, v. 34, no. 9, p. 921–924.

Korbøl, Ragnhild, and Kaddour, Aoued, 1995, Sleipner vest CO_2 disposal—injection of removed into the Utsira Formation: Energy Conservation Management, v. 36, p. 509–512.

Kreitler, C. W., Akhter, M. Saleem, 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 (2), p. 107–120.

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., 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: BEG contract report DE-AC97-80ET46617, 156 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., Mack, L. E., Milliken, K. L., and Lynch, F. L., 1997, Burial diagenesis of argillaceous sediment, South Texas Gulf of Mexico sedimentary basin; a reexamination: Geological Society of America Bulletin, v. 109, no. 1, p. 2–15.

Langeland, K., and Wilhelmsen, K., 1993, The study of the costs and energy requirement for carbon dioxide disposal: Energy Conversion and Management, v. 34, no. 9-11, p. 807–814.

Lashof, D. A., 1996, Cool solutions for global warming: Technology Review, v. 99, p. 62.

Law, David, 1996, Injectivity studies, *in* Hitchon, Brian, ed., Aquifer disposal of carbon dioxide: hydrodynamic and mineral trapping—proof of concept: Geoscience Publishing Ltd, Alberta, Canada, p. 59–92.

Macpherson, G. L., 1983, Regional trends in transmissivity and hydraulic conductivity, Lower Cretaceous sands, north-central Texas: Ground Water, v. 21, no. 5, p. 577–583.

Monastersky, Richard, 1995, Iron versus the greenhouse (oceanographers cautiously explore a global warming therapy): Science News, v. 148, p. 220.

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.

Murray, C. N., and Wilson, T. R. S., 1997, Marine carbonate formations: their role in mediating long-term ocean-atmosphere carbon dioxide fluxes—a review: Energy Conversion and Management, v. 38, supplement, p. S287–S294.

Nadis, Steve, 1997, Deep dump: Popular Science, v. 250, p. 27.

Oliver, 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.

Ortiz, Isaias, Weller, T. F., Anthony, R. V., Dziewulski, D., Lorenzen, J., and Frantz, J. H., Jr., 1993, Disposal of produced waters; underground injection option in the Black Warrior Basin: American Association of Petroleum Geologists Bulletin, v. 77 , no. 8, p. 1472–1473.

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: Geoscience Publishing Ltd, Alberta, Canada, p. 93–113.

Peterson, Fred, 1988, Sedimentologic and paleotectonic analysis of the Henry, Kaiparowits, and Black Mesa basins, *in* Sloss, L. L., ed., Sedimentary cover—North American craton, U.S.: The Geology of North America, v. D-2, p. 134–144.

Peterson, J. A., 1972, Jurassic system, *in* Rocky Mountain Association of Geologists: Geologic Atlas of the Rocky Mountain Region of the United States of America, p. 177–189.

Peterson, J. A., 1994, Regional paleogeographic and paleogeographic maps of the Mesozoic systems, Rocky Mountain region, U.S., *in* Caputo, M. V., Peterson, J. A., and Franczyk, K. J., eds., Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, p. 65–71.

Schneider, David, 1998, Burying the problem (could pumping carbon dioxide into the ground forestall global warming?), Scientific American v. 278 (Jan. '98) p. 21.

Texas Water Development Board, 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board Report 157, v. 1, 113 p.

Thomas, W. A., 1988, The Black Warrior Basin, *in* Sloss, L. L., ed., Sedimentary cover—North American craton, U.S.: The Geology of North America, v. D-2, p. 471–492.

Usui, N., and Ikenouchi, M., 1997, The biological CO_2 fixation and utilization project by RITE(1), highly-effective photobioreactor system: Energy Conversion and Management, v. 38, supplement, p. S487–S492.

Uziemblo, Nancy, and Petersen, Harry, 1983, Diagenetic components within Woodbine Formation, East Texas (abs.): American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 562–563.

van der Meer, L. G. H., 1992, Investigations regarding the storage of carbon dioxide in aquifers in the Netherlands: Energy Conversion and Management, v. 33, no. 5-8, p. 611–618.

__________ 1993, The conditions limiting CO_2 storage in aquifers: Energy Conversion and Management, v. 34, no. 6-9, p. 959–966.

__________ 1995, The CO_2 storage efficiency of aquifers: Energy Conversion and Management, v. 36, no. 6-9, p. 513–518.

__________ 1996, Computer modeling of underground CO_2 storage: Energy Conversion and Management, v. 37, no. 6-8, p. 1155–1160.

Van Engelenburg, B. C. W., and Blok, K, 1993, Disposal of carbon dioxide in permeable underground layers: a feasible option? Climatic Change, v. 23, no. 1, p. 55–68.

Wagner, W. O., 1987, Reservoir study of Cretaceous Woodbine Fields in the northern East Texas Basin: Baylor University, Master's thesis, 139 p.

Warwick, P. D., SanFilipo, J. R., Crowley, S. S., Thomas, R. E., and Freid, John, 1997, Map showing outcrop of the coal-bearing units and land use in the Gulf Coast Region: U.S. Geological Survey Open File Report 97-172, http://www.energy:/er.usgs.gov/products

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.

Weiss, Emanuel, 1987, Ground-water flow in the Navajo Sandstone in parts of Emery, Grand, Carbon, Wayne, Garfield, and Kane Counties, southeast Utah: Water-Resources Investigations WRI 86-4012, U.S. Geological Survey, 41 p.

Winslow, A. G., Hillier, D. E., and Turcan, A. N., 1968, Saline groundwater in Louisiana: Geological Survey Hydrogeologic Investigations Atlas HA-310, 4 sheets.

Woodward, L. A., 1984, Tectonic map of the Rocky Mountain region of the United States, Sedimentary cover—North American craton, U.S.: The Geology of North America, plate 2.

Yokoyama, S., 1997, Potential land area for reforestation and carbon dioxide mitigation effect through biomass energy conversion: Energy Conversion and Management, v. 38, supplement, p. S569–S573.