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GCCC Digital Publication Series #07-01

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Keywords:
CO_2 Sinks- Carolinas, Source-Sink Matching, Matching Constraints, Subseafloor Sinks, Geologic Sinks Criteria, Geographic Information System (GIS)

Cited as:
Smyth, R. C., Hovorka, S. D., Meckel, T. A., Breton, C. L., Paine, J. G., and Hill, G. R., 2007, Potential sinks for geologic storage of CO_2 generated in the Carolinas: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for Southern States Energy Board and Electric Power Research Institute (http://www.beg.utexas.edu/environqlty/co2seq/pubs_presentations/CarolinasSummary_16April07.pdf), 14 p. GCCC Digital Publication Series #07-01.

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Prepared for
Southern States Energy Board, and
Electric Power Research Institute, on behalf of
Duke Energy
Progress Energy
Santee Cooper Power
South Carolina Electric and Gas

Gulf Coast Carbon Center
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March 2007

Summary Report

Preface from power company representatives:

A consortium of four power companies in the Carolinas (Duke Energy, Progress Energy, Santee Cooper Power, and South Carolina Electric and Gas) has funded this project in cooperation with the Electric Power Research Institute (EPRI) and the Southern States Energy Board (SSEB) to take an active role in finding solutions to climate change issues. This is our first step on the path toward understanding the opportunities and constraints of carbon storage. Our motivation is to seek information that will enable application of this technology.

This document summarizes a scoping study of the current state of knowledge of carbon storage options for our geographic area. The focus is on one aspect of carbon capture and storage—identification of deep saline aquifers in which carbon dioxide (CO_2) *generated in the Carolinas might be stored. The study does not address other aspects of* CO_2 *storage projects, such as capture and compression of the gas, well construction and development, or injection. Transport of* CO_2 *is touched upon in this study but has not been fully addressed.*

The information contained in this document is primarily from review of published geologic literature and unpublished data. No field data collection has been completed as part of this study. Further work will be necessary to increase confidence in the suitability of the potential CO_2 *storage sites identified in this report. This study does not address the regulatory, environmental, or public policy issues associated with carbon storage, which are under development at this time.*

Introduction

Options for reduction of atmospheric emissions of greenhouse gases (GHG) are currently under consideration by both government (Federal and State) and industry, and interest will continue to expand (e.g., Herzog, 2001; DOE, 2005; Hoffman, 2006). Carbon dioxide (CO_2) occurs naturally in the atmosphere, but over the past few centuries concentrations have increased as a result of emissions from anthropogenic sources. At this time CO_2 emissions are not regulated in the U.S.; however, discussions on reducing the intensity of GHG emissions are under way. Technologies to separate, capture, and concentrate CO_2 from industrial emissions are under development but are not yet ready for commercial use.

Geologic storage is a process whereby concentrated CO_2, captured from industrial sources, will be injected into suitable subsurface strata or geologic "sinks" and stored for significant periods of time (thousands of years) through physical or chemical trapping (Bachu et al., 1994). The combination of carbon capture and storage is known by the acronym CCS. According to a recently released report by researchers at Massachusetts Institute of Technology (MIT) (Deutch et al., 2007), "CCS is the critically enabling technology to help reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs."

The study summarized here updates and supersedes previous CO_2 source-sink matching analyses (Hovorka et al., 2000) used in Phase I of the Southeast Regional Carbon Sequestration Partnership (SECARB), which was funded by the Department of Energy (DOE) through the Southern States Energy Board (SSEB). Funding for this study is from Carolinas power companies Duke Energy, Progress Energy, Santee Cooper Power, and South Carolina Electric and Gas, in cooperation with the Electric Power Research Institute (EPRI) and SSEB. A goal of the study is to increase understanding of the technical feasibility of subsurface geologic storage of CO_2 in order that informed decisions may be made regarding GHG issues in the region.

The focus here is to identify geologic units containing deep saline reservoirs, or sinks, that might be suitable for effective, large-volume geologic storage of CO_2 generated by power plants in North and South Carolina. All data used to evaluate the suitability of the potential geologic sinks are from preexisting geologic studies, the majority from published literature. Geologic units underlying most of North and South Carolina do not meet minimum suitability criteria necessary for long-term storage of CO_2. Hence, in order to match potential sources of CO_2 with potential sinks, a process known as *source-sink matching*, CO_2 will have to be transported before it can be injected into the subsurface and isolated from the atmosphere and freshwater resources.

Evaluation of the constraints to transport of CO_2 generated in the Carolinas, including pipeline costs, has been conducted by the MIT Laboratory for Energy and the Environment. Its pipeline cost estimates include neither the cost of capture/separation at the plant nor cost of compression or injection at the CO_2 storage site, which are beyond the scope of this assessment. In recent work to evaluate costs of CCS, MIT researchers (Deutch et al., 2007) estimated that the cost of CO_2 capture and pressurization will greatly exceed the cost of CO_2 transportation and storage.

Background

Minimum suitability criteria for geologic sinks include (1) continuity and integrity of an overlying seal; (2) depth sufficient to maintain CO_2 at high density (which corresponds to depths greater than 800 m (>2,400 ft) below the surface); (3) depth below underground sources of drinking water (USDW), where total dissolved solids exceed 10,000 parts per million (ppm); and (4) storage capacity sufficient to prevent displacement of saline water into overlying freshwater-bearing units.

Estimates of the capacity of potential geologic sinks presented in this report have been provided by coworkers at Massachusetts Institute of Technology (MIT). The MIT methodology assumes that if requirements 1 and 2 above are satisfied, the CO_2 storage capacity of a saline reservoir can be calculated using the following formula:

$$Q_{aqui} = V_{aqui} * p * e * \rho_{CO_2} \qquad (1)$$

where Q_{aqui} = storage capacity of entire aquifer (Mt CO_2)
V_{aqui} = total volume of entire aquifer (km^3)
p = reservoir porosity (%)
e = CO_2 storage efficiency (%)
ρ_{CO_2} = CO_2 density at reservoir conditions (kg/m^3)

If accurate spatial data are available for an aquifer, then the aquifer volume used in equation 1 can be calculated as an integral of the surface area and thickness of the aquifer:

$$V_{aqui} = \sum_i S_i T_i \qquad (2)$$

where S_i is the area of the raster cell and T_i is the thickness of the cell

The term "CO_2 storage efficiency" refers to the fraction of the reservoir pore volume that can be filled with CO_2. For a saline reservoir in which CO_2 can be trapped by a physical barrier (overlying seal), the storage efficiency is estimated at 2% (Holloway, 1996).

Large areas of the southeastern U.S. either are unsuitable or have low potential for geologic storage of CO_2 (fig. 1). This suitability is related directly to geologic processes that have formed the present-day substrate of the southeastern U.S. over millions of years. A schematic cross section depicting the subsurface of the southeastern U.S. is shown in figure 2. Western portions of the Carolinas are underlain by highly fractured crystalline (igneous and metamorphic) rocks of the Blue Ridge and Piedmont physiographic provinces of the Appalachian Mountains (figs. 1, 2). Fractured crystalline rocks can serve as limited-capacity fluid reservoirs but are unsuitable for large-volume CO_2 storage if they lack laterally extensive overlying sedimentary seals. Rocks in the Blue Ridge and Piedmont provinces lack suitable seals throughout the Central and Southern Appalachian Mountains.

Exposed Mesozoic-age rift basins within the Piedmont province (fig. 1) might be considered for CO_2 storage on a site-specific basis. However, they do not meet the minimum suitability criteria used in this study. Rocks in the Valley and Ridge province have low potential for geologic storage because they are extensively folded and faulted. Limited capacity sinks are likely present in isolated areas beneath the Valley and Ridge province (fig. 1), but drilling and testing will be required to document storage integrity at specific locations.

Data compiled for this study show that much of the Coastal Plain province of the Carolinas is underlain by sedimentary sequences too thin for emplacement of CO_2 at sufficient pressure or at depths far enough below freshwater resources (figs. 1, 2). Sedimentary rocks within the area outlined in red in figure 1 are more than 800 m (<2,400 ft) thick, and they are underlain by Piedmont crystalline rocks (fig. 2). Because the coastal-plain sediments are saturated with relatively fresh groundwater, injection of CO_2 would not be possible under the criteria of this study.

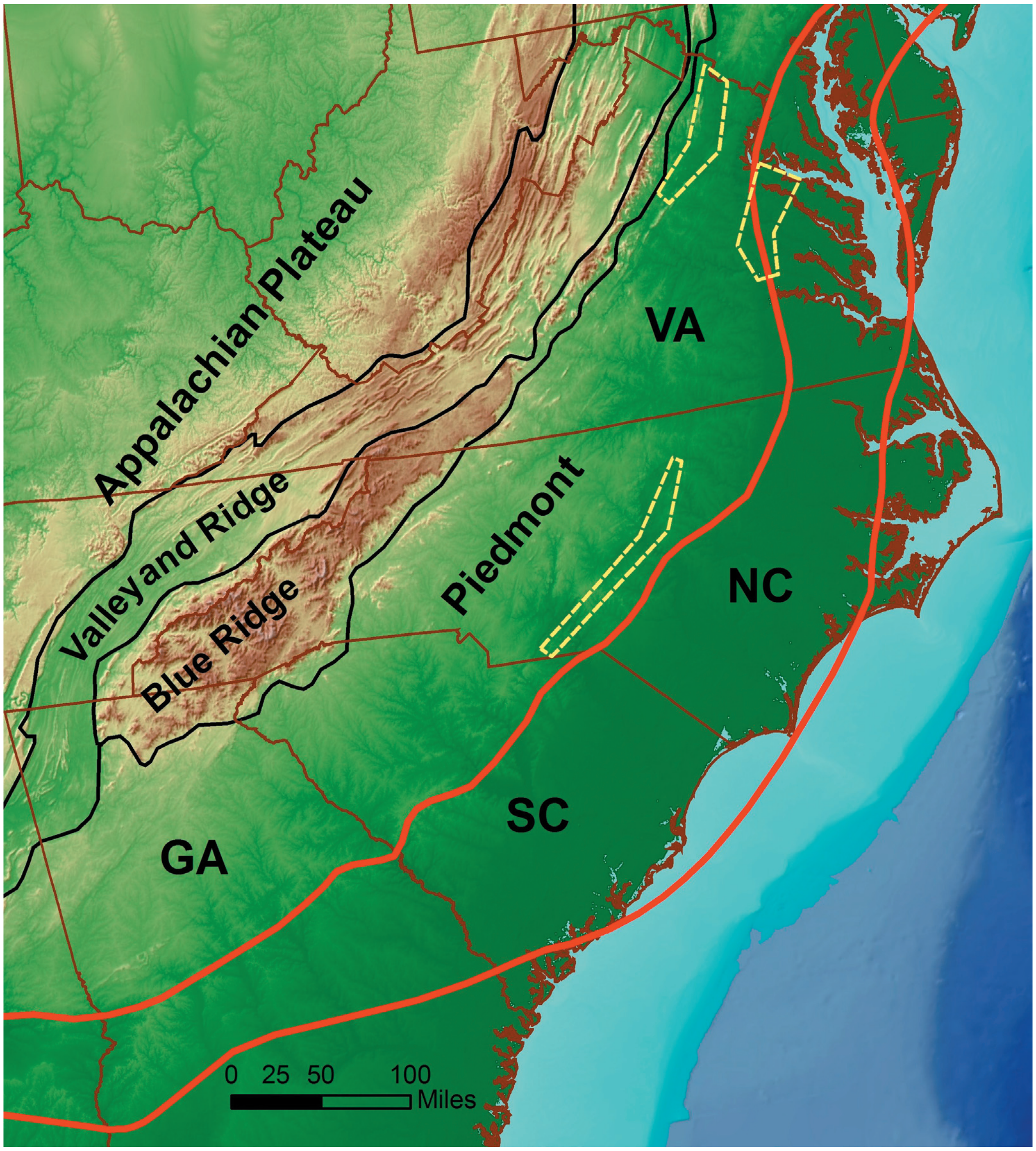

Figure 1. Physiographic provinces of the Appalachian Mountains and portions of the Coastal Plain where sediments are less than 800 m thick (outlined in red). Sources: Physiographic provinces of Appalachian Mountains modified from Fenneman and Johnson (1946); exposed Mesozoic rift basins (dashed yellow lines) modified from Olsen et al. (1991); and digital elevation models from NOAA (2006) (land) and Scripps (2006) (ocean floor). Depth to seafloor increases with darker shades of blue. Elevation of land surface increases from green to yellow to brown.

Potential Sinks

Prospective geologic sinks (i.e., those subsurface units that *do* meet minimum suitability criteria) underlie areas located in (1) isolated basins along Atlantic coastlines of North Carolina, South Carolina, and Georgia (Hatteras and South Georgia Basin [SGB] sinks); (2) offshore approximately 1 km below the Atlantic seafloor (Unit 90 and Unit 120 sinks); and (3) nearby states (Tuscaloosa, Mt. Simon, and Knox sinks) (fig. 3).

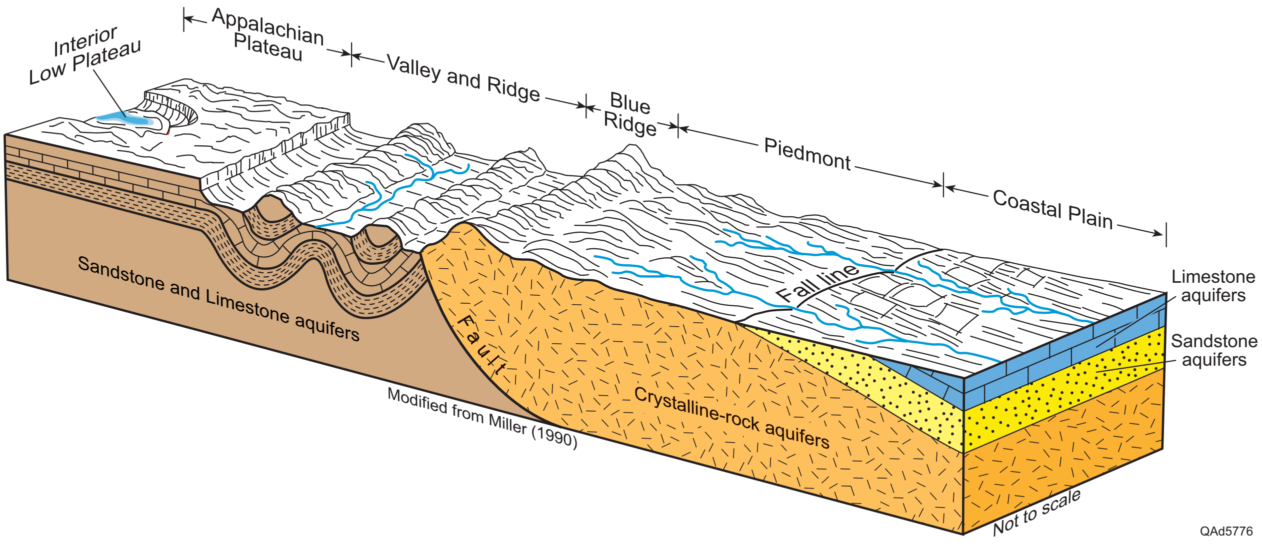

Figure 2. Schematic cross section from NW Alabama to south Georgia Coastal Plain. Source: Miller (1990).

Sinks with potential for long-term storage of CO_2 generated in the Carolinas are all deep saline reservoirs within host geologic strata. All sinks presented here have been chosen through study of existing and, in most cases, published data. Additional field-data collection and verification will be required to test the suitability of specific injection sites and refine the generalized capacity estimates presented herein. This initial assessment of geologic sinks with potential for long-term storage of CO_2 is unencumbered. That is, it is based solely on the suitability of subsurface units to store CO_2; it does not take into account environmental, economic, or socio/political issues that will need to be balanced with geologic suitability.

Potential sinks within the Carolinas are Hatteras and SGB (fig. 3). Sediments west of Cape Hatteras attain a thickness of 2.7 km (1.7 mi) (fig. 4), which is sufficient to contain potential CO_2 sinks. However, literature review to obtain hydraulic properties and other data needed to estimate capacity of specific stratigraphic units was not performed for this study.

The South Georgia Basin is the east end of a series of structural basins spanning from Alabama across south-central Georgia, southern South Carolina, and eastward onto the Atlantic continental shelf. Through previous work associated with SECARB, and what is reported herein, we have identified three potential sinks in the South Georgia Basin: (1) Late Cretaceous-age Cape Fear Formation from previous SECARB work, (2) Late Cretaceous-age Tuscaloosa/Atkinson units in Georgia, and (3) Triassic-age units that are buried beneath coastal-plain sediments and extend offshore from South Carolina and Georgia (fig. 5). These three potential sinks partly overlap in map view but span different depth horizons between 800 and 1,300 m (2,600 and 4,300 ft); they are represented as one geologic sink, SGB, in figure 3. The combined estimate of capacity for these three contiguous, vertically stacked sinks is approximately 15 gigatons (Gt).

Two potential CO_2 sinks are present in geologic strata below the Atlantic seafloor, offshore from Cape Hatteras, North Carolina,

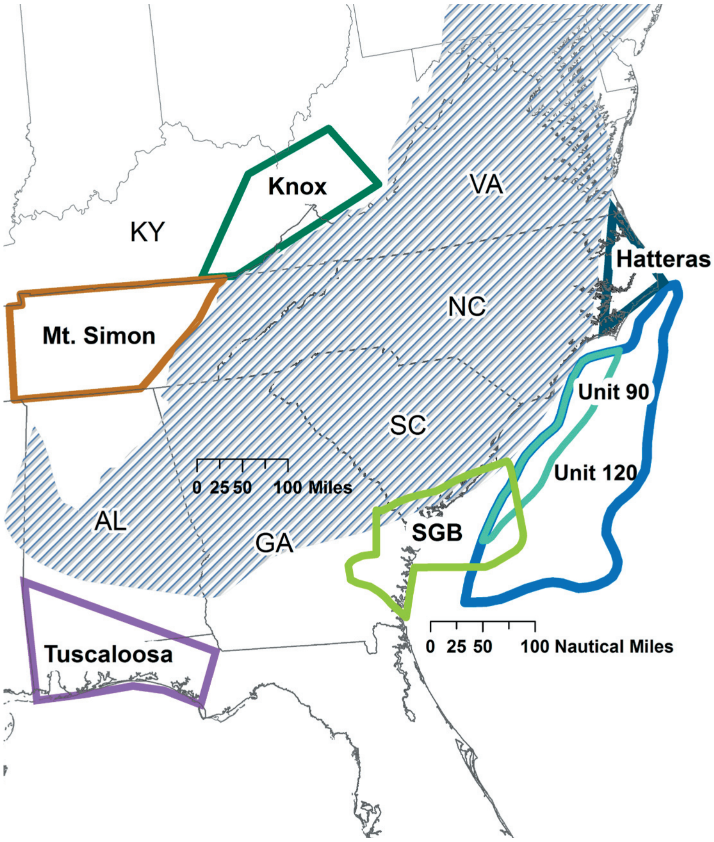

Figure 3. Location of low-potential regions (stippled area) and high-potential geologic sinks: SGB = Cretaceous- and Triassic-age geologic units in South Georgia Basin.

to Brunswick, Georgia (units 90 and 120 on fig. 3). Offshore settings involve initially higher pressures (beneath the water column) and lower temperatures at the seafloor, both of which favor denser CO_2 phases throughout subseafloor storage depths when compared with terrestrial settings. It is important to note that potential offshore activities involve injections at thousands of meters below the seafloor and should not be misinterpreted to include injection (dissolution) into circulating seawater.

The subseafloor sinks are located between 25 and 175 km offshore from the Carolinas in Upper (unit 90) and Lower (unit 120) Cretaceous strata between approximately 500 and 3,000 m (1,650 and 9,850 ft) beneath the seafloor in water depths between 50 and 1,000 m (165 and 3,280 ft) (figs. 3, 6). Both of these potential sinks are overlain by low-permeability seal layers, the shallowest of which lies between 200 m (660 ft) (landward) and 2,000 m (6,600 ft) seaward below the seafloor. Lack of extensive drilling in the Atlantic offshore from the Carolinas means that seal integrity should be excellent, but results in few available hydraulic property data. Using core data collected at other western Atlantic drill sites, we have estimated capacities of about 16 Gt for the shallower (unit 90) and up to 175 Gt for the deeper (unit 120) potential subseafloor sinks.

At present, the only subseafloor geologic storage site for CO_2 is operated by Statoil in the Norwegian North Sea. The sinks identified offshore from the Carolinas are not as well characterized as the North Sea example and would require investigation to determine suitability and to refine capacity estimates. Legal, regulatory, and policy implications of sub-seafloor geologic storage of CO_2 are unresolved at this time. However, in November 2006, a resolution was adopted by members

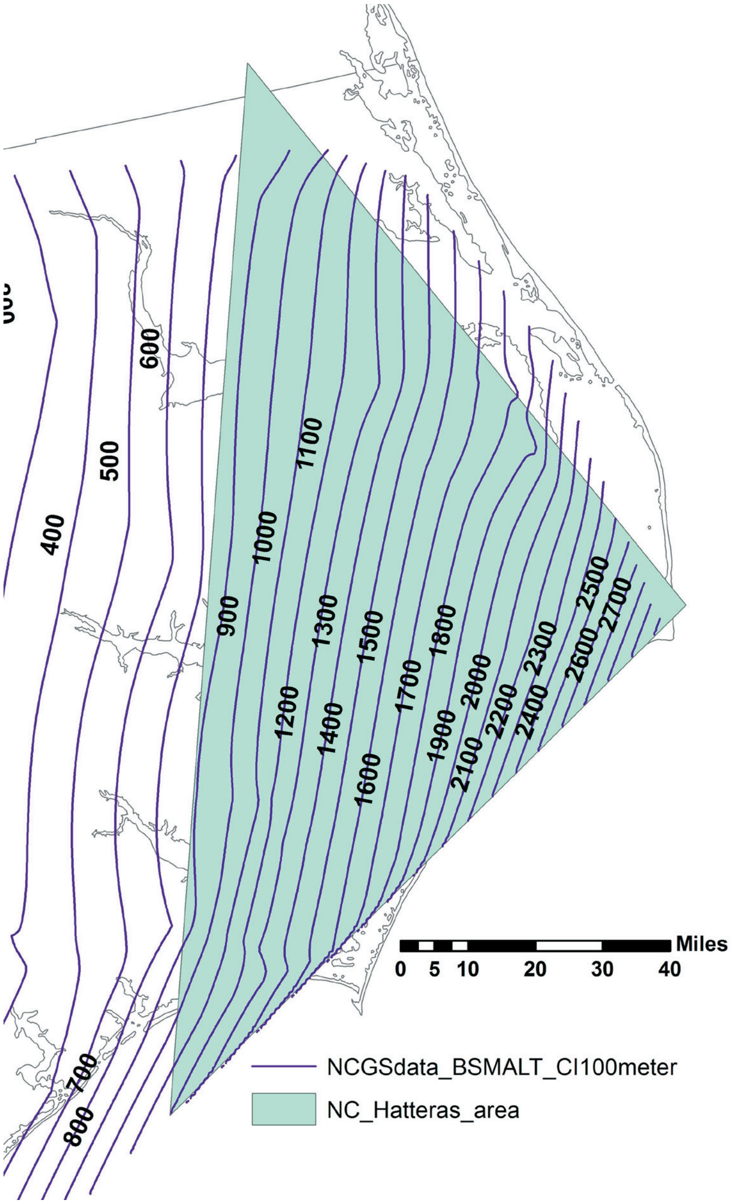

Figure 4. Depth (m) to crystalline basement rocks in the Hatteras area. Contours generated from North Carolina Geological Survey well data provided by Dr. Paul Thayer.

of the 1996 Protocol of the London Convention to “establish the legality of storing CO_2 in sub-seabed geologic formations.” Guidelines for scientific assessment of the potential for subseafloor CO_2 storage will be finalized and presented to the international community in November 2007 (IEA, 2006).

Because subsurface units underlying much of the Carolinas are unsuitable for long-term storage of CO_2, we looked outside the states for other potential geologic sinks. Two geologic units within the Appalachian Plateau province contain potential CO_2 sinks (1) the Mt. Simon Formation and (2) the Knox Group (fig. 3). Data for the Mt. Simon unit in Tennessee are from Advanced Resources International, Inc. Depth to base of Mt. Simon ranges from 1,200 to 2,400 m (4000 to 8,000 ft) (fig. 7), and thickness

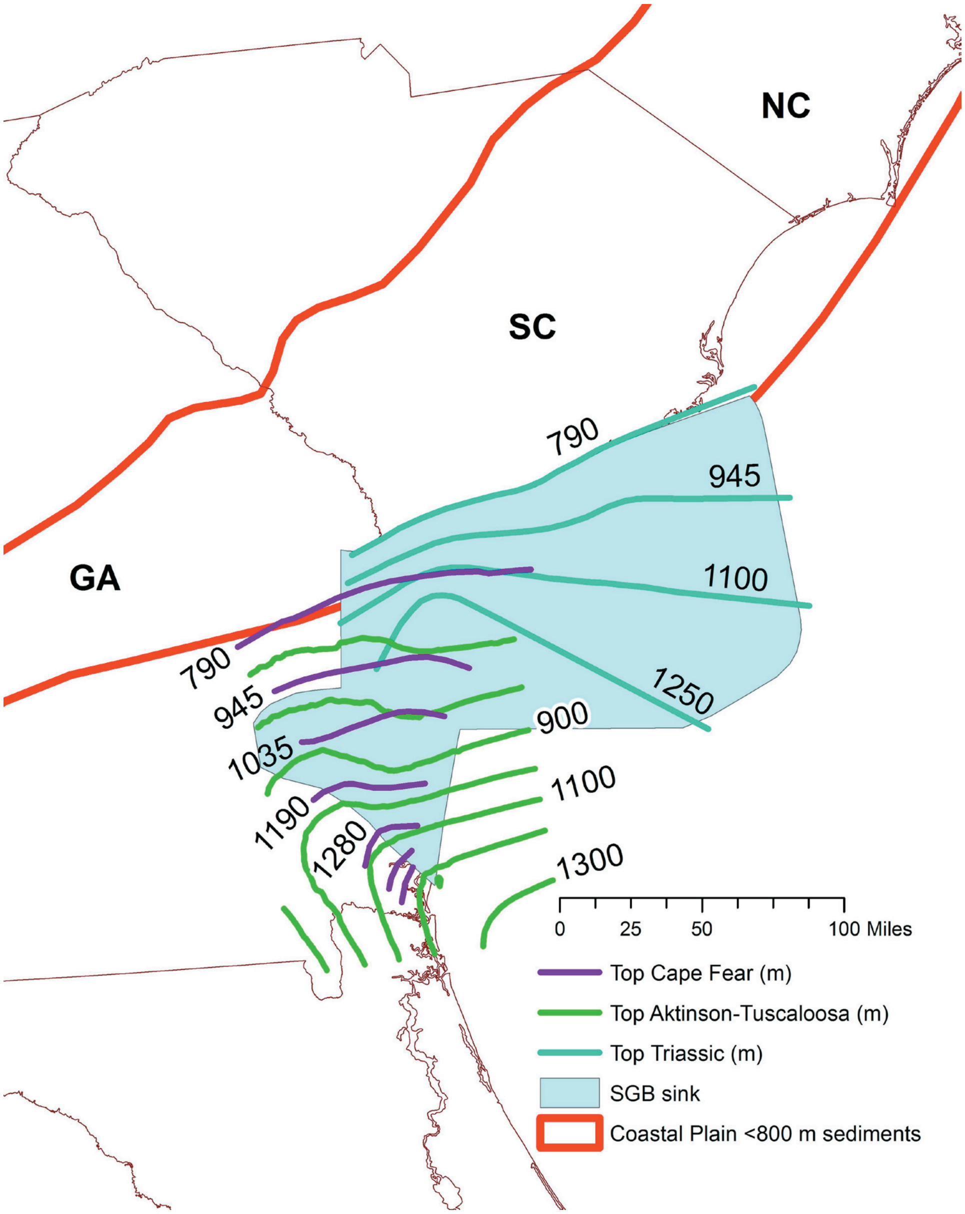

Figure 5. Contoured tops of three geologic units within the potential South Georgia Basin sink. Modified from Hovorka et al. (2000), Temples (pers. comm., 2006), Gohn et al. (1980), and Renkin et al. (1989).

throughout is approximately 30 m (~100 ft). Capacity of the Mt. Simon unit is estimated at 2.5 Gt. Additional storage in this unit may extend into adjacent states, but this possibility has not yet been assessed.

Hydrocarbons (primarily gas) have been produced from Knox Group rocks since the early 1960's, and the potential for future natural gas production from the Knox Group is great within eastern Kentucky and West Virginia (Baranoski et al., 1996). The Knox Group also has great potential for storage of greenhouse gasses. Depth below ground to the top of the Knox Group sink ranges from 800 m (2,600 ft) in eastern Kentucky to 2,600 m (8,500 ft) in southern West Virginia (fig. 8a). Thickness of strata in the Knox Group in this area ranges from 500 to 1,200 m (1,650 to 3,950 ft)

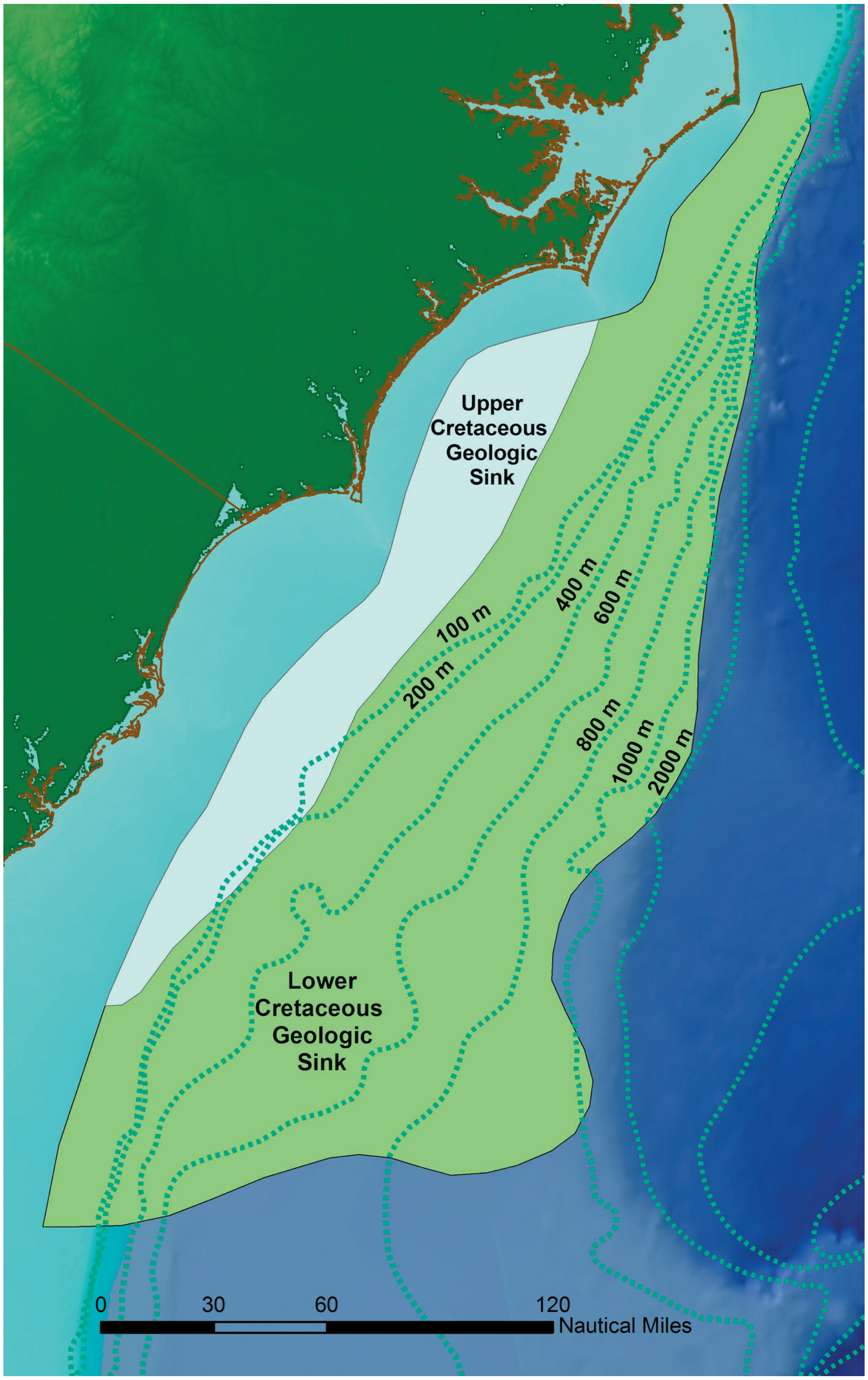

Figure 6. Seafloor footprint of Upper and Lower Cretaceous (modified from Hutchinson et al., 1996, 1997), subseafloor Atlantic sinks. Contoured water depth (m) shown in light-blue dashed lines (irregular contour interval).

(fig. 8b). Capacity of the Knox Group is estimated at about 30 Gt.

The Upper Cretaceous Tuscaloosa Formation in southwestern Alabama and the Florida panhandle is another out-of-state, potential CO_2 sink (fig. 3). Primary sources of information on the geometry, composition, and thickness of the Lower Tuscaloosa strata are geophysical logs of wells drilled for (1) oil and gas exploration and production, (2) disposal of co-produced saline water, and (3) industrial waste disposal. Depth to the top of the Tuscaloosa

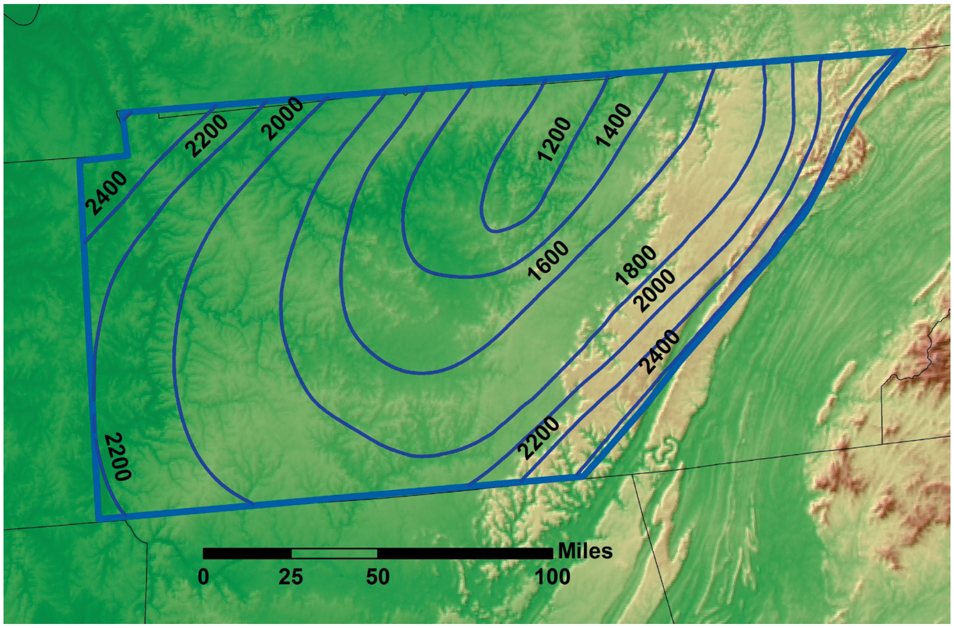

Figure 7. Base of Mt. Simon Formation in meters. Modified from Advanced Resources International data on the Mt. Simon Formation (Maria Fonkin, pers. comm., 2005).

sink ranges from about 1 to 3 km (0.6 to 2 mi); thickness ranges from 20 to 60 m (70 to 200 ft) (Miller, 1979, 1990; Mancini and others, 1987; Renkin and others, 1989), and unpublished information was provided by the Florida Geological Survey (pers. comm., 2006). A capacity of 9.8 Gt is estimated for this area. Additional assessment of the Tuscaloosa in Mississippi is now under way as part of SECARB studies.

Source-Sink Matching Constraints

Part of the source-sink matching process requires estimates of the cost of CO_2 transport to a specific potential geologic sink. For purposes of this discussion, we focused on the potential for transportation by pipeline. Estimates of pipeline costs for this study have been conducted by the MIT Laboratory for Energy and the Environment. Its pipeline cost estimates include pipeline construction, right-of-way acquisition, and operation. Neither the cost of capture/separation at the plant nor the cost of compression or injection at the CO_2 storage site are included. These elements are beyond the scope of this assessment, which is to match sources with sinks and provide a relative index of cost escalation as the distance between sources and sinks increases.

After identifying CO_2 sources in the Carolinas and using the potential geologic sinks identified by the Bureau of Economic Geology (BEG), MIT workers evaluated source-sink matching over an assumed 25-yr project lifetime. They used a Geographic Information System (GIS) method of matching sources and sinks that considers optimal pipeline route selection and capacity constraints of individual sinks. Because pipeline construction costs vary considerably according to local terrain, number of crossings (waterway, railway, highway), and the traversing of populated places, wetlands, and national or state parks, the group constructed a digital terrain map that allows ranking of these factors.

MIT generated pipeline-transport algorithms using the Carnegie Mellon University (CMU) correlation (McCoy, 2006). Because the MIT source sink matching program develops a minimum cost curve, it favors sinks that are closer to potential sources and automatically excludes more distant sinks. In order to obtain pipeline estimates for all potential sinks

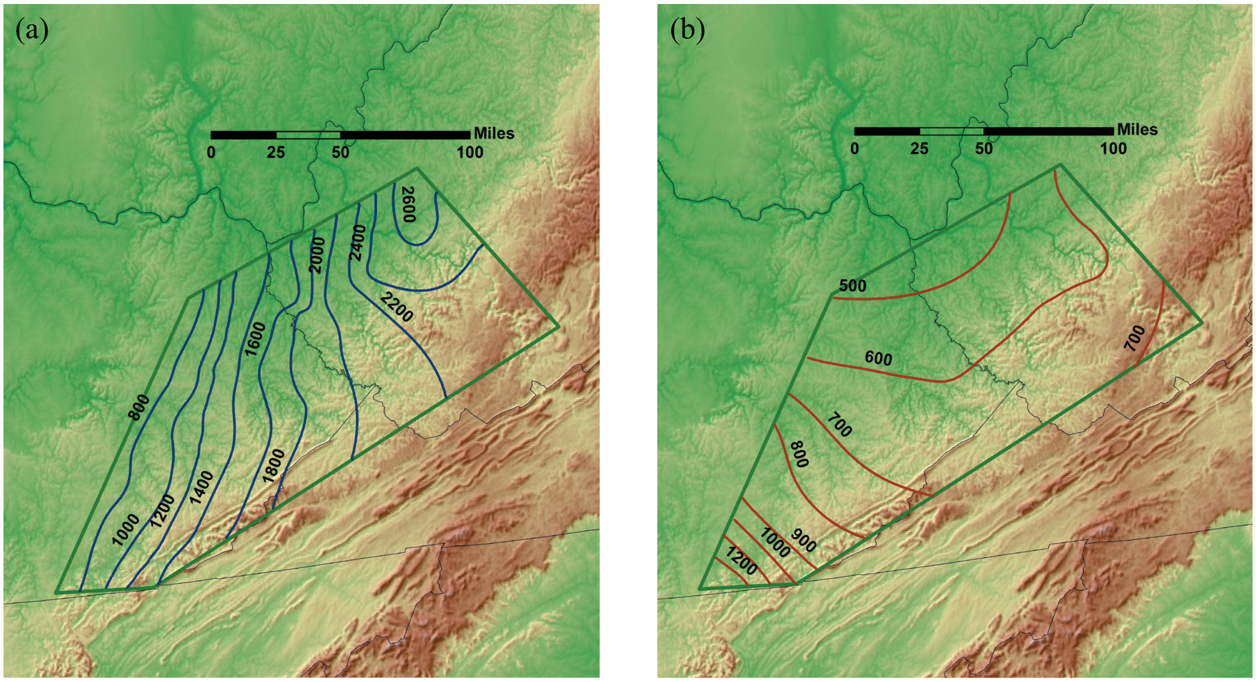

Figure 8. Potential Knox Group geologic sink; (a) structure contour on top of Knox (m) and (b) thickness of Knox (m). Modified from Baranoski et al. (1996) and Shumaker (1996).

presented in this study, MIT used a multiple scenario approach that alternatively excluded nearby sinks so as to force utilization of more distant sinks. Following are constraints for the five possible scenarios:

- Scenario 1 includes all potential sinks,
- Scenario 2 considers all sinks except the Hatteras area,
- Scenario 3 considers all sinks except the Hatteras area and subseafloor Unit 90 (Upper Cretaceous) in order to force pipeline estimates for subseafloor Unit 120 (Lower Cretaceous),
- Scenario 4 excludes the Hatteras area, subseafloor Unit 90 (Upper Cretaceous), and SGB to force pipeline estimates for Mt. Simon sink,
- Scenario 5 excludes the Hatteras area, subseafloor Unit 90 (Upper Cretaceous), SGB, and Mt. Simon to force pipeline estimates for Tuscaloosa sink in Alabama/Florida.

Summaries of estimated costs for pipelines between selected sources and potential target sinks are presented for each of the five scenarios (table 1). Total power output of the plants served ranges from 25.8 gigawatts (GW) for Scenario 1 to 24.5 GW for Scenario 5. Total pipeline construction costs range from $3.8 billion for Scenario 1 to $4.3 billion for Scenario 5. Average transportation costs vary from $3.56 to $4.21 per metric ton of CO_2.

Costs for Scenario 1 are lowest because only those potential sinks closest to the Carolinas power plants—Hatteras, Knox, Unit 90, and SGB—are utilized (table 1, fig. 3). The purpose of running MIT's GIS algorithms using scenarios 3, 4, and 5 was to obtain estimated costs for utilizing the more distant potential sinks—subseafloor unit 120, Mt. Simon, and Tuscaloosa—for geologic storage of CO_2.

Table 1. Estimated cost summary for five sink scenarios (for power plants with transportation cost <10$/t CO_2).

SINK OPTIONS	TOTAL CONSTRUCTION COST (BILLION $)	TOTAL CO_2 STORED IN 25 YEARS (GT[1])	TOTAL DESIGN CAPACITY (GW)	AVERAGE COST ($/TON CO_2)	AVERAGE DISTANCE[2] (km)	TARGET SINKS
Scenario 1	3.8	4.2	25.8	3.56	299	Hatteras, Knox, Unit 90, SGB
Scenario 2	3.8	4.1	25.3	3.63	322	Knox, Unit 90, SGB
Scenario 3	4.0	4.1	24.8	3.84	344	Knox, Unit 120, SGB
Scenario 4	4.2	4.0	24.5	4.17	370	Knox, Mt. Simon, Unit 120
Scenario 5	4.3	4.0	24.5	4.21	373	Knox, Unit 120, Tuscaloosa

[1] Gt = 1 billion metric tons

[2] Flow-rate-weighted-average pipeline distance

Discussion

Most of the power plants in the Carolinas are underlain by geologic units that are not suitable for long-term storage of large volumes of CO_2. The Blue Ridge and Piedmont physiographic provinces of the Appalachian Mountains in western portions of the Carolinas are underlain by crystalline rocks that lack sufficient overlying seals to (1) trap CO_2 in the subsurface or (2) keep it from interacting with fresh groundwater. Sediments of the Atlantic Coastal Plain are not thick enough to host CO_2 sinks and contain deep freshwater aquifers. An exception within the Carolinas is an isolated sedimentary basin encompassing the southernmost part of South Carolina that lies within the South Georgia Basin.

Subsurface storage of CO_2 generated in the Carolinas will probably require construction of pipelines to geologic sinks located some distance away from the power plants. The most likely potential geologic sinks for CO_2 generated in the Carolinas are located in (1) the South Georgia Basin (southernmost South Carolina, eastern Georgia, and extending offshore 50 to 75 mi (80 to 120 km), (2) the offshore in strata approximately 0.6 to 1.9 mi (~1 to 3 km) below the Atlantic seafloor, and (3) the Knox Formation in eastern Kentucky and southwestern West Virginia. The CO_2 storage potential for the offshore Atlantic margin is unexplored, but preliminary considerations suggest that CO_2 sequestration options are significant along the entire eastern seaboard.

Estimates of storage capacity of the potential geologic units are summarized in table 2. These estimates are based on limited and generalized data sets, which are primarily from published literature. More accurate estimates of capacity for geologic sinks will require site-specific, detailed geologic investigations. In addition, assessment of the potential geologic sinks is based solely on geologic suitability. Environmental, economic, and socio-political issues will need to be considered before determining which geologic sinks are most suitable for CO_2 storage.

Costs associated with CCS can be separated into two categories—(1) those associated with CO_2 capture and separation and (2) those associated with transportation and storage. Deutch et al. (2007) estimated that the cost of CO_2 capture and pressurization will greatly exceed the cost of CO_2 transportation and storage. The cost estimates presented in this summary report represent possible scenarios for pipeline transport of CO_2 from power plants in the Carolinas to potentially suitable geologic sinks. Pipeline construction costs are the primary cost factor in these scenarios, and they vary according to type of terrain that must be traversed. CO_2 transport costs are estimated in terms of \$/ton CO_2, which is the total cost divided by the CO_2 flow rate. Hence, transporting CO_2 at a higher flow rate results in lower transportation costs. Average transportation costs for the five different scenarios vary from \$3.56 to \$4.21 per metric ton of CO_2.

Table 2. MIT estimates of CO_2 storage capacity.

POTENTIAL SINK	**CAPACITY ESTIMATES[1] (Gt)**
SGB Triassic units Atkinson-Tuscaloosa Cape Fear	~15
Offshore Sinks	
Unit 120	~178[2]
Unit 90	~16[2]
Hatteras Area	n.a.[3]
Mt. Simon	~3
Knox	~32
Tuscaloosa	~10

Notes:

1. CO_2 storage efficiency estimated as 2 percent and all the aquifers are assumed closed.
2. CO_2 density in the offshore sites assumed to be 700 kg/m^3.
3. Detailed data are not available.

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